GRAVITATIONAL WAVES

Einstein's Key to Understanding the Universe

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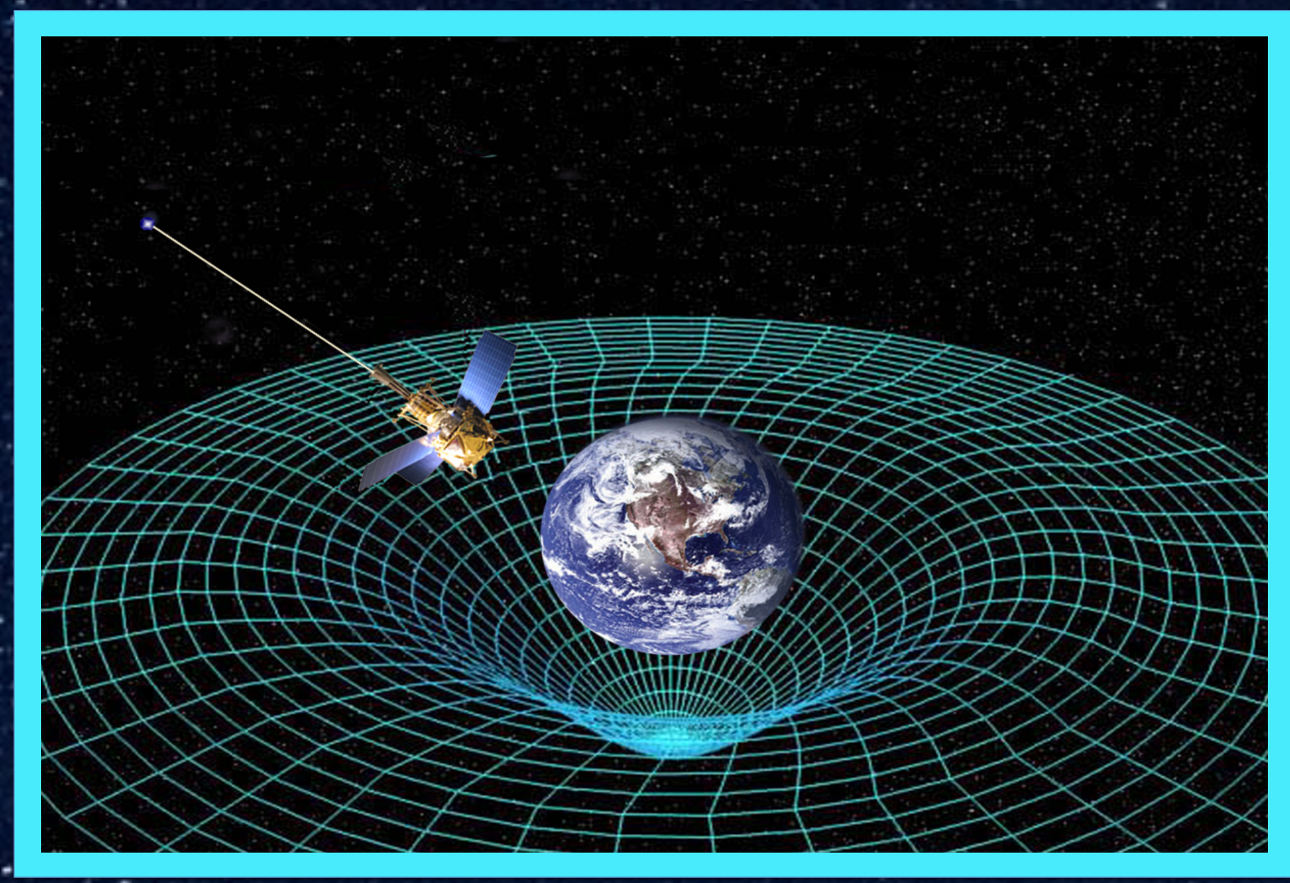


Abstract

Gravitational waves are ripples in spacetime that confirm Einstein's theory of general relativity and are the first directly measurable evidence of the existence of black holes. Two sets of gravitational waves have been measured by LIGO, the first of which was caused by the collision of two black holes 1.3 billion years ago. The ability to study gravitational waves opens up a whole new way of observing the universe; studying these waves will provide new insight into the formation of the universe, the nature of black holes, and the inner workings of other celestial objects.

