Discovering gravitational waves with LIGO

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Motivation

- Direct confirmation of the existence of black holes, including a test of the fundamental no-hair theorem.
- Tests of general relativity under extreme strong-field conditions.
- Measurement of the propagation speed of the graviton.
- Detailed information on the properties of neutron stars, including the equation of state.
- Insights into the earliest stages of the evolution of the universe through the measurement of primordial gravitational waves.
- Studies of galactic merging through the observation of coalescing massive black holes at their centers.

[Camp & Cornish (2004), Annu. Rev. Nucl. Part. Sci. **54**, 525]

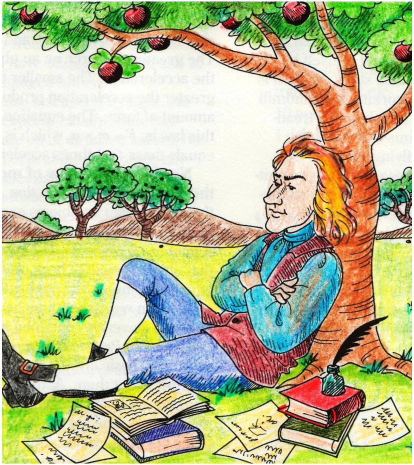
Motivation

- Gravitational waves are produced in those regions of the universe where gravitational field is strong and changing fast.
- Electromagnetic (EM) waves are produced by incoherent superposition of emission from the acceleration of individual electric charges.
- Gravitational waves are produced by coherent, bulk motions of matter so carries different information than EM.
- EM waves are strongly scattered and attenuated by intervening matter.
- Gravitational waves interact only weakly with matter so are able to penetrate the very densely concentrated matter that produces them.

Historical Background

Galileo (1564-1642) knew that the time taken by objects to fall from a given height does not depend on their physical or chemical properties.

Historical Background



400 Years back Newton (1642-1726) knew that gravity makes an apple to fall on the ground and Moon to move around the Earth.

Historical Background

In 1905 when Albert Einstein (1889-1955) was around 25 years old gave a revolutionary theory of space and time called Special Theory of Relativity of Special Relativity.

Special Theory of Relativity (STR)

Consequences

- Nothing can move faster than the speed of light ($c = 3 \times 10^8$ mt/sec).

$$V_{12} = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}. \quad (1)$$

- Mass and energy can be converted into one another.

$$E = mc^2. \quad (2)$$

Conflicts

- There is conflict between Newton's and Einstein's ideas:

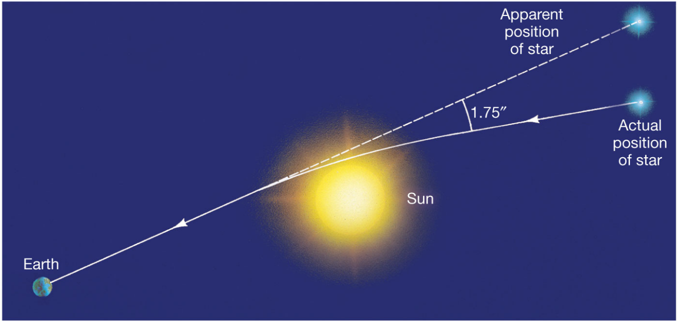
	Newton	Einstein
Speed of gravity	infinite	at the most c
If sun disappears then we will know	immediately	at least after 8 mi

- STR was valid only for objects which move with a constant speed so Einstein was looking for a theory which will work for accelerated objects (including that due to gravity) also.
[Norton, Rep. Prog. Phys. **56** (1993) 791458]

General Theory of Relativity (GTR)

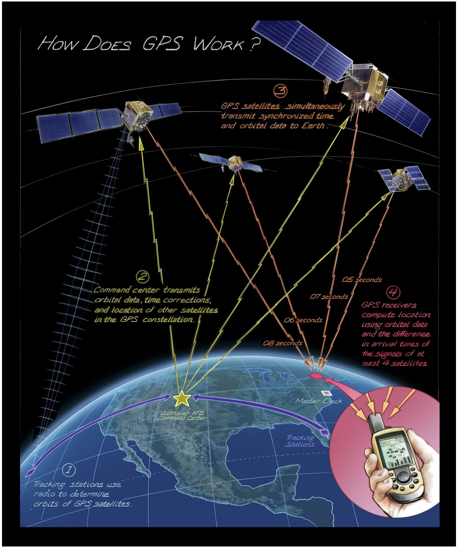
- Every object moves in the same way under gravity.
- Gravity can be associated with the geometry of space time.
- Light bends when passes through a heavy object (bending of star light by sun).
- Clocks get slowed down when moved into stronger gravitational field (GPS).

