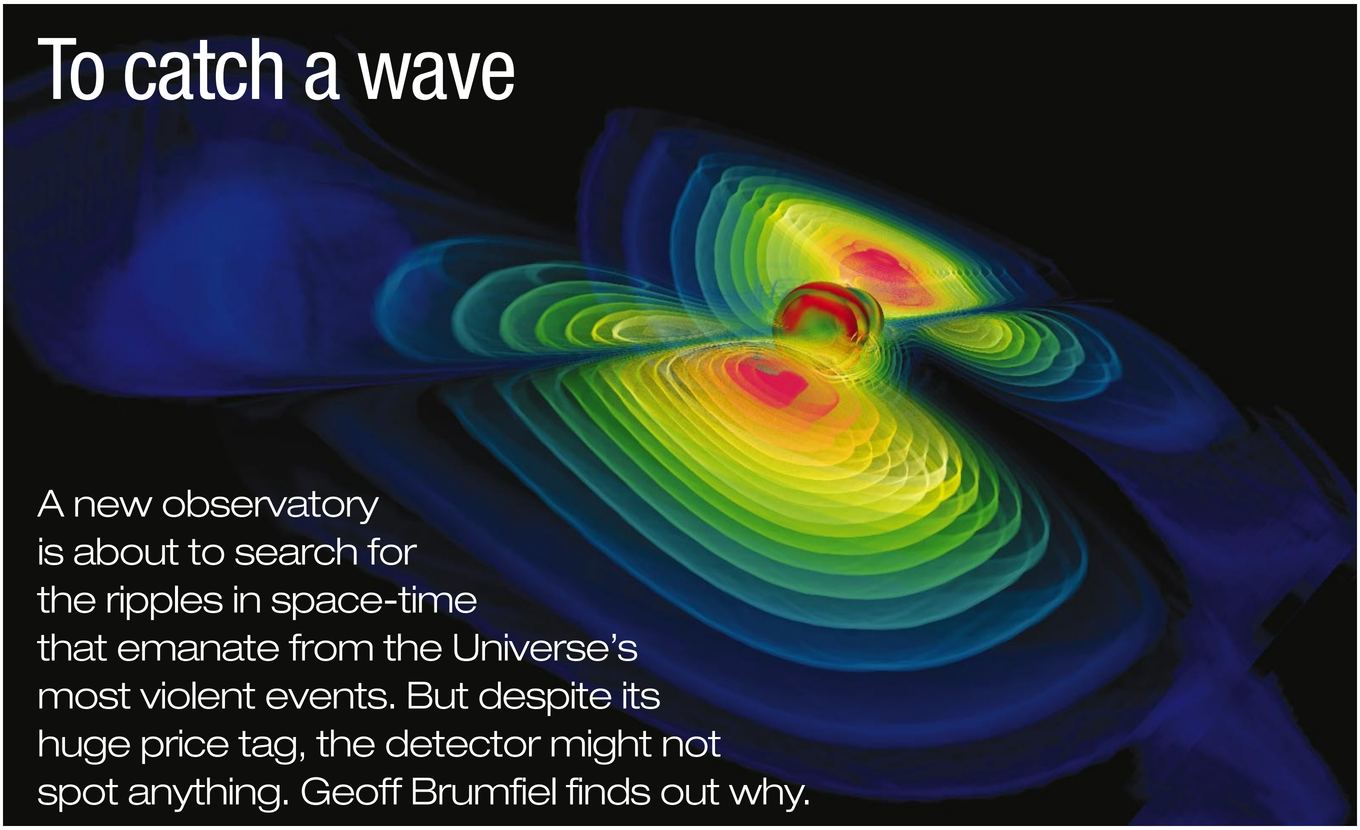
AEI/W. BENGER (AEI/ZIB)

To catch a wave

A new observatory is about to search for the ripples in space-time that emanate from the Universe's most violent events. But despite its huge price tag, the detector might not spot anything. Geoff Brumfiel finds out why.

On the muddy floodplain of central Louisiana, two concrete tubes four kilometres long cut a giant 'L' into an expansive logging plantation. Inside the tubes, laser light bounces back and forth between mirrors, creating a measuring device so sensitive it can pick up the rumble of traffic entering the site, and the vibrations as nearby trees are felled.

But as evening falls and the logging stops, preparations continue for a far more ambitious piece of detective work. By the end of this year, the Louisiana detector will be looking for gravity waves — the faint ripples in space and time generated by colliding black holes and exploding stars. If detected, the ripples will provide new tests of Einstein's theories of gravity, and a way of peering into unseen areas of the Universe.

