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# Dark matter mysteries: a true game of shadows

09 January 2012 by **Stuart Clark**
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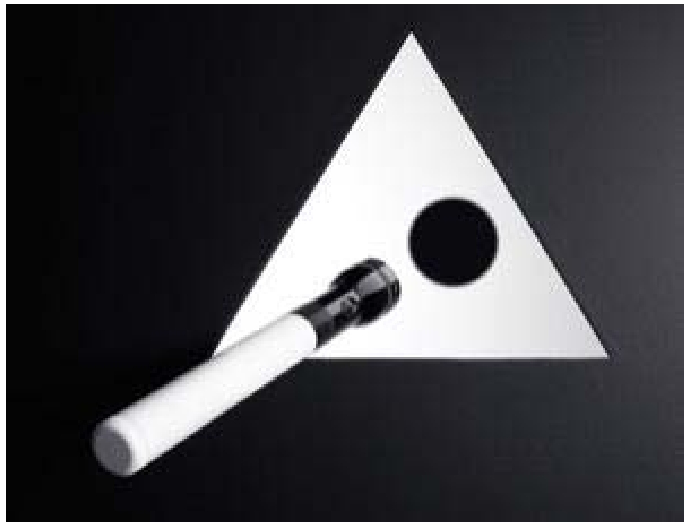
*Far from shedding light on dark matter, our first experimental glimpses of the elusive stuff have only deepened its mystique*



Throwing a light on the mysteries of dark matter *(Image: Alexander Kent)*

**Editorial:** "No more eureka moments"

IT'S a troubling time to be looking for the universe's missing matter. On the face of it, it shouldn't be. Deep underground, several experiments have been buzzing with possible sightings of dark matter, the hitherto invisible stuff that is believed to make up around 85 per cent of all matter in the cosmos. Detecting dark matter would be a major triumph.

Yet any hopes that the nature of the stuff would be quickly revealed by these first detections have been utterly dashed. The trouble is that dark matter appears to be different things to different detectors. It appears heavier in one detector than another; it appears more ready to interact in one experiment than another. In the most extreme case, it shows up in one instrument but not in another - even when both are made of identical material and are sitting virtually next door in the same underground lab.

"The present situation is pretty confusing," admits Juan Collar of the University of Chicago, who is head of the CoGeNT dark matter experiment, based in the Soudan Underground Laboratory in Minnesota. It is seeing something - hundreds of somethings - each of which could be a dark matter particle striking the detector. But if CoGeNT and the other experiments are truly seeing dark matter, then it's not what anybody thought it was.

We need dark matter. For starters, it is a form of cosmic glue that binds our galaxy together and provides the necessary gravitational force for galaxies to cluster around one another. If dark matter does not exist, it means that our understanding of gravity on the largest scales is wrong. This is unthinkable to most astronomers, who continue to pin their hopes on dark matter and use observations of the way galaxies move and rotate to help pin down its properties.

What's more, dark matter is the missing link in our attempts to move beyond the standard model of particle physics. The standard model cannot explain the masses of ordinary particles, and while it can describe three forces of nature as an exchange of "messenger" particles, it has failed to do so with the fourth, gravity. To allow it to do these things, theorists postulate as yet undiscovered particles that would have played a big part in the interaction of ordinary matter in the extreme temperatures just after the big bang, but now loaf around, having lost most of their potency.

With both astronomy and particle physics needing more particles to be identified to make sense of observations, theorists began calculating what these entities might be. They homed in on the weakly interacting massive particle, or WIMP, a sluggish entity with a mass of around 100 gigaelectronvolts (GeV), or 100 times that of a proton. That's because of a coincidence so striking that it looked frankly miraculous.

Rewind 13.7 billion years to the aftermath of the big bang and you can calculate the density of dark matter present simply from the WIMP's mass and its ability to interact with ordinary matter. By fine-tuning this mass and assuming that dark matter interacts via the weak force, physicists predicted exactly the amount of dark matter that astronomers said they needed for galaxy formation. The agreement became known as the WIMP miracle.

We might have been fooled, though. "It turns out that the WIMP miracle isn't as miraculous as we once thought," says Jonathan Feng, a dark matter theorist from the University of California, Irvine.

The first evidence that something was amiss came in 2008, when the DAMA experiment at the Gran Sasso underground laboratory in Italy reported seeing something that could be dark matter.

