Ghosts among us

We might already have seen hints of a shadow world of matter we just can't touch, says Stuart Clark

SPARE a thought for the dark-matter hunters. Every time they're on the verge of trapping the elusive stuff thought to make up the bulk of the universe's matter, it slips away. They don't see the expected signals, or they spot something exciting only to watch it fade into background noise. Each time it's the same: put on a brave face, go back to the drawing board and begin the hunt again.

Perhaps it's time for a change of tack. Instead of going after a single species of dark matter particle, maybe we should be looking for a menagerie of dark particles and forces – a whole new "dark sector". After all, there is no reason to think dark matter will be any less intricate than the visible stuff we consider ordinary, with its panoply of particles from electrons to quarks.

LEVENTE SZABO

"If you look at normal matter, our universe is enormously complicated," says Alex Drlica-Wagner, a dark matter hunter at Fermilab near Chicago, Illinois. "So it may be naive to think that the dark sector is exceptionally simple."

The talk is of an entire shadow world in which invisible particles influence one another through forces unfelt by the familiar stuff of stars and planets and us. A quixotic idea? Perhaps not. If the faint hints of a dark force emerging from one lab stand up to scrutiny, this shadow realm may already have revealed itself.

From as early as the 1930s, astronomers could see that galaxies orbit each other much faster than expected given the gravitational tug produced by their visible stars. Forty years on, we spotted that stars within galaxies also seemed to rotate too fast. Either the laws of gravity drawn up by Newton and Einstein required a substantial rewrite, or some invisible form of matter was producing more gravitational heft. Most astronomers favoured the second option – dark matter.

Whatever this stuff is made of, it must have mass so that it feels and generates gravity, but no electric charge, so it does not interact with light. Gravity's effects are so weak that physicists have to hope that dark matter does interact with some component of ordinary matter in some other way, just barely, or else we may never identify it.

For decades, the leading candidate has been the weakly interacting massive particle, or WIMP. The trouble is, a long line of exceedingly sensitive detectors has failed to record a single

sign of them. Only last month, the LUX experiment in South Dakota came to the end of a two-year search without a sniff.

WIMPs aren't quite dead yet. Some astronomers think we have seen their signature in ultra-faint dwarf galaxies surrounding the Milky Way (see "Dwarfs to the rescue?", page 31). But for others it's time to move on. "We've been looking for these for decades and we haven't found anything," says Jonathan Feng at the University of California, Irvine. "This naturally leads people to consider other, more baroque ideas."

Dark matter has taken various guises besides WIMPs over the years (see "Seven ways to make dark matter", page 30). But now there are compelling reasons to consider more extravagant alternatives. For a start, we can measure the rotation of galaxies in such detail that we can figure out how dark matter is distributed within them. Simple models suggest it should be very dense in the middle of galaxies. The latest observations, however, show that it is spread more evenly. One way to explain that is by appealing to a force that acts only between dark matter particles, pushing them apart.

That could be a game changer. "Once you start thinking about forces acting just between dark matter particles, then you are led into a whole new arena," says Feng. "You can think about a zoo of dark particles and forces all of its own. It's a brand new world."

"With the dark matter search failure, we must consider other, more baroque ideas"

The idea of a dark sector is not entirely novel. Back in 2006, astronomers studying the Bullet Cluster, an ongoing smash-up between two groups of galaxies, proposed that the collision speed was too high for the gravity of the matter involved – dark and ordinary – to be solely responsible. They figured that the additional pull must be coming from a force of attraction between dark matter particles.

More detailed simulations proved that the speed of the Bullet Cluster collision was not beyond what we might expect. But the suspicion of dark forces never went away, with researchers suggesting that anomalies thrown up by particle experiments on Earth might also hint at their existence. For example, ›

SEVEN WAYS TO MAKE DARK MATTER

WIMPS The textbook solution to dark matter is that it is a thick, slow-moving soup of weakly interacting massive particles (WIMPs). That could explain the odd way galaxies rotate – yet no detector have yet found a WIMP. If they do exist, it seems they must be lighter than we thought.

MACHOS This is the idea is that dark matter is just normal stuff hiding at the edges of galaxies – "massive astrophysical compact halo objects" that are so dim as to be invisible. Candidates include black holes or failed stars. Alas, MACHOs could only account for a tiny fraction of the universe's missing mass.

MACROS It could be that the dark stuff is made of dense clumps of quarks, the particles that, in pairs or triplets, form ordinary matter. These "macros" could be as dense as neutron stars and extremely heavy. Unfortunately, the experiments needed to spot them, such as deploying seismometers on the moon, are too outlandish to carry out.

