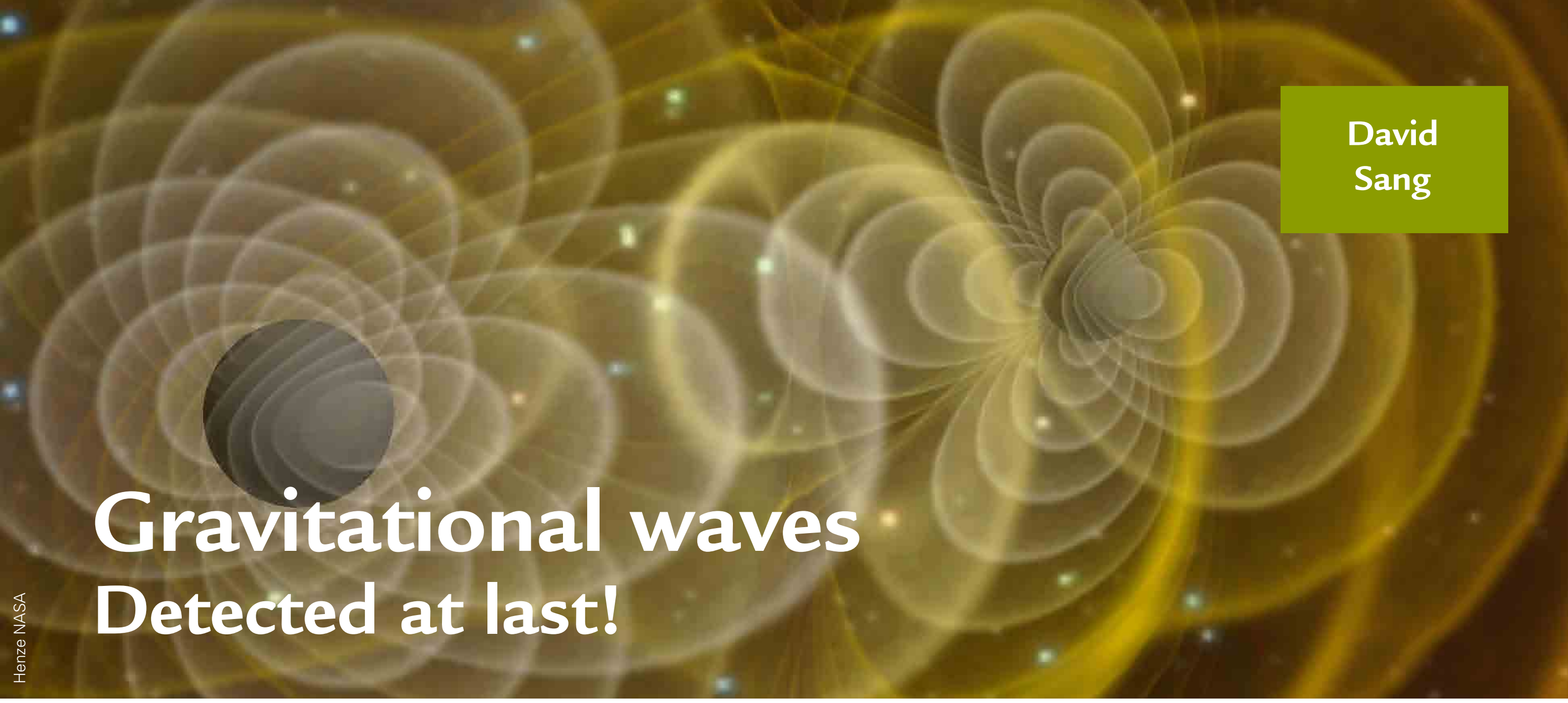


Henze NASA

David Sang

Gravitational waves
Detected at last!

On September 14, 2015, scientists working at the LIGO laboratory detected gravitational waves for the first time. So, what are gravitational waves and how are they detected?

Einstein's prediction

Albert Einstein published his General Theory of Relativity in 1916. He suggested that we should picture masses as causing distortions of the fabric of space. When large masses interact, gravitational waves will ripple out into space, rather like electromagnetic waves.

LIGO is the Laser Interferometer Gravitational Wave Observatory – here you can see the two long arms of the interferometer, at 90° to each other, used to detect ripples in space.

A weak force

Although gravity is an important force on the astronomical scale, it is the weakest of the four forces of nature. This means that, although gravitational waves transfer energy, their effects will be vey weak and difficult to detect.

Scientists realised that the collision of two black holes could produce relatively strong gravitational waves. They made computer simulations of such an event so that they would know the pattern of waves that they might expect.

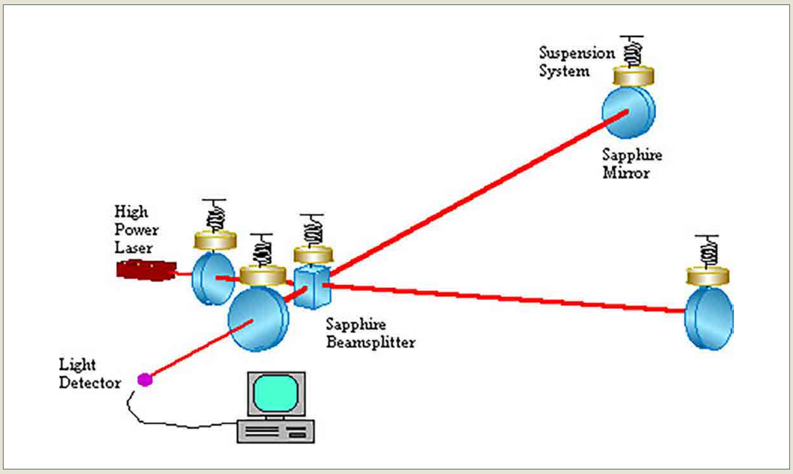
Tiny signals

In practice, it has proved enormously difficult to isolate the vibrations of gravitational waves from all the other vibrations which reach the laboratory. Traffic noise, the hum of mains electrical equipment, even the crash of a distant falling tree could be far stronger than the effect that being sought. That's why it has taken a century from Einstein's prediction to the first detection of gravitational waves.

