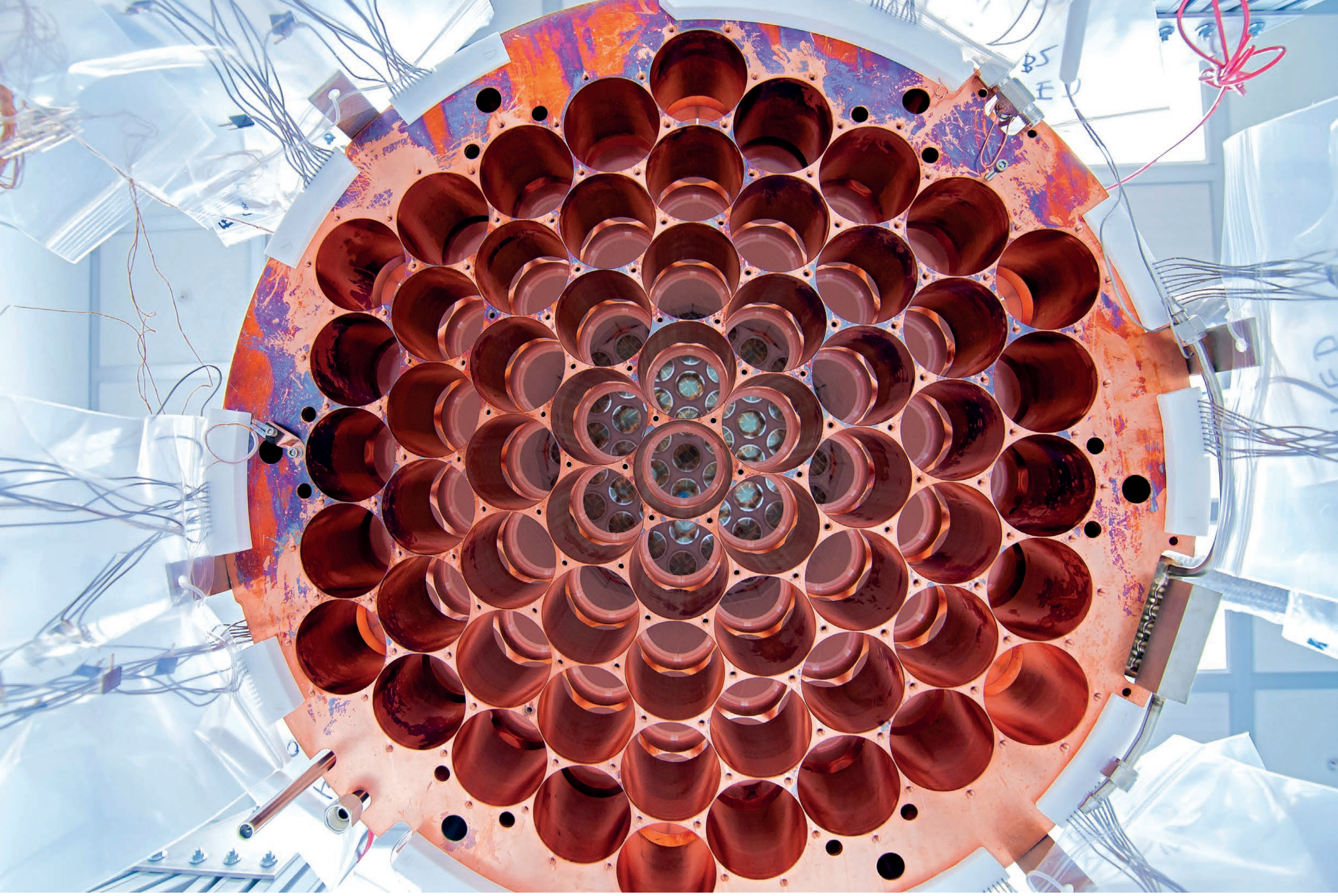


The structure used to hold the photomultiplier tubes that detect flashes of light from particle collisions in the LUX dark-matter experiment.

