Listening for Einstein's Ripples in the Fabric of the Universe

UNCW College Day, 2016

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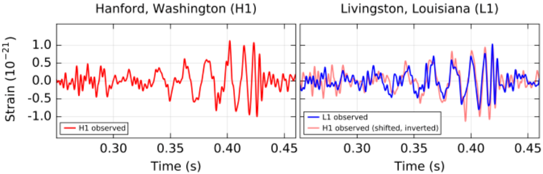


https://cplberry.com/2016/02/11/gw150914/

Outline

February, 11, 2016:
Scientists announce first detection of gravitational waves.

Einstein was right!

1. Gravitation
2. General Relativity
3. Search for Gravitational Waves
4. Detection of GWs - LIGO
5. GWs Detected!

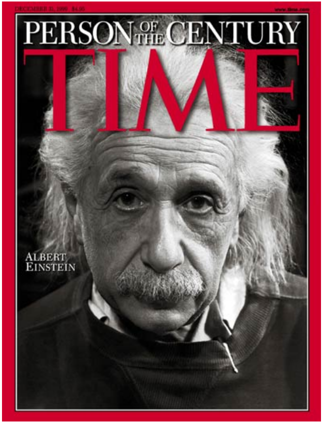


Figure: Person of the Century.

Isaac Newton (1642-1727)

In 1680s Newton sought to present derivation of Kepler's planetary laws of motion.

- Principia 1687.
- Took 18 months.
- Laws of Motion.
- Law of Gravitation.
- Space and time absolute.

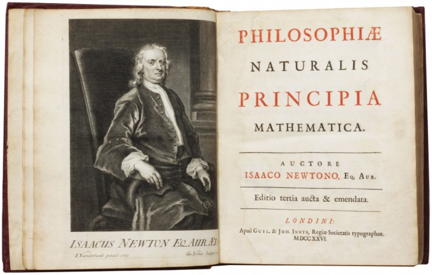


Figure: The Principia.

James Clerk Maxwell (1831-1879) - EM Waves

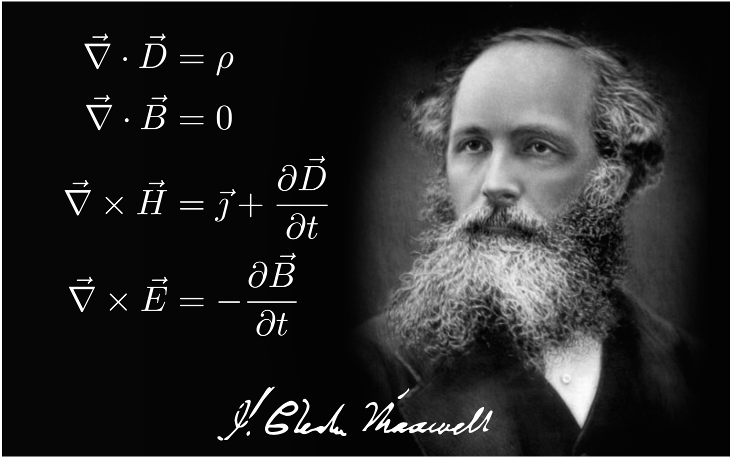


Figure: Equations of Electricity and Magnetism.

Special Relativity - 1905

... and then came A. Einstein!

Annus mirabilis papers.

- Special Relativity.
  - Inspired by Maxwell's Theory.
  - Time dilation.
  - Length contraction.
  - Space and Time relative - Flat spacetime.
- Brownian motion.
- Photoelectric effect.
- $E = mc^2$.

Figure: Einstein (1879-1955)

General Relativity - 1915

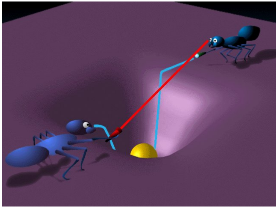
Einstein generalized special relativity for Curved Spacetime.

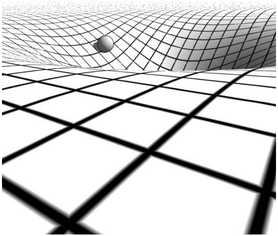
- Einstein's Equation
- Gravity = Geometry

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}.$$

- Mass tells space how to bend and space tell mass how to move.
- Predictions.
  - Perihelion of Mercury.
  - Bending of Light.
  - Time dilation.

