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Wave after wave

By observing dozens of gravitational waves – and spotting completely new kinds – we are solving some of the universe's deepest puzzles, reports **Stuart Clark**

IN A darkened room in Sweden, beneath a chandelier and surrounded by dozens of gilt-framed portraits, journalists are listening as a phone connection is established with Rainer Weiss. It is October 2017 and Weiss has just been awarded the Nobel prize in physics for spearheading the detection of gravitational waves, along with Kip Thorne and Barry Barish. The pomp and ceremony was a fitting finale to the quest to detect these elusive waves, which had been predicted by Albert Einstein more than 100 years earlier.

In truth, though, it was as much a beginning as an ending. If the traditional astronomy of telescopes is like seeing the cosmos, then gravitational wave astronomy is akin to hearing it. The discovery of these ripples in space-time had effectively given astronomers a new sense. In that room crowded with reporters, a journalist from Swedish television took the mic and asked Weiss what kind of things we might be able to learn. "Well," he began, "there's a huge amount of things to find out."

Less than five years later, and with scores of gravitational waves now detected, we are starting to see what he meant. These waves are providing us with a rich picture of the universe's most exotic objects, showing us fresh details of how stars die and explaining long-standing mysteries about the cosmic population of black holes. What's more, we seem to be on the cusp of detecting a whole new kind of gravitational wave, one that could tune us in to the frequency of some deeply mysterious objects we think were forged in the aftermath of the big bang.

OLLIE HIRST

Giant pebbles

Imagine dropping a pebble into a pond and watching the ripples spread out in concentric circles. A gravitational wave is a bit like this, except instead of a pebble, we have massive, moving objects like black holes, and instead of water, the ripples are in space-time itself and propagate in three dimensions. These waves were one of the last unverified predictions of Einstein's general theory of relativity. That is why Weiss and many other physicists banded together decades ago to try to snare them.

To do so, they built two gigantic instruments in the US that are collectively known as the Laser Interferometer Gravitational-Wave Observatory, or LIGO. These detectors each fire two precision lasers in different directions from a central starting point at mirrors that are several kilometres away. The path the beams take is the same length, so any slight difference in when they arrive back at the origin indicates a change in the space they have traversed – a sign of a gravitational wave swooshing through Earth, stretching and squashing space.

Detecting these ripples isn't easy, given that gravitational waves change space by much less than the width of a subatomic particle. But the LIGO team succeeded. These days, there are another three similar detectors: Virgo in Italy, the Kamioka Gravitational Wave Detector (KAGRA) in Japan and GEO600 in Germany.

The most useful thing about this groundbreaking work is that it gives us a window on black holes, objects that are otherwise tricky to study. Unlike stars or planets, black holes don't directly give out or reflect light. But they do sometimes crash into each other, creating waves in the fabric of space-time. "Gravitational wave detectors are doing something truly unique," says astrophysicist Thankful Cromartie at Cornell University in New York. "You're sensitive to a whole bunch of different kinds of events."

At first, there was a thrill in just hearing the "chirp" of colliding black holes. But researchers from LIGO, Virgo and KAGRA released ›

another batch of results in November 2021, which brought the total number of observed waves to 90. With so many gravitational waves now in the bag, we are in a new era, one in which we can answer questions about how the universe works on the grandest scales.

Perhaps more than any other class of celestial object, black holes mark out the history of the cosmos. They come in a variety of sizes and are formed in different ways over the life of the universe. There are stellar black holes, which are born when giant stars die and have masses from several times to tens of times that of the sun. Then there are supermassive black holes, which can be anywhere from a few million to a billion solar masses. These live in the centres of galaxies and are thought to have formed as smaller black holes merged.

Thimbleful of neutrons

Our understanding of how these types of black hole grow and relate to each other is, however, riddled with confusion. One major puzzle is the mass gap between the smallest black holes and the largest neutron stars. Neutron stars are the collapsed cores of dead stars and the second most dense objects in the universe; a thimbleful of neutron star weighs hundreds of millions of tonnes. It is thought that these stars can reach a point of such density that they collapse into a black hole. If this is true, then the lightest black holes should have about the same mass as the heaviest neutron stars.

