Discovering gravitational waves with LIGO

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Feb 28, 2016

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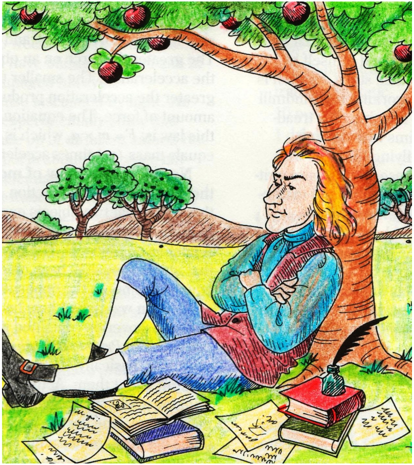
Pune-411007.

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)

There are many consequences of Einstein's special theory of relativity and two which are relevant for the present discussion are as follows:

- No physical object or effect can travel a speed greater than the speed of light (300,000,000 meter/second).
- Mass and energy can be converted into one another.

Conflict between Newton's and Einstein's ideas

- Newton's theory of gravity says that no time is needed by gravitational effects to propagate from one place to another. For example, if Sun stops gravitating Earth then this will known to anyone on Earth with no time.

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- Einstein's STR says that the fastest speed with anything can move is the speed of light so if the Sun stops gravitating Earth then on Earth we will know it only after 8 minutes (time taken by light to travel from the Sun to Earth).

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- Einstein's STR says that the fastest speed with anything can move is the speed of light so if the Sun stops gravitating Earth then on Earth we will know it only after 8 minutes (time taken by light to travel from the Sun to Earth).
- Since 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.

General Theory of Relativity (GTR)

In 1916 (we are calibrating centenary of it this year) Einstein came with a brand new theory of gravity called General Theory of Relativity.

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- Since different objects move in the same way under the influence of gravity so Einstein proposed that it is more useful to associate gravitational effects with geometry of space-time in which the objects move in place of the objects.

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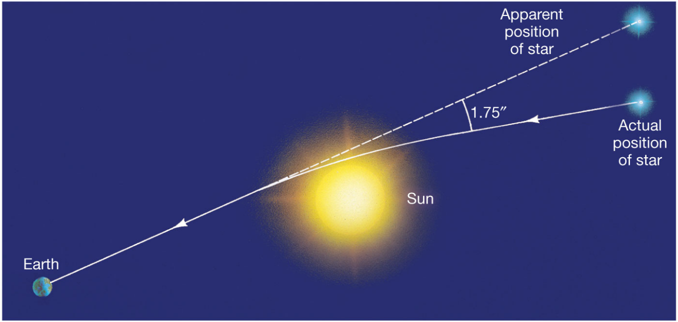
- Since different objects move in the same way under the influence of gravity so Einstein proposed that it is more useful to associate gravitational effects with geometry of space-time in which the objects move in place of the objects.
- GTR predicted that not only the path of mass changes (from a straight line to a curve) that of light ray also changes. In 1919 Eddington, a famous British astronomer observed that the path of a light ray changes by the same amount as was predicted by GR when passes close to the Sun (at the time of complete solar eclipse).

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).

General Theory of Relativity (GTR)

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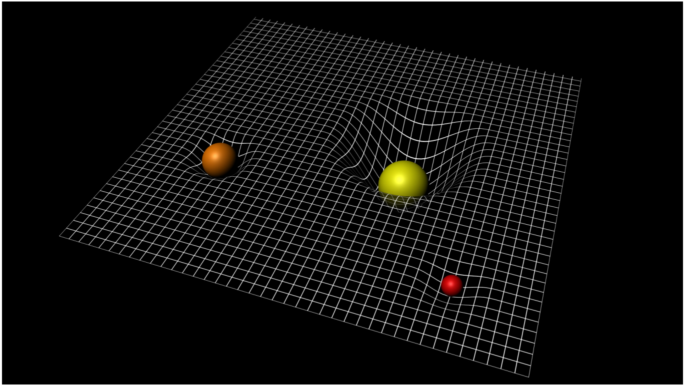
- John Archibald Wheeler (1911- 2008) summarized GTR as "matter tells space how to curve and space tells matter how to move".
- Einstein equation of GTR relates physical quantities with the geometrical quantities

$$G \propto T \quad \text{or} \quad G = kT \quad \text{with} k = \frac{8\pi G}{c^4} \tag{1}$$

- Matter/energy creates a type of "strain" in the fabric of space time due to gravity. In fact gravitational waves are detected by the strain they cause.

