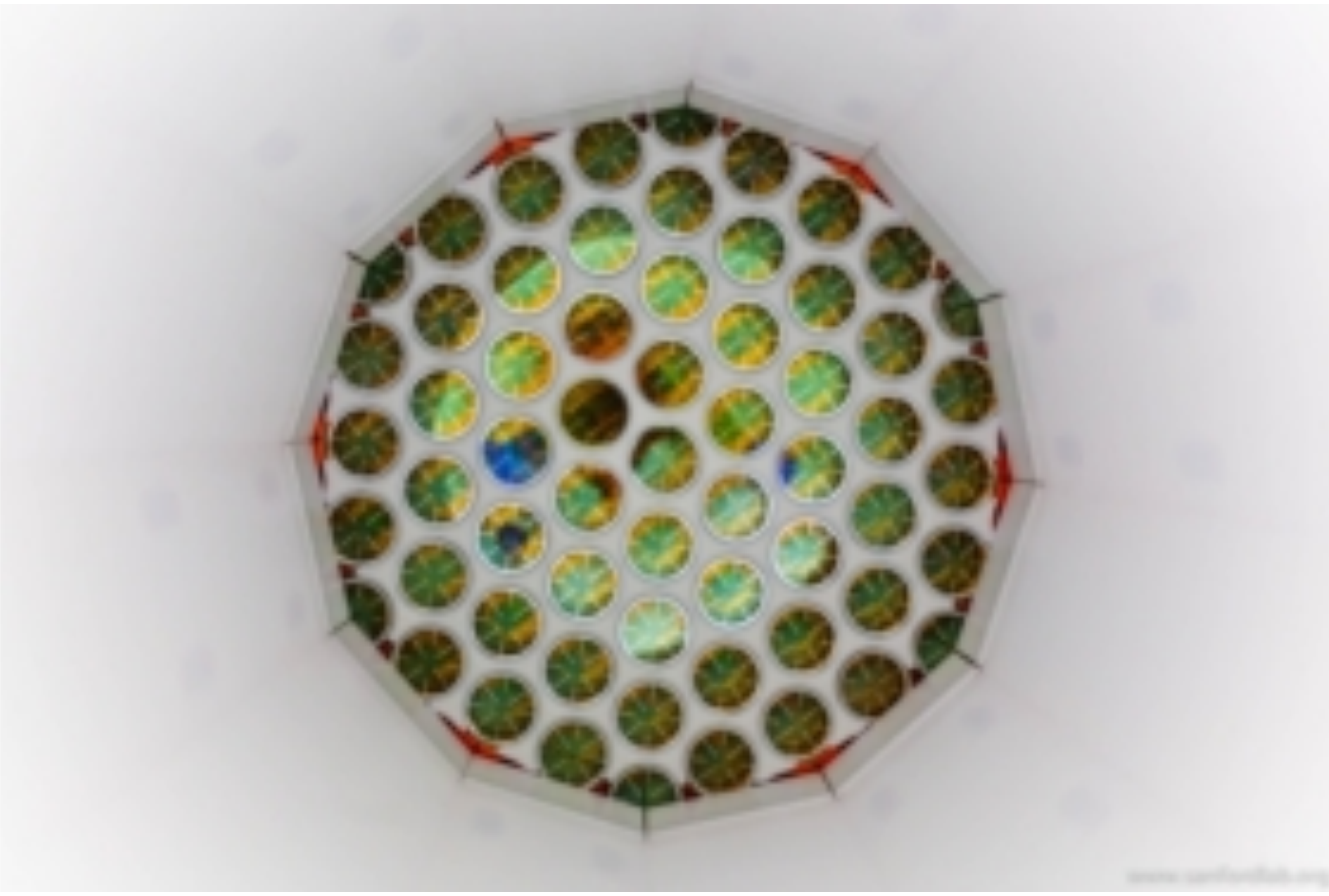
PHYSICS

Physics Confronts Its Heart of Darkness

Cracks are showing in the dominant explanation for dark matter. Is there anything more plausible to replace it?

