Discovering gravitational waves with LIGO

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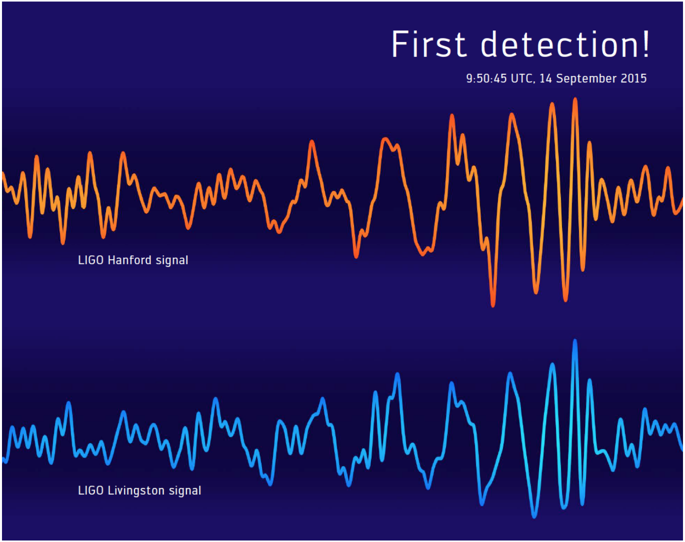
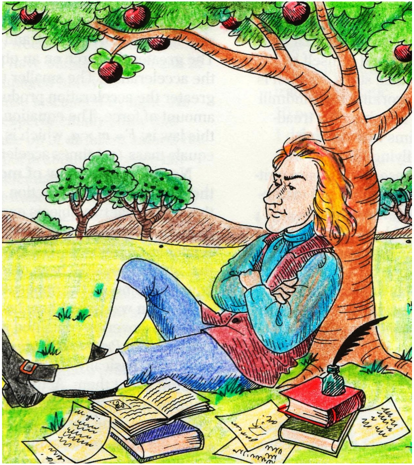
Some predictions need 100 years to get confirmed !



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

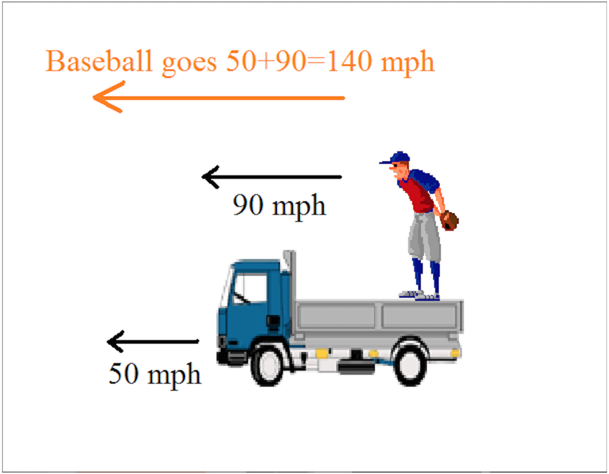


400 Years back Newton (1642-1726) knew that gravity makes an apple to fall on the ground and Moon to move around the Earth.

Historical Background

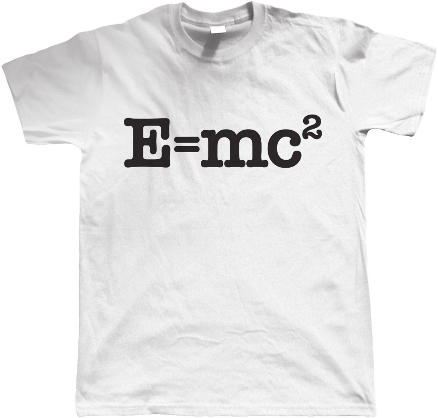
In 1905 when Albert Einstein (1889-1955) was around 25 years old gave a revolutionary theory of space and time called Special Theory of Relativity.

Special Theory of Relativity (STR)



Nothing can move faster than the speed of light.

