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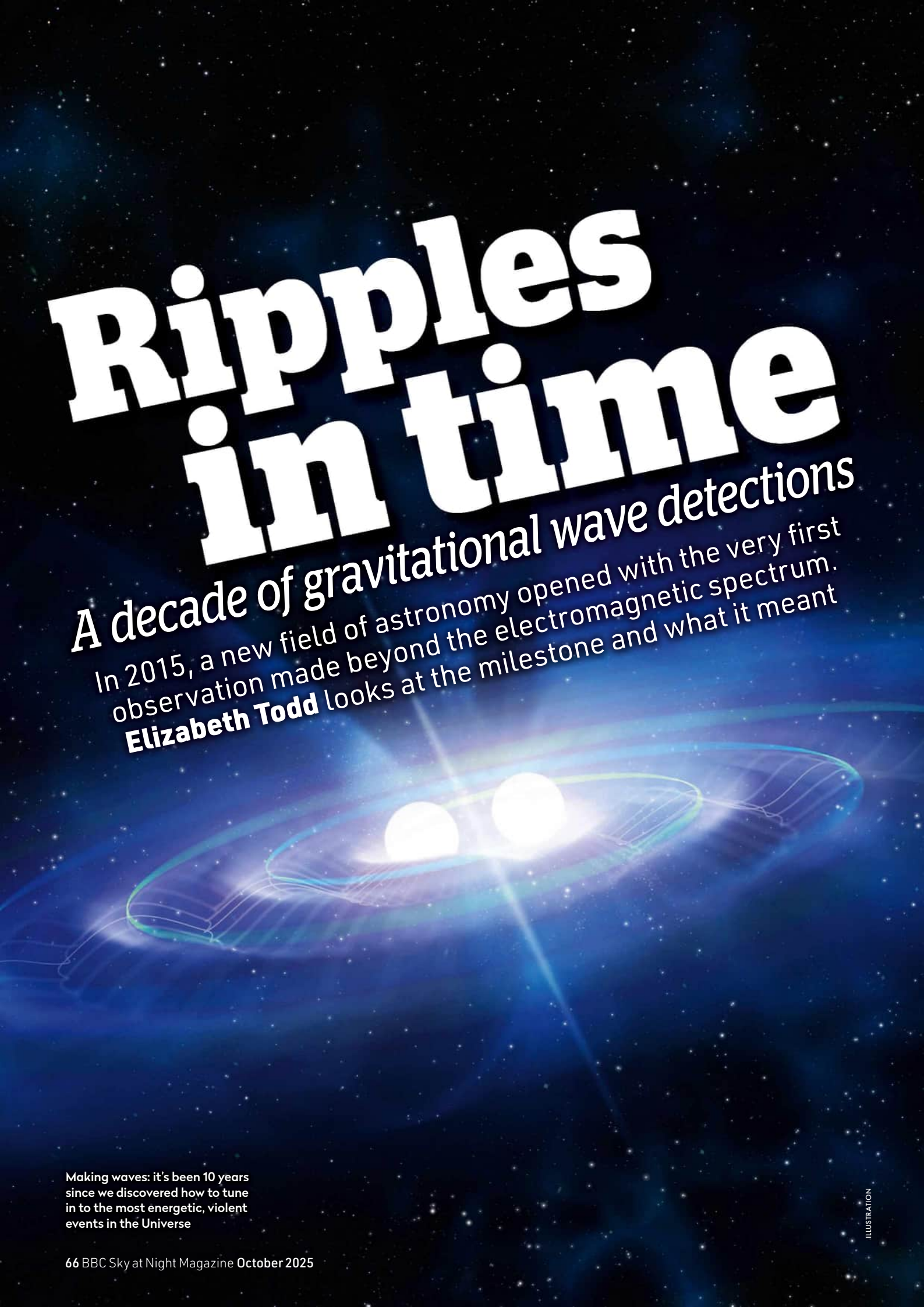
Ripples in time

