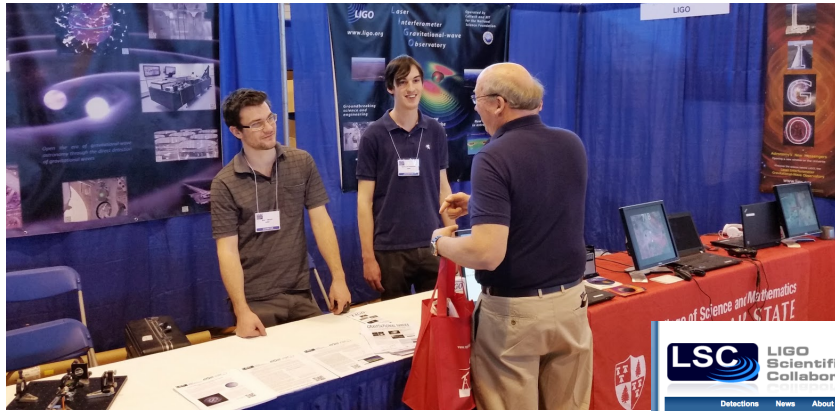


# Overview of Education and Public Outreach (EPO) Activities of the LSC

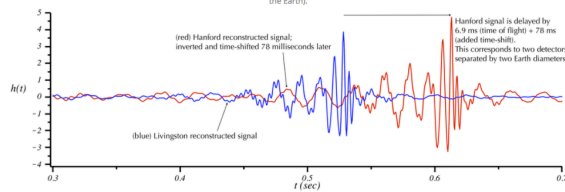
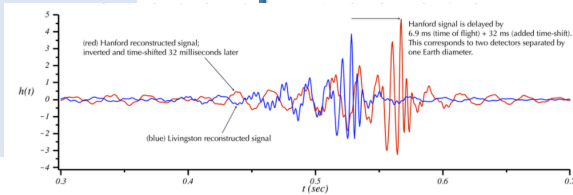


Home Español site MagyarHungarian site LSCInternal

**LSC** LIGO Scientific Collaboration

Detections News About LIGO science Educational resources Multimedia For researchers LIGO Lab site

## LIGO detects gravitational waves from third confirmed binary black hole merger



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.)



## 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 **spinning 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 <https://arxiv.org/abs/1601.06963>.

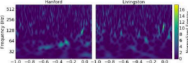
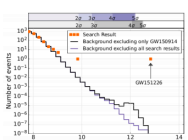


Figure 1: Plot from Figure 1 of our publication. The gravitational wave event GW151226 is observed by the two Advanced LIGO detectors with changing time and phase between sites. The signal, after it has been corrected by the detectors during the time synchronization step, is shown in red in a plot of strain  $h(t)$  versus time  $t$  (seconds). The blue line shows the detector noise after a few minutes of noise. The blue and red lines are the detector noise after a few minutes of noise. The blue and red lines are the detector noise after a few minutes of noise. The blue and red lines are the detector noise after a few minutes of noise.



Marc Favata  
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 from EPO 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.

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, SACNAC, Exhibition, White House Frontiers Conference
- **booths at professional meetings:** APS, IAU, Royal Society Summer Exhibition
- **government outreach:** brainstorming meeting after last APS meeting.



# General EPO activities

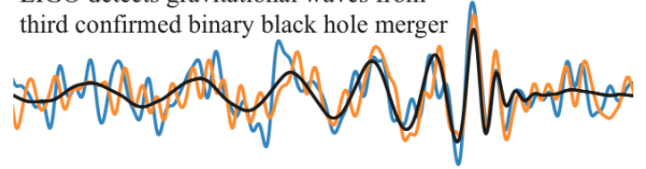
- organize press and media materials for LIGO discoveries
- developing printed or online materials on GW science
- teacher professional development: develop materials to integrate GW science into curricula at all levels; online courses for teachers.
- REU (research experiences for undergraduates) programs 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](mailto: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 detects gravitational waves from third confirmed binary black hole merger



### 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 Lettering for the background of gravitational waves with Advanced LIGO

### PRESS RELEASES

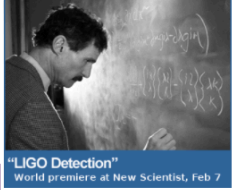
- May 31, 2017 LIGO Detects Gravitational Waves for Third Time
- Jun 15, 2016 Gravitational Waves Detected from Second Pair of Colliding Black Holes
- Feb 11, 2016 Gravitational Waves Detected 100 Years After Einstein's Prediction

### GET INVOLVED

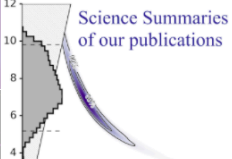
**Gravity Spy**

Help classify noise glitches in LIGO data

Search for gravitational waves and pulsars with your computer



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



# 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 products of the EPO group
- general info about the LSC

LSC LIGO Scientific Collaboration

Detections News About LIGO science Educational resources Multimedia For researchers LIGO Lab site

