# Astronomy Cast Episode 4:
# The Search for Dark Matter

**Fraser Cain:** We've had three weeks of information on planets, both Pluto's planethood, and extrasolar planets. Had enough planets – what's next?

**Dr. Pamela Gay:** Well, everyone seems to be asking us about dark matter, so let's turn to dark matter.

**Fraser:** It's actually quite timely. We've had quite a few recent news stories about direct evidence of dark matter that was discovered. I hope we'll get back to that at some point.

**Pamela:** That's exactly right. There was a recent observation of dark matter where we couldn't see the dark matter directly, but we could directly see the effects it had on background light. Light is yanked around the Universe by gravity just like mass is. The Ballet cluster, which is a merger of two different galaxy clusters, bent the light of background objects in such a way that we were able to trace out the distribution of mass and see directly that there was more mass there than we can see.

**Fraser:** Let's go back to the beginning first, and lay the foundation. How was dark matter discovered in the first place?

**Pamela:** Well, Fritz Zwicky (who perhaps is most famous for coining the term "spherical bastards" to describe people who are bastards from any direction), back in 1933 was studying the velocities of galaxies in the Coma cluster, which is a large, nearby cluster of a bazillion galaxies (there's beautiful Hubble images of this). In looking at how the galaxies were moving in relation to one another, he realised that some of them were moving a thousand km/s faster than they should be. If this was a bound system, these velocities implied that there had to be more mass than we knew about, otherwise the galaxies would be flying randomly out of the galaxy cluster in all directions. He said there's got to be mass here we can't see, and he proposed dark matter and everyone ignored him.

**Fraser:** In this situation I imagine flies buzzing around a central light, or moths going around a centre light. Something's keeping them in this place. If there wasn't this extra mass, they should've just flown away.

**Pamela:** Exactly. So gravity keeps things tied together. If the gravity from the Earth went away, the Moon would go shooting off in a straight line. If we increase the velocity of the Moon, its orbit will change. If we increase the velocity of the Moon, it will also fly off into space.

With a cluster of galaxies, when we look at the velocities of the galaxies in the cluster, those velocities reflect how much mass there has to be in the system that's keeping them tied there. If there's not enough mass, and we see a really high velocity, that galaxy is either going to shoot out of the cluster, or there has to be mass we can't see that's allowing it to stay in.

If we see just one galaxy that's going to fast, maybe it's a galaxy that's not part of the cluster that just happens to be zipping through it. But when you see tens and twenties of galaxies that are going way too fast, it implies there's definitely mass there that we can't see, and that's what Fritz saw.

**Fraser:** And nobody believed him.

**Pamela:** Not initially. It took 30 years before there was more evidence. A woman by the name of Vera Reuben looked at edge-on spiral galaxies, and measured the rotation rates. She found that stars aren't orbiting galaxies the way they're supposed to either.

What we expect is the further things are from the centre of the galaxy, the slower they should be going. So if you make a plot of velocity vs. distance from the centre of a galaxy, the velocities should eventually drop down. They don't. Instead they flatten out. In the outer parts of a galaxy, the stars are all going the same speed as you get to higher and higher distances from the centre.

This makes absolutely no sense, unless there's invisible matter that is becoming a larger and larger fraction of the galaxy's total mass as you get to larger and larger radius.

**Fraser:** Okay. If there was just the mass we could see in the galaxy, what would the stars do?

**Pamela:** They would rotate around the galaxy. They would orbit around the galaxy with slower velocities the further from the centre of the galaxy you get.

**Fraser:** And because there is additional matter that we can't see, it's more like they're all going the same speed?

**Pamela:** Exactly, they're rotating like a solid disk instead of like a bunch of individual objects. If you think about it, if you have a solid disk and you draw a line on it, all the points on that line rotate around the centre at the exact same rate.

**Fraser:** Perfect. Then if the dark matter wasn't there, or the additional matter wasn't there, it be more like that line would be curving back, over time?

**Pamela:** Exactly.

**Fraser:** Like a whip, almost.

**Pamela:** Yes.

**Fraser:** Got it.

**Pamela:** Okay.

**Fraser:** Proceed.

**Pamela:** So Vera Reuben was working with a fellow by the name of Kent Ford, and they went and measured the rotation rates of edge-on galaxies, not just one but several. They were doing this in the 1970s.

