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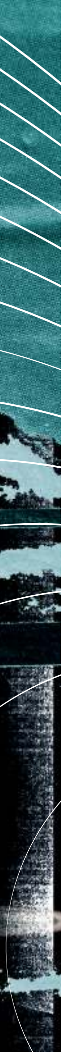
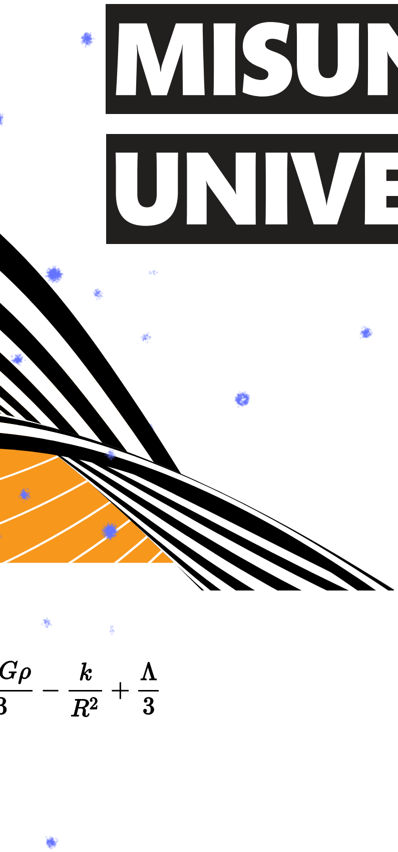


OUR MISUNDERSTOOD UNIVERSE

ONE year ago, our most powerful telescope created the most detailed map of the universe yet – and found something completely unexpected. Dark energy, a mysterious force pushing the universe apart, seems to be weakening rather than being the constant we long thought it was.

Over the next nine pages, we take a look at what this bombshell finding means for our understanding of the universe, from whether we need to update the standard model of cosmology to whether the results bring more controversial ideas, like string theory, back into the fold.



RYAN WILLS FOR NEW SCIENTIST/ADOBE STOCK

IF YOU imagine the story of the universe as a film endlessly in post-production, cosmologists would be its obsessive editors, constantly tweaking the narrative. The version they are working with is an astonishing cinematic achievement: it starts with a bang, space-time erupting out of nothing, before unfurling majestically with the formation of stars and then galaxies, sculpted by the gravitational pull of both visible matter and mysterious dark matter, all the while serenely expanding thanks to a shadowy force known as dark energy.

But it can't be the final cut. The more we peer into space, the more it seems incomplete: the story contains niggling inconsistencies and key protagonists remain maddeningly elusive. For decades, cosmologists have been struggling to refine the script.

Now, they finally have fresh inspiration from the cosmos. A powerful telescope has mapped millions of distant galaxies to trace the expansion of the universe with unprecedented precision. What it appears to be revealing is that dark energy behaves so weirdly, it can't be what we thought it was.

If confirmed, it is an exhilarating twist. Theorists are contemplating a complete rewrite of dark energy. How it all pans out is far from clear. But many are warming to the idea that we are about to produce a richer, more detailed cosmic story – one that looks very different from the current version.

"We're at an interesting moment," says Adam Riess, an astrophysicist at Johns Hopkins University in Maryland, who won a share of the 2011 Nobel prize in physics for his part in the discovery of dark energy. If someone were filming a documentary charting the making of our cosmological movie, he adds, "I would say: 'Don't go to the bathroom now.'"

Our current best picture of the origins and evolution of the universe was pieced together over the course of a century. It began in 1915 with Albert Einstein's theory of general relativity, which describes gravity as the result of massive objects warping space-time.

At the time, the universe was thought to be static, so Einstein added a calming term to his equations called the "cosmological constant". But in 1929, astronomer Edwin Hubble observed distant galaxies speeding away from one another, indicating that the universe is expanding and prompting Einstein to ditch his constant.

Then came the big bang theory. While it is gospel these days, it wasn't until the 1960s that the rival steady-state theory gave way, as astronomers discovered a sea of primordial radiation left over from the big bang – the cosmic microwave background (CMB) – with properties that matched predictions.

As our ability to peer deep into space improved, the big bang theory was no longer enough. In the 1980s, astronomers found that the gravity of visible matter was insufficient to hold galaxies together or explain the formation of galaxy clusters. The fix was to invoke invisible dark matter. A decade later, observations of distant exploding stars led by Riess and his colleagues revealed that, contrary to all expectations, the expansion of the universe is speeding up. The cosmological constant was reinstated, albeit rebadged as dark energy.

This, essentially, is the current standard model of cosmology, known as lambda-CDM. The Greek letter lambda denotes the › cosmological constant and CDM stands for cold dark matter, assumed to be made of heavy, slow-moving particles. Added to general relativity and with a few key assumptions – most importantly that the universe, on average, looks the same in all directions – it offers a compelling framework for how large-scale structure formed from quantum fluctuations in the early universe through a brief burst of exponential inflation in the first moments.

Lambda-CDM ranks among science's greatest triumphs. It combines elegance with breathtaking reach, using just six parameters to describe the entire history of the cosmos, making a host of precise predictions that have been verified by increasingly exacting observations. "It has been extraordinarily successful," says Mike Turner, a theoretical cosmologist at the University of Chicago in Illinois. "Compare it with what we had when I became a cosmologist around 1980 and, oh my God, it's more than we could ever have imagined. It's absolutely stunning."

And yet, as Turner says, it is "now much less than we're willing to settle for". That is partly just the restless nature of science: even the most successful theories are only ever approximations of a deeper understanding and, as we stress-test them with new observations, we uncover loose ends and cracks.

In the case of lambda-CDM, the loose ends are obvious. Dark matter and dark energy were only ever placeholders: they were invoked in response to observations, but without physical explanations. Despite decades of effort, physicists have yet to directly detect dark matter particles. And while dark energy is thought of as vacuum energy, the result of quantum fluctuations in empty space, it has always been troubling from a theoretical perspective. Quantum theory predicts that its strength must be some 10^{120} times greater than what is required to drive the expansion of the universe we see.

