THE HUNTING OF THE DARK

The race to detect dark matter has yielded mostly confusion. But the larger, more sensitive detectors being built could change that picture soon.

BY ADAM MANN

For a substance that is utterly invisible, dark matter does a remarkably good job of making its presence felt. Astronomers have been compiling evidence for it since the 1930s, tracing how it shapes galaxies, galaxy clusters and even bigger cosmic structures by the inexorable force of its gravity. Although its real nature is unknown, dark matter seems to outweigh the ordinary matter visible in stars and galaxies by roughly 5.5 to 1.

Down here on Earth, however, physicists struggling to answer the 'what is it?' question often feel like they're chasing a ghost. Certainly, their detectors have been giving them a lot of strange and contradictory results. Two experiments are independently seeing what seems to be a flux of dark matter streaming through their apparatus. Another detector may have seen a handful of dark-matter particles last year — although the experimenters dismiss them as background noise. And yet another experiment has found no evidence for dark matter at all.

Fortunately, this confusion is likely to be temporary. Dark-matter detectors are roughly 1,000 times more sensitive to ultra-rare events than they were 20 years ago, and that should increase by another factor of 100 over the next decade, as physicists build bigger detectors and become more skilled at suppressing the background noise than can be confused with genuine signals (See 'Dark-matter detectors'). "It would not be surprising if a year from now someone stood up and said we have done it, we've detected dark matter," says Sean Carroll, a theoretical physicist at the California Institute of Technology in Pasadena. Other physicists give a more cautious estimate of five to ten years. Nonetheless, there is a palpable sense that the field is on the verge of something big.

Most of the attempts to detect dark matter directly have started from the assumption that the stuff is a haze of weakly interacting, massive particles (WIMPs) left over from the Big Bang. The 'massive' part would explain the gravity. And the 'weakly interacting' part would explain the invisibility: the WIMPs would flow through stars, planets and people in untold numbers, almost never hitting anything.

X-rays (pink) reveal ordinary matter in a galaxy cluster, and gravitational lensing of background galaxies (blue) maps dark matter.

That assumption dictates the basic detection strategy: bring together a large target mass of material; put it deep underground to shield it from cosmic rays and other radiation that could produce misleading signals; then measure the recoil energy when a dark-matter particle finally hits an ordinary nucleus. The larger the mass of material, the more likely it is that a dark-matter particle will hit something.

Beyond those basics, setting up such an experiment requires a certain amount of guesswork. To have a significant recoil effect, for example, researchers need a target nucleus of roughly the same mass as the dark-matter particle they are seeking. It's like watching for an invisible pool ball, says Jonathan Feng, a particle physicist at the University of California, Irvine. If the target nucleus is the equivalent of a bowling ball, the impact will barely move it. If, on the other hand, the target is the equivalent of a ping-pong ball, it will hardly be capable of deflecting the dark-matter particle, and so again there will be little energy transferred. What you want is another pool ball, Feng says.

SUPERSYMMETRICAL WIMPS

Several dark-matter experiments have placed their bets on supersymmetry: a theory in which each particle in the standard model of physics would have a heavier, and so far unobserved, partner[1]. Supersymmetry predicts the existence of a WIMP called a neutralino, which would have exactly the right properties to account for the dark-matter distribution seen in the Universe. Its interactions would be feeble enough, yet its mass would be substantial — fifty to a few thousand times the mass of a proton.

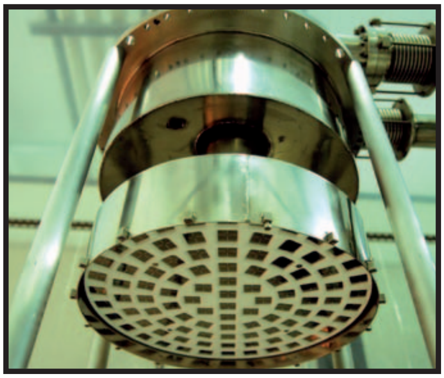
One of the most highly regarded of the neutralino detection efforts is the XENON Dark Matter Search Experiment, located in the underground portion of the Gran Sasso National Laboratory near L'Aquila, Italy, and operated by a consortium of US and European universities. As its name suggests, the experiment's detection medium is a tank of liquid xenon, which has a mass of just over 131 atomic mass units — close to ideal for detecting WIMPs at the lighter end of the supersymmetry range, which is by far the easiest place to start the search.

