DARK MATTER - Curated Transcript of BBC In Our Time podcast
https://www.bbc.co.uk/programmes/b054t3s2
Last on Thu 12 Mar 2015 21:30 BBC Radio 4

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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

Carolin Crawford
Public Astronomer at the Institute of Astronomy, University of Cambridge and Gresham Professor of Astronomy

Carlos Frenk
Ogden Professor of Fundamental Physics and Director of the Institute for Computational Cosmology at the University of Durham

Anne Green
Reader in Physics at the University of Nottingham

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Transcript:

[Melvyn Bragg] Hello. Something in our universe is missing, or rather, almost everything - most of the matter in existence. Scientists first noticed this in the 1930s, observing that galaxies were moving much faster than expected and at such speed should have dispersed or evaporated. They theorized that there must be something as yet unknown keeping the galaxies in place. The Swiss astronomer Fritz Zwicky in the 1930s called this "missing matter" at first and later as we know it now, "dark matter". At least one of our guests today claims that once we do know what dark matter is, we will have solved one of the greatest mysteries in science, linking the Big Bang with the creation of galaxies, planets, Earth and everything on it, including us. With me to discuss dark matter are

Carolin Crawford, Public Astronomer at the Institute of Astronomy, University of Cambridge and Gresham Professor of Astronomy,

Anne Green, Reader in Physics at the University of Nottingham
and

Carlos Frenk, Ogden Professor of Fundamental Physics and Director of the Institute for Computational Cosmology at the University of Durham.

[Melvyn Bragg] Carolin Crawford, what's the start of the story of the discovery of dark matter?

[Carolin Crawford] The primary evidence for dark matter is astronomical observations. And as you said in your introduction, the story starts back in the 1930s with the astronomer Fritz Zwicky, who was identifying, classifying, studying clusters of galaxies. And a cluster of galaxies is where you have a whole swarm of galaxies. You've got thousands, hundreds of thousands, all contained within a fairly small volume, a few millions of light years across, a few tens of millions of light years across, and they're all bound together under their sort of mutual gravity. So you have these galaxies that are swarming through. And what Zwicky realized is that he could use the motions of the galaxy to virtually wave the whole mass of the cluster. Every galaxy, the way it moves, it orbits through the cluster, it's kind of reacting to the gravitational pull of the rest of the galaxies in the cluster. And as you described, he discovered that they're moving too fast. They're moving at speeds of the order of 1000 km per second. The whole system should have just dispersed out into space unless you've got more mass there, more gravity there, than you ...would otherwise guess. And that mass, that gravity, is anchoring everything to keep it, as, you know, one bound entity. And at that point, he identified this idea of a missing mass. There's extra mass there. There's extra gravity within the system, but it's missing from our normal view through the telescope when we look at a cluster of galaxies.

[Melvyn Bragg] So having theorized that, the search then began in the 1930s to discover what that was, identify it, and line it up with all the other forces?

[3:37]
[Carolin Crawford] Well, yes. At this stage, you're still realizing that there is this extra component of a cluster of a gravitationally bound entity that's missing. And Zwicky started with the idea of calling it a missing mass, and within a few years, the term changed to be one of dark matter, which is what we recognize today. And it comes, again, originally from the observational evidence, from clusters and also from other gravitationally bound systems.

[Melvyn Bragg] And can you just identify for us why it's proving to be so difficult to identify this dark matter?

[Carolin Crawford] Yes, and the key here is in the name - originally it's called dark because it's not luminous. It's very, very faint. That was the original description of it. We can now extend that to say you have some matter. So it has mass. It's got gravity. But the problem is it doesn't interact with light in any way. Not only does it not give off light, it doesn't emit, it doesn't radiate light, but it doesn't reflect light. It doesn't block light to create shadows. It doesn't absorb light. And so you have this matter out there, and it's in huge amounts, sort of five times the amount of the so-called ordinary matter that we can't see because of the light it produces. And that's a huge problem for astronomers, because light is the only way that we can really test what's out beyond our solar system. And that's why it's so elusive. It's not giving off light. We can't see it with our telescopes. All we can see is the gravitational effect this extra mass has, how it pulls on objects that are luminous. So it's ... kind-of one step removed. We're inferring it's there from its influence rather than seeing it directly.

[Melvyn Bragg] I made large claims for this. I think that was in the trailer earlier on. Without dark matter, there'd be nothing at all, no planets, no galaxies... It is as important as that? Discovering what it is?

[Carolin Crawford] It is absolutely fundamental to everything in the universe. Dark matter is what anchors all structures together. Without dark matter, we couldn't have created galaxies and clustered galaxies. We wouldn't have the current universe we see, if you didn't have dark matter that initiated that process right at the beginning of the universe. So this is the link that you described. You need dark matter right at the early start of the universe in order that these structures start to form and you get anything resembling what we see around us today.

