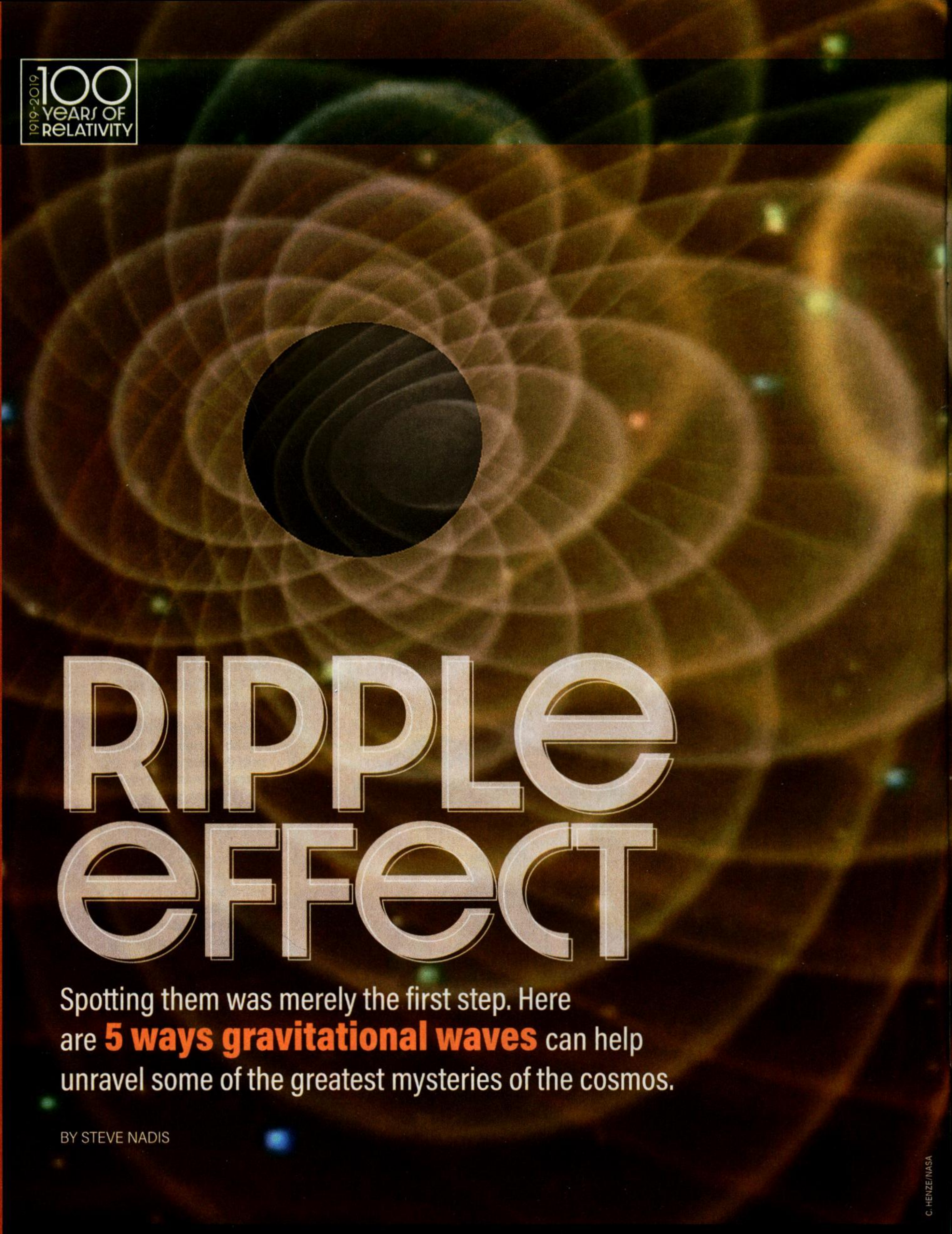

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RIPPLE EFFECT

Spotting them was merely the first step. Here are **5 ways gravitational waves** can help unravel some of the greatest mysteries of the cosmos.

BY STEVE NADIS

A three-dimensional simulation of merging black holes shows off gravitational waves — a new way of exploring the universe.