All dark matter experiments are conducted deep underground so that the overlying rocks can block out cosmic rays, fragments of atoms that have been accelerated to huge speeds by dying stars or other celestial exotica. Still, cosmic rays do get through with alarming regularity. The task of most dark matter detectors is to spot any oddballs, hits that cannot easily be explained away as cosmic rays or natural radioactivity.

The DAMA team took a different tack. Instead of looking for the needles in the universal haystack, they counted everything registered by their sodium iodide detectors and then looked for variations in the detection rates as each year progressed. They reasoned that cosmic rays would flash through space in random directions and should therefore arrive at a constant rate throughout the year. The same would be true for any radioactivity.

But researchers expect to see seasonal variations in the dark matter signal because the speed at which the Earth ploughs through the surrounding sea of dark matter changes depending on its direction of motion. As a result the amount of dark matter particles hitting Earth should rise in June, when the planet is moving through the galaxy in the same direction as the sun, and fall in December when it is moving in the opposite direction. The DAMA team claimed they had seen an annual modulation that was consistent with this picture.

But the tricksy nature of dark matter detection soon showed up. Results from another Gran Sasso experiment called XENON100, which uses liquid xenon, seemed to exclude the very dark matter particles DAMA was suggesting. Other results sided with XENON100. Then last year the tables turned again. First the CoGeNT team, which uses an underground germanium detector, announced the sighting of a similar annual modulation to DAMA. Then a third experiment in Gran Sasso, known as

CRESST, reported a set of possible detections.

## Banished to the cold

Admittedly, DAMA, CoGeNT and CRESST do not agree on what they are seeing. "Everything is very close but there's no actual overlap yet," Collar says. Yet they all point to a dark matter particle that is far too light. Far from being heavyweight couch potatoes, WIMPs are turning out to be lively flyweights with a mass of 10 GeV - just a tenth of that expected.

The conflicting detections are not the only problem. Observations of dwarf galaxies are prompting a growing number of astronomers to change their minds about what properties they want dark matter to have. The thinking is that WIMPs will not cut it any more.

More problems have come courtesy of the Large Hadron Collider at CERN near Geneva, Switzerland. If our understanding of dark matter is correct, then we should be able to make WIMPs in the LHC's high-energy collisions. So far none have shown up. WIMPs as we know them could soon be impossible.

"You can tweak all the dials in the theory and see if you can fit the detections, but the bottom line is that it is not really doable," Feng says. So is it time to abandon WIMPs?

Feng's calculations show you can still have the correct density of dark matter in the universe by lowering the mass of the particles and boosting their ability to interact. This also increases the possibility of different sorts of dark matter particles. "There are many directions to go once you start thinking beyond the WIMPs," he says.

One long-time challenger to WIMPs for the dark matter crown is the axion. This hypothetical particle might help to explain why certain weak-force reactions dominate over others and why there is more matter in the universe than antimatter.

On the face of it, axions sound promising. However, they are also slow-moving, and so axions are labelled alongside WIMPs as "cold" dark matter. The trouble with cold dark matter of any variety is that we are starting to have reservations about its existence.

Being the dominant form of matter in the universe, dark matter must sculpt galaxies into shape. So by looking at the number of galaxies in the universe, and their sizes, we should be able to learn about the properties of dark matter. "The problem that cold dark matter faces is that it cannot explain the absence of small-scale structures in the universe," says Héctor José de Vega at the Laboratory of Theoretical and High Energy Physics in Paris, France.

By small-scale he means dwarf galaxies. Simulations of cold dark matter predict tens to hundreds of times more dwarf galaxies than anyone can find. The reason is cold dark matter falls together easily because it is slow-moving and so cannot resist its own gravitational attraction. As computing power has grown, our simulations have become finer and predict clumpy clouds of cold dark matter the size of the solar system. Yet no evidence for any such substructures has yet been found.

"These problems have been known for 20 years, but they are becoming worse as the observations get better," says de Vega.

He and colleagues are discussing the need for a somewhat lighter, faster-moving particle: "warm" dark matter. Such particles would have no more than one-thousandth the mass of WIMPs. So they would resist clumping on the smaller scales and not be expected to produce so many dwarf galaxies. "Fast progress is being made on the simulations," says de Vega. "You will surely hear a lot more about warm dark matter in the future."

