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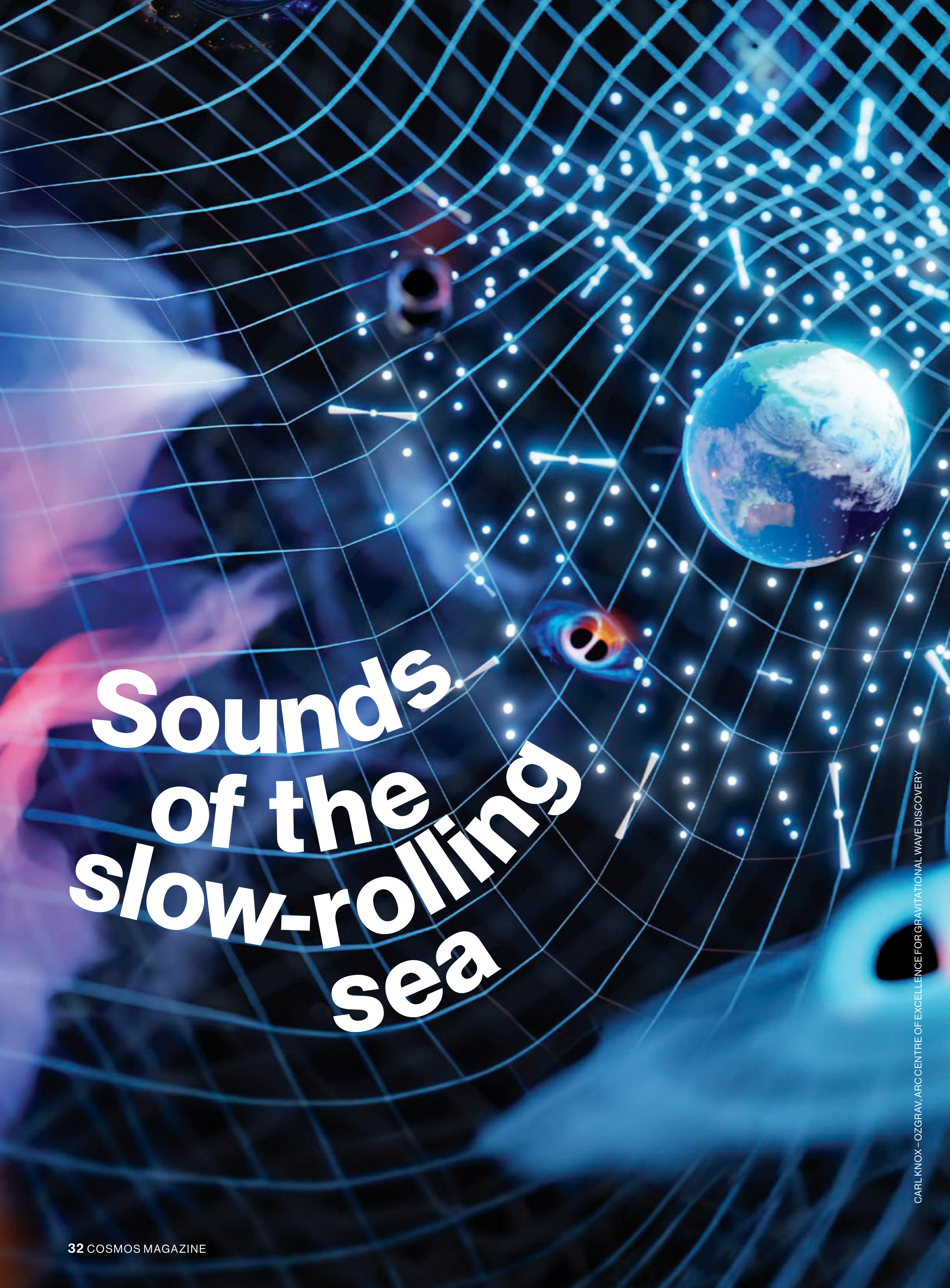


Sounds of the slow-rolling sea

CARL KNOX – OZGRAV, ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY

A galaxy-scale telescope has revealed that the universe is awash with a low, constant hum of gravitational waves. Will this change what we know about cosmic history? And will it change how we do astronomy? **Sara Webb** reports.

In June 2023 the internet lit up with excited physicists hinting they had found something ground-breaking. Imaginations ran wild: had we heard from aliens? Broken general relativity? Uncovered a hidden dimension in the universe? When the secret spilled, the truth was as good as the speculation: physicists had found evidence of a gravitational wave background.

This was an impressive feat. These ripples in the fabric of space-time are hard to spot; even booming gravitational echoes from black holes colliding fade to whispers by the time they reach Earth. Hearing the 'hum' of a low-frequency gravitational wave background required a galactic-scale detector – made up of dead stars.

So how did they do it? And more importantly, why are physicists saying that the most exciting part is yet to come? Come with me through space and time to find out if this discovery could change the way we study and understand the cosmos.

Gravitational waves 101

Wait – what are gravitational waves, anyway? Consider this your primer before we get to the world-changing stuff.