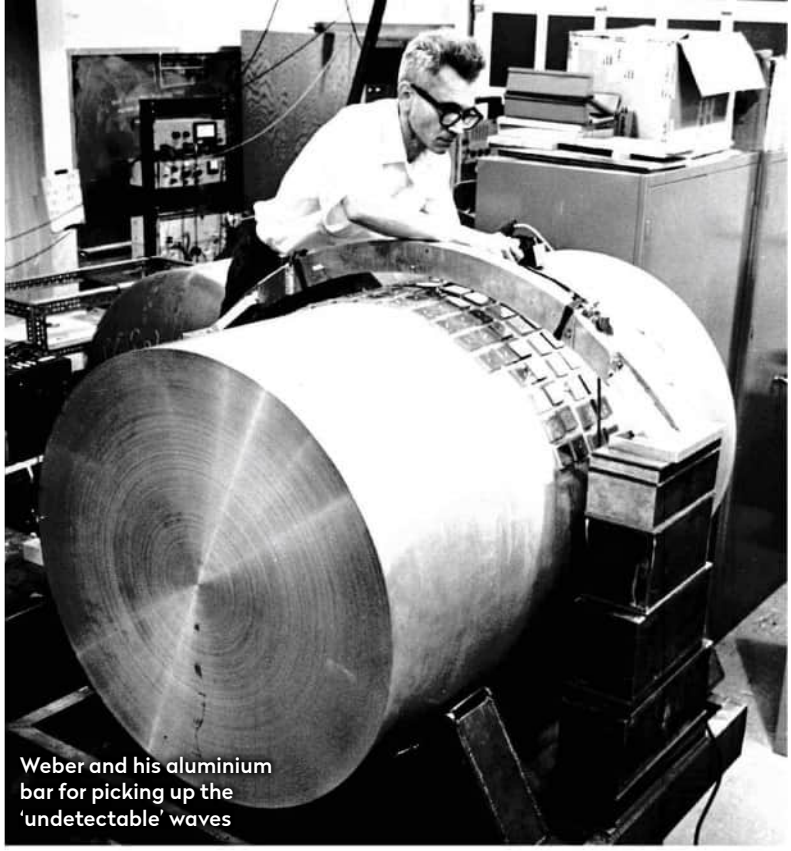
A decade of gravitational wave detections

In 2015, a new field of astronomy opened with the very first observation made beyond the electromagnetic spectrum. **Elizabeth Todd** looks at the milestone and what it meant



Making waves: it's been 10 years since we discovered how to tune in to the most energetic, violent events in the Universe

ILLUSTRATION



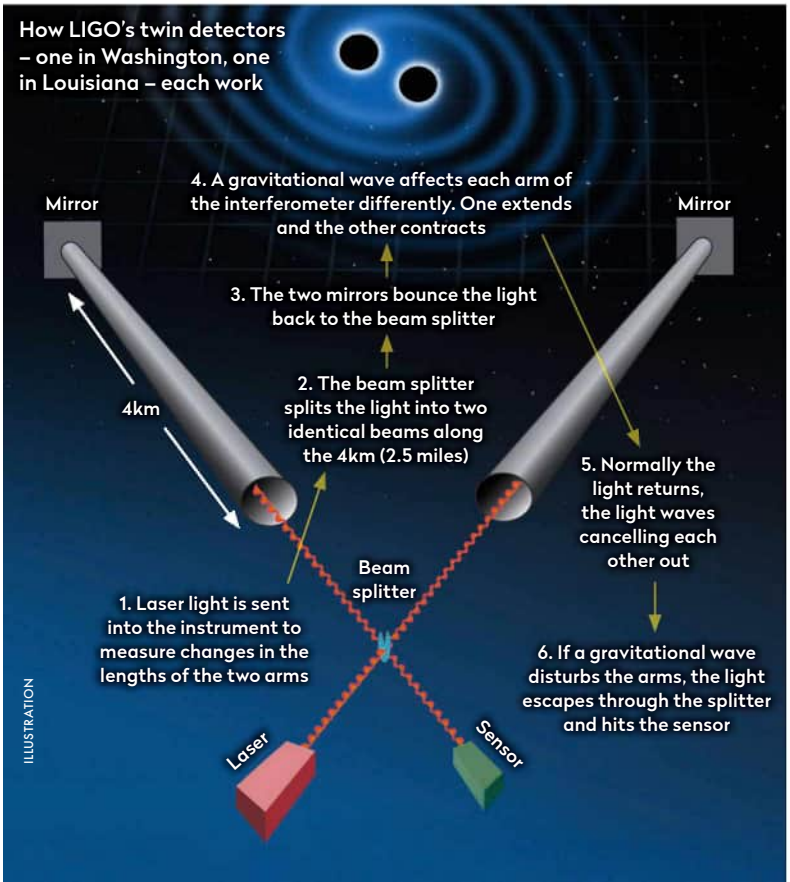
Weber and his aluminium bar for picking up the 'undetectable' waves