Bending of starlight due to gravity



In 1919 Eddington measured the deflection of starlight by Sun and that matched exactly the prediction of GR (which was double what one would have got using Newton's theory of gravity).

Global Positioning System (GPS)



Corrections due to GTR must be taken care of (due to change in gravity here on earth and in space) if we want accurate GPS.

General Theory of Relativity (GTR)

- Einstein's equation of GTR relates geometrical quantities with the physical quantities.

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{3}$$

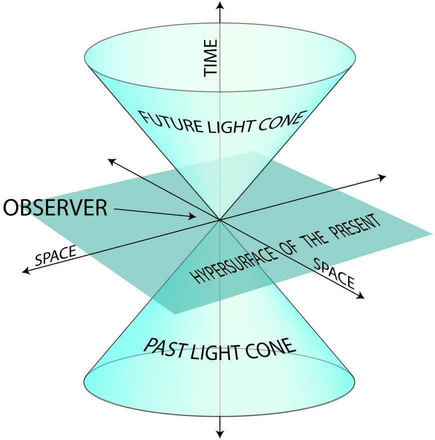
- Where the energy momentum tensor $T_{\mu\nu}$ is related to the mass/energy and Einstein tensor $G_{\mu\nu}$ commonly expressed in terms of the metric of space-time.

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu, \quad \text{where} \quad \mu, \nu = t, x, y, z. \tag{4}$$

- The invariant "distance" between two "events" x^μ and $x^\mu + dx^\mu$ when there is no gravity (Minkowski space-time) is given by:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu = c^2 dt^2 - dx^2 - dy^2 - dz^2. \tag{5}$$

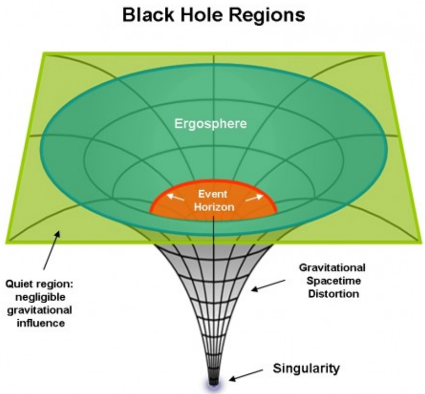
Spacetime


TIME
FUTURE LIGHT CONE
OBSERVER
SPACE
HYPERSURFACE OF THE PRESENT
SPACE
PAST LIGHT CONE

Consequences of GTR

- GTR predicts that when the size (radius) R of an object become smaller than GM/c^2, where M is the mass of the object then that object become a black holes.
- Nothing can come out of black hole since that will require a velocity greater than c.
- In other words for black holes escape velocity is too large for anything to escape.

Black Holes

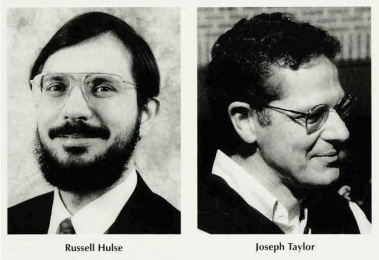


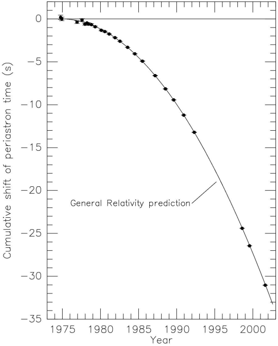
Black holes were predicted by Subrahmanyan Chandrasekhar (1910-1995) and for which he had some arguments with famous British physicist Sir Arthur Eddington. Chandrasekhar was awarded 1983 Nobel Prize for Physics.

