NEWS FEATURE

Lighting the way for dark matter

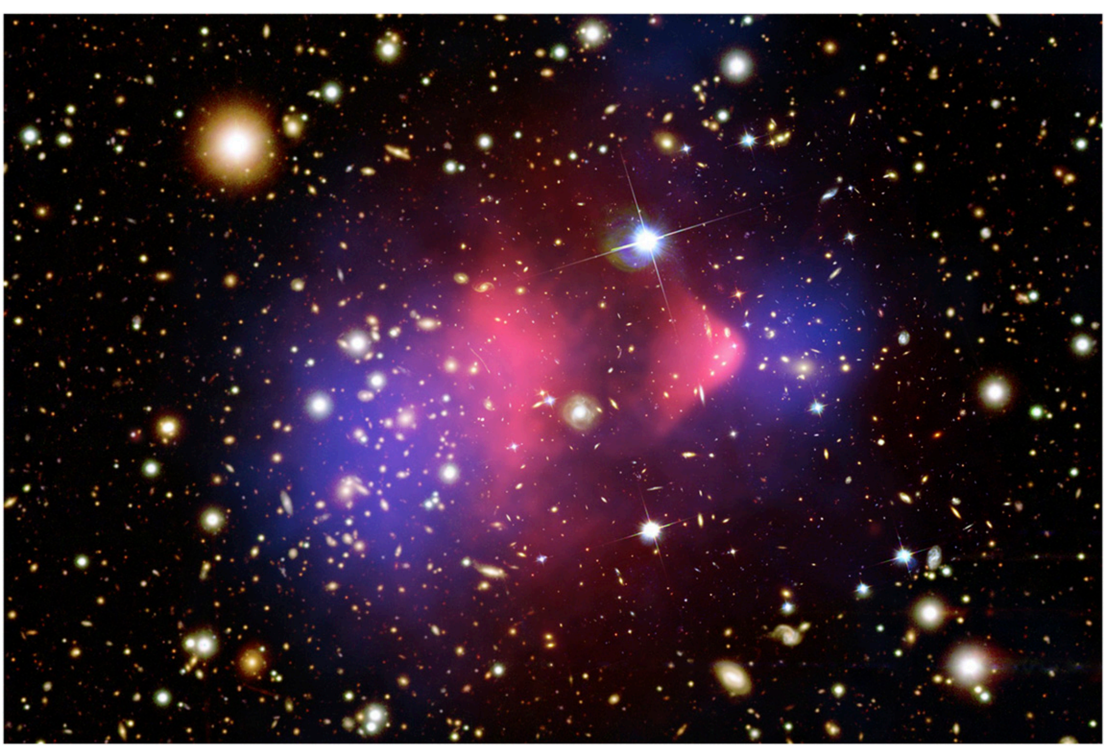
A nagging lack of evidence for weakly interacting massive particles has spurred physicists to start searching for a range of lightweight dark particles and even new dark forces.

Adam Mann, *Science Writer*

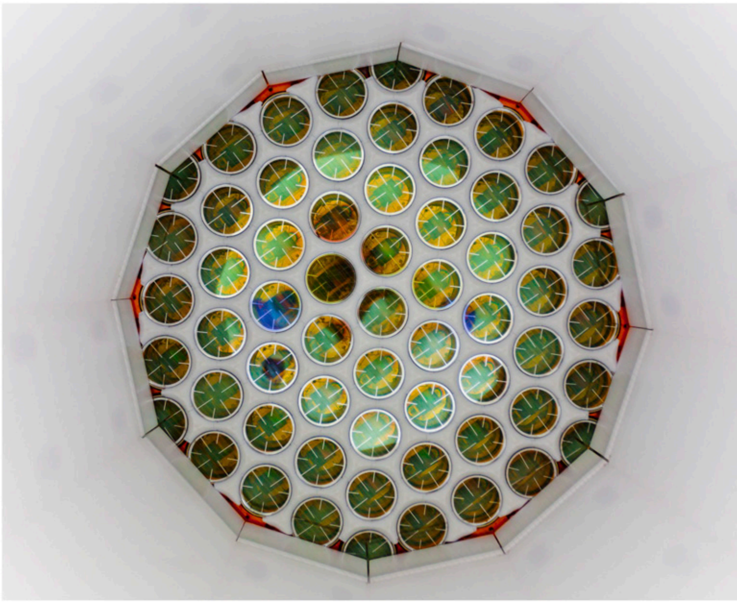
In 2015 a team of nuclear physicists in Hungary reported an anomalous bump in the signal from radioactive decays of unstable beryllium-8, corresponding to a putative new particle with 34 times the mass of an electron (1). It was largely overlooked at the time, but a year later US theorists suggested that this might point to a new force felt by dark matter, hinting that the mysterious substance is more complex than previously believed (2). Ideas about dark matter are evolving.

