

# Doing outreach with the first direct observation of gravitational waves

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# Outline

- The first two direct detections of gravitational waves (GWs)
  - GW150914
  - GW151226
- Discovery announcement
  - Players
  - Audiences
  - Strategy
  - Means & difficulties
  - Results
- Outreach resources
- Activities
- Outlook

**Caveat: many E&O actions are done at the institution level: they are not covered here.**

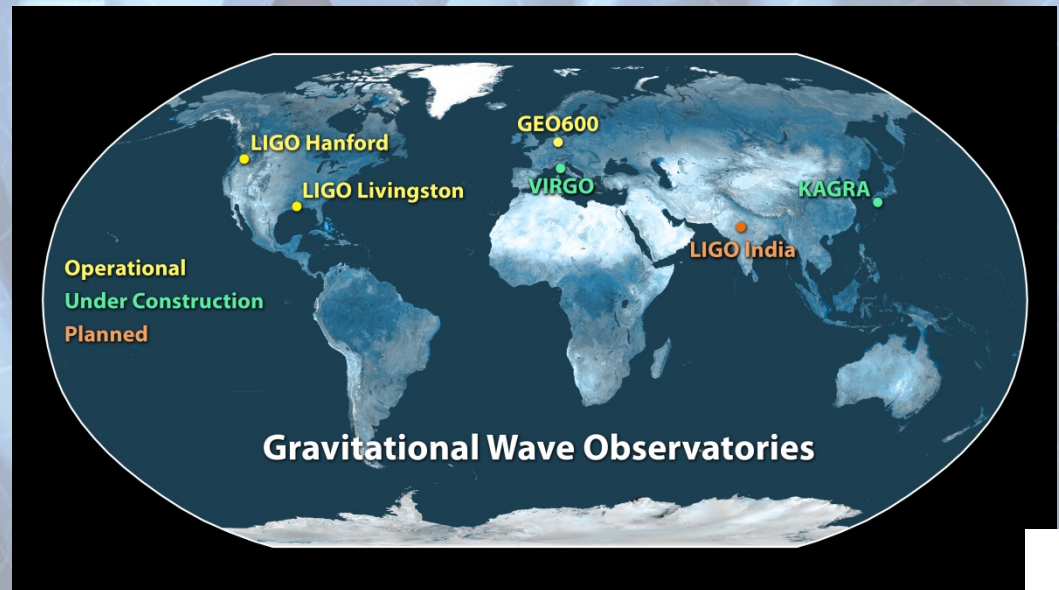
NATURE PHYSICS | VOL 12 | JUNE 2016 | [www.nature.com/naturephysics](http://www.nature.com/naturephysics)

commentary

## Defining gravity

Joey Shapiro Key and Martin Hendry

The announcement confirming the discovery of gravitational waves created sensational media interest. But educational outreach and communication must remain high on the agenda if the general public is to understand such a landmark result.

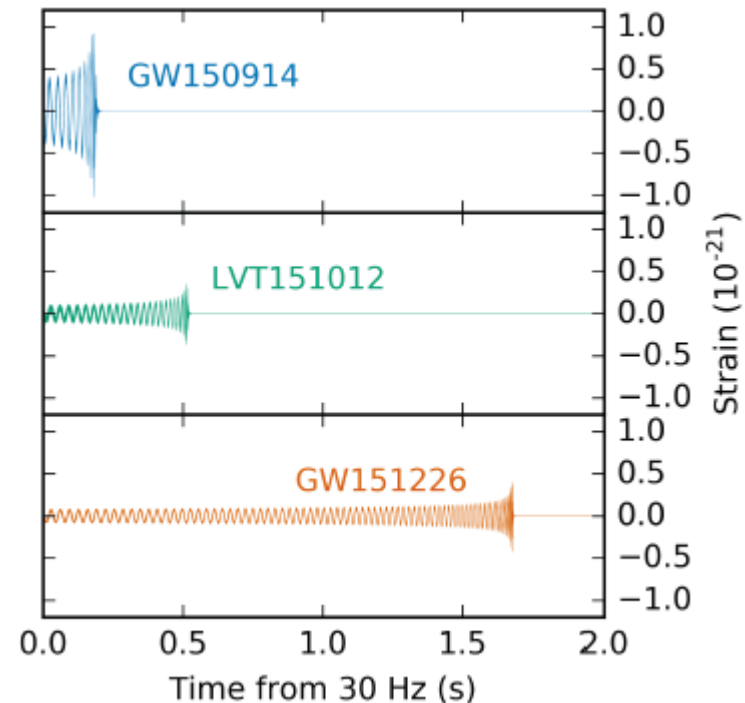


# First direct detections of gravitational waves

- Two **binary black hole (BBH) coalescences**
  - Recorded by the two Advanced LIGO detectors
  - Announced by the LIGO Scientific Collaboration and the Virgo Collaboration

Event	Recorded	Announced
<b>GW150914</b>	2015/09/14	2016/02/11
GW151226	2015/12/26	2016/06/15

- Plus a BBH candidate, LVT151012
- **First direct detection of GWs**
- **First direct detection of BHs**
- **First detection of BHs in this mass range**
- **First detection of BBHs**



- More information
  - **Astro-particle Physics and Cosmology parallel session**  
“Gravitational Wave Detection: Present and Future”
  - **Plenary talk**
  - **Public lecture**

[This morning]  
[Monday morning]  
[Tuesday night]



# Preparing the discovery announcement

- **GW150914**

- 3 minutes after data recorded: event identified online as **promising**
- Within a day: **strong BBH candidate**