[Melvyn Bragg] And, Carlos Frenk, can you explain what a galaxy rotation curve is and why it's important in this investigation?

[6:02]
[Carlos Frenk] Yes, the galaxy rotation curves play a key role in the story because they provided evidence that was in many ways neater than Zwicky's evidence. So let me tell what a rotation curve is. A galaxy like our own Milky Way is essentially a disk of stars that are rotating round and round the center of the galaxy. Now, a rotation curve is just a curve that describes how fast stars are moving around the center at different distances from the center. Now, according to Newton's theory of gravity, we would expect the stars closest to the center to be going around faster than the stars further out, just like in the solar system, where all the mass is in the sun. And then Mercury goes around really, really fast, much faster than the Earth, which goes around much faster than Jupiter, say. So astronomers were expecting that when they were able to measure the speeds of stars around the center of the galaxy, they would see exactly that. To the horror in the 1970s, they found that actually the stars were moving more or less at the same speed, a few hundred kilometers per second, regardless of where they were. And that was immediately recognized as a very serious problem, because essentially, the stars in the other parts of the galaxy is going too fast. And if all the material that produces the gravity was in the stars that we can see, those stars, far flung stars, should have already been ejected from the galaxy, ... they should have just been tossed out of the galaxy, but they were there. So it followed that there must have been something we cannot see that is producing the gravity that keeps the galaxy in place, and that then provided very, very clear-cut, neat evidence, although not accepted by everyone, for the existence of dark matter in galaxies like our own Milky Way.

[Melvyn Bragg] But it's sort of another add on gravity, isn't it? Another form of gravity?

[Carlos Frenk] It's another form of gravity. It adds to the gravity that we can see, but it actually overwhelms the gravity of the stars that we can see. So if all there was in the Milky Way was the gravity produced by the stars that we see, then the stars in the outer parts of the Milky Way should be rotating at a much lower speed than they are. So, yes, the dark matter, it makes a contribution, but it does make the lion's share of the contribution to the gravity in the outer parts of the galaxy.

[Melvyn Bragg] You mentioned the Milky Way. In the 1970s, there were computer simulations about the Milky Way and discovering dark matter ... could you tell us about that, Carlos?

[Carlos Frenk] Oh, yes, when I look at the simulations, it's really pretty astonishing, because the foresight of these two Princeton physicists, Jerry Ostriker and Jim Peebles, was really quite amazing. So they did the first simulations in a computer of a disc of galaxies like around. And, again to their horror, they found that if all they did was put stars in there, this disk would buckle up. It would crumble up into a kind of horrible looking bar. And they came up with the idea that in order to make [a] galaxy stable, one required this unseen component of dark matter. So this was what we call theoretical evidence, which, of course, is not as compelling as seeing the real thing, but in this game, it's as good as it gets. So that was another important piece of evidence for the existence of dark matter in galaxies like the Milky Way.

[Melvyn Bragg] Is that correct? Their experiments? So it didn't buckle next time?

[Carlos Frenk] Yes. They [were] very ingenious because ...computers in the 1970s were laughable by today's standards, and, I mean, the simulations were nothing compared to what we can do today. But they did manage ingeniously to assume there was some unseen.. they called it "halo", the clump of dark matter, and then a beautiful, stable galaxy was possible. So, yeah, that was another very important advance, in theory, at least.

[Melvyn Bragg] Why did they call it halo?

[Carlos Frenk] Well, I don't know whether they feel saintly or I've never understood why it's called a halo. It is a clump. I guess clump is not such an elegant word as a halo, but I think the idea is that most of it is in the outer parts, outside the galaxy. But I always think that, you know, astronomers have saintly tendencies, and it's expressed sometimes in our language.

[Melvyn Bragg] Yeah.... Anne Green, can we just stay with this galaxean ocean, which Carlin raised at the start? Why is a galaxy [cluster] of such interest to people like yourselves who are investigating this problem?

[10:35]
[Anne Green] So, galaxy clusters are interesting because they actually tell us quite a lot about the properties of dark matter. So, as Carolin's already told us, what Zwicky's research showed us is that the galaxies we can see maybe only make up a few percent of the total amount of stuff of matter that's in the galaxy. Now, the optical light that we can see with our eyes is only actually a small part of the electromagnetic

spectrum. And when you look at galaxy clusters with detectors that are sensitive to different wavelengths, you see some very different things. And so, for instance, in the 1970s, astronomers started looking at galaxy clusters using X-ray telescopes, and what they found is, as well as the galaxies we can see, the galaxy clusters contain a large amount of hot X-ray emitting gas. And there's a balance going on. Gravity is trying to call this gas in. Pressure is trying to stop it collapsing. And by looking at this balance between pressure and gravity. You can again weigh the X-ray emitting gas, and you can also compare that to the mass of the cluster as a whole. And so what they found was, there's actually a lot more hot gas in the cluster than there are galaxies, about a factor of ten, roughly. But still, that's not all of the missing mass. There's still five or six times as much stuff in the galaxy cluster on the whole as there is this hot gas. So that just added some more information about what the dark matter had to be. It wasn't this gas. It was something else.

