The will of the WISPs

While many physicists hunt dark matter in the form of WIMPs – "weakly interacting massive particles" – others have turned their attention to a lighter prey: "weakly interacting slim particles", or WISPs. **Edwin Cartlidge** reports

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According to folklore, the flickering lights reputedly seen at night over marshy land known as will-o'-the-wisps are the torches or lanterns held by lost souls condemned forever to roam through purgatory. The light is said to recede into the distance if it is approached, so luring unwary travellers away from the well-beaten track.

Hypothetical albeit not supernatural entities known as weakly interacting slim (or sub-electronvolt) particles – WISPs for short – could be argued to have a similar effect on certain physicists. Extremely light and extraordinarily elusive, WISPs are predicted to very occasionally generate the faintest flickers of light in the space around us. Those flickers have never been seen, but some scientists believe they must take place. It is a belief that draws them across the desolate landscape of low-energy parameter space, and takes them ever further from the established path of mainstream science.

That path is one of ever larger and more expensive particle colliders, built to reach ever higher energies that can yield increasingly massive, previously unseen particles. This approach has been very successful for more than 50 years, having served up many components of the Standard Model of particle physics. Most recently it yielded the mass-giving Higgs boson, which was produced at the world's most powerful accelerator, the Large Hadron Collider (LHC) in Switzerland. But physicists are not satisfied, and they hope that the LHC will also deliver more exotic particles that sit outside the Standard Model. Among the most sought-after of these are so-called weakly interacting massive particles (WIMPs).

WIMPs were proposed in the 1980s as a candidate for dark matter, the mysterious substance thought to prevent galaxies from breaking up as they rotate. Weighing some 10^{10}–10^{12} eV and interacting only via the feeble weak nuclear force and the still feebler gravity, WIMPs have properties that would make them about five times more plentiful than normal matter. This just happens to equal the abundance of dark matter that we actually do see in the universe – a matching-up known as the "WIMP miracle". WIMPs also bear a close resemblance to the lightest particle in "supersymmetric" extensions of the Standard Model, and also to the lightest particle predicted by extra-dimensions theory. "The wind behind its sails was fantastic," recalls physicist Leslie Rosenberg of the University of Washington in Seattle. "People were convinced that the WIMP was there."

> These particles could provide a significant fraction of the universe's dark matter, if not all of it

In recent years, however, that enthusiasm has waned. WIMPs have yet to show up at the LHC, even though the machine has reached collision energies of 7×10^{12} eV and in so doing excluded a significant portion of their possible mass range. They have also made no convincing appearance in a dozen or so underground experiments designed to detect the tiny amounts of energy they would give off when colliding with atomic nuclei. As Rosenberg puts it, the WIMP miracle is "looking a little tarnished now".

Enter the WISP. This generic grouping comprises a wide range of potential dark-matter particles, having masses of no more than a few electronvolts and potentially well under a millionth of an electronvolt – in stark contrast with the much more massive WIMPs. Its members range from the relatively well-known axion to the (literally) more obscure hidden photon. Their tiny masses would mean they interact extremely weakly with normal matter, via the electromagnetic force or perhaps via new forces. At particle accelerators – even ones as powerful as the LHC – their rate of production would be too low to be visible; any that are produced would be swamped by other collision debris.

Accelerators, therefore, are not the tool of choice when it comes to hunting for WISPs. A growing number of researchers are instead turning to more modest devices that exploit WISPs' expected transformation into and out of either one or two photons. These researchers have so far come up empty handed, and may remain so. But they are ramping up the sensitivities of their experiments, bolstered by astrophysical observations that they believe provide increasingly persuasive evidence for WISPs' existence. They also reckon that these particles could provide a significant fraction of the universe's dark matter, if not all of it.

"Experimentalists in the past have invested their


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energy in WIMPs, with good reason," says particle physicist Igor Irastorza of the University of Zaragoza in Spain. "But they have still not found any signal. WISPs have been a bit disregarded until recently, but maybe nature has given us those rather than WIMPs."

Tuning into axions

The most popular variety of WISP is the axion, which was proposed in the 1970s to solve a problem involving the strong nuclear force. It was not until the 1980s, however, that physicists realized axions could be the stuff of dark matter.

Unusually for a hypothetical particle, if the axion exists and it is dark matter, its maximum and minimum values of mass and interaction strength are well defined. Any lighter than about a millionth of an electronvolt and there would have been too many of them produced to explain the amount of dark matter we observe in the universe, and any heavier than around a thousandth of an electronvolt and they would have been detected by virtue of their interactions with other matter.

