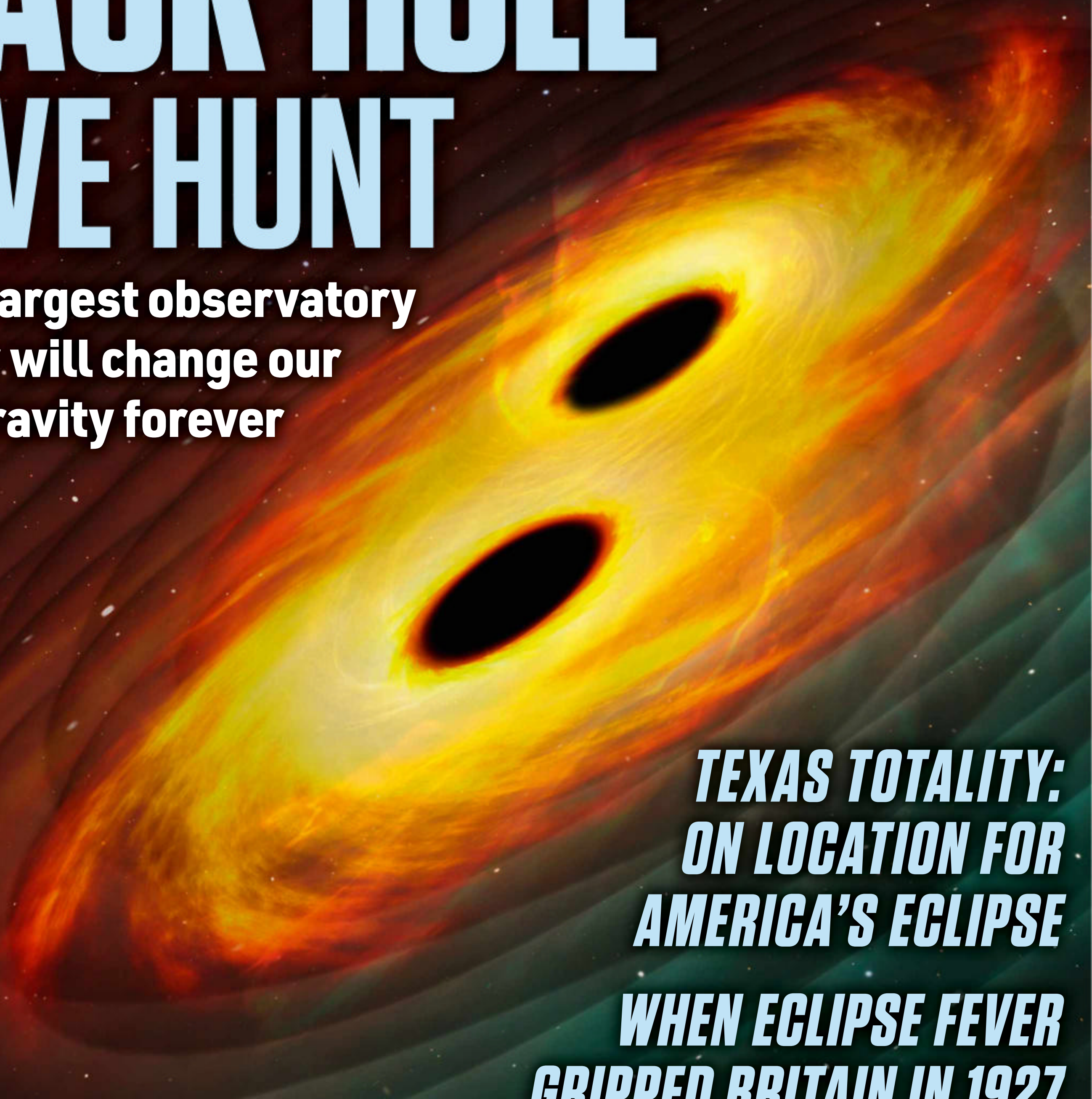
BBC

12 ANCIENT TEMPLES ALIGNED WITH THE SOLSTICE

#229 JUNE 2024

Sky at Night

THE UK'S BEST-SELLING ASTRONOMY MAGAZINE



BLACK HOLE WAVE HUNT

How the largest observatory in history will change our view of gravity forever

TEXAS TOTALITY: ON LOCATION FOR AMERICA'S ECLIPSE

WHEN ECLIPSE FEVER GRIPPED BRITAIN IN 1927

THE UNSOLVED MYSTERY OF COSMIC RAYS

SUMMER SPECTACLE: FIND NOCTILUCENT CLOUDS

TESTED: SKY-WATCHER'S NEW WI-FI MOUNT

Groundbreaking LISA (the Laser Interferometer Space Antenna) will detect subtle ripples in the fabric of spacetime caused by massive cosmic events