[Melvyn Bragg] So that's proceeding by elimination, isn't it? You're finding out what it's not.

[Anne Green] Exactly. We're looking for the things we can see and then still seeing that there's something else there as well.

[Melvyn Bragg] And so, how did the whole business start about looking at something that you can't see? Or trying to find it? ..A bit more sensible, not trying to find something that you can't see.

[Anne Green] So I guess you have to find other ways of trying to see it in inverted commas, look for effects it can have which aren't necessarily just seeing light coming from it.

[Melvyn Bragg] There's something called velocity dispersion, one of the many phrases I've come across with delight while preparing for this program. Can you tell us what significance that has?

[Anne Green] So, actually, that's something really quite simple. Dispersion just means spread. So when we say that the velocity dispersions are very large, we just mean that things are moving faster than we expected.

[Anne Green] And what does that mean? So this basically comes back to what Carolin was already telling us about. It was the velocity dispersions that Zwicky measured and found that they were far, far bigger than you would expect if all the material there was what you could see.

[Melvyn Bragg] Are these something we can learn from - these velocity dispersions?

[Anne Green] We've learned a lot from them already, but I'm not sure that there's anything more we can learn.

[Melvyn Bragg] What do we learn?

[Anne Green] That the galaxy clusters weigh far more than the galaxies we can see..

[Melvyn Bragg] Just... is it possible to quickly explain how are you looking at this stuff, and you can work out how it weigh what it weighs?

[Anne Green] So this is because it's the force of gravity that's moving the things we can see around, and the gravity is sensitive to everything. It doesn't matter whether we can see it or not. The pull of gravity is just there. So it's looking at the gravitational effects of the stuff we can't see on the stuff we can see.

[Melvyn Bragg] Using "weigh" in the sense of the word as I would use weigh - a pound of this or that or the other?

[Anne Green] More or less...

[Melvyn Bragg] I'm still baffled...

[Carlos Frenk] It's just mass. So when you say you weigh ten kilos or 100 or whatever just means you have a certain amount of mass. And when you put it on a scale, it registers as weight. But weight and mass, as we learned from Newton and Galileo are one and the same thing. So when we talk about weighing something, you just mean measuring how much gravitating mass the object contains. So Melvyn Bragg has a mass of, I don't know, 80 kilos. And that's your weight as well as your mass.

[Melvyn Bragg] [Got] it? Fine. Thank you very much for that. Carolin, can we talk about spiral galaxies and elliptical galaxies?

[14:30]
[Carolin Crawford] Carlos has already explained how a flat spiral galaxy is rotating. We can use [the] rotational motions of the stars to work out there's this extra dark matter in a spiral galaxy. You can do something similar with an elliptical galaxy. Now, most galaxies in the universe are these kind of ball-shaped elliptical galaxies. They don't have that neat pattern of rotation, but still, ... again it's a swarm of stars that are just responding to the gravity of the galaxy. And Anne's mentioned the velocity dispersion of galaxies in a cluster. You could look at the motions of the stars within the elliptical galaxy, and again, you find they're responding to much more gravity than ... what you assume, if you look at all the light and the stars of the galaxy. The great thing about elliptical galaxies is that they're much more massive than spiral galaxies; there's much more dark matter there. And you don't just have the individual stars and how they move through the galaxies. But again, like the clusters, you have a big halo of X-ray emitting gas. This X-ray gas is at temperatures of millions of degrees. It's a plasma of fast-moving charged particles. And these should have just, again, dispersed. They've got so much energy, they should just scatter into space unless you've got more gravity there to anchor them to this galaxy. So it's just another line of evidence that this dark matter is endemic to all galaxies in the universe, whether they be spiral or whether they be elliptical.

[Melvyn Bragg] I see. Carlos, can we talk about the cosmic microwave background and what corroboration that gives us for dark matter and where it takes us?

[16:08]

