Combined Lesson Transcripts: ANU-ASTRO4x Cosmology

A4_L1_V01

BRIAN: Welcome everyone to our course on cosmology, where we're going to be looking at the issues that are literally the size of the universe, as big as you can imagine.

PAUL: We're going to start off with two fundamental observations or principles that actually determine most of our cosmological thinking. One is the principal of homogeneity or uniformity. And this is saying that, basically, the universe is the same everywhere.

The second, which we'll come to in the next video, is the principal of expanding universe, which comes from redshifts and distances. And for this video, we're going to talk about what's often called the extended Copernican principle, the principle that every bit of the universe is the same. Nowhere is special.

I guess this came out of history. In history, people always thought that wherever they lived was special. My village is the center of the universe.

And eventually, people got better at exploring, they realized that didn't make sense, but then their country was the center of the universe. And then the Earth was the center of the universe, and then the solar system was the center of universe. And time after time, we felt that where we are is special, and been proven wrong.

BRIAN: So you want to say that we're no place special, but you and I know we're both special. And you know, clearly, where we are here seems special to us, and it's not like an average place in the universe, as near as I can tell. Average place in the universe is going to be a lump of cold empty space.

PAUL: Yeah, so this principle that the universe is all the same seems pretty perverse, because we know it's not the case locally. And where this picture here, the density is 20 orders of magnitude more than it is 100 kilometers above this place. That's pretty not the same.

BRIAN: OK, so locally, clearly not the same. So let's go out a little bit and think a bit about this.

PAUL: So the idea isn't that everything's identical in small scales, but on big enough scales. The question is, how big? Maybe stars would be a good place. Look at the night sky, and you see stars in every direction. So maybe the universe is just full of stars, uniformly spread all over the place.

BRIAN: But already, it doesn't. Look, I see the Milky Way here, and if I look at that with a telescope, then I'll realize that there's a billion stars in a tiny little piece there. So it's clearly not--

PAUL: Yeah.

BRIAN: --uniform there. That's different than here.

PAUL: Yeah. So that's the first failure of uniformity. Stars are not spread through the universe. They're grouped in clusters called galaxies.

BRIAN: Right.

PAUL: About 10 to the 11 of them in typical galaxy, us in the outskirts of one. OK, so that's failure.

BRIAN: And we know that this galaxy, not our own, is separated, and there's not going to be anything really near it, and then there'll be another one, all on its own. So again--

PAUL: So maybe there's a uniform-ness, maybe, universe just full of galaxies spread all around the place.

BRIAN: Oh, so you think the galaxies will be uniformly distributed?

PAUL: Even though the stars are concentrated just in the galaxies, maybe the galaxies are spread around uniformly.

BRIAN: So let's look at a map of the nearby universe.

PAUL: Yeah, so you've got us in the middle, and we are in the local group, which is two big galaxies and a whole bunch of small ones. And there are other little groups around. But then we get a bit to the side, you start seeing a cluster, the Virgo cluster, which is an enormous number of galaxies.

So clearly, galaxies are not spread uniformly. They live in groups and clusters.

BRIAN: So we're sort of on the outside of this metropolis, sort of in the suburbs of the Virgo cluster.

PAUL: Yeah.

BRIAN: And so, we're in a special place in the universe. We're on the edge of a cluster. But then there are voids, right? Up here are these voids where there's almost nothing. So--

PAUL: Yeah. I mean, how about clusters? Are cluster spread uniformly? Well, no. Just clusters have lined up. Here's an even bigger image. There's the Virgo, and then we've got Centaurus, Hydra-Centaurus cluster and other clusters. So we get super clusters of clusters, and they're arranged in, like, strings or filaments.

BRIAN: A neighborhood of clusters string around, and once again, so we haven't really found homogeneity yet. OK.

PAUL: Yeah. So this is beginning to look like a failed plan before you even started. But if we just go to even bigger scale. So one of the biggest maps was the 2dF Galaxy Redshift Survey.

What they did was, we are here, and they did a wedge across the sky, and measured the distance to a whole bunch of galaxies, about 200,000 of them. And each blue dot here is a galaxy. What we see here.

BRIAN: So this almost kind of reminds me of the foam on a cappuccino. So yeah, I see little lumps and bubbles, but it's beginning to kind of look like when you look at a cappuccino for a long ways away. It just looks like white if you don't mix up the coffee. So it's sort of maybe a hint that it's beginning to look like that.

PAUL: Yeah. So in every previous scale, you found things and they've been clustered,

so stars are clustered

in galaxies.

BRIAN: Yeah.

PAUL: Galaxies in clusters, clusters in super clusters. But super clusters don't seem to be clustered in hyper clusters, or whatever you want to call them.

BRIAN: So we're at a scale of about one to one and a half billion light years now. So we're getting pretty big.

PAUL: Yeah. I mean, we see lumps that are maybe 100 million light years across, but then there's another one, and another one, another one. And they're not seemingly lined up. And we can actually to even bigger scale still.

Piggy backing off the same survey was a quasar survey. And quasars are so bright and so distant, that we can extend out to 10 billion light years. This is just a fly-through of that. You can see the pattern here.

BRIAN: All right. So it really is almost like a sponge, or a spider web, or something so--

PAUL: Yeah. But again, looking fairly uniform. It fades out at the end. That's because you can't see any further.

BRIAN: OK.

PAUL: But if we now look at quasars--

BRIAN: Ah. That's really looking boring. This is the stuff you work on, boring stuff like this, but I don't understand. That all looks pretty random, but then, why-- maybe we are special. We seem to be a place there aren't any quasars.

PAUL: Yeah, the quasars don't like us. So we're now looking at a distance out to 12, 13 billion light years, and it is pretty uniform in different directions across the sky, but we do seem to be in a local hole. The quasars are avoiding us. And there's also an edge out here.

Now, it could be that we are in a special place, and it just is-- this is the place that quasars hate. But more likely what we're looking at here is an effect of time. Because, bear in mind, if we see a quasar over there, we see it not as it is now, but as it was, in that case, about 6 billion years ago. Because it's taken the light 6 billions years to reach us.

So what this is actually telling us, we don't see any right at the edge here, because that's back where the Big Bang happened and there hadn't been time for them to form. And then there's a great era of quasars, and there's giant black holes eating the middle of galaxies and shining like crazy.

But more recently, the black holes are still there, but they've eaten everything near them. So by and large, they've--

BRIAN: Oh, so--

PAUL: --stopped shining.

BRIAN: --there's like this age of quasars, sort of analogous to the age of dinosaurs, and for whatever reason, they've faded out. And so, we are sort of at a special place in time, but not necessarily in space.

PAUL: But odds are, if we actually lived on that galaxy over there--

BRIAN: Yep.

PAUL: --we'd see the same thing. We'd see an apparent hole around us, because we're already seeing the things that were nearby recently-- and there are not many quasars around it, we'd see lots of quasars over here. So once again, it looks like special time, but one place in the universe probably is very much like another.

BRIAN: That's convenient.

PAUL: Yes. It turns out to be a really powerful constraint on the cosmological models. That the idea that, quite opposite of the old idea that we are the center of the world, except not only are we not in the center, but nowhere is in the center. Every place, we see pretty much the same thing, once you're on these scales of billions of light years.

Yes, there are clusters and things on, pathetically, the small scale, like 100 million light years. But when you get up to several hundred million light years, things really are uniform.

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PAUL: OK, now onto our second clue, the second fundamental principle of cosmology. This comes, like so much of astronomy, from the study of spectra.

BRIAN: Ah, a spectrum. So if we remember, a spectrum is what happens when you spread the colors of light out into the colors the rainbow and we assign each color a wavelength. Remembering blue light and ultraviolet has short wavelengths, and infrared-- so we're going to have green, yellow, orange, red, infrared, as you get in the longer and longer wavelengths. And that's the wavelength of light that you're going to measure.

And we measured it in angstroms, which is 10 to the minus 10 meters per angstrom. So they're very, very short wavelengths.

PAUL: Well, we've plotted the amount of energy at each wavelength, and so you can see, these wavelengths have a lot of energy, and for these wavelengths down there don't have very much energy coming out of that particular wavelength.

BRIAN: And so when you see a spectrum like this, it's actually a mixture of two things. Part of it is because we're looking at a galaxy, in this case, full of stars and the stars are hot. And hot things glow, just like if you really turn, for example, your stove top up really, really hot, it'll start glowing red. That's because it's hot.

But then there are these little narrow lines, absorption lines, and sometimes there's emission lines, and that's due to the atomic transitions of each element. They have these places of energy motion between the electrons, they're different levels, and those show up at places of color. And so for example, hydrogen has very specific lines, for example, at 6,563 angstroms as one of the big lines of hydrogen, H-alpha. But then things like sodium, magnesium, various molecules, calcium, all have different things.

PAUL: Yeah. So this is very familiar to any astronomer, and we would look at a spectrum like this and read off which elements are there. Now, that's all well and good. But the strange thing is-- this is a key observation-- is that when you look at a faraway galaxy, you see a different spectrum from a nearby one.

So here's a spectrum of a nearby galaxy. And now let's look at the far away one, and you can see the change.

BRIAN: OK, the red one is the distant one. OK.

PAUL: And it looks the same, but shifted-- red-shifted. Moved to a longer wavelength. What you find is that every dip, or peak, or bump in the spectrum, every emission or absorption line, has had its wavelength increased by a constant ratio. And that ratio is called the red shift and written for some unknown reason as Z rather than R, and it's given by the shift in wavelength divided by the wavelength you'd expect in a nearby galaxy or in a laboratory. So what's going on here?

BRIAN: Well, we know that waves get shifted by the Doppler shift. So we hear that in sound when a police car goes by you. The sound waves get shifted, and compressed, and stretched, and the pitch changes. Light's a wave, so that same effect's going to happen. So one can use the red shift to measure velocity.

So when we see a red shift, it's like the objects are moving away from us. And the first order, that velocity can be calculated as the ratio of the shift of light is equal to the ratio to the speed of light.

PAUL: Yes. There's an approximation valid for speeds much less than the speed of light, but the galaxies we are talking about are like that. So what it's telling you is, if the lines been shifted by a 1% longer wavelength, means whatever has produced them has been moving away from us at 1% of the speed of light. That's a red shift of 0.01.

BRIAN: And so a galaxy that's been shifted by this much though, that's a big shift. So that means it's moving, apparently, at a good fraction of the speed of light. Now we're going to see that maybe it's not actual motion, but it's sort of apparently moving.

PAUL: Yeah. Now it turns out that almost every galaxy is moving away from us. There are one or two very nearby galaxies that aren't, but almost every galaxy is moving away from us. And if you plot how fast they're moving away from us against distance, you get this plot. What we're plotting here is how fast they're moving away from us. You can see that's 10,000 kilometers per second, 30,000 kilometers per second.

BRIAN: That's like 10% of the speed of light, if it's a velocity.

PAUL: Yes.

BRIAN: And then we measure distance. And we can see there's a one-to-one correspondence. The further away you go, the faster the motion.

PAUL: And this is known as the Hubble law, and its parameterised as a velocity is proportional to a constant, Hubble's constant, which is about 70 kilometers per second per megaparsec, times the distance.

BRIAN: So 70 kilometers per second per megaparsec means if I'm a megaparsec away, I expect to be moving with a velocity of 70 kilometers per second.

PAUL: Away from us.

BRIAN: Yes. But away from us. Now everything is moving away from us. This is something that Edwin Hubble discovered in 1929.

Now if everything's moving away from us, Paul, that seems to violate the Copernican principle, e.g. we're no place special. It seems like we are a special place. We're this place that everything's going away from. We're a very unpopular place in the universe.

PAUL: Yeah. Let's say you're living on some distant galaxy a billion light years away. The universe, as we've just said, may look uniform--

BRIAN: Yeah.

PAUL: But they'd be able to tell, hey, everything's moving away from that point. That point must be the worst place in the universe or something, but anyway, special. But it turns out that, actually, that's not quite the case. I'm going to show you a little calculation here.

Now this is using vectors. If you're unfamiliar with vectors we'll put in a link for you. You can go and remind yourself about this a bit.

But this is the vector form of the Hubble law equation. What it's telling us, this is us. We're in the outskirts of this galaxy over here. We got two other galaxies I call galaxy A and galaxy B over here.

And what we've said is the velocity is equal to a constant times the distance. But these got a little arrow over the top, which means they're vectors, which means that the velocity is in the same direction as the distance, and proportional to it.

BRIAN: Right. So the vectors, remember, are how far and the direction, typically, is how we can think of them.

PAUL: Yeah. So this galaxy is relatively near, so it's got a relatively small velocity, and the velocity's in the same direction as the displacement vector.

BRIAN: Right.

PAUL: This one's further away, so it's got a bigger velocity, and once again, it's in the same direction. And that's simply writing down in mathematical form, everything's moving away from us. The further away they are, the faster they're moving.

BRIAN: And so what you've stated here is Hubble's law is saying the direction and the distance is the same. So that all makes sense to me. It just says that direction, we have one answer. That direction, we have another answer. So it's just like we just saw, with direction added, OK?

PAUL: Yeah. But where this vector thing comes in very useful is if you now ask, OK, let's say you've got aliens living on this galaxy here. What would they see?

Now if they look back at us, we would appear to moving away from them at equal but opposite speed. But how about this one over here? What would they see for this other galaxy over here?

BRIAN: OK.

PAUL: So the first thing they can ask is, what's the distance, the vector displacement, from galaxy A to galaxy B? So that's, what's the vector from there to there? And that's simply xb minus xa, the vector sum.

BRIAN: So that's vector arithmetic.

PAUL: You go minus xa plus xb, and that gets you from there to there.

BRIAN: So that would be that arrow. Yes. OK. So good.

PAUL: So that's how far away galaxy B looks from galaxy A. But then we look at the velocity. The velocity of galaxy B with respect to velocity A.

And once again, the same thing applies. You've got the change in relative velocity is equal to velocity B minus velocity A. So if you go back, it's got this velocity minus this velocity is going to tell how that thing appears to be moving from its point of view.

BRIAN: OK.

PAUL: So if you do that calculation, we know that the relative velocity is velocity B vector minus velocity A. But we also know, from the last slide that velocity B is H0xb, and velocity A is H0xa.

BRIAN: Ah.

PAUL: And so if we take the H0s outside, it's just H0 times xb minus xa, which we just said up here is delta x.

BRIAN: Ah, so it's the distance times the Hubble constant.

PAUL: Yes. So the aliens on galaxy A are seeing that the velocity of galaxy B, and relative to them, is just equal to the Hubble constant times the distance, relative to them. Just what we see on Earth.

BRIAN: So that means what we've just shown, using mathematics, and we've literally proved, is that if we see this Hubble law, everyone sees exactly the same Hubble law. They see the same thing to us and to this other galaxy. We all see the same thing.

PAUL: Yeah. So in fact, this is perfectly consistent with our homogeneous uniform universe, the Copernican principle. Because not only do we see galaxies uniformly, but wherever you are, you see everything moving away. So how can you work out where the real center is?

BRIAN: Ah. Well, I guess we're going to have to think about general relativity, this. But it strikes me that if we think of the universe, it literally seems to be, the further away, the faster the motion. So that means the universe is expanding.

So let's do a balloon analogy. So let's just think of the universe as being the surface of the balloon. I'm going to put little dots on it, and as I blow the balloon up, every dot, which is a galaxy, is moving away from every other dot. So the galaxies are expanding away from each other. And the further away you are, the faster the motion will be as I blow the balloon up.

So I sort of get Hubble's law. But where is the center? It's the center of the balloon.

And what was that? That was when I started blowing the balloon up. So the center would be like the moral equivalent to the Big Bang, when you started blowing the universe up.

PAUL: Yeah. Because we can't really tell where the center is, because you can never actually measure if you're moving, or you can measure something relative to something else.

BRIAN: Yeah.

PAUL: Another analogy would be like baking up bread. Let's say you'd had a sultana load and you bake it in the oven. And we'll have sultanas as galaxies, and the dough is transparent. As it gets bigger--

BRIAN: For people not from Australia, a sultana is a raisin. So it's raisin bread or sultana bread. Yes.

PAUL: OK. So anyway, small, black things inside your bread. It doesn't really matter what they are. And as the bread gets bigger and bigger, it carries them all apart. And so every sultana will think, hey, every other sultana's moving away from us. Unless they actually look outside the loaf into of oven, they can't really tell which one's moving.

BRIAN: Yes.

PAUL: It's like with your balloon. If they look outside their sheet of balloon, they can see where the center of the balloon is.

BRIAN: Yeah.

PAUL: But we're talking about a three-dimensional universe. We can't see outside it.

BRIAN: Hm.

PAUL: This here is my attempt to simulate this. So these tastefully colored spheres are galaxies, and they're all moving away from each other.

BRIAN: They're all moving away from us, and they're getting smaller, because they're getting further and further away. So we're literally embedded in this universe. And if we ask ourself, well, where's the common center, the common center is right at the beginning of when we started when we are all crammed into the same spot.

PAUL: So from where we're sitting here, looks like everything's moving away from us. But if we were actually on that dot, or any dot, they would see exactly the same thing. So they can't really tell.

So those are our two clues. We seem to have a universe that looks the same from any point of view.

BRIAN: Yeah.

PAUL: And it's one that's, everything's moving away from every point.

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PAUL: So those are the two fundamental principles behind modern cosmology. One is that every place in the universe is the same. Once you're on a big enough scale-- which means in practice more than about 100 megaparsecs or so. And the second principle is that everything is moving away from everything else. And the further apart two things are, the faster they're moving apart.

Now, this gives us a rather strange universe, Brian, a universe where everything is moving away. And no matter where you are, even 10 billion light years away, you'd see the same sort of thing. Galaxies out to as far as you can see, in endless procession-- all moving away from you.

BRIAN: Right. And we can think about the logical extension of that. You have this universe which is seemingly expanding. But that means in the past it was different than it is in the future. Things are closer together in the past.

And so that distance is related in some sense to time. The distance things are is dependent on time. So in some weird way, time and distance, or space, are sort of related to each other.

PAUL: And that sounds a lot like relativity. In particular, the whole nature of space and time relies on Einstein's theory of general relativity. We dealt with special relativity in the violent universe course. But now we're going to talk about general relativity, which is in some sense the most fundamental theory of space and time and gravity. Now Einstein came to this by pondering something that most people didn't think was an issue.

BRIAN: Right. So in 1907 he was thinking-- as Einstein obviously did a lot of-- and he was thinking about the two types of matter that existed within the physical theory of the time.

PAUL: Yes, so, if you remember your high school physics-- well, what is mass? Brian, how would you define mass?

BRIAN: Well, in my daily job I think of mass as being the thing that gravity affects. So I have the force of m, and an m, big G, and then a distance between the masses. And there's a force between that.

PAUL: that's one equation that uses mass. It's Newton's equation of gravity-- force equals GMm over r squared. And that's actually very similar to other force equations in physics-- for example, the force between electric charges. Once again, you're going to get 1 over r squared. And you get a constant that tells you how strongly a particular particle interacts with something. Which in the case of electromagnetism is its charge. And in the case of gravity, is its mass.

BRIAN: Yep.

PAUL:So that's sort of saying that mass is a gravitational charge. It tells you how strongly something pulls and is pulled by gravity. That's all well and good, but there's another quite different place where mass comes in.

BRIAN: OK, well, that is true. So for example, if I was going to measure the force, I'd also have to worry about ma-- F equals ma. That's Newton's other-- one of his other big hits. So that one, that a doesn't necessarily have to be gravity, it could be something also.

PAUL: Yeah, so I could imagine you're sitting by the harbor in Sydney, and you have an oil tanker. And you push it. You're applying a force, but it doesn't accelerate very much. But if you have a small speedboat and you push it, it'll move. So this is telling you how much something resists being pushed around. Some big bruiser doesn't like being pushed around very much. Some small wimpy thing gets pushed around very easily.

BRIAN: Yeah. So I can use this, for example, to figure out how I'm going to be accelerated by Earth's gravity. I take the force of gravity and the F equal ma, and I equate them. And I could say a is equal to this thing from Newton's law of gravity. And that's a very useful little way to figure out what gravity is going to do to me.

PAUL: Yeah, so normally most people just said, OK. We've got one equation with mass, another equation with mass. Learn them. Repeat them in the exam. End of story.

But where it took the genius of Einstein was to think, hold on a minute. You've got mass in F equals ma. And that's kind of like inertial mass. It's telling you how much inertia something has.

And you have gravitational mass, which is telling you how strongly things gravitate. Why do they have anything to do with each other?

BRIAN: Right. And so, not only do they seem to have something to do with each other, I think his big thought was, he thought they must always have something to do with each other. And they must always be equivalent. But that turns out to be kind of a complicated thing to think through, as Einstein found out.

PAUL: Yeah, I mean, for other forces-- like electromagnetism-- it's not the case. You could have something with a very strong charge and not much mass, or something with very large mass and not much charge. So if you have an electric field, things will all accelerate at different rates.

But if you have a gravitational field, the force is proportional to the mass, and the inertia is proportional to the mass. So it cancels out. Which is why at least in a vacuum, when there's no air resistance, everything falls at the same rate.

So that's telling us that these two things-- which really have quite different concepts. One's about resisting motion, and one's about a force-- that they're proportional to each other. They are the same thing. Why?

BRIAN: So I don't think we know why, even to this day. But it's certainly, if you think that logical consistency-- OK. Here on earth, makes things work. But what happens if you want to throw in getting close to the speed of light. And then we know we have all those relativistic effects. Well how do you make those things then always be the same?

PAUL: Yeah. So it's a real puzzle. And this is what Einstein's great thought was, why these two things-- which apparently have not much to do with each other-- why are they related?

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PAUL: So we've got this puzzle. Why should a force, gravity, have something to do with acceleration? Now acceleration is about change in speed, or change in motion. So clearly this is going to have something to do with the nature of space and time.

And this is difficult. Because we have a really strong common sense view of what space and time actually are. And it's very hard for us to get rid of our common sense point of view, and to think of it as just an arbitrary mathematical construct.

So to help us do this, let's play a little game here. Let's imagine, Brian, that I'm actually not a human. But I'm an artificial intelligence. I am a computer in a box. I have no eyes, no ears, and you're just typing messages to me. And I want to know what this strange thing called space is, that you humans keep talking about. How would you explain what space is to me, as an artificial intelligence?

BRIAN: OK, well. That's going to be a challenge. So I think we think of space as being a place that things happen. I think that's sort of--

PAUL: What is a place? What is a place?

BRIAN: A place? Ah. What is a place? Ah, a place has size and distance from us.

PAUL: And what is this size and distance you're talking about?

BRIAN: Ah, so size and distance. So I measure size and distance by how far light travels in a certain moment of time?

PAUL: What is this "far" you're talking about?

BRIAN: Hmm.

PAUL: The whole trouble is that it's very circular. We tend to use-- space is where things are from different places. But what is a place? It's all very circular reasoning. I mean, can we think of any way that we can explain that doesn't involve a sort of circular reason, in terms of other words, that also imply that we know what space is? It's a hard one.

BRIAN: Well, I think you end up having to just write down a few axioms, as we do in mathematics. And then we can use the language of mathematics, maybe, to describe what space is.

PAUL: Well, let's imagine-- another thought experiment-- that space doesn't actually exist. We don't actually exist. We are just a simulation in God's supercomputer, down in God's basement somewhere, like the movie The Matrix.

So let's imagine that God has a very big supercomputer. And it has one memory register for every item in the universe.

BRIAN: OK. That's a lot of memory registers.

PAUL: Yes. God makes pretty good computers.

BRIAN: OK. Good.

PAUL: And each memory register records particle and three numbers, x, y, and z-- the coordinates in three-dimensional space.

BRIAN: Mm hmm.

PAUL: So for example, the first particle in the register-- there's no actual particle. It's just a set of numbers.

BRIAN: Yep.

PAUL: Might be this item on the tip of my nose over here. That's got coordinates let's define that as 0, 0, 0.

BRIAN: Yep.

PAUL: And you go down the next item in the register might be say, it's a neutron star in Alpha Centauri, or other end of the universe somewhere. And then the third particle might be even further away. And the fourth one might be one of the ones in your hair.

BRIAN: Yep. So we're going to put them in different memory registers, and so presumably when I get to the one that's right next to that first one-- 0, 0, 0-- I'm going to put the atom right next to it. It's going to have a number pretty close to 0, 0, 0. It'll be like 27, 32, 45.

PAUL: Yes. So what it means is, let's say my nose exploded for some reason. The radioactive element in it decayed.

BRIAN: Yep.

PAUL: Which other atoms would affected? One which is a coordinate of 4 million probably won't be affected. But one with a coordinate of 0.01 might. So what you could imagine is, you have all these different memory registers.

And then we do a time step. And we see, well that one exploded. And then we would go all the way through the register and see-- it might take God months to do this. And find out every other one which as similar coordinates.

So there'll have to be some magical-- two sets of numbers. Let's say 1, 1, 1, and 1, 1, 3. Are they close? Or are they far apart? There has to be some way of comparing these two sets of numbers to work out proximity, and therefore see if an event that hits one of them hits another one.

BRIAN: So you could literally calculate the distance between those three registers.

PAUL: Yes. So what you need is three numbers, which defines the three dimensions. And you need some way, given two sets of three numbers-- to work out whether they're close or far apart-- some measure of how things affect each other?

BRIAN: OK. So that sounds like a way of mathematically, essentially, describing space-- the set of numbers. And we could think of it as in memory. I could imagine how that might work. And of course, we had that concept of time, as well-- we're going to have to eventually deal with as well.

PAUL: Yes. So it could be that is our universe. There actually is no space. It's just a register on a computer. How could we even tell? I think I see you. But that's because photons at one coordinate have photons at another coordinate, and then interact with that memory register. The neurons in my brain fire in some sequence. But they could be in quite different parts of this supercomputer. They just have similar numbers.

BRIAN: OK. So you're saying we could be inside the Matrix.

PAUL: Indeed.

BRIAN: OK. Well, good enough for me. It's got me fooled.

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BRIAN: All right, Paul. So I'm not sure if you've illuminated us on what space is, but as near as I can understand, the idea is that space is described by numbers. Every part of space has got a number, and we can use those numbers--

PAUL: Three numbers.

BRIAN: Well, three numbers, sorry. Yes, three numbers. And that those numbers can be used to describe, essentially, how far things are apart by using mathematics. And we care about that because physical laws, like gravity and things, depend on that distance in number space. And so that's sort of an abstract way of describing space in numbers.

PAUL: So the crucial thing here is the concept of what we call the metric, which is, if you've got two things with their sets of three numbers, to work out how close they are. So let's say I've got X-Y-Z coordinates of two things on Earth. How will you work out how far apart they are?

BRIAN: Well, that's easy, because that's just what the Greeks told us. Pythagorean theorem.

PAUL: Yep.

BRIAN: Whoops.

PAUL: Here it is. So we're talking about small distances. So a delta means a small difference in x, a small difference in y, a small difference in z. If you had to go a big distance, you just add up all these small differences as you go.

And so this is just Pythagoras' theorem, that the distance is equal to the square root of the difference in x-coordinates squared, the difference in y-coordinates squared, the difference in z-coordinates squared. That's just Pythagoras' theorem.

BRIAN: If you have a three-dimensional triangle, that's X-Y-Z, that's how long the hypotenuse is. And we're going to make sure that our distances are really small here, so we can treat everything as a straight line.

PAUL: Yeah, so if you have god's supercomputer and we have lots of things with different sets of numbers, we can use this to work out if they're going to be close. And therefore, if one explodes, which things are going to be affected, for example.

BRIAN: OK. No worries. This is easy.

PAUL: Yeah. So we can simulate the universe this way. But now, let's go back to Einstein's problem, acceleration and mass.

BRIAN: Yes?

PAUL: How can we make acceleration and a force relate to each other? Maybe we need to muck-up something. When we talked about Einstein's theory of special relativity in the

Violent Universe course, we came up with idea of transforms. How you convert from one frame of reference to another, and we did horrible things to it, and that was the basis there.

So Einstein was going to be up to it again. What if we start tinkering with this?

BRIAN: Ah.

PAUL: Could that help us? Could tinkering with this--

BRIAN: Sounds to me like it's going to hurt us if we mess around with Pythagoras' theorem.

PAUL: Well, there was some mathematics from the previous century that had played with this purely in an abstract way, and Einstein managed to dig this stuff up.

BRIAN: Yep.

PAUL: And he thought, well, maybe if we muck around with this, it will give us something that can behave like a force.

BRIAN: OK. So give me an example.

PAUL: OK. So let's say we take the equation we had before, square it, but now, we're going to change it a little bit. Since we have the normal thing normally.

BRIAN: Yep.

PAUL: But let's say that delta x crosses an integer boundary. So delta x is going from 1.3 to 1.4-- just use this-- but then it goes over an integer boundary. So let's say 1.95 to 2.05-- that's across an integer boundary-- and let's use that instead. So we're going to take the modulus. So this is a positive value, that, take off 1 and square it.

BRIAN: Oh. OK.

PAUL: So what's that going to do to our universe?

BRIAN: I think it's going to make us jump around a fair bit when you get to these little edges. Let's think.

PAUL: Yeah. So here we have coordinates, X, Y, and Z, and these are the integer boundaries.

BRIAN: OK

PAUL: So let's imagine we have two things here. What's going to happen there?

BRIAN: OK. So we have two things here, and let's say one's moving a little bit that way, and we're going to move a little bit that way. Well, you move by dx and dx, and so that distance is going to be perfectly normal. It's going to be just what you had expected. So not on the boundary. And so my metric tells me that the distance I move is just the distance I should move.

PAUL: Yeah. So a particle there and a particle there, in god's supercomputer, according to this metric, are going to be close to each other, and so they're going to affect each other. So it could be, for example, two atoms adjacent on my ear.

BRIAN: OK.

PAUL: And so if one of them goes for a walk, so does the other one, because they're bound together.

BRIAN: OK.

PAUL: OK. But now, let's say, an imaginary two particles, one there and one there.

BRIAN: And we're going to be right on side, just one side of 3 or 4. 4 in this case. So just one, like 3.9999 and 4.0001. And in this case, if we try to cross that boundary, we jump, right?

PAUL: Yeah. So if we go back to here, we see delta x is very small, minus 1 square. This is going to be about 1 squared, about 1, so not very small. It's got pretty big.

BRIAN: So now, a long ways apart. And so I'm going to go think, at some level, you would normally think they'd be right next to each other. But in this case, their saying, they're a long ways apart. It's like this one's almost like being over there.

PAUL: Yeah. So it means if that one explodes, well, it won't affect that one, because they're not next to each other. They got coordinates that are similar, but the metric is changed. They're not going to affect each other.

BRIAN: But interestingly enough, they do affect something else a long ways away.

PAUL: Yeah, so let's imagine we take these two. What's going to happen now?

BRIAN: All right. So in this case, these things are an integer apart. So if I do boom here, the explosion is going to map, not here, but over there.

PAUL: Yeah. So this one's at, say, 1.99 and this is 3.01, so they're crossing an integer boundary.

BRIAN: Yep.

PAUL: And so we'd have to use this one. So the difference is like 1.01 minus 1, small numbers. Squared makes it even smaller. So it means, go back a bit, these two actually are close to each other and are going to affect each other.

BRIAN: Right.

PAUL: So what is this giving us?

BRIAN: Well, it's going to give us kind of a checkered universe, I think, where you literally have these boundaries where suddenly everything changes, your universe changes, and you affect things differently. So?

PAUL: Yeah, so it could look something like this.

BRIAN: Oh, OK. So yes. So this is, ah, yes. It looks to me like a place far, far away, long, long time ago. And so you literally got to go through, and here, you affect and you map on to here. And this is lost, except for it maps onto here and it maps onto there. So everything maps on to things that are sort of away from itself, but just a bit.

PAUL: So we could actually live in a universe with a metric like this. We wouldn't know.

BRIAN: Well, unless you cross the boundary, and--

PAUL: You can't cross the boundary, because if you go here, you're moving that way. You're going to the place which is a small metric away, which means you'll jump to there.

BRIAN: OK. So we wouldn't know. It'd just look like it's next door to us.

PAUL: So this could be our universe.

BRIAN: OK.

PAUL: Well, that's actually a rather trivial case, because we wouldn't be able to tell the difference in that one. But let's imagine something a bit more seriously weird. Instead of measuring our coordinates in X, Y, and Z, so-called Cartesian coordinates, we can measure them in cylindrical polars. We can measure them anyway we like.

Cylindrical polar coordinates, instead of measuring X, Y, and Z, you measure r, out, angle, and height.

BRIAN: And then you can get to any place you want with that coordinate?

PAUL: Yes.

BRIAN: Good.

PAUL: Just like a gun sight. So you're up and down, round and round.

BRIAN: Yeah.

PAUL: And so we've got r, theta and z. Now, in this case, the metric, if you move the r by a bit, the distance moves by that same amount. So the s square is just the r squared.

BRIAN: Yep.

PAUL: Likewise, z. You go up a bit, the distance is also going by that.

BRIAN: Yep.

PAUL: But theta's a bit different, because when you're very close to the center, an angle change doesn't move you very much. So you got a very small arm, you change the angle, it doesn't move very much. But a very long arm, you change the angle, it moves rather more. So you need an r square d theta squared for that.

BRIAN: So that's just the small angle approximation, where the arc is r theta, and that's how much you move. And of course, you got to square it here for Pythagorean's theorem.

PAUL: Yeah. The same thing we used back in the first course in the series to work out the size of things out in space. So this is our universe, common sense. But let's imagine we get rid of that r squared.

BRIAN: OK.

PAUL: So we've now got this. What's going to happen in this universe?

BRIAN: OK.

PAUL: So we can look here. We've got angle theta again. Now what's going to happen is, let's say you move from there to there. It's going to be a given change in angle.

BRIAN: Yep.

PAUL: And moving from there to there is the same given change in angle.

BRIAN: All right.

PAUL: Suppose they're actually the same ds, the same distance, according to this metric.

BRIAN: All right. So that sounds to me like it's going to change the way you move around in a universe that had this law associated with it.

PAUL: Yeah. So let's imagine there's kind of light wave coming like this. And if you remember, we talked about in the second course, Huygens' principle, which says that the light wave, both sides of it are going to move the same distance.

BRIAN: Right.

PAUL: So this particular ds would get to there, and that one would move the same ds, which would get it round to here.

BRIAN: All right.

PAUL: And from there, then move like this. So what's going to happen is, you get waves spreading out from each point on the waveform, and where they all add up in phase, it's going to move.

BRIAN: Yes?

PAUL: And that'll be the same ds which is going to be moving at a constant angle around. So that means the light wave, instead of having a straight line, would go in a circle.

BRIAN: Mm.

PAUL: Just go round and round. And the same thing would apply to matter, because matter is quantum mechanical waves.

BRIAN: Right.

PAUL: So if you try to walk in a straight line, you'd go in a circle.

BRIAN: OK, so it is possible that the distance that you would travel, you'd think as being a straight line actually ends up being curved if you have that type of metric.

PAUL: And this is beginning to sound like what we need to make Einstein's idea come true. What we need is something that could accelerate things that doesn't involve a force.

BRIAN: Hm.

PAUL: And this is getting things to go in a circle, which means acceleration, but there's no force involved. It's just changing the metric. So it's beginning to look like this might be helpful to us.

BRIAN: It's a very tricky solution, but yeah, I could see how it might work.

PAUL: There are other analogies to this which may help. At this point, normally, most people's brains are dribbling out of their ears.

BRIAN: Yes.

PAUL: So let's try and make it even worse. We'll have another analogy. One analogy is a hot plate. Let's say you've got a bug and you've got a two-dimensional universe, which is a hot plate. And let's imagine some parts of this hot plate are hot, and when the bug goes over them, it gets bigger. It expands. It's a metal bug, and so it gets larger when it gets over it.

BRIAN: OK.

PAUL: So that's a bit like changing the metric. That means the distances, ds's, are bigger here than over there.

BRIAN: Yep.

PAUL: Now the bug's just been through a cold area. It's got both legs, and they both advance the same amount like tank tracks or something, and it will go in a straight line.

BRIAN: OK.

PAUL: But now if we move it over there, then it comes over to here. It's right-hand legs have expanded because they're in this region with a different metric, a hot plate. Whereas, the left ones are still cold, and so it's going to turn. Mm. So once again, we get acceleration without force. We're just changing the metric and making things apparently accelerate.

BRIAN: Yeah.

PAUL: Another way to see it is to imagine two-dimensional creatures embedded in the three-dimensional universe. So let's imagine you're a bug that lives in a two-dimensional space. We can imagine curving that space in the third dimension. So let's imagine, for example, we had a light ray coming along here in this curved space. Two light rays like this, you'd think can just go in a straight line, but this one's actually going to go further, because it's got to dip down.

BRIAN: Oh, so it's going to rurp, like that, while this one's going straight.

PAUL: So they won't add-up in phase here, because that one's had to go further. They'll only add-up in phase if they curve around, so they've gone the same distance.

BRIAN: Right.

PAUL: So the one inside, it's gone down and up. The outer one's gone a the same distance because it's gone further around the outside of a circle. So once again, light rays are a particle, will move in a curve in a situation like this.

BRIAN: Hm, OK.

PAUL: So we seem to be getting acceleration without force. If we muck-up the metric, it makes things behave rather weirdly.

A4_L1_V06

BRIAN: So we've seen that we can describe how you move around in space by something we call a metric. And then if we mess this metric up, you can get really crazy things happening. You can have discontinuous space.

Or you might actually have curved space. So Paul, what does this have to do with Einstein's original thought of mass, and acceleration, and gravity, all being mixed into one?

PAUL: Well here's the basic idea. The idea is that the metric is actually set by mass. So if you know where all the masses are in some part of the universe, you can use Einstein's equations to calculate the metric. And it will be curved. And this is actually the explanation for gravity.

Gravity is not a force. It's just a curve of the metric. So for example, we've seen by messing up the metric, you can get things to move in circles. And that's exactly the explanation that Einstein came up with orbit. For normal Newtonian physics, we think of something going in an orbit as there's a force towards the middle making it go in a circle.

But what Einstein said is, it's not like that. What's happened is the mass is not producing a force. The mass is changing space-time around it. So the natural path-- what we call the geodesic-- the natural path of something, instead of being a straight line, is a curve.

BRIAN: So if something's going in a curve-- a rocket ship, for example, goes in an orbit around Earth. It's curved. But what about light? Light travels in straight lines, I think, going around the Earth.

PAUL: Well, we've glossed over time in this. The real metric involves time as well as space. And it turns out that the curvature of the path of a spacecraft-- it looks like it's pretty strongly curved. And of light-- which is only very gently curved-- a bit of gravitational lensing, so it's not perfectly a straight line. But in fact in space-time, the curvature of the two are the same. But we'll gloss over that for the purposes of this lecture.

BRIAN: OK. So this is the heart of what makes Einstein's theory of general relativity work, this curvature. But what does it have to do with cosmology?

PAUL: Well, let's explain how it fixes the problem of the two masses. So let's say we have this ball. And in Newtonian physics if I let go, it drops. And we would explain that by, there's a strange force coming up from the Earth.

According to Einstein, once again, there's no force. All that's happening is the ball is following its geodesic. And it's geodesic is to accelerate towards the center of the Earth at 9.8 meters per second squared. And that's simply because the space-time in this room is curved a little bit.

BRIAN: OK. So the ball is falling. When you drop it, it follows its geodesic. But you and I-- we're sitting in chairs. We're not moving anywhere. What's going on there?

PAUL: Well of course, what's happening here is that my geodesic and your geodesic is indeed to fall towards the middle of the Earth. That would be our natural state. But there's a force that's holding us up. And that case it's a force due to the springs or the foam in these chairs. That foam is compressed and pushing us up.

So the only real force-- there is no gravity force. The only real force is the force from the chair. And that's a force you can measure. You can actually see how much the chairs are compressed, and the squashing of whatever you're sitting on. So that's a very real force.

So this explains why acceleration and gravity are the same thing. That in fact, there is no such thing as gravity. It's always acceleration. When we think of gravity, for example making something go in orbit, or pushing us down in the chair, it's not. These things are just following their geodesic.

There's no force involved. When you depart from your geodesic, like us, there is a real force. But that's a force we can actually measure. It's the force of the foam in our chair.

BRIAN: So it's kind of analogous to centrifugal force, which is this force that sort of is not really there, but we often like to describe it when we look at circular motion.

PAUL: Yes, centrifugal force is what we call a fictitious force. When you're driving down the road, and the car suddenly goes to the side, you feel like you're flung to the opposite side quite strongly. It feels like a real force. But in fact, what's happening is you just want to keep going in the uniform motion of a straight line. And the real force is the side of the chair pushing sideways, your seat belt pushing you sideways.

It's the same here. We think that gravity is a force pulling things downwards. But in fact, the natural motion is to go downwards. And the actual force is what happens when you hit the bottom.

And this explains why mass-- that's inertia resisting acceleration-- that gravitational mass are one and the same thing.

BRIAN: Right. And so we're going to find out next time how this affects the whole idea of the universe and everything, through how gravity interacts with cosmology.

PAUL: That's right.

A4_L2_V01_Robertson-Walker_Metric

PAUL: So we've got a theory of space and time-- Einstein's theory of general relativity. And the idea here is that matter controls the metric which tells you how far apart any two elements close together in space actually are. And the metric might not be the normal one, Pythagoras' one, but can actually be curved-- be rather strange. And this causes things to move in funny sorts of ways. But what's that got to do with cosmology?

BRIAN: Well, I think we're pretty lucky. Because, you know, there's almost an infinite number of ways one could twist and turn space. But the universe conveniently appears to be pretty much the same everywhere. That is, that every part of the universe seems like every other part of the universe.

And there is no preferred direction. And that turns out to give us a lot of leverage on what the metric can or cannot be. And this is something that Alexander Friedmann went through and figure it out. But let's first think about how things work in spherical coordinates, which is not something people normally work in.

PAUL: OK, so we've talked about the metric before telling you if you've got two objects with position x, y, and z and how far apart they are. We've also talked about cylindrical polar coordinates, which is where you measure how far out something is around in height. But there's a third set of coordinates.

And it turns out this third set of coordinates are the ones we actually need to understand the real metric of our own universe. And these are called spherical polar coordinates. They're also coordinates used to measure positions on the sky-- latitude, RIght Ascension, Declination-- and on earth, latitude and longitude are spherical polar coordinates.

So what we've got is we measure of angle down from some pole, which is theta. We measure distance out. And we measure angle around the equator, which is phi, in this case.

BRIAN: And so I think it's pretty obvious if we want to go from distance-- so ds, remember, is just how far you're going to travel between point A and point B. And our point As are going to have coordinates r, theta, and phi. And if we want to just move out in radius by a little bit of r, well, that directly translates to s.

PAUL: Yeah. So if you just move in r, ds is going to be dr in a sense.

BRIAN: That's easy.

PAUL: Now, if you're going to change an angle down from the pole-- this would be a bit like latitude on the earth or declamation in the sky-- then if you move a given angle that your distance corresponding to that is going be bigger the further out you are. If you're very close, and I move a small angle, it doesn't go very far, was if I move a very long lever arm, the end moves much further. And this is just the small angle approximation we've talked about many times in these courses so far which is just that the distance is just r times the change of angle theta.

BRIAN: Yep. So your s, the amount that you move, is that radius times the angle in radians. And since we are definitely in the small angle approximation D theta, so it's as small as you can get, it should all work.

PAUL: Yeah.

BRIAN: Then we get to the slightly more complicated one, which is in the phi direction. And so this is why going in a circle around the earth up not at the equator but up at some latitude-- so let's say doing-- circumnavigating the earth at 45 degrees south, for example.

PAUL: Yes. And what you can see is that if you're at the equator, sine theta is just 1. So around the equator, it's just angle times radius just like you've had for theta. But as you get closer and closer to the poles, it takes less distance to circumnavigate the world at plus 89 degrees than it does at the equator. And that's factored in by the sine squared theta over here.

In fact, if actually at the North or South Pole, you can circumnavigate the entire world without moving at all. Because theta is 0 or 180 degrees. Sine of that is 0. And so there's no distance moved.

BRIAN: Yeah, and it makes perfect sense. Because if you look, this is essentially going to be the radius of the circle you're doing here is r sine theta is its size. And so that d phi is just made smaller, essentially, by that factor out in front.

PAUL: Yeah. So you've got the three components of motion-- outwards and r, downloads and theta, and round and phi. And so you're just using Pythagoras, square them all, add them together, and that gives you how far you've moved.

BRIAN: Voila!

PAUL: Voila! So that is the common sense metric for a flat universe. But the Robertson-Walker metric, which is the one that we get in the case of our own universe if we assume it's the same everywhere-- so called isotropy-- is a bit different. Not very different, but just different enough to be painful, I guess. So ds, once again. Just the same. So there's a dr squared, r squared, d theta squared, sin 1 squared, d phi.

BRIAN: It's all the same except for this and that.

PAUL: And it turns out that the universe is isotropic-- everything is the same everywhere-- this is the only possible metric.

BRIAN: Yep.

PAUL: Which is a really strong construct. We know the universe isn't uniform on small scale. So maybe the metric is different on small scales like the earth going around the sun.

But on really big scales, it has to be something like this. And we've got these two funny terms. So what's this doing here?

It's multiplying the whole thing. A of t-- this means it's a function of time. It doesn't depend on distance or angle or anything like that. It only depends on time. And what's that going to do?

BRIAN: Well, let's think. So imagine that is getting bigger over time. So if a is increasing over time, then that's a multiplicative factor in front of all of the rest of the metric, which means that the metric is going to get bigger and bigger. It's like magnifying. It's like magnifying the universe.

PAUL: Yes, so any two objects that have, say, a particular coordinate, a particular r feature, and phi, then without doing anything or going anywhere, they'll get further apart.

BRIAN: Ah.

PAUL: That sound just like what we need to make the universe expand.

BRIAN: Yeah, OK. So that's good.

PAUL: If at is getting bigger. At could, of course, be getting smaller or doing anything, really. We're going to have to come back to exactly how at behaves.

BRIAN: All right, and so then we have this other bit, which is this dr squared over 1 minus kr squared. So that is a funny term. So let's think how that might work.

PAUL: Yeah, I mean, this worries me right away. Because it seems to suggest that maybe pi could be different.

BRIAN: Hm.

PAUL: Because think of what pi is. You've got a circle. And you're got a circumference.

And you divide it by the diameter. And you get pi. What we're seeing here is for a given value of a and t, if you move in angle theta or phi, the distance is exactly what you'd expect.

Nothing's changed. But if you move in radius outwards, it could be either more or less than what we normally think, depending on whether k is positive or negative. Like, if k is positive, that's going to be 1 minus something. That's going to be divided by something small.

So we'll actually make it bigger. So if you had a circle, the circumference is going to be the same, but the radius is going to be bigger or maybe smaller if k has different value. And that sounds a bit weird.

BRIAN: Does sound a bit weird. But-- hm. I wonder if there's some analogy to what we see here on earth.

PAUL: Well, let me try and work out exactly what the pi actually would be as we change k.

BRIAN: OK, let's do that.

A4_L2_V02_Pi

Paul: OK, how are we going to measure pi? Well, the definition of pi is if we have a circle with some circumference c and some diameter d, pi is just the circumference of a circle divided by its diameter. Easy enough.

So that's something we could in principal measure experimentally. You could map out a circle by getting a whole bunch of points some distance r, d of 2 out from the center. And then go all around and measure the circumference and take the ratio of the two.

Well, let's calculate what we'd get if we assume that this Robertson-Walker metric is correct. So we've got a circle. We can pick a circle anywhere we like because we're assuming space is uniform and isotopic. So let's pick a circle of all the points where r equals r0. And let's vary just theta. So, we'll move around theta and we'll assume that phi is 0 throughout.

We're not losing anything by making that assumption because we should get the same answer for any circle. So I have a circle of radius r0 made by varying theta all the way around with phi equals 0. And there are no changes in delta phi.

Now, how are we going to use the metric to work out how big the circle is? Well what we need to do, this metric tells us the little bit of length corresponding to a little change in any of the coordinates. So we have to do is take the big change in the coordinates. So you're going all the way around the circle, or all the way across the diameter, and break it up into lots of little bits.

So let's start with circumference. We can break that up into bits corresponding to a small change delta theta in the angle. So this would be a small length here, delta s. And what's delta s in this case? Well, delta s squared is going to be a of t squared. Now, in this case, we're just changing theta. We're not changing anything else. So that's going to be 0. This term is going to be 0. So that's just r squared d theta squared.

So that tells us the element of length, delta s, is just a of t, r-- which in this case is r0-- the change in the angle. It's just a small angle approximation. So that's one little bit. We're going to have to add up all the little bits as we go all the way around the circle. Adding up lots of small bits is known as integration in calculus.

So that tells us the circumference is going to be the sum across the entire circle, which is the integral from 0 to 2 pi radians, a of t r0 and we change the delphi into a d theta as we take the limit these angle bits being very small.

Now, what is this integral? Well, a of t and r0 are both constants here. So this is just equal to the integral from 0 to 2 pi, take the a and r0 outside, d theta, which is at r0. just 1 times theta. So that's just going to be theta, form 0 to 2 pi, which is just 2 pi r0 a of t.

So that's about what you expect the circumference of a circle to be. 2 pi r0 just with the a of t factored in there because the universe presumably expanded or shrunk at some point. OK, pretty easy.

But now let's look at something a bit harder, the radius or the diameter of the circle. In this case, we're moving along here. And we have some bit delta s in there corresponding to some change in a radial coordinates, r. So in this case, r is changing but theta and phi is 0. So what that tells us is that the diameter is going to be say twice the radius. Twice the radius is going to be the integral from 0 to r0. This is just a of t dr over the square root of 1 minus k r squared. That's k there. And you get that just by taking this equation here, setting both of those equal to 0 and taking the square root of this and that.

Now, once again a of t is a constant. So you can take it out so you're looking at the integral of 1 over the square root of 1 minus k r squared. Now it turns out, this is quite a tricky integral because the functional fourth depends on whether k is greater than or less than 0. So now what we'll do is set k equal to plus 1 or minus 1 and look at the solutions to those two cases. If k is some positive value behaves like the k equals plus 1 k simply with different constants. Likewise, if k is negative but not minus 1, it's just like the minus 1 case from a different constants. So we'll just take k equals plus 1 and k equals minus 1.

How do we do that? Well, we cheat. We look it up on an online website. Or we use a computer algebra tool and that's what I'm going to use here. So this is a free online computer algebra tool using the Sage open source computer algebra system, sagemath.com. You can use it yourself. What I've done here is I've defined a variable r and then in this case, let's take it from k equals 1, in which case this is going to be a minus sign in here. We're just integrating 1 over the square root of 1 minus r squared as a function of r. And we press go. We find it comes out as the arc sin of r.

We could also look at what the situation would be if it was a positive value. So k is minus 1, that means it's going to be root 1 over square root of 1 plus r squared. And in this case, it comes out is the arc hyperbolic sin. If it were some other constant, let's say it was 1.003 times this, all that does is change the constant. So you get a constant here and a constant inside there.

So what we've found out, is that the diameter is going to be 2a of t. And it's either going to be the arc sin of r0 if k equals 1, or the arc hyperbolic sin r0 if k equals minus 1 or different constants on these otherwise. So that's telling us that the value of pi in this universe-- if you remember pi is C over d-- and c is 2pi r0 at and d is this. The 2 is cancelled. So pi is-- pi in r0 universe is called pi 0. a's of t's cancel, r0 over either the arc sin or the arc hyperbolic sin of r0.

So pi is not a constant. It will change. How will it change? Well, let's go back to our computer algebra system. So here we've got the inverse sin, so we've got r over arc sin. Let's see what that looks like.

So what it does is, we should put pi in here. This is the sin with the pi in. So it's just telling you the ratio of pi to what it should be in r0 universe. And it's telling us that pi is what you'd expect as long as r is small. But as the radius progressively gets bigger and bigger and bigger, the value of pi starts to fall.

Now, let's change to a k equals minus 1 universe. So we change it an arc hyperbolic sin there. And now if you run it, what do we get? Pi once again is what you'd expect when the universe is small, but as the radius of your circle gets bigger and bigger bigger, the value of the pi gets larger larger.

So we've learned is that pi is only a constant if k equals 0. If k is positive, pi is what you'd expect to be on small scales. But when you measured on larger and larger circle it gets smaller and smaller. If k is less than 0, then it goes the other way and pi gets larger on big scales.

A4_L2_V03_Curved_Space

BRIAN: All right, Paul. You've done the mathematics, you've shown us how pi can change as we change k mathematically. But I'm someone who likes to get my head around things by visualizing things.

Now the problem I have is we're dealing with universe a which has got three dimensions plus time. So it's four dimensions. And I can't visualize four dimensions. But it strikes me that maybe we can get rid of one of those dimensions. Or maybe even two of them.

PAUL: Yes, so one way just think about the strange geometry is to imagine that our three-dimensional universe is actually curved in a fourth dimension. That's the three spatial dimensions-- three dimensions, X, Y, and Z are curved in a fourth dimension. You don't need this. It could just be totally no fourth dimensional at all. You just change the metric.

This is something that's very helpful. But of course, as you say, thinking in four dimensions makes your brain dribble out of your ears. So a very common analogy is to imagine a two-dimensional universe. A surface, and traditionally the inhabitants of this two-dimensional universe are called bugs, and they live on the surface. And we can imagine that curved in the third dimension.

And this gives us a sort of OK analogy to these different values of k.

BRIAN: So it's not really dissimilar from being on the surface of the Earth, and us being the bugs.

PAUL: Yes.

BRIAN: Right.

PAUL: But of course, we tend to think about, we can dig into the Earth or go out into space. But you've got to imagine this is all the dimensions you have. So that's not really an option for them. So if you think about the k greater than 0, in this case pi is less than 3.141592, et cetera, then that's actually an analogy of the sphere.

BRIAN: OK.

PAUL: So how do you measure pi on a sphere? Well, let's imagine you put a flag in the middle and send your trained bugs out a given distance on each direction. They would then give you a circle. And you can go around the circumference. And you can see that circumference is going to be less than pi times the diameter.

BRIAN: So the analogy that I would use on Earth, for us earthbound dwellers, is, imagine going-- most conveniently-- to the North Pole or the South Pole. And then sending your flags down to the equator. And then you go through and you figure out the circumference relative to how far you went down. And it's not flat. It's been bent in. So that circumference is less than it should be.

PAUL: Or, even more so, you could start at the North Pole and march all the way to the South Pole.

BRIAN: Oh, yeah.

PAUL: In that case the circumference is 0.

BRIAN: All right.

PAUL: But you're gone all the way from the North and South Pole. So your radius is quite large, but there's 0 circumference.

BRIAN: Yes, OK. So that all makes sense.

PAUL: So, this is one possibility for our universal. So a k greater than 0 universes is an analogy of a sphere. And that has a number of possibilities. One is we've seen is that pi is going to be smaller than you'd expect--

BRIAN: Yep.

PAUL: --on small scales. You do a circle in your room, it's not going to be much different. But as you get bigger and bigger, so your radius is comparable to the radius of the universe, pi gets very seriously suppressed.

BRIAN: Right.

PAUL: A second possibility would be that parallel lines would actually meet.

BRIAN: Wow. So that means that, if I'm, for example, on the equator of the Earth, or the equator of the sphere, and I start heading towards the pole, the lines meet. And in this case, they actually meet at the pole. And that's despite there being 90 degrees-- 90 degrees, so that's 180 degrees-- plus I got another angle up there. So I have more than 180 degrees in a triangle.

PAUL: Yes. The parallel lines will meet in a universe like this. Of course, we're not really a two-dimensional analog. What this would mean is if you fired two laser beams outs at perfect straight line, they would eventually meet.

BRIAN: Yeah.

PAUL: Or to get a distance scale equal to the radius of the university, which is going to be very, very big. You're not going to see this in your laboratory. OK, another possibility of course, in this universe, would be if you go far enough in any direction, you'll come back to where you started from.

BRIAN: Right. It all wraps around onto itself. So you're really-- it's a universe you can't really get out of. You're kind of stuck on it-- it's finite.

PAUL: Yes!

BRIAN: Right? I can go through and add up the surface area of this sphere, and it's finite.

PAUL: Yeah. This always used to bug me as a kid, because I used to read in the cosmology books about how the universe might be finite. And that never made sense to me. How can the universe be finite? Surely it means you go far enough in your spacecraft, you'd see a big brick wall with a sign saying, "Edge of the university, do not trespass."

What's on the other side of the wall, for Pete's sake. It didn't make sense. But this is how you do it. What's actually going on, is if you go far enough-- so I fly my spacecraft in that direction-- eventually I'd come back and hit myself in the back.

BRIAN: Right. So in our own universe this would be the same. We could head out that way, and then, given enough time, you might end up where you started-- given a universe that had this shape.

PAUL: Yes. I always think this is something that should be used in a science fiction movie. That this would be the ultimate prison to put some superhero, you know, Arnold Schwarzenegger or something like that. If they had a universe-- say a radius of the few meters, the size of a room-- but it was curved like itself.

And just imagine your hero trying to get his way out. He could shoot his gun one direction, the bullets will hit him in the back. He can use a pickaxe on the floor and the debris will fall down on his head. There's nothing that he can destroy to get out of this universe. It would be a perfect prison, no possible escape.

BRIAN: Hm, OK. But this isn't the only type of universe.

PAUL: No. So that's a k greater than 0. If we go k less than 0, we have a rather more complicated shape-- which is often called a saddle shape. So here I'm showing a little animation of one of these shapes.

BRIAN: And so this is the shape made out of hyperbolas, for those who remember their geometry.

PAUL: Yeah. So in this case-- once again you have a point, and send your bugs out in every direction, and you define a circle.

BRIAN: Mhm.

PAUL: And now the circle's going to be wavy, go up and down. So pi-- the circumference is going to be more than 2 pi times the radius.

BRIAN: Right. So that means that, yeah, to dot all the little radial things, you have to travel further than 2 pi. And so this, again, would be a universe. Which is very different than what we're used to dealing with in our rooms and our pieces of paper that we draw these circles on normally.

PAUL: Yeah. And if you look at parallel lines, in this case, they'll actually diverge.

BRIAN: And so if we think about this, if we want to measure a triangle here, the angles of the triangle are going to add up to less than 180 degrees.

PAUL: Yes. Once again, you only find these differences on scales equal to the radius of curvature of the universe-- which is going to be very, very big. That's not why the triangles you draw in primary school geometry don't add up 180 degrees. That's got a quite different explanation.

BRIAN: And we should say that this one has an edge. And that's just because we have a finite screen. But this universe keeps going on. It doesn't just end right here, it goes on forever.

So if I try to measure how many square meters there is on this saddle, it turns out the answer is infinite. It goes on forever. It just keeps on going on bigger and bigger in both directions.

PAUL: OK, so we've got k greater than 0. We've got a finite universe-- where angles add up to more than 100 degrees, where pi is small and parallel lines converge. And we've got the k less than 0 universe. In which case parallel lines, if you fired two laser beams, they'll get further apart, even though they're traveling in straight lines.

And this universe is infinite. If you get k exactly equal to 0, then we're in a case of just a normal universe. It becomes the same metric we used for a conventional universe.

BRIAN: It's just a grid. It looks like a big cube-- bunch of cubes put together, right? But is that the only way you can do it? There's no exceptions to that rule?

PAUL: Well, I suppose you could muck things up a bit. Something like this.

BRIAN: So what have you done here?

PAUL: Ah, yes. Well, I've been evil here. What I have done, is I've taken a flat universe and wrapped it around on itself. So it's a cylinder. It should be--

BRIAN: So that means the cylinder goes on forever that way? Oh, I see. It just goes on and on, OK.

PAUL: Yes. I've only drawn a bit of it because I don't have an infinite screen here. In this case it's a flat universe. Because you try and measure pi here, it's basically the same as on a flat piece of paper.

BRIAN: Yeah.

PAUL: The difference being in one axis, you'd come back to where you started. And you can do a whole bunch of things like this. So you could take any of the universes we've talked about-- the spherical universe, the saddle-shaped universe, all the flat universe.

And you can do strange things to its topology and stick them back on in various ways. And so they're all more possibilities. But each of these things is-- in terms of pi, and all the geometry you can measure locally-- is one of these three families.

BRIAN: OK. Very good.

PAUL: So that's told us about k. And k gives us this geometry-- closed, open, or flat. But we haven't talked about a of t yet.

BRIAN: Yeah, that multiplicative factor out in front. So I guess we're going to have to figure out where we would get a of t, because it doesn't seem to be geometry in the same way. It seems to be more of what the universe does over time.

PAUL: Yes. So this is going to motion, kinematics. And we'll show you how that's derived in the next video.

A4_L2_V04

PAUL: In this video I'm going to derive the Friedmann equation, which is the equation that tells us how the expansion of space varies with time. So t gives us what a of t actually is. It's arguably the most important and fundamental equation in all of cosmology.

Now to work it out properly, you'd need general relativity, which is well beyond the scope of this course. What I'm going to do in this video is derive it using Newtonian physics. And it turns out that, as well as giving us the core principle, this actually gives us exactly the right answer, as well as allowing us to understand what's going on.

So looking at how things move, how are we going to do that? Well, let's use energy. We're going to use conservation of energy. For any galaxy, the total energy is going to be conserved. So total energy, let's call it u, it's going to be equal to the kinetic energy plus the potential energy. So if one goes up, the other one goes down.

Now what's the kinetic energy? The kinetic energy of a galaxy is just its 1/2 mv squared. The normal equation for kinetic energy, mass of the galaxy, velocity of the galaxy squared. Now, the potential energy is a bit harder. Let's imagine that we've got some spherical distribution of mass and an object of mass m up here. What's its potential energy?

Well, this is originally worked out in Newtonian physics. If you know the distance from the center of mass to the object, the potential energy is just a negative value, a gravitational constant, mass of this big distribution here, mass of the small thing over r. And this distance here, r, is the distance from the center of gravity of the mass to your object.

What happens if you're actually inside the object? Instead of being out here, let's say your mass is in there. Now this, it turns out, is a trick. We saw this before if you did the first course in talking about dark matter. What you can do is if you're actually inside some distribution of mass, some spherically symmetric distribution of mass, is draw an imaginary sphere at this radius. And all the mass that's outside the sphere-- so, all this mass over here-- it turns out, you can ignore. Its gravity cancels out.

All the mass inside, you can assume it's all approximated as a single lump in the middle with the same mass as that entire region. This is called Newton's Superb Theorem. It, of course, came from Isaac Newton, as did so many other things. And it's enormous simplification. It's why when the spacecraft is orbiting the earth, you can just approximate the Earth as being a point at the center of mass of the Earth.

But it's also going to be very useful to us here because of an extremely sneaky trick. You wouldn't think you could use this for the entire universe, because the universe is [? homogeneous. ?] It's not some spherical distribution of mass. But watch this trick. Let's pick a point somewhere in the universe-- it doesn't matter where-- and we'll call that's our center.

And now let's look at a galaxy of mass m at some distance r from our completely arbitrary point. It doesn't matter which galaxy you pick and which position we choose to be the center of the universe. We can pick anything we like, and we get the same answer.

Now what we're going to do is, completely arbitrarily, divide the universe in two. We're going to draw an imaginary sphere of radius r around our point. And we're going to do with all the matter inside and all the matter outside and look at its effects.

So we've got this particle m. And if this is our corporate origin, we know from the Hubble law that its velocity is-- it's going to have some velocity V outwards. And that's going to be the rate of change of r. So the kinetic energy is 1/2 mv squared. So it's a half mass of the galaxy r dot squared. Now, remember that r dot is the rate of change of r, so it's just the velocity as measured from here. So we're doing everything in this particular coordinate frame.

Of course, as you remember from the galaxy's point of view, it's stationary and this thing's moving apart. But because the universe is isotopic, we can pick any set of coordinates we like, and we should get an identical answer. So anyway, let's pick. This is our origin, so we kinetic energy equals 1/2 mr dot squared.

How about potential energy? Well, all the universe outside the sphere-- the universe is uniform and isotropic. It's the same everywhere. It's spherically symmetric. An infinite universe is spherically symmetric, I suppose, as much as anything else. It has equal mass in every direction. So what this means is all the mass further out, all the mass out here, will have no net gravitational effect. It'll cancel out. And all the mass inside, we can pretend it's a lump in the center. So the potential energy is going to be minus G the entire mass inside that imaginary purple circle m over r.

Now what's the mass inside the circle? That is just going to be the volume, which is 4/3 pi r cubed times the density. So what that's giving us is that the total energy, U, is going to be 1/2 mr dot squared minus-- substitute this into here, you're going to get 4 pi over 3 G density r squared m.

Now this may sound like a compete cheat to you. Why are we measuring it relative to this? Uniform-- it's isotropic, we could go do it in regard to anywhere else. Why this imaginary purple circle sphere and not something else? Well, it turns out that it doesn't matter. You can pick any circle you like-- any sphere, any location-- and you'll get the same answer. You'll have a different r depending where you are, but it turns out that doesn't actually matter. You'll get the same general answer whatever we do, because the universe is all the same everywhere.

OK, so that's given us our energy equation. And we know this energy, total energy U, is going to be conserved. So if the potential energy changes, the kinetic energy must change to cancel, and vice versa.

Now our next step is to do a rather tricky change in coordinates. So far we've been measuring positions and coordinates in the normal way, what are called physical coordinates. That's like the grid we've got in this image here. But if you measure it in these coordinates, then galaxies are moving. However, there is an alternative. Instead of measuring coordinates in physical coordinates, we can measuring in what are called comoving coordinates.

Comoving coordinates are the coordinates that something would have right now when the scale factor of the universe is 1. In this simulation, I've shown the comoving coordinates as the green grid-- as opposed to the grey grid, which are the physical, proper coordinates. And what you can see is that these green coordinates are expanding with the galaxies. So the galaxies remain in the same location regardless of the expansion of space.

We have to define some time when the scale factor of the universe is 1. It's typically defined as today-- in which case, the physical coordinates and the comoving coordinates are the same. But at any other time-- say, in the future-- the comoving coordinate grid has expanded to keep following the galaxy. So any galaxy will remain the same place regardless of time.

So let's put these new coordinates into mathematical form. What we're going to say is that r, which is a vector, is going to be equal to the scale factor of the universe times its comoving coordinates, x. So x doesn't change for an object. That's just fixed. r is changing. The reason it's changing is you've got this a of t.