C. FAHAM, BROWN ASTROPARTICLE PHYSICS GROUP

WHAT'S THE MATTER?

BY JEFF HECHT

The leading theory of dark matter is running out of room to hide.

Most of the Universe is missing. The motion of the stars and galaxies allows astronomers to weigh it, and when they do, they see a major discrepancy in cosmological accounting. For every gram of ordinary matter that emits and absorbs light, the Universe contains around five grams of matter that responds to gravity, but is invisible to light. Physicists call this stuff dark matter, and as the search to identify it is now in its fourth decade, things are starting to get a little desperate.

In late January, physicists at Johns Hopkins University in Baltimore, Maryland, sat down to discuss the rumours that the Laser Interferometer Gravitational-Wave Observatory (LIGO), a pair of ground-based, 4-kilometre-long instruments, had spotted the merger of two black holes of around 30 solar masses. These rumours were later confirmed as the first detection of gravitational waves, a phenomenon predicted by Albert Einstein that had escaped detection for 100 years (see page S200). But their lunchtime chat quickly turned to a different mystery — dark matter. Because the collapse of a single star normally can't make such heavy black holes, they wondered if the merging objects might be leftovers from the Big Bang. If so, could the very early Universe have produced lots of similarly sized primordial black holes? And could these black holes be the dark matter that holds galaxies together?

"When you don't know what something is, you have to consider everything," says Simeon Bird, one of the physicists at Johns Hopkins. The numbers looked good. The mass of the black holes was within a range that earlier searches for dark matter had not ruled out, and the time it took LIGO to spot the event was compatible with the merger rate that scientists had predicted. In May, Bird and his colleagues turned their discussion into a paper[1], and the theory sparked a frenzy of media coverage around the world.

The idea soon received a boost. In June, it was suggested that primordial black holes could also explain the uneven distribution of infrared light in the cosmic background[2]. By August, a team led by astrophysicist Misao Sasaki of Kyoto University in Japan largely corroborated Bird's theory, but suggested that such black holes might account for only a fraction of dark matter[3].

Astrophysicist Timothy Brandt thinks that he has found a fatal flaw with Bird's theory. Brandt, who is at the Institute for Advanced Study in Princeton, New Jersey, looked at the motion of stars within ten well-studied dwarf galaxies close to the Milky Way[4]. The movements of the few stars that are visible reveal the presence of around 100 times more matter than can be seen. But when Brandt looked closer, he found that the stars are moving too slowly, and are concentrated too tightly, for the invisible mass to be in the form of 30-solar-mass black holes. Stars in a galaxy exchange energy as they pass each other; massive stars or black holes transfer energy to smaller stars, speeding their orbits and spreading the stars out. But in these galaxies, that wasn't happening. "Either they aren't sharing energy, or there aren't these massive black holes hanging around," Brandt says.

It looks unlikely that primordial black holes are the mysterious dark matter. And as time passes without a confirmed detection, even the most heavily backed theories are beginning to look less likely. A series of experiments have systematically searched for, and failed to find, the theoretical candidates for dark matter — one by one, the possibilities are being reduced. A raft of experiments designed to finally detect, or refute, the remaining candidates are now underway, each with vastly different approaches to the problem. As more options are crossed off the list, physicists may have to explore new ideas and reconsider alternative theories such as Bird's — or accept that nature may have hidden dark matter just out of our reach.

DARK-MATTER MYSTERY

The idea of dark matter dates back to the 1930s, when Swiss astrophysicist Fritz Zwicky came to the conclusion that there was too little visible matter in the Coma cluster to account for the motion of the 1,000 or so galaxies within it. Astronomers shrugged off Zwicky's theory for decades, but in 1970, US astronomer Vera Rubin began to publish exhaustive measurements of galactic spectra that showed that the cosmos was in effect keeping two sets of books — a substantial amount of mass was missing. By 1980, Rubin and others had shown that the electromagnetic spectrum revealed about one-sixth of the matter that shaped galaxies by its gravitational force[5]. But what was everything else?