Extensive data analysis to **make the detection case rock-solid**

**Communication & outreach: all hands on deck!**

→ **Education and Public Outreach (EPO) working group**

- **5 months later: detection announcement**

- **Many players involved**

- **LIGO** Observatories  
  **GEO600** Collaboration  
  **LIGO Scientific Collaboration**
- **Virgo** Collaboration  
  **European Gravitation Observatory (EGO)**

1000+ scientists

→ LVC: **LIGO-Virgo Collaboration** (MOU, 2007)

- **Funding agencies** (USA, UK, Germany, Spain, France, Italy, etc.)
- **Labs & universities**

# Discovery announcement strategy

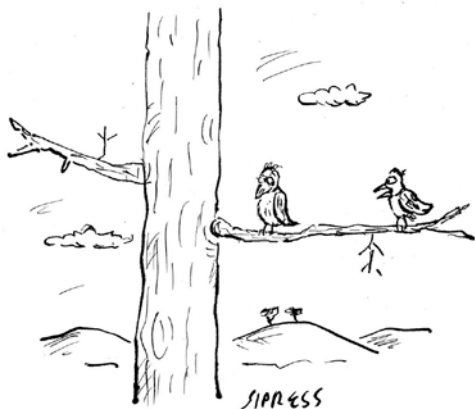
- **Keep everything secret/internal to the LVC**
  - Any analysis/check could turn the promising GW candidate into a false alarm
    - **Hope for no (major) leak**  
If any, use the (true!) reply:  
analysis in progress, results to be made public when analysis complete
  - In the end: minor annoyance, no change of plan needed
- **Target different audiences**
  - **Scientific community**
    - GW discovery = completion of a century-long quest
  - **General audience**
    - Little or no scientific knowledge
  - **High-school teachers and students**
- Develop a **wide set of educational resources**
  - From basic schematics and analogies, to science summaries of publications
- Use **social media** to promote the scientific results and the associated E&O
  - **Twitter, Facebook, Reddit**
- **Reference: announcement of the H boson discovery by the LHC experiments**

# Discovery announcement strategy

- Write a **discovery article**
  - Have it **accepted by PRL prior to announcing the discovery**
    - **Target date: February 11**, first day of the AAAS Annual Meeting in D.C. (American Association for the Advancement of Science)
- Plus several « **companion papers** » focusing on the various aspects of the analysis
- **Simultaneous announcements worldwide**
  - **Two main press conferences**: Washington D.C. (LIGO) & Cascina (Virgo site)
  - **Several satellite press briefings** – e.g. CNRS headquarters, Paris
- **At what time?**
  - Beware of time zone differences! **Compromise: 10.30 US EST**
    - Early on the West Coast (07:30), quite late in Europe (16:30) for evening news
- **Coordinated press releases**
  - **Compulsory parts**, which must be included in all press releases
    - In particular: **common start for all releases**
  - **Additional text** written at the discretion of the organization issuing the release
    - **Translation in as many languages as possible**

# GW150914 announcement: facts and figures

- Among the **Newseum front page archives** <http://www.newseum.org>
  - One of the few positive events listed...
- **200+ journalists followed the announcement**
  - Either in person or through webcasts
- **O(5,000) press articles** in the world
  - From daily newspapers to magazines
- **> 500,000 internet users watched webcasts**



*"Was that you I heard just now, or was it  
two black holes colliding?"*

© The New Yorker 2016/02/12

## Orlando Nightclub Shooting

June 14, 2016

June 13, 2016

## Muhammad Ali, 1942-2016

June 11, 2016

June 5, 2016

## Journalists Memorial Rededication

June 6, 2016

June 8, 2015

## Prince Dies

April 22, 2016

## Terrorists Attack Brussels

March 23, 2016

## Ronald (1911-2004) and Nancy (1921-2016) Reagan

March 7, 2016

June 6, 2004

## Justice Antonin Scalia Dies

Feb. 14, 2016

## Discovery of Gravitational Waves

Feb. 12, 2016

## San Bernardino Shooting

Dec. 4, 2015

Dec. 3, 2015

**961 front pages**



# GW150914 announcement: facts and figures

## • Twitter

- 70 million impressions for #gravitationalwaves, #LIGO, and #EinsteinWasRight
- 10 million for #ondesgravitationnelles
- Followers!
  - @ligo: < 3,000 → 25,000+ (after GW151226)
  - @ego\_virgo: < 100 → 1,000+
- Mentions/retweets/likes from celebrities → e.g. @POTUS

## • Facebook

- New followers as well: 9K for LIGO, 1K for Virgo

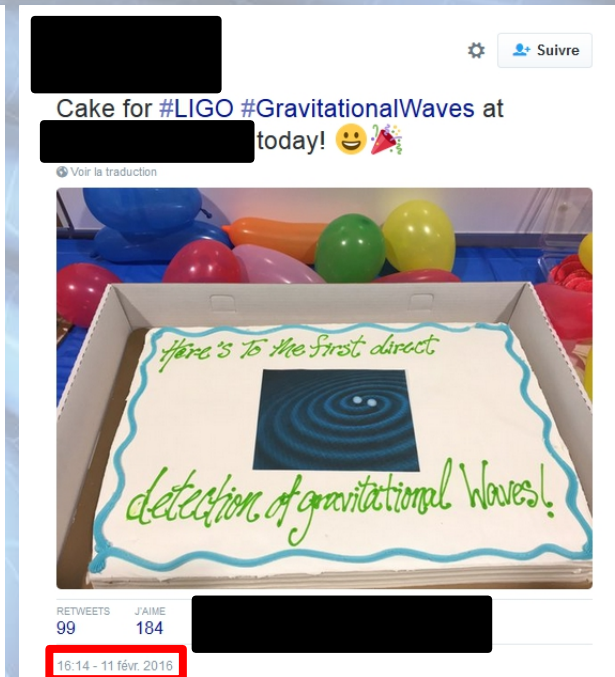
## • Reddit

- AMA (Ask Me Anything) live sessions following both announcements

## • Astronomy Picture of the Day

- 1M+ views in the week following GW150914

## • No Google doodle (yet!?)





# GW150914 announcement: facts and figures

- Press release translated into 18 languages
- Multilingual science summaries

GRAVITATIONAL WAVES DETECTED 100 YEARS AFTER EINSTEIN'S PREDICTION  
LIGO Opens New Window on the Universe with Observation of Gravitational Waves from Colliding Black Holes