Ten years ago, on 14 September 2015, a new window on the Universe was opened, giving us a novel way of studying exotic, high-energy objects such as black holes and neutron stars: the first direct detection of a gravitational wave was made by LIGO (the Laser Interferometer Gravitational-Wave Observatory). Now that a decade has passed, let's take a look at some of the events leading up to the groundbreaking detection of these ripples in spacetime and the exciting discoveries made since.

But where did the idea of looking for gravitational waves come from? Einstein himself suggested it, but he thought we would never detect them. This was taken as a challenge by many scientists, who set out to detect these 'undetectable' waves. In the 1960s, Joseph Weber began building resonant bar detectors, aluminium cylinders that would vibrate if a gravitational wave was to pass through. While the detectors were not shown to make detections, Weber's legacy lives on. Following his lead, having detectors at geographically separate locations helps to determine whether a signal is from a gravitational wave or a more local source such as an earthquake.

The first indirect evidence of the existence of gravitational waves was published by physicist Russell Hulse and astrophysicist Joseph Taylor Jr, who discovered the first binary pulsar system PSR B1913+16 in 1974. They knew, from Einstein's theory, that if the system was emitting gravitational waves, it would be losing energy and the stars would spiral into each other, their orbital period decreasing as the distance between them shrank. Now, with 50 years of data, the measurements agree with Einstein's predictions to within 1 per cent.

Elizabeth Todd is an MSc student at Cardiff University and about to begin a PhD in gravitational waves at the University of Glasgow



Perfecting the science

By the 1970s, the race to directly detect gravitational waves had begun. Research groups from all over the world began building the first prototype gravitational wave detectors, moving away from Weber's resonant bars and towards laser interferometers. These devices exploit the fact that the speed of light is always constant, another tenet of Einstein's theories. They work like this: the interferometer splits a laser beam in two, sending each half down perpendicular arms with mirrors at their ends reflecting the beams back to meet each other. Depending on the relative distances travelled, the beams can constructively interfere (add together) or destructively interfere (cancel out). Gravitational waves stretch spacetime in one direction and squeeze it in the perpendicular direction, so a passing wave changes the interferometer's arm lengths by tiny amounts, altering the interference and providing a direct way to measure gravitational waves.

After several decades of technology demonstrations, including the British–German GEO 600 detector, the first interferometer gravitational wave detectors to be built were the twin LIGO detectors in the US states of Louisiana and Washington. The hunt for gravitational waves had begun. With arms 4km (2.5 miles) long, these were later joined by the Virgo detector sited near Pisa, Italy. The first 'science runs' of this Initial LIGO setup paired with Virgo were completed between 2002 and 2010, and while they demonstrated that the detectors worked, they were not expected to make any detections. The detectors were then upgraded ▶