Inspired by his "happiest thought."





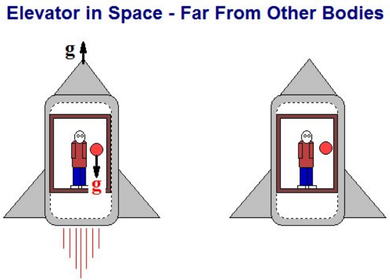
The Equivalence Principle

Bodies freely falling in a gravitational field all accelerate at the same rate.

EP 1: There are no (local) experiments which can distinguish non-rotating free fall under gravity from uniform motion in space in the absence of gravity.

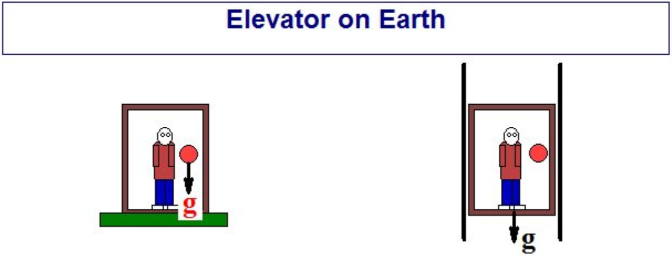
EP 2: A frame in constant acceleration relative to an inertial frame in special relativity is (locally) identical to a frame at rest under gravitation.

Elevator in Space



1: An elevator is in a rocket ship that accelerates with a constant acceleration g relative to the observer. The observer releases a ball from rest and sees it fall to the floor with acceleration g.
2: The rocket motor is switched off and the elevator undergoes uniform motion relative to the inertial observer. The released ball remains at rest relative to the observer.

Elevator on Earth



3: The elevator is on the surface of the earth. Ignoring rotational and orbital motions, the released ball falls to the floor with acceleration g.
4: The elevator falls freely in an evacuated elevator shaft towards the center of the earth. The released ball remains at rest relative to the observer.

Classical Tests

- Deflection of light - when light passes near a large mass its path is slightly bent. (1919 observed on an island near Brazil and near the westcoast of Africa.)
- Perihelion shift of Mercury (Ellipse axis shifts 43 seconds of an arc/century)
- Gravitational redshift - clocks in a gravitational field observed from a distance tick slower. (1960s- Pound-Rebka-Snider experiment)


LIGHTS ALL ASKEW IN THE HEAVENS

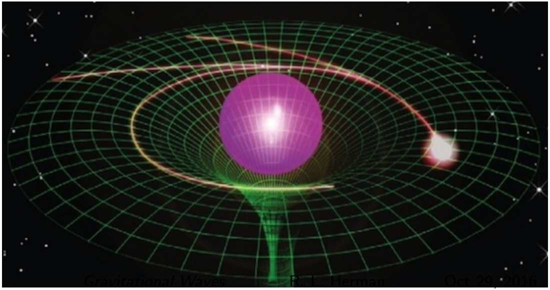
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

Karl Schwarzschild (1873-1916)

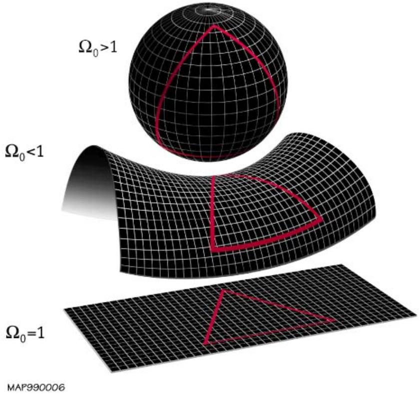
- Spherically symmetric solution.
- Communicated to Einstein before early death.
- Schwarzshild radius - point of no return.
- Later - black hole solutions.
- Roy Kerr (1963) - rotating black holes



