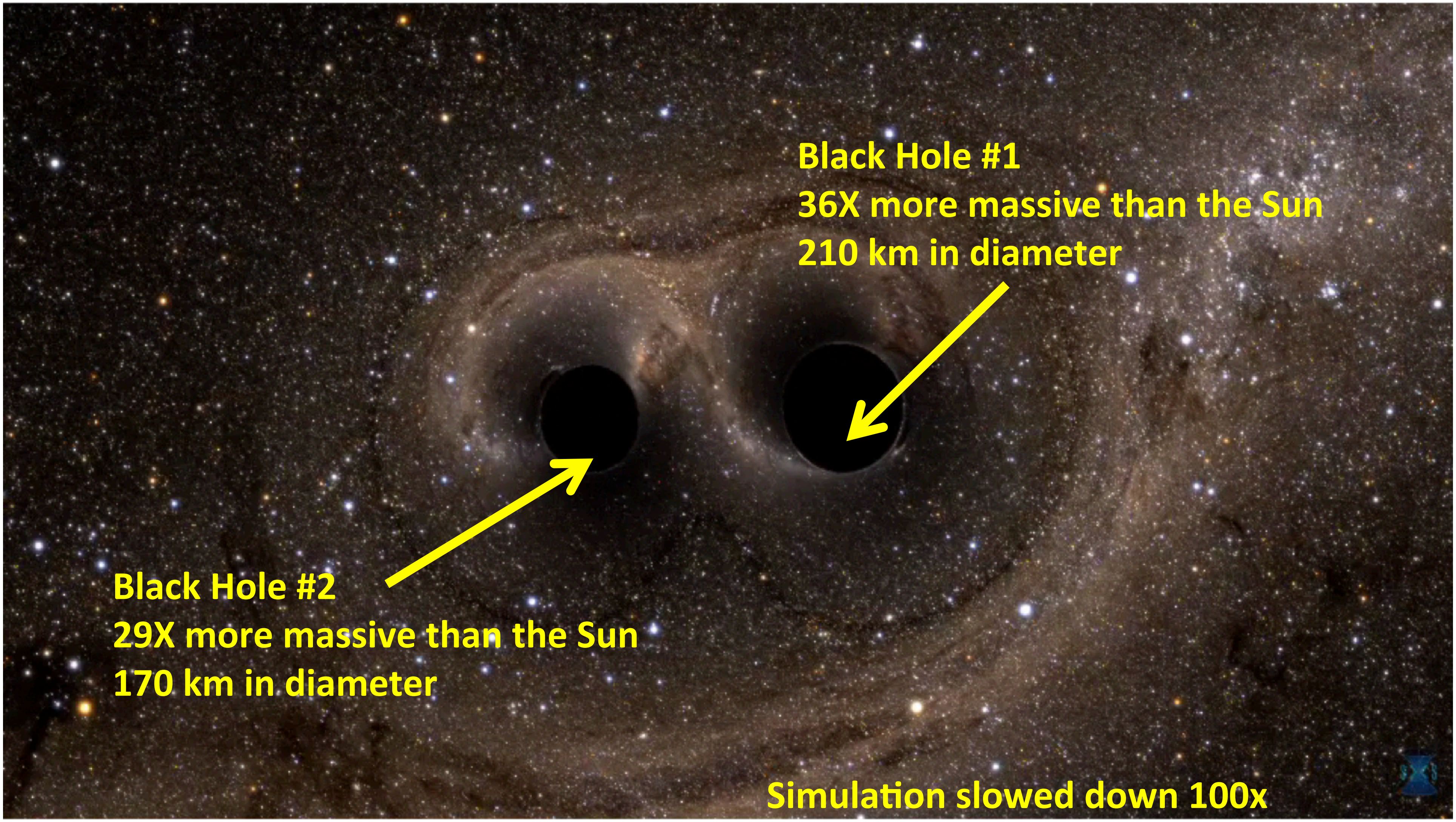
LIGO as BIG SCIENCE with Open Data

for
'Envisioning the Scientific Paper of the Future'
Jan 9, 2017, Caltech

Alan Weinstein
Professor of Physics, Caltech
Head, LIGO Caltech Astrophysical Data Analysis group
Head, LIGO Open Science Center (LOSC)

The Ballet of Binary Black Holes
1.3 Billion Years Ago (Give or Take)