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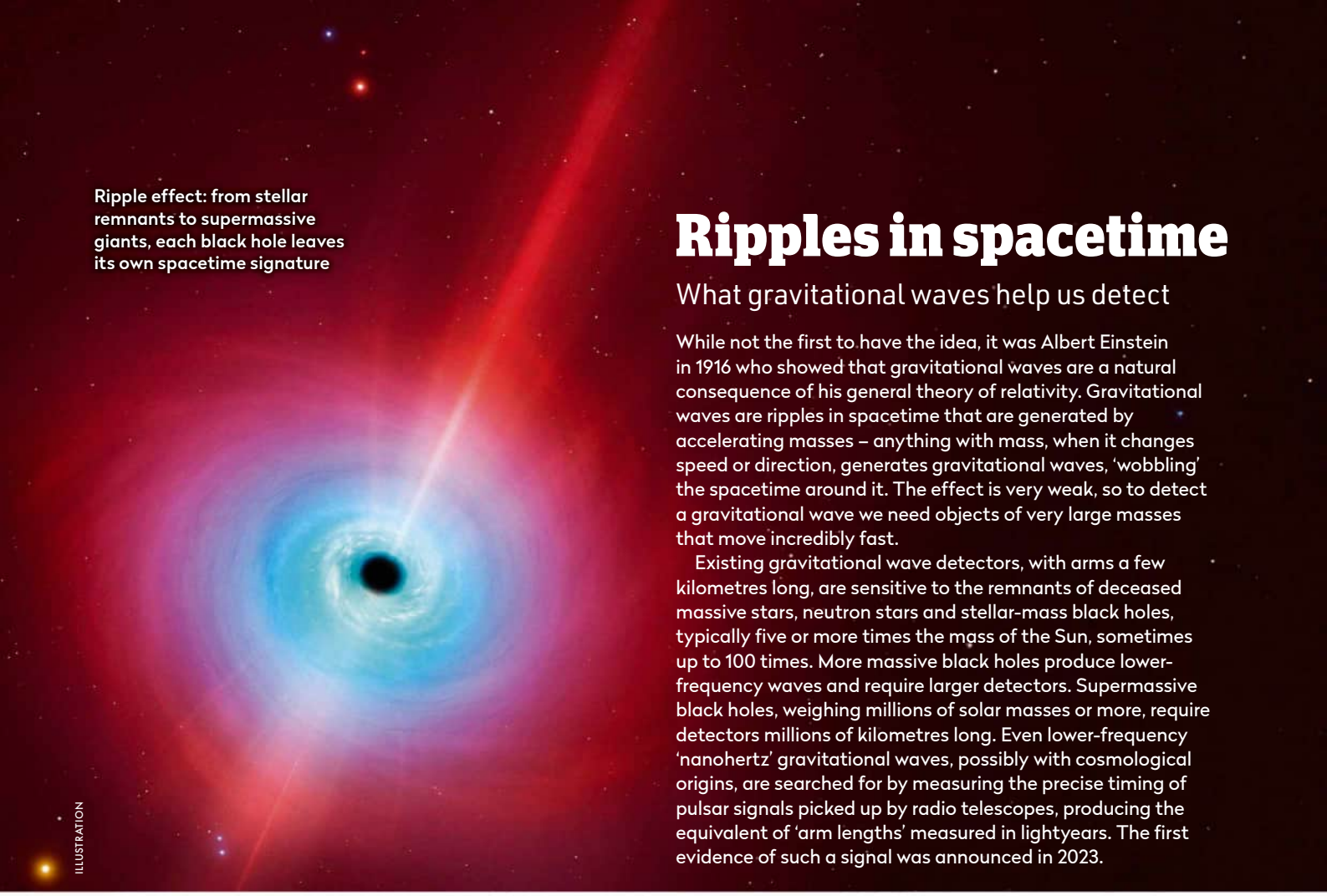


Ripple effect: from stellar remnants to supermassive giants, each black hole leaves its own spacetime signature

ILLUSTRATION

Ripples in spacetime

What gravitational waves help us detect

While not the first to have the idea, it was Albert Einstein in 1916 who showed that gravitational waves are a natural consequence of his general theory of relativity. Gravitational waves are ripples in spacetime that are generated by accelerating masses – anything with mass, when it changes speed or direction, generates gravitational waves, 'wobbling' the spacetime around it. The effect is very weak, so to detect a gravitational wave we need objects of very large masses that move incredibly fast.