> **"DARK ENERGY BEHAVES SO WEIRDLY, IT CAN'T BE WHAT WE THOUGHT IT WAS"**

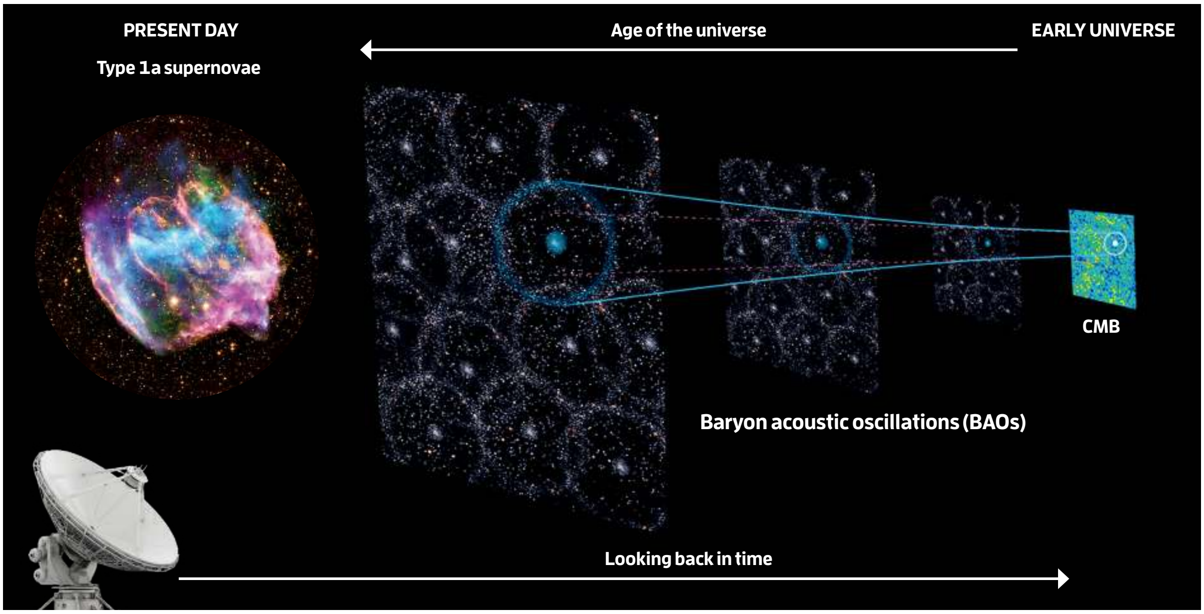
"Right now, dark energy and dark matter... they're tack-ons," says Turner. They both serve functions. There is strong empirical evidence that they exist. "But they are just phenomenological descriptions, so they're pointing to something more fundamental."

Cracks have begun to appear, too, the most notorious of which has a long history, but became recognised as the Hubble tension in 2015. It is so named because two different ways of measuring the rate at which the universe is expanding, known as the Hubble constant, disagree. When cosmologists extrapolate forwards from the CMB using the current model, they get a value of about 67 kilometres per second per megaparsec. But when astronomers measure the local universe directly, using supernovae and variable stars, the value is around 73. "It's an end-to-end test of the universe," says Riess, who argues that the fact that the two ends don't meet is a strong hint there is something seriously wrong with lambda-CDM.

Still, most cosmologists have been unwilling to give up on it. All the proposals made so far for how to resolve the Hubble tension undermine the existing model's near-perfect fit to the CMB and the large-scale structure we see today. It is also possible that the measurements underlying the tension contain subtle systematic errors.

Mapping the universe

The DESI survey looks at patterns between galaxies, known as baryon acoustic oscillations, to measure the expansion of the universe – showing us a way back to the cosmic microwave background (CMB). Supernovae are used to study the nearby universe.



SOURCE: GABRIELA SECARA, PERIMETER INSTITUTE; ADOBE STOCK; NASA

The way we measure late-universe expansion in particular relies on an intricate chain of inference, each link dependent on painstaking calibration and assumptions about stars and galaxies. The suspicion is that, with more data, the tension will disappear. "There's just too much going on there for you to say something truly definitive," says Pedro Ferreira, a cosmologist and astrophysicist at the University of Oxford.

Riess doesn't buy that. His measurements of late-universe expansion have been checked again and again, he points out, and nobody has found an error – even if some astronomers argue that independent distance measurements from the James Webb Space Telescope could resolve the tension. "It's been a decade since we discovered the Hubble tension and it hasn't gone away," he says. "It's only grown more pronounced."

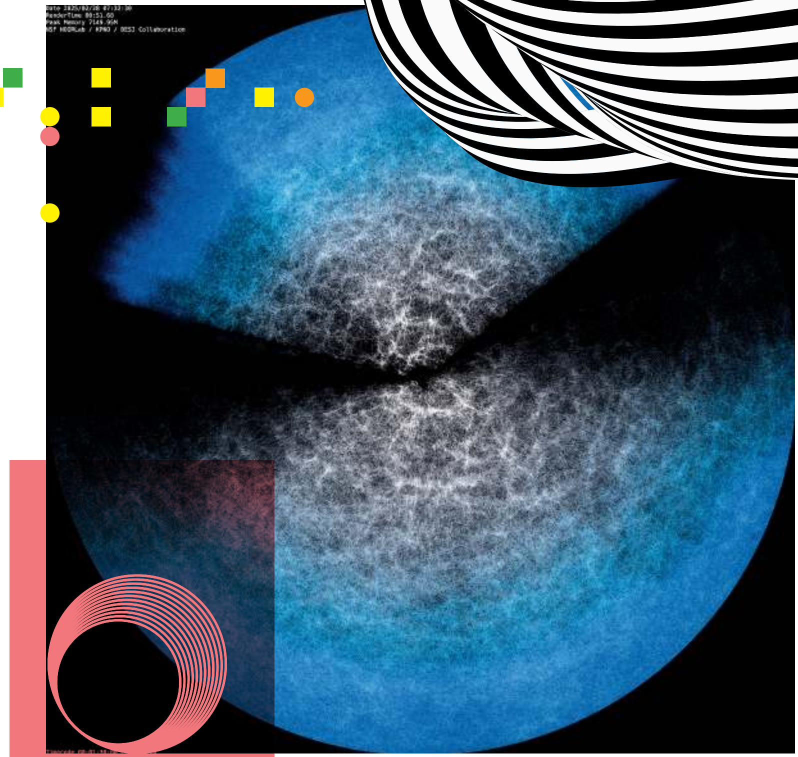
The real reason the community has been reluctant to move beyond lambda-CDM, Riess argues, is that scientists are loath to let go of any theory, especially such a successful one, until they have a better one. "People are uncomfortable just wandering in the wilderness."