WASHINGTON, DC/Cascina, Italy

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Apstsiixisamu EINSTEIN'S iigayissxinim  
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Washington, DC/Cascina Italy

Siksika (Blackfoot Indians, Canada)



## OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER

Albert Einstein's general theory of relativity, first published a century ago, was described by physicist Max Born as "the greatest feat of human thinking about nature". We report on two major scientific breakthroughs involving key predictions of Einstein's theory: the first direct detection of **gravitational waves** and the first observation of the collision and merger of a pair of **black holes**.

This cataclysmic event, producing the gravitational-wave signal **GW150914**, took place in a distant galaxy more than one billion light years from the Earth. It was observed on September 14, 2015 by the two detectors of the **Laser Interferometer Gravitational-wave Observatory (LIGO)**, arguably the most sensitive scientific instruments ever constructed. LIGO estimated that the peak gravitational-wave power radiated during the final moments of the black hole merger was more than ten times greater than the combined light power from all the stars and galaxies in the observable Universe. This remarkable discovery marks the beginning of an exciting new era of astronomy as we open an entirely new, gravitational-wave, window on the Universe.

### INTRODUCTION AND BACKGROUND

**Gravitational waves** are 'ripples' in space-time produced by some of the most violent events in the cosmos, such as the collisions and mergers of massive compact stars. Their existence was predicted by Einstein in 1916, when he showed that accelerating massive objects would shake space-time so much that waves of distorted space would radiate from the source. These ripples travel at the speed of light through the Universe, carrying with them information about their cataclysmic origins, as well as invaluable clues to the nature of gravity itself.

Over the past few decades astronomers have amassed strong supporting evidence that gravitational waves exist, chiefly by studying their effect on the motions of tightly orbiting pairs of stars in our Galaxy. The results of these indirect studies agree extremely well with Einstein's theory – with their orbits shrinking, exactly as predicted, due to the emission of gravitational wave energy. Nevertheless the direct detection of gravitational waves as they reach the Earth has been hugely anticipated by the scientific community as this breakthrough would provide new and more stringent ways to test general relativity under the most extreme conditions and open up an entirely novel way to explore the Universe.

In the same year that Einstein predicted gravitational waves, the physicist Karl Schwarzschild showed that Einstein's work permitted the existence of **black holes**: bizarre objects which are so dense and so compact that not even light can escape their gravitational field. Although by definition we cannot directly 'see' light from a black hole, astronomers have gathered a great deal of circumstantial evidence for their existence by studying the effects of black hole candidates on their immediate surroundings. For example, it is thought that most galaxies in the Universe, including the Milky Way, contain a **supermassive black hole** at their center – with masses millions or even billions of times that of the Sun. There is also evidence of many black hole candidates with much lower masses (ranging from a few, to a few dozen, times the Sun's mass), believed to be the remnants of dead stars that have undergone a cataclysmic explosion known as a **core-collapse supernova**.

Alongside this substantial progress in the indirect observation of black holes, there have been dramatic improvements in our theoretical understanding of these bizarre objects – including, over the past decade, some remarkable advances in modeling a pair of black holes (referred to as a binary) through several close orbits before they finally merge. These computer models have allowed us to construct precise gravitational waveforms – i.e. the pattern of gravitational waves emitted by the black holes as they approach ever closer and finally merge into a single, larger black hole – in accordance with the predictions of general relativity. The direct observation of a binary black hole merger would therefore provide a powerful cosmic laboratory for testing Einstein's theory.

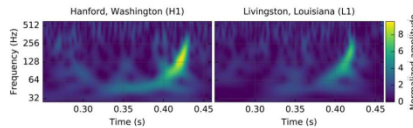
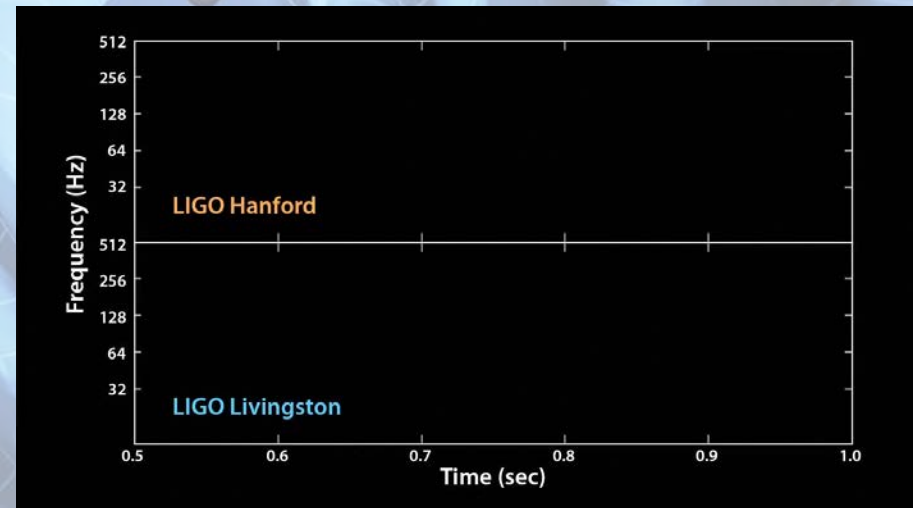


