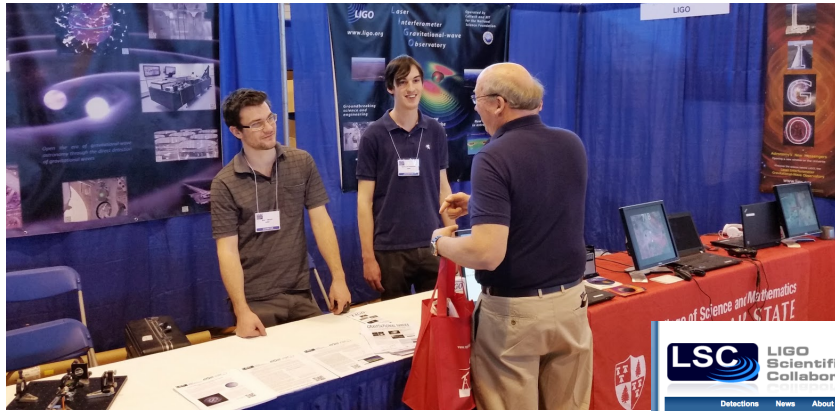


Overview of Education and Public Outreach (EPO) Activities of the LSC



GW151226: OBSERVATION OF GRAVITATIONAL WAVES FROM A 22 SOLAR MASS BINARY BLACK HOLE COALESCENCE

A few months after the first detection of gravitational waves from the black hole merger event GW150915, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has made another observation of gravitational waves from the collision and merger of a pair of black holes. This signal, called GW151226, arrived at the LIGO detectors on 26 December 2015 at 03:38:53 UTC.

The signal, which came from a distance of around 1.4 billion light-years, was an example of a **compact binary coalescence**, when two extremely dense objects merge. Binary systems like this are one of many sources of gravitational waves for which the LIGO detectors are searching. Gravitational waves are ripples in space-time itself and carry energy away from such a binary system, causing the two objects to spiral towards each other as they orbit. This inspiral brings the objects closer and closer together until they merge. The gravitational waves produced by the binary stretch and squish space-time as they spread out through the universe. It is this stretching and squashing that can be detected by observatories like Advanced LIGO, and used to reveal information about the sources which created the gravitational waves.

GW151226 is the second definitive observation of a merging binary black hole system detected by the LIGO Scientific Collaboration and Virgo Collaboration. Together with GW150914, this event marks the beginning of gravitational-wave astronomy as a revolutionary new means to explore the frontiers of our universe.

THE SIGNAL

Just like the first detection, GW151226 was observed by the twin instruments of Advanced LIGO situated in Hanford, Washington and Livingston, Louisiana. Figure 1 shows the data as seen by the two instruments during the final second before the merger took place. The animation alternates between showing the raw detector data and the data after the best-matching signal has been removed, making it easier to identify. Even then, and unlike the first detection where the signal of the event was very obvious against the background 'noise' of the instruments, in this case it is not immediately clear that there is a gravitational-wave signal embedded in the data. This is because GW151226 has a lower signal strength (inferred to as the measured gravitational-wave strain). It is also harder to see as the signal is spread over a longer time, lasting 1 second compared to 0.2 seconds for the first detection. Despite the difficulty in spotting this event by eye, our detection software was able to find the signal in the data.

HOW WAS THE DETECTION MADE?

The first indication of the signal came from an online search method, which looks at detector data almost in real time as it is recorded. Figure 2 shows the results of one of the search methods. This analysis had identified GW151226 as a gravitational-wave candidate within 70 seconds of its arrival at the Earth. About a minute later the first, rough estimates of the candidate's source

FIGURES FROM THE PUBLICATION

For more information on how these figures were generated and their meaning, see the main publication at arxiv.org/abs/1601.06969.

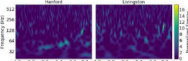
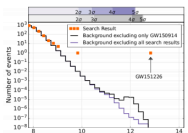
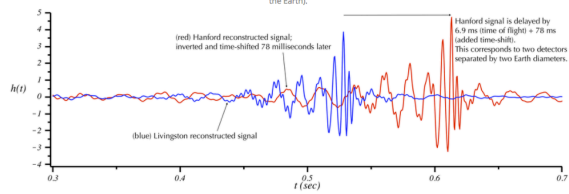
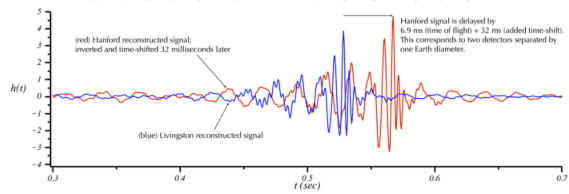


Figure 1: Plot from the final detection. The gravitational-wave strain $h(t)$ versus time t (sec) for the final second before the merger. The plot shows the raw detector data (blue) and the data after the best-matching signal has been removed (orange). The signal is spread over a longer time, lasting 1 second compared to 0.2 seconds for the first detection.

00:00 00:00

Stereo sound corresponding to the top plot above. The Hanford signal is time shifted to model the effect of two detectors on opposite sides of the Earth. (Headphones or good speakers recommended.)

00:00 00:00

Stereo sound corresponding to two detectors separated by two Earth diameters. One can clearly hear the sound in the right ear followed by the sound in the left. (Headphones or good speakers recommended.)

Marc Favata (for the LSC)
Montclair State University

This talk...

- Overview of work undertaken by the LSC EPO work.
- Summary of kinds of activities (not a complete list).
- Highlighting (i) things I like, (ii) resources useful for this audience.
- See public EPO whitepaper for more information:
<https://dcc.ligo.org/LIGO-T1600118/public>
- Thanks to those who helped with this talk, esp: Joey Key, Martin Hendry, Jonah Kanner, Shane Larson, Ryan Lang, Veronica Kondrashov, ...

Brief history of the EPO group

LSC Charter: “...carry out an outreach program to communicate LIGO’s activities and goals to the public, and to provide educational opportunities to young people.” [<https://dcc.ligo.org/M980279/public>]

LIGO Labs started outreach programs following construction completion in 1998. EPO group started in 2008.

Past EPO group chairpersons:

Marco Cavaglia, Szabi Marka, Joey Key, Martin Hendry (current).

Individual LSC institutions/groups commit annually to perform certain EPO tasks (coordinated through the EPO group). >50% of LSC groups have an EPO contribution.

Goals:

communicate LIGO science; improve general scientific literacy; increase participation in science and recruitment to STEM careers (for *everyone*).

General EPO activities

- **lectures** on LIGO/GWs to school groups of all ages, the general public, specific groups; classroom visits.
- **outreach booths:** tables w/ brochures, flyers, stickers, and hands-on activities (small interferometer, videos, video games, “spacetime spandex”, ...).
World Science Festival, USA Science & Engineering Festival, NorthEast Astronomy Forum, Royal Soc. Summer Science Exhibition, SACNAC, White House Frontiers Conference
- **booths at professional meetings:**
APS, AAS, IAU General Assembly
- **government outreach:** brainstorming meeting after last APS meeting.



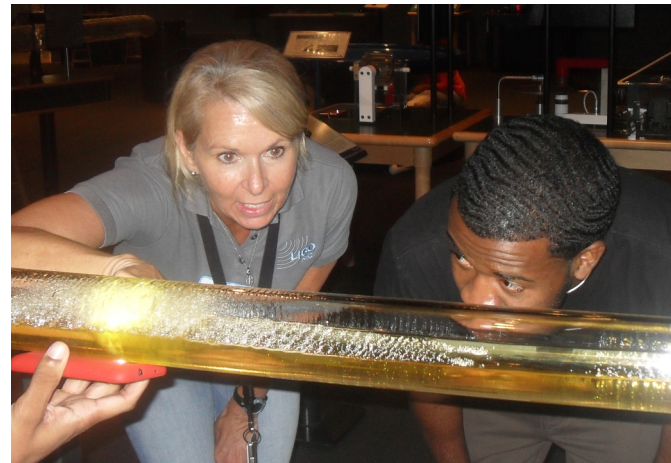
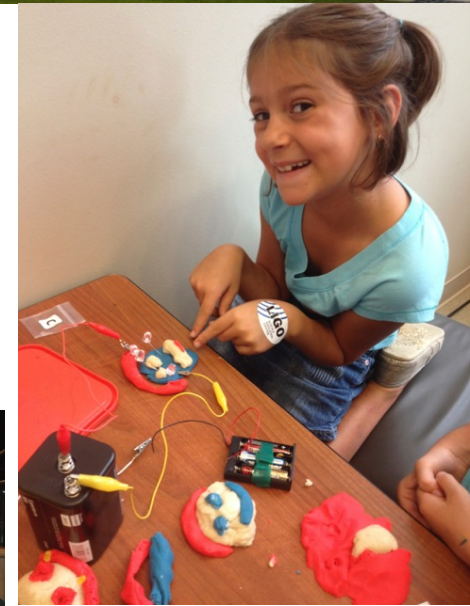
General EPO activities

- organizing press and media materials for LIGO discoveries.
- developing printed or online materials on GW science.
- teacher professional development: develop materials to integrate GW science into curricula at all levels; online courses for teachers.
- REU (research experiences for undergraduates) programs at LIGO member universities (e.g., large programs at Univ. of Florida, LSU, UT Rio Grande Valley, Caltech...).
- musical or artistic works based on GWs.
- answering public questions: question@ligo.org .