Decades of research have narrowed down the possibilities. Early favourites included not only black holes, but also other massive compact halo objects (MACHOs) made of ordinary matter. A series of studies, however, gradually ruled out most of the possibilities. For example, researchers determined that black holes between about one-thousand billionth and one-billionth the mass of the Sun would destroy neutron stars. The presence of neutron stars in ancient globular clusters therefore suggests that primordial black holes of this size are extremely rare and could not account for all the dark matter in the Universe. Bird's theory was based on the fact that no one had yet ruled out larger black holes. But in the view of theoretical physicist John Ellis of King's College London, "MACHOs are dead."

Although MACHOs have fallen by the wayside, another candidate has hung around. A decade ago, physicists were largely convinced that dark matter was made up of weakly interacting massive particles (WIMPs). These are subatomic particles that have mass, but lack a charge (so they respond to gravity, but not to light or electromagnetism). WIMPs are predicted by a theory called supersymmetry. This is an extension of the standard model of particle physics devised to fix some inconsistencies with observed physics. It posits that symmetry between two fundamental classes of particle — bosons, such as photons and the Higgs boson, and fermions, such as protons and electrons — produces 'superpartners' in the other class that differ in mass, but are otherwise similar.

WIMPs remain the leading candidate for dark matter. "Supersymmetry is beautiful mathematically," says physicist Oliver Buchmueller of Imperial College London. "With just one weakly interacting particle, we can explain all the dark matter we see in the Universe." Indeed, so well does the lightest of these hypothetical particles fit the bill for dark matter that it has been called "the WIMP miracle", says physicist Leslie Rosenberg of the University of Washington in Seattle.

With a mass of about one trillion electronvolts, the lightest supersymmetric particle (LSP) is thought to be about eight times more massive than the Higgs particle. LSPs are also anticipated to be their own antiparticle, meaning that if two LSPs meet they will annihilate each other, releasing a burst of photons that may offer a way to spot them in the Universe.

But supersymmetrical particles have proved maddeningly elusive. Physicists at CERN, Europe's particle-physics laboratory, are searching for WIMPs with the Large Hadron Collider (LHC) by smashing protons or atomic nuclei together to recreate the conditions of the early Universe. Elsewhere, researchers are looking for signs of the particles bumping into sensitive detectors or affecting astronomical objects. The longer the puzzle goes unsolved, the more twitchy the scientific community will become. "People are a little nervous," says Rosenberg.

COLLISION COURSE

The LHC's brute-force approach to the WIMP search recreates the high-energy Universe as far back as a few trillionths of a second after the Big Bang. "It's a bit of time travel," says Buchmueller. These experiments require extreme precision and perseverance. After recent upgrades, the LHC typically spends 3 to 5 hours loading the machine with particles and accelerating them to very high energies, and then the next 24 hours smashing them into each other. This cycle repeats for months, and the trillions of collisions are recorded and analysed in the hope that one hit will be just right to create the missing particle.

It's an approach that has chalked up one enormous success: the capture of the Higgs boson was reported in 2012 after a half-century quest. If dark matter is a particle, the LHC should produce it, says Buchmueller. "The question is, can we dig it out?"

Researchers won't see dark matter directly. Instead, they look for signs that energy and momentum in collisions have gone missing when they should have been conserved. Ellis compares searching for evidence of dark matter to watching billiard balls roll away after the cue ball hits them on the break shot. If the balls on one side of the group were invisible, and only the balls rolling away on the opposite side could be seen, the path and nature of the unseen balls can still be deduced, he says. Physicists are using the paths of the particles they can see to identify the paths of the dark matter that they can't.

> "THE UNIVERSE MAY BE UNKIND. IT MAY BE THAT DARK MATTER IS VERY LIGHT OR VERY HEAVY."

