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Welcome to IFLScience, The Big Questions, the podcast where we invite the experts to explore the biggest mysteries of science with your host, Dr Alfredo Carpineti. As a head's up, we apologize for some audio hiccups with this episode. In an era of video conferencing, sometimes sound quality suffers. Thanks for bearing with us.

I: Welcome to IFLScience, The Big Questions, a series where we ask experts about some of the most pressing mysteries, science, technology and humanity. I'm your host, Dr Alfredo Carpineti, IFLScience, Senior Science Writer. Today I'm sitting down with Dr Mandeep Gill from KIPAC at Stanford University and a member of the Dark Energy Survey collaboration. The question today is what is the universe made of. Dr Gill, it is a great pleasure speaking with you today. Can you tell us a little bit about yourself and your work?

R: Sure, and great speaking with you Dr Carpineti and all the IFLScience fans out there. I've followed the website on and off at times. I've always enjoyed the name. I am a scientist at KIPAC, the Kavli Institutes for Particle Astrophysics and Cosmology at Stanford. I have my doctorate in Particle Physics from SLAC doing an experiment there. I moved into astrophysics later on in life – they're actually really closely connected. I work for, as Alfredo said, Dark Energy Science Collaboration, which means that the coolest part is you get to go down and observe – sometimes from the actual telescope, which is pretty neat. I'm not going to be speaking as a spokesperson for either institution, I'm speaking just for myself, but this does reflect generally what cosmologists believe about the universe overall.

I: Awesome, thank you very much for being part of our series. Let's start with the main question: As far as we can tell, what is the universe made of?

R: Well, we used to think the universe was made of this stuff we see around us, tables and chairs, which ultimately means particles. Mostly, the stable particles are protons, electrons, neutrons and photons, the photons are what we started with. Then we got to neutrinos and then we added in all kinds of particles that you don't easily see. Most of those particles decay, muons etc, that you might have never heard of. The only ones that don't are the ones I mentioned, protons, electrons, neutrons and neutrinos and photons, and maybe gravitons. We can get into lots of things but that is the classical picture, the standard model of particle physics that physicists have known and loved since really it came together in its current form, in the late '60s. Although there was this evidence from very early on, from this thing called dark matter, way back in the 1930s like Fritz Zwicky and others. It wasn't until the early 1970s as scientists, particularly Vera Rubin, were looking very carefully at how galaxies rotate, they saw they were rotating too fast and it became very clear that there had to be more matter than we were seeing in the stuff that we do see, normally through the protons and electrons that I mentioned. We call that dark matter. That forms a very sizeable chunk of the universe. There's about six times of that in matter as there is in normal matter. Whenever I say normal matter I do mean protons, electrons, photons which are not matter but they communicate between matter. The normal stuff we've always known for many, many decades. It wasn't until Vera Rubin in the early '70s and then later that we've really said there has to be more matter.

The final major component is something people may have heard of called dark energy. What is that? Let me describe the evidence for it first, which is by the late '80s and early '90s it was clear there wasn't enough dark matter, even though there was six times as much as normal matter to explain other aspects of the universe. For example, there's a large-scale structure of the universe, how the galaxies are placed, and there wasn't enough to explain that. By the late '90s that evidence was getting more and more compelling, and then in 1998 what happened was two groups saw that the universe was expanding faster than it is now. They did this by tracing supernovae that we can talk about. They found the universe was expanding faster. For a while it was slowing down in expansion, as you would expect if there was photon explosion and things were slowing, but everything was attracting each other, things would be slowing down.

Now what we say is normally have this pie chart and in this pie chart the normal matter we talked about at the start is about 5% of the matter energy density of the universe. Dark matter is some 25% and then 70% or so is dark energy of the matter energy content, if you take a big chunk of the universe, so that's the picture we have right now.

I: So, pretty much we only know and interact with 5% of the whole universe and we can argue how much we understand that 5%, but let's focus on the dark components of the universe. How much do we know about dark matter currently?

