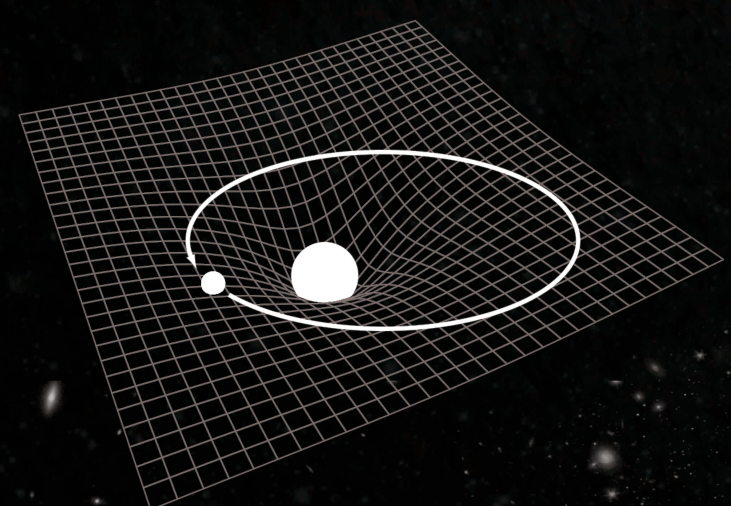
HISTORY OF GRAVITATIONAL WAVES

{RIPPLES IN SPACETIME}



General Relativity

In the 17th century Isaac Newton explained gravity as a force that all matter exerts on all other matter. This explanation stood unchallenged until the early 20th century, when Albert Einstein developed a radically different way of thinking about gravity in a series of famous papers which introduced his general theory of relativity.

Einstein's theory explains gravity as the curvature of spacetime. A massive body, like the sun, causes spacetime to bend. Objects moving through this curved spacetime follow *geodesics (shortest paths)* in the curved background. John Wheeler succinctly summarized this relation as "*spacetime tells matter how to move; matter tells spacetime how to curve.*"

Two consequences of general relativity not present in Newtonian gravity are that light is bent by gravity, and that any changes to a gravitational field propagate at the speed of light as ripples in the fabric of spacetime called gravitational waves.

Indirect Confirmation of Gravitational Waves

Imagine two stars – roughly the mass of the sun and compressed to the size of Atlanta – orbiting every few hours and spinning on their own axes twenty times per second. These ultra compact stars are neutron stars, the remnants of massive stars that have exploded as supernovae. Systems with two neutron stars orbiting one another are some of the most promising sources of directly detectable gravitational waves. In fact, they have already provided indirect evidence for the existence of gravitational waves.

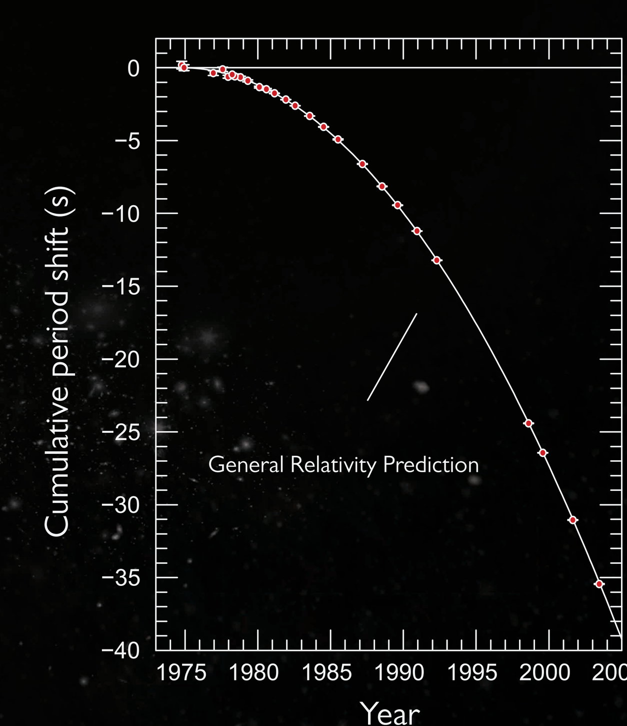
In 1974, two radio astronomers, Russell Hulse and Joseph Taylor, observed radio pulses with a period of 59 milliseconds. Their source was a pulsar, a spinning neutron star with a bright spot that acts like a lighthouse beam. We observe a pulse of radio waves every time the bright spot sweeps around to face Earth. The measurements of Hulse and Taylor showed that the pulse period fluctuated by several milliseconds over the course of several hours. They deduced that the fluctuation was caused by the Doppler shift of the signal due to the orbital motion of the pulsar around its companion.

