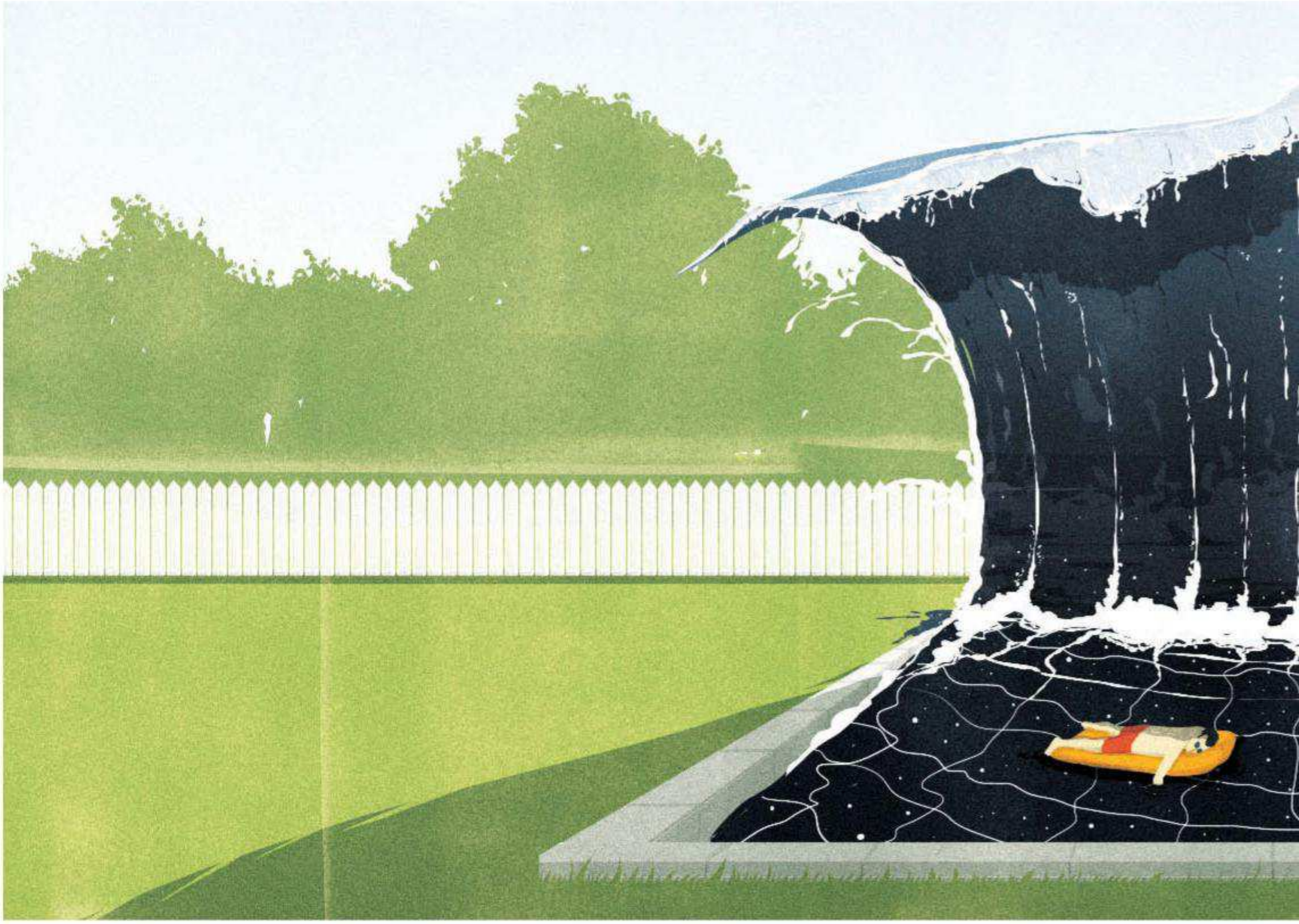


ANDREA UCINI

Total wipeout

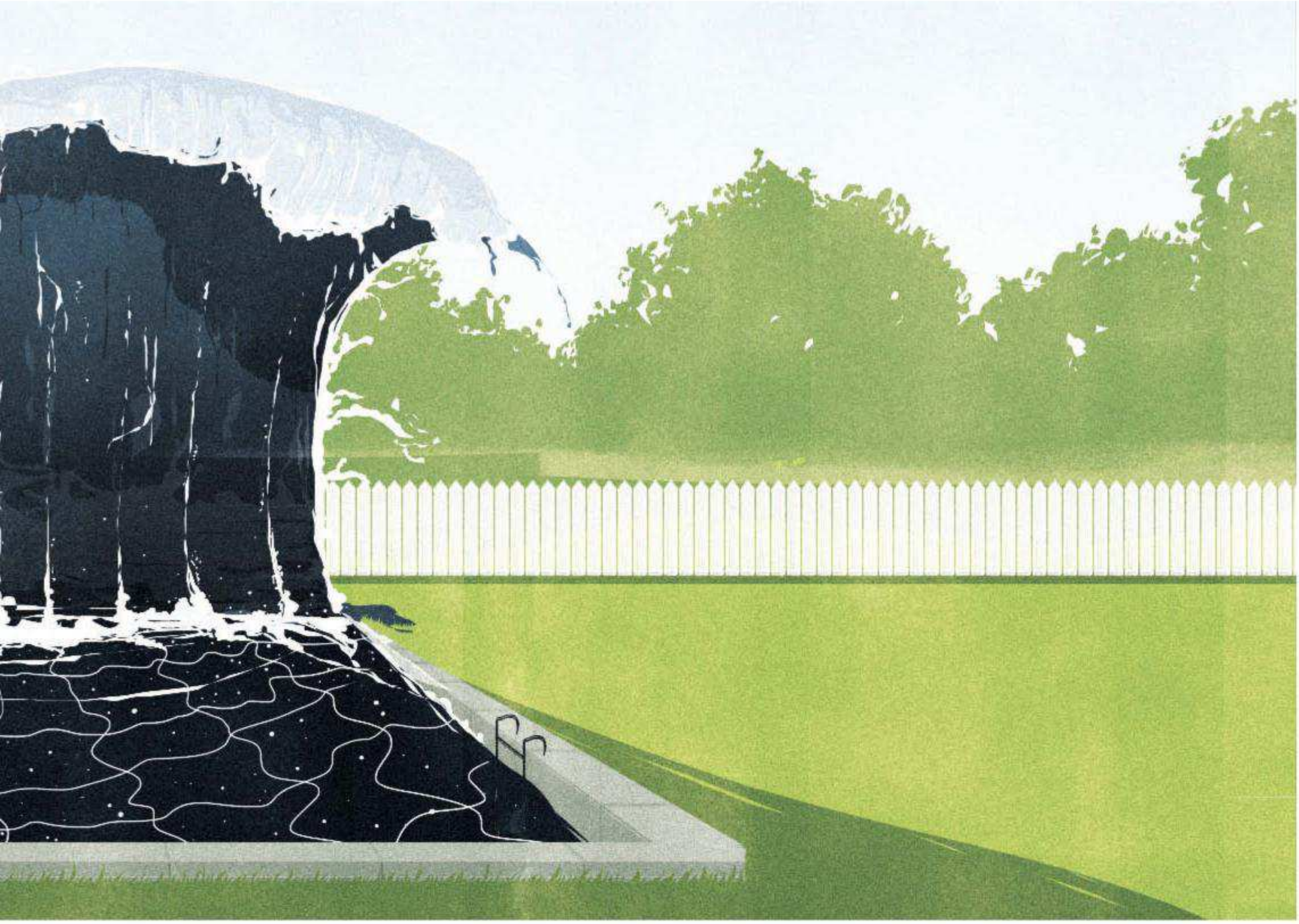
The first gravitational waves validated Einstein's theory of gravity – the ones to come could destroy it, says **Daniel Cossins**

A LONG time ago, in a galaxy far away, two black holes collided. We know this because more than a billion years later, on the morning of 14 September 2015, we felt it: in the world's most exquisitely sensitive measuring device, laser beams shifted ever so slightly as ripples in space-time washed over Earth.