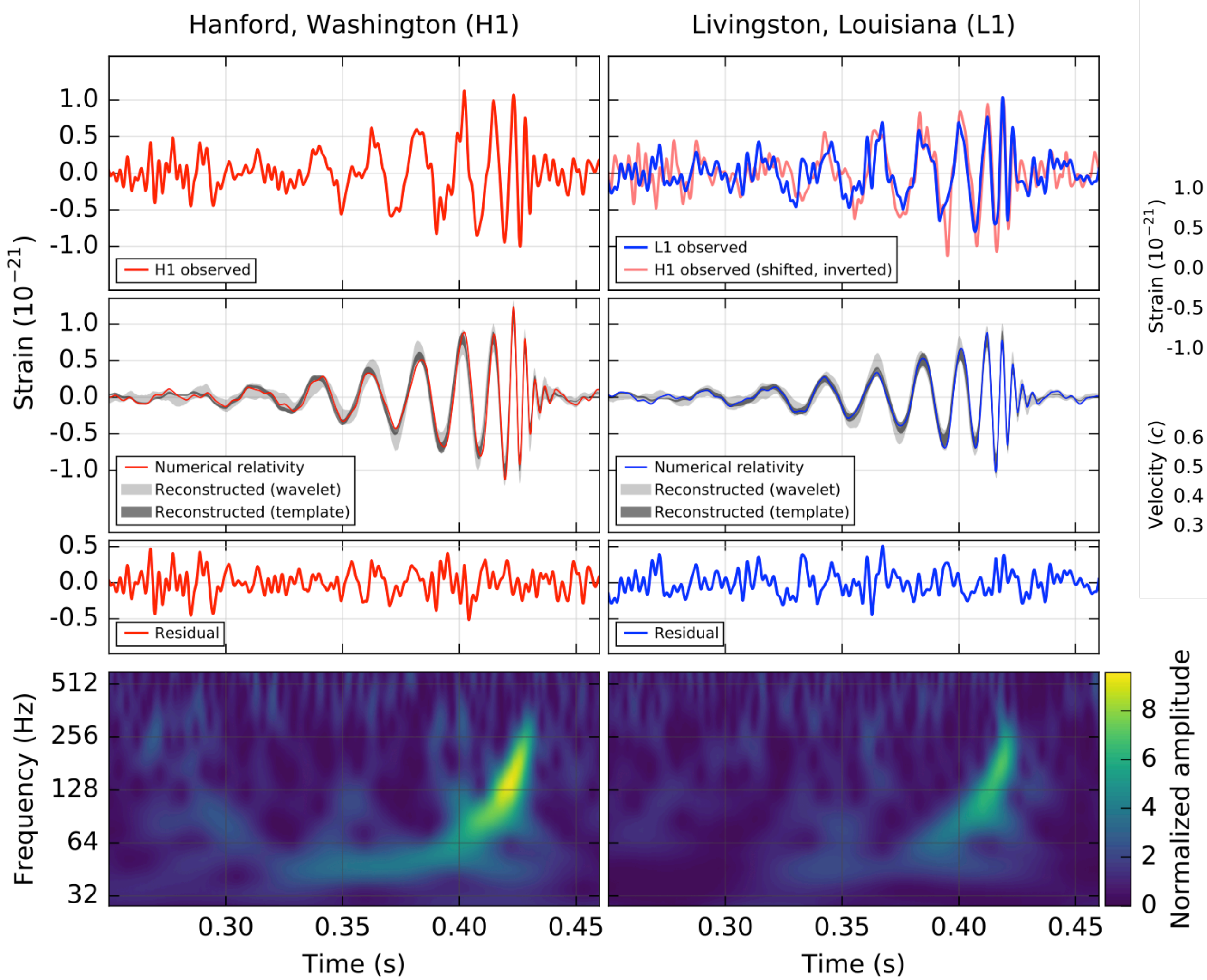
Numerical relativity (solution to $\boldsymbol{G_{\mu\nu} = 0}$) simulation
(SXS Collaboration, http://www.black-holes.org/)