### 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
- GW151226
- GW150914 (First detection)

### GENERAL DETECTION RESOURCES

#### DOCUMENTS, WEBSITES, & MULTIMEDIA

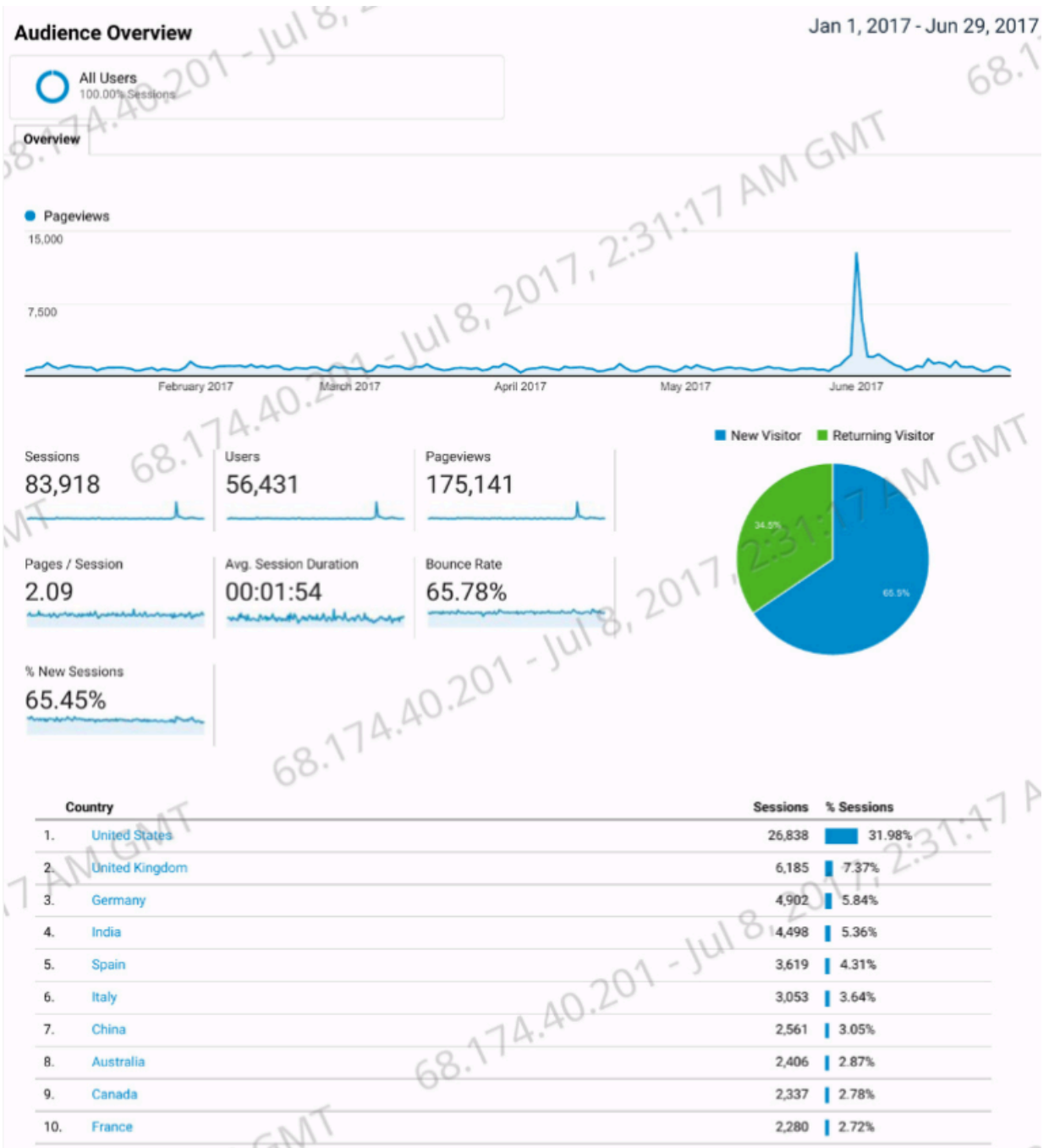
- Full list of LSC Publications. (See Runs O1 and higher for papers following the first detection.)
- Science Summaries
- LIGO Open Science Center (LOSC): Download LIGO data or explore tutorials on LIGO data analysis. See also their [data release page](#) for links to audio of LIGO events.
- Timeline 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 [mp3 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, into a 3.6-solar-mass black hole. The top two plots show data received at Livingston and Hanford, along with the predicted shapes for the waveform. 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

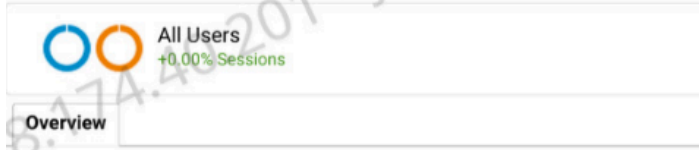
New Population of Binary Black Holes. LIGO has discovered a new population of black holes with masses that are larger than what had been seen before with X-ray studies alone (purple). The three confirmed detections by LIGO (GW150914, GW151226, GW170104), and one lower-confidence detection (LV17151012), point to a population of stellar-mass binary black holes that, when merged, are larger than 20





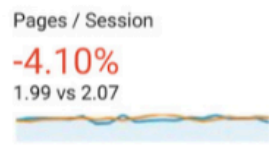
### Audience Overview

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



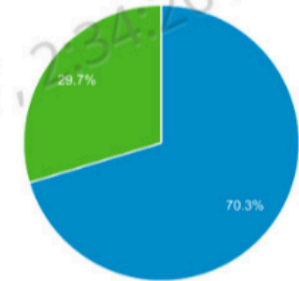
May 22, 2017 - Jun 10, 2017: ● Pageviews