Gravitational Waves

- Gravitational waves are ripples in space time created by events involving coherent motion of a large chunk of dense matter.
- Gravitational waves carry energy so any object which radiate gravitational waves must lose energy and this case be used for indirect detection of gravitational waves [Hulse-Taylor Binary system].
- When a star explodes (supernova) or a dense neutron star with a mound spins or two heavy objects (neutron stars, black holes) orbit each other gravitational waves are radiated.
- Gravitational waves are produced specific type of motion, rotating dumble, binary objects.

Hulse-Taylor system





Orbiting neutron stars or black holes lose energy in gravitational waves and as result of that their orbits and orbital periods change. In 1974 two astronomers Joseph Taylor (1941-) and Russel Hulse (1950-) observed a pair of neutron stars and confirmed this for which they were awarded Nobel Prize of Physics in 1993.

Gravitational Waves

- Gravitational waves can be quantified by the deformation in the geometrical structure they cause:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = (\eta_{\mu\nu} + h_{\mu\nu}) dx^\mu dx^\nu . \tag{6}$$

Here $h_{\mu\nu}$ is a second rank symmetric tensor with ten components (out of which can get rid of four using Lorentz Gauze $\partial^\mu h_{\mu\nu} = 0$).

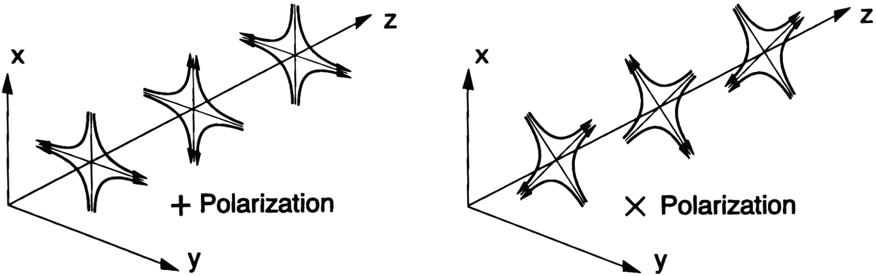
- A plane wave propagating along z-direction is given by (amplitude) :

$$h_{\mu\nu} = \begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & -h_\times & h_+ & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix} .$$

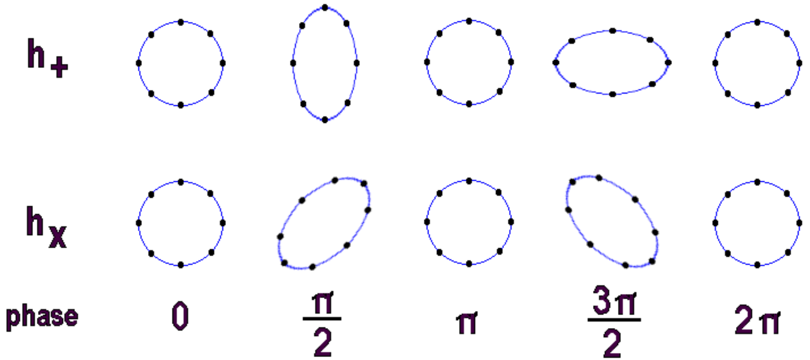
- Gravitational waves follow the following wave equation:

$$\left(\frac{\partial^2}{\partial c^2 dt^2} - \nabla^2 \right) \bar{h}_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} , \quad \text{with} \quad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2} h \eta_{\mu\nu} . \tag{7}$$

Gravitational Waves



Gravitational Waves



LIGO Response

Rep. Prog. Phys. **72** (2009) 076901 B P Abbott *et al*

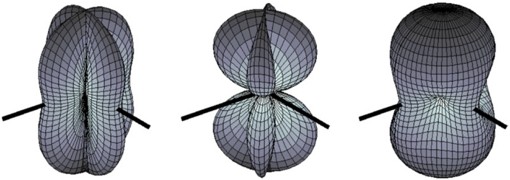


Figure 5. Antenna response pattern for a LIGO GW detector, in the long-wavelength approximation. The interferometer beamsplitter is located at the center of each pattern, and the thick black lines indicate the orientation of the interferometer arms. The distance from a point of the plot surface to the center of the pattern is a measure of the GW sensitivity in this direction. The pattern on the left is for + polarization, the middle pattern is for $\times$ polarization and the right-most one is for unpolarized waves.

