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Dark Matter: a Cosmic Ghost Story

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Introduction to 'dark matter'

There is a ghost in the Universe. Many things are 'invisible' because they do not emit light at wavelengths we can see: new-born stars glowing in the infrared, microwaves from the start of the Universe, and rapidly spinning neutron stars all shine, they just do it in parts of the spectrum that human eyes are blind to. But all of these things still emit light, of a kind. We could call this 'type one' invisibility: invisible from the point of view of human beings, but perfectly visible if you can 'see' with infrared, or microwave, or radio wave eyes. But over the last few decades, astronomers have become aware that there is something truly invisible haunting the spaces of our cosmos. Dark matter is so invisible we still have not got a glimpse of it – at all – and can only guess at its existence because we see the effects it has on the normal matter that surrounds it. As far as we can tell, dark matter is a kind of 'type two' invisible, completely dark across the entire electromagnetic spectrum. Astronomers have scanned the sky across a massive range of wavelengths, and have never even seen a hint of a photon coming from dark matter. Instead, we see the effects that trail in its wake.

We are like ghost hunters, who have to rely on creaking floorboards and squeaky doors to find their phantom. With one, rather important difference: dark matter is very real. It is so real, in fact, that our entire Universe can be thought of as mainly a Universe of dark matter, with the luminous stuff that builds the stars – and ourselves – seeming like an afterthought. In this article, I want to lay out all the reasons that astronomers have come to believe something so strange: that nearly all of our Universe is made of a substance which we have never actually seen.

Fritz Zwicky's inklings

The first hint that something might be amiss in the Universe came from a cluster of galaxies. A 'galaxy cluster' is a giant swarm of galaxies, sometimes containing thousands of members. Individual galaxies are themselves almost inconceivably big, which makes galaxy clusters some of the most mind-blowingly massive structures in the Universe. Looking at a large cluster, any particular galaxy just gets lost in the crowd.

Figure 1: Fritz Zwicky, in 1947.
Courtesy of Wikipedia Commons

In the 1930s, the Swiss astronomer Fritz Zwicky (1898–1974, *Fig. 1*) was looking at the Coma cluster and measuring the speed at which the individual galaxies were flying around. Galaxy clusters are not static things: if they were, gravity would soon pull all the galaxies into the centre, and the cluster would be no more. Instead, the galaxies within a cluster zoom around like a swarm of midges, the kinetic energy of their movement managing to stave off gravity (which is trying to pull them all together).

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Zwicky noticed something odd, though. It was quite easy to estimate the total mass of the Coma cluster: the galaxies in the cluster shine because of their stars, so by measuring how bright they are you can make a good guess of how many stars each galaxy contains. Add them all up, and you know how many stars are in the cluster, and roughly how much the entire cluster should weigh. The weirdness came in when Zwicky measured how fast the galaxies were flying around: they were going much, much faster than the gravity of the cluster could explain. They were going so fast, in fact, that there was no way for the cluster to hold them: every galaxy should be flying off into space, and the giant cluster should have dissipated into darkness long ago.

What was going on? Everything astronomers knew about gravity suggested that the cluster should be dissolving into nothingness, the component galaxies breaking free of the weak gravitational shackles and making their own way into the wider Universe. But, somehow, there the cluster was. Zwicky took a leap of the imagination: that gravity was working normally, and there was something we could not see pulling things around in ways we did not expect. Zwicky hypothesised that these galaxies were being kept inside the cluster by a massive amount of invisible matter, which exerted a gravitational pull but was completely hidden from our telescopes. He even came up with a name for the missing stuff: *"Dunkle Materie"*, German for 'dark matter'.

Much out there that we cannot 'see'

The alarming thing was (and still is) that this was not just a small correction. It was not a case of taking all the stuff we could see, and bumping the mass upwards by a few percent. Zwicky estimated that the strange dark matter in the cluster outweighed the visible stars by a factor of 200 to one. This early measurement has since been revised downwards, to about ninety per cent invisible stuff (meaning the galaxies we can see make up about ten percent of the cluster).