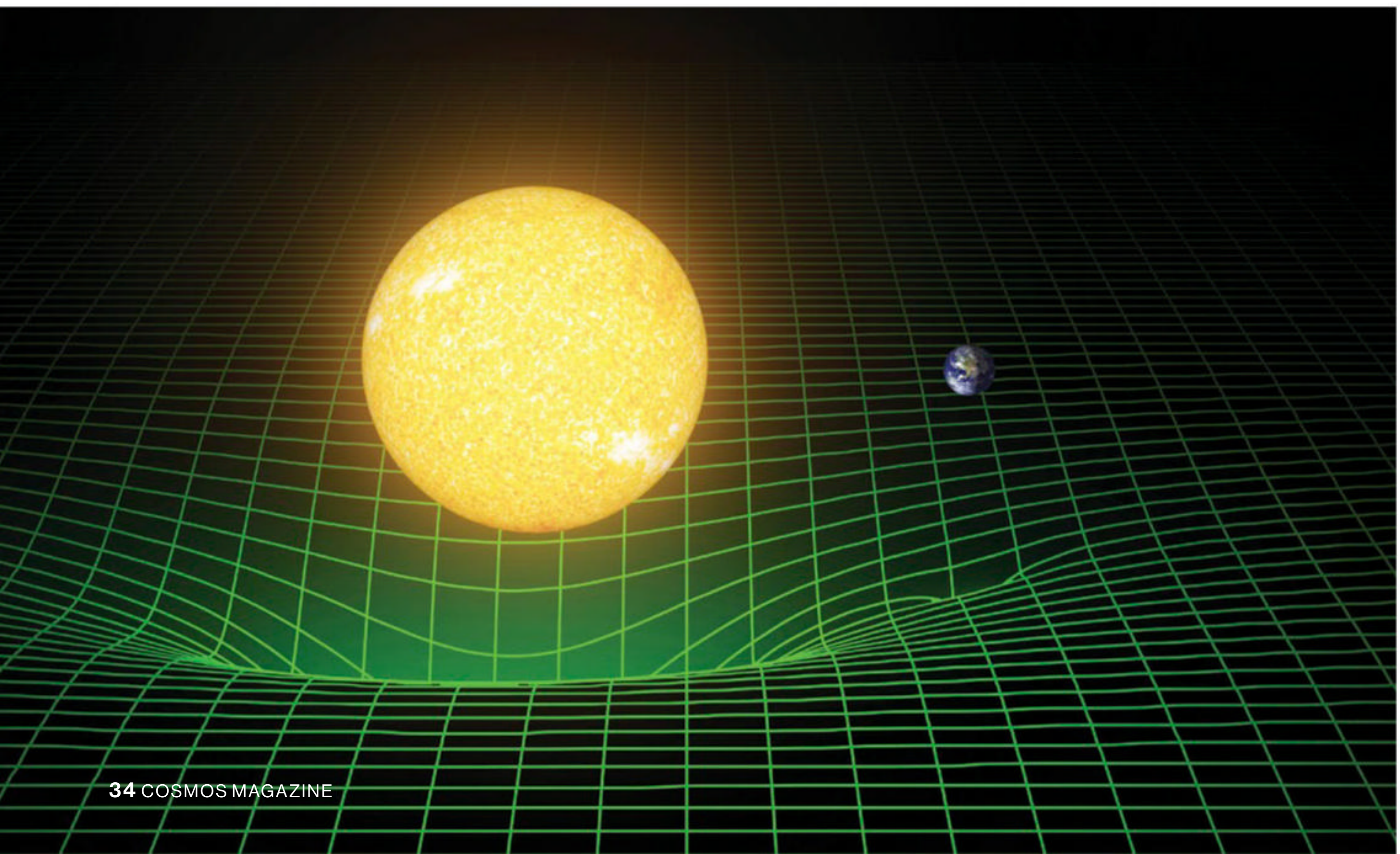
It all began, of course, with Albert Einstein.

In 1915, Einstein published his general theory of relativity, describing that the force of gravity we measure is due to the bending of space and time. Einstein was the first to propose that space and time were intertwined, and that they could be described as acting like a fabric. Picture a trampoline. If you put a bowling ball in the middle, the fabric is stretched and pulled downwards as the bowling ball's mass creates a dip. Now replace the bowling ball with a marble. It will create a much smaller dip on the trampoline. Those dips represent gravitational wells in space and time. Everything with mass – including you and I – creates these gravitational wells.