R: Some amount, when you said interact, there's four fundamental forces of physics and the ones we're most familiar with in our daily lives are electromagnetism, you see, in magnetism and electricity, it's also what holds matter together, it holds atoms together and chairs and tables together, and then gravity of course. We're stuck to the earth and that. Dark matter does interact gravitationally. That is the thing that we're most clear on that it interacts gravitationally and because that's really where it was seen. It was seen in the rotation curves of galaxies that they're rotating too fast. The more mass you have, the faster you have to rotate before falling in. As you go far out in galaxies, far even beyond where most of the stars are, so you only see tracer clouds of gas and a few stars, way out to like ten times as much as the normal lit up part of the galaxy. You keep seeing that things are rotating just too fast, it's like you're adding more and more mass out there.

The dark matter is all the way from the center of the galaxy all the way out to about 10 times as far as the break part of the disk. It's a little bit more concentrated towards the center but it's a much more diffuse cloud so it goes out. We see it there and we see it where the galaxies are located in clusters and all across the universe, so we call that large-scale structure. We see it in lensing, which is when light goes through a galaxy cluster and around it. It gets vented by all the mass in that galaxy cluster and so that is a very clear indication that there is more mass in this whole galaxy cluster, so, not just in the galaxy, but in the galaxy cluster which is a few galaxies swarming around like bees. There's dark matter all the way from the center, all the way out. We see it actually in indications way back from the cosmic microwave background radiation, CMB, from just about less than 1% of the time till now, after the Big Bang till now, is when the CMB decoupled, as we call it. We see the CMB from that time. We see it in the patterns of the CMB.

We see it just from how the light was distributed way back then, the matter was distributed which then ultimately imprints on the light that was coming to us, we see it on imprints of the CMB and in a few other places. I wanted to make clear that we don't see it in just one location galaxy rotation curves, like none of the cosmology that we have of the universe now works without adding in another mass of component, the clusters. There you go.

I: Okay, thank you very much for that explanation. Now we go to the other side, what do we know about dark energy?

R: We know a bit less about dark energy. Dark energy does not cluster in the simplest scenario. Dark energy does not seem to cluster at all anywhere in our universe. It seems to be evenly spread. We've done various searches to see if there's directionality to it, the speed of expansion, we don't see that. The simplest picture for dark energy, you didn't ask me what dark matter is yet, but the simplest picture for dark energy itself is that we take the equations for gravity which we call the Einstein equations and we add to them a constant energy density, a constant in time and space. That's unlike everything else. Also, dark matter is mysterious – it behaves like normal matter in a couple of ways. It clusters, and it also dilutes as you make a box larger. If you have a certain amount of dark matter that was sitting there in the center and you don't add more when you make the box larger, that dark matter dilutes. That doesn't happen with dark energy.

Dark energy has, well the simplest picture is that it has a constant energy density. When you make a box larger you get more energy. It's just that we don't, our conception of it is it's not a fluid, it's almost a property of space. It may be that we need to change the equations of gravity ultimately, which is not easy to do in a simple way, in order to incorporate it. As of now, all we see is this more rapid expansion of the universe. The simplest way to accommodate that is by adding this constant into the gravity equations. I can say also that Einstein himself was very well aware of this and you see this, if you look at the history, what he had… The philosophical predilection at that time was that there would be a constant, the universe was everywhere the same forever. It seemed to make the most sense. It seemed the simplest. Einstein didn't know initially that there were separate galaxies so he said he thought there were all these stars and the simplest way to make it stable was, as you can tell, dark energy has this anti-gravity effect, it makes thing expand faster. It's the only thing that does that. Normal matter, dark matter, none of those… The light gravitates, it has matter energy density, even gravitons, so they all gravitate

Dark energy, this weird property of space or even this respread energy, pushes things apart. Einstein knew about that and he said if I had a bunch of stars, then clearly they would start attracting eventually and they would have to clump. How am I going to make this stable for infinite time? Oh well, I know I can add this antigravity force in this constant energy density. It will stabilize the stars and it will keep things apart. He had added that in at that time, they called it a cosmological constant and it was only when Hubble and others found in the 1930s that in fact the universe is not that stable, there were galaxies and the galaxies were going apart that Einstein abandoned that and other people saw, well it is actually there's no need for cosmological constant at that time. It's just everything is expanding apart. The reason it took until much later to find this is because we had to look very far away and we didn't have telescopes to look at, at that time, to start seeing that this expansion of space is accelerating.

