Into the dark

Dark matter particles secretly crossing to the regular world could open portals to the universe's hidden realm, finds Daniel Cossins

WE KNOW it is out there. It makes up the bulk of matter in the universe and sculpts its grandest features with a hidden gravitational hand. And yet, despite a long campaign to expose it, the mysterious cosmic architect known as dark matter continues to evade detection.

Myriad dark-matter hunters have spent decades trying to trap their prime suspect. They may yet prevail. But their struggle has led a new wave of hunters to try a different approach. Rather than tailoring their search for a single candidate, they are embracing the possibility that dark matter consists of a panoply of particles and forces – an entire dark sector operating in parallel to our own.

This hidden realm would be accessible by only the faintest lines of communication: particles capable of carrying messages from the dark side to the world of familiar matter. Now the plan is to track those go-betweens as they pass messages through these dark portals, wiretapping them to learn about the universe on the other side. "This is a shift in the way we think about the problem," says Jonathan Feng, a theorist at the University of California, Irvine. "It has reinvigorated the search."

All we know about dark matter comes from the way stars in the outer reaches of galaxies move faster than expected, given the amount of visible mass present. So fast, in fact, that the galaxies we see should have long since been torn apart. For some physicists, this is reason enough to believe that Einstein's laws of gravity are wrong. Others insist that some invisible form of matter must be lurking behind the scenes, holding the universe together.

Pitiful WIMPs

For decades, the prime suspect has been the weakly interacting massive particle, or WIMP. This hypothetical heavy particle is attractive thanks to a remarkable coincidence dubbed the WIMP miracle: when physicists calculate how many of them would have survived from the early universe to the present day, they get exactly the amount of dark matter we need to explain our observations. The other thing in their favour is that WIMP-like particles emerged naturally from supersymmetry – a mathematically elegant theory designed to smooth over wrinkles in the standard model, our best picture of particles and their interactions.

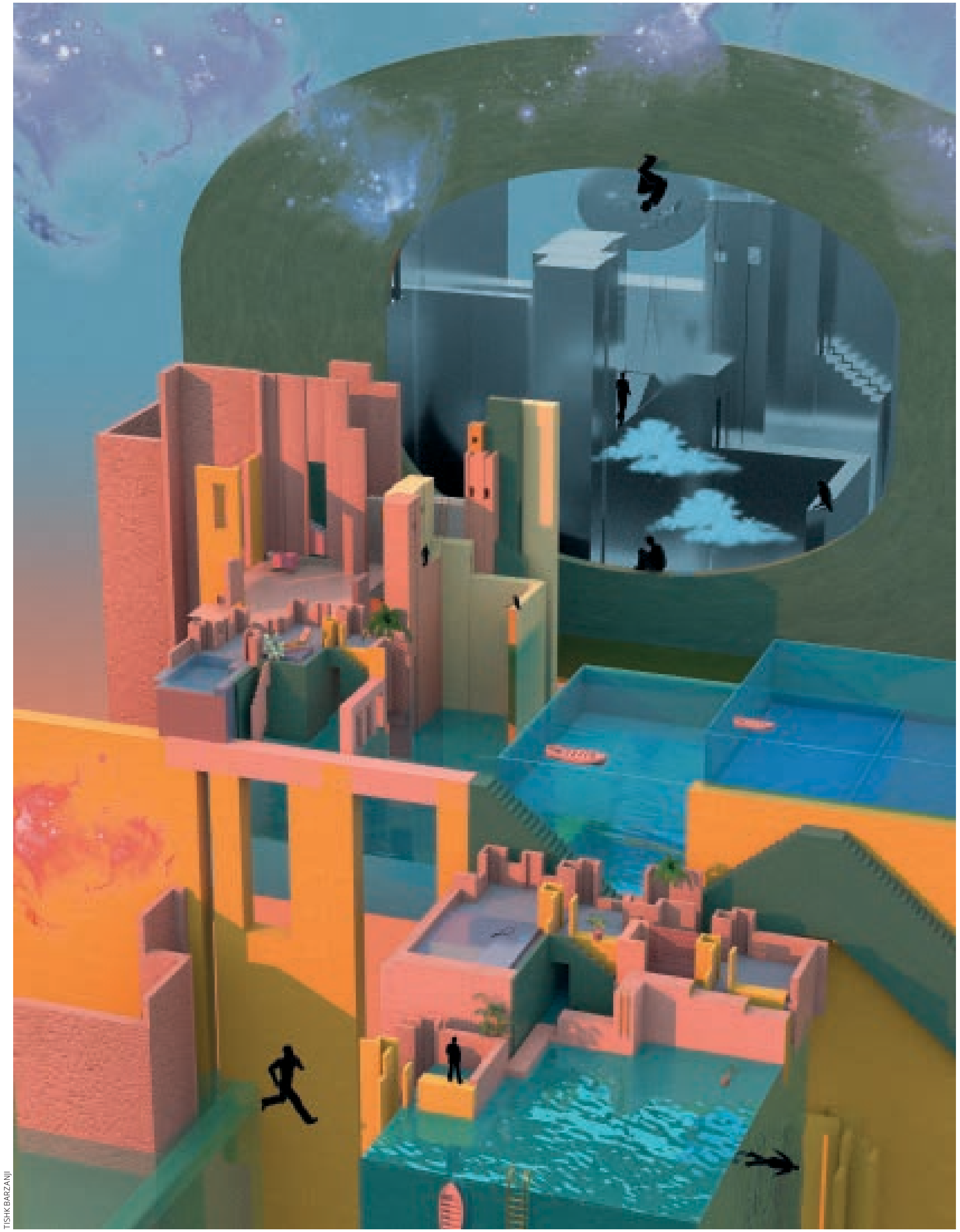
All told, WIMPs looked to be such hot suspects that it was merely a matter of smoking them out. In a boon to experimentalists, theory predicted that WIMPs would, in addition to the pull of gravity, feel the weak nuclear force, which is beefier but only works across tiny distances. This makes them capable of interacting with regular matter in experiments, and sparked a worldwide race to find them.

