D. PARKINS

Welcome to the dark side

Physicists say that 96% of the Universe is unseen, and appeal to the ideas of 'dark matter' and 'dark energy' to make up the difference. In the first of two articles, **Jenny Hogan** reports that attempts to identify the mysterious dark matter are on the verge of success. In the second, **Geoff Brumfiel** asks why dark energy, hailed as a breakthrough when discovered a decade ago, is proving more frustrating than ever to the scientists who study it.

We're underneath 1,400 metres of Italian mountain, walking through cavernous halls that lead from a 10-kilometre-long road tunnel. The scientists working within the Gran Sasso National Laboratory near L'Aquila seem ant-like in scale against the backdrop of vast metal spheres, towers and scaffolding that house their underground experiments. Physicist Elena Aprile is hurrying the group along, pointing out one project after another. She stops to take a photo of one, exclaiming at its size. We finally reach Aprile's XENON10 experiment, which is tucked away at the end of a small side tunnel. This is the project into which Aprile has poured her energy over the past few years, one of several experiments at Gran Sasso and around the world that are waiting for a passing piece of 'dark matter' to show itself.

Once upon a time, waiting for new particles to reveal themselves was a major endeavour. Scientists in the 1940s would also head to the mountains — to their tops, not to underground caverns — carrying emulsion-covered plates to capture strange new cosmic rays. But as particle accelerators became more powerful, physicists became adept at making their own novelties, and lying in wait for chance discoveries fell out of fashion. In this, dark-matter searches are something of a throwback.

They are a reminder of the past in another way, too. Ever more powerful accelerators require ever vaster detectors and ever larger teams of people to make sense of their output. The Large Hadron Collider (LHC) under construction at CERN, the European particle-physics laboratory just outside Geneva, will cost €3 billion (US$4.1 billion) and is the work of thousands of scientists and engineers. The XENON10 detector is run by just 30 scientists, and that's part of its attraction. "It's a last chance to do physics like it used to be done," says Aprile.

In the hunt for dark matter, a small team can make a big difference. XENON10 has steamed ahead of older collaborations to become the most sensitive detector for a category of dark matter called weakly interacting massive particles, or WIMPs. Other collaborations are keen to wrest the lead back, and over the next two to five years, sensitivity records look set to fall repeatedly. "A few years ago, I would have been surprised if dark-matter detectors had found a WIMP," says Leszek Roszkowski, a theorist from the University of Sheffield, UK, on sabbatical at CERN. "In a few years' time, if our ideas are correct, I will be surprised if they don't."

The dark titans

The first hints of dark matter came in the 1930s, when astronomer Fritz Zwicky spotted something odd about the behaviour of galaxies in the Coma cluster. His measurements of the galaxies' velocities suggested that the cluster was held together by more mass than he could see. He wrote: "If this is confirmed, we would arrive at the astonishing conclusion that dark

matter is present with a much greater density than luminous matter."

Cosmologists now believe that dark matter provides the scaffolding around which all other cosmic structures, from galaxies to galaxy clusters, superclusters and more, have taken shape. Astronomers are building big telescopes that can map its distribution in the heavens (see 'The search for structure', page 244). But this dark stuff cannot be the everyday matter of which stars, gas clouds and planets are made. Detailed measurements of the microwave radiation left over from the Big Bang suggest that such ordinary matter makes up just 4% of the Universe. The rest is thought to be divided between dark matter — outweighing normal matter by five to one — and a strange repulsive force dubbed dark energy (see 'A constant problem', page 245).

"If you look at the history of the Universe, it's been the battle of the two dark titans," says Michael Turner, a cosmologist at the University of Chicago, Illinois. "For the first 10 billion years, dark matter reigned, and it shaped all the structure in the Universe, and then, about five billion years ago, dark energy took over, shut off the formation of structure and got the Universe accelerating."

The idea that dark matter might not just be dark but fundamentally different from other matter gained ground in the 1970s. Planning for underground detectors similar to Aprile's began in the 1980s; but the field has heated up only recently as the sensitivity of WIMP detectors has improved — and as competing experiments have emerged to attack the problem from other angles.