What exactly makes up warm dark matter? The best bet at the moment is a hypothesised type of neutrino, known as the sterile neutrino because of its reluctance to interact with normal matter except through gravity (unlike ordinary neutrinos, which also feel the weak force). Sterile neutrinos could also help explain why there is more matter than antimatter in the universe.

Then there's the new kid on the block that some are claiming could do the job just as well: "dark atoms". Not only could dark atoms explain the lack of dwarf galaxies, it's just possible, say their inventors, that they could also explain the discrepancies between the dark matter experiments.

Christopher Wells of Houghton College in New York and colleagues began to ponder whether they could square the seemingly contradictory results from the underground experiments. They found it should be possible if the dark matter was not a single particle but the dark equivalent of a hydrogen atom - a dark electron orbiting a dark proton.

Ordinary atoms can change their energy levels under the right conditions by either absorbing or emitting a photon. A dark atom could use dark photons to do the same when it hits a dark matter detector, depending on the chemical composition of the detector.

In the case of the sodium iodide that DAMA uses, the dark atom would change its energy and be seen. However, xenon would not have the same effect on the dark atom and so the particle would go unnoticed by XENON100.

It is very early days for dark atoms, and Wells admits he has not figured out how the current pantheon of physics theories could motivate their existence, although he suggests that string theory could offer some leads. "We know nature gives us ordinary atoms, we wondered if it could do it again," he says.

## A world of pain

What's promising about dark atoms is that they could explain the lack of dwarf galaxies in our observations. Because dark atoms would emit or absorb dark photons, the universe might be full of invisible, dark light that constantly interacts with clouds of dark atoms, raising their temperature and puffing them up. This would prevent dwarf galaxies from forming in the first place. "It's still a rough, back-of-the-envelope calculation at the moment," admits Wells, who has started working on simulations to better test the idea.

Still, many researchers are not quite prepared to abandon WIMPs yet. "I don't find the arguments about dwarf galaxies very convincing," says Dan Hooper of the Fermi National Laboratory in Batavia, Illinois. "My money is still on WIMPs."

He suggests that the missing dwarf galaxies could be out there but are invisible because they are made solely of dark matter. One way to find them is to look for gamma rays, which should be produced when WIMPs collide and disintegrate. NASA's Fermi space telescope has searched for such gamma rays in nearby dwarf galaxies twice and so far found nothing. That does not necessarily mean that the WIMPs are missing, just that they are not in the form expected. And Hooper says that the results do not rule out low-mass WIMPs similar to those that may have been seen in the underground experiments.

Collar dubs the current impasse "a world of pain" and reckons that it is likely to get worse before it gets better. Now that we have begun to see something, either astrophysics is wrong, or particle physics is wrong, or our whole understanding of dark matter is wrong.

Everyone agrees that the way forward is to collect more and better data. To do that, we need more sensitive dark matter detectors on Earth, better astrophysical observations and more particle accelerator experiments.

One spacecraft that will help is the European Space Agency's Planck telescope. Launched in 2009, it is taking the most precise images of the cosmic microwave background (CMB) radiation that it is possible to take. Subtle variations in the CMB are sensitive to the rate of expansion of the universe, which itself is determined by the soup of particles present in the cosmos.

"Planck is the really big player in this," says Feng. "It could tell us for sure whether there are more particles than we have detected."

There are already hints from NASA's WMAP spacecraft that the CMB shows the fingerprints of undetected particles. These could plausibly be sterile neutrinos or even dark photons. Planck has the potential to turn these hints into solid discoveries.

But when it comes to figuring out what the dark matter actually is, there will probably be no single eureka moment. Instead, the nature of the beast will become apparent as everyone fits together their own pieces of the puzzle.

"This is like the story of the elephant," says Feng, referring to the Indian parable in which a group of blind men all touch a different part of an elephant and then compare notes to try to work out what the beast looks like. "We are all touching a different bit of the dark matter. Hopefully, at some stage, we'll be able to put them all together in the right way and discover what it looks like."

Let's hope so. The trouble is that in some versions of the parable the conflicting views are never resolved and the truth is never uncovered.

***Stuart Clark** is a consultant to New Scientist and author of The Sky's Dark Labyrinth (Polygon)*