The quadruple formula

- Gravitational waves are produced by time varying (mass) quadruple moment:

$$h_{ij} = \frac{2G}{c^4}\frac{\ddot{Q}_{ij}}{r}, \tag{8}$$

where

$$Q_{ij}(t) = \int d^3x\rho(\vec{x},t)\left[x_ix_j - \frac{1}{3}x^2\delta_{ij}\right]. \tag{9}$$

- For a system of mass M size R rotating with frequency f we can write:

$$|\dot{Q}| < (2\pi f)^2 MR^2 \tag{10}$$

and from "Kepler's" law

$$f^2 = \frac{GM}{16\pi R^3} \tag{11}$$

and so we get a rough estimate of h

$$h = 2\left(\frac{GM}{Rc^2}\right)\left(\frac{GM}{rc^2}\right) \tag{12}$$

- The luminosity L and half life period [time required to radiate half of the energy in gravitational waves] is given by:

$$L = \frac{\pi c^5}{G}\left(\frac{GM}{Rc^2}\right)^5 = \left(\frac{GM}{Rc^2}\right)^5 \times 1.15 \times 10^{53} \text{ Watt}, \tag{13}$$

and the time-scale

$$\tau = \frac{(GM/2R)}{L} = \frac{R}{2\pi c}\left(\frac{GM}{Rc^2}\right)^{-3}. \tag{14}$$

- For a binary system

$$h \approx 10^{-21}\left(\frac{15\,\mathrm{Mpc}}{r}\right)\left(\frac{M}{2.8\,M_\odot}\right)^2\left(\frac{90\,\mathrm{km}}{R},\right)$$

$$f = \left(\frac{M}{2.8\,M_\odot}\right)^{1/2}\left(\frac{90\,\mathrm{km}}{R}\right)^{3/2} 100\,\mathrm{Hz},$$

$$\tau_{\mathrm{gw}} = \left(\frac{R}{90\,\mathrm{km}}\right)^4\left(\frac{2.8\,M_\odot}{M}\right)^3 0.5\,\mathrm{s}.$$

(Direct) Detection of Gravitational waves

The first attempt for the direct detection of gravitational waves was done by Joseph Weber (1919-2000) of the University of Maryland of college park in early 1960 with the help of an Aluminum cylinder.

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

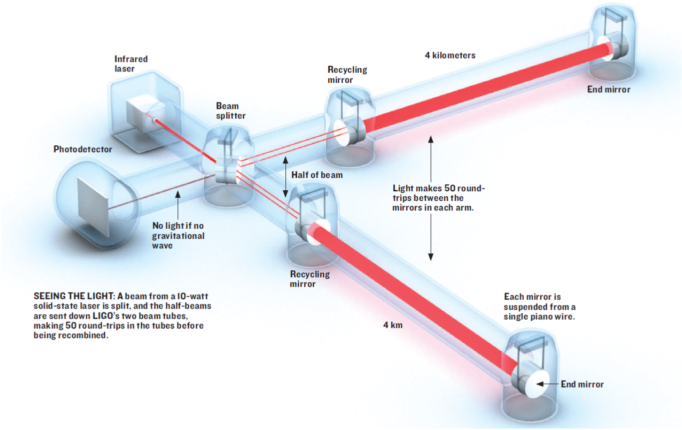
Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

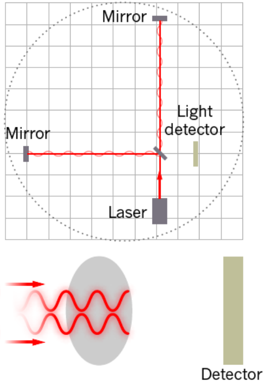
Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

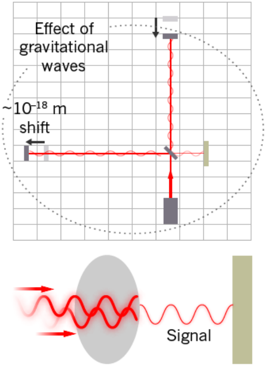
How LIGO works



Normally, the two light beams travel paths of identical lengths, so that they cancel each other out when they recombine at the detector.



