The hunt for dark matter—the missing ingredient without which our universe would not exist

Without dark matter there would be no galaxies, stars or planets. But physicists are yet to find direct proof of its existence. So where is it?

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Photo: Nasa

Most of the Universe is missing and decades of searching have so far elicited no sign of it. For some scientists this is an embarrassment. For others it is a clue that might eventually push physics towards the next frontier of understanding. Either way, it is an odd situation.

Science has hunted in vain for the missing material. Its existence has never been detected directly, only inferred from hints. Yet if the rest of what we know about the way the cosmos is structured is right, it must be about five times more abundant than all the matter we can see in the Universe.

“Dark matter” is truly ghostly stuff. It is hidden far more profoundly than black holes, about which there was much excitement in April when a beautiful image of one was produced, showing a yellow-orange blob with a black void in the middle. Although, virtually by definition, we won’t ever truly “see” light-swallowing black holes, we can see their effects on the surrounding matter and space. More to the point, we are pretty sure we know what they are made from: ordinary matter, the stuff of stars.

Dark matter is something else entirely. And yet most scientists are agreed that this elusive material must exist: without it, they find it hard to see how we could be here at all. The gravitational pull that it exerts—the only impression it leaves on the visible

Universe—is an essential ingredient for the formation of galaxies, stars and indeed planets like our own.

This is science's most necessary fiction: a stark reminder that there are some important pieces missing from the puzzle of how the laws of nature work. Its elusiveness raises fundamental questions about how we should conduct scientific inquiry. Must we, as Isaac Newton thought, only believe in what we can demonstrably prove exists? Or do scientists need the freedom to imagine what cannot yet be observed—and may never be—to pave over gaps in current understanding so that we can still walk the path?

Science has engaged in many potential wild-goose chases before. Sometimes, as with the pursuit of the particle called the Higgs boson, which was finally found in 2012, decades of faith and searching paid off in the end. But in other cases, a long and fruitless search may be concluded only by calling it off. The great difficulty is in knowing when to let go of an idea and when to persist. No science, only intuitive judgment and perhaps a propensity for stubbornness, can decide which way the scales will tip. For dark matter, it remains to be seen how they will fall.

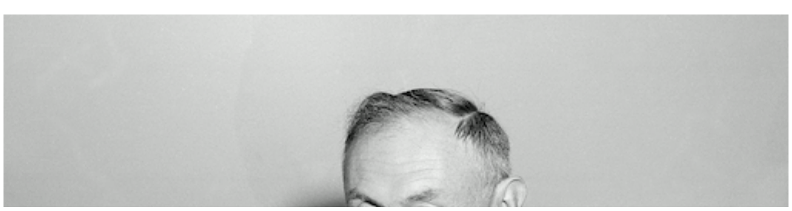
Gone like the wind

That there might be unseen stuff in the Universe is an old idea. What has changed in recent decades is our sense of how much there is out there.

At the start of the 20th century, the Scots-Irish scientist Lord Kelvin suggested that many stars might be burnt-out and lightless husks. But the French physicist Henri Poincaré soon cautioned that there couldn't be very much of this "dark matter" (*matière obscure*, as he called it), because if it had mass it would also have gravity, and if its gravitational influence were important, that would make the visible stars move differently from what we observe. We should, in other words, expect to see the effects of "invisible" matter just as we can infer the presence of the wind from the way it moves the leaves on a tree. Poincaré's verdict held up well into the 1920s, because astronomers *thought* they could fully explain what they were learning about the positions and movements of stars within our own galaxy, the Milky Way, by their mutual gravitational tug.

Things began to change in 1933 when astronomer Fritz Zwicky studied the motions of a large group of distant galaxies called the Coma Cluster, which seemed to conflict with what was expected from the gravitational influence of the visible stars and gas they contain. Zwicky calculated that the amount of dark matter needed to explain the discrepancy was immense: around 100,000 times more of it than visible matter. As late as the 1960s, this unsettling conclusion was widely resisted, but over time it became apparent that in fact *every* galaxy—our own Milky Way included—must have a lot of dark matter holding it together.

Why? Because we came to understand more about the way many galaxies, including our own, rotate in great spiral swirls of stars. The rotation creates an outwards (centrifugal) force, just like the one that makes an ice-skater's skirt flare outwards. What prevents all the stars from being flung out is their gravity, which pulls them together. As astronomers gathered better data about galactic "rotation curves"—how the circulation speed of stars around a galaxy's centre depends on how far out they are from it—in the 1950s and 60s, they found that the summed gravity of the observed stars isn't enough to counteract the centrifugal force. In 1970, the astronomer Ken Freeman concluded that "there must be in these galaxies additional matter which is undetected"—in other words, matter that is "dark." The more they looked, the more convinced astronomers became that galaxies had to be stuffed with dark matter.