And yet there is no sign of them. Nor are there indications of any of the heavy partners of known particles that supersymmetry predicts. They might yet show up, of course, but our most promising candidate is running out of places to hide just as its theoretical underpinnings are looking shaky – and that scenario has pushed scores of younger dark-matter hunters in an intriguing new direction.

What Feng and others propose is that dark matter might consist not of any one particle but of an entire catalogue, all interacting with each other through a dark force that nothing in the regular universe can feel. The components of this dark sector might even form their own atoms and molecules, opening a whole new world of dark chemistry.

That might seems outlandish, but there are good reasons to consider the possibility. After all, the stuff we consider ordinary comprises a veritable selection box of particles, so no great leap of logic is needed to assume that the same holds true for dark matter. What's more, strange observations in recent years have hinted at the existence of dark forces – an indication that dark matter may be more complex than the WIMP-hunters believe.

The first observation is that dark matter appears to be spread more evenly within ›


TISHK BARZANJI

"The portals are mathematical – you can't drive a spacecraft through them"

JNAF

The hunt is on at the Jefferson National Accelerator Facility

galaxies than the WIMP models predict – something that can be explained if dark matter particles exert a repulsive force on one another, pushing themselves apart. Particle experiments on Earth have thrown up similarly suggestive anomalies, most recently in 2016 when researchers at a nuclear physics lab in Hungary noticed a beryllium atom decaying in a way that could be explained only by invoking a new force of nature.

Claiming a dark sector exists is all well and good, but deciding how to populate it is a different story altogether. "We could guess a potentially infinite range of dark sectors," says Brian Shuve at Harvey Mudd College in California. Fortunately, we don't have to. What Feng, Shuve and others have realised is that the search can be guided by hard data rather than theoretical guesswork. If the dark sector is capable of exchanging messages with the regular universe, then those rare points of contact turn into portals that can shed light on the world on the other side.

To be clear, we aren't talking about something you could drive a spacecraft through. "What we call portals are mathematical doorways," says Gordan Krnjaic at the Fermi National Accelerator Laboratory (Fermilab) near Chicago. These doorways allow for particles capable of feeling the dark force to interact with particles of regular matter. The most promising type of portal would be a direct metamorphosis – a dark sector particle transforming into one in the standard model. Fortunately, the invisibility of the dark sector allows us to dramatically narrow down where such portals can arise. The dark constituents must be chargeless, and as such particles cannot transform into charged ones, any go-betweens must be neutral particles.

Dark messengers

The three standard model particles that stand the best chance of interacting with such a dark mediator are photons, via the so-called vector portal; Higgs bosons, via the scalar portal; and neutrinos, via the neutrino portal. "If new particles exist, these portals are our best chance of creating and detecting them," says David Curtin, a theorist at the University of Toronto. All we have to do now is watch their every move.

It could take a while, but the stake-out has already begun. The most promising of the three is perhaps the vector portal, in which processes designed to produce ordinary photons would occasionally spit out a dark photon, their shadowy alter ego. Like a regular photon, such a particle would be extremely gregarious: it would interact with anything that has electrical charge. The strength of those interactions would also be reasonably large, meaning there are lots of places to look for it and that we stand a good chance of seeing it if it is there.

Moreover, the "dark photon" doesn't necessarily have to be perfectly analogous to the regular photon. It is just a proxy for all manner of vector bosons – the class of particles to which photons belong – that could form part of the dark sector. "It is one of a long list of possibilities," says Natalia Toro at Stanford University in California.

Toro performs experiments at the Jefferson National Accelerator Facility in Virginia that has been attempting to flush out dark photons for a few years. They fire a high-intensity beam of electrons at fixed targets to generate photons in the hope that, very occasionally, they will produce a dark photon too – identifiable by its telltale decay. Others, including Shuve, have looked for evidence of dark photons by revisiting decade-old data from the BaBar experiment at the SLAC accelerator in California, which smashed electrons and their antimatter counterparts together until 2008.