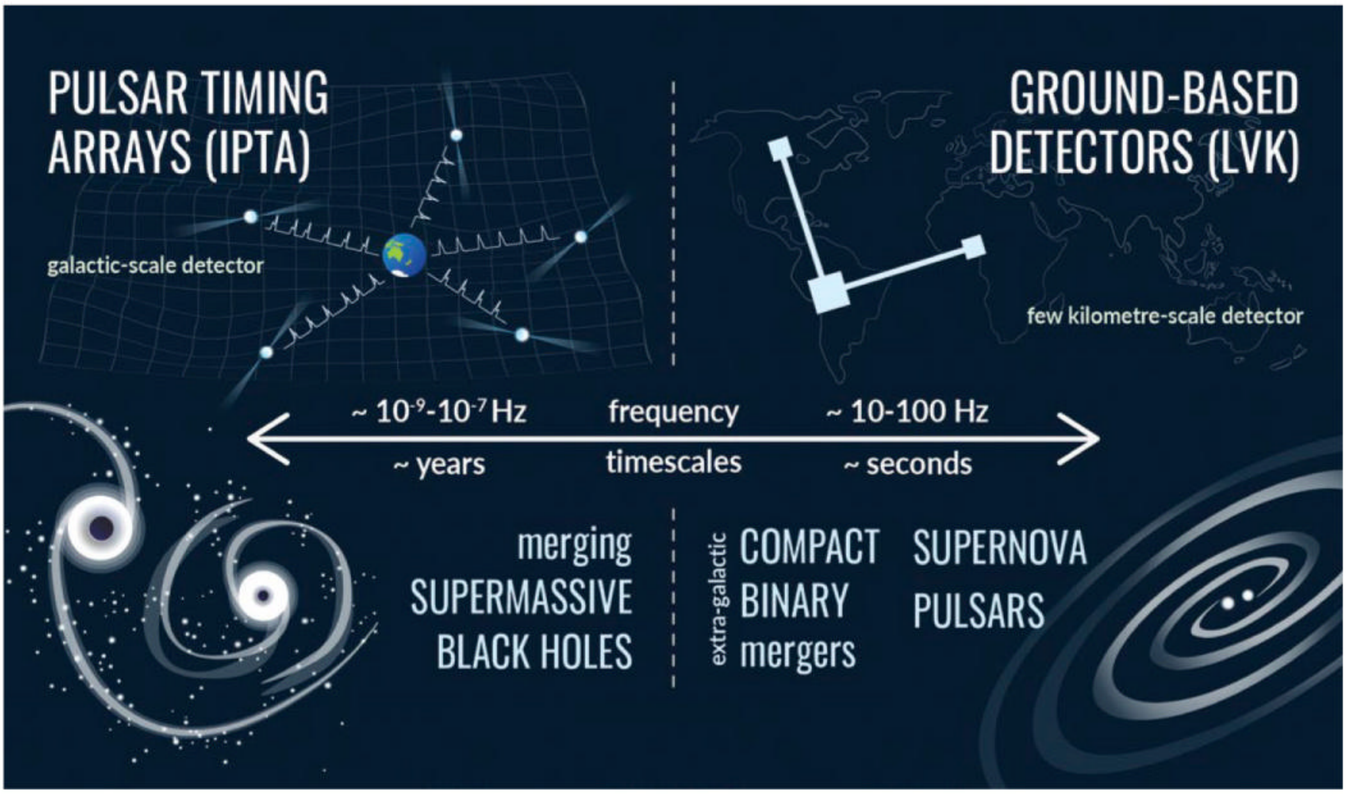
Einstein realised that gravity is not as simple as Newton envisaged. It is actually a distortion in the fabric of space-time, caused by mass and energy. The more massive the object, the bigger the curve in space-time, the stronger gravity feels. In short: matter tells space-time how to curve, and curved space-time tells matter how to move.

Einstein moved quickly. By 1916 he had used this new knowledge of gravity to postulate the existence of gravitational waves: ripples through space and time, caused by the movement of mass. Put your bowling ball back on the trampoline, but now move it up and down (i.e., accelerate its speed) – and you'll start to see ripples as the trampoline fabric is slightly bent and stretched. The physics that causes these ripples, as Einstein explained, involves the loss of energy through gravitational radiation.

It was an incredible theory and one that no one had really considered before: the fact energy could be lost through gravity. But Einstein came to suspect it could never be proven. You see, although anything with mass accelerating technically creates gravitational waves, they are so vanishingly small that detecting them is difficult. Yet in the decades after Einstein, physicists realised that detection was not impossible: we would just need stunningly precise instruments, and very energetic gravitational waves caused by enormous masses – for example, the collision of two black holes.



LIGO



Here's the thing: Einstein famously didn't believe black holes could exist

Here's the thing: Einstein famously didn't believe black holes could exist. If physicists of the last century just left it there, we wouldn't have even looked for gravitational waves, and you wouldn't be reading this article – but we did, and you are.

Gravitational waves 201

Almost exactly a century later, in 2015, we found them – using the four-kilometre-long lasers of the Laser Interferometer Gravitational-Wave Observatory (LIGO). LIGO uses instruments called Michelson Interferometers, which split a beam of light, send the two beams travelling out the same distance in perpendicular directions, then reflect the beams back to join again. If nothing in the system changes, the same light patterns occur. However, if one arm of the detector is slightly stretched or slightly contracted – say, as a gravitational wave travels through the Earth – the light pattern changes.