Since the late 1990s most researchers have posited that dark matter is probably made of weakly interacting massive particles (WIMPs): ghostly hypothetical objects that would pass through normal matter like light through a glass window. Entities with perfectly WIMP-like properties happen to appear in supersymmetry, a popular theory extending the Standard Model, the current framework describing the interactions of all known particles and forces. But experiments searching for these WIMPs have so far turned up empty, and the Large Hadron Collider has failed to reveal any signs of supersymmetry.

Although supersymmetric WIMPs remain the most-favored candidate for dark matter, their nonappearance has led some scientists to begin doubting their existence and explore numerous new models. A few physicists are turning to another kind of particle, an ultralight entity known as the axion. Others suggest that there might be many distinct dark matter particles, each with unique properties, which could combine into dark atoms and dark molecules and emit dark photons. "This generalization from a particle to a



Using observations of gravitational lensing of galaxies, astronomers have mapped out dark matter in the Bullet Cluster, which is formed by two enormous colliding clusters of galaxies. Composite image courtesy of NASA/CXC/M. Weiss.



The LUX experiment, its light sensor shown here, searches for a type of dark matter known as a WIMP. But WIMPs have failed to turn up in recent years, leading physicists to consider alternative dark matter models. Image courtesy of Matt Kapust/Sanford Underground Research Facility.

sector, which has particles and forces in it, has really opened up the floodgates," says particle physicist Jonathan Feng of the University of California, Irvine.

New technology is creating ways to find these elusive entities. In March 2017 physicists attending a workshop at the University of Maryland, College Park listed more than 100 ideas for such experiments (3). Some are already running; others should begin taking data in the next few years.

Birth of Darkness

Dark matter is known to exist because of its gravitational effects—stars in the outer reaches of galaxies seem to be moving faster than they should, given the visible material present, as if they were being tugged by some huge unseen mass. In the late 1970s a few researchers realized that as-yet-undiscovered stable particles could have been created in the fiery conditions after the Big Bang, which would account for this enigma (4). Around the same time, theorists developed the idea of supersymmetry and realized that the lightest supersymmetric particle, known as a neutralino, happened to be an ideal fit.

In the particle soup of the early universe, neutralinos would have constantly collided with and annihilated one another, producing decay products that include ordinary matter. At first the process would also run in reverse, with ordinary matter particles crashing and creating dark matter. But then as the universe expanded and cooled, ordinary matter particles would have had too little energy to create heavy neutralinos. The neutralinos meanwhile would continue to meet and annihilate. But if the neutralinos have a low probability of finding each other, they could remain in large numbers today.

Dark matter is currently thought to outweigh ordinary matter in the universe by a ratio of five to one. Using this value, theorists could ask themselves what the rate of interaction of neutralinos would have been in the early universe. By adding in the neutralino's proposed mass, which is between 50 and a few thousand times that of a proton, the calculations showed that a particle interacting through only the weak force, and not electromagnetism or the strong force, would exactly produce the current dark matter density—a coincidence known as the WIMP miracle.

Following this revelation, researchers began to invent clever ways to look for the prospective particle. They seized on the possibility of a chance encounter: although a neutralino should typically sail right through ordinary matter without leaving a trace, there is always some extremely tiny probability that it will interact with an atom via the weak force.

Beginning in the 1980s experimentalists built dark matter detection devices and placed them deep underground to protect them from interfering cosmic radiation in the hopes that a neutralino or other similar WIMP-like particle would eventually run into one of the particles in their detector, producing a measurable recoil signal.

Coming Up Empty

Recoil detection works best if the target nucleus and the projectile have roughly the same mass, so many of the world's leading dark matter direct-detection experiments use xenon, which has 131 times the mass of a proton. In January 2017 the Large Underground Xenon (LUX) collaboration, whose experiment ran at the Sanford Underground Research Facility in South Dakota, released its final results (5). They showed no dark matter collisions. Researchers working on the XENON 1-Ton (XENON1T) project in Gran Sasso National Laboratory near L'Aquila, Italy, the largest dark matter experiment of its kind, unveiled their latest data analysis on May 18, 2017, placing even more sensitive constraints on how readily WIMPs interact with regular matter (6). The Particle and Astrophysical Xenon Detector team at the China Jinping Underground Laboratory in Sichuan, China, presented findings from their second-generation detector at a conference in August 2017 (7). Again, they saw nothing.