Yes. So the cosmic microwave background radiation is nothing less than the heat left over from the Big Bang. It's quite remarkable. The Big Bang was very hot, and it had lots of radiation. And we know that when the universe was about a mere 350,000 years old, which would be the equivalent of one day in a human life, so it's still very young compared to its present age, this radiation was just emitted, and as the universe expands, the radiation cools and this radiation was discovered, amazingly, 1964 by two very famous engineers, actually, Penzias and Wilson. And this radiation, which by then had cooled down to a mere 2.7 degrees above absolute zero because it'd been traveling for so long, appears in the form of microwaves. Now, this discovery in the 1960s really nailed down the Big Bang theory because here we had evidence that the universe had once been very hot and had been expanding. And moreover, this radiation brings us news about this baby universe .... At the turn of last century, one of the most important discoveries of physics ever was made when a NASA satellite ...mapped the temperature of this microwave background radiation, as we call it, the heat from the Big Bang, and found that the temperature was actually not uniform, but patchy. It had little spots of (little, ... I'll tell you what I mean by that in a minute.) ... hot and cold radiation. Now, when I say little, these are very, very tiny irregularities. So we see [a] huge feat of engineering to be able to detect these tiny differences in the temperature of this radiation from one place to another. Now, it turns out that the spotty universe, the spots tell us about the contents of the universe. The early universe was much simpler than the universe today, and we can read off this pattern of hot and cold spots what the universe must have had in order to produce such a pattern. And what we learned from that is that the universe had not only ordinary matter, like the matter of atoms, of which we and the sun and everything else that we can see is made of, but there had to be something else, something, some form of elementary particle different from ordinary atoms, and that is the dark matter. Now, one way to think about it, I like to think about, if you're given a present in a box that's wrapped and you don't know what's in it, what do we all do? We shake it. And from the vibrations in the box, we try to infer what's inside it. But this is very similar. This microwave background are sort of vibrations. And by looking at the vibrations, we can infer what the universe contains. So this was really a very convincing evidence that the dark matter not only is there, but must be made up of some exotic kind of matter, elementary particles of some kind.

[Melvyn Bragg] That's terrific, isn't it? I mean, I'm just in wonder at all this sort of stuff - it's why we do the program. Anne Green, can I just take that on from Carlos? The 350,000 years in to the existence of what ...it broke away. Why did it break away then? What caused the breakaway? He said it broke, you said, didn't we? ... Stuff starting being emitted. What happened then to make it be emitted?

[19:49]
[Anne Green] Right. So, up until then, the universe was a very hot, dense place, and everything was broken down into nuclei, which are positively charged, and electrons, which are separate. And if an atom tried to form a very energetic photon, a particle of light will come along and kick the electron out of the atom again. So at that point, we've got this thick, gloopy mess of particles that are scattering off of each other all the time. However, at that point, then the universe has cooled down enough. The energy has dropped so that atoms can form.

[Melvyn Bragg] Why did it cool down?

[Anne Green] It's basically cooling as the universe expands from the Big Bang, the temperature drops.

[Melvyn Bragg] What's causing it to drop?

[Anne Green] It's basically conservation of energy. You've only got so much energy, and so as things expand, the energy has to go down, and hence the temperature has to come down.

[Melvyn Bragg] Okay, so we're on the track now. We are trying to find out about this dark matter. What's the most convincing, in your view, observational evidence for the existence of dark matter?

[Anne Green] Well, there are lots of things we heard already about galaxy rotation curves, and galaxy clusters. But some additional really nice evidence comes from gravitational lensing. So, gravitational lensing is a consequence of Einstein's theories of gravity. And so one of the things his general relativity tells us is that mass bends space. And therefore, when light travels through space, its path gets bent.

[Melvyn Bragg] If it hits a big mass, it has to go around it?

[Anne Green] It's more.. Consider space [to be] like a rubber sheet and so when you put a heavy object in it, it gets bent down. And so the light, as it travels through, travels along the rubber sheet and gets bent towards the heavy object and round it. And so by looking at how the path of light is distorted, you can map out how space is bent and, therefore, how the matter is distributed. And so what's particularly useful is what's called strong gravitational lensing when you get something really heavy bending space a lot. And so, in particular here, sometimes we're very lucky that we've got a big galaxy cluster, and then a long way behind it is a galaxy. And so the light from the galaxy, instead of traveling to us in a straight line, gets bent around the galaxy cluster. And so instead of just seeing the galaxy, the cluster acts like a lens. It creates images. And so you get multiple images of the galaxy distorted into arcs. And by looking at the positions and the features of those arcs, you can map out how much space has been bent by and therefore how the matter is distributed. And what you see is you see peaks where we know the galaxies are in the matter distribution. But surrounding the galaxies is a big additional lump of dark matter. And this is the dark matter halos that Carlos has been telling us about already. So it's not just telling us that the dark matter is there, but it's telling us where the dark matter is spread out, extended around the galaxies.

[Melvyn Bragg] Carolin?

[22:26]
[Carolin Crawford] I think the thing that is important as well is that you have all these different ways of detecting dark matter, whether it's from a spiral galaxy, elliptical galaxy, whether it's motions of galaxies in the cluster, whether it's through the fantastic gravitational lensing Anne was just describing. And all of these involve different detectors, different telescopes, they're InTaken in different wave bands, they're making different assumptions about the physics required in the interpretation. And yet it all comes back to the same basic answer. There's overwhelming evidence that we need more mass there than we see from the light that's available.

[Melvyn Bragg] So when did they start theorizing? We've talked about Zwicky, you mentioned. What did they begin to propose further on from that?