Special Theory of Relativity (STR)

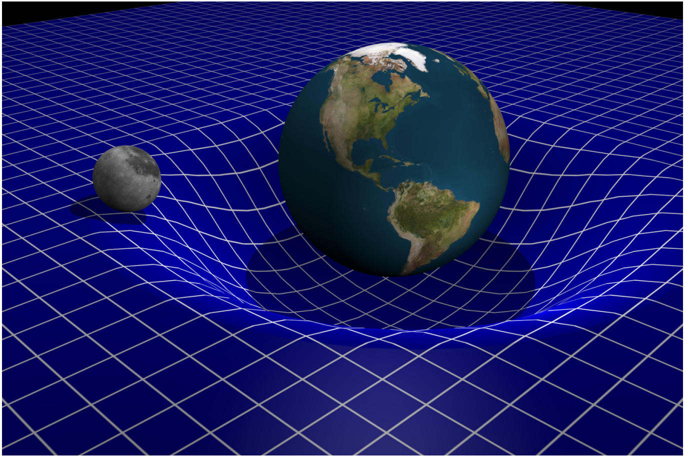


Mass and energy can be converted into each other.

Conflict between Newton's and Einstein's ideas

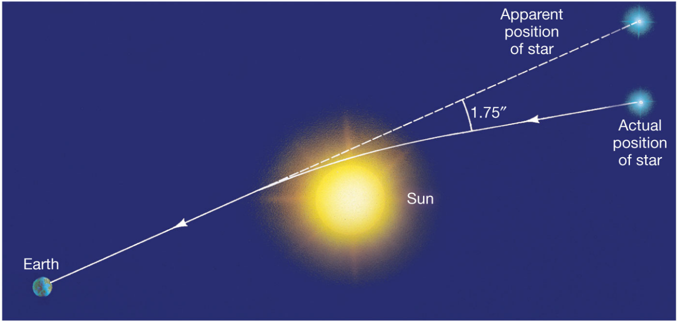
According to Newton if Sun disappears then we here on earth will know that immediately, however, according to Einstein that is not true.

General Theory of Relativity (GTR)



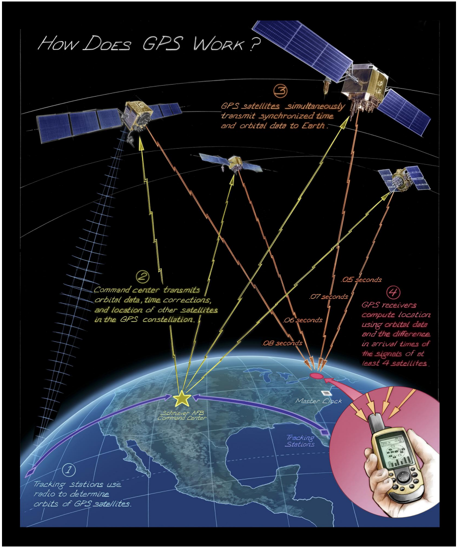
Einstein in 1916 predicted that Gravity can be associated with the curvature of spacetime.

Bending of starlight due to gravity



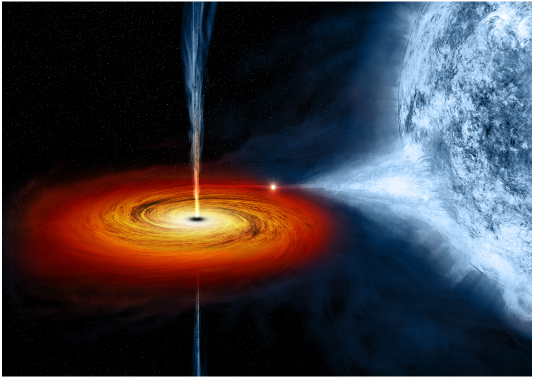
In 1919 Eddington measured the deflection of starlight by Sun and that matched exactly the prediction of GR (which was double what one would have got using Newton's theory of gravity).

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.

Black Holes

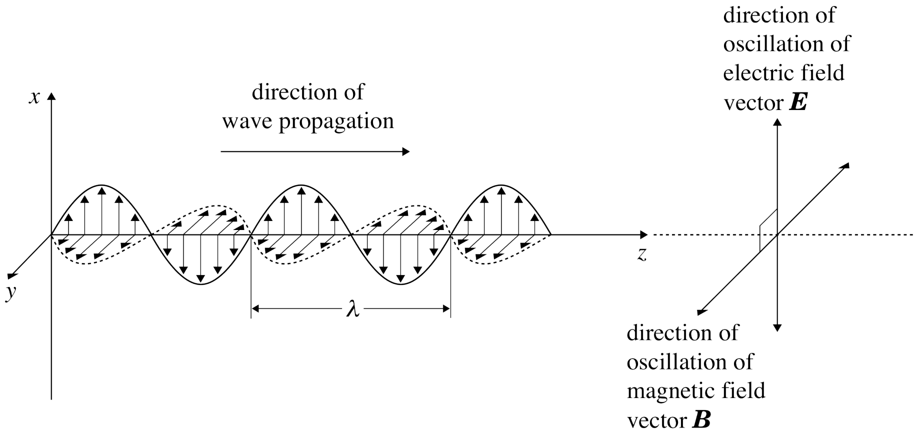


When escape velocity of an object becomes equal to the velocity of light then nothing can leave that object and such objects are called "Black holes".