Existing gravitational wave detectors, with arms a few kilometres long, are sensitive to the remnants of deceased massive stars, neutron stars and stellar-mass black holes, typically five or more times the mass of the Sun, sometimes up to 100 times. More massive black holes produce lower-frequency waves and require larger detectors. Supermassive black holes, weighing millions of solar masses or more, require detectors millions of kilometres long. Even lower-frequency 'nanohertz' gravitational waves, possibly with cosmological origins, are searched for by measuring the precise timing of pulsar signals picked up by radio telescopes, producing the equivalent of 'arm lengths' measured in lightyears. The first evidence of such a signal was announced in 2023.

LIGO detected its first wave, GW150914, on 14 September 2015, while still in engineering mode

▶ to the level expected to pick up gravitational waves from astrophysical sources, and the first observing run of the Advanced LIGO setup (aLIGO), called O1, began in September 2015.

And so it was that on 14 September 2015, almost 100 years after Einstein predicted their existence, gravitational waves were first detected directly. That first detection, dubbed GW150914 (gravitational waves are named after their detection date, in US format: 2015-09-14), was created by two black holes 1.4 billion lightyears away, each around 30 times more massive than the Sun, and each formed by the deaths of even more massive stars. LIGO was able to detect ~200 milliseconds of gravitational wave data as the black holes spiralled together before merging.

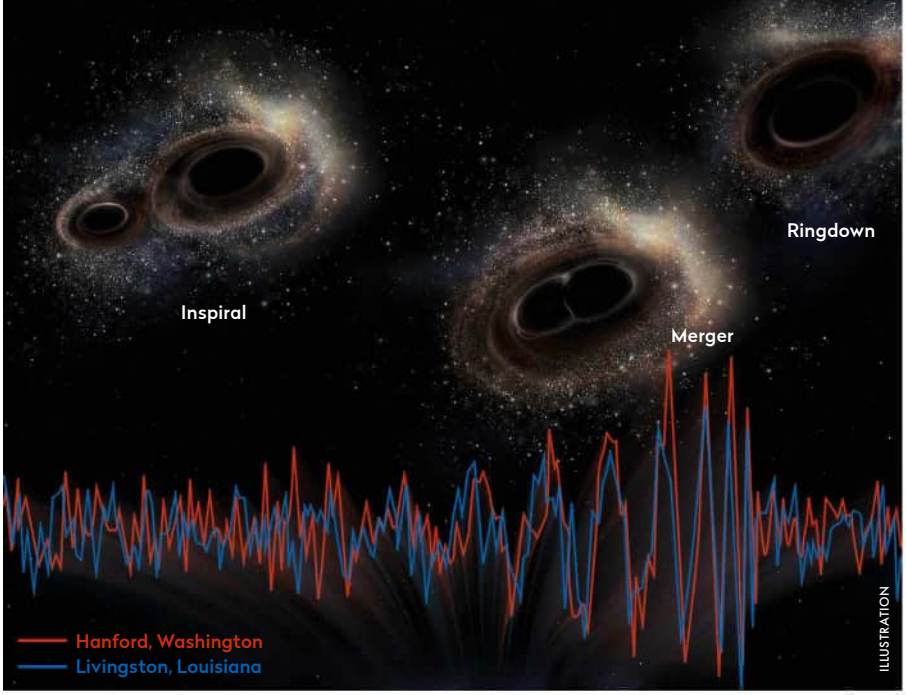
Triumph in test mode

No one expected to see a detection so soon, and there was an element of luck involved; O1 hadn't officially begun, and the detectors were formally still in testing mode. Worries that the detection was the result of a hack or a preparatory test signal spread, but were quickly allayed. Two more detections followed before O1 ended in January 2016 and the LIGO–Virgo Collaboration published its discoveries in February 2016. Accolades followed, and three key LIGO figures, Barry Barish, Kip Thorne and Rainer Weiss, won the 2017 Nobel Prize in physics.

In November 2016, the observing began again with O2, this time with increased sensitivity thanks to Advanced Virgo coming online in August 2017. Out of the eight new events, the most notable occurred on 17 August 2017, GW170817.