This first detection of gravitational waves was the culmination of an epic scientific quest, and a stunning endorsement of general relativity, Einstein's landmark theory of gravity. Since then, our detectors have seen them five more times. But this is just the start – and although everything we have learned from the first waves is consistent with Einstein's masterpiece, the coming deluge of sightings could tear it apart.

Gravitational waves carry us into uncharted waters, where the fabric of the universe is so warped and gravity so extreme that our best theories are pushed to their limits. "If there is something wrong with general relativity, we are going to find it here," says Salvatore Vitale at the Massachusetts Institute of Technology.

As engineers recalibrate the lasers to make the detectors yet more sensitive, physicists are



buzzing with anticipation about what they might reveal. Theorists are now entertaining cosmic oddities that could transform our understanding of black holes, gravity and space-time itself. Their anomalous signals will not be easy to find; in some cases we hardly know what we're looking for. But one group of physicists is claiming that we have already spotted them.

Our modern understanding of gravity was sketched out in 1915, when Einstein put the finishing touches to his theory of general relativity. Its predecessor, set down by Newton, was a suitable approximation at small scales, but it broke down once you considered objects like stars and planets. In Einstein's new picture, gravity was the result of massive objects warping the fabric of the universe to create depressions that would pull in anything nearby. Despite being tested again and again over the past century, its predictions have never been found wanting.

The one idea we could not scrutinise was that massive bodies approaching each other would squeeze and stretch space-time so dramatically that they would spread ripples out in every direction, like a pebble dropped in a pond. The trouble was that although the events thought to produce these gravitational waves were extremely powerful, the waves themselves would be incredibly gentle. Space-time is stiff; it doesn't vibrate easily. To stand a chance of seeing gravitational waves that have travelled billions of light years across the cosmos, you need to register wrinkles as small relative to us as we are to the Milky Way.

That was the challenge for the scientists who dreamed up the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the late 1960s. Today, it consists of two L-shaped detectors – one in Livingston, Louisiana, the other in Hanford, Washington. Each uses mirrors to bounce synchronised laser beams up and down 4-kilometre-long arms. When a gravitational wave passes through, the arm lengths vary almost imperceptibly – and yet the beams shift measurably out of sync.

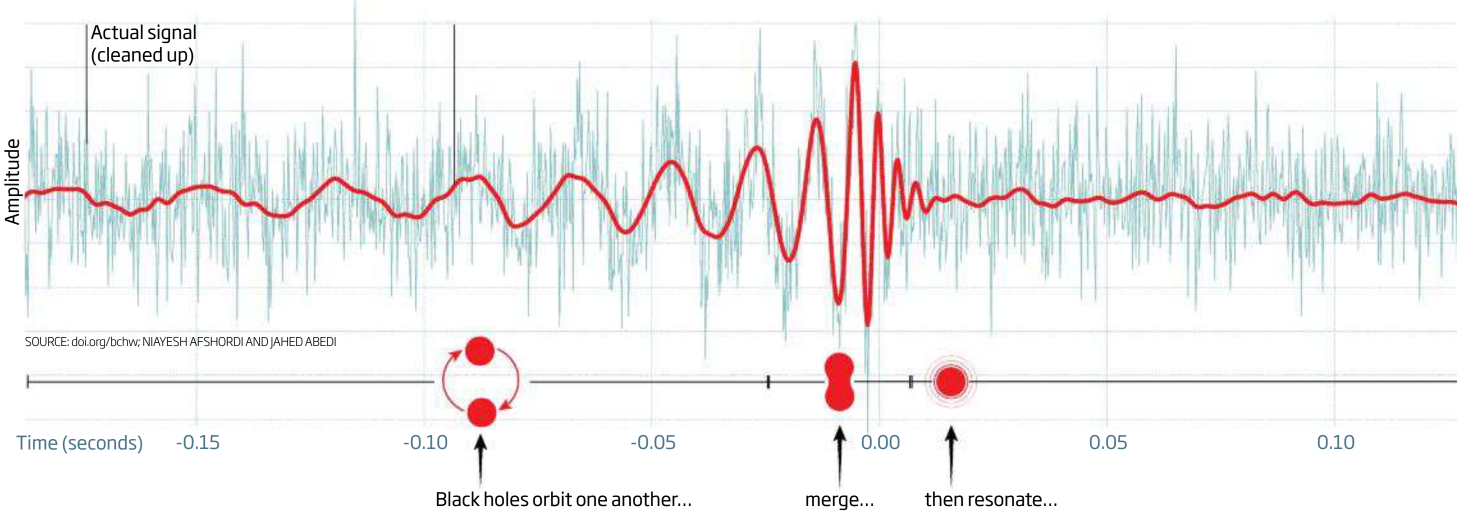
"Our picture of black holes, gravity and space-time itself could be transformed"