So if we take that and substitute it into here, what we find is that we get the total energy is equal to 1/2 m r dot squared. Now, r dot squared, if we differentiate this, is going to be the differential of that. x isn't changing, so it's just going to be a dot squared times x squared.

Over here we're just going to replace r with a of t. So it's going to be minus 4 pi over 3 g rho a squared x squared m. Now we're very close to having our final equation. We're just going to do a bit of rearranging. What we're going to do is multiply both sides by 2/ma squared x squared and rearrange. I'll leave that as an exercise for you. But if you do that, multiply both sides of the equation by this. You end up with the classical Friedmann equation, which tells you that a dot over a squared equals 8 pi g over 3 times the density minus kc squared over a squared.

Now, what's this k? Well, k is where we bundled up all the constants we don't care about. So we have k equals minus 2u over mc squared x squared. Why have we bundled all that up? Well, everything else here-- a dot over a, g density, is independent of where you are, what location you've got. So this is all going to be the same for any particle in the universe. Likewise, c and a going to be the same for any part of the universe.

So therefore, as everything else is going to be the same everywhere, and we've assumed the universe is isotropic and uniform, that means k must be the same everywhere. So somehow, these x's and the u must cancel out and give you a constant. And in fact, it turns out that this k is exactly the same as the k we found in the Robertson-Walker metric-- so the one that gave us the curvature of space. It's come back over here.

So that's our equation, the Friedmann equation, derived using Newtonian physics. But as I said, you get exactly the same answer if you do it using general relativity.

A4_L2_V05

BRIAN: Whew, boy Paul, that was a lot of work. But I want us to think about what you just did. You took general relativity, and we went through with that concept. And you have derived in a universe, which is isotropic, an equation-- an equation of motion that takes all of general relativity and makes it into a single, ordinary, differential equation which we can hope to understand, rather than the normal 16 non-linear, linked, differential equations which are general relativity. So this is a major triumph. And I know it wasn't easy, but it's a very important equation.

PAUL: And for the next few videos, we're going to talk about how we solve this equation, what the results are, and its general behavior. It is a differential equation, because it's got calculus. And it's got a da by dt in here. So it's actually secondary university math to solve these things. But we'll show you with a bit of effort, you can get a lot of the way there.

We're going to start off by asking about how this equation behaves right , now at this particular instant in time.

BRIAN: OK.

PAUL: So, what we know is, right now our universe is expanding. And the evidence of that, if you remember, was the Hubble law. We had a graph-- all sorts of different galaxies-- showing how far away they are and how fast they're moving. So what does this Friedmann equation tell us about that?

BRIAN: So if we look through and just remind ourselves what that Hubble law is in vector form, we have the velocity of an object, of course, is defined as how it changes over time. So that is written as dr dt, the vector.

PAUL: Yes. We're assuming we ourselves are positioned at 0, so everything's measured away from us.

BRIAN: Right. And we can measure that as the size of the motion. So that's like the speed. And then here we give the velocity in the direction and the length of that distance.

PAUL: So these vertical being-- these are vectors. But this is just telling us it's the amplitude of the vector. So that's the amplitude of the velocity divided by amplitude of the distance, times the distance. So that would cancel with that, and this would just give us this.

BRIAN: Right.

PAUL: OK. So that's telling us that the vector velocity is given by the ratio of these two scalar numbers, that's times the vector distance. But if we remember from the Robertson-Walker metric, that's r-- the distance to something-- is just a times its coordinates.

BRIAN: Right, where a is not acceleration here. It's the scale factor. It's the thing that tells you how big the universe is.

PAUL: OK. So we can then substitute in, if we differentiate this. x are what we call co-moving coordinates. Those are the fixed coordinates that don't change as the universe expands. But the distance of something is going to change, because a of t is going to change. Might get bigger. Might get smaller. We don't know yet.

So what that's telling us is that the velocity is going to be given by a dot over a.

BRIAN: Hmm. Times the distance. So that's just the Hubble law.

PAUL: Yes, it is. So a dot over a, the rate of change of the scale factor divided by the scale factor, is going to be telling us how fast space is expanding.

BRIAN: Right.

PAUL: And that's what we've got here.

BRIAN: So the Hubble law there.

PAUL: Yes.

BRIAN: And so that means that we could rewrite that equation right now-- what's going on right now-- in terms of the Hubble law.

PAUL: Yes. So we give us, the Hubble's constant squared is this times the density right now, plus this over the scale factor right now. We normally define the scale factor today as 1.

BRIAN: Right. And so there we've used the fact that a dot over a squared was on that side of the equation on the previous slide. All right. So how fast the universe is expanding right now is going to be related to the density, and then something to do with the size and the curvature. But one could imagine that the universe we live in has no curvature, for example.

PAUL: Yes. And so the first thing you can tell is that Hubble's constant isn't really a constant, as at different times, the density is going to different. And the scale factor's going to be different. And so, Hubble's constant a billion years in the past, or a billion years in the future is not going to be the same. So maybe it shouldn't really be called Hubble's constant. I mean--

BRIAN: Hubble's parameter.

PAUL: Hubble's parameter. And so, Hubble's constant is Hubble's parameter value right now, if you like.

But yes, we can also-- remember, we talked about the values of k and how they make the universe curve one way or the another. But this gives us a way to work out what k is. We could, in principle, work it out by trying to measure pi on a really large scale. But that's pretty hard.

BRIAN: If we measured the density right now--

PAUL: And Hubble's constant.

BRIAN: We measure Hubble constant, then we could presumably solve for what this is. And that would potentially give us an idea of how to measure k.

PAUL: Yes. So the simplest case is k equals 0, which is our flat universe. And that's the dividing line between these three models. If we get k equals 0, it just means this equals that. So we get this here. And we can solve that to find the density. And this gives us a critical density which will vary with time, again. So this is the critical density right now, at t0, which is defined as today. It's going to be 3 Hubble's constant today squared, over 8 pi G. The are all constants.

BRIAN: And so this is a critical value at k equals 0. So if the density is higher than this, then it turns out that we have a universe that has more than a critical density. k, then, instead of being 0, becomes plus 1. And if you're below this density, then k has--

PAUL: A negative value.

BRIAN: That negative value, right.

PAUL: And what is this value if you plug in Hubble's constant of about 70 kilometers per second per megaparsec-- which is roughly what we think it is today-- that comes out about as about 9 by 10 to the minus 27 kilograms per meter cubed.

BRIAN: That's a very small number, compared to the 5500 kilograms per meter cubed that the Earth has.

PAUL: But if you turn that into astronomical units, that's about 10 to the 11 solar masses per cubic megaparsec.

BRIAN: Oh. So that's-- 10 to the 11 solar masses. Well, that's about a galaxy. That's about what galaxy weighs, like the Milky Way.

PAUL: And cubic megaparsec is roughly the distance between galaxies.

BRIAN: So that means that the amount of stuff, if we look astronomically, is close to this value.

PAUL: So it is a very low density. But that seems to be not too far off the actual density of the universe.

BRIAN: Hmm. OK.

PAUL: So it's not obviously vastly higher or vastly lower. So it could be the universe is not too far off of k is 0, a flat universe. It could be one side or the other, but its not going to be 100 orders of magnitude of one way or the other.

BRIAN: So presumably, measuring that is going to be one of the big things that we need to talk about within cosmology.

PAUL: Yes, so critical density is absolutely crucial. It's so crucial that we give it its own parameter, Omega, which is defined as the ratio of the density today to this critical density.

BRIAN: Ah. So that means that if Omega equals 1, then the universe is flat, k equals 0.

PAUL: Yes, and if Omega is greater than 1, that's telling us we're in a positive k universe, which is the spherical universe, finite. And if it's less than 1, we're in one of these saddle-shaped universes.

BRIAN: Oh, OK. So that's a very useful parameter.

PAUL: OK. So density's clearly going to be absolutely crucial here.

BRIAN: Yep.

A4_L2_V06

PAUL: So now let's look at how we solve the whole Friedman equation. We've got the values right now. But how's it going to change as the universe gets younger or older? Well, we know what this is today.

The crucial thing is going to be how the density changes. We can in principle measure density right now. But how is the density going to change as time goes forwards or backwards? That's going to be the one thing we need to know to solve this equation.

BRIAN: Mmm, OK. So let's see. So in principle, we sort of know what a dot over a is. That's the Hubble constant. I helped measure that as part of my PhD thesis.

So we know that. And we sort of can measure to first order what the density is right now. But I mean, clearly, we can figure out how the density is going to change over time, isn't it? It's pretty straightforward.

PAUL: Well, if we assume there's only a finite amount of stuff per unit volume in the universe, the law of conservation of matter energy, it is pretty straightforward. Now, there was, back in the early days of cosmology, a theory that in fact more matter was being created-- in this case a steady state universe.

BRIAN: So that matter was being created out of the ether, sort of to speak.

PAUL: Yes. We talked about this in the first course. So we're not going to consider it further here. Let's assume that matter is conserved and you have a finite amount of it.

So in that case, you've got a box of given size. And it's got a certain amount of stuff in it. And the length of each side is going to be-- its L0 times a of t.

BRIAN: Yep, so I've got a box and then I let the universe get changed in size. So let's just say it gets a little bigger.

PAUL: OK, so what's going to happen is as the universe gets bigger, every length is going to get bigger. The width, the height, and the depth of the box is going to get bigger. So the volume is going to go up as proportional to a cubed. But the amount of stuff inside the box isn't going to change. Because you just assume conservation of matter.

BRIAN: So if we think of like an atom, if you've think you've got 10 atoms in a box, they have a density. They have a mass. And then the box gets a cubed larger in volume. So the density is going to drop as a cubed just like you've shown here.

PAUL: Yes So this is pretty straightforward, then. The density just goes as 1 over a cubed. So--

BRIAN: No problem. OK.

PAUL: Problem solved?

BRIAN: OK, we're done?

PAUL: Well, that's true if you've got matter whose rest mass dominates its motion. But we know from Einstein that if things are moving close to the speed of light, actually the bulk of their matter comes in their kinetic energy, their motion.

BRIAN: A-ha

PAUL: So for example, photons have no rest mass at all. But they still have-- they still weigh something. That's because they're moving so fast.

BRIAN: That's right. They do have an energy or a mass equivalent then, don't they?

PAUL: So for things that are getting close to the speed of light or at the speed of light-- like light, for example-- things are a little bit more complicated than this. We know from quantum mechanics that the energy of a photon-- and the same thing applies to anything close to the speed of light-- is going to be Planck's constant times its frequency.

BRIAN: H nu. Or, if we like to work in wave length, which I always find it a little easier to think about, hc over lambda where I've replaced nu with c over lambda.

PAUL: c is speed of light and Lambda is just the wavelength. OK, so in this case, as the photon-- anything relativistic is going to be flying through space. It's going to stretch.

Space is going to expect. It's going to pull the front and the back further apart. The space between the front and the bank, the a of t, the ds from over here, is going to get larger and larger. Its space is expanding.

BRIAN: So if the wavelength gets longer, that means the energy is going to drop.

PAUL: Yes.

BRIAN: That's interesting. So what's that do when we put everything in the box?

PAUL: Well, so now we've got a box full of, say, photons or waves. As space gets bigger, sure, the box is going to get bigger. You've got the same number of photons in the box. So the energy x is going-- the mass density is going to go 1 as a cubed. But in addition, each photon has lost energy.

BRIAN: Right. And it's lost energy by how much the box is magnified. So you got that volume of the box a cubed. And then the length of the box--

PAUL: The length of each photon will be stretched.

BRIAN: Length of the box which stretches the photon gives you an extra factor of a. So 1 over a to the fourth. And that takes me then the density of light, for example, and the density of atoms are changing as a different rate over time.

PAUL: Now, you might think that this is violating some conservation of energy. Where is this energy going from the photons being stretched? We're going to-- if you remember, when we derive the Friedman equation, we use energy conservation to derive it. So the drop in energy here or in matter inside has gone into a potential energy of space.

BRIAN: Right

PAUL: But yes, you're absolutely right. This means that if you had matter and energy at the same density today, in the future if space is expanding, the density of the radiation is going to get smaller compared to the density of the master.

BRIAN: Yep, OK.

PAUL: So in fact, today, we know that the density of mass of non-relativistic particles are actually considerably more than that of radiation.

BRIAN: It's about 5,000 times more.

PAUL: But as you go further and further back in time, so a of t gets smaller because we're in an expanding universe, because the radiation density is going over as 1 over a to the fourth, whereas matter is only 1 of a cubed, sooner or later, radiation is going to dominate, isn't it?

BRIAN: Yeah, so you go back and it's 5,000 to 1 right now, and since one's going down as a to the fourth, the other one is a cubed, we take the ratio. The ratio goes back as 1 over a, which means that when the universe was 5,000 times smaller than it is now, then matter and radiation were about the same. And before that time, radiation was the most important thing in the universe.

PAUL: OK, so it's actually rather complicated to solve the equation for some complicated mix of radiation and matter. But in practice, you can treated it as normally as one case or the other. So very early on, roughly before the first thousand years of the universe, radiation dominated. So you should use one over a to the fourth. Whereas anything since the first thousand years, matter dominates. So you can use one over a cubed.

BRIAN: Yes. So unless something else is in the universe, as we're going to talk about-- because we think the universe has got more than just radiation and normal matter in it, it turns out.

PAUL: And we'll come back to that later. By and large, if we assume there was just radiation and matter, and we'll ignore dark energy and other things like that for the moment, then we've now got all the ingredients we need to actually sold Friedman's equation.

A4_L2_V07

BRIAN: All right, Paul. I'm excited. It looks to me like we have all the ingredients necessary to solve the Friedmann equation.

PAUL: Now, This equation is a differential equation, which is second-year university math. So what we're going to do is we're going to solve it using an approximate numerical method. It actually turns out for the real universe you have to use it numerically. There is actually no proper analytic mathematical solution to it. So you're not losing anything by doing this.

BRIAN: Yeah. Now, that numerical solution may be something that none of you have really seen before. But it's built up on the very fundamental basics of calculus, so you should be able to understand it and follow it pretty easily.

PAUL: Yeah. So the basic idea is we know everything here right now. We're going to define a of t as 1 right now.

BRIAN: Why are we going to do that?

PAUL: Well, can define it as anything we like. We can call it 47 or 2, or anything you like. This just defines the coordinates we use. This is telling us a ratio of x to r. And we can measure the coordinates in anything we like. So let's just define the scale factor as 1 right now.

BRIAN: So that's very convenient, is what you're saying.

PAUL: Yes.

BRIAN: OK.

PAUL: And if you look at this in some literature places you'll sometimes see people sometimes define k as either being plus or minus 1. That means a is not going to be 1 right now. You can choose either assumption you like. For this calculation, we're going to assume that a is 1 now, means k can have a range of values.

BRIAN: Could be bigger than 1, or less than--

PAUL: Less than zero. So OK, so let's assume the scale factor is 1 now. So we're measuring the size of the universe at any time in the future and past relative to its size now. And we know a dot right now from Hubble's constant. And let's assume we know what the density is now. At least we'll assume a density now, some fraction of the critical density, maybe more or less than the critical density. So then we can go forward.

BRIAN: And how it changes back in time, so no problem.

PAUL: So all ingredients are there. So what we need to do is work out a dot, which is the rate of change the scale factor, da by dt. Right now, it's given by just rearranging this equation, taking the square root and moving a up the slide there.

BRIAN: Ah. So we have the change of a is equal to a plus this other junk, some of which is going to change also as a function of a. OK.

PAUL: Yes. Density is going to go as 1/a cubed, or a to the 4th. This is 1/a squared over there. So this makes it rather complicated to solve. So we've got density goes as density today is either 1/a cubed or 1/a to the fourth, depending on whether a radiation relativistic stuff, or matter-dominated. Now, the method we're going to use here is the simplest possible numerical method. This is called Euler's method.

BRIAN: Euler, yeah. I never knew who this guy "Euler" was when I went to university. I knew there was this guy named Euler-- E-U-L-E-R. Turns out, he's Euler. So just in case you haven't put that together, I'll tell you.

PAUL: OK. So this method is the simplest possible numerical method. In practice, in real world, you'd solve it using a more complicated method. But this actually gives you a quite accurate enough answer. This is for any purpose you'd really want. What it's telling us is, let's say we know a of t right now. We do, because we defined it as 1. What's the a of t going to be some little time in the future, or some little time in the past?

Now, if you make that time step, that delta t, small enough, a isn't going to change very much over this time interval. Density isn't going to change very much over this interval. So as long as you make delta t small, we can solve this equation we've dealt with previously because these things are all going to be more or less constant over a small time interval.

So the idea is the a at some time the future, or sometime in the past, is going to be the a of now plus a dot, the rate of change of a, times delta t.

BRIAN: Yeah. As the level that this isn't changing over that time, delta t, it's exactly right, because we have to remember that, of course, a dot is da/dt, or delta a over delta t, where those delta t's are really, really small.

PAUL: Yeah. So this is actually basically the definition of calculus. It's saying that how much something moves is equal to where it is now, plus the gradient times the time.

BRIAN: All right. And so you put together a little program, a little spreadsheet to go through and calculate, a little program.

PAUL: Yes. We've got a little Python program that will take you through this. And it's available on the web page here. And so you can pick any value of density that you like and see how the universe is going to change going into the future. But before we show you the results of this program, let's actually trying and think through how it's going to behave. You should never trust any program until you can see in your brain how it's going to behave.

BRIAN: Good.

PAUL: So let's pick the simplest case, k equals 0, a flat universe. What's going to happen now? Well, the last term here disappears, because k is 0.

BRIAN: Yep.

PAUL: So you just get a dot is equal to a, 8 pi G rho 0 of a cubed is for matter-dominated. It'd be a to the fourth for radiation-dominated. So that's telling us for matter-dominated. What have you got?

BRIAN: So we added up what the change of a is equal to-- is proportional to 1 over the square root of a. So that means that when a is really small, the rate of change in the universe is really big. But then as a gets bigger and bigger and bigger, eventually the universe expansion get smaller and smaller, because 1 over a really big number becomes a very small number.

PAUL: So what it's telling us is that the universe we know that a dot is positive right now, the universe is expanding. And it's always going to be positive. The universe will always expand. No matter how big a gets, this is always going to be 1 over square root of a number. But as the universe gets older and older and older and bigger and bigger, the rate of expansion will decrease, but it will never reach 0. It'll all but what? As a goes through infinity, it'll reach 0, but not before infinity.

BRIAN: So we expect the universe to sort of grind to a halt. It never quite reaches the halt.

PAUL: Yes. So if you get the output of the program, it turns out this particular case, k equals 0, you can solve. And we'll show that in the reference notes. So what you get is, if it's matter-dominated, a of t goes as t over t0 to the 2/3. The traditional method is the 1/2 power. But this is, again, what we've seen. Starts off expanding very fast, and always drops off, because going as 1 over root t slows down and slows down and slows down, but never stops.

BRIAN: OK. I kind of like that as the universe. Seems sensible to me.

PAUL: OK, so that's the flat universe, k equals 0, and it will last forever. It will keep on expanding, but it'll be expanding pretty slowly in the far future. How about k greater than 0? What's this equation do now?

BRIAN: All right, so let's think. So we've got this a dot term. And we're going to have to multiply. We're going to have to, I guess, look at the Hubble constant. That's how fast the universe is expanding squared. And density is going as density now divided by a cubed or a to the fourth. And then here we have a squared, which means as a gets big, this-- sorry?

PAUL: Firstly, both these things are going to get smaller. But this one's going to get smaller faster, because it's going as 1 over a cubed, or a to the fourth. There's only 1 over a squared.

BRIAN: Right. So that means that as we let the universe evolve, this will end up eventually being bigger than that term because of that a squared versus a cubed or a to the fourth.

PAUL: But hold on a minute. If this term gets bigger, we said k is positive. That's minus. That means a dot is going to have to be a negative. The universe is going to have to stop expanding and start shrinking.

BRIAN: All right. So that when that turns, when this begins to dominate over that, the universe is going to change gears, effectively go into reverse. So that tells you expect the universe, as it gets bigger-- well, bigger-- eventually it'll change signs. So that's a very interesting issue here, isn't it?

PAUL: Here's what you get if you solve this using the same program. And you can see the universe is getting bigger at the present, but it will slow down, slow down, and eventually it'll stop at the point where the second term becomes equal opposite to the first term. And then it's going to start shrinking.

BRIAN: Right. So the universe begins with the Big Bang here, but you seem to be hesitant to plot the Gnab Gib here, Paul.

PAUL: It's set to go to 30. But yes, the universe will eventually come back to 0 size at the end. So everything'll expand, stop, come back together into what's often called the Big Crunch.

BRIAN: Yep. The Gnab Gib, much better word.

PAUL: "Gnab Gib" being Big Bang spelled backwards.

BRIAN: Yeah. So OK, so this is an interesting universe that sounds like it's very exciting at the beginning and at the end.

PAUL: OK, so this is what we get for k greater than 0-- which is a closed, spherical universe, if you like. How about k less than 0? Well, in this case, this term is still going to dominate when a gets big enough.

BRIAN: Yep.

PAUL: But now, because that's negative, there's a minus sign. Minus times minus equals plus. So that term over there will be a plus. And we've got a dot over a here. So that means we've got a squared up there, a squared at the bottom. So this is going to be a constant, kc squared.

BRIAN: Right. So a constant amount of acceleration, that's like just having the rocket engine on forever. So you're going to get bigger and bigger and bigger.

PAUL: Yeah. So in this case, if we're moving fast to begin with and slow down, but it won't slow down to 0. It'll slow down to kc squared. So it'd have an asymptotic value straight line up here, which means it'll keep expanding very fast.

BRIAN: Right. So a universe that keeps going, not dissimilar to giving, for example, a rocket escape velocity. Even though you turn the rocket ship's engines off it keeps on going away from Earth if you get it going faster than the escape velocity.

PAUL: Yes, very much an analogy to throwing a ball up in the air. So if, for example, I throw it up slowly enough, it'll come back down again. And that's equivalent to the k greater than 0 case.

BRIAN: Yep.

PAUL: The universe expands and then shrinks again. If I throw it at just the escape velocity, it will cruise to 0 velocity to infinity, which is the k equals 0 case. And if I throw it really fast, then it will keep on bombing up to infinity at some high speed like a rocket. And that will make--

BRIAN: Or like one of the Pioneer space probes or something, yeah.

PAUL: Yes. And that will head off something like this. So these are our three models o the dynamics of the universe. In our simple model here, we have a universe that will come back to a halt, a universe that keeps going forever, and a universe that keeps going forever faster.

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BRIAN SCHMIDT: So this is amazing. We have the story of our universe encapsulated in a single differential equation-- a single equation, the Friedmann equation-- that allows us to figure out what is going to happen in the future, depending on the state of the universe now.

PAUL FRANCIS: And it all seems to depend on this density, Omega we call it-- the ratio of the density of the universe to the critical density, which also tells us the value of k, which is the curvature of space. If the Omega is greater than the critical density-- Omega is greater than 1-- then that's telling us the universe will eventually stop expanding and start shrinking back down again, and come together again with galaxies raining down in some enormous big crunch, or Gnab Gib. It's a pretty horrible way to end.

BRIAN SCHMIDT: Yeah, it wouldn't be good to be in the universe when everything's coming together at the end, because it would be a pretty fiery ending at the very end.

The part about that universe that is finite in time-- because it's finite in space. There's a finite amount of real estate. And while the universe seems very big now, in the future, if it were for example, coming together in that Gnab Gib, it wouldn't be much of it left at the very end. And so it has that interesting characteristic of telling us how much real estate there is out there in the universe.

PAUL FRANCIS: Yes, so we have universe that's finite in space and time. It has a definite beginning, a definite end. And there's only so much of it. You don't hit a brick wall that says "the end." But you just-- if you go far enough in one direction-- come back to where you started from.

And in principle you could tell you're in this universe, because if you measure pi on really large scales, you will find it's less than it's canonically supposed to be. And parallel lines would converge, which in principle you could measure in some way. I suppose you could count-- maybe not measure the circumference of a circle. Measure the volume, by counting how many things are within a given radius, and seeing how that changes.

BRIAN SCHMIDT: So in the little Python program, people can play around and see what the trajectory of the universe is. They could also play around with whether or not the universe is made up of photons, or made up of normal matter. And so that-- you might think that would change how the universe moves forward. And clearly it does.

But the general scenario is the same. If you're a universe that only has photons in it, then you slow down. You just slow down faster. And then you collapse faster, if you're made of photons than if, for example, you're made out of normal matter.

PAUL FRANCIS: Yes, so it makes curiously little difference apart from speeding things up. I personally like the universe with Omega equals 1 or even less better. I mean, I don't know what you feel about that. I always take a straw poll in my class and ask which ones people prefer. And it usually splits the class half and half.

If you have an Omega less than 1 or equal to 1, then the universe will keep on expanding forever. It's infinite in both space and time.

BRIAN SCHMIDT: I'm a man who definitely prefers a universe that ends has a beginning. It seems symmetric and, you know, I don't have to ponder infinity then.

PAUL FRANCIS: I like pondering infinity. I like a universe that goes on forever. Unfortunately as we'll deal with later in the course, while the universe may go on forever, we won't. The universe will eventually die of heat death, of exhaustion, of free energy, of entropy. So it's a dying universe with a bang or a whimper, but we're going to die one way or the other.

BRIAN SCHMIDT: Yeah, that's true.

PAUL FRANCIS: So which of these models is true? Can we actually observe whether the universe is going to come back together again or keep expanding forever, or even something stranger of course?

BRIAN SCHMIDT: Well, that's a very interesting question. It's one that I've spent a good portion of my career trying to understand. And so in order to do that, we're going to have to go out and literally look at the universe, observe what the universe is doing, and try to measure what it's doing, rather than impose our own prejudiced beliefs onto the universe. I don't think it really cares.

PAUL FRANCIS: So we're going to talk about that a bit later in this course. We'll actually talk about the measurements and how they've come up with a very surprising answer. But first, this whole thing is dependent upon our assumption that the universe is typically the same everywhere and uniform. And that itself is actually a very weird one. So next time we're going to talk about the theory of inflation, which explains why this uniformity is actually there in the first place.

A4_L3_V01_Introduction

PAUL FRANCIS: Everything we've talked about so far in our model of the universe was relying on the assumption that the universe is isotropic. It's the same everywhere. But that poses a problem, a really difficult problem that led to the Theory of Inflation, which is what we're going to talk about the next few videos. Here's the problem.

Let's say I look out in one direction 13.8 billion light years away. And I see galaxies, stars, whatever, gas, microwave background. And let's say I look in the opposite direction or any direction the same distance. So you've got two regions of space, 13.8 billion light years this way and 13.8 billion light years that way. And they both have the same density. They both have the same temperature. They both have the same everything that we can measure to incredible precision.

Now, that's a bit weird. Normally, if you see two things that are the same density and pressure and everything, it's because they've been in contact at some point. So let's say for example, you have a bucket of hot water and cold water. If you mix them, they'll coming into thermal equilibrium and they'll all be the same temperature, the same density, the same composition.

So if we see things at distant edges of the universe and they're the same, surely that indicates the two things were at some point mixed together.

BRIAN SCHMIDT: Yeah, and so if you think about looking back, for example, to the cosmic microwave background 13.8 billion years ago, you're going to 13.8 billion years that direction. And then I'm going to look behind me 13.8 billion years the other direction. And you can ask well, there's no way that part of the universe could have communicated with that part because that's how long, you've literally used the entire age of the universe to go from that side of the universe just us. And the other ones use the entire age of the universe to go from the other direction to us, which means they would need a much, much longer to ever have a chance to talk to each other.

PAUL FRANCIS: Yes, so these two regions are 27 or so billion light years apart. And the universe is not 27 billion years old. So how could they ever have communicated with each other?

BRIAN SCHMIDT: So that seems to be a missing ingredient. Because when you follow the equations of the Friedmann Universe, that there is at no time those things will have ever been able to be in contact, even when the universe was really, really tiny. Because what it was that small, it wasn't very old. And light still would not have had a chance to go from that side to that side. So we have a problem.

PAUL FRANCIS: Yes how do they? No, it could just be that maybe you've got to decide it's going to be like that. Let's make everything the same, why not.

BRIAN SCHMIDT: Yes, but I think here in science we want to try to come up for a reason. So we need to come up with a theory that naturally explains how it could've happened. And that's one of the problems. But it's not the only problem. We actually have two other problem.

One of the other problems we have is if we go through and we look at the universe, we see that it's very close to having that magical value of density which is where it's flat, where k equals 0. And you wouldn't expect that because if the universe is a little more dense than that, or a little less dense than that, it wants to sort of runaway from that magical value.

PAUL FRANCIS: Yes, so let's say when the universe was a nanosecond old or something, it was a little bit more than the critical density. The critical density then would be much more than it is now. But let's say it was 10% more than that, that means universe would re-collapse, get smaller and smaller. It means the density would get higher and higher, which means it would be even further off the critical density, which means it'll contract even faster.

So if the universe was a bit lower than this density, then it'll expand faster. The density will drop even more so. So you'd expected in the universe if it was anything other than critical density, it would runaway one side or the other. If it was even one part in a million off just after the Big Bang, it would now be hundreds of orders of magnitude of one way or the other, vastly more dense or vastly less dense.

We don't know that the universe is exactly this k equals 0. But we know it's pretty close within a factor of 10 or so. And if it's within a factor of 10 now, it must have been within a factor of millions of decimal places just after the Big Bang. Once again, why?

BRIAN SCHMIDT: So we'd like a theory to fix that. And then there's the other problem, is that we're here at all. And we're here because gravity was able to take a part of the universe that was a little denser right after the Big Bang and collapse it down. And indeed there's a pattern, a pattern of density fluctuations, or lumps and bumps that the universe was born in that kind of defies explanation. It's almost like the universe was born with white noise. So that static we hear on radio. There's a certain amounts of bumps and lumps that are equal across all scales. And we need to understand why that happened.

PAUL FRANCIS: Yes, we've been assuming the universe is uniform. But of course, if it was totally uniform, it would stay uniform. Nothing would ever form. It would just be steadily cold or gas and radiation as the universe got bigger and bigger. We need there be lumps to turn into stars, and galaxies, and clusters of galaxies, and super clusters. And the interesting thing as you said, is this it turns out there's structure on all scales pretty much. There is small lump that to turn to small things like galaxies and big lumps that turn to big things like super clusters of galaxies. As far as we can tell, the amount of lumpiness on all these different scales is about the same.

And where did these lumps come from? If they weren't there, we wouldn't exist. So we're very glad they're here, but where do they come from?

BRIAN SCHMIDT: So inflation as a theory was dreamed up in the early 1980s by Alan Guth and a number of other people. Seems to sort of be the panacea to all these problems. It can explain these three fundamental questions we have about essentially the initial conditions of the universe.

PAUL FRANCIS: So let's talk you through this theory of inflation now.

A4_L3_V02_Symmetry

PAUL FRANCIS: So we've got these three puzzles about the universe. How are we going to solve them? Well, this is a situation where the particle physicists come in, and they've got two fundamental principles they often use.

BRIAN SCHMIDT: That's right. So if you ever meet a particle physicist, they're really into two things. One is simplicity. Well, not simple maybe in the traditional form of the word. Very complicated mathematically, but simple in terms of the way it works the same everywhere, for example.

And symmetry. Symmetry is the idea of how things can look the same in any situation. And Paul will talk a little bit more about this.

PAUL FRANCIS: Yeah. So, the part of simplicity that matters here is that we know there are four forces of nature. Electromagnetism, which holds our bodies together. The strong force holds nuclei atoms together. The weak force, which we talked about in course 3, in terms of neutrinos interacting with matter. And gravity.

Now to a particle physicists, this is too many. A universe with four forces, what's the equations that have to be memorized?

BRIAN SCHMIDT: There should only be one. One rule.

PAUL FRANCIS: One rule. And so they naturally thought that maybe there's way of combining these, at least the first three of these forces. Gravity turns out to be very hard to combine with the other ones. This already happened in the 19th century. There was electricity and magnetism, which were previously seen as two forces, have been unified by Maxwell and other people, so maybe we could do something else and combine these three forces.

BRIAN SCHMIDT: That's the notion of simplicity, is you may have to work in 11 dimensions to get all four things to work together and have horrifically complex mathematics, but then you would have one rule. That's the simplicity we're after.

PAUL FRANCIS: So simple rules though the mathematics may be horrific, and in fact usually is in these situations.

And back in the 1970s, a group of people came up with theories that would actually combine at least the first three. They're called gauge field theories or Yang-Mills fields, and the idea is that there's a field, this gauge field or the Higgs field, which permeates space, and it tells particles how to behave. If it had a value of zero, all the forces would ace the same on a particle. So in fact, there wouldn't be four forces. Only maybe one. But if the gauge field has a particular different value, that means that it reacts differently to charge and to color, and it therefore behaves like the forces are all different. So it's these forces are all really the same, but there's this mysterious, invisible, unobservable field that permeates space that makes it act different.

BRIAN SCHMIDT: Right. And normally, we think of the energy state of the universe as being the thing that tells this single thing how to behave. And at low energies, like we're at right now, we've got these three, and gravity fits in there somehow. We're not quite sure how yet. But when the universe was very young, maybe they acted as one.

PAUL FRANCIS: So that's simplicity, and that's how it fits in. Can we fit these forces together? And we've got these gauge field theories to do that.

Then we get to symmetry. Now symmetry is something that's taught in ordinary primary school, and normally it's taught purely in geometrical terms. For example, this is a symmetrical shape because you flip it over this way or flip it over that way, it looks the same.

BRIAN SCHMIDT: You can even rotate this by so many degrees, 1/5 of the circle.

PAUL FRANCIS: And it will look the same. But to a physicist, we have a more general definition of symmetry. This is the idea that you have a transformation, something that changes things, and if you change things but they remain the same, that's a symmetry. So in this case, one transformation would be to flip it, and it remains the same so it's got a symmetry. Likewise the rotation by 1/5 of a circle. That's a transformation but it remains the same, so it's a symmetry.

But there are other examples of this. Perhaps the best one is translational symmetry. If I do an experiment here, I move over here and do the same experiment, there's been a transformation. I've moved, but the laws of physics and hence the results of the experiment are the same.

BRIAN SCHMIDT: This turns out to be very useful, and the world would be a very funny place if that were not true. And we often use that in determining these laws that that is true. You need it to be true because reality as we know it would fall apart if it were not true.

PAUL FRANCIS: Yes, and we used this in the previous course to deal with relativity. And in fact, it turns out that if you make this assumption that all the laws of physics are symmetrical-- under transformation that moving doesn't change anything-- you can actually derive Newton's laws of motion and the conservation of momentum from that.

Likewise we have time symmetry. If I do an experiment now, I do it a week from now, the laws of physics should be the same. That's a symmetry in time. The transformation is going forward through time. The experiment are the same, so it's a symmetry, and it turns out you can deduce energy conservation from that.

BRIAN SCHMIDT: This is one of the advantages of physics over, for example, economics, which my wife studies, where the experiments turn out to change over time because people change. It makes it much, much harder.

PAUL FRANCIS: So we have these two fundamental principles that particle physicists like symmetry and simplicity. The trouble is there's a bit of a conflict between them here. We've just talked about unifying all these forces. So we've got one force that can behave like lots of different things, and that seems almost to violate symmetry. Why should it choose to behave like this rather than behave like that?

BRIAN SCHMIDT: Right. So we need to have something where it doesn't really act symmetrically at some point.

PAUL FRANCIS: But it turns out that there's an example we can get from a different area physics, which is solid state physics, that can help explain these things. This is called spontaneous symmetry breaking, and the idea is that you can have symmetrical laws of physics which have non-symmetrical, asymmetrical results.

And the example would be a crystal. We always think of crystals as prime examples of symmetry, but in a crystal all the atoms are lined up in particular directions, but why one direction rather than another? It kind of seems like a crystal has to make an arbitrary decision.

BRIAN SCHMIDT: Why am I going to go that direction rather that direction?

PAUL FRANCIS: You take, for example water, and you cool it down until it goes below freezing, and then it has to form crystals. The crystals will have to pick a direction to line up. Why one direction rather than randomly as they were before? That seems almost to violate symmetry.

And the way we explain this is with an energy diagram, what's called a Mexican Hat energy diagram. I don't know if Mexicans actually wear hats with quite this big a brim, but--

BRIAN SCHMIDT: It's a sombrero which sort of goes out of control on the edge.

PAUL FRANCIS: So the idea is that let's say you have a water molecule. It can point, line up, this way or that way. In reality, it would be a three dimensional thing. It can point any way. But let's simplify and say it can either line up that way or line up that way.

And here's the energy depending which way it's lined up. So it turns out that when you're water, your energy level is up here, and that means it can be pointing any way, and it will jump back and forth between this as the atoms jostle around.

BRIAN SCHMIDT: So it'll be going doop, doop, doop, depending on where it is here in this diagram.

PAUL FRANCIS: That's because the energy level is up here, but let's say you cool everything down. The energy level of the water goes down until eventually at zero it hits here. Now if you cool it below zero, this is no longer really possible. It has to make up it's mind. It had to go either one way or the other.

Now this is a symmetrical Mexican hat. It's not like any realistic Mexican hat I've ever seen. It's very symmetrical. But it forces the water to make a decision. It has to go one way or go the other. And in fact, if you cool down a bit of water or crystallize something as a solution, you'll find the different bits go different ways. There might be one bit over here that starts forming a crystal pointing that way, one bit over here that forms a crystal pointing this way.

BRIAN SCHMIDT: And then you get these really cool structures were you get sort of a crystal on a crystal coming together at different angles. Not so much in water, but you'll see that in, for example, salt crystals and things. And that's where one thing has literally broken the symmetry in one direction and another bit in a different direction. They eventually have to come together.

PAUL FRANCIS: And it turns out this idea of a Mexican Hat energy diagram and spontaneous symmetry breaking is going to be fundamental to explaining our cosmological conundrums.

A4_L3_V03_Inflation

BRIAN SCHMIDT: All right Paul, so it turns out that when the particle physicists look at the Higgs Theory, the Higgs Field, they predict that it's going to have this shape, the shape of a Mexican hat. And how can that help us understand the universe?

PAUL FRANCIS: Well, it's a very good analogy to cooling water down. When the universe is very, very small say, 10 to the minus 50 of a second after the Big Bang, the energy level might be really very high up here. And that means the Higgs fuel is going to change in value anywhere from there to there. And one average is just going to be middle. So it might be from quantum mechanical fluctuations briefly this way or briefly that way. But most of the time it's going to be 0. And because it's 0, that means the forces are all going to behave the same. So everything's unified.

BRIAN SCHMIDT: So that means that at that point, electromagnetism, gravity, potentially the strong force, the weak force, are all going to behave the same because it's really the average of all of them at the same time.

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: Because things are able to move throughout this energy diagram which we have to think is not just being a single plane but actually in multidimensions.

PAUL FRANCIS: Indeed. But of course as space expands, it gets cooler. The energy levels drop. And they drop, and they drop, and they drop until sometime maybe about 10 to the minus 40 of a second after the Big Bang, they touch down here.

BRIAN SCHMIDT: You suddenly find yourself abruptly grounded, to sort of speak.

PAUL FRANCIS: Yes and the energy level will keep dropping. And now, the field has to make up its mind. It has to go one way or the other. And so it's going to end up maybe over here or over here or in some other multidimensional Mexican hat in some other direction. But it's not going to be 0 anymore.

BRIAN SCHMIDT: So essentially, it's going to plop down and then kind of slide down the slope one direction or the other.

PAUL FRANCIS: And if it goes over here, it'd have to make up it's mind. It might decide we're going have a strong force that's strong and a electromagnetic force that weaker. A weak force is even weaker. Or it might down here. The forces might be permuted. So what we call the weak force in the university over here might be called a strong force, or some different combination of the laws of physics and forces swapped around. It's got make up its mind and give and asymmetrical outcome.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: How does this help us. Well, if that was all there was to it, it's a nice way to reconcile unification with symmetry. But the thing that's potentially very exciting for cosmology is what if something gets stuck up here?

BRIAN SCHMIDT: Ah, so this is the moral equivalent that I'm coming down fast from jumping out of a helicopter will a parachute on, with the pair of skis. I'm going to go heli skiing out and rather than a helicopter. And I land on a very flat plateau on the top of the hill expecting to ride down the valley. But there's essentially no slope. So there's no place for me. I just get stuck where I'm at.

PAUL FRANCIS: Yes you cab almost imagine it's like the universe being a ball that's sitting on the top here. As long as it remains on the top, If the top of this hat is very flat, it won't go anywhere. Eventually some, random quantum mechanical fluctuations will star it rolling down one side or rolling down the other side, which side it goes is going to be random. But in principle, if the top of the site is very flat, it sits up here for quite some time.

BRIAN SCHMIDT: So I'm going to be stuck at this very high energy level while the universe expands.

PAUL FRANCIS: Yes, so the energy level of the universe will keep on dropping. I might get down to here while all the time you're stuck up there. And that's what's called a false vacuum.

BRIAN SCHMIDT: Right, so the real vacuum is down here at 0. And this top hill where you get stuck in, is false vacuum.

PAUL FRANCIS: Yes. And this false vacuum has energy relative to the true vacuum which is the difference from there to there. And that is absolutely, absolutely enormous. 1 cubic millimeter of the universe back then, the amount of energy in the false vacuum then, would be to taking absolutely every galaxy we can see in the observable universe combining with an antimatter galaxy at the same amount, destroying entire university residual energy. And that would be just 1 millimeter of universe back then. In fact, it's a million, million times less than 1 millimeter right then. So absolutely staggering amounts of energy and hence mass because they're interchangeable in every tiny bit of space that stuck in the false vacuum.

BRIAN SCHMIDT: OK, so if we think about how this is going to look in one of our equations, the Friedman equation that we talked about, it's going to be interesting. Because we have the change of the scale factor, And we're going to have this amazing amount of energy in the form of what we call density. But remember energy and density are interchangeable. So that's going to be huge so you're going to have a constant, times a huge value is what the and the change in the size of the universe is going to be proportional to this.

PAUL FRANCIS: Yes and so, if you take the square root, you're going to get a dot over a equals square root of something enormous which is still pretty enormous. Bring a over to this side and you're going to get a dot the rate of change of a is going to be proportional to an enormous amount of times a

So what that means, the universe is going to be expanding really fast.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: And then it's just going to get bigger. And then it'll expand even faster.

BRIAN SCHMIDT: So it says that the rate that the universe expands is proportional to how big the universe is. So if I my size is 10 , and I'm changing by 10% per second, then that would make me 11. And then my next change would be 10% of 11 which is 1.1. And that's what we call exponential growth, like inflation, for example of a common.

PAUL FRANCIS: The mating of rabbits from in Australia.

BRIAN SCHMIDT: Exactly, breeding of rabbits. Anything exponential has that characteristic. So we expect exponential growth.

PAUL FRANCIS: It sort of looks something like this. Here's the scale factor of the universe versus time. And it will grow. As it grows, the scale factor gets larger so it grows faster. So the scale factor is even faster and faster. And it goes up like a rocket.

BRIAN SCHMIDT: Whoosh.

PAUL FRANCIS: Actually much faster than a rocket.

BRIAN SCHMIDT: Yes, I wished that I had a rocket that could exponentially take off. All right, so we're going to have an interesting universe that is going to grow incredibly fast.

PAUL FRANCIS: Yes, and this is the core idea of cosmic inflation.

A4_L3_V04_Fixing_the_problems

PAUL FRANCIS: So we've got this idea that the universe gets trapped in a state of false vacuum, and as a result for some brief period of time back when it was incredibly young, expands absolutely like crazy. But how does this actually solve our three enigmas?

BRIAN SCHMIDT: Well, let's start with the first one. The fact that if I look at two things on the sky, they have essentially the same temperature now. They seem almost exactly the same. The only way we know how to do that is for them to have been in contact in the past. So the problem is when we run the universe back when this doesn't happen, you get a trajectory. And I take those two points and boom, back at the time of the Big Bang here at t equals 0, they're still separated. They never had a chance to get together and talk to each other.

Now let's think of a universe that exponentially expands. So that's one which is kind of minds its own business and suddenly goes woo. So instead of being extrapolated back here, it means you've given the universe the time to literally go and get together. And so it's a finite amount of time. The two objects are right next to each other so they can be at the same temperature. So that's a good start.

PAUL FRANCIS: Yeah, so that the bits of the universe are much closer together out here than we would otherwise expect, which allows them to actually merge. Then during the expansion, they were expanding faster than light. You might think nothing can travel faster than light. But actually, nothing's moving. It's just being carried apart by the motion of space. So in fact, they can travel faster as matter if space is doing all the work. And so that carries them apart to the current distances where they cannot contact each other. But they could have been in contact in the past. So that's nice.

BRIAN SCHMIDT: OK, so there's one thing.

PAUL FRANCIS: Tick.

BRIAN SCHMIDT: So let's think about the next one.

PAUL FRANCIS: So curvature, the idea here was that we know that the universe is fairly close to being flat. We're not sure how close yet. But if it was curved, either it was a spherical universe or a saddle shaped universe, it should get more and more curved or more and more saddle shaped as time goes on. And so by now, even a very small deviation in beginning should have amplified into enormously small or enormously curved, one way or the other. And if fact, we know it's pretty close to flat at the moment.

BRIAN SCHMIDT: But if we exponentially expanding the universe, you're going to take a curved piece of universe and you're going to make it really, really big. And so suddenly, it still looks a little curved, but not as curved as before. Now imagine magnifying that by 60 orders of magnitude, which is what we think may have happened in the early universe. Then that idea is you make a circle bigger and bigger. You can actually on a computer, for example, make it out of straight lines. Well, our little part of the universe, the curvature will look like a straight line it will look flat.

PAUL FRANCIS: You take any shape you like, no matter how curved and you expand it by 60 orders of magnitude. And any bit you're going to see locally is going to look pretty flat after that.

PAUL FRANCIS: Yeah, it's sort of like the Earth actually. This is why people think the earth's flat. At least some people do because it looks flat to them locally.

PAUL FRANCIS: OK, so there's another tick. It solves this problem. How about the origin of the lumps that make the universe have galaxies?

BRIAN SCHMIDT: So let's start random universe off, you don't end up with this map, this map of how galaxies make this cosmic foam. So if you're expanding exponentially, something by 60 orders of magnitude, then you're going to take something smaller than an atom and expand it to the size of the universe.

PAUL FRANCIS: But we know that on scales small as atoms, space is not smooth because of quantum mechanical fluctuations. We've talked about this a little bit in the very first course in the series. So-called empty space isn't really empty. You've got particle, anti-particle pairs spontaneously appearing and disappearing. And this sounds like fantasy, but it's actually quite measurable in our laboratories. In fact, it's being tested every day on labs around here at the ANU.

So the idea would be that these tiny quantum fluctuations that happen to be happening just at the moment inflation took off would get stretched enormously. And so a fluctuation that might have been the size of an electron, end up forming a super cluster of galaxies today.

BRIAN SCHMIDT: And one of the interesting things is normally if you think of Paul and I as being a set of quantum fluctuations-- and you'll be real matter and I'll be anti or whatever-- we are formed. But because the universe is exponentially expanding in that very tiny period of time allowed by the Heisenberg Uncertainty Principle, we've expanded so much that now we're further than the speed of light can connect us.

PAUL FRANCIS: So we can never recombine.

BRIAN SCHMIDT: So we can never recombine. We become suddenly real particles, not virtual particles. Real particles. And that's what we think made the bumps and wiggles in the universe. They're amplified particles that have been created to be huge. And it turns out, you get a very specific white noise look to what the bumps and wiggles should look like. And that's exactly what we need to make the patterns of galaxies.

PAUL FRANCIS: A so called scale free spectrum means there's equal amounts of lumpiness on every scale from very small up to very large. There is one problem here before we give this a big tick. It does predict that there should because fluctuations. It says they come from quantum mechanics, and it predicts the relative amounts of big and small one should be the same. But the amplitude is completely arbitrary. It could predict the fluctuations are a billion times bigger. So everything would collapse tomorrow in a black hole a nanosecond after the Big Bang. Or a billion times smaller, in which case nothing would ever have formed. That all depends on the crucial exact shape of this Mexican hat, which isn't really a firm prediction from the theory. So it gets the spectrum right and the existence right. But there's still a bit of a fudge factor in there for the right size of these fluctuations.

BRIAN SCHMIDT: But it does get ticks. I'm a very skeptical person here who was around before the structure of galaxies were measured. It got that right in advance. And before the curvature of the universe was measured, it got that right in advance. And indeed, I thought the universe had curvature when I was studying it as a graduate student. It turns out, it doesn't have much just like this theory predicted.

PAUL FRANCIS: So it's a good theory. A theory that can actually predict things ahead of time. It's all too easy to come up with a theory after the event that explains things. Politicians do that all the time. But to actually appear to predict something before it happens, that's a good sign.

BRIAN SCHMIDT: Yeah.

A4_L3_V05_End_of_Inflation

PAUL: Now hold on a minute, Brian. This doesn't really sound like our own universe, expanding exponentially at some incredible rate.

BRIAN: Well, it is expanding exponentially. But not an incredible rate yet. So the idea that this would have started in the past seems to indicate it would have had to finish at some point.

Also, we wouldn't be here, because the universal would be expanding literally faster than the speed of light.

PAUL: Yes, I mean, if inflation had kept going, by now every atom would be within the horizon length of any other atom. So nothing could ever form.

BRIAN: Right. So you'd be an individual atom, all on your own. So something has changed that.

PAUL: It's got to stop it.

BRIAN: So let's look at that Mexican hat again.

PAUL: So how's it going to stop it? Well, I guess it's going to roll off the top and eventually reach the bottom.

BRIAN: Right. So if I land on that hill with my skis, one could imagine that even if it's perfectly flat, I will get a quantum fluctuation that moves me a little closer to one direction until eventually I do hit a bit of hill. And of course, once I get some slope, then I'm really going to slide down pretty quickly. I'll gain speed and slide down to the bottom at some point. But it does require some sort of-- either this has to be perfectly flat, or for me to get moved over by some quantum fluctuation.

PAUL: How long it's going to take is going to depend on the exact curvature up here. Which is very unclear in the models. The slow roll and fast roll models in inflation have different amounts of slope on the side here. But that's the basic idea. So what you might have is a universal-- and I've done in blue here the bits that's inflating that's all still stuck in that force vacuuming, and growing exponentially.

BRIAN: OK, so everything in blue is growing exponentially-- just faster than you can imagine, has that incredibly high energy, it's full of energy, growing exponentially.

PAUL: But let's say a couple of bits-- maybe this bit down here, that bit down there-- have rolled off the top, and landed down at the true vacuum.

BRIAN: OK, so-- OK, so here, whatever reason, that part of the universe rolled down, and something-- it's now at a lower energy?

PAUL: So it's going to be that's the stable of the new lower energy.

BRIAN: Yeah.

PAUL: And it could be that one rolled down one way, and this bit rolled down some other way.

BRIAN: Well, so if you roll down the hill differently, that means the way the forces of nature work together might be different.

PAUL: Yeah, they might swap with each other, so--

BRIAN: So you're saying, then, the laws of physics here, and the laws of physics there, might well be different, because the symmetry would have been broken differently.

PAUL: That's right.

BRIAN: Oh, OK.

PAUL: So you've got regions of the universe, which are now expanding at a much more sedate rate, with possibly different laws of physics. And this is actually a very-- and what we talked about earlier, cooling down water. Just imagine you've cooled down water.

BRIAN: Yeah.

PAUL: Once ice crystals start to form, they might form in different directions, different parts of the water. And then they'll start to expand very rapidly.

BRIAN: Right. So I start getting a lattice this direction, and a lattice that direction there.

PAUL: Because if you're got a false vacuum near here, you're going to want stick onto this and follow it out. These regions are going to expand at the speed of light.

BRIAN: Oh, so they're expanding at the speed of light, so they're going to end up colliding with each other, aren't they? So they're going to end up looking--

PAUL: Well you think of it as something like this.

BRIAN: --like that? So we should be able to see that in the universe?

PAUL: Yeah. You might imagine we might be in this universe over here. And we'd be able to look over here, and there'd be a boundary where it's bumped into another bit of force with different laws of physics, which can be kind of cool.

BRIAN: Well, we do have one issue though. This is exponentially expanding. So it's span expanding fast than the speed of light can in that exponential expansion.

PAUL: Yeah. So actually, that's what would happen. They would actually touch.

BRIAN: Right.

PAUL: They'd just fly out. They'll expand, but the space between them is growing exponentially. And even the speed of light can't compete with exponential growth.

BRIAN: Right. So you're going to have this little universe here nucleate as like a little crystal and blow up. And we're going to have this other one on the other side, so far apart they can't see each other. And then you get all these little island universes, so to speak. Little island universes going off in all directions.

PAUL: And possibly new regions will form, maybe with even different laws of physics. And then they too will start expanding. They'd get carried apart. So this is actually an interesting way of having an eternal universe. This is the idea of eternal inflation.

That while our particular universe-- we're living in one of these regions-- we see a definite beginning in the Big Bang, the whole thing could keep going forever. That you have this universe, most of which is inflating, but every now and then a bit nucleates, and forms a normal universe. Which expands like crazy and gets carried away. And then another bit nucleates and gets carried away. So you're endlessly generating more universes out of a sea of inflation.

BRIAN: And since this inflation is going literally faster than light can travel, you really end up with this bizarre situation where the universe goes off in all directions. And no other part of the universe-- of one universe-- ever talks to another one. It strikes me as rather hard to test.

PAUL: Indeed. And you'd think you might run out of the false vacuum, and individually everything would nucleate. But of course, it's going exponentially. So no matter how much nucleates, there's always more to it.

BRIAN: Right.

PAUL: It's growing faster than it could ever nucleate out.

BRIAN: Right. So it really does go on forever. It does seem like the ultimate free lunch at some level.

PAUL: Yes. And of course, this all depends on ideas of the exact shape of this Mexican hat, which are very untested.

BRIAN: Yeah.

PAUL: And in fact, in the next video we're going to ask Lawrence Krauss, a local theorist who spends a third of his life here, and understands these things far better than you or I--

BRIAN: Yes.

PAUL: --to actually talk us through how realistic this whole thing is. Before we get onto that, you had something you--

BRIAN: Yeah, so you know--

PAUL: --news about this Mexican hat diagram.

BRIAN: That was really something that a number of people have said, and including Stephen Hawking. And he was saying, the value of the Higgs particle that we've measured, and the value, it turns out, of one of the quarks-- the top quark-- are such that when you put those into our theory-- particle physics-- that the Mexican hat has a brim that turns over, and then goes down forever that direction-- and that side as well. So it's like we're in-- the idea would be, if that were true-- is we would be in a false vacuum now. And there's a hill between us and where this turns over.

But if we were to ever get over that hill, by, for example, quantum fluctuation, we would have a wild ride-- the universe would-- at the speed of light, down the hill until something else changed. Which means that if that were to happen, the universe would suddenly-- from our point of view-- disappear. Because it would, whatever part of it, would come towards us at the speed of light, and everything would be gone instantly.

Now, I have to admit I'm not terribly worried about this. Because you will, by definition, not know it's going to hit you. And when it does hit you, it doesn't matter, because at the speed of light you're gone.

But we really don't understand the particle physics well enough. Or have we even measured the Higgs mass in the top quark well enough for us to be really worried about it? But it does show you kind of the wild things that are possible in the mind of a particle physicist.

PAUL: So let's go and talk to a particle physicist, Lawrence Krauss, about how realistic this whole thing is.

A4_L3_V06_Krauss_inflation1

BRIAN SCHMIDT: Welcome. And today, we have with us Professor Lawrence Krauss from the Origins Project at the Arizona State University. Lawrence is a theoretical physicist. Paul and I, tend to be what we call observers. And so we have a very different way of looking at the universe, as we're going to explore the topic of inflation.

So inflation, we've been talking about as a way to sort of make the universe sensible, as it starts out. So do you see the evidence for inflation being strong?

LAWRENCE KRAUSS: Well, it's grown a lot. Inflation was a beautiful idea, actually an idea in search of a theory for a long time. As you've probably talked about, it's the only fundamental physics way of understanding the smoothness of the universe and the apparent flatness of the universe, all the paradoxes of the Big Bang. It's a beautiful idea. And it kind of smells right, if you're a theorist.

But the problem is we didn't have any direct theory that predicted it. And other than postdicting these notions of flatness and uniformity, the question was, did inflation make any predictions which could be tested? Because that's the key aspect of a really successful theory, is it's got to be falsifiable.

BRIAN SCHMIDT: Yep.

LAWRENCE KRAUSS: One of the early predictions, besides flatness and isotropy, is the notion of the generation of primordial fluctuations, which would later collapse to form all the structure we see in the universe today. And inflation predicts such fluctuations and such structure in a really beautiful way. In fact, by using quantum mechanics, remarkably. What it does is it turns quantum fluctuations in fields, during the period in which the universe is expanding, into classical density fluctuations. If it's really true, then we're all here due to quantum fluctuations, which I find amazing.

There are characteristics of these quantum fluctuations in inflation that are testable. The first is that they predict so-called adiabatic density fluctuations and that they're Gaussian. They're Gaussian random fluctuations. Those are properties of quantum mechanics.

When we look out at the microwave background, radiation, one of the key aspects of that observation is to look at those primordial fluctuations as characterized in temperature differences across the sky. And amazingly, all the characteristics of those fluctuations are in agreement with inflation. And so I'd say that once we tested that with great accuracy in the CMB, the stock in inflation went up.

BRIAN SCHMIDT: So one of the things you said was that this is the only way to test with particle physics theory. So I want to probe that. Is it really the only way? It's certainly the only way we seem to have right now. But some people are out there doing other things, within that regime, to find another way to give you essentially the same answers.

LAWRENCE KRAUSS: Well, you anticipated what I was going to say, because I want to be clear and honest about this. Because the predictions of inflation are in great agreement with the structure of the fluctuations of the cosmic microwave background. But what you didn't give me a chance to say is that they could have been in agreement even if it had been different.

Inflation is a very robust theory. But at some level, it's malleable. In particular, the nature of fluctuations that are produced depend upon the specific inflationary model. And we don't know the inflationary model.

So if inflation could have agreed with more or less anything we saw, you might say that's not a very robust test to inflation. But there is a more robust test to inflation. And, in fact, it's what many people would call the smoking gun that we've been looking for. Which is the fact that inflation generates not just density fluctuations, fluctuations in all fields, it generates fluctuations in gravity. And those get turned into gravitational waves. And inflation unambiguously predicts a spectrum of gravitational waves, which is independent of all the detailed models-- the nature of inflationary models.

The scale of inflation determines the intensity and amplitude of gravitational waves. The spectrum is basically flat on the sky. It means it's the same power on all scales.

And that prediction of inflation is robust. Namely, it's not model dependent. And once it was recognized that that was the case, and it was recognized that you could look for that signature in the microwave background-- there's two ways, of course, to look for gravity waves. We look for gravity waves directly on the ground with large-scale interferometers. And Australia plays a role in that, in fact.

But it turns out that those aren't really sensitive to the kind of gravitational waves which are very long wavelength, that are residual waves from inflation. And you might look for it in time variations in millisecond pulsars or binary pulsars. But again, they're not yet sensitive.

But the gravitational waves that come from inflation produce two effects. And I'm happy to say, about 30 years ago, we predicted one effect, which is that gravitational waves are quadrupole waves. Namely, they squish space in one direction and they stretch it in another.

And what they would produce, effectively, if you think of the last scattering surface, where the cosmic microwave background is produced, if a large-scale gravitational wave comes by, an electron, which is about to scatter radiation towards us, would see a hotter universe in one direction and a colder universe in another direction. Well, that will be reflected, in a sense, in direct anisotropies in the microwave background. And if gravitational waves are big enough, then you predict-- you can see it. And we argued, in fact, if the scale of inflation was high enough, they could have accounted for all of the initial anisotrophy that was observed by the COBE satellite in 1992, which really was mostly sensitive to particle radiation.

But it turns out that we've now looked at the microwave background a lot more in the last 30 years. And those anisotropies are not seen. But the same kind of squishing and stretching means that an electron will see higher intensity electromagnetic fields in one direction and lower in another. And if you think about it, when it scatters radiation, it will produce radiation that is polarized when that radiation comes towards us. The electric fields will be stronger in one direction than another direction.

And it's polarization that has a very particular characteristic. It's kind of a twisting pattern.

BRIAN SCHMIDT: Right.

LAWRENCE KRAUSS: That other sources don't produce that kind of twisting pattern. And so once it was recognized that gravitational waves for inflation could produce polarization of the microwave background, that became the holy grail. I would say that, for all cosmic microwave background experimentalists, that was the next great leap forward. And so there were a lot of experiments developed-- and ongoing experiments-- looking for that because that would really be the smoking gun.

This year, in 2014, earlier in the year, an experiment-- the BICEP experiments-- BICEP2-- reported a result which looked exactly like gravitational waves from inflation-- and I mean exactly. The characteristics on scales and the spectral characteristics were identical to what you'd expect from inflation. It was a surprise because the amplitude was so high that we might have thought some other experiments might have seen it, like the Planck satellite, although there were reasons that it might not.

And it was a real shock to people. And I must say, people got very excited. In the interim, it's been recognized that potentially polarized dust in our galaxy might mimic the signal, not all aspects of the signal. And frankly, when I look at it as a theorist-- and an observer, you may feel differently-- I would still say the characteristic signal-- the signal looked more like inflation than dust. But it could be an unfortunate accident. And it's up in the air.

By the time this airs, this will be resolved, probably. Because the Planck satellite is doing measurements of dust in a better way. And other experiments are looking at polarization.

And we should know, I would say for certain, within the period of a year, whether this signal is real or not. And if it is real, it will have changed everything. Because that will mean that, in principle, inflation really happened. And we know it empirically, as well as being the best theoretical model of the early universe that we have.

A4_L3_V07_Krauss_inflation2

PAUL FRANCIS: Now Lawrence, to make inflation work we need an inflaton field, a field with a strange potential Mexican hat thing that causes the false vacuum and the negative pressure. Now, is that just something people said, well, we need to make it a fresh step. Let's invent a magical force that does this. Or is there actually some physical reason for believing there might actually be a field in the universe with the right energy and this rather weird potential.

LAWRENCE KRAUSS: Well, the answer to that question is yes and no. The point that you should realize is that, look if you're a particle physicist, there's lots of things you can just invent to solve problems of cosmology. But the question is, are they well-motivated?

And inflation was actually developed not because people were searching for a cure for these problems. In fact, most particle physicists didn't even know these cosmological problems existed. It was motivated because, in fact, at the scale which we now may have measured gravitational waves at, at that scale we think the three non-gravitational forces in physics come together into what's called a Grand Unified Theory.

And it was thinking about the physics of Grand Unified Theories that led Alan Guth originally to realize that one of the consequences might be inflation. So in fact, it is extremely well-motivated. The idea of spontaneous symmetry breaking, and the fact that there may be some field in the universe that gets some expectation value, that has some magnitude invisible field throughout all of nature, may sound very strange.

But again, that's now on better footing than it was before, as well, because two years ago at the Large Hadron Collider in Geneva we discovered the Higgs particle. And the Higgs particle is related to a field that was predicted to exist throughout all of empty space that literally gives mass to the particles that make up your body, my body, Brian's, body, and everything we can see in this room.

It was a bold theoretical idea. Many people had great confidence that it was true. Frankly, I thought it was a little too simple to be true. I thought Nature would come up with something a little more inventive. But it's true.

So there are fields that affect the characteristics of particles. And if there's a field that has energy associated with it, at very high energy it will affect the expansion of the universe. In fact, the acceleration of the universe that Brian discovered could be due to a similar field, but one that has very, very little energy.

In fact, the big puzzle for us is, if there is such a field, why is this energy so small? If there was the same phenomena happened at the Grand Unified scale that happens at the electroweak scale, it could may produce inflation.

Now, let me make this clear. There's a field of the electroweak scale that gets a value in space, and what that does is cause the electromagnetic force and the weak force to suddenly start to look different. Before that they looked identical. When that field gets its value, photons, which travel through space, don't interact with that field-- and behave massless-- but the particles that convey the weak force, the so-called W and Z bosons, interact with that field and get a mass.

So that's what we call spontaneous symmetry breaking and those two forces which were once the same now look different. Now, at the Grand Unified scale, it looks like not only does that electroweak force get unified at the scale of the Higgs particle, but it gets unified with the strong force. We can do predictions based on real calculations and measurements, and we would predict, in principle, that they come very close together and they might be unified, and a very similar phenomena can happen.

There's a big difference. So the idea of spontaneous symmetry breaking is very well-founded. The scale at which inflation could happen is very well-founded, and is a natural scale in particle physics. We don't just invent it to solve some cosmological problem.

That's the good news. The bad news is twofold. First of all-- happily for us, actually-- for some reason that we don't understand, when the Higgs field gets its value throughout space, that doesn't carry any energy associated with it.

If it did, if it carried an amount of energy that you'd naturally expect it to do, the expansion of the universe would have been so fast that galaxies would never have formed and we wouldn't be here to have this discussion. We still don't understand that.

BRIAN SCHMIDT: So we would have got an acceleration back a long time--

LAWRENCE KRAUSS: We would have got the acceleration you observed, but it would have been so great you wouldn't have ever been born to observe it. And we don't know why it has no energy.

If the field that gets an expectation value at the GUT scale does get the kind of energy we would expect, then you'd naturally get inflation, OK? In principle, you'd get inflation. But there are some additional features, some wrinkles, which mean that the kind of models that produce inflation are very special.

So as natural as the idea of inflation is, the models that produce it are a little fine-tuned. Here's the first aspect. One thing is that we actually can try and extrapolate the strength of the known forces, if all the particles we observe are all the particles that exist, and they don't come together at a single point. You don't get Grand Unification.

In order to get Grand Unification, you have to change things. And one of the things we predict is that there should be a new symmetry of nature, called supersymmetry, which if it produces particles at the scale that we might measure at the Large Hadron Collider when it turns on again in 2015, we change the nature, the ways in which the forces change, and the fact they do all come together at a single point. That is one of the greatest motivations for thinking that supersymmetry exists.

So we need something new in order to motivate having Grand Unification. So that something new may not exist, OK? We don't know. That's one wrinkle.

But the other wrinkle is that when this field gets an expectation value, it's involved in what's called a phase transition. And phase transitions can happen very fast. In fact, the electroweak phase transition when it happened when the universe was a millionth of a millionth of a second old, since we now have measured its parameters, we think happened very fast, OK?