But as yet, they haven't found any. In 2015, LHC experiments produced hints of a 750-gigaelectronvolt (GeV) boson, about six times the mass of the Higgs particle, but, in August, these were revealed to be nothing more than a statistical fluctuation. There has been no sign of supersymmetric particles or dark matter at masses up to 1,600 GeV, where physicists had expected to find them. Ellis says that the ongoing 2016 run should yield much more data and give a better indication of whether the expected dark-matter particles really exist. So far, none have been reported.

Dark matter lacks a charge, and so doesn't respond to electromagnetic force. The only way to directly detect the particles is if they bump into atoms of ordinary matter. But because dark matter seems to be very tiny, and the atoms that make up the world are mainly empty space, most of it zips through unscathed.

A detection like this seems like a long shot, then. But so much dark matter exists that, every once in a while, a particle should hit an atomic nucleus head-on and cause a detectable reaction. Several groups have built instruments to spot these bumps, which transfer just kiloelectronvolts (keV) of energy from dark matter to an atomic nucleus. That's the kinetic energy of a particle travelling at only about 0.1% of the speed of light. But such collisions are "incredibly rare events", says Ellis.

Physicists picked the most sensitive target materials that they could find, those with nuclei most likely to react in a detectable way to a dark-matter collision. These targets, such as xenon and sodium iodide, are cooled to close to absolute zero to make it easier to spot the small amounts of energy transferred from dark to ordinary matter. Detectors were initially small (grams monitored for a day) to test their feasibility, but were scaled up (a tonne observed for a year) to increase sensitivity. Burying the detectors deep underground helped to keep potential interference, from cosmic rays and nuclear decay, for example, from overwhelming dark-matter signals (see ‘Dark-matter detection’). But time and again, searches found nothing except background noise. Each experiment excluded a range of possible masses and collisional cross-sections. They showed no trace of the LSP predicted by the simple versions of supersymmetry that had seemed so promising as the WIMP miracle (see ‘Hide and seek’).

In July, researchers working with the world’s most sensitive dark-matter instrument reported that it, too, had come up dry in its final run. The LUX (Large Underground Xenon) experiment ran for 20 months, monitoring 370 kilograms of liquid xenon cooled to millikelvin temperatures at the 1.5-km-deep Sanford Underground Research Facility in South Dakota. It found not a single WIMP. But the LUX group aren’t giving up. “There’s more space left for WIMPs than you might think,” says Simon Fiorucci, a physicist at the Lawrence Berkeley Laboratory in California who works on LUX. The latest run improved LUX’s sensitivity by a factor of four, helping to rule out more possible masses for dark matter.

To explore the remaining range of masses that are accessible to experiments, the LUX team is assembling an upgrade: LUX–ZEPLIN. The experiment, which uses seven tonnes of liquid xenon, should be taking data by 2020. Fiorucci is optimistic about the quest. “I see WIMPs as quite viable,” he says. But others are not as confident, and that includes project sponsors at funding agencies, Rosenberg notes.

HARD EVIDENCE

The wild card in the search for dark matter is a project based in Italy called DAMA (for DArk MAtter). The team has claimed to have detected dark matter consistently since the late 1990s. “They’re seeing something,” says Fiorucci, but the big question is what. Like many others, he is not convinced that it’s dark matter.

DAMA has taken a unique approach. Instead of trying to eliminate background noise so that it can record individual collisions, the observatory counts everything and looks for annual variations in the signal level from highly purified sodium iodide crystals located 1.5 km beneath Italy’s Gran Sasso mountain. The team’s hypothesis is that, when Earth’s orbit lines up with that of the Sun, Earth sweeps through a larger volume of space per second than when it moves in the opposite direction. The observatory, therefore, should encounter more dark matter when the orbits line up than it does half a year later. DAMA has recorded this annual peak at the same time through 14 annual cycles, says physicist Rita Bernabei of the University of Rome.