IN FEBRUARY 2016, ALBERT EINSTEIN made history, again. That's when physicists announced they'd finally observed what the great scientist's theories had predicted 100 years earlier: gravitational waves.

The first confirmed sighting of gravitational waves — distortions of space-time, literally ripples in the fabric of the universe — was a tremendous feat, earning Nobel Prizes for the key developers of the Laser Interferometer Gravitational-wave Observatory (LIGO). The waves' ultimate source was just as fantastic as the engineering that went into detecting them: two black holes smashing together, their enormous gravities sending undulations throughout the cosmos.

This achievement, the culmination of a multidecade-long effort, was justifiably celebrated. But while it resolved the long-standing issue of whether gravitational waves existed, it also marked a starting point for a whole new journey.

Before, astronomy had been based solely on studies of electromagnetic radiation and exotic particles like neutrinos and cosmic rays. But the tiny gravitational ripples, along with our recently acquired ability to see them, ushered in a novel way to study the universe.

Gravitational waves offer independent cross-checks on established avenues of research, while revealing phenomena we haven't seen before — and may not have imagined. In addition to the great (and previously unavailable) views we now have of the violent crashes between black holes and other superdense objects, gravitational waves may also clue us in to what transpired within a split second of the Big Bang itself. They could show us, moreover, how the universe has been expanding ever since. And while the sighting of gravitational waves offered a vindication of Einstein's hallowed principles, researchers can now subject general relativity to its most stringent tests yet, possibly revealing its shortcomings.

Researchers are already studying five topics ripe for exploration in the burgeoning era of gravitational wave astronomy.

1 THE FIRST BLACK HOLES

In some ways, black holes are simple objects. Whenever a spot in the universe ends up with more mass than it can handle, it may form a singularity — a point of near-infinite density where the usual rules of physics break down. Nothing that gets too close, including passing light, can elude its gravitational pull. At the center of every black hole, astronomers believe, a singularity of this sort resides.

The oldest known black hole appeared more than 13 billion years ago, about 690 million years after the Big Bang, but the first ones could have materialized much earlier: within a fraction of a second of the Big Bang. (Theorists think they might have formed when high-density regions in the turbulent newborn universe collapsed.)