AXIONS A punier version of the WIMP, axions would interact even less with ordinary matter. That suggests WIMP detectors might have spotted them – but they haven't. The jury is still out, at least until dedicated experiments such as the Axion Dark Matter Experiment return a verdict.

STERILE NEUTRINOS Neutrinos pass through other matter almost as if it doesn't exist, but they are too light and zippy to be dark matter. Sterile neutrinos are a heavier, more aloof version. Signs of them have emerged in underground detectors, only to quickly disappear. We've also seen a suggestive excess of X-rays coming from galaxy clusters – but failed to pin down the sources.

GRAVITINOS The graviton is a particle proposed by the theory of supersymmetry to mediate the force of gravity, and the gravitino is its hypothetical "superpartner". It nicely fits the bill for a dark matter particle. The trouble is there is still no sign of the many heavy partner particles predicted by supersymmetry.

MOND Modified Newtonian dynamics (MOND) doesn't make dark matter so much as remove the need for it, by tweaking the laws of gravity. That makes many physicists uncomfortable. Now a hybrid model exists in which a phase-changing form of dark matter acts like WIMPs inside galaxies but modifies gravity on larger cosmological scales.

a long-standing discrepancy between theory and experiment over the magnetic properties of ordinary matter particles called muons, a heavier version of the electron, might be explained by invoking a dark-force carrying particle. Now Feng thinks we might have found the most compelling evidence for such a particle so far – in a nuclear physics lab in Hungary.

Attila Krasznahorkay of the Institute for Nuclear Research at the Hungarian Academy of Science in Debrecen leads a team looking at the radioactive decay of beryllium-8 nuclei. Beryllium is a naturally occurring light element that is stable when its nucleus contains four protons and five neutrons. But with just four of each, the isotope Be-8 splits into two helium nuclei in the blink of an eye. Previous experiments had hinted at something odd about this particular decay, and Krasznahorkay and his colleagues wanted to pin it down.

To make Be-8, they fired protons at a wafer-thin sheet of lithium-7. The beryllium decayed, releasing pairs of electrons and their antimatter counterparts, positrons. In standard particle theory, most of those pairs should be emitted in roughly the same direction as the incoming proton beam. But the Hungarians found that there were two unexpectedly prominent side streams, coming out almost at right angles to their expected direction. This was the sort of behaviour you would expect if the decay created a slow-moving particle that lived for short time before itself decaying into an electron and positron, which it would spit out in almost opposite directions.

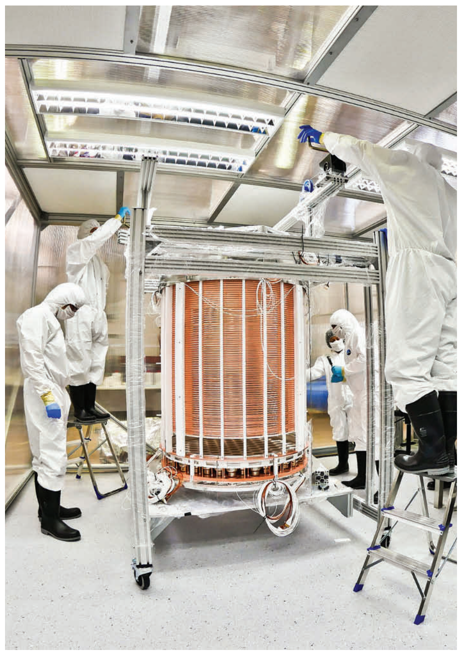
When the team calculated the mass of this hypothetical particle, they found that it fitted nothing in the standard model of particle physics. Instead, their numbers suggest it has a mass of around 17 megaelectronvolts – just 33 times that of an electron and far lighter than any WIMP. No known force of nature could create such a particle.

Having investigated the anomaly for three years, the team published their results in 2015. They refer to their particle as a "dark photon". By analogy with the way the photon carries electromagnetism, this particle would carry an unknown force between dark matter particles.

The paper passed pretty much unnoticed – until Feng came across it. From the description, he could see nothing wrong with the experimental set-up. "They did a lot of cross-checks and they could not make the effect go away," says Feng. "They have seen hundreds of events now. The likelihood of this result happening by chance is one in 200 billion."

Taking the results at face value, Feng and his colleagues sought their own explanation. They also wanted to address a nagging doubt: given that the Hungarian team spotted this putative new particle with an experiment well within the capabilities of most physics labs around the world, why had no one else noticed anything before?