Surfing spacetime with LISA

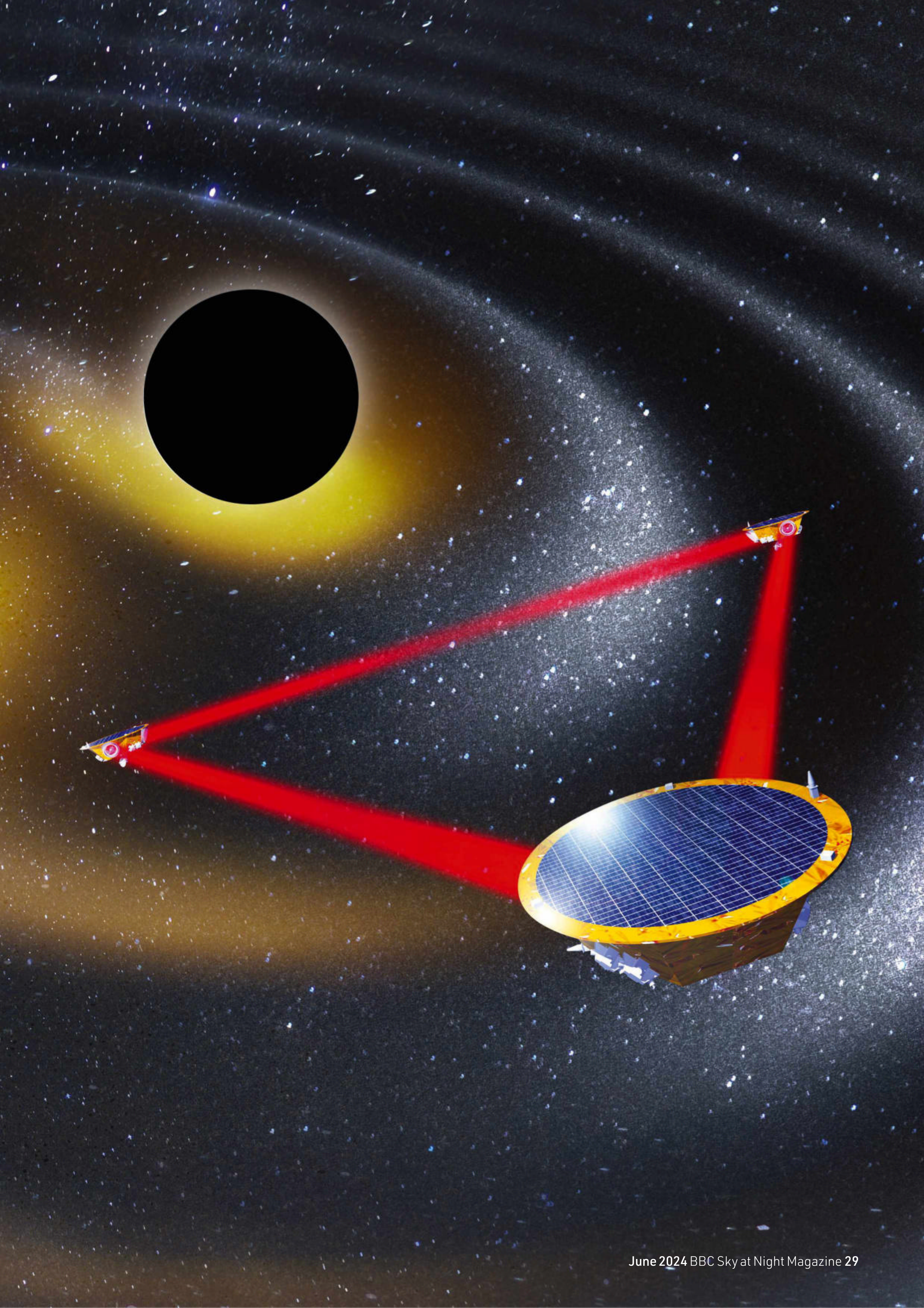
A new era of gravitational wave astronomy is on its way as the ambitious upcoming LISA space mission joins a host of huge detectors on Earth. Charlie Hoy explains

In September 2015, some of the most sensitive instruments ever built made a remarkable discovery: the first-ever detection of tiny ripples in space and time, known as gravitational waves. Created by a pair of black holes spiralling towards each other and crashing together, the observed wave travelled through space at the speed of light until it was detected by two separate observatories here on Earth.