One way to detect axions is by observing the pairs of photons they are thought to turn into. Conservation of momentum dictates that axions, which have an intrinsic angular momentum, or spin, of zero, cannot decay into single photons, which have a spin of one. But it does permit them to transform into pairs of photons, since these can have spins pointing in opposite directions that cancel one another out. Unfortunately, axions are incredibly inert – far more so even than the famously elusive neutrinos – which means that the transformation into photon pairs would be extraordinarily rare. That fact, however, hasn't put physicists off trying to detect them.

Mary Levin, University of Washington

CERN

The hunt is on Experiments looking for axions – the main WISP candidate – include the Axion Dark Matter Experiment (left) and the CERN Axion Solar Telescope.

One approach is to use what's known as a "haloscope". This uses an antenna to pick up an excess of photons at a frequency corresponding to half the predicted mass of an axion. But rather than relying on axions to spontaneously decay, it uses a large magnetic field that allows axions to "steal" a photon and emit another photon – the stolen photon scattering off the axion and so acting as if it were emitted by it (an idea originally put forward by University of Florida physicist Pierre Sikivie in 1983). Magnet and antenna are then housed in a microwave cavity of a suitable length, so that the cavity can "ring" at the wavelength of the axion radiation.

Rosenberg leads a small team that has built a \$30m haloscope known as the Axion Dark Matter Experiment (ADMX) at the University of Washington in Seattle. This uses an 8 T magnet and ultralow-noise SQUID amplifiers. With the recent addition of a dilution refrigerator to limit thermal noise as far as possible, the experiment is due to start taking data this month. It should operate initially for three years and then run for a further two years at higher frequencies.

According to Rosenberg, the ADMX is unusual as it will, he claims, either discover axions or rule them out as dark-matter candidates. "Dark-matter folklore dictates that you can't make a definitive experiment," he says, referring to ever bigger WIMP detectors placing ever more stringent, but not conclusive, limits on dark matter's interaction strength. "We have already started to poke about in the range of allowed axion models, and when we are finished we will have gone through all the plausible models."

Solar flair

The ADMX has a couple of drawbacks, however. Its use of a resonator means it is sensitive to one very narrow band of frequencies at a time; scanning all of the frequencies of interest therefore takes a long time. More fundamentally, the experiment is based on the assumption that axions are dark matter. In other words, it assumes that axion production did take place at the beginning of time, as hypothesized, and that axions are therefore all around us and can be measured. It is possible, however, that axions exist, but don't have the right properties to constitute dark matter.

An alternative approach to axion detection makes no such assumption, but instead focuses on an object that would without doubt produce axions, if they exist. That object is the Sun. The Sun's plasma produces strong electromagnetic fields that would convert some of its photons into axions, which would stream to Earth. Some of those axions would then convert back into pairs of photons with X-ray wavelengths, which could be detected using a device known as a "helioscope".

The first helioscope, realized at Brookhaven National Laboratory in the US in 1992, employed a stationary 1.8 m long, 2.2 T dipole magnet. Successive generations of helioscope have used larger, moveable magnets that can track the Sun, first in Japan and then at the CERN Axion Solar Telescope (CAST), which has achieved axion sensitivities about 40 times higher than that of the Brookhaven device.

Now physicists are planning a fourth-generation machine, the International Axion Observatory (IAXO), that would crank sensitivities up by another factor of 20. Unlike its predecessors, IAXO would use a specially built magnet, consisting of eight flat, 21 m long superconducting coils interspersed with as many bores arranged circularly inside a cylindrical cryostat. The resulting 5 T toroidal field would thread through each bore at roughly right angles and convert some of the putative axions passing through into X-rays that would be focused to 0.2 cm^2 spots in eight corresponding detectors.

Having obtained provisional backing from CERN, which may host the detector, the IAXO collaboration is now working on the technical design. According to Irastorza, who is collaboration spokesperson, construction of the SFr50m device could start in the next two to three years, with observations getting under way around five years later, funding permitting.

Beyond the axion

Whereas haloscopes and helioscopes both seek to detect WISPs produced naturally, experiments in a third category known as "light shining through a wall" aim to generate their own. These facilities generally employ a laser, a pair of magnetic fields either side of an opaque wall, and a photon detector. The idea is that the detector will register a signal only if photons from the laser have transformed into WISPs ahead of the wall and those WISPs have then converted back into photons on the other side (WISPs passing straight through solid objects).