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



XENON

Even the cleanest, most sensitive detectors have failed to lay a glove on dark matter particles

Galactic smash-ups hint that dark matter is more complex than we thought

The hypothetical dark photon, as well as carrying the dark force between dark matter particles, should also carry a little bit of ordinary electromagnetism. So it should occasionally interact with the protons and electrons in normal matter. But when Feng and his colleagues calculated the strength of this interaction, the plot thickened. "There was no way this could be a dark photon," says Feng. "If it were, we should have seen hundreds and thousands of other effects in other experiments and particle accelerators."

If not a dark photon, then what? Feng's team searched for other ways a dark particle could be interacting, albeit slightly, with familiar matter to cause the anomalous beryllium decay. They found that, to be consistent with everything we have seen in experiments designed to characterise the known forces of nature, it must interact not with protons and electrons, as a conventional photon does, but with the neutrons inside the beryllium nuclei. This is a property beyond the scope of physics as we know it, which might explain how the particle slipped by unseen in previous dark matter searches. Feng's team call the interloper a "protophobic X boson".

Not everyone is convinced of claims of a whole shadow world beyond the visible material universe. Rouven Essig at Stony Brook University, New York, is sceptical of both the experimental result and the attempts to deduce a particle that might explain it. "I don't think anyone has written down a compelling or natural candidate yet," he says.

At least the theory can be tested. Feng's X boson is of a size that should allow several current experiments to show definitively whether it exists or not. "The nice thing is that we have a concrete target now and these experiments can actually check this," says Essig. "I don't think this anomaly is going to stick around forever."

Indeed, the race is on to confirm or refute the Hungarian group's original findings and look for more examples of the X boson at work. The DarkLight experiment at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, is already searching for particles in the mass regions where Feng's team calculated it should be (see "I'm shooting for a beam of dark light", page 32). The LHCb experiment at CERN's Large Hadron Collider near Geneva, Switzerland, will also look for it in the decays of quarks and their antimatter counterparts.

"Sooner or later the standard model must break, so every anomaly must be looked at"

Some researchers have expressed reservations because the Hungarian team has reported anomalies before, only for them to disappear on further investigation. Feng is undeterred. "No one has identified a weakness of this experiment," he says. "Do they have a specific problem with the experimental results, or is it just general scepticism?"

To his mind, the current situation of general cluelessness surrounding dark matter means the X boson is well worth pursuing, regardless of any qualms. "We know there is dark matter and it is not explained in the standard model," he says. "There must be an explanation, so sooner or later the standard model will have to break. Every anomaly must be looked at."

Others are yet to be persuaded. "All of these ideas are very interesting, but I wouldn't say that we have a compelling reason to abandon the simpler dark matter picture yet," says Josh Simon, an astrophysicist at the Carnegie Observatories in Pasadena, California. The problem with a complex dark sector, he says, is that it is going to be even harder to put to the test than the elusive WIMPs and their ilk. "It becomes very difficult to make any predictions about what we should observe."

But then again, Simon goes on to say, just because a theory is complicated doesn't make it wrong. "Nature doesn't have to give us something that is easy to test." ■

Stuart Clark is a consultant for *New Scientist* and the author of *The Unknown Universe* (Head of Zeus)

DWARFS TO THE RESCUE?

Dark matter might not be as gloomy as its name suggests. If this mysterious substance is made of weakly interacting massive particles (WIMPs), as most physicists believe, then they would come in matter and antimatter versions. When the two come into contact, they would produce a shower of high-energy photons known as gamma rays.

In 2009, researchers at Fermilab in Batavia, Illinois, thought they had caught a glimpse of such a signal coming from the centre of the Milky Way. Most astronomers now think that was a false alarm. Galaxies tend to be crowded with billions of stars, making it almost impossible to rule out other sources for the gamma rays.

It's not quite game over, however. In the past few years, astronomers have discovered a nearby population of ultra-faint dwarf galaxies, so named because each contains no more than a few hundred million stars. These mini-galaxies are also thought to hold unusually high concentrations of dark matter, making them the ideal place to look for its gamma-ray glow. "If we don't see it here, we never will," says Josh Simon at the Carnegie Observatories in Pasadena, California.

Maybe we already have. In 2015, we found a new dwarf galaxy called Reticulum II just 100,000 light years away, prompting Alex Geringer-Sameth at Carnegie Mellon University in Pittsburgh, Pennsylvania, and his colleagues to take a closer look. They downloaded observations from the archive of NASA's Fermi gamma-ray space telescope and, sure enough, they found what appeared to be an excess of gamma rays.

Critics say there could be hidden gamma-ray sources beyond Reticulum II. The possibility is hard to rule out and there are no plans for new instruments to provide more accurate observations. Unless we discover more nearby dwarf galaxies to test, a certain identification of WIMPs remains a long shot (see main story).