Andrew Saintsing: Hi, you're tuned into 90.7 FM KALX Berkeley. I'm Andrew Saintsing, and this is The Graduates, the interview talk show where we speak to UC Berkeley graduate students about their work here on campus and around the world. Today I'm joined by Vetri Velan from the Department of Physics. Welcome to the show, Vetri.

Vetri Velan: Hey, Andrew. Thanks for having me on.

Saintsing: Yeah, it's so great to have you here. I'm really interested to learn more about your research because you study dark matter and, to be honest, I have kind of a limited, maybe not even a limited, understanding of what dark matter actually is. So, can you tell me more about it?

Velan: Of course. So, the simplest answer is actually maybe the one you'll like the least, which is we don't know either. But I can go a little bit more into detail than that. The idea is that we have a lot of evidence that in the universe there is all this missing matter which we call dark matter.

Saintsing: What do you mean by missing? Sorry if you're about to say.

Velan: I was, but that's okay. So, what we can do is we can look at galaxies and galaxy clusters, and we can look at the speed at which they rotate, and we know that the way in which galaxies rotate is going to be governed just by Newtonian gravity.

Saintsing: So, galaxies are rotating as in, like, we're talking about there's a center like the sun is the center of our solar system and everything's rotating around that? Or are you talking about like they're moving relative… the galaxy is moving relative to the rest of the universe in some way?

Velan: Oh, good question. Yeah, no it's like the movement of the planets around the sun.

Saintsing: Okay, right so we're talking about the stars in the galaxy rotating about the center of the galaxy. So, we're rotating around our sun, and then our sun is rotating around, I guess, the black hole in the middle of the Milky Way.

Velan: Yeah, exactly, and so what you do is you can look at a lot of galaxies, you know, not just the Milky Way. You can look at a whole bunch of galaxies, and you can look at how fast they're rotating. And the speed at which they're rotating is going to be given or is going to be related to the amount of mass in the galaxy because the more mass of the galaxy the higher the gravitational force. And as a result, the stars are going to be moving faster around the center of the galaxy. So, what we can do is we can just work backwards, and we can take the speed of the stars, and we can convert that to the mass of the galaxy, and we can calculate how much mass is at different distances from the center basically. But there's another thing we can do which is we can say, “okay, let's just look at all the stars in the galaxy.” Not just in the visible, but in all types of electromagnetic radiation.

So, you look at radio waves, look at X-rays. I think actually people mostly look at X-rays. And you can, from that, calculate what is the mass of the galaxy, just saying, you know, how much stuff is there in the galaxy? And, therefore, what's the mass of the galaxy? And you got the mass from the rotation speeds of the stars, and then you just say well those numbers should match. They should equal each other. And they don't. And so, it turns out that the galaxies are rotating much too fast. And in fact, you would, when you do the calculation and you try to figure out how much mass there must be in the galaxy for them to be moving that fast, there has to be at least like (it depends on the galaxy of course) but there has to be at least like five or six times as much mass as we can actually see using light. This missing component of the galactic mass is what we call dark matter.

Saintsing: Yeah, so this is just stuff that's contributing mass but that we can't see, we can't detect.

Velan: Exactly. And in fact, I'm actually giving you like a very, very old story of the puzzle. I'm giving you roughly the story that was first theorized in the 1930s by Fritz Zwicky, really understood much more carefully in the 1970s by Vera Rubin. But you know this is the story kind of as we knew it let's say in the 70s and 80s or so. More recently we have a lot more measurements that also point to dark matter. That, for example, includes measurements of how fast the universe is expanding as a whole. So, not just looking at individual galaxies. We're looking at the expansion of the entire universe. You can also calculate from that how much dark matter is in the universe as a whole, and you find again that it's somewhere around five or six times as much as the amount of normal matter (which is just like atoms)

Saintsing: So, that's cool that the multiplying factor (like five to six) it's like the same then based on…

Velan: It's similar. Not necessarily… I was just… I'm giving averages. So, like the five to six is for the universe as a whole, and then, so then it must be true for the average galaxy. But the ratio for any given galaxy varies quite wildly. So, my conclusion, or the point you should take away from that is that there is this puzzle that exists where there are tons of astrophysical and cosmological measurements that all say there must be dark matter. And so, my question as a particle physicist (I'm not an astrophysicist. I'm not a cosmologist. I'm a particle physicist.) My question is: what is the nature of the dark matter? What is the fundamental dark matter particle?

Saintsing: Okay, so like what's a fundamental particle?