Gravity creates "curvature" in space-time



Black Holes

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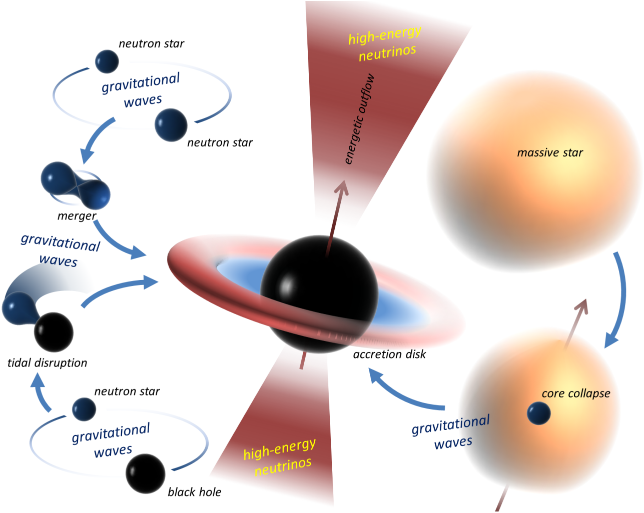
- Escape velocity for any astrophysical object (planets, stars etc.,) depend on its mass and size and increases with increasing the mass and reducing the size of the object.
- When escape velocity of an object becomes equal to the velocity of light then nothing can leave that object and such objects 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.



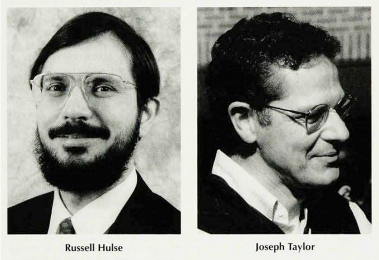
[Courtesy : ligo.org]

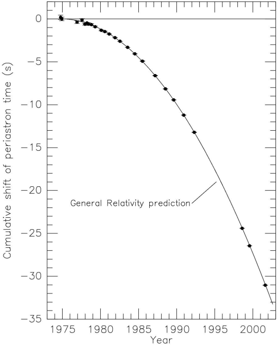
Sources of gravitational waves

Gravitational waves are generated by:

- Dying stars in supernovae explosions.
- Rotation of a dense object that is not quite symmetrical.
- Pairs of black holes or neutron stars orbiting each other.
- Physical process happening in the early universe.

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.

Proposal of LIGO

In late 1960 Rainer Weiss (1932-) of MIT proposed that in place of using a metal bar, laser beams can be used for detecting gravitational waves.

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In late 1960 Rainer Weiss (1932-) of MIT proposed that in place of using a metal bar, laser beams can be used for detecting gravitational waves. The idea was that a beam of laser can be split into two parts which are sent along two tunnels perpendicular to each other. After reflecting from the mirrors, hanging at the end of the tunnels, beam are sent to a photo-detector which measure any difference in the paths of the beams caused by gravitational waves.

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

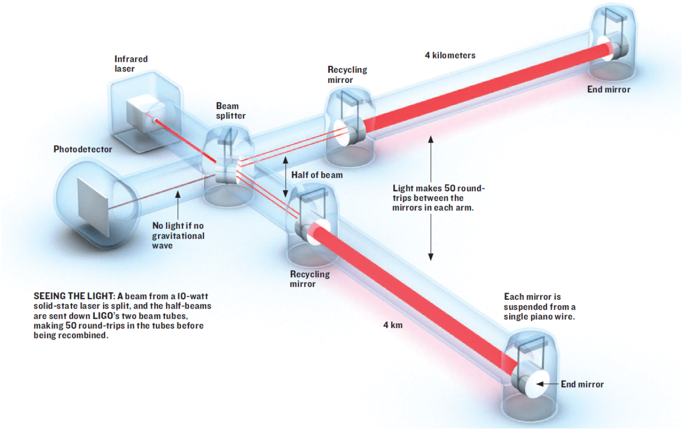
Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

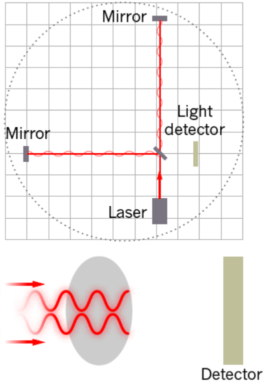
Frederick J. Raab
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

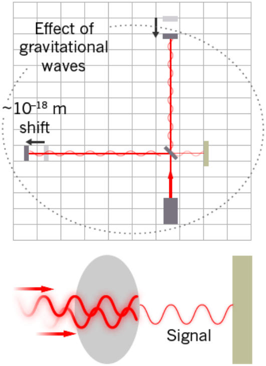
How LIGO works



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 Approved

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- MIT and Caltech were give the responsibility of building and managing LIGO.