Among the main quarries of light-shining-through-a-wall experiments are WISPs known as "axion-like particles" (ALPs). A more generalized form of the axion, these spin-0 particles would generate pairs of photons in a magnetic field like their more famous counterpart, but could in principle assume any combination of mass and interaction strength.

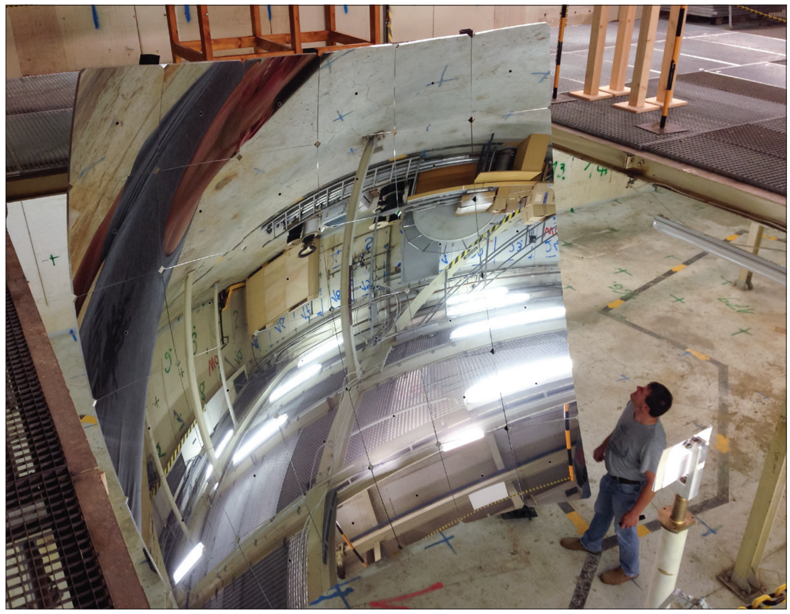
In 2006 researchers working on an experiment in Italy called PVLAS reported what appeared to be photon-to-ALP interactions taking place inside their detector. A year later, however, following fresh measurements, they concluded that their anomalous results were nothing more than experimental artefacts.

To test the Italian claim, scientists at the DESY lab in Hamburg had in the meantime built a similar experiment, the Any Light Particle Search (ALPS). They did so quickly using whatever equipment they could get their hands on, including a spare dipole magnet from the HERA particle accelerator that had fortuitously remained installed on a test bench. Following the negative results from PVLAS, which were confirmed by rival experiments, the lifespan of ALPS looked set to be short. But astrophysical evidence then emerged suggesting that WISPs might exist after all.

That evidence was based on very-high-energy gamma rays that had been emitted by distant sources. Such radiation is expected to be absorbed before it gets to Earth through its interaction with extragalactic background light. The fact that we can see it – so the reasoning goes – could be explained if magnetic fields permeating space cause the gamma-ray photons to convert into ALPs, which then travel unimpeded through the cosmos before re-converting into photons close to us.

These results persuaded the DESY team to design an upgrade of its experiment – ALPS II. "We got more and more convinced that WISPs might be real," says Andreas Ringwald, a theorist at DESY who is co-spokesperson for ALPS II. "So we thought we shouldn't just finish with our experiment, but instead strive for an improvement in its sensitivity to allow us to enter unchartered territory."

With funding of just €2m – a very modest sum by particle-physics standards – Ringwald and colleagues aim to increase the experiment's sensitivity to ALPs by more than a factor of 1000. They plan to do this by employing 20 magnets from the now long-since decommissioned HERA, upping the laser power from 1 to 150 kilowatts, and boosting the conversion of ALPs back into photons by installing an optical cavity behind the wall. DESY experimentalist and collaboration spokesperson Axel Lindner says they hope to have the upgraded facility ready by 2018.



Ralph Engel

Out of obscurity
The FUNK experiment in Germany is looking for hidden photons, a WISP candidate that cannot be detected directly but can hopefully be discovered using a large mirror.

Hide and seek

Other experiments, meanwhile, have been looking for an altogether different kind of WISP: the hidden photon. If such a particle exists and has a small mass, it might "oscillate" into ordinary photons just as neutrinos oscillate from one "flavour" to another. We cannot detect hidden photons directly, but could infer their presence if we see normal photons disappearing and then reappearing as they travel through space.