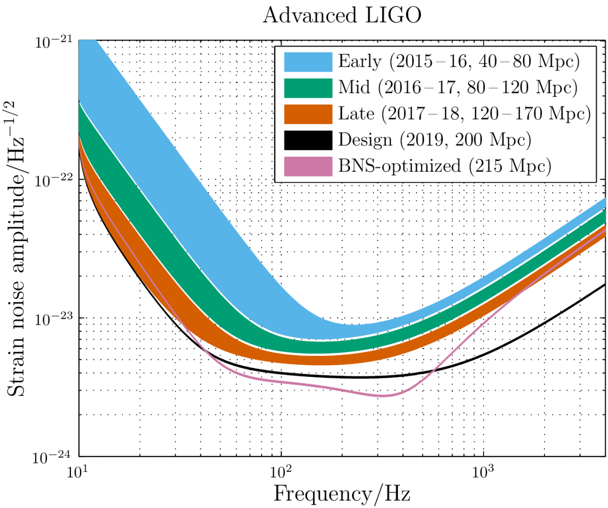
When a gravitational wave passes LIGO, the tunnels deform slightly and the distance travelled by each beam changes so that they no longer cancel out. This produces a measurable signal at the detector.



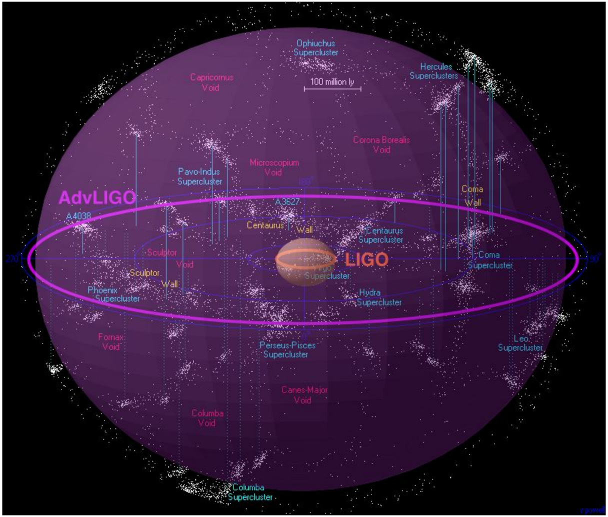
LIGO Hanford

LIGO Livingston

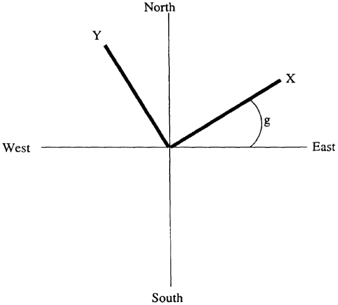
Advanced LIGO sensitivity



Advanced LIGO visibility



LIGO reponse to gravitational waves



The response of a ligo detecor is characterized by the detecor tesnor d_{ij} which can be written in terms of the arms X and Y of the LIGO:

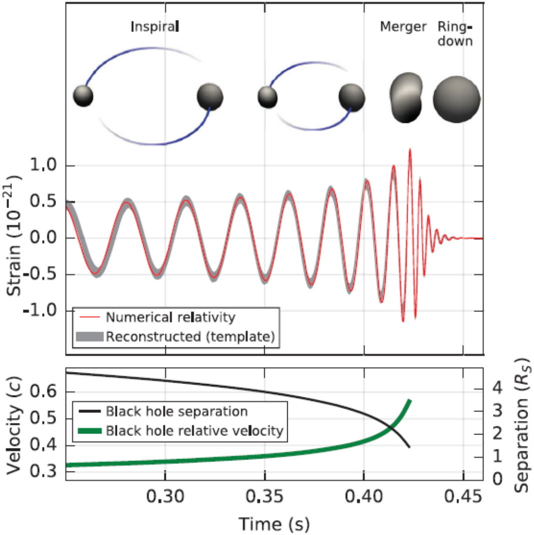
$$d_{ij} = \frac{1}{2}(X_i X_j - Y_i Y_j). \tag{15}$$

Although the input to a LIGO detector is tensor quantity h_{ab} but the output is a scalar quantity $h(t) = h_{ab}(t) d^{ab}$ i.e., the time series.
[John T. Whelan, LIGO-DCC T1100431]