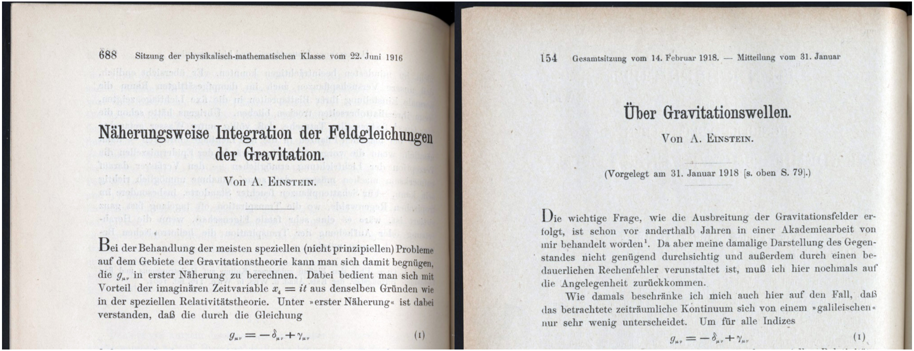
GR Applied to Cosmology - 1920s

- Einstein Applied GR to Cosmology (1917).
- Alexander Friedmann (1888-1925).
- Georges Lemaitre (1894-1966) Expanding universe.
- Hubble - Expanding universe data.
- Einstein's greatest blunder.

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}.$$



Einstein Predicts Gravitational Waves - 1916, 1918



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

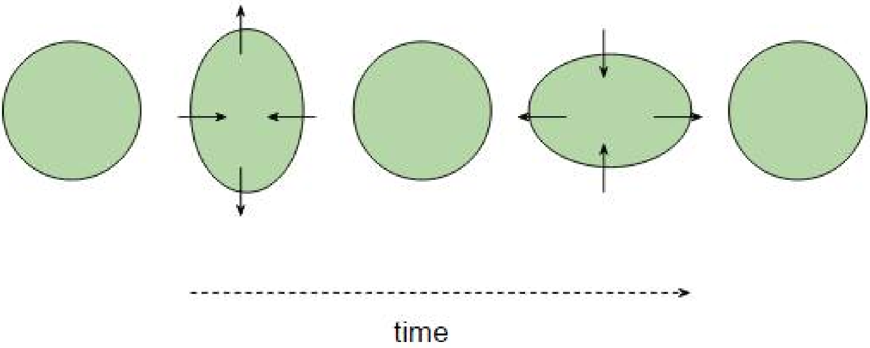
Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

1917 - Ripples in spacetime due to accelerating masses (like EM waves from antennae) or collisions.

Varied his opinion as to existence and ability to detect GWs.

Gravitational Waves



Waves stretch spacetime in one direction and compress in other direction.

Gravitational Wave Sources

Gravity is Weak and needs strong sources:

- Nonspherical Supernovae.
- Nonspherical Spinning stars.
- Binary Systems (Taylor-Hulse binary pulsar).
- Stellar Collapse - Oppenheimer and Snyder 1939.

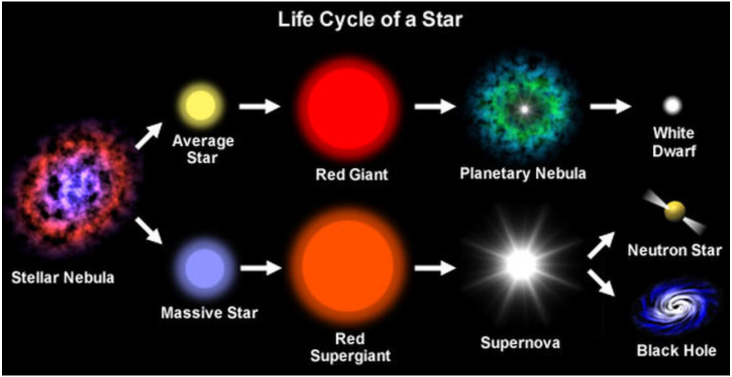


Figure: Binary Pulsar

Joseph Weber (1919-2000)

To detect GRS one needs a detector and right frequency range.
First attempts by Joseph Weber (1960) with mass resonators.