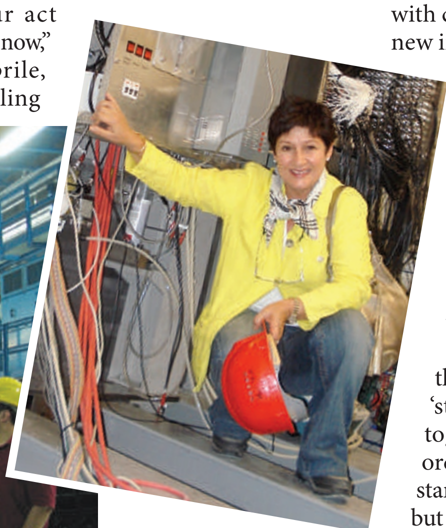
Producing particles

Most of the particles that theorists have suggested as possible WIMPs are massive — at least 100 times the mass of a proton. Their size has kept them beyond the reach of particle accelerators, but the LHC could well change that, and produce in the lab what the dark-matter detectors have so far failed to capture in the field.

While researchers at the LHC have a new collider to tackle the problem, astronomers are taking yet another approach. Some of the WIMP particles that theorists are fond of might give off distinctive bursts of γ-rays or other odd signatures when they interact with each other; satellites and telescopes are now looking for such signals.

But the scientists trying to catch a piece of dark matter using their underground experiments still hope to get there first. "If you don't get your act together now," says Aprile, "the feeling is that you're going to be too late." Even those who have worked at CERN in the past, such as dark-matter researcher Bernard Sadoulet, now at the University of California, Berkeley, hope for a return on their investment in direct searches. "Of course after putting 20 years of my life into this thing, I would like to see it first," says Sadoulet.

J. HOGAN



Elena Aprile hopes her underground detector will catch dark matter.

Any of these experiments could individually provide evidence for a dark-matter particle. To date, there has been only one claim of direct particle detection, and that remains controversial (see 'Contested results'). So multiple lines of evidence will be essential for scientists to claim with confidence that they have discovered a new ingredient of the Universe — especially because that particle might point to a new framework of physical laws.

"There's never been a more fun time to wonder about dark matter," says physicist Max Tegmark of the Massachusetts Institute of Technology in Cambridge. "It really feels like we are on the brink. There are these different roads to dark matter and they are all on the verge of coming through."

No one knows what dark matter is, but they know what it's not. It's not part of the 'standard model' of physics that weaves together everything that is known about ordinary matter and its interactions. The standard model has been hugely successful, but it also has some problems, and in trying to fix these, theorists have predicted hordes of new fundamental particles. At first, these hypothetical particles were viewed as unwelcome

CONTESTED RESULTS

Has dark matter been seen already? The DAMA collaboration based in Italy claims that an annual oscillation in the number of events registered by its underground detector is a dark-matter signal, but others are sceptical. "It is getting more and more difficult to reconcile DAMA with all the other results in the field," says Bernard Sadoulet, spokesperson for the CDMS, a competing dark-matter detector in the United States.

Over the course of a year, the number of dark-matter particles hitting Earth is expected to vary because the planet's velocity with respect to the rest frame of the Galaxy (and that of the Galaxy's dark matter) changes. In the summer, Earth moves in the same direction as the Sun does about the Milky Way's centre, so their velocities add together; in the winter these motions are opposed.

The DAMA experiment, based at the Gran Sasso National Laboratory near L'Aquila, Italy, looked for this effect between 1995 and 2002. Sure enough, the detector registered more particles hitting its 100-kilogram sodium iodide target in the summer than in the winter, and the team concluded that DAMA was seeing dark matter.

The problem is that other detectors searching for dark matter have failed to see any particles with the properties they would expect from the DAMA results. Critics of the experiment worry that other factors that could give a seasonal variation — such as temperature differences, or changes in conditions underground — were not fully accounted for. DAMA scientists say they have addressed these issues, and argue that the dark-matter particle must be something more exotic.

Hopes of moving the debate forward rest on an upgraded detector called DAMA/LIBRA, from which results are expected before the end of 2008. **J.H.**

BENDING THE RULES

Careful measurements in the 1970s showed that the outer stars of galaxies travel too quickly for the gravity of the galaxies' visible mass to hold on to them. Dark matter was invoked as one way to provide the extra gravity needed. But not everyone agrees that a new form of matter is necessary. Some scientists proposed modified newtonian dynamics, or MOND, as a way to explain the observations.

First suggested in 1981, MOND holds that gravity weakens less slowly with distance than expected. The modern version of the theory has a few supporters, but it hasn't gained wider acceptance because there are many cosmic observations it struggles to explain.