The nature of the field changes. The way the forces behavior changes. Nothing remarkable happens. In order for the field that makes inflation happen, to make inflation happen that phase transition can't happen very fast, because if it does, all of the energy stored in empty space that would cause the acceleration of the universe gets released into particles and radiation. And of course, the whole point of inflation is that you've got to have at least 60 e-folds of expansion to explain the paradoxes we now see today in the universe.

So the universe has to get stuck in this metastable state. Well, getting stuck in a metastable state is not that much of a problem, but eventually inflation has to end, so you and I can be here. And that means the characteristics of the model that produces inflation are somewhat fine-tuned.

PAUL FRANCIS: So it's something like the shape of the Mexican hat has to be--

LAWRENCE KRAUSS: The shape of the potential

PAUL FRANCIS: --the right flatness at the top and the right rolling over.

LAWRENCE KRAUSS: It has to be flat enough so that the field doesn't quickly fall off and release all its energy. But it can't be too flat and never release its energy, otherwise inflation doesn't end.

So the problem is that there is no natural model that we have right now that produces inflation. If you did the simplest, most naive model that produced Grand Unification, it probably wouldn't produce inflation. So we're not driven.

I mean, if there was a natural model, it'd be wonderful, because we'd say, let's compare every observation to the predictions of that model. But the problem with inflation is, it's well-motivated as an idea. The scale is well-motivated. But right now, it's an idea rather than a theory. And we don't have a model, which is why we want to measure gravitational waves and other features of the universe, because it's probably the only way we'll be able to measure the particle physics.

We build the Large Hadron Collider to look at that Higgs particle, but to build a collider to measure the physics that's relevant at Grand Unification, it would have to have a diameter of something like the Earth moon's orbit. It's never going to happen. And so the universe may be the only way to test these ideas.

So inflation is well-motivated in principle, but in practice the models are a little contrived, and we don't yet understand the physics. The only way we'll understand it-- we theorists can come up with lots of contrived models. That's what we get paid to do, Brian would probably say. But in fact, we rely on experiment to tell us which direction is the right one, and we don't know.

But one of the interesting things about inflation that's been recognized is that it doesn't have to end very effectively. One of the big problems when Alan Guth first developed inflation was, how do you get it to end? Andrei Linde pointed out that, in fact, not ending is better than ending, in general, because what you can have-- and in general, from many inflationary models-- will be so-called eternal.

Because what will happen is that the fields will stay in a metastable state in most places. Every now and then, for various reasons-- quantum fluctuations or other processes-- it'll get kicked out of that state and a phase transitional will happen, and it will produce a Friedmann-

Robertson-Walker expansion, a hot, big bang universe. And that's what presumably happened in our universe.

But that's not all of space. That's just a small seed, if you wish. And if this idea is correct, most of space is still expanding exponentially. Most of the what we would now call a "multiverse," namely most of the what is all a space is not our universe. Our definition of the universe has change.

In fact, that's probably a very important thing. When I was young-- and maybe before Brian was born, I don't know-- we used to think of the universe as being everything there was, everything there is. That definition has changed. The universe now, for theorists and, I think, observers, is rather that amount of space with which we will one day be able to communicate or could've communicated. Namely, it's that region that can have a causal impact to us. That's our universe.

But we don't pretend that that's everything. There can be stuff outside of our universe, stuff we'll never be in contact with. If inflation is right and it's eternal, most of space is, in fact, outside of our universe, and most of space is still inflating. And in other regions of that eternal inflation, another universe may be popping into existence today. Another Friedmann-Robertson-Walker expansion may be occurring this instant, and other ones could have occurred in the past, and other ones could occur in the future.

That idea is fascinating, because it changes our picture of what may be possible in the universe, and we'll probably get to it. It's led to a lot of speculations that some people are very comfortable with-- particularly observers-- but some of us theorists are, too. But inflation, the idea that inflation is eternal, it's probably more likely that it isn't. It's harder to end inflation globally than it is to have it go on and just have small regions become universes.

Well, I don't know if you have a question that you want to ask. I could anticipate it, but one of the facets that's also, again, good and bad-- there's two sides to every coin-- is that if you could have many universes, inflation can end in different ways. It turns out the symmetry breaking can happen in different ways, and it replaces.

Just like ice crystals. When you form ice crystals on a window, the crystals can point in many different directions locally, and if you lived on one of those ice crystals, that one direction would be very special. In our universe, the forces of nature evolved in the way they are. But it could be, in another universe, the symmetry breaking happened in a different way, and that would mean the laws of physics are different in that universe.

A4_L3_V08_Krauss_inflation3

PAUL: So Lawrence, you're suggesting this idea that inflation goes on forever, and different parts of the universe will crystallize out and form universes like our own. But this is almost kind of a way of merging the steady state and the Big Bang theory, because you have a universe that, well, our particular bit of it has a definite origin. The universe, as a whole, is going on forever.

LAWRENCE KRAUSS: Well, in fact, in a philosophical sense-- and I hate to use that word-- inflation does, in a way, on the larger scales, reproduce a steady state kind of picture. Because it's saying, on the larger scales, on the multiverse scales, the multiverse is always looking the same. It's inflating and at any instant, there are universes being created, there may be ones that are dying.

And so, on large scales, the universe doesn't change. Its always-- I mean, locally it does, but globally, it always looks the same. Locally of course, in any given universe, there's a big bang. So in a sense, inflation for the multiverse does sort of resurrect, but in a well-motivated physical way, unlike the standard steady state theory.

It motivates the fact that-- I mean, let's step back. Inflation is remarkable. It seems almost magical. It's the ultimate free lunch, as Alan Guth has said, because it defies common sense.

But nature loves to defy common sense. That's why we do science. At least, that's why I do science. Because we force our beliefs to conform to the evidence of reality rather than the other way around.

Because inflation literally means that space is being created. Space is growing exponentially during the period of inflation. And what's even weirder, our observable universe before inflation began was smaller than the size of a single atom. Think about that. All 100 billion galaxies, each containing hundreds of billions of stars that we can now see in our universe, all of that energy was contained in a region smaller than the size of an atom.

By the time inflation ended, that region was probably the size of a basketball or a baseball, or maybe you'd call it a soccer ball here. So it causes the universe to puff up. But there's, sort of, just as much energy per unit volume at the end of inflation as there is in the beginning.

It looks like the total energy of our universe, it increased by a factor of 10 to the 90th. What happened to conservation of energy? Crazy.

Well, it turns out that the reason the universe expands exponentially is because when you solve the equations of general relativity for a empty space having energy, that empty space not only has energy, that energy has a negative pressure. It's very different than all of the energy associated with matter and radiation for which the pressure is positive. And what that means is that, as the universe expands, space does work on the vacuum.

So the expansion of the universe because of negative pressure is constantly dumping energy in because space is doing work on the universe as it expands, instead of the other way around. With matter and radiation, the matter isn't doing work on the expanding universe because it's pressure is 0. But radiation is doing work on the expanding universe, which is why radiation redshifts with an extra factor of the expansion scale.

For empty space having energy, the universe does work on it, and it looks like you're getting energy for free. The ultimate free lunch.

SPEAKER: So in some sense, there's a gravitational potential energy change which is canceling out the vacuum energy change in the energy of the photon.

LAWRENCE KRAUSS: In fact, it was inflation that first made it clear that gravity, by having negative pressure, in some sense, the gravitation of potential energy could be negative and it could counter-balance the positive energy of matter, and you could play the two against one another. And in fact, a flat universe which was results from inflation, at least on our scale, has 0 total gravitational energy, which is one of the reasons why, I've been arguing, the universe could come from nothing.

Because if you were going to create a universe from nothing, what would you make the total energy? And it was that realization that the total energy of our universe can be 0 that, for me, profoundly changed the way I thought about the universe and its origins.

SPEAKER: Well, thank you very much, Lawrence. We will have you back in later sections of this course.

A4_L4_V01_Measuring_mass

BRIAN SCHMIDT: All right Paul, you and I are observers. We're not theorists. And these theorists come up with these crazy ideas of crazy ideas of the universes coming and going and expanding forever, and maybe turning in reverse. We want some facts. And so we've seen that almost everything depends on how much stuff there is in the universe. So how do you think you would go about trying to figure out how much stuff there is in the universe?

PAUL FRANCIS: Yes, so the idea was that if the density is over this critical threshold, the expansion of space will eventually stop and things will come back together again. And we're also a universe that has a spherical closed finite geometry where if there's not enough mass it will expand forever at a nice fast rate. Well, that's pretty easy. We'll just have to measure the density of the universe. We can't really take a bit of the universe here because this is not an average part of the universe. Most of the universe is in deep intergalactic space.

But we know how much star weigh. So we count the number of stars in the typical galaxy, 10 to the 10, 10 to the 11 or something like that.

BRIAN SCHMIDT: Yeah

PAUL FRANCIS: And so that gives us the mass of the galaxy. And we count all the galaxies. We take a picture like this one the very deep Hubble Space Telescope image, and we count the galaxies per cubic megaparsec or something and get a density.

BRIAN SCHMIDT: OK so, if we do that-- and I won't say I've done this, but people have-- and if you go through and you count up all the stars, you get a number which is about, oh, maybe a couple tenths of a percent of the critical density, that number of 9 times 10 to the minus 27 kilograms per meter cubed. So we get sort of one part in 1,000 or so.

PAUL FRANCIS: OK. So that's game over. The universe's density is too low, so it's an open universe and will expand forever.

BRIAN SCHMIDT: Good, OK. Good, done. Yeah, but I worry there might be something out there other than just stars.

PAUL FRANCIS: And indeed, as we talked about in the first course in the series, there's a lot of other stuff out there beyond stars, the so-called dark matter. How do we know that's there? Well if you look at a nice spinning spiral galaxy like this one, you could measure how fast things are spinning around using the Doppler effect. And for anything to spin in a circle there must be a centripical force towards the middle of the circle to balance the rotation. So we know the speed, we can therefore look at how much force there must be towards the middle. And that must be supplied by gravity. The gravity the galaxy must be holding things together so they don't all go flying off into space.

So we can measure how fast things move around the outskirts of galaxies and therefore use that to weigh the galaxy. And what do we find?

BRIAN SCHMIDT: Well, in 1970 Ken Freidmann, who's here at the ANU, did this for the first time in detail, and used radio waves to actually measure gas a long ways out. And he found a very funny thing, that galaxy was spinning much, much faster than the amount of stars would indicate there was mass, sort of almost like a factor of 5 or 10 more than you would expect. So there was missing matter.

And then Vera Rubin did this for many, many galaxies. It's a pattern we keep on seeing everywhere. And Bosma in The Netherlands also did it. So it's a consistent pattern that we see in almost every galaxy. They're spitting much faster than they should given the stars in them.

PAUL FRANCIS: So there's clearly a lot of something dark, particularly dark matter, that we can't see it as we talked about in the first part of the course. Most likely it's in the form of some weirdo a subatomic particle. At least. Most of it is. And while there's some of it in galaxies, when you get to bigger bigger scale, you see more and more it. For example, if you look at clusters of galaxies-- here's a galaxy cluster-- this is a composite image, the white part of it's taken with the Hubble Space Telescope and the purple is taken in x-rays of the Chandra Space Telescope. And this cluster of galaxies, has two pieces of evidence of dark matter here.

First of all, you can see these elongated shapes around here. That's gravitational lenses. That's background galaxy's light being bent around. And by looking at the amount of bending, you can look at how much mass there is in the cluster. And once again, it's an awful lot more than the mass of all the starts you can see in it.

BRIAN SCHMIDT: And there's really no way it's going to miss anything. It's pretty sensitive to what's ever there.

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: More or less.

PAUL FRANCIS: Anything that does gravity.

BRIAN SCHMIDT: Anything that has gravity.

PAUL FRANCIS: But also the purple color here is x-ray gas, very hot gasses falling in. And from pressure balance of this, perhaps trying to pull it in, pressure's trying to push it out, we can measure the pressure by looking at the temperature and intensity. You can work out once again how much mass there is. And once again, the answer comes out to agree with the gravitation lens in this, far too much mass in here.

BRIAN SCHMIDT: Right, so that gas is like 10 million degrees. So it's moving very quickly, but it's puffed up to a megaparsec across, 3 million light years. And so, you've got to have a huge amount of stuff. So we add up everything that's there. We sort of get 20% of the way to the universe being just right to being flat. So game over. We're there. We're done. Right?

PAUL FRANCIS: 20% is an open universe, pretty close. But theorists didn't like this because inflation should really force the density/flatness of the universe to be very, very close to critical density. Whereas we are a factor of 5 off. Couldn't there be some more mass around on even bigger scales?

BRIAN SCHMIDT: There might be. There's just a lump of a couple million light years across. So maybe we need to look at bigger scales. And there's reasons to be maybe suspicious.

PAUL FRANCIS: Yes, now on bigger scales still, there is a way to find out the mass. And that's by what are called peculiar motions. Now as you remember, we talked about, a few lessons ago, the idea that space is expanding, the Hubble Law that everything is moving away from us. And you might have thought at the time, hold on a moment. I've heard that not every galaxy is moving away from us. In particular, a very nearby galaxy, Andromeda M31, is moving towards us.

BRIAN SCHMIDT: At 240 kilometers per second.

PAUL FRANCIS: Here's a simulation of what's going to happen to us and Andromeda. So this is the Milky Way galaxy and we're talking about the number of billions of years here.

BRIAN SCHMIDT: From now.

PAUL FRANCIS: From now. And we're going to see coming in behind Brian in a second Andromeda M31.

BRIAN SCHMIDT: We go off rotating and here's Andromeda minding its business, coming towards us at 240 kilometers per second.

PAUL FRANCIS: Yes, So it's blue shift and not red shift. If you look at the spectral lines, they move to short wavelengths rather than long wavelengths.

BRIAN SCHMIDT: I seem to be obscuring it.

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: OK.

PAUL FRANCIS: OK, so we are 3 billion years in the future.

BRIAN SCHMIDT: We are going and what's going to happen. Oh gosh, this doesn't look good in 3.8 billion years. Oh, they-- well, It's sort of a train wreck. They've sort of gone right through themselves because of course they're made up of stars and a little bit of gas. There will be a lot of gas that will collide. But this will sort of merge together and make a super galaxy.

PAUL FRANCIS: Yes so, what's going on here. How can another galaxy be moving towards us when we've just heard about space expanding?

BRIAN SCHMIDT: So maybe we can use the peculiar motions of the entire sky. And let's think about how we might do that.

A4_L4_V02_Peculiar_Motions

PAUL FRANCIS: So in addition to the overall expansion of space, we seem to have some things that are moving towards us. These are peculiar motions. "Peculiar" because they don't fit in with the Hubble law.

Where are these things coming from? Well, there's a sort of balance between two things going on. If you have two galaxies floating in space, the space between them is going to be expanding and pulling them apart. But their gravity is going to be pulling them together.

I've put together a simulation showing this with spheres, instead of galaxies. And you can see these things are all being carried apart. But gravity is also pulling them together.

BRIAN SCHMIDT: Very slowly.

PAUL FRANCIS: So expansion of space is carrying things apart. Things are a long way apart or carried apart quite fast. But likewise, gravity is coming in here and pulling things together. So you see just up here, things sticking together.

BRIAN SCHMIDT: I kind of like how they burp. They belch when galaxies, one of them eats the other one. Well done.

But at the same time-- so the universe is expanding and the individual things that are close to each other, are getting closer. So you're getting a universe that's beginning to have voids in it, and lumps, and bumps of clusters.

PAUL FRANCIS: And you often get swarms of galaxies orbiting around each other at high speed, like the one down there. Then a big empty region and another group or cluster of galaxies.

BRIAN SCHMIDT: So if I were right in the middle, looking out, I would see a Hubble law. But then I'd see all these perturbations to it, where things-- some will be coming towards me, some are going away from me, depending on the gravitational field around the side.

PAUL FRANCIS: So on large scales-- so if you and I are very far away, the gravity between us is going to be very weak. So we're not going to have much motion due to our mutual gravity. But there's a lot of space between us to carry us apart. So the expansion of space is going to win.

If we're very close together--

BRIAN SCHMIDT: Yup.

PAUL FRANCIS: --then the gravity is very strong. And there's not much space to expand between us. So in that case, gravity will probably win.

BRIAN SCHMIDT: So whoa, boom. Yeah.

PAUL FRANCIS: And if we're somewhere in the middle, it's going to be a bit confusing.

BRIAN SCHMIDT: It is. OK. So how does this work in the real universe?

PAUL FRANCIS: OK. So here's a map of the local part of the universe, with us in the middle, in the Local Group. So we've got the Local Group, which is us, Andromeda, and a whole bunch of small galaxies like the Magellanic Clouds. And on this scale, gravity totally wins. It's much more important.

BRIAN SCHMIDT: We're all bound together, sort of like a swarm of bees. Yeah.

PAUL FRANCIS: And the same thing applies to any galaxy cluster, like, for example, the Virgo Cluster over here. Internally, within it, the gravity is much stronger than the expansion. So the thing is just going to swarm around.

BRIAN SCHMIDT: So the Virgo Cluster, from memory, is about 16 megaparsecs or 50 million light years in distance. And when we observe the galaxies there, they're moving at a rate, on average, of about 1,100 kilometers per second. So that's how much space is expanded.

But that's so massive, we know that gravity is pretty strong. And it seems that we're falling in at about 300 kilometers per second. Which means if there was no gravity at all, it would appear to really be about 1,400 kilometers per second. So there's that peculiar motion that we can sort of see in that case. That's quite hard to measure though.

PAUL FRANCIS: Yes. So on scales of about 1, or 2, or 3 megaparsecs, gravity wins. And things are stuck to each other by more than the expansion of space.

By the time you're out to 10, 20 megaparsecs, like the Virgo Cluster, the expansion of space wins. It is moving away from us. But it doesn't win convincingly. It's a narrow margin of victory. So of order, 300 kilometers a second motion, superimposed on the new overall expansion.

When you get out further and further and further, you're still getting these random, 300 kilometer per second type motions. But they're now superimposed on a much bigger value. So if you're going away at 30,000 kilometers a second, 300 kilometers a second isn't much of an error.

BRIAN SCHMIDT: Yeah. It's 1% problem. And most of the time, in cosmology, we don't worry too much about 1%. Although we're getting pretty good at it now, where we do have to worry about it.

PAUL FRANCIS: OK. So small scales, peculiar motions dominate. Big scales, not really. The expansion of space dominates.

BRIAN SCHMIDT: So let's think about how we can take all the information in the sky and put it together and try to measure the force of gravity.

PAUL FRANCIS: Yes. Let's use this kind of motion to tell us how strong gravity is. This was done by the 2dF Galaxy Redshift Survey here in Australia. And what they did was they did a survey that had absolutely huge number of galaxies. And they'd take strips on the sky. And for each galaxy, they'd measure where it was in the strip and then measure its redshift.

Now if there were no peculiar motions, redshift would tell you distance. But because there are peculiar motions, there's other peculiar masses and funny effects going on. And once they've got a plot here, is, for each galaxy, they've plotted the relative position of every other galaxy. And so they might take galaxy number 1 and plotted where every other galaxy is. They've plotted the relative redshift up here and the relative position across the sky along here.

BRIAN SCHMIDT: So what you got to go through is you're going to measure how far apart they are in velocity, put that plot; how far apart they are on the sky, as the other one. And you do that for every pair of galaxies. And then when you got a lot of galaxies, you'll make it that color. When you have very few, you'll make it that color.

PAUL FRANCIS: Now if galaxies were just distributed randomly, there'd be no more chance to seeing galaxies close to each other, than far away. So this diagram would just look like an absolutely uniform shade of color.

BRIAN SCHMIDT: It talks about the average difference in redshift. And the average distance in separation on the sky would be the same.

PAUL FRANCIS: And galaxies wouldn't be closer. But, in fact, galaxies tend to be gregarious, like people. If you want to know where to find a person, the most likely place is close to another person. Likewise, if you'd like to find another galaxy, the most likely place is close to another galaxy. And that tells you this is going to be high in the middle and low further out.

BRIAN SCHMIDT: But it also tells you that if you're moving-- if I'm being attracted to you-- I'm going to have a peculiar motion. So I'm going to have a velocity which is different. I'm going to be falling towards you. Which means my velocity is going to be closer to yours, if I'm falling towards you, either behind or in front, than if I'm not related to you at all.

PAUL FRANCIS: Yeah. So if there were no peculiar motions, then the redshift, the velocity, would indicate purely distance. And as you'd expect this whole diagram to look like a perfect circle. Because the odds of two things being separated along the line of sight, as opposed to a perpendicular line of sight, should be the same. Once again, we're assuming we're not in a special place universe.

So this curve should be symmetrical, like a perfect circle. And the odds of finding one galaxy close to another galaxy should be the same in any direction. But what you actually see are two funny things. One thing you see is a sort of stripe along here. These are called fingers of God. And you see them in them in all these redshift diagrams. It looks like there are fingers of galaxies pointing at the Earth.

BRIAN SCHMIDT: Yeah. And so that's what you see when you actually look at a cluster, like we showed you. The galaxies come in and they sort of do a mix master. You could sort of see it in your simulation.

And they swarm around each other, as a swarm of bees. And that's right next to each other. So that's right in the center of the clusters, you see that. So that's very small separations. You see very large velocities.

PAUL FRANCIS: Yes. So the velocity differences are very large. Not because they're at different distances, but simply because they're moving back and forwards in a massive cluster. So that gives us a finger of God. So God is not actually pointing at us in these diagrams. It's just "a swarming bees" motion.

Then on the outskirts, it looks a bit pancake. It's actually squashed the other way.

BRIAN SCHMIDT: This is splashed.

PAUL FRANCIS: And that's because things are actually falling in towards each other.

BRIAN SCHMIDT: Yup. So things here are falling in towards the center. Things here are falling into the center. And so you see a squishiness. And so that's squishyness-- the more squishy it is, the more stuff there is in the universe, on average.

PAUL FRANCIS: And so this was used to actually estimate how much mass there is on really large scales, including all the dark matter. And it turns out it comes out to about 30% of the critical density. You're still not at that critical density.

BRIAN SCHMIDT: So you're 30% So, again, it looks like we're done. Game over.

PAUL FRANCIS: Well, is that really the case? I mean could there perhaps be-- let's imagine there was some form of dark matter that had a really high temperature, so the particles moved around fast. That means they wouldn't coalesce to form clusters or superclasses of galaxies. That would mean they'd pretty uniformly everywhere.

And if that was the case, we wouldn't be able to them, would we? Because there would be equal amounts of dark matter on the left, and on the right, and above, and below. So you wouldn't move. It wouldn't cause any motions. And could we even see something that uniform?

BRIAN SCHMIDT: So you wouldn't want to see it. But it would cause another problem, Paul. It would mean we could never have formed to begin with. It would have not allowed our gravity to have formed the galaxy to begin with. Because that force of gravity would have pulled us apart and not allowed the formation of the Milky Way.

So we couldn't see. We'd blind to it here. But the fact that we exist at all tells us that that's not there. So I think we can safely cross that out.

PAUL FRANCIS: OK. So we seem to have got our answer to this, that the universe is open. That there's not enough mass to do it. But as we'll see, that's not quite the whole story.

A4_L4_V03_Geometry

PAUL FRANCIS: So that's one cosmological test. We can measure the density. There seems to be a suggestion there's not enough matter in the universe to be critical flat. It actually must be open.

But there's another possibility. Remember we talked about depending on the density of the universe, you get different geometries. The universe could be a spherical geometry, something like this, in which case, pi is less than 3.149592. And eventually, if you go far enough, you go all the way back.

BRIAN SCHMIDT: I've always wanted to do an experiment, Paul, which is where we're here at Earth, and we get a graduate student. We actually get two graduate students. And you send one off that direction as fast as you can-- we'll say 99.99% of the speed of light-- for a billion years. And another one that direction, same deal. And then after a billion years we all get together and measure the angles between us. And that, if they add up to more than 180 degrees, we know we're in that universe.

PAUL FRANCIS: That's the problem. It would be nice to measure the geometry by trying to see if the angles don't add up, or if pi is not right, or something like that. But if the universe is curved, it's curved on scales of billions of light years, so we'd need to have a billion year experiment at the speed of light to do anything.

But is there some way we can actually try and measure the geometry of the universe just stuck here on Earth by just looking?

BRIAN SCHMIDT: Well, one thing to think about is if I go through and I measure the volume-- or the area in this case, but the volume of a spherical universe-- it's going to be less as I go to larger and larger radii than in the flat case because my value of pi is changing. And so that's a way we might be able to think about looking and seeing how much stuff there is out at different distances.

PAUL FRANCIS: So if we could find something that was spread uniformly through space?

BRIAN SCHMIDT: Galaxies.

PAUL FRANCIS: And count the number within the volume, and as the volume gets bigger and bigger, if it's a flat universe, the number per unit volume should remain the same. But if it's a universe of spherical geometry like this, as we make our spheres bigger and bigger and bigger, than we're going to increase less. Eventually, if you made it all the around to the far end of the universe, you might not see anymore galaxies at all.

BRIAN SCHMIDT: Great idea.

PAUL FRANCIS: Likewise, if it was a saddle shaped universe, an open universe, which is what we're thinking from the dark matter, in that case there's more volume that we'd expect from 4/3 pi r cubed out to large distance. So as you go fainter, the number of galaxies should increase faster.

BRIAN SCHMIDT: OK. So let's think about the number of objects we're going to see.

PAUL FRANCIS: Per unit volume.

BRIAN SCHMIDT: Per unit volume.

PAUL FRANCIS: The trouble with that is we can't easily measure distances to these things. We're going to come back that big time a bit later on in this lesson. But if you remember in the first course when we were talking about gamma ray bursts, we came up with an interesting way around this problem. If you have a population of things that are all the same scattered through space, the ones that are near-- they all have the same luminosity-- the ones that are near are going to appear bright to us, and the ones are going to be further away are going to appear fainter.

But there's more volume if you go further out. So as you look fainter, you should see more and more of the things, because you're reaching a bigger volume of the universe. We did the calculation back then and showed that the number we see should be proportional to the flux to the minus 3/2 power.

BRIAN SCHMIDT: And that's because the volume, the number goes as the cube of the distance, but the flux or the brightness goes down as the square. So you get the volume with the cubed the distance, and square is the diminishing of flux. So that's how that comes out.

PAUL FRANCIS: OK. So this is a possible test. We should find something that's spread through the universe-- quasars, radio sources, galaxies, gamma ray bursts, whatever-- and count how many bright ones there are, and how many that are a bit fainter and a bit fainter and a bit fainter. And the number count should go like this if it's a flat universe. If it's a closed universe, the numbers will increase less. If it's an open universe, they'll increase more.

But there is a complication. In calculating this, we assumed the inverse square law so the idea was that if something is a given luminosity, the flux we see is equal to the luminosity divided by the area of the sphere that includes us because the photons have to spread over a bigger and biggest sphere. But that's also going to be affected by curved space.

So imagine if you're on something like this, and you've got a light source over here that's shining out. The photons have to spread out over a sphere whose surface area is less than 4 pi r squared. so it's going to make them appear brighter than we'd otherwise expect.

BRIAN SCHMIDT: Right. And if you're in the saddle universe, it's the opposite. It ends up being spread out over a larger space. So that means the distance we infer from how bright something is is going to be a little different. It's actually going to depend on the shape of the universe.

PAUL FRANCIS: Yes. And in fact, we can calculate this for different models. And the way we do it is we can come up with something called the luminosity distance, which is not the same as the distance you get with a tape measure. It factors in the size of the sphere. It also factors in the fact that the photons get stretched by the expansion of space and the fact that the arrival times of the photons get a whole bunch of photons arriving, maybe one a second, because of the expansion of space, it might be one every two seconds.

So you have to factor all those things in. It's complicated, but for any given cosmological model, you can work out what this it, and we'll put a link into the course to a calculator so you can see it for yourself. And so you can then use a modified version of the inverse square law. So it all becomes a bit mathematically complicated, but for any model, you can predict what you see.

And what do we see? We see too many things.

BRIAN SCHMIDT: The universe is just full of stuff.

PAUL FRANCIS: And there are too many faint things compared to bright things.

BRIAN SCHMIDT: So doesn't that just mean the universe is open?

PAUL FRANCIS: well, it could, and that was what people often thought when they first encountered this. But it's a bit confusing because we have to be looking out at distances of billions of light years, and that means we're looking back 20%. 30% of the age of the universe. And it could be that galaxies were just different back then than they are now. In fact, almost certainly they are.

BRIAN SCHMIDT: Yeah, because these galaxies are very, very small, and it turns out they're much smaller. Because if we calculate how big they are, they'd be much, much smaller, the average galaxy here, than what we would see in the Milky Way, for example. So these galaxies just don't really look like the galaxies that we see around the Milky Way today on average.

PAUL FRANCIS: You'd think you can count the number galaxies per unit volume, but for a start, galaxies might collide with each other, so the numbers could be going down because of galaxy collisions. But more importantly than that, no telescope can measure the number of galaxies in a given volume. All you can measure is the number of galaxies above some brightness threshold in a particular volume.

And so you can say down to the limit of a particular telescope, we can see so many galaxies in the unit volume. But it could be that in the early universe, galaxies are brighter than they are now because they just formed lots of stars, and if the stars have only just formed, the very massive, hot stars are still going to be around, and they put out tons of light per unit mass.

BRIAN SCHMIDT: We certainly know they're changing over time because if we look back 13.8 billion years ago, we know there were no galaxies at all, so something's changing over time. So galaxies are changing over time, so that's going to really mess this measurement up.

PAUL FRANCIS: So in principle, this is a really nice way of measuring geometry, but in practice, you have to fully understand how galaxies evolve with time to use it because you have to subtract that off to find out what's really going on with the geometry. And we don't understand the evolution of galaxies in anything like enough detail.

BRIAN SCHMIDT: That's actually one of the big questions of astronomy, is how do galaxies evolve? So it seems like a bit of a problem here for us.

PAUL FRANCIS: So it sounds like measuring geometry, nice in principle, won't work in practice.

A4_L4_V04_Scale_Factors

PAUL FRANCIS: So we've see that we can get a lower limit on the density of the universe, but that's not really telling anything. It looks like there's not enough matter to make it flat, but there could be some more matter we've missed. We've looked at trying to use the geometry of space to work things out, but that's not going to work because there could be evolution in what's going on in space that confuses us. So we're a bit stuck here. What can we do?

BRIAN SCHMIDT: Well, one idea is maybe we need to look at how all the matter in the universe affects how the universe actually expands. So that would be one approach.

PAUL FRANCIS: Yeah. So we know that the matter affects the dynamics, how the scale factor went at the time with the Friedman equation. We've done that. We know that at the moment, space is expanding, so at time t equals today, a of t is getting bigger, so it's sloping up this way.

But in the past, it could be one of these three models you'd be talking about.

BRIAN SCHMIDT: Right. So this is the dynamics of the universe depending on how much stuff there is in the universe. So if the universe is completely empty, gravity's not doing anything, and so the universe just keeps expanding at the same rate.

PAUL FRANCIS: We know that's not true. We know there's at least some matter in the universe.

BRIAN SCHMIDT: Well, there might be a very, very little amount of stuff. Maybe we're puny and insignificant.

PAUL FRANCIS: And then you've got a curve, which this would be for a universe which has density less than or equal to the critical density, so it goes up, and keeps on going out here, and either keeps on as a steady line or flattens out but never curves downwards.

BRIAN SCHMIDT: Right. And then you have the really exciting universe, the universe which is slowing down so quickly that it literally reaches a maximum size, and then goes in reverse. So literally, you are weighing the universe depending on how much these lines are curved. The more gravity there is, the faster and harder the lines curve.

PAUL FRANCIS: And we can't see the future, but we could, in principle, look at the past and see which of these curves is going on. So look at how much faster universe the is expanding at the beginning and how rapidly it's slowing down.

BRIAN SCHMIDT: So all that we have to do is to be able to look into the past.

PAUL FRANCIS: And we have a big advantage over the historians here that we can do that, because light travels at such a pathetically slow 300,000 kilometers a second. I mean, totally miserable. That means when you're looking at anything as a reasonable distance, for an astronomer, you're looking at it not as it is now, but as it was in the past. All we can measure is the red shift.

We talked about this extensively in the first course and a little bit earlier in this course. The redshift is how much the spectrum line have been moved, and that's telling us how much space has expanded. Because a line starts of a certain length, and then if the line is stretched 10%, it's got a red shift of 0.1, and that means the universe is 10% bigger now than it was at the beginning.

BRIAN SCHMIDT: And that's because those photons stretch with the expanding universe. They get pulled around as the universe expands.

PAUL FRANCIS: So it turns out that the scale factor when it was emitted is going to be less than it was now because it's getting bigger. So this is always going to be less than 1 if you assume the scale factor today as 1, and how much less is given by 1 plus the redshift. So if you see a supernova at redshift 1/2, that means it's going to be 1 over 1 plus 1/1, so one over 1.5. That's at about 0.7 or something.

BRIAN SCHMIDT: Yeah, 2/3. And so that means the scale factor of the universe is 2/3 of what it is today. Very convenient.

And we can measure those red shifts incredibly accurately. One part in 100,000, no problem. One part in a million even, potentially possible.

PAUL FRANCIS: Yeah. So red shifts, OK. That's easy, then. All solved. Then we just measure the red shifts for a bunch of things that tells us how bit the universe was in the past?

BRIAN SCHMIDT: I'd say that's going to tell us the scale factor, but then we need to know the time.

PAUL FRANCIS: Yes, that tells us how far up we are, but it doesn't tell where you are this way.

BRIAN SCHMIDT: So we just need to have a clock on all of our galaxies, and it will be solved. We just use our big telescopes, and we'll look at Big Ben or the moral equivalent, and it'll tell us how many billion years after the Big Bang it is.

PAUL FRANCIS: Yes, well, that would be nice. But unfortunately, no one's put gigantic megaparsec-scale clocks on all these supernovae and galaxies out there.

BRIAN SCHMIDT: We need to construct one in the Milky Way for other people to have our benefit.

PAUL FRANCIS: Yeah, I'll try putting that in for the Australian government to fund it.

BRIAN SCHMIDT: Yeah, that's a good proposal.

PAUL FRANCIS: But we could use distance, because if we know how far away something is then if it's 100 light years away, the lights been traveling for 100 years. If it's a million light years away, the lights been traveling a million years. So if we know the distance, then we know how long the light's been traveling.

BRIAN SCHMIDT: Well, to first order. That distance is a little funny in the universe because the universe is actually expanding, and so we're going to have to be very careful how we do this. But in principle, I agree it's possible.

PAUL FRANCIS: Yes, so you have to worry about what sort of distance. We've already talked about luminosity distances. There are also other distances in astronomy which have to allow in different ways for the expansion of space and the weird geometry, but we know how to handle all that. And so for a given cosmological model, we can calculate the actual light travel time distance. This is a form of distance telling you how long the light's been travelling for. So what we need to do is measure how far away these supernovae or whatever, the galaxies, actually are. Easy, right.

BRIAN SCHMIDT: So we just pop out a ruler between me and you, and we're done.

PAUL FRANCIS: Would that it were so easy.

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: Now of course, this is the arguably hardest thing in observational astronomy, getting distances. You want to get a fight going between two astronomers, ask them how did you measure the distance? It's a bit like archaeologists. People think archeology is all about wandering around tombs, looting giant treasures, but in fact it's endless arguments about the date of some little shard of pottery or something like this. For astronomers, it's how far away is that galaxy? Is it 14 or 17 megaparsecs away? And that's a good way to get a fight going.

BRIAN SCHMIDT: And this is what I did for my PhD thesis and eventually did later on in life, and it's a very controversial but a very important part of modern cosmology.

PAUL FRANCIS: So let's talk you through the traditional way in which distances are measured.

A4_L4_V05_Distance_Ladder_1

PAUL FRANCIS: Now the traditional way of measuring distances in space is what's called the distance ladder. Why a ladder? Because there's a whole bunch of rungs. The trouble is any given method for measuring how far away things are only work over a given range of distances.

So for example, parallax is a very good method that only for if things that are very nearby. Type 1a supernovae is another very good method of measuring distances, but because the supernovae are rare, you haven't got any close enough, so it's only useful for very large distances.

So what you do is you use one method for nearby. Use that to calibrate the next method which gets you a bit further. Use that to calibrate the next method still, the next step of the ladder, and slowly work your way up to bigger and bigger distances. We have to get out to distances of hundreds of megaparsecs to actually measure anything here, and we have a lot of steps in that.

Now the first step is probably the simplest of all. It's parallax.

BRIAN SCHMIDT: Right. So parallax is very useful because it is a method based purely on geometry. And that's useful because you're going to be able to measure a distance which you understand really, really well, and the distance is going to be what we would call absolute. It's going to be something we measure in meters. It's going to be like a real ruler, so it's very useful.

And it essentially is just taking the motion of the Earth around the Sun and the fact that it causes an angular motion of distant stars relative to even more distant stars. It's the moral equivalent of putting your finger out in front of your face, and changing your eyes back and forth, and seeing your finger move against something in the background.

PAUL FRANCIS: Now we call this the first step. There's really even a zeroth step, which is to actually work out how far the Earth's orbit around the Sun is.

BRIAN SCHMIDT: Right. And that was one of the reasons why Australia was settled by the British Empire, because Captain Cook was down here to look at a transit of Venus where you could use the fact that Venus was going in front of the Sun, and use parallax of when you saw it on one side of the Earth and when you saw it on the other side of the Earth. And there, the size of the Earth becomes the baseline that you're measuring. And so that's sort of the founding of modern Australia, was based on that rung of the distance ladder.

PAUL FRANCIS: Nowadays, we can do it using radar bounced of satellites and planets. This is very accurate, so we almost won't worry about that. That's extremely precise.

BRIAN SCHMIDT: Yeah, a few centimeters right now.

PAUL FRANCIS: So the idea is that the star here, being the foreground of those stars over there, would appear in a different place at the two different times.

Now you can calculate the angle. It's defined as the angle you get moving one astronomical unit. So in fact, as the Earth goes around, it's going two astronomical units around, so something will appear wobble by twice its parallax. And the definition is that if something is 1 parsec away, you get 1 arc second of parallax. That's actually the definition of a parsec.

BRIAN SCHMIDT: Right. And since there's 206,265 arc seconds in a radian, that tells you that a parsec is 206,265 times the astronomical unit. That's how I remember what a parsec is. Because I know we're 150 million kilometers from the Sun, but I can never remember how many kilometers in a parsec.

PAUL FRANCIS: OK. So the whole thing's solved. We've got a really good way of measuring stars.

BRIAN SCHMIDT: Yeah. The only problem, Paul, is that 1 arc second is a very small unit in the sky. And when I take an image here in Australia, for example, it is very rare that I can actually get a resolution of 1 arc second due to the atmosphere. So it strikes me that if we're going to make very accurate measurements here, we have a problem, which is how on Earth do we measure the parallax that accurately?

PAUL FRANCIS: Because 1 arc second gets us out to 1 parsec, but there are no stars within 1 parsec. The nearest star is about 1.3 parsecs away. So any start we're going to want to watch is maybe 10 parsecs away? 20? So we're going to do much better than that to get anything at all.

BRIAN SCHMIDT: So it's a real big challenge, and with a modern telescope we can probably measure parallaxes from the ground maybe one part in a hundredth of an arc second by being very, very careful, but that's still not going to get us to only a handful of stars.

PAUL FRANCIS: OK. So this is our first step of the distance ladder, and in principle it's wonderful. It's nice and simple. It's all based on geometry. We understand what's going on. The trouble is that the angles are just so damn small that it's really hard to measure more than a handful of stars, and before you got more than a few parsecs away it's starting to get pretty inaccurate.

However, the most accurate measurements around today for most stars come from the European Space Agency's Hipparcos satellite, and that was good enough to get us out to the nearest cluster of stars, the Hyades cluster. That's the first step of the distance. That gets us out to the Hyades cluster.

And now we get the second step, which is main sequence fitting.

BRIAN SCHMIDT: Just to remind us how stars work, stars burn hydrogen during what we call the main sequence. It's what our Sun's doing right now. And the rate that they're able to convert hydrogen to helium depends on their mass, and that also tells you their temperature. So you get this beautiful relationship of temperature versus brightness. And so down here, we have a measurement of the color, and temperature depends on color.

PAUL FRANCIS: And this is essentially a measure of flux, so it's telling us how bright they appear to be from the Earth.

BRIAN SCHMIDT: And so we have these stars of lower mass, and heavier and heavier and heavier stars follow this main sequence.

PAUL FRANCIS: These are the red ones, and they are not so bright, so these would be red dwarf stars. And then you go up to stars like our Sun, and keep on going up to--

BRIAN SCHMIDT: Our Sun's about right there. There's a couple wacko little stars here. Those are stars that have left the main sequence and started burning hydrogen in their shells rather than in their core.

PAUL FRANCIS: We'll come back to them later. But the idea is, OK, we've got a nice trend here. We can fit a line through here, and that's been shown here. And then we can go out somewhere much further away, in particular, out to the Large Magellanic Cloud, the galaxy orbiting our own over here. And this is near enough, about 160,000 light years, that we can pick out individual main sequence stars here if we try hard.

BRIAN SCHMIDT: Right. So there's about 10 billion stars in this galaxy, and by looking as accurately as we can with the best telescopes, we can go down, and we can see that same main sequence.

PAUL FRANCIS: So we can then compare our fit for the main sequence here with our fit for the main sequence in the Hyades. We know how far away the Hyades is because of the first step of the distance ladder, the parallax.

Now we know that the flux we observe is going to be luminosity divided by 4 pi D squared. That's the inverse square law. We covered that in great depth in the first course in the series, and we've hit it again repeatedly all the way through.

Now if you rearrange this, it means if you have two objects, we can have the ratio of the fluxes gives you-- or the square root of that gives you the ratio of the distances. So if we can look at the main sequence in the Hyades and the main sequence which will appear much fainter in the Large Magellanic Cloud-- it'll appear much fainter because it's much further away-- the ratio of the two gives us the ratio of the distances.

BRIAN SCHMIDT: Yep. That's the square root

PAUL FRANCIS: We can look at how far away the Magellanic Clouds are, easy.

BRIAN SCHMIDT: Yeah. There is one little problem, though, Paul.

PAUL FRANCIS: You would say that.

BRIAN SCHMIDT: Yeah. Which is the Hyades is made up of stars that have a certain amount of metallicity. That is, metallicity to us is anything heavier than lithium, including lithium, and there's a lot more metals in the Hyades than in the Large Magellanic Cloud. And we know that changes how bright stars are. And we know sort of how well that is theoretically, but we don't have it down perfectly.

PAUL FRANCIS: And also this main sequence that we've talked about, the stars don't sit exactly in the same place. As they get older, they move sideways a little bit here. Our own Sun is getting steadily more luminous even though it's sitting on the main sequence. And so the things will steadily move in this direction, and so do we know the age of the stars in the Magellanic Clouds compared to those in the Hyades that well?

BRIAN SCHMIDT: Well, it turns out that the Large Magellanic Cloud has stars of a big, broad age, whereas the Hyades are all pretty much one age, and so that's another little correction we're going to have to make. And so, yeah, we can probably make the corrections to a few percent, I guess. Maybe 3% to 5% would be a good guess.

PAUL FRANCIS: Maybe, maybe not. It's really hard to know how accurately you can make it.

BRIAN SCHMIDT: And this, of course, is one of the best rungs in the extragalactic distance ladder.

PAUL FRANCIS: It just gets worse from here.

A4_L4_V06_Distance_Ladder_2

PAUL FRANCIS: OK. So we've got this main sequence emitting method. It has its problems. But then everything has its problems. Can we just go and use it to other more distant galaxies, further away than the Magellanic Clouds?

BRIAN SCHMIDT: Unfortunately, Paul, stars are faint. And so even if we go to the Andromeda spiral, a star like our Sun, which is sort at the upper end of that main sequence, is so faint that, although you can barely detect it at the Hubble Space Telescope, the problem is it's going to be confused with other stars that are right next to it. And so you just sort of get a blurry mess. And so you really can't do it, even to the nearest big galaxy, the Andromeda spiral.

PAUL FRANCIS: So we need a third step in the distance ladder. We need something that's brighter than main sequence stars, like a giant star. And we need these things to be common enough that we can find some of them in the Magellanic Cloud, so we use it to calibrate the system.

BRIAN SCHMIDT: And preferably, really easy to identify.

PAUL FRANCIS: And luckily, there are such stars. Cepheid variables, of which this is an example.

BRIAN SCHMIDT: Oh, a very pretty star.

PAUL FRANCIS: Now, these are giant stars. So they're nice and bright. And you can see them out to much greater distances. What makes them really interesting is they pulse.

BRIAN SCHMIDT: Um. So that makes them easy to find and to identify.

PAUL FRANCIS: Yes. What happens is they've got a layer in the atmosphere, which is doubly-ionized helium, which turns out to be almost completely opaque to the heat coming out from inside. So the heat inside can't get out through this layer. And so it builds up and it builds up.

And, of course, if you get gas and you make it hotter, and hotter, and hotter, the pressure is going to go up. The pressure outside isn't going to change. So the pressure gradient is going to get steeper, which is going to push things out, just like a piston in a steam engine.

BRIAN SCHMIDT: Plus, the whole thing's going to pop up like a giant balloon. You're essentially building up heat in, yeah?

PAUL FRANCIS: Yes. So it'll expand outwards. But as it expands outwards, that's doing work. Force times distance is work.

BRIAN SCHMIDT: Yup.

PAUL FRANCIS: So energy is going in to work against potential energy. And that's going to cause this helium layer to cool down.

BRIAN SCHMIDT: Ah. And then it won't be doubly ionized, I bet.

PAUL FRANCIS: Yeah. When it gets cool enough, it'll stop being doubly ionized. And it will be like opening the blinds on a window. The radiation can now escape.

BRIAN SCHMIDT: Oh. And so suddenly, all the radiation will escape. And so the thing will be bright. But it will cool down rapidly, which means it's going to want to contract.

PAUL FRANCIS: Yes. So it'll shrink back down again. And as it shrinks, of course, that gravitational potential energy is turning back into heat. And so it'll start warming up.

BRIAN SCHMIDT: And then you'll double-ionize helium again. And it'll start trapping all the light again. So it'll be faint, but heating up.

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: So you seem to going to get this big, pulsating star.

PAUL FRANCIS: That's right. And what's really useful about the thing is, firstly, they're easy to spot because they pulse. So what you do, you take lots of pictures over and over again and look for bright stars that change in brightness. And there's a very particular sawtooth pattern they show, which shows how they change in brightness.

But then, even more interesting, is what's called the Leavitt law, worked out by Henrietta Swan Leavitt back in the early 20th century. And what she found is that if you look at the pulsation period, and you look at the absolute magnitude, which is telling you the luminosity, how bright they really are, there's a correlation between the two.

BRIAN SCHMIDT: That sort of make sense when you think about because big stars burn their hydrogen or all their nuclear fuel more quickly. So they're brighter. And if you think about that whole process, that pulsation, it's going to depend on how big and extended the star is and how much gravity it has.

So you can imagine it would depend on the mass of the star. And indeed, these resonances depend on the mass. And they ring like giant bells, effectively.

PAUL FRANCIS: And the period is 10 days, 20 days, 30 days, up to 80 days, or so. So that's a measurable period. And at optical wave-- this is optical wavelengths-- it's not that good a correlation. There's a fair bit of scatter. If you go up to infrared wavelengths, it gets really quite tight, quite a nice correlation.

So this looks pretty straightforward. What you do is we start off by calibrating this in the Large Magellanic Cloud. There are lots of Cepheid variables there. And we know how far away it is because of the main sequence fitting. And so we get these plots. And it's actually where this plot came from.

And then that tells us-- if we see something with an given pulse, what's its luminosity is. And then you go to look at more distant galaxy. And you find some things that are the same pulse.

And we once again use the inverse square law. We use the ratio of the fluxes. And that gives us the distance. So easy and solved.

BRIAN SCHMIDT: Yeah. There are a couple issues, Paul.

So one thing you'll notice is they do have a lot of scatter down here in the optical wavelengths. So if you go-- let's look at that picture of a Cepheid. One of the reasons it's such a pretty object is there's a lot of junk around that. And that stops scattering the light of that star.

And so that junk is going-- normally, you can't see all that junk. So you don't really know how much junk there is. And so that junk, that dust, will affect how bright they appear.

Now, you get around that in the infrared, as we've seen. Because pretty much in the infrared, there's not a lot of scattering. But there's a few problems with Cepheids in the infrared. One, it's really hard to observe in the infrared. And it turns out they don't pulse much in the infrared.

So they're very hard to identify in the infrared. You have to have really good quality data. So what we normally do is we find them in the optical and then observe them in the infrared, knowing what they are. But even so, once again, as stars, how much metals they have in their atmosphere is really going to determine how bright they are in detail. And once again, the Large Magellanic Cloud has less metals than normal, other galaxies. So there's a correction we're going to have to make for them.

PAUL FRANCIS: And no one knows what this correction is. I mean there's a lot of controversy over whether the Cepheids with more heavy elements are brighter or fainter than the ones with less heavy elements for a given period. And no one really knows.

BRIAN SCHMIDT: Well, we've made lots of observations. And I would say it's very uncertain. And some people say it's almost no problem and some people say there's quite a big effect. And so that is a problem that's going to be saddled with these stars. Which at some level, are considered by many astronomers as the panacea to our distance measuring problems in astronomy.

PAUL FRANCIS: So you can use it to measure the distance to a galaxy like this one.

BRIAN SCHMIDT: This is the Andromeda spiral. And Hubble actually found a Cepheid in this in 1923. And so that was one of the first galaxies where they realized they were a long ways away, using this same technique.

PAUL FRANCIS: Though actually the answer they got was quite wrong. First of all, because they calibrated using an earlier scale they used were incorrect. And secondly, there are two different types of Cepheids and they get confused.

BRIAN SCHMIDT: It is true. But on the other hand, at the time, many people thought these were in the galaxy. And he realized they were 1,000 times further away.

PAUL FRANCIS: So you got to do it in an order of magnitude, which is quite enough to--

BRIAN SCHMIDT: Yeah. That's good for astronomy.

PAUL FRANCIS: Now, can we then go and use Cepheids all the way out to the edge of the universe to measure the expansion of space?

BRIAN SCHMIDT: So, unfortunately, no. With ground-based telescopes, it's pretty easy now to find Cepheids in this star. We could do it in 19--

PAUL FRANCIS: In this galaxy here.

BRIAN SCHMIDT: --sorry, in this galaxy. And we could do it in 1923.

But if we want to go out, let's say 10 times further than this, which is still only 7 megaparsecs, really a nearby part of the universe, then the objects are going to be 100 times fainter. And that turns about to be about what you could do with a modern 8-meter telescope, in a really good site. Because you can sort of go out another factor 10 than this. But that's still not very far. That's just in the--

PAUL FRANCIS: It's only halfway to the Virgo cluster.

BRIAN SCHMIDT: That's right. And so the galaxies are going to be very much affected by their motions due to gravity at that distance.

PAUL FRANCIS: OK. So what's actually being used is yet another step in the distance ladder. We use Cepheids to get out to maybe 6 or 7 megaparsecs. And within that radius, you find a fair number of galaxies. Not that many, but there's some dozens of galaxies in that sort of radius. And now, you're going to use galaxies themselves as the next rung of the distance ladder. And there are various things you can do about it.

One of the most widespread is what's called a Tully-Fisher relation. What you do is you measure how rapidly the galaxy is rotating. And it turns out that correlates with the brightness. So let's look at the black points here, which are the spiral galaxies.

What you can find is, if you look at how rapidly they rotate here, that correlates with their true brightness. Once again, it's calibrated by these nearby galaxies, where you can get Cepheid distances. It's different for other sorts of galaxies. But just consider the spirals for the moment.

And there is a correlation there. And so--

BRIAN SCHMIDT: Well, there should be a correlation. These things are rotating. It's just like measuring the mass of the Sun, with the motion of Neptune, right?

PAUL FRANCIS: Well, yes and no. It's telling you that the mass, which depends mainly on the dark matter, correlates with the light, which depends mainly on the stars.

BRIAN SCHMIDT: Ah. Yeah, that dark matter stuff. Oh.

PAUL FRANCIS: Yeah. So it's actually kind of interesting because it's telling us that there's a correlation between the dark matter and the luminous matter, which wouldn't be obvious. And we don't know what the dark matter is.

BRIAN SCHMIDT: But on the other hand, at least we can use this pretty much anywhere we see a spiral galaxy. But it doesn't look very accurate.

PAUL FRANCIS: Yeah. There's an awful of scatter around this.

BRIAN SCHMIDT: Yeah. So that is going to be a problem because this doesn't tell us how many kilometers away a galaxy is. It tells us this galaxy is that much further than that galaxy. So it's a relative distance.

So we are going to have to calibrate it very accurately. And presumably we're going to want to use Cepheids to do that. But there are not very many galaxies we can measure Cepheids for. And that scatter is going to mean it's going to be tough to really pin down the distances accurately.

PAUL FRANCIS: Yes. If you want to look at some distant reaches, we can find millions of galaxies and measure it. So we get a very accurate law out there. But we have to calibrate it against nearby ones. We just can't see far enough to get enough points to calibrate it very well.

BRIAN SCHMIDT: Yeah. So it turns out, I believe, that the scatter for this method is about 18% per distance.

PAUL FRANCIS: Which is a killer.

BRIAN SCHMIDT: Yup. Oh, well.

Ah. Then there's type Ia supernovae. I like type Ia supernovae.

PAUL FRANCIS: Yes. So we've talked about these already in the previous courses. We talked about the distance scale in course one and we talked about the physics behind them in the violent universe course. But for those who haven't done those previous courses, I do want to remind us what they are and why they are so wonderful.

BRIAN SCHMIDT: So type IA supernovae are some of the largest explosions in our universe. And we're pretty sure that they result when a white dwarf, a degenerate ball of electrons effectively, reach a point where that whole ball ignites and converts the carbon and oxygen in the white dwarf to things like nickel, and cobalt, and iron. And that produces a huge ball of expanding junk, that is incredibly bright, about 5 billion times brighter than our Sun.

And the process that creates this seems to always produce more or less the same thing. If you ignite a ball of degenerate electrons, you almost always get more or less the same thing. So you can measure distances with these objects that are very bright, to about 6% or 7%. And that's a lot better than 18%, it turns out.

PAUL FRANCIS: But the main problem with these-- my turn to say that now-- is that there aren't that many nearby type Ia supernovae that you can calibrate. So while it's very good for relative distances of one supernova against another, they're just such rare events that there aren't that many of them that have happened close enough in recent historical times that we've had good telescopes to observe them, that we can actually calibrate out the distances fairly accurately.

So it's once again, the near calibration. We have to use Cepheids, or Tully-Fisher, or something like that. To work out how far away the nearby ones are. Use that to set the luminosity. And then you can use them as a yardarm across the entire universe.

BRIAN SCHMIDT: Yeah. So, unfortunately, the last one in the Milky Way was 400 years ago. The last one in the Large Magellanic Cloud we think was about 1,000 years ago. We're not really sure. We just see the remnant. We've never seen one in the Andromeda spiral.

Indeed, we had one of the closest ones in living memory earlier this year, which was about 4 megaparsecs away. But it was enveloped in a bunch of dust. So we couldn't actually use it to measure distances. So they do have their own little problems.

A4_L4_V07_Conclusions

PAUL: So what have we learned so far? We've found out that we have about 30% of the density we need. Maybe more, but certainly 30%, which isn't enough to give us a flat universe. Our attempt to use geometry really failed, because we can never tell what's geometry and what's evolution.

And this whole idea of trying to imagine the scale factor, and how it changes versus time, is looking promising. But the only way we could make it work is we can measure distances. And that's proving to be really hard. Now, this has been a great controversy for decades in astronomy.

BRIAN: It has. I mean, when we go back to well before we were students-- well, when we were students it was still a controversy. And that would've been in the early 1990s. But even if you go back to the '50s and '60s, here at Mount Stromlo we had George De Vaucouleurs come up and use the now-destroyed 30-inch telescope-- the Reynolds telescope-- to go out and look at galaxies and try to measure their distances. He consistently got a value for the Hubble constant

which is 100 kilometers per second per megaparsec. So if a galaxy's a megaparsec away, on average it will be moving 100 kilometers per second away from us. Well, that would be the red shift.

Allan Sandage-- who trained some of the astronomers at Mt Stromlo, and a big person at Carnegie in the United States-- well, he consistently got numbers around 50 using a similar set of techniques. And they really, as near as I could tell, didn't like each other very well. And so, when I went to school and I decided to measure the Hubble constant, it was because it was 50 or 100.

And of course, when I went out and did my best is-- we're going to find out the new techniques in the next set of lectures-- when you get a number in between, turns out you were sort of despised by both sides. And so, it was really bad behavior when it really comes down to it. Because people were entrenched with a value, not the science behind it.

PAUL: And they also had different approaches. De Vaucoulers's approach was an everything in the kitchen sink approach. His idea was that any one of these distance measures we talked about could have flaws. But if you take 100 different distance measures, then on average they should be good.

Allan Sandage believed that if you have 100 different things, you're just averaging 100 different sources of bias and uncertainty and error, and you're just going to get worse and worse. What you should do is try and pick one or two gold-standard methods and really pursue them very carefully.

BRIAN: Yeah, and in some sense it really depends on whether or not you think those 100 ideas that De Vaucouleurs would be using, they were really reasonable estimates. You can ask the question, have you seen the Prime Minister? No.

How tall do you think he is? And then average a bunch of that. Are you going to get a good answer? The answer is, probably not.

PAUL: You're going to get a good understanding of how big people think the Prime Minister is, but may have been no resemblance to the actual height.

BRIAN: Yeah. On the other hand, the other problem you have is, there were no gold standards. There was nothing. And so they squeezed blood out of a stone unsuccessfully, I think. That's where we ended up with these problems.

PAUL: If it hadn't been so interesting-- I mean, this is the fate of the universe. If it had been trying to discover, I don't know, evolutionary pathways of type-O stars, people wouldn't have bothered. It would have just been too difficult. People would have said, look, today the observations are not good enough, the theory is not good enough, let's move onto something that's more possible. The reason that people were drawn like moths to a flame to this was because it is the fate of the universe.

BRIAN: Yeah, the fate and the age of the universe. And, in this case, I genuinely believe-- having met both sides-- genuinely believe they thought they had the right answer and the other person was an idiot. And of course, what we're going to find out is, neither had the correct answer. Both were wrong.

PAUL: OK, so let's continue. We're going to talk now about even more problems that make this even harder than we've already talked about. And then we'll go and talk about the amazing transformation this field has been through in the last 20 or so years. So much so that there's actually a real consensus about what's coming on now, and how that happened.

BRIAN: It's been an amazing 20 years.

A4_L5_V01_Dust

BRIAN SCHMIDT: So Paul, you can see that the distance ladder is a little complicated. And we have this nasty stuff, like dust, that is spread through the cosmos, causing us problems.

PAUL FRANCIS: Oh, dust isn't nasty. Dust is really pretty. I mean just look images like this taken at the Anglo Australian Ttelescope. What you're seeing here is stars. And these dark patches here, it's not gaps in the stars. It's dust clouds, interstellar dust clouds, blocking the light from the background things.

This is just gorgeous. You can even see it with a naked eye. Here's a picture I took of the 74-inch telescope at Mount Stromlo. We're showing the center of the Milky Way in the background.

And what you can see up here is the dark bits, the dark lanes in the middle of the Milky Way, is where the dust is blocking the stars. But also, off to the slide, you can see it's got a somewhat reddish color here. And that's where there's not the really thick dust. There's a little bit of thin dust that's blocking some of the light. Now, this is just really pretty.

And you can see it in other galaxies as well. And once again, it makes things gorgeous. This sort of spiral pattern you're seeing here is not actually where the stars are. The stars are pretty uniformly distributed. The spiral pattern is mostly due to dust blocking out certain areas and making it all look so gorgeous. So how can anyone not like dust? It's just so gorgeous.

BRIAN SCHMIDT: Pretty, it might be Paul. But, unfortunately, in terms of what I like to do, which is to measure distances, dust is everywhere. And the fact that it helped create the Earth, is no solace to me when I try to measure the distance to this galaxy.

So this galaxy, for example, is full of Cepheids. The Cepheid variable stars are scattered around it. But most of them end up landing, with some amount of dust, unknown, in front of them. And that means when I try to measure the distance, I get too far of a distance whenever there's dust in front of it. And I get about the right answer when there isn't.

PAUL FRANCIS: And you have to bear in mind, you see, for example, really strong dust here. But there's probably dust there, and there, and there as well. It's just a bit fainter. But almost every line of sight, through almost any spiral galaxy, is going to go through at least some dust. There are no real dust-free views.

BRIAN SCHMIDT: That's right. Only if they're way up on the top side, sort of out of the plane of the galaxy. And these big, dark areas, we don't worry too much about. Because there's so much dust there, you just can't even find the stars there. So that's not the problem. It's the insidious stuff that's everywhere.

It's like-- well, it's like the dust around your house. It's always there. And there's nothing you can do to get right of it.

PAUL FRANCIS: Well, is there a dust that's actually not very much like the dust around your house? I mean the dust around your house is actually mostly flakes of skin, human skin, which is definitely not the major contributor to the interstellar dust. In fact, it's probably more like smoke on earth. The particles are very much smaller than dust. You couldn't see them with the naked eye. They're probably microns, or even nanometers, across in size, very tiny grains.

And this means, because they're so small, they're comparable in size to the wavelength of light very often. And so they have a really strong effect on things about the same size as they are, which typically means blue light. Those that have less and less effects at longer and longer wavelengths.

So what we're doing here is I'm plotting the wavelengths, starting with very blue, and going out to the side infrared. And we're plotting what fraction of light can get through a cloud of dust.

Now, if you have a thin cloud of interstellar dust, it'll looks something like this curve over here. So the infrared light mostly gets through. Maybe about 99% of it's getting through. But as you get to shorter and shorter wavelengths, the fraction getting through gets less, and less, and less. And so you're using maybe 40% of the light in the blue.

Now, if you ran up the amount of dust, and have more, you might get something like the second curve. In the infrared, you're now losing 2%. By the time you're down here, in the green or the blue, you're losing nearly all the light. And at even more dust, it gets worse still. But it gets worse primarily at the blue.

So this, it occurs, is also a way to find out how bad the dust is and to correct for it. So what you could do is instead of just taking a picture at one wavelength, you could, say, pick two wavelengths, say a blue and a red wavelength. And you measure how bright your Cepheid variables, or your supernovae, or whatever they are, at these two wavelengths.

Now, you have to know what color they are if there's no dust. You probably just take the bluest thing you can find and treat that as it's got no dust. It's probably still has small amounts of dust. But you can mainly ignore that.

And then for another one, you can say, well, it sits down at 10% in the blue, compared to the red. That probably means it's on this curve. Whereas if it's down by twice as much in the blue and the red, it's probably this curve. If it's down near 90 times as much in the blue as the red, it might be that curve.

So by looking at two colors and seeing-- you don't how much it's down in either, but you could look at the ratio. And if it's a very big ratio of red to blue, that means there's lot of dust going on. It looks red to the eye and to the telescope.

So surely, you could measure the color and say, well, that one looks very red. Therefore, it must be on this curve. And that will then read out from the curve, how much of a correction to make and look at how far it really should be.

BRIAN SCHMIDT: Oh, Paul, if only things were so easy. So there's a number of problems. The first problem is-- let's just take Cepheid variable stars, our venerable tool for measuring distances.

It turns out that Cepheid variable stars have a range of colors. So when I do this ratio, I don't know what to compare it to. Is it the blue part of the Cepheid or the red part? So that means I'm going to have uncertainty when I apply it to a given Cepheid. But that's just the beginning problem.

So a type Ia supernova, for example, I could try to use it. Now, type Ia supernovae are pretty well-behaved, we think, in their color, although probably not perfectly. But then we look, and not all dust is the same. You plotted these curves like they're the only ones. But, in fact, there can be different dust laws because the dust has different sizes.

And we see this with the type Ia supernovae all the time. There seems to be bigger dust and littler dust. And we don't know which it is, unless we get huge amounts of data, which is just simply not practical in most cases,

PAUL FRANCIS: Yeah. I've got two different dust extinction curves. And they both have the same ratio of red to blue. But there are actually quite different amounts of absorption, twice absorbed as the other. And we know this is a problem. I mean this is actually some work I do because I like dust. I actually try to measure properties of dust in distant quasars.

And you can find, particularly at blue and ultraviolet wavelengths, they're also just features. The dust is probably produced in winds of red giant stars mostly. But then some of it is destroyed, particularly through hard radiation, like a supernovae or a quasar is nearby. That can destroy some of the dust grains in the other ones. There can be chemical reactions that change them, catalysis on the surface. That has to be really complicated.

But different sorts of dust properties and different ratios of big dust to small dust, you can get very different curves. So this color method may work as an average. But it's not that great.

BRIAN SCHMIDT: It's true. So the obvious thing to do is just not to work here, but to work over here, where the effects are much smaller.

PAUL FRANCIS: And indeed, here's an optical picture of galaxy NGC 253. And you can see it's very broken up by dust. If you look at the same thing out at the wavelength of two microns in the near-infrared, from the two-micron sky survey--

BRIAN SCHMIDT: It's almost a completely different looking galaxy. And you can see the stars are the same. So it gives it away. But, yeah, all those stars. It has a big bar across the thing. It looks completely different.

PAUL FRANCIS: There's still a bit of dust you can see in here. But it's got very much better. So working at the infrared works well. I mean some work I did-- this is what's called a blob, a giant-forming cloud of gas in the early universe, Blob 6, this one is.

Look at the optical, you don't see very much. At the infrared, it's a whopping great collection of massively star-forming galaxies. You wouldn't even see this over here. So it makes a huge difference going out to the infrared.

BRIAN SCHMIDT: So the infrared is clearly where we want to work. The problem is observing in infrared is really, really hard from the ground. It requires, to do accurately, very big telescopes, very good sites. And it turns out that our detectors are really problematic in the infrared.

PAUL FRANCIS: Yes. We normally use charged-coupled devices, the silicon chips the same as you've probably got in your cell phone or digital camera. The trouble is silicon has a band-gap energy that corresponds to a photon with a wavelength of about 1.1 microns. What that means is to detect a light falling on it, the photon has to have enough energy to knock an electron away from its lattice position. And anything in the infrared can't do that.

