Published on *Up Close* (https://upclose.unimelb.edu.au)

#240: Mass nebulous: Our evolving understanding of dark matter

VOICEOVER

Welcome to Up Close, the research talk show from the University of Melbourne, Australia.

SHANE HUNTINGTON

I?m Dr Shane Huntington. Thanks for joining us. Over the last 100 years we have built increasingly large and sophisticated telescopes, even placing them in space. These scopes allow us to peer into the distant reaches of the universe, in effect, to look back in time. Our observations of the universe have led to significant changes in our understanding of how stars, galaxies and other exotic objects work. It turns out that common objects such as galaxies do not work as we predict they should and for the last 80 or so years astrophysicists have been challenged to accurately predict their rotation. Dark matter, which is said to constitute the vast majority of the matter in the universe, is a potential explanation for these discrepancies. But to date dark matter has not been observed directly and so understanding remains elusive. For a closer look at dark matter we are joined today on Up Close by cosmologist Dr Katie Mack, a Research Fellow with the Astrophysics Group in the School of Physics at the University of Melbourne. Welcome to Up Close, Katie.

KATHERINE MACK

Thanks. It?s good to be here.

SHANE HUNTINGTON

You work on dark matter. Could you give us a description in sort of broad terms of what dark matter is?

KATHERINE MACK

So dark matter is the largest component of the matter in the universe and it?s made of something that we don?t yet understand. So we know what atoms are, what know what everyday objects are made of protons and neutrons and electrons. We have a standard model of particle physics, which contains all the particles that we?re aware of, all the particles we?ve understood in detectors and in laboratories. Dark matter is something else. It?s something that doesn?t interact with light so far as we can see. It doesn?t interact with other particles in any way that we?ve been able to detect except that it has gravity. So we?re able to observe that it has gravitational effects on things but we?re not able to observe it in any other way so far.

SHANE HUNTINGTON

Now, you mentioned it makes up most of the universe. What?s the rest?

KATHERINE MACK

Well, it makes up most of the matter in the universe, and that?s an important distinction. The vast majority of the energy budget of the universe is made of dark energy, which is something even weirder that I probably don?t have time to go into but it?s something that?s responsible for the way that the universe is expanding at the moment. Dark matter is the majority of the matter component so it?s most of the stuff that has gravity, most of the stuff that interacts with the gravitational force, has mass and then the rest is things that we understand, like atoms, you know, ordinary particles. We call them baryons in astronomy, generally, but that?s not the most general term but that?s the way we talk about it. So ordinary matter or what we call luminous matter, stuff that has interactions with light, that?s the rest.

SHANE HUNTINGTON

So this is the stuff we can see there is.

KATHERINE MACK

Yes.

SHANE HUNTINGTON

Like you and me, the stars that are visible; the visible galaxies, the parts of the universe that we can look through a telescope and observe directly.

KATHERINE MACK

Yes but that?s only about four per cent of what?s actually in the universe.

SHANE HUNTINGTON

Why do we call it dark matter? We can?t see it but is there any specific reasoning behind that term?

KATHERINE MACK

It?s called dark basically just because we can?t see it. It doesn?t emit light and it doesn?t interact with light and it doesn?t produce light. It?s dark in the sense of being invisible more than it?s dark in the sense of being black. It?s not black, it?s just we just can?t see it.