LIGO's first detection was of gravitational waves formed when two black holes merged 1.3 billion light years away. As the waves rippled through space-time from this energetic event, Earth was stretched the slightest amount – less than a thousand times smaller than a proton – but remarkably, LIGO's interferometers detected it.

In under 10 years, we've detected more than 85 other mergers of massive objects. But these are all discrete events: single massive booms echoing across the universe, mostly from black holes colliding. These events create something called high-frequency gravitational waves, which are short and sweet and easy(ish) to detect. However, astronomers have theorised for decades that low-frequency gravitational waves should exist, hiding in the background of the universe.

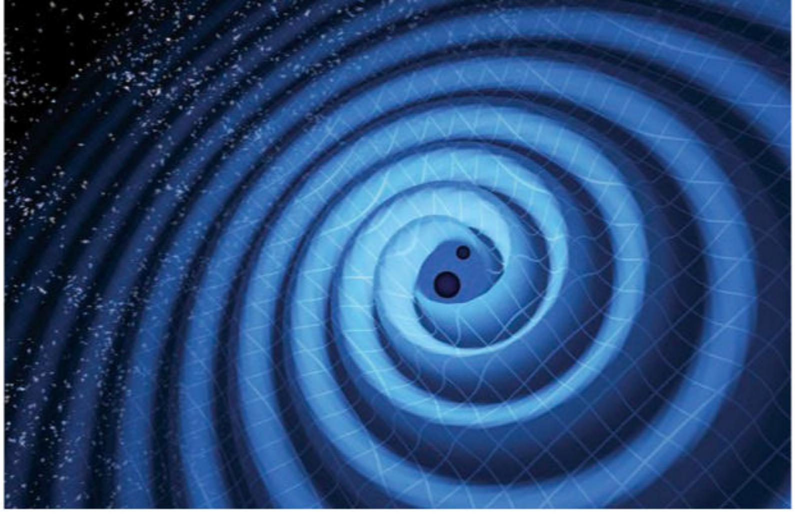
The gravitational wave spectrum ranges from high-frequency waves with periods on the order of seconds, to lower-frequency ones with periods of years. Spotting these much longer ones requires larger detectors, ones we can't build on Earth: astronomers had to use pulsars distributed across the galaxy.

Remember that any mass accelerating creates gravitational waves. With this logic we'd expect the universe to be awash with these ripples, a cacophony of movement adding up to a background hum. If we could hear it, these background ripples might even hold clues of the universe during the first moments of its existence.

(Pulsar) timing is everything

To detect a background of gravitational waves in a completely different range of frequencies, LIGO wasn't going to cut it. We needed a different approach: an epic, astronomical-scale experiment.

SHANIKA GALAUDAGE



Even more curious is that we often see galaxies merge in our universe

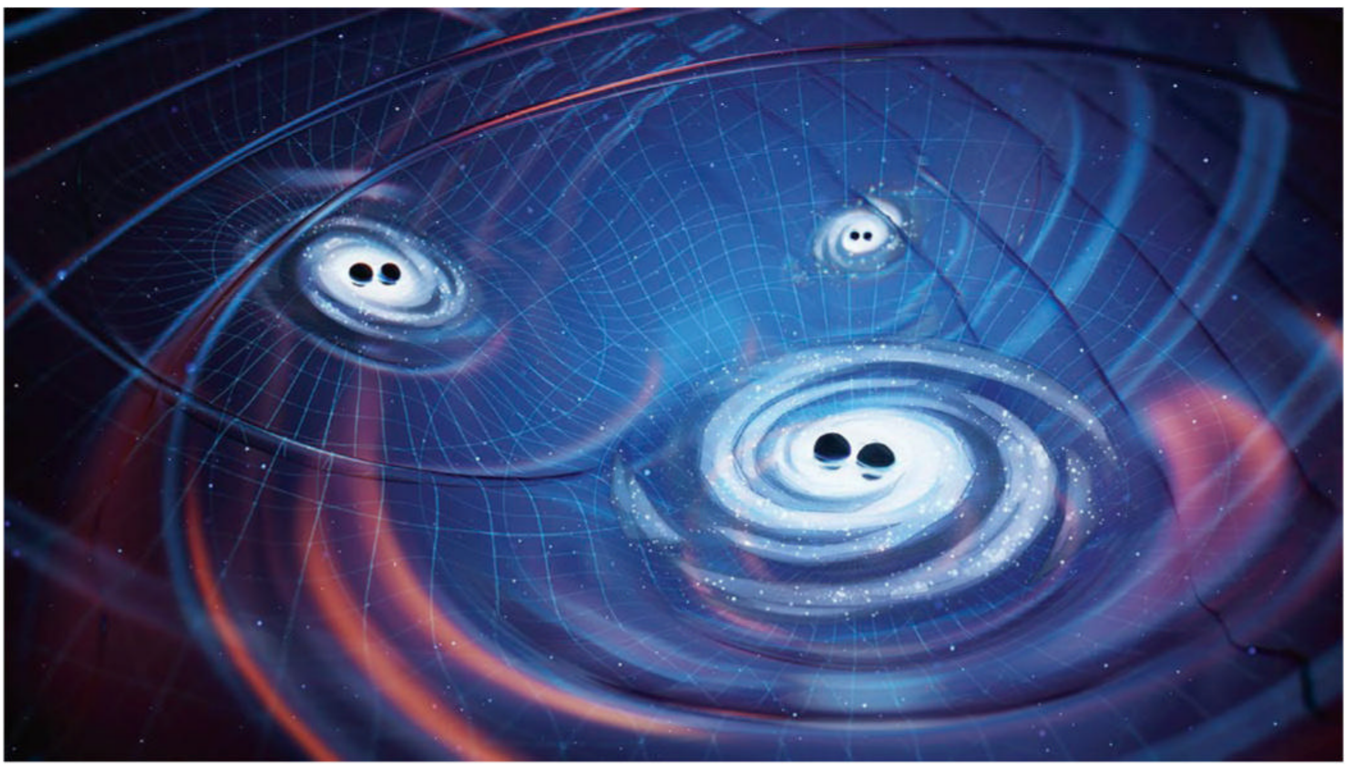
Instead of using lasers, scientists turned to cosmic lighthouses. When massive stars die, they generally form either a black hole or a neutron star. Neutron stars are incredibly dense, rapidly rotating and highly magnetised objects. Most are only 20 km across, but weigh at least the mass of our Sun. These little objects are hard to find; we can't generally see them in optical light, but we can spot them in radio light, because as they spin they emit a beam of electromagnetic radiation from their poles, mostly in radio wavelengths.