In 1975, she finally came out and said at a meeting of the American Astronomical Society, "these things aren't rotating the way they're supposed to. There's got to be some sort of dark matter, dark mass that we can't see, that forms a halo around the visible part of galaxies." She did mathematics to show if you add invisible mass in this proportion, where the amount gets larger and larger with larger radius, then we can simulate what we're actually observing. So dark matter is just our way of saying "there's stuff here we can't see." We're not saying what it is, we're just saying we can't see it.

**Fraser:** The evidence has mounted up over time, right?

**Pamela:** Exactly. As we look at more and more spiral galaxies, we see they're not rotating the way they should. As we look at more and more galaxy clusters, we see things aren't orbiting the way they should. As we look at things merging together, the way the objects fall into the core of the colliding galaxies, or the colliding clusters, they're not falling in the way they should.

In fact, the way our entire Universe is evolving implies there's mass out there that altered the way the Universe was born. This is where cold dark matter models come in, where we say that originally there had to be something slow moving that exerted gravitational effects that slowed down the interactions of the hotter, normal particles that were able to form galaxies and stars because of it.

**Fraser:** Okay, so we can't see it, so what is it?

**Pamela:** Yeah, I wish I knew that exactly. Pretty much everyone wishes they knew what it was exactly. But there's theories.

**Fraser:** I was just hoping maybe you'd figured it out.

**Pamela:** Yeah… not enough coffee this morning I guess.

So, there's theories. There's the idea that perhaps it's stuff that we just can't see but is normal, everyday stuff, like we call this baryonic matter - any matter that's made up of three quarks, that defines us, it defines our planet, anything that interacts normally, that's baryonic matter. We suspect there's some stuff out there we just can't see, like little tiny dwarfs, free-roaming planets, neutron stars, black holes… We can't see this stuff all the time.

**Fraser:** Right, so anything that has mass, but isn't necessarily bright.

**Pamela:** Exactly.

**Fraser:** Right, so for example, people on Alpha Centauri wouldn't necessarily be able to see my car

**Pamela:** Right

**Fraser:** Because it's not giving off light, but at the same time it's there, it's massive, it's participating in the Universe.

**Pamela:** Exactly. In fact, if you think about it, at one point, Neptune was dark matter. We were able to look at the orbit of Uranus and say, "oh, there's got to be something else out there that's gravitationally effecting how this planet moves" and anytime we can say there's something we can't see that has a gravitational effect, we're describing dark matter.

Using a lot of mathematics, astronomers were able to predict the location (or at least, two mathematicians were able to predict the location) of where Neptune should be, and it was observed.

Now, today we're going out and we're saying, "we think there's some stuff we can't see in the halo of the galaxy" so teams like the MACHO project are going out and are looking for -- the MACHO project is actually built out of an acronym. They're looking for MAssive Compact Halo Objects (where if you take the M-A from "macho" and then the C, H, and O you get MACHO), so they're looking for black holes, neutron stars, brown dwarfs, free-roaming planets, by the way their gravity effects the light of stars and galaxies in the background.

**Fraser:** So the MACHO team is looking for…

**Pamela:** MACHOs!

**Fraser:** Regular stuff, that we would be able to see and go, "that's mass, that's matter" maybe it's a black hole that's completely baffling, but it's still something we can wrap our heads around.

**Pamela:** Exactly, and they are finding it – but they're not finding it in huge amounts. So we've identified about 4% of the mass in the Universe. There's another 22% of mass that's dark matter. 74% of the Universe is dark energy – and no one knows what dark energy is.

**Fraser:** We'll deal with dark energy on another show. We need to completely blow people's minds this time around.

But with that 4%, that 4% includes both the stuff that's clearly obvious, but also estimated to be there but we just can't necessarily see it?

**Pamela:** Right. So this leaves us looking for another 22% of the Universe. A very small, small amount of this is going to be free-roaming planets, white dwarfs, black holes… but we know that this is a very, very small amount because when we do calculations on what happened during the Big Bang, we can match our theories to the observed elemental abundances in stars. When we look at really old stars, we see a certain amount of deuterium in the stars (deuterium is hydrogen that has an extra neutron in it). When we look at the deuterium abundance, deuterium only gets destroyed in nuclear reactions: it doesn't get created anymore. What we have was created in the Big Bang. If there was more normal matter, more baryonic matter, than just a few more percent, then we wouldn't see as much deuterium as we see.

So using lots of scary theory, lots of nucleosynthesis models during the big bang, we're able to say how much deuterium there should be, how much helium there should be, and we're also able to say there should be a certain amount of dark matter that we will never be able to see using normal methods – this is the non-baryonic stuff.

