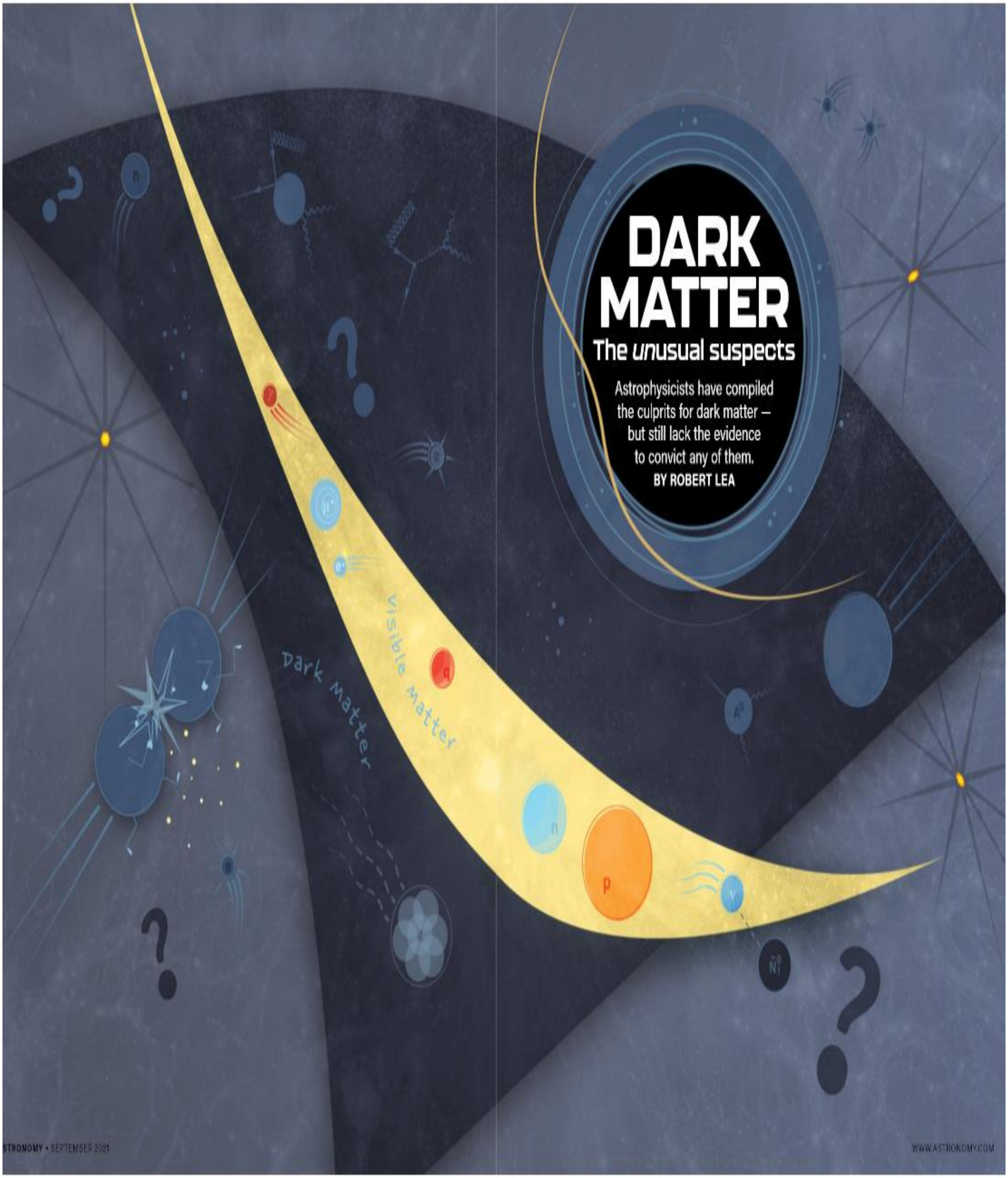
DARK MATTER

The *un*usual suspects

Astrophysicists have compiled the culprits for dark matter — but still lack the evidence to convict any of them.

BY ROBERT LEA



Over the centuries, our understanding of the cosmos has grown by leaps and bounds. But it wasn't until relatively recently that astronomers discovered around 85 percent of the matter in the universe takes on a bizarre, foreign form: dark matter. Just like detectives in the best crime thrillers, astronomers must hunt for this puzzling substance by searching for subtle clues, sifting through convoluted evidence, and, critically, identifying likely suspects.

"Dark matter is the name scientists have given to the particles which we believe exist in the universe, but which we cannot directly see," says theoretical physicist Johar M. Ashfaque, a data scientist at the U.K.'s East Kent Hospitals University NHS Foundation Trust. Ashfaque first became interested in dark matter while earning a Ph.D. focused on string theory, at the University of Liverpool.