Although both efforts have come up empty-handed so far, the search has stepped up a gear. The more intense your beam, the more photons you produce, and the greater your chances of making a dark one. Those are the odds that several new higher-intensity experiments are hoping to exploit, including the Heavy Photon Search at the Jefferson Lab and Dark Light at the SLAC accelerator. As of last month, there is also the PADME experiment outside Rome. "It's a very lively area," says Toro. "But the truth is that we're really just getting started."

That much was clear in March 2017, when the entire field came together at the behest of the US Department of Energy, which is eager to find out how to get the biggest bang for its buck in pursuit of dark matter. There was no shortage of proposals for experiments aimed at rooting out dark photons. Among the most ambitious pitches, however, was one touting a new detector at the Large Hadron Collider near Geneva, Switzerland. Instead of using the photon as a bridge between the two worlds, Curtin and his team wanted to use a different portal, and spy on the Higgs.

The Higgs boson and its associated energy field are famous for giving other fundamental particles their masses. In a dark sector populated by massive particles, it makes sense to think of them getting their mass from a dark equivalent. Curtin says the best way to properly explore the Higgs portal is to produce lots of Higgs bosons – and the only place we can do that is at our most powerful atom smasher. Indeed, Curtin reckons the LHC might have been producing dark Higgses all along. But whereas the regular Higgs falls apart before it can escape our detectors, the dark Higgs' tendency to avoid interactions means it might be long-lived enough to get away scot-free.

We already know such long-lived particles exist, so there is no reason to think new particles from the dark sector won't also travel a great distance before they decay. The long-lived particles we find might be the dark Higgs or another kind of particle from the dark sector that interacts with the dark Higgs, says Curtin. "The only way to know is to find the long-lived particles and study their properties."

That might seem a quixotic task. After all, in theory, these particles could decay anywhere. But cosmological observations place a limit on how long they can last – roughly 0.1 seconds – so the trick is to cover a sufficiently large area around the LHC to catch them, regardless of the direction they travel from the point of collision. That is precisely why Curtin and his colleagues have proposed a new detector at the LHC to catch them. They call it MATHUSLA, after Methuselah, the biblical character who lived to the ripe old age of 969.

It would essentially amount to a huge barn above the beam line, with detectors hanging from the ceiling to track any particles that make it this far. With a cost of about $50 million, MATHUSLA wouldn't be cheap. But Curtin says it could be ready by 2026, when the LHC will be producing at least 10 times more Higgs bosons than it does now. "This is our best chance to see long-lived particles, including the dark Higgs," says Curtin.

MATHUSLA might also shed light on the third dark portal, provided by the neutrinos. As the smallest, lightest and least sociable of the known particles, neutrinos may seem uninteresting. In reality, though, they are bursting with mysteries. Not only are the three types of neutrinos somehow capable of transforming into one another at will, a process that is still not completely understood, but their masses are incredibly light for no good reason.

"It's possible the LHC has been producing dark Higgs bosons all along"

To explain these mysteries, physicists have invented a heavier fourth "sterile" neutrino that would be even harder to spot than the other three. Such a particle has all the hallmarks of a dark matter mediator, one capable of travelling through the neutrino portal to transform into regular matter.

The trouble is that, unlike the photon and the Higgs, neutrinos can only feel forces, not carry them. That means yet another particle would be needed to allow particles of dark matter to interact with the sterile neutrino. "That makes things more complicated," says Miguel Escudero at the University of Valencia, Spain, and probably explains why the neutrino portal has largely gone under the radar.

Keeping watch

Only in the past couple of years have people like Escudero begun to explore scenarios in which the dark sector talks to us through sterile neutrinos. The models they have come up with are promising, but depend on the confirmed discovery of a sterile neutrino. Several experiments are currently on the hunt, and hints of one coming from an experiment called miniBooNE at Fermilab grabbed headlines earlier this year. But for Escudero, it is premature to even suspect it could be the emissary to the shadow world we seek.

If we ever do start reliably producing such things, however, they will bring exciting new leads in our long quest to identify dark matter. "If the dark photon we identify decays invisibly, for example, meaning it decays to dark matter, that would tell us that the dark matter is lighter than the dark photon," says Feng. "Suddenly, we would know that dark matter is lighter than something. That would rule out 99.9 per cent of our theories."

It is impossible to say which, if any, of the portals will reveal the dark sector. In fact, to ask the question is to miss the point, says Flip Tanedo at the University of California, Riverside: "The reason we're squeamish to say 'here are the best candidates' is because we no longer think that way."

His generation is not driven by the same sense of certainty as previous generations, gripped as they were by supersymmetry fever and the rush to find WIMPs. "We're a bit humbler," says Tanedo. "We focus more on the experiments we can do to find something that will guide us." ■

Daniel Cossins is a feature writer at *New Scientist*