May 2, 2017 - May 21, 2017: ● Pageviews

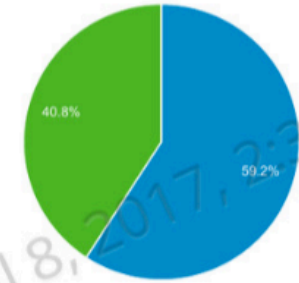


■ New Visitor ■ Returning Visitor

May 22, 2017 - Jun 10, 2017



May 2, 2017 - May 21, 2017



The screenshot shows the LIGO Scientific Collaboration website. At the top, there are navigation tabs for 'Detections', 'News', 'About', 'LIGO science', 'Educational resources', 'Multimedia', 'For researchers', and 'LIGO Lab site'. Below this is a section titled 'SUMMARIES OF LSC SCIENTIFIC PUBLICATIONS' with a sub-section 'DETECTION PAPERS'. It lists several papers, including GW170104, GW151226, and GW150914, with brief descriptions and links to the full papers. A photo on the right shows two people looking at the LIGO Hanford Observatory. Below the photo is a caption: 'Visitors at LIGO Hanford Observatory gaze down the site's X arm. Half of the 4-kilometer length of the arm is visible in the photo. (Credit: LIGO Laboratory)'.

# 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 team and further edited by EPO.
- translations (~5 languages) for detection summaries.
- ~66 summaries since 2011.



## 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 Observatory. 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 (referred 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 [Physical Review Letters](#).

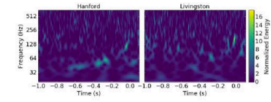
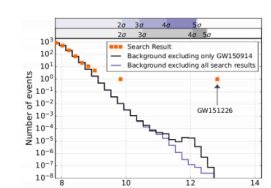


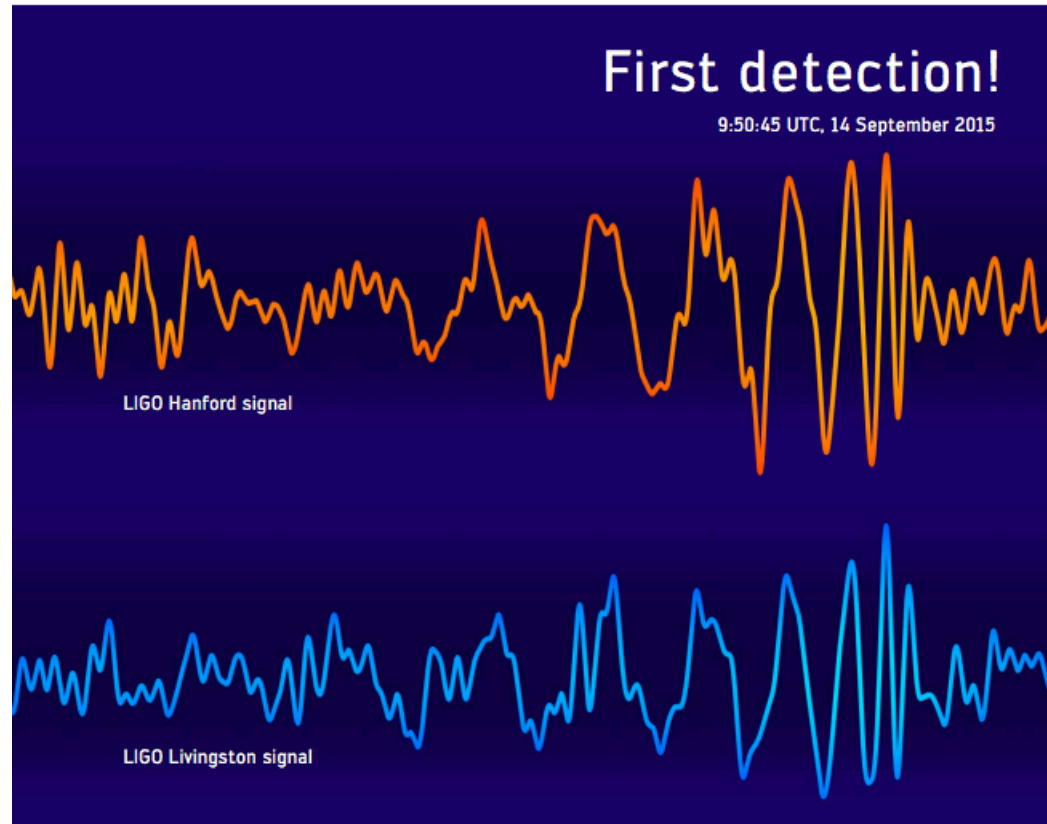
Figure 1. (Adapted from Figure 1 of our publication). The gravitational wave event GW151226 is observed by the twin Advanced LIGO detectors (LIGO) (red and blue) (animation right). The region shows the data received by the detectors during the last second before merger as the signal arrives at a detector as a function of time and frequency. To verify that a real gravitational wave has been observed, we compare the data from the detectors against a pre-defined model for merging binaries. To check us to the gravitational wave signals which are buried deep in the noise from the instruments and search pipelines to find the one. The computer system (the search) can see whether there is a detector that will receive something in this region. Most gravitational waves are detected by a much easier to identify. The signal can be seen searching at a frequency in the two detectors from some together. The signal is much easier to spot by eye than the first detector.