"This material appears to have mass, but it does not appear to absorb or emit any electromagnetic radiation," he explains. "Given the fact that it does not send us any light, it is not difficult to understand that it has been hard to discover anything about the nature of these mysterious particles."

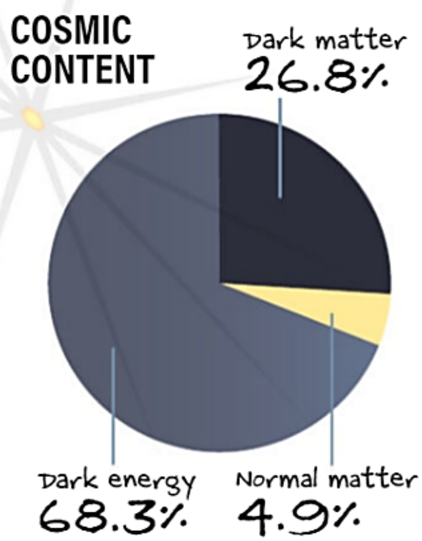
Despite dark matter's elusiveness, scientists have been able to shed some light on the problem. The majority of our knowledge about dark matter comes from the fact that although it doesn't interact with light, it does interact with normal matter via gravity. That's how we know it exists.

The collective gravity of all normal (baryonic) matter locked up in a galaxy's stars, planets, and gas isn't strong enough to bind that galaxy together as tightly as we observe. Without dark matter, astronomers would see stars on the outskirts of galaxies orbiting much more slowly than those near the center. Yet, starting with observations of the Andromeda Galaxy made by Vera Rubin and Kent Ford in the late 1970s, that's not what researchers have found. They instead see that visible matter at the outer edges of galaxies orbits faster than expected, suggesting galaxies contain an invisible form of non-baryonic (dark) matter.

Collecting evidence

Astronomers' meticulous identification of the indirect effects of dark matter is akin to police or private detectives gathering clues to help them identify the likely perpetrators. Of course, no murder mystery could possibly consider everyone a potential wrongdoer. First, investigators must narrow down the suspects. And that's the approach scientists have taken with dark matter.

Over the past several decades, researchers have managed to work out some of the characteristics of dark matter particles — specifically, the mass range in which dark matter candidates should fall. Physicists generally consider dark matter particles to have a mass between about 10^{-24} and 10^{28} electron volts (eV). That's a huge range, and it admittedly doesn't narrow down the suspect list very much. To put these masses into context, recent measurements of neutrinos — particles so light that hundreds of thousands of them stream through your body every second with no discernible effect — put them at a mass of roughly 1 eV. So, dark matter particles could fall anywhere on a wide mass range that spans from fantastically lightweight to superheavy particles like primordial black holes. Still, several experiments that are combing the cosmos for dark matter particles have managed to narrow down their potential masses even further, at least for specific hypothesized particle types.

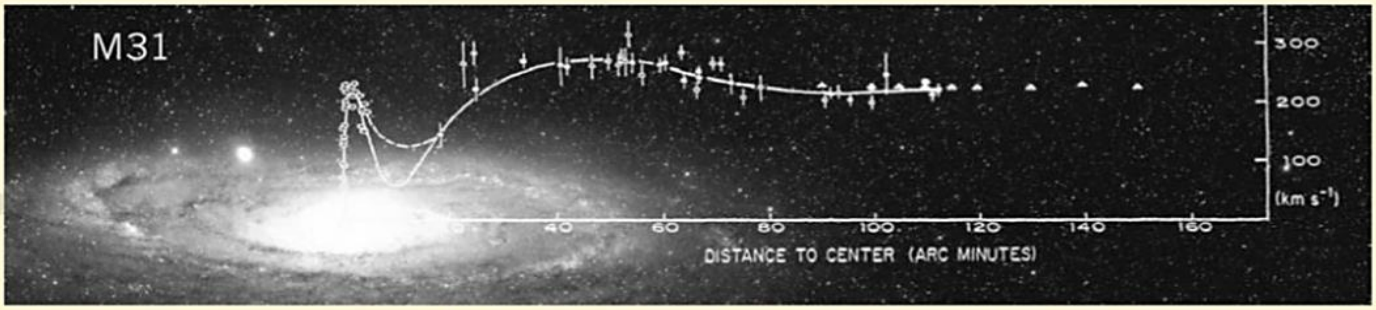


Knowing the mass range of potential dark matter candidates is valuable because mass and energy are intimately related. Their connection comes via mass-energy equivalence, which is a key consequence of Einstein's famed formula, $E = mc^2$. So, by having good estimates of the masses of dark matter particles, researchers know the energy ranges in which they should search for them. It's like a detective studying footprints left behind at the crime scene to estimate the size of the perpetrator and help map the areas they frequented.