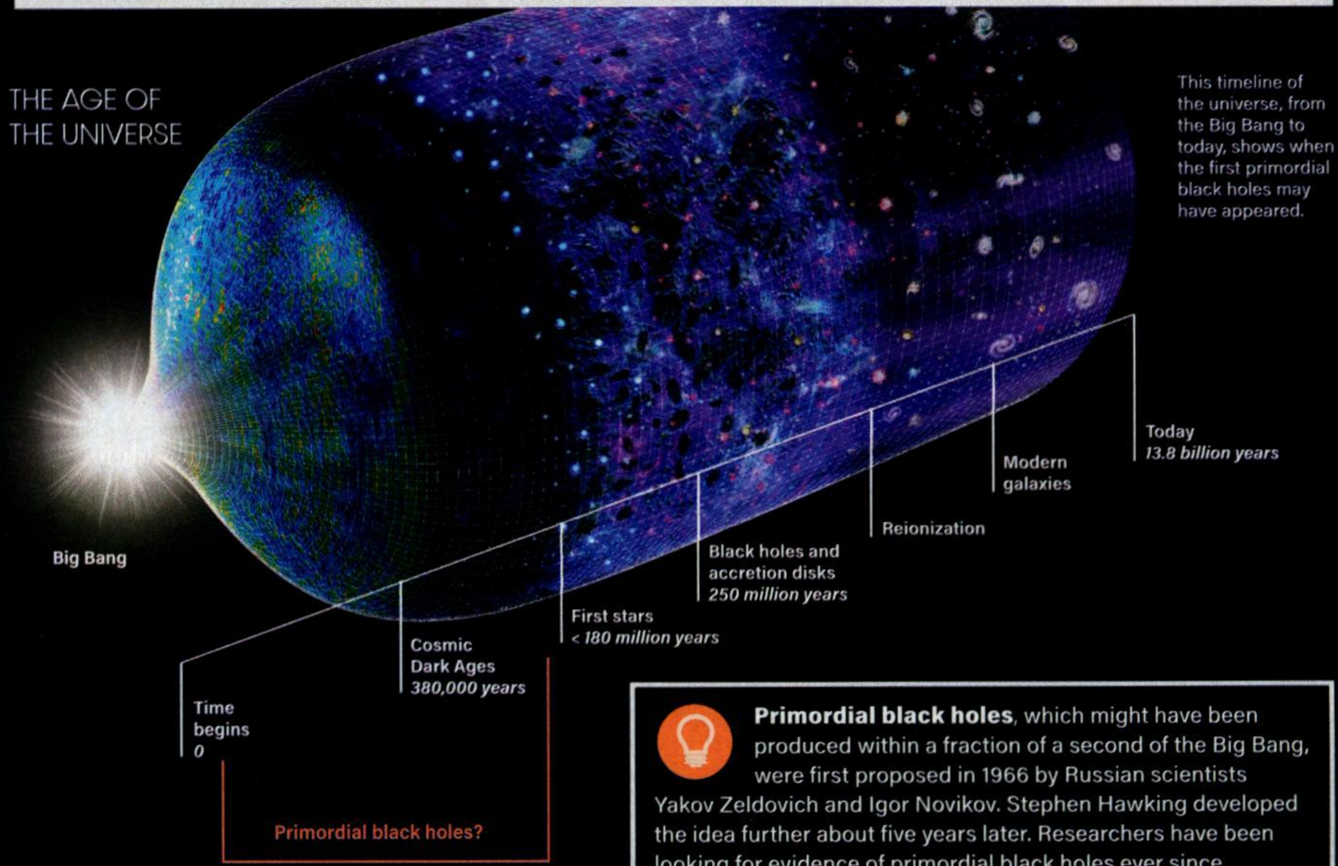
Assuming they exist, these so-called primordial black holes would be different from the most common variety, which form when a massive star exhausts its nuclear fuel and can no longer withstand its own gravity. As a result, while normal "stellar" black holes are considered well-established features of the universe, primordial black holes have remained hypothetical and mysterious for half a century. But a new technique, relying on gravitational waves, may reveal their presence.

Astrophysicists Savvas Koushiappas of Brown University and Avi Loeb of Harvard University have devised a simple way to search for primordial black holes. It revolves around searching for gravitational ripples caused by ancient black holes colliding, the best means of detecting them today.

The duo started by reasoning that in the very early universe, primordial black holes were the only kind possible, since star-based black holes can't form before stars themselves. So, they estimated the earliest possible time a pair of stellar black holes could possibly have crashed together, reasoning that any gravitational ripples seen before then must have been caused by primordial black holes. Based on conservative assumptions, they found that the first stellar black holes could not have formed and crashed until at least 67 million years after the Big Bang.

So if LIGO sees waves from black hole mergers taking place before that cutoff, it would mean one of two things: The first and most exciting possibility is that primordial black holes really do exist, thus confirming a long-standing conjecture. As a bonus, Koushiappas and Loeb have determined that primordial black holes could make up some of the universe's still-unexplained dark matter, so the finding could offer a partial solution to one of astronomy's biggest mysteries.

The second interpretation is simply that the standard cosmological picture is somehow amiss. "Either way," says Loeb, "it would be big news, telling us there's some new physics here that we don't fully grasp."



This timeline of the universe, from the Big Bang to today, shows when the first primordial black holes may have appeared.

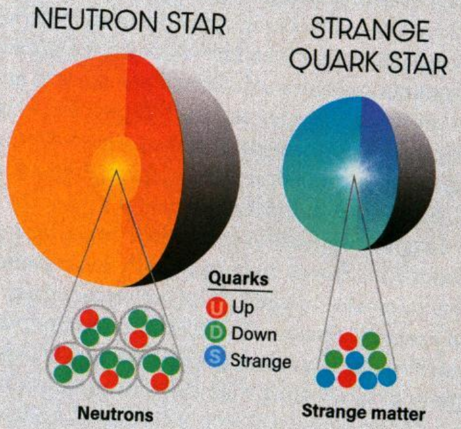
Primordial black holes, which might have been produced within a fraction of a second of the Big Bang, were first proposed in 1966 by Russian scientists Yakov Zeldovich and Igor Novikov. Stephen Hawking developed the idea further about five years later. Researchers have been looking for evidence of primordial black holes ever since.