Andy Bohn, François Hébert, and William Throwe, SXS

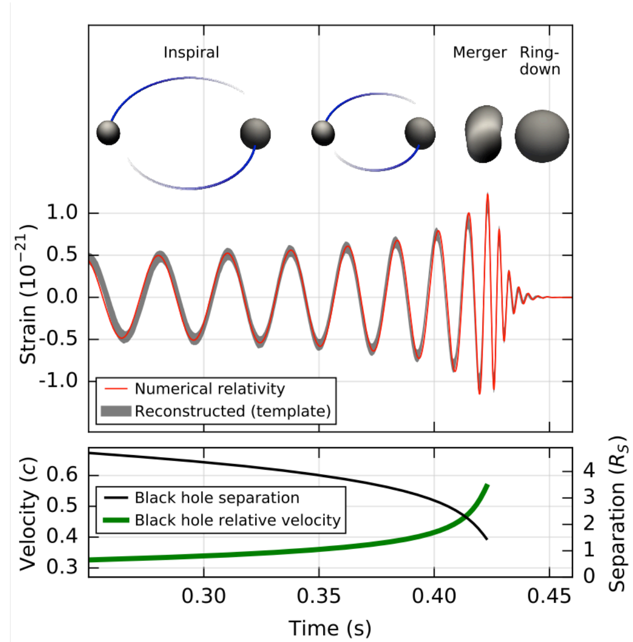
GW150914

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016

https://dcc.ligo.org/LIGO-P150914/public/main



Whitened and band-passed [40-300] Hz

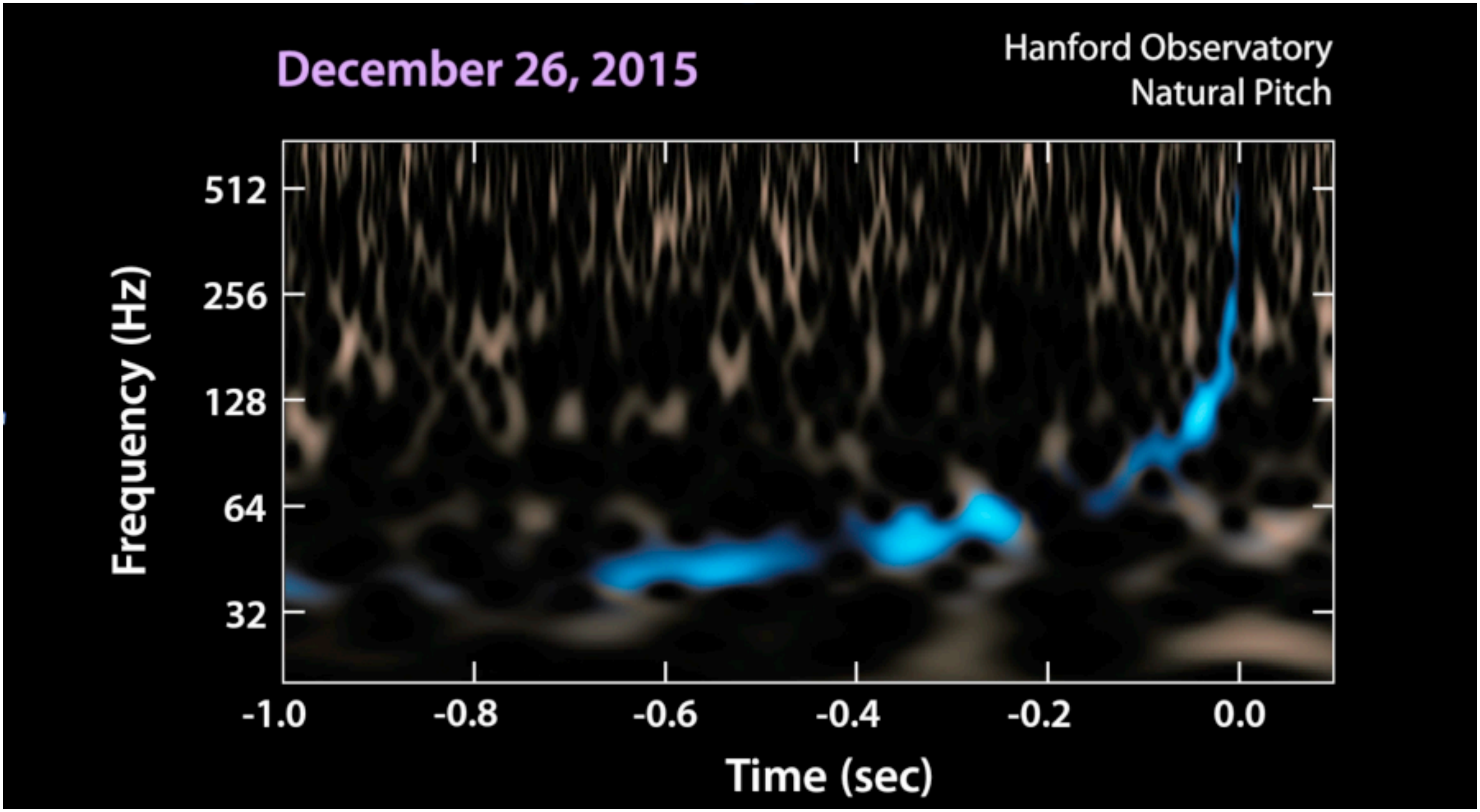


Reconstructed (no whitening)