About this author

Philip Ball
Philip Ball is a science writer

Fritz Zwicky calculated that there was much more dark matter than visible matter in the Universe.
Photo: ANONYMOUS/AP/SHUTTERSTOCK

Liam Fox interview—A world beyond Europe

A forward thinking approach

Dark matter isn't only demanded by galactic rotation curves. It has also come to seem like an indispensable part of the story for how the Universe came to end up looking the way it does. The Universe began in a rapid, explosive expansion from a tiny volume—the Big Bang—and as it cooled, subatomic particles condensed as atoms, which in turn clumped together into clouds of gas and dust from which stars and galaxies were born. This cosmos-creating clustering process—by which slight irregularities in the cosmic gas become amplified into dense knots—seems to be possible only with the help of the additional gravity supplied by dark matter: the pull of early ordinary matter on its own wouldn't be enough. "Dark matter is everywhere," says astrophysicist Carlos Frenk of Durham University, "and -galaxies grew inside clumps of it in the early Universe. Without dark matter, there would be no galaxies."

We can be eerily precise about how much of it there must be. If we can find out just how unevenly matter was spread in the early Universe—which can be deduced today by measuring very tiny differences in the "background temperature" of space across the whole sky—we can figure out exactly how much dark matter the Universe needed (and thus contains now) to a precision of better than 1 per cent. The answer: it should exceed the mass of all known visible matter by a factor of around five.

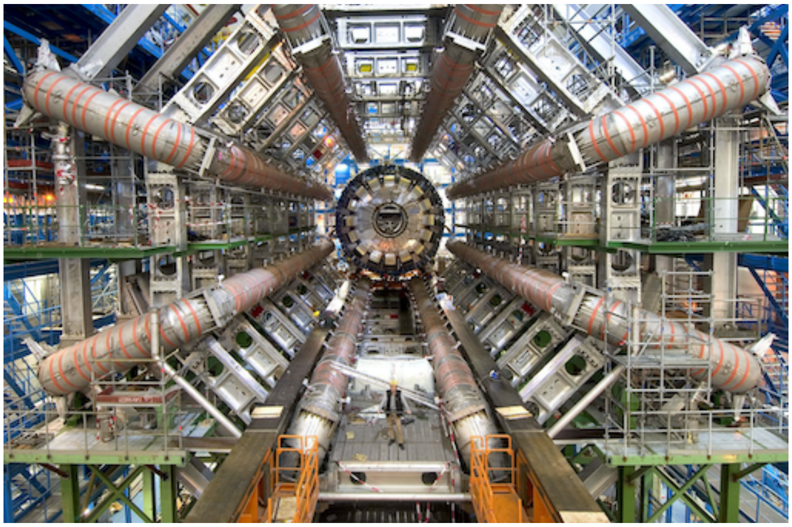
Blowing hot and cold

So there is a lot of it about. But what actually is it? Dark matter seems to do nothing but gravitate. Other objects feel its mass, but it doesn't interact with light, or absorb or radiate heat, or in fact heed ordinary matter in any other way. That's a deeply peculiar way to behave, and doesn't match any of the known fundamental particles.

For a time, though, researchers hoped to avoid the need to invoke completely new types of particle. They wondered if at least some dark matter might be accounted for by the neutrino, a particle that barely interacts with the others. But as we have learnt more about neutrinos that theory has bitten the dust. Another idea popular in the 1980s and 90s was that dark matter might be ordinary matter condensed into very small clumps such as tiny planets or small and very dim stars (red and brown dwarfs) that drift through space on the outskirts of galaxies. These putative objects were dubbed Massive Astrophysical Compact Halo Objects or "Machos." But careful astronomical searches have shown that Machos can't account for any significant fraction of dark matter, and the hypothesis is now essentially abandoned.

Since the late 1980s, most physicists have instead accepted that dark matter is likely to be made up of fundamental particles that are currently unknown to physics. This leaves them having to "invent" new particles or objects that might explain dark matter, guided only by the properties that seem necessary to explain the astronomical observations.

"The most likely hypothesis is that [dark matter] is an elementary particle created very soon after the Big Bang," says Frenk. The big challenge is to find any clues about what these particles are like. One might come from dark matter's "temperature." It might be "cold"—crudely speaking, the particles move slowly, with very little energy—or made of faster-moving particles and thus "warm."


The Large Hadron Collider could help with the search. Photo: Shutterstock

Frenk and his colleagues hope to distinguish between the warm and cold possibilities by looking closely at one manifestation of dark matter in the visible universe. It has been known for a century now—since Einstein's theory of general relativity in 1916—that gravity distorts spacetime and can bend light. A massive object like a galaxy can therefore act like a lens, bending and focusing the light from a more distant source behind it. In some cases, this can make the distant object look like a ring, known as an Einstein ring. Light is also bent around black holes, as it is in that already iconic image from April.