# ligo magazine

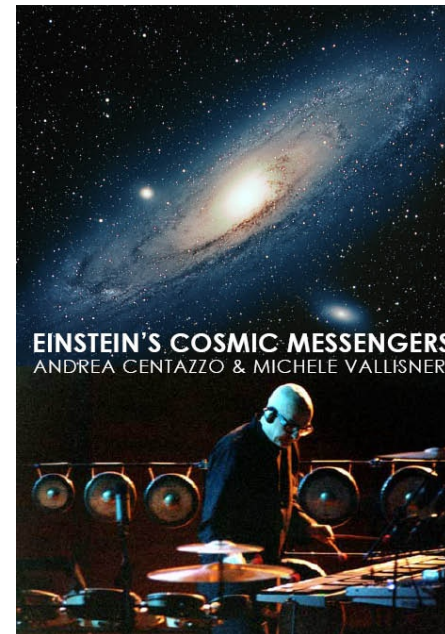
- published twice per year
- highlights news, research, events, personal stories from within the LSC.
- focused on internal LSC audience, but useful to others in GW community.
- 10 issues so far.

## LIGO MAGAZINE issue 8 3/2016



# museum and artistic exhibits

- traveling exhibit: “Astronomy’s New Messengers”
- <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://www.epcmusic.com/space>  
GWs & exoplanets music project (Arther Jeffees)
- “Chasing the waves” musical comedy (Glasgow).



# social media

LSC promotes LIGO news and EPO activities via facebook and twitter.

**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.

A Facebook post from the LIGO Scientific Collaboration. The post features a green LIGO sign on the left and a waveform graph on the right. The graph shows two overlapping waveforms, one orange and one blue, with a black line representing the combined signal. The text 'GW170104' is at the top right. Below the graph, there are interaction buttons for 'Liked', 'Following', 'Share', and 'More'. The profile name 'LIGO Scientific Collaboration' and handle '@LigoScientificCollaboration' are visible.

A Twitter post from the LIGO Scientific Collaboration. The post features a circular LIGO sign on the left and a waveform graph on the right. The graph shows two overlapping waveforms, one orange and one blue, with a black line representing the combined signal. The text 'GW170104' is at the top right. Below the graph, there are statistics: 2,779 tweets, 138 following, 44.6K followers, 559 likes, and 1 list. The tweet text reads: 'I am the Laser Interferometer Gravitational-wave Observatory. I look for space-time ripples.' The tweet is dated 11 Feb 2016 and includes hashtags #GravitationalWaves, #BinaryBlackHole, and #EinsteinWasRight.

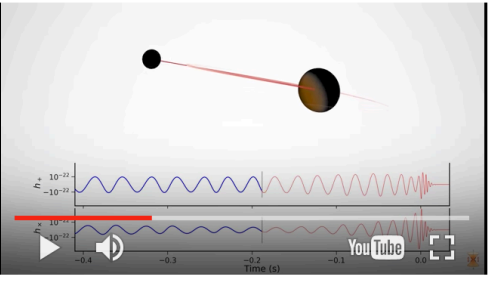
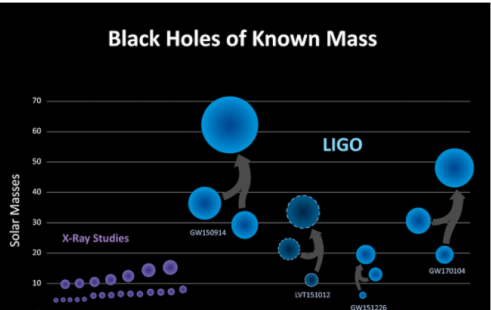
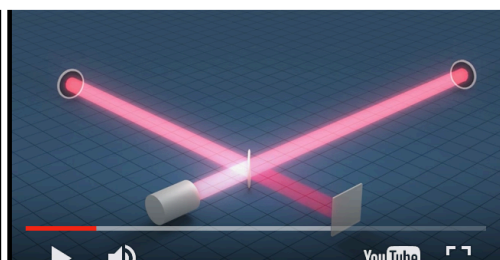
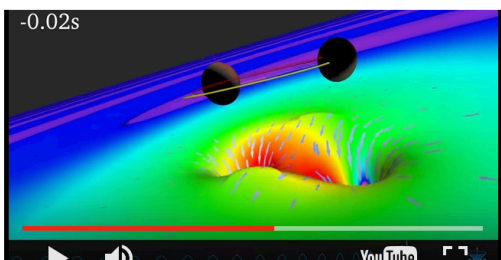
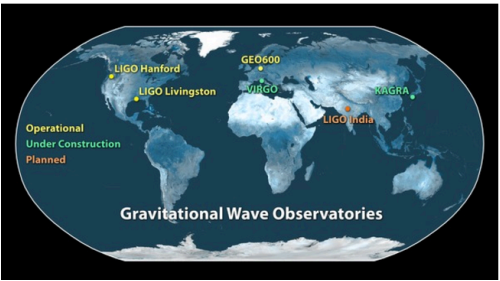
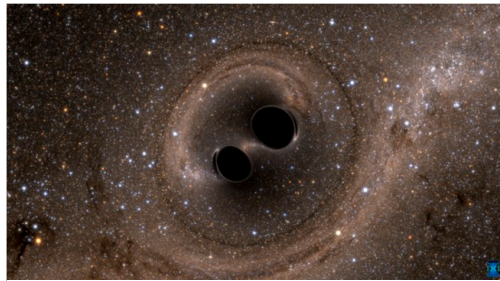
A YouTube page for LIGO Virgo. The page features a video player with a waveform graph. The video title is 'LIGO Virgo'. Below the video player, there are navigation buttons for 'Home', 'Videos', 'Playlists', 'Channels', and 'About'. The page also includes a 'What to watch next' section with recommendations for other LIGO-related content.