The first neutron star was discovered in 1967 by Jocelyn Bell Burnell, a PhD candidate at Cambridge University in the UK, who was analysing data from the newly built Cambridge radio telescope when she noticed peculiar pulses, from the same patch of sky, day after day. Bell Burnell had discovered the first pulsar.

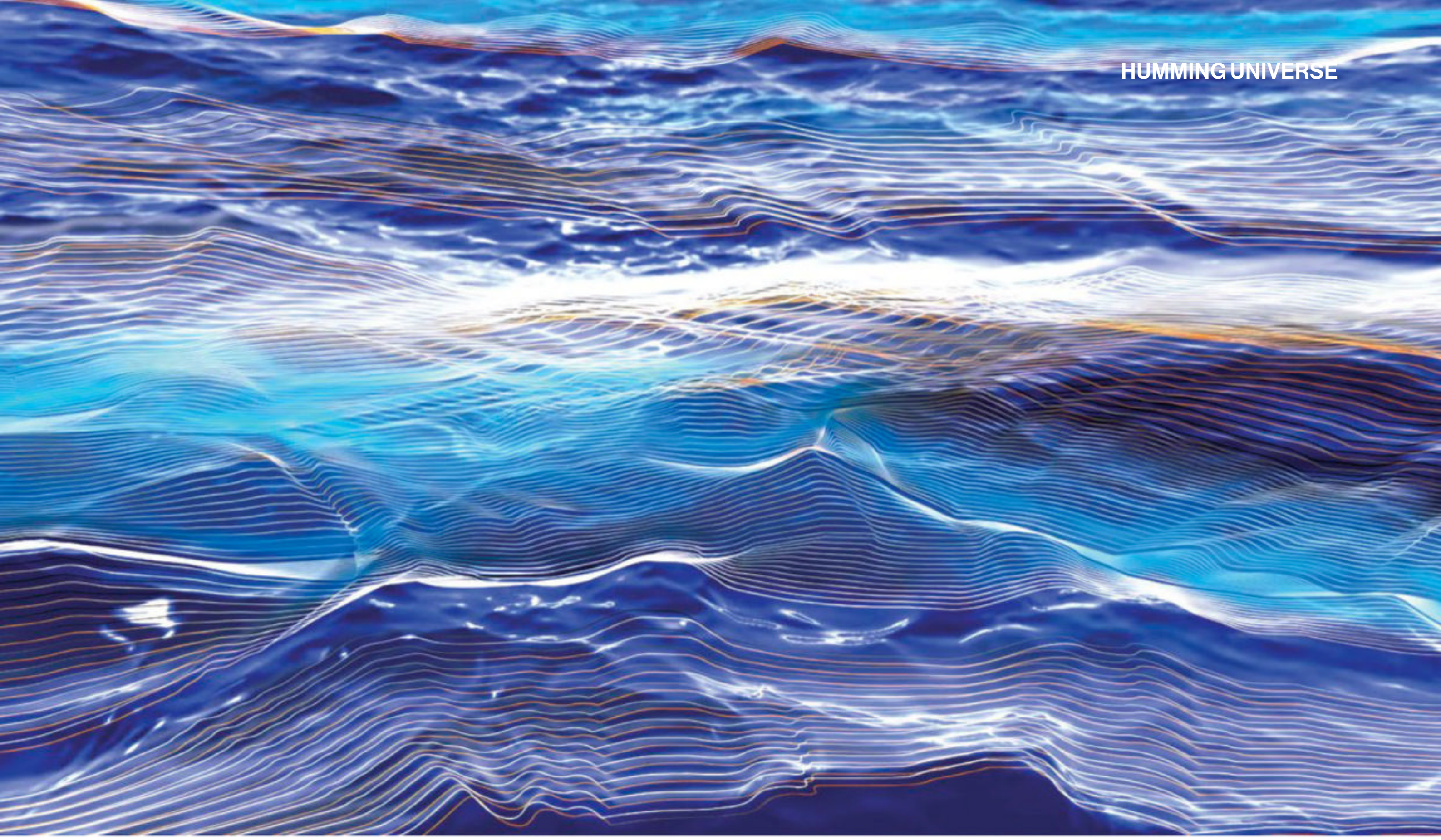
After 57 years, we've discovered more than 3,000 of these cosmic lighthouses, and we're using them to map space and time in our galaxy. Pulsars are incredibly predictable and so astronomers use them as precision timing instruments. The pulses we see from Earth generally don't change unless there is interference – just like LIGO's laser beams. What could possibly interfere with a pulsar's signal? Perhaps very long gravitational waves stretching space between us and them?