BRIAN SCHMIDT: Yup. They just sort of go right through the silicon. It's transparent, effectively.

PAUL FRANCIS: So you start needing to use exotic semiconductors, instead of silicon, which you can pick up on any beach. You start using indium antimonide or mercury-cadmium-telluride. And that puts the price though the roof, a, because the elements are rare and expensive. But secondly, because they're not being manufactured in millions of camera phones all over the place. It's a very complicated, difficult manufacturing process, which puts the price through the roof.

BRIAN SCHMIDT: And the other problem is these same detectors are used by the defense industry, which means it's actually really hard to even get them at all because they're considered to be "top secret."

PAUL FRANCIS: So many countries are not allowed to import these things at all because of the military export rules.

But even if you've got these wonderful detectors, then you've still got a problem. And that's at most infrared wavelengths, you're close to the wavelengths at which the black body of Earth's temperature emits. So try to work at, say, 5 micron wavelengths, your telescope is going to be glowing. Because at 5 microns, you and I, and the telescope, and the dust in the Earth's atmosphere are all glowing like crazy. So it's like trying to work in the dome with the lights on and the telescope made of fluorescent tubes.

BRIAN SCHMIDT: Yeah. So you have that background problem. And then you have another problem, which is the diffraction of light. When you're working in the infrared, the telescope is closer to the wavelength of light. And so your resolution shrinks down.

So we want to look at something like a Cepheid, normally, if you're looking at it in the blue light, you can see it because it's a nice, sharp image. When you look at the infrared, it's blurry. So all these things make it really hard to observe in the infrared.

A4_L5_V02_Bias

PAUL: Now, one of the wonders of astronomy is the gorgeous pretty pictures. And here's a typical random gorgeous pretty picture, taken by the Cassini spacecraft showing Saturn. And that's actually Earth in the background over there.

And these things are lovely. Now, is this what all astronomical images are like? Is this what the images you take are like?

BRIAN: I wish my images looked like this. This is more about what an image that I take looks like. So this is a picture of a random piece of sky. And what you see here is this mottled pattern. And that's because the sky is full of a random photons that are arriving from things we just can't see, or just from the atmosphere.

And then, I'm going to be interested in something really, really faint. Not something like that, but more like something like that, all right. And so that isn't much. And so there's only a few extra photons arriving above the background.

PAUL: We'd also be looking at things we only pick up a few photons an hour from them. And you're going to get, over same time, hundreds of photons from sky emission, from zodiacal light and other stuff. And it's all going to be a random arrival. Unless you're expecting 10 photons a minute, it doesn't mean every one arrives regularly. In practice its random.

It's like buses, maybe five arrive at once, or you get none for an hour. Which is what produces this whole mottling pattern. And what this means is that when you try and measure how bright something is, you're not going to get it precisely right no matter how good your telescope is. It might that, for example, you're going to have an error of plus or minus 10 photons.

BRIAN: Yep.

PAUL: Now, let's imagine you got a whole bunch of things at different redshifts, and the nearby ones are going to be bright. Have a high-- there's a log flux here-- and the faraway ones are going to be faint. Now this one, you might be getting a million photos from your object.

So at uncertainty of plus or minus 10 photons on a million is going to give you almost no uncertainty. But as you get fainter and fainter, these ones, you might only be getting your one photon an hour. In that case a 10 photon uncertainty is going to give you serious grief.

BRIAN: That's right.

PAUL: So your errors are going to go up and up and up as you get fainter and fainter and fainter. And this is pretty much inevitable. Its very nature of how the observations work.

So this is what the aerobot looked like. So let's say you did a sample, and you measured hundreds and hundreds of-- these could cepheids or supernovae or something like that-- it's got--

BRIAN: So you've done like a Monte Carlo, what we would say. You've gone through, and you've taken the uncertainty, and you've just randomly created something with that uncertainty?

PAUL: That's right. And it would look something like this. So they'd be pretty tightly clustered up here, and spread out.

BRIAN: Right. So this is all well and good, but we're going to have a problem here, of course, because when we actually go out and look at the sky, I only see things to a certain brightness. That is, I don't get to get all of the-- I don't get to see everything here, because I can't tell they actually exist at some point.

PAUL: If you could see all these ones-- the ones that were up here, and the ones that are down there. If you only had two or four data points, they could randomly be up here and they could give you grief. But if you could do an ensemble of thousands of these things, in principle you could average your way through the middle of all these things, and get a line-- something like that.

BRIAN: Yeah.

PAUL: But as Brian said, we're not going to see all of them. Because let's say you've got 10 photons worth of noise, something that only picked up 10 photos, it's probably not real.

BRIAN: Yeah. It's a 2 in 3 chance that it isn't real, if you think every part of the sky has got a 50-50 chance of being real.

PAUL: Yeah. So you probably need to be something up around maybe 30 or 50 electrons-- photons. I call these electrons, because every photon that hits produces an electron in your detector. So you'd need to be 3 or 5 times the noise level before you're really confident things a real. Otherwise you're just going to get swamped by random celestial fluctuations.

So let's say this is our cutoff here. We've decided that that's the faintest we can go and believe it. So we're not going to believe anything below there.

BRIAN: And that means you're going to lose all of these objects that are too faint.

PAUL: Yeah. If you tried to count them, you'd get these. But you'd also get a million other spurious ones.

BRIAN: Right.

PAUL: So it's really very-- you can't count these things, no matter what you want to do. And that means what you're actually going to see is something that looks like this.

BRIAN: Yeah.

PAUL: You see, you got a correlation you're going to find is going to curve up.

BRIAN: So what we're trying to do is measure-- if you think about what we're trying to do as a function of redshift, we want to measure the relative flux of an object back in time. But we're going to be getting the wrong answer right where we're interested in the information-- where what the universe is doing counts.

PAUL: Yeah. And these ones are going to appear brighter than they should be, because you've lost all the faint ones. And because they are brighter, we think they're nearer. So that will curve our entire curve of scale factor versus time and give us the wrong answer.

BRIAN: Right. And you may think, OK, what we need to do is just build a bigger telescope, and see the bright one. So if I get a bigger telescope, one could imagine shrinking this to even larger redshifts. But there's another effect we have to worry about that's a little more subtle. Which is that the objects themselves are not perfect. They're not all the same brightness.

There are brighter than average, and there are fainter than average. And so the brighter than average ones we can see over a bigger volume of the universe. And so even with a big telescope, what we end up seeing at the edge of our sample-- even if we cut it off for bright objects only-- because we always see the brighter-than-average objects. And they always end up biasing our result unless we fix that problem.

PAUL: I saw an interesting example of this with some of my thesis work. We went and did a survey of 1,000 quasars. And then, five years later, I went back and reobserved 50 of them to see how much their brightness had changed-- because quasars change in brightness all the time. And of that 50, every single one had got fainter.

BRIAN: Mm.

PAUL: You'd imagine half would have gone up and half would have gone down, but every single one went fainter. What's happening here? Well of course, our original survey had a flux limit.

And so we're likely to catch the ones that were at the brightest stage. Because at that point, there are intrinsically far more faint ones than bright ones. So you're far more likely to catch a faint one that happens to have been bright, than an even brigher one that happened to have been faint. Because there are just far more faint ones out there.

BRIAN: Yeah, and you see them over that huge volume when they're bright, and a very tiny volume when they're faint. And so, yeah, that's a normal selection effect we have to worry about.

PAUL: Well, could you just ignore the ones near the limit of your survey? Just deal with the ones that are not hard to spot, where there's oodles of brightness?

BRIAN: You cannot get rid of this problem, because there's always this effect of things coming in and out. And it turns out the better your distance method, the smaller the scatter is, intrinsically, that makes things better, it turns out, by the square of how good a distance indicator you have. So if you have something like Tully-Fisher, we talked about, that has an 18% scatter, and a Type IA supernova that's 6% scatter. That is a factor of 3 difference. It turns out the effect is 9 times worse for Tully-Fisher, the square of their relative differences.

PAUL: Could you model this whole thing? Actually do a Monte Carlo simulation like this and try to estimate how big the effect is-- and therefore correct for it somehow?

BRIAN: That's exactly what we do. And if you use a method like Type IA supernovae, that have small intrinsic scatter, then you can probably model things out to a few percent. But when you have a bigger problem, then the problems get 9 times worse, for example. And then instead of being a couple percent, they become 18%, which is probably bigger than you want.

PAUL: OK. So we've talked to through classical way of measuring distances-- the classical distance ladder. So we start off with parallaxes, main-sequence fitting, Cepheid variables-- Tully-Fisher, supernovae, each with their problems.

As well as the problems each of them have, some of which we understand some of which we don't understand. There's the problem of dust and the problems of these sorts of biases coming in. I mean, this sounds pretty hopeless. Do we just give up?

BRIAN: Well, it is a reason why that for almost 100 years, the measurement, of especially the Hubble constant, where we're trying to measure the absolute distance, has been so hard. Because you've had to literally Daisy chain all these things together with all these problems. And so it's only recently that we've really begun, as a community, to think-- we've measured it to 10%.

PAUL: So we'll now go on to talk about some of the recent-- just in the last 10 or 15 years-- improvements. Which have taken what's traditionally been a very controversial, chaotic, disputed field, and actually started to give it something almost resembling precision.

BRIAN: Yep.

A4_L5_V03_HST

PAUL FRANCIS: So we've seen that measuring distances is an almost impossibly hard problem. There are just so many reasons why it's difficult. But it's also absolutely vital to understand what universe we actually live in as opposed to what the theorists tell us.

However, things have got much better. Now why is that, Brian?

BRIAN SCHMIDT: Well, it's because we've invested a huge amount of money, $2 billion plus, in the Hubble Space Telescope. And the Hubble Space Telescope was really designed to go out and solve the distance ladder problem, to be able to have the resolution and sensitivity to literally see Cepheid stars in not just a handful of nearby galaxies, but in lots of nearby galaxies.

PAUL FRANCIS: Here's a recent paper showing a nearby galaxy, and you can just about see the green, red, and yellow circles indicate various Cepheid stars in this galaxy. And you can see it's finding lots of them in a much more distant galaxy. How far out can it go?

BRIAN SCHMIDT: I think the most distant Cepheid it's done reliably is at about 30 megaparsecs, so that's a volume that is 10 cubed further than we used to be go go. So it's a lot further.

PAUL FRANCIS: And in particular, first of all, you can get many more galaxies, and therefore calibrate things like Tully-Fisher much more accurately. But you could also, within that larger volume, find a reasonable number of galaxies that have hosted type 1a supernovae.

BRIAN SCHMIDT: That's right, and this is one of the reasons my colleague, Adam Riess, who helped discover the accelerating universe with me and our team, has been going out and trying to measure accurate distance to the nearby galaxies, so he could calibrate these type 1a supernovae.

PAUL FRANCIS: It turns out that in addition to this, which is what Hubble was built for, it had a rather unexpected, another benefit, in terms of getting distance ladder, which is the trouble with Cepheids is you can measure the Cepheids here-- so they repeated pictures and look for the brightness changes, measure the brightness-- and then compare that to the Leavitt law back to the Large Magellanic Cloud. But we still don't know how far away the Large Magellanic Cloud it. But it turns out that the Hubble Space Telescope has an instrument called the Fine Guidance Sensor, which is actually not supposed to be a science instrument. It's just supposed to help it line up on target and stay pointing.

But it turns out that this instrument allows you to measure parallaxes much more accurately than anything else at the moment, and so it has actually been able to get distances out far enough that you can actually measure parallaxes for a small number of Cepheids in our own galaxy, in the Milky Way. It's only about 10, I think, at the moment, and the errors on distances are still about 10% or 12% or thereabouts. But nonetheless, if you can bypass the Magellanic Cloud and measure Cepheids in our own galaxy, our own galaxy has a high amount of these heavy elements, very similar to other galaxies like this one that we're looking for. So the whole question about whether the Cepheids vary with the different amount of the heavy elements in the Magellanic Cloud can be bypassed.

BRIAN SCHMIDT: Yeah. So this had been sort of an unexpected gain from the Hubble Space Telescope, and it turns out that in looking at the distant universe, they've also added an infrared camera to the Hubble Space Telescope, and that's had an extra benefit. So Adam Riess, when he goes out and does one of these Cepheid distances, he uses the optical camera to find the Cepheids, and then he goes and uses this camera meant to look at the distant universe to take pictures of those areas. And you can see it's a mess, right?

So let's just look here. Here's a picture in two areas of the infrared, and the dust is much smaller here. It's almost negligible. And then you'll see, for example, a Cepheid here or a Cepheid here. And these are in the other color.

And the problem you have, of course, is that one star or is that several? So it's a real problem that the Hubble Space Telescope is just barely able to do, but it has been a way to get rid of that pesky problem of dust.

PAUL FRANCIS: It would be even better if we could measure parallaxes to Cepheids, a lot of them in our own galaxy. At the moment, we can measure it for maybe ten, to rather low precision, and the trouble is these tend to be the lower mass ones, the more common ones.

BRIAN SCHMIDT: Those are the closer ones, yep.

PAUL FRANCIS: Whereas the ones we actually want, the ones we're seeing-- these ones-- tend to be the higher mass, brighter ones, so you're not quite comparing like with like. So they can calibrate the lower mass ones, but then you have to use the slope of the correlation in the Magellanic Clouds to go to the further ones. And maybe that works, maybe it doesn't. It's just a step you'd like to avoid.

BRIAN SCHMIDT: Maybe it depends on the metallicity again. So what we really need is a dedicated space mission to measure astrometry--

PAUL FRANCIS: Parallaxes.

BRIAN SCHMIDT: Parallaxes, where objects are the sky, very, very accurately.

PAUL FRANCIS: And the European Space Agency has recently launched one called Gaia which has start its project and is going to be completely awesome. This instrument doesn't look particularly deep. It doesn't look particularly faint. It doesn't go at funny wavelengths or anything like that. But it's incredibly stable. Nothing changes, so you can look for these very slight wobbles with unbelievable precision. It's also put out at the Lagrange point, not close to the Earth. Otherwise the heat from the Earth would warm it up and cool it down as it goes in and out of the shadow, and give you all sorts of grief.

The thing is basically a rotating cylinder containing a number of mirrors and telescopes inside, looking out from the slits in the side, and all protected by a sunshade. So a rotating oil drum, well-insulated.

BRIAN SCHMIDT: And so as it rotates around, the stars come in, and it's detected by essentially a black box. It's a very complicated instrument. Because one of the problems is being way out at the Lagrange point, you're so far away that it's very difficult to have a high speed data link. And this thing is going to literally scan the entire sky, every star, billions of objects, and it can't afford to send the data down as images. What it has to do is have an on-board black box that goes through and looks at the images, and measures everything exciting about it, the so-called metadata, which is a big deal in Australia right now because our politicians don't understand metadata very well. That metadata is going to be shipped down to Earth, and over five years or so, you'll have covered the entire sky.

PAUL FRANCIS: And it has two beams about 105 degrees apart or something like that, and it's measuring the position relative to very high precision of these two beams, so it'll know where everything is in the sky relative to something far away, and then later it'll be at some different orientation and measure this one relative to that one. And it will go over and do it over and over again, measuring to get absolute positions of everything to an enormous precision.

And it will be able to measure parallaxes out to how far?

BRIAN SCHMIDT: I think it's getting into a couple kiloparsecs, so several thousand parsecs. And that means we'll be able to see many, many stars, many, many Cepheids. We'll learn a lot about not just the distance scale, but how the Milky Way formed, because we'll be able to see the motions, and it turns out the chemistry, of essentially every star nearby in the Milky Way.

PAUL FRANCIS: So in a few year's time, when they get all the data-- they can't really get any data until it's all finished because they have to map the whole sky because of the differential measurement. They can't just publish this little bit of the sky and that little bit. They have to get everything, and then put it through a horrendously complicated data analysis process. But when it's all done, we will actually have nailed Cepheids to many billions of stars in our own galaxy, and the Cepheids within that will allow us to get that first step that is really accurate. So the combination of Hubble Space Telescope plus Gaia will get the Cepheid distance scale on a much more secure footing.

A4_L5_V04_Eclipsing_Binaries

BRIAN SCHMIDT: So Paul, with the Hubble Space Telescope, we've been able to calibrate a handful of galactic Cepheids. We have the ability to observe in the infrared. But that handful of Cepheids is really going to be a problem. So for that reason, we keep on going back to our old friend, the Large Magellanic Cloud.

That's got 10 billion stars. It's got a lot of Cepheids in it. But we need to really nail it's distance. And would be good to get a distance to it, which is a ruler distance. One that we know is absolutely correct, not a relative distance.

PAUL FRANCIS: And a lot of people are working on this. There are new papers on the distance to the Large Magellanic Cloud coming every week, I would say at the moment. Actually, that's been the case for at least the last 50 years. Much of the early work at Mount Stromlo was working out rough distances to this.

And there are a few methods now coming along which are actually very direct. And I'd like to talk about one of them because it's kind of neat. And it's probably the best at the moment, though there's some competition. And this is actually a spin-off of something we've talked about in the earliest parts of this course, which is gravitational microlensing surveys.

BRIAN SCHMIDT: Right. So if you recall, back in 1993, at Mount Stromlo, we discovered the first microlensing of one object going in front of the others. But to find that, that project was looking at 50 million stars all the times. And so you get the chance to find lots of rare objects. And that project has been replaced with some major projects based around the world. And so these surveys are going through and finding very rare stellar systems in, for example, the Large Magellanic Cloud, over by you, or the bulge, over by me.

PAUL FRANCIS: Yes. And if you remember, we talked about this in two other parts of the previous courses. One was looking for dark matter, which was the original purpose. The idea was that every now and then, something would pass in front of the Magellanic Cloud, the dark thing, and make one of the stars get brighter. It turned that is not a major contributor.

The second thing we talked about was in the exoplanet course and this time looking at the bulge over here. And once again-- every now and then a planet will pass in front of the star, the background, and make it appear brighter because of gravitational lensing. We're now going to talk about a third use of these surveys, which is to find a particular sort of binary star. These are well-separated, eclipsing binaries.

Now, what's going on here is you have two normal, probably pretty big stars orbiting around their common center of mass. It's pretty easy to find eclipsing binaries when the two binary stars are very close in because they have eclipses very often and they don't have to particularly edge-on before you see an eclipse. But these ones, where they're much further apart, are much harder to spot because they have to be almost exactly edge-on to actually see the eclipse. The eclipses are pretty rare.

But these are the ones that we really care about because we want the two stars to be normal stars, as if they were isolated. In the close eclipsing binaries, the stars disturb each other. They pull matter from one to the other, they distort each other, they get tidally locked. All sorts of things are strange. Whereas these ones are so far apart in terms of the properties of a star, so it doesn't matter that the other star is there.

BRIAN SCHMIDT: And that means we can treat them as "spherical cows," which means we can understand them. And if they're distorted, then all the little, simple physics tricks we use aren't so easily done. And so you're not so sure about them.

PAUL FRANCIS: So once one of these microlensing surveys has found these well-separated eclipsing binaries in the Magellanic Clouds, the first thing you do is get spectra. And you can measure the spectrum of the two different star components. You get two different sets of lines superimposed on each other, moving backwards and forwards.

And what you see here is the velocity of the two stars. And one goes up and then goes down, and then goes up. The other one is in reverse, because they're both going at different directions around their common center of mass.

BRIAN SCHMIDT: And we can tell these two stars are very similar of mass because the two curves are almost the same magnitude in size.

PAUL FRANCIS: It's not a perfect sine wave, which is telling us they're not in circular orbit. But just like in that simulation, they're in an elliptical orbit. So they'll be going faster here, when they're being close to each other. And they'll be going slower out here, when they're further apart. But they still never get too close to each other.

BRIAN SCHMIDT: Yup. So that allows us to go through and to essentially calculate what they're doing in their orbits, very accurately.

PAUL FRANCIS: So we get the speed from the Doppler effect. We work out how many kilometers a second they're moving. So we know how fast they're going. And the Doppler effect doesn't depend on distance. So the distance doesn't matter.

The second thing we can you look at is the change in brightness, when one goes in front of the other. So this is a bit complicated to model because you have to allow, for example, limb darkening. The outsides of the star is not as bright as the middle. And they won't go, bang, in front of each other. They'll probably have a glancing incidence where they clip each other.

But a detailed look at this, you can work out those exact things, and by a detailed fitting of this. And so from this, we know how fast they're moving. And this tells us how long it takes one to go in front of the other. You know, speed and time, that give us the distance. So this tells us the radius of the two stars--

BRIAN SCHMIDT: Oh.

PAUL FRANCIS: --independent of anything.

BRIAN SCHMIDT: Yeah. So you have a ruler, the radius of a star independent of the distance. And that turns out to be a very powerful tool to measure how far away these stars are. Effectively figuring out how many watts they're producing.

A4_L5_V05_Surface_brightness

BRIAN SCHMIDT: So Paul, I've asserted that we're going to be able to use these eclipsing binaries to measure essentially how many watts they're emitting or how far away they are. How are we going to do this?

PAUL FRANCIS: Well, we know the radius of these things. If we knew the brightness per unit area of the surface, we could work out the luminosity, and hence use the inverse square to work out how far away they are. But do we know that?

Well, it turns out we can find very similar stars, stars of the same color in our own galaxy. But the trouble is they're too far way to measure parallaxes. But if we could measure the brightness per unit area of these nearby stars, even though we can't measure the distance, we could then assume it was the same for these stars in the Magellanic clouds, and then look at the distance. And there's something that really helps us here, which is the concept of surface brightness.

BRIAN SCHMIDT: Oh, OK. So let's see. Here we have you in front of a dome, which is 10 times closer than the much bigger dome that's in the background. But we always say that brightness goes as the distance squared. I know that's 10 times further away. Yet that and that appear, more or less, the same brightness. That seems rather odd.

PAUL FRANCIS: Yeah. It is rather odd. But if you budge over a bit, you can see the two slabs, and here you've got the Earth. Let's imagine we had two slabs, each putting out the same amount of brightness per unit area. Now in this case, the brightness, the flux we receive on the Earth will go as 1 over d squared, so the further one's twice as far away. So we get only one quarter of the flux from it, so that's the inverse square law as you'd imagine.

That's not quite the situation we were at here. Because this square, it's the same angle, but because they're looking at something further away, it's actually-- that's probably only what? 50 centimeters worth of dome, whereas this is probably several meters worth of dome. So what we've actually got to consider is the angle subtended by the slab.

This thing here may be subtended angle feet, and that's the angle from the top to the bottom, whereas the further one, because it's further away, subtends the smaller angle. So remember, we've talked many times in this course about how the angle, when it's small, is roughly given to the length, divided by the distance-- r over d. so if d is twice as big, the angle is only half as big.

But that's linear angle. What you really care about is actually something we haven't talked about before called solid angle. Solid angle is basically what fraction of the total sphere something covers, so it's like an angle area. And that's kind of like theta wide, theta down, so it's going to be like theta times theta. And so that's going to go as r squared over d squared. r squared is basically the area divided by the distance squared.

BRIAN SCHMIDT: Oh, so the total solid angle, that angular area is dropping as the distance squared as well. Oh, OK.

PAUL FRANCIS: That's right. Now we can define surface brightness as the flux per unit solid angle. And so flux obeys the inverse square, so it goes 1 over d squared. But then so does solid angles. We've just said also goes 1 over d squared. So the ratio of the two, which is called surface brightness, is just going to be the flux divided by the solid angle, which is going to be the luminosity over r squared, neither of which depends on the distance to this thing. It just depends-- that's just the power put out per unit area.

So that's all the surface brightness is. It doesn't depend how far away it is. So if you could measure the surface brightness of one of these similar stars of our own galaxy, it's going to be the same as one in the Magellanic Cloud. No corrections needed whatsoever.

BRIAN SCHMIDT: That's very convenient.

PAUL FRANCIS: But how can you measure it? I mean we can measure the flux we get from something, but we'd have to know the solid angle of a nearby star to be able to measure the surface brightness.

BRIAN SCHMIDT: Oh, well, this is where some new technology comes into play, where we can go through and measure very accurately nearby stars' radius using interferometry.

PAUL FRANCIS: Yes, so there are a number of these experiments around the world. One of the pioneering ones was here in Australia. And the idea is you take two typically quite small telescopes separated by maybe 10 or 30 meters or something like that, and they both collect the light. But rather than bring them to the detector, they send it down to relay mirrors, typically into a vacuum chamber or an underground chamber or something like that, and then they beam the two light rays to some beam combiner in a shed in between or an underground bunker or something like that. And here the two light-rays are what we call coherently interfered with each other, so you're actually looking at the interference between the waves.

BRIAN SCHMIDT: And so you're going to have light waves coming down to one telescope, and you're going to have light waves coming down to the other telescope. And if you can get those light waves lined up so that the peaks and the troughs are the same, then you'll get this pattern of their interference where you'll get bright and faint. And that's when you know you've got them lined up.

PAUL FRANCIS: So if you start with 0 size, all the light rays are going to come perfectly lined up. As a star gets bigger and bigger, some of the light waves are going to come from a very slightly different angle from the other ones, which will actually cause not quite the perfect lineup. And by seeing how imperfect this lining up is, you could actually measure the angular size, and hence, the solid angle, of the stars out to much greater distances than you can actually measure the distances to, the more parallaxes.

Here's one these things. This is the very large telescope interferometer in Chile. Other important ones as one near Narrabri right here in Australia, the US Naval Observatory near Flagstaff in Arizona has one. There's one at Mt. Wilson, and there are various others around the world. And these combine-- like in this case, it's not from the giant telescopes in the background usually. It's usually these little small ones that could be moved around here bouncing the light down the tunnels, combining it and measuring the radii of the stars.

So you have the radius of the star. We can measure the flux from the star. We can therefore work out the surface brightness. Talking about 3% precision, and if we know the surface brightness of a similar star in our own galaxy, we can then use it to go out to the Magellanic Clouds, and measure the surface brightness there.

So we're now looking at our binary things. We know the surface brightness. That's the brightness per unit area. It's going to be the same no matter how far away it is. We also know the radius of these stars because of the eclipses. So the luminosity is going to be the surface area times the brightness per unit area.

BRIAN SCHMIDT: Right. So we've now managed to take that radius measurement, convert to a surface area, times the surface brightness, and we've measured the luminosity, which is how many watts our star is, and so we've calibrated our light bulb in an absolute sense. So when we measure how bright the object appears, we can use the inverse square law to measure its distance.

PAUL FRANCIS: Assuming there's no dust.

BRIAN SCHMIDT: Assuming there's no dust.

PAUL FRANCIS: So at long last, we can get a distance for Magellanic Clouds, and the author of this is claiming about 3% precision.

BRIAN SCHMIDT: Yes, and this is one of the-- well, the most accurate way we have to the large Magellanic Cloud, and a way that is incomparable accuracy, it turns out, to those parallax distances measured to the Milky Way Cepheids.

A4_L5_V06_Megamasers

BRIAN SCHMIDT: So you know Paul, this whole extragalactic distance scale hierarchy is a real mess. It's almost embarrassing.

PAUL FRANCIS: There's a lot of things to go wrong in there.

BRIAN SCHMIDT: Yeah. It's really, really not good. What we really need is a way from going from our own galaxy to other galaxies, big galaxies, using a geometric method like parallax that we do to the nearest stars, but in one step and getting rid of all these little rungs where, quite frankly, we could easily slip off and hurt ourselves, get the wrong answer.

PAUL FRANCIS: It turns out that there is a method that's just been developed in the last decade or so which has a lot of promise for us. And this actually using masers. Now, you're already familiar with lasers. You have them in your DVD players and fiber optic communications and everything. Masers are basically the same, only it's microwave wavelengths rather than visible light.

And let's just remind ourselves of how these things actually work. The basic idea behind a laser or a maser is you have energy levels. In the case of a maser, they're molecular energy levels in the case of atomic energy levels, but it doesn't really matter. And electrons can be in-- a molecule can be in different states here. And what you need to make a laser or a maser work is what's called a population inversion.

Normally, all the electrons are in energy states down in the bottom level. But if for some reason-- maybe you're zapping something, heating it up or something-- you get large numbers of atoms in the top state.

BRIAN SCHMIDT: So you get more in the top state than the bottom state.

PAUL FRANCIS: Yes. Then if you get a photon coming along from outside which has just the right energy that's equivalent to this energy level gap, it will come along, and it will actually trigger, stimulate, the electron or the energy state to jump down.

BRIAN SCHMIDT: Right. So that's called stimulated emission, because when it drops down it'll emit a photon.

PAUL FRANCIS: Yes. And what that means is that instead of getting one photon with this energy, you get two. But the really important thing is they're perfectly in phase with each. They're perfectly lined up, perfectly in the same direction. And if you have a long enough progression of this, whatever it is that's in this population inversion, a photon can turn into two, four, eight, sixteen.

BRIAN SCHMIDT: So you get a cascade, a runaway, almost like a nuclear reaction of photons. All you have to do is somehow excite and get all these things up in these high energy states.

PAUL FRANCIS: And you have to have a long enough distance to go through. Now in a laser on Earth, you normally have two semi-silvered mirrors on both sides. The light can bounce backwards and forwards many, many times.

BRIAN SCHMIDT: Well, you say "semi-silvered" you actually mean they're like 99.99%, and they only let a little tiny bit of stuff out at either end, right?

PAUL FRANCIS: Yes, that's right. Fully silvered would be even better, but you want the laser to come out at some point. But you think this would be something you'd see in the laboratory. But it turns out these actually occur in space. And in particular, there's a small number of active galaxies which have incredibly strong maser emission-- these are "mega masers" because of their incredible power-- coming right from the center. It's not the whole galaxy, it's only from your dot in the middle.

BRIAN SCHMIDT: Right in the center. So this is in NGC4258. It's a galaxy that is about 7 megaparsecs, so roughly 22 million light years in distance. And it's funny, it's one of the nearest objects that has a semi-active black hole in its core.

BRIAN SCHMIDT: Yes. So it's got an active galactic nuclei. We've talked about them in the previous course. What that means is there's a big black hole in the middle with a swirling disk of gas around it, and that gas is really hot as it swirls faster and faster around the black hole before falling in. And it seems that central black hole and the disc around it is where this maser is coming from. Now, if you take a spectrum of this, you find something like this.

BRIAN SCHMIDT: This is a radio spectrum, right?

PAUL FRANCIS: That's right. As this is a maser, it's coming out as microwave radio frequencies, so you use a radio telescope. And what you can see is it's not just one emission light. It's a whole bunch. This is actually OH, water vapor. So it's really water in this thing, and it's being stimulated into the upper energy level and jumping down. But we see a whole series of very narrow spikes, narrow components of different positions and different velocities.

BRIAN SCHMIDT: And these are different times. This is going back in 1997 all the way up to 2000. So this is three years worth of data. And so we have different frequencies. And we know that masers emit things at a very precise energy level, that energy difference between the two levels. So we know what that is to seven decimal places, or something.

PAUL FRANCIS: OK. So we seem to have a whole bunch of compact clumps moving at different speeds in the middle of this galaxy, emitting this water vapor maser emission. Now because these radio-emitting clumps are incredibly bright and incredibly small, we can use a technique that we can't normally do, which is called very long baseline interferometry.

BRIAN SCHMIDT: Or VLBI, as we like to say.

PAUL FRANCIS: VLBI, yes. And the way this works is you take radio telescopes like this one at Parkes in Australia. Normally, a radio telescope has a pretty blurry image. Because of the diffraction limit, it can only see very blurrily what's going on.

BRIAN SCHMIDT: Yeah. So remember that the diffraction limit in radians is the wavelength of light divided by the diameter of the dish. Very big dish, 70 meters here, but the wavelengths of light we want to look at here is very long. It's on the order of several centimeters. So that ratio isn't a very big-- sorry, is quite big. So it's not very precise.

PAUL FRANCIS: However, what you can do is you can combine different radio telescopes all around the world-- and occasionally, even in space-- and for each radio telescope, you can record the signal as it comes in. Now, radio waves, you can actually record the full phase of the signal. Optically, you just count photons. So you can't do this in optical wavelengths without actually bouncing mirrors between the telescopes.

But in radio, you can actually coherently record a signal with its full phase, usually on racks of DVD players or something like this. And then you can ship a box full of DVDs with a signal from one radio telescope to another one and combine them all and have devices called correlators that look for patterns by combining the signal from, say, a telescope in Eastern Australia, Western Australia, New Zealand, Japan, all around the world. And by combining the signals, as long as the thing you're looking at is incredibly bright and incredibly small, you can get absolutely amazing precision.

BRIAN SCHMIDT: Because you're actually using the telescopes as a giant telescope with a lot of holes in between. So you can take the telescope, for example, at Parkes in Australia, combine it with one, for example, in South Africa or in Hawaii and stare at the same thing. And you end up essentially having a telescope that's 10,000 kilometers across instead of only 70 meters. So you've got a very, very big diameter of the telescope at the bottom, which means you get really, really amazing resolution, assuming the object is bright enough to be seen.

PAUL FRANCIS: It means you can actually get micro arc second resolution. You're lucky if you can get a million times worse than that on a optical telescope. So when this works, it doesn't work very often, but it does work for masers. You can get image sharpness that's about a million times better than you can achieve by any other technique.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: It's pretty amazing. And when they use it on this, they can map these dots around in the middle of this galaxy. And what you can see, this is a map of the sky, is they're in a kind of line. There's a bunch of red-shifted ones on one side. These are moving away from us. A bunch of them not red-shifted or blue-shifted in the middle and a blue-shifted one on the other side. It's kind of like a spinning disc. So you've got the blue side moving towards us, and the red side moving away.

BRIAN SCHMIDT: OK. And then if we zoom in here, let's just get ourselves here. So we're going to look and we're going to zoom in here and. And these things seem to be a small pattern of what's going on there, but not much. And these things actually do have an interesting pattern and another interesting pattern. So if we think of it as a disc, it's sort of a warped disc. It's not just a nice pancake.

PAUL FRANCIS: And if we look at a position, velocity diagrams, what we're plotting here is the velocity against the position. So these are the ones on the left, those are the ones on the right. And what you can see is velocities go up over here. In the middle, they're going down as a straight line, and then something like this.

BRIAN SCHMIDT: Right, OK. And that almost looks like a square root, which is what Kepler's Law would predict if these things were rotating around a mass.

PAUL FRANCIS: Yeah. So these ones out here on both sides are almost perfectly fitting what you'd expect if this was orbiting around the central black hole.

BRIAN SCHMIDT: All right. So you can think you have this big disc with the hands-- sorry, I'm off things. And so I'm rotating like that. So one's going to come towards you, and one's going to be going away from you.

PAUL FRANCIS: But in fact, the bits closer enough in have to move faster, because they've got more gravity to fight off. So it's rather hard, you have to move your shoulders faster than your arms.

BRIAN SCHMIDT: Yeah, because I'm fixed, so I don't actually count as a gravitational system.

PAUL FRANCIS: So in fact, the ones going closer and moving faster and faster--

BRIAN SCHMIDT: Right.

PAUL FRANCIS: How about these ones? What's going on there?

BRIAN SCHMIDT: Oh, so those are the ones that are like the lighthouse going past you like that. And so when they're directly at you, there's almost no velocity. But then you pick up that sine curve, right? So--

PAUL FRANCIS: Yes, they're moving sideways.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: And so when they're back in front, they're perfectly at right angles, so there's no velocity. A bit on one side will be a little bit away, or a bit towards you.

BRIAN SCHMIDT: Right. So these things are moving so fast at 1,000 kilometers or 1,500 kilometers per second that you're going to pick up that little sideways motion just from the small little angle multiplied through,

PAUL FRANCIS: Yeah. So what you've got is, for some reason, you've got this disc around the black hole. And there are clumps within this disc. And they're presumably being heated up, because all [INAUDIBLE] spiraling around a black hole, which is a pretty violent environment. And that's [INAUDIBLE] population inversion, and it's the masers. But the masers aren't coming from all parts of the disc. They're coming from three very specific parts.

You've got a line along the slide here. The lumps there are masing. A line along the slide there where they're masing, and the bit right in front of the black hole where they're masing.

BRIAN SCHMIDT: Ahh, OK. So I--

PAUL FRANCIS: But the bit over here, for example, or over there are not masing.

BRIAN SCHMIDT: So it sort of makes sense though if you think about how a maser works. You need to have a photon be created which is going to cascade to another one to give another two, four, eight. But you need those not to be red shifted, because if they get red shifted, they're no longer going to be able to stimulate the emission of the next object. So you need to have spots where there's not going to be any big red shift.

PAUL FRANCIS: Yeah. So you want-- if a random photon is emitted by a cloud of gas but it goes through another cloud of gas, that other cloud of gas is going to be at the same velocity along the line of size. So here, because everything's moving perpendicular to the line of size, that's the case. So you get a photon that maybe even starts from near the black hole-- that's very, very hot-- and then every cloud of gas, they're all moving sideways at different speeds. But it doesn't give you a Doppler effect.

BRIAN SCHMIDT: Right. So the Doppler effect is the sine of the angle away. The sine is essentially 0. And so the sine of 0 is 0, so--

PAUL FRANCIS: So quite a small signal can get amplified and amplified and amplified as goes along. But also here, along this line here, the gas is briefly moving straight towards us. So that means once again you've got a whole bunch of gas. It's like the edge of the circle, which is at the same velocity. So once again, there's amplification. Whereas if you're looking further forward, where it's curving obliquely, in that case if a photon wants to go this way, it has to go through gas at different speeds. And so it won't get amplified very much.

So probably there is maser emission coming from everywhere in the disc, but the maser emission from here is being beamed off in some different direction. Only from here and here is it being amplified in our direction.

BRIAN SCHMIDT: In our direction, OK. That makes a lot of sense.

PAUL FRANCIS: OK.

BRIAN SCHMIDT: So we have a beautiful system which looks a little complicated, but actually compared to most galaxies, it looks rather simple. You have these curves that are sort of Keplerian, we think.

PAUL FRANCIS: Mmhm.

BRIAN SCHMIDT: And we have these objects in front that are moving. But the interesting thing, of course, is we know how far these things are apart. We know what the angular size is. And just like the eclipsing binary, I bet, since we're going to be able to measure the velocities and stuff, we're going to be able to convert that stuff to a physical size.

PAUL FRANCIS: Well, there are two more things we have to measure. And these are things that we really need very long baseline interferometry to find. One is we can look at the spectrum, where you see all those spikes. And by looking over 10 years, we can actually see the spikes will change in wavelength, quite measurably. The only reason they can do this is because they're masers, they're such very, very narrow spikes. With radio telescopes, you can get incredibly good spectral resolution. And so you actually see the shift in velocity. And of course, shift in velocity is acceleration.

BRIAN SCHMIDT: Ooh. And acceleration going in a circle is going to be v squared over r.

PAUL FRANCIS: Yes. So particularly for the ones in the front, you can see the change because they're accelerating towards the middle. The acceleration is always centripetal. We should be able to see the change in velocity. So that's going to be a really crucial clue.

The other really crucial clue is for the ones in front, you've actually-- if you observe from years apart, you can actually see them moving. Now, this is almost unheard of in any galaxy other than our own to see the sideways motion. But you can actually, with incredible micro-arcsecond resolution, and very long base interferometry, actually see as they're moving sideways, and then measure their sideways velocity.

BRIAN SCHMIDT: So this sounds like a good time, Paul, to go and take the data and go through and try to see how we might measure the distance to this galaxy in detail.

PAUL FRANCIS: Yes. So let's go look at all these different clues and try and put them together to see if we can actually get a distance.

A4_L5_V07_Maser_Distance

PAUL: OK, we have all this wonderful data about the maser. How can we use it to actually measure its distance? Well, let's take stock of what we actually know.

We're on the Earth over here. And in the middle of the maser we have a black hole, which I will draw in blue, so it shows up. It holds unknown mass m. And we can see a whole bunch of blobs orbiting it.

Let's, for a minute, just consider one blob out here to the side and one blob in front. What can we measure? Well, we can measure the velocity of this blob out of here. It's in the Doppler effect, so we'll call that V1. We can't measure the distance from the black hole, but we can measure the angle.

So let's draw an imaginary line along here and one up there. And we can measure that angle Theta. What we want, of course, is the total distance here.

How about this blob in the front there? What we know about that is its acceleration. We look at how much its velocity is changing, which is going to be ported towards the center, so we know some acceleration a.

And we can also measure its angular speed sideways. So let's imagine it's actually at an angle, very small angle phi in here. And what we can measure is the rate of change of phi-- phi dot.

Two other things we don't know. We don't know this radius here, which I'm going to call r1, how far the sideways things are. And we don't know how far in front, called r2, the blobs that we see along the line of sight r. So we know V1, Theta, acceleration a, and phi dot. And we want to work out is D, the distance from the Earth to this maser.

OK, so let's start off with let's call this Blob 1 here and call this one Blob 2. In reality, you'd do the circulation for many, many blobs on both sides, but the bare minimum you need is one blob to the side and one blob in front. So if you take Blob 1, now we don't know r1, but we do know that it's equal to Theta times the distance. So we know that r1 equals Theta times the distance using the small angle approximation that we've used many times in the course.

The other thing we know is we can balance centrifugal force against gravity. So we know that m of the blob, small m, V1 squared of r1 equals the gravitational force G big M with a black hole small m over r1 squared. So rearranging that we find that the mass of the actual blob cancels out, one of the r1's cancel. And we get an expression for the unknown mass of the black hole, which is the mass of the black hole equals r1, which is ThetaD times the velocity, which we know, squared over G.

So the only thing in this equation we don't know is how far away the maser is from the Earth. OK, so it's a good start, but not enough by itself. We've got two unknowns D and m in this equation. We need another equation to solve it.

So let's go for Blob 2. Now, in this case, we know a bunch of stuff. We know the acceleration. And the acceleration, whenever anything is going in a circle is this over here mV squared over r. That's actually the force of acceleration is divided by the mass.

So the acceleration, which we can observe by looking at how much the Doppler shift changes is going to be equal to the velocity of the second object-- let's call that V2-- V2 squared over r2, which doesn't really help us, as we don't know the V2 or r2. Let's rearrange it to make r2 the subject. So r2 equals V2 squared over a.

So what we'd like is another equation for r2 which we use to cancel this out. And once again, we can balance centrifugal force against gravity, which gives us that G big M small m over r2 squared equals small m V2 squares over r2, just as we did above. So if we rearrange that, we find that r2 equals GM over V2 squared.

So now we've got two equations-- this one and this one-- both of which give us r2. If we set them equal to each other we can hopefully get rid of r2, which we don't really care about. So let's set those two equations equal to each other. And again, the expression for the acceleration a equals V2 to the fourth over GM. And now the r2 canceled out.

We arranged that to get M. And we get M equals V2. Now, V2 is just phi dot times the distance, small angle approximation again. That's going to be phi dot D to the fourth over Ga.

So it's a second equation for the mass. We have the first equation up here. So what we can do is set them equal to each other. So we get ThetaDV1 squared over G-- it's all we got from Blob 1-- is equal to phi dot to the fourth D to the fourth over G times acceleration.

So the G's cancel. One of the D's cancels. And what we find is D equals the cube root ThetaV1 squared a over phi dot to the fourth power.

So we can work out D in terms of only things we can measure, theta, how far away the side dots are from the center, the doppler velocity of those side dots, the acceleration of the object in front, and the angular speed of the object in front raised to the fourth power. In practice, of course, you have to worry about whether these dots, blobs are actually moving in perfect circles, whether the disc is actually warped. On the other hand, you typically have lots and lots of different blobs to use. So you can try and calculate these two expressions over lots and lots of the different ones and try to fit them all simultaneously, so you can get some pretty good data here.

A4_L5_V08_TRGB

PAUL FRANCIS: Now, we've talked about a whole bunch of different techniques getting better and better. We're still very reliant on Cepheid variables. The reason is that, generally speaking, the galaxies that have masers are not necessarily the ones that have the supernovae.

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: So you want something which allows you to transfer the distance you get from the maser galaxies to the ones that have type Ia supernovae. And then you can supernovae to go out to huge distances. At the moment, we're very reliant on Cepheid variables to do that.

BRIAN SCHMIDT: And we've seen that they're not perfect. So it would be really good to hedge our bets and look to see if there's another method that we could use, like Cepheids, to cross-check our work.

PAUL FRANCIS: Actually, there is another method, called the tip of the red giant branch, which was actually pioneered by Gary Da Costa, here at Mount Stromlo. And let's explain how this works. It's using a different sort of very bright star.

Now, this is a HR diagram, a Hertsprung-Russell diagram. So we're plotting color here, it's blue stars on this side and red stars on that side.

BRIAN SCHMIDT: Low mass, high mass typically,--

PAUL FRANCIS: Um-huh.

BRIAN SCHMIDT: --when they're on the main sequence.

PAUL FRANCIS: And luminosity up here. Now, we've seen this before. We normally had the main sequence of stars, which originally would've gone all the way up here. So these would be the very massive stars, burning very fast, and all the down to the red dwarfs, with our Sun somewhere in the middle.

BRIAN SCHMIDT: Yup.

PAUL FRANCIS: However, this HR diagram is not for just a bunch of stars in our galaxy. It's for a globular cluster, M55. Now, in a globular cluster, all the stars formed in one burst, right at the beginning, pretty much.

BRIAN SCHMIDT: Yeah. So these stars are probably more than 10 billion years old.

PAUL FRANCIS: And what's happened here is originally there would have been a main sequence all the way up here. But these stars sort of come to the end of their lives, stopped burning hydrogen, and moved off the main sequence and exploded. And then the slightly lower mass ones sort of moved off, and so on, and so forth. So by now, after 10 or 12 billion years, all the main sequence stars above there have gone.

BRIAN SCHMIDT: Right. And this is about 8/10 of a solar mass. So our Sun, if it would have had this chemical composition, would have lived its entire life for this globular cluster.

PAUL FRANCIS: So the top here tells you some estimate of the age of the globular cluster. And what you can see is the stars that were around here, have moved off and joined what's called the red giant branch, where they've become much bigger and much more luminous.

BRIAN SCHMIDT: And that's because they've run out of hydrogen in their cores, as we'll see.

PAUL FRANCIS: And what these things look like is they've burned all hydrogen in the middle. So they've now got a core of helium. Now, this helium is supported by what's called degeneracy pressure. This is a quantum mechanical thing.

Those of you who did the violent universe course would have heard vast amounts about this then. But basically, the laws of quantum mechanics means that the electrons, when you squash them into a very tiny space. have to acquire a certain amount of speed. And that speed holds the whole thing up and stops it collapsing.

So the lump in the middle is no longer doing fusion. It's just sitting there, a very hot, very dense lump, supported by this quantum mechanical motion of the electrons. And the actual fusion is happening in a shell around the outside, which is where the hydrogen is burning to form helium.

BRIAN SCHMIDT: Right. So hydrogen shell burning out here, making helium. And the helium, which is heavier than the hydrogen, is going to be settling down on this core.

PAUL FRANCIS: So you've got like a very hot helium snow, or silt, or sediment, or something, slowly accumulating on the surface of this degenerate helium core, which is kind of like a white dwarf in the middle of a star. But as this helium cools, that one is going to get bigger, and bigger, and bigger. And once again, we talked about in the violent universe course, there's a maximum size that a core, that's supported by this quantum mechanical degeneracy pressure, can reach.

BRIAN SCHMIDT: And we should say it hasn't become bigger in length. It actually becomes bigger in terms of its mass. It actually is becoming smaller in its length.

PAUL FRANCIS: Yes. It's like some pile of bean bags. You pile up bean bags on top. And the extra weight compresses them more. So any more bean beans, they actually make your pile smaller, rather than larger.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: So as more and more mass is piled up, then the core gets smaller and smaller and denser and denser. And that means the electrons have to move faster to be able to support it all. And at some point, they're getting close to the speed of light and they just can't go any faster.

BRIAN SCHMIDT: Yeah. So in practice what happens is the core here shrinks to the point where you can take 3 helium atoms at a time and slam them together to make carbon. And so you actually ignite this helium relatively quickly, compared to most things that happen in the star.

And so you suddenly start burning stuff in the core. The helium to carbon, and oxygen, it turns out, which produces a huge amount of energy. Which is going to cause the star to rearrange itself and become a red giant.

PAUL FRANCIS: So astronomically speaking, in the blink of an eye, the whole star rearranges itself and forms a new sort of star, now with burning helium to form carbon, nitrogen, oxygen, things like that in the center. And still with shells of burning other stuff around the outside.

At this point, it moves off the red giant branch and jumps over here to the horizontal branch. And then various complicated things happen, depending on what the mass of the star it started with. They'll go through different phases of burning different things in the middle of the shells around the outside. And they'll move around to here. Maybe even come back to this giant branch. Some of them will turn to Cepheid variables. There's a patch up here where they're actually Cepheid variables.

But what we're interested in is this red giant branch, where the star is just a core of helium in the middle and the hydrogen burning shell. Because this sudden transformation, when the middle lights up, will happen at a very precise mass, that only by the laws of pressure and quantum mechanics. So it's set by fundamental physical constants.

BRIAN SCHMIDT: And it doesn't really matter if you're a slightly bigger or a slightly smaller star, the laws of quantum mechanics don't care if you're a one solar mass star or half a solar mass star. They care about the laws of what hbar is effectively.

PAUL FRANCIS: So it should always happen at the same energy, at the same mass. So these things should all look the same.

That is exactly the same reason why type Ia supernovae are the same. Once again, it's set by the same physics of quantum mechanics balancing gravity. Once you go over a certain mass, you're going to get the explosion. So these are kind of like ultra mini, type Ia supernovae in the middle of stars.

BRIAN SCHMIDT: Yes. All right. So let's look in detail how this would look in a galaxy, which we've heard about, NGC 4258. This is the galaxy that has the masers in it.

So it's a special galaxy. It turns out a lot of Cepheids have been observed in it. And we can go and compare that to what the tip of the red giant branch looks like.

And so you can see that little stream of stars, whose nuclear reactors are getting stronger and stronger and stronger. And they reach this limit where they say, OK, that's as fast as I can go. I'm going to start burning carbon and I'm going to go zoom off that direction.

PAUL FRANCIS: Yes. So to make clear, we're zooming in just on a little bit around here.

BRIAN SCHMIDT: Yep. So we're going to zoom in on that little bit.

And so we see all those stars. And then, bam, there's a limit where there's some other types of stars, called asymptotic giant branch stars up here, we're not going to worry about right now. But there's this pile-up of stars and then none.

And we can actually see exactly where this is. This is a little filter that people have gone through. And they're looking for an edge here, of where there are stars and where there are fewer stars. And you can see right where it's at there.

PAUL FRANCIS: And this is very useful technique. It goes out to roughly the same sort of distances that Cepheids do. So it can be used as a cross-check on Cepheids to make sure that we can transfer the distance from the maser galaxies to the ones with the type Ia supernovae.

And it's also observationally quite easy because if you just need to take one really good Hubble Space Telescope image of a galaxy. Whereas if you get Cepheids, you need to take dozens of images to look for the change in period and the oscillation and measure all that. So you just get one narrow bin and-- oh, two actually, in two different colors.

BRIAN SCHMIDT: Yeah. The other advantage is that this works very well in old populations of stars. And Cepheid variables only occur in young populations of stars. So it's the type we use for measuring distances. And so this allows us to work, for example, on elliptical galaxies as well, which also host type Ia supernovae.

PAUL FRANCIS: Yes. Because type Ia supernovae come from quite old-- no one is quite sure what they come from exactly. But they're the old population.

BRIAN SCHMIDT: Older populations, yeah.

PAUL FRANCIS: So another a very useful method. And by and large, it gives the same answer as Cepheids.

BRIAN SCHMIDT: OK, so we have another arrow in our quiver for understanding the extragalactic distance scale. And Paul, it strikes me that this is as good as it's going to get right now. So it's time to talk about the answers.

PAUL FRANCIS: Yes.

A4_L6_V01_Dark_Energy

PAUL FRANCIS: OK. Time to use all these bright, shiny new toys and give us some answers. Now if you remember, what we're trying to do here is look at how the scale factor of the universe varies with time. So we've got time. And this is today, the present.

And we can measure the scale factor by looking at the redshift to distant things. And we can measure how far back in time by looking at the distance, as we've been talking about at great length. And so, in principle, we can work out the shape of this curve.

BRIAN SCHMIDT: Yeah. So this is what I did for my PhD thesis, Paul. So I was able to look back about 5%, so with a scale factor changed by about 5%, so a small amount. And I could measure essentially over what length that change of 5% referred to. And so that allowed us to measure the Hubble constant, how fast the universe is expanding now.

And so for my PhD thesis, I got that the Hubble constant was 73 kilometers per second, per megaparsec, plus or minus 9. And so that gave us an age of the universe, when you run the universe back in time, of about 14 billion years.

And indeed, the person who brought me to Australia, Jeremy Mould, who was the director of Mount Stromlo at the time, was one of the three people leading the Hubble Key Project. And they got 72 in kilometers per second, per megaparsec. It's almost exactly the same answer I did. Their answer was better than mine. And that was in 2001.

So we more or less agreed back then, using the techniques we've just showed you, that the Hubble constant was about this value of-- a little more than 70 was the best answer back 10 years ago.

PAUL FRANCIS: And not that far different from the best answer now.

So that was one thing. And that was telling us if you extrapolated back, it's a straight line. If the universe was really empty, it would be 14 billion years old.

But, of course, the universe isn't empty. It's got matter in it. But maybe not very much, we're not quite sure. So you'd expect it actually to be a bit younger than that because the curve should curve down to some extent.

BRIAN SCHMIDT: That's right. So if you had that critical density universe, that number is 2/3 of the age. So 2/3 of 14 billion years is like 10 billion years. And 10 billion years is a problem because when we showed you the tip of the red giant branch diagram, that globular cluster, the nuclear physics tells us those stars are like 12 billion years old. And we want the universe to be older than the stuff in it.

PAUL FRANCIS: OK. But presumably you could take your method now. You were using type Ia supernovae to measure distances. And you can see out much further than you've done in your thesis.

BRIAN SCHMIDT: That's correct

PAUL FRANCIS: So in principle, you could then actually look at ones way out, maybe halfway back to the Big Bang, and see is their distance a bit shorter or a bit longer, and measure which of these you're at.

BRIAN SCHMIDT: Yeah, that's right. So in our first course, we described the experiment in detail, where we look back to when the universe was half its current age, to see which of these curves the trajectory of the universe was on, so could get the real age of the universe from the Hubble constant.

PAUL FRANCIS: This is work that got the Nobel Prize. We're not going to go over it again here because you can always go back to course one and have a look at it. But briefly, what did you discover? Which of these curves was it?

BRIAN SCHMIDT: So, of course, when we looked down here, we found that none of these curves were the correct answer. Rather, we had a curve which seemed to be such that the universe was speeding up over time. And so since it's speeding up in the past, it means it's probably going to speed up into the future.

So that's a-- well, it was a crazy result. And when we saw it, we, of course, thought we had made a horrible mistake. It took us a couple months to convince ourselves that our work seemed to be right.

We weren't quite sure why. And quite frankly, we're still not quite sure why. But, yeah, the universe was not doing what it was supposed to. It's not slowing down. Its speeding up.

PAUL FRANCIS: And how do we make this happen? Let's go back to Friedman equation, we've see many, many times. And it turns out that right back in the early days of the equation, Einstein had put a modification in here, which can actually explain this.

We've see that normally the Friedmann equation will give you these things that curve downwards. But back then, Einstein had a problem. He looked at this equation. He'd seen that space had to either expanded or contracted. This was before Hubble had proved that space was expanding.

Einstein thought, ah, that's ridiculous. Space can't expand or contract. So he put a fudge factor in, lambda, over here, so that the universe could actually be stationary. It actually turns out it wouldn't do that because it would be unstable. But that was his idea. And then a year or two later, Hubble came along and said, hey, surprise, the universe is expanding.

BRIAN SCHMIDT: Well, 12 years later. And Einstein said, oops, that was a big mistake. Why did I do that? I acted like a donkey, is what he was quoted as saying, in doing that.

And so when you look at this Friedman equation, you can see you have this constant out here. And so when you're looking at the change of something over time is equal to a constant, well, that's the equation for exponential growth. That's like the number of rabbits is equal to a proportional number of rabbits--

PAUL FRANCIS: Yeah. So what this means--

BRIAN SCHMIDT: --the change in the number of rabbits.

PAUL FRANCIS: -is let's treat this side of the constant. You take the square root of a constant, it's still a constant. So you got a at the of change of a equals a constant times a, to bring that side of the equation. So the rate of change is proportional to the scale factor.

So as the scale factor gets bigger, the rate of change gets bigger. So it gets bigger even faster. So it's even faster. So the whole thing runs away.

And it turns out this is actually very similar to something we were talking about when we did inflation. Because it's equivalent to having a constant density, a density that if you make space bigger, it doesn't get diluted but remains the same. So this is actually equivalent to having a density of omega lambda equal to this value down here.

And we saw what happened with that because this is exactly what inflation theory is telling you. If you had a constant density, you get growth that looks something like this.

BRIAN SCHMIDT: Yeah. But the bizarre thing about our universe is that this exponential growth, we think, started about 7 billion years ago. And the universe is about 14 billion years old, 13.8. So it just happened about half the age of the universe ago. So we're right down here at the beginning of it.

And that's a funny place to be. It's kind of unusual to have got something exponentially growing in the first e-folding, as we would say.

PAUL FRANCIS: Yes. And we'll come back to that issue. So it's a real puzzle.

This was what was called dark energy, which just means it's something what makes this happens. It might be the lambda. That's just a fudge factor. It doesn't have any physical meaning. It's just a number that Einstein put into the equation.

BRIAN SCHMIDT: So dark is always a euphemism in astronomy for something we can't see or really understand very well.

PAUL FRANCIS: Yes. So dark energy doesn't tell us, other than it's something that does stuff, and we don't what it is.

BRIAN SCHMIDT: Yup.

PAUL FRANCIS: A good title though-- ah, it sounds exciting.

So one possibility is exactly what we talked about for inflation, which is doing the same thing, driving exponential growth. That we have some field that fills the universe. I don't what field it is as nothing is really predicted by particle physics.

BRIAN SCHMIDT: There would be some undiscovered particle that's there and has a field, analogous to the Higgs boson, but not the Higgs boson.

PAUL FRANCIS: Yes. But it would have to be a much lower energy field and lower mass particle. Otherwise, it would have all happened back at the era of inflation, rather than now. This is a very, very anemic, weak cousin of whatever the field was that drove inflation early on.

And once again, let's arbitrarily assume it has the spontaneous symmetry break, this Mexican hat potential. And so it could be that at about 7 billion years ago, the universe's energy came down to here. And it's now stuck in a set of false vacuum up there.

And that this omega lambda is due to the gap between the energy of the universe and the energy up here. And presumably, at some point, maybe 100 or a thousand billion years in the future, maybe the universe will roll off the slide and settle down. So inflation might be a transient era.

BRIAN SCHMIDT: Yeah. It might be. And it may even be rolling off the side now. It turns out when it's stuck here, it looks just like the cosmological constant.

And as it starts to roll down here, it changes a little bit. Its density-- this is equivalent to the density changing over time. And so when it ends up down here, it could have a completely different set of parameters. But while it's up here, it's constant in its energy. And it looks just like the cosmological constant of Einstein's origin.

PAUL FRANCIS: Yes. We'll talk a bit later about the attempts to actually measure whether this density of the dark energy is actually changing with time. Because that might give us a clue about whether it's something like this.

Another possibility is, in fact, the energy of the universe obeys a more standard, single curve. But just that the 0 point is not at 0.

So even when you get a bit of empty vacuum, and at it's lowest energy state, the energy is still a 0 point energy. The energy is not 0 when everything's gone away. It's totally relaxed. So to make a bit of space as empty as you can, have nothing going on, it still was an energy above 0.

BRIAN SCHMIDT: Right. And to particle physicist, this is a pretty ugly diagram. Because they don't think this should be a tiny, little value. They think this might be a huge value. But a little tiny value, which appears to be what we see in the universe, that doesn't make a lot of sense to them.

PAUL FRANCIS: They like this diagram. They don't like the fact that this is so small. You could very easily have something this where it 100, or is a magnitude bigger, in which case inflation would have taken off very early on. Or 100 orders magnitude smaller, in which case we'd never know about this. But having this value, it's-- um.

BRIAN SCHMIDT: Well, they really want it to be 0. They like it to-- not even 100 orders of magnitude. They'd like it to be 0 or really big, which are the two natural values, from their point of view, for it.

PAUL FRANCIS: So it seems like we need a particle physicist to talk about what could possibly be going on with this here. So let's go back to Lawrence Krauss and see what he has to say about this.

A4_L6_V02_Krauss_Dark_Energy1

PAUL FRANCIS: Now one of the real puzzles about dark energy is that at the moment our understanding is that dark energy and dark matter are to within a factor of 3 or so, the same in their contribution to the overall universe. But dark energy gets bigger as the universe gets larger, whereas dark matter's effect gets smaller as things get carried further apart. So in general, at any time in the history of university, the two should be wildly different.

So it struck many people as a real puzzle that these two things which seemingly have different origins and bases should at this particular instant that we're around questions have about the same size to within a factor of 2 or 3 and aren't, for example, 100 orders of magnitude one bigger or one smaller. Which they will be for most of the evolution of the universe.

So we've got Lawrence Krauss back here again to tell us a bit about this coincidence. Is this a real problem?

LAWRENCE KRAUSS: It's a huge problem. I have to correct you, though. Dark energy doesn't get bigger. At least if it's the kind of dark energy we think, it remains constant. As the matter gets smaller, the energy density--

PAUL FRANCIS: The energy density gets bigger. The universe gets bigger, so there is more of it.

LAWRENCE KRAUSS: Yeah, the total energy gets bigger. Yes, absolutely. As a theorist, I tend to think in terms of energy density because it's what you plug in Einstein's equations.

BRIAN SCHMIDT: But it becomes more dominant. Omega cosmological constant or whatever becomes bigger.

LAWRENCE KRAUSS: In the far future, yeah. This is the only time in the history of the universe, if the dark energy is constant, which those two numbers were even remotely close, and it's a real problem. It's driven, I would say, many theorist literally crazy because why should 13.8 billion years after the Big Bang those two numbers be close?

There's nothing special about the current time. In fact, it's very anti-Copernican. It's the ultimate. We live in a random location in a universe with nothing special. There's no combination of fundamental parameters that makes 13.8 billion years very special.

Yet if this is right, those two energy densities cross a few billion years ago and are within a factor of 3 or so today, that is completely inexplicable. And in fact, the second thing that's completely inexplicable about it, the energy scale of dark energy is not natural. It's 120 orders of magnitude smaller than we would have naively predicted, or even 60 orders or magnitude smaller, than we would have predicted based on any fundamental particle physics. And to be self-serving, which you can edit out if you want--

PAUL FRANCIS: Go for it.

LAWRENCE KRAUSS: When it looked to some of us theorists like the only way to make a universe sensible was to have a cosmological constant and have dark energy, and when I first began to propose it, it was mostly I certainly didn't believe it. No one else did. But we proposed it as a way to fit everything together, but mostly it was to point out that something must be wrong, because surely there couldn't be such an energy in empty space. So I was very happy to propose it. As I say, no one believes it, and then Brian went ahead and discovered it.

BRIAN SCHMIDT: So that was a 1995. Now at that time, there was the notion of quintessence that Paul Steinhardt also proposed in 1995, the same basic idea that something like dark energy must be there. And his whole idea of quintessence is to try to make it be not such an unusual value. Maybe you could elaborate for us?

LAWRENCE KRAUSS: The point is-- the interesting thing is quintessence-- you might argue that this energy in empty space is very ugly because it appears to be very small, and why should there be a coincidence today? And we'll get to that.

The amazing thing about quintessence as it has all of that ugliness plus more ugliness.

BRIAN SCHMIDT: So describe what quintessence is.

LAWRENCE KRAUSS: Quintessence is the idea that basically what we're measuring today is not that different than what happened during inflation. It's just an energy in some field that's stuck there.

PAUL FRANCIS: So it's a field that behaves a bit more like matter, so it gets diluted as the universe gets bigger acceleration.

LAWRENCE KRAUSS: Well, it's not matter. No, no. It's like the inflaton field. It's a field that gets an expectation value throughout energy-space, all of the space, which momentarily gives energy in empty space. But it's not a fundamental energy of empty space.

Now, what's always bothered me about quintessence is that any reasonable model of quintessence, if it's going to produce inflation like we see today, it will produce something that is basically completely indistinguishable from a cosmological constant, from the energy of empty space, so there's no observational way to tell the difference. The only way you could tell the difference is somehow with that field we're changing over time, if it had a potential which was dipped and that field was changing, and then the so-called equation of state of that field would be different than a cosmological constant.

And there's been a host of work on that regard, and I view it as sort of make work for graduate students to get PhD theses, because the fine tuning that's required for that to happen is ridiculous. Moreover, it doesn't resolve the really fundamental problem. In particle physics before the discovery of dark energy, everyone would have said-- in fact, we all were able to go to bed at night-- by assuming the energy of empty space is zero. Quantum mechanics says empty space should have energy.

It should have lots of energy. As I say, in general, 120 orders of magnitude more than what we measure. We all assume that some symmetry of nature would make it precisely zero because that's a natural value. If what Brian has measured is truly an energy of empty space, it's 120 orders of magnitude smaller than we'd naively expect, but it's not zero, and that is a problem of unprecedented proportion in physics.

But it may not be the ultimate energy of empty space. It may be that empty space ultimately has energy zero, but that would require a solution of this cosmological constant problem. It would require a solution we don't have. What cancels out the energy of all these other fields that makes it precisely zero?

For quintessence to be relevant, you have to first solve the cosmological constant problem. You first have to invent some new thing that makes the energy of everything else precisely zero, and then add some unbelievably contrived field which has very small energy and moreover is changing. It's so crazy that I know it's wrong, and I will tell you that, in fact, if-- I will make a prediction now, and whether there may be students in 2130 that are still watching this MOOC, I don't know. Hopefully, they'll be better ones by then.

BRIAN SCHMIDT: Oh, no way.