That's a picture, so Einstein knew that it could be there. It had been, people had had this dim awareness over time that it was a possibility, but it wasn't until '98 that people said, oh it is true, the universe is expanding faster and we need to put this in, or this is the simplest thing we can put in to actually make space expand faster. It has this very specific amount of constant energy and density, and I told you right now it's 70% of the matter energy density of the universe. But as I told you, as boxes get larger matter, normal matter, and dark matter keep diluting the dark matter, dark energy does not dilute in anyway so it eventually takes over. We might get to that later here but I know some of your questions were about the future of the universe, so I'm looking ahead as we all look ahead to the future of the universe. That's our picture.

I: Well thank you for that, and I think we can move into the next question which is dark matter is some particle of some sort...?

R: Okay, let me address that.

I: Let's address what dark matter is?

R: Right, dark matter is something we don't know. I told you all the pieces of evidence and the way I say it is if you asked any cosmologist "is there dark matter?" they would bet their house. They would bet anything that they own that there's dark matter out there, because when you study something enough you see the evidence every day. Now, if you asked them to bet their firstborn child or their hand, we can talk about levels of bets, what they will say, let's be clear, is that there's only two possibilities. That's there's a dark matter particle as you said, or some kind of dark matter. I'll get to that in a second that's out there or that you have to modify gravity. I told you that there's a modification, it's more likely that we modify gravity or it embeds into a larger string theoretic framework or something for dark energy. It's harder to do that for dark matter, we've tried in different ways to modify it, but maybe not impossible.

I want to keep that logical possibility out there because we have not found dark matter as much as we've tried. What is dark matter? Well, the reason that in the early 70s I told you there was evidence that there was more matter and people got excited because there's also a theory coming out called super symmetry which helped with some particle physics problems that are a whole different thing, having to do with the Higgs boson and things like that. The mass of the Higgs boson and the super symmetry helped with those particle physics problems. In fact, it's not just some additional theory, it's a fundamental symmetry that seems very natural for space time. We've not seen SUSY, we usually call it SUSY. Sometimes the really nice models on paper don't come out to be true. It's not ruled out yet, either.

Now, what happens in SUSY is if you introduce this particular mathematical thing called R-parity, you have the least lightest super symmetric particle that can't decay into anything else, but it doesn't interact with matter in any way either. It was a natural candidate for dark matter.

Many people said, oh, this is really nice. We're killing many birds with one stone, if you like to kill birds, or you can use other analogies. This was very nice and natural and people said, well this is cool. We'll have the LSP, that ultimately also got classified in the larger frame as a weakly interactive massive particle, a WIMP which people may have heard of. There were other candidates for WIMPs from other theories that were a little less motivated, but people through… I said that it doesn't interact at all, so people, you could dial in a little bit of interaction, so it would interact a little bit.

That was a weakly interacting part, just like neutrinos which we… There's a very good analogy with neutrinos, neutrinos were derived in '32 or so by Wolfgang Pauli who said, momentum doesn't look like it's being conserved in neutron decays. There has to be a third particle coming out in addition to the proton and the electron, I'll theorize and call it a neutrino, little neutron… There were a lot of Italians around that were your countrymen, Alfredo. That was theorized by Pauli and what they knew from looking at the ways that it would have to interact was that it would be very different to detect. It wasn't until the mid-50s that it was found in Savannah River, Georgia, next to a nuclear reactor. It's big detectors next to a reactor. They detected there was neutrinos.