THIS PAGE: R. FULLER, NATIONAL SCIENCE FOUNDATION. OPPOSITE: ALISON MACKEY/DISCOVER. BACKGROUND: NSF/LIGO/SONOMA STATE UNIVERSITY/A. SIMONNET

2 STRANGE MATTER

In *Cat's Cradle*, novelist Kurt Vonnegut imagined a new form of crystallized water called "ice-nine" that was so stable it would only melt at high temperatures. It was also a contagious configuration: Any liquid water that comes into contact with ice-nine would immediately freeze, transforming into more ice-nine.

Physicists speculate that something similar might be happening within the cores of neutron stars. These objects are the corpses left over after the violent deaths of stars too small to become black holes. The density within a neutron star is so high (roughly 100 trillion times greater than liquid water) that the star's original atoms have broken down into neutrons, protons and electrons, with the protons and electrons then squeezed together to form more neutrons. It's literally an entity made up of nothing but neutrons, hence the name neutron star.



Source: CXC/M Weiss

The ice-nine comparison goes like this: Under sufficiently high pressures, the neutrons within the dense cores of such stars revert to their basic constituents, the up and down quarks that make up the protons and neutrons of ordinary matter. However, this is an unstable arrangement, similar to a precariously balanced domino. In a neutron star, it turns out that a roughly equal assortment of up, down and the heavier strange quarks — a mixture called strange matter — would be more stable than a mélange of up and down quarks alone. It just takes a tiny bit of energy to convert an up or down quark into a strange quark, and the process releases enough energy to transform nearby quarks into strange ones, just as knocking over the first domino in a long row could take down the whole bunch.

"Once a seed of strange matter is formed, it can grow indefinitely and convert the whole neutron star into a strange star," says Pedro Moraes, an astrophysicist at Brazil's National Institute for Space Research. And since no lab on Earth could reproduce those conditions, the best way to find out whether strange matter exists, he says, is by studying a neutron star's interior. And the best way to do that? Study the gravitational waves that travel unobstructed, at the speed of light, straight from the heart of such objects as they crash together.

Europe's Einstein Telescope, a possible next-gen ground-based gravitational wave detector, should be able to spot strange stars. Consisting of three 6-mile-long arms, it would be located entirely underground.

A merger between ordinary neutron stars produces distinct gravitational waves. If a neutron and a strange star collide, an advanced gravitational wave detector could easily tell the difference. It comes down to the frequency of the waves themselves, says Moraes, which "will be higher when the system contains one strange star and higher still in the case of a strange star binary." As the two objects get closer, they spiral toward each other in gradually shrinking orbits; since strange stars are smaller and denser than neutron stars, they can follow smaller orbits during this phase. This allows the objects to circle more rapidly, increasing both the strength and frequency of the gravitational wave emissions.

Not only would such a finding settle the question of whether strange stars exist, it could also indicate whether strange matter really is the universe's most stable form of matter, capable of turning everything it touches into more strange matter — ice-nine on a cosmic scale. If that's true, anyone partial to the molecular structure that shapes our world — and our lives — would be advised to keep a safe distance.

3 EXTRA DIMENSIONS

We're all familiar with the four dimensions of Einstein's relativity: height, width, length and time. The notion of extra dimensions beyond those four sounds like science fiction, but that's been the focus of scientific inquiry for at least a century.

In 1919, German mathematician Theodor Kaluza suggested to Einstein a way of combining gravity and electromagnetism into a single, cohesive force — a longtime goal of physics — but it required five dimensions. String theory in the 1980s went even further, positing the existence of *six* additional tiny and unseen dimensions in an attempt to unify the particles and four known forces of nature into a single framework. That theory has led to important advances in theoretical physics and mathematics, though it still awaits empirical validation.