Now scientists are setting their sights on grander goals, hoping to observe the entire Universe, looking back in time to its very origin, with gravitational waves. In January 2024, the European Space Agency (ESA) gave the green light for an international team of scientists to begin building the largest gravitational wave detector ever built – only this time it will be in space. Its name is LISA, the Laser Interferometer Space Antenna, and it will revolutionise our understanding of the Universe.

Gravitational waves are ripples in space and time, similar to those formed on the surface of water when a pebble is dropped from a height. Gravitational waves, however, are caused by some of the most violent astrophysical events in the Universe, such as black holes smashing together. They were predicted by Albert Einstein in his general theory of relativity more than a century ago. According to theory, gravitational waves ▶

Charlie Hoy is a gravitation researcher and a member of the LIGO–Virgo–KAGRA collaboration and LISA consortium



Massive disturbances like black holes merging, stars exploding, neutron stars colliding and even the Big Bang itself send tremors out across space

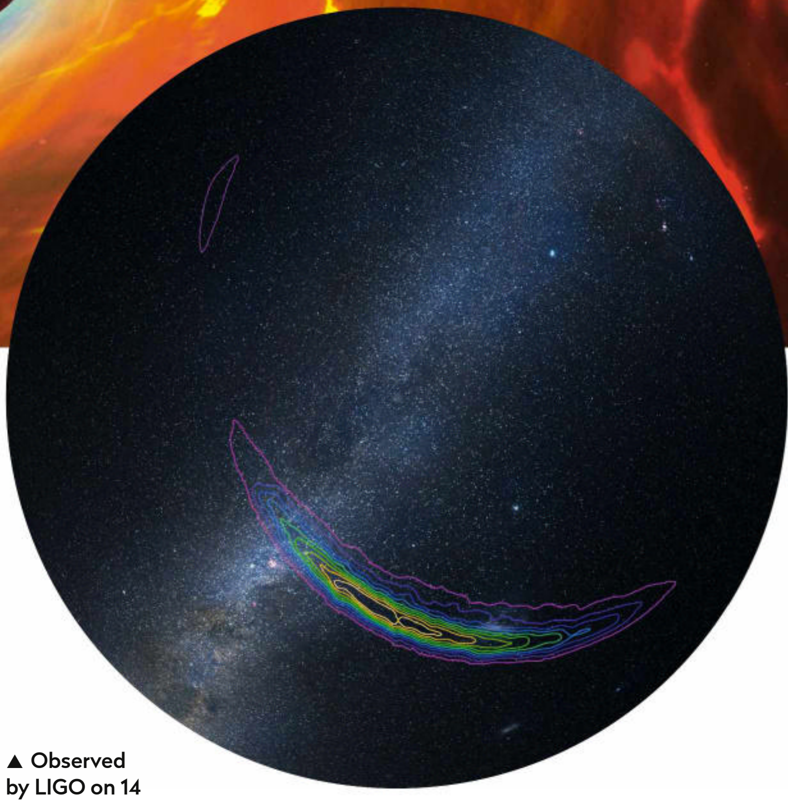
ILLUSTRATION

▶ expand and contract spacetime itself. Everything, including you and me, will stretch and squeeze as a gravitational wave passes by. Thankfully, although gravitational waves are thought to be like tsunamis at the source, by the time they reach us here on Earth their effects are minuscule; so small, in fact, that gravitational waves produced by some of the most energetic events in the Universe are thought to only stretch and squeeze the entire Earth by a fraction of the width of an atom.