But the champagne corks are yet to pop. DAMA’s results are inconsistent with those of instruments that have used other elements, such as xenon. And a perceived sense of secrecy around the project has added to the difficulty of replication. Most researchers think that DAMA is detecting something other than dark matter, although Bernabei says that no one has offered an alternative for the pattern.

To resolve the discrepancy, Frank Calaprice, a physicist at Princeton University in New Jersey, is putting the DAMA results to the acid test. “I take their signal very seriously,” he says. His project, called Sodium-iodide with Active Background Rejection (SABRE), will use a sodium-iodide detector similar to DAMA’s. But by improving sodium-iodide purity and using an external radiation detector to reject background events unrelated to dark matter, Calaprice hopes to reduce noise to one-tenth of that of the DAMA experiment. The system, also at Gran Sasso, will start taking data in 2017 with a pair of 5-kg crystals, and scale up to 50 kg of sodium iodide over time. To test whether the annual DAMA signal is due to dark matter, a second, 50-kg SABRE array is being built in a new underground lab in a gold mine in Victoria, Australia. If dark matter is responsible for the annual signal, it will appear at the same time in both the Northern and Southern hemispheres. If the annual variation differs between the two labs, it would indicate another cause, such as atmospheric effects. “I’m open-minded, not trying to prove them wrong or right,” Calaprice says. “I’m just trying to do a good experiment.”

B. WANKERL/MPP

View from a Lindau Young Scientist

“We’re excluding so much parameter space that I sometimes feel dark-matter detection must be right around the corner. I’m trying to test models of sterile neutrinos as dark matter. Sterile neutrinos would be the heavier, right-handed counterparts to the active neutrinos we have detected. There have been some hints of them in X-ray satellite data, but the situation is as yet unclear.”

Maximilian Totzauer, PhD student at the Max Planck Institute for Physics in Munich, Germany attended the 66th Lindau Nobel Laureate Meeting.

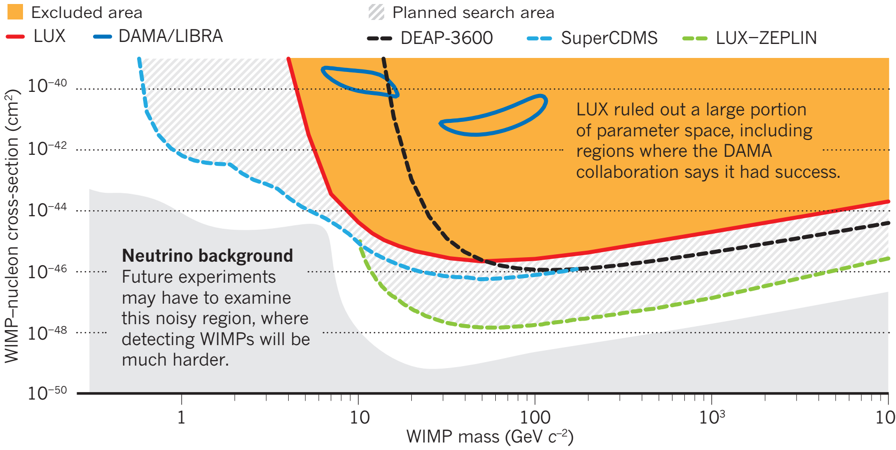
Calaprice isn’t alone in his efforts. As part of an experiment called COSINE-100, researchers are planning to conduct a similar test using 100 kg of highly purified sodium iodide. The project is a collaboration between the Korea Invisible Mass Search (KIMS) and DM-Ice groups. KIMS installed the detectors 700 metres underground at the Yangyang laboratory in South Korea this summer. Operation will start in the autumn, and will allow researchers to make “a pretty strong statement about DAMA”, says Francis Halzen of the University of Wisconsin, principle investigator for the IceCube Neutrino Observatory (see page S198). IceCube’s South Pole base is also home to the DM-Ice group, which is currently waiting to install 250 kg of sodium iodide detectors of its own. “The experiment doesn’t cost much, but it relies on drilling new holes in the ice,” says Halzen. A date for the drilling has yet to be confirmed.