LIGO : A timeline

1970s	Early work on gravitational-wave detection by laser interferometers, including a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources
1979	**National Science Foundation (NSF) funds Caltech and MIT for the laser interferometer research and development**
1983	MIT and Caltech jointly present results of the kilometer-scale interferometer study to NSF. Receive NSV committee endorsement on new large programs in physics
1984	LIGO founded as a Caltech/MIT project. National Science Board approves LIGO development plan.
1986	Physics Decadal Survey and special NSF panel on gravitational wave interferometers endorse LIGO
1990	**National Science Board** (NSB) approves LIGO construction proposal, which envisions initial interferometers followed by advanced interferometers
1992	NSF selects LIGO sites in Hanford, Washington, and Livingston, Louisiana. **LIGO Cooperative Agreement signed by NSF and Caltech**
1994-95	Site construction gegins at Hanford and Livingston locations
1997	The LIGO Scientific Collaboration (LSC) is established and expands LIGO beyond Caltech and MIT, including the British/German GWO Collaboration, which operates the GEO600 interferometer in Hannover, Germany.
1999	**LIGO inauguration ceremony**
2002	First coincident operation of initial LIGO interferometers plus the **GEO600** interferometer
2004	**NSB approves Advanced LIGO**
2006	**LIGO design sensitivity achieved.** First gravitational wave search at design sensitivity. **Science Education Center** inaugurated at the LIGO Livingston Observatory.
2007	Joint data analysis agreement ratified between LIGO and the **Virgo Collaboration,** which operates the Virgo interferometer in Cascina, Italy. Joint observations with enhanced initial LIGO interferometer and Virgo.
2008	**Construction of Advanced LIGO components begins**
2010	**Initial LIGO operations conclude; Advanced LIGO installation begins**
2011 - 2014	Advanced LIGO installation and testing
2014	**Advanced LIGO installation complete**
2014-2015	Advanced LIGO sensitivity surpasses Initial LIGO
September 14, 2015	***During an engineering test a few days before the first official search begins, Advanced LIGO detects strong gravitational waves from collision of two black holes.***
2016	**January: First observing run of LIGO advanced detectors ends**

Compact Binary Coalescence (CBC)



The discovery paper !

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)

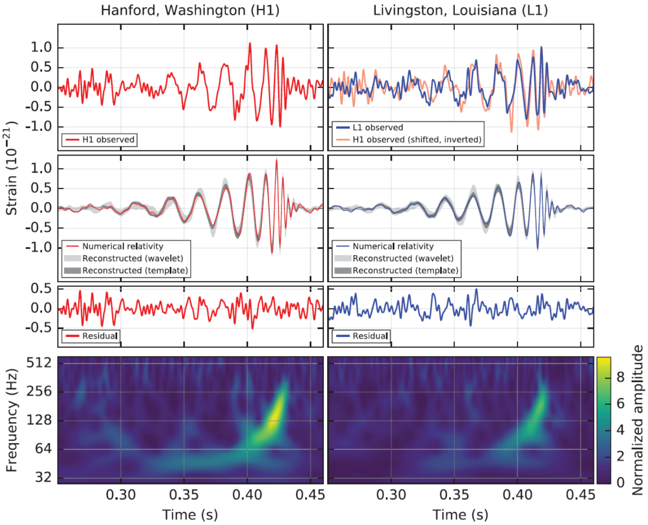
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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