SHANE HUNTINGTON

Now, no one?s actually detected dark matter, so how do we know that it?s actually there? It seems like an incredible construct.
KATHERINE MACKRight. Well, we know that something is there, basically, so we know that there is more stuff that has gravity than the stuff that we see. We haven?t detected it directly in terms of having a particle detector or an accelerator or something like that and seeing the particle physics effects of it but we do see the gravitational effects of it. So the way we see it is by looking at the way things in the universe are moving. For instance, one of the first discoveries of the concept of dark matter was by looking at the way galaxies rotate. All galaxies have some kind of rotation, some kind of movement. Our galaxy is a spiral galaxy, it?s moving sort of as a disc. The way that the stars are moving around the centre of the galaxy can tell you about how much matter is in the galaxy. Just as looking at the orbits of planets in our solar system would tell us about how massive the sun is, similarly looking at the way that stars and galaxies are rotating around the centre of the galaxy can you tell you how much mass is in the galaxy. And n all the galaxies we?ve looked at, the stars at the outer parts of the galaxy, the stars, the gas, everything that?s moving around the outer parts of the galaxy, are moving too fast for the matter that we see to be holding it all together. So if it was just the matter we saw then the stars would be flying off into space. So there?s something there, there?s something more that?s holding all those stars together and holding the galaxy together and keeping it from flying apart. What that is, is we call that dark matter.

SHANE HUNTINGTON

Why have we gone with the idea of it being another type of matter instead of just perhaps a different understanding of the physics of very large length scales and how gravity works and so forth? Why that option? It seems as though we could have gone a few different ways here.

KATHERINE MACK

Right. Well, there are a few reasons why we think it?s an actual new component of the universe instead of an alteration in the way that gravity works. So one is that we?ve been able to measure the number of particles of ordinary matter in the universe as a fraction of the total matter in the universe by looking at things like the cosmic microwave background, which is the leftover light from the Big Bang. We can see fluctuations in that, that tell us something about how many ordinary particles there are. And when we look at that we see that the number of ordinary particles suggested by the way that those fluctuations are distributed says that there are not enough to make up all the matter in the universe. Also the way that galaxies formed in the early universe, they couldn?t have formed that way without dark matter because ordinary matter has different properties. When ordinary matter comes together it has collisions, it heats up, it has interactions with radiation and so on that would make it harder to form galaxies. So we know that there has to be something that doesn?t interact so much with other particles, that forms the glue to hold galaxies together, because if it was just ordinary matter the galaxies wouldn?t be the shapes that we see, they wouldn?t be the sizes that we see, they couldn?t have formed in the way that we have seen them forming.But one of the most compelling reasons we think that dark matter is a separate thing and not just a misunderstanding of gravity is by looking at collisions between clusters of galaxies. So there?s a famous one called the Bullet Cluster. It got a lot of attention a few years ago when it was discovered but collisions between clusters of galaxies can separate the dark matter from the ordinary matter. The way that works is the clusters of galaxies collide. And when they collide the ordinary matter sort of gets stuck in the middle and the dark matter moves right through, because dark matter when it collides with itself and with other particles, it doesn?t heat up, it doesn?t slow down, it doesn?t stop, it just passes right through in this sort of weird ghostly way.So the dark matter was able to pass through in that cluster collision and become separated from most of the ordinary matter. As it happens, most of the ordinary matter in clusters of galaxies is hot gas that fills the cluster of galaxies. The galaxies themselves in clusters are placed far apart so those come right through the collision as well. So what you end up with is a big clump of hot, ionised gas that you can see an X-ray radiation in the centre and then two separate groups of galaxies and dark matter on the sides and you can use something called gravitational lensing to see that most of the mass is separated from most of the luminous matter. That separation tells us that it really is something different from just having luminous matter be stronger, have stronger gravity, because they really are separated by huge distances.

SHANE HUNTINGTON

So you?re essentially looking at two different events then, aren?t you? You?re looking at an event where the matter that can interact in terms of the way it normally does - so you know, collisions, it could be heat and all these things - that?s one way. But then the second way with dark matter is it only interacts through gravity.

KATHERINE MACK

Yes.

SHANE HUNTINGTON

So objects can pass through each other almost. They interact gravitationally but nothing else happens. I suppose that allows you to separate those two events, almost, as completely different things.

KATHERINE MACK

Right. Right. Exactly.

SHANE HUNTINGTON

I?m Shane Huntingdon and you?re listening to Up Close. In this episode we?re talking about what we know and what we don?t know about dark matter, with cosmologist Dr Katie Mack. Katie, let?s talk a bit more about dark matter itself, this illusive substance. There must be a range of theories that explain its properties. Which of these theories are currently in the lead and which ones are being left by the wayside as we search for the true nature of dark matter?