MOND seemed to get a further knock last summer when NASA announced "direct proof of dark matter" from observations of two colliding galactic clusters.

NASA/M. MARKEVITCH *ET AL.*/D. CLOWE *ET AL.*

Astronomers can study dark matter by looking at how light has been bent around galaxy clusters, a phenomenon known as 'gravitational lensing'. Lensing revealed the mass distribution of the clusters to be distinct from that of the clusters' hot gas.

Researchers concluded that the 'bullet cluster' (pictured) had formed when one cluster tore through another. They suggested that the galaxies' gas got caught up in the collision, but the dark-matter particles shot straight through.

MOND researcher HongSheng Zhao of the University of St Andrews, UK, agrees that this is evidence for some kind of dark particle. But he doesn't accept that it rules out MOND — arguing that MOND plus ordinary neutrinos can explain the observations. Pursuing alternative theories is healthy, says Zhao, and this interpretation will be tested by future measurements of neutrino masses. **J.H.**

additions, but now some of them are leading candidates for dark matter. "These days a theory without a dark-matter candidate is not considered an interesting one," says Roszkowski. "The existence of the dark-matter problem is perhaps the most convincing evidence for physics beyond the standard model."

Many of today's leading theories for physics beyond the standard model are variations of 'supersymmetry', which posits that each ordinary particle has a heavier supersymmetric partner. Several of these partners have been put forward as candidate WIMPs, and, remarkably, calculations of the number of such WIMPs expected to be left over from the Big Bang match cosmological observations of dark matter. This coincidence helped to strengthen the case for dark matter being a new kind of particle, although the numbers take some getting used to. Assuming a typical WIMP has a mass 100 times heavier than a proton, models of the dark matter in the Milky Way predict there will be roughly ten billion WIMPs passing through one square metre of Earth every second. For these particles to zip by unnoticed requires ordinary matter and light to barely register their presence.

It also makes WIMPs incredibly difficult to spot. Calculations suggest that almost a million billion dark-matter particles pass through Aprile's XENON10 detector every week — yet only the tiniest fraction would ever be detected. The XENON10 experiment works on the principle that a passing WIMP should very occasionally bump into a xenon atom — a fat target, with 54 protons and 54 electrons. Such collisions would release energy through a handful of photons and electrons, which can be detected by sensitive instruments.

In common with other experiments that aim to directly detect dark matter, XENON10 is housed underground because the rocks above it absorb particles and radiation, such as cosmic rays from outer space, that might otherwise confuse the data. The challenge for the experimental teams is to block out as much of this 'background' as possible and see what's left.

> **"You could jump up and down and say we've found ten WIMPS, but of course we haven't."**
> — Elena Aprile

Aprile announced XENON10's first results earlier this year[1]. The findings are yet to be published, but they took the community by surprise, not least because the previous best result belonged to an underground experiment using totally different technology. Rather than trying to trap dark-matter particles in a 15-kilogram vat of xenon liquid as the XENON10 detector does, the Cryogenic Dark Matter Search (CDMS) in Minnesota looks for vibrations and charge created by particle collisions in a very cold crystal of germanium and silicon. Until Aprile's result, experiments with noble liquids had been lagging behind.

In its first run, XENON10 registered 10 events over 60 days that couldn't be instantly dismissed. "You could jump up and down and say we've found ten WIMPs, but of course we haven't," she says. Aprile's team ruled out half of the events on closer inspection, and the rest were assumed to be background signals that slipped through the analysis. The researchers would have needed at least 15 events that could not be explained in other ways to think they'd caught a whiff of a WIMP, and Aprile says that, even then, they would need to understand the background better before claiming a direct detection.

Setting limits

In the meantime, a negative result is still important. The sensitivity of the XENON10 detector allows the researchers to set limits on the properties that a hypothetical WIMP might have — such as how heavy it is and how much it interacts with matter. This is crucial information when what you are hunting for is as mysterious as a dark-matter particle. XENON10 now claims a tighter limit than the previous best result. The experiments are starting to eat into the regions where supersymmetry predicts WIMPs should be (see 'WIMP hunting').

Other projects are close on XENON10's heels, searching for particles that might interact even more feebly. To improve their chances of finding a particle, dark-matter detectors need to do two things: get bigger and reduce the background.