But even this more conservative estimate tells the same basic story, which we are still trying to understand today: the Universe we see with our telescopes is just the tip of the iceberg. There is a vast 'shadow Universe', far greater than our familiar cosmos, right in front of our eyes. As you can imagine, a revolutionary claim like this was not without its detractors. To banish the spectre of dark matter, the possibility was raised that we might need to alter the law of gravity. Some astronomers instead believed that the observations were in error.

Figure 2: Professor Viktor Ambartsumian.
Courtesy of Wikipedia Commons

The astronomer Viktor Ambartsumian (1908–1996 *Fig. 2*) preferred the idea that things were exactly as they seemed, and galaxy clusters were indeed in the process of flying apart. This was difficult to square with the fact that the Universe seemed to contain an abundance of clusters that had very much not flown apart over their several billion-year lifetimes. But the alternative – that we might have simply not noticed most of the Universe – seemed too awful to contemplate.

The thirty years following Zwicky's findings were rather quiet for dark matter studies. No one knew how to explain Zwicky's result, but no one was particularly keen on adding massive amounts of a completely unknown (and invisible) ingredient to the Universe, based solely on some strange galaxy clusters. Zwicky's cluster was essentially filed under 'strange anomalies to be figured out later', and all but forgotten.

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Figure 3: Vera Rubin in the 1950s.
Courtesy https://www.kveller.com

Vera Rubin

Vera Rubin (1928–2016, *Fig. 3*) entered the field of astronomy with big ideas. Her first presentation of her work at a conference, long before she started her PhD, was titled 'Rotation of the Universe'. She had used telescopes to measure the movement of galaxies, in an attempt to investigate whether the whole Universe of galaxies was spinning around some enormous cosmic axis, like a scaled-up version of the Solar System.

Figure 4: Prof. George Gamow
Courtesy of Wikipedia Commons

Even though her efforts had a sturdy theoretical footing (she was inspired by an earlier paper by the cosmologist George Gamow (1904–1968, *Fig. 4*), who suggested the same thing), her work received a frosty reception, and she later chalked up her grand ambitions to 'the enthusiasm of youth'. The rejection of her first research project, turned her away from researching the hyper-competitive 'hot topics' of the era. By the mid 1960s, the cosmic microwave background was newly-discovered, and everyone was racing to understand the identity of mysterious 'quasars'. But Rubin wanted a quieter corner of science, away from the scientific battlegrounds of the cutting edge. As she later said, "I decided to pick a problem that I could go observing and make headway on – hopefully, a problem that people would be interested in, but not so interested in that anyone would bother me before I was done". The problem that she chose, that she hoped people would be 'not so interested in', led to one of the most important discoveries of the twentieth century.

Figure 5: Horace Babcock.
Courtesy of Wikipedia Commons

Figure 6: Edwin Hubble.
Courtesy of Wikipedia Commons

Rubin decided to dedicate her time to understanding the motion of galaxies. There had been some initial attempts to understand how galaxies spin – the astronomer Horace Babcock (1912–2003, *Fig. 5*) studied the rotation of Andromeda back in the 1930s, and even found hints of something strange – but no one had actually observed the spinning in systematic detail. This was as much down to a lack of instruments as a lack of interest: measuring the rotation of a galaxy is a tricky observation to make. You can measure the speed of something by taking its spectrum (like Newton did with his prisms), and checking for velocity shifts in the spectral lines. This is how Edwin Hubble (1889–1953, *Fig. 6*) famously measured the expansion of the Universe: he took spectra from several galaxies, and saw how fast they were moving. Vera Rubin, however, wanted to make a far more delicate measurement. To see how an individual galaxy is spinning, you need to take several spectra from different locations within each galaxy (near the centre, near the edge, and so on).