LIGO Lab

- Science Education Center (Livingston site; a mini science museum)
- smaller exhibit hall at Hanford.
- tours of LIGO
~8000(H) to 12000(L) yearly on-site contacts.
- school field trips.
- teacher workshops.

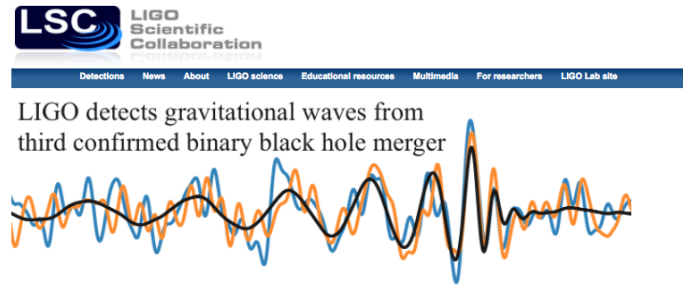


ligo.org

LSC's main global communication tool.

Key products:

- updates on LSC news/events.
- “detection” pages (links to publications, press releases, and related multimedia).
- science summaries.
- collecting/curating resources of the EPO group.
- general info about the LSC.



NEWS

- Jul 7, 2017 July 2017 update on LIGO's second observing run
- Jun 16, 2017 First triple lock of LIGO and Virgo interferometers
- Jun 1, 2017 LIGO detects third confirmed binary black hole merger
- Mar 29, 2017 LSC elects David Shoemaker as new spokesperson
- Mar 15, 2017 Read the March 2017 Issue of LIGO Magazine
- Mar 9, 2017 LSC mourns the passing of LIGO co-founder Ronald Drever
- Feb 3, 2017 Science Summary: Searching for continuous gravitational waves from pulsars
- Jan 27, 2017 LIGO Leadership recognized by National Academy of Sciences and American Astronomical Society prizes; LIGO Team recognized by Royal Astronomical Society
- Jan 26, 2016 LIGO Detection documentary film to premiere on New Scientist on February 7
- Dec 13, 2016 Listening for the background of gravitational waves with Advanced LIGO

PRESS RELEASES

- May 31, 2017 LIGO Detects Gravitational Waves for Third Time
- Jun 15, 2016 Gravitational Waves Detected from Second Pair of Colliding Black Holes
- Feb 11, 2016 Gravitational Waves Detected 100 Years After Einstein's Prediction

GET INVOLVED

Gravity Spy Help classify noise glitches in LIGO data

Einstein@Home Search for gravitational waves and pulsars with your computer

"LIGO Detection" World premiere at New Scientist, Feb 7

Science Summaries of our publications



DETECTIONS

Information about gravitational-wave detections made by LIGO to date.

Jump to a separate page for a specific event (listed in reverse-chronological order), or see the [General Detection Resources](#) section below for further information on LIGO detections.

- GW170104
- GW151228
- GW150914 (First detection)

GENERAL DETECTION RESOURCES

DOCUMENTS, WEBSITES, & MULTIMEDIA

- Full list of LSC Publications. (See Runs O1 and higher for papers following the first detection.)
- Science Summaries
- LIGO Open Science Center (LOSC): Download LIGO data or explore tutorials on LIGO data analysis. See also their [data release page](#) for links to audio of LIGO events.
- Timeline and brief history of the LIGO project.
- The Caltech Media Assets page for GW150914 contains a wealth of useful documents, graphics, and video.
- Sounds of Spacetime: A website that explains LIGO detections and gravitational-wave physics via the analogy between gravitational waves and audio signals. (Montclair State University)
- Black Hole Bubble Diagram: Interactive graphics showing known stellar-mass black holes from gravitational-wave candidates and X-ray binaries. (Cardiff University School of Physics and Astronomy)
- LIGO Gravitoscope: An interactive tool that lets you compare visions of the Universe in a range of wavelengths. Also shows locations of detected gravitational-wave signals. (Cardiff University Astronomy and Astronomy Instrumentation Groups)
- Gravity Spy: a citizen-science project to help LIGO search for gravitational waves by improving glitch classification.
- Einstein@Home: use your computer's idle processing time to help search for pulsars using gravitational wave, radio, and gamma-ray data.
- Educator's Guide: Contains background material on gravitational waves and classroom activities that align with K-12 science standards. (Sonoma State University)
- Image gallery hosted at the LIGO Lab site.
- LSC Youtube Channel, Facebook page, and Twitter page.
- "Chirp" ringtones from the first two LIGO detections. (Instructions). GW150914 [m4r file (iPhone) | mp3 file]

AT A GLANCE

GW150914 signal observed by the twin LIGO observatories at Livingston, Louisiana, and Hanford, Washington. The signal came from two merging black holes, each about 30 times the mass of our sun, lying 1.3 billion light-years away. The top two plots show data received at Livingston and Hanford, along with the predicted shapes of the waveforms. These predicted waveforms show what two merging black holes should look like according to the equations of Albert Einstein's general theory of relativity, along with the instrument's ever-present noise. Time is plotted on the X-axis and strain on the Y-axis.

Black Holes of Known Mass

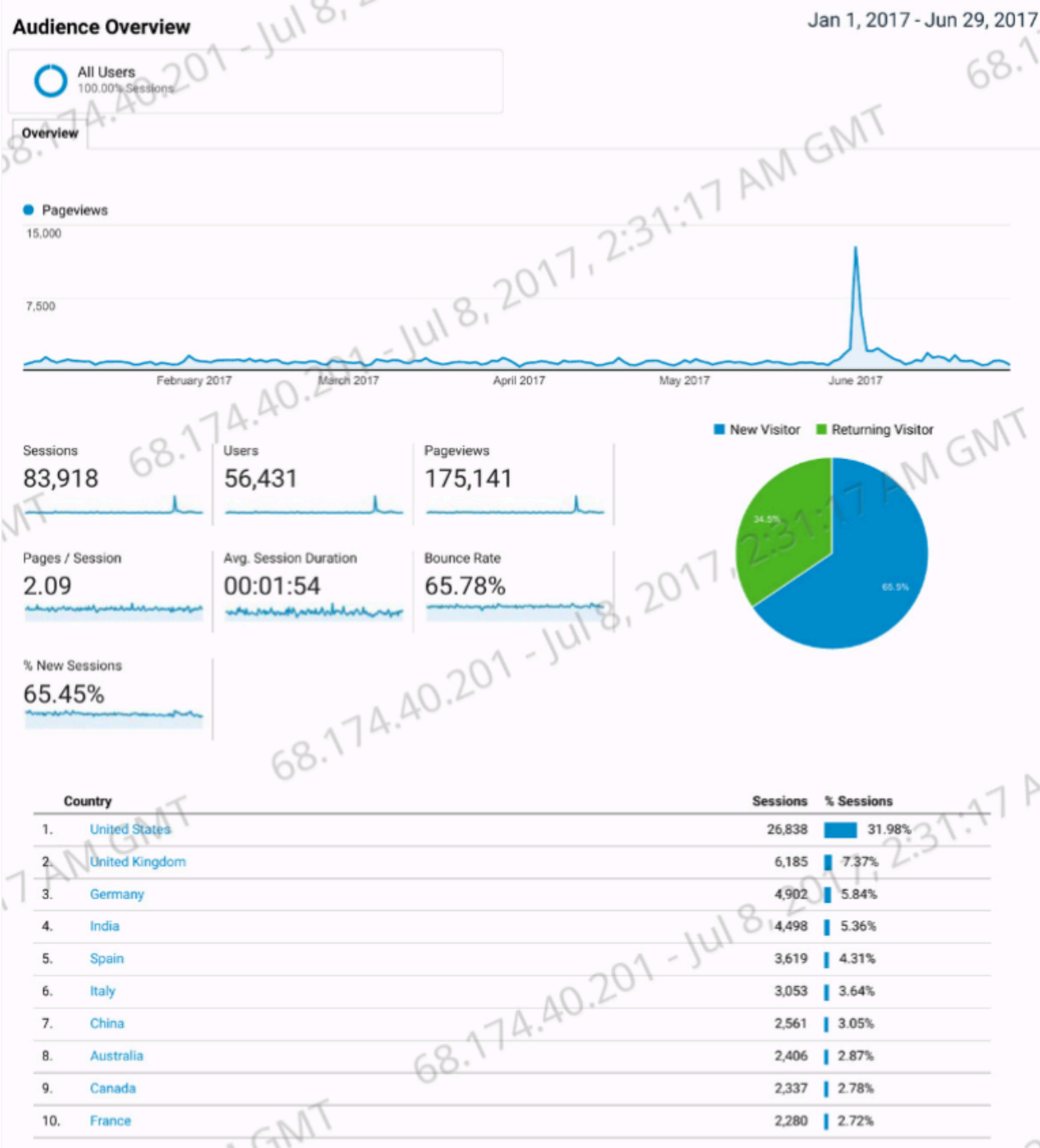
New Population of Binary Black Holes. LIGO has discovered a new population of black holes with masses that are larger than what had been seen before with X-ray studies alone (purple). The three confirmed detections by LIGO (GW150914, GW151228, GW170104), and one lower-confidence detection (LV17151072), point to a population of stellar-mass binary black holes that, once merged, are larger than 20 solar masses.