What we need, by that logic, are observations that more clearly point the way to something better. The good news on that front is that a new generation of telescopes designed to probe dark energy has begun to deliver in dramatic fashion, such as the Dark Energy Spectroscopic Instrument (DESI).

Mounted on a telescope in Arizona, DESI combines a huge mirror with 5000 robotically controlled optical fibres that automatically lock onto distant galaxies, one after the other, in quick succession – far faster than previous dark energy surveys.

Since 2021, it has been surveying millions of galaxies to gauge their redshift, or how much the light they emit has stretched due to cosmic expansion, an indicator of their distance from us. And because galaxies are at different redshifts, we can compare a characteristic spacing in their distribution – a slight preference for galaxies to be separated by a particular distance – to reconstruct how the universe's expansion rate has changed over time.

To calibrate those distances, DESI has also been measuring a subtle imprint left over from the early universe, known as baryonic acoustic oscillations (BAOs). Like ripples on a pond frozen in ice, these BAOs preserve a pattern in the separation of galaxies that provides cosmologists with a "standard ruler" for measuring cosmic expansion (see "Mapping the universe", left). The idea was to produce the most accurate, precise, three-dimensional reconstruction of cosmic expansion ever made. The latest version, released in March 2025 and based on three years' worth of data, or 15 million galaxies, contained a bombshell that has sent shockwaves through cosmology.



The Dark Energy Spectroscopy Instrument's new map of the universe

DESI COLLABORATION/DOE/KPNO/NOIRLAB/NSF/AURA/R. PROCTOR

When DESI researchers combined this with the latest data from supernovae – which tightly constrain the expansion of the nearby universe – and the CMB, then checked how well it all fits with lambda-CDM, they found that the current model doesn't match up, at least not as well as one that allows the strength of dark energy to change over time. The headline finding was stark: dark energy appears to be weakening, and isn't a cosmological constant after all.

"It was actually quite frightening," says Will Percival, an astrophysicist at the University of Waterloo in Canada who is part of the DESI collaboration. Of course, there was a high level of scrutiny, he says. "But in many ways, this is exactly what people have been waiting for. Experiments that take us into the unknown and give us unusual, unexpected results are incredibly exciting."

And as if that wasn't enough, the DESI results also suggest that in the early universe, dark energy may have dipped below the so-called phantom divide – the threshold below which its repulsive power would have been far stronger than the cosmological constant allows – before swinging back up again.

"What we're seeing now with the DESI results, I like to call it beautifully bizarre," says Eric Linder, a physicist and cosmologist at the University of California, Berkeley. "Not only ›

The Dark Energy Spectropscopic Instrument surveys the night sky

THE REGENTS OF THE UNIVERSITY OF CALIFORNIA, LAWRENCE BERKELEY NATIONAL LABORATORY

> “EXPERIMENTS THAT GIVE US UNEXPECTED RESULTS ARE INCREDIBLY EXCITING”

are they off from the cosmological constant, they’re off in a way that nobody was thinking about before.”

At this stage, the DESI results aren’t strong enough to claim a bona fide discovery. The analysis only favours evolving dark energy with a statistical significance of 4.2 sigma at best, some way short of the 5-sigma gold standard, making it a result that could yet vanish as more data comes in – and the phantom crossing indication is even less secure. “I’m on the fence about it,” says Ferreira, echoing the caution expressed by many in the field. “We’ve just been here so many times before.”

Even so, there are reasons to think the DESI results might be different. “It’s the first time where I’ve actually gone ‘Ha!’,” says Catherine Heymans, an astronomer at the University of Edinburgh, UK. “The method they use is one of the cleanest possible measurements of cosmic expansion we can make. It’s much harder to pick arguments with this than it is with the Hubble tension.”

Not that that has stopped people trying. In May 2025, George Efstathiou, an astrophysicist at the University of Cambridge, put out a paper claiming that the evidence for evolving dark energy is shaky for two reasons. The first is that the discrepancy with lambda-CDM only becomes apparent when the supernova data is included in the analysis. The second is that the DESI team’s statistical analysis relies on assumptions made in advance about how plausible different cosmological models are, known as “priors”, which Efstathiou argues unfairly favour evolving dark energy models.

Where there is consensus, however, is that if the DESI results do strengthen with more data, they would deal a serious blow to lambda-CDM. “In that case, it is exciting, because it means we have to think again,” says Ferreira.

In a paper published in August 2025, Riess and observational cosmologist Alexie Leauthaud at the University of California, Santa Cruz, argued that we may be witnessing the demise of lambda-CDM and that we must now prepare to move beyond it. Excitingly, for the first time in 25 years, we have a real clue as to what something better looks like.