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.

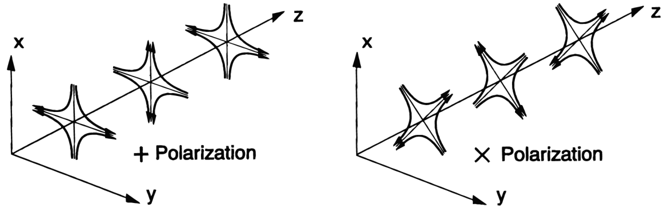
Electromagnetic Waves



A plane polarized EM wave propagating along z-direction is represented by:

$$E(z,t) = E_0 \cos[\omega(t - z/c)]\hat{x} \tag{1}$$

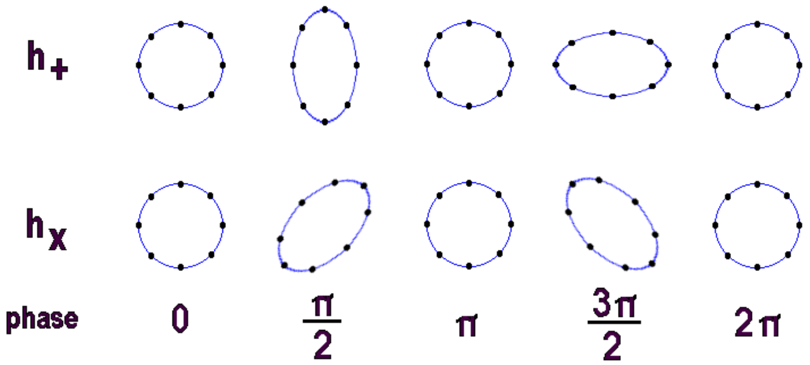
Gravitational Waves



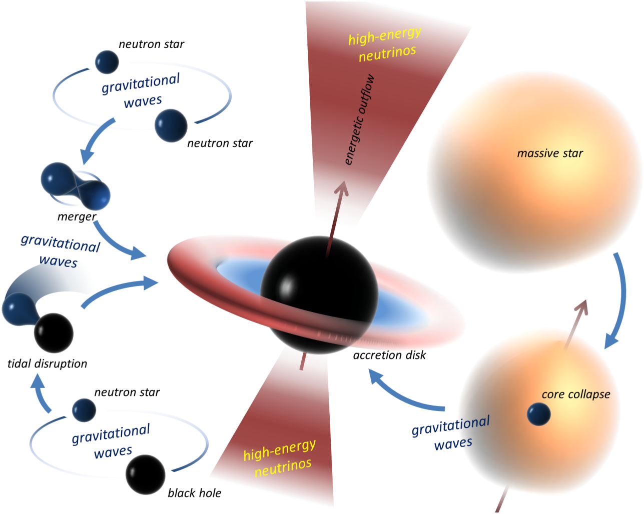
A gravitational wave propagating along z-direction is represented by:

$$h_{ij}(t,z) = \begin{vmatrix} h_+ & h_\times \\ h_\times & -h_+ \end{vmatrix} . \cos[\omega(t - z/c)]. \quad (2)$$

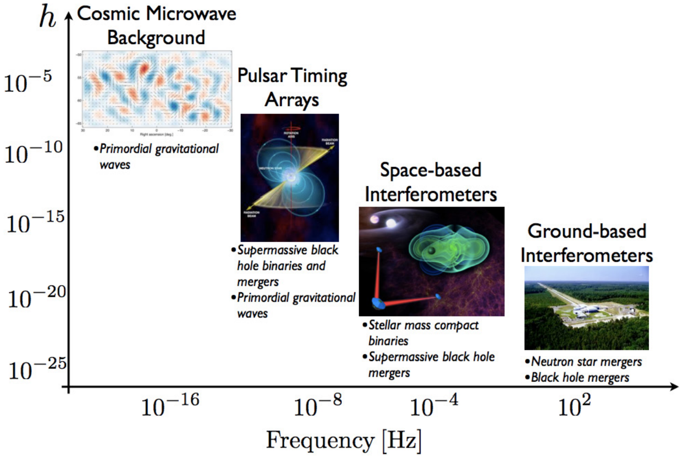
Gravitational Waves



How gravitational waves are generated ?