Figure 1. (Adapted from Figure 1 of our publication). The gravitational wave event GW150914 observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) detectors. The two plots show how the gravitational wave strain (see below) produced by the event in each LIGO detector varied as a function of time (in seconds) and frequency (in hertz, or number of wave cycles per second). Both plots show the frequency of GW150914 sweeping sharply upwards, from 35 Hz to about 150 Hz over two tenths of a second. GW150914 arrived first at L1 and then at H1 about seven thousandths of a second later – consistent with the time taken for light, or gravitational waves, to travel between the two detectors.

- Graphical and multimedia resources



Visit our website at  
<http://www.ligo.org/>



#GravitationalWaves  
#BinaryBlackHole  
#EinsteinWasRight

# Educational resources & activities

- **A variety of projects**
  - Developed either before the detections, or to go along with them  
→ Only a sample presented in this talk
  - New projects in preparation as well
- **For more information**
  - LIGO labs: <https://www.ligo.caltech.edu/page/educational-resources>
  - LSC: <http://www.ligo.org/public.php>
  - Virgo: <http://public.virgo-gw.eu/language/en>
- [question@ligo.org](mailto:question@ligo.org): **forum to ask questions**
  - Hundreds of questions answered so far
- LOSC : LIGO Open Science Center
- Educational activities
- Site visits
- Magazines & medias
- Online resources
- Citizen science
- Serious games & apps

GW150914: FACTSHEET			
<small>BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)</small>			
<small>first direct detection of gravitational waves (GW) and first direct observation of a black hole binary</small>			
observed by	LIGO L1, H1	duration from 30 Hz	~ 200 ms
source type	black hole (BH) binary	# cycles from 30 Hz	~10
date	14 Sept 2015	peak GW strain	$1 \times 10^{-21}$
time	09:50:45 UTC	peak displacement of interferometers arms	$\pm 0.002$ fm
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc	frequency/wavelength at peak GW strain	150 Hz, 2000 km
redshift	0.054 to 0.136	peak speed of BHs	~ 0.6 c
signal-to-noise ratio	24	peak GW luminosity	$3.6 \times 10^{56}$ erg s <sup>-1</sup>
false alarm prob.	< 1 in 5 million	radiated GW energy	2.5-3.5 M <sub>⊙</sub>
false alarm rate	< 1 in 200,000 yr	remnant ringdown freq.	~ 250 Hz
Source Masses	M <sub>⊙</sub>	remnant damping time	~ 4 ms
total mass	60 to 70	remnant size, area	180 km, $3.5 \times 10^5$ km <sup>2</sup>
primary BH	32 to 41	consistent with general relativity?	passes all tests performed
secondary BH	25 to 33	graviton mass bound	$< 1.2 \times 10^{-22}$ eV
remnant BH	58 to 67	coalescence rate of binary black holes	2 to 400 Gpc <sup>-3</sup> yr <sup>-1</sup>
mass ratio	0.6 to 1	online trigger latency	~ 3 min
primary BH spin	< 0.7	# offline analysis pipelines	5
secondary BH spin	< 0.9	CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
remnant BH spin	0.57 to 0.72	papers on Feb 11, 2016	13
signal arrival time	arrived in L1 7 ms before H1	# researchers	~1000, 80 institutions in 15 countries
delay	Southern Hemisphere		
likely sky position	face-on/off		
likely orientation	resolved to ~600 sq. deg.		

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds. Acronyms: L1=LIGO Livingston, H1=LIGO Hanford, Gly=lightyear=9.46 x 10<sup>17</sup> km; Mpc=megaparsec=3.2 million lightyear; Gpc=10<sup>9</sup> Mpc; fm=femtometer=10<sup>-15</sup> m; M<sub>⊙</sub>=1 solar mass=2 x 10<sup>30</sup> kg

# LOSC: LIGO Open Science Center

- <https://losc.ligo.org/about>
- **1 hour of data released for both events**
  - The GW channel « h(t) »
  - Along with the discovery announcement
- **Tutorials**
  - Python-based
  - Technical difficulty adapted to the user

## More discoveries from LIGO!

### Data Releases from two events and a candidate event

released 2016 June 15:

Event of December 26, GW151226: Chirp mass 9

released 2016 June 15:

Candidate event of October 12, LVT151012: Chirp mass 15

released 2016 Feb 11:

Event of September 14, GW150914: Chirp mass 30

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The [LIGO Laboratory's Data Management Plan](#) describes the scope and timing of LIGO data releases.

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### Jupyter notebook

See the new tutorial on signal processing with LIGO data, as a Jupyter (iPython) notebook.

[Tutorial on Binary Black Hole Signals in LIGO Open Data](#)

## Data release for event GW150914

This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about a confirmed astrophysical event observed by the gravitational-wave detectors, and to make the data around that time available for others to analyze. There is also a [technical details](#) page about the data linked below, and feel free to [contact us](#). This dataset has the Digital Object Identifier (doi) <http://dx.doi.org/10.7935/K5MW2F23>

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### Summary of Observation

The event occurred at GPS time 1126259462 == September 14 2015, 09:50:45 UTC. The false alarm rate is estimated to be less than 1 event per **203,000 years**, equivalent to a significance of **5.1 sigma**. The event was detected in data from the [LIGO Hanford](#) and [LIGO Livingston](#) observatories.