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Take enough spectral snapshots, and you can build up a picture of how the stars inside the galaxy are whirling around, a bit like combining reports from several spread-out weather stations to build up a picture of a hurricane. Using a brand-new spectrometer, the most sensitive in the world at the time, Rubin observed our nearest neighbour galaxy, Andromeda, taking spectrum after spectrum to paint a picture of the way it was spinning. It was not long before she ran into the problem: Andromeda was spinning much too fast. Something was pulling the most distant stars in the galaxy around much faster than could be attributed to the weak gravity of the galaxy we could see.

Being a careful and talented observer, Vera Rubin moved on to other galaxies to confirm her result. And the more she found, the more the results stayed the same: galaxy after galaxy was spinning much too fast. Zwicky's weird cluster results had been all but forgotten at this point, so there was no obvious explanation for what was happening. Everything we understood about gravity told us that galaxies should be spinning themselves to pieces, frantically whirling around so fast they should tear themselves apart. But, nevertheless, intact galaxies were all around us. Something must be holding galaxies together.
If Zwicky's cluster findings were like the first inklings that something was amiss, Rubin's meticulous observations allowed astronomers to truly understand the problem at hand. Rubin was the first person to take the extra step and explain how her strange rotations came to be. She realised that if you took the galaxy we could see, and added a cloud of invisible 'stuff' spread out throughout the galaxy, the excessive speeds at the outer edges would make perfect sense. This was the second sighting of the cosmic ghost. Yet another piece of evidence now pointed to the existence of a vast amount of completely invisible material, which not only filled up the spaces inside distant galaxy clusters, but seemed to exist *inside galaxies themselves*. It seemed this missing matter was far more pervasive than anyone had thought. Our Milky Way too, presumably, contained a vast unseen reservoir of this dark material: it seemed that even the empty spaces between the stars in the night sky contained an invisible Universe. Going forward, astronomers had to ask themselves two questions: firstly, could this invisible matter possibly be real?

Figure 7: Prof. Carl Sagan.
Courtesy of NASA

Carl Sagan's (1934–1996, *Fig.* 7) aphorism, that extraordinary claims require extraordinary evidence, seemed to act as a warning. The idea that around ninety per cent of the Universe was completely invisible and ignored until the 1970s is a pretty extraordinary claim, after all. But even if this invisible matter proved to be real, astronomers had a second, critical, question to answer: what on Earth *is it?*

Searching For Dark Matter

In the spring of 1876, four men struck gold – quite literally – in the Black Hills of South Dakota. They named their discovery 'Homestake', and over the course of the following century the Homestake Gold Mine went on to produce well over a thousand tonnes of gold, worth tens of billions of dollars at today's prices. The mine finally closed up shop in 2001, driven out of business by crashing gold prices and soaring costs, and lay abandoned for several years. But a deep hole in the ground, it turns out, is rather useful for a particular astrophysical experiment. In late 2009, in a cavern nearly a mile below the Earth's surface, one of the world's foremost dark matter detection experiments was constructed deep inside the old Homestake mine. At first glance, this sounds rather ridiculous: there cannot be many worse places for observing the wonders of the Universe than a mile underground. But if our astronomical suspicions are correct, and dark matter is indeed a strange and unknown particle, then deep underground might just be the only place we have a chance of spotting it.

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Weakly Interacting Massive Particles (WIMPs)

I am going to step back a bit, and lay out exactly what our 'astronomical suspicions' are when it comes to dark matter, which will explain why building underground detectors makes some sense. Our current best bet is that dark matter is some kind of WIMP – a 'Weakly Interacting Massive Particle'. The 'particle' aspect speaks for itself – we think dark matter is a tiny subatomic object, similar to the familiar protons, neutrons, and electrons that make up atoms. The 'massive' aspect means that we have good reason to believe that the dark matter particle is fairly heavyweight, as particles go, being potentially tens or hundreds of times as heavy as a proton. The reason for this ties into the overall structure of the Universe: if dark matter was a tiny particle, smaller and lighter than a proton, then it would whizz around too fast to form clumps and there would be no way for structures like galaxies to form. In our Universe all galaxies are embedded within invisible clouds of dark matter – and the only way for dark matter to clump together into these galaxy-spanning clouds is if the dark matter particle is rather ponderous and slow-moving: in other words, *massive*. ('Massive' is a relative term, of course: even a really heavy particle, 1000 times heavier than a proton, would still be a billion billion times lighter than an ant.)