Gravitational wave spectrum



Generating gravitational waves

- Gravitational waves are generated by time varying quadruple moment:

$$h_{ij} = \frac{2G}{c^4} \frac{\ddot{Q}}{r} \tag{3}$$

- For a system of mass M, size R rotating with frequency f we get:

$$|\ddot{Q}| < (2\pi f)^2 M R^2. \tag{4}$$

- From Kepler's law we know:

$$f^2 = \frac{GM}{16\pi R^3} \tag{5}$$

- From the above equation we get:

$$h = 2\left(\frac{GM}{rc^2}\right)\left(\frac{GM}{Rc^2}\right) \tag{6}$$

- Roughly gravitational wave luminosity is given by:

$$L = \frac{\pi c^5}{G}\left(\frac{GM}{Rc^2}\right) = \left(\frac{GM}{Rc^2}\right) \times 1.1 \times 10^{53}\ \text{Watt} \tag{7}$$

- The time needed for the system to radiate its half of the energy as gravitational waves:

$$\tau = \frac{(GM^2/2R)}{L} = \frac{R}{2\pi c}\left(\frac{GM}{Rc^3}\right)^{-3} = \left(\frac{R}{90\text{km}}\right)^4 \left(\frac{2.8M_\odot}{M}\right)^3 0.5\text{sec.} \tag{8}$$

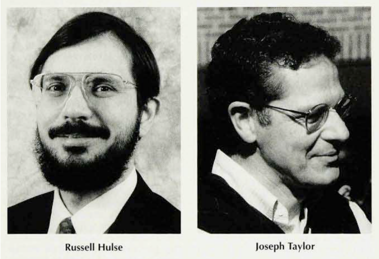
- The frequency of radiation:

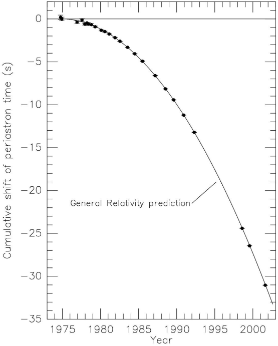
$$f = \left(\frac{M}{2.8M_\odot}\right)^{1/2} \left(\frac{90\text{km}}{R}\right)^{3/2} 100\text{Hz.} \tag{9}$$

- The strain is given by:

$$h = \left(\frac{M}{2.8M_\odot}\right)^2 \left(\frac{90\text{km}}{R}\right) \left(\frac{15\text{Mpc}}{r}\right) 10^{-21}. \tag{10}$$

Hulse-Taylor system



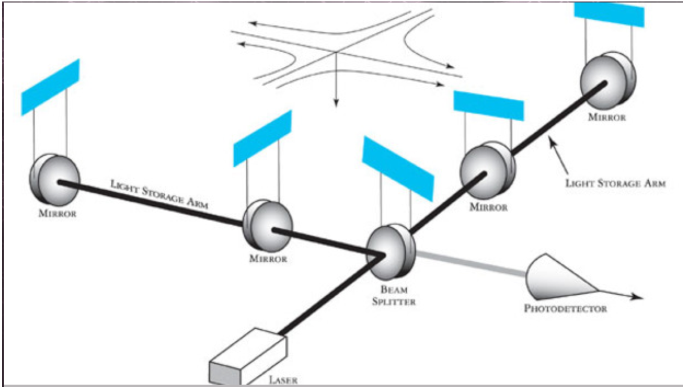


Orbiting neutron stars or black holes lose energy in gravitational waves and as result of that their orbits and orbital periods change. In 1974 two astronomers Joseph Taylor (1941-) and Russel Hulse (1950-) observed a pair of neutron stars and confirmed this for which they were awarded Nobel Prize of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

(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.