- There are [Science Summaries](#), covering the information below in ordinary language.
- There is a [one page factsheet about GW150914](#), summarizing the event.

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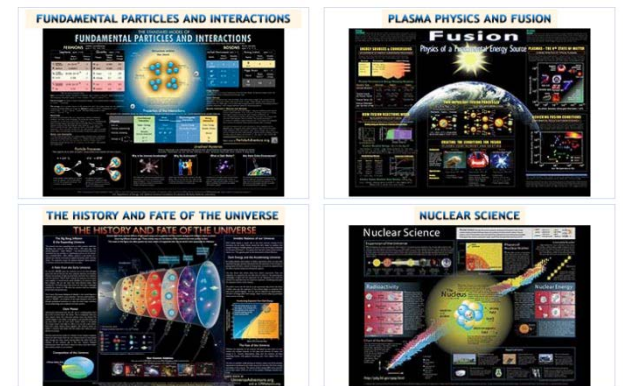
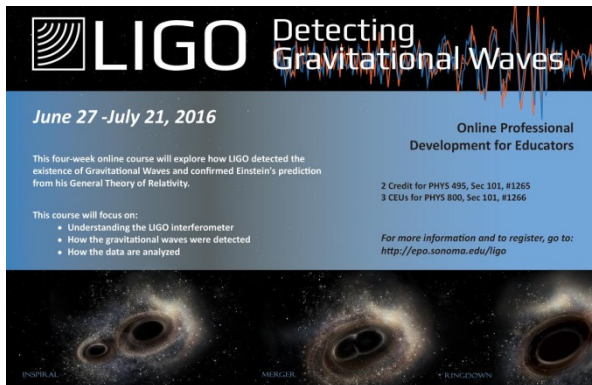
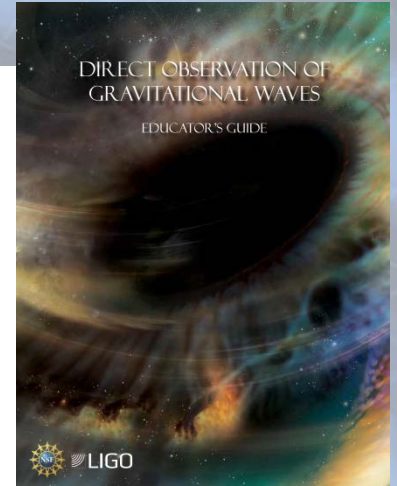
### How to Use this Page

- **Click on the section headings below to show available data files.**
  - ([click to Open/Close all sections](#))
- There are lots of data files available in the sections below, look for the word **DATA**.
- Click on each thumbnail image for larger image.
- See the papers linked below for full information, references, and meaning.
- Many of the data files linked below have heterogeneous formatting; if you have any questions, please [contact us](#).



# Educational activities

- Many resources available through [ligo.org](http://ligo.org) and the Observatory websites
  - See URLs on slide 10
- **GW Educator's guide**
  - [http://www.cpepphysics.org/images/LIGOEdGuide\\_Final.pdf](http://www.cpepphysics.org/images/LIGOEdGuide_Final.pdf)
  - Updated to include the GW detection
- **4-week online course** [last month]
  - 2015 course: <https://universe.sonoma.edu/cosmo/course/view.php?id=3>



- **CPEP poster to be released soon**
  - <http://www.cpepphysics.org/gravitation.html>
  - Gravitation + GW detection





# Site visits

- **GW Observatories can be visited**

- LIGO Hanford: <https://www.ligo.caltech.edu/WA/page/lho-tours>
- LIGO Livingston: <https://www.ligo.caltech.edu/LA/page/Tours>  
→ <https://www.ligo.caltech.edu/LA/page/Science-Education-Center>
- EGO / Virgo: <http://public.virgo-gw.eu/visit-us>

- **Constraints**

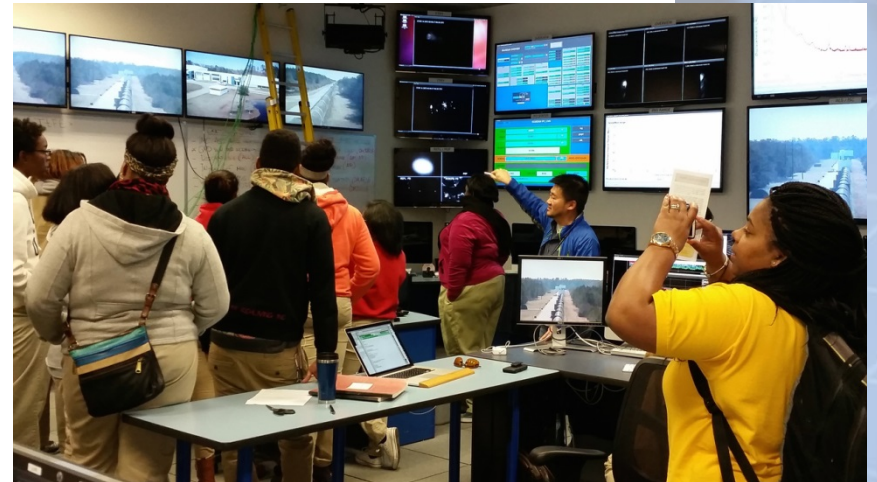
- Site locations – countryside
- Limited manpower available
- Seismic vibrations!