**Fraser:** Okay, so there's a certain amount of matter out there, that we just can't see. It's just invisible.

**Pamela:** Exactly. We can only see it through its gravitational interactions.

**Fraser:** So what is it?

**Pamela:** Well, for lack of a better term, we call it WIMPs: these are Weakly Interacting Massive Particles.

**Fraser:** So we've got MACHOs and WIMPs

**Pamela:** Exactly – not the most creatively named, but it's kind of humorous.

So weakly interacting massive particles are one of the holy grails of particle physics. These are things that don't generally interact via the electromagnetic force, so they're not interacting with light, not doing any of the things that protons do oh-so-well.

We're not sure what they are; there's theories they come out of super-symmetric particles, there's all sorts of theories. Exactly what the truth is will hopefully be figured out by the Large Hadron Collider, which will come online in the not-too-distant future at CERN in Europe.

So we have this class of objects. We call them WIMPs and beyond that… we don't' know much. But there's also things like neutrinos. Neutrinos don't generally like to interact, they're the anti-social part of the particle world. They're fast moving, have a small amount of mass, and they're non-baryonic. Our Sun emits them, nuclear reactors emit them… they're out there, and they're going to be making up part of this dark matter constituency.

**Fraser:** So do neutrinos have mass and interact with regular matter? Like with gravity?

**Pamela:** They interact with gravity, they do have mass… they don't like to interact, but when forced they will interact in mines filled with cleaning solution, but that's sort of a topic for another show.

**Fraser:** Now if you added up all the estimated mass of neutrinos, does that do the trick?

**Pamela:** Not at all. There have to be other things out there.

**Fraser:** So what is it?!

**Pamela:** We don't know!

[laughter]

This is the part of particle physics where you write "here be dragons". There's nothing else to say! There's theories. This is one of those great unknown parts of science that makes it an interesting time to be alive. Anytime they say there's still no great questions, just look at dark matter and dark energy.

**Fraser:** Are there anymore ideas? Let's hear some more theories.

**Pamela:** So there's this thing called Modified Newtonian Dynamics, which basically says "let's just throw out most of dark matter, and instead change our theory of gravity." The idea is that as you get to larger and larger separations between two masses, this extra term kicks in and modifies the attraction between two things.

It's a fascinating theory that came out by a guy named Mordehai Milgram in 1983. It can't fully account for what's going on in clusters of galaxies, it can't deal with the third peak in the Cosmic Microwave Background, basically if you plot out the distribution of the sizes of the irregularities in the microwave background, you can get different acoustic waves. The first and second peak can be matched with Modified Newtonian Dynamics, the third one can't. All three peaks can be matched with cool dark matter models.

**Fraser:** We're going to have to come back and explain some of that.

**Pamela:** In another show.

**Fraser:** In another show.

**Pamela:** So the main idea is MOND can't fully explain the Cosmic Microwave Background looks. It can't explain clusters of galaxies, but it can explain everything else.

**Fraser:** So with MOND, you're essentially saying the laws of gravity work differently on the large scales.

**Pamela:** Yes.

**Fraser:** That what you think is gravity – and not enough gravity from regular matter, and having to have something like dark matter, is really just you not understanding gravity properly.

**Pamela:** Exactly. The thing about this that is a little bit scary is as a scientist I'm required to say that anytime there are two theories and one of the theories fits my data better than the other theory, I have to go with the theory that fits my data better, no matter how much I don't like it.

MOND is able to fit some stuff better than dark matter models. Specifically there's this thing called the Tully-Fisher relationship, that basically says the rate at which a galaxy is rotating is directly related to how much light it gives off. This implies the fraction of dark matter, as a function of radius and a function of mass, has to somehow be magically tweaked to always make this relationship work. That's kind of weird if you think about it: it's sort of like saying you always have the exact same ratio of adults to children (or something silly like that). With MOND they're able to look at their equations and empirically derive why galaxies' rotation rates and luminosities match perfectly.

So, there's this weird back of the brain, "ooo, I have to pay attention to this thing going on" where maybe we're looking at two different problems. Maybe there is dark matter we can't see. MOND can't explain galaxy clusters, it can't explain the Cosmic Microwave Background, but maybe there is also this other term to gravity that we don't understand that is explaining galaxy rotation rates.