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- Barry Barish who was the PI of LIGO in 1994 writes "We said that with initial LIGO, detections would be possible and with Advanced LIGO detections would be probable".
- During the first phase of LIGO from 2002 to 2010 (initial LIGO) Hanford and Livingston saw nothing still NSF was satisfied with the progress and granted 205 million USD for the upgrade into Advanced LIGO.

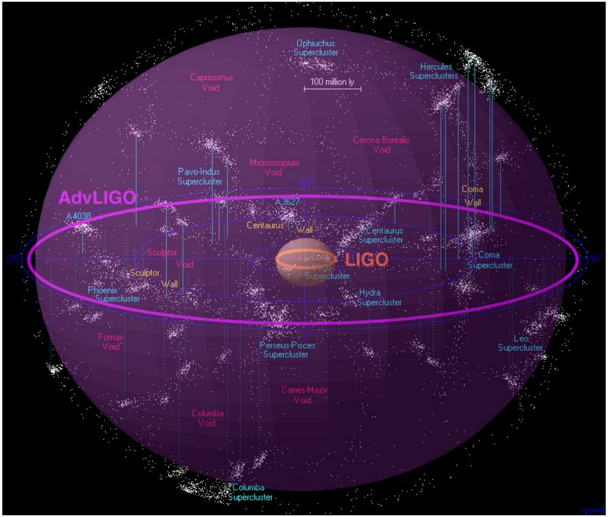
LIGO Hanford

LIGO Livingston

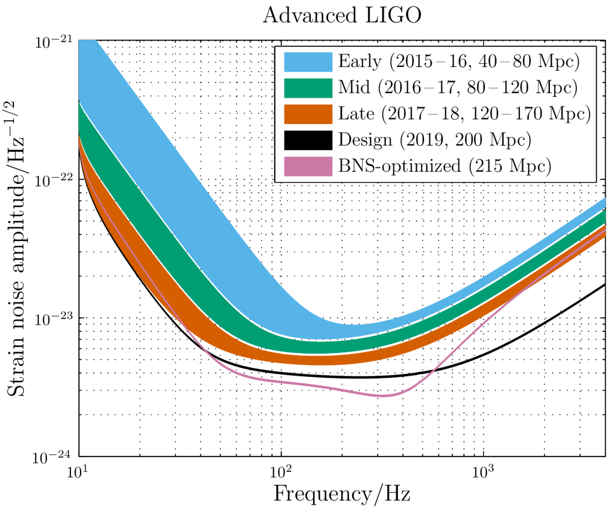
The discovery of gravitational waves

- Upgrade of the LIGO was complete in the early 2015.
- Sensitivity of advanced LIGO is at least 3 times higher that that of initial LIGO.
- As a result of better sensitivity Advanced LIGO can “see” far more volume of the universe than the initial LIGO.

Advanced LIGO visibility



Advanced LIGO sensitivity



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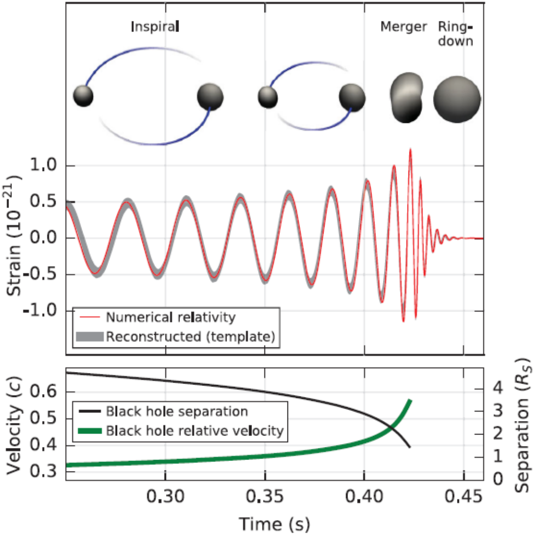
- Both the LIGO detectors which were "locked" and doing their "Engineering run" got a signal on Sept 14, 2015 more or less at the same time.
- The signal "matched" with that of the merger of two black holes of roughly 30 times more massive than the sun.