- University of Maryland.
- Announced detection of GWs 1968-9.
- Weber bars: multiple aluminium cylinders, 2 meters in length and 1 meter in diameter, Analogous to antennae for detecting gravitational waves.
- GWs Interact with matter compressing and stretching.
- Never duplicated.

Taylor-Hulse Binary Pulsar PSR B1913+16

Existence of gravitational waves - Joe Taylor and Russel Hulse - 1974.

- Pulsars: pulsating radio star. Rapidly rotating neutron star.
- Magnetic lighthouse.
- Regular flashing
  - 2x each cycle - 17 per second.
- Regular variations - 7.75 hrs and 3s differences due to elliptical orbit.
- 305 m Arecibo Radio Telescope in Puerto Rico.

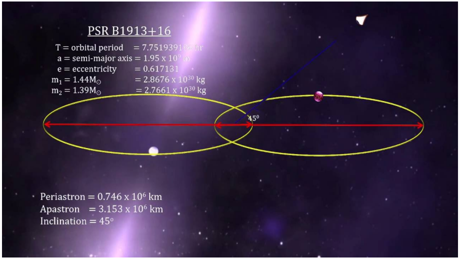


Figure: Binary Pulsar

Binary Pulsar PSR B1913+16 and General Relativity

- Tested Einstein's Prediction of radiation loss as gravitational waves.
- Calculated masses, periastron (closest distance), and apastron (furthest distance).
- Energy Loss: $\frac{dE}{dt} = 7.35 \times 10^{24}\text{W}$.
- Orbital period change: $\frac{dT}{dt} = 7.65$ milliseconds/yr.
- First indirect observation of gravitational waves.

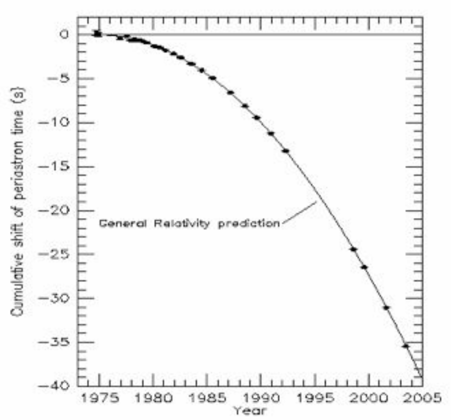


Figure: Binary Pulsar

Co-founders of LIGO

- Rainer Weiss (1932)
  - MIT, Experimentalist.
  - invented the interferometric gravitational wave detector (1972).
- Ronald Drever (1931)
  - Glasgow, Experimentalist.
  - recycle of laser light to increase optical path length.
- Kip Thorne (1940)
  - Caltech, Theoretical Physics.
  - *Gravitation*, Misner, Thorne, Wheeler.
  - Wormholes
  - *Contact* (Sagan), *Interstellar*.

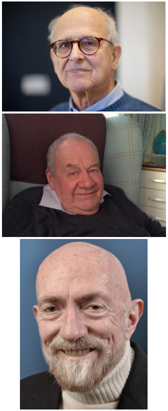


Figure: Weiss, Drever, Thorne

The Interferometer

Laser beam splits into two beams in each arm.
Beams recombine resulting in interference patterns.

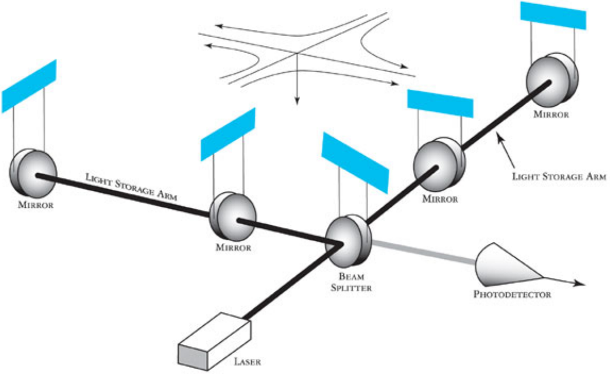


Figure: Interferometer - Interference of laser beams to detect small distortions.