ligo.org

web stats:

first 6 months of 2017

~9400 users/month



ligo.org

web stats:

19 d period,

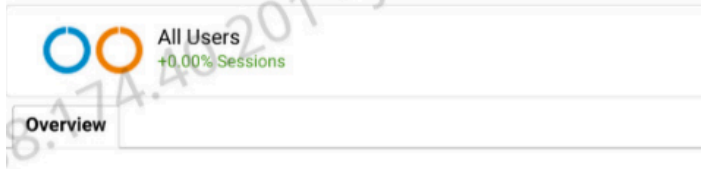
typical vs.

detection

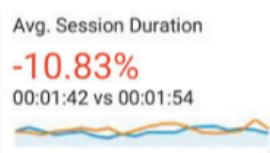
~3x more users

Audience Overview

May 22, 2017 - Jun 10, 2017
Compare to: May 2, 2017 - May 21, 2017

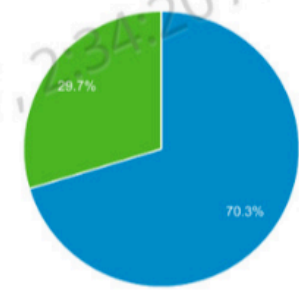


May 22, 2017 - Jun 10, 2017: ● Pageviews
May 2, 2017 - May 21, 2017: ● Pageviews

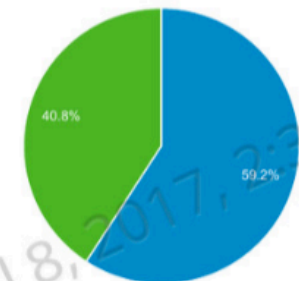


■ New Visitor ■ Returning Visitor

May 22, 2017 - Jun 10, 2017



May 2, 2017 - May 21, 2017



ligo.org: science summaries

- one of our key EPO products.
- web page summaries of published papers; also pdf “flyer” versions for handouts at booths/ events.
- produced by members of paper writing teams and further edited by EPO.
- translations (~5 languages) for detection summaries.
- ~66 summaries since 2011.

The screenshot shows the LIGO Scientific Collaboration website. At the top, there are navigation links for Home, Español site, MagyarHungarian site, and LSCinternat. Below that is the LSC logo and the text 'LIGO Scientific Collaboration'. A menu bar contains links for Detections, News, About, LIGO science, Educational resources, Multimedia, For researchers, and LIGO Lab site. Underneath, there are sub-links for Intro to LIGO & Gravitational Waves, Science Summaries, Popular Articles, Frequently Asked Questions, Magazine, and Advanced LIGO. The main content area is titled 'SUMMARIES OF LSC SCIENTIFIC PUBLICATIONS' and lists several detection papers with their titles and dates. A sidebar on the right features a photo of two people looking at a detector arm and the text 'LOOKING DOWN A DETECTOR ARM'.

The image shows the LIGO Scientific Collaboration logo on the left and the VIRGO logo on the right. The VIRGO logo consists of several curved lines forming a stylized 'V' shape.

GW151226: OBSERVATION OF GRAVITATIONAL WAVES FROM A 22 SOLAR MASS BINARY BLACK HOLE COALESCENCE

A few months after the first detection of gravitational waves from the black hole merger event GW150914, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has made another observation of gravitational waves from the collision and merger of a pair of black holes. This signal, called GW151226, arrived at the LIGO detectors on 26 December 2015 at 03:38:53 UTC.

The signal, which came from a distance of around 1.4 billion light-years, was an example of a compact binary coalescence, when two extremely dense objects merge. Binary systems like this are one of many sources of gravitational waves for which the LIGO detectors are searching. Gravitational waves are ripples in space-time itself and carry energy away from such a binary system, causing the two objects to spiral towards each other as they orbit. This inspiral brings the objects closer and closer together until they merge. The gravitational waves produced by the binary stretch and squash space-time as they spread out through the universe. It is this stretching and squashing that can be detected by observatories like Advanced LIGO, and used to reveal information about the sources which created the gravitational waves.

GW151226 is the second definitive observation of a merging binary black hole system detected by the LIGO Scientific Collaboration and Virgo Collaboration. Together with GW150914, this event marks the beginning of gravitational-wave astronomy as a revolutionary new means to explore the frontiers of our Universe.

THE SIGNAL

Just like the first detection, GW151226 was observed by the twin instruments of Advanced LIGO situated in Hanford, Washington, Louisiana. Figure 1 shows the data as seen by the two instruments during the final second before the merger took place. The animation alternates between showing the raw detector data and the data after the best-matching signal has been removed, making it easier to identify. Even then, and unlike the first detection (where the signal of the event was very obvious against the background ‘noise’ of the instruments), in this case it is not immediately clear that there is a gravitational-wave signal embedded in the data. This is because GW151226 has a lower signal strength (referred to as the measured gravitational-wave strain); it is also harder to see as the signal is spread over a longer time, lasting 2 seconds compared to 0.2 seconds for the first detection. Despite the difficulty in spotting this event by eye, our detection software was able to find the signal in the data.

HOW WAS THE DETECTION MADE?

The first indication of the signal came from an online search method, which looks at detector data almost in real time as it is recorded. Figure 2 shows the results of one of the search methods. This analysis had identified GW151226 as a gravitational wave candidate within 70 seconds of its arrival at the Earth. About a minute later the first, rough estimates of the candidate’s source

FIGURES FROM THE PUBLICATION

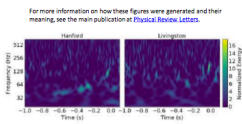
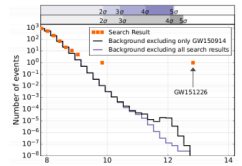
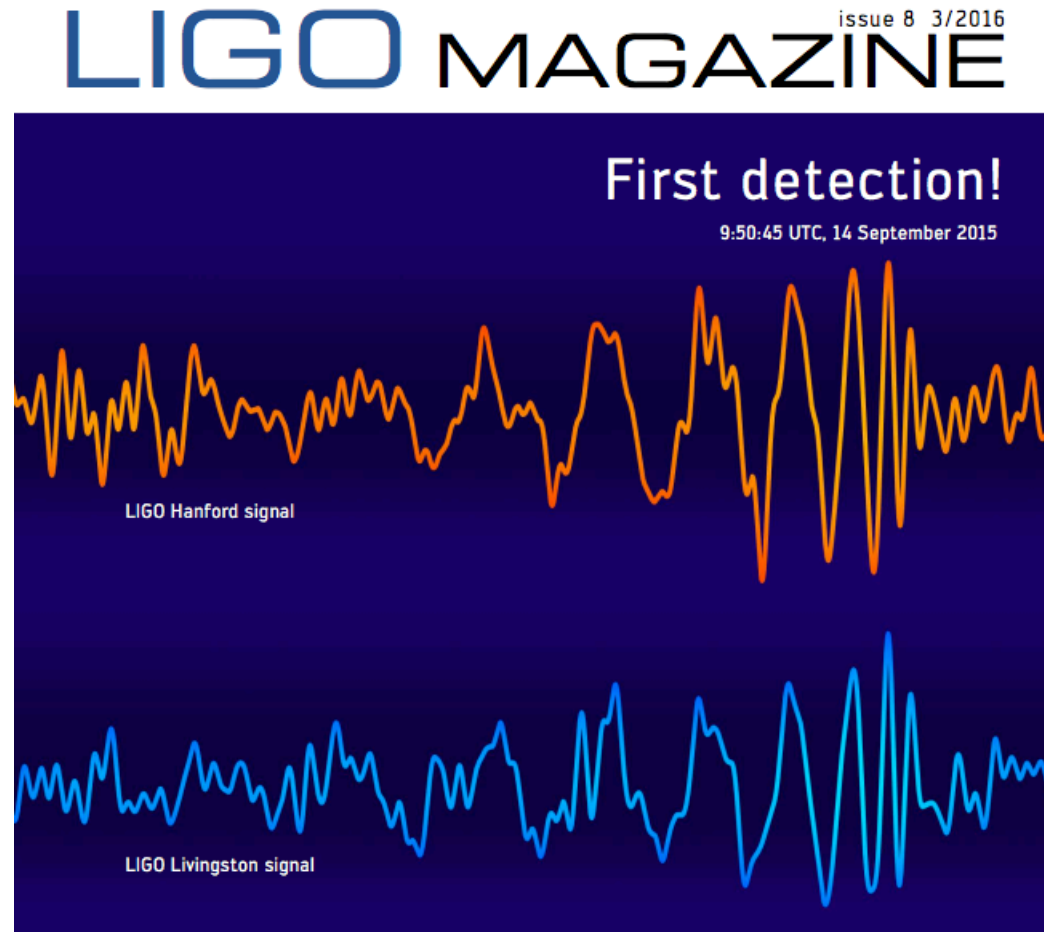