Designers of a rival xenon-based experiment, Zeplin-III, have taken great care to minimize stray signals reaching their detector, and this experiment is expected to yield results within the next year or two. The Zeplin project, a UK collaboration, started life in the early 1990s and the team had been in talks with Aprile before she decided to strike off on her own. "It's frustrating that they came into this game when we already had the Zeplin designs and picked off the best bits," says project spokesperson Tim Sumner of Imperial College, London, "but we should take the positive out of it; it shows the technology works."

With their latest 12-kilogram detector

installed in the corner of a potash mine in Cleveland, UK, the group is confident: "We have faith that Zeplin-III will be better than XENON10," says Sumner. This will help set even tighter limits on background noise, but "the glory will come with the first detection".

Closer to home, XENON10 has several rivals at Gran Sasso. The container that Aprile snapped a picture of during her tour will soon be the centrepiece of WARP, the WIMP Argon Programme, an experiment led by Carlo Rubbia, who won a share of the Nobel Prize in Physics in 1984 for his part in the discovery at CERN of the force-carrying particles known as the *W* and *Z* bosons. WARP will use a large vat of liquid argon to trap dark matter. "This is serious competition," says Aprile, who is a former student of Rubbia's.

Aprile is also upgrading XENON10 over the next few months by reducing the background and increasing the detector's size to 60 kilograms of liquid. A bigger vat boosts the chances of finding a WIMP, because having more mass makes it more likely that a dark-matter particle will interact. "The next step that is sensible is to go to one tonne; it doesn't make any sense any more to screw around with these little things," Aprile says.

Paying the price

But bigger detectors require more money. In a report published on 13 July, the Dark Matter Scientific Assessment Group, established last year by the US Department of Energy and National Science Foundation, recommended that US funding for dark-matter research be bumped up from less than $4 million per year to $10 million annually. This won't fund experiments at the tonne-scale, but it should accelerate testing of the different technologies, says Hank Sobel, chair of the group. The panel recommends that another review be carried out in 2009 to decide how to move to large-scale detectors.

It is easier to scale up the liquid approaches than the solid-state experiments, but the CDMS detector can more easily identify and eliminate background. The CDMS did undergo an upgrade a year ago, from one kilogram of germanium to four. That should mean that its next result, due at the end of the summer, will equal or better that of XENON10. "Over the next year, we should be able to increase our limits by at least a factor of 10 or 15, or discover something," says Sadoulet, who is the spokesperson for the CDMS.

Despite the enthusiasm, there is still a chance that nature will refuse to cooperate, and the experiments will chase ever better limits but never detect a particle. Some of the WIMP candidates predicted by supersymmetry are "essentially undetectable", warns Roberto Trotta, a theoretical physicist at the University of Oxford, UK. The particles may be too heavy to be created by the LHC and at the same time too weakly interacting to be detected by the underground experiments. "I think in the next ten years, we are going to see big discoveries; if not we are going to be in big trouble," says Trotta.

A. ROSZKOWSKA

"These days a theory without a dark-matter candidate is not considered an interesting one." — Leszek Roszkowski

When the LHC smashes together its protons in 2008, WIMPS might be created in the messy outpouring. The collider's detectors wouldn't be able to register these directly, but they would show up as 'missing mass' when the physicists piece together the energy budget of the collisions. Because such evidence is indirect, finding a WIMP signature at the LHC would not confirm it to be dark matter. "There would still be a window open," says Roszkowski. For example, a particle might be stable for the fractions of a second that it takes to fly out of the collider, but then decay elsewhere. That means a second route — direct detection — would be necessary too. "We absolutely need both to resolve the dark-matter problem," he says.

But the collider can provide additional theoretical context. For instance, should it be lucky enough to identify a particle, the LHC should be able to place it in a supersymmetric family tree.

Different supersymmetry theories predict superpartners with different masses — including the axino, gravitino or neutralino — as WIMP candidates. The dark-matter candidate is always the lightest partner, because this can't decay into anything else. Many of the simplest models predict that the neutralino, a particle that is a combination of the superpartners of four other particles, will be the lightest, and thus stable enough to have survived from the Big Bang until now. Consequently, this strange particle — it acts as its own antiparticle — is the most popular WIMP candidate among particle physicists.