LAWRENCE KRAUSS: It's impossible, right, Brian? But the only sensible kind of energy of empty space there isn't a cosmological constant is one that looks just like it, and therefore since I first proposed and since it was measured, even after that, I would argue that the equation of state, w, this equation of state parameter, is precisely minus 1. And although we've got to go out and measure it, and it's important to continue to do that, I would argue that we won't see any deviations from minus 1. Because really the most likely candidate for the energy of empty space is precisely the energy of empty space. Any of these other models are ugly squared.

BRIAN SCHMIDT: So let's just look at that. So we have the idea of Einstein's cosmological constant. That is just the ground state energy of the universe, and it's there, and we're stuck with it.

LAWRENCE KRAUSS: We're stuck with it.

BRIAN SCHMIDT: That's fine. That's one idea. We have the idea of this field which you're arguing is almost guaranteed to have an expectation value, an equation state, which is so close to being that what we expect from Einstein's cosmological Constant.

LAWRENCE KRAUSS: Well, I would expect it would be constant. It would be like the inflation in the early universe, that you wouldn't expect it to start changing. If it's there if, if it's stuck, why start changing after 10 to the 10th years and not 10 to the 10th to the 10th years?

But it does mean-- and maybe this is where you're going, and I don't like to anticipate-- I would argue there's a reasonable likelihood that that's the case. It really is some field stuck in some metastable state, which means it's possible that sometime in the future that a phase transition could be completed, which by the way could change the nature of everything, and everything that we see in the universe could disappear. Matter could become unstable. Protons, all the particles we know of nature, could change, and the universe will really, for all intents and purposes, end as far as life is concerned. That's a possibility.

A4_L6_V03_Krauss_Dark_Energy2

BRIAN SCHMIDT: So we're going to talk about the end of the universe later on in the course.

LAWRENCE KRAUSS: OK.

BRIAN SCHMIDT: But I guess I'm curious to know is there any other alternatives to a and b? Is it just going to just be that general relativity is wrong in some way that we haven't anticipated?

LAWRENCE KRAUSS: Well, we don't know. The great thing about not knowing is you don't know. And that's fine, We don't know about quantum gravity. We don't have a theory of quantum gravity. And that means we can't say what happened at t equals 0, the Big Bang.

And it may be that quantum gravity would reveal something-- in fact, we fully expect that general relatively will change. At microscopic scales, it will change. The problem, however, is that the scale of this energy density is not the scale at which quantum gravity would naively produce effects.

So if it was, we'd say there's some quantum phenomena that'll explain this. This scale is so much larger in distance scale and smaller in energy scale, that it really is inexplicable. And the other thing I should say is when Einstein put in the cosmological constant, he put it in as a fudge factor because he was trying to solve a problem that didn't really exist. He was trying to explain the static universe. And the universe wasn't static.

But it was just a fudge factor for a long time. But the point is now that we understand quantum mechanics and quantum field theory, even if Einstein hadn't invented it, someone else would have. Because it is a property of all quantum mechanical systems, even a harmonic oscillator, that it has some ground state energy in it. It has hbar. And it'll have hbar omega, depending on the nature of the oscillator.

And so it is incredibly natural to expect, on quantum mechanical grounds, that empty space should have energy. That's not what's weird. What's weird is why the value is so low.

BRIAN SCHMIDT: Yeah.

LAWRENCE KRAUSS: And usually, if you're a theorist, usually the answer-- the ultimate answer is not what you expected. That's why we need to keep on exploring the universe.

So ground state energy is one possibility. Quintessence is a very unlikely-- something that's really changing. A field that gets stuck is a possible answer. But again, why it has the value it has is strange.

And the other possibility is something else. And nature may pick something else. We just don't know the answer.

BRIAN SCHMIDT: OK.

PAUL FRANCIS: So you haven't really got back to the original puzzle of why there's this coincidence?

LAWRENCE KRAUSS: OK, let's get back to that. Because that is a real-- regardless of what the cause of dark energy is, it is an incredible coincidence that the two, normal matter and dark matter, have around the same energy. And by the way, I will say that was one of the motivations of quintessence. Because if you have a field that's somehow changing along with matter, then you might be able to make those two things remain close.

Again, as a theorist, I would argue that there's really no good way to do it. And it was mostly public relations that suggested you could. I've looked at that a lot and thought of it a lot. And I don't think there's any good way to do it. But that's one possibility. Just because I can't figure out a way to do it, doesn't mean it doesn't happen.

But the other possibility is that it really is a coincidence. But I want to go back to when we were talking about inflation, to the realization that inflation says there could be many universes. And maybe, in each universe, there's some field that has some expectation value that's different at low energy. And therefore, there's different late-time expansions.

It has been realized-- and I think Steve Weinberg was the first one to point it out-- that if you look and say, well, there's an energy of empty space-- and there are many universes. If you make those two assumptions, that it's different in every universe, then it's true that if the energy of empty space were much bigger than it is today, say 50 times bigger than it is today, then galaxies would never have formed. And if galaxies wouldn't have formed, then stars wouldn't have formed, then people wouldn't have formed, and astronomers wouldn't have formed.

So we can say the universe is here because there are astronomers that can measure it. It sounds like design. But it's not. It's kind of cosmic natural selection. We'd be very surprised to find ourselves living in a universe in which we couldn't live.

But it may mean that that ultimate physical quantity that describes our universe is an accident and another universe is different. And it may mean that life like us can only evolve in a universe in which the energy of empty space is not much bigger than it is. And that's why it's so absurdly small.

That idea, which goes by the name of the anthropic principle-- it's really not-- doesn't deserve the word "principle"-- is a possible idea. But even so, I want to point out that many times in the last century, the anthropic principal has been employed to explain otherwise inexplicable results. Later on, we always discovered a fundamental theory that explained it. So, so far, it hasn't got a good track. And if I were betting on it, I wouldn't bet on it.

But also, there's another aspect, which isn't emphasized enough. It is true that if the energy of empty space were vastly different than it is, then life forms like us wouldn't form. It doesn't tell us that no life forms would form, first of all. But secondly, that's not the only parameter in nature. The energy of empty space is just one.

What if, in other universes, the mass of particles were different and the energy density that result were different? We don't know the locus of all possibilities. And so we don't know that in a universe with a vastly different cosmological constant, if the other parameters were different, that life couldn't form.

And since we don't know, it's rather pretentious to claim that this is the only possible universe in which life can exist. And therefore, in fact, you could-- and I've done this. I've written papers on this, as have other people. You could imagine changing other parameters in a way that would predict that the cosmological constant should be very, very different, on average, for life forms to exist, than the one we measure, making us very strange, instead very natural.

So this is all kind of metaphysics at this point. We don't know. And that's one of the reasons why it's so exciting to probe inflation, potentially experimentally, because when we learn more about fundamental particle physics, we'll find out which of these ideas goes out the window.

BRIAN SCHMIDT: So in terms of it being metaphysics or not, it's sort of is metaphysics. But the one reason you might say it isn't is that Steven Weinberg, when he came up with this idea, predicted in advance the value of the cosmological constant. He didn't get it exactly right. But it's pretty damn close.

LAWRENCE KRAUSS: Yeah. The model says it should be about the same order we see now. That is really remarkable. That is absolutely remarkable.

And maybe it's true or maybe it's just an accident. Because, frankly, from a theoretical perspective, if you have many different universes, and the laws of physics are different in each one, it's hard to imagine why only the cosmological constant would change and no other parameter.

And Steve's calculation, which was remarkable and prescient and simple, requires that to be the only parameter that varies in all different universes. And that seems kind of unnatural. But it is a remarkable statement, that in 1987, Steve-- I think that's when he wrote that paper, in Reviews of Modern Physics-- said that if there's energy of empty space, it should be about the amount we see. I mean, frankly, we knew it couldn't be much larger, already.

BRIAN SCHMIDT: Right. Because we wouldn't exist.

LAWRENCE KRAUSS: And so as a theorist, I would say it's easy to predict things just below the threshold of observation. And we've done that a lot. We used to predict density fluctuations, which were larger. And then the observer said no, no, no. We always predicted it to be a little bit less. And lo and behold, they were a little bit less.

And the cosmological constant is about as large as it could be for someone like you to have stumbled upon it, frankly. If it were much smaller, we'd never know about it. And by the way-- well, we'll get to the future of the universe later. So I don't want to get there now.

PAUL FRANCIS: Thank you. And we'll have you back again later.

LAWRENCE KRAUSS: OK.

A4_L6_V04_Lensing

PAUL FRANCIS: So we've seen what's almost classical, old-fashioned cosmology, if that's not an oxymoron, the whole idea of trying to find distances and redshifts and use that to measure the whole universe, that goes back to Hubble.

BRIAN SCHMIDT: Thanks, Paul, old fashioned.

PAUL FRANCIS: Ah, yes, well.

We're now going to talk about, in some sense, the weirder, stranger, less common sense type ways of doing it, which come into their own in the last 20 or 30 years. And are now very competitive and possibly more powerful than some of the old traditional methods.

BRIAN SCHMIDT: Yeah. And some would say kind of cooler as well.

PAUL FRANCIS: We wouldn't. But--

BRIAN SCHMIDT: Yeah.

PAUL FRANCIS: And we're going to start off with gravitational lensing. We'll around to microwave background lumps, which is the killer method at the moment. But lets start off with gravitational lensing, which is kind of cool as well. This is something we've talked about earlier in the course.

The idea is that, in this case, we've got a cluster of galaxies. And its gravity is actually bending the light of background galaxies. So you see these in arc-shaped patterns. Those are galaxies far behind the cluster, whose light has been distorted and bent.

And we talked about it, in the first course, as a way of measuring how much dark matter there is in the universe. And we talked about it in the exoplanet course as a way of finding external planets.

And this is useful for cosmology, it turns out. It's got three effects, one bad and two good. Now the bad one-- just imagine-- let's imagine that the supernova went off in this galaxy here.

BRIAN SCHMIDT: Well, that would be good. Because that would be at about a redshift of 4 and we'd be able to see it.

PAUL FRANCIS: But you want to measure how bright this is, the distance scale. And the brightness you're measuring is not going to be the real brightness.

BRIAN SCHMIDT: Yeah. So it turns out that we do need to worry about, when we look at distant objects, whether or not they're magnified, or it turns out, more commonly, demagnified. Because if you have a big clump of galaxies, things get magnified in front of it.

But most parts of the universe have a void of galaxies compared to the average. So that means objects are demagnified a little bit.

PAUL FRANCIS: Of course, energy is conserved. So over all the mass, there must be a total balance. So if you're going to amplify in some areas, you must deamplify in others to make up for it.

BRIAN SCHMIDT: Right. So at some level, it's not a problem because you just look at the entire universe. But then we have that little pesky problem of selection bias. Because I can see more distant objects when they're brighter than they should be. And that gives me a bigger volume.

So I'm going to preferentially find the objects that have been magnified, rather than demagnified. And that turns out, when you look at really distant objects, a redshift of 4-- well, it's complete bias because it's the only way we can possibly find them. And we haven't actually found one at that redshift yet.

But it's a couple percent effect in the nearby universe. So it's not a huge effect right now. But when you get to sort of beyond a redshift of maybe 2, it starts becoming a pretty serious thing we need to worry about.

PAUL FRANCIS: And a lot of people are working at improving the accuracy. At the moment, you've got what, 7% accuracy for supernova distances. So a 2% error is not really a problem. But if we ever manage to get big enough samples-- that's the one supernova. At these large numbers of supernovae, the beginning error is much smaller. And then it can become serious.

BRIAN SCHMIDT: And it is. We don't have that many at the very large distances yet. So it's not yet a horrible problem. But it is one we need to worry about.

PAUL FRANCIS: So that's the bad effect. However, there are some good effects as well.

One is that you can actually use gravitational lensing in a few special cases to get a direct geometrical distance. We talked about this using binaries. We talked about using masers. This is a third way of doing it.

And here's the basic idea. What we're looking at now is a foreground galaxy.

BRIAN SCHMIDT: Yeah. And this is a model of the galaxy. And you can see how well you can model the system, almost perfectly.

PAUL FRANCIS: So what's happening is we've got a galaxy here. And in the background, not another galaxy, but a quasar.

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: And the light from the quasar is being bent around and giving you what's called an Einstein ring. So there's a second image here and three images over there, that are a bit merged together. And so you're actually seeing three different images, or four different images, of the background quasar.

And the crucial thing is that the light has to go-- let's say, here's our galaxy. You're the Earth. And the light can go over the top to reach you or under the bottom. And it will going slightly different distances.

BRIAN SCHMIDT: Yup. So each of these images travels a slightly different pathway.

PAUL FRANCIS: And from the modeling of the lens, you can actually estimate what those distances are. Now, by itself, that wouldn't be an issue. But let's imagine the quasar is changing in brightness. And quasars do all change in brightness.

So here is actually the brightness of the different images here. And you can see they're all jumping around. This is presumably some sort of weather happening in the accretion disk around the giant black hole in the quasar that's causing the change in brightness.

But it doesn't matter what's causing it. What matters is you should see these changes delayed in the different images because the light is has to go different distances to reach us.

BRIAN SCHMIDT: Yeah. So let's look at this little thing that's an a. It happens just a little bit later in b. It's happens a bit later in c and a lot later in d.

So that allows you to go through and take this model of the math, which sort of tells you how much stuff is there. And this time tells you-- times the speed of light-- the actual physical distance of the system. And so that allows you to literally, geometrically, measure the distance to these objects.

Now, this has been a challenge. There's been a lot of, I would say, work that has gotten a variety of answers. So people have sort of lost confidence in this method. But more recently, the people doing it have been able to do these incredible models, which I have to, and I find breathtaking.

But they've also decided to be very, very circumspect. And what they do is they change the scale of the model when the people who are trying to make the models. They don't actually get to know what the answer is that they're getting. They have to play around with it. And everything is what we say, blinded. So that when they get a value for the Hubble constant, they can't put any of their own biases in the method.

And so now that they've done that twice. And they're getting answers which are respectable in terms of their uncertainty. And I think if they can do that about another 10 or 15 times, they could build up a very interesting measurement of distance scale with this method.

PAUL FRANCIS: OK. And another method that's getting a lot of work and publicity at the moment is what's called weak gravitational lensing. Remember, back here, we've got what's called strong lensing. So you got really big arcs.

But let's imagine you don't have a big cluster of galaxies, but just some random bit in the universe in the foreground. Even so, the background galaxies are going to be just a little bit distorted. And so here's a simulation of it.

So let's say here's a bunch of background galaxies and you put a cluster in front. You will see that right in middle, you get these big arcs.

BRIAN SCHMIDT: Yeah. Those are big, strong ones, right?

PAUL FRANCIS: These things are a bit lined up. And this particular case here, we see they're all spherical to begin with. So any elongation you get here will be privy to gravitational lensing. In practice, of course, that is elongated all by themselves, the disks.

And so you got take the random orientation, as here. And then superimpose a bit more, lining up from gravitational lensing. But, in principle, if you get really big samples-- and we're talking millions.

BRIAN SCHMIDT: Millions upon millions. So we're really talking a billion for the really big samples, a billion galaxies. And you can build up-- it's not just these bits. But out here, there's a small signal of what's there.

PAUL FRANCIS: And just getting one galaxy doesn't tell you much. But the average of all these things, you can see maybe they're a bit preferentially aligned in one direction.

BRIAN SCHMIDT: Right. And you could actually take that alignment and build up a map of the cosmos, of how mass is distributed across the universe. And that turns out-- it depends on how much dark energy there is, for example, in the universe.

PAUL FRANCIS: Yes. So one thing it does it gives a check of what we learnt from the peculiar motion, the check of what the total mass of universe is. But also, you can, in principle, do this in a whole bunch of slices. You can estimate rather roughly how far away a galaxy is by looking at its exact colors. Because as it's redshifted, its spectrum will move through the different filters you're observing and cause changes in colors. It's called a photometic redshift.

And so you get a rough estimate how far away the galaxies are. So you can look at one slab of galaxies, another slab of galaxies, another one, further and further away. And look, for each slab, at these distortions. And therefore, you actually get a three-dimensional, almost a tomographic model of the mass. And look at how the number of clusters, the density of the clusters, and so on, varies as a function of time.

And that, once again, is a very strong constraint on various cosmological models. Mainly on how much mass there is, but also on how long you've had to make it grow. And dark energy tends to change the rate at which things grow. So it also gives you a constraint on dark energy.

BRIAN SCHMIDT: Yeah. So we're right at the beginning of this being able to being done successfully. There are some big experiments that have detected it, and have been able to do these maps, and are beginning to get cosmological constraints. But in the next five to 10 years, there are going to be space missions fly, that do this for literally most of this sky, for billions of objects. And those have the potential to revolutionize how we do cosmological measurements.

A4_L6_V05_Primordial_Nucleosynthesis

BRIAN SCHMIDT: So Paul, we keep talking about dark matter and dark energy. And we should, because they seem to be 95% of the universe. But it would be good to really understand how many atoms there in the universe, since what we really know exists here on Earth. And we want to make sure we're not being led astray by underestimating how many atoms there are through-- well, maybe it's some gamma ray gas or something we can't easily see. So it would be good to come up with a way to count how many atoms there are in the entire universe.

PAUL FRANCIS: To count the normal matter, like the stuff we're made out of, as opposed to this exotic dark matter, whatever that is.

BRIAN SCHMIDT: That's right.

PAUL FRANCIS: And there is a way to do it, one we talked about briefly in the first course, which is primordial nucleosynthesis, if I can say that right. So this is the nuclear reactions that happened when the universe was very young.

The basic idea is that between when the universe was around about a minute and about 3 minutes old, the density and pressure everywhere in the universe was much higher than they are now. And they were about right to have fusion reactions going on across the entire universe.

BRIAN SCHMIDT: Yeah. The conditions were analogous to what's going on in the center of our Sun.

PAUL FRANCIS: And the main reaction that's going on here is you take protons and neutrons and you combine them to form deuterium. And the deuterium doesn't last very long before something happens to it. It has a number of different pathways. It can go into form helium 3 or it can go to form lithium.

BRIAN SCHMIDT: And deuterium, it turns out, is heavy hydrogen, as it's sometimes referred to in movies. But it is the least stable form. Well, I won't say the least stable form of hydrogen. But it's not very stable. It's very easy to convert into something else.

PAUL FRANCIS: And there's a very brief period when it's around. Early on, as we talked about in the first course, it blown apart by the photons and what's now turned into microwave background.

But there is a window when they no longer have enough energy and when it can go down these various reactions. And it moves rather rapidly to one of these things. And from thence, it can go by many reactions to actually form helium.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: And we know the universe ended up as roughly 20% helium and 80% hydrogen.

BRIAN SCHMIDT: Yes. And most of the deuterium in the universe ends up being converted to helium, the helium that we see throughout the universe and in our balloons.

PAUL FRANCIS: And that's what gives us a bit of a clue. Because if you got deuterium in the early universe, and its got anything else around, it's going to merge with that something else and go to helium. So there's a certain maximum possible density of deuterium you're going to get. If it's any higher than that, it will collide, merge, end up as something else.

So presumably, you started off with more deuterium. And everything went away, until the remaining atoms of deuterium are so few and so far between that in the short period you've got before this whole reaction stops, they don't turn into anything else. So what that means is almost independent of what you start off with, you're always going to end up with the same amount-- the same density of deuterium left over. Because it's just whatever the density is when they're far enough apart that they won't collide or interact and get destroyed. And that's a very interesting sort of measurement stick.

So the idea is let's say you had a universe which had lots of baryons-- baryons being protons, neutrons, anything like us-- to begin with. And they're going to go through this nuclear synthesis stage. And they're going to turn into hydrogen and helium and the standard amount of deuterium. So you're going to get a particular ratio. In this case, there's going to be a lot of hydrogen and helium, to only a little amount of deuterium.

But let's imagine instead, you had fewer baryons to begin with. So you're now talking about a smaller number of baryons. Once again, it's going to go through the action. And it's going to turn into exactly the same amount of deuterium, which is as much deuterium as get away with, with it just spread out enough so it can't destroy itself. But there's not going to be less leftover.

So what this means is, as you start with fewer baryons, the ratio of deuterium to everything else is going to go up. Not because the amount of deuterium is changing. The deuterium density is always going to be the same. It's just that it's less than everything else.

BRIAN SCHMIDT: So this is a convenient little way to figure out how many baryons there are. It's a barometer, but not in the weather sense.

PAUL FRANCIS: Yeah. And some people can do these calculations. And this is nuclear physics. It's pretty well understood because it's useful for killing people.

And you get the deuterium to hydrogen ratio, which is pretty small. It's only between 10 to the minus 3 and 10 to the minus 6 on this graph. And you get photons per baryon. That's actually the number you get.

We actually know the density of photons because we can measure them. They're in the microwave background today. And so this actually tells us how many baryons there were.

BRIAN SCHMIDT: Right. And so all we have to do is being able to figure out how to measure how much deuterium there is in the universe. That should be easy. I can go into the ocean. The ocean is full of deuterium, Paul.

PAUL FRANCIS: Well, yes, in principle. The trouble is that, of course, deuterium is also going to be either destroyed or created in nuclear reactions in the stars going on subsequently. So if we look in the oceans, or we look on Earth, or look in the Sun, we cannot be sure that the ratio of deuterium to hydrogen we see there is the same ratio it was to begin with.

BRIAN SCHMIDT: Well, not only can we not be sure, we're almost sure it isn't the same. Because, for example, a star like the Sun destroys most of the deuterium throughout its lifetime.

PAUL FRANCIS: Yeah. In fact, deuterium tends not to be created. It sort tends to get destroyed because it's such an unstable thing. You put it anywhere nuclear fission, it's going to get blown to pieces and turned into something else.

BRIAN SCHMIDT: And so since we know that the Sun is about 1.4% metals, that is stuff not created in the Big Bang, we know there's been a lot of processing of that material. It's all mixed up. And so we really need to look at pristine material, stuff that stars have not had a chance to chew through. And that's not so easy. There's not a lot of pristine material in the Milky Way, for example.

PAUL FRANCIS: And this one thing that we talked about in the earlier parts of this course, the idea of trying to find the very first stars. If you can find a dwarf star that was one of the very first to form, just after the Big Bang, and it didn't have any heavy elements in the gasified form, it will have produced have some elements and destroyed the deuterium in the center. But for certain sorts of dwarf stars, there's no mixing between the surface and the outside. So the outer layers of the star should still, in principle, be nice and pristine and clear.

And that's something that there's more research on here at ANU. And no one's ever found a really pristine, very first star. But they've found some that aren't too far off. And you can try measure deuterium in those.

BRIAN SCHMIDT: And it turns out not to be so easy because deuterium is a lot like hydrogen. It has this extra neutron in it. And so that neutron causes its energy levels to be shifted, it turns out by a very small amount.

PAUL FRANCIS: Yes. You're trying to look for an absorption line of just deuterium that's right next door to an incredibly strong hydrogen line, because hydrogen is everywhere, in huge amounts. It's very, very difficult task.

But one place where it may be slightly easier is not in stars, but in intergalactic gas clouds. Once again, this is something we talked about a bit earlier in the course. The idea is if you look at a distant quasar or a distant gamma ray burst, as the light from it travels through space, every now and again, it will pass through a gas cloud. And it will take a bite out of it.

And this absorption line will be mostly be due to hydrogen. These are called Lyman-alpha Forest lines. And you can just read out the spectrum like a scroll. Say yes, it went through gas here, gas there, gas there. But in principle, right next to hydrogen line, you could see a much fainter deuterium line.

BRIAN SCHMIDT: Yeah. And they have the advantage of not being-- a star has the problem where the gravity on a star is quite strong. And hydrogen lines get broadened pressure, by the pressure. And so deuterium can be quite hard to measure in them.

PAUL FRANCIS: So here it is actually possible. It has been measured.

You're still not sure that these things absolutely are pristine. In fact, we know that many of these gas clouds do have some heavy elements in. So maybe it's the original number, maybe it isn't. But it probably gives us some estimate of what the original number is.

BRIAN SCHMIDT: Well, we could certainly imagine going and looking at several of them and seeing-- for example, you wouldn't expect the-- the pristineness shouldn't always give the same answer. So it's worthwhile to go out and have a look at these and see if we get a consistent answer.

PAUL FRANCIS: And this has been done. And it's telling us that the bulk of the dark matter cannot be in the form of baryons. So maybe it's about 30% of the universe is dark matter. But of that 30%, 25% has to be something that doesn't engage with nuclear reactions. And maybe about 4.5% or 5% is actually in the form of baryons. Which is still a lot more than all the baryons we can see in stars. There must be some very hot, diffuse baryons out in deep intergalactic space that we can't easily see.

BRIAN SCHMIDT: Yeah. So that this number is consistent with between 3.5% and I think 5% baryons of the universe, is sort of the best number. So, OK. So that's consistent with this story of 95% of the universe being something else. Because about 5% of the universe looks like it can be baryons by this method.

PAUL FRANCIS: OK. So now let's go on to perhaps the most powerful method of all, the microwave background lumps.

A4_L7_V01_CMB

BRIAN SCHMIDT: So Paul, throughout my career people have been talking about the cosmic microwave background. And it was always this thing that held great promise to change the way we understand cosmology. And since about 1998, those dreams have really come true.

It already had won two Nobel prizes-worth, it turns out, by 1998, although they weren't awarded-- the second one-- until 2005. But it's worth to go back and think about this cosmic microwave background and how it can change our understanding of cosmology. Because it turns out to be this beautiful experiment, exquisite experiment in space, using physics we can understand here on Earth.

PAUL FRANCIS: So what is the microwave background? This is a video we showed in the first course. But the basic idea is when the universe was very young, you've got particles, protons and electrons, baryons if you like. And they're all ionized. Electrons have been split off from the protons and neutrons. And you've got photons, which in this part--

BRIAN SCHMIDT: Photons are little guys.

PAUL FRANCIS: --are the green ones over here. And these are all bound together. Because as the atoms, the protons and neutrons, are ionized, the photons can't get past and then bounce off. So you've actually got, let's say, a baryon/photon fluid. The two are coupled together.

But as time goes on, the whole thing is expanding. And eventually, as just happened there, it becomes sufficiently cool. The electrons can combine with the protons and neutrons and form neutral atoms. And at that point, they become transparent. They no longer interact with the photons. And the photons have been flying free ever since that time.

BRIAN SCHMIDT: And so we have this time when the photons are bouncing from baryon to baryon. That's like a fog. That's analogy to having a fog everywhere. Because the photons can't travel in straight lines.

And then suddenly the universe recombines. The baryons recombine. And, voila, the fog is suddenly lifted on the universe.

PAUL FRANCIS: And it goes transparent. And so here is looking at it very early on. There are actually a billion photons to every baryon. That's because originally there was a mixture of matter and antimatter. Most of it annihilated, even only one part in billion left over. So I've grossly underestimated the number of photons for every baryon, over here.

BRIAN SCHMIDT: And we have no idea why that happened. That's one of the big mysteries of the universe.

PAUL FRANCIS: That's something we talked about in the first course in the series.

But as things slowly cooled down, this glowing fog is still a glowing fog, getting cooler and cooler. And suddenly it becomes transparent.

But you can see, once it became transparent, all these photons are released. And they're still flying randomly, in every direction, through space. And, in fact, they're still raining down on us in huge numbers, on Earth today. And this is the cosmic microwave background, picked up by radio astronomers back in the 1960s.

BRIAN SCHMIDT: And it's sort of like driving out of a fog bank and being able to look back at the fog bank. And you get to see exactly what's going on, on that surface of that fog bank.

PAUL FRANCIS: Yup. So if you look out in any direction, we'll see this fog bank in the distance. And we can do an image of it across the entire sky. And here's what it looks like.

BRIAN SCHMIDT: So this is what it looked like in 1964. And in case you're looking for some detail there, this is the entire sky, looking exactly the same. It really was just radio waves coming from all directions on the sky, with equal intensity.

PAUL FRANCIS: Yes. And not exactly the most interesting picture in astronomy.

BRIAN SCHMIDT: Ah, no.

PAUL FRANCIS: However, as time went on, people got more precise measurements. And they were able to discover that if looked in great detail, it wasn't completely uniform. There was a rather slight pattern to it. And here's that pattern.

BRIAN SCHMIDT: OK. So let's do the little thing, right through the center. You've plotted this such that the galaxy goes right through the center.

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: So you can see there's some messy stuff. And one might expect there to be radio waves emitting, at this frequency, from stuff in the galaxy, through synchrotron radiation.

PAUL FRANCIS: That's right.

BRIAN SCHMIDT: So we can understand at least that part of it.

PAUL FRANCIS: But it's all the strongest thing. The strongest source is up here, not in the plane of the galaxy. What's that?

BRIAN SCHMIDT: Well, it's not just a source. It's like there is-- it's higher frequency here and lower frequency there. And it's a giant curve. And if you plot what this looks like-- and I were to plot a line of intensity from here to here-- it would look like a perfect cosine, a perfect cosine.

PAUL FRANCIS: What's going on here then?

BRIAN SCHMIDT: Well, the Doppler shift, if you think about it, is going to redshift or blueshift light. And if you're going at some direction to that, then there's going to be a cosine. So maybe it's that. We're moving that direction, towards the-- so that's the cool spot. I get confused.

It's blueshifted. We're moving in the direction of the blueshift and have the redshift to the waves behind us. So imagine we were moving at 680 kilometers per second, in that direction. Then you might be able to explain exactly what we see here.

PAUL FRANCIS: Yes. It's in some sense like you're driving down a road in the rain. The rain is hitting the front of your-- even though the rain is falling vertically, it seems to you much harder from the front, than the back. That's because you're moving into it. We are moving through the sea of particles.

This is, in part, due to the motion of the Earth around the galaxy. Part due to the motion of the galaxy around the Andromeda. Part due to the fall, all that into the Virgo cluster. And part, the motion of us and the Virgo cluster, towards something called the Great Attractor. So this is the overall motion of us, with regard to anything, at 680 kilometers per second.

So, OK. Well, that's taught us something quite neat. It's how we're moving against the microwave background, at the closest thing we have to an absolute standard of motion.

BRIAN SCHMIDT: Oh, it really is like an absolute frame of reference, something I was always told we wouldn't have. But the way the universe is constructed, we sort of do.

PAUL FRANCIS: Yeah. Anyway, let's take that out. So let's take it out. This is called the dipole. So let's take that out, take out the effect of our motion.

And here's what's left over. This is now data taken from the best measurement to date, which is from the Planck satellite, launched by the European Space Agency.

BRIAN SCHMIDT: So this is just really in the last year, this data. And we've observed it at several frequencies, or several wavelengths, going from the relatively low 30 gigahertz. So that's something we use for even communications here on planet Earth. All the way up to these very high frequencies, which you can only see out in space.

PAUL FRANCIS: And what you can see is the Milky Way Galaxy and emissions from dust. It turns out you get spinning dust grains in space, possibly lined up by magnetic fields. And they radiate at these frequencies. There's quite a lot crap, especially down at the higher frequencies. That tends to dominate what's going on.

BRIAN SCHMIDT: Have I mentioned how much I hate dust?

PAUL FRANCIS: Once or twice, Brian, once or twice.

BRIAN SCHMIDT: Yeah. So you have is this dust. And you have synchrotron radiation from just electrons and magnetic fields interacting in the Milky Way.

PAUL FRANCIS: And, in fact, you get quasars contributing and also some things like that.

BRIAN SCHMIDT: But by observing in these nine different frequencies, you can go through and you can model everything. And it turns out everything in the sky is what we think is to be some sort of power law. That is, the log of the flux is proportional to the log of the wavelength, except for black body radiation, which has the curve of Planck's radiation law.

PAUL FRANCIS: So the microwave background is a blackbody spectrum, whereas pretty much everything else is a power law. So what you could do is you can try and work out what the power law slope is for this sort of dust, that sort of dust, the quasars, things from the emission. And by combining all different wavelengths, you can then fit these power laws, take them off, and see what's left over.

BRIAN SCHMIDT: Yes. You take off the power laws and you leave the blackbody.

PAUL FRANCIS: Now, this is not easy.

BRIAN SCHMIDT: No.

PAUL FRANCIS: And it's somewhat controversial because they're probably not pure power law-- I mean different power laws. And indeed, the debate is currently raging about the BICEP2 results, whether it's real or whether it's an error in subtracting off all these other things going on.

BRIAN SCHMIDT: And even in this group, there are groups that are complaining about the map here at 217 gigahertz, as being a little not quite right. And so has that make tiny, little deviations in the map we're going to show you now?

PAUL FRANCIS: But if we take our current best guess at subtracting all these things off, you end up with something that looks like this.

BRIAN SCHMIDT: So what we see here are little bumps and wiggles. And these bumps and wiggles turn out to be sound waves. Sound waves that are very, very long relative to the ones we hear. And you will see that there are great big, cool areas and very large, warm areas. But then there's this little tiny mottling pattern, which turns out to have a very specific size on the sky.

PAUL FRANCIS: And what you can actually do is measure what the sizes are of the characteristic lumps here. So this is saying, if you've got a high bit on the sky, and you look a bit away from it, is it also likely to be high or is it likely to be low? And if you plot that, you get something like this. So what you processing here is angular size versus lumpiness.

BRIAN SCHMIDT: Yup. So this is a lumpometer, effectively. And so where you have lumps of a given size-- let's say all the lumps in the sky are exactly one size--

PAUL FRANCIS: There's a big peak at that size and nothing anywhere else.

BRIAN SCHMIDT: --then there would be one peak at that size. And so what we see is there is a lot of lumps. And that characteristic mottleness is here at about 1 degree. But then, there are ones here at roughly 2, or a 1/2 degree, and 2/10 of a degree.

PAUL FRANCIS: At the bottom here.

BRIAN SCHMIDT: Yep. And smaller and smaller.

So if we were to zoom in on this, it turns out you can see almost 15 little lumpy peaks. And those, it turns out, are sort of the harmonics of the universe, if you'd like to think of it.

PAUL FRANCIS: Yes. And we'll talk about the physics of those in a bit.

Maybe we have a digression of how you actually measure lumpiness as a function of scale. And this is analogous to spectrum analysis in, say, music. Let's say we have a note-- "la." You can break it up into its component frequencies.

So what you're doing is you're taking the actual waveform of the sound and breaking it up into sine waves. And it turns out any periodic function at all can be broken up into a bunch of sine waves.

In this case, it's not just a straight line, it's on a sphere. But there's something similar you can do in a sphere, which is breaking it up into spherical harmonics, as they're called.

So what you can do-- this is the first order spherical harmonics, which is just uniform for the sky. Second order, which would be high and low, or high and low, and high and low. It's under any pattern that's only on scales of 90 degrees, can be made up by some combination of these three.

And then you get smaller scales still. Well, now you got four, two bright and two patches on the sky. And once again, any pattern with two bright and two dark can be made up by some combination of these five. And you keep on going to higher and higher order. And you get all these patterns, spherical harmonics, which allow you to reproduce any pattern by adding together enough of these.

BRIAN SCHMIDT: So to give you an example, we like to call this one the dipole. OK. So the dipole, it turns out, using these shapes, we can perfectly reproduce that cosine shape on the sky, of our motion. It turns out we can use that completely to describe that. But when we have something more complicated on it, we have to go to higher and higher orders of these things.

PAUL FRANCIS: These would be called your quadrupoles.

BRIAN SCHMIDT: Yes. Octopoles and--

PAUL FRANCIS: --and so on.

BRIAN SCHMIDT: --all sorts of things beyond that.

And so the game is you go through and you make the shape on the sky, out of these shapes. And you will notice that these shapes-- for those of you who can back to your chemistry days-- they look a lot like the orbitals that a atom has, where an electron is allowed to be. And indeed, they are essentially the same functions.

And if you can remember from those days, you have something known as the l-value. So this would be l equal 1, l equal 2, l equal 3, l equal 4. And you have the m-values, which is these ones here, plus or minus 1, et cetera; plus or minus 2; plus or minus, blah, blah, blah.

PAUL FRANCIS: And this is actually how you measure these things. What you do is you take the pattern on the sky and break it down into its multipole components.

And so, for example,-- there isn't any 1, because that would just be uniform brightness. But this point here is 2. This is the dipole. And that's hard to measure because you have to take dipole of our own motion.

And then this will be order number-- the next order down, 3. Then 4, and 5, and 6, and so on. And that's how they actually break it down into how much lumpiness there is on different scales. They look at how strong the different multipoles are. We do a multipole breakdown. They're going all the way out to multipoles in the year 2500, or so.

And with balloon experiments and South Pole experiments, they can go to even higher multipoles. And that looks at the really small-scale structure.

BRIAN SCHMIDT: The really tiny stuff. And so there's fancy mathematical techniques that turn out to be very powerful using this. That's why we use it. But ultimately, this is telling us that, if we want to break things down, we're going to be able to describe that lumpiness of the universe of having essentially this one-degree scale of these spherical harmonics.

PAUL FRANCIS: OK. So let's see if we can actually explain the physics of where these characteristic spikes actually come from.

A4_L7_V02_Acoustic_Waves

BRIAN SCHMIDT: All right, Paul. So we've just measured how big the lumps and bumps of the universe are. That's a very complicated looking diagram. Is there a way we can better understand that?

PAUL FRANCIS: OK, well, let me have a go at explaining these things. Basically they're driven by what are called the acoustic peaks, and they're driven by almost a form a sound wave from the early universe. And here's my best attempt to explain where these things come from, borrowed very heavily from an online tutorial from Wayne Hu, who is one of the experts on this thing.

And the basic idea is that very early on, the universe was expanding like crazy because of inflation. We've already talked about that. And the tiny quantum mechanical fluctuations had been stretched over enormous distances. And then inflation stops, and suddenly you've got a universe expanding as a much more sedate rate, and it's not entirely uniform. So there's going to be very slight fluctuations. Some bits may be a little tiny bit denser than other bits.

BRIAN SCHMIDT: And so you've given a representation of that by-- you've expanded it by about a factor of 10 to the 5 here compared to what it would really be like.

PAUL FRANCIS: Yes. The real fluctuations are actually much, much than this, but we wouldn't be able to see them.

BRIAN SCHMIDT: Yeah.

PAUL FRANCIS: And that's a very important factor, because what it allows us to do is use what's called linear physics. What it means is, let's enlarge this. So this is now even more drastically enlarged compared to what's really going on. Because these fluctuations are so small, it turns out in the physics you can treat them in isolation.

So you could, for example, take just this peak, and work out what happens to that, and what happens to this trough, and work out that. And then just add all the answers together, and the sum of the answers will actually give you the full answer.

BRIAN SCHMIDT: Right. OK.

PAUL FRANCIS: And that doesn't work if the density's much higher.

BRIAN SCHMIDT: Business then these things interfere with that. Yeah.

PAUL FRANCIS: But because the fluctuations are so absolutely tiny, you can just break this up in any way you like, and then just treat each part of it separately, and then add them back together again at the end.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: And the way you normally break these things up is into sine waves of different frequencies. This is called a Fourier decomposition, and it's a very, very common mathematical trick that if you go onto the university mastering physics, you will encounter an awful lot. It's taught to you in second year maths at ANU, for example. And this green curve here, which is the same one we saw before, what I've done here is broken it up into its component sine waves.

And it turns out if you add all these different sine waves, the different periods and amplitudes and phases together, you actually get that green curve.

BRIAN SCHMIDT: OK.

PAUL FRANCIS: Now, what this means is we don't have to study how a complicated pattern involves, we can just calculate what happens to a sine wave. So let's take a sine wave like this, and let's try and see what happens as this evolves between the end of inflation, which is-- what, 10 to the minus 40 per second after the Big Bang, right through another 300,000, 400,000 so years afterwards, when the microwave background is set free.

BRIAN SCHMIDT: OK, so just a quick review here, because this is pretty complicated, you're going to represent what the universe really looks like, which is a bunch of sine waves.

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: And now you've just pulled out one of those.

PAUL FRANCIS: Yep.

BRIAN SCHMIDT: And of course, there will be a thousand more of these, or even more, but we can do them independently. So we're going to work on this one, see what the answer is, and then we can do the same process for all the other sine waves.

PAUL FRANCIS: That's right.

BRIAN SCHMIDT: And then we're gonna add them all together to get our answer.

PAUL FRANCIS: That's right.

BRIAN SCHMIDT: OK. Good.

PAUL FRANCIS: OK. Now, this is density against position. Of course, really, it's a three-dimensional thing. We've just done a one-dimensional slice through the universe here.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: And this density curve is actually going to be both the density of dark matter and the density of normal matter, and in fact the density of photons as well, because after inflation, it turns out they're all going to go together, to some extent. So let's first of all think about how the dark matter is going to move. So we've got dark matter, and it's a little bit denser here than it is over there. So what's it going to do?

BRIAN SCHMIDT: Well, let's see. So dark matter is attracted by gravity, and it doesn't interact in any other way, so it is going to be attracted to where there is high potential. So it's going to be attracted to where the gravity is strongest.

PAUL FRANCIS: Right. So the stuff down here will fall in there, the stuff over there will fall.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: So as time goes on, the dark matter is going to behave in a very simple way. The lumps are just going to get bigger, so stuff's going to move from the troughs to the nearby peaks, and so the dark matter fluctuations are just going to get bigger and bigger.

BRIAN SCHMIDT: So they grow, and it literally is just this linear process where you sort of just literally stretch the scale.

PAUL FRANCIS: That's right. Now, I should mention that at the same time, of course, space is expanding like crazy, so if I wanted to show this properly, I should also be making the graph go sideways enormously at the same time. But that's too complicated, and the graph would get so big we wouldn't be able to see it. So what I've done is I've used what we call co-moving coordinates. I've actually factored out the expansion of space.

BRIAN SCHMIDT: And in mathematics we also factor out the expansion of space. You can just sort of get rid of it for now, and then add it back in at the end.

PAUL FRANCIS: For any economists out there, it's like inflation adjusted prices.

BRIAN SCHMIDT: That's right.

PAUL FRANCIS: The same actual matter sitting here and here, and actually further apart, because of expansion of space. But we factored that out.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: OK. So hopefully you're following us so far. That's what the dark matter is going to do. It's very simple. And now let's talk about the Baryon-Photon fluids. Now remember, because all the particles of Baryons, particles like what make us up are ionized, so the electrons will be ripped out of the protons, protons, a light, an ancestor of the micro background, can't get past ionized particles. It's a glowing form. They're all trapped together.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: So they're all bound together, so if one moves, the other must move. They can't flow off separately. So what are they going to do? So let's say we've got some Baryon-Photon fluid here. It's going to do exactly the same as the dark matter. It's going to fall in. So end of story, same thing happens with that?

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: Well, not quite, because here's our picture of a Baryon-Photon fluid before it's being compressed. So you've got these photons sitting in between the electrons and protons.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: And because they're all bound, as it shrinks, these things are going to move together, and that's going to compress the photons between them. Give them a high energy.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: So they're getting caught up, and that means they're gonna have radiation pressure pushed back. And remember this a billion of these to do one of those. So what that means is as it shrinks, it's going to be-- it's like the photons are acting like a really good elastic inside, and they all push back. And in fact, they will bounce. It will fall in, and then bounce outwards again, by the photons acting like a sort of spring inside.

BRIAN SCHMIDT: OK, so the photons, as you compress them, want to heat up. They push. Presumably you're going to have some momentum, and it's actually going to overshoot a little bit, get to that, just like compressing a spring, then it's going to get to a point it's going to push out. And so you're going to get-- it's almost like a giant spring.

PAUL FRANCIS: That's right. So what's going to happen is the stuff's going to fall in, and then bounce out again.

BRIAN SCHMIDT: OK.

PAUL FRANCIS: And then it will pile up in between the dark matter peaks, and once again it will squash there, and then it will fall in again. And it'll do this over and over again. So here's a simulation of this. This is now the other way around, so the potential wells where the extra dark matter is, this is gravitational potential, so more matter equals lower potential.

And you see the Baryons as the orange spheres falling in and out, with the springs, which is the photons, in between them. And it just bounces in and out. So right now there's a lot of concentration down there, the concentration up there, and it alternates between a concentration at the bottom, and a concentration at the top.

BRIAN SCHMIDT: Right. And this is a pretty lossless process. It's not like a bad spring here that heats up on Earth, and loses its elasticity. Everything's really going pretty much in and out almost exactly the same.

PAUL FRANCIS: Yes. If you tried this on Earth, of course, first of all it would bounce quite strongly, and then friction would slow it down. But here there's nowhere for the energy to go, because the photons and the Baryons are locked together. So in principle, it could just keep on bouncing forever. It's a perfect spring.

BRIAN SCHMIDT: Right. OK. Good.

PAUL FRANCIS: OK, so that's what happens on, say, lumps of this size. You're gonna have stuff bouncing in and out. But of course, remember, we've actually got lumps on many different sizes. So we've got, say, this high frequency sign, which would be the small lumps in the universe, and you've got bigger lumps in the universe. And the same thing's going to happen here. The stuff's going to come in and come out.

But it's not going to do it at the same frequency. I mean, what determines how long it's going to take to, say, fall in and bounce out, do you think?

BRIAN SCHMIDT: Well, the ability to fall in is going to be roughly at the speed of sound, because you have pressure, and pressure goes as sound. So my guess is the speed of sound will govern stuff.

PAUL FRANCIS: Yes, so roughly speaking, things will fall in at the speed of sound. And what's the speed of sound this early in the universe? It's extremely fast.

BRIAN SCHMIDT: I believe it is something like 1 over the square root of 3 times the speed of light.

PAUL FRANCIS: OK, so that's, what, 50-something percent?

BRIAN SCHMIDT: It's 57% of the speed of light, I think is what it is.

PAUL FRANCIS: OK. So the stuff's going to fall in extremely fast, 50-odd percent of the speed of light, and then bounce out.

BRIAN SCHMIDT: Yep.

PAUL FRANCIS: But for the bigger lumps, it's got further to move. It's going at the same speed, the speed of sound, but it's got further to go. So that means these things will oscillate more slowly than those ones. This one goes in and out pretty quickly, whereas this one's going to take longer. It's going at the same speed, but it's got further to go.

BRIAN SCHMIDT: Yep. So if you think of it, you're going to be doing the same speed like that, and then I'm going to be doing the same speed, but I'm just going the same speed, but I'm at a smaller distance. Yes. OK?

PAUL FRANCIS: OK. So we're going to get is a sort of orchestra coming along, here. I'm now plotting-- previous plots were showing density versus position. What I'm now going to show you is density versus time. So this is a different graph, and it's visually the same. So up here, for example, would be a really big sine wave.

So these are the really biggest lumps in the universe. And because they're so big, it takes longer than this graph for anything to fall into anything.

BRIAN SCHMIDT: Right.

PAUL FRANCIS: But then as you go down this plot, these curves show smaller and smaller scale lumps, and as the lumps get smaller and smaller, the stuff can fall in and out. So it's fallen in, then it's just gone up, and it's fallen out. it's fallen in, and the really small lumps, it's got time to fall in and out lots and lots of times. So you've got to imagine it's a bit like an orchestra, and that's the double bass, and this is a piccolo. And they're all playing at the same time, but at different frequencies.

BRIAN SCHMIDT: OK, so what we have here, just as a review, this is for a really long length sine wave. So like a sine wave that's--

PAUL FRANCIS: A sine wave with density versus position. So really big scale fluctuations. These might be-- what are they, oh, 500 megaparsec scale, something like that.

BRIAN SCHMIDT: Right. And so this one would be quite a quick little sine wave in space, and it turns out to be a quick little sine wave in time as well. Beautiful symmetry here.

PAUL FRANCIS: That's right. And it turns out you can actually take this orchestral sound and bring the frequency up by a huge factor and play it.

BRIAN SCHMIDT: OK. Do you think it sounds like Beethoven, or something?

PAUL FRANCIS: Well, let's try playing it.

[SOUND PLAYS]

OK, so what you've heard there is a big drop in frequency, and that's because of the overall expansion of space. And it really doesn't sound very much like Beethoven, because--

BRIAN SCHMIDT: I was gonna say--

PAUL FRANCIS: There's too many--

BRIAN SCHMIDT: Beethoven ain't gonna roll over for that.

PAUL FRANCIS: Too many different notes playing at the same time.

BRIAN SCHMIDT: Yep. OK. Very interesting.

A4_L7_V03_Power_Spectrum

BRIAN SCHMIDT: All right, Paul, so we've heard the music of the Universe. Now, I guess I'm kind of curious, because it seems to me, to first order, we're going to have all these different scales, different bits and pieces coming in. It's all kind of random. Seems to me we're just going to get an omelette the end of it. It's doesn't seem like we should get any real pattern. How do we get a pattern out of all of this?

PAUL FRANCIS: Well, what's going on, of course, here is that this whole symphony keeps going for certain length of time until, at this point, the Universe has become so large, the temperatures dropped so much, that the electrons can combine with the protons to form hydrogen. And suddenly the Universe goes transparent.

BRIAN SCHMIDT: And the sound speed will go from very much close to the speed of light to being more like 100 kilometers, like it is here on Earth. So, yes, it will change the Universe dramatically.

PAUL FRANCIS: And the photons are no longer locked to the baryons, and so they can fly freely. In fact, the photons from this moment, ones that are raining down on us right now. So what we see when we look at the microwave background is a snapshot of this particular moment.

So what I'm going to ask is what are we going to see if we look at that particular moment? And we can talk about this on different scales. Just remember our graph was showing how lumpy the Universe was on different sizes. So these are on really big scale. So these three are all really big lumps.

Now, what's happened there, well, the density's maybe started going up, the stuff has started falling in. But because these lumps are very, very big, there hasn't been enough time in the Universe for stuff to fall in significantly.

BRIAN SCHMIDT: Right, so if we see any lumps on scales that big, that means this process hasn't really done anything. So what we see is what the Universe was born with on those big scales.

PAUL FRANCIS: Yes, so that's corresponding to this part of the diagram over here. So these are the really big scales like in 19 degrees, 18 degrees on the skies. So they're the low-order multipoles. And here there's not much in the way of fluctuations. What there is a direct imprint leftover from the initial conditions.

BRIAN SCHMIDT: Yeah.

PAUL FRANCIS: OK, so not much over there, but potentially what there is very interesting, because it hasn't been modified by the [INAUDIBLE] right back to the [? error ?] of inflation here.

BRIAN SCHMIDT: Right, unfortunately, they are very big. So that means you're not going to have very many of them. And they're going to be very hard to measure accurately because they just aren't very many.

And so it's like taking a poll of 20 people. Well, you get an answer, it's just not very accurate. So it's going to be a problem there.

PAUL FRANCIS: Yeah, it's a shame, but not much there.

BRIAN SCHMIDT: We need more than one universe to poll.

PAUL FRANCIS: Yeah, that would certainly help. OK, but now let's look at slightly smaller lumps. So those are like 20-degree lumps.

These might be 1-degree sized lumps on the sky. In this case, there's just about been time for the stuff to fall into the lump and reach its peak compressions. It hasn't yet been time for it to bounce out again.

BRIAN SCHMIDT: So we have a scale that's coming, that's going, and it stopped. We got it right at that moment.

PAUL FRANCIS: So this is in fact going to be the horizon length of the Universe, which means that is how far a photon going at 57% of the speed of light traveled in the whole age of the Universe up to recombination.

BRIAN SCHMIDT: So it's sort of the sound horizon?

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: It's the limit of what sound could travel in the age of the Universe, OK.

PAUL FRANCIS: And that's where you see really big peaks.

BRIAN SCHMIDT: Oh, now the fact that we have a lot of big peaks-- So we just have a lot of big peaks, but it's going to be amplified. If we go back to the previous slide, you will note that when things come in, they, for example, this one, they're going pretty quickly, and then they slow down at the top of a sine--

PAUL FRANCIS: Sine waves are flat at the top.

BRIAN SCHMIDT: They're flat at the top, so you spend a lot of time around that scale and a lot of time, it turns out, around this scale. So not only you're going to have bigger bumps here, then you are going to have the fact is you're going to have lots of things right around this scale are all going to pile up and spend their time at that point. OK.

PAUL FRANCIS: Yes, that's right. So what we're seeing here are the lumps of the Universe which have just had time for this baryon-photon fluid to fall in and not yet bounce out.

BRIAN SCHMIDT: OK.

PAUL FRANCIS: Now if you go to a slightly smaller scale, we now look at things where it's had time to fall in and bounce halfway out. You've got to imagine it's going in, out, in, one. This one, it's gone in and it's gone a halfway out.

BRIAN SCHMIDT: So it's gone halfway out--

PAUL FRANCIS: So it's gone back to where it started from, basically, the whole effect took place. So it's going to give you actually a pretty uniform density. So not very many lumps at all on that scale. It's smoothed out.

BRIAN SCHMIDT: Right, and since it's moving very quickly, this is where the sine curve is changing the most quickly. It's the place where they're not going to be really any pileups at all.

PAUL FRANCIS: Yeah, so that give you a trough there. So there's not so much fluctuations there. But then you can go to here. So in this case, it's fallen into the dark matter lump, bounced out. And now it's considered in between the dark matter lumps.

BRIAN SCHMIDT: OK, so we've come down, we've bounced, we've gone out, and we've stalled because--

PAUL FRANCIS: Yeah, if you've got another sine wave over here. So we've both gone in together and then we've both bounced out. So now we're concentrated here in between the two.

BRIAN SCHMIDT: In between the two lumps. And again--

PAUL FRANCIS: Yeah, it's a flat bottomof the--

BRIAN SCHMIDT: Yes, so flat bottom, so there will be a lot of them there.

PAUL FRANCIS: In that case, you've got another peak there.

BRIAN SCHMIDT: OK, interesting.

PAUL FRANCIS: And then as you keep on going down this curve, you can see ones where once it's back to 0 density fluctuation, so it'll be another trough. And then here is where it's gone in, gone out, and gone in again. And it'll give you the next peak.

BRIAN SCHMIDT: Right. And you could imagine that these are all going to sort of be multiples of each other, because it's almost like harmonics in sound.

PAUL FRANCIS: That's right. It's exactly like waves of a violin string or an organ pipe. You get it 1, 2, 3, 4. In this case, instead of being bound physically, say by the ends of the violin string at both cases, so bound by time.

You've got inflation at the beginning and, when the Universe became transparent at the end, and you've got to fit your 1 wave, 2 waves, 3 ways in there. So you get this whole series of discrete peaks.

BRIAN SCHMIDT: Right. And they just keep on going on and on, and on.

PAUL FRANCIS: Because they do get weaker, as you go down here. So what's going on there is in fact the end of recombination was not instantaneous. So up here, everything's bound.

Over here, electrons and protons start combining each other, and so it starts becoming transparent. The photons can now move a bit. And then as time goes, they'll get to move further and further. But it's not suddenly go from opaque to transparent. The fog gradually thins out.

BRIAN SCHMIDT: OK, so on a really big scale, it's not going to make much difference, because that time that a transference is not very long, relative age of the Universe. And so they're not going to be able to move much. They're not going to go from a dark to a light part. But when you get to really small areas, they're going to be able to move from one lump to the other because of that transparency issue.

PAUL FRANCIS: Yes, so they can spread around. So the small-scale things get suppressed because the photons can randomly work their way from a peak to a trough and vice versa, or they're still partially bound. Until it eventually becomes totally transparent, and they just fly freely to meet us. So it's giving us this decline down there.

BRIAN SCHMIDT: The mirroring out which we call Silk damping.

PAUL FRANCIS: Yes, so damping tail. OK, so actually we can explain this whole thing remarkably well.

BRIAN SCHMIDT: Oh, well done, Paul. That's a great piece of physics explained. And that's a really complicated piece of physics that we didn't really understand very well, even when I was in graduate school. And now-- voila, we can teach it here on this course.

PAUL FRANCIS: And it turns out, as we'll see in the next video, to be a really interesting bit of physics in terms of measuring what's going on with the cosmology of the Universe.

A4_L7_V04_curvature

PAUL FRANCIS: OK. Let's see how we can use this to measure cosmological parameters. Now the benefit of this whole linear physics thing is that it's actually mathematically very simple, very straightforward, because you can break everything up into its components and treat them all separately, which means we can calculate it with exquisite precision.

So it's not as complicated or messy as the universe more recently, which is very hard to calculate like trying the supernova explosion. Yuck. But this, everything's linear, everything's simple, everything's small. And what this means is you can calculate how long, for example, the scale of those first peaks are. These are the ones where stuff has just fallen in, the first peak. And that's basically just how far sound can travel in that time.

BRIAN SCHMIDT: Yeah. So that's a very simple scale. Very good.

PAUL FRANCIS: You have to allow for the fact that space was expanding all the time while it was going on, but we can do that. That's also pretty straightforward mathematically. So this gives us a standard ruler.

BRIAN SCHMIDT: Ooh, a standard ruler, and so we can see how big that ruler looks. That's similar to seeing how bright something appears as a function of distance. We have the ability to calculate how long a ruler looks as a function of distance.

PAUL FRANCIS: So we've talked about using standard candles a lot in this course, so things of known brightness. Then you see how bright they appear to be, and that gives you the distance. And principally, you can also see something that's of known length. If you know how long something really is, and you move it further away, it should look smaller, so that gives you the distance.

So in principle, we know how long this is, because we can calculate the physics of the early universe. We can measure what angle, which is about 1 degree, these lumps appear to be, and that will give us a distance, which is just going to be an angle in radians equals the length divided by the distance to it.

BRIAN SCHMIDT: Well, that distance has to be a bit of a special distance. Right, Paul? It's not just your normal ruler distance. We have to worry about the fact that the universe is expanding, and so when I look at, for example, a ruler back in time, the light waves are going to be going out, and then they get kind of sucked back in, because the universe was smaller in the past. But we can take care of all that, thanks to general relativity and the Robertson Walker metric that we talked about.

PAUL FRANCIS: That's right. So we can take care of all that. So it's not quite as simple as this, but the basic principle is right. However, this turns out to be very sensitive to the geometry of space. So here, let's say it's just l over d, but what happens if we lived in a saddle-shaped universe? This is the open universe we talked about early on. So here, you've got length l, once again, but now the angle's smaller.

BRIAN SCHMIDT: Right. And so that's going to change, if we go back to our equation with distance. So effectively, what we would do is we calculate a distance using general relativity, such that this is true. We say, this is true.

PAUL FRANCIS: True, you've got a definition of distance to fit that.

BRIAN SCHMIDT: That's right. And then we're going to see that, effectively, this is equivalent to saying there is 180 degrees in a triangle, effectively. And now when we have a universe shaped as a saddle, that's not true. And so the universe is going to distort what things look like very sensitively once we take care of all the other bookkeeping of general relativity.

PAUL FRANCIS: This is right back to what we talked about last time about trying to measure the geometry. At last, we can do it, because we've got a standard ruler that we can actually see out there in space. If on the other hand, we're in a closed universe, a spherical universe, in this case, the angles inside a triangle add up to more than 180 degrees. So now this angle here is going to be bigger than just L/D.

BRIAN SCHMIDT: Right. So this, effectively, this type of universe essentially magnifies, distorts, makes things look larger. And the other universe makes things look smaller, and so we should be able to differentiate the shape of the universe by how long that ruler looks like, all things else being equal.

PAUL FRANCIS: And that's been done, so what did we get? Well, we found that within 1%, the universe is flat.

BRIAN SCHMIDT: And we should say, you put down omega matter plus omega lambda, but what we really mean is omega anything here. If there's something we're missing, it adds up on this side of the equation. So everything adds up to the universe.

PAUL FRANCIS: Because you remember, there wasn't enough matter to make the universe flat, but it turns out that this lambda, this dark energy, could also flatten the universe out. So it presumably indicates some of the matter plus lambda plus anything else weird that's going on adds up to 1. And considering the universe, it's actually pretty damn near flat.

BRIAN SCHMIDT: Right. And there's no way to hide from this. No matter what you throw on the universe, it's going to be seen in the shape of the entire universe.

PAUL FRANCIS: So it could be just a little bit one side, a little bit on the other side of this geometry. But it's pretty close. And of course, inflation will predict that it'll be pretty much exactly 1.

BRIAN SCHMIDT: That's right. So it's an interesting way to look at inflation again, and it predicted in advance, you should see something like this.

PAUL FRANCIS: If it had come out at 0.8, inflation would be dead.

BRIAN SCHMIDT: Yes. Absolutely.

PAUL FRANCIS: Here's a simulation from Wayne Hu again showing the actual effect of changing the geometry of the universe. And what we're looking at here is the fluctuation spectrum as we change the universe's, the sum of curvature and dark energy. So it's telling you from an open to a closed universe.

BRIAN SCHMIDT: Right. So essentially what we're doing here is we're raising the curvature in one case, and then this line here is with curvature. What happens is the universe changes in curvature, and then the blue one is if you change the amount of cosmological constant. So you can see almost nothing happens until the very end about the cosmological constant. But we're really sensitive to the shape of the universe, and so this is a great way to go through and to measure essentially how big the bumps and wiggles are of the universe, and that tells us the shape of it. Very accurate.

PAUL FRANCIS: Yes. And you can see the effect of the shape is more or less just to move to things sideways, so you get the same pattern imprinted on the microwave background. All that's happening is that pattern appears to us to be a smaller or larger angle depending on what sort of geometry we're in.

BRIAN SCHMIDT: Yeah. And you can sort of understand that, because when we run the universe back in reverse, you really are at a state where the universe is more or less in the same state, no matter what it's made out of now to first order back then. And so you expect those acoustic waves to essentially be the same independent of things like the cosmological constant.

A4_L7_V05_baryons

PAUL FRANCIS: Now, one thing that will affect the acoustic waves is the density of the universe. Now, if you remember, these acoustic waves with the dark matter potential wells and the baryon-photon fluid that's falling and then bouncing out. Now, if there were no dark matter potential wells, this would just be a sound wave, like the ones moving around this room right between us. So things are just going in and out, in and out. And in-oscillations and the out-oscillations would be the same.

But if you've got dark matter and you also have to have baryons mixed in with the photons fall down. If it's pure photons falling, they don't have much mass. But if there are baryons mixed in, then when they're going into a potential well, gravity's assisting them, they'll go faster.

When they're coming out, they're climbing up a hill. And certainly, when I'm climbing up a hill I go much slower than when I'm going down. And so what you'd expect is an imbalance. The oscillations when they fall in will be fast and dramatic, and the ones when they go out would be a bit more drawn out and more pathetic.

BRIAN SCHMIDT: Yeah.

PAUL FRANCIS: And this will affect the different peaks. So for example, this is the first acoustic peak. And this is where the matter's just had time to fall. And these are lumps so big that things, when they just fall in, are of the age of the universe at that point.

But here's a second peak. And here they've fallen in, bounced, and come out. So we're actually picking them up when they are in between the dark matter lumps. So this one is falling in. That one's going out. And we'll keep on going all the way down here.

BRIAN SCHMIDT: Yeah, in, out. In, out.

PAUL FRANCIS: So what you'd expect is if there's a lot of dark matter and particularly a lot of baryons, you'd expect the odd number of peaks-- 1, 3, 5, and so on-- to be a enhanced, because that's where you're falling into the dark matter potential wells, and the even-number ones to be weakened, because that's when you're bouncing out.

BRIAN SCHMIDT: But of course it is a ratio a little bit between how much baryons there are, how much dark matter there is. So it's a little bit complicated.

PAUL FRANCIS: Yes, and also if you have more dark matter, that means the lumps are bigger to begin with. And so things are going to start off oscillating more. So it's a rather complicated thing. But it is all nice linear physics, which means it can be calculated very precisely. And here, once again, is some simulation that's showing what's going on here.

BRIAN SCHMIDT: So this is a baryometer. So this is omega baryons. So that's what fraction of the universe is baryons. And so we actually have omega matter here as well. We just keep that value at a constant value.

We see what happens as we add more and more baryons to the universe. And you can see that this curve, for example, comes up, and the second one goes down. So the reverberation drops, and the compressions go up.

PAUL FRANCIS: And if you change, instead, the total amount of matter?

BRIAN SCHMIDT: Right, so in this case, we're keeping them out. Baryons fixed. So we're just going to make more and more dark matter in this case. And so you can see that as you go through and make the universe heavier and heavier, these curves actually drop in their overall fluctuation strength.

PAUL FRANCIS: And by fitting the detailed shape of these curves, you can learn omega matter. So all matter and dark baryons is about 31.5% of the critical density of the universe.

BRIAN SCHMIDT: Yes. And this is from the Planck experiment, the best experiment we have at this point. And then the other thing we can measure is how many baryons or the atoms we're used to.

Look at this exquisite precision that we can do that with-- 0.048 and then three zeros and a 5 is the uncertainty. Remarkable. I would've never thought we could have done anything this well.

PAUL FRANCIS: And this is pretty much agreeing what we learned from the primordial nucleosynthesis that told us that about this amount from the deuterium to hydrogen ratio had to be in the form of baryons. But most of the mass in the universe could not be in the form of baryons. And so we've got 2 totally independent lines of evidence-- one from nuclear reactions in the early universe element ratios and one from wiggles in the microwave background. And they're giving us the same answers.

BRIAN SCHMIDT: Yeah, but usually it's a good sign you understand things very well.

PAUL FRANCIS: Yes. And this number here is also agreeing fairly well with what we measured from looking at galaxy clusters and large-scale structure, peculiar motions, and also from weak gravitational lensing. So these all seem to be telling us that the master we see in these clumps on very large scales is about all the matter there is.

BRIAN SCHMIDT: Yeah. And I should say that there's still a little bit of controversy over this number especially, because the two satellite experiments-- WMAP that just finished and Planck, which is finished as well, but still under analysis-- there's a little bit of question about how the backgrounds were moved. And so the uncertainty in this may be just a little bigger than the number here. We'll see. I think time will tell us.

PAUL FRANCIS: So combining all these model elements you can get a really remarkably good fit to the data. So the points here are the data. And the red line is the model with the parameters we've just been talking about. And really, it's a very complicated shape. And that's an extraordinarily good job.

BRIAN SCHMIDT: Yeah, and essentially, whenever you can predict something in advance that well, there's really no way around it. And this model has baryons in it-- fine, we know about those on Earth. It has omega matter or dark matter. So you need to have that in there as well.

And it turns out it needs to have the cosmological constant, or the whole thing would be shifted in a different direction. So it really does bring together this crazy universe, 95% of which we don't understand. But you can predict exactly what you see in the Universe.

PAUL FRANCIS: If you want to come up with a rival theory of cosmology, you've got to be able to explain this to this level of precision. And that's a very, very tall order.

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: There is one anomaly here, or possible anomaly. Up here on the very large scale, so multiples, in the 20s. Both the WMAP data and the Planck data were a bit lower over here. You'll see it's a bit down there.