KATHERINE MACK

Well, there are a number of different models for what dark matter might be made of. One of the early ideas about dark matter was that maybe it was made of black holes. The idea was that there might be black holes in the halo of the galaxy, the halo being the spherical distribution of matter surrounding our galaxy. This idea was called massive compact halo objects with the acronym, MACHOS, and so the idea was that they were these big clumps of matter, these big black holes that were circling around in the galaxy.That idea?s less favoured at the moment, partially because we?ve been looking for the effects of these black holes, if they were there. They would do things like change the way that the galactic disc is distributed, they would disrupt the disc, and they would disrupt stars that are orbiting each other. We haven?t seen those and we would expect to see gravitational lensing effects from these black holes passing between us and clusters of stars, and we haven?t seen that.So it?s probably not made of black holes, although there are certain masses of black holes where we don?t have such good constraints on them but they?re harder to make in the early universe. So that?s a different story but less favoured at the moment.The most popular explanation is that dark matter is made of some new elementary particle called the Weakly Interacting Massive Particle, with the acronym WIMP. It if is a Weakly Interacting Massive Particle, it?s something that?s not in the standard model of particle physics. One of the most favoured possibilities is that it?s something from super-symmetry, which is an extension of the standard model of particle physics that would be useful for a number of different reasons and might produce a particle that could account for the dark matter. So that?s the most popular explanation. There are a number of other possibilities. One is called axions which is a kind of theoretical particle that was hypothesised to solve a problem in the theory of the strong interaction in particle physics and that?s also not ruled out. With WIMPs there are also a number of ways to look for that, both with particle physics experiments and using astronomical observation.So there are a lot of leads, there are a lot of ideas but so far all we?ve been able to do is rule out some possible iterations of these ideas, and there are a number of ideas that are still viable that we?re not sure about yet.

SHANE HUNTINGTON

When we talk about looking for some of these particles, in a recent episode of Up Close we talked about the great news of a Higgs boson being detected in the new accelerator in Europe. Is it likely we?ll use a similar sort of acceleration device to detect these massive particles? In terms of massive, we?re not talking about something like the Higgs here necessarily, are we? Is it more mass related to the size of a neutron? Do we have an idea of where that sits in the mass range? You know, there are so many different types of particles.

KATHERINE MACK

Well, there?s a wide range of masses but this particle could be, mostly less massive than the Higgs boson but there?s, as I say, a range. It is possible in certain models to produce a dark matter particle in a particle accelerator. So with the simplest WIMP model of dark matter, the dark matter particle if it collided with another dark matter particle very directly would annihilate and turn into standard model particles, just like if you had a piece of matter and a piece of anti-matter colliding they would annihilate and turn into gamma rays. Similarly, if the dark matter particle is this particular kind of super-symmetric WIMP then it would not annihilate with itself, if it had a very direct collision.And so there are ideas to look for the annihilation radiation but there are also ideas to use collisions of standard model particles to make the reaction go the other way and make dark matter particles. So if you can have two dark matter particles collide to create standard model particles, then you take two standard model particles and collide them to make dark matter particles. So they?re trying to do this at the Large Hadron Collider at CERN, looking for basically missing energy in the collisions. So looking for collisions where you would collide two protons and then see the effects of that collision and see a bunch of particles coming out but a missing energy. So you count up all the particles and all the energy that comes out and there?s something missing and that could be a dark matter particle. So that?s the way to look for it in a collider.

SHANE HUNTINGTON

So this is very different to when we consider the way we go after other weakly interacting particles, like the neutrino where we can directly measure the neutrino?s interaction with heavy water. This is something else, isn?t it? Again, we?re inferring the particle?s existence. Is there a possibility we?ll be able to directly measure one of these particles?