By Lee Billings on August 31, 2016



Sensors on the Large Underground Xenon dark matter detector can register the emission of just a single photon from a dark matter interaction within the detector's giant xenon tank. So far, however, no signs of dark matter have been seen. *Credit: MATT KAPUST, SANFORD UNDERGROUND RESEARCH FACILITY*

Physics has missed a long-scheduled appointment with its future—again. The latest, most sensitive searches for the particles thought to make up dark matter—the invisible stuff that may comprise 85 percent of the mass in the cosmos—have found nothing. Called WIMPs (weakly interacting massive particles), these subatomic shrinking violets may simply be better at hiding than physicists thought when they first predicted them more than 30 years ago. Alternatively, they may not exist, which would mean that something is woefully amiss in the underpinnings of how we try to make sense of the universe. Many scientists still hold out hope that upgraded versions of the experiments looking for WIMPs will find them but others are taking a second look at conceptions of dark matter long deemed unlikely.

Whatever dark matter is, it is not accounted for in the Standard Model of particle physics, a thoroughly-tested "theory of almost everything" forged in the 1970s that explains all known particles and all known forces other than gravity. Find the identity of dark matter and you illuminate a new path forward to a deeper understanding of the universe—at least, that is what physicists hope

WIMPs would get their gravitational heft from being somewhere between one and a thousand times the mass of a proton. Their sole remaining connection to our familiar world would be through the weak nuclear force, which is stronger than gravity but only active across tiny distances on the scale of atomic nuclei. If they exist, WIMPs should surround us like an invisible fog, their chances of interacting with ordinary matter so remote that one could pass through light-years of elemental lead unscathed.

Undaunted, experimentalists have spent decades devising and operating enough cleverly named WIMP detectors to overflow your average can of alphabet soup. (CDEX, CDMS, CoGeNT, COUPP and CRESST are just the most notable examples that start with the letter C.) The delicate work of detecting any weak, rare and fleeting interactions of WIMPs with atoms requires isolation and solitude, confining most detectors to caverns, abandoned mines and other outlier subterranean spaces.

One of the latest null results in the search for WIMPs came from the Large Underground Xenon (LUX) experiment, a third of a ton of liquid xenon held at a frosty –100 degrees Celsius inside a giant water-filled tank buried one and a half kilometers beneath the Black Hills of South Dakota. There, shielded from most sources of contaminating noise, researchers have spent more than a year's worth of time looking for flashes of light emanating from WIMPs striking xenon nuclei. On July 21 they announced they had seen none.

The next disappointment came on August 5 from the most powerful particle accelerator ever built: CERN's Large Hadron Collider (LHC) near Geneva, Switzerland. In 2012 after it found the Higgs boson—the Standard Model's long-predicted final particle that imbues others with mass—many theorists believed the next blockbuster result from the LHC would be a discovery of how the Higgs (or other hypothesized particles very much like it) helps produce the WIMPs thought to suffuse the cosmos. Since spring 2015 the LHC has been pursuing these ideas by smashing protons together at unprecedentedly high energies at rates of up to a billion per second, pushing into new frontiers of particle physics. Early on, two independent teams had spied a telltale anomaly in the subatomic wreckage, an excess of energy from proton collisions that hinted at new physics perhaps produced by WIMPs (or, to be fair, many additional exotic possibilities). Instead, as the LHC smashed more protons and collected more data, the anomaly fizzled out, indicating it had been a statistical fluke.

Taken together, these two null results are a double-edged sword for dark matter. On one hand, their new constraints on the plausible masses and interactions of WIMPs are priming plans for next-generation detectors that could offer better chances of success. On the other, they have ruled out some of the simplest and most cherished WIMP models, raising fresh fears that the long-postulated particles might be a multidecadal detour in the search for dark matter.

Edward "Rocky" Kolb, a cosmologist now at the University of Chicago who in the 1970s helped lay the foundations for the generations of WIMP hunts to come, declared the 2010s "the decade of the WIMP" but now admits the search has not gone as planned. "We are now more in the dark about dark matter than we were five years ago," he says. So far, Kolb says, most theorists have responded by "letting a thousand WIMPs bloom," creating ever-more baroque and exotic theories to explain how WIMPs have managed to dodge all our detectors.

