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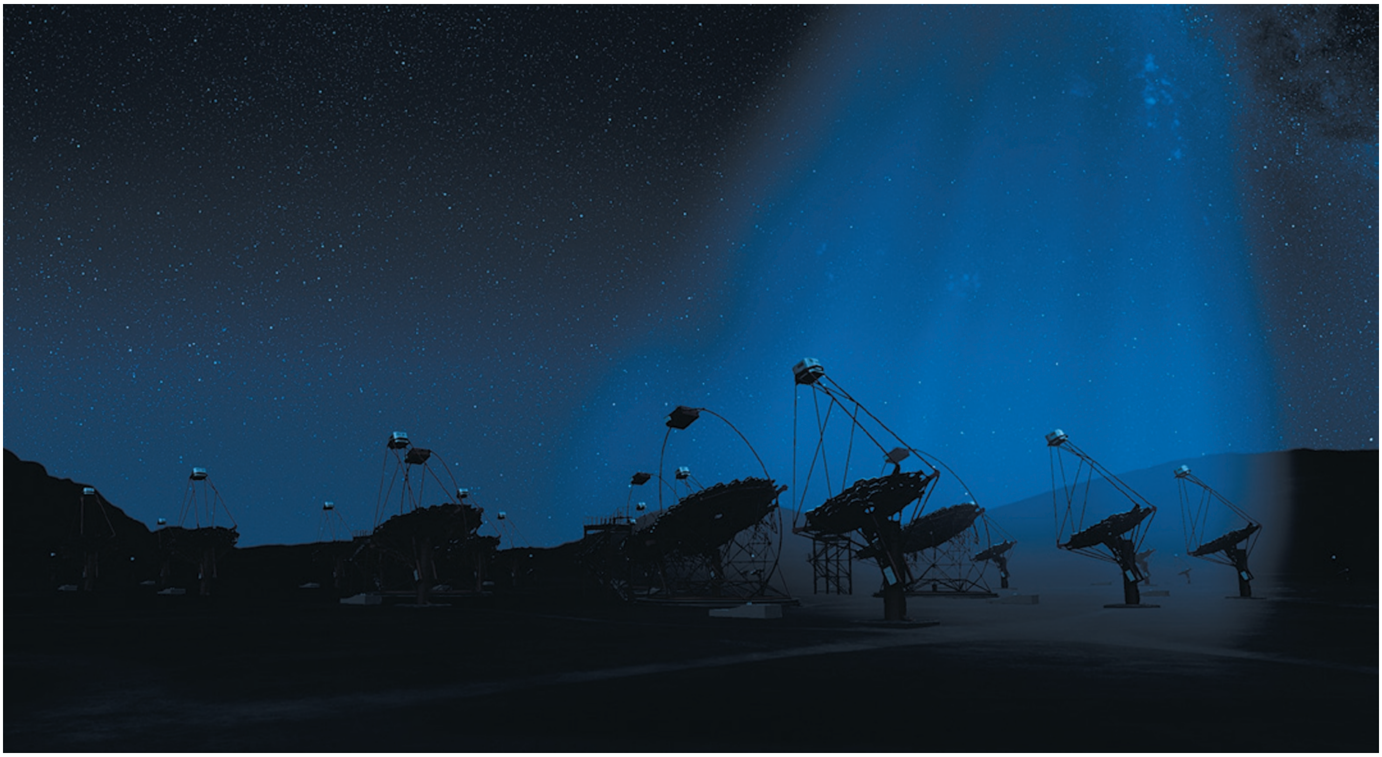


DESY/MILDE SCIENCE COMM/EXOZET

The proposed Cherenkov Telescope Array (artist's impression) might detect light flashes from γ-rays produced when dark-matter particles interact.

Broaden the search for dark matter

Bold strategies are needed to identify the elusive particles that should make up most of the Universe's mass, say **Mario Livio** and **Joe Silk**.

Dark matter is living up to its name. In spite of decades of compelling evidence from astronomical observations showing the existence of matter that neither emits nor absorbs electromagnetic radiation, all attempts to detect dark matter's constituents have failed.