LIGO Locations

- Laser Interferometer Gravitational-Wave Observatory (LIGO) located in Livingston, Louisiana, and Hanford, Washington, USA.
- Funded by the National Science Foundation (NSF) and others.
- Conceived, built, and operated by Caltech and MIT.
- 1,000+ scientists from universities in United States and 14 other countries; 90+ universities and research institutes; $\approx$ 250 students.

Figure: Hanford, WA site.

Figure: Livingston, LA site.

LIGO Locations

- Arms 4 km long ($\approx$ 2.5 miles) 1.2 m diameter tube - sensistivity.
- Far apart - eliminates background events.
- Largest sustained ultra-high vacuum (8x the vacuum of space)
- 300,000 cubic feet (about 8,500 cubic meters) at one-trillionth the pressure of Earths atmosphere.
- International detectors include VIRGO in Italy, GEO in Germany and TAMA in Japan.

Figure: Hanford, WA site.

Figure: Livingston, LA site.

Physics Event 1 Announced: GW150914

11 February, LIGO announced its 1st detection of gravitational waves.

- September 14, 2015 at 5:51 a.m. Eastern Daylight Time
  - 1st detection gravitational waves
  - 1st confirmation binary black holes exist
  - Livingston 7 milliseconds later Hanford
- Displacement $4 - 5 \times 10^{-18}$ m
  - 4000-5000 times smaller than a proton!

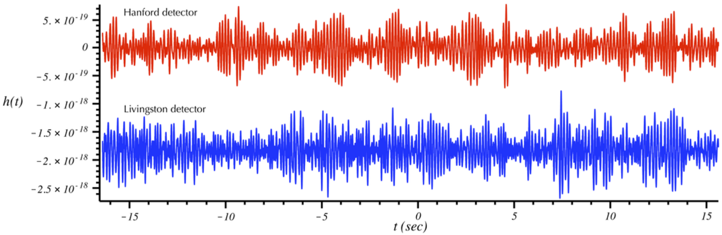


Figure: Signals from Livingston and Hanford.

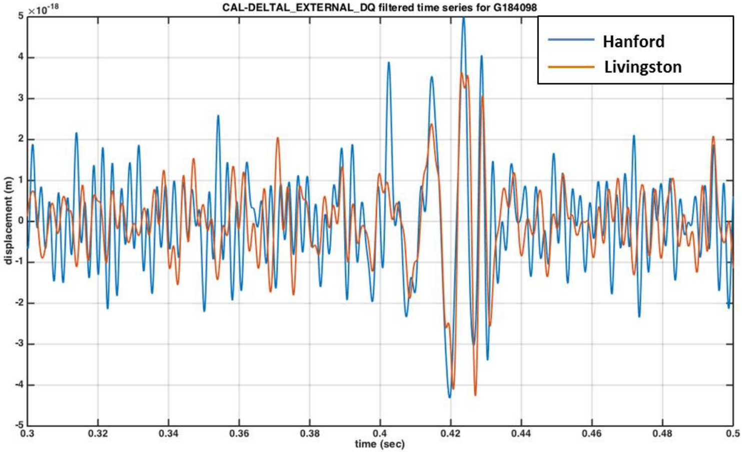
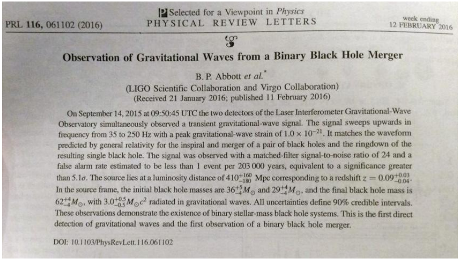


Figure: Time series.

Analyzing Data and Reporting Results

- 5 months of silence!
- Compared signal to templates.
- 1 out of 200,000 templates.
- 1st est: 20-40 solar masses.
- 2nd round narrowing of masses.
- 3rd round - Numerical relativity using parameter estimates.
- Now the evidence was in.
- Paper Nov-Jan 21 sent for peer review.
- Press conference, Feb 11, 2016, 10:30 A.M. EST.



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

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.

DOI: 10.1103/PhysRevLett.116.061102

Figure: First publication Feb. 11.

First Sounds of Black Hole Merger

Analysis of signal - removing background noise and locating signs of event.