Rounding up the regulars

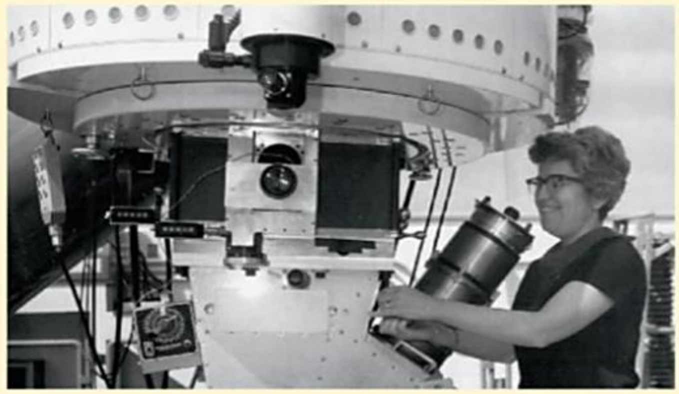
Mass alone, however, is not enough to pin down the particles responsible for dark matter. By examining other characteristics of the suspected culprits, such as how they interact with the known forces of nature, scientists can tighten the net even more. And although many of the most probable candidates for dark matter are hypothetical particles, their theorized existence is still based on real evidence compiled over the decades.

The possible forms of dark matter are typically divided into two categories: cold dark matter (CDM) and hot dark



Vera Rubin and Kent Ford discovered that observable matter near the outskirts of the Andromeda Galaxy (M31) rotates faster than it would if the galaxy were only composed of regular matter. This view of M31, captured by the Palomar Sky Survey, is superimposed with a plot of the radial velocities of both optical (dots) and radio (triangle) sources in M31. If the galaxy contained no dark matter, these velocities would significantly decrease with increasing distance. VERA RUBIN AND JANICE DUNLAP

Rubin (left) and Ford (white hat) check on their equipment at Lowell Observatory in 1965 during one of their first observing runs together. CARNEGIE INSTITUTION, DEPARTMENT OF TERRESTRIAL MAGNETISM



Rubin operates the 2.1-meter telescope at Kitt Peak National Observatory. Ford's spectograph is attached to the telescope so they can measure the radial velocities of matter at different distances from galaxies' centers. NOAO/AURA/NSF

matter (HDM). However, these category names don't refer to temperatures. They refer to speeds, with HDM particles traveling at nearly the speed of light and CDM particles moving at much slower, non-relativistic speeds.

One oft-proposed CDM candidate is weakly interacting massive particles, or WIMPs. These hypothetical particles are dubbed "weak" because they only interact through two of the four fundamental forces: the weak nuclear force and the gravitational force. WIMPs don't interact with anything through either the strong nuclear force or the electromagnetic force — something we know is also true for dark matter.

Joel Primack, an emeritus physics professor at the University of California, Santa Cruz, says, "Heinz Pagels and I were the first to point out in our 1982 article in *Physical Review Letters* that the lightest supersymmetric partner particle is a natural candidate to be dark matter. … And the lightest supersymmetric partner particle would be a WIMP."

Still, if astronomers want to prove WIMPs are responsible for dark matter, they need to catch them red-handed. WIMPs might provide clues about their existence by occasionally bumping into ordinary matter and, via the weak nuclear force, making those atoms emit light that can be picked up by extremely sensitive instruments. Yet despite multiple searches, direct evidence of WIMPs remains elusive.