Figure 1: (Adapted from Figure 1 of our publication). The gravitational wave event GW151226 is observed by the two Advanced LIGO detectors, LIGO Livingston (left) and LIGO Hanford (right). The spectrograms show the data recorded by the detectors during the two-second signal duration. The signal varies as a function of time in seconds and (bottom), in terms of the number of wave cycles per second. To be visible both in spectrograms, we require the signal to be present in the detectors against a pre-defined set of results for merging binaries. This allows us to find the event and search for other signals in the data. The spectrograms were generated and analyzed by software. The signal is much more difficult to see than the first detection (shown).



ligo magazine

- highlights news, research, events, personal stories from within the LSC.
- published twice per year.
- focused on internal LSC audience, but useful to others in GW community.
- 10 issues so far.
- <http://ligo.org/magazine/>



social media

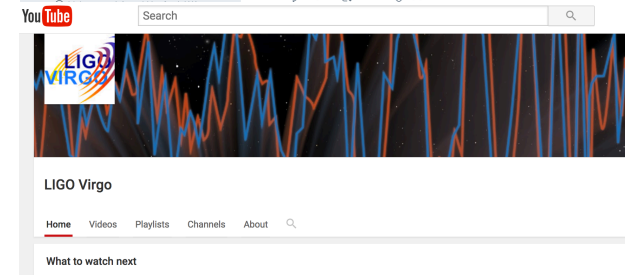
LSC promotes LIGO news and EPO activities via facebook and twitter.
(links at bottom of ligo.org)

facebook stats: ~18,750 followers.
GW170104 post reached ~35,000 people.

twitter stats: ~45,000 followers.
~1.8 million views in June 2017.
~70 million reached for GW150914.

youtube page: collection of LIGO-related videos.

reddit: AMA (“ask me anything”) events for 3 detections hosted by LSC members.



reddit

comments other discussions (1)

6 Jun	ANTI-POACHING PILOT/Y GUY Specialized Profession	27 Jul	VACUUM REPAIR MAN Specialized Profession	8 Jun	PLASTIC SURGEON Medical	5 Jul	NASA JUNO PROJECT Science	9 Apr	FORMER CIA CASE OFFICER Military
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Please check out our [Rules and FAQs](#)

This is an archived post. You won't be able to vote or comment.

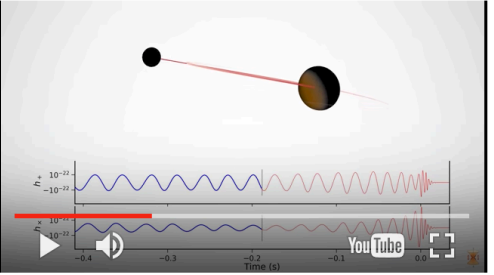
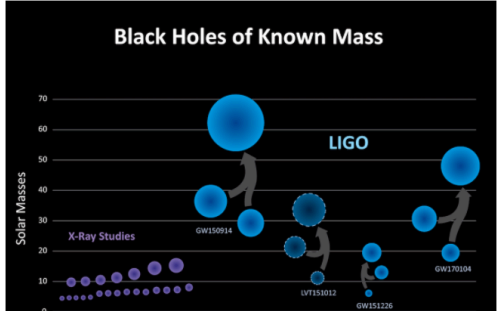
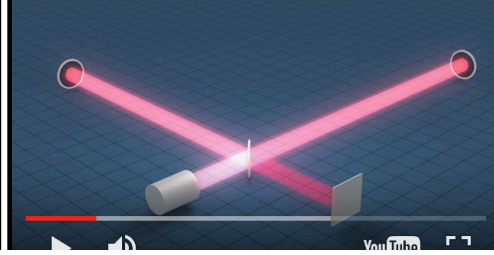
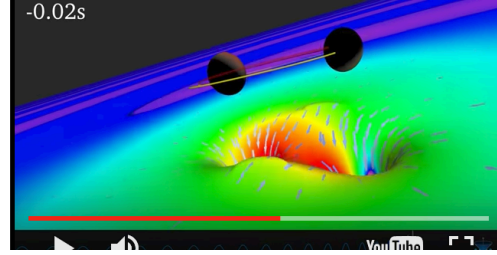
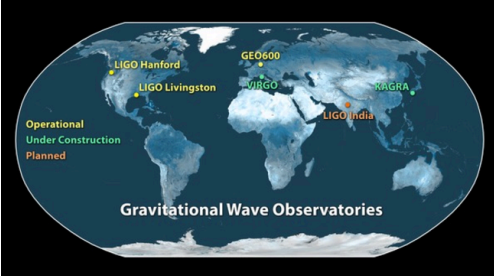
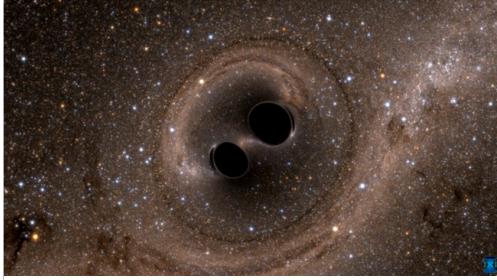
We are the LIGO Scientific Collaboration, and we have made the first direct detection of gravitational waves and the first observation of two black holes merging. Ask us anything!

SCIENCE submitted 1 year ago * by LIGO_Collaboration LIGO

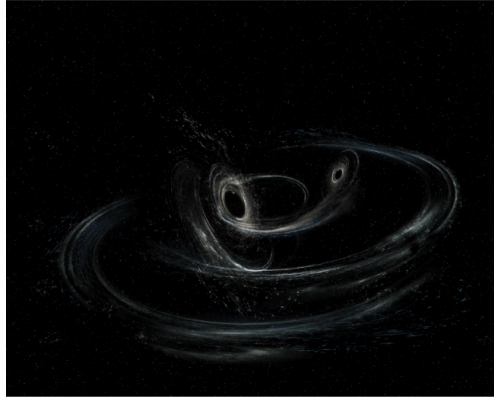
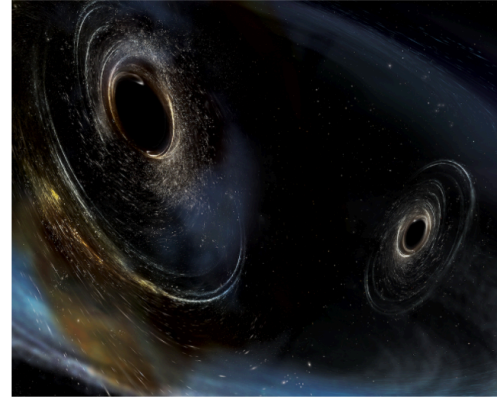
Hi Reddit, we will begin answering questions starting 2:15 PM EST. We have a large team of scientists from many different timezones, so we will continue answering questions throughout the weekend. Keep the questions coming!

detection-related multimedia products

- videos, animations, NR simulations, interview clips.
- figures, images, and artists' illustrations for use by media.
- factsheets and infographics on detected events.
- available at ligo.org, ligo.caltech.edu