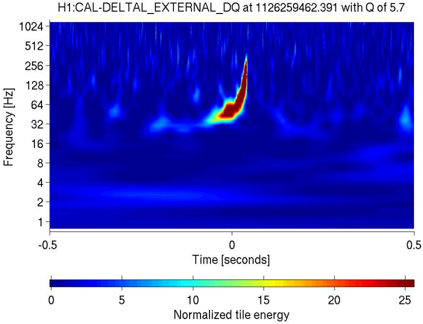


Figure: Hanford chirp.

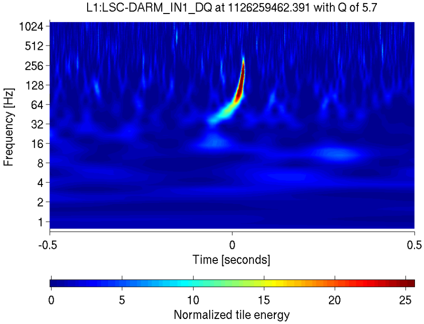


Figure: Livingston chirp.

Chirp - the frequency increases or decreases with time. Sign of binary system merger.

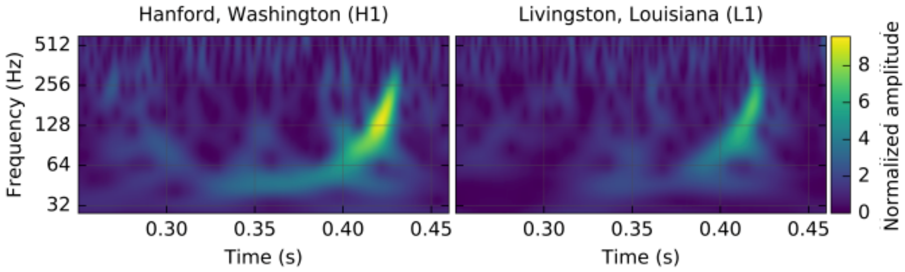


Figure: Chirps.

Listen: `https://www.ligo.caltech.edu/video/ligo20160211v2`

Numerical Relativity Template

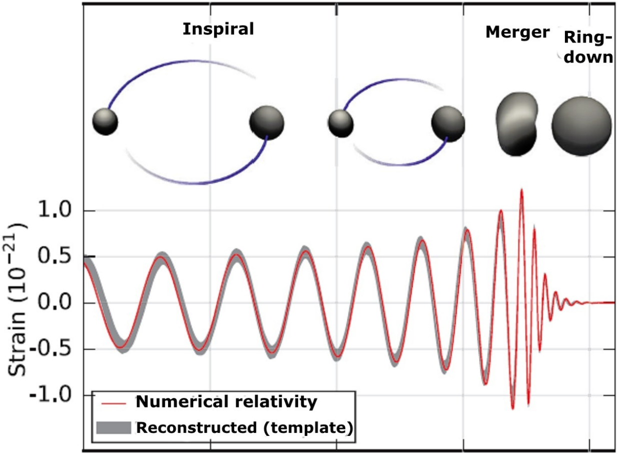
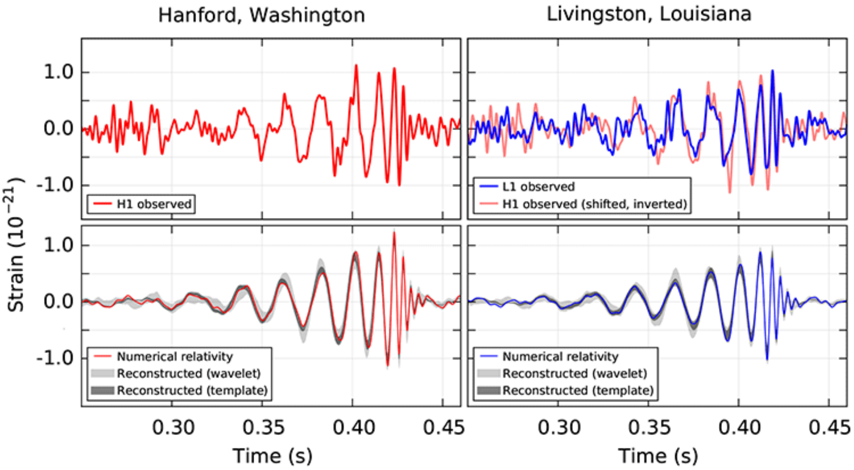


Figure: Black hole inspiral.