Compact Binary Coalescence (CBC)



- The signal was 0.2 second long and within this duration its frequency and amplitude were changing exactly in the way they were expected.
- In next few month a team of more than 1000 scientists spread over hundred institutes of a dozen countries (including some of us from India) scrutinized the data.
- By the end of 2015 it was clear that the signal was genuine after ruling out all other possibilities.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Joined January 2009
Born on September 17
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Photos & videos
Narendra Modi @narendramodi · 20m
Hope to move forward to make even bigger contribution with an advanced gravitational wave detector in the country.
463
986
Narendra Modi @narendramodi · 21m
Immensely proud that Indian scientists played an important role in this challenging quest.
421
878
Narendra Modi @narendramodi · 22m
Historic detection of gravitational waves opens up new frontier for understanding of universe!

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)

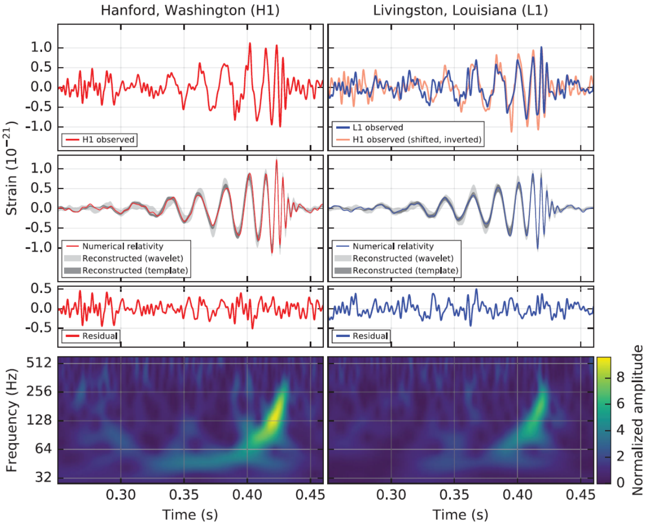
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Time (s)
0.30
0.35
0.40
0.45
Normalized amplitude

Why the discovery of gravitational waves is important ?

- If we wish to know what is happening in the far remote places in the universe we have two options:
  1. Have a visit.
  2. To study anything which comes from there.
- The first option is ruled out due to practical reasons.
- Before Galileo started using telescope only light from the brightest object in the sky was available to understand those. Galileo started a new era by looking far deeper into space than anyone else.

Why the discovery of gravitational waves is important ?

- After the WWII radio equipment (telescopes) became easily available and the technology was developing fast so astronomers started to observe the universe in radio waves.
- The universe looked completely different and far more interesting when observed in radio waves as compared to visible light and a new window of the universe was opened.
- In the last 50 years many other new windows of the universe have been opened i.e., gamma, X-ray, Infra-red etc. .
- LIGO has opened another window of the universe in terms of gravitational waves.

- It is important to keep in mind that different physical process happening in the remote parts of the universe radiate energy in different form.

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- The information which is available in one type of waves many not be available in other waves.
- In particular, many objects in the universe may be totally dark when looked through electromagnetic waves but may be glowing in gravitational waves.
- Since 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

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 A- A+

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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.

PUNE, LATE CITY, 20+4(NEWSLINE) PAGES, ₹4.00

The Indian EXPRESS

JOURNALISM OF COURAGE

FRIDAY, FEBRUARY 12, 2016 DAILY FROM: AHMEDABAD, CHANDIGARH, DELHI, JAIPUR, KOLKATA, LUCKNOW, MUMBAI, NAGPUR, PUNE, VADODARA WWW.INDIANEXPRESS.COM

A leap towards theory of everything

Gravitational waves detected, Einstein vindicated after 100 yrs

SETH BORENSTEIN
WASHINGTON, FEBRUARY 11

IN AN announcement that electrified the world of astronomy, scientists said Thursday that they have finally detected gravitational waves, the ripples in the fabric of space-time that Albert Einstein predicted a century ago.

Some scientists likened the breakthrough to the moment Galileo took up a telescope to look at the planets.

The discovery of these waves, created by violent collisions in the universe, excites astronomers because it opens the door to a new way of observing the cosmos. For them, it's like turning a silent movie into a talkie because these waves are the soundtrack of the cosmos.