Photomultiplier tubes lining the inside of the XENON tank look for the characteristic flash of light called scintillation that would be generated if a xenon atom had recoiled from the impact of a WIMP. The XENON collaboration's first detector, built in 2006, used around

X-RAY: NASA/CXC/CFA/M. MARKEVITCH *ET AL.*; OPTICAL: NASA/STSCI; MAGELLAN/UNIV. ARIZONA/D. CLOWE *ET AL.*; LENSING MAP: NASA/STSCI; ESO WFI; MAGELLAN/UNIV. ARIZONA/D. CLOWE *ET AL.*

DARK-MATTER DETECTORS

Today's dark-matter detectors are 1,000 times more sensitive than their predecessors. The detectors coming on line will have bigger targets, making them even more sensitive.



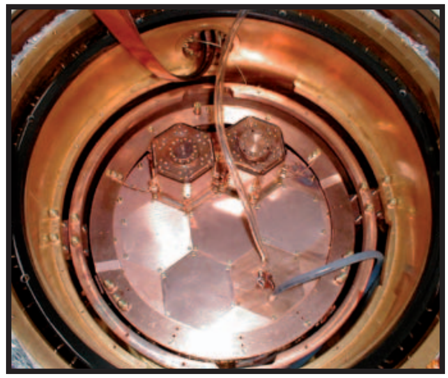
XENON100 COLLABORATION; DAMA/LIBRA COLLABORATION

XENON100

LOCATION: Gran Sasso, Italy
TARGET: 161 kg liquid xenon
MASS RANGE: 10–100 GeV
START DATE: 2009
FINDINGS: No detections

DAMA/LIBRA

LOCATION: Gran Sasso, Italy
TARGET: 250 kg sodium iodide crystal
MASS RANGE: Light dark matter
START DATE: 2008
FINDINGS: Annual oscillations



CDMS COLLABORATION, FERMILAB

CDMSII

LOCATION: Soudan, Minnesota
TARGET: 230 g germanium, 105 g silicon crystals
MASS RANGE: 10–100 GeV
START DATE: 2004
FINDINGS: Two detections. Background noise?

15 kilograms of xenon and found nothing that could not be attributed to background radiation. The team then upgraded to a bigger, more sensitive, 161-kilogram version in 2009, dubbed XENON100.

Although an initial 11-day data run on this detector still failed to find any particles[2], that result was significant in itself: WIMPs with a mass of less than 100 gigaelectronvolts (GeV) should have shown up, says Laura Baudis, the physicist who leads the XENON group at the University of Zurich, Switzerland. Because they didn't, those lower masses could be ruled out. Unfortunately, the results from a subsequent, 100-day run remain obscure: the researchers are still struggling to deal with unexpectedly high levels of background radiation caused by trace contaminants in the xenon[3].

PURE AND SIMPLE

An experiment searching a similar mass range is the Cryogenic Dark Matter Search (CDMS) in the disused Soudan mine in northern Minnesota. As a detection medium, the CDMS team uses a collection of germanium and silicon crystals, which are among the only solid elements that can be made with high enough purity to be usable for detecting dark matter. When the detector is operating, these crystals — which are about 10 centimetres across — are cooled to a temperature of just 40 millikelvin, so any heat associated with a WIMP impact can be detected.

Now running its second-generation experiment, called CDMSII, the collaboration generated some excitement early last year when it reported two detections that could be interpreted as dark-matter signals[4]. Despite the hubbub, the team is reserved. "We don't claim this is significant; we see a lot of events at this low threshold and most of them are plausibly background," says Jeffrey Filippini, who works on the CDMS team from the California Institute of Technology. If those two events are discounted, the CDMS team gets much the same result as the XENON collaboration: null findings that effectively rule out low-mass WIMPs.