Which isn’t to say it is going to be easy to figure it all out. Although the DESI results gave us a clear steer on dark energy’s physical properties, sending theorists into a frenzy, the picture of cosmic expansion they render makes it incredibly difficult to find the right formula. The simplest solution is to say that dark energy comes not from the vacuum, but is instead a kind of field similar to those that describe light or the nuclear forces. But these models require suspiciously precise fine-tuning to have dark energy grow stronger in the past few billion years, rather than some other time. More importantly, they alone can’t reproduce the phantom crossing.

Many theorists prefer to focus on models in which dark energy interacts with gravity, rather than evolving independently. The idea is that gravity begins to work differently at some point because there is a transfer of energy between ordinary matter and dark energy. “That’s how you can understand that the energy density [of dark energy] could increase and then decay,” says Alessandra Silvestri, a theorist at Leiden University in the Netherlands who has shown that such a model fits the DESI data better than lambda-CDM. “This is really the only model that seems to work.”

There are also models where dark energy exchanges energy with dark matter, allowing the latter to slowly decay into the former as the universe expands. This idea is particularly appealing from a theoretical perspective because it connects the two biggest unknowns in cosmology.

The problem with all these interacting models is that we should have seen evidence for them in existing observations of planetary orbits, for example, and we haven’t. Moreover, while it is possible that the interactions are so vanishingly small that they would have evaded

$$S_0 = 1, S_1 = \sin(r)$$

detection, they could still violate the sacrosanct law of energy-momentum conservation.

What we have, then, is an abundance of ideas – none of which does the trick. "We really have no idea," says Ferreira.

For Ferreira, and for Riess too, that suggests we shouldn't just try to patch up dark energy to better match the data. Instead, we should think about what we can learn if the DESI results really are the final nail in the coffin for lambda-CDM. "We should pause a little bit and reflect," says Riess. If we are in the first throes of another major leap in our understanding of the universe, he argues that cosmologists need to think carefully about how to navigate it – not only in terms of long-standing assumptions regarding what a better theory looks like, but also how they find it.

We may yet discover a theory as simple and elegant as what we already have. Or it might be that the best explanation is more complex – a hotchpotch including multiple dark energy fields, multiple kinds of dark matter, interactions between the two and/or a new take on gravity at cosmological scales. "This focus on elegance and simplicity, it comes from particle physics," says Riess. "But who's to say that it works so well at the scale of the cosmos as a whole? The universe looks pretty complicated from where I'm standing, so I think we need to be open-minded."

The solution may even lie in alternative cosmologies, such as a cyclical universe or string theory (see "A cosmos made of string", page 36) or perhaps even a bizarre form of black hole (see "A surprising source of dark energy", page 38).

Observations, as ever, will be our guide. DESI is still collecting data, with another data release expected in 2027. But cosmologists are also expecting big things from the European Space Agency's Euclid space telescope and the Vera Rubin Observatory in Chile, both of which started releasing data last year. That should give us greater confidence in the emerging picture of expansion, or not. But it will also allow us to see it from previously unexplored redshifts.

Ferreira is less optimistic. In a 2025 paper, he and his colleagues argued that because cosmological surveys can only probe a limited period of the universe's expansion history, many different theoretical models can produce nearly identical behaviour over that interval. As a result, Ferreira reckons that even with all the new data coming in, "we will be left with a large family of models which are essentially observationally indistinguishable from the point of view of the cosmological data".

The danger is that we will end up exactly where we were with the Hubble tension – an impasse in which many cosmologists aren't prepared to let go of lambda-CDM because they don't trust the data that would break it without a better theory in place, and little prospect of finding that theory any time soon. Riess describes this scenario as "Kuhnian purgatory", in reference to the philosopher Thomas Kuhn's ideas about how scientific progress plays out, and worries it will lead to inertia. "Trying to pull the sword out of the stone, it's hard work… and you might not get a lot of papers out of it. But let's not forget that sword is still stuck in that stone."

That said, he suggests the problem lies not with the data to come. Rather, it is that the community places too much weight on a model developed before new data came along, and not enough on the data itself. Whenever a tension arises within lambda-CDM, he says, the inability to explain it is held up as evidence against the new observations – which explains why the community fixates on unknown errors and more measurements only breed more doubt. "When you live with a standard model for 20 years, a lot of people have spent most of their career with it," says Riess. "Even the idea that this might not be the whole story, it's jarring."

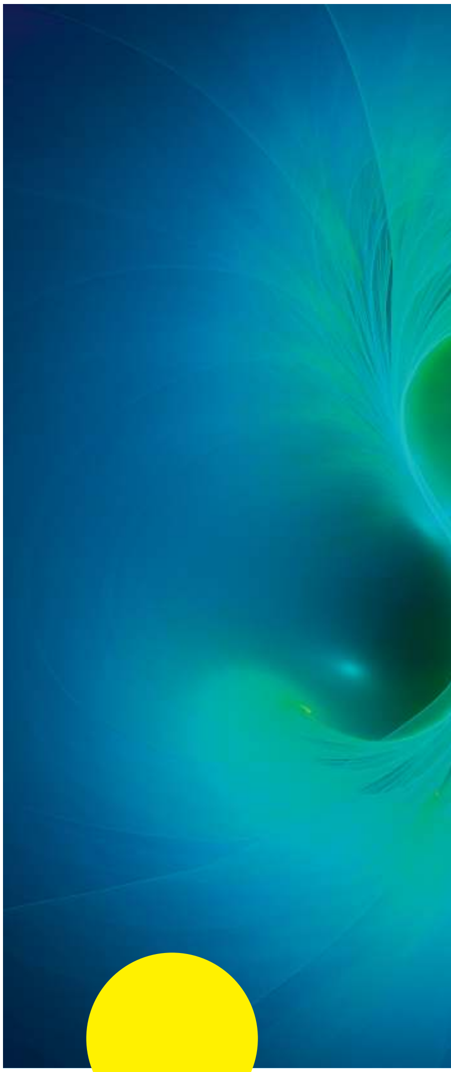
Maybe this is just the nature of paradigm shifts. They will always be marked by conflict, and lambda-CDM will not go gently into the night. But that's not necessarily a problem. "You want the defenders to look for anything that looks a little suspicious in the data. You also want the revolutionaries, the people who are willing go beyond what we already have," says Linder. "The back-and-forth, while it may look antagonistic, it's actually healthy."