KATHERINE MACK

Well, there are number of direct detection experiments as well and those are based on interactions between a dark matter particle and the standard model particle where basically they?re looking for dark matter particle to just bump into a particle in their detector so they?ll have a large tank of some kind of material. They?ll have detectors all throughout this material and they?ll put it deep underground in the bottom of a mine under a mountain or something like that so that there aren?t any cosmic rays coming down from space to mess up the experiment. They?ll shield it carefully with lead and so on and then they?ll just wait for something that can pass through just about everything else to bump into one of their particles and impart enough momentum to make it move and maybe ionise something or create some kind of interaction that can be picked up by these detectors. So there are some very good constraints on dark matter from looking for these interactions with detectors and not seeing it.

SHANE HUNTINGTON

The one area that you haven?t mentioned is around detecting the gravitational effects. Is it possible in a laboratory environment to do those given this is the only way in which it interacts with ordinary matter, or is that something we can only do on an astronomical scale?

KATHERINE MACK

You really need an astronomical scale for that because even if the particle is relatively massive, for an elementary particle it?s not nearly massive enough to detect the gravitational effect and it would be moving very quickly, as the galaxy is filled with dark matter and the earth is moving through that galaxy and so it?s sort of moving through this fluid of dark matter particles and they?re just passing by at hundreds of kilometres per second. So we would never be able to measure the gravity of these particles if we were able to capture one individually.

SHANE HUNTINGTON

Is it true that as with neutrinos, you know, many of them passing through us every second, is this the same with dark matter?

KATHERINE MACK

Yes.

SHANE HUNTINGTON

Do we assume they?re coming through us all the time and they don?t affect us?

KATHERINE MACK

Yes, that?s the idea. If they are these elementary particles then they should be passing through this room right now.

SHANE HUNTINGTON

I?m Shane Huntingdon and my guest today is cosmologist Dr Katie Mack. We?re talking about dark matter here on Up Close.Katie, let?s talk about astronomical observations now, because that?s your area of focus. How do these help us to determine what the nature of dark matter is?

KATHERINE MACK

Well, I mentioned before that it?s possible that dark matter has self annihilation, where if two dark matter particles collide directly enough they could annihilate into standard model particles and produce some kind of radiation. So the main way that we?re looking for dark matter particle physics in the universe is by looking for radiation from dark matter annihilation out there in the universe somewhere.The way to do that is to look for places where we might have really large concentrations of dark matter - for instance in the centre of the galaxy you would have quite a lot of dark matter in centres of other galaxies, in small satellite galaxies that are orbiting in our galaxy - and look for gamma radiation or look for particles that are being produced in those clumps of dark matter, using things like gamma ray detectors, and try and use that to study the annihilation of these dark matter particles, if that?s occurring.

SHANE HUNTINGTON

So this is around dark matter essentially interacting with itself. I can imagine a scenario where just like with normal matter, given the same gravitational rules presumably apply, do you end up with effectively dark matter stars that just don?t put out illumination but presumably have incredibly high density, and does that then lead to these sorts of interactions between dark matter particles in themselves?

KATHERINE MACK

It?s hard to get dark matter into as dense a clump as you could get in a star. Because dark matter doesn?t have particle interactions in the way that ordinary particles do, it?s hard for it to sort of settle down into a very tight clump. Because the particles will be moving past each other quickly and they?ll have this angular momentum that it?s difficult to get rid of.So this is part of the reason I mentioned before that the galaxy is surrounded by a spherical halo of dark matter, whereas the ordinary matter is in a disc and the ordinary matter has flattened into a disc because of these kinds of interactions between the particles. When you spin something that?s ordinary matter it will flatten into a disc. Dark matter doesn?t do that because it doesn?t interact with itself so much so it stays in this puffier configuration. And generally dark matter will not condense into very tight clumps in the same way that ordinary matter does. It will be very dense in the very centre but in a sort of smoothly varying density as it goes out.