But that's a big if. The crashing trees and passing trucks — not to mention minor earthquakes — are hampering the final development of the detector. And because theoretical physicists are not sure what the waves look like, no one knows exactly what to expect. Leaders of the project — the Laser Interferometer Gravitational-Wave Observatory (LIGO) — admit that the Louisiana device, and its companion at Hanford in Washington state, might not initially spot anything. But, given that the detectors have a total cost of US$296 million, some researchers are wondering how they ever got built.

No one has ever detected a gravity wave directly since they were first postulated 90 years ago — although physicists concur that


LIGO

Bent on success: the L-shaped LIGO facility in the middle of Louisiana (above) hopes to corner gravity waves produced by events such as a black hole colliding with a neutron star (simulated, top).

the waves do exist. Albert Einstein's general theory of relativity, published in 1916, predicts that large masses in rotating systems should produce ripples in space-time (see 'General relativity for beginners', opposite). Einstein realized that these gravity waves would stretch and squeeze any object that they pass through, but dismissed the idea that anyone could ever detect them. A typical gravity wave passing through the Earth, for example, would stretch the planet by just 10^{-16} metres. "Einstein thought they were just too difficult to detect," says Rainer Weiss, a physicist at the Massachusetts Institute of Technology.


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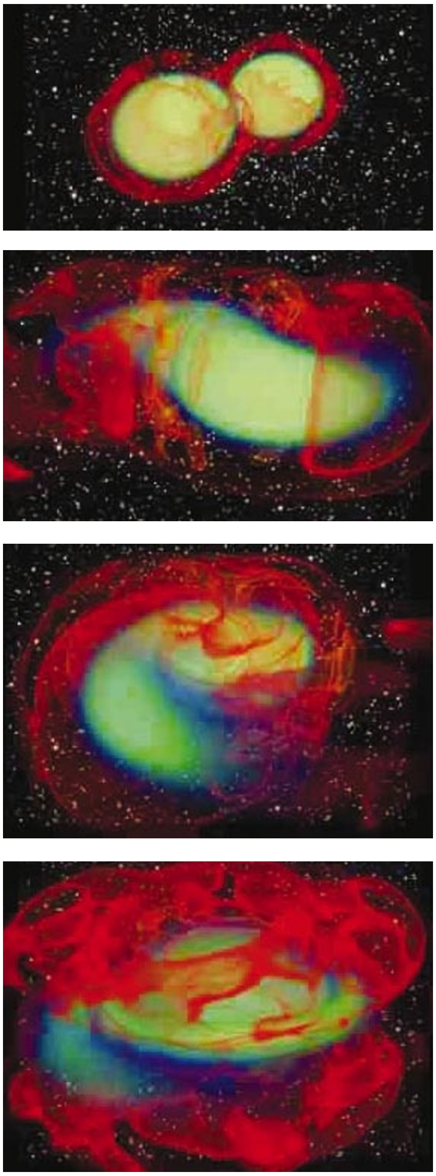
The first gravity-wave hunter, Joseph Weber.

The chance to detect gravity waves directly is exciting because it would confirm Einstein's theoretical prediction. But the extreme events that create the most powerful waves provide a further incentive. "It's a completely different world," says Weiss. "If you're near a black hole, space is so contorted and curved that straight lines don't extend very far. Nearby clocks move at different rates, and nothing stands still." And, because dust and debris often surround these objects, many believe that the only way to learn about them is through the gravity waves some configurations of black holes emit.

Attempts to detect the waves date back to the 1960s. The first detector, the brainchild of Joseph Weber, a physicist at the University of Maryland, College Park, consisted of an aluminium bar 2 metres long and 1.5 metres in diameter. Weber predicted that the bar would ring as if struck by a hammer if a passing gravity wave caused its length to expand and contract momentarily.

In the late 1960s, Weber stunned the



WASHU/AEI/W. BENGER (AEI/ZIB)

Early insight: spiralling neutron stars, modelled here, offered the first evidence for gravity waves.

physics world by announcing that he had detected gravity waves passing almost simultaneously through bar detectors in Maryland and Chicago. The waves appeared to have changed the length of the bars by 10^{-15} m. But sceptics pointed out that waves this powerful could only come from events involving a significant fraction of the Milky Way's mass. "If you actually calculated what he was allegedly seeing, the Galaxy would be wiped out in about a million years," says Weiss. As time went by, it became clear that Weber's statistical analysis of his results had been flawed.

But Weber's announcement captured the imagination of many young scientists. "I was fascinated by it," recalls Tony Tyson, a physicist at Bell Laboratories in Murray Hill, New Jersey, who was a graduate student at the University of Chicago at the time. By the mid-1970s, Tyson had built larger bar detectors, as had other groups around the world. Although none successfully detected gravity waves, interest in the field continued to grow, thanks in part to the first indirect evidence for the existence of the waves.