- **Defined timeslots for visits**

- ~Monthly opening days
- School field trips and private tours to be booked in advance
- Special events – e.g. Researchers Night

- Much more requests and larger attendances since discoveries announced

- **Projects to develop virtual visits – both standalone and live**



# Magazines & medias

## LIGO magazine

- <http://www.ligo.org/magazine>
- Latest issue (8) : March 2016
- Next issue available soon



## the gravitational voice

### News from EGO and VIRGO

- <http://www.ego-gw.it/public/hletter/hletter.aspx>
- Latest issue (30): April 2016

## Youtube channel

- <https://www.youtube.com/channel/UCMATJmzibndbcdY8s9Prhjj>
- Explainer videos, talks, GW events, sources & simulations

### The waveform explained

**[BLACK HOLE] CPN AXIS**  
A BLACK HOLE IS ONE OF THE MOST EXTREME OBJECTS IN THE UNIVERSE. IT HAS ONLY TWO CHARACTERISTICS: ITS MASS (HOW MUCH MATTER IT CONTAINS) AND ITS SPIN (HOW MUCH IT ROTATES AROUND ITSELF).

WHEN YOU HAVE TWO BLACK HOLES IN A BINARY SYSTEM, THINGS GET MORE COMPLICATED. WE NOW HAVE THE MASS AND SPIN OF BOTH BLACK HOLES. THE SPINS STAY THE SAME SIZE DURING THE COBBIT, BUT THEIR DIRECTIONS WIGGLE AROUND IN A PROCESS CALLED PRECESSION. THE GRAVITATIONAL WAVES BEING SENT FROM THE BINARY ALSO TEND TO WIGGLE. THE BINARY IS AND WHICH WAY IT IS ORIENTATED.

**[CPN]**  
AS THE BLACK HOLES ORBIT EACH OTHER, THEIR SPIN CHANGE DIRECTION. THIS ALSO CAUSES THE ORIENTATION OF THE COBBIT TO TWIRL BACKWARDS AND FORWARDS A LITTLE. THE PRECESSION LEAVES AN IMPRINT ON THE GRAVITATIONAL WAVES: THEY BECOME LOUDER AND QUIETER AS THE SPIN WIGGLE AROUND. THE PRECESSION DEPENDS ON THE SPIN OF THE COBBIT COMPARED TO EACH OTHER AND COMPARED TO THAT OF THE COBBIT. THE SPIN OF THE MORE MASSIVE BLACK HOLE HAS A LARGER EFFECT THAN THAT OF THE SMALLER ONE.

WE DON'T SEE MUCH SIGNAL OF PRECESSION IN OUR SIGNALS. THIS MAY BE BECAUSE SPINS ARE SMALL. THE PRECESSION WIGGLE THE WIGGLE AREN'T VISIBLE. CO A COMBINATION OF BOTH, SINCE THE SIGNAL IS SHORT, WE WOULD NOT EXPECT TO SEE A LARGE EFFECT IN ANY CASE!

**[REDSHIFT]**  
THE EXPANSION OF THE UNIVERSE AFFECTS GRAVITATIONAL WAVES IN A COUPLE OF WAYS. AS THE UNIVERSE EXPANDS, IT STRETCHES THE WAVES TRAVELLING THROUGH IT. THIS IS WELL KNOWN IN ASTRONOMY AND IS CALLED REDSHIFT. AS WAVES TRAVEL MORE DISTANCE TO HAVE A LARGE EFFECT, THE WAVES MUST HAVE TRAVELLED A LONG WAY.

THE FIRST EFFECT IS THAT THE FREQUENCY OF THE WAVE CHANGES. THIS HAS THE SAME IMPACT AS CHANGING THE MASS: THINGS FURTHER AWAY APPEAR MORE MASSIVE. THE SECOND EFFECT IS TO CHANGE THE AMPLITUDE, WHICH IS THE SAME AS CHANGING THE DISTANCE. WE OFFTEN TALK ABOUT THE LUMINOSITY OF STARS WHICH WORKS THE SAME WAY BUT ISN'T THE SAME AS IF WE MEASURED THE DISTANCE TO THE SOURCE AND THEN THE MESSAGE.

IF WE GET ENOUGH MEASUREMENTS OF HOW GRAVITATIONAL WAVES ARE REDSHIFTED, WE COULD POSSIBLY LEARN SOMETHING ABOUT HOW THE UNIVERSE IS EXPANDING.

**[INCLINATION]**  
THE WAY THE BINARY IS FACING THE EARTH DETERMINES THE GRAVITATIONAL WAVES WE SEE. IF IT'S FACING US, THE SIGNAL IS QUICKEST. BUT IT'S EASIER TO SPOT SMALL CHANGES CAUSED BY THE BLACK HOLE SPIN. IF IT'S FACING US, THE SIGNAL IS LOUDEST. BUT IT'S HARDER TO TELL IF THE COBBIT WIGGLES BECAUSE OF PRECESSION. WE HAVE A GREATER CHANCE OF BEING A FACE-ON BINARY BECAUSE THEY CAN BE DETECTED FROM FURTHER AWAY.

**[TOTAL MASS]**  
THE TOTAL MASS OF THE SYSTEM DETERMINES HOW LONG IT TAKES FOR THINGS TO HAPPEN. HEAVY SYSTEMS ARE BIGGER, AND SO CHANGE MORE SLOWLY. THE GRAVITATIONAL WAVES ARE AT LOWER FREQUENCIES, WHICH MEANS THAT YOU CAN ONLY SEE THE FINAL PARTS. LIGHTER SYSTEMS PRODUCE GRAVITATIONAL WAVES AT HIGHER FREQUENCIES, SO WE CAN MEASURE MORE OF THE SIGNAL.