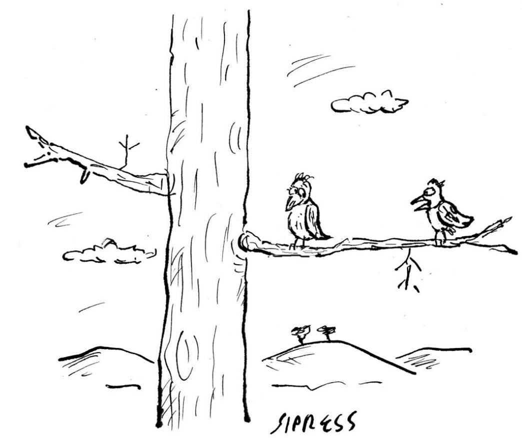
Audio:

- filtered data
- freq-shifted data
- reconstructed & shifted

The Sounds of Space-Time



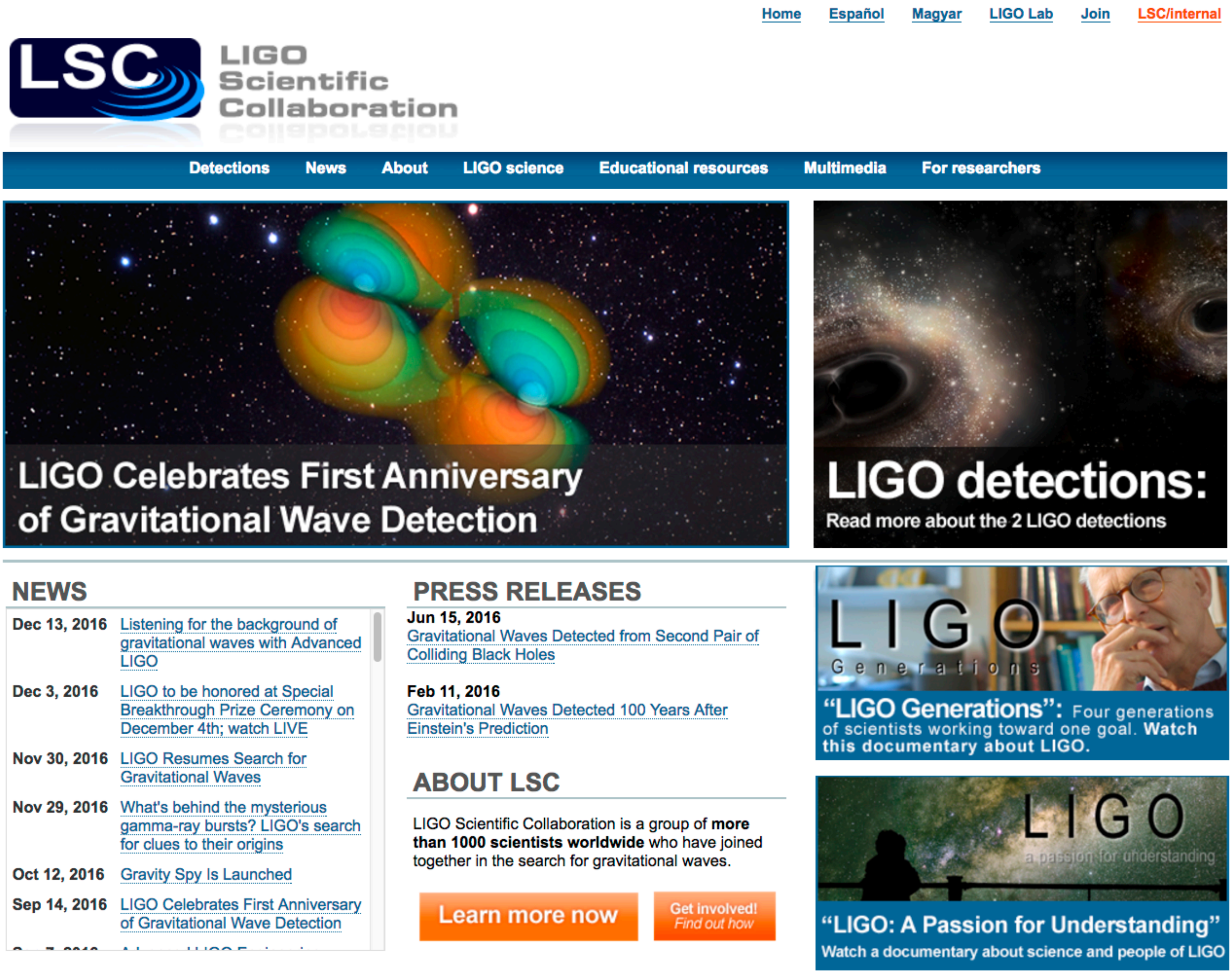
After it hit our detectors …
it hit the media



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

https://www.ligo.caltech.edu/

http://ligo.org/



http://ligo.org/about.php

ABOUT THE LSC

The LIGO Scientific Collaboration (LSC) is a group of scientists seeking to make the first direct detection of gravitational waves, use them to explore the fundamental physics of gravity, and develop the emerging field of gravitational wave science as a tool of astronomical discovery. The LSC works toward this goal through research on, and development of techniques for, gravitational wave detection; and the development, commissioning and exploitation of gravitational wave detectors.