SHANE HUNTINGTON

Now, you mentioned gravitational lensing, and in the introduction I mentioned the idea that the further out in the universe we look the further back in time we look. So if you can infer the presence of dark matter due to this lensing effect that is caused by massive objects, what does that tell us about the history of dark matter throughout the universe from the point of the Big Bang? Is it the same amount we have now as we had then or has it changed significantly?

KATHERINE MACK

Well, the mass of the universe has always been dominated by dark matter, as far as we can tell. We?ve looked at the fluctuations in the matter at the very earliest times that we can see when the cosmic microwave background was produced - it was something like 300,000 years after the Big Bang - and we see the mass of the universe was dominated by dark matter even then.So the fraction of the mass in the universe that was dark matter is the same. How dominant that is in terms of the overall energy budget of the universe has been changing because as time has gone on, the universe has become more dominated by dark energy, which as I said is another topic for another day but the dark energy is completely dominant and it?s 17 per cent or something of the universe now and it was much less at earlier times.

SHANE HUNTINGTON

Now, you?re working in particular on building dark matter into simulations of the early universe. Why are you doing this?

KATHERINE MACK

What I?m interested in is finding out how dark matter might have affected the earliest stars and galaxies and how it affected the growth of the cosmological structure over time. And the reason that I?m looking at the early universe, early from the sense of several billion years ago, is because those first objects that were forming, if dark matter was doing something like annihilating or decaying or having some kind of particle interaction, it would have been more important to those early objects than it is today in the sense that today we have lots of stars and galaxies, we have radiation being produced by all sorts of astronomical processes. In the earliest times, before there were a lot of stars and galaxies, that tiny amount of radiation coming from dark matter annihilation if it was occurring would have been relatively much more important.So it could have affected the way that the very first stars and galaxies were forming and if it did affect the way the very first stars and galaxies were forming, then that would have a cumulative effect on how structure formed throughout the universe.And specifically, right now, there are a number of huge observational efforts trying to look at the way that the very first stars and galaxies were forming and trying to see how the universe went from being a cold dark place to being lit up and filled up with ionised gas and everything. Things like the Square Kilometre Array that?s being built partially here and partially in South Africa, things like a number of different large radio-telescope arrays, these are all being built to understand how structure formation occurred in the universe and how the first stars and galaxies formed and evolved.And if dark matter has been having a big effect on that, if dark matter changed the way the first structures were evolving, then that will change the results that we?ll see in these telescopes and it will make it harder to understand how those first stars and galaxies were formed, unless we really understand what the dark matter might have been doing.

SHANE HUNTINGTON

Now, we?ve had knowledge of the need for something like dark matter for some 80-odd years; why is that we?re only just starting to put this into simulations of the early universe now? I?m hoping the answer is just it was too hard for everyone else, Katie.

KATHERINE MACK

There are a couple of reasons. The simulations that we?re doing now are becoming much more sophisticated and it?s becoming feasible to put real dark matter particle physics into simulations now. Typically, the way that cosmological simulations work is that they only simulate dark matter in the sense of they put in gravitational effects of something that has no particle interactions at all. This is a sort of idealised form of dark matter where it just has gravity and they use individual particles to simulate the effects of dark matter and they just don?t let those particles have any interactions with each other, other than gravity. And then they show the build up of structure over time using that. Then they put the gas physics and they put the other kinds of particle physics and radiation and stuff on top of that, after the fact. And only now is it becoming feasible to put more gas physics, more particle physics into these simulations in a more integrated way.And it?s becoming clear that just pretending that dark matter has no interactions with anything other than by gravity - which still could be true but based on our best understanding, theoretically, is probably not true - that misses something important in these simulations. And so putting the particle physics of dark matter into these simulations is now becoming much more feasible and becoming much more relevant to the kinds of observations that we can do. Because in the past, looking at the evolution of the first stars and galaxies was really not feasible observationally but now we?re building things like the Square Kilometre Array and we?re using new techniques and radio astronomy to really dig deeper into that first epoch of galaxy formation. So these effects, if they?re happening, are going to become important for understanding the new data that we?re going to be having.