A Reddit post from the LIGO Scientific Collaboration. The post features a waveform graph. The post title is 'LIGO: Generations | A film by Kai Staats by LIGO Virgo'. Below the graph, there are statistics: 45 views, 2 months ago. The post is categorized under 'Science' and 'Military'. The post text reads: '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!' The post is submitted 1 year ago by LIGO\_Collaboration.

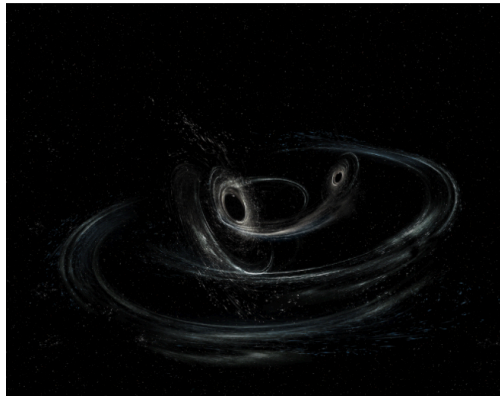
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# detection-related multimedia products:

- videos, animations, NR simulations, interview clips.
- figures, images, and artists' illustrations for use by media.
- available at [ligo.org](http://ligo.org), [ligo.caltech.edu](http://ligo.caltech.edu)



Animation of the inspiral and collision of two black holes



# films:

- 3 LIGO films by Kai Staats (Over the Sun LLC)
- “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/>



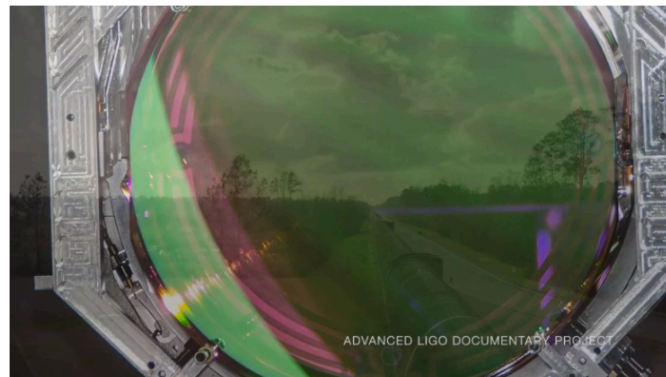
**LIGO Detection**

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.

Getting Started  
Tutorials  
Data  
  Events  
  Bulk Data  
Timelines  
My Sources  
Software  
GPS ↔ UTC

Welcome to the LIGO Open Science Center

About LIGO  
Get Started with LIGO data  
Join the E-mail list for updates  
For general information on LIGO, please visit [ligo.org](http://ligo.org)  
If you have LSC credentials, you may go to the [development site](#)

Discoveries from the LIGO detectors!

released 2017 June 1:  
Event of January 4, 2017: GW170104: total mass 50

## key products:

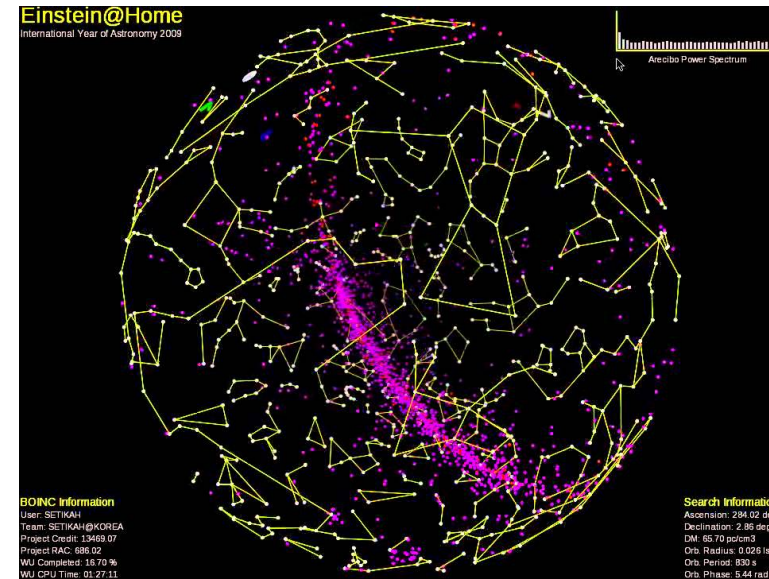
- h(t) data segments near detected events
- past (S5, S6) and future data releases for science/observing runs.
- some data from publication figures.
- documentation and software tools for using data.
- python-based tutorials: play with the data to extract detected signal.
- ~100 users/day



# Citizen science: Einstein@home



- distributed computing project; analyzes data during computer's idle time.
- search for continuous GWs from spinning neutron stars. Also look for new pulsars in radio or gamma-ray data.
- Key results: FILL IN



# 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

GRAVITY SPY ABOUT CLASSIFY TALK COLLECT BLOG

LIGO has announced its third gravitational-wave event! Look for a special surprise when classifying on workflow Neutron Star Merger and above.