Laser Interferometric Gravitational Wave Observatory (LIGO)



Basic schematic of LIGO's interferometers with an incoming gravitational wave depicted as arriving from directly above the detector. (Image: LIGO)

LIGO Hanford

LIGO Livingston

LIGO Subsystem : Suspension

Class. Quantum Grav. **32** (2015) 074001 J Aasi *et al*

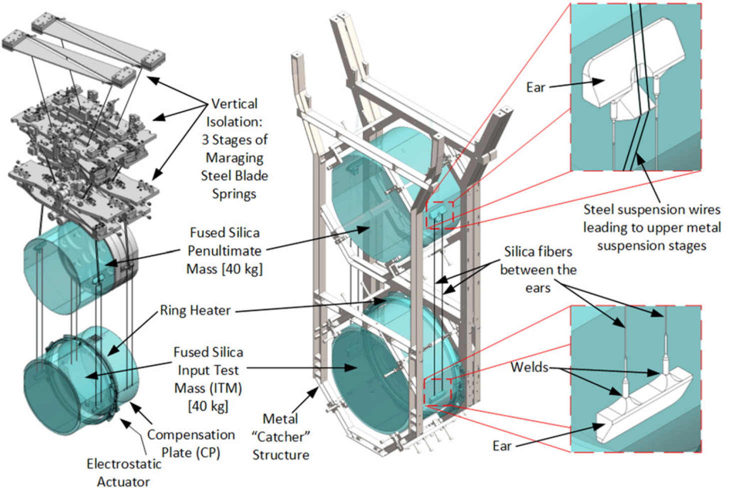
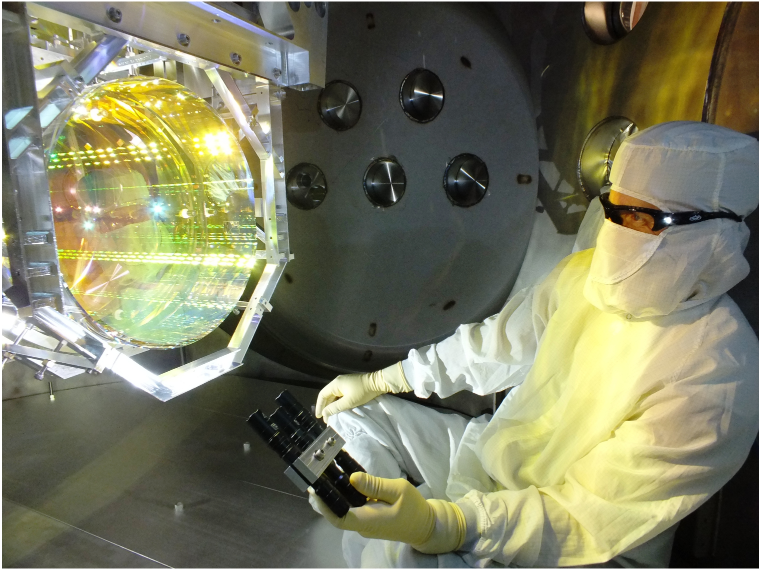
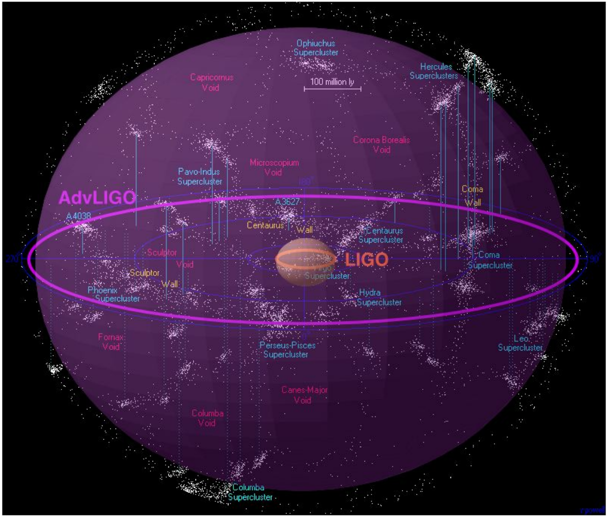


Figure 8. Quadruple pendulum suspension for the Input Test Mass (ITM) optic.