Something that was partially to fundamentally keep momentum conservation, a very basic principle of particle physics, of all our physics up till that time, it has to do with the fundamental symmetry of translation that's preserved. If I go from here to here, space is the same. That's where momentum conservation comes out of, these are not random things. They're very deep in the theory. It's very difficult to break some of them. Because of that, they theorized the neutrino and it wasn't found until 25 years later. Now, that's the analogy with dark matter, that in the early '70s it was very clearly there, through indirect means, this indirect evidence showing that something's got to be there. We thought we would find it. Now, many more than 25 years have passed since then and people have looked, they've built very large detectors, actually at SLAC there's one, we helped build this one that's going into a mine in South Dakota.

We've made them larger and larger where we build these dark matter detectors to see if, just like neutrinos, we have to have a lot of matter so that even if you have trillions of things, particles coming through every second, which is the case for us with neutrinos, they come from the sun, there's trillions going through us every second, we only have a few interact in our body our entire lives. That's how rarely they interact. If you made a million times as big as me, you would have a few interacting every day. That's the idea with dark matter is we've said, well even if it interacts very little, we will build this very big detector and we keep building them and maybe it will interact. There's one difference that dark matter, as I told you, we only have the evidence of it for sure from gravitation, so even though there's theories for what it could be, those are not locked down theories.

We have to know that the interaction could go to zero with normal matter. The interaction could go to zero, let me say that again. That is it may never interact with us except for gravitationally and there are those models as well. Although these were well-motivated theories, we have not seen a dark matter particle yet and now it's 50 years since 1970, 51. What is dark matter, let's go back. Dark matter can be anything that gravitates and clumps. We can go all the way from… There's been another particle physics motivated candidate for a while, called an Axion, so it can be anywhere from an Axion which is 10-20eV or 10-26 x mass of electron, eV/C^2

I: **It's extremely light.**

R: Extremely light, right. With 26 zeros, 1x mass of an electron, all the way through WIMPs, they're about a million times something of the mass of an electron all the way up. I told you they were the most motivated candidates for a while. Now people are looking for axions in different ways, they have been looking again, we haven't seen those. All the way through some other candidates to something called, and this is probably the most recent fashionable thing, something called primordial black holes which weigh several times what the sun weighs, okay, or in that range, they could be somewhat lighter, up to that. There's a cut off where you destabilise galaxies if they get too heavy. Any of these things do cluster. The axions cluster in clouds even though they're still light, they cluster. The primordial black holes they're actual mass and they cluster.

All these have arguments for and against their existence but there's about, I told you there's about 80 orders of magnitude in mass between them. It's one of the most undetermined theories out there as far as what it is. If you ask me personally, I don't know. I actually like primordial black holes. There's some astronomers that will say we should have seen more lensing and there's some evidence against them. It's not totally flinched. I would say the story is not closed there either. That's why people still talk about them. You see papers come out and they got much more popular after the LIGO detections about five or six years ago. What we saw was that LIGO was detecting less massive… There were a lot of black holes. There were less massive ones up to massive ones. People were like, oh this is cool, maybe some of these are primordial which means they're there from very early, well, around the Big Bang time. I can talk about that if you want to know…

They're different than most of the black holes that we have, they're called stellar mass black holes. They're formed when huge stars like Betelgeuse collapse, their core collapses and it becomes a black hole. Eventually, some of them form together and you get super massive black holes at the centre of the galaxies as maybe you have studied back in your astrophysics time. Those are stellar mass and we've had a decent picture of those for a while. Stellar mass is super massive, but the primordial ones maybe in a different mass range. They have a different origin. As long as they cluster they'd be find for dark matter. There's be a good amount of them. They're my favorite. Do I believe in them, I wouldn't bet a house, I wouldn't bet my car on any of these. I would bet anything I have that, as I told you, there's some dark matter candidate out there or you modify gravity. I bet on a dark matter candidate, I just don't know that we're going to ever detect on in any way, other than gravitationally which is as it is, so that's where we are with those.