A third route to detecting neutralinos will search for evidence of their destruction. Because

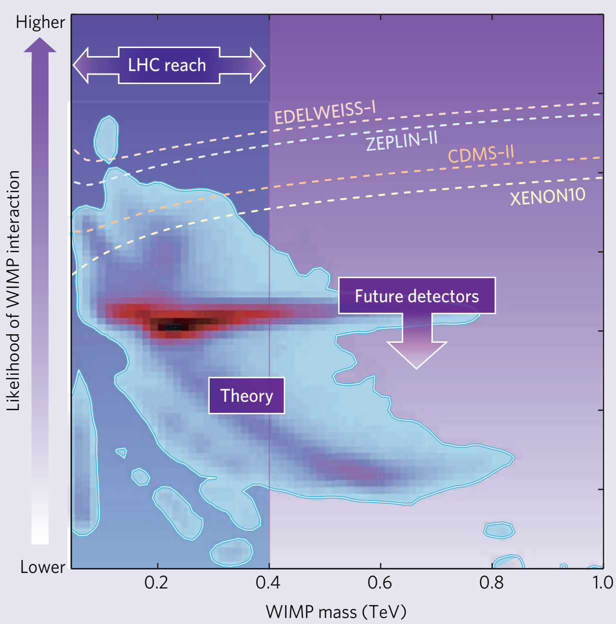
WIMP HUNTING

So far, detectors hoping to catch dark-matter particles known as WIMPS haven't found a thing, but it isn't all bad news.

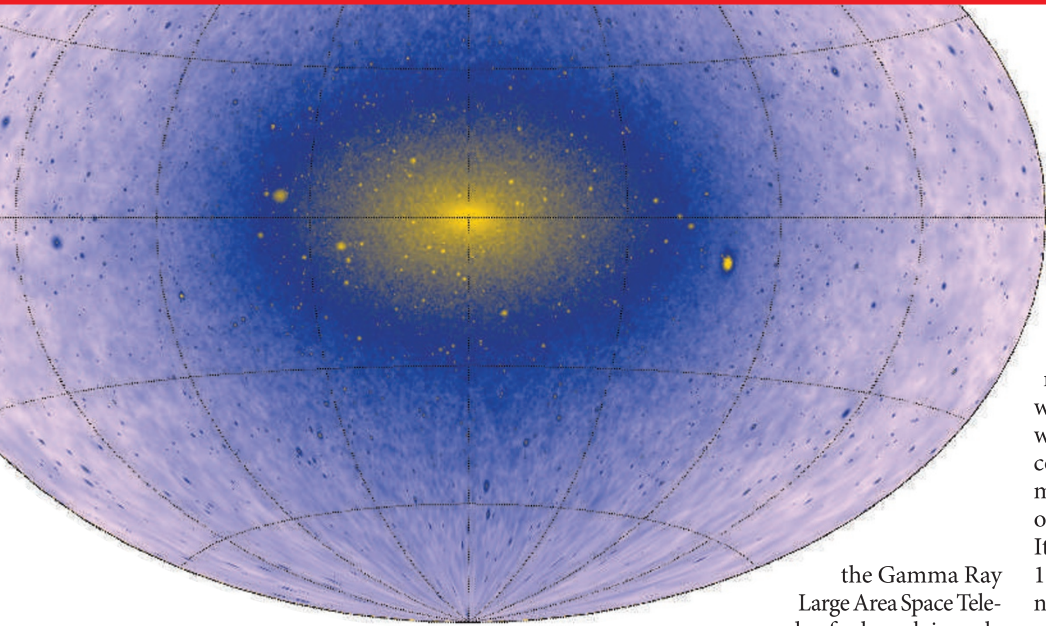
Physics models that predict the existence of WIMPs can be used to calculate their likely properties. In this plot, the splodges define one guess about what the neutralino (a popular WIMP candidate) might look like[2].

Particles with properties above the detector-sensitivity limits (see lines across the plot) are ruled out by the experimental results so far; anything below them, including most of the theoretical splodge, is still possible.

Within the next few years, the detectors should reach the red heart of the splodge, where calculations say the neutralino is most likely to lie. Meanwhile, the Large Hadron Collider might make some neutralinos, but only if their mass is light enough. **J.H.**



L. ROSZKOWSKI ET AL. J. HIGH ENERGY PHYS. (IN THE PRESS)



M. KUHLEN, J. DIEMAND & P. MADAU

Now you see it: dark matter in the Milky Way could generate a γ-ray glow.

neutralinos are their own antiparticles they should annihilate each other in regions where they are close enough together to bump into each other. This self-destruction could show up in the form of γ-rays, neutrinos or matter and antimatter particles.