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

J. Powell,[36] J. Prasad,[14] V. Predoi,[91] S. S. Premachandra,[114] T. Prestegard,[84] L. R. Price,[1] M. Prijatelj,[34] M. Principe,[87] S. Privitera,[29] R. Prix,[8] G. A. Prodi,[89,90] L. Prokhorov,[49] O. Puncken,[8] M. Punturo,[33] P. Puppo,[28] M. Pürrer,[29] H. Qi,[16] J. Qin,[51] V. Quetschke,[83] E. A. Quintero,[1] R. Quitzow-James,[59] F. J. Raab,[37] D. S. Rabeling,[20] H. Radkins,[37] P. Raffai,[54] S. Raja,[48] M. Rakhmanov,[83] C. R. Ramet,[6] P. Rapagnani,[79,28] V. Raymond,[29] M. Razzano,[18,19] V. Re,[25] J. Read,[22] C. M. Reed,[37] T. Regimbau,[53] L. Rei,[47] S. Reid,[50] D. H. Reitze,[1,5] H. Rew,[120] S. D. Reyes,[35] F. Ricci,[79,28] K. Riles,[98] N. A. Robertson,[1,36] R. Robie,[36] F. Robinet,[23] A. Rocchi,[13] L. Rolland,[7] J. G. Rollins,[1] V. J. Roma,[59] J. D. Romano,[83] R. Romano,[3,4] G. Romanov,[120] J. H. Romie,[6] D. Rosińska,[127,43] S. Rowan,[36] A. Rüdiger,[8] P. Ruggi,[34] K. Ryan,[37] S. Sachdev,[1] T. Sadecki,[37] L. Sadeghian,[16] L. Salconi,[34] M. Saleem,[108] F. Salemi,[8] A. Samajdar,[123] L. Sammut,[85,114] L. M. Sampson,[82] E. J. Sanchez,[1] V. Sandberg,[37] B. Sandeen,[82] G. H. Sanders,[1] J. R. Sanders,[98,35] B. Sassolas,[65] B. S. Sathyaprakash,[91] P. R. Saulson,[35] O. Sauter,[98] R. L. Savage,[37] A. Sawadsky,[17] P. Schale,[59] R. Schilling,[8,b] J. Schmidt,[8] P. Schmidt,[1,76] R. Schnabel,[27] R. M. S. Schofield,[59] A. Schönbeck,[27] E. Schreiber,[8] D. Schuette,[8,17] B. F. Schutz,[91,29] J. Scott,[36] S. M. Scott,[20] D. Sellers,[6] A. S. Sengupta,[94] D. Sentenac,[34] V. Sequino,[25,13] A. Sergeev,[109] G. Serna,[22] Y. Setyawati,[52,9] A. Sevigny,[37] D. A. Shaddock,[20] T. Shaffer,[37] S. Shah,[52,9] M. S. Shahriar,[82] M. Shaltev,[8] Z. Shao,[1] B. Shapiro,[40] P. Shawhan,[62] A. Sheperd,[16] D. H. Shoemaker,[10] D. M. Shoemaker,[63] K. Siellez,[53,63] X. Siemens,[16] D. Sigg,[37] A. D. Silva,[11] D. Simakov,[8] A. Singer,[1] L. P. Singer,[68] A. Singh,[29,8] R. Singh,[2] A. Singhal,[12] A. M. Sintes,[66] B. J. J. Slagmolen,[20] J. R. Smith,[22] M. R. Smith,[1] N. D. Smith,[1] R. J. E. Smith,[1] E. J. Son,[125] B. Sorazu,[36] F. Sorrentino,[47] T. Souradeep,[14] A. K. Srivastava,[95] A. Staley,[39] M. Steinke,[8] J. Steinlechner,[36] S. Steinlechner,[36] D. Steinmeyer,[8,17] B. C. Stephens,[16] S. P. Stevenson,[45] R. Stone,[83] K. A. Strain,[36] N. Straniero,[65] G. Stratta,[57,58] N. A. Strauss,[78] S. Strigin,[49] R. Sturani,[121] A. L. Stuver,[6] T. Z. Summerscales,[128] L. Sun,[85] P. J. Sutton,[91] B. L. Swinkels,[34] M. J. Szczepańczyk,[97] M. Tacca,[30] D. Talukder,[59] D. B. Tanner,[5] M. Tápai,[96] S. P. Tarabrin,[8] A. Taracchini,[29] R. Taylor,[1] T. Theeg,[8]

Results



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
distance	1.3 Gly, 410 Mpc
redshift (z)	0.09
Detector Frame Masses	**M⊙**
total mass	70
chirpmass	30
primary BH	39
secondary BH	31
remnant BH	67
Source Frame Masses (equal to detector frame masses divided by (1+z))	**M⊙**
total mass	65
chirpmass	28
primary BH	36
secondary BH	29
remnant BH	62
mass ratio	0.8
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
spin in orbital plane	?
arrival time delay	