So that is the 'Massive Particle' aspect of WIMPs. What about the 'Weakly Interacting' bit? To explain this, it is important to first understand that there are only four so-called 'fundamental forces' in the Universe. These are gravity and electromagnetism (both of which we notice in everyday life), along with the 'strong' and 'weak' forces which operate on tiny scales inside the nuclei of atoms. That is it – those are the only four forces that exist, anywhere in our Universe. Of course, in school we learn about a whole zoo of different forces, including pushing, pulling, friction, air resistance, spring tension, and so on. But this is one of those lovely cases where reality is far simpler than it first appears: the vast array of different forces we notice around us all boil down to the four fundamental forces. It is actually even simpler than that: because the strong and weak forces only operate inside atoms: all the forces we actually notice in our day-to-day lives are versions of either gravity or electromagnetism. Frictional forces, for example, are caused by the tug of little electromagnetic bonds between two surfaces being formed and broken. The tension in a rope is caused by the atoms and molecules inside the rope electromagnetically pulling on each other. Even simple pushing and pulling forces are just electromagnetism, when it comes down to it: if I shove my mug across my desk (after double checking that it is empty), the 'pushing' force I exert comes from the electrons in my hand electromagnetically repelling the electrons inside the mug. Because matter is mostly empty space, even the illusion of solidity is created by electromagnetism. If my body was not subject to electromagnetic interactions, my hand would pass straight through the mug (though if this was the case I would most likely be distracted by my body disintegrating into mist, my constituent atoms freed from the electromagnetic shackles that bind them together).

Out of these four fundamental forces, WIMP dark matter responds to just two of them. WIMPs notice gravity (they better had do: that is how we discovered dark matter after all), and they respond to the 'weak' nuclear force – but that is it. That is where the 'Weakly Interacting' part of its name comes from. WIMPs completely ignore both the strong nuclear force, and – importantly – electromagnetism. The strong force is not particularly important for this discussion, and from here on we can forget it. Its job is to stick protons together, so it does not play much of a role when it comes to dark matter. But the fact that WIMP dark matter ignores the electromagnetic force turns out to be very important indeed. This is what makes dark matter 'dark' in the first place. Light, after all, is just an electromagnetic wave, and when something 'shines' – like a lightbulb radiating visible light, or cold dust in our galaxy emitting in the infrared – it is a result of electromagnetic goings on. A lightbulb shining, for example, is caused by electrons inside the bulb jumping up and down their energy ladder, which creates electromagnetic waves. When you see something in front of you, you 'see' it because light reflects from the object – and reflection, ultimately, is caused by electromagnetism. I can see my cat next to me because electromagnetic waves of light hit my cat's fur, causing the electrons in the fur to wiggle around and bounce the light back. If you had some material which ignored the electromagnetic force, it would not be able to emit, reflect, or absorb light: it would be completely *dark*.