For example, models of dark matter in the Milky Way suggest that annihilation of neutralinos concentrated in the Galaxy's dark-matter halo and in the galactic core could generate a γ-ray glow (see picture). Satellites such as the Gamma Ray Large Area Space Telescope, due for launch in early 2008, could spot this. Moreover, annihilation of neutralinos clumped in the core of the Sun could be inferred from measurements made by neutrino telescopes, such as the IceCube Neutrino Detector being built at the South Pole, because such annihilation would generate higher-energy neutrinos than expected from other processes.

But what if dark matter isn't a neutralino or even a WIMP? Some proposals to explain dark matter don't depend on supersymmetry or WIMPS at all. These range from doing away with the need for dark matter by modifying the laws of gravity (see 'Bending the rules') to suggesting other types of particle altogether.

The main rival to the neutralino is the axion, first proposed by particle physicists in 1977 to resolve a glitch in the standard model. Many theorists believe that the axion will eventually be found, but it is unclear whether its mass and interactions will match cosmological expectations. Already the axion mass is constrained on one end by theory and on the other by observations of supernovae. It is consequently predicted to be at least 10 million million times lighter than a typical neutralino.

The Axion Dark Matter Experiment, at the Lawrence Livermore National Laboratory in California, aims to give a definitive answer to the axions' part in dark matter. Leslie Rosenberg, co-spokesperson for the experiment, says the team expects results by 2011, after the detector moves to its final home at the University of Washington in Seattle. Axions interact so weakly that they are rarely produced in particle colliders, so the experiment will look for signs of axions using a radio receiver that can detect tiny particle energies.

There are far fewer searches for axions than there are searches for WIMPs. Rosenberg thinks this is partly because the technology

THE SEARCH FOR STRUCTURE

When it was first conceived, almost a decade ago, it was known as the Dark Matter Telescope. With one of the largest astronomical mirrors ever cast, and a unique wide field of view, it was designed to pick up the faint lensing of light produced by clumps of dark matter from distant galaxies, revealing dark matter's mysterious behaviour and, perhaps, its nature.

It has been renamed the Large Synoptic Survey Telescope (LSST). The more generic name reflects the degree to which the telescope's capabilities will be exploited by an ever wider range of astronomers. When the LSST starts its surveys sometime next decade, dark-matter mavens peering into the depths of space will rub virtual shoulders with those looking for the asteroids closest to Earth — and with the aficionados of dark energy. Although dark energy had not even been discovered when the LSST was first dreamt up, the new telescope should provide the sort of structural data that scientists need to deepen their understanding of the Universe's acceleration (see 'A constant problem', opposite).

But despite the LSST's accumulated endorsements, it has not reached the front of the queue for receiving money from the US National Science Foundation. Without a firm commitment on its $375-million budget, no one can say for sure when construction at the top of Cerro Pachón, the 2,682-metre peak in Chile that has been chosen as the site, will actually get under way. Meanwhile, an upstart rival, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) is already being assembled atop Mount Haleakala in Hawaii with the help of funding extracted from the Department of Defense by a friendly senator.

Thanks to Senator Daniel Inouye (Democrat, Hawaii) Pan-STARRS gets about $10 million a year through the Air Force as a congressional 'earmark', and the team involved is using that cash to get its telescope up and running as soon as possible. Team members have bought electronic equipment off eBay to save time and money, and the telescope design is simple and quickly assembled, according to project director Kenneth Chambers, an astronomer at the University of Hawaii in Honolulu.

The first of the 1.8-metre telescopes built to the Pan-STARRS design, called PS1 (pictured opposite), saw first light in June of last year. The team is currently installing a 1.4-gigapixel camera — ten times the size of the camera used for the Sloan Digital Sky Survey, the most accomplished deep-space survey to date — and hopes to have its first survey data by autumn. The novel part of the project will come later, though, when this first telescope gets three identical companions.

The idea of multiple mirrors and cameras is not to increase resolution, as an interferometer does, but to improve sensitivity. All the signals from a given object will be added together by computers no matter which camera recorded them. The distributed design also provides the system with effective immunity to false data created by cosmic rays striking individual cameras, says Nick Kaiser, Pan-STARRS principal investigator and an astronomer at the University of Hawaii in Honolulu.