Yet the XENON and CDMS results contradict those from other experiments, the operators of which claim to have detected the very low-mass WIMPs ruled out by the first two. Perhaps the most intriguing, and most controversial, of these experiments is the Dark Matter Large Sodium Iodide Bulk for Rare Processes (DAMA/LIBRA), which shares space with XENON at Gran Sasso. DAMA works on the principle that the Sun's orbit around the centre of the Galaxy carries the Solar System through the invisible cosmic background of dark matter at some 220 kilometres per second. So detectors on Earth should have dark matter flowing through them at that velocity, modulated by an annual variation of 30 kilometres per second as the planet orbits the Sun.

The DAMA team, which looks for the scintillation of recoil events inside sodium iodide crystals, claims to have followed just such a periodic dark-matter signal for thirteen years[5]. However, the crystals cannot distinguish between WIMPs and background events from ordinary radiation in the detector's surroundings, so this result depends on the assumption that background events occur at a constant rate that does not vary with the season. If that result is valid, it flies in the face of the XENON and CDMS findings.

"If the main signal was as big as they claim, we and other teams would have seen it," says Leo Stodolsky of the Max Planck Institute for Physics in Munich, Germany, who works on a collaboration called the Cryogenic Rare Event Search with Superconducting Thermometers (CRESST), also at Gran Sasso. Voicing a scepticism shared by many non-DAMA physicists, Stodolsky says that any number of seasonal processes could release subatomic particles that would mimic DAMA's results for dark matter, including something as simple as snow melting and refreezing in the mountains above the lab.

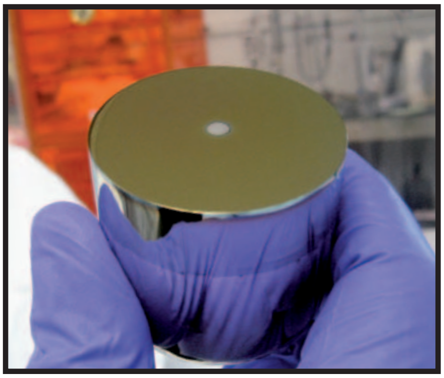
Further eroding DAMA's position is that no other dark-matter experiment is looking for a periodic signal, so its results cannot be directly replicated. Yet, despite the criticisms, the DAMA signal gets stronger each year. "DAMA has been very courageous," says Juan Collar, a physicist at the University of Chicago in Illinois. "They went out and made a claim" when most other physicists were still inclined to dismiss their results as background noise.

Collar leads an effort called Coherent Germanium Neutrino Technology (CoGeNT), whose detector sits near the CDMSII in the Soudan mine. CoGeNT uses germanium crystals tuned to detect incoming particles with much lower masses than those sought by its neighbour. It was originally intended to explore this range to rule out the existence of low-mass WIMPs, but its results only ended up making things murkier.

Around the time that the CDMSII reported its 'nearly nothing' findings, CoGeNT released data from its first 56 days of operations[6]. The results showed hundreds of particle events that could be interpreted as dark matter with a mass between 7 and 11 GeV.

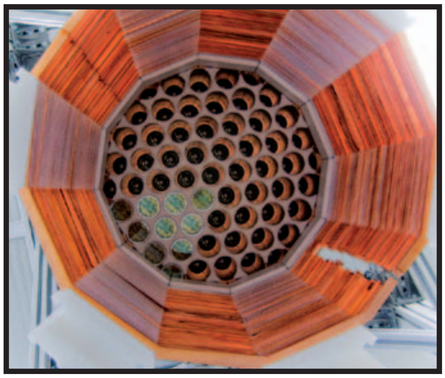
These could also be the same particles that DAMA is detecting, but physicists have been quick to offer a more sober reading. "For CoGeNT,

COGENT COLLABORATION



CoGeNT

LOCATION: Soudan, Minnesota
TARGET: 500 g germanium crystal
MASS RANGE: <10 GeV
START DATE: 2004
FINDINGS: Hundreds of detections