Indeed, the fact that cosmologists are gearing up for a fight might itself indicate we really are poised for another revolution. The one thing we can say for certain is that, after a long period of harmony, cosmology is entering an era of tensions that make it a whole lot more interesting. "We're looking forward to all this new data, which, I think, will thrill us all," says Linder. "It's just an incredibly exciting time."

Daniel Cossins

A COSMOS MADE OF STRING

With hints that dark energy may be weakening, two controversial ideas have been given a boost



DAVID PARKER/SCIENCE PHOTO LIBRARY

If the strength of dark energy really does diminish over cosmic time, as hinted at by the results from the Dark Energy Spectroscopic Instrument (see "Our misunderstood universe", page 31), the implications could be huge. It could provide fresh impetus for proponents of alternative cosmologies that change our understanding of the fate of the universe. It might even be telling us something profound about the deepest structure of space-time.

"There certainly are very, very interesting possibilities for changing a lot of physics," says Eric Linder, a physicist and cosmologist at the University of California, Berkeley.

According to the standard model of cosmology (known as lambda-CDM), our best attempt to explain the evolution of the cosmos, in its first moments, the universe underwent a split-second spell of exponential expansion. Known as inflation, this explanation seems to provide a reason for why the universe is so smooth, flat and homogenous on its largest scales. But inflation has its critics, most prominent among them Paul Steinhardt, a physicist at Princeton University. "Inflation doesn't work," he says bluntly, adding that it requires unlikely initial conditions, is too flexible and leads to a multiverse scenario that many find implausible.

Steinhardt has long made the case for an alternative hypothesis known as the cyclic universe, in which the universe endlessly expands, contracts and bounces back. To make such models work, however, dark energy has to evolve.

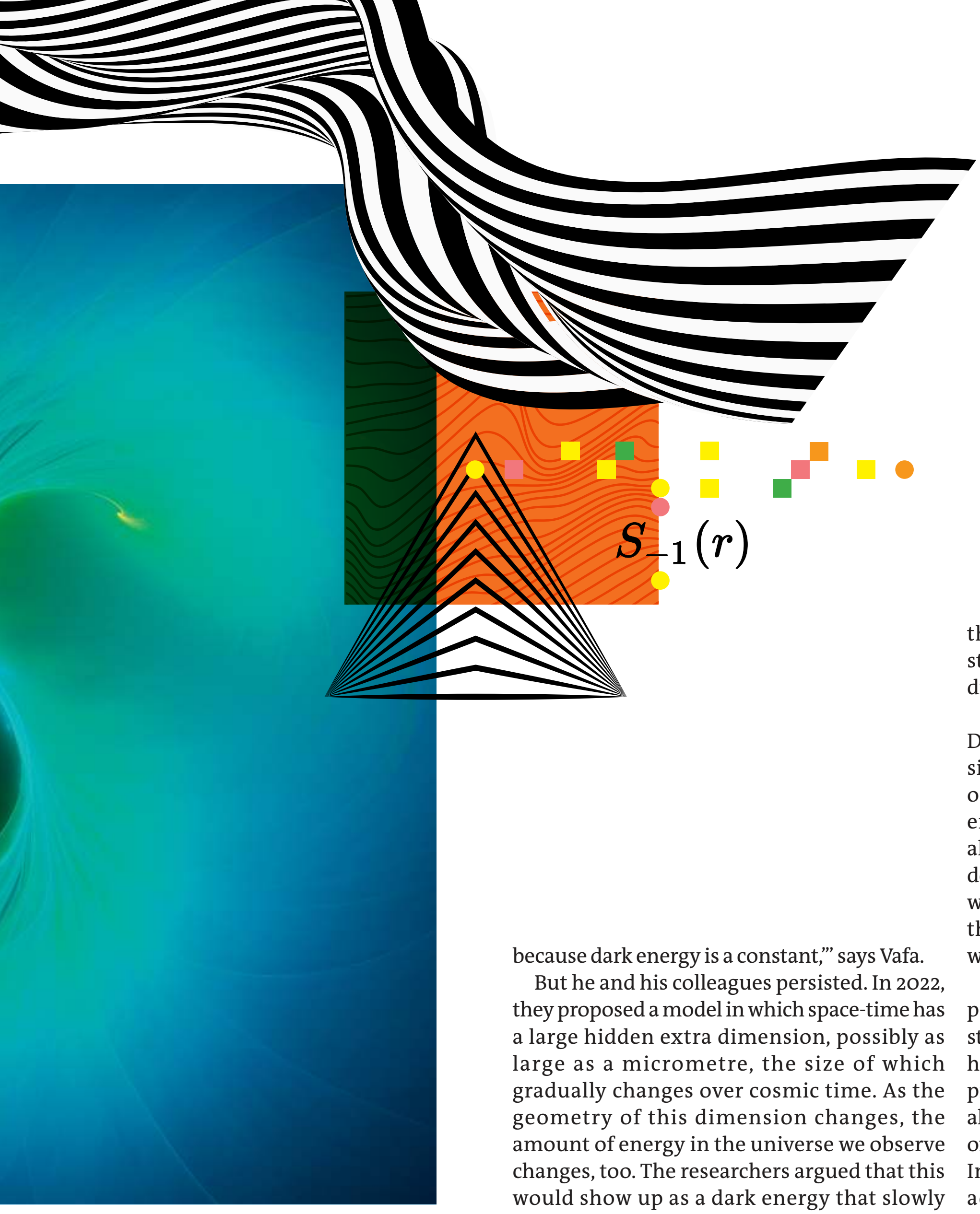
"It must be some kind of decaying dark energy that stops accelerating the expansion of the universe, starts decelerating it and then eventually causes contraction, leading to a bounce and a new cycle," says Steinhardt. The first part of that at least – that the acceleration of expansion is slowing – is precisely what we seem to be seeing with the DESI data.