THE TOTAL MASS OF THE SYSTEM SETS SEVERAL PARAMETERS. ONE MOST EASILY MEASURED FOR REALLY MASSIVE SYSTEMS IS MEASURING THE TOTAL MASS BEFORE AS WE ONLY SEE THE MERGER AND RINGDOWN. BUT FOR LIGHT SYSTEMS, LIKE BINARY NEUTRON STARS, WE MEASURE THE CHIRP MASS FIRST (AS WE ONLY SEE THE INITIAL ONWARDS) IS SOMEWHERE IN THE MIDDLE.

**[STAGES]**  
ONE OF THE REASONS WE DIVIDE UP THE GRAVITATIONAL WAVE SIGNAL IS BECAUSE DIFFERENT TECHNIQUES CAN BE USED TO TELL THE WAVES AT DIFFERENT POINTS. THE EARLY SIGNAL CAN BE CALCULATED USING POST-NEWTONIAN THEORY (THIS STARTS WITH NEWTON'S THEORY OF GRAVITY AND ADDS LITTLE CORRECTIONS). FOR HOW THINGS CHANGE IN GENERAL RELATIVITY, THE MERGER CAN BE CALCULATED USING BLACK HOLE PERTURBATION THEORY (THIS STARTS WITH THE FULL EQUATIONS OF GENERAL RELATIVITY AND SEES HOW IT BEHAVES TO SMALL CHANGES). THE MERGER CAN ONLY BE CALCULATED USING NUMERICAL RELATIVITY (SIMULATIONS OF THE FULL EQUATIONS OF GENERAL RELATIVITY WHICH TAKE LOTS OF COMPUTING POWER). THIS HAS ONLY BEEN POSSIBLE IN THE LAST 10 YEARS, SO THE MERGER WAS THE LAST PART OF THE PUZZLE.

IF WE HAD A BINARY CONTAINING NEUTRON STARS INSTEAD OF BLACK HOLES, THE INITIAL WOULD BE MUCH THE SAME BUT THERE WOULD NOT BE THE SAME MERGER AND RINGDOWN. THE SIGNAL WOULD BE MUCH MORE POWERFUL (FEATURING NEUTRON STARS BEING SQUISHED APART, BEFORE COLLAPSING AND COLLAPSING TO A FINAL BLACK HOLE).

**[AMPLITUDE]**  
THE SIZE OF THE SIGNAL, ITS AMPLITUDE, DEPENDS ON HOW FAR AWAY THE BINARY IS. IF THE DISTANCE WERE TWICE AS BIG, THE AMPLITUDE WOULD BE HALF THE QUANTITY. A SIGNAL IS THE HIGHEST IT IS TO DETECT.

AND THE LESS WE CAN LEARN ABOUT ITS PROPERTIES, THE HEAVIER SYSTEMS PRODUCE LOUDER GRAVITATIONAL WAVES AS THERE IS MORE MASS MOVING AROUND TO CREATE THE WAVES.

THE SIGNAL AMPLITUDE DEPENDS UPON THE WAY THE BINARY IS FACING ITS NEIGHBOUR AND ITS POSITION IN THE SKY. THE DETECTORS ARE NOT EQUALLY SENSITIVE TO GRAVITATIONAL WAVES FROM ALL DIRECTIONS. THE SIGNAL IS LOUDEST WHEN THE SIGNAL IS DIRECTLY ABOVE OR BELOW A DETECTOR.

**[RINGDOWN]**  
THE RINGDOWN PART OF THE SIGNAL COMES FROM THE FINAL BLACK HOLE. SO IT DEPENDS UPON ITS MASS AND SPIN. THE FINAL MASS IS ALMOST THE SAME AS THE TOTAL MASS OF THE TWO INITIAL BLACK HOLES (SOME ENERGY IS LOST CARRIED AWAY BY THE GRAVITATIONAL WAVES). THE FINAL SPIN DEPENDS UPON THE SPIN OF THE INITIAL BLACK HOLES AND HOW THEY WERE ORBITING AROUND EACH OTHER WHEN THEY MERGED.

**[SKY]**  
WITH MULTIPLE DETECTORS WE CAN WORK OUT WHICH DIRECTION THE GRAVITATIONAL WAVES CAME FROM BY LOOKING AT THE TIME WHEN THE SIGNAL ARRIVED AT EACH DETECTOR. THIS IS SIMILAR TO HOW YOU CAN LOCATE THE SOURCE OF A SOUND USING YOUR EARS.

WE CAN GET SOME EXTRA INFORMATION ABOUT THE DIRECTION FROM HOW LOUD EACH SIGNAL IS. SINCE EACH OF THE DETECTORS HAS ITS BEST SENSITIVITY IN A DIFFERENT DIRECTION, AND SINCE THE WAVES IS IN ITS CYCLE.

**[CHIRP MASS]**  
THE WAY THE SIGNAL CHANGES DURING THE MERGER IS PRIMARILY FITTED BY A COMBINATION OF THE BLACK HOLE MASSES. WE CALL THE CHIRP MASS IF WE SEE LOTS OF CYCLES OF NOTCH. WE CAN MEASURE THE CHIRP MASS REALLY WELL (BETTER THAN A FRACTION OF A PERCENT). WHEN THINKING ABOUT WHAT WE CAN LEARN FROM GRAVITATIONAL WAVES, PEOPLE OFTEN FIRST THINK ABOUT THE CHIRP MASS.

**[DIPLOMA]**  
h = Gm<sup>2</sup> / c<sup>3</sup> r

h THE GRAVITATIONAL VOICE

ISTORICAL DETECTION!