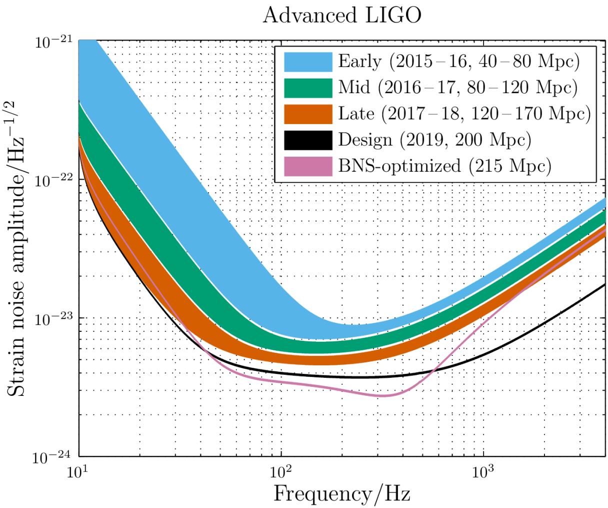
LIGO Subsystem : Optics



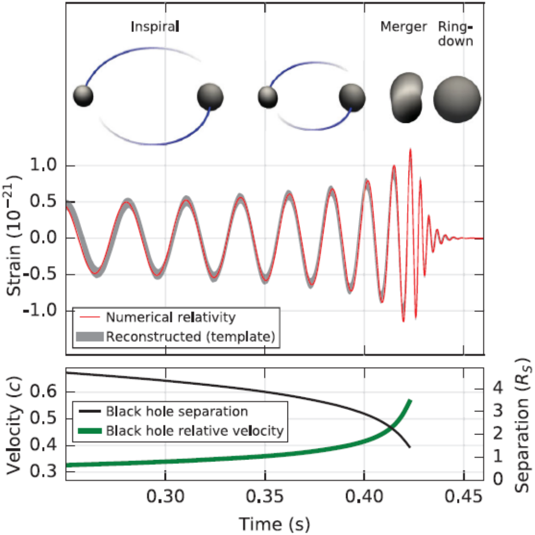
Advanced LIGO visibility



Advanced LIGO sensitivity



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)

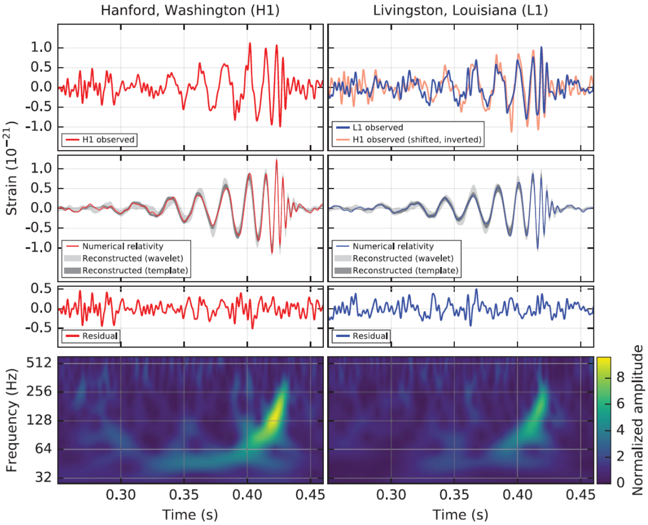
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches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

Information extracted from the signal GW150914

The signal:

Date: 14 September 2015

Time: 09:50:45 UTC

Peak strain: $\sim 10^{-21}$

Peak frequency: ~150 Hz

Arrival time difference between Hanford and Livingston: ~7 ms

Where:

Distance: ~1 billion light years

Redshift: ~0.09

Location on sky resolved to ~600 square degrees (most likely southern hemisphere)

Orientation: face-on/off

The source:

Primary black hole

mass: ~36 solar masses

spin: <0.7

Secondary black hole

mass: ~29 solar masses

spin: <0.9

Gravitational wave energy output equivalent to ~3 solar masses

Final black hole:

mass: ~62 solar masses

spin: ~0.7

Why the discovery of gravitational waves is important ?

- In the last 50 years many other new windows of the universe have been opened i.e., radio, gamma, X-ray, Infra-red etc.
- LIGO has opened another window of the universe in terms of gravitational waves.

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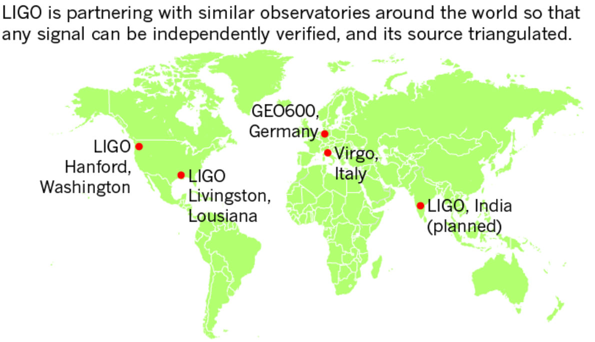
- Gravitational waves hardly interact with the medium through which they pass so we can see far deeper into the space (and so back in time) than any other form of waves.
- The energy released in events, like merging of two black holes, is so huge that they are the second loudest events in the universe after the big bang.

Network of detectors



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.

***

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

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.