Despite numerous experiments — using high-precision pendulums, beams of energetic particles and other sophisticated tools — scientists have not yet found any evidence of extra dimensions. But if we want to understand our universe, it's important to know for sure whether there's more to space-time than the four dimensions we can readily perceive. CERN physicist David Andriot and his colleague Gustavo Lucena Gómez, formerly at the Max Planck Institute, have proposed a new way of finding out: Evidence of extra dimensions, they say, might be concealed within the ripples of gravitational waves.

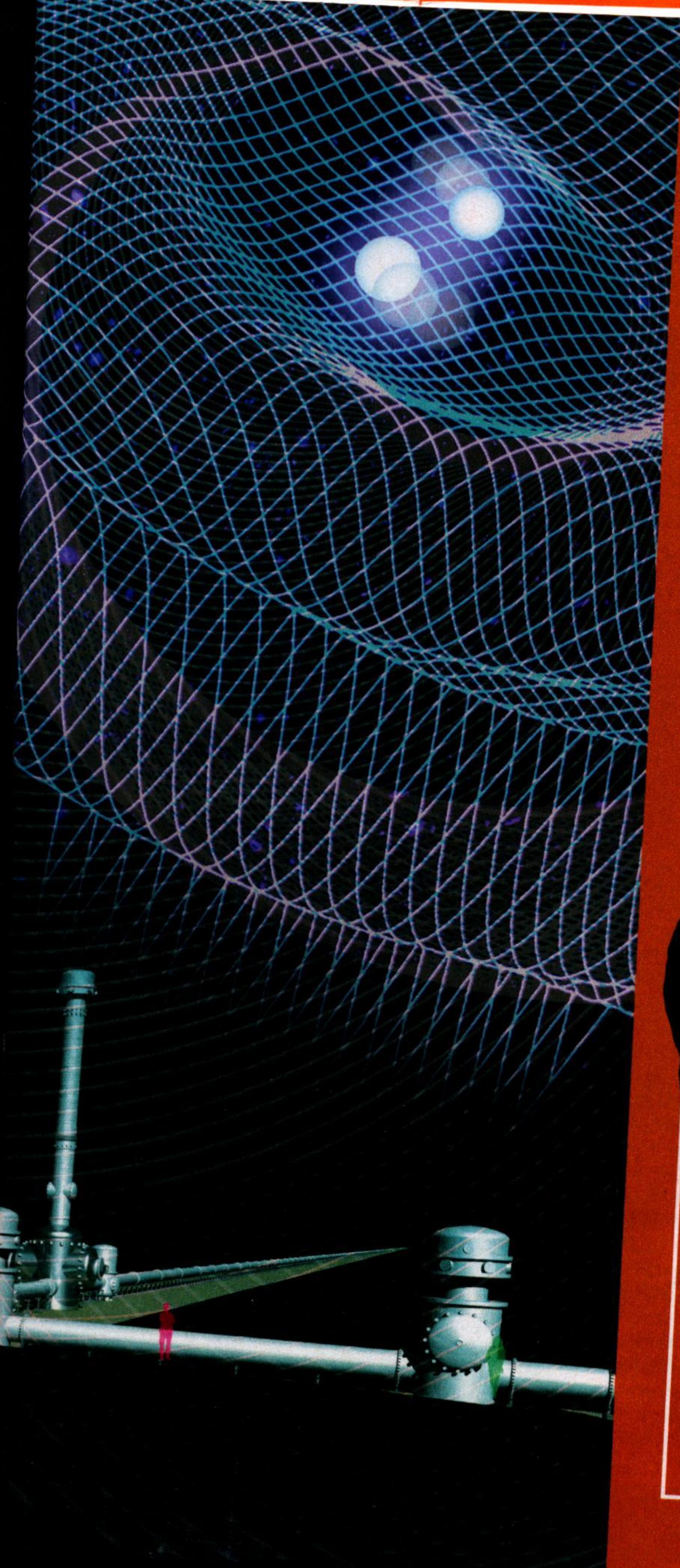
These waves shrink and stretch space-time as they move through it. Suppose you're looking at your computer, Andriot suggests, as a gravitational wave comes toward you, right out of the screen. This wave, according to general relativity, would extend, say, the vertical axis of your screen and contract the horizontal axis for a fraction of a second, and then the reverse, rapidly switching back and forth as it approaches your face.