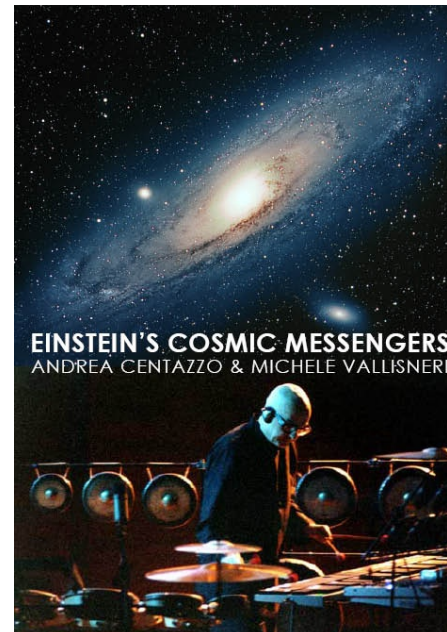


Animation of the inspiral and collision of two black holes



museum and artistic exhibits

- traveling exhibit: “Astronomy’s New Messengers.”
<http://ligo.phy.olemiss.edu/LIGOexhibit/>
- <http://celebratingeinstein.org/>
series of events including “black (w)hole” audio/
visual art installation, “a shout across time” dance-
interpreted lecture + original film w/ live orchestra.
- Centazzo/Vallisneri’s multimedia concert
<http://andreacentazzo.com/ecm/>
- GWs & exoplanets music project
(Arthur Jeffes)
<http://www.epcmusic.com/space>
- “Chasing the waves” musical
comedy (Glasgow).
<http://www.gla.ac.uk/events/sciencefestival/eventsandprojects/projects/chasingthewaves/>



films

- 3 LIGO films by Kai Staats (Over the Sun LLC)
<https://vimeo.com/album/3233854>
- “Listening to the Universe” VR film
<https://with.in/watch/the-possible-listening-to-the-universe/>
- advanced LIGO documentary project:
<https://vimeo.com/ligofilms>
- short video interviews by GEO600 Team:
<http://scienceface.org/>



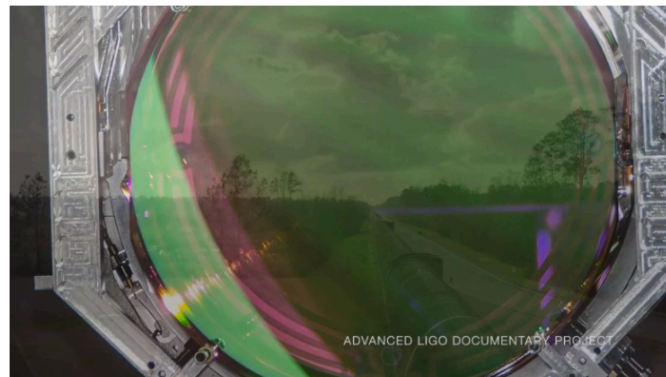
LIGO Detection

6 months ago



LIGO Generations

2 years ago



Mirrors That Hang On Glass Threads

[aLIGO Documentary Project](#) | 5344 plays



LIGO, A Passion for Understanding

2 years ago

LIGO Open Science Center (LOSC)

Main public portal
for LIGO data:
losc.ligo.org

key products:

- h(t) data segments near detected events.
- past (S5, S6) and future data releases for science/observing runs.
- some data from publication figures.
- documentation and software tools for using data.
- python-based tutorials: play with data to extract detected signals.
- ~100 users/day

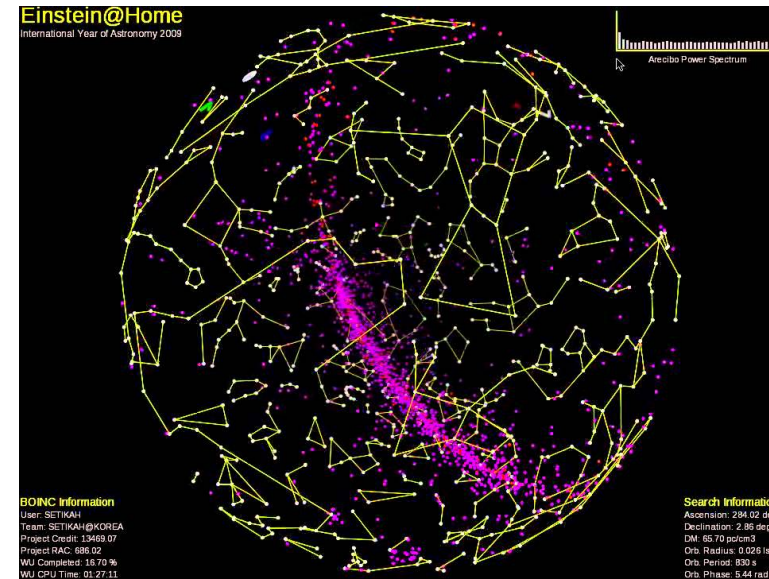


The screenshot shows the top portion of the LOSC website. At the top left is the LIGO logo. To its right, the text reads "LIGO Open Science Center" followed by "LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation." Below this is a navigation menu with links: "Getting Started" (highlighted in red), "Tutorials", "Data", "Events", "Bulk Data", "Timelines", "My Sources", "Software", and "GPS ↔ UTC". On the right side, a "Welcome to the LIGO Open Science Center" banner contains the text: "About LIGO", "Get Started with LIGO data", "Join the E-mail list for updates", "For general information on LIGO, please visit ligo.org", and "If you have LSC credentials, you may go to the [development site](#)". Below the banner, a section titled "Discoveries from the LIGO detectors!" (highlighted in red) lists a "released 2017 June 1:" event: "Event of January 4, 2017: GW170104: total mass 50".

Citizen science: Einstein@home

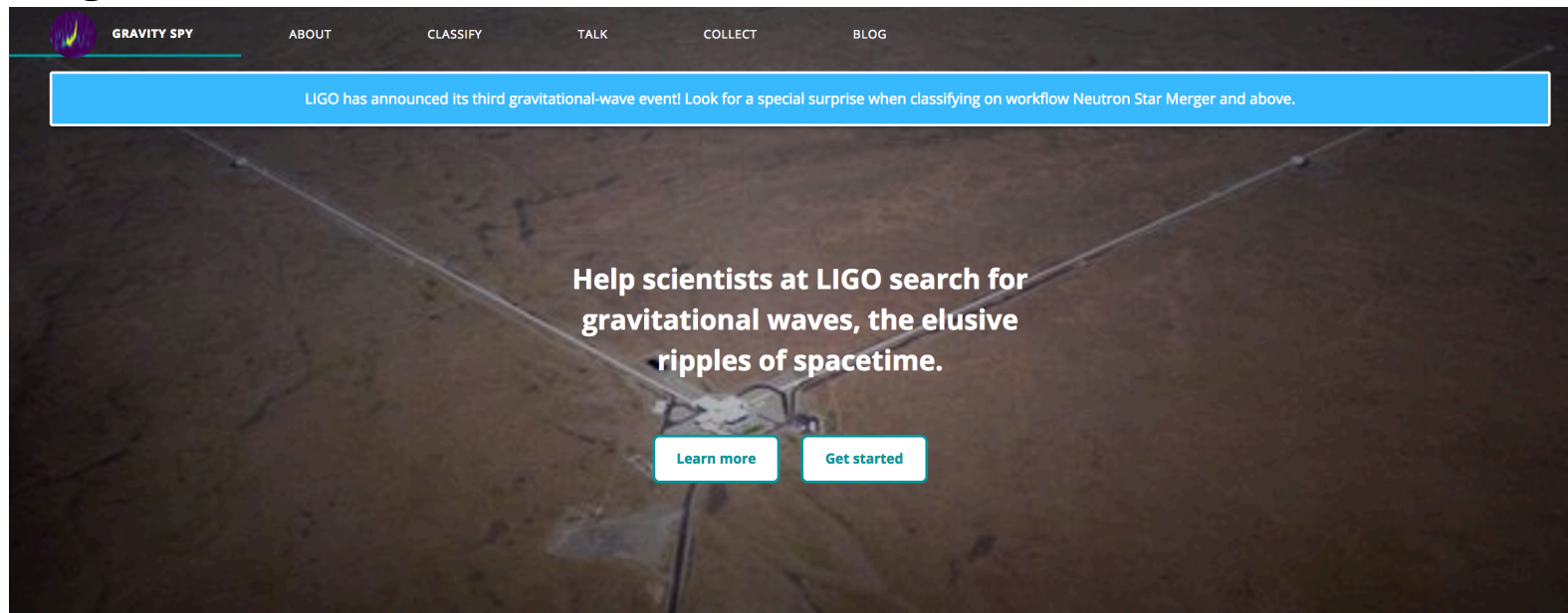


- distributed computing project; analyzes data during your computer's idle time.
- search for continuous GWs from spinning neutron stars. Also look for new pulsars in radio or gamma-ray data.
- Key recent results:
 - 13 new gamma-ray pulsars (Jan. 2017).
 - most massive double neutron star system (Nov. 2016).
 - measurement of braking index of new gamma-ray pulsar (Nov. 2016).
 - 13 new radio pulsars discovered (Aug. 2016).
 - limits on GW amplitude and ellipticity from spinning neutron stars (Sep. 2016).