In a joint detection between LIGO, Virgo and over 70 telescopes covering gamma ray, radio, X-ray and optical light, a flash of electromagnetic waves originating in the galaxy NGC 4993 was seen to coincide with a gravitational wave signal. This was the first multi-messenger detection, using both gravitational and electromagnetic waves to find the source, a binary neutron star merger – more than four decades after Hulse and Taylor had discovered the first binary pulsar. The merger formed a kilonova, an object less bright than a supernova, but with an afterglow that was still visible for over a year after the first detection. Using data collected from both gravitational and light waves, these multi-messenger events usher in the prospect of understanding the nature of neutron stars and making an independent measurement of the Universe's expansion.

Gravitational wave detectors are highly sensitive instruments and so are



▲ **The 0.2-second signal for GW150914 matched the inward spiral, merger and ringdown (final period of settling) of a pair of black holes, each around 30 times the mass of the Sun**

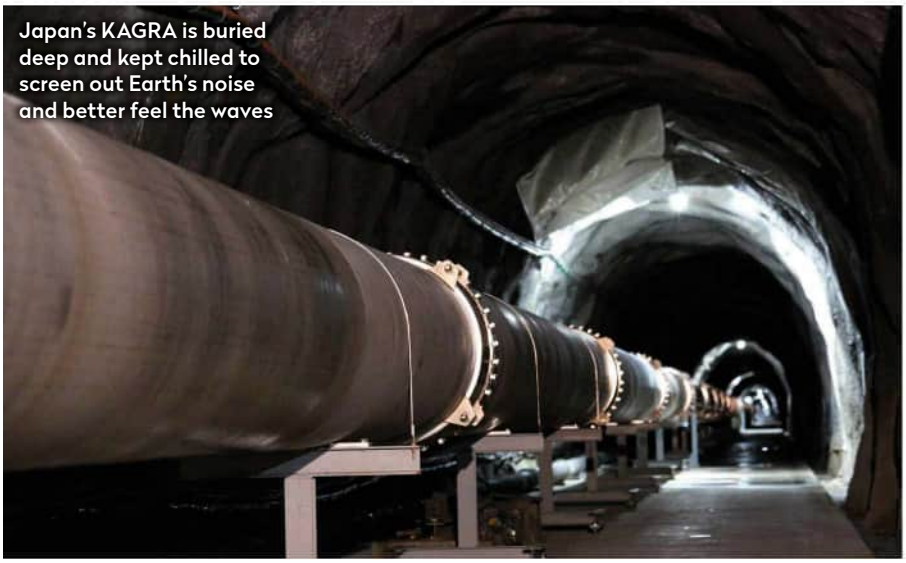
susceptible to many non-astrophysical sources, like seismic noise and human activity (trucks, trains, or even electronics). To combat this, scientists in Japan built a gravitational wave detector 200 metres underground, in the Kamioka mine. This detector, called KAGRA, uses cryogenic technology to cool its mirrors to reduce thermal effects, another prominent noise source, and started observing for the last two months of the third observing run, O3, in February 2020.

A single gravitational wave detector alone can't pinpoint a merger's location; two produce a ring or arc of possible locations in the sky. Adding more detectors to the search narrows down the directions a wave could have originated from, in a similar way to using triangulation when navigating.

Before the O3 observing run, the detectors' sensitivity was significantly upgraded, so that the maximum detection range of binary black holes was nearly doubled. Such an increase in detection range meant the detectors were sensitive to over five times the volume of space, bringing the total detections to almost 100.

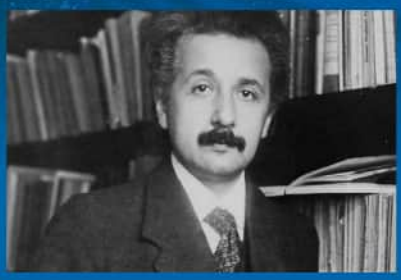
Filling the mass gap

The source objects have a wide range of masses, but observations show a gap between the most massive known neutron star, at around 2.5 solar masses, and the least massive black hole, at around five solar masses. One of O3's more intriguing events, 2019's GW190814, originated from the merger of a black hole 23 times the mass of the Sun with a much smaller object just 2.6 times the mass of the Sun. Whether that lower-mass object was the lightest known black hole or the heaviest neutron star is unknown, but either way, LIGO and Virgo had detected something sitting in the mass gap for the first time, challenging explanations of this system's formation. ▶