But if the gravitational wave is also passing through extra dimensions, it will deform space in an additional way called a "breathing mode." Both the vertical and horizontal axis, Andriot explains, "will grow together and contract together, and then again get extended and contracted [together]. The same would happen in a gravitational wave detector. So it looks as if your screen, or detector, was ... breathing."

Physicists will have enough operational detectors to spot this new breathing mode deformation once Japan's KAGRA gravitational wave telescope is fully operational later this year, joining LIGO and the European Virgo interferometer. If researchers detect this mode, Andriot says, it would tell us either that the universe definitely has extra dimensions, or that "gravity doesn't behave the way that we think it ought to" — both explanations that would redefine physics.

The KAGRA detector will be housed underground, use sapphire in its detection mirrors and work at temperatures of just 20 kelvins (minus 424 degrees Fahrenheit).

ASTRONOMICAL OBSERVATORY OF JAPAN



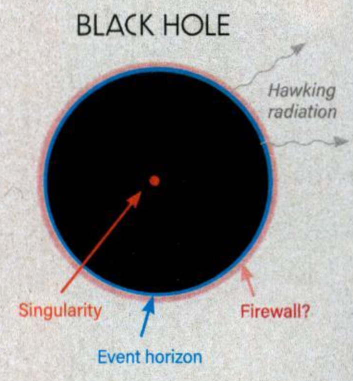
WHAT WOULD EXTRA DIMENSIONS LOOK LIKE?

It's hard for our brains to imagine. A classic example involves a rope climber and an ant: The climber can move only up or down along the rope, effectively limited to travel in one dimension. But an ant could crawl *around* the rope, too, moving in a dimension inaccessible to the climber.

4 EVENT HORIZONS

One of the best-known features of black holes is the event horizon — the invisible surface enveloping the shrouded interior, marking the point beyond which no escape is possible. Should you cross this dividing line, however, you wouldn't even notice. It's a sobering reminder to proceed carefully in deep space.

A lesser known aspect of black holes is their temporary nature: Stephen Hawking demonstrated in 1974 that black holes slowly leak radiation until they disappear completely. That suggests that any information contained within a black hole would eventually disappear as well — a major violation of quantum theory. That's a problem: Because they can't both be right, either general relativity or quantum mechanics must need modification in some way.



If black holes really are surrounded by hot firewalls, gravitational waves would likely produce a series of telltale echoes confirming their presence.

In 2012, researchers offered a quantum solution that sacrifices a piece of relativity. They suggested that just outside the event horizon lies a more noticeable boundary called a firewall — a sheet of hot, high-energy particles that would incinerate any matter passing through it. Information, however, could still eventually escape from such a modified horizon, appeasing quantum theory.