General Relativity

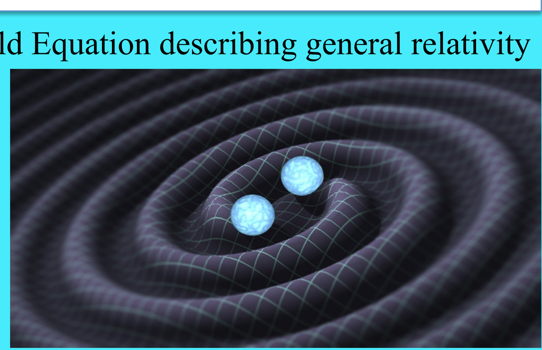
Albert Einstein's theory of general relativity, published in 1915, was a revolutionary description of gravitation that has formed the basis of much of modern physics. Einstein stated that **spacetime has a curvature** directly related to the **energy and momentum of matter and radiation**.

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = (8\pi G_N/c^4)\, T_{\mu\nu}$$

Einstein's Field Equation describing general relativity

Implications:

- gravity slows down time *(gravitational time dilation)*
- gravity bends light *(light deflection* and *gravitational lensing)*
- gravity can cause ripples in spacetime *(gravitational waves)*
- massive stars eventually become black holes



Artist's depiction of gravitational waves

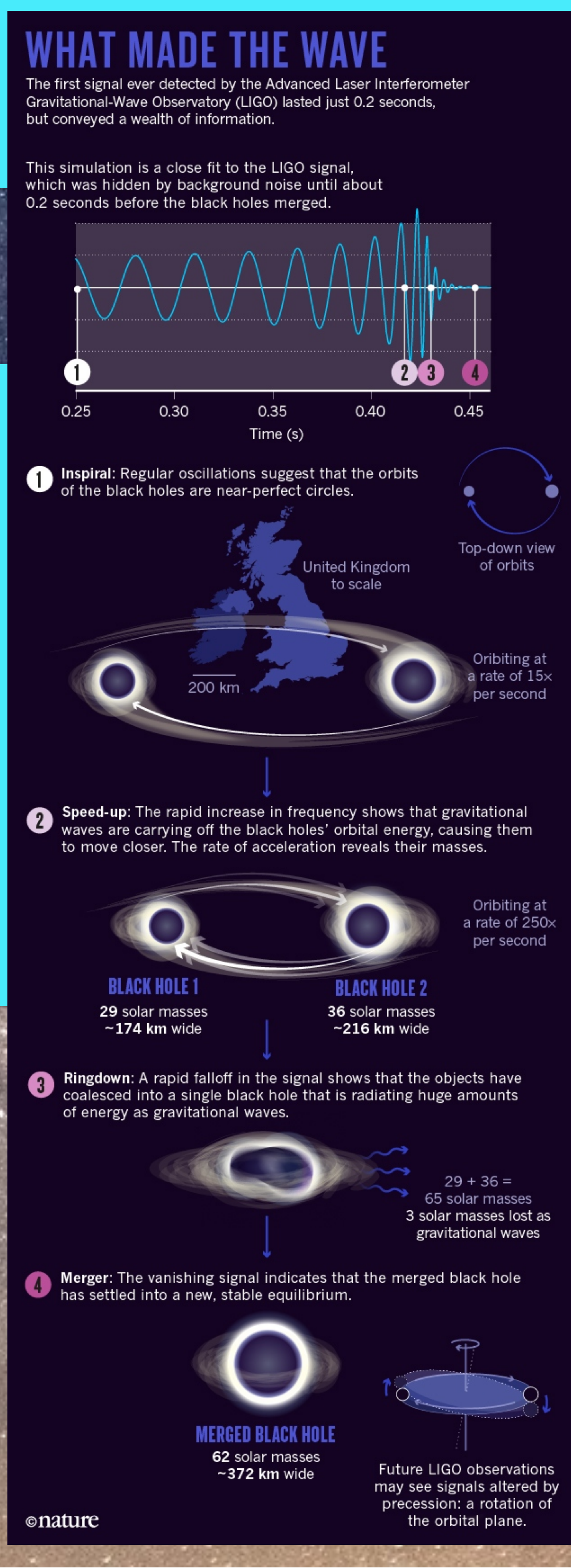
However, there remain **unresolved differences** between Einstein's general relativity, which accurately describes the behavior of extremely large and high-mass objects, and quantum field theory, which accurately describes the behavior of extremely small and low-mass objects. The two sets of theories cannot currently be combined into a **master theory**, suggesting that they are inaccurate or incomplete. The LIGO measurements of gravitational waves provided important data supporting Einstein's general relativity, but the search for a master theory remains an open line of research.

Black Holes

- a large amount matter compacted into an extremely small space, usually formed by dying stars large enough to become a supernova
- cannot be observed through x-ray, light, or radiation

When two black holes are in close proximity, they can begin **orbiting** each other, losing energy and accelerating in the process; eventually, they **collide** and become a single black hole. This collision releases a large amount of energy in the form of **gravitational waves**, which radiate outwards through the universe like ripples on still water.