Perhaps, some suggest, these researchers have not been looking in the right place. Between 2008 and 2011, results from a few direct-detection experiments seemed to suggest the existence of dark matter particles between 1 and 10 times a proton's mass, below the threshold where xenon-based devices would see them. Since then, many of these results have been discounted. But this was a wake-up call to many physicists: might dark matter particles be a little lighter than originally thought? If such particles interacted with normal matter using the weak force, they would have already shown up in accelerator experiments not specifically designed to look for them. So theorists began to wonder if perhaps dark matter was even further removed from our ordinary world of protons, neutrons, and electrons than previously suspected.

Into the Dark Sector

Astronomers meanwhile have shown that dwarf galaxies seem to have puffy halos of dark matter, rather unlike the dense dark matter cores predicted from cosmological simulations assuming ordinary WIMP dark matter. This puffiness could happen if the invisible substance can interact with itself, using forces like ordinary gas molecules—prompting some theorists to suggest that dark matter could be combining into nuclear states like normal atoms and molecules. Perhaps it lives in a world with its own bevy of particles and forces almost entirely tangential to the universe we inhabit: what particle physicists call a hidden sector.

If we have any hope of discovering this dark sector, these new forces must have some interaction with ordinary matter. A few researchers think they've already seen hints of such interactions in a short-lived particle called the muon, whose magnetic moment does not entirely line up with predictions from the Standard Model; a dark sector force could account for this discrepancy (8). Forces are carried by particles, and the particle carrying this presumed force would act much like the force-carrier of electromagnetism, the photon, but have a mass between several and a few hundred times that of an electron. It has been dubbed the dark photon.

Physicists at Jefferson National Laboratory have been hunting for these since 2010, when the A′ Experiment began slamming a high-intensity beam of electrons into a thin tungsten target hoping to produce a few dark photons. Other projects at Jefferson, searching at different energy ranges, include the Heavy Photon Search, which first ran in 2015, and the DarkLight experiment, which fires its electrons at a hydrogen gas target and took some initial data this year. DarkLight will also be able to look into the Hungarian beryllium result—which is in the right mass range but would be an especially weird version of a dark photon, needing to interact with neutrons but not protons to explain the data thus far. Because of this contrivance, some physicists remain skeptical that what the Hungarians saw is truly a new force. Additional information should be forthcoming in 2018, when the electron beam at Jefferson is upgraded and DarkLight is able to investigate the anomaly further.

Although most dark matter proposals have focused on relatively heavy particles, some theorists are exploring the possibility that it is actually extremely light. A major puzzle in modern physics has to do with the neutron. Being neutral, it has no interaction with electric fields. But curiously, it reacts to magnetic fields, almost like a little compass needle. Why should the neutron interact with only one component of the electromagnetic force? In 1977 physicists Roberto Peccei and Helen Quinn proposed that a hidden mechanism tunes down the neutron's interactions with electric fields (9). Shortly thereafter, other theorists realized that this mechanism gave rise to a particle they called the axion.

The Lighter Side

Axions would be neutral, ghostly, and extremely light, less than a millionth or even a billionth the mass of an electron. With such low masses, they would be produced at much higher densities in the early universe. Every cubic centimeter of the cosmos would be packed with axions. This would make axions behave less like particles and more like a field, and if the axions' energy field oscillates just around zero, it would produce the gravitational effects necessary to be dark matter. "Here's a particle that people thought ought to exist anyway, and it just happened to solve dark matter," says physicist Gray Rybka of the University of Washington in Seattle. "It killed two birds with one stone, and so it's really worth looking for."

Should an individual axion happen to run into a xenon-based dark matter direct-detection experiment, it would barely budge the ordinary atoms, "kind of like a spit wad hitting a train," says physicist Jeffrey Hutchinson of Florida Gulf Coast University in Fort Myers. So most axion-hunting experiments take advantage of the putative particle's lightweight nature. According to quantum mechanics, all particles behave like waves, vibrating with a frequency that depends on their mass. The axion's uncertain mass could correspond to a frequency anywhere from 250 hertz up to 2.5 terahertz.