This brings us to the International Pulsar Timing Array (IPTA), which consists of four research teams in Europe, North America, India and Australia. Each is searching for low-frequency gravitational waves by monitoring the arrival times of pulses of more than 100 millisecond pulsars, thousands of light-years apart. While ground-based detectors can detect gravitational waves from 10 hertz to 10 kilohertz, the sheer size of the IPTA is sensitive to gravitational waves from 10^{-10}Hz to 10^{-6}Hz.

In 2023, it was the results of the IPTA that sent those shockwaves around the world, when multiple teams reported the first evidence of a gravitational wave background.



LEFT: NANOGRAV. TOP: LIGO.



CARL KNOX – OZGRAV, ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY

Australia's contribution is called the Parkes Pulsar Timing Array (PPTA) project.

"Murriyang [the 64-metre-wide CSIRO Parkes radio telescope in NSW] has been observing millisecond pulsars to detect gravitational waves since 2004, and as a result is the world's longest-running pulsar timing array experiment," says Daniel Reardon, an astrophysicist at Swinburne University and part of PPTA.

Reardon led one of those papers that broke the internet in June 2023, in which the PPTA team found that their analysis of 18 years of data was consistent with an isotropic gravitational wave background. What this means is that in all directions, a similar signal of a gravitational wave background is present.

But the data is still a bit of a mystery.

"We don't know the source of the gravitational waves yet," Reardon points out.

One theory is that the gravitational wave background is created by supermassive black holes, which are found at the centres of most galaxies, including our own. Each is millions to billions of times the mass of our own Sun, and one of the greatest mysteries in physics currently is exactly how and when these giant monsters formed. The smaller, merging black holes that we see with LIGO are remnants of massive stars exploding at the end of their lives. Supermassive black holes, however, can't be explained by stellar death alone. Even more curious is that we often see galaxies merge in our universe – and when they do, we'd expect their supermassive black holes to merge too. In theory, these events would help create the gravitational wave background.

Remember the Sun and Earth curving space-time on the previous spread? The top left image shows what happens if two such masses start to move, creating ripples of gravitational waves; these are the kind we first detected in 2015. But these waves are being created everywhere, all the time, such as from orbiting supermassive black holes (opposite left), creating a sea of interfering waves. Across the physical and temporal span of the universe, the constant creation of these waves from many different sources adds up to a stochastic background of overlapping signals (represented above).

But according to Reardon, the new detections aren't exactly as expected.

"If it is the symphony of all binary supermassive black holes in the universe, then it's a little louder than expected and has hints of other interesting properties," he says.

Potentially these gravitational waves occurred earlier in the universe than we first expected. This would be groundbreaking, as we don't know how and when these supermassive black holes formed in the first place. Understanding when they started to merge could help us unlock the secrets of their formation.

Beyond supermassive black holes, another theory suggests that a gravitational wave background could have origins in the Big Bang itself.

In principle there might be gravitational waves left over from cosmic inflation, less than one second after the very beginning of time, when the universe suddenly expanded faster-than-light. Many physicists believe that this expansion magnified quantum fluctuations – tiny, random energy changes – which then became the seeds of all the large-scale structure of the universe today.

"It's possible that gravitational waves created from quantum fluctuations could have been amplified by inflation into low-frequency gravitational waves," Reardon says. "But for it to be observable we'd need certain conditions to be satisfied."

These conditions relate to the fundamental physics of the pulsars themselves, and those conditions aren't currently satisfied. It's much more likely the signal we recently detected is from merging supermassive black holes, just occurring slighter earlier in the universe then we expected.