Group members are bullish about the possibility of getting significant findings on dark matter and energy before the LSST comes online. "The real advantage of Pan-STARRS over the LSST is that being a small, fast, somewhat entrepreneurial group, we're there

needed to find them is less familiar to particle physicists. In addition, he says, "there's a tremendous bandwagon to supersymmetry, and WIMPS are riding on that". Even if dark matter turns out to be something completely different, the experimental teams are determined to track down their particular quarry and get an answer, one way or another. "I live with that with the impatience of the Italian woman that I am," says Aprile. "I am just going fast ahead with the next step, making the detector better."

But success for one type of experiment doesn't have to mean failure for another. Scientists prefer simplicity: if they find WIMPS, then they don't need axions, and vice versa. But why not have both? Dark matter might prove to be a richer problem than anyone is expecting. Tegmark hopes for this outcome. "This could be a wonderful surprise. It's very arrogant of us humans to say that just because we can't see it, there's only one kind of dark matter." ■

Jenny Hogan is a reporter for *Nature* in London.

1. Angle, J. *et al.* preprint at http://arxiv.org/abs/0706.0039 (2007).
2. Roszkowski, L., Ruiz de Austri, R. & Trotta, R. preprint at http://arxiv.org/abs/0705.2012 (2007).

See Insight, page 269, and Editorial, page 225.

A constant problem

Why is dark energy, hailed as a breakthrough when discovered a decade ago, proving so frustrating to the scientists who study it?

In 1998, two teams of astronomers reported that the Universe was pulling itself apart. This came as something of a shock. That the Universe was expanding had been known since the 1920s, but conventional wisdom held that this expansion was slowing and was likely, in the distant future, to come to an all but complete halt. Then, in the late 1990s, observations of distant supernovae showed that the expansion was not slowing down at all. It was speeding up. This discovery was incredibly counterintuitive, recalls Charles Bennett, an astronomer at Johns Hopkins University in Baltimore, Maryland. "I just didn't believe it."

Within a few years, however, he and almost all his peers could withhold their belief no longer. The observations became stronger. And the expansion provided a way out of a theoretical impasse. Observations of the Big Bang's afterglow made by various groups, including Bennett's, indicated that the Universe's gravity had flattened it out. But other observations suggested that it simply didn't contain enough matter to have that much of a gravitational effect — even when as-yet-undiscovered forms of dark matter were included in the sums (see page 240).

Happily, the theory of relativity requires energy, as well as matter, to have a gravitational effect. And it turned out that the amount of energy needed to drive the acceleration was pretty close to that needed to solve the flatness problem by means of its gravity. 'Dark energy', as it quickly became known, seemed poised to provide great insight into the origin and future of the cosmos, says Michael Turner, a cosmologist at the University of Chicago in Illinois. "This seemed to be the piece that made everything else work."

But a decade further on, researchers seem to have swapped one theoretical conundrum for a bigger one. Follow-up measurements have

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seven or eight years earlier," says Chambers. But integrating the four data sets and processing the data will be no mean feat; building the first telescope was, comparatively speaking, the easy part.

The LSST is revolutionary in different ways. On top of its unique mirror design, there's the sheer amount of data that it will accumulate. Its 3.2-gigapixel camera should, over the course of the telescope's life, produce more than 100 petabytes of data. That's as much information as contained in the whole genome of every animal on Earth, according to Tony Tyson, the astronomer at the University of California, Davis, who has headed the LSST project since its days as the Dark Matter Telescope. The sheer amount of data to be made sense of is one of the reasons the LSST is happy to have formed a partnership with Google. The Sloan Survey gathered data at a rate of 200 gigabytes a night; the LSST is aiming for 30 terabytes.

B. SIMISON

The databases produced by both the LSST and Pan-STARRS will provide astronomers with more than just measurements of dark energy and matter. Both telescopes plan to image wide swaths of the sky multiple times, allowing astronomers to spot things moving in the Solar System, as well as changing phenomena in the depths of the sky. The potential for discovery is enormous, says Tyson. Kaiser agrees. "You're going to get a sort of movie of the sky," he says.

For now, it seems that Pan-STARRS has the edge in the race to map out the Universe's darkest quarters. But if the LSST team is put out, then the group does its best not to show it. "If they make discoveries before LSST gets online, great," says Steven Khan, the LSST deputy director at the Stanford Linear Accelerator Center in California. "To date it hasn't really been a problem." "It's healthy to have both Pan-STARRS and LSST," Tyson adds. **G.B.**