SHANE HUNTINGTON

It took some 50 years for the Higgs boson to be confirmed as a particle. We?re about 80 years in on dark matter. How far away, given all these new telescopes and so forth being built, do you think we are before we?ll be able to definitively say this is real, we have some direct, if indirect, observations but direct evidence of this that we?ve seen through these telescopes?

KATHERINE MACK

Well, you know, I don?t want to make a prediction on that. People have been saying for quite a long time, oh, it?s a year away; oh, it?s two years away, that kind of thing. There are some experiments that claim to have already detected something that they think might be dark matter. There?s an experiment called DAMA/LIBRA in Italy that has seen a signal that looks like it could be a modulation of the signal based on the way that the earth is moving through the dark matter halo of the galaxy. They?ve had that signal for a number of years and nobody?s been able to confirm it and there are reasons why it?s difficult to fit it into models of dark matter, so that might be a signal. There are a number of other detectors that have seen things that they think could be signals of dark matter, though they?re all very low significance. So there are a number of hints. There are astronomical observations that see anomalous radiation coming from the galactic centre and we don?t know what it is and it could be some kind of dark matter effect or it could be something like pulsar emission that we just don?t understand, or some other astrophysical effect.So there are quite a lot of anomalies and a lot of hints and things that could be signals that we?re still trying to figure out, you know, is that real, is that really dark matter, is it an instrumental effect, is it something on the sky that we don?t understand? Over the next few years hopefully we?ll at least understand what those are and understand better how those possible signals and possible hints all fit together into one big picture, and maybe that will be a picture of dark matter or maybe it will be a picture of better understanding our instruments.I think that understanding all those anomalies will probably happen in the next couple of years. As for actually detecting dark matter, who knows. I wouldn?t want to hazard a guess on when that would happen.

SHANE HUNTINGTON

Katie, in a previous episode we spoke to Professor Rachel Webster in particular about the James Webb Telescope. This is now a reality and will soon be still heading up into space. How will that aid in the search for the dark matter?

KATHERINE MACK

Well, James Webb Space Telescope will be looking farther back into the universe than we?ve ever seen with ordinary light. I mean, we?ve seen the cosmic microwave background with microwaves but it will be looking with infrared light and we?ll be able to see some of the earliest galaxies that have ever formed. So looking at the shapes of those galaxies, looking at how those galaxies evolved and the kinds of stars in those galaxies and so on, will give us much better understanding of the earlier evolution of galaxies and stars. By using things like simulations that include different kinds of dark matter interactions we might be able to use the results from the James Webb Space Telescope to tell us about what dark matter might have been doing in early times in terms of its particle physics.

SHANE HUNTINGTON

And the Square Kilometre Array, that?s also something that?s been a big ticket item over the last couple of years, to come online relatively soon?

KATHERINE MACK

And yes. So the Square Kilometre Array will be able to see how the gas in the universe is evolving by looking at the radiation coming from the hydrogen gas over time. And so it will be a very complementary kind of observation because something like James Webb Space Telescope will look specifically at the galaxies and at the things that are glowing brightest in the universe. The Square Kilometre Array will better be able to see the hydrogen gas at early times. And putting those together will give us a much better big picture of what?s going on and how the gas is turning into stars and galaxies.

SHANE HUNTINGTON

Dr Katie Mack, cosmologist with the Astrophysics Group in the School of Physics at the University of Melbourne, thank you for being our guest today on Up Close and talking to us about the search for dark matter.

KATHERINE MACK

Thank you. It?s been great to be here.

SHANE HUNTINGTON

Relevant links, a full transcript and more info on this episode can be found on our website at upclose.unimelb.edu.au. Up Close is a production of the University of Melbourne Australia. This episode was recorded on 19 March 2013. Our producers for this episode were Kelvin Param, Eric Van Bemmel and Dyani Lewis. Audio engineering by Gavin Nebauer. Up Close is created by Eric van Bemmel and Kelvin Param. I?m Shane Huntingdon. Until next time, goodbye.

VOICEOVER
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