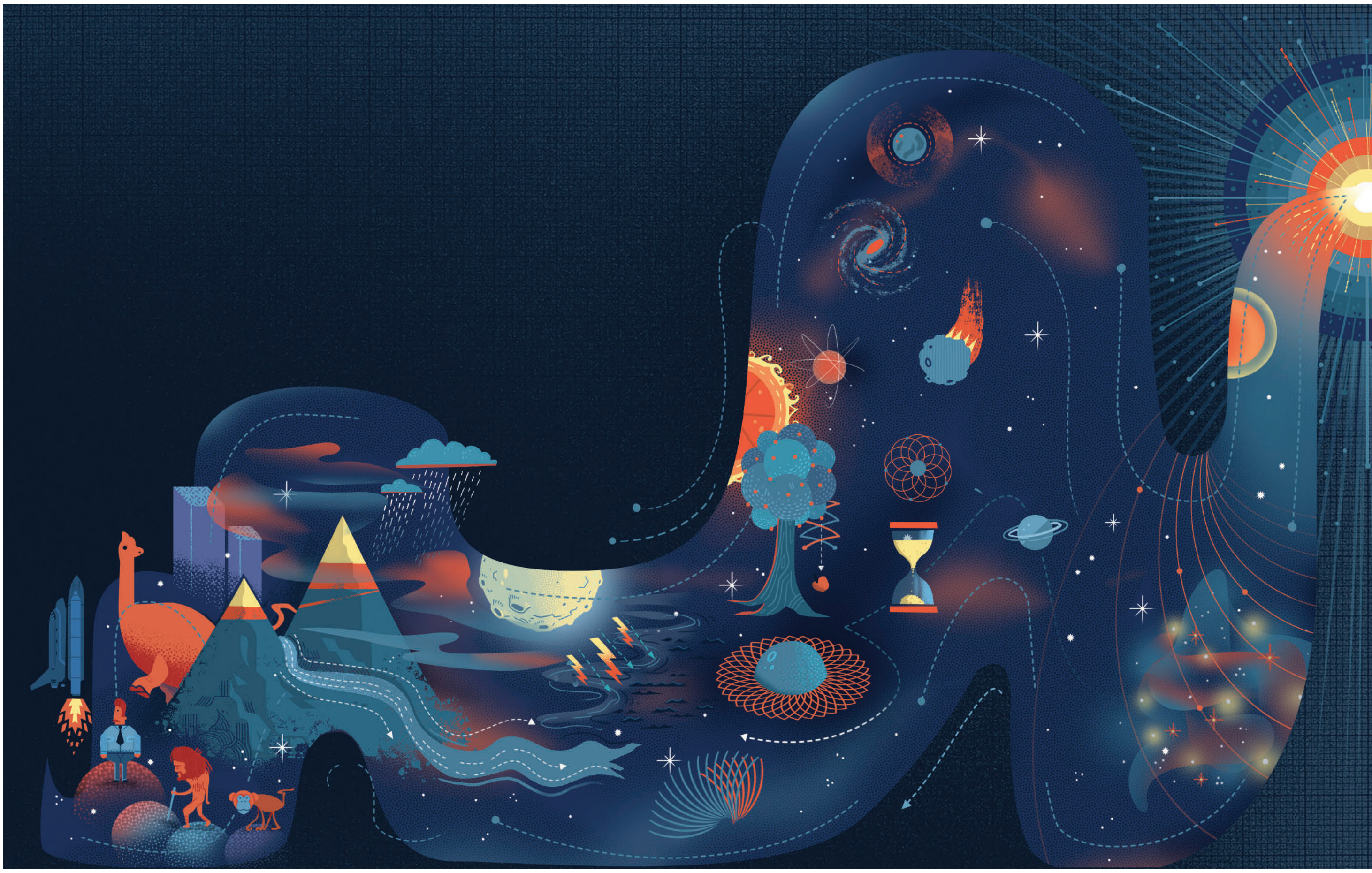


GRAHAM CARTER

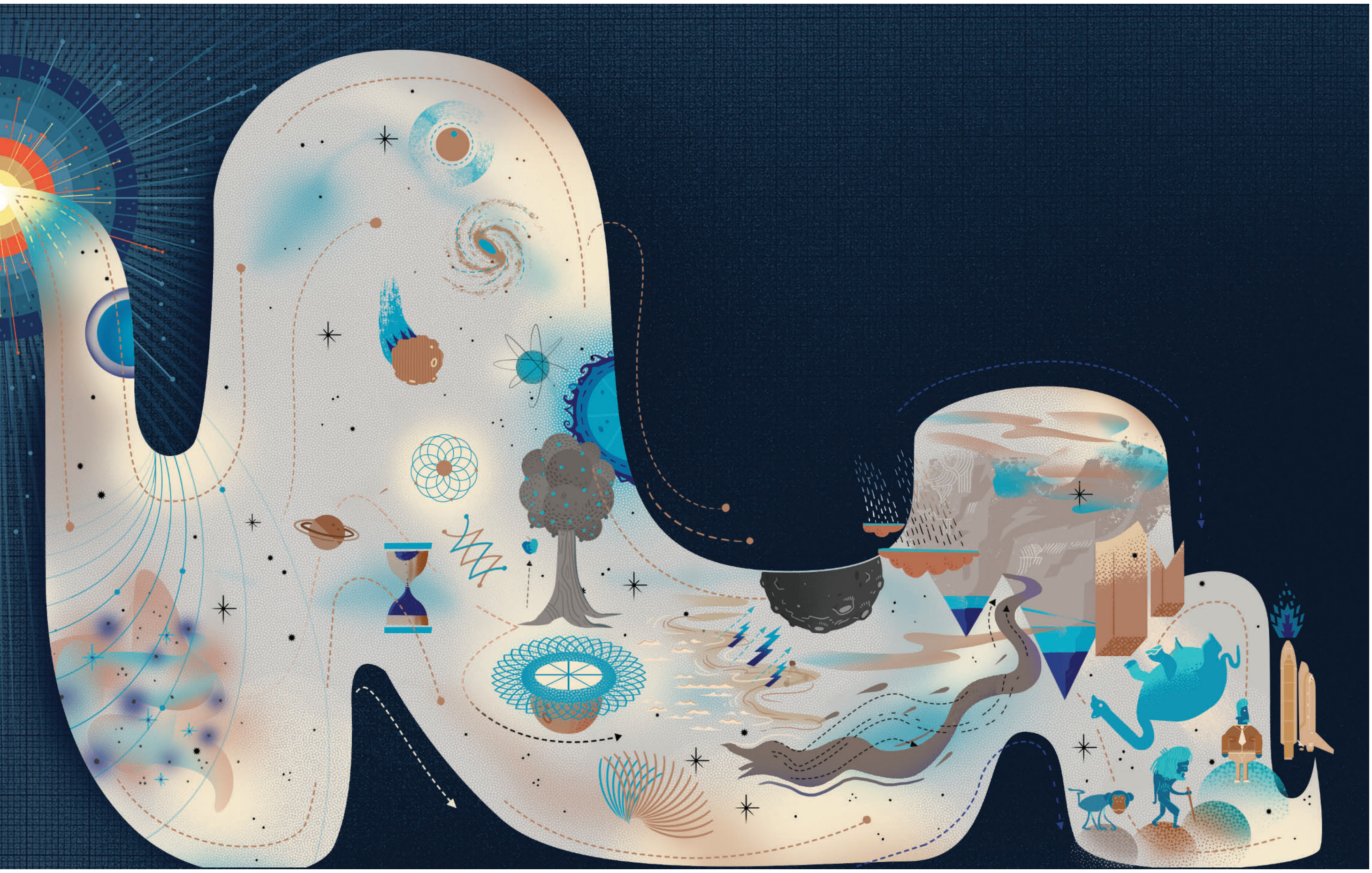
Welcome to the antiverse

Mysterious particles uncovered in the Antarctic could be evidence of a mind-bending mirror universe, reveals **Jon Cartwright**

IN THE Antarctic, things happen at a glacial pace. Just ask Peter Gorham. For a month at a time, he and his colleagues would watch a giant balloon carrying a collection of antennas float high above the ice, scanning over a million square kilometres of the frozen landscape for evidence of high-energy particles arriving from space.

When the experiment returned to the ground after its first flight, it had nothing to show for itself, bar the odd flash of background noise. It was the same story after the second flight more than a year later.

While the balloon was in the sky for the third time, the researchers decided to go over the past data again, particularly those signals dismissed as noise. It was lucky they did. Examined more carefully, one signal seemed to be the signature of a high-energy particle. But it wasn't what they were looking for. Moreover, it seemed impossible. Rather than



bearing down from above, this particle was exploding out of the ground.