The presence of dark matter is inferred from its gravitational effects. Stars and gas clouds in galaxies and galaxies in clusters move faster than can be explained by the pull of visible matter alone. Light from distant objects may be distorted by the gravity of intervening dark material. The pattern of large-scale structures across the Universe is largely dictated by dark matter. In fact, about 85% of the Universe's mass is dark, accounting for about one-quarter of the total cosmic energy budget.

Despite its ubiquity, the nature of dark matter eludes us. Negative results have flowed from searches for candidate particles to explain it. In 2013, the Large Underground Xenon (LUX) experiment — the most sensitive detector of its kind — in the Homestake Mine in Lead, South Dakota, reported no signs of dark matter in its first three months of operation[1]. The Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, has found no evidence for the existence of what some think are the most likely culprits: supersymmetric particles, theoretically predicted partners to the known elementary particles.

Is there light at the end of this dark tunnel? Possibly — but only if searches become bolder and broader. More varied particle types should be sought. Definitive tests need to be devised to rule out some classes of ▸

dark matter and some theories. If dark matter remains undiscovered in the next decade, then physicists will have to seriously reconsider alternative theories of gravity.

EXOTIC PARTICLES

We know a little about dark matter[2]. Because it does not absorb light or interact with electromagnetic waves, the majority of it cannot be made of baryons — particles of ordinary matter, including protons and neutrons, which are composed of three quarks. And dark matter must lie beyond the standard model of particle physics to avoid upsetting Big Bang nucleosynthesis, the theory of which successfully predicts the observed abundances of light elements such as deuterium, helium and lithium arising from interactions in the early Universe.

The main constituents are expected to be weakly interacting massive particles (WIMPs)[3]. These particles have masses a few tens to thousands of times that of the proton. WIMPs interact among themselves and with ordinary matter gravitationally and through the weak force, but not electromagnetically or through the strong nuclear force. To explain the way in which galaxies form and cluster, dark-matter particles should be relatively slow moving, or 'cold'. If they were faster, and could move easily beyond the dimensions of a protogalaxy, many structures visible today would have been washed out.

What kind of particles might WIMPs be? Many physicists guess the most likely candidates are the lightest of the supersymmetric (SUSY) particles. Theories of the early Universe contain mathematical symmetries that allow for each known particle, such as the electron, photon or quark, to have a (yet undiscovered) massive partner. Just after the Big Bang, almost all of the heavy SUSY particles decayed or annihilated one another — but the lightest SUSY particles, unable to decay any further, were stable and survived.

The number of SUSY particles remaining depends on their masses and interaction strengths, which can be predicted from theory. The properties must be just right for the relic particle density to match that needed to explain the observed effects of dark matter. Light SUSY particles fit that bill, motivating a plethora of experiments to try to detect them. Yet no WIMPs have been seen.

Finding new particles is challenging. It took four decades to spot the Higgs boson. But through current and planned experiments we should be able to rule out several candidates for dark matter in the next decade. The goal is to detect the particles that constitute the massive halo of dark matter that surrounds the Milky Way as they pass through our detectors at rates of a few per second per square metre[4]. Because they interact so weakly, it takes a huge effort to capture them. If we are lucky, a 300-day run of LUX, scheduled to begin later this year, could detect WIMPs. Or it may take bigger detectors — and more than one method (see 'What's the matter?').

Some estimate that detectors with 100 times more mass than LUX will be needed to see WIMPs at the rates expected. LUX ZEPLIN, a planned upgrade that could begin operation around 2019, would use 7 tonnes of liquid xenon compared with LUX's current 370 kilograms. We may yet require 100-tonne detectors, but that is the practical limit. Further sensitivity is thwarted by an irreducible neutrino background, mainly from supernovae, the Sun and cosmic rays hitting Earth's atmosphere.