This isn't to say that the DESI results provide evidence for cyclic cosmologies. We may yet find systemic errors in the measurements and analysis, and it is entirely possible that dark energy weakens without ever producing a contraction or a bounce. If hints of decaying dark energy do firm up, however, that would lend credence to Steinhardt's long-standing argument. "I tend to be very conservative and very patient," he says. "What I would say, however, is that now the game is afoot."

The same could be said for another controversial idea that has received a shot in the arm from the DESI results. Broadly speaking, string theory says that everything is ultimately made of vanishingly tiny strings, compactified into hidden extra dimensions, whose vibrations manifest as the various particles and forces we discern. It rose to prominence in the 1980s because it seemed to offer a route towards a theory of quantum gravity, reconciling quantum theory and general relativity into what some call a theory of everything.

But string theorists have long struggled to

"THERE CERTAINLY ARE VERY, VERY INTERESTING POSSIBILITIES FOR CHANGING A LOT OF PHYSICS"



construct models of the universe with a small, positive cosmological constant. In a series of papers published in 2018 and 2019, theoretical physicist Cumrun Vafa at Harvard University and his colleagues built on a set of proposals known as the Swampland conjectures, which aim to distinguish theories of particles, forces and space-time that can arise from a consistent theory of quantum gravity from those that cannot. Using this framework, they suggested that dark energy can't be a cosmological constant but must instead be a kind of field – similar to the one thought to have driven inflation – whose energy changes over time.

At the time, such a proposal conflicted with the long-held belief that dark energy stayed the same over cosmic time. "People were saying: 'String theory is ruled out because dark energy is a constant,'" says Vafa.

But he and his colleagues persisted. In 2022, they proposed a model in which space-time has a large hidden extra dimension, possibly as large as a micrometre, the size of which gradually changes over cosmic time. As the geometry of this dimension changes, the amount of energy in the universe we observe changes, too. The researchers argued that this would show up as a dark energy that slowly weakens. "There's nothing exotic [here] from the perspective of string theory," says Vafa. "The extra dimension is changing, and both dark energy and dark matter are responding to it."

It is easy to see why the DESI results are intriguing for string theorists: Vafa and his colleagues had predicted dark energy should be gradually weakening, and now that seems to be what we are seeing. Indeed, when Vafa and his team analysed the DESI data combined with other cosmological datasets in 2025, they found their model fits far better than lambda-CDM and about as well as the best conventional models that allow dark energy to evolve. The difference here, he says, is that their model includes a physical explanation for what we are seeing. "This is why I'm so excited," he says. "It's very satisfying."

To be clear, the DESI results don't offer concrete evidence for string theory. For starters, the extent to which they prefer evolving dark energy over a cosmological constant still depends on which other cosmological datasets they are combined with. What's more, non-stringy models that don't invoke hidden extra dimensions fit the existing data equally well.

But if we assume for a moment that the DESI data holds up and the statistical significance grows to discovery level, evidence of weakening would not only remove an empirical obstacle to string theory, it would also weaken the argument that string theory doesn't offer testable predictions. "We came up with this model years ago," says Vafa. "Now they're observing it, and it looks exactly like what we expected."

To make good on the notion that this might provide observational evidence in support of string theory, however, theorists like Vafa would have to build a sharper model that makes more precise predictions, distinct from non-stringy alternatives, and show that it fits the full range of cosmological data better than other options. Intriguingly, the framework already hints at additional testable signatures, including departures from the standard picture of how dark matter evolves and deviations from general relativity at micrometre scales.

Some cosmologists are unconvinced the DESI results have any bearing on fundamental physics at all, even if they do firm up. "Dark energy operates on certain scales, and that is what we can talk about," says Pedro Ferreira, a cosmologist and astrophysicist at the University of Oxford. "[When it comes to] what happens at quantum levels, I don't think we can go there."

Others are open to the possibility that these hints could have ripples well beyond cosmology, not least because they might give us a first glimpse into the deep quantum structure of space-time. "What Cumrun Vafa has come up with, it's the most interesting thing I've seen," says Mike Turner, a cosmologist at the University of Chicago in Illinois. "This is where cosmology and particle physics come together. We're digging at really fundamental things, so the knock-on effects can be tremendous."

Daniel Cossins

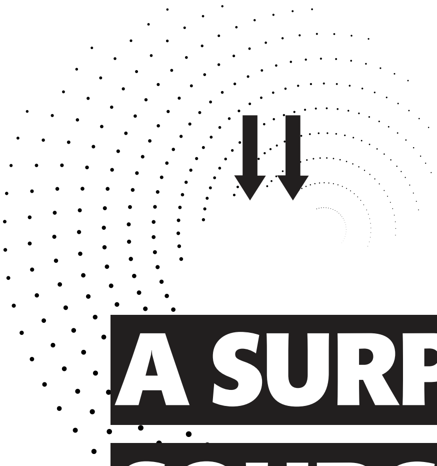
A SURPRISING SOURCE OF DARK ENERGY

A bizarre type of black hole could resolve three different cosmic mysteries – including what is happening with dark energy

SPACE-TIME is being driven apart. Every second that passes, the universe expands faster and faster. What is propelling this dramatic acceleration is an enigma, though – one scientists have known about, and searched for, for decades. Still, we are no closer to understanding it. We call it dark energy, but we know next to nothing about what it is or where it comes from. Nevertheless, it makes up about 68 per cent of the universe.

It would be reasonable, however, to assume this mystery has nothing to do with black holes: behemoths so gravitationally powerful that once something is drawn in past a certain point, it can never escape. They pull matter towards them, so how could they be driving the universe's expansion? Yet that's exactly what a small group of astrophysicists is suggesting.