The LSC carries out the science of the LIGO Observatories, located in Hanford, Washington and Livingston, Louisiana as well as that of the GEO600 detector in Hannover, Germany. Our collaboration is organized around three general areas of research: analysis of LIGO and GEO data searching for gravitational waves from astrophysical sources, detector operations and characterization, and development of future large scale gravitational wave detectors.

Founded in 1997, the LSC is currently made up of more than 1000 scientists from dozens of institutions and 15 countries worldwide. A list of the participating universities.

THE LIGO OBSERVATORY

The Laser Interferometer Gravitational-Wave Observatory (LIGO) consists of two widely separated installations within the United States -- one in Hanford Washington and the other in Livingston, Louisiana -- operated in unison as a single observatory. LIGO is operated by the LIGO Laboratory, a consortium of the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Funded by the National Science Foundation, LIGO is an international resource for both physics and astrophysics.

JOIN THE LSC

Institutions interested in joining the LIGO Scientific Collaboration should contact the LSC Spokesperson. Prospective members must arrange an MOU with LIGO Laboratory and the LIGO Scientific Collaboration and present their proposed collaborative program at an LSC meeting. New memberships are approved by a two-thirds majority vote of the LSC Council.

New members, please check The LSC Beginner's Guide for helpful information on first steps after joining the Collaboration.

LSC'S COMMITMENT TO DIVERSITY

As members of the LIGO Scientific Collaboration, we recognize the importance of diversity to enrich our research and scholarship. We pledge to provide a welcoming, inclusive environment to talented individuals regardless of characteristics such as, but not limited to, physical ability, race, ethnicity, gender, sexual orientation, economic status, or personal religious practices, and to support the professional growth of all collaboration members.

We also pledge to work to increase the numbers of women and under-represented minorities that actively participate in the LSC, to pursue recruitment, mentoring, retention and promotion of women and under-represented minority scientists and engineers and to maximize their contribution to excellence in our research. As a collaboration, we will strive to create a professional climate that encourages inclusion and that respects and values diversity.

LSC Statement on Diversity

AT A GLANCE

Click on map image for an interactive map of participating LSC institutions. Map courtesy of zeemaps.com

(As of January 2016)

Total members: 1006
Total institutions: 83
Countries represented: 15
Founded in: 1997
Mission:
Detection of gravitational waves (GW)
Use GW to explore fundamental physics of gravity
Develop GW observations as a tool of astronomical discovery
Areas of research:
Analysis of GW search data
Detector operations and characterization
Development of future large-scale GW detectors
Funded by: Public and private sources
Governed by: The Collaboration Council
Spokesperson: Prof. Gabriela Gonzalez, Louisiana State University
Assistant Spokesperson: Prof. Marco Cavaglia, University of Mississippi

LIGO Scientific Collaboration

Trinity University
University of Maryland 1856
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
Whitman College
American University Washington, DC
University of the West of Scotland UWS
Texas Tech University
清華大學 Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics Albert Einstein Institute
University of Strathclyde
Michigan
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique
Università degli Studi del Sannio
Massachusetts Institute of Technology
Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
University of Cambridge
The University of Chicago
Montana State University
Southern University and Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
University of Birmingham
The University of Melbourne
UIB Universitat de les Illes Balears
University of Washington
UTRGV
University of Wisconsin UWMilwaukee
GEO 600
Cardiff University Prifysgol Caerdydd
Northwestern
Syracuse University
Universität Hamburg
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

LIGO, the LSC, and publishing scientific papers

- The LSC is BIG SCIENCE – more than 1000 scientists and engineers, around the world, meeting by telecon every day (often, 10 in parallel).
- The GW community, beyond the LSC: Virgo, KAGRA, Numerical Relativity, many small research groups in theory & experiment
- A large fraction of researchers in GW science are members of the LSC, Virgo, KAGRA, NR; almost the whole field!
- *Everyone's primary career goal* is to publish their research in scientific journals.
- Every paper treads a line between brevity / clarity, and completeness / detail.
- Full collaboration papers have "Science Summaries" for students, teachers, press.
- Data for most figures are available as ascii text.

OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER

Read this summary [in PDF format] in Chinese | French | German | Japanese | Spanish

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.