That strange finding was made in 2016. Since then, all sorts of suggestions rooted in known physics have been put forward to account for the perplexing signal, and all have been ruled out. What's left is shocking in its implications. Explaining this signal requires the existence of a topsy-turvy universe created in the same big bang as our own and existing in parallel with it. In this mirror world, positive is negative, left is right and time runs backwards. It is perhaps the most mind-melting idea ever to have emerged from the Antarctic ice – but it might just be true.

The ambitions of the balloon experiment, the Antarctic Impulsive Transient Antenna (ANITA), were never so grand. Earth is constantly bombarded by particles known as cosmic rays that come from the furthest reaches of space, some of which have a million times more energy than we can generate with our best particle accelerators. Cosmologists are curious to know what these ultra-high-energy cosmic rays are made of and where they come from, but these questions are difficult to answer. For one thing, the trajectories of the rays are distorted by our galaxy's magnetic fields, making their point of origin almost impossible to trace.

"No known physics can account for the perplexing signal"

Luckily, whatever does generate ultra-high-energy cosmic rays almost certainly generates a more useful beacon: neutrinos. Owing to their lack of charge, these tiny particles are unswayed by magnetic fields, and zip through space in straight lines. As a consequence, locating the origin of a neutrino – and that of any cosmic rays generated in tandem – is simply a matter of extrapolating its trajectory backwards from its point of impact. And that is where ANITA comes in.

When a high-energy neutrino plunges into the Antarctic ice, it creates a shower of charged particles that generate radio waves. If ANITA detects these radio waves emanating from the surface, its researchers can figure out where the neutrino struck, and work out the origin of the accompanying cosmic rays. "There's nothing unknown about the process," says Gorham, an experimental particle physicist

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at the University of Hawaii and principal investigator at ANITA.

Yet it couldn't explain what the researchers identified in 2016. Instead of crashing into the ice from overhead, the high-energy particle they were dealing with seemed to have erupted from the ground, presumably having entered Earth on the other side. Normal, low-energy neutrinos can make such a journey, because they pass through matter with ease. But high-energy neutrinos hit an object as solid as a planet in something akin to a particle belly-flop: they simply can't pass through it unhindered. Neither can cosmic rays.

The next idea was to try some creative workarounds. Neutrinos come in three known types: electron, muon and tau. None of these can traverse matter at high speed, but the tau neutrino can very occasionally transform into another particle known as a tau lepton, before reverting to a tau neutrino. It was just possible that a high-energy tau neutrino survived the transit through Earth by performing this type of shape-shift on entry. But it was a contrived idea, and the ANITA scientists knew it. "Not everyone was comfortable with the hypothesis," says Gorham.

The whole puzzle only got worse in 2018, when ANITA spotted another apparent signal of a massive particle erupting from the ground. An independent analysis by Derek Fox and others at Pennsylvania State University showed how unlikely spotting two events of this type ought to have been. According to their calculations, the chances of a tau neutrino getting a free pass through Earth during an ANITA flight twice was one in a million. "Now we're out of easy explanations," says Gorham.

The harder ones take us beyond physics as we know it. For more than 40 years, particle physics has been governed by the standard model, a set list of particles and forces that has proven remarkably accurate at explaining the natural world. But in times like these, researchers are often tempted to go off menu. Ivan Esteban at the University of Barcelona in Spain, for example, has suggested that the culprit could be the axion, a hypothetical particle predicted in the late 1970s to redress an imbalance in one of the four fundamental forces of nature. He believes the radio signals could be caused by axions turning into photons as they interact with Earth's magnetic field.

> **"CPT symmetry has never been broken. But it spells trouble for the universe"**

Meanwhile, Fox and his colleagues have turned to supersymmetry, a hefty extension to the standard model in which every known elementary particle has a twin that is typically more massive. They believe a supersymmetric tau, or "stau", stands much better odds of making the journey through Earth and generating the ANITA signal. The trouble is, other experiments designed to detect supersymmetric particles, such as the Large Hadron Collider at CERN near Geneva, Switzerland, have resolutely failed to do so. That has led many physicists to look askance at predictions that depend on supersymmetry.