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This is our current model for dark matter: some kind of yet-to-be-discovered particle which exerts a gravitational force but completely ignores electromagnetism, making it utterly invisible to light. Unfortunately for scientists, this electromagnetism-ignoring property makes dark matter very, very tricky to find. Recall that electromagnetic interactions are what gives matter the illusion of being solid: without electromagnetism, you could pass straight through walls like a ghost. And this is exactly what dark matter does. Our best theories and observations tell us that dark matter exists in the form of an invisible sea of WIMPs spread throughout our galaxy, which our Solar System constantly sails through. As the Earth spins through this dark matter ocean, countless trillions of spectral dark matter particles pass through it every second. Even your body is permeable to dark matter WIMPs: in the time it takes you to read this sentence, millions of WIMPs will pass harmlessly through your body. As amazing as this is, it presents a difficult problem for astronomers: dark matter is also going to pass straight through any dark matter-detecting-machine we could conceivably build. It really does seem that the problem is unsolvable: we are surrounded by a vast shadow Universe of ghostly particles, which will remain forever fleeting and out of reach.

Or perhaps not. WIMPs ignore electromagnetism (which is why they can so frustratingly waltz through physical matter), but we think they should be subject to the weak nuclear force, which operates inside the nuclei of atoms. And while atoms are mostly empty space, they are not entirely empty space. The nucleus, even though it only makes up a vanishingly small fraction of an atom's total size, still presents a target for a travelling WIMP. The occasional lucky (or unlucky) particle of dark matter which scores a direct bullseye hit on an atom's nucleus will smash into it, transferring energy to the atom and bouncing off in a random direction like a microscopic billiard ball. And this collision is something that we should be able to see, if we look carefully enough. Direct hits will be very, very unlikely, but gather enough material and wait patiently enough, and you should eventually see a tiny spark – the tell-tale signs of a dark matter particle pinging off the nucleus of your waiting atom. If you were to do this experiment on the surface of the Earth, you would detect mostly false-positives caused by cosmic rays. Cosmic rays are fast-moving particles which arrive from space, and are caused by anything from the Sun to nearby black holes (they are also one of the hazards of being an airline pilot: one long-haul flight gives you about an X-ray's dose of cosmic radiation). Cosmic rays, as powerful as they are, are made of ordinary matter (mostly protons) and are blocked by the ground. This is why physicists built a dark matter detector in the old Homestake Mine: a mile of rock looks like empty space to a dark matter particle, but is perfect for blocking cosmic rays. Using a dark matter detector on the surface of the Earth is a little like trying to listen for a faint whispered voice in the midst of a noisy gig. But a detector experiment buried a mile underground has a chance to block out the noise, and hear the whisper of dark matter. Maybe.

The specific dark matter 'smoking gun' that experimenters are searching for is a signal that cycles over the course of a year. The reason for this relates both to the Earth, and our Galaxy as a whole. Picture our Milky Way, embedded in a vast galaxy-spanning cloud of dark matter. The Sun orbits the centre of the Milky Way at around 250 kilometres per second (taking more than 200 million years to complete one orbit). From our point of view, ploughing through this invisible cloud, we can imagine this acting as a dark matter 'wind' that blows across our Solar System (*Fig. 8*). Now, think about the Earth orbiting the Sun amidst this dark wind. For half the year, we will be sailing into the dark matter wind, and the number of dark matter detections should increase (like driving fast into a rainstorm, and seeing more drops hitting your windscreen). For the other half of the year, the opposite is true: we will be sailing away from the wind, and the number of dark matter detections should fall. This is the critical piece of evidence that scientists are desperately looking for: an annual cycle, with their dark matter detectors being most active in June (when we sail into the dark wind), and being least active in December.