THE LIGO DETECTORS

LIGO is the world's largest gravitational wave observatory and one of the world's most sophisticated physics experiments. Comprised of two giant laser interferometers located thousands of kilometers apart, one in

FIGURES FROM THE PUBLICATION

For more information on how these figures were generated and their meaning, see the main publication at Physical Review Letters.

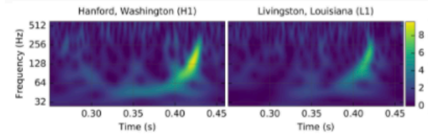


Figure 1. (Adapted from Figure 1 of our publication). The gravitational wave event GW150914 observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) detectors. The two plots show how the gravitational wave strain (see below) produced by the event in each LIGO detector varied 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.

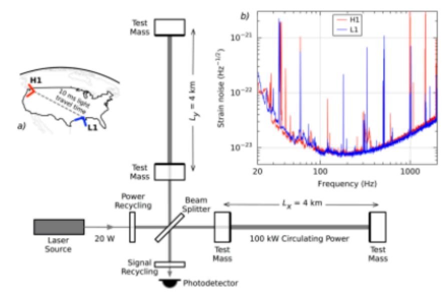
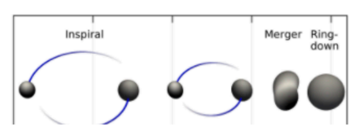


Figure 2. Simplified diagram of an Advanced LIGO detector (not to scale), including several of the key enhancements to the basic design: an optical cavity that reflects the laser light back and forth many times in each arm, multiplying the effect of the gravitational wave on the phase of the laser light; a power recycling mirror that increases the power of the laser in the interferometer as a whole; a signal recycling mirror that further optimizes the signal extracted at the photodetector. These enhancements boost the power of the laser in the optical cavity by a factor of 5000, and increase the total amount of time that the signal spends circulating in the interferometer. Inset (a), on the left, shows the locations and orientations of the two LIGO observatories, and indicates the light travel time between them. Inset (b) shows how the instrument strain noise varied with frequency in each detector near to the time of the event. The lower the instrument noise, the higher the detectors' sensitivity. The tall spikes indicate narrow frequency ranges where the instrument noise is particularly large.



LIGO Document Control Center (DCC) (eg, https://dcc.ligo.org/LIGO-P1500227/public)
Probably has tens of thousands of documents.
Private version for circulation to LSC collaborators.
Public version includes data associated with publication results, figures, tables.

PUBLIC LIGO DCC

LIGO Document P1500227-v12

Home Recent Changes Topics Login

Localization and broadband follow-up of the gravitational-wave transient GW150914

Document #:
LIGO-P1500227-v12
Document type:
P - Publications

Login to modify

Other Versions:
LIGO-P1500227-v11
27 Apr 2016, 19:44

Abstract:
A gravitational-wave (GW) transient was identified in data recorded by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) detectors on 2015 September 14. The event, initially designated G184098 and later given the name GW150914, is described in detail elsewhere. By prior arrangement, preliminary estimates of the time, significance, and sky location of the event were shared with 63 teams of observers covering radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities. In this Letter we describe the low-latency analysis of the GW data and present the sky localization of the first observed compact binary merger. We summarize the follow-up observations reported by 25 teams via private Gamma-ray Coordinates Network circulars, giving an overview of the participating facilities, the GW sky localization coverage, the timeline and depth of the observations. As this event turned out to be a binary black hole merger, there is little expectation of a detectable electromagnetic (EM) signature. Nevertheless, this first broadband campaign to search for a counterpart of an Advanced LIGO source represents a milestone and highlights the broad capabilities of the transient astronomy community and the observing strategies that have been developed to pursue neutron star binary merger events. Detailed investigations of the EM data and results of the EM follow-up campaign are being disseminated in papers by the individual teams.

Files in Document:

- Main manuscript (GW150914_localization_and_followup.pdf, 2.0 MB)

Other Files:

- BAYESTAR sky map (GCN 18858) FITS file (bayestar_gstlal_C01.fits.gz, 90.0 kB)
- BAYESTAR sky map (GCN 18858) Mollweide projection plot (bayestar_gstlal_C01.pdf, 74.4 kB)
- Fig. 1: Timeline of observations (timeline.pdf, 221.4 kB)
- Fig. 2: LIGO/Virgo sky maps (contours.pdf, 483.6 kB)
- Fig. 3: Footprints of follow-up observations (tiles.pdf, 1.1 MB)
- LALInference sky map (GCN 18858) FITS file (LALInference_skymap.fits.gz, 191.5 kB)
- LALInference sky map (GCN 18858) Mollweide projection plot (LALInference_skymap.pdf, 78.4 kB)
- LIB sky map (GCN 18330) FITS file (LIB_skymap.fits.gz, 2.6 MB)
- LIB sky map (GCN 18330) Mollweide projection plot (LIB_skymap.pdf, 79.5 kB)
- cWB sky map (GCN 18330) FITS file (skyprobcc_cWB_complete.fits.gz, 733.2 kB)
- cWB sky map (GCN 18330) Mollweide projection plot (skyprobcc_cWB_complete.pdf, 75.0 kB)