There is, of course, another possibility—that WIMPs are not the solution to dark matter we should be looking for. "WIMPs emerged as a simple, elegant, compelling explanation for a complex phenomenon," Kolb says. "And for every complex phenomenon there is a simple, elegant, compelling explanation that is wrong."

LOOKING FOR A MIRACLE

Among the WIMP hunters, though, the operating assumption is that they simply have not looked hard enough, says LUX spokesperson Richard Gaitskell. Because of uncertainties over the exact mass and interaction strength of these elusive particles, the WIMP search space spans eight orders of magnitude. If WIMPs are very massive, there may only be one or two within the space of your clenched fist at any given moment; if they are very light, billions must pass through you each second. Creating a detector to encompass that vast range is like designing a net to catch a certain species of fish that can be the size of a red blood cell or of a city or anywhere in between.

Gaitskell and other WIMP hunters are betting that bigger detectors will yield better results, and have plans for a new generation of experiments with dramatically larger sizes and sensitivities. "I started looking 28 years ago using a 10-gram detector," Gaitskell says. "Today we're using a detector that is a third of a ton of liquid xenon. And within the next 10 to 15 years we will look with detectors that are 100 tons."

In the absence of actual empirical evidence for WIMPs, a single, very persuasive theoretical argument that they must exist has sustained the years of steady investment in searches for them. Physicists call it "the WIMP miracle." The miracle stands on two speculative legs.

The first leg stretches back all the way to the first instants of cosmic time. Straightforward extrapolation of the Standard Model to that primordial epoch suggests that WIMPs should have been produced in enormous numbers in the dense, hot plasma that filled the universe immediately after the big bang. Most of the WIMPs would collide with and annihilate one another at relativistic speeds, producing ordinary particles as a result. This process would weaken as the universe expanded and cooled, leaving a “relic” population of cold, slow WIMPs behind. Plug in the known strength of the weak force, which mediates this process, and you can calculate how many relic WIMPs should exist today. The answer—about five times more WIMPs than ordinary matter—aligns with dark matter’s observed abundance.

The miracle’s second leg links WIMPs to the modern-day mass of the Higgs boson. Measured at the LHC to be more than 130 times heavier than the proton, the Higgs is one of the most massive particles known. Yet the tenets of quantum mechanics suggest the Higgs mass should be unstable, interacting with known particles to grow trillions of times higher. Unless, that is, its runaway growth is somehow being canceled out by new, yet-to-be-discovered massive fundamental particles. Such particles are a signature prediction of supersymmetry, a popular extension of the Standard Model that fills in theoretical gaps by positing each particle has an accompanying “superpartner.” Many supersymmetry theories predict the lightest superpartner would be a stable, neutral, weakly interacting particle—that is, a WIMP. This is the phantom particle the LHC has been seeking—and failing to find—in its latest collisions. “It’s remarkable how these two entirely separate lines of evidence converge to tell you these particles can exist and give you the right kind and amount of dark matter,” says Neal Weiner, a dark matter theorist at New York University. “That’s the WIMP miracle.”

In recent years, however, theorists have suggested WIMPs are not as miraculous as they seem. In 2008 Jonathan Feng and Jason Kumar, both then at the University of California, Irvine, showed how supersymmetry could also produce a hypothetical class of particles much lighter and more weakly interacting than WIMPs. “These particles result in the same amount of dark matter we see today but they aren’t WIMPs,” Feng says. “This upsets the apple cart because it is just as well motivated theoretically. We call it the WIMPless miracle.”

The decaying theoretical underpinnings for simple WIMP models, paired with the ever-growing list of empty-handed detection efforts, have led Feng and many others to propose that WIMPs are part of a much more complicated picture: An entirely new hidden realm of the universe filled with multiple varieties of dark particles interacting with one another through a suite of dark forces, perhaps exchanging dark charges via bursts of dark light. Because they offer theorists many more variables to play with, such "dark sector" models can be reconciled to fit into the ever-tighter straitjacket of facts placed on dark matter by new data.

The downside is that this sprawling flexibility makes them very difficult to conclusively test. "With the dark sector, you're free to invent almost whatever you want," says David Spergel, an astrophysicist at Princeton University. "Now that we have lost the guidance from the WIMP miracle, the space of available models is huge. It's a playground where we don't know what the right choices are—we now need more hints from nature about where to go next."