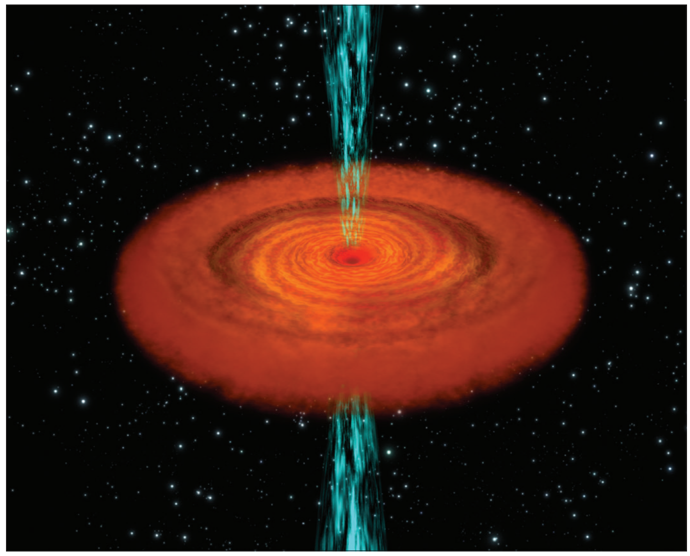
A couple of light-shining-through-a-wall experiments have looked for hidden photons, so far without success. These are the CERN Resonant WISP Search (CROWS) and the Microwave Resonator Group Axion Converter (ORGAN) at the University of Western Australia in Perth, both of which operate at microwave frequencies. ALPS-II also plans to join the search.

A more unconventional approach is being taken by a mainly German collaboration named FUNK – Finding U(1)s of a Novel Kind – which uses a $13\,m^2$ section of a spherical aluminium mirror at the Karlsruhe Institute of Technology. The idea is that any incident dark matter in the form of hidden photons would excite electrons in the mirror's surface, causing standard photons to be emitted at right angles to that surface. Since other standard photons bouncing off the mirror collect at a focus midway between the sphere's surface and its centre, a receiver placed at the sphere's centre could in principle allow any tiny hidden-photon signal to be distinguished from background light.

The researchers have finished aligning the mirror's 36 segments and are now in the process of attaching a set of low-noise photomultiplier tubes to target hidden photons at optical frequencies. Collaboration spokesperson Babette Döbrich of DESY estimates that they could have their first results within a year.

The art (and science) of letting go

Each variety of WISP experiment has its advantages and disadvantages, being designed to hunt for certain kinds of particle and optimized for particular



Going the distance The fact that very-high-energy gamma rays make it from distant sources such as quasars to Earth could be explained if they convert into WISPs for part of their journey.

regions of parameter space. But that doesn't prevent physicists from having favourites. Theorist Jonathan Feng at the University of California, Irvine, for example, believes the theoretical motivation for axions puts the ADMX in a strong position (helioscopes and light-shining-through-a-wall experiments having little or no sensitivity to axions as opposed to ALPs). "The ADMX is probing the heart of the axion parameter space," he says. "In that sense I would give it a slight edge over other experiments."

Indeed, Feng describes hidden photons as "more of a fishing expedition". But he argues that the pay-off from a potential discovery would be enormous. "These experiments may see nothing, but success would give you an entry point into a whole new world," he says. Hidden photons, he points out, might be accompanied by a whole slew of other particles, such as hidden electrons. "It would be a huge stimulus to new research, and much more revolutionary than the discovery of the Higgs boson."

For the moment, WIMPs remain physicists' overall favourite for dark matter. But they are looking less of a shoo-in than they were a few years ago. They may appear after the LHC starts colliding protons at energies of 1.3×10^{13} eV next month, following a two-year shutdown for maintenance. Or they may pop into being in around a decade, when the LHC is due to start operating at higher intensities. However, if they don't appear by then, Feng says he "will start working on other things".

Axion pioneer Sikivie, who is convinced that at least some, and perhaps all, dark matter is made up of ALPs, believes some physicists may be reluctant to give up on WIMPs. "Theorists can always find ways to circumvent null results," he says. "Supersymmetric models have a lot of parameters and you can change your predictions to go to various corners of parameter space."

WISP hunters and foolhardy travellers, it seems, are not the only ones unable to resist a bright, receding object. ■