The story goes like this: all matter that falls into black holes goes through a process that turns it into a kind of radiation. This, in turn, exerts a force on the space around it. Such an effect would be too small to notice in the immediate surroundings, but add together all the black holes in the universe and it starts to mount up to something that could be pushing everything inexorably away from everything else.



This wild idea began on the fringes, and has appeared in many iterations over the decades. But more and more cosmologists have been paying attention to it over the past few years – as it turns out to offer a potential explanation for not one, not two, but three mysteries of the universe. "It's not fringe any more," says Kevin Croker, a cosmologist at Arizona State University. "It's highly controversial, but it's not fringe."

Black holes offer themselves up as a potential source of dark energy precisely because they are so perplexing. "Most of the structures in the universe, like galaxies and clusters, have very little effect on dark energy. But there has always been one possible exception," says Niayesh Afshordi, a cosmologist at the University of Waterloo in Canada. "Black holes [after all] are much more mysterious than everything else."

It all comes down to the point at the centre of a black hole where gravity is so strong that matter is compressed to infinite density. Known as an astrophysical singularity, this has always been seen as something of a placeholder for physics we don't yet understand. "Nobody believes in a singularity," says Gregory Tarlé, a cosmologist and astrophysicist at the University of Michigan who is a prominent figure in the study of these cosmologically coupled black holes, so called because they would be coupled with the large-scale behaviour of the cosmos. In reality, he says, something prevents a singularity from forming. "What's going to stop it is if the matter that's causing this collapse somehow turns into dark energy."

Nobody knows exactly how it would happen. But Tarlé compares it to the very early moments of the universe, when everything was a hot soup of radiation. In the moments after the big bang, the cosmos cooled and much of that radiation coalesced into matter. Inside cosmologically coupled black holes, that process would happen in reverse. This wouldn't affect their gravitational pull, though, which is based on energy density, not specifically matter.

"If you try to understand how a single particle of dust can turn into radiation, that's not known," says Massimiliano Rinaldi, a physicist and cosmologist at the University of Trento in Italy. "But we assume that it can happen – this conversion is not as crazy as it sounds."

For a long time, the consensus has been that black holes can only really affect their immediate surroundings. "The idea was sort of 'what happens in Vegas, stays in Vegas', but that's not true," says Croker, one of the pioneers

$$c^2 d\tau^2 = c^2 dt^2$$

$$R^2(t)\left(dr^2 + S_k^2(r)d\psi^2\right)$$

"SEEING THE DATA FOR THE FIRST TIME, OUR MOUTHS KIND OF DROPPED OPEN"

DEBORAH FERGUSON/UT AUSTIN, BHAVESH KHAMESRA/GEORGIA TECH, AKARAN JANI/VANDERBILT UNIVERSITY/LIGO

of the cosmologically coupled black hole concept. "People like to throw a causality argument: why could this stuff here affect things that are so far away? But it's not just one of them, it's tons of them, and they're all over the place. It's this aggregate effect."

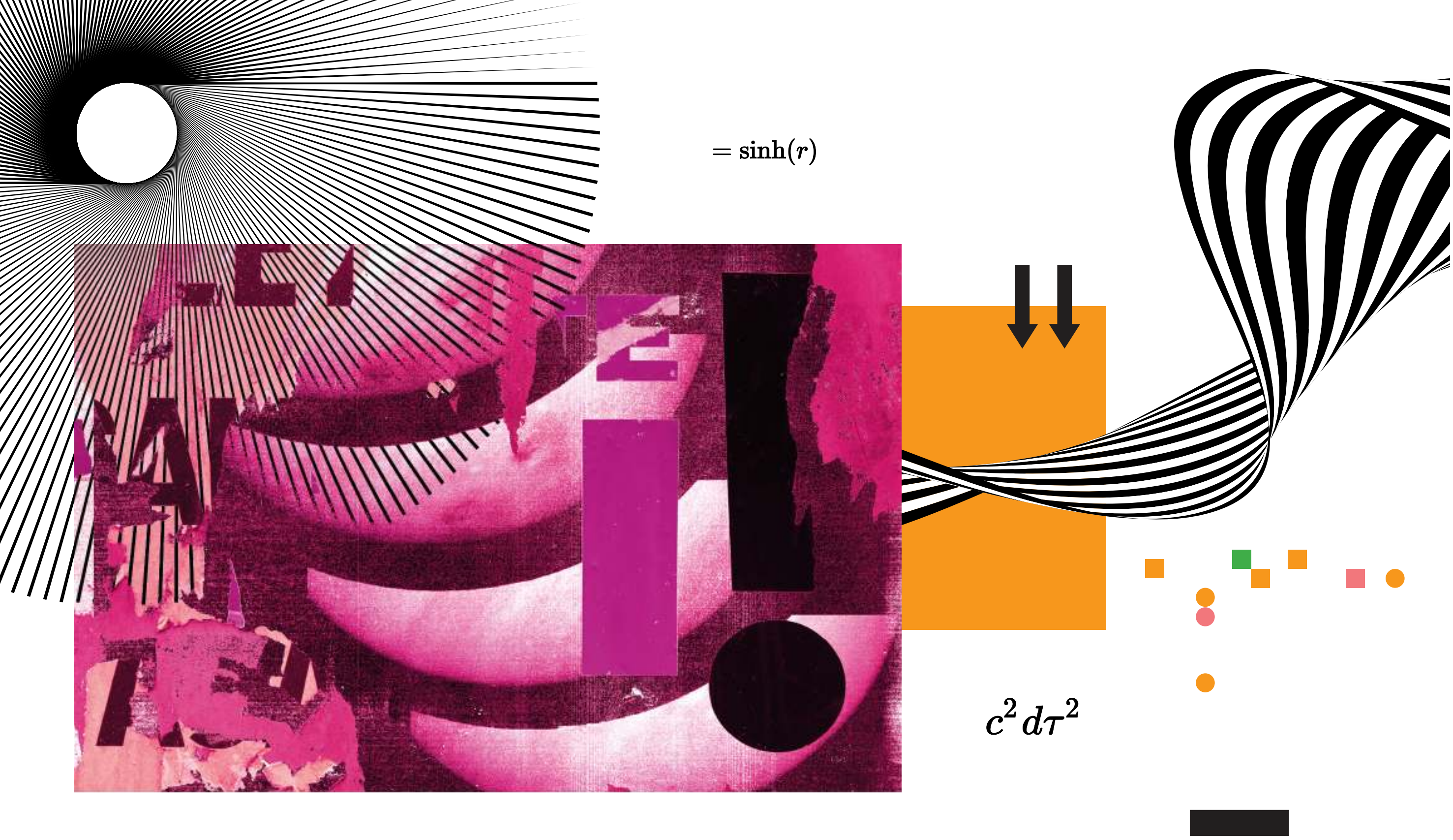
If you threw a bunch of matter into a single cosmologically coupled black hole, it might not affect the cosmos writ large, he says. On the other hand, if you had a fleet of cosmic dump trucks pouring matter into these black holes all over the universe, you could speed up its expansion. It is a bit like a balloon filled with many smaller balloons: inflate the smaller ones and the big one will be forced to expand as well. If these black holes are real, then, as a population, they must be inextricably tied to the overall structure of the cosmos.