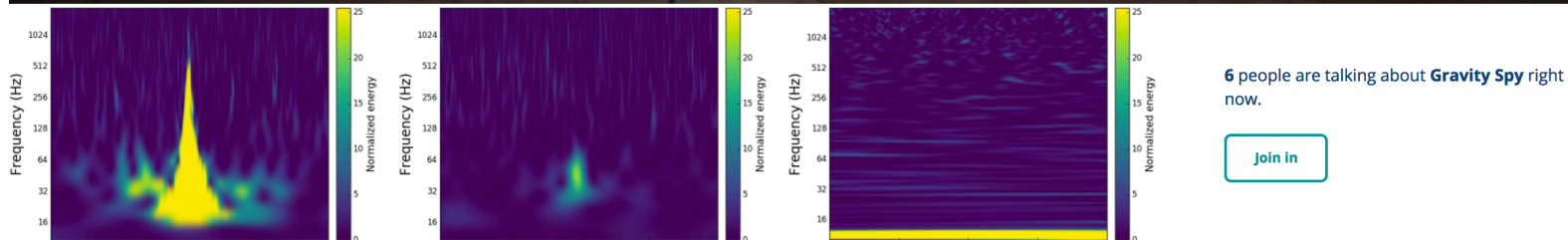


Citizen science: GravitySpy.org

- volunteers help classify LIGO glitches; train machine learning algorithm and identify new glitch classes.
- ~9000 volunteers, ~2.2 million glitches classified.
- currently using O2 data.

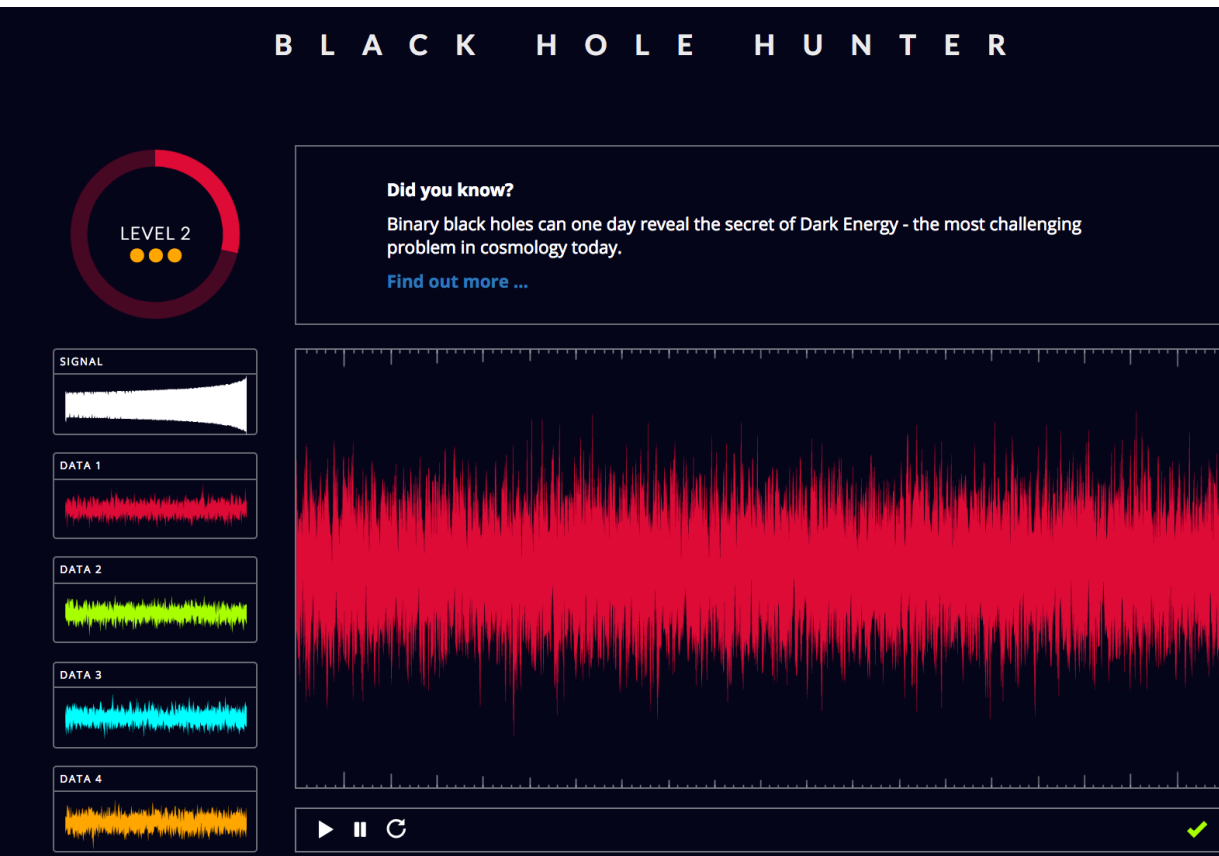


The screenshot shows the GravitySpy.org website homepage. At the top, there is a navigation bar with the logo and links for ABOUT, CLASSIFY, TALK, COLLECT, and BLOG. A blue banner below the navigation bar contains the text: "LIGO has announced its third gravitational-wave event! Look for a special surprise when classifying on workflow Neutron Star Merger and above." The main content area features a background image of the LIGO detector arms with the text: "Help scientists at LIGO search for gravitational waves, the elusive ripples of spacetime." Below this text are two buttons: "Learn more" and "Get started".



Games & apps

- 4 games/apps developed by laserlabs.org, gwoptics.org (U. of Birmingham)
- Black Hole Hunter (Cardiff. U.); <http://blackholehunter.org/>



Latest Games and Apps

Our apps and games that we use for social media, Windows PCs and Android and iOS phones.



Pocket Black Hole

A simple app that allows you to take a photo of your friends and promote its download afterwards.



Stretch and Squash

Stretch and Squash distances between objects to be stretched and squashed.

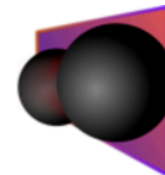


Space Time Quest

In Space Time Quest technology for your own hall of fame.

Under Development

Apps we are working on right now are listed below. We don't know when these apps will become available.



Black Hole Master

An fast arcade-style game with a black hole opponent, using only black hole development in the N-body simulation. Pong is still available.

soundsofspacetime.org

- An audio exploration of the physics of gravitational-wave signals.
- Explain what physical effects influence the gravitational wave signal [showing $h(t)$ plots and corresponding audio].
- Provide audio for all GW source types.
- Detailed pages for detected events.
- A tool for training students.



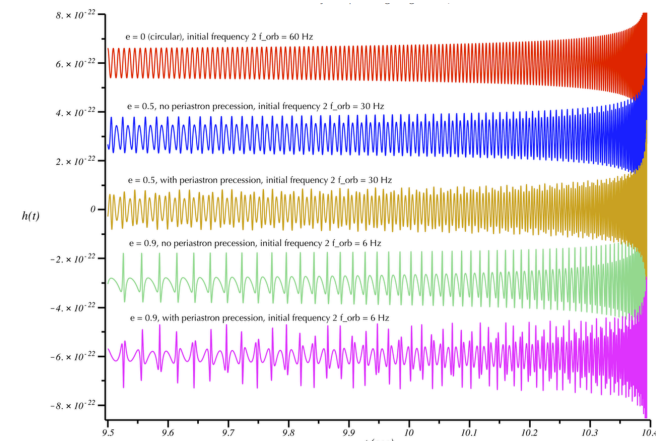
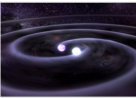
Welcome!

Our purpose is to explore the physics of gravitational waves via an analogy to audible sounds. Gravitational waves (GW) are ripples in the fabric of spacetime produced by colliding black holes, neutron stars, supernovae, and other astrophysical phenomena.

There is a worldwide effort to detect these waves using giant laser interferometers (like LIGO) or by monitoring pulsars using radio telescopes (like NANOGrav). This effort had its first major success with the detection of a gravitational-wave signal by the twin LIGO observatories on September 14, 2015. This was followed with additional detections in December 2015 and January 2017. These events represent the beginning of gravitational-wave astronomy. We are now able to perceive the universe in an entirely new way—by “listening” to the sounds of spacetime.

To learn more about gravitational waves, click on [What are Gravitational Waves?](#) More information about the first detection can be found at our [Detection page](#).