A computer simulation of the production of gravitational waves as two black holes merge

Detection with light

The LIGO observatory uses a laser interferometer to detect the slight distortions in space which occur as a gravitational wave passes the Earth.



A powerful laser sends a beam of light into a beam splitter. Each half of the beam then travels along a 4 km arm of the interferometer. At the end it reflects back from a heavy mass.

The beams are recombined by the beam splitter.
If they have travelled exactly the same distance they will arrive at the detector exactly in step with each other. This gives constructive interference and a strong signal.

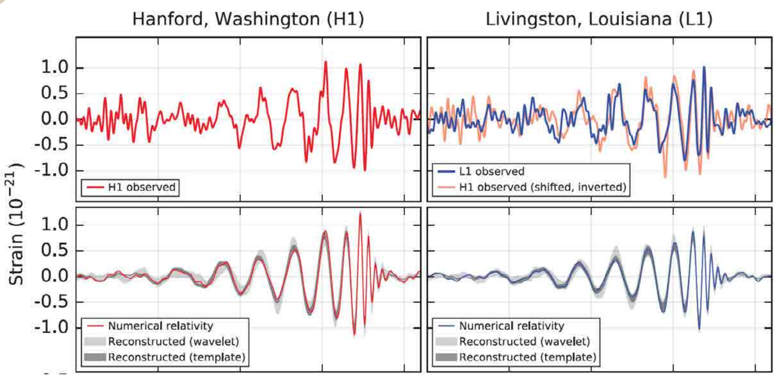
However, if one of the two arms has been lengthened or shortened by the passage of a gravitational wave, one beam will have travelled slightly further than the other and the waves will be out of step, causing destructive interference.

Detecting a cosmic collision

The LIGO lab detected gravitational ripples produced when two black holes with masses of 29 and 36 solar masses collided 1.2 billion years ago. The waves have been spreading out through space ever since so that they were very weak as they passed Earth.

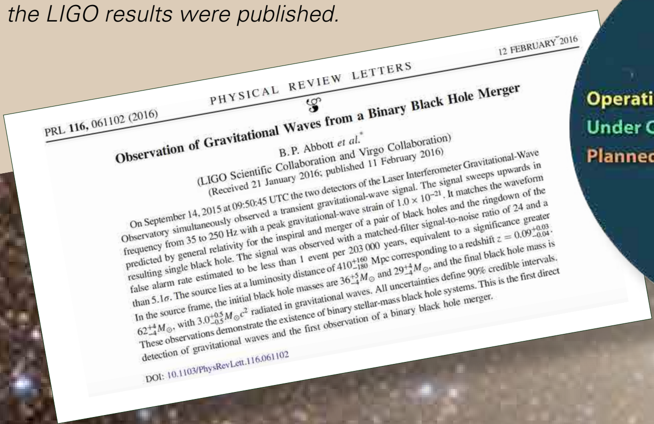
Europe has a gravitational wave lab near Pisa, Italy. You can see the two long arms of the interferometer.

Gravitational wave observatories are likely to be built in space. Here, the European Space Agency's LISA Pathfinder spacecraft is being prepared for launch.



Gravitational vibrations detected by LIGO. In fact, there are two labs at opposite ends of the USA; the graph at top left is from the lab at Hanford in Washington state. Upper right is the graph from the lab at Livingston, Louisiana (blue), compared with the Hanbury graph. The lower graphs are the patterns predicted by computer simulations.

Publishing the results: more than 1000 authors were credited when the LIGO results were published.



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Observation of Gravitational Waves from a Binary Black Hole Merger

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On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

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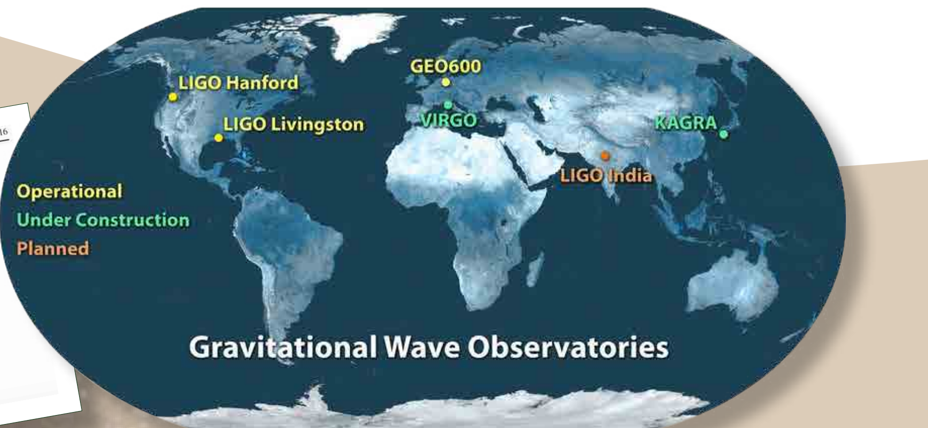

In future, with observatories around the world, it will be easier to tell the direction of travel of gravitational waves.