In 1974, physicists Russell Hulse and Joseph Taylor, then at the University of Massachusetts in Amherst, used a radio telescope to observe a pair of neutron stars orbiting one another. Hulse and Taylor realized that the stars would be emitting gravity waves, and so would be slowly losing energy and moving closer together. They tracked the stars for four years, and in 1978 announced that their orbits were changing in exactly the way predicted by Einstein's theories. The finding, still the best observational evidence for gravity waves, helped win Hulse and Taylor the 1993 Nobel Prize in Physics.

Pulling together

Now the race was on to build a device that could detect gravity waves directly. "We knew the scientific pay-off from success would be tremendous," says Kip Thorne, a theoretical astrophysicist at the California Institute of Technology (Caltech) in Pasadena. Thorne and others at Caltech were keen to host the device, and in the late 1970s decided to recruit Ronald Drever, an experimental physicist from the University of Glasgow, UK, to help them design a new kind of detector.

Drever had experience of building L-shaped devices called Michelson interferometers. Incoming laser light is split into two beams at the corner of the L, and each beam races down one leg to a mirror where it is reflected back to centre. As the beams recombine, they create an interference pattern with a dark spot over a light-sensitive detector. If a gravity wave, or any other disturbance, changes the length of either leg, the intensity of light at the detector changes. By studying the change in intensity, researchers can determine the change in the light's path. Interferometers are not necessarily any more sensitive than Weber bars, but they can detect a much wider range of frequencies of gravity wave.

The Caltech team was joined by Weiss, who had been working independently on interferometer detectors. In 1985 they submitted the proposal for LIGO to the National Science Foundation (NSF), calling for a pair of interferometers, which they claimed would detect disturbances of about 10^{-19} m in the relative path lengths of the lasers. Hundreds of millions of dollars would be needed to construct their devices. Yet right from the start, the researchers were not completely certain whether they would detect anything.

The scientific uncertainties clouding LIGO were, and still are, twofold. On one hand, the theorists were unable to predict the precise size and frequency of the waves that they hoped LIGO would detect, raising doubts about the optimal detector design. And no one was sure how regularly gravity waves reach Earth. If collisions between black holes are rare, for example, it might take centuries to spot a single event.

There were also technical problems. Researchers working on Weber bars experienced minor earthquakes that constantly shook their labs. The tremors posed a significant problem, as their frequencies — between 0 and 100 hertz — are similar to those of the gravity waves that theory predicts should be most abundant.

Designed for life

To avoid these difficulties, the NSF advised that the project should have the potential to be upgraded if the initial design failed to spot anything. "We were told many times by the NSF: 'Don't go for something that is just going to end after one attempt'," says Weiss.

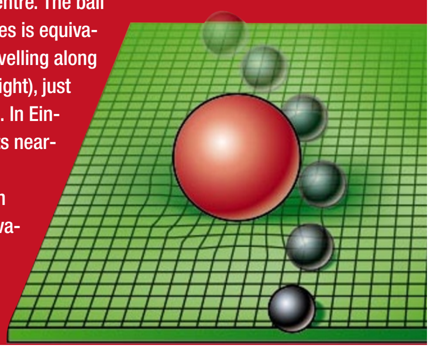
The plan was to start with two geographically separate facilities large enough to hold high-power lasers, seismically isolated optics, and several interferometers. Using two detectors would allow potential sightings to be double-checked.

The first interferometers were to be built from commercially available components. Their main function would be to test the sophisticated electronic and computing systems needed to run the experiment. The

General relativity for beginners

Albert Einstein's general theory of relativity describes gravity as a distortion in the four dimensions of space and time. Visualizing this is difficult, but a two-dimensional analogy makes it clearer.

Imagine a sheet of rubber with a bowling ball at its centre. The ball is a planet, and deformation of the rubber surface it creates is equivalent to the way that real planets distort space. Objects travelling along the sheet will roll down the slope towards the bowl (see right), just as gravity would draw a passing comet towards the Earth. In Einstein's theory, the Earth attracts objects because it distorts nearby space, just as the bowl distorts the rubber sheet.



Now imagine two bowling balls spiralling around each other. This would create ripples on the rubber sheet, equivalent to the gravity waves produced when two stars orbit each other. By studying the ripples, observers can learn about the stars' movements.

team would then install more sensitive second-generation interferometers.

In 1989, the NSF gave the plan its formal backing. "There was a comfort factor with LIGO that you don't always get with big-money projects," says Frederick Bernthal, the NSF's deputy director during the latter half of LIGO's planning period. "Even if you never saw a gravity wave, the leading-edge technology involved with building LIGO was just extraordinarily impressive."

Political persuasion

The LIGO team now had to convince Congress that the project was worth funding. Robbie Vogt, the Caltech physicist who was then director of LIGO, led an intensive year-long lobbying campaign. One of his speeches caught the attention of Bob Livingston and Bennett Johnson, then a Louisiana representative and senator, respectively. They were impressed by the idea, and wanted to use the cutting-edge science — and the associated jobs — to boost the economy of their state.