I: **Also, I think my next question is, you've explained so much about the effects of dark energy and dark matter on the current state, how dark energy is pushing the universe apart at an accelerated rate, how dark matter is keeping galaxies and the cluster of galaxies together. If our understanding of them is correct, what can we expect in the future, the far future, what is the destiny of the universe if your theory is correct?**

R: Right, that's a very natural and reasonable question and the simple answer is one that some cosmologists are not terribly happy about. I had an office mate, not too many years after dark energy was discovered. He was British and said, I'm kind of depressed about this whole thing because what it looks like in the simplest picture is that dark energy takes over. I told you that it dominates over the other things. Even though, in the early universe it was a very small percentage because everything was so dense, so dark matter and normal matter dominated everything. Now, as that stuff gets less and less dense as the stars burn out over billions and trillions of years, everything gets diffuse and then eventually everything gets cold and dark and that's how it is. We have a very cold, dark fizzling out. In the very far universe we expected black holes also to radiate through Hawking radiation they radiate out their energy and so all the black holes that are there would also radiate their mass into neutrinos and you'd just think there's be a fuzz of neutrinos, and it would not be very interesting or warm to live in.

I don't worry that much because at the moment it's far away off, so if there's any kids listening, don't worry kids. Go ahead and buy your beachfront property wherever you need to be, climate change will be a worry for that. It's a much more urgent concern for humanity, that is happening. The other thing is not only is it far away off. We've had many different pictures of how the universe is. Einstein had this steady state of course early on. There was just one earth and then we came to a expanding universe and then maybe people thought there was a cyclic universe, it was bouncing back and forth. Now we've discovered dark energy and we say that the universe is expanding faster. These are all true, these are all true. These are all phases of how we've pictured our universe. They're incomplete and at each stage being incomplete and it maybe that they're always incomplete. The next thing that we discover might be different to that. We will discover that dark energy maybe is a little less powerful. It's maybe not exactly cosmological constant, that's still possibly the case.

In the far distant time our universe will re-collapse or we live in a multiverse, whether there's other universes and our universe will possible collide with one of them. There are various scenarios. I'm not going to put a lot of stock into any of them. All I'm saying is our picture is always incomplete. The thing that matters to us is our life and the earth and the descendants and this far future of the universe really should not concern anybody too much at the moment. It's a very different kind of thing to worrying about our life or the earth or anything like that. That's what you'll hear from cosmologists.

I: Let's talk about the dark energy survey. Recently there's been the publication of it, three years' worth of data, and it's the most precise understanding of cosmology that we have achieved so far. Why is that important?

R: Well there's a few reasons it's important that we continue exploring this. One is that dark energy for example is fairly new. It's in the last 22, 23 years humanity has found it and it's still very new to us. We don't get it and so why is there this weird component and is it really the cosmological constant. That's what we're trying to aim at. Dark energy survey, through several different means, looks at this question, particularly through weak lensing. The results you saw yesterday were primary weak lensing based. There was a little bit of discussion about this. That lensing, weak gravitational lensing is because light is being bent by galaxies and dark matter, galaxy clusters from where it first originates to us. It's become a powerful technique especially in the last 20-ish years. Those are the most precise results because dark energy survey has taken the deepest, widest picture yet of the universe. We have 500 million galaxies or so, a very large number of galaxies, half a billion galaxies that we've imaged, the most of any data set ever. It will only be exceeded by Rubin Observatory which is taking over and will start in a couple of years. It's being built. It's only about 25 miles away, so you can see it if you're at dark energy, the DES camera and telescope which is called the Blanco telescope down there in Chile.

If you're at the Blanco, you can see LSST and you get to it through a very circuitous route along all these roads. It takes much longer to get to it because you're in the very dry mountains and these roads take such a long time to get up there. It's a beautiful site, very desolate, beautiful in its desolation. Rubin Observatory will start taking data and that will be then, for the next decade that is going to be the pre-eminent ground-based experiment that is going to really tie down, even better, a cosmological constant. We're at the few percent 10, or a few percent level of uncertainty on whether the dark energy is really a cosmological constant, whether it changes in time or space right now. Rubin will pin that down to less than a percent. Then, at that point if it's really still in that range and we don't see any variation, then we have to think of other ways we can try and look for deviations from it or what's next.