LUX

LOCATION: Homestake, South Dakota
TARGET: 350 kg liquid xenon
MASS RANGE: 10–100 GeV
START DATE: 2011
FINDINGS: Not yet started

XMASS

LOCATION: Kamioka, Japan
TARGET: 1,000 kg liquid xenon
MASS RANGE: 10–100 GeV
START DATE: 2011
FINDINGS: Not yet started

LUX COLLABORATION; KAMIOKA OBSERVATORY, ICRR, UNIV. TOKYO

the signal and the background could easily be mistaken for the same thing," says David Kaplan, a physicist at Johns Hopkins University in Baltimore, Maryland. The team has decided to wait a full year after its initial publication, to see if its findings show the same seasonal fluctuation as DAMA, before announcing any new results.

TOTAL ANNIHILATION

Meanwhile, a debate has broken out over another way to detect dark matter. One of the many oddities of dark-matter particles is that they can be their own antiparticles: put enough of them in one place, and they should start annihilating one another, producing γ-rays in the process. In particular, the centre of the Milky Way should be producing excess γ-radiation because dark matter is expected to concentrate there, says Dan Hooper, an astronomer at the Fermi National Accelerator Laboratory located near Batavia, Illinois. And Hooper claims to have found evidence for these γ-ray excesses in data from NASA's Fermi Gamma-ray Space Telescope[7].

"If you were to ask what kind of a signal you would want to see with dark matter in the galactic centre, this would be what you expect," says Neal Weiner, a theoretical physicist at New York University. The results are consistent with a dark-matter particle of 7.3–9.3 GeV, a range that fits well with the findings from both CoGeNT and DAMA.

> "BEFORE YOU BELIEVE THAT YOU HAVE DARK-MATTER ANNIHILATION, YOU HAVE TO RULE OUT ALL THE OPTIONS."

Other researchers remain sceptical. "The galactic centre is so complicated that before you believe that you have dark-matter annihilation, you have to rule out all the options," says Doug Finkbeiner, an astronomer at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. Finkbeiner points out that the signal could come from undetected pulsars — rapidly rotating neutron stars that produce copious amounts of high-energy radiation.

Still, Hooper's results have given researchers food for thought. "It's a case of too many coincidences," says Collar. When findings from three detectors all start to point towards dark-matter particles of similar mass, he says, "you start to wonder if they're not coincidences any more".

Such thinking has led theorists such as Feng to take a fresh look at all the results to see whether they can come up with a coherent idea of what dark matter might be. If CoGeNT and DAMA are right, says Feng, then they are not detecting the expected dark-matter particle, the neutralino, as it should not be as light and interact as strongly as the results indicate. So perhaps dark matter is some very different particle — or perhaps the model of a single WIMP is not correct.

"If you look at the few per cent of the Universe that comprises us, it's quite complex," says Philip Schuster, a physicist at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, referring to the known 'particle zoo' predicted by the standard model that includes such oddities as muons, neutrinos and quarks. "It's a little insane to believe that the other 85% of the Universe would be so simple," he says.

Along with his collaborators, Schuster is working to find evidence for a more complex theory of dark matter, called the 'dark sector'. This sector could include multiple types of dark matter and a number of dark forces, which, like ordinary matter, could combine to form dark atoms. It is being tested in an experiment called the A Prime Experiment (APEX), at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, which will accelerate a high-energy beam of electrons and search for relatively heavy force-carrying particles radiating from them. "It might tell us that the Universe is a lot broader than we suspect," says Natalia Toro, a physicist who works at the Perimeter Institute and with Schuster on APEX.

The good news is that both the XENON100 and CoGeNT collaborations are expected to release their first full year's worth of data this year. And larger, more sensitive detectors, such as the Large Underground Xenon (LUX) and Xenon neutrino Mass (XMASS) detectors, are scheduled to start operations not long afterwards. "While we are in a 'he said, she said' situation now, it won't be like that indefinitely," says Weiner. "We will have enough information to settle this in the next couple of years." ■

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