For Neil Turok at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, all such proposals are needlessly complicated. Rather than inventing hordes of new particles to explain mysterious phenomena, he believes we should work with what we know already. "Particle physics has gone from being the most economical predictive theory we know, to the least, and an amazing number of people have accepted that," he says. "Well, I haven't."

Turok's passion for keeping things simple might have led him to a remarkable solution to the problem of the ANITA signals. Initially, he was concerned with a field very remote from the Antarctic ice: the immediate aftermath of the big bang. One of the few guides to help study this period is the notion of symmetry, the idea that physical laws remain the same under certain transformations.

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The balloon-mounted ANITA experiment surveys more than a million square kilometres of Antarctic ice for signals from cosmic rays

We refer to these symmetries by shorthand. C, for example, is short for charge conjugation symmetry, which holds that flipping the charge of a particle – replacing it with its antimatter equivalent, in other words – has no effect on its essential behaviour. P stands for parity transformation symmetry, under which the physics in one scenario is indistinguishable from that in its mirror image. T represents time reversal symmetry, which means that a process played backwards in time doesn't violate any physical laws.

One or two processes involving fundamental particles are known to violate the C, P and T symmetries individually. In all such cases, however, the other two symmetries are also violated to compensate, so that, taken as a whole, CPT symmetry is never broken. "No one has ever found a way to avoid it," says Turok. "It's a very deep statement about nature."

In 2018, Turok and his Perimeter Institute collaborators, Latham Boyle and Kieran Finn, set out to discover what CPT symmetry would mean if it also held in our universe's earliest moments. They found that their resultant calculations placed strict limits on the types and numbers of particles spewed out in the big bang. One of these was a heavy "right-handed" neutrino. This is, contrary to Turok's guiding philosophy, a hypothetical particle, but one that is widely believed necessary to counterbalance the mass of the neutrinos we already know about, which are called left-handed because of the way they spin. With its abundance fixed by CPT symmetry, Turok and his colleagues found that if they tuned its mass just right, it matched the photofit of one of the universe's most elusive substances – dark matter, the universe's missing mass that physicists have been seeking for decades. "We couldn't believe it," says Turok. "The right-handed neutrino just dropped out as a dark matter candidate."

Dark matter candidates aren't hard to come by. This one, however, had a mass of 500 million billion electronvolts, or about one million-billionth of a gram. What Turok didn't know at the time was that this was dead in line with the mass of the particle ANITA had seen.

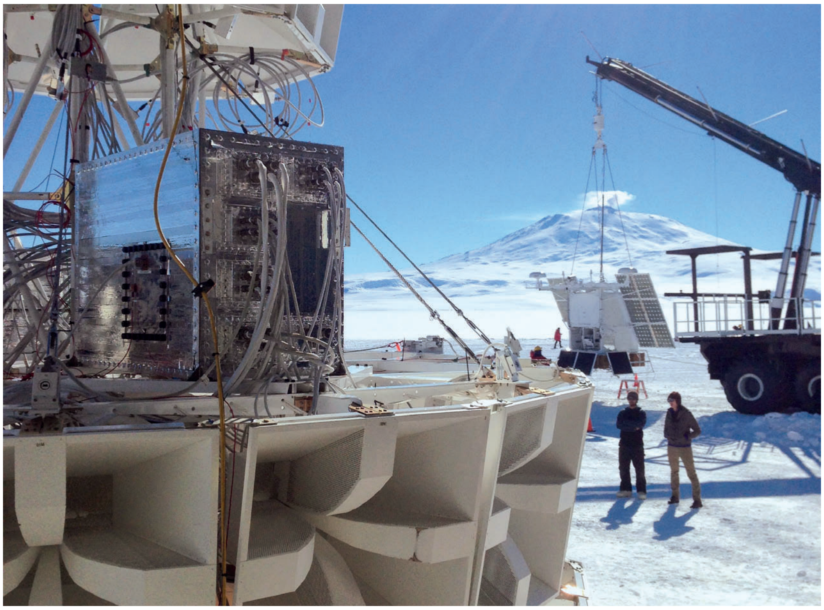
Fearful symmetry

Theorist Luis Anchordoqui at the City University of New York in the US and his colleagues were the first to point out the coincidence. They suggested that, over millions of years, right-handed neutrinos pervading the cosmos have been scooped up by Earth's gravity, nestling in the planet's interior ever since. And they also predicted that these dark matter particles occasionally decay into Higgs boson and tau neutrino pairs, thereby creating the ANITA signals. "The ANITA energy is exactly the one these guys are predicting," says Anchordoqui. "That's the amazing thing." It is a specific, quantitative prediction, and it is backed up by experiment, a rare thing in particle physics right now.