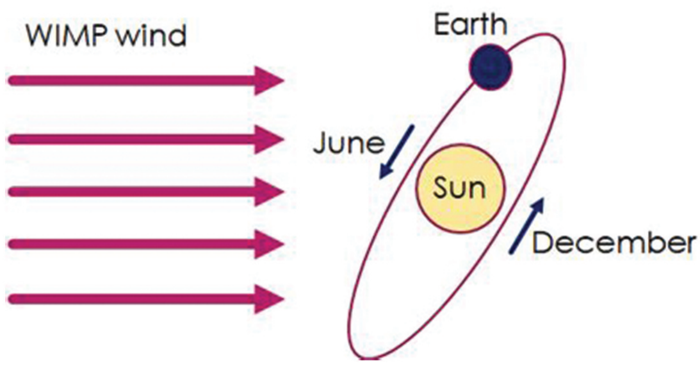

Figure 8: Solar wind.
Courtesy https://medium.com

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The LUX experiment

The experiment in the Homestake mine – known as LUX (*Figs. 9 and 10*) – is not alone. A 2019 review article lists twenty-one different dark matter detection experiments, in which all kinds of exotic materials (from crystals to liquid xenon to tanks of superheated CFCs) sit underground, in abandoned mines and below the Antarctic ice, waiting for the tell-tale sparks of dark matter particles ricocheting off the patently waiting atoms. These efforts have been underway since 1987 – over thirty years of waiting and watching.

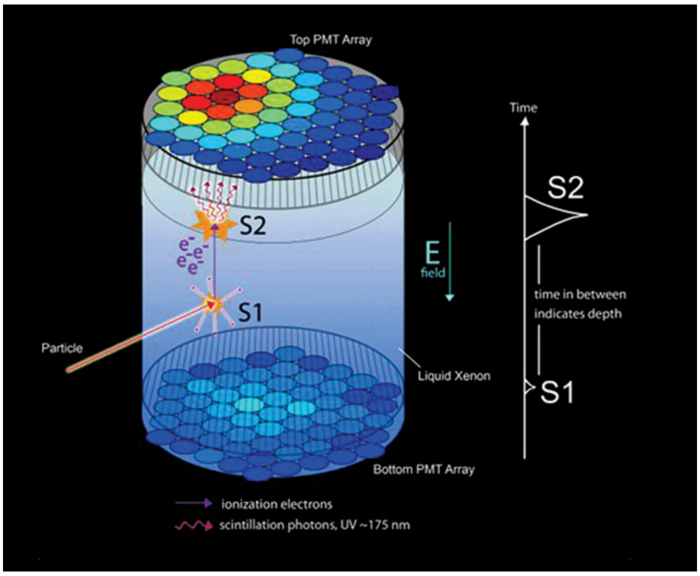

Figure 9: The LUX experiment
Courtesy of www.indiatimes.com

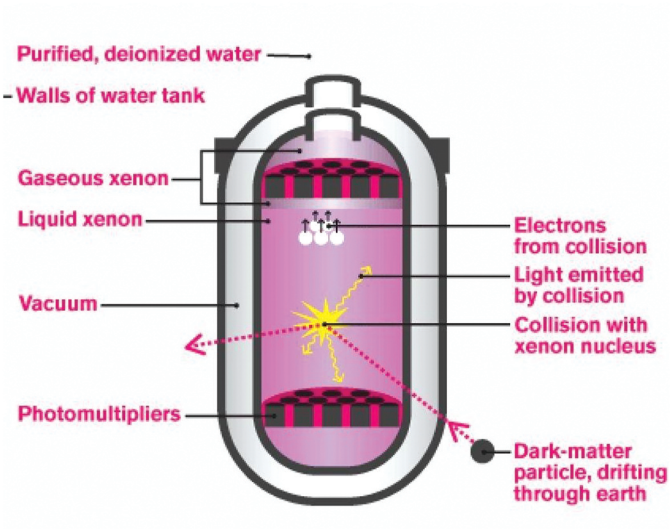

Figure 10: Another representation of the LUX experiment.
Courtesy of www.symmetrymagazine.org

The (rather controversial) DAMA experiment

One controversial dark matter experiment has even reported an annually-varying signal, exactly as would be expected from WIMP dark matter. This experiment is called DAMA (*Fig. 11*), and is located 1400m below the Gran Sasso d'Italia mountain in the Apennines.