The situation may be that we have only scratched the surface of the full diversity of particles and forces in nature—only focusing on quarks, photons and the like because they are so familiar and accessible to us. In which case we would be "like a drunk who only looks for his lost keys under lampposts because that's where all the light is," Weiner says. "There are scenarios we simply cannot test with our current technology. On the other hand, if you are creative, maybe you can make new lampposts."

DARK HORSES

Of all the other lampposts now known, few if any tick all the right boxes for theorists. Like WIMPs, some of these alternative dark matter candidates also have compelling theoretical underpinnings. Their relative obscurity, some experts say, is partly due to the fact that they are not as phenomenologically rich as the WIMP hypothesis, offering fewer enticing signals and interesting questions for experimentalists and theorists to seek and study.

Last year a team of researchers won a Nobel Prize for discovering that ghostly, weakly interacting particles called neutrinos come in three "flavors" and possess mass. The three neutrino varieties are not massive enough to account for dark matter, but by virtue of having mass at all they open the possibility for the existence of a fourth—a massive, so-called "sterile neutrino."

“Almost all neutrino mass-generation mechanisms require the existence of sterile neutrinos, and it would be very easy for some of these sterile neutrinos to account for the dark matter,” says Kevork Abazajian, a theorist at U.C. Irvine. But no search for sterile neutrinos has ever found them, including the most sensitive ever performed, reported in late August from a team using the IceCube Neutrino Observatory in Antarctica.

Another perennial dark horse candidate for dark matter is the axion, a hypothetical weakly interacting particle first postulated in 1977 to explain and resolve otherwise mysterious asymmetries in quantum interactions. For axions to explain dark matter, they would need to occupy a relatively narrow range of masses and be far lighter than WIMPs, potentially making them even harder to detect. “If we don’t find the WIMP, theorists will just switch their bets to axions,” says Peter Graham, a physicist at Stanford University who studies axions and other dark matter candidates.

Beyond WIMPs and dark sectors, sterile neutrinos and axions, there are even more exotic possibilities for dark matter, although they occupy the fringes of physics.

Black holes that might have been created shortly after the big bang could constitute the universe’s hidden mass, but they would have to exist in such abundance that we would likely have already discovered them through other means. Even so, our searches for such “primordial” black holes have not yet been thorough enough to entirely rule them out as the source of dark matter. Alternatively, dark matter could be the hyperspatial footprint of particles zipping through a hidden, neighboring dimension—except no convincing evidence of extra dimensions has emerged at the LHC or any other accelerator.

Most jarringly, dark matter could be largely illusory, indicative of a flaw in our understanding of gravity via Einstein’s theory of general relativity. Various theories of “modified gravity” that suggest the force weakens under certain circumstances can explain some dark matter observations—particularly the dynamics of galaxies—but struggle to account for dark matter–attributed details astronomers see in galaxy clusters and in the big bang’s afterglow.

But, as with the preference for WIMPs over axions and sterile neutrinos, some physicists suspect the widespread distaste for modified gravity is at least partially due to the sociology of scientists rather than the scientific process itself. “Modified gravity isn’t ‘pretty’ in the eyes of particle physicists,” says Sabine Hossenfelder, a theorist at the Frankfurt Institute for Advanced Studies in Germany. “Inventing new particles is what particle physicists do for a living; of course that’s what they prefer.”

Whatever their preferred candidate might be, the biggest concern for many physicists grappling with dark matter is not that the concept will eventually be seen as somehow invalid or entirely mistaken—the observational evidence for dark matter’s existence is overwhelming. Instead they worry that dark matter’s identity might simply prove to be irrelevant to other great mysteries in physics and thus offer no new paths toward understanding the true nature of reality.

“The desire is for dark matter to not only exist but also to solve other outstanding problems of the Standard Model,” says Jesse Thaler, a physicist at Massachusetts Institute of Technology. “Not every new discovery can be a revelation like the Higgs, where afterward theories suddenly fit together much better. Sometimes new particles just make you say, ‘Who ordered that?’ Do we live in a universe where each discovery leads to deeper, more fundamental insights or do we live in one where some parts have rhyme and reason but others don’t? Dark matter offers either possibility.”