Shudders in spacetime

Detecting such small changes might appear an impossible task, but the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) managed it (see 'How to catch a gravitational wave', opposite). The first observation, dubbed GW150914, was caused by the cataclysmic collision of two black holes, each with a mass around 30 times that of our Sun. At the precise moment the two merged, the amount of energy emitted in gravitational waves was larger than the luminosity of all stars in the visible Universe added together.

Since this Nobel Prize-winning discovery, additional gravitational wave detectors joined the observational campaign, and close to 100 signals have been observed by the LIGO–Virgo–KAGRA collaborations (a partnership encompassing four separate detectors located around the world) across three distinct observing runs. The treasure trove of knowledge gleaned from these observations has already transformed our understanding of the cosmos. They have revealed that black holes collide far more frequently than expected, uncovered the origin of exotic elements such as platinum and gold, and constrained fundamental properties of black holes such as their mass and spin.

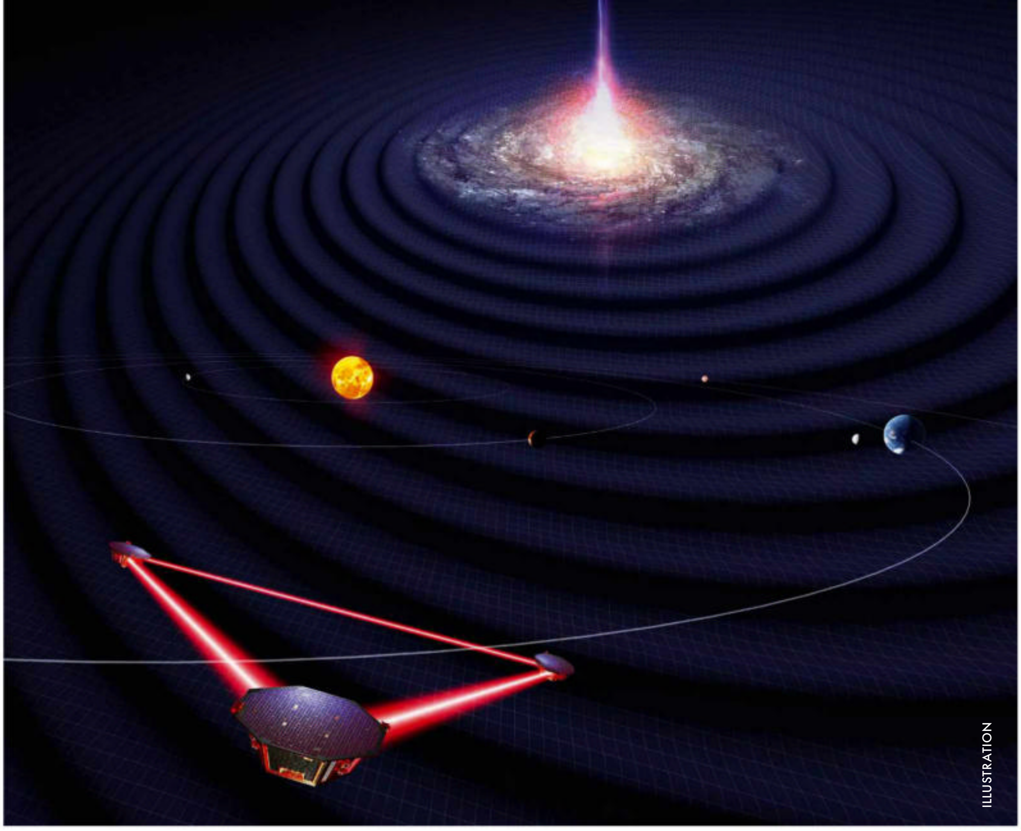


▲ **Observed by LIGO on 14 September 2015, the first-ever confirmed gravitational wave was the ripple from two black holes spiralling together**

In the 2020s, the existing gravitational wave detectors entered an ambitious commissioning period where numerous upgrades were applied to the instruments. On 24 May 2023, the LIGO–Virgo–KAGRA collaboration entered its latest 18-month observing run, otherwise known as the fourth gravitational wave observing run, O4 (though the run was briefly paused between 16 January and 10 April for maintenance and additional improvements). O4 will be 30 per cent more sensitive than previous iterations, making it the most sensitive search for gravitational wave signals to date.