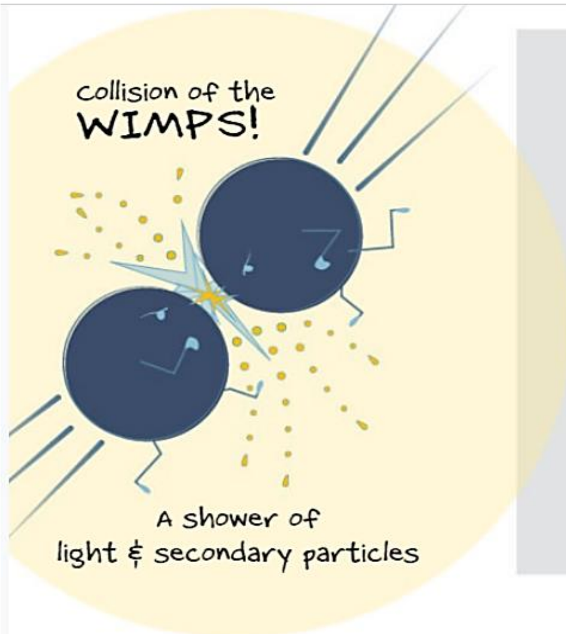
SUPERSYMMETRY AND DARK MATTER

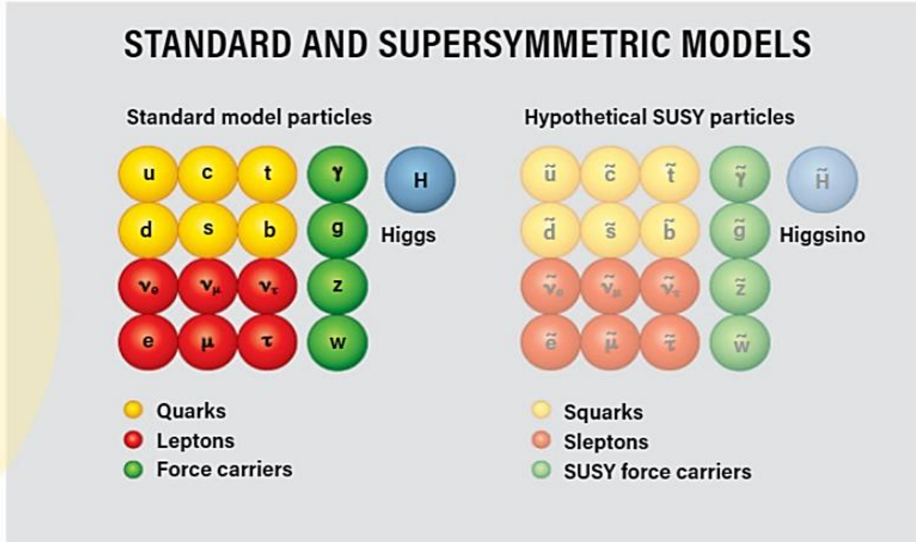
Supersymmetry (SUSY) is an extension of the standard model of particle physics that aims to fill some gaps within the model. SUSY leads to Grand Unified Theories, or theories of everything, that unite quantum mechanics and general relativity.

One of the most significant takeaways of SUSY is the idea that all particles in the standard model have a supersymmetric partner. So for quarks, there are squarks. Leptons are reflected by sleptons. And force-carrier particles, like photons for electromagnetism, have SUSY counterparts, too. This model extension exists primarily to explain how the Higgs boson can interact with all particles to give them mass, yet still remain so light itself. The supersymmetry particles allow for a light Higgs boson and an equally light SUSY counterpart, the Higgsino.

How does this connect to dark matter? Of all of the hypothetical particles suggested by SUSY, one, the so-called lightest supersymmetric particle (LSP), could be responsible for dark matter's effects. Certain theories predict that this LSP wouldn't decay into a particle in the standard model. And if the LSP exists, it must be electrically neutral, or it would be captured by Earth's magnetic field and reveal itself. This would mean the LSP lingers around the universe, not interacting with much. And when it does, it only does so via gravity, like dark matter.

Still, there is no experimental evidence of supersymmetry, and thus no evidence of the LSP. But if supersymmetric particles exist, they should eventually reveal themselves in particle collisions conducted at facilities like CERN's Large Hadron Collider (LHC). And thanks to recent upgrades, physicists will soon witness more collisions than ever, upping the odds of spotting rare particles. This makes the LHC and future particle accelerators vital tools for investigating dark matter. *—R.L.*





Researchers have already found some indirect evidence, though. When two WIMPs collide, they don't just bounce off each other or pair up. They obliterate each other in a powerful burst of pure energy. "Gamma rays from the center of the Milky Way nicely fit the predictions of WIMP annihilation," Primack says. Still, he cautions, "there are other possible explanations," as similar emissions are caused by high-energy cosmic rays and other types of particle collisions.

Another potential line of indirect evidence comes from physicists who run simulations of the early universe. These computer-generated universes commonly see WIMP lookalikes pop up and survive to the modern day, and their numbers are close to the abundances physicists predict based on our current understanding of dark matter.

Yet, by and large, astronomers can't seem to inextricably tie WIMPs to dark matter. This is because physical processes like interactions through the weak force and annihilation are extremely rare. Pinning dark matter on WIMPS is a tall order that requires detectors housed deep beneath Earth's surface to block out cosmic noise. One such detector is the Large Underground Xenon (LUX) experiment, which aims to detect WIMPs using canisters of xenon located 5,000 feet (1,500 meters) below ground in South Dakota.