It's not all theoretical, either. The first piece of evidence that black holes may be cosmologically coupled came in 2023 with the revelation from Croker, Tarlé and their colleagues that the small balloons do, in fact, seem to be expanding: black holes across the universe appear to be growing at unexpectedly high speeds. Even what Croker calls "maximally boring" supermassive black holes, which should barely be growing at all, are keeping pace with the universe's expansion. "It was the first time we saw something significant that said that once black holes are formed, they create this dark energy, and then the [dark] energy grows as the universe expands," says Tarlé.

Perhaps the biggest objection to this hypothesis is that we have no idea what cosmologically coupled black holes would look like or how exactly they would behave. "The problem is that we don't have a mathematically precise solution that describes these objects – we have an average," says Rinaldi. Without that solution, it is impossible to tell, for example, if the behaviour of cosmologically coupled black holes as they merge would match observations we have of that process. "The task is very, very difficult because the equations are horrible, but there might be a breakthrough at some point – it just needs time," he says.

In the few years since the idea was first developed, time and intensive research have shifted it from being something rejected by many serious cosmologists to become something that is at least seen as plausible. One reason for this is that it appears to match up with the puzzling recent results from the Dark Energy Spectroscopic Instrument (DESI) in Arizona that suggest that dark energy may be weakening over time (see "Our misunderstood universe", page 31). "Seeing the data for the first time, our mouths kind of dropped open," says Tarlé. "It was very clear that dark energy was changing in time."

But if the effects of dark energy come from cosmological coupling with black holes, the DESI results make sense. The formation of black holes follows the same trend as star formation, which peaked around 10 billion years ago and has been steadily slowing since then. Not only would this explain the lessening amount of dark energy hinted at by DESI, it would also help account for another major cosmic mystery. ›



"BLACK HOLES ARE MUCH MORE MYSTERIOUS THAN EVERYTHING ELSE"

The Hubble tension relates to a discrepancy between the two main ways of calculating the universe's expansion, one based on measurements of relatively nearby objects, and another based on using the standard model of cosmology to extrapolate forwards from measurements of light remaining from the big bang. Adding cosmologically coupled black holes to our model of cosmology may not entirely solve this problem, but it significantly eases the tension by providing an explanation for why the two methods deliver conflicting results: the times they probe in cosmic history would have had different rates of expansion.

There are several other proposed explanations for the Hubble tension and the apparent weakening in dark energy, but they tend to rely on exotic hypothetical phenomena beyond our standard understanding of physics. "[The idea of cosmologically coupled black holes] relies upon general relativity and nothing else – and that's a plus," says Rinaldi. Perhaps surprisingly, that makes it a relatively conservative proposition in the context of these two problems.

Now, Tarlé, Croker and a group of colleagues have added another piece of evidence to what they call a "three-legged stool" of observations that line up with their predictions. This final leg is a bit different from the other two, in that it is a mystery in particle physics. The behaviour of the universe allows cosmologists to create a budget for how much mass it contains, which can then be used to calculate the mass of each type of particle.

That's all well and good, except when it comes to neutrinos, tiny – but, crucially, not massless – particles that interact so rarely with other matter that they are sometimes referred to as "ghost particles". Taking into account the new DESI data, neutrinos would need to have a negative mass for the budget calculations to work. As it shouldn't be allowed to be negative, it must be zero.

But if matter is turning into dark energy inside black holes, that affects the balance of the cosmos. Cosmologically coupled black holes would make room in the mass budget by converting regular matter into dark energy. It turns out they would create just enough leeway for neutrinos to not only have a positive mass, but one that lines up with experimental measurements.

Are these three pieces of evidence enough to fully bring the hypothesis of cosmologically coupled black holes in from the cold? "Right now, the stool of evidence that we've offered has the three legs. We think we can sit on it," says Croker. "Other people in the community may think it's dangerously janky, but my hope is that, at some point, some other people will jump on this as well."

That has already started happening. The earlier research on cosmologically coupled black holes was done by small research groups, each with only a handful of collaborators, but the latest paper, on the neutrino masses, has 50 co-authors.

As is always the case with this sort of controversial proposal, what researchers really need are better models – in this case, solutions to the "horrible" equations – and more data. The latter, at least, is forthcoming. DESI is still gathering more observations of galaxies, and several other large surveys of the universe are under way. "It's a detective story: there is an obvious suspect that is acting very suspiciously and there is an obvious crime," says Afshordi. With three clues that black holes may be behind the universe's accelerating expansion, more and more detectives are on the case. "But, of course, the hard part is making that connection." ∎

Leah Crane