This increased sensitivity will result in a gravitational wave detection every two or three days, compared to every week as seen previously. The increased number of gravitational wave signals will improve our ability to infer the true population

MARK GARLICK/SCIENCE PHOTO LIBRARY/GETTY, LIGO/AXEL MELLINGER, UNIVERSITY OF FLORIDA/SIMON BARKE, CHRISTIAN OFFENBERG/ALAMY STOCK PHOTO



> *"LISA will use lasers to precisely measure the distance between each satellite and monitor changes"*

of black holes in the local Universe. However, if we want to set our sights on grander targets and detect gravitational waves from the Universe's birth, we must venture to a new location – space.

▲ **To detect the waves, three identical craft will exchange laser beams over millions of kilometres**

LISA's triple threat

LISA, the Laser Interferometer Space Antenna, will be a gravitational wave detector in space, and the largest scientific instrument ever built. It will be comprised of three individual and identical satellites flying in a triangle formation separated by 2.5 million km (1.5 million miles) – more than six times larger than the orbit of the Moon around Earth. Similar to existing gravitational wave detectors on Earth, LISA will use lasers to precisely measure the distance between each satellite and monitor changes in the light's arrival time. It will be able to detect gravitational waves in the 0.1mHz to 1Hz window, a low-frequency region that can't be detected by ground-based observatories.

Though similar to current observatories in principle, LISA poses many additional technical challenges ▶

How to catch a gravitational wave

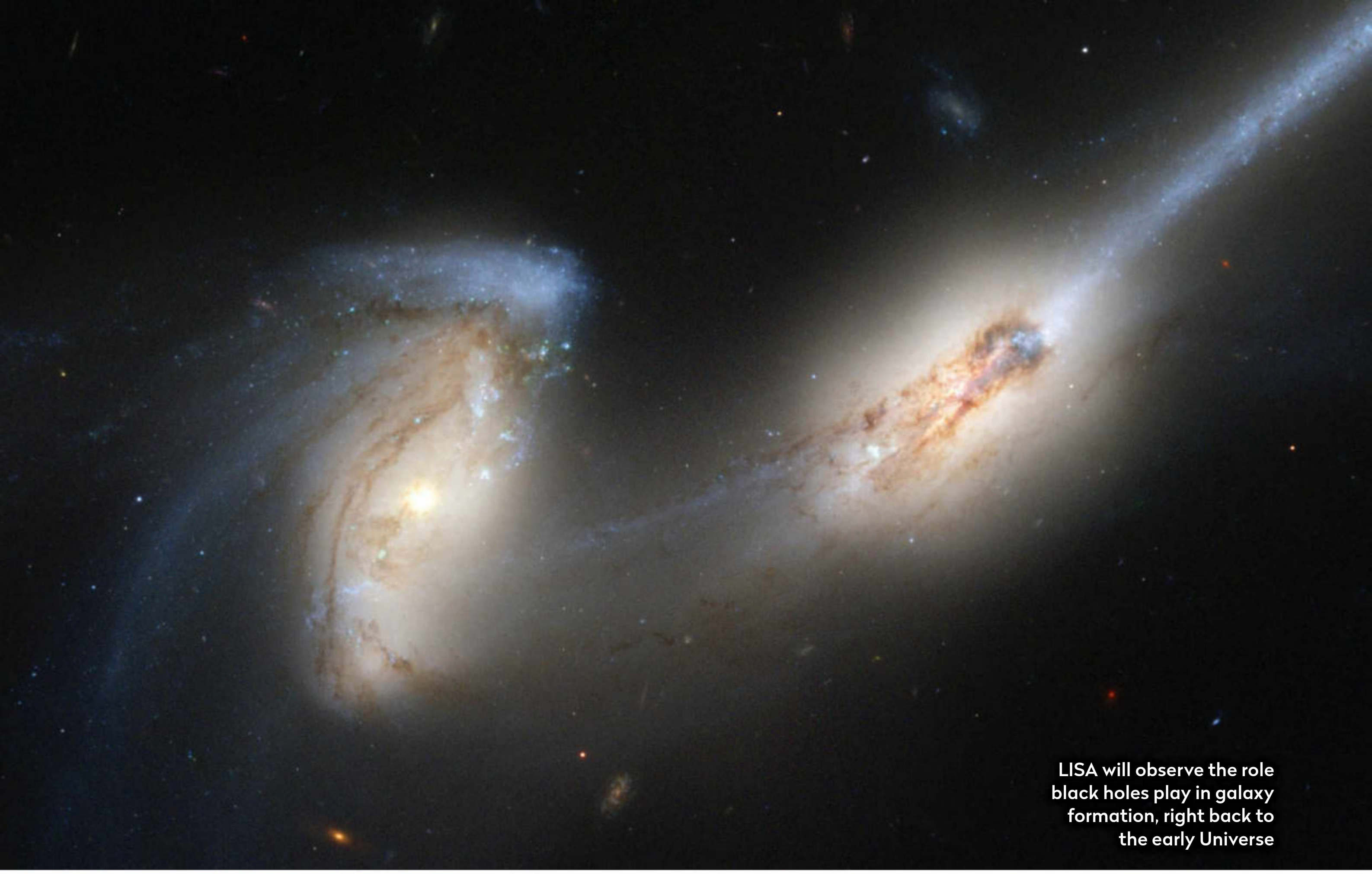
Astronomers use lasers to detect when a gravitational wave passes by