Numerical Relativity Template Comparison



Determining the Black Hole Masses

- Merger of 29 and 36 solar mass objects.
- Detected over 2-hundreths of second.
- Over 0.2s frequency changed from 35 to 350 Hz over 8 cycles.
- Schwarzschild radii $\geq$ 210 km and 350 km apart.
- 1.3 billion years ago.
- Frequency of signal indicated black holes.

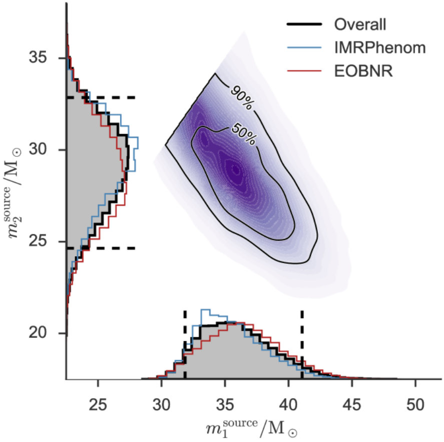


Figure: Final mass.

Final Black Hole

- The final object was a 62 solar mass black hole.
- Mass difference (29+36=65) radiated as gravitational waves.
- Confirm's Einstein's Prediction from his quadrapole formula.

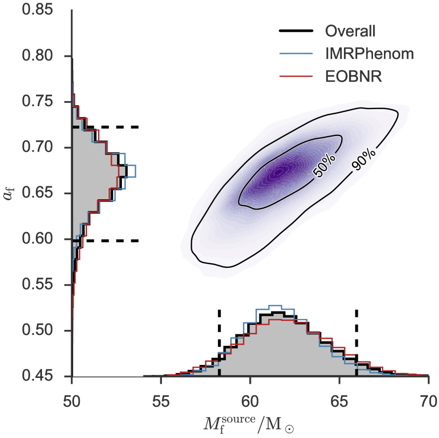


Figure: Final mass.

Physics Event 2 Announced: GW151226

15 June, LIGO made a 2nd announcement of a gravitational-wave detection.

- December 26, 2015 at 03:38:53 UTC.
- Merger of black holes 14, 8 solar masses, yielding 21 solar mass BH.
- Spent more time (1 s).
- 1.4 billion yrs ago.
- Wave energy from 1 solar mass difference.
- Livingston 1.1 milliseconds before Hanford.

Summary

- Einstein's prediction of gravitational waves in 1916 confirmed.
- Verification that black holes exist.
- Marks the beginning of the new field of gravitational-wave astronomy.
- New observation tool vs optical, radio waves, x-rays.
- Video Summary: `https://www.youtube.com/watch?v=RzZgFKoIfQI`

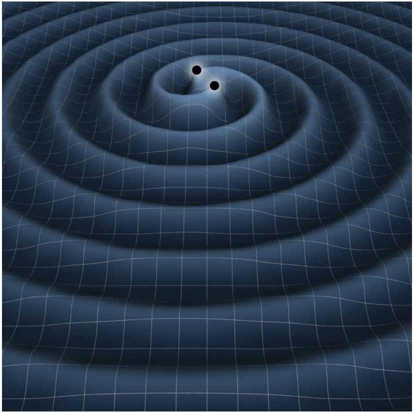


Figure: Black hole merger.

Further Reading

- *Black Hole Blues* - Janna Levin - Book (April 2016) on the story of gravitational wave detection
- *The Science of Interstellar* - Kip Thorne (The science behind the movie).
- *A Perfect Theory* - Pedro Ferreira (History of General Relativity).
- *Black Hole* - Marcia Bartusiak.
- *Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time* - Marcia Bartusiak.
- *Black Holes and Time Warps: Einstein's Outrageous Legacy* - Kip Thorne.

Thank you! - hermanr@uncw.edu