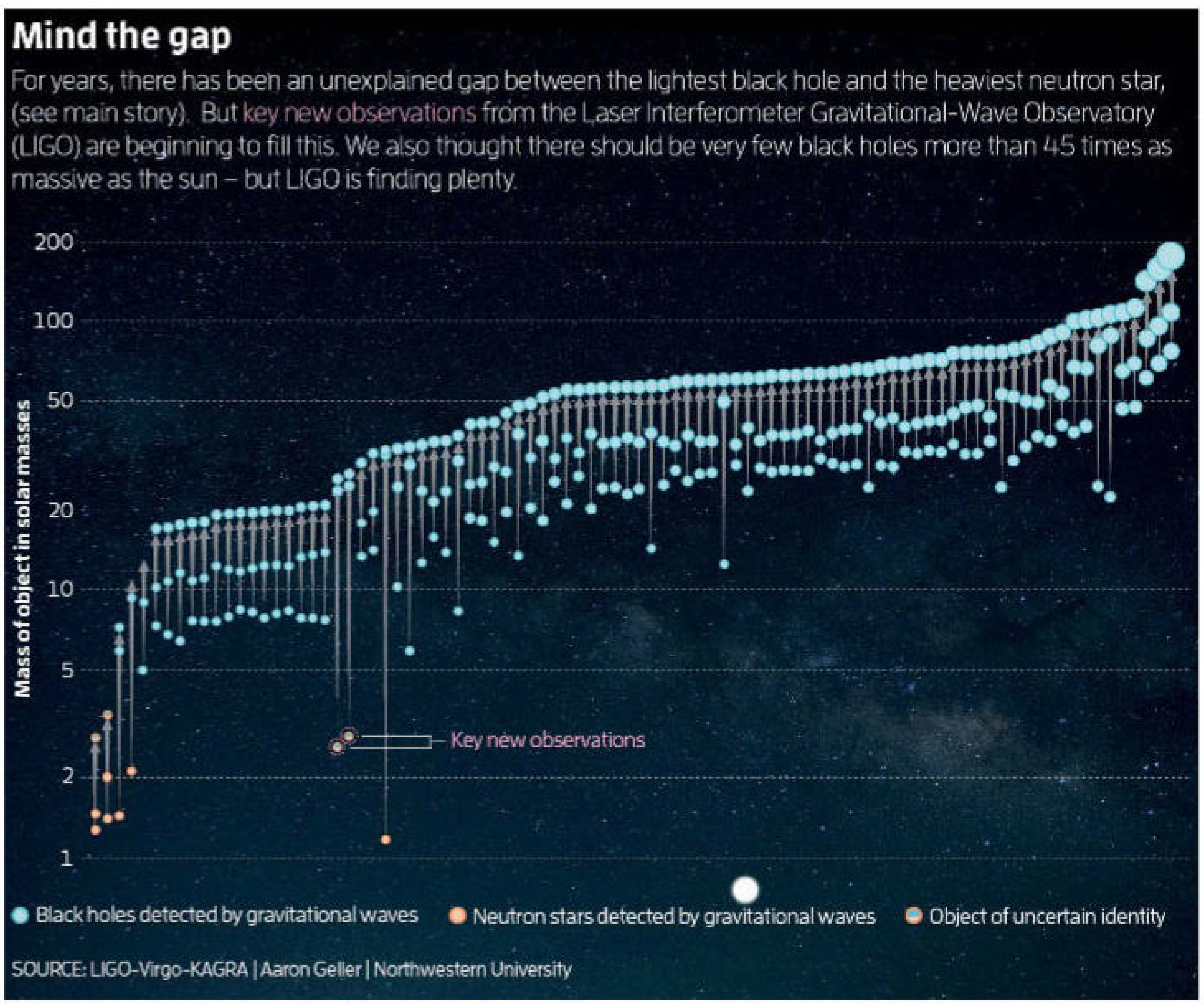
But that isn't what we see. Even before LIGO, we had ways of estimating the mass of black holes and neutron stars. These suggested that the heaviest neutron stars got no heavier than about twice the mass of the sun, while the lightest black holes were no lighter than about five solar masses. In 2010, Feryal Özel at the University of Arizona called attention to the paucity of objects of two to five stellar masses, sparking debate about whether we had seriously misunderstood neutron stars. In the first few years after LIGO was switched on, we still didn't see anything definitive in this "mass gap".

But with the data released in November, that has changed (see "Mind the gap", right). There have now been at least two events in which a black hole swallowed some smaller object – another black hole or a neutron star, we can't be sure which – that weighed in at 2.6 solar masses, squarely within the mass gap. A third sighting from LIGO caught a black hole eating a 2.1-solar-mass neutron star. Meanwhile, Cromartie and her colleagues spotted a neutron star that was 2.19 solar masses using radio telescopes.

"At first, there was a thrill in just hearing the 'chirp' of colliding black holes"

Katerina Chatziioannou at the California Institute of Technology, who is part of the LIGO collaboration, says these detections are telling us that the mass gap is an observational bias. LIGO is better at detecting more massive objects. "We're very good at seeing black holes of 30 solar masses, but less good at seeing black holes of five solar masses," she says. Mass-gap objects are out there, it seems, they are just hard to spot. LIGO is currently being upgraded such that it will be more sensitive to lighter objects when it switches back on later this year.