BRIAN SCHMIDT: And remember, this is the part of the Universe where this part of the Universe and this part of the Universe are much longer wavelengths than sound can travel. So this is what the Universe was effectively born with after inflation. So for whatever reason, it appears that we're just the quantum fluctuations seem to be missing on that scale, compared to what you expect at other sales.

But the problem, of course, is that's 20 degrees, so you don't get very many of them across the sky. Which ultimately means there's a lot of uncertainty, uncertainty we'll never going to be able to get around because we only live in one Universe. And the Universe only has so many of those scales across it that we could see.

PAUL FRANCIS: Yes, there are arrow balls here simply because we were in one place in Universe. We'd have to move 10 billion light years and take another picture and another 10 billion light years and take another picture, that would be able to bring down the statistics here. But that's not going to happen any time soon.

BRIAN SCHMIDT: Yeah, and the challenge, of course, is that the uncertainty here is-- well, I would say the unusualness here is about 5% of universes you might expect something this anomalous. So it's not horrible, 1 in 20. But it's sort of in that very uncomfortable place, where you feel like you're missing something.

PAUL FRANCIS: Yeah, so maybe this is a clue to something new and strange going on. Or maybe it's a 1-in-20 fluke.

BRIAN SCHMIDT: Yeah.

PAUL FRANCIS: I wouldn't walk across a bridge that had a 1-in-20 fluke chance of collapsing under me, so I wouldn't bet the farm on that. But it may be suggestive, but how else are you going to pursue this further, I don't know.

BRIAN SCHMIDT: No, it's not easy. I'm kind of hoping someone on the other side of the Universe has beamed a message, a picture of the cosmic microwave background, from their perspective. And it'll be coming in at some point in the near future, when the Universe was much younger from their point of view.

PAUL FRANCIS: So anyway, these are the amazing results we get from the cosmic microwave background and isotropic peaks, acoustic peaks. But this is a gift that keeps on giving. There's actually more to learn from these acoustic peaks, which is actually how the imprint on Universe that we see right today.

A4_L7_V06_BAOs

BRIAN SCHMIDT: So Paul, this cosmic microwave background is really an amazing gift that the universe has given us for exploring. It's almost like a physics class experiment out in the farthest reaches of the universe. And the amazing thing is it keeps giving. Not only can we do the experiment in the cosmic microwave background, it turns out we can see those ripples today.

PAUL FRANCIS: Yes. This is absolutely amazing. This blew me away when I learned this is possible. We've talked about all these peaks in the microwave background. So this is telling us there were lumps on the scale back at red shift over 1,000. But of course, if there was a lump then, that means there were more photons in these cases at that scale. There was also more matter, both more dark matter and more baryonic matter. And so that presumably is telling us that there were lots of lumps on this scale, this scale, this scale in the distribution of matter back all that time ago. But presumably those lumps of matter have just sat there ever since.

BRIAN SCHMIDT: That's because the universe recombined when we see this.

PAUL FRANCIS: No more bouncing.

BRIAN SCHMIDT: No more bouncing. That was it. Everything just stayed put. It was only acted upon by gravity. And although that's only a degree in the sky, that's a long ways when it comes to distances now.

PAUL FRANCIS: So in principle, this area here-- although on that particular scale, there could be lumps of matter. And as time goes on, those lumps will get bigger and bigger as they suck more and more matter in. And they might have turned into clusters of galaxies and super clusters and things like that by today. So in principle, you could actually see this right now. You could look around the universe and say, are galaxies clustered preferentially on certain scales? And those scales would be these particular lumps from the oscillation, the acoustic peaks right early in the universe.

BRIAN SCHMIDT: Right. So if we go out, we'll look around in space, and for example here, with a giant Redshift survey. And what our prediction is, we should see those lumps and bumps in that distribution of galaxies. But it's a big scale. So it's a scale that's kind of hard to see. It's a good fraction of that Redshift survey right there.

PAUL FRANCIS: So a number of these surveys were done. You need to get measured positions of a lot of galaxies to make this work.

BRIAN SCHMIDT: Many hundred thousand.

PAUL FRANCIS: Hundreds of thousands. And you have to have a really good control of any errors. So for example, if you're a bit more likely to see them in one part of the sky than another because you had better weather when you were observing over here than over there, that would give you a spurious signal that would mimic what you're actually looking for. So you have to be able to calibrate all these differences out with exquisite precision.

People have done this, and what we put in here is how strongly galaxies, clusters. This is from the Sloan Digital Sky Survey, which is one of the two surveys, along with the 2dF Galaxy Redshift Survey that came up with a result, both back in 2005. And on small scales, this is very strongly clustered. This is just things like the Virgo cluster in our local group.

This is just galaxies being sucked towards other galaxies. So that's not telling us anything about early universe physics. That's telling us things happened more recently. But by the time [INAUDIBLE] scales of 100 megaParsecs, that's so enormous that galaxies are not appreciably attracting each other on those sort of scales.

BRIAN SCHMIDT: They moved only a tiny little bit. So they're at where they were back at the time of the Big Bang, just with the expansion of the universe.

PAUL FRANCIS: Well, you can see it clusters strongly. It drops off. It drops off. It drops off. And then suddenly there's a little bump over here.

BRIAN SCHMIDT: A little bump. So we're magnifying that bump up here. And so we see that there is an excess of galaxies at this distance of about 100 megaParsecs, just a little bit more. And I should say there's a Hubble constant down there, which we're going to ignore for now.

PAUL FRANCIS: Yes. So this is actually for-- the current value of the Hubble constant corresponds to about 150, 160 megaParsecs. And so it does seem that on those very large scales, the universe is lumpy to this day. And this is just the remains of those acoustic peaks.

BRIAN SCHMIDT: So that means we have a scale now that we know how long it is in meters based on the physics of the cosmic microwave background. Now, that sounds like it could be useful.

PAUL FRANCIS: It is. And we can not only measure it today by looking at nearby galaxies, but we could also go and look at more and more distant samples of galaxies. In each case, [INAUDIBLE] sample a few hundreds of thousands of galaxies. But you could do a sample of the nearest 200,000 galaxies, then ones that are a bit further away, and a bit further away again. And each of them, you could measure how they're clustered, and each of them you can look for this little peak.

BRIAN SCHMIDT: Little bump, OK.

PAUL FRANCIS: And people have done that and are continuing to do this. And what that gives you is a standard ruler at a whole bunch of different distances. So the nearby one, or the way out to one that's at the microwave background, [INAUDIBLE] 1,080.

BRIAN SCHMIDT: OK. So instead of with the supernova, where you measure how bright things are, and you'd see that they're getting fainter, here we're saying the rulers are getting smaller, although it turns out they do get bigger because of the universe being smaller in the past. We're able to go back and literally measure another way to measure distances. And we have the added value that we have the nearby objects. And then we have this really distant measurement as well at a redshift of almost 1,100, which you just simply can't get any other way.

PAUL FRANCIS: So this is giving us an independent test of how the universe evolved with time. Why do people care? Well, the thing that's really driving these sort of surveys at the moment is trying to understand what the hell this dark energy is that you discovered. Because at the moment, we've got not much clue. It's making the universe expand faster now.

One possible clue would be how it's evolved with time. Is it always behaving the same, all the way through time, so giving a perfect exponential growth curve? Or is it maybe getting stronger or weaker with time? And if we could find any clues to how exactly it's evolving with time, that might give us at least one clue to what the hell this thing is, which at the moment we have very little idea.

BRIAN SCHMIDT: Well, we certainly could falsify Einstein's cosmological constant, which makes a prediction that it's always the same everywhere in the universe at all times.

PAUL FRANCIS: Now, it turns out the way we normally parametrize this is we set the density of this dark stuff, whatever it is, is proportional to the scale effect of the universe to the power written here. And the parameter of question is w.

BRIAN SCHMIDT: And that w is what we call the equation of state. You can think of it as sort of the ideal gas law, except for it's for gravity. And it's a way of parametrizing essentially how the density of material changes as you expand space.

PAUL FRANCIS: Yes, this gives the density of the dark energy. And for Einstein's theory, this lambda says w is minus 1. So that gives us a to the power of 1--

BRIAN SCHMIDT: Minus 1. 0 times 3 is 0.

PAUL FRANCIS: So it's a to the 0, which is a constant. So it's telling us, just as we know, that for Einstein's model, it's like a 0 point energy, and it doesn't vary the density with time. But it could be something a bit different. So for example, we talked about maybe it being one of those Mexican hat potentials. In that case, it might be rolling down the side of the Mexican hat as we speak. In which case, w's going to have a different value. This is going to be going down as time goes on, as the universe gets bigger.

BRIAN SCHMIDT: Right. So instead of minus 1, it might be minus 0.9. In which case, you would get the fact that the densities falling off slightly differently. And that means that the equation for distance is going to be slightly different.

PAUL FRANCIS: Yes. The universe would be getting a bit less exponential. However, in principle, there could be some strange theories that would have it even go the other way. So it actually starts to get even faster as it gets bigger.

BRIAN SCHMIDT: That would be kind of scary.

PAUL FRANCIS: So we have no particular reason to believe w's anything different from minus 1. But you don't know until you look.

BRIAN SCHMIDT: Right. And one of the advantages of these baryon acoustic oscillations compared to supernovae is we know the physics of this ruler is sort of fixed. So we don't really expect it to change back in time because it's just a ruler that we can see way back at the time of the cosmic microwave background.

PAUL FRANCIS: It's imprinted by basic physics. It's been there ever since.

BRIAN SCHMIDT: With the supernovae that I tend to study, we know they are a star that explodes. And the universe is changing back in time how stars were. They have different amounts of iron in them, for example. And they're maybe not as old in the past when they explode as they are now. These things are possible.

So we're not quite so sure that the supernovae aren't going to be affected. And there's another really big difference, which is this bloody dust stuff that I hate. Dust makes objects appear fainter, but dust does not make rulers change their length. So that's a little thing that they get to circumvent. Very useful.

PAUL FRANCIS: So what are we finding so far? What is the value of w that's coming up at the moment?

BRIAN SCHMIDT: Well, I'm proud to say that the answer they get is almost identical to the supernova answer within the error bars. They're not quite as precise as the supernova measurements are yet, but give it another few years. They're going to have huge surveys of galaxies, where they'll be able to match or probably exceed the precision of supernovae in the next 5 or 10 years.

PAUL FRANCIS: And the value of w is?

BRIAN SCHMIDT: The w value is the same as the supernovae, which is Einstein's minus 1 cosmological constant. Seems to be right bang on still, as well as we can measure it.

A4_L7_V07_Degeneracies

PAUL FRANCIS: Now, there is bit of a problem or a complication here. We've said that a given measurement, like the microwave background or the acoustic oscillations in the galaxies today, or supernovae, tell you a particular cosmological parameter. But it's not quite that simple, is it?

BRIAN SCHMIDT: No. There are uncertainties. And the uncertainties are actually pretty big in any of the given experiments. So let's take the most recent measurements of the cosmological constant and the total matter density of the universe from supernovae, which are shown here in this-- is that blue or purple? I'm colorblind.

PAUL FRANCIS: It's blue.

BRIAN SCHMIDT: It's blue. It's hazardous being an astronomer, being colorblind.

So what this is saying is this inner line here is saying that we're 2/3, or actually 68.3%, sure that the real answer lies in here. And for the cosmic microwave background, it turns out we're 68% in this little, narrow bit; very small this way; but very long this way. So we really are not actually sure what's going on, except for from here to here.

PAUL FRANCIS: And so this graph, to make clear, this is telling you the amount of omega matter and matter of the universe. This is telling you the amount of dark energy. And what this is saying is that if you just had the microwave backward measurements, it could be here, which would be 70% matter and 20% dark energy. Or it could be up here, so 80% and 20%.

Basically, what this is telling us is the measure of the universe is geometrically flat. So it's telling you the sum of these must add up to 1. But it's not telling you actually which combination.

Any combination adds up pretty close to 1, somewhere along here is central. But it is actually ruling out this. It couldn't be there or couldn't be there. It's got to be somewhere on this narrow stripe.

BRIAN SCHMIDT: Right. So you have what we would say, covariance, if you want, of the parameters. Or it means you've measured something. But you haven't measured quite what you want, which is what's omega matter or what's omega lambda? You measure the combination together.

PAUL FRANCIS: This is often called degeneracy, in the sense that what you know is some combination of two things, not one by itself. And so we know if we knew the value of one, we could calculate the other. But we don't know which combination, along this line, is sitting there.

BRIAN SCHMIDT: But conveniently, the supernovae are degenerate this direction. That is, we measure a combination of omega lambda and omega matter in this direction. And the cosmic microwave background is an "almost," at 90 degrees; not quite, but close. So that means that if we take this and this, we get a really accurate number together, which is going to be sort of in here, together.

On top of that, we also have the baryonic acoustic oscillation measurements, which turn out to be something sort of in this direction. And when we add those together, we get this tiny little area, where everything's consistent together. And so we're able to zero in to a very precise value of omega matter and omega lambda, it turns out.

PAUL FRANCIS: And no one of the surveys by itself would be able to do. It's only with a combination of them that you get this very precise constraint.

BRIAN SCHMIDT: That's true. So that makes it very useful. I should note though, that if you want to get rid of the cosmological constant, you really can do it with any one of these experiments-- or sorry, none of these experiments allow the cosmological constant not to exist. All of them require it at this point.

PAUL FRANCIS: And we're lucky that they all overlap. So we've got this one and one that overlap over here. And then we got this other, that's not shown, from the background [INAUDIBLE]. And it luckily goes up there. If it had gone off over here, there would have been no place where all three of these things matched.

BRIAN SCHMIDT: And then we would know we would have a problem. And that would have been exciting. Although it would mean we wouldn't understand what's going on very well.

PAUL FRANCIS: Here's another example of one of these plots. Now, we're plotting w, which, remember, is the equation of state parameter. It's telling you where the dark energy becomes bigger or lower density as the universe expands, against omega matter. And you've got the microwave background measurements. Here you got supernovae measurements.

BRIAN SCHMIDT: And they cross again. And again, we also have that baryonic acoustic oscillation measurements, which cross through here as well.

So once again, when we add it all together, you get this nice little gray area, where we put all the information together. And it's quite interesting to see where it lands, omega matter of about 0.3, and the equation of state parameter of minus 1.

PAUL FRANCIS: That's what Einstein said.

BRIAN SCHMIDT: What Einstein said. So it looks like whatever is going on, that same story of 30% of the universe being omega matter and 70% is this stuff that has an equation state almost exactly what Einstein said, which is stuff that does not change over time.

So if we're rolling down the Mexican hat, we're very close to the top. And that would be an unfortunate place to be because it's kind of hard to tell that we're there in any sensible way.

PAUL FRANCIS: Um-huh. So we could put all these things together and, for example, take stock of our universe. This is what our universe is made of.

And we know from this combination of things that it's about just over 30% matter and just under 70% dark energy, dark energy with an equation state parameter consistent with minus 1. And we also know, from the primordial nucleosynthesis, the deuterium to hydrogen ratio, that's it's about 4.9% ordinary matter and the rest must be something that's not made of baryons, or some weird subatomic particle.

BRIAN SCHMIDT: Yes. And so it's a funny universe. But, geez, we have a lot of precision here. And I should say that I think maybe there's still a little bit of uncertainty. This is the best measurement we have right now. But there's still some uncertainty whether or not we might have some little errors creeping in, in some of the experiments.

And so face value, this is the best answer. Maybe we can talk a little later on about how robust these numbers are.

PAUL FRANCIS: Yeah. So what do universe do we live in? We live in a universe that's flat, to within 1%, or maybe even a bit better than that now.

BRIAN SCHMIDT: Yeah. It's better than a half a percent. And pretty much, there's no way around that. All of the measurements, even with the uncertainties, really nail, with the cosmic microwave background, that that answer seems to be right.

PAUL FRANCIS: I mean the age of the universe, with a precision unmatched since Archbishop Ussher said it was 4004 BC.

BRIAN SCHMIDT: Yeah, in October.

13.798 billion years, plus or minus 0.037, that is incredible precision.

The one thing we're not sure about is whether or not the universe is open, eternal, or infinite. Because it's on that knife edge, where you can't tell. So that's an interesting place to be. And, of course, that is what inflation said we would be close to. But it doesn't actually tell us the real answer.

PAUL FRANCIS: It doesn't tell you if you're or closed. It does tell you if you're eternal. Because you've got a cosmological constant in there, it's going to keep on going forever. Unless it decays somehow, somewhat.

BRIAN SCHMIDT: Unless it decays. And that Mexican hat allow that to occur in the future.

And I should say, I had a bet with my office mate, Sean Carroll-- hello, Sean. Sean is a well-known cosmologist to this day.

And when we were graduate students in 1991, I bet him a bottle of very nice Port, that in 2011, 20 years from the day we made the bet, that we would not be able to measure the geometry of the universe, or omega, to better than 30%. And here we are, in 2014. It turns out even in 2011, at the time our bet, we could do it 30 times better than I was expecting. So I lost the bet. But Sean shared the Port with me, very nice of him.

PAUL FRANCIS: Oh, well.

One thing there's still a bit of controversy over is the value of Hubble constant, the expansion right now. Here's a variety of different recent measurements. So these are the measurements from different microwave backgrounds, satellites, and from Cepheids, and other things like that. And they are jumping around a bit. I mean the error bars all overlap.

BRIAN SCHMIDT: There is a little bit of a systematic error, where these are all measuring how fast the universe is expanding nearby. And these are using the cosmic microwave background to go through and take a model, where you take what's happening now and shrink it to a factor of 10 to the 9, more dense in the past, where you have these acoustic oscillations bouncing around.

And there seems to be a little bit of difference. It's not huge. We like to call this tension, which makes life interesting. It means we have something else to do.

I should say, for example, this measurement though, has already moved a little bit down since the time of this diagram. So that's resolved it a little bit. And there is some controversy, even between the Planck and the WMAP teams, we can talk about later on.

PAUL FRANCIS: But it's still amazing. No one believed 20 years ago that we could measure anything in cosmology to anything like these precisions. We truly live in an era of precision cosmology.

A4_L7_V08_Conclusions

BRIAN SCHMIDT: So here we are today with quite an amazing set of observations and a theory that all seems to more or less hang together. We have a universe that's 13.8 billion years old. We have a universe, which is 5% of atoms or baryons, and 70% dark energy, 25% dark matter. And when we use this theory to predict things, we're able to predict in advance every observation we've been able to make so far. So from my perspective, this is truly one of the great triumphs of science in living memory.

PAUL FRANCIS: From my point of view, whenever I hear something like great triumph of science and high precision, that sets off the alarm bells ringing in my mind, because the human race has been there on cosmology many times dating back to the ancient Egyptians. We thought we've got it all sussed, and we've been wrong over and over and over again. So let's explore a bit how solid this really is. I mean, even five years ago, it wouldn't have such a good consensus. It's very, very recent. It hasn't yet had time to survive lots and lots of tests.

So how solid is this? I mean if you're having a bad nightmare, what do you think could go wrong with this whole thing?

BRIAN SCHMIDT: Well, I think the big worry is ultimately scientists are people, and people are a herd animal, and we tend to follow the leader a little bit too much. And we've had problems in the past where, for example, if you look at the best value for the speed of light, it converged to the wrong answer. And then it switched when people realized there was a mistake. And so there is some worry, I guess, that maybe we all know what the answer is, and we all get the same answer, that we're not being quite careful enough as we should, because we are, as I said, we are human.

So if there's any problem, I think that's the one that worries me the most, because we do have a consensus of quite disparate methods that are coming to this rather crazy conclusion that 95% of the universe is stuff we don't really see here on Earth directly. And we have a very good measurement of the age of the universe, and all of that seems to hang together. So as I said, it's more one of whether or not we trust ourselves and whether or not we're being honest with ourselves about the measurements.

PAUL FRANCIS: But each one of these individual measurements, typically, doesn't give you an answer to the cosmological parameters. It just gives you some degenerate band. And you need multiple measures to cross over and mark the spot. Do we have enough independent measurements, because if you get just two things crossing at a spot, any two measurements will do that. It's like we're always told when doing cartography, you never just do two lines converging.

You do three so you get a sense of uncertainty. Do we have enough situations where there are three or four different independent measurements all agree to give us some confidence that we really have got a right answer? It's not just a coincidence of two things fitting together?

BRIAN SCHMIDT: Yeah. So if we look at, for example, that whole paradigm of having dark matter, dark energy in a sort of a 70/30 split with 5% baryons, to my mind, there's really four or five lines of evidence that go together. We have the supernovae that march out acceleration, and they give a confidence interval, which turns out you can sort of tell that it just doesn't fit a universe without a cosmological constant. But maybe they're wrong. OK.

Then you have the large scale structure of galaxies out there, and there's two different measurements you can make for those. The old style measurement, we just look at how they're spread across the sky, and that allows you to very accurately measure the matter density of the universe. And that gives you a constraint. The cosmic micro-- and then there's the baryonic acoustic oscillations, where we see that ruler, splash marks left over from the cosmic microwave background and big bang.

And that allows you to essentially reproduce the supernova measurements as a ruler moving out to the cosmic microwave background. Now quite remarkably, the supernovae and that ruler, due to baryonic acoustic oscillations, really agree very accurately. I mean as accurately as they should.

PAUL FRANCIS: Supernovae could be thrown out if you had some gray dust or something in the universe, but that wouldn't affect the ruler measurement. It's actually length as opposed to brightnesses.

BRIAN SCHMIDT: That's right. So that concordance is pretty strong, and I personally think you almost have to have someone cheating to make that go away. Finally, you have the cosmic microwave background, which sort of works with everything else to do a new set of constraints, which is ultimately that the universe is flat. And we're beginning to squeeze some more information out of that. All of these different constraints combine into one magic spot, which is the model we have.

So you really need to have a bunch of them or two of-- more than two of them be wrong at this point. And it's possible, but they're going to be wrong in a way that conspires, and to my mind, that would almost have to be human conspiracy, a frailty of humans deluding ourselves that we don't really know something as well as we do.

And I should say there's other things that fit in. We measured the Hubble constant as well, and that more or less fits in. We go through, and we measure things like the age of the oldest stars, and that's about the right answer as well. So is this at a-- it all fits together every way we can look at it. It seems too good to go away at this point.

PAUL FRANCIS: Now in some sense, this means you've got a lovely mathematical model. You've got a universe flattened out by inflation and dominated by dark matter and dark energy. But isn't this just kicking the can down the road, because we don't know what the field was that caused inflation. We don't know what dark matter is. We don't know what dark energy is. So all we've learned is there's something unknown that has a particular equation of state. Something else has a different equation of state. And something else unknown that must have a Mexican hat with just the right brim shape. So you've just pushed up one problem into another one, haven't we?

BRIAN SCHMIDT: Yeah. We have. And this is a particularly-- how do I say-- striking example of how we do that. But we do that all the time in science. When you talk about how a cell works, well, a cell is made up of atoms, and we break it down into a cell. Well, what's a cell? Well, we know what a cell looks like. But it's not a fundamental description of how human life works. Nothing is.

And indeed, I would argue there's probably not a fundamental description of anything that we do in science. So yes, we have dark matter, and we're not quite sure what it is. We have dark energy. We don't quite know what it is. We have something that caused inflation. We really don't know what that is. But we have those basic ideas in the same way we say that cells are made up of these things that behave in a certain way. We have combined things and essentially made a structure, which we give a name to, that has a certain level of behavior.

And so we can test that model, which yes, has a lot of missing information, and we can test it against predictions. And the quite remarkable thing is think of what that cosmic microwave background looks like. It has 17 little bumps that are exactly where they need to be. I mean that's like going through and saying, I have a model for Beethoven's brain, and you say, oh, I don't think so. And I say, well, my prediction is on this day in 1793, he would have done bum-bum-bum-bum, and if that happened, you would say, oh, geez. You're pretty good actually.

And so that's sort of where we're at. I promise you we haven't got everything perfectly right, but I think the big concept is right, because it's just too good at predicting things. And so it may well be 100 years from now, we don't call it dark matter, we don't call it dark energy--

PAUL FRANCIS: It has to behave in this way.

BRIAN SCHMIDT: But it has to behave in that way. And so we haven't thrown away Newton's laws of gravity now that we have Einsteinian gravity. We know they're not really correct. We have a different way of thinking about it, but they're still relevant. So I think what we've talked about is still going to be relevant now and, quite frankly, into the distant future.

A4_L8_V01_Time_Arrow

PAUL FRANCIS: So we seem to have a pretty good model of the whole universe here. It fits all the data quite nicely. Is there anything missing though?

BRIAN SCHMIDT: Well, Paul, the one thing that's bugging me is it seems to me that everything we've talked about, you should be able to make it all happen in reverse of the same way that things are going forward. So it seems to me that we're missing something about the fact that the universe marches forward. That is, the arrow of time goes one direction towards the future.

PAUL FRANCIS: Yes, all the laws of physics we've got here are reversible. You run them in reverse. We can actually look at the universe around us. I've run some clips backwards. You don't see this happening very often. Water turning into ice cubes. A ball spontaneously jumping off the table.

BRIAN SCHMIDT: They're useful.

PAUL FRANCIS: Yeah. People being flung out of the swimming pool onto diving boards by the water. So what's going on here? This is a situation where if you play it in reverse it looks silly?

BRIAN SCHMIDT: Yeah. So clearly we have an arrow of time in physical laws, so I think maybe we need to think a little bit about this more deeply.

PAUL FRANCIS: Now as you probably know, this is thought to come from the second law of thermodynamics from the concept of entropy, and entropy is loosely described as chaos, and so in popular culture, entropy is supposed to be turning order into chaos. Things fall apart. Disintegration happens.

BRIAN SCHMIDT: Yeah. I think one person's chaos is another person's order possibly. So if we think about this in a little more detail, is this order, does the cosmic microwave background order or chaos compared to, for example, the modern universe?

PAUL FRANCIS: I mean it seems a bit of a paradox. If you take the popular version of turning order into chaos, our universe almost seems to be going in reverse. We started from just a random wilderness of gas molecules heading in random directions, and that then turned into highly structured things like galaxies and stars and nebulae. Much less uniform, much more structured than it was to begin with, and then these in turn turned via solar system formation, evolution into life forms such as this. Highly sophisticated.

BRIAN SCHMIDT: So did we pick the queen as chaos, or do we think she is very refined and orderly?

PAUL FRANCIS: So this section, we're going to be talking about the arrow of time, and does the universe actually bucket? Are we going from chaos into order in contradiction to this? Is there something different in cosmology from the normal day to day life, or is there actually some way in which this is far more chaotic than a random microwave background?

And to start off with, let's deal with the simplest case of entropy, which is heat equalization. This is the classic example of this. Let's say you have two metal blocks, and one is hot, and one is cold. And you put them next to each other in the vacuum, so they're not exchanging any heat with anywhere else. What would happen?

BRIAN SCHMIDT: Well, it's pretty clear. I think we all know that the hot block and the cold block are going to become the same temperature. More or less, the same temperature if they're made out of the same material.

PAUL FRANCIS: Yes. So the heat will move from the hot one to the cold one until they end up at the same temperature, whereas if you put two equal temperature blocks together, you'll never get heat sucked out of one into the to make one uneven. So this is the simplest example of an arrow of time. So let's see if we can actually understand what causes this.

So to understand this heat equalization, we have to understand what heat is. So in a solid is a model of atoms in a solid, and you've got the atoms, and the orange strings are like the chemical bonds that hold them together. In this case, it's a nice rectangular crystal lattice, but the same thing applies to other sorts of crystal in other shapes. And what heat is is just the energy of motion. In fact, the heat energy is roughly half from the kinetic energy in the particles and a half from the potential energy in the springs.

BRIAN SCHMIDT: Right. So everything is vibrating around here and sort of being held together by the motion compared to everything else. And if we were to heat this material up, it would start moving more and more, and we'd get more and more bouncing.

PAUL FRANCIS: Yes. So the model we're going to use is another one of Einstein's models. That guy gets everywhere. And the idea here is that we'll treat an atom as being in a box. So we'll ignore the collective motions on things, and just treat it as being able to oscillate in three axes. So it can go x-axis, y-axis, and z-axis. And that's too simple a moral. It would, for example, preclude sound waves moving through things. But this model will get us a long way. Just treat every atom as being independent.

So what this means is in each axis, it's going to behave like what we call a harmonic oscillator. You may have done simple harmonic motion school of physics. And it's like a single atom, something on a spring sliding backwards and forwards. And for something like this, you could do the potential energy, which is the energy in the chemical bonds of the springs, against position. And it has lowest energy when it says equilibrium position, but you can move it away from there. But you have to push to do it, put energy in.

And what would normally work in the classical picture is that you have an atom up here, lot of potential energy. It'll start moving down towards the bottom. Potential energy will go down, but therefore kinetic energy will just go up, so it'll start moving faster. So down here--

the kinetic energy will have to be up here to balance it out, so the energy will remain constant, so it turns into kinetic energy. But it will run up the other side and turn back into potential energy. And so it oscillates backwards and forwards. Potential to kinetic, potential to kinetic, and so on.

BRIAN SCHMIDT: So if you do bungee jumping, more or less, you're going to be moving down here. This is when you're jumping off things. It's also the same effect of a clock when you have a pendulum and stuff. It can be described in this same way.

PAUL FRANCIS: That's the classical picture, but we have to look at the quantum mechanical picture here. Now we talked about this in the violent universe course at some length. But to summarise briefly, that atom's actually a probability wave, a quantum mechanic wave, much like a violin string, or a sound wave trapped in an organ pipe. And it has to have a node, a 0 at both ends, and it means you can only oscillate in certain frequencies.

You have one frequency, which is the fundamental, which is where you just go up in the middle and down. You can have the next harmonic, which goes two wiggles, and you can have three, four, five, and so on wiggles. And the more wiggles you have, the more energy your particle has. So in quantum mechanics, instead of being able to have any energy up here, it can only have discrete energy-- this one, this one, this one, this one. It turns out for harmonic oscillator, they're actually equally spaced.

BRIAN SCHMIDT: Very convenient.

PAUL FRANCIS: So you have one quantum, two quanta, three quanta, but you can't have one and a half or two and 1/2 quanta. It's all fixed. And for normal pendulum or bungee jumping, the same thing applies, but these quanta are so close together you'd never even possibly conceivably notice. But when you're talking about a single atom, these things are actually fond of a part that makes a real difference.

A4_L8_V02_Oscillators

PAUL FRANCIS: Now, let's imagine we have an atom, and it has basically three oscillators, one for each axis of motion. And let's say we give it 4 quanta of energy.

BRIAN SCHMIDT: So the four is arbitrary here, but we've got to start somewhere.

PAUL FRANCIS: So let's say arbitrarily we do four. It's small enough we can count them all. So we've got the three oscillators, x, y, and z. And how can we put them? How many ways can we put 4 quanta in there?

BRIAN SCHMIDT: Wow, OK. So we just need to start counting. So should we start with the x there, Paul?

PAUL FRANCIS: Yes, so we could put four quanta here and have these two at the ground state. So in that case, it will be moving enormously along the x-axis, but not along the y or the z.

BRIAN SCHMIDT: So that's one.

PAUL FRANCIS: That's one possibility. Or we could put the quanta in y.

BRIAN SCHMIDT: And one can imagine we can do it all in z as well. Yes?

PAUL FRANCIS: Indeed. So that's given us three possibilities. But is that all?

BRIAN SCHMIDT: Eh, well that we can start splitting it. So maybe we'll do only part of it in x.

PAUL FRANCIS: Yes, so let's say you have 3 in x, 1 in y, 0 in z. And then we can run the changes on that, 3, 0, 1. Put the here 1, 0. And so more possibilities now. This actually gave us six possibilities to add to it. So it went up to nine ways we could do it. But there's even more.

BRIAN SCHMIDT: Yes, there are. So go down.

PAUL FRANCIS: 2, 2, and 0, 2, 1, and 1, and so on and so on and count them all out. And we've ended up with 15 different ways in which we can distribute 4 quanta in one atom between three directions of motion.

BRIAN SCHMIDT: Yep. And you can go through and count through them all yourself, although we've got the cheat sheet here for you.

PAUL FRANCIS: Now, in-- we're now talking about the subject called statistical thermodynamics. The total amount of energy, which in this case is 4 quanta, is called the macro state. And the micro state is the different ways you can distribute those quanta. So in this case, these are the micro states. So we have 1 macro state, 4 quanta, and in this case, 15 micro states.

BRIAN SCHMIDT: Right. So in this case, you can imagine you have a certain amount of energy, which is the 4 quanta, and you want to figure out how many different ways can our object express that energy? And it turns out 15 under this circumstance. So OK, good.

PAUL FRANCIS: OK. Now, the fundamental assumption we're going to make here is if you do have an atom, it will constantly be changing micro state. It probably wouldn't happen if this was a single atom by itself, but you've got to imagine this atom is one in a vast collection of other ones. It's going to be bumping off other ones.

And in this whole chaos of things, bumping off other ones and vibrating, moving around, it's going to switch micro states. And the fundamental assumption we're going to make is that in this whole chaotic process of thermal motions, that all micro states are equally likely, and it moves between them at random all the time.

So that actually gives us enough to work at what happens in a situation like two blocks put together. Let's imagine we've got-- instead of two blocks, we've just got two atoms. Each of it translating the three directions before, and once again we've got 4 quanta. But now we can share those 4 quanta between the two atoms.

BRIAN SCHMIDT: Ah. So we have the same amount of energy, going to be shared in two atoms so there's going to be a lot more states in this case. Many, many different ways to share that 4 quanta worth of energy.

PAUL FRANCIS: So it might be like a molecule where the two are actually bound together, so the energy could go from one to the other. And once again, we're going to assume that the energy can-- all the different micro states, as long as they have the same total amount of energy, i.e., 4 quanta all up, all different micro states, for example, all the energy in one, all the energy in the other, are equally likely. So once again, we can add it up. So we could have, for example, all 4 quanta over in this atom and none over there. So I've got all the energy, and you've got nothing.

BRIAN SCHMIDT: So we've already figured out that's 15.

PAUL FRANCIS: Yeah. Or you can have all the energy and I could have none, which is down at the bottom.

BRIAN SCHMIDT: That's another 15.

PAUL FRANCIS: Yeah. So this in this case, there's 15 possible states for me, but only one state for you, everything in the ground. Whereas the other way around, it would be 15 for you and only one for me. But we could also work it out-- let's say we had three. You could add up the total number of possibilities for distributing three, just like we did for four. And it turns out there are 10 of them. And you've now got 1 quantum. So it's pretty easy. You've got three sets.

BRIAN SCHMIDT: I've got three different places I could put mine, yep.

PAUL FRANCIS: So the total number of states-- and there are 10 possibilities for me and three for you. So you have to multiply them together. So for each of my states, you could have each of your three states. So 10 times 3 is 30. And now we go down to two each. And the number of possibilities for here turns out to be six. You can count them yourself, you don't believe that. And you've also got six possibilities.

BRIAN SCHMIDT: And I've got six as well.

PAUL FRANCIS: But that means we've actually got 36 between us.

BRIAN SCHMIDT: So that's the one that gives us the most possibilities, OK.

PAUL FRANCIS: And symmetrically down here.

BRIAN SCHMIDT: Symmetrically down the other direction. And as we add all those up, we get 126.

PAUL FRANCIS: Yes. And you could do a histogram. You can see that the number of micro states for all the different cases is most if I have two and you have two.

BRIAN SCHMIDT: So it's most likely that we share the energy, but it's not guaranteed.

PAUL FRANCIS: No. So we're beginning to get some clue of how we can understand physically the fact that the heat tends to equilibrate. We're assuming that none of the micro states is more possible than any of the others. It's just that there are more micro states when we have equal amounts of energy. So I've lost more chances. You've gained more chances. I've dropped the number of things. But prior to the two when you multiply them together is most, and we've got about the same.

BRIAN SCHMIDT: So if I were to go through and take a block, which happened to be one atom, and another block that happened to be one atom, and I put a small amount of energy in between them, then it's quite likely they'll end up at the same temperature. But under this state, because of quantum mechanic having a lot of uncertainty, it's not actually guaranteed. But of course, our blocks typically are made of more than one atom.

PAUL FRANCIS: Indeed. So let's try and work out what we'd do if you had lots of atoms.

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BRIAN: All right, Paul, so we're going to have blocks that we want to look at that have more than one atom. So that means we're going to have to do this for n atoms. Now, I'm thinking counting states. What, are we already at 126 with two atoms? This is going to get a little tedious. So there must be a little mathematical trick that we can use to count our states.

PAUL: And indeed there is, using probability theory. It's a classic probability problem. You may have done it, some permutations and combinations at school-- this situation of trying to take colored balls out of the sack.

So let's say we have the sack and it contains 5 balls, and they're all numbered. And number 1 and 2 are blue, and 3, 4 and 5, orange. Now if you don't see the relevance to this to thermodynamics, hold with us.

BRIAN: Yes.

PAUL: It will come. Let's say it's a lottery or something like this. You take all little balls out of the bag and put them in a row. How many different rows are you going to get?

BRIAN: OK. So let's take the first ball out.

PAUL: Yep.

BRIAN: So there's 1 of 5. I got 5 balls in the bag. I got 5 possibilities then.

PAUL: OK, and then you get the second one out.

BRIAN: And then I take the second ball out. There's only 4 there now, so there's going to be 4 possibilities, and then 3, then 2, then 1. So I'm going to have to multiply those all together.

PAUL: So it's 5 times 4, times 3, times 2, times 1-- that's known as the 5 factorials. An exclamation mark afterwards indicates that you're just multiplying all the integers up to there together.

BRIAN: Yes.

PAUL: And that comes out as 120. So there's 120 different combinations you can draw out of that. But let's say we now rub the numbers off the balls. So we don't actually care whether blue ball number 1 came out first, or blue ball number 2 came out-- all we care was it was a blue ball.

BRIAN: OK.

PAUL: So we no longer care which order the red ball's in, or the blue one's-- we just care about how many sequences of red and blue you're going to get. So for example, 4, 2, 1, 3 and 4, 1, 2, 3 will be the same, as far as we're concerned. Because it's just a blue ball-- it doesn't matter which way around they are.

BRIAN: Right. So we're going to group into groups of 2 and 3.

PAUL: Yep.

BRIAN: That is, 2 balls, 3 red balls, and there's 5 in total. So we're going to count how many come out this way. And so we're going to have to figure out the fact that out of the 120 total permutations up here, how many combinations have the blue and the reds coming out individually?

PAUL: So what we can do is-- we know there are 120 total possibilities-- but we can divide that through by how many look the same to us. So for example, we've got for each combination that are going to be, there could be one with a blue ball first and the other blue ball second-- so blue ball 1 and 2. So we have all different ways we could arrange 2 balls, which is just 2 factorial. In this case, it's just 2-- 1 times 2, and so we can divide by that.

And also, we've got the 3 red balls, and there are various ways we can arrange them. So it could be 3, 4, 5 or 5, 3, 4 and so on. And we look at how many different possibilities, the way of arranging the red balls, and again divide by that which just gives us 3 factorial, which is 3 times 2, which is 6. And so we're dividing by 2 factorial by 3 factorial and that gives us 10.

BRIAN: So that's a clever little way of doing this. So how is this going to fit into our quantum states, Paul?

PAUL: Well it turns out, very easily. So the idea is let's say we're going to arrange q quanta among n oscillators. So it could be-- so far we're beginning with 4 quanta amongst 3 oscillators. So that's 1 atom-- it would be 4 quanta amongst 3 oscillators. So what we can think of as being like our blue and our red balls are the quanta and the boundaries.

BRIAN: OK.

PAUL: So in this case you got three places-- you got a boundary here and a boundary there. So if you got n oscillators, you got n minus 1 boundaries between them. So what you could do is just imagine you've got a bag containing boundaries and quanta, and you pull them out in some random order. In this case, there are 4 in the first one, so you pick out all 4 quanta first. And then we have the two boundaries-- we've got quantum, quantum, quantum, quantum, boundary, boundary.

BRIAN: OK.

PAUL: So that's one possibility. Let's say we had 1, 2 and 1, and now you've drawn out a quantum, boundary, quantum, quantum, boundary, quantum.

BRIAN: OK.

PAUL: And something like this would be quantum, quantum, boundary, boundary, quantum, quantum.

BRIAN: Yep.

PAUL: So you're basically just taking your quanta and boundaries-- it's just like red and blue balls. You don't care which boundary is where. You don't care which quantum is where, because all quanta are indistinguishable from each other. So it's exactly the same situation we just talked about, which is if you've got q quanta and n oscillators it means n minus 1 boundaries. The total number of micro states is going to be q plus n minus 1, so that's the total number of all the things you're permuting factorial.

BRIAN: Right.

PAUL: Divided by-- we don't care which order the quanta are in and we don't care which order the boundaries are in, so we divide it by these factorials.

BRIAN: OK. So as you said, it's exactly analogous to the red and blue balls. It's just that this is 1 collection of things we care about. That's the other collection of things we care about. And their combination, their addition to the other, is the total number of possibilities. So it's exactly analogous.

PAUL: OK, so let's see what's some numbers we get from this. So instead of having one atom, let's have about the smallest particle you could ever manufacture-- a nano particle with 100 atoms, which are still vastly smaller than anything we're going to deal with in the real world, by and large, and if you work on nano fabrication. So this means it's got 300 oscillators, because each atom can vibrate in each of three directions.

BRIAN: Yep.

PAUL: So how many ways can you distribute 100 quanta of energy here?

BRIAN: Wow. OK. So if we just plug and chug with our formula--

PAUL: So we've got 100 quanta. You've got 300 oscillators. So it's 300 minus 1 boundaries, so 299 boundaries. So you've actually got 399 factorial divided by-- we don't care which order the quanta are in, so divide by 100 factorial. We don't care which order the boundaries are in, so divide by 299 factorial, and that comes out as a few by 10 to the 96.

BRIAN: Don't try this on your calculator at home. My calculator is not going to like taking 399 factorial.

PAUL: Indeed. In fact, it's like you need a whole new system of numbers to deal with that But you could work this out, go on to Mathematica or something like that. I'm sure Wolfram Alpha could do this for you.

BRIAN: So there's a huge number of ways of distributing that energy amongst those atoms.

PAUL: So let's ask, for example, what are the odds that all 100 quanta are in one of the atoms.

BRIAN: OK.

PAUL: So in this case you could work out how many microstates, 1 atom. See, now I've got 3 oscillators, so 2 boundaries and 100 quanta. And there's quite a lot of ways you can arrange those. It's actually about 5 by 10 to the 5 possible ways to arrange 100 quanta in 1 atom.

BRIAN: Right.

PAUL: But that's still an awful lot less than the 10 to the 96.

BRIAN: Yeah, so it's 500,000 chances out of 10 to the 96 possibilities.

PAUL: So you're about 10 to the minus 90.

BRIAN: 10 to the minus 90? That's like less than the number of atoms in the universe.

PAUL: Drastically less.

BRIAN: Yeah. So that is very unlikely-- not impossible, but you wouldn't want to be waiting up for it, that's for sure.

PAUL: So we could apply the same thing to the situation when we have, say, 2 blocks. Let's make them different size-- so one's, say, 2/3 the size of the other.

BRIAN: Yep.

PAUL: So let's say we've got 300 oscillators here and 200 oscillators there. So about 100 atoms and about 67 atoms, and we've got a total of 100 quanta distributed between these two. Once again, we can do the sums.

Let's say you have all 100 here and none there, 99 here, 1 there, and so on. And for each of them you can use the equation we've just worked out to work out the total number of microstates and multiply them together. And what you find is this distribution of the number of quanta in the bigger block, and it averages out at about 2/3.

BRIAN: Well, it's, 60 out of-- 60% which is, since we've done 300 out of 500 which is 60%, it does exactly on average exactly what you'd expect-- it gets 60% of the energy.

PAUL: And there's some range. But for example, being down here or up there, all the energy in one or the other, is 10 to the 114-- in this case, unlikely. It's still possible. There are stints where all the energy is here and here. But odds are you're 1 in 10 to the 114, which is not good odds.

BRIAN: But on the other hand, it is quite interesting that if you were going to make a precision thermometer, which effectively is a way of measuring the energy of something, you're going to want to use something bigger than 100 atoms. Because you see that there is a reasonable chance to move around by even 10% in the system. So 100 atoms does jiggle around due to this quantum mechanical effect already.

PAUL: But if you now go to, say, 1,000 oscillators of each, then it's starting to get very narrow.

BRIAN: Yes.

PAUL: And then 10,000, 100,000-- you're now up to the 10 to the 1,000, 170 up there.

BRIAN: Right. So that's a very large number of ways. And you can imagine that 1,000 atoms, of course, is a tiny little block. Any respectable block is going to have 10 to the 26 or something atoms in it.

PAUL: So you're talking about 10 to 26 factorial, which I think even Wolfram Alpha would have trouble with.

BRIAN: Yes.

PAUL: And I'm not sure how you could even write that down in any sensible notation.

So in principle, you could have two blocks that all the heat goes into one or the other, but the odds against it are in the factorial of 10 to the 23, or something like that. So do you call that yes there is a chance, or do you call it no? I mean, yes, there is a chance. But when the chance is that small, in some ways no is actually the more honest answer.

BRIAN: Yeah, I have to admit, Paul, in life, my rule of thumb is if the chances are less than being struck by lightning on a given day, then I say it just doesn't happen. That's the way I do it.

PAUL: And this makes being struck by lightning look like most common thing in the universe.

BRIAN: Exactly.

A4_L8_V04_Entropy

PAUL FRANCIS: So we've seen that if we make the assumption that every atom has its possible states, and because they're all in some sort of mixture of the two blocks together, atoms are constantly bumping into one another and exchanging quanta. And the quanta are equally likely to be at any micro state. And all these micro states have the same total energy. And so any of them are equally likely. You might think this would lead to total anything goes, but in practice if you add up the total number of possible states to any realistic number of atoms, it's going to drive you very rapidly to thermal equilibrium, everything being at the same temperature.

So is this the explanation for the arrow of time? Let's see if it can actually explain what's going on. We should mention this is actually the definition of entropy. Entropy is defined as a constant designed to fit with a macroscopic model times the natural log of the number of micro states.

BRIAN SCHMIDT: OK. So we have a model here for entropy, and as a mathematical way of describing it. So one could imagine, as you get more and more micro states, then the entropy rises. This coefficient in front that gives it a unit that we're going to be able to compare to energy, for example, later on.

PAUL FRANCIS: Yeah. So what this is telling us is that it will tend to move into the situation with the most micro states, not because those micro states are any more common than any other micro state, just because there are so many of them that if you are randomly moving between all the micro states, which is our key assumption here. So that really is random thermal motion, those things jiggling backwards and forwards. You are going to end up most likely in a state with a lot of micro states rather than a state with very few micro states. And that's going to be the state with the maximum entropy. So this is the second law of thermodynamics. Entropy always goes up and plateaus in the maximum state.

BRIAN SCHMIDT: OK, so let's think about how this helps our arrow of time.

PAUL FRANCIS: Well, if you take the first situation, the ice melting, it's all pretty straightforward. This is just what we've been talking about. You've got water and ice, and the energy initially was mostly in the water and went into the ice until it equalized out. But how about the second situation, the ball? So a ball sitting on a table and suddenly flings itself upwards. Why does that happen? Well, again, you could look at what happens in the reverse process. I take a ball, and I drop it. So as the ball's flying downwards, the table atoms are going to be randomly moving all over the place.

BRIAN SCHMIDT: A little thermal motion. The ball hits it.

PAUL FRANCIS: The thermal energy in a table is enormous. I do this calculation with my first year physics students. You take a cricket ball, and you fast bowl it. You work out the kinetic energy of the world's fastest bowler compared to the energy gain you get by putting the ball in your pocket for a few minutes so it warms up by 1 degree.

And it turns out the energy of warming up a cricket ball by 1 degree in your pocket dwarfs the energy you get from the world's fastest fast bowler. The random energies of the atoms moving around in a ball just sitting on the table are much bigger than anything you can throw it at. So there's actually huge amounts of energy in the table. So the ball lands on it, and when it lands, it's going to briefly depress the table underneath it. And so you're going to get a very ordered velocity field.

BRIAN SCHMIDT: Right. So ordered velocity field, yes?

PAUL FRANCIS: But then as it sits there, maybe bounce a couple of times, and then comes to a rest, it's going to go back to being random. That energy you've imparted has ended up as warming up very slightly the table.

BRIAN SCHMIDT: Yes. So you've increased the random motions a little bit, but then those motions are random.

PAUL FRANCIS: Yeah. So you've got to look at all the possible micro states here, which is for each atom, it could be moving in any direction. So you've got x, y, and z. And because they're moving in any direction, it's all random. In principle, there is a micro state that looks something like this, where while the atom is far away from the ball and moving all over the place, the ones underneath are all pointing upwards. This would be like-- let's say that's a z axis. It would be all these things have all their quanta in the plus z direction, as opposed to the x's and y's.

BRIAN SCHMIDT: And this would be a state that would cause the ball to suddenly leave the table and go into your hand very conveniently.

PAUL FRANCIS: Yes. But of course, you can once again count all the possible states and ask what fraction of them would result in a ball jumping out. And so you can do a sort of Venn diagram. So you've got all the possible configurations, and the ones that will result in the ball leaping off the table. And that's going to be a very, very, very small fraction of the total.

BRIAN SCHMIDT: Probably a number like 10 to the 1,000 to the 1,000 to the 1,000, or some huge number. Very unlikely.

PAUL FRANCIS: So it's actually exactly the same thing. What we've got is a whole bunch of states, and they're all equally likely. So in fact, of all the micro states, the ones that fling the ball into the air are just as likely as a state over here or a state anywhere else. It's just there aren't very many states that were aligned. There are an awful lot where the ball just sits on the table.

So just like we're talking about temperature moving between two blocks, the state with all the energy in one block is just as likely as any other state. It's just there aren't very many states like that. Whereas there's an awful lot more states with energy distributed. And by awful lot more, we're not talking about 10 times more. We're talking about 10 to the 100 to 100 to 100 to 100 more, so much so that this basically never happens. Indeed, I've never yet seen a ball fling itself off the desk.

BRIAN SCHMIDT: And it's just as well. I think the universe is random enough as is without having the ability to have crazy things happen.

PAUL FRANCIS: And the same thing would apply for someone coming out of a swimming pool. In principle, when someone dives into a swimming pool, they initially would produce ordered motions of the water. So now you've got to imagine each little bit of water, which way is it moving. But those things break up into eddies and swirls, so they're called Kolmogorov cascade. And ends up just warming up the pool slightly.

And in principle, you could be swimming along in a swimming pool suddenly when all the atoms near you happen to have large z velocities and fling you randomly out to a nearby diving board. But once again, thankfully, the odds of that are extraordinarily unlikely. OK, so this is kind of making sense.

So does this is actually apply to everyday environments, like your messy rooms or civil wars? People often talk about countries falling apart or teenage bedrooms getting messy. This is actually not by teenagers. This is my own study. So I can't blame anyone else for this one. Can we actually apply this whole principle of micro states and counting them at entropy to situations like this?

BRIAN SCHMIDT: Well, it's not completely clear. So let's just think what we have here in this room. We have a lot of books. And so let's just only worry about the books at this point. And you'll note that the books actually show a fair bit of order. They're all on the shelves. They're not just randomly strewn on the floor.

PAUL FRANCIS: If you look closer up, you'd find, for example, this row here's all the Agatha Christie's, for example. Science fiction's over there.

BRIAN SCHMIDT: I have a row of Agatha Christie's as well, yeah. So OK. So if you think about the total number of states, for example, where all the Agatha Christie's are down there, that's a very small number of states compared to all ways the books can be configured.

PAUL FRANCIS: If you have a number, n, of books, and all the possible ways in which they can be arranged, then maybe you've got some boundaries that might correspond to the edges of the shelves. Then we could do the same calculation. And of all the possible states, the vast majority would be chaotic. The fraction of states which you'd go in and say this is ordered-- all the Agatha Christie's are together, all the Jane Austen's are together, and so on-- that should be a very tiny fraction of the overall total possible number of states. So this kind of works.

BRIAN SCHMIDT: Well, it sort of does, except for of course this room finds itself in a state of relative order, where you're in a very unusual state. If you think about what you might expect, you wouldn't expect to find all the Agatha Christie's. That's a very improbable act if it was just random.

PAUL FRANCIS: So we've got one part of the whole entropy argument, which is a whole bunch of states. And the chaotic ones vastly outnumber the ordered ones. But the second assumption we need to make this work is that you're equally likely to move between any state. So if, for example, every time we took a book out to read, we just, instead of putting it back on the shelf, just threw it randomly into the room or put it back at random with a blindfold on, that would maybe approximate the situation that we've talked about in thermodynamics, where the thing is. Or if, at night, the book pixies came up and randomly moved things around, in that situation, then yes, you'd never have a tidy room. It would rapidly develop entropy. But that's not really a good approximation in this case.

BRIAN SCHMIDT: Yeah. I mean, the best approximation is what happens after you and I are gone a million years, what this bookshelf looks like in a million years. Then that's going to start looking, I bet you, a bit more random.

PAUL FRANCIS: Indeed. OK, so for thermodynamic situations, this all works pretty well. It explains why balls don't jump off tables. It explains why ice cubes don't unmelt out of water. It explains why you don't get flung out of a swimming pool. So it's giving us the arrow of time. It's not at all clear that it explains why teenagers' bedrooms are so messy or why countries fall apart.

Because they're certainly true that the micro state part of the argument works just fine, but are they equally likely to move between them? Not so clear in that situation. The things that cause, say, a country or a room to move between micro states is not really a random process.

But how about the universe as a whole? Now we've talked about temperature being uniform, being a high entropy state, and temperature being ununiform, being a low entropy state. So it tends to go from ununiform to uniform. But the universe has gone the other way. It was incredibly uniform at the microwave background era, and now the difference in temperature from one place to another is enormous. So isn't that violating things?

And also talk about life forms like ourselves. We maintain a temperature that's different from around us. We are highly ordered. Yet we probably came out of things in some sort of stagnant pool, which was not highly ordered. So yes, we have this arrow of time. It all works nicely, kind of. But how could we explain things like that?

BRIAN SCHMIDT: Sounds like maybe we need to bring in an expert.

PAUL FRANCIS: OK. So we have here at ANU Dr. Charley Lineweaver, who is a expert who's spent a lot of time thinking about this. So let's see what he has to say about this all.

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PAUL FRANCIS: So we've seen that this concept of entropy explains the arrow of time. The idea is the system would will generally move to a situation with lots of micro states rather than one with only a few. It can go the other way, but generally, the odds are in something like 10 to the 1,000 against it happening. And this explains all sorts of things.

However, as we mentioned earlier, that seems to give us a bit of a paradox. This law that entropy always increases statistically, which is also called the second law of thermodynamics, says for example, if you have a hot object and put it next to a cold object, what would happen is the heat will flow from the hot object into the cold object until the temperatures even out. But that's exactly the opposite of what we see in the universe. As we described earlier, we start off with a microwave background, which is extremely uniform. But now there are immense differences in temperature.

So to help us understand this paradox, it's a great pleasure to have Charley Lineweaver here, one of my colleagues here at ANU, who has thought long and hard about this. So Charley, is this a paradox? Does it violate the second law of thermodynamics? What's happening with entropy here?

CHARLEY LINEWEAVER: Well, I think the arrow of time to understand it, you need to start out with a low entropy situation and go to a higher entropy. For example, I have a cup of very hot water here. It's too hot to drink. And it's cooling down because the room is colder.

So if we start out-- as you pointed out, the microwave background is the same temperature, isothermal, to about a few parts in 10 to the-- about minus-- 10 to the 5. So it's very, very, very equilibrium. It's at equilibrium.

And not only that, it's also in chemical equilibrium. And also remember it's the material at that time was also very spread out. There were no stars, no planets, no galaxies. The matter hadn't congealed, hadn't collapsed on itself. So it's very smooth in many, many ways. And that's why we say, oh, it's at equilibrium.

And then you asked the question, well, how did it get out of equilibrium? The answer to that question I think is simple, but it's complicated because we don't understand it very well. But let me try to give you a simple example.

Lawrence Krauss talked to you about inflation. This is a little add on we have in the very beginning of the Hot Big Bang model. And this add on says something like vacuum energy, false vacuum energy-- there's a lot of energy in the vacuum. Just like if you have a pendulum and you hold it up and you hold it up here it's got a lot of energy and then you let it down, and it turns into kinetic energy. Similarly, in the very early universe, we think that the vacuum was full of potential energy. It's called the potential energy of the inflaton.

PAUL FRANCIS: Yes, this is the Mexican hat potential we talked about, being up at the top.

CHARLEY LINEWEAVER: It could be many different shapes. That's one that's very popular. But the point is that we think that there during inflation, we go through a point where we convert that potential energy into real energy, into matter, you and me for example. So how much matter gets dumped into the universe depends on how much potential energy there is, just like how much kinetic energy you get out of the swing depends on how high you hold the swing.

So we think of the early universe as evenly distributed matter. Remember, this vacuum energy is unclumpable. Therefore, when it dumps into the real universe, it will not be clumped. It will be homogeneously distributed. And that's the key.

When you say, well, wait a minute, if it's homogeneously distributed, is that high entropy or low entropy? And the weird part now is that we think that is the lowest entropy you can do with matter. And then you'll say, well, wait a minute. If I have a perfume bottle here and all the perfume is in the bottle, and I let it out, then joo-joo-joo-joo-joo, it will spread out and the even distribution of the perfume molecules will be highest entropy.

And now Charley comes along and says, the even distribution of matter is the lowest entropy. And the reason that those two are different is because the perfume molecules and the diffusion is controlled by kinetic energy and the homogeneously distributed matter is controlled by gravity.

For example, if you take that perfume bottle and make it a trillion, trillion times bigger and put it in an empty space, molecules will not go like that. They will stay there because it will be gravitationally dominated. The same reason why we have our atmosphere in the Earth is held on to the Earth by the gravitational force of the Earth.

So what I'm saying is that the initial conditions, whether they're high entropy or low entropy, depends on whether you're kinetic energy dominated or gravitational energy dominated. The early universe is gravitationally dominated. Therefore, it's low entropy despite the fact that the photons that we measure are at isothermal conditions and therefore, at equilibrium.

PAUL FRANCIS: So just-- we talked about earlier in the course how structures form. You get these very small primordial fluctuations left behind by quantum mechanics and the era of inflation, which then by gravitational instability get bigger and bigger. So we understand the mechanism--

CHARLEY LINEWEAVER: The important point about that is that it's homogeneously distributed. Very, very few overdensities. The tiny, tiny overdensities. 10 to the minus 5 overdensity. That's essentially very smooth.

PAUL FRANCIS: Yes. So does that actually mean that the second law of thermodynamics just doesn't apply in this situation?

CHARLEY LINEWEAVER: No, no.

PAUL FRANCIS: Or do you define some new form of entropy?

CHARLEY LINEWEAVER: No, that's right. Right. We have to define a new form of entropy. And now I should give you a caveat. We don't understand how to write a formula that says, here's the entropy as a function of how collapsed matter is.

That's something that's a new field. We're not sure how to write this down. A few people have made some conjectures, like Penrose, about the Weyl conjecture. I won't go into that. But the point is that in gravity, because it has negative heat capacity, it's just the reverse of what we're used to. That's why you don't find gravity in thermodynamics books.

You look under gravity in the index, you will not find it. Hundreds and hundreds of books on thermodynamics have been written about-- well, written about thermodynamics, but gravity is not included. If you're going to talk about the entropy of the universe, you have to include gravity. And that means you're going to reverse the sign of the entropy that you're used to.

For example, what I'm saying is that when the matter is evenly distributed, that's the lowest entropy state. When matter has collapsed into a black hole, that's the maximum entropy state with one caveat that this thing is going to evaporate into massless particles that then spread out everywhere.

PAUL FRANCIS: Thank you.

A4_L8_V06_Charley_2

PAUL: So Charlie, you've said that the explanation for how the universe seemingly violates the second law of thermodynamics is there is-- we have to deal with gravity in a different way. That gravity, you have to reverse the side, and make everything work differently, and no one's quite clear on how this works, but there seems to be something going on there.

But how about the second paradox? Let's say that, we assume all has worked somehow, and we've got things on Earth, and somewhere four billion years ago, we had some little stagnant pool or some clay molecules, whatever it might be. And somehow after that, something that was capable of reproducing itself was produced by some random chemical reaction, and it had babies, and they had babies, and after four billion years of evolution, we end up with the pinnacle of evolution, such as ourselves.

Doesn't that also-- I mean there's no gravity really going on here, but does this also violate the increase of entropy if we're going from apparently very disordered stuff or some sort of stagnant pool to highly ordered organisms such as ourselves and our viewers here? And gravity won't get us out of this one.

CHARLIE: No. Gravity won't, but this is only an apparent violation. But instead of talking-- before we talk about evolution, let's just talk about you sitting here. You had breakfast this morning, and I haven't had my lunch, and this is what I'll be eating for lunch. And these are essentially carbohydrates, and I'm breathing oxygen. And essentially, I will extract the chemical energy here. I will burn it inside of me by breathing oxygen, and then putting out CO_2. So I'm a factory that's burning stuff, right? So to stay alive, I have to put in low entropy material into my body, and essentially have electrons falling deeper into potential wells, and I get that energy out, and that's what helps me to talk, and think, and reply to you.

So right now, neither you nor I or any life form on this planet is violating the second law. For example, here's a nice piece of thing. It's very well-organized. But what these green things are, they're chloroplast in there. They accept the light from the sun, and then they use that energy to organize themselves, just like I'm using this energy to organize myself to produce ATP, so I'm making my hand go up and down, and my vocal cords go like this. So no life form violates the second law like that.

But now let's talk about evolution. So, well, let me bridge those two. So your whole life, you are eating, eating, eating, putting out CO_2, and peeing and pooping, and if you take all of that together, take Paul Francis over here, and all of his excrement over here, and all the heat that you've produced, add them up. The total will be more entropy than would be the case if you did not exist. If that's the case, and I'm sure it is, then you have not made the world-- your complexity here, your low entropy ball here has increased the entropy globally. So the presence of life increases the global entropy of the universe.

So let's talk about evolution now. So when we say, you traced-- OK, we started out with something simple, and now we're really complicated. But you've probably heard of a Ponzi scheme, and that is I think the complexity that you see around you is what you're doing is looking at the 1%, and saying, wow, the 1% is getting richer, but you're forgetting about all the excrement and all the people at the base of the pyramid who are giving you that free energy to produce that complexity.

In other words, your complexity has a cost, and when you take those costs and compare it to the low entropy complexity that you have, put them together, you will, in fact, get a total that's larger than it was. And so that, I think, is the simplest way to understand that the increasing complexity that might or might not be there in evolution-- it's still a controversial subject, but let's just suppose it is-- to the extent that it's there, it has come at the price of exporting lots and lots of entropy to the rest of the universe, making it harder for those guys at the bottom of the pyramid, those other slimy balls and pulls, to evolve into something more complex.

Then for the same reason that when you have a Ponzi scheme, you keep on adding people at the bottom, adding people at the bottom. The person at the top gets more complex or richer, but if you stop adding people at the bottom, then you do not get more complex. So complexity has a price. It comes at a price of free energy. As long as that free energy is there, you can keep extracting it, and that's what we're doing. Digging up oil, putting up solar panels, but that's at the price of extracting free energy from the system, and therefore producing more entropy than would be the case if we did not exist.

PAUL: So you can almost think that life forms are doing the second law of thermodynamics work for them. The are nature's way to increase entropy. Is that a reasonable way to think of it?

CHARLIE: Yes. That's called the maximum entropy production principle. You could think of it that way. And I have. As a matter of fact, in a paper I wrote recently, it said something like, instead of thinking of, we eat food-- instead of thinking, yeah, we eat food, you could say, food has created us to eat it to undo the chemical gradient that we feed off of.

Just like a hurricane. I mean there's a pressure, temperature, humidity gradient that produces a big structure that goes like this, and that undoes the pressure gradient, undoes the humidity gradient, and it lives off those gradients, and then makes it disappear. And that, I think, is what life is doing. It's undoing as many gradients as it can get its hands on

PAUL: So this presumably indicates that there must be a supply of low entropy or free energy--

CHARLIE: There is.

PAUL: --that's driving us. So it's supposed to be the sun in the case of life on Earth.

CHARLIE: Predominately, yes. But there are also redox potentials in the Earth. I mean the Earth is not in equilibrium here. Right? We have a dense center that's very hot, and then it's cool. We have volcanoes coming out, and for example, the hydrothermal vents where life might have gotten started, we have chemical disequilibrium.

Whenever you have chemical disequilibrium, you could make a redox reaction, particularly if you can catalyze that. Then you can extract more energy. That doesn't necessarily have to come from the sun, but life at the surface is predominantly powered by the free energy that we have coming from the sun.

Now it's an important point that free energy, what is free energy? Because there's a difference between energy and free energy. The 6000-degree degree photons coming from the sun, hitting the Earth-- the Earth is about 300 Kelvin, so about 20 times cooler, and then the photons that are radiated here, there are 20 times as many. So one solar photons turns into 20 photons coming from the Earth, and that's increasing the entropy of the universe.

PAUL: OK. Thank you.

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PAUL FRANCIS: So you've told us that the Universe started at a very low-entropy state, but there was something funny going on with gravity that we don't fully understand that's allowed it to form structures and come out of thermal equilibrium. You've talked about life as something that's almost evolved to help it accelerate its own process. So can you give us a history of the free energy, the low-entropy set that we are using to keep ourselves alive at the moment. Where did that come from, if you go all the way back?

CHARLEY LINEWEAVER: Well, if you go all the way back, the answer seems to be that if you start a universe with inflation, you have a homogeneously-distributed distributed false vacuum energy which then dumps into the universe, dumps real matter into the universe. That is the best explanation we have. And if that's the case, homogeneously-distributed matter is all ready to clump. And so it's lowest entropy.

That's how you solve the low-entropy problem. I don't think it's as problematic as you think. Just it's just the reverse of what is normally the case with perfume in a room. And that's because simply you're gravitationally dominated, not kinetically dominated.

So you start out with low entropy. Then you get clumps, clumps, clumps. When you form those clumps, they start to heat up, then they form stars. Interestingly, when you form a star, you have hydrogen-helium. If in the Big Bang you had burned hydrogen-helium to iron, then you wouldn't have stars.

So the fact that you have hydrogen-helium around means that you don't start out with highest-entropy material. That would be iron. You start out with hydrogen-helium and, therefore, you can burn it. And then it releases.