Sterile neutrinos

Unlike WIMPs, scientists have had success detecting neutrinos, which are chargeless, near-massless particles that share the weakly interacting properties of WIMPs. However, because neutrinos travel at nearly the speed of light, they don't fit the CDM model. Still, that doesn't rule out neutrinos as an HDM candidate.

Some physicists have hypothesized that the various known flavors of neutrinos (electron, muon, and tau neutrinos) have a much more massive cousin: the sterile neutrino. These particles would likewise barely interact with regular matter and ignore electromagnetic influence, but they might also have enough mass to account for dark matter.

Despite their heft, sterile neutrinos should be trickier to collar than common neutrinos, as the latter are abundantly produced by stars, including the Sun. While standard neutrinos occasionally interact with ordinary matter via the weak force and gravity, sterile neutrinos would only interact through the latter. And because even sterile neutrinos would be relatively low-mass particles in the grand scheme of things, observing their tiny gravitational effects is extremely challenging.

This challenge, however, could be lessened in the very near future. In April 2021, researchers at the KArlsruhe TRitium Neutrino Experiment (KATRIN) narrowed down the search for the sterile neutrino by reducing the range of the particle's proposed mass to less than 1 eV. KATRIN will continue to seek evidence of sterile neutrinos by observing the radioactive decay of protons within heavy water to neutrons, with each event releasing an electron and a neutrino. The larger the mass of the released neutrino, the less energy the released electron has. So, if sterile neutrinos are occasionally emitted during the decay process, researchers should be able to detect a discernible signal in the energy spectrum of the released electrons.

Although WIMPs and sterile neutrinos share some notable features with our mugshots of dark matter, not all possible dark matter suspects have to be heavyweights like them.

Axions: The featherweights

For years, WIMPs were the uncontested frontrunners for dark matter. But more recently, another type of particle, first theorized in the 1970s, is becoming a stronger contender in physicists' minds. These particles — dubbed axions after a popular brand of detergent (because they would clean up the dark matter problem) — are similar to photons. But whereas photons are massless, axions still possess a tiny amount of mass, perhaps a billionth the mass of an electron.

Searching the universe for such lightweight particles may be akin to dusting the entire planet for a single fingerprint, but that's basically what's occurring at the Axion Dark Matter eXperiment (ADMX) underway at the University of Washington. The ADMX G2 project depends on an axion helioscope, which uses a powerful magnetic field to convert

The LUX detector, seen here during the assembly process, relies on photomultiplier tubes that can detect photons emitted during collisions between dark matter and xenon nuclei. MATTHEW KAPUST/SURF

Riding atop a large transport vehicle, KATRIN's enormous 200-ton spectrometer makes its way through the narrow streets of the German village Leopoldshafen in late 2006. Altogether, this essential component of the neutrino-hunting experiment traveled some 5,600 miles (9,000 km) over the course of more than 60 days to reach its final destination at nearby Karlsruhe Research Center. KARLSRUHE TRITIUM NEUTRINO EXPERIMENT

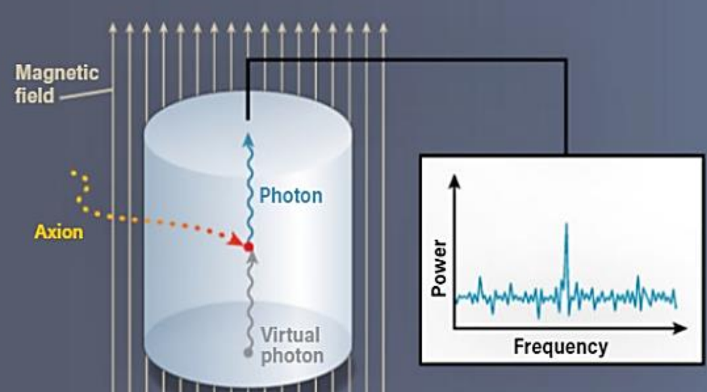
dark matter axions into microwave photons. While the researchers haven't yet managed to spot an axion (you would be reading a very different article if they had), like the KATRIN team has done for neutrinos, the ADMX team has placed important constraints on the possible mass range of axions. This enables other scientists to limit their searches to ever-narrower energy ranges.

Despite being exceptionally tiny and light, axions could account for the massive gravitational influence of dark matter, as long as they are packed incredibly tightly throughout the universe. Axions are also one of the most interesting candidates for dark matter partly because their existence could simultaneously solve another troubling mystery in physics: They might explain why the early universe seemed to favor matter over antimatter, despite the two initially existing in equal amounts. This is called the charge parity (CP) violation problem, and axions could fix it.

The temptation of killing two birds with one stone has only served to bolster theorists' desire to add axions to the short list of possible dark matter suspects. "The axion is the best solution to preventing CP violation," says Primack. But he also warns against settling for an answer out of convenience: "[Axions] could do that and still make no significant contribution to the dark matter density of the universe."