But achieving this sensitivity was only half the battle. It also took a monumental effort to figure out what the signals coming out of LIGO should look like, and how we could tease them apart from all the other vibrations passing through the detectors. Astonishingly, the 900-strong LIGO Scientific Collaboration pulled it off. They can not only spot a gravitational wave from across the universe, but even decode the information these distortions carry. That's how we know the masses of the black holes producing these waves, for instance, or that the collisions of ultra-dense neutron stars can seed the cosmos with heavy elements.

Even so, the era of gravitational wave astronomy has barely begun. Since LIGO's second observing run ended in August 2017, the detectors have been receiving upgrades that will significantly improve their sensitivity. They have also been joined by a third detector, Virgo, near Pisa in Italy. The result is that, when the third run starts later this year, we should be picking up gravitational waves at least once a week – and the signals will be clearer than anything so far. That will ramp up the chances of seeing something that doesn't fit with general relativity. ›

Unexpected echo

The first gravitational wave signal ever detected was exactly what Einstein's theory of general relativity predicted from two black holes merging. What it didn't predict is an echo one team of researchers think they spotted a fraction of a second later



SOURCE: doi.org/bchw; NIAYESH AFSHORDI AND JAHED ABEDI

"This is not to denigrate Einstein," says Richard O'Shaughnessy at the Rochester Institute of Technology, New York. "But there are good reasons to think his theory breaks down on some scales." The best-known difficulties are two cosmological ingredients thrown in to bring general relativity's predictions into line with observations: dark matter, which is unseen stuff dreamed up to explain why galaxies seem to rotate faster than their measured mass allows; and dark energy, a mysterious influence pulling the universe apart at an ever-increasing rate.

Then there is the fact that general relativity is incompatible with quantum mechanics, the theory of all the fundamental particles and forces – excluding gravity. For the most part, quantum theory reserves its predictions for the world of the very small. But when it comes to black holes, it has something important to say. According to Einstein's picture, the event horizon of a black hole represents the surface beyond which nothing can escape its pull. For all its importance as a physical border, the horizon itself is insubstantial – that is, there is nothing there. But quantum mechanics suggests there should be a firewall, a ring of high-energy particles that would incinerate anything that passes.

There was never any way to test the idea. But soon after LIGO's first detection in 2015, two independent teams proposed that a firewall, or indeed anything of substance at the event horizon, would reflect gravitational waves from colliding black holes. "As long as there is something there, you should get echoes," says Niayesh Afshordi at the Perimeter Institute in Waterloo, Canada, who leads one of the groups. "The question is, how long after the merger to expect them."

In 2016, Afshordi's team came up with a simple model for what could be at the horizon and figured out how far apart the resulting echoes would be. Then they looked at the publicly available LIGO data. What they found was jaw-dropping: for each of three gravitational wave signals they checked, the black-hole mergers were indeed followed by echoes at precisely the intervals predicted (see graph, above).