Velan: Yeah, good question. So, many of your listeners probably know that the way in which we tend to think of the world around us is that the fundamental unit of matter is the atom. And so, everything, from you, me, the air, the rocks, the trees, is made up of atoms. And you probably also learned in your physics and chemistry class that atoms are made up of protons, neutrons, and electrons. So, electrons are a fundamental particle, and by fundamental particle I just mean that it's not composed of anything else. The electron is the electron, and there's nothing inside an electron.

Saintsing: We know that for sure?

Velan: 99% of physicists would agree with me on that. There are certainly some people who try to look for electron substructure. And in fact there are other people who try to look for just substructure to the standard model of elementary particles in general. But in general most people would agree with me.

Saintsing: How would… what does it mean to look for substructure in a… can you… you can't see an electron, right?

Velan: Yeah, you absolutely can. Yeah, it's, in fact, it's not even that hard actually. So, like what's a good way to see an electron? So, you know a good way to see an electron is to build a really dense block of material. This is something we call a calorimeter, and you have a big block of material, and as the electron passes through the block of material if it has high enough energy then the electron will ionize the atoms around it. Those atoms will also give off their own electrons. But now you have a whole bunch of electrons that are produced, and if you put them in an electric field then they will be very energetic and produce even more electrons. So, you can get this kind of shower of particles from one individual electron that you can then see.

Saintsing: What do you mean by see?

Velan: You can hook it up to charge sensors, where the electrons are drifted away from the original track of the original electron, and the secondary electrons are all collected on charge sensors. And then, you measure the voltage of the charge sensors. Okay which doesn't sound like seeing. But it really is because you can, you know, by doing a strategy like this you can see a track of an electron. You can actually see it like in fact. And (I'm thinking of something more modern like because it's what I'm used to) where you're doing some type of computer programming to, you know, do some type of 3D visualization but honestly there are experiments you know decades ago called bubble chambers and cloud chambers where… let's look at a l bubble chamber, I guess. In a bubble chamber, you have a whole bunch of super-heated water (which means water above its boiling point). So, it's water in the liquid phase but you treat it very carefully and you can bring it above the boiling point. But as you have a high energy particle like an electron pass through the water, then it's in this very unstable equilibrium because it's liquid but it's above its boiling point. So, when the electron ionizes these atoms around it. It creates a disturbance and then the water actually will evaporate and will form little bubbles. And you can see the tracks of these bubbles in like a photograph for example.

Saintsing: Okay, so essentially, you're looking for its effect on the world around it and that is seeing it?

Velan: Yeah, yeah.

Saintsing: I see. And okay, so we can see the electron, but how do we know that it can't be broken down?

Velan: That's a great question. So, the best way in which we're able to do something like that is just smashing things together with a lot of energy. In the same way that, you know this is going to be a little silly right, but like if you have a box with some um stuff inside (some chocolates, some toys, whatever), another box with some chocolates and toys, and you want to know what's inside them, one really you know kind of fun way to do it is to smash the boxes together. The outside of the boxes will break, and then you can see what's inside. This is not totally different than how we find new particles. Moving back to the electron, one way that we can look for electron substructure is by smashing electrons together and seeing what comes out. And we've never observed anything coming out.

Saintsing: Okay, so electrons: they're fundamental particles. There's nothing that comes out when we smash them. But I think you're going to say other parts of the atom aren't.

Velan: That's exactly correct. So, the proton and the neutron are not fundamental particles. The proton and the neutron are made up of what are called quarks.

Saintsing: Okay, so there are quarks in that, and we know that because we smashed together protons?

Velan: Yeah, exactly. And we do this all the time. I think we're doing it right now. I can't actually remember at the moment, but the Large Hadron Collider, which is the big particle collider in Geneva, Switzerland, they are smashing protons together.

Saintsing: Okay, so we smash things together, and stuff comes out. And so, then we get to the level of fundamental particles, and I guess the… like we use some effect of these fundamental particles on the world around them to see them. And quarks would have a different effect on the world than an electron, and so, we would know that this is a quark and this is an electron.

Velan: Absolutely, yeah. And so, we build what's called the Standard Model of particle physics. And in the Standard Model, there are a fixed amount of fundamental particles. There's a finite number of pieces of the puzzle that you can put together to build the universe. The number of fundamental particles is actually higher than you might think. It depends on how you define it, but if you define it in the most generous way possible, then the number that you get is 61.

Saintsing: So, we have a bunch of fundamental particles, and we have a bunch of fundamental particles that we have observed, but you're interested in finding that 62nd or however many, and that is the fundamental particle that would be the fundamental to dark matter.