Despite understandable caution, Primack thinks axions could be a leading contender for dark matter. "Axions and

DETECTING AXIONS WITH ADMX

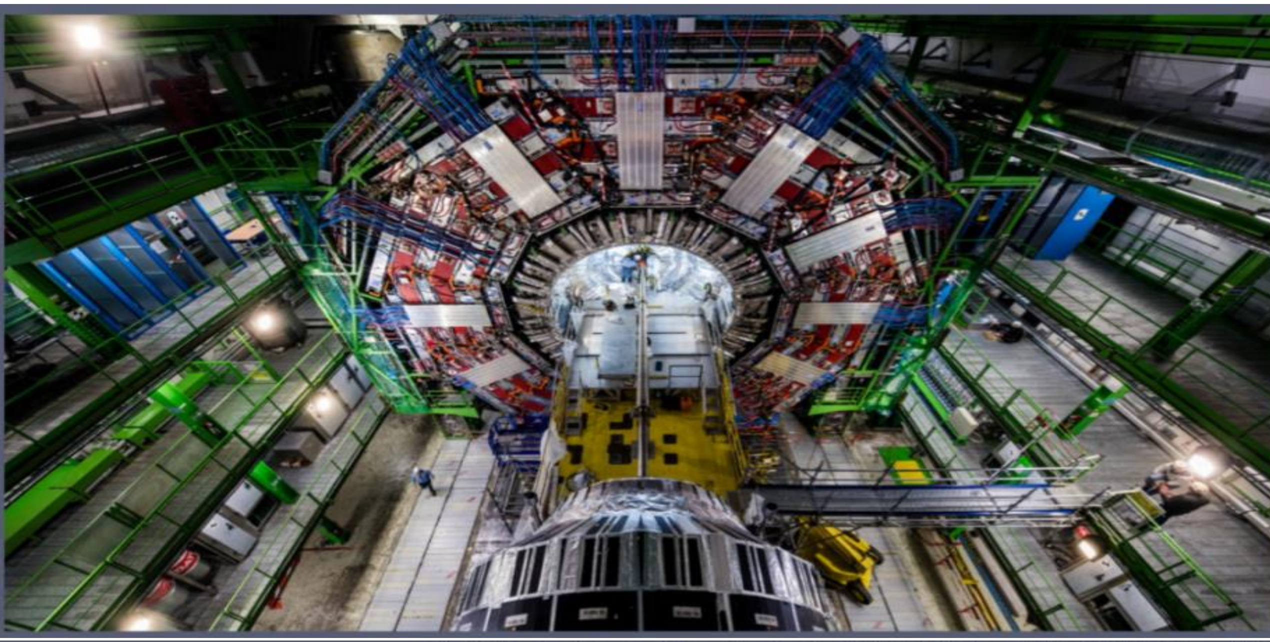


The Axion Dark Matter eXperiment (ADMX) relies on a strong magnetic field streaming through a cylindrical cavity to hunt for the dark matter candidates. If the theory of axions is correct, a sensitive microwave receiver should be able to pick up a faint boost in power generated within the cryogenically cooled and tunable microwave cavity when an axion converts into a photon. ASTRONOMY: KELLIE JAEGER AFTER C. BOUTAN/PACIFIC NORTHWEST NATIONAL LABORATORY/APS/ALAN STONEBRAKER

BREAKING THE LAW! CP VIOLATION

The universe abounds with matter, yet is relatively lacking in antimatter. This disparity must have started early in the cosmos' history because if the ratio of matter to antimatter were exactly equal, they would have completely annihilated each other long ago. That would have left a universe devoid of matter in any form, leaving only energy behind. Yet, billions of years after the Big Bang, the cosmos is still filled with plenty of regular matter.

The thinking goes that some hidden force (and associated field) might explain the matter-antimatter imbalance of the early universe. The axion was originally suggested as a particle emerging from this field by the independent teams of Roberto Peccei and Helen Quinn, and Frank Wilczek and Steven Weinberg. *—R.L.*



Physicists and engineers work to replace the pixel detector of the Large Hadron Collider's Compact Muon Solenoid (CMS) experiment in this image, taken March 7, 2017. More recently, the LHC received new high-luminosity upgrades, giving it a greater chance to spot rare particles like X17. MAXIMILIEN BRICE/CERN

REASONABLE FORCE?