Or were they? Afshordi's calculations suggest that with no firewall, the chances of obtaining a similar signal from random noise would be 1 in 100, falling significantly short of the 1 in 3 million figure required to convince his peers. If Afshordi's claims do check out, however, it would be the first direct contradiction of general relativity. That would leave two options. Either Einstein's theory would need to be rewritten to accommodate the firewall, or we would have to abandon the notion of black holes altogether. In that case, general relativity could still survive more or less intact, so long as some pretender emerged to mimic the behaviour of these cosmic beasts (see "When is a black hole not a black hole?"). "Either way, it would be a big revolution," says Paolo Pani at Sapienza University of Rome.

Naturally, not everyone is convinced. When members of the LIGO collaboration completed their own analysis earlier this year, the chances that random noise could have caused a similar signal doubled. The team also pointed out that the strongest evidence for echoes came from the black hole merger with the lowest statistical significance. In other words, the loudest echoes came from the faintest signals, which is suspicious. "Imagine someone was shouting at you and you hear no echo, but

WHEN IS A BLACK HOLE NOT A BLACK HOLE?

One of the hallmarks of black holes is that you can't see them. Their density is so great that nothing - not even light - can outrun their pull. But if you see gas or dust or stars drawn to an invisible gravitational heavyweight, chances are you have spotted a black hole.

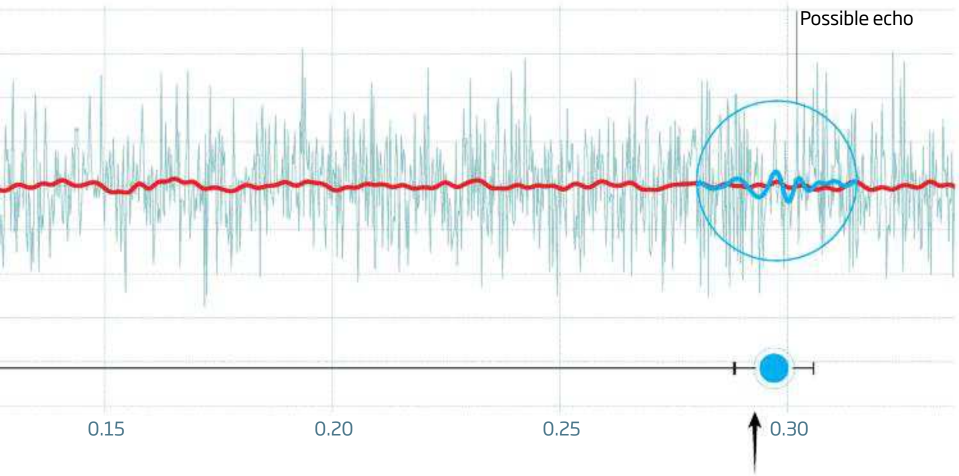
Or have you? Some cosmologists propose that what we have long assumed to be black holes might be something else entirely: exotic hypothetical entities known as boson stars.

Unlike most matter, which is made of particles called fermions, these objects would be made of bosons - which are capable of packing much more densely and acting in perfect harmony. In theory, if some as yet unknown bosons had the right properties, these blobs could get so massive as to distort space-time in much the same way we expect from a black hole, only without collapsing to become one.

Alas, they too would be invisible - and their constituent particles couldn't even be found in particle colliders, says Paolo Pani at Sapienza University of Rome. "The only way to see them would be through the way they interact with gravity, which makes gravitational waves almost our only hope to detect these kinds of objects."

Pani is among those working to figure out what observational signatures would distinguish pairs of boson stars from black holes. "We would expect boson stars to vibrate differently," he says.

Even if we do find them, however, boson stars are unlikely to consign black holes to the dustbin of cosmology. Boson stars are less compact, says Pani, so it is pretty much impossible for them to account for all our observations.



…and, potentially, reflect gravitational waves off their event horizons

> **"Either Einstein's theory will need to be rewritten, or we have to abandon our notion of black holes"**

then you hear a whisper and get echoes from that," says Nicolas Yunes at Montana State University. "Doesn't that seem a bit weird?"