That's what the Sun is doing. It's turning hydrogen into helium. And then if it were more massive, it would go all the way to iron. So that's a chain of events that requires the gravitational contraction to do that.

And so it's like having water trapped up here in a lake, and then you're digging a hole through, let it go through. And then you can make a water wheel go, as these hydrogen turns into helium, helium turns into silicon, silicon turns into iron. Then you're at the bottom, then you're at sea level and you can't get any more energy out of that.

But then what you can do is collapse into a black hole which sits there. And if it's really big, it'll start to evaporate after many, many years-- 10 to 100 years, or so. The most super massive black holes in the Universe will evaporate after about 10 to 105 years. And then they'll turn into photons. And then that truly will be the Universe will be in a heat death, an equilibrium, out of which no life form can exist, because you need free energy, not just energy, to exist.

Remember, the first law of energy is conserve. Second law-- entropy increases. When you're at equilibrium, entropy is at a maximum. And you just have statistical fluctuations around that. Life forms can't exist out of that.

PAUL FRANCIS: Would that also apply if the Universe eventually re-contracted to a big crunch at the end? Would that change anything or would time still have the same direction all the way through that?

CHARLEY LINEWEAVER: Well, a lot of cosmologists have tried to use this bouncing universe to regenerate-- you contract, but when you're contracting, you're not violating the second law of thermodynamics. No one has figured out a way to do that, because many people think it's just a mathematical identity. And so when you contract the Universe, although it's getting hotter and hotter, you are not getting to be lower entropy.

There's no way to reset the entropy dials. That will start low again. Unless somehow in a way we don't understand, we can then dump, take all the energy of that universe and put it into a false vacuum. That's a reversal that I've never heard anybody talk about. And so all bets are off when it comes to that.

PAUL FRANCIS: And in a long-term fate of the Universe, we've talked about the second law of thermodynamics, the increase of entropy as a mathematics identity. But it's a probabilistic mathematical identity.

CHARLEY LINEWEAVER: Yes.

PAUL FRANCIS: So in principle, if you have a universe that's infinite, you're going to get little fluctuations around the mean from time to time. Is that ever going to be enough to sustain life?

CHARLEY LINEWEAVER: Well, if you and I are fluctuations, when you do the calculation of what happens to fluctuations around an equilibrium value, they quickly return to the equilibrium value. And we could say, well, are we returning to that? Well, not very quickly.

Well, here for example, here we have a little nice little model of a low-entropy universe because, I played with for about 5 minutes and I got the only 2 blue ones here. But the point is about the mathematical identity, if I shake this up, then chances are that they will be more blue over here and more orange over here. So on the other hand, there's a small chance that those 2 blue will go over here and they'll be lower entropy.

But let's see what happens if we go like this. And then what happens? Oh, look at that. We have 4 orange over here and 4 over here. So it's going towards equilibrium. I don't know if that answered any questions, but my PhD student bought this as an example of entropy.

PAUL FRANCIS: Well, thank you very much.

CHARLEY LINEWEAVER: You're welcome.

A4_L9_V01_introduction

PAUL FRANCIS: Now in this, the final lesson of the cosmology section, we're going to let our hair down and deal with the really speculative, way-out issues. And let's start off by thinking about what we've learned so far.

We've got this wonderful concordance cosmology, this precision cosmology. The trouble is that it relies on having an inflaton field to drive inflation, it relies upon dark matter, and it relies on dark energy. And we don't know what any of these three things actually are.

So where are we going to go from here? Given we have a universe built about three unknown things, and oh yes, that 5% of stuff we actually understand. 95% of the universe, we don't know what it is.

So Brad, do you think there is going to be any progress observationally on solving these mysteries over the next, say, 10 years?

BRIAN SCHMIDT: Well certainly it's my hope. Because when everything looks good, the best thing to do is look a little harder. And normally there's some mistakes. So, I think the hope is by digging deeper into dark matter and its properties, dark energy and its properties, thinking about perhaps inflation and its properties-- we have the opportunity even to test that possibly-- we're going to hopefully find something that doesn't look quite what we expect, And in that sense, we'll learn something.

PAUL FRANCIS: I guess there are two possibilities here. One is that we could get more and more accurate measurements. So, say, the equation of state parameter or the distribution of dark matter. And it will all fit. Standard model. The model we've just talked about. And that, in some sense, is a pessimistic point of view. Because everything just fits that. It doesn't give us any clues as to what they all actually are.

This is the trouble that particle physics has been in for some decades now. They came up in the '70s with a standard model of particle physics which has been far better than anyone expected. It just fit every piece of data that's come along since too well. So they've got no clues as to anything better.

BRIAN SCHMIDT: Yeah. They sort of have a box that really fits together neat and nicely. There are, of course, a couple mysteries in particle physics. The fact that there are matter at all is a bit of a mystery. The fact that neutrinos have mass. Those are things that they haven't yet been able to explain.

And what this stuff is that we see astrophysically, dark matter, it looks like it should be a particle. The current theories don't explain that. So, there is hope that at least there's something there. But they're sort of in the going out in a very large field with a very small torch and looking for the keys and they haven't found anything yet.

PAUL FRANCIS: Yeah. So I guess the optimistic point of view would be that we get more and more precise measurements with all these parameters and we find something that doesn't fit the model. A surprise. Much like, we had a model before your work on dark energy. And you've got the observations of the supernova, and it didn't fit. And that was really exciting. So when the models fit, they're so boring. So let's hope there are some really amazing, unanticipated things buried in the data. As we get better and better measurements, they will show up.

BRIAN SCHMIDT: And the good news is, things are pretty good. But there are at least a few things to go and look at more closely that don't quite fit.

PAUL FRANCIS: Yes. These anomalies, these things that don't quite fit the current model, At the moment, none of them is really compelling. But there might be a few signs or flag posts to where there might be new physics coming in.

One of these discrepancies we've already talked about, which is that for some of the microwave background multipolls there's two little power. But that's going to be very hard one to pursue.

BRIAN SCHMIDT: Yeah, because there's only one universe to look at. So that's going to be a tough one to pursue, I'm afraid.

PAUL FRANCIS: How about dark matter? Are there things that don't quite fit with our theories of dark matter?

BRIAN SCHMIDT: Well of course, we're missing the particles. So one could hope to look for a particle, and we've talked about how you might do that. But then, if we look astrophysically, there's a funny few things. We have a model of how dark matter should distribute itself in the universe. And because it only interacts by gravity, it's pretty simple, relatively speaking, to do that. So, one of the things you predict is how many galaxies there are of different sizes. And when we go out and look at the universe, the universe is full of big galaxies just like the model predicts.

But when we get down to the little galaxies around our own Milky Way, we don't see the little galaxies which should be there in large abundance.

Now it might be just due to complicated baryonic physics. The atoms we're associated with may for whatever reason not be associated with these little clumps of dark matter. In which case, you just wouldn't be able to see them.

But it could also be that dark matter is not completely cold. It actually has a velocity that is interesting. And that turns out that would smear things out and perhaps make its behavior on these scales of galaxy sizes a little different than the nominal, really big massive dark matter particle we haven't yet discovered.

PAUL FRANCIS: Yes, on very large scales at the microwave background, the dark matter theory behaves beautifully. It's only on the small scale. So one possible anomaly is the lack of tiny galaxies.

Another one that's very controversial is what happens right in the middle of galaxies. We talked about this a bit in the first course. But some computer simulations predict that if you plot the density of dark matter, it should have a real peak, a cusp, in the middle of galaxies. And in fact, the observations seem to show a much flatter distribution of matter.

Now, this is a really hot observation to make because there's a lot of baryons in the middle of galaxies. So, unless you can subtract them very accurately, it's unclear. And also, it's really pushing the limits of the numerical simulations. So, some people think this is a problem, some people don't. But these are both propped up on small scales. And so there have been a lot of exotic suggestions for ways you could modify dark matter if these problems turn out to be real. And we don't know they're real yet.

So, you've talked about one having slightly higher speed. We could've also talked about dark matter that can maybe interact with itself. Self-interacting dark matter. So two dark matter particles don't just fly past each other, they maybe bounce off or transform in some way.

BRIAN SCHMIDT: But if they do that, then they should, when they interact, they're going to do something like put out photons that you might actually be able to see.

PAUL FRANCIS: And there have been claims that people have seen these. There's a mysterious gamma ray haze around the middle of our galaxy and it's not at all clear where it's coming from. There are many other contenders, so it's by no means definitely. But also, people talk about many other things like Bose-Einstein condensates of dark matter, and so on. But at the moment, how do you assess that? Do we know there's a problem here? Is it suggestive?

BRIAN SCHMIDT: Certainly, to my mind, enough to be interested in. And at some level, the theory we've talked about doesn't actually care about dark matter's detail properties as long as there's dark matter there. And everything we've just described actually is more or less dark matter as assumed by the model. It's the details of the dark matter that we really want to understand.

So, I don't think there's a problem, I think there's an opportunity to go and sort out what dark matter is. And I feel relatively confident. I think there is a reasonable opportunity in the next 10 years we're going to sort out what dark matter is. And that will be a huge discovery when it happens.

PAUL FRANCIS: Now, even if we manage to figure out dark matter and dark energy even what it's inflation fuels actually are. And in some sense, that still leaves us with the biggest problem of all, which is where did the universe come from in the first place? And when we can observe back to redshift 1,000 or so from the microwave background, we can go back to only a minute or so after the Big Bang. By looking at nuclear reactions in our particle accelerators, we can duplicate conditions back to about maybe 10 to the minus 9 of a second after the Big Bang. So we know how matter behaves in those conditions. And if this inflation theory is right, that pushes us back to maybe 10 to the minus 40 of a second. So, much further back.

But of course, that's still not all the way back to the Big Bang. What happened at 10 to the minus 50 of a second? 10 to the minus 100? 10 to the minus a thousand? 10 to the minus a million? 10 to the minus, 10 to the minus, 10 to the minus, 10, et cetera.

BRIAN SCHMIDT: Or is there even that? I mean, you're presuming there is a T equals 0. But it's not completely obvious to me. When we talk about the Big Bang, we have to be careful. What we're really talking about is a time when the universe was really hot and dense, where the clock was sort of reset.

And so we can go back to that time of inflation, which is 10 to the minus 35 seconds is our best guess, and it may well be we can probe that by looking at gravitational waves ringing through the universe. We may have detected them, we may not. We will figure that out soon enough.

But we can look back to that far. But what comes before that? That almost becomes a metaphysical question. Because it's not clear we can know. It's not clear we can observe. And the ideas we've talked about of eternal inflation, well how do you test those? It's not at all obvious.

PAUL FRANCIS: So we can't really push our laws of physics behind. Because we've got relativity which deals, as we've talked about in this course, with curvature of space time. Very massive things. We've got quantum mechanics, which is all about waves, deals with very small things. But for this, the entire universe as we know it has been in both. And we don't have a theory of quantum gravity. Rather, we have too many and there are no evidence to distinguish them.

So, we can't observe this early on. We've got no good theory. What are we going to do? I think it's probably time we got some theoretical input on this.

BRIAN SCHMIDT: Yeah, that's probably a good idea.

A4_L9_V02_Krauss_Conclusions1

PAUL FRANCIS: Now, throughout the set of courses Brian and me have had a very skeptical point of view about understanding the very origin of the universe. We can duplicate in our labs conditions when the universe was maybe ten to the minus nine of a second old. And so we kind of know how matter behaves under those sort of energy conditions. But when we push further back still-- say 10 to the minus 20, 40, 100, 1000 of a second-- we very rapidly go beyond the level that we are ever going to test with any conceivable particle accelerators.

We also don't have good theories for this. Because we know that we have relativity, which deals with very massive things, and quantum mechanics with small things. When you have things that are both massive and very small, the two theories really don't mix. We need a grand unified theory of everything. And there is no consensus on what this theory might actually be.

So from my point of view, we've got no good theory. We've got no good experimentation. So should we just be giving up? Should we just leave this to the philosophers and poets and rabbis and priests and imams? Now to give the opposite point of view, we are very pleased to have Lawrence Krauss back here again. A reminder, Lawrence Krauss is a regular visitor and visiting member here, and also works at Arizona State University. Lawrence, should be just give up on the start of the universe? Can we ever know anything about it?

LAWRENCE KRAUSS: Oh, that's so anti-scientific. I want to quote Winston Churchill, who said never, ever, ever, ever give up. And it worked for him. The point is-- and definitely, definitely we should never leave things to priests or imams. We've seen what's happened in the world when we did. The point is, we don't know what we don't know. But to argue that we'll never know something requires a level of arrogance that's far more extreme than even assuming we might know.

We don't know what science can show until we try. And so we just got to keep trying. And it is absolutely true that we are quite limited in what we can see. But new discoveries add new wrinkles and cause theorists like me to think about new things. Certainly the discovery of dark energy added a new wrinkle. It caused us to realize there was something fundamentally wrong with our picture.

And that happens all the time, if we're lucky. It hasn't happened in a long time at a microscopic level in particle accelerators. It is true that accelerators are limited. But there are lots of possible observations that can push our picture back, empirically, back to almost the very beginning of time.

BRIAN SCHMIDT: So let's just look at that. So we have the Large Hadron Collider, which is going to be operating, we hope, at the TeV scale. So that's a fraction of a second. And it's going to hopefully look, and perhaps it will find new particles. But do we really have a way to test how the early universe works based on those observations?

LAWRENCE KRAUSS: Well, look. If we discover-- look, physics is connected. So particles are just not particles. They're part of a theoretical framework. And if the Large Hadron Collider, for example, does discover the framework of supersymmetry, then we have fundamental theoretical models that will not only be constrained by that, that will make predictions about what happens at much smaller scales.

Because the theories must fit together in a certain way. And quantum mechanics tells us how they evolve as a function of energy. And ultimately, therefore, since in the early universe we're going to higher and higher energies we can know how the laws of physics behave. If we discover supersymmetry, for example, it will tell us with high confidence that our ideas of grand unification are probably correct. But that word is probably.

So you might say that-- again, you might say Lawrence, that's just speculation. You can hope, you can be very hopeful. You can say it happens with high likelihood. But how can we know? Well, in physics we never really know anything. We just test things. And then we get better and better ideas of what's true. But there are other possible handles other than direct accelerators that can give us a handle on new physics. We don't know where it will come from.

One possibility on the ground is that we build large detectors underground, large water detectors, looking for protons to decay. It turns out if there's a grand unified theory we would predict that diamonds aren't forever. But you don't have to sell your diamonds, because they last a long time. We predict now that protons will decay, but with a lifetime exceeding 10 to the 35 years.

It's actually possible to potentially measure that. How can you do that? 10 to the 35 years is a lot older than the age of the universe. Well, if there's a possibility that a proton will decay randomly once every 10 to the 35 years, if you get 10 to the 35 protons you might find one decaying each year. And that's why we have these huge tanks of 50,000 tons of water underground-- the Kamioka mine, for example, in Japan.

So if we saw proton decay that would tell us immediately about the physics of grand unification, which would happen at a time when the universe was not a billionth of a second old but a billionth of a billionth of a billionth of a billionth of a second old. And that would send our empirical understanding of the universe forward by leaps and bounds.

But we may not need to do it there. We may have already done it. We've talked earlier about gravitational waves. If we measure gravitational waves, if the ones that have been claimed really are from inflation--

PAUL FRANCIS: The gravity waves seen in the microwave background--

LAWRENCE KRAUSS: and seen in the microwave background, that the BICEP2 experiment seen in the polarization of the microwave background. If those gravity waves really are from inflation-- and we can test that idea in many ways-- then it tells us not only did inflation happen, which is profoundly important, but it tests the physics at that same scale, a billionth of a billionth of a billionth of a billionth of a second after the Big Bang. It means that we could test our ideas back to almost the beginning. But that's not the beginning.

BRIAN SCHMIDT: So then we get to the beginning. OK. So we can take things back down to this very early scale of the universe. But some people, including yourself, ask the question well, how did we even get to there? And that's kind of a troubling question for me, is how do you create the universe? How do you have a beginning to the universe? It strikes me, from pure philosophy, that the universe must have always existed.

LAWRENCE KRAUSS: Well, you know, first of all there are more things in heaven and earth than are dreamt of in your philosophy, Brian.

BRIAN SCHMIDT: Yes.

LAWRENCE KRAUSS: But more importantly than that, that's what's great about physics. It causes us to realize that what we think is sensible is not always the case. And we now realize, as I've argued based on what we know, that more and more-- if you ask what would be the characteristics of a universe that was created spontaneously from nothing without any supernatural shenanigans, they'd be exactly the characteristics of the universe we live in.

Because as I think we've talked about in an earlier lecture, the total energy of our universe appears to be 0. And quantum mechanics says that nothing is unstable. Not nothing is unstable, but nothing is unstable. Namely in empty space there are particles popping in and out of existence all of the time. And if you wait long enough, even empty space will produce particles.

If we had a quantum theory of gravity-- which we don't have and we may never have. But if we get empirical data pointing us closer and closer to that time, my suspicion is it's not impossible to imagine that we will come up with a quantum theory of gravity. But a quantum theory of gravity tells us the following, even without knowing what it is. The variables in general relativity are space and time. Just like the variables in particle physics models are particles and forces.

And quantum mechanics says for particle physics models that those particles and forces are fluctuating due to quantum mechanics. Any quantum theory of gravity would involve fluctuations in space and time. And in fact would allow spaces and times to spontaneously appear where they hadn't before. Closed universes would appear. Spaces that literally didn't exist before would suddenly exist. Our universe could have been one.

Now when you ask what happened before, there are two answers that are possible. One is it's not a good question. Because if space is created, then time is created. And time may be an emergent property of our universe. There may have been no before t equals 0.

Now that flies in the face of everything we understand of causality and all of the standard things we understand. But that may just be the case. We may have to have a new understanding. If there was no before, then there was no before. And that means there was no cause, if you like cause and effect.

The other possibility is, it comes from inflation, is that the multiverse could be eternal. And universes like ours are popping into existence at any time. And so for us the beginning was at t equals 0. But for another universe the beginning is today. And there may be some global time in a multiverse. And there may be universes being created every instant. We just don't know the answer.

BRIAN SCHMIDT: So let's look at the first of those. So the second one is a universe that essentially exists forever. And I use the term in our universe being everything that is our universe and other universes. The first one is saying there really is-- and you wrote a book about this, called A Universe from Nothing. Where the universe as we know it is spontaneously created out of nothing. But nothing still includes a physical set of laws that allow it to happen.

LAWRENCE KRAUSS: But that's the only thing. You have no space, you have no time, you have no matter, and you have no radiation. That's a pretty good version of nothing. Namely by nothing--

BRIAN SCHMIDT: But you still have physical laws.

PAUL FRANCIS: You still have the laws of physics.

LAWRENCE KRAUSS: Hold on, we'll get to the physical laws in a second. Let me just point out, however, that even the theologians and philosophers who like to try and debate nothing-- and as often said they're experts at nothing-- but would argue what is nothing? Nothing is nonexistence, they would say. And it is in every sense, our universe didn't exist before it existed. Nothing we see in our universe existed except maybe the laws of physics.

BRIAN SCHMIDT: Right. And they would have had to exist--

LAWRENCE KRAUSS: No.

BRIAN SCHMIDT: --essentially forever.

LAWRENCE KRAUSS: But the answer is not necessarily so. Because there are multiverses-- not just the kind that are proposed by inflation but arising from string theory-- in which all of the laws of physics, even the nature of space, the number of dimensions, everything is variable. And it could be that it's not that there were fundamental laws of physics. It's that every different kind of law of physics is possible.

And if you have every different set of possibilities fluctuating around, and even the laws themselves come-- then even the laws in our universe spontaneously came into existence when our universe came into existence. So if you have every kind of law, it's like having no law. Now that's pure speculation, I will admit. But it's perfectly plausible. Now the only thing that really seems to be constant in that picture is quantum mechanics.

Because you want spontaneous things to happen without a cause, which happens all the time in our universe. The photons being emitted by the lights in the studio were emitted when an atom deexcited. But there was no cause of it. It just happened, if you wish. I mean, we know the laws tell us it must happen, but there was no cause. Quantum mechanics allows spontaneous creation.

Maybe quantum mechanics isn't universal, either. We just don't know. But as I say, that's an open question. And it may mean that the law-- there's two possibilities. Either an infinite number laws, or there's one set of laws that allows reality to exist. And those laws have been eternal and will be eternal. And that may be the possibility, too. And we don't know the answer.

But the point is it's not as if we may never know the answer. We may be able to probe that very question. But independent of that question, the point is that I find it remarkable as a scientist that something that I wouldn't have imagined would have been possible 30 years ago, that 100 billion galaxies each containing 100 billion stars could spontaneously come into existence without violating any known laws of physics.

That not only seems to be possible, but highly plausible. And that's why I wrote the book. Because I think it is amazing that science has brought us to that threshold.

A4_L9_V03_Krauss_Conclusions2

PAUL FRANCIS: So Lawrence, you're pushing the idea that in some sense, quantum mechanics is the most fundamental thing we have. The whole randomness of it, though even it might not be fundamental. Now to me as a skeptical empiricist, experimental astronomer, quantum mechanics is a prime example of a theory that theorists would never have come up with by themselves. The data was overwhelming for 100 years before any sort of theoretical framework comes by and even the basics of quantum mechanics like the two slit experiment really is very hard to understand in any philosophic, coherent way.

LAWRENCE KRAUSS: No one can understand quantum mechanics. We can't, intuitively, understand it. I mean, talking mathematics.

PAUL FRANCIS: So let's imagine we didn't have any experiments. Let's say that the quantum mechanical scale was another 50 orders of magnitude smaller than it really is. Then we would never have discovered quantum mechanics. There's no way a theorist would have come up with this.

What if, as we push back to the very, very early universe-- not merely the era of inflation, but maybe another 100 orders of magnitude earlier than that-- there is something new coming in? Almost every time in the history of science when we've pushed way beyond, I go to good old Newtonian physics that work perfectly well for things weighing in kilograms, travelling a few beats per second like me on a bicycle. And then it broke down either when we got very fast or when we got very small.

We now have the laws of quantum mechanics, which work for everything we can explain. Downward from scales of 10 to the minus 20 of a meter, up to the universe. But let's say, if there could well be laws of physics coming in on much smaller scales, is this possible? And, will we ever know? And what could we do if that's the situation?

LAWRENCE KRAUSS: The answer is, we don't know. That's what's great about being a scientist. You're allowed to say you don't know. And that's what makes science worthwhile, because you don't know and that's why you keep looking. It could be that there's an ultimate theory of everything and we'll understand. I'm skeptical of that as a theorist. It could be as Feynman said, the universe is like an onion. That we keep peeling it back and discovering new layers. That's not a defeat. All we want to understand is a little bit more about how the universe works.

We may never have an ultimate understanding of everything, but that's OK. As my friend Frank Wilczek says, "it's OK, I just want a theory of something." And that may be the case, and we just don't know the answer.

And I will agree with you as a theorist, that ultimately, we theorists can push back. But it is inevitably experiment that drives our thinking. Feynman said, "science is imagination in a straitjacket." And that's what it is. The straitjacket is provided by experiment. And it's not even usually a straight jacket. It's actually a window, because it allows you look to places you never thought you'd see before.

BRIAN SCHMIDT: So let's just say there is a theory of everything, and we found it. Do you think we would ever know we found it?

LAWRENCE KRAUSS: [SIGHS] It would have to have certain characteristics that I think theorists would argue-- and it's a little technical to talk about, but-- I can imagine a theory of everything that would be unambiguous. However, I can imagine many theories of everything that would not be unambiguous.

And so, we'll just wait and see. We'll wait and see. The excitement for me as a theorist is that we are closer to being able to empirically address questions about the universe on all of its scales than I would ever imagine when I was a graduate student. And the surprises that have taken place have been unimaginable. And I fully expect that the biggest surprises will be in the future. And in fact, every day I wake up and I'm surprised if I'm not surprised.

PAUL FRANCIS: Let's look at where the future of astronomy might go. So let's imagine that we get lucky with a large hadron collider and we discover some evidence for super symmetry. And let's imagine we also get lucky with the gravity wave data and the microwave background, And so between those two, we can hopefully nail down the era of inflation.

But where do we go from there? Let's say we've got inflation nailed down and we work out all the various consequence of that. That gets us back to maybe 10 to minus 40, 10 to the minus 50 of a second, the Planck time. But where are we going to go beyond that? There's nothing more to get out of the microwave background. The microwave background at that point would be--

LAWRENCE KRAUSS: It wasn't always the case that astronomy contributed to the fundamental physics. There have been various times. It could be that astronomy and cosmology become trying to understand the later revolution. How things formed. A theory of everything really isn't a theory of very much, as one of my colleagues have said. We still wouldn't explain how oatmeal boiled. There's a lot about the universe that even if you had a fundamental theory, that you need to understand why do black holes form before galaxies. And If so, why? And what relationship do they have to the galaxies?

-In some of the physics of the early universe, there's still the open question of dark energy. Although I'm pretty convinced as a theorist, we're not going to learn more about it than we now know, which is not very much. But it could be that we discover by extending the kind of observations we've made, that the dark energy in the universe is changing. And that would be a profoundly important discovery with impact for the future. And impact for particle physics.

So, we don't know what new things we're going to see. It could be that there is something else that will change our picture of the early universe. We just don't know. We do know, when we think about the future-- and I've thought a lot about the future as well as the past, and written about it-- that if the universe we live in, if the dark energy is constant, then we live in the worst of all possible universes for the future of life as far as I'm concerned. And I find that very heartening, not disheartening.

But the expansion of the universe will continue to accelerate. And in a time which is measurable. And in fact, there'll be stars. In 2 trillion years, there will still be main sequence stars around in 2 trillion years. There will still be potentially organic material and astronomers powered by solar radiation that can look out at that universe.

What will have become our Milky Way galaxy after it merges with all the other galaxies into one in our region? It'll will be one large galaxy. We'll look out, and see nothing. All the rest of the galaxies in our universe will have disappeared because it'll all be moving away faster than the speed of light, which is allowed by the laws of general relativity.

And for me, I find that very poetic. Because the observers then will imagine a picture that we had of cosmology 100 years ago. Remember, before Hubble, the astronomers thought first of all that our universe was constant in time. That there was one galaxy, our Milky Way, surrounded by an eternal, empty universe that had been around forever and would be around forever. In the far future, 2 trillion years, it could be that astronomers arise, do everything they could do discover electricity, magnetism, and quantum mechanics, go out and measure, and see exactly that-- a single galaxy surrounded by empty space.

Eventually, of course, they'll die. The stars will collapse into some massive black hole which will, in principal, evaporate. The universe will become cold, dark, and empty. And that's the future. And as my friend Christopher Hitchens said, when I've talked to him about that, he says, well, the answer to the question "why is there something rather than nothing?" may be, "just wait. There won't be for long."

But that's the future as it might be, as Charles Dickens would say.

BRIAN SCHMIDT: That's sort of the most likely future given what we know now.

LAWRENCE KRAUSS: Given what we know now. But, as I'm happy to have said, that I've also written a paper with my friend Mike Turner that shows that no matter what observations we make, it's impossible to know what the future will eventually be. Because let's say the dark energy that Brian discovered is really not there, it's a mistake. "Oh well, it's a big mistake. We apologize." But it turns out, you might say, well then we know the future. Because Einstein told us a closed universe will collapse and an open universe will expand forever, et cetera. Well, it turns out, there could be a dark energy which is much smaller than Ryan could've ever measured. And there still may be one. So even if that dark energy goes away, there could be another one.

So even in that case, an open universe can collapse, a closed universe can expand forever. And it turns out, unless you have either a theory of everything or an infinite number of measurements, the future is uncertain. And that cosmic mystery, for me, is very enlivening. Because it's the search rather than the knowing that for me, gives satisfaction.

BRIAN SCHMIDT: So let's talk about some of the extreme ends of the universe. So, we've talked about that cosmological constant is more or less constant. And so within 100 billion years, the nearest galaxies will be so far away you wouldn't know they're there. Our stars of the Milky Way will last for much longer than that. And those stars will die. You'll end up with white dwarfs orbiting each other. A lot of them will eventually coalesce to form a black hole. Some will evaporate off.

So do we end up with everything being a black hole and evaporated little stars on their own? Presumably, if you're a little star that's flung out, your sort of all on your own some. And so you're actually not a black hole, you're a white dwarf out on your own.

LAWRENCE KRAUSS: And there will be stars that are ejected from our galaxy. In fact, I wrote a book called Atom where it involves such a star. But even those may have a bad future. Because it's true. If that's the case, then there will be dead lumps of matter which would be almost infinitely far apart, so they don't mean much, but they'll still be there.

But if are our ideas of grand unification are correct, it's worse. Because remember, protons decay. And eventually, if it's true, it's just like literature. Beginnings and endings are often tied together. Proton decay and the physics of the early universe are responsible for why we're here. But they may be responsible for its demise as well. Because if protons decay, then the protons of those white dwarfs will decay. And eventually, they'll produce radiation which will dissipate. And universe really will become cold, dark, and empty.

BRIAN SCHMIDT: But on the other hand, we don't understand dark energy. And so, as you've already said, it's very hard to predict what we call dark energy might be. It might suddenly go through a phase transition and turn into something that's very attractive and reverse what's going on.

LAWRENCE KRAUSS: It could be that. It could destroy everything we see. I'm very happy to say that when I was working here at ANU last summer I came up with a model which saved the universe. It's probably wrong. But it actually could show that there's a kind of dark energy that would decay that would be imperceptible. If it decayed and produced stuff, we'd never notice it here in the studio. And so it would allow us to survive and keep asking questions. We just don't the answers.

BRIAN SCHMIDT: So what's the timescale that the universe can change directions from what it's doing right now? Can it do it in an impossible short amount of time if it wants to?

LAWRENCE KRAUSS: Well, it could. It could be impossibly short because there could be a phase transition. If it happens, it happens at the speed of light everywhere. So it could be that the field decays and everything changes before we finish this question.

Barring that, we know that the dark energy isn't classically changing very fast. We know that from constraints from observations. So, unless there's some quantum change like that-- a phase transition-- the universe will continue to go on as it is now for at least probably 100 billion years.

BRIAN SCHMIDT: So what about the idea, since we haven't measured the equation of state of dark energy, what happens if it is below minus 1? So this is dark energy that becomes more and more dense over time as the universe evolves.

LAWRENCE KRAUSS: Now, I have to say, as a theorist-- I know you love to talk about it-- as a theorist it's even uglier than quintessence--

BRIAN SCHMIDT: Oh it's certainly ugly, yes.

LAWRENCE KRAUSS: --ugliest, it's exponential of ugliness. Because there's no-- and I repeat-- there is no fundamental particle physics theory that allows an equation state less than minus 1. It violates pretty well most of the rules that we know of about nature. But if it's true, that means the universe ends at a finite time. Because the dark energy right now-- the acceleration of the universe isn't affecting you and I and the three of us in the studio. It's so small that we're not accelerating along with it. But if the dark energy density increases, then that repulsive force will increase.

And right now it's soft of accelerating the universe. If it increases, the force will be large enough that that repulsive force will beat out the attractive force of our galaxy-- the gravitational force-- and break apart our galaxy. If it continues to increase, it'll break apart stars. If it continues to increase, it'll break apart planets. Eventually, it'll break apart atoms. And in a finite time, there'll be this big rip. And literally, everything, including the fabric of space, will break apart. And then we'll have to understand McCormick answers. It's a very poetic picture, but it is highly unlikely.

BRIAN SCHMIDT: I kind of like it. Because you end up with an exponentially expanding universe of almost infinite density. Which kind of sounds like how we were born. It's almost a rebirth, isn't it?

LAWRENCE KRAUSS: Well, in a way, maybe. But I mean, the great thing about the universe, Brian, is that it doesn't give a damn what you want or what I want. And so we'll just wait and see.

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PAUL FRANCIS: Now, we've had a lot pretty pessimistic futures for any possibility of whatever we evolve into hundreds of billions of years from now. The big rip, which is possible unlikely, or the heat death of entropy, or everything turning into black holes, or proton decay. But I'd like to ask Lawrence one final time, is there any future which doesn't involve the demise of our descendants?

LAWRENCE KRAUSS: Is there any hope for the universe? This is, in fact, a fun question. I've been having an ongoing debate with Freeman Dyson about it. The simple answer is maybe. Because you could-- you know, life like us can end, and it will end. I mean, we're going to end. Life-- unless we escape our solar system, it'll end when the sun encompasses the Earth, but you could imagine, of course, lots of possibilities. And you could imagine life forms that are very different than anything we can see, I mean, even when protons decay, there may be life forms that are made of electrons and positrons that are distant and Freeman is very inventive, and will come up with those possibilities.

The answer is, ultimately, and a colleague of mine, Glenn Starkman, and I looked at life needs energy to operate. And it turns out, ultimately, it all comes down to the single question, will the universe continue to expand and accelerate forever? If it does, then Freeman I agree that life must end, because the amount of energy you have access to is finite in such a universe. So ultimately, if the energy of empty space remains what it is, life will end. I think there's no debate about that. There's no way you can save it, even with the most exotic kind of black clouds that Fred Hoyle imagined, which are just sort of dust particles moving in space that have some consciousness, which is something that Freeman came up with when we were debating.

But if that isn't the case, you might imagine, it's possible to imagine, something like a black cloud which actually could persist, in principle, forever in an eternally expanding universe. Whether we-- it's still an open question whether that black cloud could have thought processes. We don't have time to go through it. These things I've actually thought about.

BRIAN SCHMIDT: How does it get its energy to do anything?

LAWRENCE KRAUSS: Well, it basically the motion-- the classical motion of the particles in the cloud is enough to encompass thoughts, if you wish, and the red shift away, but they never go quite to 0. And it-- you could imagine-- it turns out the phase-- this is a little technical, but the phase space, the classical phase space, allows an infinite amount of information to be processed.

The question-- really, when you're talking about life, you're talking about information processing. And the question in the debate that Freeman and I have had is can you imagine processing an infinite amount of information? Because that means you're living forever. OK, and the answer is, probably not. In fact, I've shot down almost every example he had. If there's an energy of empty space, the answer is precisely absolutely not.

If there isn't, then the question is still not resolved, I would bet against it. That's the bad news. But the good news is that-- there's a little bit of good news here-- life will end in our universe, but if the universe is eternal, and expanding forever, there can be quantum fluctuations locally, and eventually those fluctuations could produce, potentially, a very dense object or series of objects, maybe even galaxies, that will produce life in the future. So even though no life itself could persist forever, life may die out in the universe, but in the future, it may be reborn again. We don't know.

PAUL FRANCIS: Now, the one infinite universe you were talking about was the idea of this eternal inflation, where you have inflation continuing and producing, nucleating big bangs all over the place. In that situation, presumably, while our own bit of the flat space is going to decay, there could be other ones.

LAWRENCE KRAUSS: Oh absolutely. In the picture of eternal inflation, I thought you were talking about our universe, I again, use the word universe to mean everything we can have contact with. In eternal inflation, there's great hope because eternally, there will be universes that are being born. They'll be causally disconnected. They won't know about us, or anything-- or ever know that we existed, but you could be happy to know that in the future, there will be other universes-- in fact, it brings up truth philosophical problems, because in such a situation where there are potentially an infinite number of universes, this conversation that we're having will happen an infinite number of times in exactly the same way, and in slightly different ways. In a different universe I could be asking you the questions.

And this idea of infinit-- infinities produce real problems. And so it's something at some theorists are now thinking about is how can you handle those kind of infinities if there are an infinite number of universes. Because literally, even if our uni-- actually, if our universe is eternal. Even a single universe, you could imagine everything will happen the same way, and slightly different ways an infinite number of times. It won't be as if it'll be us, it'll be recreations of us that are either approximations, or essentially identical. But in an infinite-- in an inflationary universe, that's certainly happening. And so, there's always hope that if we screw it up in our universe, the some other civilization in another universe won't.

BRIAN SCHMIDT: Thank you very much.

LAWRENCE KRAUSS: Thank you. I live in hope.

A4_L9_V05_Conclusions

BRIAN SCHMIDT: So certainty abounds in what we can and cannot learn about our universe. But as you can see, optimism abounds of what is possible. Of course we don't know until we try. And so one way to go forth is to just keep going as hard as we can. And assume that we're going to be able to learn everything we can imagine about the universe. Paul, are you optimistic about what we're going to be able to learn in the future?

PAUL FRANCIS: I certainly agree with Lawrence that we should never give up on this, and pursue it for all the we're worth. Will we get the ultimate answer through science? I have my doubts about that. I mean, there are a number of things that worry me. One is surprises. I mean, your discovery of dark energy was a surprise.

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: But it's clearly fundamentally important. And we couldn't possibly have a cosmological theory without it. But let's imagine dark energy being even 10 times weaker than we currently observe. There's no way we could measure it, or certainly if it was 100 or 1,000 times weaker. But it would still be important. What if there are important things that are just too small for us to measure in the era and the part of the universe that is accessible to us?

BRIAN SCHMIDT: So we're really talking about limits of knowledge. So for example imagine instead we were born, oh, 100 billion years in the future. We would not be able to see the cosmic microwave background anymore. It would be faded beyond all oblivion. And indeed, all the galaxies we've talked about would more or less all be gone as well. So you really wouldn't be able to do the cosmology we do today. So that begs the question, is there a limit to knowledge at any given time when we can see with our own theories that it's going to disappear in the future?

PAUL FRANCIS: Yes, so if you imagine people forward here 100 billion years or so from now, when there are no other galaxies visible, even if they were infinitely intelligent could they have figured out what we currently know about the universe? And it's not at all clear. It may well be the answer is no. Even no matter how clever they were, no matter what observation they made with no matter what facilities, it's not at all clear they could learn anything.

Because there's things that are missing. And presumably the same thing applies to us now. There may well be things that were really important when the universe was 10 to the minus 100 of a second which have now gone beyond discovery. And nothing we can do, no matter how smart we are. We could have brains the size of planets and it won't help us.

BRIAN SCHMIDT: Right. So let's just talk about, then, that beginning of the Big Bang. We have the whole notion of OK, so what was the Big Bang? Was there anything before the Big Bang? Those questions to my mind are not clearly going to be answerable. I mean, I can't say they're not going to be answerable. But you're with Lawrence, you think we should keep on trying on those things.

PAUL FRANCIS: We should absolutely keep on trying. But actually I get a real sense of deja vu on this whole stuff. Because-- I mean, Lawrence was talking about when we go back to the beginning of the universe you can always say what happened before that. But the whole idea of what happened before relies on time and causality. And clearly time itself may have started at the Big Bang. And so what happened before the Big Bang, it's bad language. It's much like with quantum mechanics. We can ask questions in language, but our language is so tied up in common sense they don't make sense there.

But this actually reminds-- this is nothing new. I mean, we're now debating the whole idea of causality. If A causes B causes C, what caused the first thing? Where did this whole chain start? And the whole idea of time starting makes that really difficult. But this is something that philosophers have been debating for hundreds of years, nothing new to modern cosmology.

Exactly the same problem occurs in classical theology. OK. So let's imagine you say that why is the universe here? Well, God made it. But then what made God? Or why did God decide to make it? Whenever you push something back, you still have to explain something else. And the theologians have the whole ontological argument, saying that maybe God is by definition the unmoved mover, the thing that doesn't need causation.

So it's kind of interesting that we're now coming full circle. And we're now talking about things that can cause themselves in very much the same way that theologians hundreds of years ago talked about God as something that can cause him or herself.

BRIAN SCHMIDT: So is that the same as saying that God has always existed, or the universe has always existed? Or you're saying that causation is a little different than that.

PAUL FRANCIS: Well, that would resolve the causation issue, if the universe is infinite, like an infinite inflation argument, or God has always been there. But to my mind it doesn't really solve the problem. We've still got the question of why is there something rather than nothing.

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: We're right back to Descartes, and probably much before that. Why does anything exist? In religion the whole issue is of why is God good? I mean, God can define himself to be good. But I could define myself to be good, and no one would believe it. There has to be some outside standard of goodness.

And so likewise even in Lawrence's wildest dreams you still need there to be laws of physics. And they can be somewhat variable, but there has to be a law telling you how variable, and that they vary. Where did that come from? I mean, that fundamental issue is a really interesting issue. It's not clear to me we've made any progress. We haven't gone backwards. We've maybe got a few clues. But we're, in some sense, I'd say no further ahead than we've been for 2000 years.

BRIAN SCHMIDT: Is this a job for science, then? I mean, if we think about science at its core science is about having a set of ideas, of principles, which you test with observation. And what you're talking to me about here doesn't strike me as really fitting in to science when it comes down to the existence of the universe itself.

PAUL FRANCIS: Yeah. I guess my personal feeling would be this is not a question science could address. But I'd like to be proven wrong on that. Science has addressed a lot of other questions that no one has thought it could ever have addressed. At the moment I can't see how science can possibly address these things. So I think this is a job for the theologians and the priests and the rabbis, and so on. Lawrence would disagree violently with that. What do you think on this?

BRIAN SCHMIDT: Well, I think what we're going to end up doing is if it's science, we will do it as science. And people will be on this interface that's a little uncomfortable, I think, for me personally. But what I think we're going to end up doing is where we think we can make progress.

I think scientists like myself, as we start trying to get the third 9 on the equation of state parameter of dark energy, and you realize you're going to use an infinite amount of money to get the next 9. You start working on something else where it's easy to make progress. And so I think in the end there's clearly lots of places to make progress in science. We haven't exhausted those.

But it might be there are some dead ends, maybe permanently but maybe temporarily. Who knows? I bet-- I would describe this is a place which I would say, for me at least as an observer, is definitely a dead end right now. So maybe I'd like to work on how did the first stars in the universe form, for example.

PAUL FRANCIS: So when you try to pick a field to do research, and you're trying to sign up with a PhD Supervisor, you have a spectrum of problems. You've got the really interesting problems that you're not going to make any progress on. And I think--

BRIAN SCHMIDT: That's right.

PAUL FRANCIS: --why does the universe exist is one of those. And then you've got the really boring problems that are very easy to make progress on. Like exactly how many A5 stars are there in the constellation of Orion? I mean, we could answer that. But who cares? It's boring. And so the knack is trying to find that middle ground, something that is interesting enough that you want to devote your life to it. And that when you run a MOOC about it, people will actually tune in and watch it. But not so-- not impossible.

BRIAN SCHMIDT: Yeah. So the art of being a scientist is not just answering questions, it's asking them. And that's what you're really getting down to, is asking the right questions.

PAUL FRANCIS: So on that note, we actually kind of conclude the section of the course that deals with cosmology. However we're not going to finish everything here. We've got a special bonus for you. We've got an extra lesson we're going to put in where we're asking a lot of people about what the future of astrophysics across all of the topics we've covered in all four courses is, and where we're going to be going over the next 100 years. So stay tuned.

A4_L10_V01_Telescopes

BRIAN SCHMIDT: All right, Paul, so we're coming to the very end here of our fourth course. So we've really had a chance to talk everything that we know about the universe in the past. We've speculated about the things we don't know. So I think it's time to think a little bit about the future.

That is, what do we think we're going to learn in the next 10 or even 100 years. And we could speculate a little bit ourselves, but maybe it would be fun to go out and ask some famous people around the world what they think.

PAUL FRANCIS: Now this is almost certainly a waste of time, because efforts to predict the future of any research-- this has been the whole nature of research, is finding things you don't know. So how can you predict source? It drives us mad, when the government asks you to write down a detailed plan of everything you're going to learn by doing the research over the next five years, as governments love to do.

BRIAN SCHMIDT: That being said, you do have to start somewhere. And so I think it's good to start planning the future this way. So I wouldn't say it's a waste of time, but it's probably not what's really going to happen. But I think it's good to think what people are thinking about now.

PAUL FRANCIS: Yeah, it's interesting to look back say, 20 years, and look at what people were predicting back then in various documents where things are going to go. And they missed dark energy and they missed exoplanets.

So almost certainly, the biggest astronomy discoveries of the next 20 or 100 years are not going to be the ones we're going to talk about today. And let's do our best go. especially in 100 years.

BRIAN SCHMIDT: Yeah, 110 years ago, if you think back, people thought that physics was done, and it was time to go do something else. And they definitely got that wrong, so we're probably playing the same game. But we do need to start somewhere, and so we should start with telescopes.

Because we do have some really exciting telescopes coming up, and we're already starting to build these things. And so it's certainly going to be one of the more certain things we have about the future.

PAUL FRANCIS: Yes. For the next 10 years at least, the telescopes that are going to be revolutionizing astronomy in the next 10 years are already being built. So we can predict this fairly accurately. It may be the only thing in this whole lesson we can predict fairly accurately.

So how about optical telescopes? At the moment, we've got the cutting edge telescope of 8 to 10 meter apertures around the world. And there are, what, 12 or so of those around the world? What next? Can we build telescopes any bigger?

BRIAN SCHMIDT: Well, one of the most exciting things, I think, is the next generation of extremely large telescopes. There's three of these being planned, and the one that we at ANU are involved in is called the Giant Magellan Telescope.

And this is a telescope that's roughly 25 meters across, and it's going to be located on Las Campanas Observatory, near the Magellan telescopes, which are 6 1/2 meters.

PAUL FRANCIS: So this is in the Atacama Desert north of Chile.

BRIAN SCHMIDT: That's right. And so you can see this is constructed from 7 mirrors, each one 8.2 meters across. And so they all work together as a giant mirror.

And there's a little bit of gaps in between them, which you'd sort of like not to have. But it's almost impossible to build a mirror 25 meters across out of a single piece of glass.

PAUL FRANCIS: Yes. Some of the other projects are actually using-- like the Keck telescopes-- hexagonal bits of mirrors that are actually bolted together. So you don't have the seams between them, but it's very hard to make it very smooth as you go off the edge of one hexagon to the other. Whereas these ones are at least, individually, very, very smooth.

BRIAN SCHMIDT: That's right. And so this telescope will look up through the Earth's atmosphere. And we know from earlier parts of this course that the earth's atmosphere causes us problems. It causes twinkling, or turbulence.

And what we're able to do is to get around this by having these mirrors up here-- there are seven of them, one for each of these mirrors-- move at 100 times per second-- or even maybe even 1,000-- and take out the atmospheric effects.

And so when we go through and look at this thing, an integral part of this telescope-- as you'll see in just a second here-- is the laser system, that allows us to take out the effects of the atmosphere. So the telescope itself will go through, the light will come down from each of those mirrors, go onto one of these mirrors, and then gets collected behind the main mirror.

And we're expecting this telescope to come online in roughly 2020, when it should get first light. We have one of those seven mirrors completely done. We have two of them cast, and the next-- the fourth mirror-- is being cast, essentially, right now-- coming up in the next couple months.

PAUL FRANCIS: They've blown the top of the mountain to flatten things out there already, so the site works are already underway. It's always a strange game of brinkmanship in these early telescope designs, because you need to get the money, but people often don't want to commit money to a telescope unless they're convinced it's going to get built. And you can't convinced them it's going to get built without building some bits, which requires the money.

And so this whole game the fundraising is actually one of the biggest and most formidable challenges of the whole thing. But a large fraction of the money-- though not always all-- is available for this one.

And the other two extremely large telescope projects-- the TMT project, which will be in Hawaii, and the European extremely large telescope, which will also be in Chile, though on a different mountain-- they're all playing this game of starting to build, or starting to design, trying to raise money.

But hopefully all of them will be built seven or eight years from now. Almost certainly at least one or two of them will be built.

BRIAN SCHMIDT: Yeah, I think it's quite likely all three of them will be built, and they will be the thing that empowers us in the future to look, literally, to the edge of the universe in optical light. But of course, optical is not the only thing. We also have radio.

Now radio is a place where we're starved, literally starved, for signal. Because radio waves aren't very powerful, and things don't emit a lot of stuff. But radio is also something you can make a really, really big, because you can literally take antennas and add them together in the computer, and you don't have to have this precision milling of glass to a nanometer.

PAUL FRANCIS: So the radio astronomers of the world, instead of having three rival consortia-- maybe they're better at collaborating than optical astronomers-- and they decided to build one really big telescope, which is called a square kilometer array, because the idea is it all over a total collecting area of a square kilometer.

However, they couldn't agree on where it's going to go, so part of it will go in South Africa and part of it will go in Australia. And the idea is that you get-- there'll actually be multiple different types of telescopes. This is the low frequency component, and low frequency radio waves-- it's like TV antenna, almost.

And they're arranged in these little circular patches. And each patch will be connected to the fiber optic cables, and they combine-- see, they're from large numbers of these patches. It has to go in a place where there are no radio transmitters. You want somewhere that's flat and empty, and Australia does flat and empty very well in the Outback. So this is part of Outback Western Australia.

Here is the second part of it, which is a survey telescope it actually uses dishes. And we see, a lot of them are in the central cluster, but you may have seen we flew over a bunch of them scattered much further out. So while there's a central core, some of them go out to hundreds of kilometers away.

BRIAN SCHMIDT: Right. And so both of these telescopes are to look at hydrogen-- hydrogen gas-- neutral hydrogen gas, that normally emits a light or a radio of 21 cm length. And so the survey is going to look in the relatively nearby universe, this telescope right here.

And then the one that looks like the little Christmas trees, that's to look at the hydrogen from when the universe didn't have stars or galaxies, it was just full of cold gas. And so the hope is we'll be able to literally see how the gas in the universe formed the first stars, and then with this array, see how the galaxies in action.

Again, we expect the first phase of this telescope to start being constructed about 2020.

PAUL FRANCIS: And there are some pathfinders to explore technology already in operation.

BRIAN SCHMIDT: That's right.

PAUL FRANCIS: And more expensive than either of those-- in fact, more expensive than both of them combined--

BRIAN SCHMIDT: Yes.

PAUL FRANCIS: Would be the next generation space. We've see so many results from the Hubble Space Telescope in this course. And this is its successor, the James Webb Space Telescope, which has had a number of near death experiences at the hands of Congress, because its costs have blown out so much.

And the basic idea here is this telescope will work-- have a much bigger mirror, to begin with. The mirror has to actually fold out.

BRIAN SCHMIDT: Yeah, so it's 6 1/2 meters across-- the mirror--

PAUL FRANCIS: As opposed to 2.4 meters for Hubble Space Telescope. So that immediately gives it a huge boost of power. The other thing that gives it a huge boost of power is it's going to look at infrared wavelengths. And infrared over space has the biggest advantage over the ground, because they're not fighting the emission from everything.

It also has this enormous sun shade, which will allow it to cool down enormously, because you really don't want your telescope glowing at the same wavelength that you're trying to observe.

BRIAN SCHMIDT: Right, and so this whole shield actually allows this thing to passively cool down to about 40 degrees Kelvin, so it doesn't need to have liquid nitrogen, or liquid helium, or anything on board. It does this all on its own.

And the shield is about the size of a tennis court. And I saw that, just earlier this year, that they actually had it full out itself as a practice run in a giant room in the United States. So it's getting very close, and this is supposed to be launching in 2018.

It doesn't sound like it's going to be too much later than that, because if its much later than that, it will cost even more than it has, and so I think there's every reason to believe that this will launch. It's a very complicated spacecraft, the most complicated spacecraft ever made. And so we keep our fingers crossed it'll work.

PAUL FRANCIS: So there's a lot coming down the tracks on that time scale.

A4_L10_V02_BrianCox1

BRIAN SCHMIDT: All right, so we are beginning to wind up this fourth class on cosmology, and we thought we would be-- I'd like to take the opportunity to interview various people from around the world to find out their view of what might be happening. So Paul and I here today have Brian Cox from the University of Manchester. Thank you, Brian, for coming in from your busy schedule wandering around the world. He happens to be in Camber today, so it's great to have you here.

BRIAN COX: Pleasure.

BRIAN SCHMIDT: And so, Brian, I want to just get a sense of where you see physics has been. And now, you are a particle physicist more than an astrophysicist like Paul and I, so what do you see as being the big thing that's happened in your lifetime, your physics lifetime, in the area of physics?

BRIAN COX: Well, in particle physics, it must be the discovery of the Higgs particle. Now, that's-- initially when I talk to people about that, they say, well you've just discovered another particle. There's several reasons why it's very important. One is that it completes. And I'll qualify that a minute, but it completes what we call the standard model of particle physics. It's a theory that's been around for a long time, initially proposed in the '60s, refined throughout the '70s and '80s. And so it was the missing link, the thing that gives mass to the other particles.

So that's one side. Many people have said it means that we really understand physics and quantum field theory very well, because as a prediction the idea that this thing, this condensate, if you like, something that condensed out into empty space in the very early stages, less than a billionth of a second after the Big Bang, and gives mass to the other particles through the particle's interactions with that field. That's interesting. If you can predict that, it means you understand a lot about field theory.

BRIAN SCHMIDT: And you can predict it from advance even though we had never seen a particle of the type the Higgs was, that's quite remarkable.

BRIAN COX: Well, this is the second point. It is a-- it's a completely different kind of particle, a so-called scalar particle. So a fundamental scalar field, this is the first example. And we talked about cosmology, there are other examples, potentially, of where they may exist in nature. One is inflation, this turn is exponential expansion of the universe. Before the Big Bang, if you use the Big Bang as being the time when the universe was hot and dense if that's the semantics you choose, that could be a field of the same character as the Higgs. Similarly, people speculate, dark energy, the accelerated expansion of the universe, of course, which you got the Nobel prize for noticing, measuring.

Again, people speculate that could be a field such as this. So I think that's very interesting in itself. The interesting thing now, of course, is to see whether indeed, that's what it is. It probably is a Higgs particle. All the measurements we've made so far with the large Hadron collider point in that direction, but we haven't fully characterized it yet, by any means. And there are different theories that predict different sorts of Higgs particles, multiple Higgs particles. There's a theory called the MSSM, the minimally supersymmetric standard model, in which there are five Higgs particles. Could it be one of those? Possibly. So the challenge l see now, when it switches on in spring 2015, is to go and characterize that particle precisely, measure it's interaction with the other particles, and see precisely what it is.

PAUL FRANCIS: I mean, could the Higgs particle actually be directly involved in either of the two cases? We've talked of exponential growth of the universe. You talked about inflation, where you have this mixed potential and it drove this incredible expansion. And we've talked about the same thing again with dark energy. Could the Higgs particle, as discovered so far, be involved in either of those, or do you need something else with similar properties but not exactly the same?

BRIAN COX: It's a brilliant question, this. And when I discuss with my theory friends some of them will say there are people trying to build some kind of unified picture in which the Higgs may play that role. It's the wrong energy scale, if you like. The Higgs is a mystery in the way that it behaves, the way it interacts with space time. It's certainly, at first sight, way too big to be dark energy. Oh there's many orders of magnitude too large, but it's also many order of magnitude too small to be the thing that caused inflation, or drove inflation, if indeed they're the same character.

So nobody knows, but it's interesting that it's the right sort of thing. So there are people are trying to build some kind of unified theory of those. I mean, I think these are the big questions where particle physics and cosmology are interacting now. It's how-- we're talking about a quantum theory of gravity, probably. We're talking about how things like the Higgs interact with space time. You could just plug that into Einstein's equations, and see what happens, and the universe just explodes, basically. So each one of the big questions in physics, why doesn't it do that?

BRIAN SCHMIDT: So we also have some other questions about physics that we've discussed that overlap with particle physics. For example, we know that the universe is full of the atoms the baryons that we're made out of. The antimatter part of us doesn't seem to be here. We have 10 to the 9 photons in the universe for every atom. What's going on there? Why is there that asymmetry? You have a complete theory, but it doesn't predict there's any asymmetry.

BRIAN COX: That's absolutely right. We call this CP violation in particle physics. So we've seen differences in behavior between matter and antimatter. And what's called the B system for example. So there was a big experiment at Stamford for many years called BaBar, they did precision measurements on these things called B mesons. And so we see a difference in behavior. But it's way too small to produce, as you said, the matter antimatter asymmetry in the universe, and this huge excess of photons over the other particles that we see. So again, that's not understood. Some people speculate that it's something to do with the neutrino sector.

So that's the other big discovery, perhaps, in my scientific lifetime. These particles called neutrinos, so three of the 12 fundamental particles of matter have mass. Now, that wasn't known when I first started in physics, and it's known now. How they get their mass is a tremendously interesting area. In the standard model, you can just write down that they interact with the Higgs field. But they have tiny masses compared to the particles, so it looks potentially unnatural, and so there are other theories, so-called see saw mechanisms, and think like-- there's different theories about how the neutrinos can get their mass, and there are experiments looking at trying to probe that area now. So the neutrino sector is another very poorly understood piece of particle physics, because they interact so weakly, they're very difficult to observe.

PAUL FRANCIS: Now, if we look forward about 10 years maybe, it's a short term horizon, how do you see experimental particle physics contributing to our understanding of cosmology over the next 10 years? Is it going to do much to help us solve all these puzzles that baffle us at the moment? I think the obvious place it could is dark matter. So dark matter, you know there's 5 times as much dark matter as matter. Undoubtedly that's true, as you probably discussed in the course.

BRIAN SCHMIDT: Indeed.

BRIAN COX: And it looks like it's some kind of particle, probably, although there are other theories. And we have theories, which, actually, I think before the large hadron collider switched on, most people would've favored so called supersymmetric theories, where essentially, you double the number of fundamental particles. And the lightest supersymmetric particle can be a very strong candidate for dark matter. Those theories tend to have more Higgs particles as well, five in the case of the so called MSSM. I think it may have been a surprise to people that it looks like the standard model stands up on its own with 1 Higgs particle. And that causes theoretical problems. And I think, most theoretical physicists, I would guess-- and that's an interesting word, most-- but I suspect most would have said no, I think we're going to find supersymmetry. Now we haven't yet, but it's not ruled out. But large areas of the parameter space are now ruled out with LHC, but it's still possible, undoubtedly. And that would be the great discovery, it would be a bigger discovery than the Higgs particle.

BRIAN SCHMIDT: Yeah, my colleague, Frank Wilczek, who's been a lot to do with developing those is still willing to, I think, take bets that SUSY will be seen eventually. I have to admit, it's not completely obvious to me, but I'm always a skeptic in these things.

BRIAN COX: I mean, it's a natural thing. It's a space time symmetry that hasn't been used, Frank would say, he'd be right, the only one with a spin symmetry. And also it mathematically is very pleasing. It saves you from a lot of the problems that the standard model Higgs particle generates mathematically as well. So it looks like it's something that should be there, if you like the aesthetics of fundamental particle physics.

PAUL FRANCIS: Do you think we'll know one way or the other in the next 10 years, once the LHC goes up to higher energies and runs again? Well, we don't know how massive these particles are. To do the job, the aesthetically nice job, the mathematically pleasing job, they should be within reach, you would think, of LHC. So we need precision measurements now of the Higgs. As you say, we need more energy, but also more what we call luminosity. Because particle physics is a statistical science, so the more protons we can collide together, the more chance we have of seeing these massive particles if they exist.

PAUL FRANCIS: Because they're rare events, so you need to have a lot of collisions to see them. Yes, so that's the main-- the LHC is going up in energy, but it's also going up a lot in number of collisions per second.

BRIAN SCHMIDT: So do you think it's going to be most likely to come from the LHC, or what about these direct detection events, where we put a detector down in a mine, and wait for a year, and hope for a couple direct collisions that light up the detector.

BRIAN COX: Yeah, sure, because the thing about the dark matter particles is they must interact only by the weak nuclear force. Surely that's the case. So therefore they will, in the same way that neutrinos collide occasionally, and we have solar neutrino detectors, like Kamiokande in Japan. You can have dark matter detectors. And there are many of those there, and the hope is that one of the dark matter particles will collide. And that's an equally plausible way of seeing one-- more plausible-- they're very massive, and outside the energy reach of LHC. That's the only way we're going to see them. Those are the two sides of physics. I suppose it's the-- it shows the difference between astronomy and particle physics, in a way. Because astronomy, you look at nature. That's one way of doing it. And the other way is more Lab based. You create your conditions yourself.

PAUL FRANCIS: Well, we'd like to put a black hole in the lab, but we haven't quite got the funding for that.

BRIAN COX: Yeah well, you never know with the quantum theory of gravity, you might be able to do it, if you could drop Planck scale down a bit with extra dimensions or something. Who knows?

PAUL FRANCIS: We'll see. It seems like we're playing with fire when we get there.

BRIAN COX: Indeed.

A4_L10_V03_BrianCox2

PAUL FRANCIS: So now let's get really speculative and say there are still perhaps the most fundamental questions of all, like why is there anything rather than nothing? Why did the Big Bang happen? Did you press the big red button marked Do Not Press?

If you look 100 years down the track, which of course impossible, but let's do it anyway, how would you see experimental particle physics being able to address even more fundamental questions on that sort of time scale?

BRIAN COX: It's an interesting question, actually, and we're facing it now because accelerators require decades to plan and build. And the question is do we need another one at the moment?

It's a fundamental question in particle physics, because you don't just build them speculatively. You need to know how big you need to build it, what energy you need to build it at. Otherwise, you won't get the money, basically, and neither should you, I think, if you have no idea what you're doing.

So the thing is what we're going to do is we've got to make precision measurements of the Higgs particle to try and understand how that works.

Now the LHC can do that to an extent. There's a better way of doing that, ultimately, which is to build what is called a linear collider, which collides electrons and antielectrons together. And where you can build Higgs factory, a very clean environment to look at the Higgs.

So that might be the root. It might be precision measurements of the Higgs. Or if you get the hint that supersymmetry is there, or you indeed detect those particles, then you have a whole new particle zoo to explore. And then you design the machine depending on the questions you have to ask.

And the reason the LHC was built, by the way, is because that energy, the Higgs particle, either had to exist or the standard model was broken. So it was a guaranteed energy. You know that in that energy, so-called "unitarity."

Essentially what happens to the standard model when you take the Higgs out, the LHC energy, is you get predictions for things with a probability greater than 100%. So the model breaks, so you've got to put something else in there. So that's why we built the LHC.

So particle physics is at an interesting point, actually. We need to know is accelerator physics, is building an accelerator the next thing you would do? Is there a goal in mind? You can't just go fishing by building it. There are plans to build a 100 kilometer in diameter machine at CERN. But you wouldn't do that just because you've thought we'll have a little pop at it and see what happens.

[INTERPOSING VOICES] our fishing now?

BRIAN COX: You need to know. But that will come from precision measurements. There are huge numbers of questions. It's certainly not a complete theory. I don't think really any particle physicist thinks the standard model is complete.

Although it technically just about can be up to very high energies. But you end up with all sorts of contrived knobs you've got to twiddle to do that. So it doesn't feel that it should be complete up to the Planck scale let's say.

BRIAN SCHMIDT: So let's be a pessimist and say LHC goes and we don't find anything that's like supersymmetry. We get no clues. I mean building a giant linear collider, very expensive. That might give us some insights. It might not. 100 years from now, is this field just going to die unless we start discovering something?

BRIAN COX: Well, it's a very good question, because I'm not, I don't think scientists should be tribal. We're all physicists and we're all trying to answer these questions. And I think it's true that if we don't see any more particles then the only thing you can do is make precision measurements, particularly the Higgs. You need a Higgs factory.

One of the things we really want to do is measure the Higgs. It's called the self-interactions. We want to collide Higgs particles together. That's very important. And it's difficult to do that.

You can do it, with LHC lots of statistics but it is difficult. So you'd want a clean environment to measure that. That allows you to map out this potential. The Higgs potential, the Mexican hat potential, the wine bottle. Whatever you want to call it. You can map that out if you can watch Higgs particles colliding.

So you want to build-- what you want is a Higgs collider in a very clean environment. And you can do that. And so that might be the way to proceed.

Also, the neutrino sector I think is extremely interesting. So you'd want to probe that. That's not understood, I think. So there's a lot of experimental particle physics to do. But it might be different ways of doing it.

It might be about precision, which is what we did throughout the '80s, really, and '90s with the LEP collider. It was about precision physics. So to make precision measurements. And often discoveries come from precision, as well. So that might be the future.

Or of course we might uncover this whole zoo of particles. And that's why the LHC the next 10 years at LHC are going to be extremely significant, I think, even if we discover nothing. And then it's surprising. Then you really start wondering.

The standard model has no business being as successful as it is. That's the thing. There's no reason why it should be so good. No one thought, as I think Frank Wilczek said, when they built the thing that it would be-- it would stand up to 20 or 30 years of precision measurements. It's a triumph in that respect.

BRIAN SCHMIDT: Well, I have to, myself, not really looking forward to being surprised by nothing. So let's hope for being surprised by lots of things. But on behalf of Paul and me and our massively online open course here, cosmology, thank you so much for joining us today.

BRIAN COX: Pleasure.

A4_L10_V04_LisaKewley

PAUL FRANCIS: Our next guest is Lisa Kewley, who's very active on research on galaxies and how they evolve over the last ten or twelve billion years. So Lisa, what do you think is the biggest astronomy breakthrough in the few decades?

LISA KEWLEY: I think the biggest astronomy breakthrough is the discovery of the cosmic microwave background. And this happened in 1964, so it's about five decades ago. But what it really did was it brought the Big Bang theory from just an idea and a theory into a solid picture, that we now think really happened in the universe.

And it was an accidental discovery. There were two astronomers in the US-- in fact, lots of astronomers around the world were trying to discover the cosmic microwave background at the time, it wasn't just these two. But they had built a very sensitive radiometer, which is a thing that measures the power that comes out of a the radio telescope.

And they also had a very nice radio telescope dish, which they attach it to. And when they attached it, they discovered that there was this radiation that was coming from everywhere in the sky, and they didn't know what it was from.

And they first thought it was bird droppings-- pigeon droppings, in fact. And so they got out the telescope and they cleaned it all off, and then they shot the pigeons.

And then what they did is they measured it again-- still there. And they didn't know what was, so they called their friend at Princeton and asked him what it might be. And he said, well it might be the cosmic microwave background. So they agreed to publish two papers, one on the discovery and one on the interpretation of the fact that it probably likely came from the Big Bang.

PAUL FRANCIS: So do you see that discovery as being the most important part, or the subsequent measurement of all the deviations? So we've talked a lot about the deviations, the fluctuations that tell us all about that time right after the Big Bang.

LISA KEWLEY: So I think they're both extremely important. We wouldn't have been able to measure the deviations without the initial discovery. But then-- and I think what makes something a great discovery is then it opens up an entirely new field of research, which is what this did.

Because suddenly we could investigate the cosmic microwave background, and we're still investigating the cosmic microwave background right now, even looking for gravitational waves.