When black holes merge or other energetic cosmic events perturb spacetime, the gravitational waves they



Same as above but zooming in to show the final second before merger.

▶ 00:00 ◀ 00:00 ◀▶

(red curve) circular orbit, $e=0$ (headphones/subwoofer recommended).

▶ 00:00 ◀ 00:00 ◀▶

(blue curve) Moderately elliptical, $e=0.5$, periastron precession off (headphones/subwoofer recommended).

▶ 00:00 ◀ 00:00 ◀▶

(gold curve) Moderately elliptical, $e=0.5$, periastron precession on (headphones/subwoofer recommended).

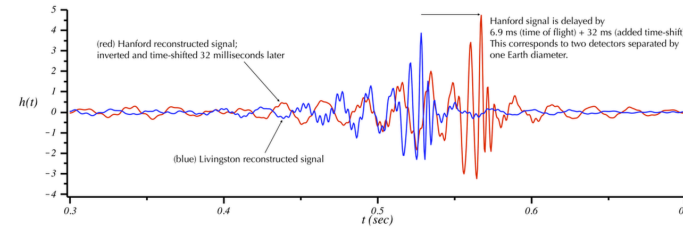
▶ 00:00 ◀ 00:00 ◀▶

(green curve) Highly elliptical, $e=0.9$, periastron precession off (headphones/subwoofer recommended).

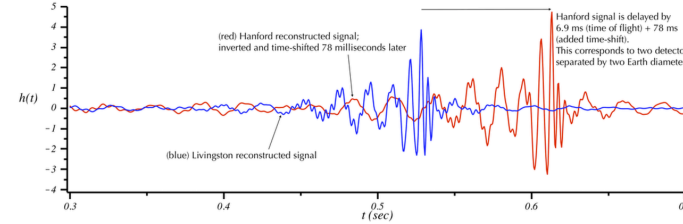
soundsofspacetime.org

Features to explore:

- effect of varying masses on circular inspiral.
- effect of higher harmonics.
- effect of varying eccentricity and turning periastron advance on/off.
- effect of varying spin; turning precession on/off.
- effect of including merger/ringdown.
- stereo audio for all detections including: raw data, filtered data, template.
- effect of time-of-flight (left ear/right ear).
- comparison of 4 GW events.
- illustration of phase shift from Lorentz violation.
- coming soon: sounds from NS spin-down, supernovae, stochastic background.



Similar to the above two plots except an additional time-shift has been added to the Hanford signal (corresponding to two detectors on opposite sides of the Earth).



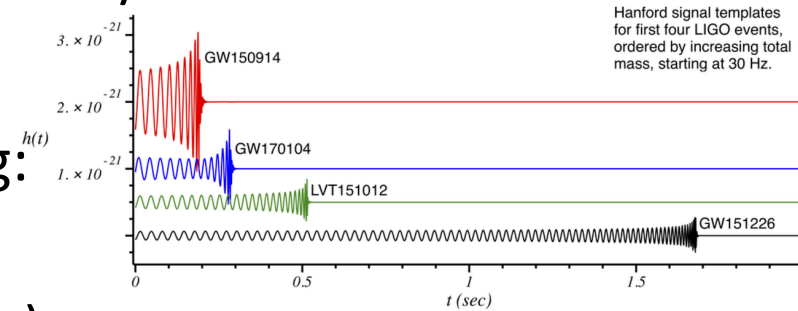
Same as above except a time-shift of 78 milliseconds was added to the Hanford signal corresponding to two detectors separated by two Earth diameters.

00:00 00:00

Stereo sound corresponding to the top plot above. The Hanford signal is time shifted to model the effect of two detectors on opposite sides of the Earth. (Headphones or good speakers recommended.)

00:00 00:00

Stereo sound corresponding to two detectors separated by two Earth diameters. One can clearly hear the sound in the right ear, followed by the sound in the left. (Headphones or good speakers recommended.)



Hanford signal templates for first four LIGO events, ordered by increasing total mass, starting at 30 Hz.

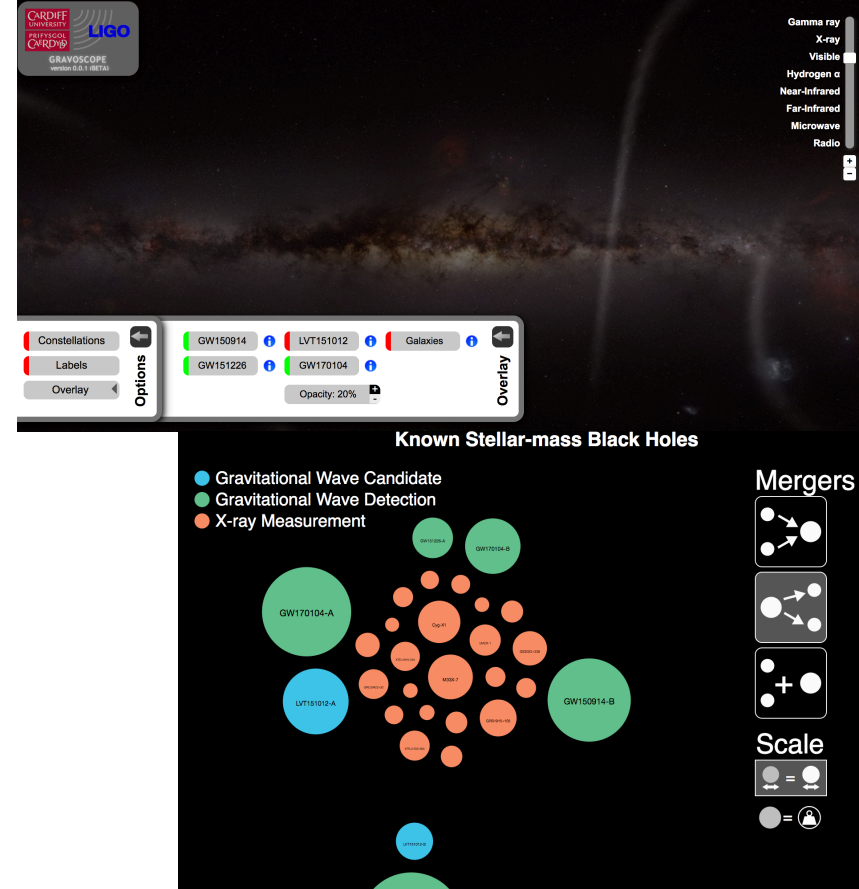
Hanford waveform models for all LIGO events so far, ordered by increasing total mass (lower masses on bottom). [Data courtesy of Ben Farr and the LIGO team.]

00:00 00:00

Stereo audio of first four LIGO events in order of decreasing mass: GW150914, GW170104, LVT151012, GW151226. Signal starts at 30 Hz. Volume is scaled in proportion to signal amplitude. (Hanford/left, Livingston/right; headphones or good speakers recommended.)

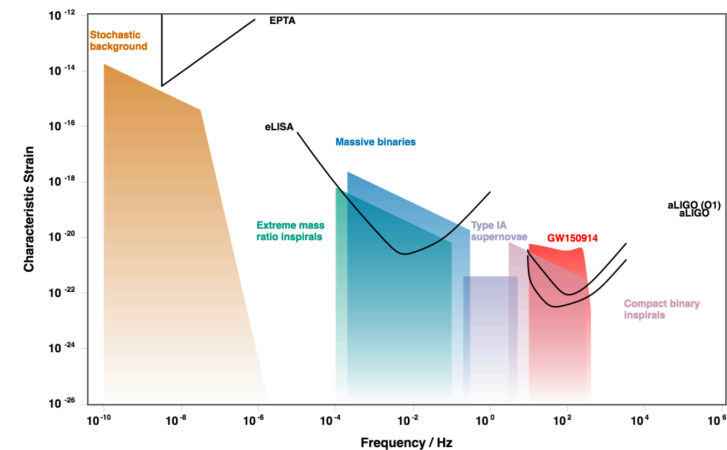
other interactive websites

- *gravoscope*
interactive skymap (Cardiff U.)
<http://astrog80.astro.cf.ac.uk/Gravoscope/>
- Known BH Masses
interactive figure (Cardiff U.)
<https://gravity.astro.cf.ac.uk/plotgw/bhbubble.html>
- GW sensitivity curve plotter
(U. Cambridge)
<http://rhcole.com/apps/GWplotter/>



Gravitational Wave Detectors and Sources

By Christopher Moore, Robert Cole and Christopher Berry from the Gravitational Wave Group at the Institute of Astronomy, University of Cambridge



Thorlabs collaboration

- Developed Michelson interferometer kit; sturdy, high-quality (\$2648). Good for upper-level undergrad lab courses. Contributed discussion of LIGO to product manual.

https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10107

- future work: LSC members working with Thorlabs to develop lower-cost demo interferometer (<\$500), as well as more advanced add-ons for the existing Michelson kit.