For now, many cosmologists believe that Afshordi's claims are premature. But that could change as theorists get better at modelling the signals they expect firewalls to produce, and as the data analysis improves.

One thing is for sure: the hunt for black hole echoes is well and truly on. The LIGO collaboration has even made this one of its official goals. "Now we have competition," says Afshordi. "They are a huge force so, on the one hand, it is intimidating. But it is nice that this has been recognised as a worthwhile exercise."

The gravitational waves washing in over the next couple of years should definitively settle the issue. "Oh it's beautiful," says Luis Lehner, also at the Perimeter Institute, who was not involved in the studies. "When LIGO switches on again we're going to have many more events, so if this thing is real the signal will get stronger – and if not, we move on."

"That's what's so nice about this scenario," adds Pani. "This is something that can be verified or ruled out in the next few years."

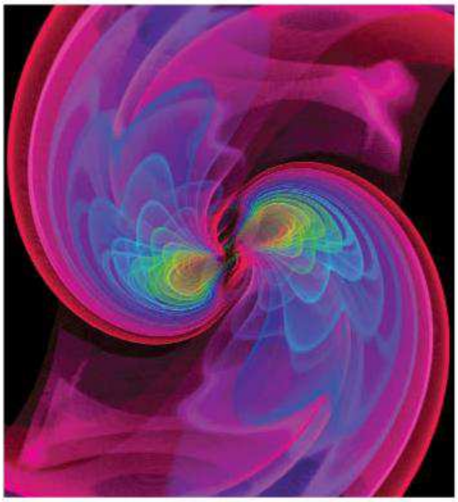
Still, others prefer to chase less speculative prospects. Rather than seeking exotic phenomena with dramatic consequences for Einstein's theory, they are tweaking the underlying equations to see what they imply for LIGO observations. In some cases, these modifications could solve cosmological conundrums. In others, they might smooth the way to a viable quantum theory of gravity.

Either way, says Yunes, "with modified theories of gravity, you're building on solid foundations". You don't have to make up the shape of signals based on ill-defined ideas of what to look for. Instead, you add fresh ingredients to Einstein's equations and solve them to build a full prediction of what you expect to see in these extreme conditions. Then you test it against the data.

The trick is to find weak spots in those foundations. General relativity has several core principles and from those arise specific predictions: that gravitational waves will travel at the speed of light, for instance, or that they preferentially corkscrew anticlockwise along their direction of travel. "You break one of these principles and then you ask what would be the consequences," says Yunes.

The LIGO detections so far have already killed off several modified theories of gravity that purported to explain dark matter or dark energy, including some that predicted space-time ripples would travel at below the speed of light. But there are plenty more where they came from.

Merging black holes send out ripples in space-time - that is, if they exist



Yunes, for his part, is partial to a theory that conjures an extra field into existence. It couples to gravity in such a way that it would explain why matter was not annihilated by antimatter in the first moments of universe – and thus why the universe isn't filled with radiation alone. Such modifications imply that gravitational waves would be more likely to corkscrew clockwise rather than anticlockwise. That would, in turn, mean we would observe black holes spiralling into one another much faster and more violently than relativity predicts.

Emanuele Berti at the University of Mississippi is among those exploring alternative theories of gravity. "We all have our own favourites," he says. "But the broader point is that these theories are mathematically tractable." In other words, we know how black holes should behave if these theories are correct, so we can accurately predict how the gravitational waves they produce should look.

In that regard, firewall echoes have some catching up to do. But with LIGO's upcoming campaign promising so much quality data, even those who remain unconvinced are happy to admit that we can now entertain them with a straight face. "The LIGO collaboration has been extremely conservative for good reasons," says Lehner. "But now we know it can detect gravitational waves, the possibilities embolden riskier strategies. This is just the beginning of this story, and it's going to be amazing." ■

Daniel Cossins is a features editor at *New Scientist.*
Hear gravitational wave researcher **Stephen Fairhurst** speak about the latest developments at New Scientist Live 20-23 September
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