Help scientists at LIGO search for gravitational waves, the elusive ripples of spacetime.

Learn more Get started

Frequency (Hz) Normalized energy

Frequency (Hz) Normalized energy

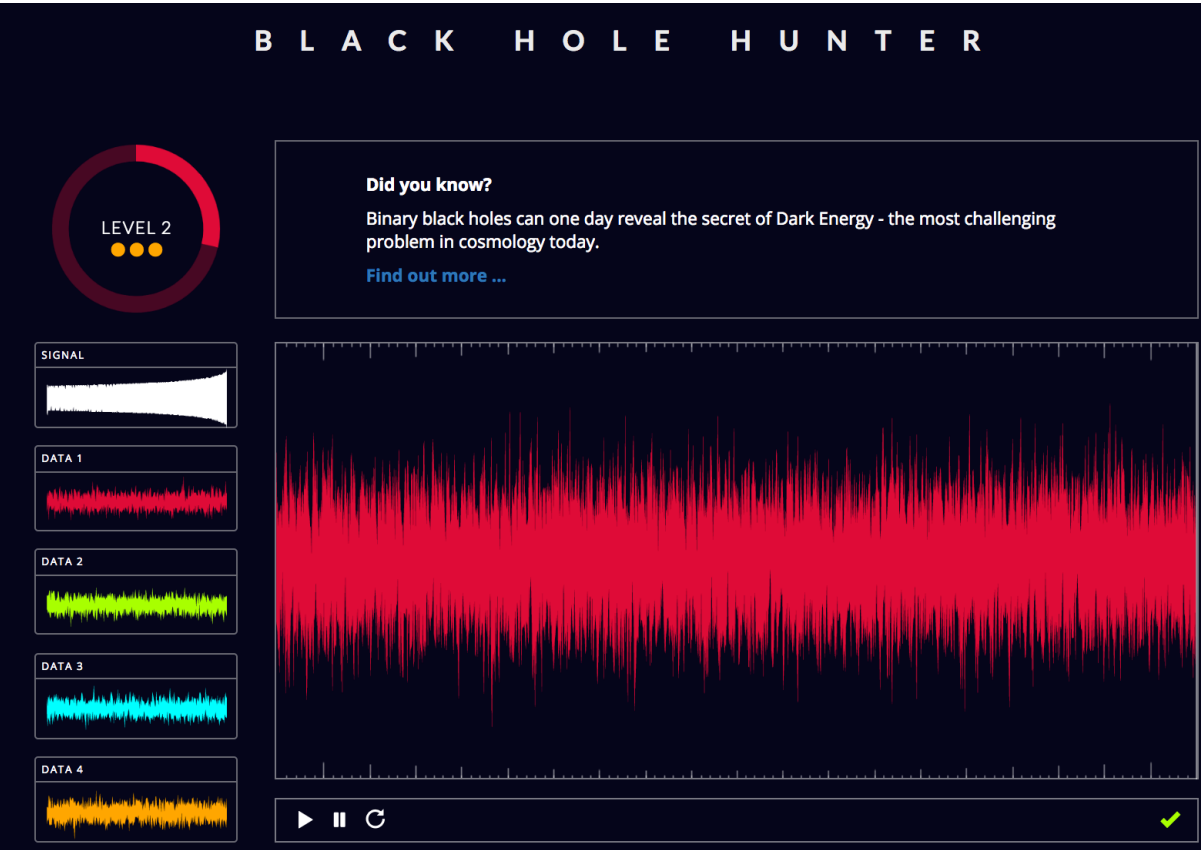
Frequency (Hz) Normalized energy

6 people are talking about Gravity Spy right now.

Join in

# Games & apps

- 4 games/apps developed by LaserLabs/gwoptics.org (U. of Birmingham)
- Black Hole Hunter (Cardiff. U.)



## Latest Games and Apps

Our apps and games that we use for social media on 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.



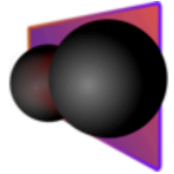
**Stretch and Squash**  
Stretch and Squash distances between objects to be stretched and squashed.