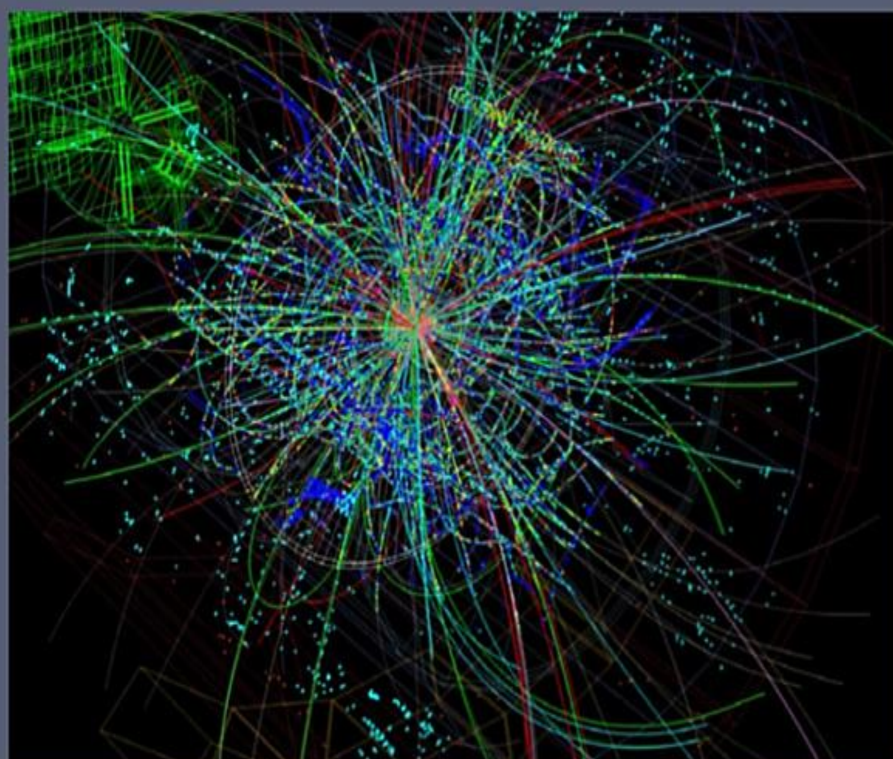
CONNECTING DARK MATTER TO A FIFTH FORCE

Physicists aren't just considering subatomic particles as possible culprits for dark matter. For instance, various versions of MOdified Newtonian Dynamics (MOND) attempt to revise our well-tested theory of gravity to account for dark matter's perceived effects. Perhaps the issue isn't that scientists misunderstand how gravity works, but rather that there exists an unknown fundamental force.

The four known fundamental forces depend on force-carrying particles called bosons. Photons act as the boson for electromagnetism. Gluons are responsible for the strong nuclear force. W and Z bosons serve the weak force. And physicists believe the gravitational force is carried by gravitons, though these particles have yet to be detected.

Gravity doesn't play well with the other known forces, though — at least, not on the tiniest of scales. And some think this could be because we're missing a force altogether. This hypothetical fifth force would also need a force-carrying boson, which is provisionally named X17 and would sit outside the standard model.

In 2003, researchers showed that a particle similar to X17 would weakly communicate forces between dark matter particles in a way that is similar to how photons interact with baryonic matter particles (hypothetically, at least). There is some limited evidence of X17's existence, mainly from observations of the decay of beryllium and helium isotopes made by the NA64 experiment team at CERN's Super Proton Synchrotron (SPS) particle accelerator. Yet the existence of X17, and thus a fifth force of nature, is still far from confirmed. Fortunately, the Large Hadron Collider (LHC) might turn up evidence of X17 when its upgraded LHCb experiment, which seeks another particle called the beauty quark, restarts in 2023. *— R.L.*



Particle tracks are shown here emanating from the first high-energy collision between a proton and a lead ion at the LHC in 2012. By analyzing the plethora of particles produced in such collisions, researchers are continuously working to unravel the many mysteries of the standard model. P. CHARITO/WIKIMEDIA COMMONS supersymmetric WIMPs remain the two candidates that are motivated by non-cosmological arguments," he says, "and they have the virtue that they interact with ordinary particles — and are thus detectable."