Japan's KAGRA is buried deep and kept chilled to screen out Earth's noise and better feel the waves

Milestones in gravitational wave astronomy



May 1916: Albert Einstein predicts gravitational waves

September 1974: Hulse and Taylor's binary pulsar discovery using the Arecibo radio telescope

March 1990: first European Pulsar Timing Array observations

1994: construction of LIGO begins

August 2002: Initial LIGO begins science observations

September 2015: LIGO detects GW150914 from a black hole merger

August 2017: Advanced Virgo starts observing

August 2017: GW170817 detected, produced by a neutron star merger; multi-messenger astronomy begins

April 2020: KAGRA starts observing

April 2023: LIGO-India construction is approved

June 2023: first evidence from pulsar timing arrays announced

March 2025: O4 observing run surpasses 200 detections

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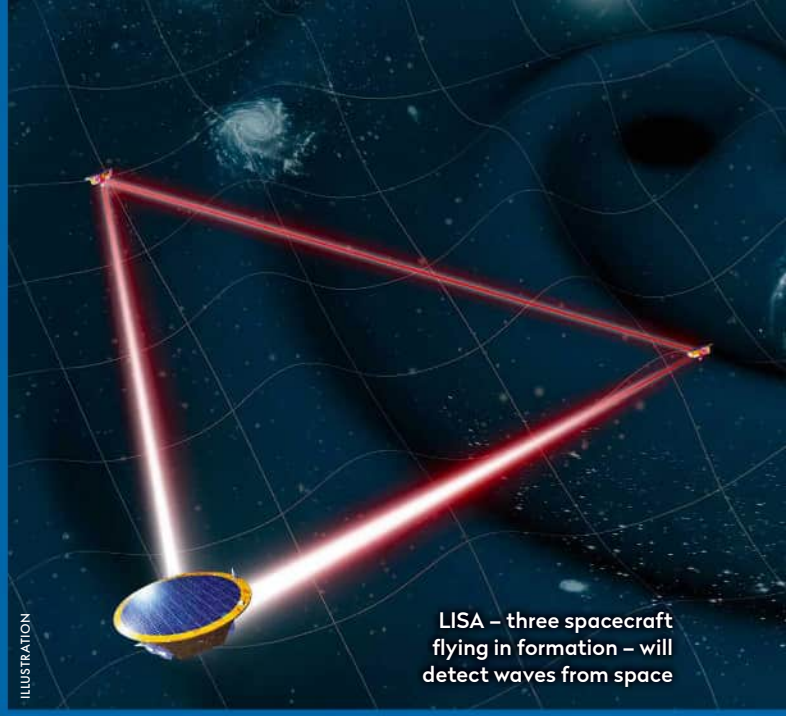
Future detectors

What's on the horizon for gravitational wave science in its second decade?

Following post-O4 upgrades, observing run O5 is planned for 2028–31, after which even more significant upgrades will be made. At the start of the next decade, the plan is for a fifth detector, LIGO-India, to join the search for gravitational waves. Plans are also proposed to construct two brand-new detectors in the US and Europe: Cosmic Explorer, with arms 10 times longer than LIGO's, and the Einstein Telescope, with 10km (6.2-mile) arms built underground and cooled cryogenically. These aim to detect virtually all mergers of stellar-mass black holes in the observable Universe.

The 2030s will also see the launch of the first space-based gravitational wave observatory. The Laser Interferometer Space Antenna (LISA) is led by ESA in collaboration with NASA and an international consortium, and comprises three spacecraft millions of kilometres apart. LISA will search for the mergers of supermassive black holes in the hearts of distant galaxies, and much lower-mass white dwarf binaries within our own Milky Way. LISA has already had a technology demonstration mission, LISA Pathfinder, heralded as one of ESA's most successful test missions ever.

Meanwhile, researchers are using data from the LIGO–Virgo–KAGRA collaboration to push Einstein's theories to the limit and even hunt the signature of some models of dark matter.