Topics:

- External Collaboration
- Compact Binaries
- Astrophysics / Multi-messenger
- GW Bursts

Authors:

- LIGO Scientific Collaboration
- Virgo Collaboration

Author Groups:

- LVC

Keywords:
ER8 O1 EM follow-up detection G184098 GW150914 multimessenger

Notes and Changes:
Preprint version of published article

Collaboration publication policy

- The LSC has a complex publication policy, parts of which are controversial
- Almost all publications from results of astrophysical data analysis have full LSC/Virgo author list, ~1300 people, in strict alphabetical order (B. Abbott et al)
- Many papers have additional authors, collaborators who help in different ways
- Papers undergo careful, critical internal review –
  often, 10+ person-years for a single review!
- "small author list papers" are encouraged, and they get "courtesy" critical internal review
- We always post papers on arXiv (gr-qc) before submitting to journals.
- Public release of data adds complexity: random passers-by can use our open data to write papers about what they find (signals!?),
  but LSC members *cannot* (until a long waiting period has elapsed).

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. . .

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ORCiD

Some of our papers have not just a long author list and institution list, but even a long list of collaborations!

THE ASTROPHYSICAL JOURNAL LETTERS, 826:L13, 2016 JULY 20
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LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION,
THE AUSTRALIAN SQUARE KILOMETER ARRAY PATHFINDER (ASKAP) COLLABORATION, THE BOOTES COLLABORATION,
THE DARK ENERGY SURVEY AND THE DARK ENERGY CAMERA GW-EM COLLABORATIONS, THE *Fermi* GBM COLLABORATION,
THE *Fermi* LAT COLLABORATION, THE GRAVITATIONAL WAVE INAF TEAM (GRAWITA), THE *INTEGRAL* COLLABORATION,
THE INTERMEDIATE PALOMAR TRANSIENT FACTORY (IPTF) COLLABORATION, THE INTERPLANETARY NETWORK,
THE J-GEM COLLABORATION, THE LA SILLA–QUEST SURVEY, THE LIVERPOOL TELESCOPE COLLABORATION,
THE LOW FREQUENCY ARRAY (LOFAR) COLLABORATION, THE MASTER COLLABORATION, THE MAXI COLLABORATION,
THE MURCHISON WIDE-FIELD ARRAY (MWA) COLLABORATION, THE PAN-STARRS COLLABORATION,
THE PESSTO COLLABORATION, THE PI OF THE SKY COLLABORATION, THE SKYMAPPER COLLABORATION,
THE *Swift* COLLABORATION, THE TAROT, ZADKO, ALGERIAN NATIONAL OBSERVATORY, AND C2PU COLLABORATION,
THE TOROS COLLABORATION, AND THE VISTA COLLABORATION
See the Supplement, Abbott et al. 2016g, for the full list of authors.

(Received 2016 February 29; Accepted 2016 April 26; Published 2016 July 20)

ABSTRACT

A gravitational-wave (GW) transient was identified in data recorded by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) detectors on 2015 September 14. The event, initially designated

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The URL for this search is http://arxiv.org:443/find/all/1/all:+AND+Collaboration+AND+LIGO+Scientific/0/1/0/all/0/1

Showing results 1 through 25 (of 192 total) for all:(Collaboration AND (LIGO AND Scientific))

1. arXiv:1612.02030 [pdf, other]
   Directional limits on persistent gravitational waves from Advanced LIGO's first observing run
   The LIGO Scientific Collaboration, the Virgo Collaboration
   Comments: 14 pages, 4 figures
   Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Astrophysical Phenomena (astro-ph.HE); Instrumentation and Methods for Astrophysics (astro-ph.IM)

2. arXiv:1612.02029 [pdf, other]
   Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run
   The LIGO Scientific Collaboration, the Virgo Collaboration
   Comments: 14 pages, 6 figures
   Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy Astrophysical Phenomena (astro-ph.HE)

3. arXiv:1612.01615 [pdf, other]
   Is GW151226 a really signal of gravitational wave?
   Zhe Chang, Chao-Guang Huang, Zhi-Chao Zhao
   Subjects: **General Relativity and Quantum Cosmology (gr-qc)**