Don't leave town

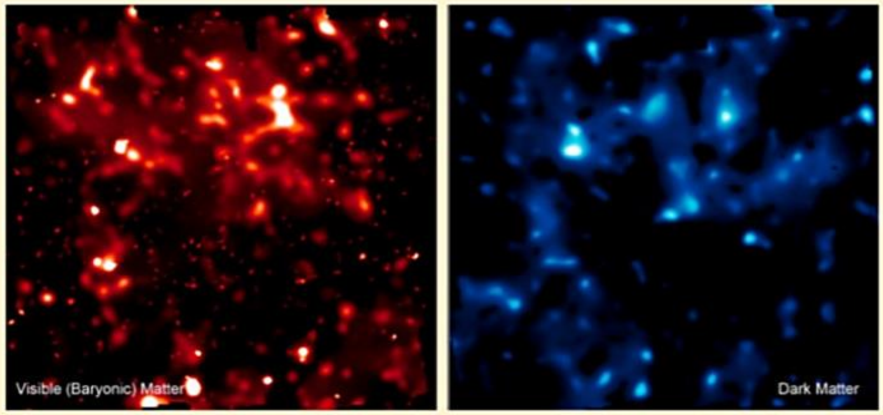
Unlike the current favorites, some former dark matter candidates aren't hypothetical, or even all that strange. But just as detectives release suspects with strong alibis, astronomers and physicists have had to clear multiple particles of interest from any definitive involvement with dark matter.

One example: massive astrophysical compact halo objects, or MACHOs, which include the invisible (to us) remnants of dead stars like some white dwarfs and neutron stars, stellar-mass black holes, and even failed stars like brown dwarfs. These bodies are still composed of regular matter, so although their matter might be exotic by Earth standards, it still interacts with the fundamental forces in predictable ways. The only reason we can't see MACHOs is that their light-producing processes have ceased (or never started in the first place) or are so reduced that we can't detect electromagnetic radiation from them.

Still, MACHOs have largely been ruled out as dark matter because the mass estimated to be locked up in these objects isn't sufficient to account for the strength of dark matter's observed gravitational effects. Thus, if dark matter was actually composed of MACHOs, these objects would need to be much more prevalent than astronomers currently calculate.

Another explanation for dark matter that has fallen out of favor over the years posits that the substance doesn't exist at all. These so-called MOdified Newtonian Dynamics (MOND) theories suggest dark matter is merely a cosmic illusion, a result of our flawed understanding of how gravity works on the grandest scales.

But MOND theories have so far faltered because, while they can account for many dark matter-related phenomena, they can't explain all of dark matter's observed effects. So, even if we were to modify our well-tested theories of gravity, astrophysicists would still be missing a major piece of the dark matter puzzle.



These false-color images captured by the Hubble Space Telescope compare the distribution of normal matter (red) to dark matter (blue) in the universe. The map covers an area of the sky nine times larger than the Full Moon, making it one of the best maps of dark matter ever obtained. NASA/ESA/R. MASSEY

"None of the attempts to [explain dark matter's effects] without dark matter, such as MOND, have succeeded," Primack says. "At best, they explain a small fraction of the observational data." So, for now, MOND and MACHOs seem to be off the hook.

Other alternative explanations for the effects of dark matter include a fifth fundamental force of nature or clusters of tiny primordial black holes left over from the earliest moments of the universe. But, yet again, both of these theories have problems.

As of yet, there is little evidence to suggest a fifth fundamental force of nature. Meanwhile, primordial black holes, which would have been created by gravity fluctuations in the very early universe, sound like promising candidates for dark matter. That's because, like any black hole lacking a glowing accretion disk around it, they don't produce light. Plus, if primordial black holes are as lightweight as some theories predict — holding as little as 1/100,000th the mass of a paperclip — they wouldn't create any of the violent effects that astronomers depend on to catch their more massive counterparts. The main evidence for primordial black holes currently comes from high-pitched gravitational-wave signals picked up by the Laser Interferometer Gravitational-wave Observatory. Yet these signals can also be easily explained by other known phenomena.

Homing in

The dark matter mystery may not yet be solved, but intrepid cosmic sleuths have compiled mug shots of the likely suspects, as well as confirmed alibis for some others. It now seems it's only a matter of time before researchers are able to pin dark matter on the right culprit.

In fact, the net could already be closing. In early 2021, a team from the University of Sussex in the U.K. revealed that they had managed to narrow the potential mass range of dark matter particles to between 10^{-3} and 10^{7} eV. Not only is this a significantly trimmed range, it also rules out both ultralight particles and their supermassive counterparts. The researchers culled this new energy range by considering the effects of quantum gravity. However, quantum gravity is still purely hypothetical, so the newly constrained range needs much more evidential support before it is widely accepted.

There also remains the possibility that the true explanation for dark matter is something scientists haven't yet dreamed up. And in that case, 85 percent of the mass in the universe might remain incomprehensible for years to come.

"The nightmare about dark matter is that it might be a kind of particle that doesn't interact even weakly with ordinary matter, except by gravity," Primack says. And that, he adds, "would make it undetectable." If indeed this turns out to be the case, dark matter just might be committing the perfect cosmic crime.

Robert Lea *is a freelance science journalist based out of Liverpool in the United Kingdom.*