Modern gravitational wave detectors, such as LIGO, Virgo and KAGRA, use a technique called interferometry. The observatories consist of a giant L-shaped structure that splits a single laser beam to shine down two paths at right angles to each other, then reflects the beams back towards each other. The idea is that when a gravitational wave passes by, one of the paths will get slightly stretched while the other is slightly squashed. This means that the laser along one path will have travelled further than the other and, as a result, will arrive slightly later. This ever-so-slight change in timing alters how the waves interact, which the detectors are able to pick up.


LIGO's Louisiana detector works in tandem with another in Washington State

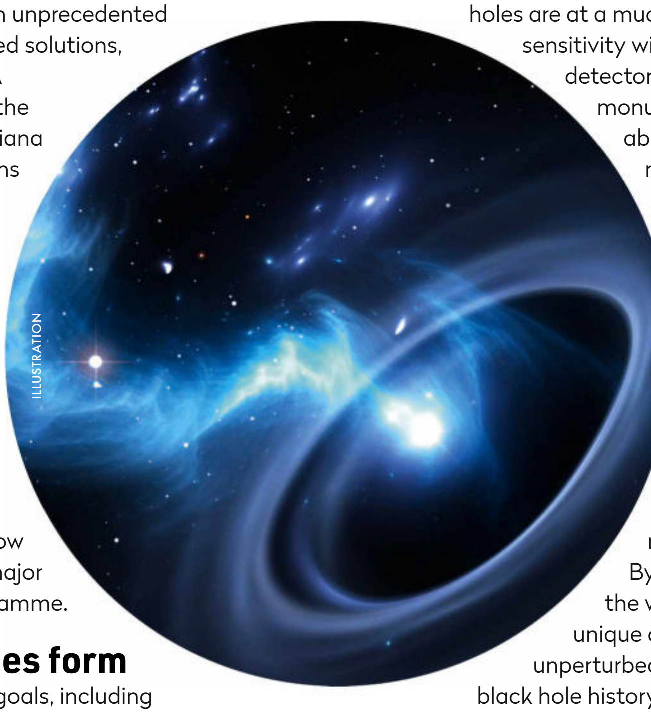
At the time of the first gravitational wave observation, LIGO was able to measure the stretching and squeezing of space with a precision equivalent to a fraction of the width of a proton. LIGO in the USA is comprised of 4km (2.5 miles) arms, while Virgo in Italy and KAGRA in Japan have 3km (1.8 miles) arms. These can detect gravitational waves with a wavelength of 150km–20,000km (15Hz up to a few kHz), made by events such as collisions between black holes and similar objects, weighing around the mass of our Sun.

Gravitational waves from the Universe's birth, however, have much lower frequencies and longer wavelengths, and so need a detector with longer arms. While on Earth we don't have the luxury to build a one-million-kilometre-long interferometer – and atmospheric and seismic activity would limit its sensitivity to low frequencies – in space we have no such limitations and can build wave detectors as large as we need.