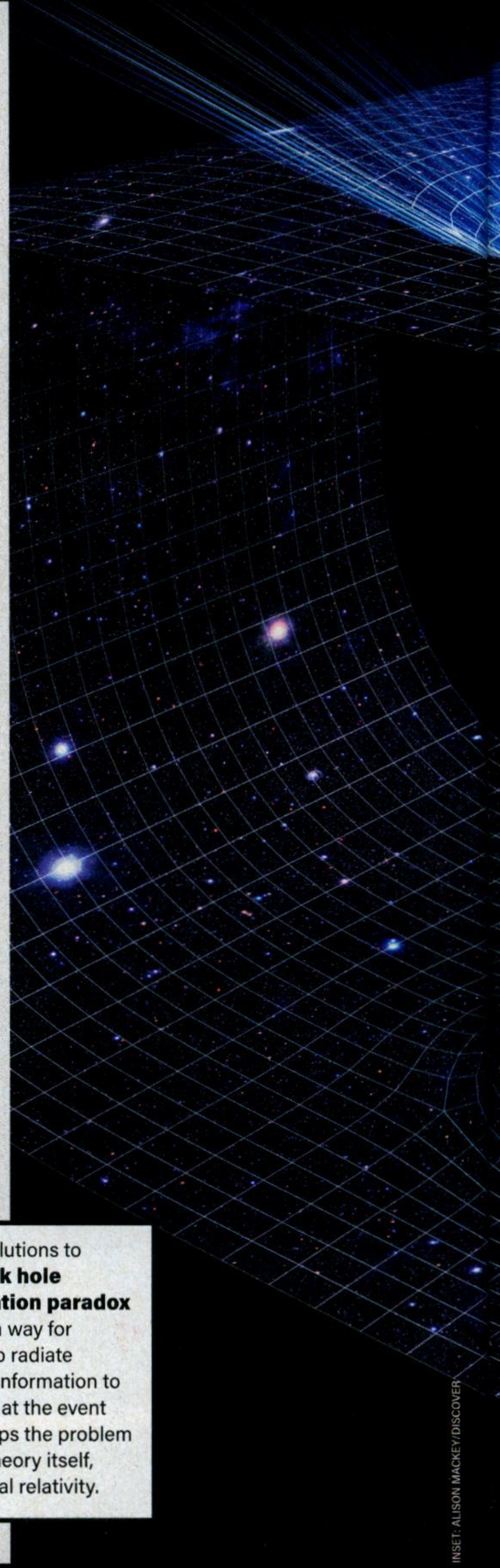
It's remained purely theoretical, but gravitational waves may provide evidence that firewalls really exist. We know that when two black holes merge into one, they emit these ripples, which ring out after the merger like the prolonged reverberations of a bell after being struck. During this time, the melded black hole's gravitational signature will look different if it has a firewall: It will produce echoes, says physicist Vitor Cardoso of the Instituto Superior Técnico in Lisbon.

After a merger, some of the resultant gravitational waves head outward, perhaps destined to reach a detector like LIGO, while others head inward, toward the black hole's center. If there's just an event horizon, Cardoso says, these latter waves would "keep on going, never to return." But if those waves instead hit a firewall on their way in, some would be reflected outward, like echoes bouncing off a canyon's walls. A portion of those could reach LIGO, and another portion could bounce off something else nearby and head back toward the black hole. Some of those waves would again rebound off the firewall, perhaps eventually reaching LIGO as an even fainter signal. The process would continue until the signals die out, too faint to detect.

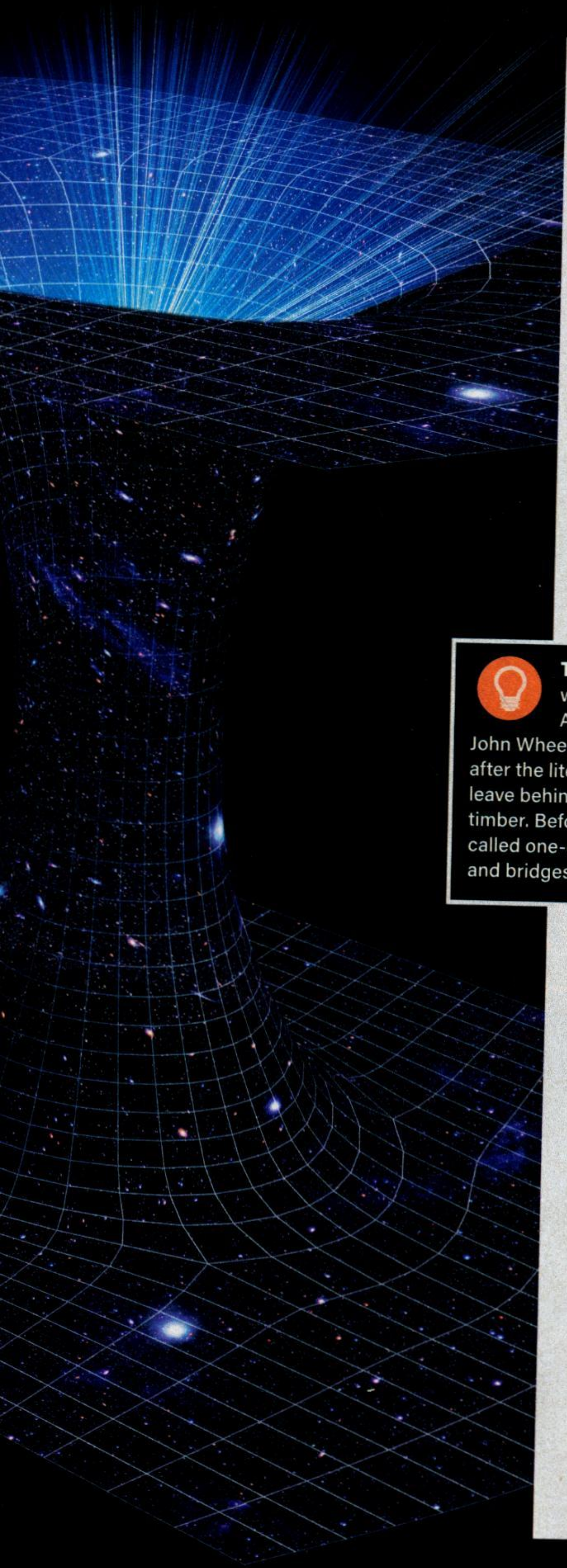
Niayesh Afshordi, a physicist at the University of Waterloo and Perimeter Institute, saw hints of such echoes in the combined data from LIGO's first three detections. The chance of it being a statistical fluke are 1 in 100, he says. Those odds might sound pretty good, but they're still well short of the 1 in 100,000 threshold that physicists demand. While waiting for new, more precise data to arrive from LIGO and other facilities, Afshordi and his colleagues are refining their strategies for identifying these echoes.