[23:21]
[Carolin Crawford] Well, if you've got some mass that's incredibly dark, the obvious place to start is that it is some ordinary matter that's just not luminous. And you might ... want to start thinking about things like a planet or a gas cloud or perhaps what happens when a star reaches the end of its life and it turns into a black hole or some other compact object. Or even things called brown dwarfs, which are things that didn't quite get massive enough to turn into a star and shine properly. All of these are made up of ordinary matter. We call this "baryonic matter" because it's made of atoms, and atoms are made of neutrons, protons and electrons, which are known as baryons. So baryonic matter means ordinary matter. So your first idea that is naturally explored is that you've just got vast quantities of rocky planets or lumps of rock or failed stars or black holes. But there are problems with this interpretation where you cannot get the observations to match - many problems with the interpretations. But the most basic thing is, if you have ordinary matter [it will not have] an absolute zero temperature - it is going to give off some kind of radiation. And if it's a planet, it could give off infrared radiation. A gas cloud maybe would absorb light. And you have the problem now that with today's detectors, if there was enough of this ordinary matter in the quantities we need to account for the dark matter, we would have detected the glow from it. So the people quite rightly now have largely dismissed the idea that this dark matter is ordinary matter that's just very faint. Then the problem is, of course, you have to go to a much more exotic kind of explanation and that's when we get to non-baryonic matter.

[Melvyn Bragg] And that's when Carlos comes in with your computer modeling...

[Carlos Frenk] Yes. So before I tell you the computer modeling which I will do in a second with great pleasure, I think to me, really what clinches the fact that the dark matter cannot be ordinary matter is this microwave background radiation that we were talking about before. Because that unambiguously tells us how much ordinary baryonic matter there is in the universe. No questions asked. It's a really precise measurement with an accuracy of 1%. And it [also] tells us how much total mass there is - and the two just don't add up. The bulk of the mass has to be something different from baryonic dark matter. So to me, that is really the argument that clinches it. In addition to the ones that Carolin said. So let me tell you about the computer simulations, ...which is what ... what I do. I make my living from that..

[Melvyn Bragg] And ... made a reputation on that as well. But never mind, we're living in this...

[Carlos Frenk] But I work on this day, today. But coming here allows me to step back and realize how amazing it is, what we actually do with these computers. Because what we do, essentially is to recreate the entire evolution of our universe. And [it] sounds grandiose, but it is. Now, the way we do this is as follows. We now know that when the universe was very young, and I really mean very, very, very young..

[Melvyn Bragg] What's young in your terms? I'm very suspicious of you a lot with figures...

[Carlos Frenk] Well, it's a decimal point, and then imagine 34 zeros and one. That fraction of a second..

[Melvyn Bragg] Okay, I'll give you young. We didn't go on...[laughter]

[Carlos Frenk] Now, we now know, and we have evidence for this from the microwave background that happens, that the universe began with a big ...not just a big bang, but a big period, [we call] inflation, when it expanded very quickly for a short period of time. And the main thing about inflation from our point of view is that this process seeded the universe with tiny little irregularities, what we call a quantum origin, we call these quantum fluctuations. Now, these small irregularities are the initial conditions for everything that evolved in the universe thereafter, for galaxies and for everything else. So the way we do the simulations is quite simple. We have these initial conditions, a starting state, which we represent mathematically, and feed that into a big computer. Secondly, we make an assumption about what the dark matter consists of. Thirdly, we instruct the computer on how to solve the equations of physics, Einstein's relativity and so on. And fourthly, we let it compute, often for months in a row. Big computers can do this. And what comes out at the end, and this really is quite astonishing, are universes when you make the right assumptions about the dark matter that look just like the universe in which we live. Now, the latest generation of simulations is really quite astonishing. And I like to challenge often my battle hardened astronomy colleagues by showing them images of galaxies that came out of a computer from this process, from these quantum fluctuations to the present, alongside images of real galaxies, and I challenge them to tell me which is which. And more often than not, they fail. So we can create realistic universes in the computer that are beautiful, except we know everything about them so long ... as we make the correct hypothesis for the nature of the dark matter.

[Melvyn Bragg] So Durham challenges the world, and not, for the first time! Anne Green, what's the current mainstream view of the particles that make up dark matter?

[28:27]
[Anne Green] Right, well, particle physics are very creative. We're very good at inventing particles. Sometimes they turn out to exist, for instance, the neutrino and antimatter, and sometimes they don't. You just have to go looking. So there's a wide zoo of possibilities for the dark matter with huge range of different masses and different properties. But probably the most popular and arguably the best motivated are things called weekly interacting massive Particles, or WIMPs for short. And they do just...

[Melvyn Bragg] Isn't that rather unfortunate? Never mind...

[Anne Green] Because I think [it] was actually the astronomers we've got to blame for the [name] WIMPs.

[Melvyn Bragg] Anyway, it was not on purpose, was it?

[Carlos Frenk] It is because the alternative that Carolin was talking about before, where these ordinary matter, Jupiters, fake stars.. They were called Massive Astrophysical Compact Halo Objects, or MACHOs. So it's MACHOs versus WIMPs.