Dark-matter particles might be created in colliders. The LHC is expected to resume operation in 2015 at an energy of 14 teraelectronvolts (TeV), twice the energy that led to the discovery of the Higgs boson. SUSY particles and signatures of departure from the standard model might be glimpsed. But the lack of any SUSY signals so far suggests that we may need much higher energies to see them. A 100-TeV collider, which many particle physicists support as the next step after the LHC, is slated to begin construction around 2020 and would be exciting for dark-matter searches[5].

"Some theorists have even started to wonder whether dark matter exists."

DIFFICULT TO DETECT

Other dark-matter experiments have made intriguing detections, the interpretations of which are still debated. The DAMA/LIBRA experiment, and its predecessor, at Gran Sasso National Laboratory in Italy, have been looking for changes in the flux of dark-matter particles hitting Earth for 14 years. As Earth orbits the Sun and as both travel through the Milky Way, the velocities of the two bodies combine. For half the year, their velocities are in the same direction; for the other half, they are in opposition. This produces an annual modulation in the rate at which the dark-matter particles, travelling in random orbits, fall on the detector.

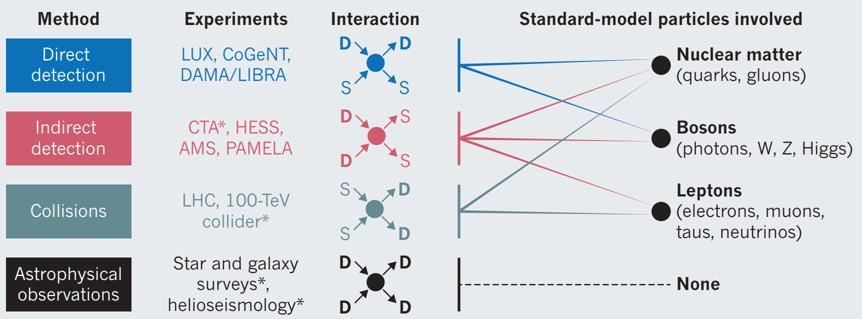
In 2013, the DAMA/LIBRA team reported[6] such a variation with an accumulated high statistical significance (more than nine sigma). Similar cycles, consistent in phase but with an amplitude larger than expected, were seen (with low statistical significance) independently earlier this year in just over three years of data from the CoGeNT (Coherent Germanium Neutrino Technology) Dark Matter Experiment[7] in Soudan, Minnesota. Yet most physicists query whether the DAMA/LIBRA results really are because of WIMPs and not some other annual phenomenon, such as neutrons leached from the rocks surrounding the underground experiment in response to seasonal temperature variations.

Indirect attempts to detect dark matter[8] have been equally inconclusive. The Alpha Magnetic Spectrometer (AMS-02) on the International Space Station reported[9] last year an excess of positrons in the cosmic-ray spectrum up to 350 gigaelectronvolts (GeV), consistent with being produced by dark-matter particles colliding and annihilating. These results strengthened similar reports from the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite. But the positrons could have other origins, such as winds from pulsars (rapidly rotating neutron stars). Observations with AMS-02 at higher energy in the next two years might distinguish between these hypotheses.

Another source of excitement was the detection last year with the Fermi Gamma-ray Space Telescope of an excess of γ-rays near the Galactic centre, where dark matter should concentrate. A narrow spectral line at 130 GeV apparently associated with the

WHAT'S THE MATTER?

Dark-matter particles (D), such as weakly interacting massive particles and axions, can be spotted through their interactions with various types of standard-model particles (S) or with themselves. Experiments may detect them in four ways: directly; indirectly, by the particles such as photons they give off when they interact; in colliders; or through astrophysical observations.



LUX, Large Underground Xenon experiment; CoGeNT, Coherent Germanium Neutrino Technology Dark Matter Experiment; CTA, Cherenkov Telescope Array; HESS, High Energy Stereoscopic System; AMS, Alpha Magnetic Spectrometer; PAMELA, Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics; LHC, Large Hadron Collider. *Planned experiment or observations.