This process remained unconfirmed until late 2015.



LIGO Measurements

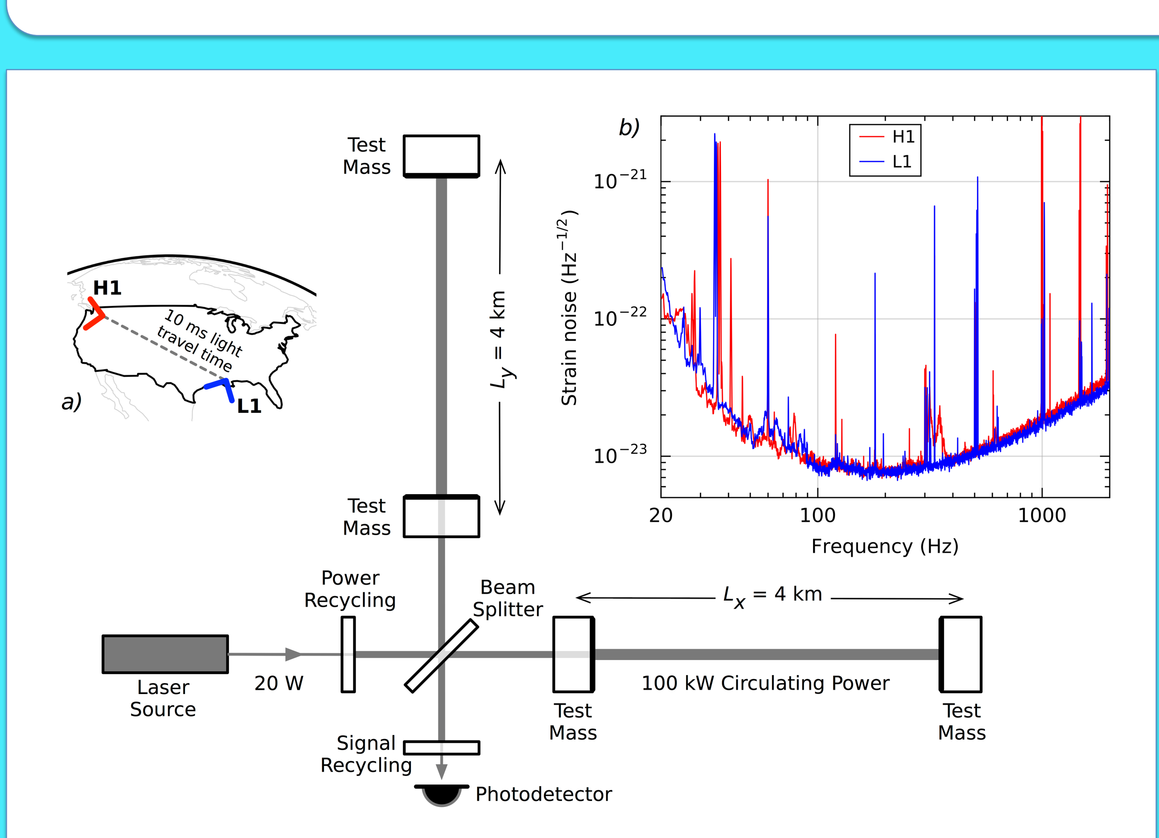


Diagram of the LIGO detector arms. Inset a) shows the locations of the two LIGO observatories, while inset b) shows the variation of the instruments' strain noise close to the event.

In 1980, US National Science Foundation began funding the study of interferometers at MIT and Caltech; their joint efforts led to the **Laser Interferometer Gravitational-Wave Observatory (LIGO)**, located in Louisiana and Washington. Each observatory has two perpendicular arms, each 4 km long and equipped with a series of lasers and mirrors. When a gravitational wave arrives, the arm stretches or contracts by about 1/10,000 the width of a proton, causing the lasers to desynchronize.

On **14 September 2015**, the LIGO detectors recorded gravitational waves caused when two black holes, 29 and 36 times more massive than our sun, merged 1.3 billion years ago. A second wave was detected on 15 June 2016.

Conclusion

LIGO's measurements confirm the existence of gravitational waves and provide concrete evidence for Einstein's 1915 theory of general relativity. Scientists expect that gravitational waves will allow them to study the universe in ways never before possible. To this aim, the European Space Agency has proposed the **Laser Interferometer Space Antenna (LISA)**, a series of three spacecraft designed to measure gravitational waves from space beginning in 2030.

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