Where we see starlight being bent in this way in the absence of visible ordinary matter, then we can infer dark matter's presence. By looking closely at the ring-like "gravitational lenses" caused by dark matter, Frenk and his colleagues hope to tell whether or not it is gathered into very fine-grained clumps—which only cold dark matter permits. Frenk says that knowing if dark matter is warm or cold would be almost as good as detecting the actual particles it contains, because it will winnow down the current profusion of candidates.

Waiting for a Wimp

The necessary—almost tautological—characteristics for dark-matter particles are that they have mass (and hence gravity) but otherwise interact only extremely weakly (if at all) with light and ordinary matter. A popular vision of this minimal set of features has been christened Weakly Interacting Massive Particles, or Wimps.

If Wimps are indeed weakly interacting, rather than non-interacting, then you'd expect every now and then—very rarely—one of them might smash into a particle of ordinary matter and actually feel it. Such a collision should, like other high-energy particle collisions, produce an observable shower of other particles and radiation. That's the hope behind current experiments to detect dark matter directly, some of which have been running since the 1990s. Many of these detectors are placed deep underground, where they are shielded from cosmic rays that could cause spurious signals.

One of the most sensitive is XENON100, which consists of a tank of around 60kg of liquid

xenon, a chemically inert substance, buried under Gran Sasso mountain in central Italy. Collisions of dark matter particles with xenon atoms should produce a flash of light that detectors would register. XENON100 ran from the early 2010s, but no unambiguous sign of a Wimp was ever found. It was then upgraded to XENON1T, containing about two tons of xenon to increase the chance of a collision. Initial results, released in 2017, still showed nothing. There are now plans to make the detector mass even greater.

It's been the same story with a slew of other such experiments with fancy acronyms, such as Cosme, Demos, IGEX, DAMA/LIBRA, Edelweiss and Cresst, over the past three decades. So why don't researchers just conclude there is after all nothing to be found—that dark matter needs a different sort of explanation? Well, Wimps are hard to give up—for complicated reasons that reach to the heart of contemporary particle physics.

It's to do with that famous Higgs boson, detected in the Large Hadron Collider (LHC) at Cern in 2012. Everyone expected the Higgs, but its observed mass was rather smaller than predicted, potentially requiring awkward fudging. To fix the problem, you can apply a theory called supersymmetry, under which each of the known particles is predicted to have a so-far unobserved "supersymmetric" partner which could, among other things, "cancel out" some contributions to the Higgs mass and thus lower the prediction, reconciling it with what is observed.

"The Higgs particle was predicted in the 1960s, and was only discovered over 40 years later.
We have only been looking seriously for dark matter for 20 to 30 years"

Where does all this fit in with dark matter? Well, some of the putative supersymmetric partner particles have precisely the properties expected of Wimps, and should exist in just the right quantities too. Supersymmetry looked like it could be the exact solution to the dark matter puzzle. But, frustratingly, this neat story isn't panning out. The simpler and more elegant versions of the supersymmetry theory predict evidence that should have been detectable by now. Sadly, it hasn't been found.

Frenk concedes that "supersymmetry is under the cosh at the moment." A version of the theory could be saved with clunky, complex tweaks, which could also salvage the Wimps account of dark matter. But this clunkier theory would be unable to explain that strangely low Higgs boson mass—which was a big part of the attraction in the first place. We'd lose the sense of everything falling into place at once, and end up with an account that would feel like a bit of a bodge.

So the search goes on and, says Jonathan Feng of the University of California at Irvine, "we theorists shouldn't just sit around waiting." There are "a lot of relatively small, cheap, and fast experiments" that could be done, he says. He has proposed a particle detector called Faser, barely bigger than a fridge, that could be added to the LHC and potentially see Wimp-type particles that the big detectors would miss, simply by looking in the right part of the particle beam. However, some physicists feel it is time to seriously consider whether dark matter might not be due to Wimps at all, but to something else entirely.

It's a particle Jim, but not as we know it

One of the favourite alternative candidates for a dark matter particle is called an axion, a hypothetical particle that—if it exists—would solve a riddle about the particle called the neutron. Theory has long predicted that this neutral building block of the atomic nucleus should be more charged on one side than the other; evidence for this, however, has not emerged. Axions could explain that failure. But if they are real, they are very elusive. The Axion Dark Matter Experiment has been operating since 1996 in Seattle, using very strong magnetic fields (which could convert passing axions into microwave radiation) to detect them. Like all other dark matter searches, it has seen nothing so far.