BRIAN SCHMIDT: So let's think a little bit more into the future. So speculating about the future is probably futile, yet we do it all the time, and how we plan our lives, actually. So what do you see as being the most exciting thing that you think's going to happen, if we were to have this conversation 10 years from now? We'd say, since 2014 what's the big thing that will have happened in astronomy over that time?

LISA KEWLEY: So the next ten years is a really exciting time for astronomy, because what's going to happen is all that all of our current telescopes that we have right now are going to become what we would call intermediate size. And say we're entering as revolution in size of telescopes, and so we're going from telescopes that are about 8 or 10 meters-- as our largest telescopes-- to telescopes that are 20 or 30 meters.

Our radio telescopes are also increasing massively in size. Our space telescopes are going to increase massively in size. And the last time this happened was in the late 1990s, when we were building our 8 to 10 meter telescopes, and now large radio telescopes that we have now.

And what those telescopes did in the late 1990s was that they opened up a whole new area of discovery space. And so, for example, the discovery of the fact that the universe is accelerating was enabled by the fact that we had larger telescopes in space and larger telescope on ground.

And also, for example, the discovery of extra solar planets wouldn't have been possible without these large telescopes on ground. And so I think we're going to enter a new discovery space again-- major discovery space-- by having these large telescopes on the ground, as well as in space.

And it opens up whole new areas. In particular, I think we're going to really be able to understand what happened much closer to the Big Bang. The epoch of re-ionization, where the first stars and the first galaxies formed. That's what we're really going to try to probe.

And also we're going to try to understand whether other planets might be able to harbour life, so we're going to be able to study planet that are the same size as earth, and then look at what's in their atmospheres. What are they made of, and could they possibly be life on them. So I think it's very exciting.

BRIAN SCHMIDT: So what do you think you will discover in the next 10 years?

LISA KEWLEY: I'm trying to bridge the gap between what we understand now about galaxies, looking back about 12 billion years to the epoch of re-ionization, so I'm looking into the amount of ionizing radiation in galaxies.

And what I hope to discover is how the ionizing radiation changed in galaxies across cosmic time, going right back to when the first galaxies formed in the universe.

BRIAN SCHMIDT: So really trying to figure out how galaxies themselves got started in this universe.

PAUL FRANCIS: Now if we look further ahead, which is even more futile, but let's do it anyway. Now let's look maybe 100 years ahead. What do you think will be the big breakthroughs that the astronomers 100 years form now will say, gosh, the last 100 years have been exciting, here's what we've learned.

LISA KEWLEY: So I think in 100 years, there will have been new entirely new parameter spaces are opened up in astronomy for discovery. So for example, we will have detected gravitational waves. Once we detect gravitational waves, then it's a bit like the comic micro background, because that opens up that particular thing-- gravitational ways to study of physics, real fundamental physics in the universe. So we're going to be able to see whether Einstein's general relativity was correct, and we'll be able to really try to look at the physics of super massive black holes. Black Holes that are merging.

But I think what we're going to be doing in 100 years is trying to understand the physics of the universe. Very close to the Big Bang, and also just a fundamental things like General relativity, or whether there needs to be different theory.

BRIAN SCHMIDT: You're not worried about running out of fuel on the way there? That we just sort of run out of ideas, and we run out of technology?

LISA KEWLEY: No, it hasn't happened so far. I think what's happened so far is that we look back over history-- every time we have larger and larger telescopes, and more and more discoveries. It actually makes more questions to answer, rather than less.

PAUL FRANCIS: Great, thank you very much.

LISA KEWLEY: Thank you.

A4_L10_V05_McClelland1

PAUL FRANCIS: A large part of the progress of astronomy over the last 70 years has come from opening up the whole electromagnetic spectrum. Back in 1940, we basically only did astronomy at optical wavelengths. Since then, we've explored radio, x-ray, gamma ray, infrared, ultraviolet, and this has revolutionized astronomy.

But now we're kind of stuck. We do the entire electromagnetic spectrum. In principle, there are ultra hard gamma rays, ultra low frequency radio that are still to be observed, but they don't get anywhere near the earth, so that's never going to tell us very much unless we can get observatories outside of our galaxy.

So what can we do? Well, one possibility is to use an entirely new spectrum, the spectrum of gravity waves. To talk us through that, it's a great privilege to have David McClelland, who's director of the Centre for Gravitational Physics with us, who is leading our effort to find gravity waves.

DAVID MCCLELLAND: Thank you very much, Paul.

PAUL FRANCIS: So David, what's a gravity wave?

DAVID MCCLELLAND: Well, Paul, as you know, Einstein's general relativity explains gravity as arising from mass curving space time. So if mass curves space time, if space time can be curved, it means it's flexible. Now, anything that's flexible can support waves, and waves in space time curvature are gravitational waves.

PAUL FRANCIS: So what does a gravitational wave look like when it hits you?

DAVID MCCLELLAND: Well, it's quadrupole in nature, so as it passes through objects it causes them to distort, like distorting a circle. You get squashed in one direction, while squeezed in the other.

Then the sign changes. You get squeezed and squashed in one direction, and stretched in the other. So it's a squashing and a squeezing, stretching and squeezing, as a gravitational wave passes through.

So they're passing through us all the time. We're being stretched and squeezed by gravitational waves as we speak.

PAUL FRANCIS: So what would actually create a gravitational wave?

DAVID MCCLELLAND: Well, they arise from any motion which is not spherically symmetric, any matter moving in a non-spherically symmetric manner can generate gravitational waves. Two objects which are circling around each other will generate gravitational waves.

The problem, of course, is that these effects are extremely small.

PAUL FRANCIS: Yes, I'm not noticing you elongating and squashing as you sit here, so why not? Why aren't the gravity waves doing that to you?

DAVID MCCLELLAND: Well, space time is flexible, but it's extremely stiff. That means it needs very violent events to generate even the smallest amplitude of a wave.

So for example, if we have two neutrons stars a few mega parsecs away orbiting each other, as they're going to crush in, they're going to change. They're going to generate a gravitational wave whose strain-- which is the way we measure gravity waves. It's the length change divided by the length.

Remember something stretches out, so we want to measure how much that length changes as a fraction of the separation. So for a pair of neutron stars which are colliding, that change is 1 part in 10 to the 24.

PAUL FRANCIS: That's as measured at the earth, presumed to be much bigger if you're actually close to the neutron stars.

DAVID MCCLELLAND: It's much bigger, but it's still a very small effect. So in our region of the earth, it's about that 10 to the minus 24 is the strain.

PAUL FRANCIS: So that means, let's say humans are about a meter in length-- maybe 2 meters in length if you're possible playes-- so 2 meters times 10 to the minus 24, so 2 by 10 to the minus 24. Given that the nucleus of an atom is 10 to the minus 15 of a meter, we're talking about a billion times less than the nucleus of an atom.

DAVID MCCLELLAND: Yes, it's an extremely small effect. So the more mass of the objects which collide, the larger the amplitude. So the typical sorts of amplitudes we may be looking for on earth over the next few years are more like 10 to the minus 18 to 10 to the minus 19 of a meter.

So it's more like 10,000 times smaller than the size of a nucleus. It's an almost unimaginably small effect. In fact, if I stop and think about it too long, I think this seems pretty ludicrous.

However, we're only a factor of 10 away from doing that.

PAUL FRANCIS: Now this seems completely impossible. You're trying to look for changes in length of your 1/10,000 the nucleus of an atom. I mean, how can we possibly hope to do something like that?

DAVID MCCLELLAND: Well, Paul, one of the methods we use is called interferometry. We're going to use Michelson interferometry. So a Michelson interferometer is a laser beam which shines onto a mirror, which splits the laser beam into two. One laser goes off in one direction, the other one in a perpendicular direction for 4 kilometers, where they're reflected off a mirror, comes back to the beam splitter, where we look for the interference.

The change in the pattern of one wave when it's combined with the other wave-- and that interference will tell us about anything which has caused changes along those two perpendicular arms.

PAUL FRANCIS: Presume it's relative changes.

DAVID MCCLELLAND: Relative changes. So remember, the gravitational wave causes a stretching and a squashing. So one arm stretches, the other squashes. So if I have a laser interferometer, this length, this laser beam is measuring a shorter distance. This one is measuring a longer distance, and we can measure that by the interference pattern.

PAUL FRANCIS: Now we haven't got a 4 kilometer long experiment here. Where are these things actually located?

DAVID MCCLELLAND: Well, there are a number of them. There are about three of these long interferometers around the world-- two in the United States, which is called the LIGO project. And LIGO is Laser Interferometer Gravitational Observatory.

And there's one in Europe, in Pisa. That's a French, Italian and Dutch project, and it's called Virgo.

PAUL FRANCIS: So what we're doing here is developing technology for LIGO, is that right?

DAVID MCCLELLAND: Yes, we are. These instruments-- it sounds quite a simple. You just measure this change compared to that change, this arm changing compared to that one. But there are so many things that cause those differences in lengths to happen.

There's the earth's seismic noise. If you just put one mirror on the ground here, and another one there, the earth is vibrating. So that seismic vibration, which is 1 micron in size, that's 10 to the 12 times bigger than the effect we're trying to measure.

Then there is quantum noise we have to worry about, then thermal noise. The mirrors are hot, so they're fluctuating with energy.

PAUL FRANCIS: The atoms are jiggling around.

DAVID MCCLELLAND: Atoms are jiggling around, and that jiggling around in this arm is different to that arm. So this jiggling around causes a different effect on the laser beam to that jiggling around. So somehow we have to make our instrument insensitive to that.

There is things-- just guest particles passing through the laser beam changes the refractive index, which also is going to create a problem for us. So we need to put our systems in gigantic vacuum tubes-- 4 kilometer long in one direction, 4 kilometer to the other, 1 meter diameter vacuum, at-- the largest ultra high vacuum systems ever made.

PAUL FRANCIS: Now is this LIGO currently capable of detecting enough-- small enough strain to be able to pick up gravity waves?

DAVID MCCLELLAND: Well we ran the first generation of LIGO up to about 2010, 2011, where it reached about a factor of 10 to the limits wanted. So we needed to, and we'd been planning over that year-- it was already known when LIGO was designed that it wouldn't be sensitive enough.

But the US National Science Foundation funded it to prove the principal, and then funded the next stage to get that next factor of 10. Now, laboratories like this one in particular-- we're working on the techniques and technologies to take us that extra factor of 10 down in sensitivity, so we can finally see gravitational waves.

PAUL FRANCIS: So what source of noise you haven't overcome to get that extra factor of 10?

DAVID MCCLELLAND: Well, one of those sources of noise is called thermal noise. The fact that the mirrors are fluctuating with the Brownian motion, which is going to mask the signal unless we do something about that-- then one of those things we need to do is to measure that effect, and see if we can use ultra pure materials to make it smaller.

PAUL FRANCIS: So one of the big sources of noise we're going to have to overcome to get this extra factor of 10 insensitivity is the thermal noise, the random vibrations of the atoms in the mirrors. And this is what this experiment here is addressing. So would you like to explain what's going on here?

DAVID MCCLELLAND: Yes, this experiment is to understand the thermal noise properties of the materials which we're going to be using in, not just advanced LIGO but the next generation beyond that. We're already planning for LIGO Voyager. And LIGO Voyager is going to have a range out to a redshift 1. So it's going to see a lot of sources.

But we need to understand the thermal noise of the materials we use in that device. One of the materials is called silicon. Now, silicon is extremely well known, of course. It's a big industry.

But we want to build mirrors out of silicon that of this size, and we want to cool them down to 120 kelvin. And we want to understand how the thermal noise of the mirror varies as we change the temperature.

So we have to set up an experiment which is almost like a mini interferometer. So what we've got here is a vacuum chamber. So inside this vacuum chamber, we've got an ultra high vacuum level. All of the gas is being pumped out.

Coming down the side here is an isolator. It's a series of pendulums, at the bottom of which we're filtering out seismic noise. Now, this is an interesting little experiment one can do. You can take a pendulum-- if I had one here, it'd be an easy experiment--

If you move the top of a pendulum very fast, simple mechanics tells us that if you move it above the resonance frequency of the pendulum, the pendulum doesn't move much at all. So we filter out seismic noise by using that filtering effect of the pendulum.

So then at the bottom of that we have an optical table, a bench which has optical cavity in it. Now an optical cavity has one mirror made of silicon, and then a front mirror. And the light bounces between the silicon mirror and the interrogating mirror.

And we're using the light to measure the properties of the silicon. So we start off with our laser, which called a 1064 nanometer laser here. So all these optics condition the laser so that it's got the right shape to be shone in, down through a periscope into this port here, into the vacuum system, where the little cavity is with the silicon mirror on it-- the silicon flexion.

The light then reflects off that cavity, comes back in through this isolator, onto a photo detector here. And we may use the information received on that photo detector to measure the displacement of the noise, which is fluctuating in that system.

And then we're comparing that noise to the properties of the predictions from what's called the fluctuation dissipation theorem, just how big the thermal noise is, what should it be, does it fit theory.

If that works, then we know that silicon is going to be a good material to use in future detectors. So that's the main property we're after in this particular experiment.

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PAUL FRANCIS: So in principle, David, we can deal with the thermal noise by cooling everything down as close to absolute 0 as possible, however impractical that might be in practice. And you can also improve things by getting these ultrapure materials. But that's going to get rid of the thermal noise. But there's a more fundamental of it, which is quantum-mechanical noise. Even if you cool something down as much as you like, it's still going to be moving because of the uncertainty principle.

DAVID MCCLELLAND: That's right.

PAUL FRANCIS: What can we do about that? Is that hopeless? Because that's, once again, much bigger than what we're trying to measure.

DAVID MCCLELLAND: Quantum noise, as you've learned in the course, affects everything. In terms of light, it's the light-- the quantum noise which is on the light field which is affecting our measurements. And it's the light that bounces off the mirrors. And it's the light we're using to infer the measurement. So the way we look at uncertainty in a light beam is its amplitude and its phase. No matter how well we build a laser beam-- in the classical world we can make it perfect, perfectly measure its amplitude. Quantum mechanics says the amplitude fluctuates.

PAUL FRANCIS: It's kind of like thinking there's a stream of photons, almost, like a machine gun of photons that are going to ricochet off in some random arrival pattern.

DAVID MCCLELLAND: So that's the counting effect. There's a number of ways to interpret--

PAUL FRANCIS: As always with quantum mechanics.

DAVID MCCLELLAND: --quantum noise. And the quadrature, or the phase amplitude picture, is the one that we like.

PAUL FRANCIS: OK.

DAVID MCCLELLAND: If you want to in an interferometer, what we're measuring is a wave coming from one arm and a wave coming from the other arm. And those waves interfere. And what's important is the phase difference between them. We want to measure that phase difference to tell us about what happened to the mirrors. But if the phase is accompanied with some noise, some quantum-mechanical noise, once the phases are too similar we can't separate out the phase any more. And that's a quantum-mechanical limit to how precisely you can measure two phases, or the phase difference between two beams.

PAUL FRANCIS: So what can you do about that? I mean, it's quantum mechanics. Is there anything you can do?

DAVID MCCLELLAND: Well, we can't beat the uncertainty principle. And the uncertainty principle tells us that the noise or the phase uncertainty multiplied by the amplitude uncertainty has a lower bound plane that's the h bar. But that doesn't stop us from saying, can we make a laser beam whose phase is very, very precise but its amplitude is very, very noisy?

Now that wouldn't matter if we were trying to measure phase. If we could make a very, very precise phase light beam and we don't care about the amplitude, we can make a precise measurement of phase. We do that by using something called squeezing. It's a quantum optics effect.

You take a laser beam. You shine it into a nonlinear crystal made of periodically poled lithium niobate or potassium, whichever one you want to use. That light then undergoes a nonlinear conversion process. And when it comes out the parametric effect has squeezed the phase that made the amplitude noises.

PAUL FRANCIS: Is that what's happening here, then?

DAVID MCCLELLAND: It's actually not what's happening in this particular experiment. That's on the table behind me in a big box, is our squeezing experiment. Now where ANU is very-- we've done an experiment using this squeezing effect on a 4 kilometer interferometer in the US on LIGO. We took a squeezer made in this laboratory over to the US two years ago and demonstrated that this effect works.

PAUL FRANCIS: OK. So what's happening here?

DAVID MCCLELLAND: Well, the next problem, and I've just pointed out, we make the amplitude very noisy. And if you don't care about the amplitude, that's all right. But what is amplitude doing? That laser is hitting the mirrors of our interferometer. And it's exerting a force on the mirrors. The force noise is bigger the bigger the amplitude noise. So if we put all of our noise of our laser beam into the amplitude, we're buffeting the mirrors around now.

PAUL FRANCIS: That's why your phase is perfect. It's reflecting the shaking mirrors.

DAVID MCCLELLAND: It's reflecting the shaking mirrors. This is the sort of Heisenberg microscope thing. When you try to measure something precisely, you interrupt its motion. So we need to be able to use-- we have to worry about that radiation. It's called radiation pressure noise, in fact.

Now in the instruments we've built to date fortunately where the radiation pressure noise dominates there's all sorts of other noises we haven't got rid of. There's the seismic noise, the thermal noise. But in the generation we're building next we're going to clear all that up. And we're going to be faced with quantum radiation pressure noise. And so then instead of squeezing the phase we have to squeeze the amplitude. If we make the amplitude very, very precise then it's not bouncing the mirrors around anymore.

PAUL FRANCIS: But then won't that again kill you by giving your amplitude back?

DAVID MCCLELLAND: But this is where the transfer function of the mirror works out. The transfer function of the mirror means that the radiation pressure noise dominates at low frequencies. The photon or shot noise, the phase noise dominates at high frequencies. So we build a squeezer whose squeeze quadrature, phase or amplitude varies as a function of frequency. And we can capture quantum noise reduction right across the frequency band.

It's a fascinating experiment. However, it's not been demonstrated before. This has not been seen. Quantum radiation pressure noise in gram-scale interferometers has not yet been observed, let alone the kilogram mirrors in LIGO. So this experiment here is being set up so that we can try and measure quantum radiation pressure noise. So that we can then use our squeezes to reduce the quantum radiation pressure noise in this experiment.

So we can't build a 4-kilometer-long interferometer in this lab. But we can build something which is called a torsion-bar interferometer. So now instead of measuring mirrors which are changing in shape like this, we're using the torsion motion. So one torsion bar is rotating like that. Another torsion bar rotates like that. And we measure the separation from the tips of the torsion bar. And this is a very precise, very clever way to make a very high precision interferometer. Unfortunately, one that hasn't measured gravitational waves, because the length is--

PAUL FRANCIS: Too small.

DAVID MCCLELLAND: --too small. But it does let us measure-- hopefully measure quantum radiation pressure noise. And then shine our squeeze states into that and show that we can reduce that noise, and how we can reduce that noise. So that in-- I think we're looking maybe five years in the future, we'll be taking that technology and installing that on the LIGOs and the VIRGOs.

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PAUL FRANCIS: So DAVID MCCLELLAND, with all these amazing techniques do you think that any time soon we're actually going to be able to measure gravity waves?

DAVID MCCLELLAND: Well this is a really important question, Paul. I expect that within the next-- before the end of this decade, we will have measured directly for the first time gravitational waves. However it's a very complex question to answer, because it depends on a number of things.

Statistics, for example, we're not really sure how many of the binary neutron star inspirals are out there. And every time a new inspiral is discovered, our statistics get better and better. But if we take that into account we're very certain of the waveform that will be generated. So it's just how many are out there. With our current estimates I think we've got a better than 75% chance of seeing gravitational waves by the end of this decade.

PAUL FRANCIS: So this is from inspiraling neutron stars.

DAVID MCCLELLAND: From inspiraling neutron stars.

PAUL FRANCIS: They meet their doom, and that last few minutes or seconds as they go all the way in.

DAVID MCCLELLAND: Yes, the signal is a chirp. It starts off with the low frequencies and it finishes at about a kilohertz. So it goes [WHISTLE] and that's the end of the collision. And these two neutron stars merge.

What comes out of it? Probably a black hole, which is also vibrating and generating its own gravitational waves. But that mess that comes out of gravitational waves has so much information in it that recording and understanding that information will tell us a lot about those systems.

PAUL FRANCIS: So these discoveries will be made with, presumably, advanced LIGO. Are there other experiments out there with different technologies to try and measure gravity waves?

DAVID MCCLELLAND: Yes. Well, just like the electromagnetic spectrum-- which covers many orders of magnitude-- so does the gravitational wave spectrum, from the very, very low frequencies up to the audio band, and some people believe into the megahertz frequencies. The very, very low frequencies is pretty famous over the last year, because that's the subject of the BICEP2 experiments, as to whether there's a signature of inflation built in these gravitational waves from the early universe.

At around the nanohertz, we're looking at what are called pulsar timing arrays. These measure the effect that a passing gravitational wave has on a spinning neutron star. And by measuring the effect that a wave has on a group of spinning neutron stars throughout the universe, we can measure gravitational waves using that effect. That's in this nanohertz band, where Australia is pretty famous with the Parkes Pulsar Timing Array for that sort of work.

PAUL FRANCIS: Yeah, so the BICEP2 frequencies you're talking about are wavelengths of billions of light years. You're never going to measure them directly, the entire galaxy is being moved around. So unless you could-- the way we measure them in the microwave background of these nanohertz ones, we moved the entire earth, we can measure the position of the earth relative to these distant pulsars.

DAVID MCCLELLAND: To the distant pulsars.

PAUL FRANCIS: You're not going to see distortion within the earth from those things.

DAVID MCCLELLAND: No, it's a unique signature that comes from this change that we see by looking at those pulsar residuals that come out of the experiment. The changes in the timing, that's where the signal is going to be.

PAUL FRANCIS: There's still a large frequency range between nanohertz and the megahertz you've been talking about.

DAVID MCCLELLAND: Yes, there is. And in that space there is something called the space antennas. LISA is the most well known. This is a group of three satellites which have flown around the earth. And their arm length separation is 5 million kilometers. You might recall that I said that what we're trying to measure is a strain, which is a change in length divided by length. So the much longer the length, the much better we're able to make that measurement.

So if we can go to space, we can have not 4 kilometer lengths, such as the LIGO, but we can have 5 million kilometer lengths. And there we're looking at the millihertz band, which is the band where there are things like white dwarf binaries. Now the LISA, the space antennas could almost be confusion limited by the number of sources of gravitational waves that they will see. We're so confident that if LISA flew and didn't see gravitational waves, general relativity would be well and truly on the edge of disaster.

PAUL FRANCIS: So do you think LISA is going to fly? And if so, when?

DAVID MCCLELLAND: Well, LISA has a launch date, a European launch date of 2034. So it's a long way from now. Hopefully we will have been observing gravitational waves on the earth from 17 years before then.

PAUL FRANCIS: So for these ground-based experiments at the higher frequencies, you've said that advanced LIGO should be able to pick up at least a handful of these chirps over the next decade or so. Where to from then? That can be very interesting in itself. But do you think that we'll be able to get several orders of magnitude more sensitivity, and start picking up things further, and other things?

DAVID MCCLELLAND: Well, the chirp is-- the end spiral is only one of the sources we're looking at, of course. There are four types of sources. One of the sources is stochastic backgrounds. We'll be looking with LIGO for stochastic-- perhaps more like foregrounds. We're going to be looking not at the primordial stochastic background but other backgrounds that might be out there. We're looking at spinning neutron stars--

PAUL FRANCIS:so the cumulative effect of vast numbers of chirps, and things like that? Or--

DAVID MCCLELLAND: Yes. So with that, then there's the actual CW sources. The neutron star spins in its gravitational waves. How big that wave is depends on how big the bump might be on a neutron star. We don't know that--

PAUL FRANCIS: so if they are perfectly spherical, there won't be anything, but if there is a

-mountain, which might be like a millimeter high, or something. Then that spinning around will generate gravity waves.

DAVID MCCLELLAND: But once we measure that signal, we can then understand the equation or state of the crust. Because that's what has to distort to give us our waves. We then have other sorts of bursts that we're looking for. And supernova is a classic example. Now, supernova is such a complicated thing that we really don't know what the shape of the signal is going to be. But if it's an asymmetric collapse in a supernova, we'll pick that up.

So these are the types of sources which a ground-based detector is going after. With LIGO we might see two or three sources-- with advanced LIGO, two or three sources a year. So we have plans to improve that sensitivity by a factor of ten.

PAUL FRANCIS: How are you going to do that?

DAVID MCCLELLAND: Well, we need to use quantum states of light. That's one of the necessary methods. We'll probably need to cool the mirrors down to get rid of thermal noise. We'll need to use better suspension systems, high quality coatings, all of these technologies which are doing what advanced LIGO does better and better. But the quantum effects on this are going to mean that we're going to put mirrors which are 40, 50 kilograms scale size into quantum states.

So we're going to be able to measure gravitational waves with massive objects, 40 kilometer long instruments, measuring the weakest signals in the universe generated by the most violent events, limited by quantum mechanics. Now that's a fantastic field of research.

PAUL FRANCIS: Sounds like fun.

A4_L10_V08_Katie_Mack

PAUL FRANCIS: Now one of the biggest questions astrophysics has been addressing is what is dark matter? What is most of the universe made out of? Now, we know there's very large amounts of dark matter, but what actually is it? We believe it's some sort of nonbaryonic particle, but what?

Questions don't come much bigger than that. To help us address this question, it's a great pleasure to have Dr. Katie Mack from the University of Melbourne, who's a famous astro-tweeter at @astrokatie. We'll put the link below the video. She has a background in combining particle physics and astrophysics, and so she's an ideal person to tell us about what dark matter could actually be.

Now all over the world, Katie, there are experiments in caves trying to measure dark matter particles as they fly through. And some of these groups claim they've actually detected it. What do you make of this?

KATIE MACK: I think it's complicated. I think it's difficult. The experiment is a very difficult one to do. You have to take your detector, put it deep underground to shield it from cosmic rays and then you have to put in a lot of other shielding because of things like nuclear decay in the walls of the mine or whatever you're in. And so there are a lot of ways you can get confused and think that something bumping into something in your detector was a dark matter particle. And so this is a very difficult measurement.

PAUL FRANCIS: So what have these very difficult experiments actually found?

KATIE MACK: Well, so there have been a number of different results, and some experiments have found a signal that looks like a particle that could have been dark matter has come into the experiment and bumped something within the target material. And that might be consistent with a dark matter particle coming in, but it could also be consistent with some kind of background particle, some kind of cosmic ray, some kind of nuclear decay-- anything like that.

There's another experiment that's seen an annual modulation in their signals. They've seen a few more events at one time of year than at another time of year. And that would be consistent with there being more dark matter when we're moving into the dark matter wind than when we're moving out of it. So basically, we orbit the sun. And the sun is going around the galaxy, and so sometimes we're moving toward the dark matter and sometimes we're moving away. So that might be a signal of dark matter, but it could also be something like the backgrounds changing with the seasons. And we haven't figured that out yet.

So there are a whole bunch of different signals. They may or may not be dark matter. They can't all be dark matter because they disagree with each other. And some of these experiments have to be showing us something other than dark matter-- or maybe just nothing at all.

PAUL FRANCIS: Now, one possible way to find out what dark matter would be, would be some theories suggest that dark matter particles actually would interact with other dark matter particles and produce a photon, maybe; a gamma ray; or an x-ray; or something like this. And this is most likely to happen where the dark matter's at its densest, which is actually close to the middle of galaxies. Now, some people are claiming to have seen these signals. What do you make of that?

KATIE MACK: I think that, again, that's also really difficult. The reason that's complicated is because the areas that are most dense in dark matter-- like the center of the Milky Way, the center of other galaxies, center of galaxy clusters-- are also the places where there's a lot of astrophysics going on. Our Milky Way center, for instance, has a number of stars. It has dust. It has pulsars. It has a supermassive black hole and accretion and various kinds of outflows. And that's a really complicated area.

And so trying to find an excess signal of something in the galactic center and say, oh, that must be dark matter rather than just some kind of astrophysics we don't understand. That's a really difficult call to make. So we've seen excess gamma rays from the galactic center. We've seen extra x-rays from centers of galaxy clusters. We've seen positrons coming from possibly all directions. And we don't know for sure whether these are a signal of some new physics, like dark matter, or some new astrophysics like maybe a population of pulsars that we didn't know about before. So that's another area where I think that there have been some really interesting clues, but we can't yet say if it's dark matter or if it's just something else that we don't understand.

But this is an area where I think that in the next few years we can make a lot of progress, because we can try and really put together the consequences in all different wavelengths for these kinds of interactions. So if we say, dark matter should give you a gamma ray signal, what would you see in the x-rays? Or what would we see in radio or neutrinos? And getting that self-consistency and really seeing what we expect in all different wavelengths is where we can really make progress in that.

PAUL FRANCIS: Now both the sorts of observation we've talked about-- looking for the effects of dark matter interacting with itself or with an experiment somewhere in a mine-- rely on dark matter interacting via the weak force. We know that dark matter interacts via gravity-- otherwise, we wouldn't know it's there. We know it doesn't interact via either the strong or electromagnetic forces or we'd have seen it a long time ago. But do we actually know it interacts via the weak force? I mean, if it only interacted via gravity, we might never find out what it was.

KATIE MACK: Yeah. This is where the theory is really the only thing that's guiding us. We think that it has to interact via the weak force mostly because that's a way to produce dark matter in the early universe. So we can calculate how dark matter would annihilate and come together and be produced by standard model interactions in the early universe.

And if the weak force is what's governing that, then as the universe expands and those interactions become less common-- like they're very uncommon today-- then the amount of dark matter that would be left over after all those interactions have gone on and stopped would be about the right amount of dark matter to explain the dark matter we see now. And so that's sort of our theoretical bias that says that the weak force interaction makes a lot of sense.

If it did interact only with gravity-- I mean, that's not ruled out. We haven't seen any solid evidence for interactions of anything other than gravity, but it would be really hard to make dark matter that way. We think that all the particles in the universe come out of the Big Bang, come out of this sort of early primordial soup. And the only way to get dark matter out of that would be if it did interact via something other than gravity with standard model particles. And so if it was just gravity, we wouldn't have any way of getting the dark matter into the universe. It would have to be some very strange process where it just appears through something we don't understand. So it makes much more sense if dark matter does have a weak interaction.

PAUL FRANCIS: Now one of the claims made for the Large Hadron Collider that's in Geneva is that it might be able to discover what dark matter is. Could you explain that?

KATIE MACK: Yes. There are two ways that the LHC might give us some clue about dark matter. One would be just by seeing evidence of supersymmetry. So if supersymmetry, exists, if there are supersymmetric partners of all of the fundamental particles of nature, then that would give us a clue the supersymmetry is a way to go and that dark matter could be a kind of supersymmetric particle. And that would fit into that paradigm very well.

PAUL FRANCIS: Where are we up to now with the supersymmetry and the Large Hadron Collider?

KATIE MACK: Well, at the moment, we've seen nothing. We've seen no evidence for supersymmetry at all. And so--

PAUL FRANCIS: Would you have expected to this point?

KATIE MACK: We would. So it depends on the model supersymmetry. There are some models that are harder to find, but we're being pushed into more of those difficult models of supersymmetry-- the less sort of simple models and therefore the less appealing models. So at the moment, we don't really know.

But the other way that the LHC could give us a clue for dark matter would be if the LHC were able to produce dark matter. In the same way that dark matter particles can come together and annihilate and produce standard model particles, standard model particles might be able to come together and produce enough energy to make dark matter particles.

And so what you would look for in the LHC would be a proton collision where you have the collision. You count up all the energy of all the particles that come out, and there's something missing. And that would be a clue that maybe a dark matter particle was produced and escaped the detector completely because it didn't interact with anything, any of the instruments. So we're looking for that missing energy signature. Unfortunately, we haven't seen that yet either. So at the moment, the LHC is only giving us limits on what dark matter could be, but it hasn't given us any evidence for the particle itself.

PAUL FRANCIS: So it looks like we've got three possible ways to discover what dark matter is-- the experiments in the mines, looking for some sort of signal from astrophysics, or the Large Hadron Collider.

KATIE MACK: Yeah.

PAUL FRANCIS: Combining all these three, what's your personal gut feeling? Do you think 10 years from now when we hold a back up interview, we'll know what dark matter is?

KATIE MACK: I do think so. I do think so. I may be optimistic, but I think that in the next couple of years, we'll have a much better idea of what to do with the direct detection experiments. We're building new experiments that will do directional detections, so they'll be able to tell you which direction the particle came from, if there is dark matter coming through. That'll give us a lot of really important information. We're also doing more observations of signals in the sky, and we're going to follow up on all the ones we've seen and figure out if those might be dark matter. And the LHC's is going up to higher energies, which might help. Maybe we'll see it in LHC.

So I do think that in the next 10 years, we'll know. There's a chance that we won't if we're very unlucky. And if the dark matter is a lot harder to detect than we expected, then we won't see it. But I think we'll at least have a much better idea if it could be supersymmetric or if it could be one of the other theories that has been going around

PAUL FRANCIS: So let's say we're pessimistic, and it manages to evade the direct detection experiments because some of its interaction cross section is wrong or its energy is wrong. It doesn't annihilate with each other because of a low cross section. And supersymmetry, no evidence for that shows up then.

Would supersymmetry be dead if no evidence shows up after the upgrade?

KATIE MACK: It wouldn't be dead. It would be painted into a very ugly corner.

PAUL FRANCIS: Yeah, so severely injured but not dead maybe.

But if we're pessimistic and say, that's the case, where would we go from now? Can we make the direct detection experiments 1,000 times better?

KATIE MACK: Unfortunately, there's a limit to what you can do with direct detection. Because if dark matter interacts with a small enough cross section, then we'll never be able to see it in ordinary direct detection because it'll be drowned out by the signal of neutrinos bouncing off of the things in your sector. And neutrinos, you can't get rid of those. But that's where--

PAUL FRANCIS: Short of several million kilometers of lead.

KATIE MACK: Right. But that's where directional detection helps. So the direction the neutrinos come from should not necessarily be the same as the direction the dark matter comes from. There are certain directions where we're on a planet going around a sun, moving through a cloud of dark matter. And so we should be able to see a difference in the amount of dark matter coming from the direction of where we're moving through the other direction. So directional detection should help. But there's no point in just continually building bigger and bigger detectors without directional detection because at some point that doesn't do you any good.

PAUL FRANCIS: Great. Well, thank you very much.

KATIE MACK: You're welcome.

A4_L10_V09_Matthew_Colless

PAUL FRANCIS: It's a great pleasure to have here, Matthew Colless. You've seen a lot of the work that he's done already earlier in the course because he was the leader of the 2dF Galaxy Redshift Survey, and we've seen that rotating red diagram showing the distribution of galaxies and the motions of these things many times. He's also our director here at the moment. So Matthew, welcome.

MATTHEW COLLESS: Yeah. Good to be here, Paul.

PAUL FRANCIS: Now the standard question we're asking is-- What's been the biggest breakthrough in astronomy since you've been a professional astronomer?

MATTHEW COLLESS: Well, it's not so much a single breakthrough as a continuous stream of breakthroughs. I work in observational cosmology, like Brian. And for us, the field has changed out of recognition over the 30 years that I've been in the business. When I started out, we knew nothing about dark energy. We knew nothing about dark matter. We had very little idea of what any of the fundamental cosmological parameters actually were. And all of those things have been changed out of sight over those 30 years. It's just been an incredible ride for those of us involved in this particular profession.

BRIAN SCHMIDT: Can you identify any reason why there was this revolution? Did you think-- You got your Ph.D in 1987. So in 1987 it was a pretty murky picture, we didn't know what was going on. Did you think it was all going to be this crystal clear by 2014?

MATTHEW COLLESS: No. It wasn't clear to me that was going to be so clear, but the signs were there. And I mean, one of the things that struck me immediately when I started doing my Ph.D at Cambridge was the whole CCD revolution, which was just really beginning to pick up at that point. In the early to mid '80s, we suddenly went from photographic plates to CCD detectors. And it was clear that technology was driving observational cosmology very rapidly indeed. At that point, it was taking it far faster than theory could keep up. And so there's been this ongoing arms race between observation and theory with one leapfrogging the other at a time. And during that period it's always been the technology that's taken it over. The satellite technology that's enabled us to go from the ground-base measurement to the microwave background, to the exquisite measurements we now have with WMAP and Planck, and so on. And on the ground, of course, the increase in telescope aperture as well. We started out when 4 meter telescopes were the rule, using photographic plates. We now have 8 and 10 meter telescopes with powerful CCD detectors. And we're about to go to the 25 and 30 meter telescopes, which will be yet more powerful still. And so throughout, technology has been the driving force and that's allowed the observational cosmologists to race out in front, make new discoveries, and drag theory along after them.

BRIAN SCHMIDT: So let's go through and think a little bit about the future. So we're asking you to think about-- Let's say over the next 10 years you've highlighted there's some new technology. What's it going to give us, do you think? Let's-- I want you to forecast. Now, we know this is hard to do in practice, but give us your best guess, 10 years from now what you think you're going to say was the most exciting thing over the last 10 years.

MATTHEW COLLESS: So what I hope I'm going to be able to say over the last 10 years has been the most exciting thing, 10 years from now, is that we'll have actually identified the dark matter particle. We will actually know what it is. In fact, we may even discover that it's more than one thing. It's Ockham's razor to lead you to believe that it's exactly one species of particle. But I hope that from laboratory experiments, we will actually know what these things really are. And that will clean out at least one area and give us a big clue as to things beyond the standard model of fundamental physics right now. I also hope that we'll have nailed down exactly what the nature of dark energy is in the astrophysical cosmological context. In other words, we will know what the impact of dark energy is on the evolution of the universe. Now we may not understand the physical origin precisely, but we should at least know that it behaves, let us say, exactly as one would predict for a cosmological constant. And so there will no longer be much room for argument about that. Whether or not that will lead to a real theoretical understanding is not so clear to me. And of course, 10 years from now I'm hoping that the big new telescopes like the Giant Magellan Telescope that we're involved in here at ANU will be up and running. And I'm hoping that those will lead to big, new breakthroughs as well. One of the things I'm hoping for there actually, is not so much in my field of observational cosmology, but in understanding planets around other stars. One of the things I'm really looking forward to is using those telescopes to probe the atmospheres of a planet. Actually knowing what's in the atmosphere of planets around other stars is going to be pretty fantastic and really going to change the way people, in general, think about our universe.

PAUL FRANCIS: Now, the next 10 years we have a fairly good idea of what telescopes are going to be like because they are all currently being designed and under construction. But let's look a bit further forward, maybe 50 or 100 years. You said that since about the 1970s when the first CCDs started coming back along we've had this exponential increase on observing, having that continue? I mean, the CCDs are already over 90 percent efficient at many wavelengths. Are we going to hit some limits? I think it's going to slow down and maybe some other thing is going to drive it? Or do you think we can keep on with this exponential increase in performance beyond the next 10 years? I think we're fairly safe in the next 10 years, but when it goes 20, 30, 40 years, are things going to slow down?

MATTHEW COLLESS: No, I really don't think so. Unless the human race manages to make our planet less habitable or at least less economically viable than it currently is, I don't think technology is about to hit the real fundamental physical limits that exist. There are some, and you've pointed out one of them already. But there are so many other areas where we're nowhere near them. We're just beginning, for example, to make the most of neutrino astronomy and gravitational wave astronomy. Those things are in their complete infancy right now. And 100 years from now I'm hoping those will be tools that are as familiar and as common to astronomers of that time, as electromagnetic radiation is today. I also hope that we'll be doing much more from space and that we'll be able to get the human race up and out into space so that we can do wonderful things like put a giant radio telescope on the far side of the moon, where free from radio frequency interference, and able to do astonishing things because of the sensitivity that it will be able to achieve. I also hope that we will know enough about planets around other stars that we'll be beginning to consider, 100 years from now, actually going to visit some of those stars. Now that's 1000-year project perhaps. But I hope that in 100 years from now, we'll actually have been able to say yes, there are targets worth visiting where we can go and learn about other habitable worlds, maybe even worlds that might contain life. And although I doubt it will be me that we'll be taking those journeys, I certainly hope that it will be my children or my grandchildren or even the artificially intelligent grandchildren of the human race who take that journey and go out and visit the stars.

PAUL FRANCIS: OK. Thank you very much.

MATTHEW COLLESS: My pleasure.

A4_L10_V10_charley

PAUL FRANCIS: So to continue our set of interviews of people who might have some interesting ideas about where astronomy is going, we're very pleased to welcome back my colleague Charley Lineweaver, who we saw earlier in the entropy section of this course.

So Charlie, what do you think has been the biggest scientific or astronomical breakthrough since you've been a professional scientist?

CHARLES LINEWEAVER: Well, for me, that has to be the discovery that we made in 1992, of fluctuations in the microwave background. Why? I mean, it's, a), personal, that my supervisor got the Nobel Prize for discovering these fluctuations. But I think it just opens up the whole idea of we now have a scientific picture.

Cosmology has turned into precision cosmology. And that means that-- we used to wave our hands and say the universe is about 10 to 20 billion years old. And now we say it's 13.78 billion years old and we're working on the next digit. That's what I mean by precision cosmology.

So that means that our whole vision of how we got here, and where we're going, and where we've come from, that has got a lot more scientific input into that story. It's not retired engineers pontificating. We really have a lot of good evidence and we're getting more every day.

So the exciting picture for me is-- scientific revolutions come when you change the vision of who you are. For example, the Copernican Revolution, why was that so important? Hey, we're all going around the Sun. Well, that's because it took the Earth-- our chosen place, our place that we love so much-- and put it over here. And that changed who we thought we were.

And I think any good scientific revolution does that. For example, Freud did that or Darwin did that. He said, hey, we're a special animal. And he said, well, we're an animal. And that type of changing who you are is probably the most important part of science, I think, and probably the reason for science.

And I think what we're doing now is understanding how we got here. And I think the next biggest discovery will be the detection of life in the universe. Because we're not sure what life is. And maybe there will be aliens that will come and kill us instantly or maybe they'll help us fill out an application to the galactic club and we'll all be like a giant UN in the galaxy. Or something weirder, weirder, weirder.

And that's not too far off. Because in the next 10 or 20 years, we will have instruments that will be able to sense-- sniff out-- the atmospheres in the infrared spectra to see if there are gases out of chemical equilibrium, that would be the telltale signs of life on the surfaces of those other rocky planets, which we now know are everywhere in the universe.

PAUL FRANCIS: So talking about next 10 or 20 years, you think there's a good chance we'll see so-called biomarkers, things that indicate that life is there. That will be pretty exciting. How do you think that will change humans' perception of ourselves?

CHARLES LINEWEAVER: Well, I'm hoping that humans will be on this planet for a while. People talk about the technological singularity, in which our computers get smarter than we are. And they start computing themselves and programming themselves. And then I'm not sure what a human being will be after.

We'll get knocked off our pedestal as the most intelligent, Homo sapiens. We'll have the Computo sapiens. And we'll be some subsapiens.

So that's coming. It's on its way. So that's one big problem.

But discovering life elsewhere-- or you just said, oh, you'll just sniff out life, what will that mean? Well, I think it will start us on a long journey towards trying to define what life is in general. And I don't think we know. We pretend we know. But we don't know.

And we would like to know if there's other beings out there, who have intelligence, who could colonize the galaxy. And have figured out the physics and figured out the exact history of the Big Bang, even before the Planck time, or something.

So if we find life-- "intelligent life"-- that'll being an incredible undermining of our ego and maybe help us do something, I'm not quite sure what. But in any case, it will revolutionize our idea of who we are. And that, I think, is it an incredible, mind-blowing thing. It's going to scare everybody. But it might provide some hope as well. We have to be optimistic.

PAUL FRANCIS: You suggested that we don't really understand what life is.

CHARLES LINEWEAVER: I did. I definitely--

PAUL FRANCIS: Doesn't that mean that if we find life in space, we not might recognize it is?

CHARLES LINEWEAVER: That's right.

PAUL FRANCIS: How would we even tell? In the next 20 years, we might see some strange nonequilibrium chemistry. How could we tell if its life?

CHARLES LINEWEAVER: Right. Exactly. That's a good-- very excellent question. And I wrote a chapter that says, we have not detected extraterrestrial life, or have we? And that is, if you redefine life as being a far from equilibrium, dissipative system, like we are, like hurricanes, like fires, then we've already detected life. Stars are life forms.

But most people say, well, wait. That doesn't happen. That doesn't make any sense. It's doesn't have any DNA or something, or the information content is not there.

And then you say, well, do you have to have information content inside yourself or can you have your information content outside yourself? Now we're learning you're going to sequence your DNA completely, put it in a test tube, and say, hey, do you want a child? OK, press a button.

So therefore, your information is then exported. And then your reproduction will be exported. And, well, is that life?

How far can you go along that path and still call it life? I don't know. But I think this dichotomy between life and non-life is a silly one, that we have to get rid of if we want to really understand how we got here.

But so far, we're stuck with it. And so that's why I feel uncomfortable by answering a question, how will you recognize life? You don't need to recognize life because in biology, whenever you go back in time, you are undoing the structure that you're trying to understand-- for example, your eyeballs, or your brain, or whatever.

We take your eyeballs and go back in time, they turn into things that-- oh, well, they're proto-eyeballs. You go back even further, they're proto-proto-eyeballs. And so the same thing with life. You take life-- oh, we understand that.

You go early and say, wait a minute. Is that life or is that just an autocatalytic reaction? Oh, is that an autocatalytic reaction is that a semiautocatalytic reaction? So you undo the concepts that you're using to ask the questions. And that's the most powerful form. Unlearning such things is the most powerful form of learning, I think. And that's what we're for.

PAUL FRANCIS: So this time scale of 10 or 20 years, you suggested we'd be likely to discover biomarkers out there. Do you think we'll actually have any evidence of intelligent life or is that going to be much further out?

CHARLES LINEWEAVER: Well, I've argued that-- well, I have argued that we don't know. Well, I've said the human-like intelligence is a species-specific characteristic.

That is, we look around us on Earth and say, oh, we're the only smart ones here. Are we alone? When we ask the question, are we alone, we say, we are the homo sapiens. And "alone" means are there any other functionally equivalent Homo sapiens out there, with whom we can talk, or they can build radio telescopes and rocket ships, et cetera?

And I think that human-like intelligence is a species-specific characteristic. And therefore, we should not expect it elsewhere. Most people think, oh, it's really good if you're smart. And therefore, it's a universal adaptation. And therefore, we should expect it elsewhere.

And I've argued strenuously against that because it's been tested on Earth. Those tests are called Australia, New Zealand, South America, Madagascar, in which you have a large continent, in which landlocked creatures are evolving independently of each other. So you have multiple experiments.

And when you ask the question, on these continents, is anything there evolving to fill this intelligence niche, which we think is there? And the answer seems to be no.

You go to Madagascar and say, oh, what evolved there during the 50 million years it's been independent, or on Australia. What evolved on Australia during the 100 million years, that was an independent experiment, before humans arrived? And what is the most human-like thing or the most-- filling the intelligence niche?

And the answer is nothing that we can identify. There has been no progress anywhere we can see towards being more human. And so I think it's kind of vain for us to think that our human-like intelligence is a convergent feature of evolution. And therefore, we should expect human-like intelligence elsewhere.

PAUL FRANCIS: So looking further afield, if you go out 100 years from now. So where do you think astronomy will be doing in that time? Do you think on that timescale we'll have found something that we would accept as intelligence out there in space or--

CHARLES LINEWEAVER: No, no, no. Like I said, I don't think we're going to find what we consider to be intelligent out there. I think we'll find something and it'll be weird. It'll certainly be a far from equilibrium, dissipative system and need to extract free energy from the universe, just like we are doing. It's not going to violate the second law.

But whether it will use what we consider to be human-like intelligence to make oil rigs, and make little globes here, and make television cameras, I am very skeptical of that. Although most physicists disagree with me. Most physicists and astronomers think, hey, their brains are so big that surely this is a universal adaptation. Therefore, we should expect physicists out there. And they think math is the language that should be used to communicate with these extraterrestrials.

But I think we should take biology more seriously on Earth and what has happened here. And when we try to communicate to other species-- for example, I think music is a much more-- or just touching is a more effective way to communicate across species, than math or science. And that should tell us something.

I'm not sure what, other than-- other than we shouldn't necessarily try to write equations that go beep, beep, beep, beep, use Morse code. If you ever tried Morse code with your dog, it doesn't work very well. But if you try petting it and feeding it-- music, they don't do so well with music. But dolphins do well with music.

PAUL FRANCIS: All right. Thank you very much.

CHARLES LINEWEAVER: You're welcome.

A4_L10_V11_Naomi_Mathers

PAUL FRANCIS: Now, if we're going to make any progress in astronomy over the next 10 or 100 years, we're going to need better telescopes, better satellites, all sorts of instrumentation. And that's going to be a formidable challenge in many ways.

To help us talk through some of the challenges that are facing us in some of the work we're doing here at ANU about that, it's a great pleasure to have Naomi Mathers, who's an engineer here at the technology center, Advanced Instrumentation and Technology Center here at the ANU. So welcome, Naomi. What sort of people and skills are we going to need to drive progress in astronomical instrumentation and space instrumentation, do you think, over the next 10 years?

NAOMI MATHERS: For the sort of projects we're looking at with the giant Magellan telescope and some of the satellites are really large, complex multi-discipline systems. So that means we need mechanical engineers, optomechanical engineers, we need computer scientists, we need systems engineers to bring all of that together.

We need really good project management. Some pretty good accounting. So really, it's everybody who makes this very high precision instrument give you the science you need.

BRIAN SCHMIDT: And how does that interact with scientists like Paul and myself?

NAOMI MATHERS: That's actually one of the greatest challenges, getting the science requirements, but actually being able to realize on that. So the engineers have to be very good at understanding some of the science, but also feeding back to the scientists what's possible, because as we do research in engineering, we come up with new technologies, new materials, and new ways of doing things to help you do your science better.

BRIAN SCHMIDT: And so we're not in your part of the building, and we're in our part of the building. We never talk. We actually work pretty collaboratively to--

NAOMI MATHERS: Oh, most definitely. And that's becoming more and more important. So the Square Kilometer Array, the giant Magellan telescope. Those are international projects, so it's not just in our building, but you multiply that nationally, globally. So we really do need people who can communicate, and also communicate with the community and the next generation to bring them through, so we've got the skills.

PAUL FRANCIS: Are there enough people out there with these skills? Is it easy to find people who have the communication skills, and the project management skills, and the technical skills, and can talk to astronomers?

NAOMI MATHERS: I wish we had more. I think as we're bringing the students through working on projects, it's really giving them the hands on experience that makes the difference. Students who are problem solvers. Not just technically brilliant, but we want them to be able to think and be creative. So it's definitely a challenge, but we've got them out there. We've got a talented group.

BRIAN SCHMIDT: So let's talk about some of the details. Behind us we have this big thing that people will see is called the Wombat Extra Large Space Simulator. Why would we want something like that here at Mount Stromlo?

NAOMI MATHERS: So we actually need it for both the astronomy and the space activities. For the astronomy, so the high precision instruments for astronomy and now often cryostats. So they work at cryogenic temperatures in a vacuum. Space systems work in the same environment, so we have to prove they work.

So we need a thermal vacuum chamber, which is what we call a space simulation facility, to prove that these mechanical systems can work in these really, really extreme environments.

BRIAN SCHMIDT: So one of the interesting things we've talked about in this course is how in order to make telescopes, the next generation of large telescopes work, we need to correct the atmosphere with adaptive optics. And so that's something we're developing here, but quite to my surprise, we're actually using that to do things that are not directly related to astronomy now.

NAOMI MATHERS: No, no.

BRIAN SCHMIDT: So what are we doing with this technology?

NAOMI MATHERS: So one of things, once you correct for the atmosphere, astronomers see the stars more clearly, and we can see space debris more clearly. So we can see much smaller pieces of debris, and we can see them, we can track them more accurately.

So this is really important for spacecraft operators, so that if there's going to be collision with a piece of space debris, they can get a warning system, so we can tell them to move the satellite out of the way. At the moment, because we can't see it accurately enough, they often just leave it there and cross their fingers.

PAUL FRANCIS: See what happens.

NAOMI MATHERS: Yes.

BRIAN SCHMIDT: So we don't want to get a Gravity the movie type situation.

NAOMI MATHERS: No.

BRIAN SCHMIDT: And are we doing this all on our own?

NAOMI MATHERS: Most definitely not. So we have this, we're doing this cutting edge research. So we've partnered with one of the companies we work with on the mountain, Electro Optic Systems, and also with companies around the world. Lockheed Martin, Optus Satellites, NASA, the Japanese, because satellites orbit the whole globe.

So this is very much an international problem, and an international collaboration. So we have our new cooperative research center based up at Mount Stromlo.

PAUL FRANCIS: And one of the other things I know we're interested in here is micro satellites.

NAOMI MATHERS: Yes.

PAUL FRANCIS: We've talked in this course about things like the James Webb Space Telescopes. If you have $6 billion burning a hole in your pocket, that's one way to do things. But most of us don't have that much money sitting around, and also 20 or 30 years worth of design time. So can you tell us a bit about what these micro satellites are, and some of the challenges involved in designing them?

NAOMI MATHERS: So one of the challenges is to fit all of the systems you want, and all of the science you want in a very small platform. One of the advantages is that they're much cheaper to build, much quicker to build, and they drive innovation. So as we're seeing electronics being miniaturized, we're seeing a lot more computer processing, some of the new photonic systems, we can do the same signs that was done on a larger platform on a much smaller platform.

Within the limits of optics. But these are great for universities. So Australia is actually building three of these micro satellites, or cube sets, as they call them. Little 10 cm x 10 cm x 10 cm. A standard that can be multiplied like LEGO blocks. So it's also standardizing satellite production, which brings down the cost.

BRIAN SCHMIDT: Great.

PAUL FRANCIS: Great. Well, thank you very much.

NAOMI MATHERS: My pleasure.

A4_L10_V12_Paul

BRIAN SCHMIDT: So we've seen quite a wide range of views of what people think the world's going to look like 10 or even 100 years in the future. So Paul, I think it's time for us to think about this. And why not start with you? Paul, what is the world, our view of the world, going to look like 10 years from now? What's fundamentally going to have changed?

PAUL FRANCIS: I think for astronomy I think the big thing that I'm going to see in the next 10 years I reckon, I'll probably be wrong, is finding solar system analogs, exoplanets. At the moment we've found hot Jupiters. We found super Earths. We're just on the brink of being able to find other solar systems like our own, with earth-like planets and Jupiter-like things and Jupiter-like orbits. So just on the hairy edge.

BRIAN SCHMIDT: So do you think our solar system is going to be common, or you think it's going to be kind of rare?

PAUL FRANCIS: If I was a betting man, which I am not, I would say fairly common. But I think we're beginning to get a few hints that not 100%, maybe not even 50%. But I think there are going to be a lot of things, at least superficially, like our own solar system out there.

BRIAN SCHMIDT: Right. And do you think we're going to be able to use the new technology? What do you think we're going to be able to do when we study these solar systems with the new extremely large telescope, JWST, ALMA, all these square kilometer array?

PAUL FRANCIS: I think we're going to be able to find solar system analogs, and probably find earth-like planets, maybe via micro-lensing or more precise radio velocities around dwarf stars and so on. On the next 10 years, we're not going to be able to learn anything about earth analogs. But I think we are going to learn a lot more about the bigger planets around these things. We're going to get much better particularly imaging. We're going to be able to see a lot more of these things, And what their spectra are like.

And so we're actually-- they're going to stop being just a list of M sine i and radius, and actually start being fleshed out as actual real worlds with atmospheres and rotation and temperatures and things like that.

BRIAN SCHMIDT: Do you think we're going to be able to have a theory that really explains why there are so many hot Jupiters, why there are stars of all these different masses? I mean do you think us getting-- that new data will allow us to really develop good theory?

PAUL FRANCIS: I don't think we're going to have a sudden breakthrough on this. I think it's going to get better. And we're going to get more pieces in place. But this is just really messy physics. And so it relies on physics all the way from micro scale up to scales of parsecs. and even if you extrapolate Moore's Law forward 10 years, the computer is not going to be fast enough even then to really simulate the full range. They'll be getting closer. We'll have a better understanding. But I think this is something that's going to improve gradually, step by step over decades.

I'll be surprised if there's a sudden breakthrough, and everything falls into place, very pleasantly surprised, but I'm not holding my breath.

BRIAN SCHMIDT: OK. So let's be more speculative. Let's look to that 100 year time scale. What are we going to know? What's the big things we're going to learn about 100 years from now?

PAUL FRANCIS: Well, something that interests me actually is the human aspect in this. Because on that sort of timescale, it's not at all clear it's humans that are going to be doing the discovery, so much as some sort of human machine hybrid. I mean if you think about all the barriers that's going to stop us progressing. I mean we could end up in the situation like particle physics, where we've built the biggest telescopes we possibly can.

If you look at where astronomy as made progress over the past, I'd say in the early part the 20th century, the progress is mostly coming out of physics. Physicists discovered new nuclear physics and quantum mechanics. And we imported those things. And it allowed us to explain things we've known about for a long time, but not been able to understand.

That kind of stopped around 1950 but, say from 1950 through to 2000, a lot of progress was driven by opening up to the electromagnetic spectrum. We could suddenly observe many waves that we hadn't done. So first radio astronomy, then x-ray astronomy, infrared, sub millimeter, microwave background. But we now have done, we have physics and theories that explain everything we can see. We have observations across the entire electromagnetic spectrum.

How about the '70s onwards, a lot of progress has been driven by improving sensitivity. We went from, if you compare say the Anglo Australian telescope in 1976 when it's commissioned to today, the same telescope is 1,000 times more powerful, more than 1,000 in some measures. Because of charge coupled devices detectors, wider fields of view. But we're now up--

BRIAN SCHMIDT: We're about as good as it can be. Right?

PAUL FRANCIS: So if that's run out, because there's no more spectrum to explore. Physics is not going to give us any more insights on things we can see on a day-to-day basis. Sensitivity is already nearly 100%. Where do we go? So that's one possible boundary. I think that can be overcome if we go into space. If we stop, we might just have to build really big telescopes. So on a 100-year time scale I'm expecting telescopes with collecting areas of hundreds of square kilometers floating in orbit around Pluto or something like that. Intoferometers out there.

If we have that, it would require a breakthrough in rocket technology.

BRIAN SCHMIDT: Absolutely, yes.

PAUL FRANCIS: But that's not impossible. I think there's no fundamental physical reason why they can't get things into space at a 100 times cheaper than at the moment. There's no, if you just do the energy calculations it's a technological problem. But there's no fundamental physical law. Whereas making our telescopes on earth that much better, there are fundamental physical barriers that are going to come across.

But that really leads us to the other barrier, which is how smart humans are. We've got the problem that the total volume of astronomical knowledge, in fact, volume of knowledge across all the sciences is doubling roughly every 8 or 10 years. And we're not getting twice as smart every 8 or 10 years. Speaking for myself.

So, how do we deal with this? So if you want to learn to cutting edge now in a four-year degree that's going to take eight years, a decade from now, and it's going to god knows how many years, 100 years from now. The response humans have made is to become more specialized. So we are far more specialized. In Galileo's time one person could be across all the sciences.

By the time of somewhat like Maxwell or Einstein, you could be maybe across all of physics. But nowadays people can't be even across all of astrophysics. They'd be specializing in say supernovae or quasars or something like that. One dreads to think how specialized we'll have to be 100 years from now. And that's going to be a real problem I think.

BRIAN SCHMIDT: Maybe a bottleneck. Do you think it's going to be a bottleneck of what we're able to do?

PAUL FRANCIS: Yes, because so often the unexpected discoveries happen from cross fertilization between different fields. And if we have to learn just about a very, very narrow field, it may be that the human brain is going to be what limits us. And that's where computers are going to come into. I mean we don't know whether the Moore's law improvement to computers is going to keep going for 100 years. Most likely it will hit some sort of bottleneck at some point.

But if it keeps going, even 30 years or so, we're going to have computers that are in some respects smarter than us. Though normally the greatest achievement is not from computers versus humans. It's from the human computer hybrid. And we're already kind of at that situation. There's no way we could process data from sky map or telescope without that very intricate interweaving of human brains and computer brains, each doing what they're best at.

And that's going to get just more impressive I think. So maybe what we're going to be looking at is almost like cyborg astronomers, where probably not physical implants, but some combination of using the best elements of computers and the best of humans. And it would be very interesting to see how that plays out.

BRIAN SCHMIDT: Are you worried about, how do I say, the machines taking over?

PAUL FRANCIS: Yes.

BRIAN SCHMIDT: Yes?

PAUL FRANCIS: I think you'd be foolish not to be. Part of me devoutly hopes that Moore's law runs out of steam sometime in the next 20 or 30 years and leaves humans in charge of the world. But in some sense, would that be so bad? I mean at least in terms of astronomy, if we have computers that are smarter than us. We can sit back and watch the MOOCs they produce, and see the wonders they come back. We normally are not disappointed if our children are smarter than we are. And maybe we should not be supported if our creations of computers can do things that we can't.

BRIAN SCHMIDT: OK. I will say the whole thing kind of scares me. But we're always scared of the future I guess. Right.

A4_L10_V13_Brian

PAUL FRANCIS: And now for the last take of the last lesson of the course, I'd like to throw this question back at Brian. OK. So Brian, where do you think the big breakthroughs going to be happening over the next 10 years?

BRIAN SCHMIDT: Well, I think there's going to be a lot happening in the next 10 years. You talk about planets. I think we're going to start even being able to look in the atmospheres of planets, and look for the first signs of life. I doubt if we'll find it. But we're going to be able to start at least doing that question.

I see us being able to look to-- see the, literally, the first stars in the universe, seeing the first supernovae. Really understanding how the lifeless universe became the very exciting universe we live in today. And the big, extremely large telescopes and JWST will literally be able to piece together how those first stars formed. And we'll be able to piece together the Milky Way, star by star, compare the fossil record to the direct fossil record that we see by looking so far in the past. And I'm pretty optimistic about dark matter. I think there's a very good chance we're going to discover the dark matter particle. And that will revolutionize probably not astronomy so much, but as particle physics.

Because if they open that up they're going to have probably a whole wealth of other things that happens there. So for me, those are the big things that I see have sort of a 10-year horizon. They'll be a lot of other things, of course, that I haven't predicted but to my mind, those are almost sure bets. Well, dark matter is not a sure bet, but I think the beginning of-- the epic of stars, being able to look for the signs of life in other nearby planets, those look pretty solid to me.

PAUL FRANCIS: And let's finally go much further out to 100 years. Where are we going to be then? What are the big issues, you think?

BRIAN SCHMIDT: So the 100 years I find quite challenging. Like you, the human aspect is something that concerns me. Maybe not so much on the computer side, although that is an interesting one, but I-- We're manipulating the genome in a way, which is quite remarkable. And I see humanity, one way or another start mucking around with our own DNA to try to make us better, make us super in some way. There's going to be huge ethical questions around that and it does kind of scare me, but I see that as being something that happens.

PAUL FRANCIS: Yes, I always wonder about-- if we prolong life long enough, everyone lives to 1000, then we are still going to be the senior professors 1000 years from now and that could close down progress quite well if the old Gods stay around forever and never die.

BRIAN SCHMIDT: Especially if we go senile as part of the process. But-- So you know, it is challenging. I mean I do see lots of challenges. The world is changing rapidly. The next 100 years, we're going to have to cope with having too many people on the planet and sort that out, and science and technology will be in the middle of that. For astronomy itself, my guess is 100 years from now, we will have discovered life on another planet. That I think, if were able to make progress, I think we'll have done that by then. I think we'll almost certainly know what dark matter is by then, if it is a particle. If it's not a particle, then we may well not know. I don't think we're going to know what dark energy is yet. I think that could still be the--

PAUL FRANCIS: It could still be a problem 100 years from now.

BRIAN SCHMIDT: Yeah, I don't think we'll have been able to link together quantum mechanics and gravity yet. I just see that as being an incredibly hard problem. And I don't know when that's going to happen, some light switch will go off in someone's brain probably. But on the other hand, I may well be wrong on that pessimistic prognosis for dark energy.

Because it may well be that these big experiments we do over the next 10 years to say-- What is the equation of state of dark energy? If they come back with something other than Einstein's cosmological constant, unchanging over time, if we get something that is changing over time. Then we're going to have the crowbar in the little crevice and we're going to be able to work on it. And that's why those precision measurements are interesting and useful as they provide perhaps, the crack in something that looks impenetrable.

So, the 100-year timescale is a little scary, but it's exciting. And as with you, I will hopefully be able to watch 40 or 50 years of the next 100 years. Many of the people watching this course will be able to see a good fraction of those 100 years.

PAUL FRANCIS: And will be the people doing much of this.

BRIAN SCHMIDT: Yeah, and so if you think back 100 years in 1914, people were wondering whether or not this war that had broken out in Europe was going to be a big thing. They were wondering whether or not these automobiles were ever going to become something that was really useful. They had read Jules Verne trying to figure out what Jules was thinking about, making his submarine powered the same way the sun is. We didn't understand any of that. So, I think it's going to be really exciting just to sit back and watch but, a little scary. It's like a roller coaster ride I have a feeling.

PAUL FRANCIS: And we'd both been talking about what's been extrapolating what's going on at the moment. These are the questions that we know now, which of them will be answered. But of course, if you'd asked 20 years ago, what were the big questions? You wouldn't even ask the question, what is dark energy? You didn't even know it existed.

So my hope is that we're going to have a few more really big surprises. You go back to 1950, and of course, they didn't know that quasars existed. They didn't know-- Most of the questions we're trying to answer now weren't even asked back then. So to my mind, the really exciting thing is going to be totally out of left field, unexpected things that are going to come through. And the questions that they're going to be debating then will be questions we couldn't ask now because we didn't know they were real.

BRIAN SCHMIDT: I agree. But I promise you, whether or not there's life on other planets will still be an interesting question until it's answered.

PAUL FRANCIS: So that concludes this part of the course and in fact, that is the end to of the entire series of four courses. We hope you've enjoyed listening to us and interacting with these courses. We very much enjoyed teaching and filming these things.

BRIAN SCHMIDT: And I would just encourage-- Learning is a lifetime activity, so please go out and explore the universe on your own terms. And thank you for spending your time with us over these 36 lectures for those of you who have done the whole course.

PAUL FRANCIS: For those of you who haven't, we will be starting all over again.