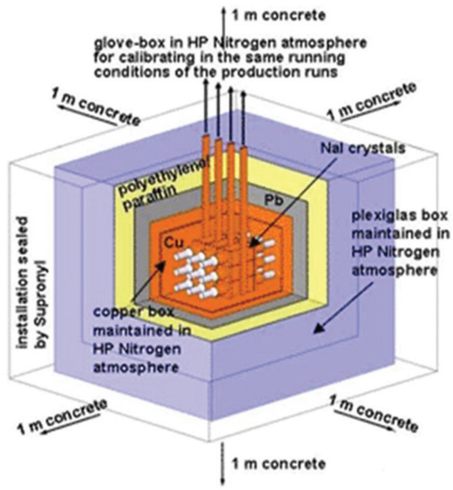

Figure 11: The rather controversial DAMA Dark Matter. NaI(Tl) stands for Thallium (Tl) doped Sodium (Na) Iodide scintillation crystals.
Courtesy of http://archive.sciencewatch.com

Year after year, DAMA has reported seeing flashes from their buried sodium iodide crystals which peak in June and tail off in December, exactly as predicted. While this sounds like a Nobel Prize in the making, there is a hitch: no other detection experiment has seen anything. If the reports from DAMA are real, then several other experiments all over the world (many of which are more sensitive than DAMA, including the Homestake mine experiment LUX where we started this section) should have seen it as well. The mystery is not helped by the fact that the DAMA team are unwilling to reveal the actual data from their experiments. The normal practice among scientists after making a discovery is to make the data public, so the community can double- and triple-check your results, to make sure no errors or mistakes have crept in by accident. The secrecy of the DAMA team has, of course, only increased scepticism towards their findings. While the DAMA team still maintain that their signal is real evidence for dark matter, most people in the community believe that their results can be explained by background noise, like annual temperature variations in their mountain tunnels.

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No definitive evidence for Dark Matter

To date, no experiment has been able to find definitive evidence of dark matter. Over the years there have been several strange anomalies which got people excited for a short period of time, but these almost always turn out to be statistical flukes, fading away into background noise when more data are taken.

As experiments get more and more sensitive, the complete absence of evidence for dark matter gets harder and harder to explain. Astronomers are trying to catch an unseen fish in a net, and with each passing year we manage to use a finer and finer mesh – but, as yet, no fish has turned up. Luckily for us, we do not have to be worried just yet. Every detection experiment that fails to find dark matter still gives us valuable information about what dark matter is not – a bit like a systematic game of cosmic hide-and-seek, where each empty room can be crossed off your 'to search' list before moving on. Of course, if we get to the end of the house and we still have not found dark matter, then it is time to go back to the drawing board and start to wonder what is going on. But as of right now there are still plenty of nooks and crannies to explore: many shapes and sizes of potential dark matter candidates which we have not yet been able to rule out.

The enduring mystery of dark matter

The existence of dark matter is one of the most enduring mysteries of science. All our astronomical observations tell the same story: that the world we know and see and understand is just the luminous tip of the iceberg, resting atop of a far greater invisible Universe. Without this dark material, there would be no Universe as we know it: galaxies would have not formed, and we would not be here. We owe our existence to dark matter, whether we know about it or not. And while it has eluded our initial attempts to catch it, remember that the Universe is under no obligation to be easy for us to understand: thirty years of trying (and failing) to detect something is not much, in the grand scheme of things. It is entirely possible that future scientists might look back on our modern efforts to detect dark matter the way that we look back on Galileo's attempt to measure the speed of light using lanterns – well intentioned, but doomed to failure by the simplicity of our tools and the crudity of our understanding. The answer to the dark matter puzzle might turn out to be more strange than we currently imagine – some unknown exotic particle, rather than just a WIMP. But whatever dark matter turns out to be, every year our search gets more sophisticated, and every year the solution to this profound mystery gets closer. Fingers crossed.

(The article is based, with the publisher's kind permission, very closely on Chapter 7 of the author's recent book 'The Invisible Universe')

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