Velan: Right, in fact, one of the first things that people thought about when they realized there was this dark matter is (you know the first question you ask is) “well. is it just a particle that we already know exists? Is it one of those 61?” But unfortunately, it's not. We have, you know, tried all of them, and none of them work.

Saintsing: What do you mean you've tried them? Like, do you have dark matter?

Velan: No, no. By try, it's very easy. You just take the particle, and you understand how it affects the world around it, and you understand how dark matter affects the world around it, and you just say they're not the same. So, I'll give you a great example. So, could dark matter just be comprised of electrons? That's, you know, one of the fundamental particles. Could it just be comprised of electrons? And it can't because the dark matter, one of the really key features of dark matter, is that it doesn't interact with light or else we would have seen it through light. And any particle with an electric charge will interact with light. So, it can't be an electron because those have electric charge, and it can't be a quark because those have electric charge. So, you're able to get rid of a lot of those options that way. Then what you can also say is that, well, the dark matter needs to be long lived. It needs to be relatively stable, meaning if I have the particle, it can't just decay spontaneously. And a lot of the fundamental particles in the Standard Model do decay spontaneously. So, most of the fundamental particles are thrown out because they don't interact. Or they do interact with light which dark matter doesn't. And because they decay rapidly or because they decay rapidly which dark matter doesn't. There is one other category of fundamental particle that we know exists that does not fit in any of these categories, so it's not electrically charged, and it doesn't decay, and it's called the neutrino. Just about every nuclear fusion or fission process will produce neutrinos. So, every nuclear reactor on earth, every nuclear radioactive source, the banana you might have had for breakfast this morning is a little radioactive. If you fly, you're getting exposed to a little bit of radioactivity in the upper atmosphere. All of those are producing neutrinos. It's a very light particle to the point where determining what its mass is is one of the biggest puzzles in physics today. Because it's so light that no one actually knows how heavy it is. Even though we don't know what the mass of the neutrino is we know what's the maximum mass of the neutrino. We know that it is less than a certain number. And that number is far too small to be dark matter. Okay, so we've ruled out based on electrical charge, decay time, and mass. And now, we've eliminated every single one of the fundamental particles we know exists.

Saintsing: All right, so now we got to go looking for this fundamental particle.

Velan: Exactly. So, there's a whole bunch of types of dark matter particles that people theorize, and I'm going to be… my experiment is looking for just one type of dark matter particle, and that is called the weakly interacting massive particle or WIMP. We've got a lot of fun names in physics. So, the WIMP is a particle with about the mass, somewhere between one and a thousand times the mass of a proton. It's also weakly interacting, meaning that when a WIMP passes by a normal let's say nucleus… let's say a WIMP passes by a proton or a neutron or just the nucleus as a whole, the probability that it interacts with that nucleus is very, very low. But non-zero. So, we say that… okay, let's say the dark matter particle… let's say I'm a dark matter particle, I'm somewhere in space, and I'm making my way towards the Earth. So, I make my way through the atmosphere. I pass by a whole bunch of oxygen and nitrogen and stuff, doesn't matter. I pass through human civilization, there's all these trees and buildings and people, it doesn't matter. I don't notice any of it. I pass through the Earth, and I say, you know, it doesn't matter. I don't notice any of it. I pass through a mile of the Earth's crust, and then I finally get to the LUX-ZEPLIN experiment, or LZ for short. The LZ experiment is located a mile underground in the Black Hills of South Dakota in what used to be the old the largest gold mine in North America. LZ, when built (it was supposed to be completed this year, and then we had a global pandemic, and so as a result things are a bit delayed), but when it is built, the experiment will contain seven tons, that's 7000 kilograms of liquid xenon. So, okay, so I'm a WIMP, and I make it through the Earth and don't notice any of it. I pass into our facility, and I pass into the xenon volume, and then, just by chance, I happen to see a xenon atom, and I happen to collide with its nucleus, a very rare occurrence, but maybe it happens. And then what will occur is that the WIMP will transfer its kinetic energy to the xenon nucleus and produce what's called a nuclear recoil where the nucleus of the atom is kicked. And a lot of kinetic energy has just been transferred to the nucleus of the atom.

Saintsing: So, you're going to get like a ripple or something in your xenon tank?