CARLOS FAHAM

The LUX experiment detects photons produced when dark-matter particles interact with liquid xenon.

excess could indicate dark-matter-particle annihilations or decays. But a similar line from Earth's atmospheric limb implies that at least part of the signal must be instrumental in origin. A conclusive test may come in the next couple of years from the HESS (High Energy Stereoscopic System) γ-ray telescope in Namibia, which is observing the inner Galaxy in the 100 GeV to 1 TeV energy range.

The null results from LUX, the LHC and many other experiments are narrowing the range of possible particles that could explain dark matter. As claimed detections pop up only to disappear, physicists are becoming justifiably sceptical about every announcement of a discovery.

Some theorists have even started to wonder whether dark matter exists. Since the 1980s, a few have proposed modifying the theory of general relativity to do away with the need for dark matter. Such radical ideas are increasingly invoked to address another grave problem in astrophysics: the origin of the 'dark energy' that accelerates the expansion of the Universe. Most researchers think that we are far from needing new physical laws, especially because experimental avenues are still open. But unpleasant surprises are always possible.

There are two worst-case scenarios. First, dark matter may not comprise one type of particle — as many current searches assume — but many. Second, the particles might interact only gravitationally, and could be practically invisible to conventional detectors.

NEW DIRECTIONS

Existing experiments should run their course. But new approaches are needed to tease out dark-matter particles in the next decade.

A dark-matter modulation experiment, such as DAMA/LIBRA or CoGeNT, in the Southern Hemisphere would gauge the extent of Earth's seasonal effects, which would be out of phase relative to the north.

Clumps or streams of dark matter moving through the Milky Way, distorting the rate at which particles hit detectors, should be visible as disturbances in the motions of the roughly one billion nearby stars that will be tracked by the European Space Agency's newly launched GAIA satellite during its five-year mission.

At the LHC and other next-generation accelerators, particle collisions with missing energy — drawn by an unknown particle — or other unexpected signatures could illuminate the dark sector.

We must also broaden directed searches and exploit astrophysical methods. First, we should look towards more massive particles, such as the SUSY particles. It will be difficult to detect heavy particles directly because there will be fewer of them. But γ-ray astronomy may help. The Cherenkov Telescope Array — an international project to build more than 100 ground-based telescopes to capture light flashes from γ-rays scattered by the atmosphere — should after 2015 open the window to 100-TeV energies. This energy coincides nicely with the highest limit on the WIMP mass expected from fundamental physics arguments. Such particles would generate TeV γ-rays when they annihilate or decay.

Second, broader categories of dark-matter particles should be sought. Like ordinary matter, dark matter could be complex, perhaps carrying a small charge, or having internal states akin to the electron levels of an atom. Changes in the Sun's oscillations as clouds of 'millicharged' particles scatter off electrons in the solar plasma might be detectable through helioseismology. Gravitational lensing could measure the more-spherical dark haloes of distant galaxies, which are expected if dark-matter particles interact electromagnetically, albeit feebly.

Third is the axion. Predicted to explain an anomaly in quantum chromodynamics, the theory of the strong force, the electromagnetic signatures of axions have been long sought in the lab without success. String theory suggests types of ultralight axion that would be slightly more 'warm' than cold dark matter. Mixes of cold and warm dark matter, perhaps also including neutrinos[10], might explain, for example, why there are fewer dwarf galaxies than cold-dark-matter scenarios predict.

Astrophysicists should look for unusual signals in old stars, such as neutron stars and white dwarfs. As stars orbit their galaxy, they accumulate WIMPs. Collected in the core of a neutron star, WIMPs might form a tiny black hole that could eventually devour the star, causing a violent explosion — an event that has yet to be seen. Helioseismology could also probe the effect of WIMPs on the Sun's temperature profile.

To refine theoretical and experimental strategies, particle physicists and astrophysicists need to communicate better. The number of dark-matter-candidate particles to be explored is limited, bounded at low masses by our failure to see anything and at high masses by the constraints of theory. A multidisciplinary approach to explore the 1–100 TeV mass–energy range should be the next frontier for the dark-matter community. ■

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