The multiverse that I mentioned is a very popular possibility. It says, well there's many universes out there and ours was the one born with this number of exactly what it is, that's allowed us to evolve. There's other universes with very different physical laws that humans couldn't involve in, and many scientists find that unsatisfying because it feels like a cop-out. It feels like, well you haven't explained anything, you just said there was a bunch of random chance and so that doesn't tell me anything about our particular universe and, you know, I don't know what to say to any of these things. The multiverse is far beyond anything that's detectable right now and I'm an observational cosmologist. I'm much more concerned about what are the things that we can get to within our lines and detect. Like I said, science may have an incident extent. It doesn't disprove, I always like to be very clear and I hope your IFLScience fans understand this, people will say Einstein overthrown, this overthrown, quantum mechanics overthrown and, yes, we have a different paradigm and a different picture but whenever we go to the next stage, we expand.

We expand our picture of science and understand more. We still reduce back, in our normal world Newtonian mechanics works just fine. You have to go to extreme masses to get Einstein in relativity to matter, like black hole stuff. Yes, it does get used, actually our GPS satellites have to account for Einstein in relativity time delays otherwise we'd be off on GPS by a couple of miles. In very sensitive cases you have to use it, but most of our lives we can use Newtonian mechanics very well, that's one example. Everything's got to reduce, we keep building on science. Science is always there, science is an interesting phenomenon in human, if you want to call it a phenomenon. It's our way of describing the universe that just works. I always say it's special because the aliens would have to find the same science, they would have to find the same protons and neutrons and relativity in all that stuff. They might have much more, no doubt. I always want to be humble about where we are because 100 years ago some people thought there was so much science that they'd discovered it all and then quantum mechanics and relativity and all those things came out right after that.

We're always expanding but I do believe that it's human independent… I'll call it a belief, I just say this because we have this… What do they call it, post-modern science. Science is different and it does not make it the most important thing, Alfredo. Probably love is the most important thing in human affairs, but as I think even they say in the movie, Interstellar… It's special in human affairs and it should inspire us as Karl Sagan always said, towards greater heights. It's special in that it's independent of humans, it's just there in the universe. We don't know why the universe is here, we don't know how it got here, all I'm telling you is the big bang happened and it's got to here. We're discovering these laws. Maybe we'll go deep past the big bang at some point. We will discover things. I don't know if we can ever answer that question, why are we here. I know I'm getting a little philosophical. I minored in Philosophy at school so… It's always in my mind.

I: We're happy to hear philosophy.

R: My mind goes in those directions. It's a natural question, we all want to know why are we here, why are things here, where are we going, right? These are the questions cosmologists ask but we ask them where we can make advances in our science. I can't know if there are aliens, I don't know, I haven't seen them visit us. It's possible. We evolved somehow on the earth so it's possible but I don't know for sure. Questions like that, when we have to be humble and admit our ignorance when it's there too. That's something that often humans have a hard time doing admitting that. It's like yes, we don't know, we're here. We know some things, we learn some things that life is beautiful, like the Italian movie talks about and we should do good things while we're here and love one another and all those things. That's what there is. It's definitely a little bit beyond science but it always comes up when we have these conversations, well when I have these conversations.

I: I think that is actually a fantastic note to conclude on. Thank you very much for your time. It's been an absolute pleasure to discuss with you how much we know, or how little we know and how much we don't know about the universe. Thank you so much.

R: Thank you, Alfredo, and thank you to all the IFLScience fans out there, take care, bye, bye.

Thanks for listening to IFLScience, the big questions, don't forget to subscribe so you don't miss any future episodes and in the meantime visit IFLScience dot com for all the biggest news stories from the world of science. Until next time…

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