There are also surprises in the latest data when it comes to the most gigantic stellar



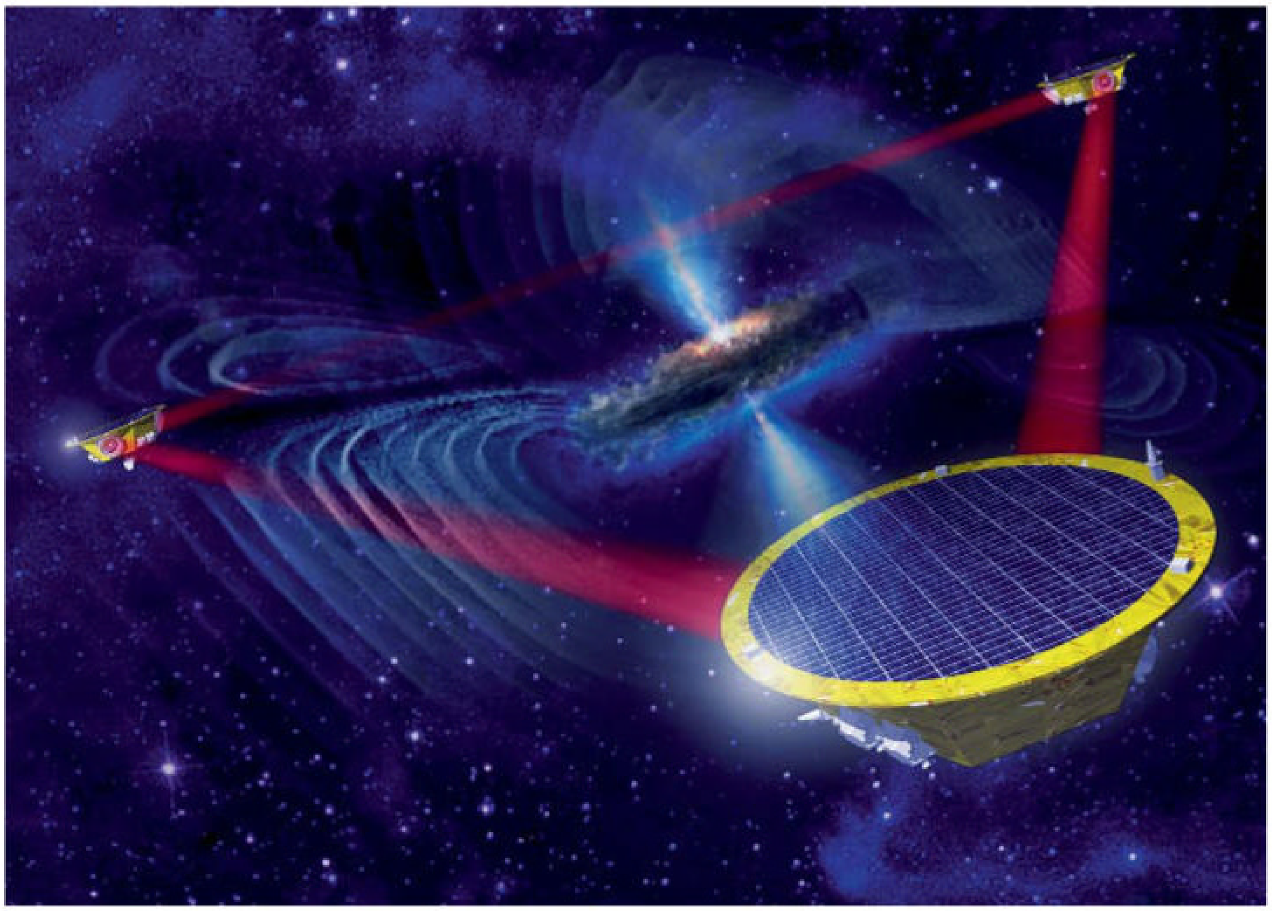
OUT OF THIS WORLD

One reason detecting gravitational waves on Earth is so tricky is that our planet throbs beneath our feet. When you are trying to detect the unimaginably tiny squashing and squeezing of space caused by colliding black holes, the last thing you want is any seismic vibrations in the ground shaking the equipment.

That is why the European Space Agency (ESA) has hatched a plan to get away from those bad vibrations by putting a gravitational wave detector in space. Known as the Laser Interferometer Space Antenna, or LISA, the mission is staggering in ambition. It will work according to the same principles as the Laser Interferometer Gravitational-Wave Observatory on Earth (see main story), but instead of timing the path of laser beams on the ground, LISA will fire lasers from one free-floating craft to two others, each exactly 2.5 million kilometres away.

As the lasers bounce between these spacecraft, they will register the minuscule changes in their relative position caused by passing gravitational waves. While LIGO is designed to snare the waves produced by black holes of about 30 solar masses, LISA should be capable of seeing much longer waves from larger black holes: ones with hundreds of thousands or even millions of solar masses each.