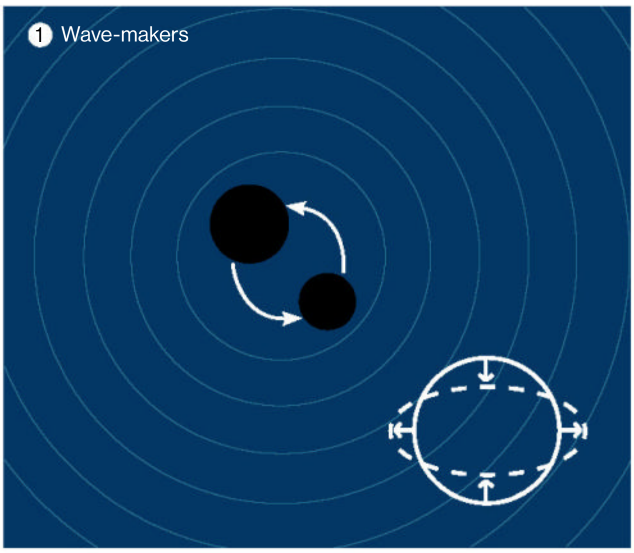
Old universe, new frontiers

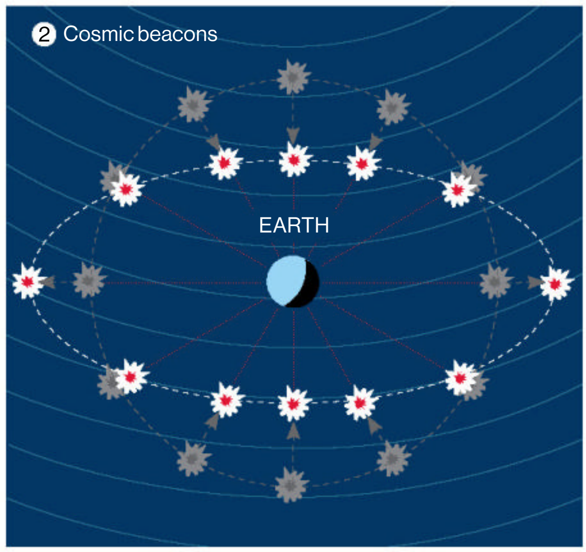
Gravitational waves – and particularly a gravitational wave background – are a game-changer for astronomers, who have the challenging job of determining the very nature of the universe: its shape, size and make-up. For a long time this task was limited by our ability to detect light, which is historically the dominant way that we receive astronomical information. Over the centuries, improving technology has allowed us to capture more and more light from the cosmos, beyond optical light and across the range of the electromagnetic spectrum. This light has given us insight into different time periods and different kinds of events: infrared light, for example allows us to peer back billions of years ago and see the very first galaxies, while ultraviolet light allows us to trace star formation within galaxies.

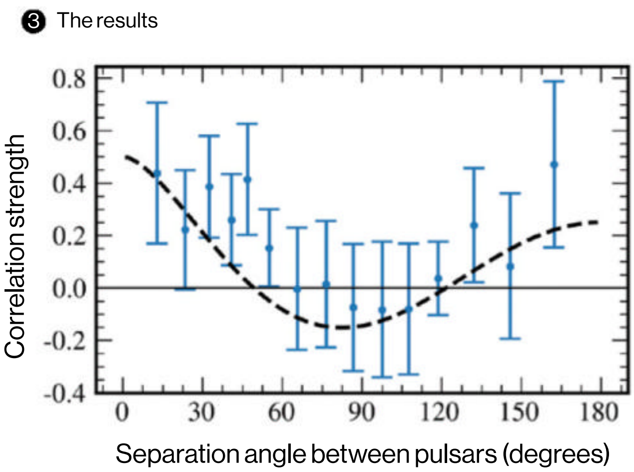
One of astronomy's most revelatory discoveries was made in the early era of radio telescopes, only a few years before Bell Burnell's work on pulsars. Across the Atlantic in New Jersey, US, two scientists spotted the earliest light we can see: the cosmic microwave background (CMB).

It was 1965, and Robert Wilson and Arno Penzias were employed for Bell Laboratories working with the Holmdel Horn Antenna. The