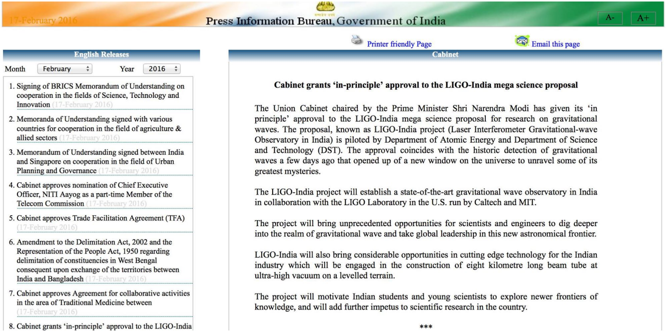
signal-to-noise ratio	24
false alarm prob.	< 2×10^{-7}
false alarm rate	1 in 200,000 yr
coalescence rate	2-400 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fermi
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	3 M⊙, 5% of mass
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^2
consistent with general relativity	Yes
graviton mass bound	< 1.2×10^{-22} eV
online trigger	~ 3 min
# offline analysis pipelines	5

Network of detectors

LIGO is partnering with similar observatories around the world so that any signal can be independently verified, and its source triangulated.

In order to localize a gravitational wave event in the sky we need a network of detectors.

LIGO India



17-February 2016

Press Information Bureau, Government of India

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English Releases

Month February Year 2016

1. Signing of BRICS Memorandum of Understanding on cooperation in the fields of Science, Technology and Innovation (17-February 2016)
2. Memoranda of Understanding signed with various countries for cooperation in the field of agriculture & allied sectors (17-February 2016)
3. Memorandum of Understanding signed between India and Singapore on cooperation in the field of Urban Planning and Governance (17-February 2016)
4. Cabinet approves nomination of Chief Executive Officer, NITI Aayog as a part-time Member of the Telecom Commission (17-February 2016)
5. Cabinet approves Trade Facilitation Agreement (TFA) (17-February 2016)
6. Amendment to the Delimitation Act, 2002 and the Representation of the People Act, 1950 regarding delimitation of constituencies in West Bengal consequent upon exchange of the territories between India and Bangladesh (17-February 2016)
7. Cabinet approves Agreement for collaborative activities in the area of Traditional Medicine between (17-February 2016)
8. Cabinet grants 'in-principle' approval to the LIGO-India

Cabinet

Cabinet grants 'in-principle' approval to the LIGO-India mega science proposal

The Union Cabinet chaired by the Prime Minister Shri Narendra Modi has given its 'in principle' approval to the LIGO-India mega science proposal for research on gravitational waves. The proposal, known as LIGO-India project (Laser Interferometer Gravitational-wave Observatory in India) is piloted by Department of Atomic Energy and Department of Science and Technology (DST). The approval coincides with the historic detection of gravitational waves a few days ago that opened up of a new window on the universe to unravel some of its greatest mysteries.

The LIGO-India project will establish a state-of-the-art gravitational wave observatory in India in collaboration with the LIGO Laboratory in the U.S. run by Caltech and MIT.

The project will bring unprecedented opportunities for scientists and engineers to dig deeper into the realm of gravitational wave and take global leadership in this new astronomical frontier.

LIGO-India will also bring considerable opportunities in cutting edge technology for the Indian industry which will be engaged in the construction of eight kilometre long beam tube at ultra-high vacuum on a levelled terrain.

The project will motivate Indian students and young scientists to explore newer frontiers of knowledge, and will add further impetus to scientific research in the country.

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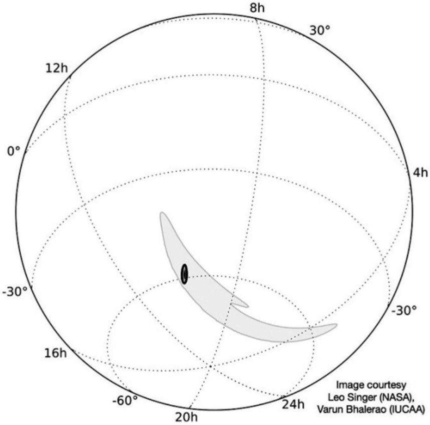
Govt. of India has given "in principle" approval of the LIGO India.

LIGO India



LIGO India will improve localization.

LIGO data centre at IUCAA

Thank You

My LIGO Hanford Visit

With LIGO Hanford director Dr. Fred Raab and Prof. Sukanta Bose.

Team India !

Some of the members from India who are part of LSC.