But if the premise underlying the idea is true, that spells trouble for the universe as we know it. One consequence of CPT symmetry holding in the very first moments after the big bang is that our cosmos would have contained equal quantities of matter and antimatter. Infamously, these two don't get along, and would have promptly annihilated one another, leaving only energy behind. The fact that matter vastly outnumbers antimatter today leads many cosmologists to think that CPT symmetry wasn't always as rigidly adhered to as it is today. By doubling down on its infallibility, Turok and his colleagues were left with a major question: how does our universe even exist?

As it turns out, the answer lies in CPT symmetry itself – and it is mind-blowing. To understand it, consider one of the most basic particle processes we know of: the creation of an electron and its antimatter counterpart, a positron, in the presence of a strong electric field. In strict adherence to CPT symmetry, however, there is another way of viewing this: the positron is an electron that travelled backwards in time until the moment of electric-field generation, and then turned around to go forwards in time. Weird as it sounds, the two descriptions are entirely equivalent, and there is no way to find out which is "real".

Turok's extraordinary prediction is that something similar happened to our universe. The conventional view of the big bang is that it was the moment of creation for a single ›



A mystery particle spotted by ANITA in 2016 could be evidence of a parallel universe

RYAN NICHOL/UCL PHYSICS & ASTRONOMY

cosmos that is almost completely devoid of antimatter. But for CPT symmetry to be conserved, then the big bang would have had to create two parallel universes, with most of the matter funnelled into one – ours – and most of the antimatter ending up in the other. In the other universe, everything would be upside-down and back to front, and any stars or planets it might contain would be made of antimatter rather than matter. Even more astonishingly, this anti-universe would be contracting backwards in time towards the big bang, rather than expanding away from it.

Turned on its head

At least, that is what it would look like from our point of view. Just as CPT symmetry dictates that a positron travelling forwards in time is equivalent to an electron travelling backwards in time, so too is our impression of the anti-universe relative. To inhabitants of the anti-universe, it is our universe that is upside down, shrinking towards the big bang and filled with the "wrong" sort of matter. We can't know which universe we are in, only that the other universe is, relatively speaking, backwards. In cosmic terms, this means that time isn't an arrow imposed by some external observer. It is more like a personal weathervane, pointing in whichever direction it is that our universe expands.

This is a radical departure from the existing view of cosmology, and Turok is the first to admit that there are one or two loose ends. But he believes he and others will be able to resolve the remaining difficulties without the need for any new particles. "If we can, there will be no contest anymore: our theory will be infinitely better than anything else," he says.

Yet there is potentially a spanner in the works. If ANITA has indeed caught the right-handed neutrino that the anti-universe idea predicts, common sense dictates that other neutrino observatories ought to have caught it, too. Towards the end of last year, the neighbouring IceCube experiment – which continuously watches for flashes of light generated as the decay-products of neutrinos blast through a cubic kilometre of Antarctic ice – announced that it had found no high-energy neutrinos coming from the direction claimed by ANITA.

"This anti-universe would be contracting backwards in time"

This isn't a killer blow for the anti-universe. Anchordoqui points out that the track of a high-energy tau neutrino can be mistaken for that of a lower-energy muon neutrino, of which IceCube has spotted at least one. It is a controversial view, but it suggests that both ANITA and IceCube may have discovered tantalising evidence for a parallel universe.

There are many other avenues for support, too. The anti-universe idea predicts that the big bang ought to have generated no primordial gravitational waves – ripples in space-time that many cosmologists are hunting but have failed to detect. And it predicts that the lightest of the three neutrinos is actually massless, a finding Turok believes could be confirmed in the next five to 10 years. It is by hard predictions such as these that the anti-universe idea will live or die. "We've tied our hands," he says.

Meanwhile, the focus is returning to the Antarctic, and the possibility of capturing more massive particles as they explode from the ground. It has been three years since ANITA's fourth flight descended softly to the ice, and an analysis of the latest data is still in the making.

Gorham is reluctant to preview the contents. "We don't know how to represent it yet," he says. "But we've got something." ∎

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