The longest-running of these axion hunts is the Axion Dark Matter Experiment (ADMX) at the University of Washington, which consists of a metallic cavity placed inside a powerful magnet and cooled to 4.2 Kelvin. Axions vibrating at the resonant frequency of the chamber can be converted into detectable microwave photons. As ADMX runs, rods move within the cavity to change its effective size and scan through different potential axion masses, like a listener tuning through radio stations.

"Here's a particle that people thought ought to exist anyway, and it just happened to solve dark matter."

—Gray Rybka

ADMX finally hit the sensitivity necessary to detect likely axion masses in January 2017. The collaboration expects to examine some of the most-favored axion mass ranges, between 500 megahertz and 10 gigahertz, over the next five or six years and is researching technology that can search even higher frequencies.

But the axion might be too light for ADMX, so other projects are now getting off the ground. The Dark Matter Radio consists of an electric circuit surrounded by a superconducting shield that blocks ordinary electromagnetic waves but would produce a measurable voltage if an axion penetrated it. A pathfinder version of this experiment began taking data in August 2017. Perusing a similar low mass range is the A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus experiment, which generates an immense magnetic field in hopes of detecting the signature of an axion—namely a tiny wavering in the field. Another pathfinder experiment under construction is the Cosmic Axion Spin Precession Experiment (CASPEr), which will use nuclear MRI technology to search for an oscillating electric charge inside the neutron to try to tease out the axion. CASPEr will be sensitive to axion masses far below the other detectors, all the way down to around 200 Hz.

WIMPs Still in Play

The supersymmetric WIMP is not out of the running yet, and most of the dark matter community remains focused on xenon-based detectors. XENON1T's most recent data analysis was from only its first 34 days. "Now we are really starting to look into new territory where somebody has never probed," says physicist Elena Aprile of Columbia University in New York City, who leads the project. "We are all very hopeful, and we will keep exploring uncharted waters."

Both Aprile's collaboration and the LUX team are working on next-generation devices, which will be an order of magnitude larger and far more sensitive than the current generation. Aprile says it will be at least another five years before WIMPs would be ruled out—and they might show up at any point before that.

Physicists keep pushing to discover dark matter in as many ways as they can imagine. Data from old particle accelerator experiments are being reanalyzed to look for anomalies, and many particle accelerators are being retrofitted to search for dark photons. Research and development have proliferated on technology that could detect lightweight dark matter particles. Upcoming experiments include the Sub Electron Noise Skipper-CCD Experimental Instrument and Dark Matter in CCDs project, which would search for dark matter slamming into silicon-charged coupling devices, and the Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield program, which would use a graphene detector. Researchers are also developing devices utilizing electrons, crystalline germanium, and superfluid helium and many other direct-detection methods.

As long as dark matter's influence can be seen in the universe, it will remain a tantalizing target for experiments. "It's really one of the deepest mysteries in particle physics, and we have so many good ideas for how to detect it," says particle physicist Jesse Thaler of the Massachusetts Institute of Technology in Cambridge. "If human ingenuity has anything to say about it, there will be an excellent chance of detection, hopefully in my lifetime."

1 Krasznahorkay AJ, et al. (2016) Observation of anomalous internal pair creation in ^{8}Be: A possible indication of a light, neutral boson. *Phys Rev Lett* 116:042501–042506.

2 Feng JL, et al. (2016) Protophobic fifth-force interpretation of the observed anomaly in ^{8}Be nuclear transitions. *Phys Rev Lett* 117:071803–071809.

3 Battagleri M (2017) US cosmic visions: New ideas in dark matter 2017: Community report. arXiv:1707.04591v1.

4 Lee BW, Weinberg S (1977) Cosmological lower bound on heavy neutrino masses. *Phys Rev Lett* 39:165–168.

5 Akerib DS, et al.; LUX Collaboration (2017) Results from a search for dark matter in the complete LUX exposure. *Phys Rev Lett* 118:021303–021311.

6 Aprile E, et al. (2017) First dark matter search results from the XENON1T experiment. arXiv:1705.06655v2.

7 Ji X (2017) New world-leading upper limits for spin independent WIMP-nucleon cross section from PandaX. Available at https://pandax.sjtu.edu.cn/node/300. Accessed August 18, 2017.

8 Bennett GW, et al.; Muon (g - 2) Collaboration (2004) Measurement of the negative muon anomalous magnetic moment to 0.7 ppm. *Phys Rev Lett* 92:161802–161807.

9 Peccei RD, Quinn HR (1977) CP conservation in the presence of pseudoparticles. *Phys Rev Lett* 38:1440–1443.