This highly relativistic orbital system offers one of the best laboratories for testing gravitational theories. Hulse and Taylor were able to determine that the periastron (point of closest approach) advances by 4 degrees per year – approximately 35,000 times the relativistic correction for the advance of Mercury's perihelion.

After several years of observation, they determined that the orbital period was decreasing by about 75 millionths of a second per year. This is in excellent agreement with the general relativistic prediction that the orbit should decay by losing orbital energy in the form of gravitational waves. While the frequency of gravitational waves from this system are too low to be directly observed with current detectors, the exact prediction of the rate of orbital decay is strong evidence for the existence of gravitational waves.

In 1993 the Nobel committee awarded Hulse and Taylor the Nobel prize for "the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation." Since then, other pulsars in binaries have been observed, and in all cases the rate of their orbital decay is consistent with the change expected from the emission of gravitational waves.

Similar binaries composed of two neutron stars and/or black holes orbiting one another more rapidly than the Hulse-Taylor binary could emit gravitational waves strong enough to be detected directly.



The Hulse-Taylor plot of pulsar PSR B1913+16

Data from J. M. Weisberg and J. H. Taylor, Relativistic Binary Pulsar B1913+16: Thirty Years of Observations and Analysis, July 2004.

Gravitational Waves

When matter accelerates, the change propagates outward as a ripple in the curvature of spacetime. Einstein's equations can be reduced to a wave equation in certain cases, thus demonstrating the existence of gravitational waves in the theory.

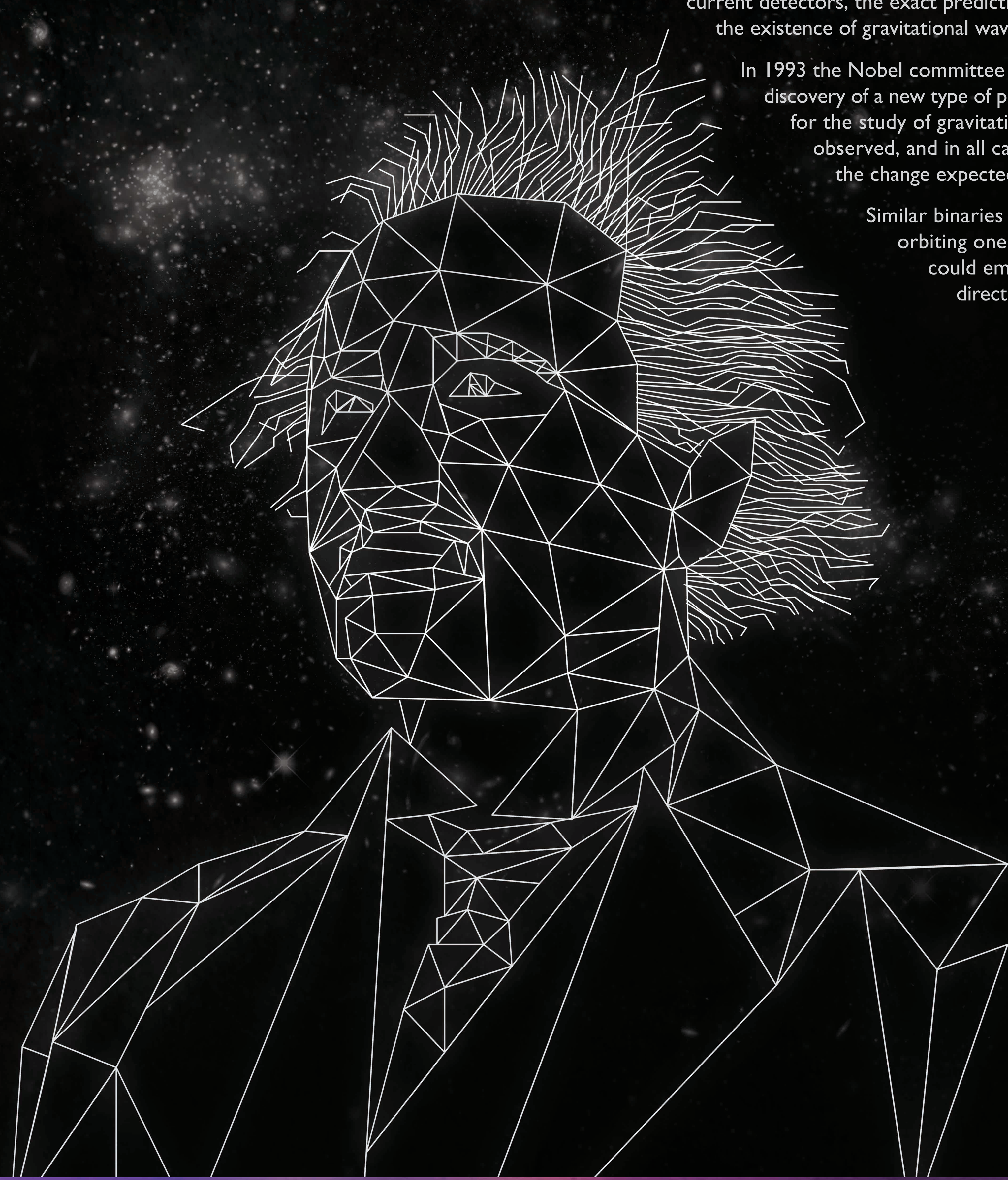
Electromagnetic waves can be taken as an analogy to gravitational waves. Electromagnetic waves are oscillations in the electric and magnetic fields produced by accelerating charges. Gravitational waves are oscillations of space time produced by accelerating masses.