Evidence of echoes wouldn't guarantee that black holes are enclosed within firewalls, but it would call into question the standard picture of an imperceptible event horizon, as derived from general relativity. It could also mean that some of the objects we thought were black holes may be something else altogether: wormholes.

Other solutions to the **black hole information paradox** include a way for infalling objects to radiate away data, or for information to somehow remain at the event horizon. Or perhaps the problem lies in quantum theory itself, rather than general relativity.



INSET: ALISON MACKEY/DISCOVER



WORMHOLES

5

In 1916, one year after Einstein presented the equations of general relativity, Austrian physicist Ludwig Flamm found a solution to them that described a "wormhole," a small tunnel connecting two different parts of the universe, or our universe to another.

Wormholes have long been popular fixtures in science fiction as handy ways to get around by offering a kind of cosmic shortcut. Gravitational wave astronomy may help us find out whether these space-time tunnels or "bridges" (as Einstein called them) have any basis in science fact.

Theorists have raised the possibility that some of the objects we thought were black holes could actually be wormholes. A 2016 paper by Vitor Cardoso and his colleagues found that wormholes — which would be as massive and compact as black holes, but lacking an event horizon — could emit the same kind of gravitational echoes as a firewall-encased black hole. Researchers at Katholieke Universiteit Leuven in Belgium reached similar conclusions in 2018.

The term *wormhole* was coined in 1957 by American physicist John Wheeler. He named them after the literal holes worms leave behind in fruits and timber. Before that, they were called one-dimensional tubes and bridges.

The two kinds of objects may seem different, but the idea that they could have similar gravitational signatures is not as shocking a suggestion as it sounds. "Wormholes are modifications of black holes," says KU Leuven physicist Thomas Hertog, a former student of Stephen Hawking. They're essentially just different solutions to the same equations.

If we find definitive echoes within gravitational waves, Cardoso says, it would be hard to figure out which kind of object produced them, a firewall or a wormhole. Many within the general relativity community, he adds, maintain that "anything that resembles a black hole must be a black hole," making it hard for a radically different idea like wormholes to gain credence.

Then again, for about 50 years, most physicists did not accept the existence of black holes, either. They acknowledged the mathematical validity of the solutions to the equations of general relativity, but did not believe the universe actually created such objects. Time and data helped change the community's mindset.

At the moment, the evidence for black holes is much, much stronger than it is for wormholes. "But there's a lot we don't understand," Cardoso notes. "So it's good to keep an open mind." And if it turns out that wormholes really do exist, we might have to keep an open mind about humans traveling through them someday — and not just in the movies. D

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