We know the technology works because ESA launched a demonstration mission in 2015 called LISA Pathfinder. It was a great success. Still, we will have to wait a while for LISA to come online – it is scheduled to launch in 2037.



EADS ASTRIUM

The LISA detector will aim to detect gravitational waves in space

black holes. The heaviest stars yet discovered are more than 200 times the mass of the sun. But when one of these stars dies, we think the explosion is so powerful that nothing is left, not even a black hole. In fact, according to our best understanding of these events, no black hole heavier than about 45 solar masses should be created from a supernova, no matter how massive the star was.

But LIGO is detecting black holes that tip the scales at 60 solar masses and beyond. Even accounting for the bias of the detector towards heavy objects, there are more of these monsters than expected. This might be telling us that we have misunderstood supernovae, or perhaps that black holes grow to such sizes by merging with each other.

Using gravitational waves to study the supermassive black holes – the ones that are millions of times heavier than the sun – could tell us more about cosmic history. Today, one of these behemoths sits at the centre of pretty much every galaxy, providing the gravity gluing its stars together. To get to their present sizes, older, smaller galaxies and their supermassive black holes must have merged. But we have never been able to peer far enough back in time to see this happen.

These colliding supermassive black holes would have given off gravitational waves. But the actual collisions are expected to be rare, and because the orbital speeds would be low, the waves would have lower frequencies than those observed up until now. A LIGO-style detector would never be sensitive enough to see them – unless it was put in space (see "Out of this world", left).

But there is another way. Even before they merge, orbiting supermassive black holes give out weak gravitational waves. Individually, these are insignificant, but when combined with those being given out by all other such black hole pairs across the universe, they add up to an incessant, infinitesimal burbling of space-time that criss-crosses the cosmos. It is known as the gravitational wave background.

This background is actually a million or more times "louder" than the LIGO signals, but a full wave undulation lasts for years. Detecting it would mean measuring an oscillation that is still far less than the width of an atom and takes place over the course of years. "The nature of the signal itself is very different," says Joe Simon at the University of Colorado, Boulder.

Simon and Cromartie are part of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) project, which aims to measure this signal. ›

JEE SEYMOUR IMAGES

Radio telescopes, such as the Green Bank Observatory in West Virginia, can observe pulsars

NANOGrav uses conventional radio telescopes to monitor fast-spinning neutron stars called pulsars. As they rotate, pulsars send out regular beams of radio waves into space, like a lighthouse, which serve as extremely stable clocks. NANOGrav has been timing signals from dozens of pulsars across the sky for a decade. Any tiny discrepancies in when the flashes arrive here could be a sign of the ripples of the gravitational wave background.

"With so many gravitational waves spotted, we can start answering the big questions"

Black hole revelations

About a year ago, the NANOGrav researchers announced an analysis of almost 13 years of data for 45 pulsars. In it, they saw hints of a signal that could be the background. They haven't yet resolved the signal well enough to be sure, but the NANOGrav team has since combined its data with that of two similar pulsar timing arrays in Europe and Australia to form the International Pulsar Timing Array collaboration. This triumvirate announced in January that in the combined data set, the signal stayed put, providing a stronger suggestion that this is no false alarm.

Even if this is the real deal, it won't be possible to deduce anything about individual supermassive black holes. Instead, astronomers would model versions of the universe in computers, each with different populations of giant black holes and varying merger rates, and see what kind of gravitational background signal should be produced. By comparing the models and the real data, we should be able to deduce a lot about the kinds of black holes out there in the cosmos.

The most exciting prospect would be if the computer models couldn't be made to fit the data. This might mean that we will be forced to invoke another type of black hole entirely to balance the books.

In some interpretations of the big bang, fluctuations in the density of space in the first seconds of the universe could have produced tiny black holes. It is far from certain whether these so-called primordial black holes existed, or if they are still out there. But if they are, they provide an elegant solution to several problems in cosmology. Most appealingly, they could be the secret identity of dark matter, the invisible stuff thought to be guiding the motion of galaxies.

According to Suvodip Mukherjee at the Perimeter Institute in Waterloo, Canada, the gravitational wave background could provide us with the first concrete evidence of primordial black holes. "I find this possibility very fascinating," says Mukherjee. He and his colleague Joseph Silk at Johns Hopkins University in Maryland recently showed that it should be possible to distinguish regular and primordial black holes in the gravitational wave background.

First, though, we must unambiguously detect the background signal. To that end, the NANOGrav team is analysing another three years of data from almost 60 pulsars. This should tell us for sure whether we are seeing the gravitational wave background. But as our first detection of gravitational waves taught us, that will be only the beginning. "It's not going to end once we say we've detected the gravitational wave background," says Cromartie. "That's when our science really starts." ■

Stuart Clark is a consultant for *New Scientist*. His latest book is *Beneath the Night* (Faber)