**Fraser:** What experiments are in the works that are going to help provide some light on dark matter?

**Pamela:** We're always looking for more places to get data. We are trying to find those Weakly Interacting Massive Particles, using collisions at the Large Hadron Collider. We are looking for gravitational lensing as a way to map out the mass in galaxy clusters more accurately. We're constantly probing new size scales, looking to see if we have dark matter in star clusters. The answer for the little tiny star clusters, called globular clusters, that swarm around our galaxy, is no. There is no dark matter in globular clusters.

We have to somehow come up with a unified theory that explains why some things have dark matter and some things don't, that somehow finds what this missing matter is, and can explain it. Perhaps these weakly interacting massive particles are something we haven't figured out yet, and someone just needs to be creative enough, and smart enough to predict what they are and give us a theory to look for them.

**Fraser:** I get a lot of email, and I see this a lot on the forum: a lot of people just don't like it. They don't like it because they don't understand it or it doesn't make sense in their concept of reality. I think that my answer is "too bad." Something is going on. Something isn't matching. Out there, there is evidence there is something we don't understand.

Just because we can't necessarily see it with our eyes, we can… if you put on your "gravity eyes" then it's as clear as day. I think a good example of that is when you look at a fire, you don't see the heat coming off of it, but if you put your hand out, you can feel the infrared radiation. You can't see infrared radiation, but you sure can feel it. That's very similar to what we're dealing with here: if you look at the Universe with "gravity eyes" the dark matter's everywhere.

**Pamela:** We, as scientists aren't allowed to have emotional responses – we can't help it, we're human beings, but our logic circuits require us to look at the Universe and say, "things aren't moving the way they're supposed to." The way things move is determined from gravity and mass. Either there's more mass out there, either we don't understand gravity, or both.

Most theories are going in the direction that dark matter's the way to go. Dark matter is, right now, the only thing that can explain what's happening in clusters, what's happening in galaxies. There's a little bit of black magic going on in order to get rotation rates and luminosities to consistently come out with the Tully-Fisher relationship, but the theory works everywhere, if a bit ungracefully. Then, there's this Modified Newtonian Dynamics thing, taunting us in the corner.

**Fraser:** So what's this most recent discovery about the direct observation of dark matter? That's not entirely true, but what did they see?

**Pamela:** Gravity bends light. If I have a nice, spiral galaxy in the background and I put a distribution of mass in front of it, its image is going to get distorted in specific ways depending on the shape of the mass in front of it. There's lots and lots of stuff out in the background parts of the Universe. The chances that I'm going to get lucky if I have a cluster of galaxies, that something's going to get distorted in the background, is pretty high. With the Ballet Cluster we have two galaxy clusters in the process of merging together, so we have lots and lots of mass working to distort the light coming from background objects.

There are people who can run these amazing computer models that look at the way the light is distorted, and work backwards to figure out what mass is doing the distorting. When they do this, they are able to directly map where the mass that we can't see must be located on top of the mass that we do see. It's a way of mapping out a room with your eyes closed: you can do it, it's just not as easy as doing it with your eyes open. They're getting results that say: here is the missing mass. We know where it is, we still can't see the stuff, but we know exactly where it's located.

**Fraser:** I reported on this a bit in Universe Today. I recall that these two clusters collided. When galaxies collide, they often pass right through each other, because the chance of stars and planets colliding with each other is very low. These galaxies pass through each other like ghosts, but the gas in the two galaxies actually did have friction and run into each other, so what you got was as the galaxies passed through each other, the stars and planets flew right past each other while the gas had enough friction it slowed down.

You ended up with a change in the distribution of the mass between the galaxies and this cloud of gas. They were then able to calculate the distribution in the dark matter, and found that the dark matter didn't collide as well. So the dark matter was frictionless, the stars and planets were frictionless, but the gas did have friction: it collided and slowed down. The dark matter passed through each other and right past stars and planets as well, which was brand new.

**Pamela:** There was two different ways. I tend to be a visual thinker, so I was focussing in on the way the light got bent, but you're entirely right: there's also the kinematical arguments where we look at this and see all the heated up gas that is piled up in the centre of these two collisions (that's mapped out in x ray light, where we can see this high, high temperature gas), then we look at the stars in the galaxies as individuals and they did pass right through each other, and the dark matter did the same thing according to the maps. SO we're able to say yes, this is non-interacting stuff, and it's doing everything that a non-baryonic group of whatever should be doing.

**Fraser:** The evidence is still out there, and we will continue to report on it when new stuff comes out. It's what a lot of people are looking for, so I think over the next few years and decades, we're going to have some really interesting new research and results.

*This transcript is not an exact match to the audio file. It has been edited for clarity.*