The screenshot shows the Thorlabs website product page for the Michelson Interferometer Educational Kit. The page features a red header with the Thorlabs logo and navigation links. The main content area includes a product image of the kit, a list of features, and a detailed description of its application in gravitational wave detection. A sidebar on the right lists related items like laser modules and mirror mounts. A navigation bar at the bottom highlights the 'Interferometry and LIGO' section.

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Products Home / Thorlabs Discovery - Educational Products and Kits / Michelson Interferometer Educational Kit

Michelson Interferometer Educational Kit

- ▶ Designed for Education, Demonstration, and Classroom Use
- ▶ Easy-to-Use Kits Include Components Plus Educational Materials

THORLABS Discovery

LASER RADIATION
DO NOT STARE INTO BEAM
CLASS 2 LASER PRODUCT

Related Items

- Education Kits
- Laser Modules
- Standard Kinematic Mirror Mounts
- Fixed Optic Mounts

Overview Experiments Kit Components **Interferometry and LIGO** Kit Comparison Feedback

Gravitational Wave Detection with Michelson Interferometers

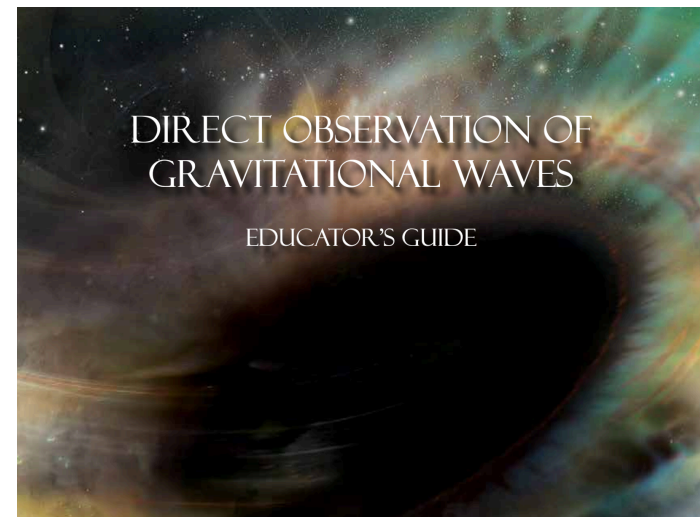
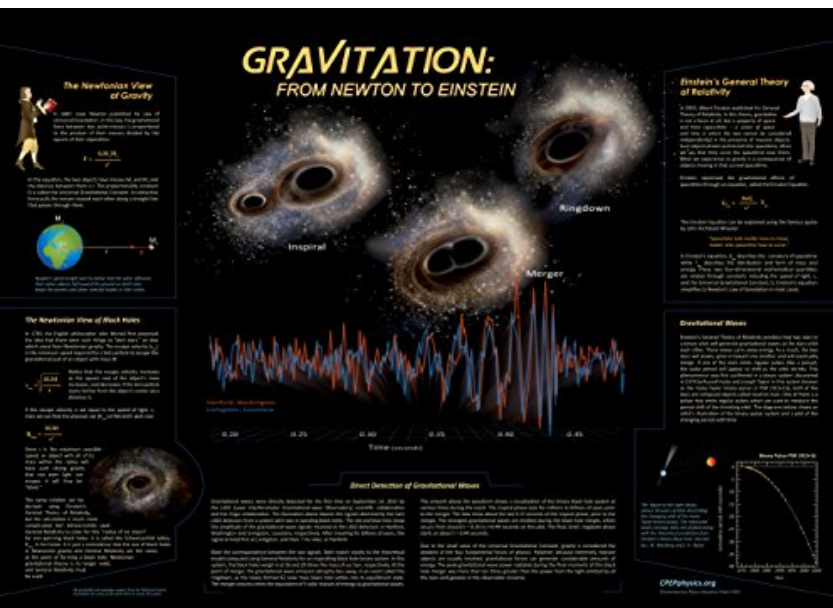
A recent application of the Michelson interferometer that attracted a lot of international attention is gravitational-wave detection. Gravitational waves are oscillations in spacetime curvature produced by colliding black holes, neutron stars, and other astrophysical processes that involve a dense concentration of mass-energy moving at relativistic speeds. A network of laser interferometers has been constructed in several countries to detect these waves. This includes the Laser Interferometer Gravitational-wave Observatory (LIGO) in the United States, VIRGO in Italy, GEO600 in Germany, and KAGRA in Japan. All of these experiments consist of a Michelson interferometer with kilometer-scale arm lengths. The mirrors are suspended and free to swing in the plane of the interferometer. A passing gravitational wave will shrink the mirror-beamsplitter distance in one arm of the interferometer while stretching that distance in the other arm. The oscillating shrinking/stretching pattern induced by the passing wave is recorded as an oscillating signal in the photodetector.

On September 14, 2015 the twin LIGO detectors (in Washington state and Louisiana) made the first direct detection of a gravitational wave. The signal (which was measured with high confidence in both detectors) was produced by an orbiting pair of black holes that merged together about a billion light years away. This signal caused the LIGO mirrors to move by about 10^{-18} meters, or nearly one-thousandth the diameter of a proton. Michelson interferometers can thus perform some of the most sensitive length measurements possible. LIGO and its partner observatories are vastly more complicated than the interferometer in this kit, but the fundamental physical principle behind their operation is Michelson interferometry.

Once the Michelson interferometer is assembled, it can be used as a simple classroom demonstration of the operating principles behind gravitational-wave detectors like LIGO, Virgo, and GEO600. In those kilometer-scale interferometers the mirrors are free to swing in the plane of the interferometer. Those waves shrink one arm of the interferometer while stretching the other arm. In this kit, the mirrors do not swing, but the effect of a gravitational wave can be mimicked by a local oscillating mirror.

Online courses on GWs

- developed by Lynn Cominsky and collaborators at Sonoma State Univ; <https://universe.sonoma.edu/cosmo/>
- lecture notes + exercises.
- good for training undergrads in GWs.
- also educator's guide (for ~middle school); <https://dcc.ligo.org/LIGO-P1600015/public>
- Gravitation poster for CPEP (Contemporary Physics Education Project); <http://www.cpepweb.org/>



Resource collections

- www.astro.cornell.edu/~favata/gwresources.html
- www.astro.cornell.edu/~favata/outreach.html
- wiki.ligo.org/LAAC/WebHome
- ligo.org/detections.php
- coming soon: new resource letter on gravitational waves in American Journal of Physics.

gravitational-wave resources

This page is meant to provide a resource for beginning students who are interested in learning more about general relativity (GR) and gravitational waves (GW). It is not meant to be a comprehensive listing, but merely a collection of books, articles, and other resources that I have found useful. Enjoy!

Fast ways to learn about GR:

- Read chapters 5, 12, and 16 of Shapiro & Teukolsky's "Black Holes, White Dwarfs, and Neutron Stars". While you won't appreciate all the details, this is the fastest way I know of to gain a concise understanding of GR, black holes (BH), and GWs.
- The second fastest way is to read Chapters 1, 2, and 24–27 of Blandford and Thorne's "Applications of Classical Physics". This (soon to be published) book, which formed the basis of the Ph136 course at Caltech, is an immense resource for not only relativity but also statistical physics, optics, elasticity, fluid mechanics, and plasma physics. It is a modern-day version of the Landau–Lifshitz series (focused on classical physics).
- Richard Price's article titled "General relativity primer" in the American Journal of Physics provides a nice concise description of GR. See also the related [comment by Tryon](#).

Great introductory text books on GR

- Schutz's "A first course in general relativity" is an excellent introductory book that I primarily used to learn GR. It follows the standard (tensors-first) approach.
- Hartle's "Gravity: An introduction to Einstein's general relativity" is considered by many to be the best book for learning GR. It takes a "physics-first" approach, delaying the introduction of tensors. I used this in teaching an undergrad GR course.
- A General Relativity Workbook, by Thomas Moore is excellent. It closely follows but slightly improves upon Hartle's text. It introduces a bit more tensor analysis in the beginning, presents each topic in concise chapters, and leads the student through all derivations. Much of the text contains partly blank pages where the student must fill in derivations and hand them in to the instructor. This is part of Moore's attempt to increase students' classroom engagement and reduce lecturing. I plan to use this the next time I teach GR.

Conclusions:

- LSC EPO group has been developing a wide variety of resources.
- Useful for informing the public, educating students (including undergrads), and providing resources for web and print media.
- **Suggestions for us?**
What resources would you like to see developed?
New ways to disseminate our materials?
New audiences to reach?