**Space Time Quest**  
In Space Time Quest you can see the technology for your own hall of fame.

## Under Development

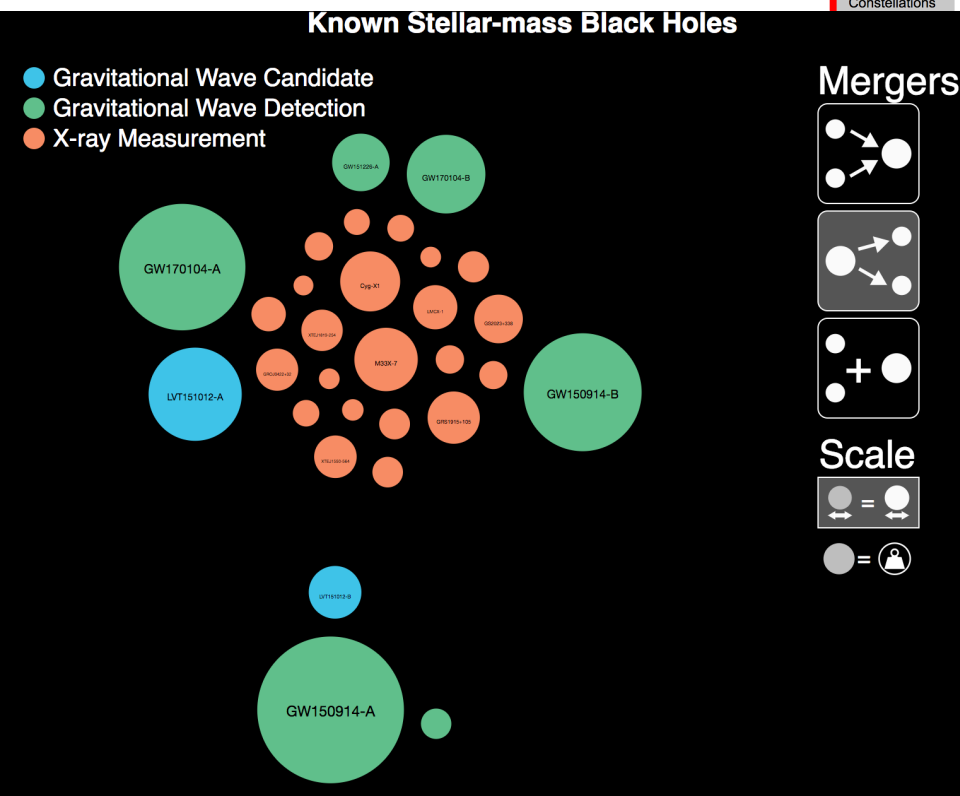
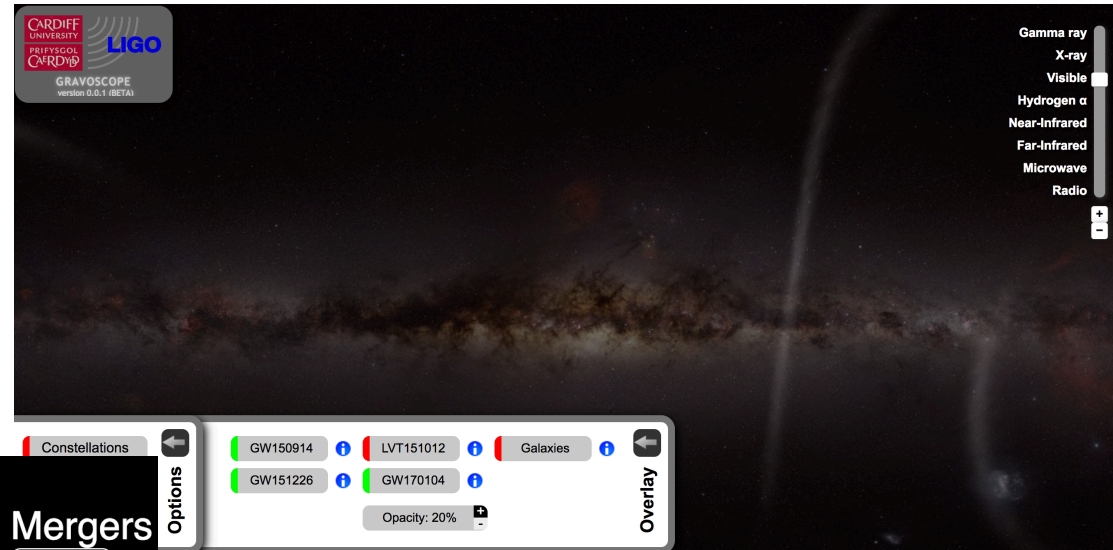
Apps we are working on right now are listed below. We don't know when these apps will become available.



**Black Hole Master**  
An fast arcade-style game with a single opponent, using only Newtonian physics. Development in the N-body simulation is still available.

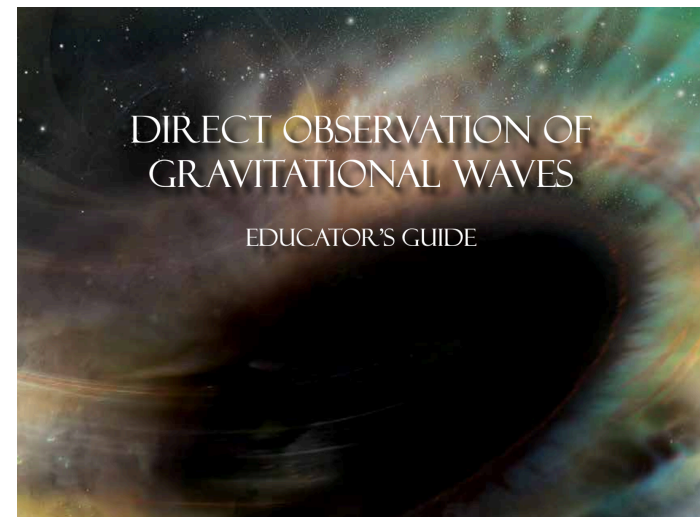
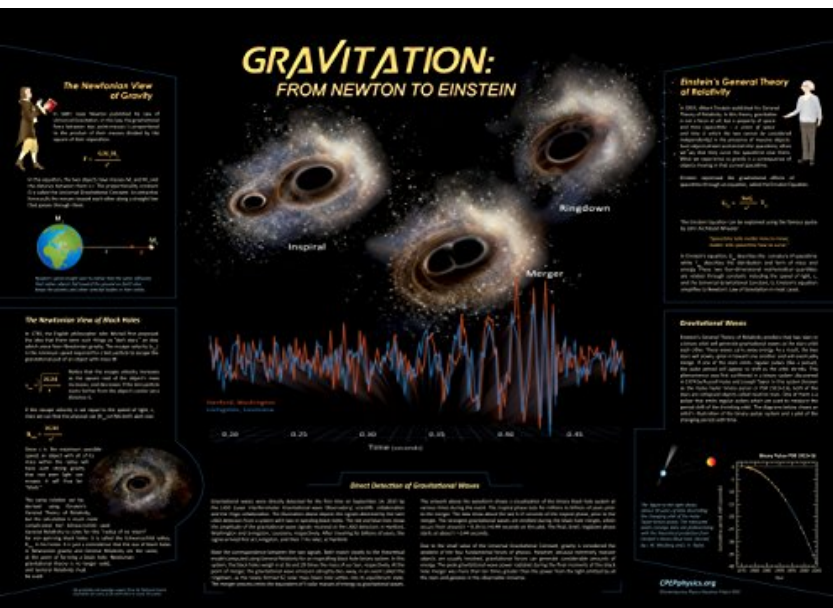
# other interactive websites (Cardiff U.)