To understand the effect of gravitational waves, imagine that several particles are arranged in a ring of radius L in a constant gravitational field. As a gravitational wave passes, the particles are deformed into an ellipse with semi-major axis L+dL and semi-minor axis L-dL, back through a ring into the same ellipse rotated through 90°, and finally back to a ring. This is a single wave cycle. A gravitational wave stretches spacetime itself in this manner as it passes.

The strength of a gravitational wave is measured in, **strain** h, the fractional change in the size of an object as it is deformed. At leading order, the strength of a gravitational wave is determined by how rapidly the quadrupole moment of its source is changing $h \simeq \frac{G}{c^4}\frac{d^2Q/dt^2}{D}$, where Q is the quadrupole moment of the source and D is the distance from source to observer.

In principle, any mass accelerating in a non-spherically-symmetric way produces gravitational waves – for example, waving your hand would create them. However, because $\frac{G}{c^4} = 8.26\ 10^{-45}\,\mathrm{kg}^{-1}(\mathrm{m/s}^2)^{-1}$ is such a tiny number, it takes massive objects undergoing extreme acceleration to create waves that we could ever hope to measure.

This means we must look to the most energetic processes in the universe – the big bang, supernovae, two neutron stars merging – to find sources of observable gravitational waves.

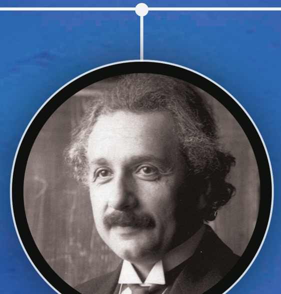


(background credit: Gareth Johnson)

1905

Einstein publishes his famous paper on special relativity.

The fundamental hypotheses are (a) that the laws of physics are the same in every inertial frame, and (b) the speed of light is invariant between inertial frames.



1907

In his review of special relativity, Einstein proposes the equivalence principle:

"...we shall, therefore, assume the complete physical equivalence of a gravitational field and the corresponding acceleration of the reference frame. This assumption extends the principle of relativity to the case of a uniformly accelerated motion of the reference frame."

1911

Einstein renews work on gravitation.

He realizes that the bending of light is a consequence of the equivalence principle and that it might be measured in astronomical experiments.

(credit: NASA, ESA, Andrew Fruchter (STScI), and the ERO team (STScI + ST-ECF))

1913

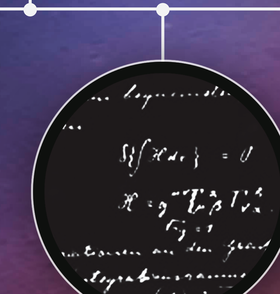
With Grossmann, Einstein publishes a paper which uses ideas of non-Euclidean geometry.

Important tools for the future are outlined. Gravity is a manifestation of the curvature of spacetime, and the fundamental field is the metric (distance) tensor of the curved spacetime.

1913 – 1915

Einstein continues work on tensor analysis and gravitation.

He has detailed correspondence with Levi-Civita and Hilbert about his ideas.



1915

Einstein publishes his general theory of relativity.

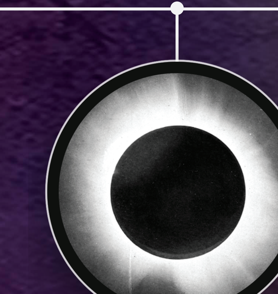
1916

Einstein publishes the first paper predicting gravitational waves in general relativity. One of the equations predicting the strength of gravitational waves has an error.

1918

Einstein publishes a new paper on gravitational waves which corrects the error in the previous paper.

(credit: Princeton University Press)



1919

Sir Arthur Eddington and collaborators observe light from distant stars bending around the sun during a solar eclipse. The result is a spectacular confirmation of this prediction by general relativity which makes headlines around the world.

LSC LIGO Scientific Collaboration

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