WIDER POSSIBILITIES

Although WIMPs are still the leading candidates for dark matter, explanations that are more of a long shot are being dusted off. The lightest ‘wrap’ particles in Kaluza–Klein theories, for instance, could be dark-matter candidates, if they are stable. Proposed in the 1920s, the theories posit that higher-order dimensions curve around themselves to look tiny. Such theories “are given less attention than the lightest supersymmetric particle, but

HIDE AND SEEK

The size range for a weakly interacting massive particle (WIMP) becomes narrower with every unsuccessful experiment. These experiments search ‘parameter space’ — dark-matter mass against the probability of dark matter interacting with ordinary matter. LUX (Large Underground Xenon) has ruled out a large area. If detectors DEAP-3600 and SuperCDMS at SNOLAB in Canada, and the LUX–ZEPLIN detector in South Dakota, also fail to find dark matter, the room for WIMPs to hide will be even narrower.



LUX ruled out a large portion of parameter space, including regions where the DAMA collaboration says it had success.

Neutrino background
Future experiments may have to examine this noisy region, where detecting WIMPs will be much harder.

SOURCE: DM TOOLS

are definitely out there", says Ellis.

One of the strongest alternative explanations is that dark matter is a class of theoretical particle called axions. Like WIMPs, these were proposed to solve a problem with the standard model. The theory suggests that fundamental particles called quarks have a hidden axial symmetry. Like supersymmetry, axions would, in Rosenberg's words, solve the "flaws in the standard model, not too badly wrong, that keep theorists up at night".

Rosenberg views low-mass axions as ideal dark-matter candidates. Extremely long-lived, very cold and highly unlikely to bump into other matter, their lack of charge would make them nearly invisible to normal matter and radiation. Fiorucci says that they are "the only other explanation for dark matter" that is consistent with what is well understood about particle and nuclear physics.

But like supersymmetric particles, axions have yet to be found. Experiments so far have limited axion masses to between 1 and 100 microelectronvolts — around 16 orders of magnitude less than the Higgs mass. As part of the Axion Dark Matter Experiment, Rosenberg is attempting to detect axions by trapping them inside a cavity that oscillates at microwave frequencies and contains an intense magnetic field. The experiment's US$1.5-million annual funding is mostly provided by the US Department of Energy. After four years of preparation, construction and preliminary testing, the experiment is set to begin operation in July 2017. It will run until 2021, which should cover most of the mass range that has yet to be searched. But even if axions are not detected, that wouldn't prove that they don't exist, only that we can't see them.

The concern that dark matter may simply be undetectable is a genuine one. "The Universe could be unkind," says Fiorucci. "It may well be that dark matter is either very light or very heavy, or its density is too low where the Earth is." It might be hidden by noise or overlooked for another reason, much like dwarf galaxies were until recently. "We are never guaranteed a positive result," he says.

But Buchmueller recommends patience. After 20 years working on WIMPs, supersymmetry and dark matter, he has no doubts about the course of research. "The Higgs boson was postulated in 1964 and discovered in 2012," he says. "I am not really surprised it has taken us 30 years and we haven't seen anything yet. It may take another 20. Right now, it would be premature to give up." ■

Jeff Hecht *is a science writer based in Auburndale, Massachusetts.*

1. Bird, S. *et al. Phys. Rev. Lett.* **116,** 201301 (2016).
2. Kashlinsky, A. *Astro. J. Lett.* **823,** L25 (2016).
3. Sasaki, M., Suyama, T., Tanaka, T. & Yokoyama, S. *Phys. Rev. Lett.* **117,** 061101 (2016).
4. Brandt, T. D. *Astrophys. J. Lett.* **824,** L31 (2016).
5. Rubin, V. C., Ford, W. K. Jr & Thonnard, N. *Astrophys. J.* **238,** 471–487 (1980).