A galaxy-size detector







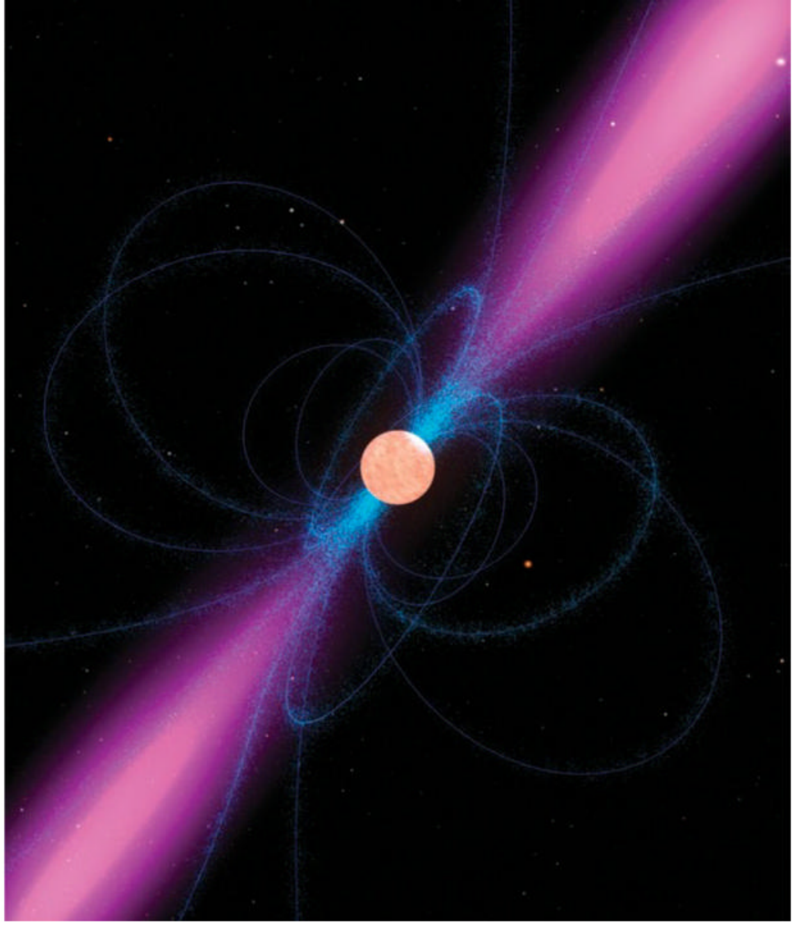
1. When supermassive black holes orbit each other, their masses squish space-time in one direction and stretch it in the other, creating long, low-frequency gravitational waves. 2. When the waves pass through our galaxy, they squeeze and stretch space-time between Earth and pulsars (see image on opposite page). This changes the exquisitely precise timing of radio signals from the pulsars. 3. Observing these minute changes in hundreds of pulsars reveals a distinct pattern of correlated timing offsets consistent with general relativity – thus showing the presence of gravitational waves. This is the graph of the results!

NANOGRAV

Horn was sensitive to microwave light, a subsection of high-energy radio waves, and Wilson and Penzias were exploring the instrument's potential uses for radio astronomy.

But their measurements were humming with excess noise, no matter which direction the Horn was pointing. They worked tirelessly to eliminate any possible sources of interference, even rebuilding parts of the Horn and cleaning away pigeon poop, but to no avail. In the end, Wilson and Penzias concluded that the noise was likely coming from beyond our galaxy.

Only 60km away at Princeton University, physicists had theorised that microwave light could be found left over from the beginning of the universe. We know now that the noise detected by the Horn was exactly that: leftover light from approximately 380,000 years after the Big Bang, now scattered evenly across the entire observable universe and stretched out to microwave wavelengths.



Pulsars are key to the recent GWB discovery. They're a highly magnetised type of neutron star: an ultra-dense, fast-spinning dead star. Their strong magnetic field funnels jets of particles to the poles, sending out powerful beams of radiation that – like a lighthouse – can only be seen when they're pointing towards Earth. As the pulsar spins, the light flashes towards us in extremely precise intervals, ranging from milliseconds to seconds.

STOCKTREK IMAGES / GETTY IMAGES

"When we look at things far away, we are seeing them as they were a long time ago"

In the years since, studying the CMB has been crucial to the study of the early days of cosmic existence, providing the best data we have about the infant universe before stars and galaxies formed.

While the cosmic microwave background is based on very different physics to the gravitational wave background (GWB), it's possible that the GWB also has the similar potential to revolutionise astrophysics. Monash University PhD candidate Rowina Nathan, who was involved in the PPTA gravitational wave study, says the GWB could yield information that is inaccessible with traditional electromagnetic astronomy.

"Due to the speed of light, when we look at things far away, we are seeing them as they were a long time ago," she explains. "Presently, the furthest we can see is the cosmic microwave background, as that is when the universe became transparent to light. The gravitational wave background may be a way to 'see' past this, to a time before the universe was transparent to light."

Nathan adds that the new GWB results are also tantalising astronomers with clues of new and exciting physics.

"A key idea in cosmology is that the universe is homogenous and isotropic – basically that when you zoom out far enough the universe is approximately the same in all directions," Nathan says. "If we see significant variance in the background, say it's stronger in one direction than another, this could disprove this, having significant implications for our understanding of the formation of the present-day universe."

If that statement doesn't make you excited, it should! If the universe isn't the same make-up or structure in all directions, we might need to take a lot of physics back to the drawing board. Say we don't see merging supermassive black holes in a particular direction – could that mean galaxies are made up differently in different places? This astronomer thinks it's extremely unlikely, but a very exciting possibility none the less.

The gravitational wave background is a relatively new kid on the block but one to keep our eyes on – because the IPTA teams are nowhere near finished with their work.

"In the next few years, we can look forward to the IPTA combining all 115 pulsars to calculate a higher statistical significance of the GWB detection," he tells me. This means the teams will have more data to help them confirm the signal, as well as adding in continuing observations.

I, for one, can't wait to see if the universe will surprise us.

SARA WEBB is an astrophysicist working at Swinburne University. Her last story, on the probes that might find alien life in our Solar System, appeared in Issue 98.