What else is on the menu? Plenty! There is fuzzy dark matter, superfluid dark matter, particles called Wimpzillas, particles that emerge from extra dimensions. Another possibility is the so-called -"sterile neutrino," a special kind of neutrino proposed to explain why neutrinos have mass at all, when the Standard Model of particle physics predicts that they should not. There are neat ideas about how sterile neutrinos might have been generated in the early Universe—but they are expected to decay, rather as radioactive atoms do, and so it's not clear if they would last long enough to explain the amount of dark matter we can infer today.

Alternatively dark matter might, some say, consist of "primordial" black holes: tiny by normal astrophysical standards (10 times the mass of the Sun) and made in the Big Bang. Some researchers have proposed that we might, perhaps, find a "signature" of such entities in gravitational waves—the ripples in spacetime predicted by Einstein a century ago, which were finally detected only in 2015.

In sum, the hunt is as varied as it is inconclusive. An optimist might say we shouldn't despair—there remain plenty of places for dark matter particles to hide. A pessimist might retort that the fact we can spin so many theoretical webs while consistently failing to see anything suggests that this corner of physics is governed by rampant speculation. Could it be time to rethink dark matter altogether?

What if, for example, it is not actually matter at all? Perhaps the effects in galactic rotation curves that we attribute to it could instead be a sign of something being amiss rotation curves that we attribute to it could instead be a sign of something being amiss with our theory of gravity. Einstein's general relativity accounts for gravity at the scale of the solar system, but could there be some weakening of the force at the galactic scale? Some now offer these ideas, called Modified Newtonian Dynamics, as the reason why no dark matter particles have been seen. But even if we are prepared to revise our understanding of gravity in this way, we still won't have answered all the puzzles dark matter poses—in particular its roles on the larger-than-galactic and cosmic scales.

"This is not the first time scientists have searched in vain for something they are sure must be there"

And so we are driven back to a hunt for new particles. "Introducing just one new particle," says Feng, is "the most elegant, minimal, and satisfying solution to a host of astrophysical problems one could ever imagine." Which makes it all the more maddening that we just can't find any such particles.

Some researchers believe we are entering a new era in this great but vexing search. As dark matter looks ever less likely to emerge neatly from existing theories or to resolve other outstanding problems, they say, it is ever less obvious where to look for it—so perhaps we must simply do so wherever we can, without prejudice or preconceptions. "I caution against putting too much weight on any particular candidate for dark matter," says theoretical astrophysicist Dan Hooper at the particle-physics laboratory Fermilab in Illinois. "We need to cast a very wide net, experimentally speaking, and test as wide a range of scenarios as possible."

But Frenk is not ready to give up on old ideas such as Wimps. "Nature doesn't give up its secrets cheaply," he says. "The Higgs particle was predicted in the 1960s, and was only discovered over 40 years later. We have only been looking seriously for dark matter for 20 to 30 years."

There's no guarantee, though, that dark matter will ever be found. What if, for example, it is *really* dark, made from a ghostly particle such as the "gravitino," posited by supersymmetry, which doesn't interact (except gravitationally) with ordinary matter at all? Then there will never be any observable collisions, and we might only ever have indirect glimpses of what it is.

So what's the matter?

This is certainly not the first time that scientists have searched in vain, over many years or even decades, for something they are sure must be there. The current quest, with its reliance on ultra-sensitive measurements for an influence with cosmic ramifications, resembles the efforts in the late 19th century to detect the ether, the all-pervasive fluid that was incorrectly thought to carry light waves. Physicists clung to the idea even after experiments (highly sensitive for the time) in the 1880s failed to see evidence of it. Only in 1905 did Einstein's theory of special relativity show that it was not needed to understand light after all. Contrast that, though, with gravitational waves, which were also long sought in measurements made at the limits of technical feasibility, but which did turn up in the end.

Sometimes you need to keep the faith; at other times you need to abandon a deeply held conviction. The norms of scientific methodology offer no guidance about which path to take. All you can be sure of is that, once the problem is resolved, it won't be hard to find people who say either "I never doubted it" or "I always had my doubts."

Science isn't about sticking only to rigorously confirmed facts—to Isaac Newton's hypothesis *non fingo*, "I make no hypotheses." Supposing things to be true and standing by that supposition in the face of ignorance and the absence of evidence, maybe even for a lifetime, is not only useful but sometimes essential. As Erwin Schrödinger said, "In an honest search for knowledge you quite often have to abide by ignorance for an indefinite period… The steadfastness in standing up to [this requirement], nay in appreciating it as a stimulus and a signpost to further quest, is a natural and indispensable disposition in the mind of a scientist."

Or as Samuel Beckett put it, "in the silence you don't know, you must go on, I can't go on, I'll go on."

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