Velan: You're going to get quite a ripple indeed. So, what's going to happen is this nuclear recoil is going to be visible in the form of two main signals. So, first off, this nucleus you have one atom to start with, but this nucleus has a lot of kinetic energy so it's going to transfer its energy to the atoms around it. So, you have this one xenon nucleus but it's going to transfer its energy to the stuff around it because it's just a ton of kinetic energy. And so, what you're going to have happen is a lot of the atoms are going to have… are going to be so excited that their electrons are ionized. So, the electrons are just ejected from the atom because there's just so much energy and the electrons are like, "I gotta get out of here." The second thing that'll happen is some of the atoms will get excited not to the point where the electrons are ionized, but just to the point where they're excited to a higher energy level in the atom. And when they de-excite and when the atom comes back to its what's called its ground state, then that energy will be emitted in the form of light. In the form of light. And so, what you have is these two signals. You have a bunch of electrons that are produced, and you also have a bunch of light that's produced. And we can detect both of those signals using these really sensitive light sensors basically. So you have the light that's detected by these incredibly sensitive detectors called photomultiplier tubes. These are sensors that can detect as low as just one individual photon of light. And then, you also have the charge which is actually converted to light through some process. And then, that light is also measured by the photomultiplier tubes. So, basically in the end what you're seeing is that this nuclear recoil produced this charge and this light and both of them are being detected in our detector by these sensors.

Saintsing: I got you. Okay, and so, I assume that it's underground and it's xenon because these are things that will be specific to the WIMP and won't get reactions from other stuff.

Velan: So, that's a fantastic question. So, you actually asked two questions. So, let me do both of them. So, the first one is: why are we underground? And the second one is: why do we use xenon? So, to answer both of those actually I need to tell you a bit of a secret, (which is not a secret at all in my field) which is that the story that I just told you while correct also happens for plenty of things that are not dark matter. So, you can have tons of other particles that interact in the xenon and give you nuclear recoils. Or they could interact with the electrons of the atom, and they can give you electron recoils and you just have all these sources of energy being injected into your detector. So, that's not good. So, there's two ways to deal with that, and we do both of them. So, the first way is to just understand all your sources of other activity. So, you just very, very, very carefully understand all your sources of background that exists in your like other stuff that could be interacting in the detector that might mimic your dark matter signal, that might look like dark matter. So, we do that. But then the other thing we do is we just try to build the detector in a way that there are fewer of these background events, that you know there's just as few as possible of these extra events that would occur. Xenon helps because xenon is very, very dense. It's about three times the density of water. Xenon that's close to the walls of the vessel will have a lot of background activity, but what you can do is you can just reject all that stuff, and you can just look in the center of the detector. And in center of detector, it's quiet. There's not much background.

Saintsing: I see. I got you. Okay, so you're underground, you're using xenon. You're basically trying as hard as possible to limit whatever you see to these very specific molecules that you're theoretically proving exist.

Velan: They're not molecules.

Saintsing: Right, right. Particles.

Velan: Right, that's exactly right. And I will just say that these interactions are very, very rare. I will give you an example. We expect that in 7 tons of xenon, if we're lucky maybe, we will see a few interactions per year from dark matter particles, from WIMPs, unfortunately.

Saintsing: We have run out of time for the interview, so I will have to wrap things up here. Usually at the end of interviews we give a chance for our guests to address the audience on anything that might have come up that they want to go back to, or anything that didn't come up that they'd like to mention. So, is there anything you'd like to address the audience on before the interview wraps up?

Velan: Sure, I'll just conclude by saying that the universe is a really fascinating place and filled with a lot of unexpected phenomenon. It turns out that between dark matter and something we didn't talk about at all called dark energy, between those two things, the amount of stuff in the universe that's made up of the same matter as you and me (atoms, protons, neutrons, and electrons) that only makes up less than five percent of the total stuff in the universe. The universe is dominated by dark matter and dark energy. These are two questions. These are two things that we don't understand, and so there is still so much that we don't understand about the universe that allows people who are interested in it to really tackle these questions head on and try to understand what the universe is made of.

Saintsing: Nice. Yeah, too bad we… now I need to know more about dark energy.

Velan: I can give you an explanation next time, or I can, you know, give you a reference to someone who knows more than I do.

Saintsing: Cool, I'll take that reference outside the interview.

Velan: Sounds good.

Saintsing: Yeah, thanks so much for being on the show, Vetri. It's been a lot of fun learning more about particle physics. Today I've been joined by Vetri Velan from the Department of Physics. We've talked about dark matter and just about regular matter in the universe and how we deal with it in our daily lives and how we can detect it. Again, thanks so much for being on the show.

Velan: Thank you so much, Andrew.

Saintsing: Tune in in two weeks for the next episode of The Graduates.