"Until this moment we had

CONTINUED ON PAGE 2

GRAVITIONAL WAVES: THE INDIA LINK PAGE 8

THE UNIVERSE IN A NEW LIGHT PAGE 11

Express House, Plot No. 1205/2/6, Shirole Road, Shivajinagar, Pune-411004 I India, E-mail: pune.newsline@expressindia.com, Phone: 67241000, Fax: 67241148

PUNE Newsline
The Indian EXPRESS

SATURDAY, FEBRUARY 13, 2016
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TALK, Page 4
Through the Lens

SIMPLIFYING EQUATIONS

IUCAA film to help you decode science of gravitational waves

Gravitational Wave Astronomy, which simplifies Einstein's theories, will be uploaded on *YouTube* soon

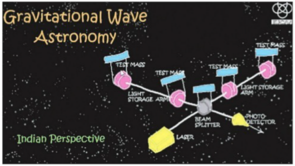
ANURADHA MASCARENHAS
PUNE, FEBRUARY 12

THE NEXT time you refer to maps on your smart phone using global positioning system to navigate your way, remember it was Einstein's theory of relativity that simplified your life.

In a six-and-a-half minute film, scientists at the Inter University Centre for Astronomy and Astrophysics (IUCAA) have tried to introduce basic ideas of the theory and highlighted the role of Indian scientists who helped detect the gravitational waves. IITian Manish Jain, who now works with teachers and children to popularise science, has added a dash of spice to the film that makes the complex theory seem really simple.

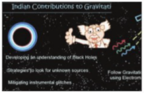
Just why the global positioning system works so accurately is because of Einstein's theory of relativity that deducted 37 microseconds from clocks, says IITian Manish Jain, who actively works at the Science popularisation centre of IUCAA by making short films based on research.

"Most scientists do amazing research that gets published in highly-technical journals. To reach the common man, we have to simplify the research and explain how the theory of relativity discovered 100 years ago by Einstein is applied in day-to-day life by 2.6 billion people in the form of smart phones and GPS," Jain said.



A still from *Gravitational Wave Astronomy—Indian Perspective*. IUCAA

Noise from so many sources corrupt gravitational wave data and make it



Various contributions made by Indian scientists in understanding

HOPES HIGH ON A LIGO DETECTOR IN INDIA

A DAY after the announcement of gravitational waves being detected, scientists at IUCAA have now pinned their hopes on the formal approval of a proposal to set up a Laser Interferometer Gravitational Wave Observatory (LIMO) in India. "The Prime Minister in a tweet has expressed happiness over the role of Indian scientists in the detection of the waves and we hope this will be translated to setting up a detector like the one in USA," IUCAA director Professor Somak Raychaudhury told *The Indian Express*.

LIMO, a system of two identical detectors constructed to detect incredibly tiny vibrations from gravitational waves, was built by MIT and Caltech researchers. The twin detectors are located in Livingston, Louisiana, and Hanford, Washington.

An observatory in India would be at the right distance from the two existing observatories in the US to calculate precisely the nature of gravitational waves. "It will also give Indian astrophysicists an

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EXPLAINED

SOCIAL INTELLIGENCE

They're bothering a unique, valuable human being who deserves happiness. Ask for help. Don't fight alone. Big hug.

J K ROWLING, Creator of Harry Potter, 6.74 million followers on Twitter, to someone who asked the author to teach her how to "scare the dementors that have been living under (her) bed" because she was "tired of being sad all the time".

SIMPLY PUT: AN EARTHLING'S GUIDE TO THE PLACE OF NO RETURN

Imagining black holes: countless, ravenous, unimaginably massive

Scientists announced last week that they had recorded the sound of two black holes colliding a billion light years away, fulfilment of the last prediction of Albert Einstein's General Theory of Relativity. What's a black hole, the region in space where the gravitational pull is so strong that not even light can escape it?

The black hole is a hungry beast.

It swallows everything too close, too slow or too small to fight its gravitational force — even light. With every planet, gas, star or bit of mass it consumes, the black hole grows.

It holds the key to all (or most) knowledge.

Pretty much everything we understand about how the universe works, depends on the black hole. The firewall paradox — the question of how you would die inside a black hole; probably the biggest debate in physics currently — calls to question the most definitive theories of science. Einstein, Joseph Polchinski or Stephen Hawking, or none, everything we know about the universe could change if we could know for certain what happens to information inside a black hole.

It can sing — though you can't hear it.

In 2003, an international team led by the X-ray astronomer Andrew Fabian discovered the longest, oldest, lowest note in the universe — a black hole's song — using NASA's Chandra X-ray Observatory. Though too low and deep for humans to hear, the B flat note, 57 octaves below middle C, ap-