- gravascope interactive skymap
- Known BH Masses interactive figure



# 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) ADD dcc LINK
- Gravitation poster for CPEP (Contemporary Physics Education Project); <http://www.cpepweb.org/>



# Thorlabs collaboration

- Developed Michelson interferometer kit; sturdy, high-quality (\$2648). Good for upper-level undergrad lab courses. Contributed discussion of LIGO to product manual.
- 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 displays the Thorlabs website interface for the Michelson Interferometer Educational Kit. The top navigation bar includes the Thorlabs logo, a search bar, and links for account creation and login. Below this is a secondary navigation menu with categories like Products Home, Rapid Order, Services, The Company, Contact Us, and My Thorlabs. The main content area features a large product image of the kit with various components like mirrors, beam splitters, and a laser. Text on the page highlights that the kit is designed for education and includes easy-to-use components. A sidebar on the right lists related items such as Education Kits, Laser Modules, and Kinematic Mirror Mounts. At the bottom, there is a section titled 'Gravitational Wave Detection with Michelson Interferometers' which provides a detailed explanation of how these devices are used in advanced scientific experiments like LIGO and Virgo.

**THORLABS** Create an Account | Log In Search (0) \$ Dollar ENGLISH

Products Home Rapid Order Services The Company Contact Us My Thorlabs

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. In this kit, the mirrors do not swing, but the effect of a gravitational wave can be mimicked by a local

# Resource collections

- [www.astro.cornell.edu/~favata/gwresources.html](http://www.astro.cornell.edu/~favata/gwresources.html)
- [www.astro.cornell.edu/~favata/outreach.html](http://www.astro.cornell.edu/~favata/outreach.html)
- [wiki.ligo.org/LAAC/WebHome](http://wiki.ligo.org/LAAC/WebHome)
- [ligo.org/detections.php](http://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.

# 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.



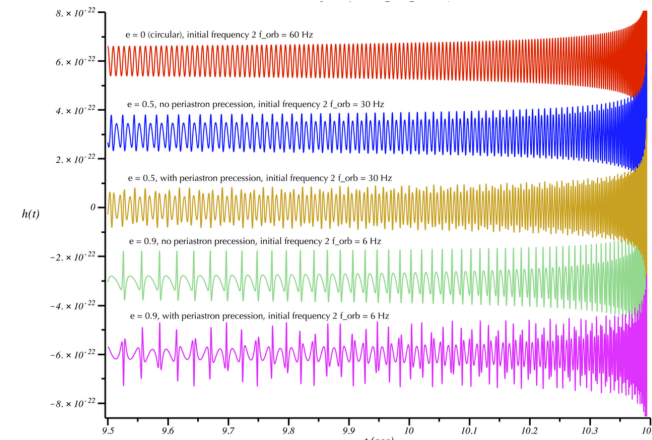
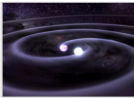
## Welcome!

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 by 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.



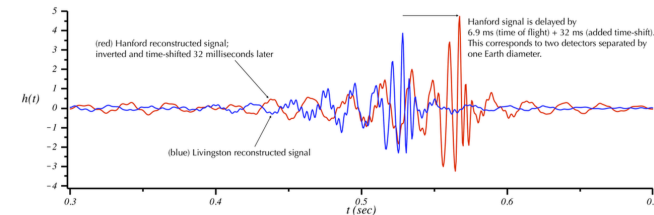
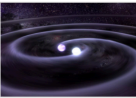
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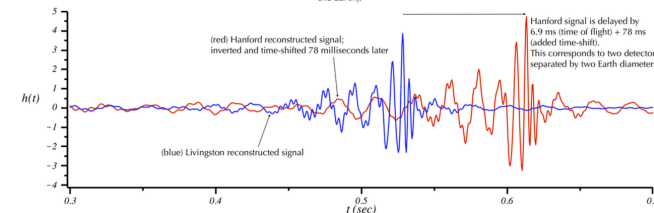
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Similar to the above two plots except an additional time-shift has been added to the Hanford signal (corresponding to two detectors on opposite sides of the Earth).



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.)

# 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?