The NSF helped to smooth the way by giving the Livingston site in Louisiana a high rating in a survey of possible locations. And at the time, no one thought to worry about the disturbances caused by falling trees. The site for the other detector at Hanford was on unwanted, government-owned land that had previously been used for nuclear-weapons construction.

Although it had the NSF's blessing, some scientists remained worried about the project's cost. Many were, and still are, reluctant to criticize publicly a project that has the backing of prominent universities and the government, but some voiced their concerns at the time. "As a physicist I am fascinated by this experiment and would like to see much of it funded," Tyson told the science committee of the House of Representatives in March 1991, "but not at the expense of hundreds of individual principal investigator grants." As part of his testimony, Tyson submitted comments from more than 60 physicists and astronomers, all expressing doubts about the plans. But LIGO was already on a roll, and had support from the Louisiana politicians. Congress approved the project in autumn 1991.

With the political battle won, researchers have spent the past decade designing and building the two observatories. Both are now almost ready to begin the search for gravity waves. But the start of data acquisition will not be marked with a fanfare — hopes of immediately detecting gravity waves remain low.

Barry Barish, a high-energy physicist at Caltech and the current director of LIGO, says that whether or not you expect LIGO to see anything still depends on what model of gravity-wave production you favour. "And the theories are kind of crummy," he adds. In the years since LIGO was first proposed, estimates of the frequency and power of detectable events have actually decreased.

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The construction of LIGO has inspired other similar projects, such as the GEO 600 in Germany.

"They were wildly optimistic in their initial assessments of the potential sources," says Jerry Ostriker, a theoretical astrophysicist at Princeton University in New Jersey. Ostriker, a long-time critic of LIGO, believes that today's estimates give even the future versions of the giant machines only a slim chance of seeing anything.

Noise, noise, noise

The technical difficulties have also persisted. Construction of the facilities finished over two years ago. But in 2001, a 6.8-magnitude earthquake at the Hanford site knocked mirrors and other optics against their mounts and delayed the project by three months. The most difficult issue, however, has been filtering out one source of noise after another. The tree-felling at Livingston restricts operations to evenings and weekends. Even at these times, LIGO must take account of phenomena such as 'Earth tides' — the shifting of the Earth's core every 12 hours caused by the Moon's gravitational pull.

These effects can be compensated for by electronically adjusting the mirrors to filter out false signals. But each time the researchers filter out a signal, they must be sure that they have not interfered with previous adjustments. It is a bit like tuning in a faint radio signal over the static, explains Mark Coles, director of LIGO's Livingston observatory. "It's sort of unglamorous," he adds.

Some researchers question whether the noise will ever be reduced to a level that will allow gravity waves to be detected. "There's this big question mark: how much further is noise going to allow them to go?" says Tyson. Data collection, which had been due to start this summer, has now been put back until the end of the year at both sites.

But LIGO researchers remain confident. "It wouldn't be a total surprise if we detect something fairly early," says Barish. "But I'd be shocked if we don't within a decade." And after three years of operation, the researchers plan to apply for money to upgrade LIGO. They hope, for example, to add more powerful lasers and to improve seismic isolation.

But whatever the results, LIGO will have boosted the field of gravity-wave detection. Since it was commissioned, similar projects have begun in Germany, Italy, Australia and Japan. One of these — Virgo, based near Pisa in Italy — will probably come online after LIGO in 2003 and should be similarly sensitive. Doubts remain about whether these other projects can overcome the problems, such as seismic noise, faced by LIGO, but if more than one of the devices detects waves, they could pool their data to pinpoint the source.

Plans for a space-based gravity-wave detector are also in the works. Physicists in Europe and the United States are designing an interferometer that would travel around the Sun in an orbit similar to that of the Earth. Known as the Laser Interferometer Space Antenna (LISA), it would consist of three satellites in a triangle, each separated by 5 million kilometres. LISA would have a similar sensitivity to LIGO, but should find it easier to capture the elusive low-frequency signals that seismic noise can obscure. If funding can be secured, work on LISA will begin within a few years, with the aim of launching the spacecraft by the end of the decade.

Projects such as LISA show that LIGO is more than just a detector — its construction has also helped to build a community of researchers. In the United States, the giant devices have become nuclei for hundreds of gravity-wave researchers at 30 institutions across the country. "We have experimenters who are looking at the next generation of detectors. We have theorists who are interested in the data," says Weiss. "And they're not old like me. That's the biggest development." ■

Geoff Brumfiel is *Nature*'s physical sciences correspondent in Washington.

LIGO ▸ **www.ligo.caltech.edu**
Virgo ▸ **www.virgo.infn.it**
LISA ▸ **lisa.jpl.nasa.gov**