[Melvyn Bragg] I see. ... I'll just leave it at that and I interrupted you...

[Anne Green] But anyway, for the WIMPs at least, it's a good acronym. They do exactly what their name says. They're weekly interacting, they interact only weekly with each other and the normal stuff. So that would explain why we haven't seen them to date. And they're very heavy. They weigh maybe a few times a proton up to 1000 times what a proton does. And they're a good dark matter candidate for two reasons. Firstly, they'd be automatically produced a tiny fraction of a second after the Big Bang in the right amount to be the dark matter. That's somewhat non trivial - you could have far too many of them or nowhere near enough. But the WIMPs, they have just the right density to be the dark matter. And then the other reason we think these particles might exist is it turns out that they turn up in particle physics models that have been proposed for other reasons, and specifically to unify the four fundamental forces we know about into a single force. So that's why WIMPs are probably the best particle dark matter candidate.

[Melvyn Bragg] Carolin, are there any alternative views about the particles making up dark matter?

[30:16]
[Carolin Crawford] Well, again, before you moved to WIMPs, a lot of which, as Anne said, are quite hypothetical particles that emerge out of theories, one candidate that was proposed was the idea of a neutrino. And at least this is a particle [that] we know ... exists. It fills the universe, it's everywhere, it doesn't have a charge, so it doesn't interact with radiation. And you could think that if each of these tiny particles had a certain amount of mass and there are so many of them, trillions of them, that you could account for the dark matter. The problem with this is, first of all, that the upper limits to the mass from experiments are too small now for a neutrino to account for the dark matter. But more fundamentally, if the neutrino is light, it's moving very, very fast. It's moving at close to the speed of light. And this has implications for the size of structures that it starts forming. Carlos has described these computer simulations where you have the dark matter ... clumping together in the early universe. If that dark matter was moving very fast, it's very difficult to trap it in small condensations. The kind of structures you grow are enormous - on the scales of galaxies, on the scales of clusters. That's not what we see and it's not what the models predict. So you're producing [with the neutrino hypothesis]... top-down... you start with large structures going to small models, [whereas] what we see in the universe is the, rather inelegantly termed, bottom-up version, whereas small structures start first and grow to larger. So the point about neutrinos is they travel too fast, they'd predict too large structures that don't fit with the computer models or the observations, and they don't have the right amount of mass. So even though neutrinos looked good to begin with, I think they're largely discounted now. And then there are other examples of, again, exotic particles. There's the "axion", which is an example of one of these lightweight hypothetical particles that emerges from a theory, but it's very difficult to track, and, again, is out of the mainstream ideas of what could cause the dark matter.

[32:18]
[Melvyn Bragg] Carlos Frenk, you've been computer modeling on many things, but including cold dark matter. We have cold dark matter, hot dark matter and warm dark

matter. So you've been concentrating on cold dark matter. Why is that and what have you found?

[Carlos Frenk] Well, the reason I've been concentrating on cold dark matter is because I started with hot dark matter in the 1980s. The hot dark matter were the neutrinos that Carolin just talked about. And my great big first disappointment as a scientist was running the first simulations of a universe where we had assumed that the dark matter was made of neutrinos, which are also known as hot dark matter for the reasons Carolin explained - they moved very fast. And it was so disappointing when we saw the Universe come out of a computer and didn't look anything at all like the universe in which we live. So that was a big disappointment. But this is the 1980s; I was young then and cocky, and I thought, right, we now ruled out hot dark matter. Let's go for the next target, which was cold dark matter. Let's rule that one out. Because the way you make science, you rule things out in order to eventually be left with the correct assumption. So I set out in the 1980s to rule cold dark matter out. And now, 35 years later, I'm still trying to do it. So often I say my career has been a failure because I set out to rule this out and I can't now. So cold dark matter is a very different kind of particle and it is exactly the sort of particles that we need to put into our computer simulations to produce these faithful representations of our universe. Now, however, the case is not closed yet because ...

[Melvyn Bragg] You've still got a chance...

[Carlos Frenk] We still get a chance for something in between. And this is fascinating from the point of view of particle physics. Because when we look ...So cold dark matter essentially explains everything we see on large scales. It explains something we call "the cosmic web", which is the way in which galaxies are distributed in the universe. They are not distributed at random. They appear.... They form along filaments. Yes, and that cosmic web is actually predicted by the computer simulations in the 80s and 90s and has now been detected in surveys of galaxies. However, the dark matter could still be warm and it's very difficult to tell cold from warm. But we're trying....

[Melvyn Bragg] Anne Green, how closer scrutiny will Carlos's experiments stand up to bear?

[Anne Green] Well, they tell us an awful lot and in particular the most important thing is that the dark matter has to be cold or maybe a little bit warm but sort of certainly not too warm.