LISA will observe the role black holes play in galaxy formation, right back to the early Universe

▶ that need to be solved before it can launch in the mid-2030s. Are we even able to place objects within a spacecraft in a near-perfect gravitational freefall, while controlling their motion with unprecedented accuracy? In order to test proposed solutions, ESA led a test mission called LISA Pathfinder, which launched from the European spaceport in French Guiana in 2015. Within the first two months of operations, LISA Pathfinder successfully demonstrated that the technology required for LISA is possible. The final results, published in 2018, far exceeded expectations and in January 2024 ESA formally adopted the LISA space mission, recognising that the mission's concept, design and technology are advanced enough to start building the instrument. LISA is now firmly established as one of the major missions in ESA's upcoming programme.



▲ Even the low-frequency signals from light objects plunging into supermassive black holes will be in LISA's sights

Watching how galaxies form

LISA will address many scientific goals, including understanding how galaxies form. Although there is no direct evidence, galaxies are thought to be formed from the mergers of hundreds to thousands of smaller protogalaxies (a cloud of gas undergoing active star formation). Since nearly all galaxies have massive black holes at their centres with masses ranging from 1,000 to 10 million times the mass of our Sun, when two galaxies merge, the two massive black holes at their centre will eventually find each other, merge and release a huge amount of energy through gravitational waves. Unfortunately, the gravitational waves from merging massive black holes are at a much lower frequency than the sensitivity window of existing ground-based detectors. Thankfully, owing to LISA's monumental size, it will be uniquely able to observe the collision of massive black holes, from the current-day Universe all the way back in time to when the Universe was 0.18 billion years old (its estimated age is 13.7 billion years).

Similarly, LISA will observe stellar-mass compact objects falling into massive black holes, otherwise known as extreme mass ratio inspirals, creating gravitational waves without the need for some cataclysmic event. By measuring the properties of the waves produced, LISA will yield a unique census of isolated and relatively unperturbed massive black holes, a relic of black hole history.

Testing Einstein

LISA will even be able to test Einstein's theory of gravity in the most extreme regime that can ever be probed. The strongest gravitational waves are produced by systems with the largest gravitational fields – for example, the merger of massive black holes. Recent breakthroughs have allowed us to solve Einstein's equations of gravity on a computer and

NASA/HOLLAND FORD (JHU) THE ACS SCIENCE TEAM AND ESA, PITRIS/ISTOCK/GETTY IMAGES, MARK GARLICK/SCIENCE PHOTO LIBRARY/ALAMY STOCK PHOTO

If it can pinpoint where waves start, LISA could finally hand astronomers a stable Hubble constant

Helping to solve cosmology's biggest problem

Gravitational waves could unlock the secret of our Universe's expansion

Although it's well known that the Universe in which we live is expanding, scientists cannot agree on how fast that expansion is happening. The 'Hubble constant', which quantifies how fast objects in the Universe are moving away from us, is used to measure how fast the Universe is moving apart, but it changes depending on whether you look to the nearby or distant Universe to measure it.

Amazingly, gravitational waves can provide an independent measurement of the Hubble constant. The gravitational wave signal can be used to estimate how far away the signal originated, identifying a potential set of host galaxies. By combining this with measurements of how fast those galaxies are moving away from us, otherwise known as their redshift, we're able to directly measure the Hubble constant.

Although this is possible with ground-based gravitational wave detectors, their current sensitivity makes it difficult to identify how far away the source is, and therefore conclusively identify the host galaxy. However, LISA will measure the source's distance to high accuracy. This should help constrain the origin of the gravitational wave to a single host galaxy and consequently provide unparalleled estimates for the Hubble constant.

"By identifying loud gravitational waves, astronomers will be able to compare with predictions, creating the most stringent test of general relativity to date"

thus make high-precision predictions of how such gravitational waves should appear. By identifying loud gravitational waves from the mergers of such massive black holes, astronomers will be able to compare with predictions, creating the most stringent test of general relativity to date.

Similarly, the final phase of a gravitational wave signal should allow astronomers to verify something called the no-hair theorem, which states that black holes can be completely described by three properties: their mass, charge and angular momentum. The last stages of a gravitational wave signal describe the properties of the final black hole, allowing for the no-hair theorem to be tested.

LISA will be a revolutionary instrument, both in terms of its design and what it promises to achieve for gravitational wave research. The adoption of LISA by ESA represents a tremendous milestone in the LISA mission. An international team of scientists are now hard at work building the largest astronomical observatory ever built, opening an unprecedented new window into the Universe, revolutionising our understanding of cosmology and gravitation. No doubt, there will be some surprises in there too.