# Online resources

- **GW150914 and GW151226**
  - LIGO: <http://ligo.org/detections.php>
  - Virgo: <https://owncloud.ego-gw.it/index.php/s/WGB7jLJvU9tW7sF>
- **Well-known online medias**
  - Minute physics: <https://www.youtube.com/watch?v=YHS9g72npqA>
  - PhD comics: <http://phdcomics.com/comics/archive.php?comid=1853>
- Misc.
  - **Known stellar-mass black holes**: <https://gravity.astro.cf.ac.uk/plotgw/bhbubble.html>  
→ Basic information (mass, discovery, etc.) + visual comparison of their « sizes »
  - **Gravoscope**: <http://astrog80.astro.cf.ac.uk/Gravoscope>  
→ Combine electromagnetic and GW sky maps
  - **GWplotter** : <http://rhcole.com/apps/GWplotter>  
→ Detector sensitivities and sources
  - **Inside Advanced Virgo**: <https://www.youtube.com/watch?v=6raomYII9P4>
  - **Sounds of spacetime**: <http://www.soundsofspacetime.org>



# Citizen science

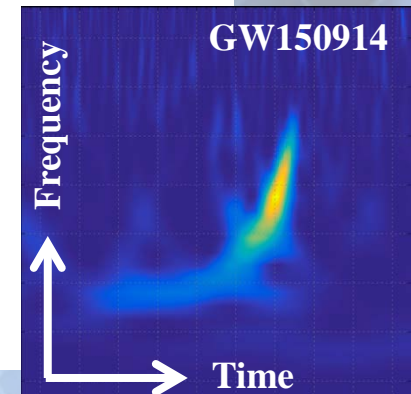


- **Einstein@Home** project
  - <https://www.einsteinathome.org>
  - Use computer idle time to look for GW signals coming from pulsars
  - BOINC framework

<http://boincstats.com/en/stats/projectStatsInfo>

Project name	Users	last day	Hosts	last day	Teams	last day	Countries	last day	Total credit	last day	Last update
BOINC combined	3,859,708	2,505	14,368,301	5,829	105,031	2	277	0	24,001,926,536,329	26,131,517,261	2016-07-24 08:30:41
Bitcoin Utopia	2,645	0	6,862	3	336	0	98	0	20,542,116,997,637	24,043,653,301	2016-07-24 07:10:15
Collatz Conjecture	59,716	11	397,015	34	1,652	1	179	0	584,541,452,909	871,575,986	2016-07-24 06:10:21
PrimeGrid	91,671	9	268,691	31	2,954	1	197	0	498,712,754,118	233,456,859	2016-07-24 06:10:16
GPUGRID	30,780	4	62,466	0	1,523	1	155	0	416,156,950,753	200,691,350	2016-07-24 05:10:11
SETI@Home	1,636,237	166	4,026,091	443	63,705	1	233	0	351,564,716,811	144,054,215	2016-07-23 22:14:06
MilkyWay@home	203,497	16	459,228	46	4,169	0	214	0	271,971,023,377	42,529,640	2016-07-24 06:10:38
Einstein@Home	435,566	69	1,550,014	174	11,398	1	226	0	251,169,301,879	172,851,162	2016-07-24 08:10:56
World Community Grid	509,398	41	2,651,820	411	24,900	2	225	0	216,115,277,893	100,945,150	2016-07-24 01:11:12
POEM@HOME	57,018	13	1,273,374	1,986	1,816	0	183	0	135,236,001,800	131,143,710	2016-07-24 07:10:15

- **Gravity Spy** [*coming soon!*]
  - <https://daily.zooniverse.org/2016/02/19/coming-soon-gravity-spy>
  - Users will help classifying instrumental noise transients using time-frequency maps of the glitches
    - Background identification and removal is a key task to improve the detector sensitivity to real GW signal
  - Zooniverse portal





# Serious games & apps

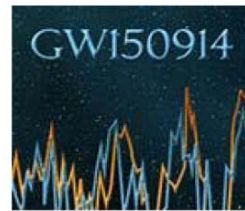
- **Black hole hunter:** <http://www.blackholehunter.org>
  - Listen to audio files, look for compact binary coalescence signals buried in noise
- **Space time quest:** [http://www.gwoptics.org/processing/space\\_time\\_quest](http://www.gwoptics.org/processing/space_time_quest)
  - Simulation game to design a GW detector
- **Black Hole Pong:** [http://www.gwoptics.org/processing/blackhole\\_pong](http://www.gwoptics.org/processing/blackhole_pong)
  - Use black hole gravity to deflect a ball and score
- **Pocket Black Hole:** <https://www.laserlabs.org/pocketblackhole.php>
  - Distort pictures by mimicking light-bending effects of a black hole



- **Stretch and squash:** <https://www.laserlabs.org/stretchandsquash.php>
  - Shows how GW distort space-time

# Outlook

- **A wide range of E&O activities related to GW and GW detection** by giant interferometric detectors
- **First two discoveries changed everything**
  - **K. Thorne, 1983:**  
*“That the quest ultimately will succeed seems almost assured. The only question is when and with how much further effort .”*
  - **D. Reize, 2016/02/11:**  
*“Ladies and gentlemen. We have detected gravitational waves. We did it!”*
  - **More audience**
  - **Real data** (and excitement) to share
- **More observation runs to come**
  - **Improved detector sensitivity**
  - **Global network of instruments**  
+ electromagnetic follow-up  
→ Source sky localization



GW150914  
GW150914 accessories and gifts

Visit the **Cafepress online shop:**  
<http://www.cafepress.com/ligosc>

A way to raise funds for E&O



LSC and LIGO



LIGO Virgo

→ **Dawn of the GW astronomy**