ILLUSTRATION

LISA – three spacecraft flying in formation – will detect waves from space

▶ Today we are coming towards the end of the fourth observing run, O4. In the break between O3 and O4, upgrades were again added to the LIGO detectors, so that it is now known as A+ LIGO. The upgrades reduced thermal and quantum noise (the latter by exploiting the quantum nature of light) and further increased the detection range.

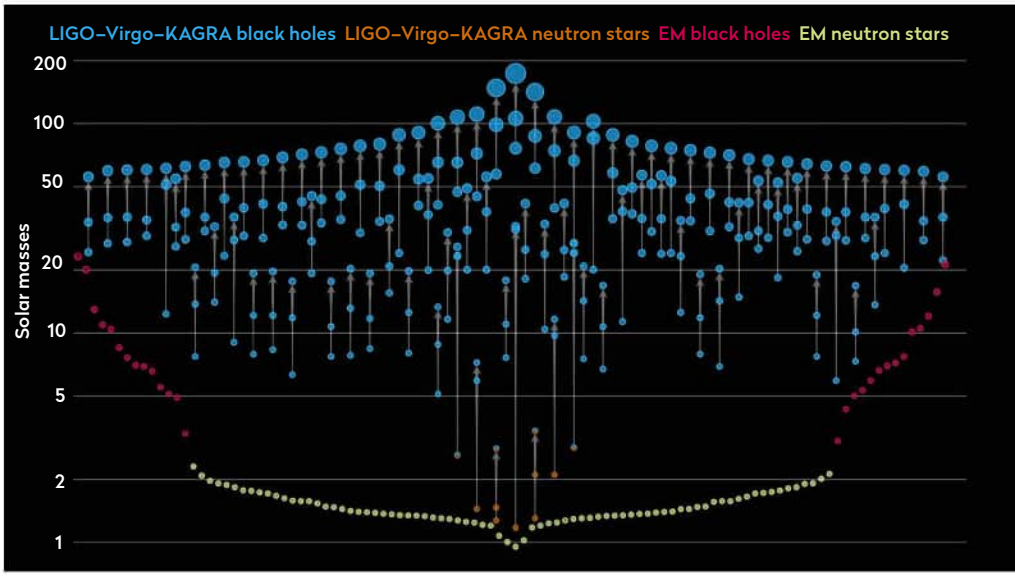
Where next?

To date, over 200 gravitational wave events have been detected during O4 alone, including the heaviest merger ever detected by LIGO, GW231123. Intriguingly, it's possible that the two black holes that caused this event, 137 and 103 times the mass of the Sun, were the result of a previous generation of mergers. Many more exciting events are expected to be detected before O4 ends in November 2025, with the final stages coinciding with the first observations of the Vera C Rubin Observatory in Chile. This will test collaborative efforts to make more multi-messenger detections of binary neutron star mergers.

While gravitational wave data provides us with a lot of information about the nature of black holes and neutron stars, including how they form, it can also be very useful in other areas of fundamental physics, such as testing Einstein's theory of gravity and the search for dark matter.

While the detectors were built to identify gravitational waves from colliding black holes and neutron stars, astronomers at Cardiff University have used data from the LIGO detectors to look for something else: dark matter particles. For their analysis, this team used software made for the music industry to analyse the data amazingly fast, producing results in real time. No evidence for dark matter has been found yet, but the search continues.

Using gravitational wave data, we have been able to set upper mass limits on the theorised gravity particle, the graviton, test the validity of current black hole models, and see how well general relativity can describe extreme situations. So far, the results appear to confirm general relativity. However, this isn't to say Einstein's theory is the last theory of gravity we will ever need, and the search continues for a theory of quantum gravity. But that is what's most exciting about physics: one day we will find something even Einstein can't explain, and it will be up to a new generation of scientists to find the solution.



▲ Gravitational waves detected, in ascending order of mass and coloured according to the source object/event that created them (arrows show the minimum and maximum mass of the source object), plus those discovered via electromagnetic telescopes

ESA | LIGO, VIRGO, KAGRA, AARON GELLER, NORTHWESTERN