ARTHUR MCDONALD

Dark-matter detection

When it comes to detecting dark matter, neutrinos will eventually get in the way. Arthur McDonald, director of the Sudbury Neutrino Observatory in Ontario, who won the 2015 Nobel Prize in Physics for his part in the discovery of neutrino oscillations, explains why.


QUEEN'S UNIV./PHOTO BY BERNARD CLARK

When astrophysicists look out on a dark night, they see that the outer stars of galaxies are moving too fast — the gravitational attraction of all the matter we can see glowing within galaxies is not enough to hold the stars in their trajectories. We think that there are particles in the dark spaces, we just don't know what they are.

There are two schools of thought on dark matter. One is that it is embodied in a theoretical particle called an axion. For a short while, I was involved in the CERN Axion Solar Telescope (CAST) experiment, which used a prototype magnet for the Large Hadron Collider to look for axions that might have been produced in the Sun's core. None have been seen, but the experiment has explored a significant range of parameters where axions could exist.

The second line of thinking is that dark matter is weakly interacting massive particles (WIMPs), perhaps predicted by a proposed extension of the standard model of particle physics called supersymmetry. Direct detection of WIMPs involves looking for their occasional collisions with ordinary matter.

I'm now working on the DEAP-3600 experiment at SNOLAB in Sudbury, Ontario. We're trying to detect WIMP collisions with 3,600 kilograms of liquid argon. When noble gases are excited, they give off a flash of light that we can watch for. But it's not just dark-matter particles that cause argon to scintillate like this, so we have to minimize interference. Fortunately, at two kilometres below Earth's surface, SNOLAB is one of the deepest underground laboratories in the world; cosmic rays are almost entirely prevented from reaching our detector and causing a spurious signal.

We can also use the properties of liquid argon to discriminate between the radioactive background and the type of event that would arise from a WIMP hitting an argon nucleus. If a collision occurs, the argon nucleus would recoil and give a signal that lasts around ten nanoseconds. Other kinds of ionization event typically last 10 microseconds — 1,000 times longer. So by simply recording how long the light from one of these interactions can be seen, you're able to distinguish a real dark-matter signal.

DEAP-3600 will eventually be several times more sensitive than the LUX (Large Underground Xenon) experiment in the Black Hills of South Dakota, which uses liquid xenon. It's quite conceivable to increase sensitivity another 10 or 100 times with argon or xenon in future experiments. But once you improve sensitivity by a factor of 100 or so, you start to encounter events caused by neutrinos striking your detector. Neutrinos pass straight through Earth, so you can't avoid them simply by digging deeper underground. It's especially problematic when looking for low-mass WIMPs — at masses below about 10 gigaelectronvolts, neutrinos from the Sun reduce the maximum sensitivity you can reach by a factor of at least 1,000. It's funny really: the same things that were the object of our SNO experiment 15 years ago are going to get in the way.

Looking for seasonal variation, the method used by a dark-matter project in Italy called DAMA does get around the neutrino background problem. But the DAMA approach is fraught with controversy as to whether the signal is really coming from dark matter. A more conclusive technique would be to look at the directionality of an event, because we have some idea of the direction in which we interact with dark matter. But that may require a gaseous detector, and a detector with 100,000 kg of gas is going to be orders of magnitude bigger than one with 100,000 kg of liquid. Simply excavating the enormous cavities required at depths of at least several kilometres is going to be extremely difficult.

There is a detection experiment coming to SNOLAB that we're very enthusiastic about. It's called SuperCDMS, and, when it starts operation around 2020, it will be about as sensitive as you can get in the 10 GeV mass region before solar neutrinos begin to interfere. With SuperCDMS going almost to the limit of sensitivity in search of low-mass particles, and the DEAP experiment looking for particles with masses greater than 10 GeV, it's a very satisfying situation for the laboratory to be in. ■

INTERVIEW BY RICHARD HODSON