[Melvyn Bragg] Right.. Carlos, are we saying that dark matter... What about direct detection? Is that possible? I mean, there's different ways of getting there and Carlos is ridiculously modest. I mean, he's made an awful lot of progress from the notes I've read. Okay, never mind. What about direct detection?

[Anne Green] It's almost impossible just by its definition to directly detect,

[Melvyn Bragg] As you said earlier on the program...

[Anne Green] Yeah these WIMPs, they move through matter, they will flood through the Earth all the time. Even my hand here you'll have several hundreds of thousands passing through my hand every second. It depends on which WIMP you want them to be. They will pass through your detector. So how you need to the direct detection is really looking for evidence that a WIMP has been there. It's almost like looking for a ghost. You're looking, perhaps for evidence from a particle collision, that some of the energy and momentum has been carried off by an invisible particle which reveals the WIMP. Or you're looking for those moments when, in passing through all the ordinary matter, even though the WIMP is tiny and the nucleus of an ordinary atom is tiny, there's a head on smash. And that head on smash between the WIMP and the nucleus of an atom imparts some energy which is then released, perhaps as a microscopic temperature change or just like a single photon flash of light.

[Melvyn Bragg] So you must be very excited, Carlos, because they are turning on CERN today again.

[Carlos Frenk] Oh yes, absolutely,

[Melvyn Bragg] Because that's indirect evidence, isn't it?

[Carlos Frenk] Well, actually, CERN could actually make dark matter make it in the laboratory. And I was pretty confident that in the first round of CERN they would find it. But they have not in the first run. But many people believe that they will see evidence, either direct or indirect by discovering something called supersymmetry, which is the theory that predicts the WIMPs the most. One of the theories that most naturally predicts the WIMPs. So I'm hopeful, but perhaps I'm an optimist that in the next six months to a year the newspaper headlines will say the dark matter has been made in Geneva of all places.

[Melvyn Bragg] Well, was Zwicky in Switzerland... no, he was in America.

[Carlos Frenk] He was in America, but he was Swiss. He came from there..

[Melvyn Bragg] Anne Green?

[Anne Green] So, as Carlos says, it would be fantastically exciting if the LHC managed to make WIMPs, but on its own, that wouldn't solve the dark matter problem because it wouldn't actually tell us that those particles were the dark matter in galaxies and galaxy clusters and across the universe. So that would be fantastic, but it would only be the first step. We'd still want to do the sorts of things that Carolin's been talking about, as in the direct detection experiments in the lab, trying to look for the dark matter particles themselves interacting with nuclei in the lab.

[Melvyn Bragg] Are there other groups of people doing similar or analogous computations, computer computations, as you're doing? Carolin, do you want to talk about other work that's going on?

[Carolin Crawford] Yeah. Well, with any result, you always want to compare it to other simulations. And so there are several groups who are doing amazing computer simulations. It's an experiment. So in the same way that you have many different computer simulations competing, and you hope agreeing with the answer, it's the same way as you will have many different kinds of experiments and different ways of looking for the direct detection of the dark matter, you hope that they will come to the same answer.

[Melvyn Bragg] Sorry, Carlos, do you want to come in?

[Carlos Frenk] Well, I was going to say, just to supplement these detection experiments that we just heard from Anne and from Carolin, that there is another way that one could potentially detect dark matter. And I thought I'd done it actually, but it turns not to be the case. And that is this - everywhere in nature there are always exceptions. We said that dark matter is dark. Well, it is dark most of the time and in most places - occasionally it can shine. Would you like me to tell you about that?

[Melvyn Bragg] I'm agog...

[Carlos Frenk] What happens is this if the dark matter is a WIMP, the chances are that these are very strange particles because they're their own antiparticles. Now, you know that when matter and antimatter come together, they blow up. They are annihilated producing a puff of radiation.

[Melvyn Bragg] That has always baffled me. Why we're here now.. never mind...

[Carlos Frenk] Well, it's because the universe, for reasons we're beginning to understand, is mostly made of ... matter, not antimatter. But the microwave background radiation we were talking about before came from an isolation in the early universe. But let me get back to our story here. So the dark matter is almost very likely it's own antimatter. But it's so diffuse that particles of matter and antiparticles of dark matter never collide, except in very extreme situations. Like for example, in the center of the Milky Way. There the densities are so huge that the particles of dark matter actually collide with one another. And because they don't, they're their own antimatter, they produce radiation, very energetic radiation, what we call gamma rays, which is radiation even more energetic than X-rays. In 2005, NASA launched the satellite, the Fermi satellite, to look for gamma rays, for gamma radiation. And there are now claims that the center of the Milky Way is glowing in gamma rays and that that is a signal of dark matter in the center of the Milky Way.

[Melvyn Bragg] Anne, what other forms of detection are there now?

[40:18]
[Anne Green] Well, when the WIMPs come together and annihilate, as Carlos has just described, as well as producing high energy gamma rays, they can also produce antimatter, things like positrons and antiprotons. There are also experiments, for instance, something called AMS-02 on the International Space Station that are looking for the antimatter. And in that case, we possibly have seen an excess in positrons. But what's not clear there is whether it's due to dark matter annihilating. It turns out there are also possible astrophysical explanations like pulsars and supernovae. So in that case, it's not so clear that that's a sign of dark matter.

[Melvyn Bragg] On a range from one to ten, Carolin, how far are you along the path to getting to where you hope you'll get to about understanding dark matter?

[41:02]
[Carolin Crawford] Well, it's one of these things that it could change the next few months if the LHC is successful. These experiments are running all the time, either on the space station, or in mines underground, looking for evidence of WIMPs, either from annihilating or colliding with atomic nuclei. And anything could change. It's really exciting. We could know the result in a month. We might have to wait 20 years... We're all poised for exciting news, but we don't know when it's going to come.

[Melvyn Bragg] And when we do know, Carlos Frenk, what's it going to do to the nature of our understanding of the universe?

[Carlos Frenk] I think it will completely change our perspective of who we are and why we're here, because the discovery of the dark matter would corroborate this amazing cosmic story that we've been unveiling over the last 30 years, in which the dark matter is the main protagonist, because it is dark matter that is responsible for the formation of galaxies. Without dark matter, there will be no galaxies, no stars, no planets, no people. So to me, our origins are intimately linked to the nature of the dark matter. So to me, the discovery of the dark matter would be an advance to human knowledge on the same level as the discovery of Darwinian evolution.

[Melvyn Bragg] Well, thank you very much, Carolin Crawford, Anne Green and Carlos Frenk. We have a new producer for In Our time, Simon Tillotson. His predecessor, Thomas Morris, is moving on and alas, out of the BBC. For five years, Tom was a wonderful man to work with and a fine producer of this program, widely appreciated. He'll be much missed.

And the In Our Time podcast gets some extra time now with a few minutes of bonus material from Melvyn and his guests.

[Melvyn Bragg] Did we get most things? Usually when we have this little PS, I'm told about the things we didn't talk about. So what didn't we talk about that was important?

[Carolin Crawford] The only thing I'm suck in it is the end. It's also important we've focused on the astronomy, but these are new exotic particles that we don't know exist. So the particle physicists will also be really happy should we find dark matter..
..because its.. new physics beyond the standard model. It'll give us some clue about unifying gravity with the other forces, so it'll be complete door to a complete physics.

[Anne Green] You [Carlos] don't sound convinced?

[Carlos Frenk] No, I'm not convinced that we will know about quantum gravity or about things like that, but

[Carolin Crawford] It'll tell us something which will point us in the right direction rather than all going in the ...

[Carlos Frenk] I've said this for a long time, the discovery of the dark matter within the next five years to be expected. But I've been saying this for 15 [years] but now I really mean it because, I mean, there really is a race. It is a little bit like I'm sure it must have been like this in the 1950s with the double helix that people knew something like that had to be there and there are groups everywhere trying to get to it. Here we have the same situation. There are groups all over the world competing. It's a real race because ...

[Melvyn Bragg] Should I put money on you then, Carlos?

[Carlos Frenk] Yeah, sure. I would say, looking at the sensitivity of these experiments now, how they improve over 30 years, they improved in sensitivity by factors of billions. And I think they're now the experiments in the regime which you do expect these particles to show up and if they don't, then that would really be very bad news for physics.

[Melvyn Bragg] ...Sorry, Caroline...

[Carolin Crawford] Well, I was going to say with all of these things, they're all giving tantalizing evidence which could be that matter. But I mean, it's like these facts that are talked about where they're looking for the signal of the collision they're running and the first results, they discovered nothing. The gamma rays that you described from the center of the galaxy, there could be other sources for that light in the center of the galaxy. Similarly, the positrons that Anne mentioned on the cosmic ray detectors, again, they could be from dark matter annihilation. It's all still tantalizingly circumstantial.

[Melvyn Bragg] Should we have had that in the program? Have we misled our listeners?

[Carolin Crawford] Maybe I'm not as optimistic as Carlos. I think that as we go, we keep pushing the experiments further and further and we're still not fighting these wretched particles.

[Carlos Frenk] ... But listen, Carolin you know full well nature doesn't give up its secrets cheaply. It makes you work for them.

[Carolin Crawford] That's true.

[Carlos Frenk] But if you work hard enough, it reveals them to you. So I think we're just working hard enough now and again. These are very, very difficult experiments. It took 30 years to discover these temperature irregularities in the microwave background. We knew they had to be there, but the experiments had to be built. So it's only 30 years. The first dark matter experiments were in 1982. So we're only 32 years, 33 years, since. And this is difficult, but they have to be there.... it doesn't work without it.

[Melvyn Bragg] I love the fact that you're working in Durham, where people used to come... It was one of the great shrines in the early Middle Ages where people came for miracles... It's a good track record there. You should be okay...