4. arXiv:1611.07947 [pdf, other]
   Search for Gravitational Waves Associated with Gamma-Ray Bursts During the First Advanced LIGO Observing Run and Implications for the Origin of GRB 150906B
   LIGO Scientific Collaboration, Virgo Collaboration, IPN Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, B. Allen, A. Allocca, P. A. Altin, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, P. Aufmuth, C. Aulbert, A. Avila-Alvarez, S. Babak, P. Bacon, M. K. M. Bader, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, et al. (943 additional authors not shown)
   Comments: 20 pages, 6 figures, 3 tables
   Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; General Relativity and Quantum Cosmology (gr-qc)

5. arXiv:1611.07531 [pdf, other]
   Effects of waveform model systematics on the interpretation of GW150914
   The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, B. Allen, A. Allocca, P. A. Altin, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, P. Aufmuth, C. Aulbert, A. Avila-Alvarez, S. Babak, P. Bacon, M. K. M. Bader, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, J. C. Batch, et al. (940 additional authors not shown)
   Comments: 29 pages, 9 figures
   Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; High Energy Astrophysical Phenomena (astro-ph.HE)

6. arXiv:1611.02972 [pdf, other]
   All-sky search for short gravitational-wave bursts in the first Advanced LIGO run
   The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, B. Allen, A. Allocca, P. A. Altin, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, P. Aufmuth, C. Aulbert, A. Avila-Alvarez, S. Babak, P. Bacon, M. K. M. Bader, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, J. C. Batch, C. Baune, et al. (927 additional authors not shown)
   Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; High Energy Astrophysical Phenomena (astro-ph.HE)

Publishing in journals

- We always post papers on arXiv (gr-qc) before submitting to journals.
- We usually publish in Physical Review D (PRD), Physical Review Letters (PRL), Astrophysical Journal (ApJ), Classical and Quantum Gravity (CQG), and increasingly, Physical Review X (PRX; online-only, fully open access journal launched in May 2011).
- We are turned off by the editorial heavy-handedness of Science and Nature, and rarely if ever publish there.
- No one appreciates journal editors who change titles, actively edit text, or demand to know the details of contributions from each of 1300 authors.
- No one likes to pay to publish! (We review each other's work for free!).
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- There is no LSC policy for who pays for publishing; somehow, one institution or the other (usually, LIGO Lab) pays.

https://www.ligo.caltech.edu/page/detection-companion-papers

Detection Papers

GW151226 - LIGO's Second Detection

- **"GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence"**
  Published in *Phys. Rev. Lett.* **116**, 241103 (2016) -- **Open access article**
- **"Binary Black Hole Mergers in the first Advanced LIGO Observing Run"**
  Accepted by *Phys. Rev. X*
- **GW151226 Data Release**

GW150914 - LIGO's First Detection

Discovery Paper

"Observation of Gravitational Waves from a Binary Black Hole Merger"
Published in *Phys. Rev. Lett.* **116**, 061102 (2016) -- **Open access article**

Related papers

- **"Observing Gravitational-wave Transient GW150914 with Minimal Assumptions"**
  Published in *Phys. Rev. D* **93**, 122004 (2016) -- **Abstract**
- **"GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO"**
  Published in *Phys. Rev. D* **93**, 122003 (2016) -- **Abstract**
- **"Properties of the Binary Black Hole Merger GW150914"**
  Published in *Phys. Rev. Lett.* **116**, 241102 (2016) -- **Open access article**
- **"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"**
  Accepted by *Astrophys. J. Lett.*
- **"Astrophysical Implications of the Binary Black-Hole Merger GW150914"**
  Published in *Astrophys. J. Lett.* **818**, L22 (2016) -- **Open access article**
- **"Tests of General Relativity with GW150914"**
  Published in *Phys. Rev. Lett.* **116**, 221101 (2016) -- **Abstract**
- **"GW150914: Implications for the Stochastic Gravitational Wave Background from Binary Black Holes"**
  Published in *Phys. Rev. Lett.* **116**, 131102 (2016) -- **Abstract**
- **"Calibration of the Advanced LIGO Detectors for the Discovery of the Binary Black-hole Merger GW150914"**
  Submitted to *Phys. Rev. D.*
- **"Characterization of Transient Noise in Advanced LIGO Relevant to Gravitational Wave Signal GW150914"**
  Published in *CQG* **33**, 134001 (2016) -- **Open access article**
- **"High-energy Neutrino Follow-up Search of Gravitational Wave Event GW150914 with ANTARES and IceCube"**
  Published in *Phys. Rev. D* **93**, 122010 (2016) -- **Abstract**
- **"GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"**
  Published in *Phys. Rev. Lett.* **116**, 131103 (2016) -- **Abstract**
- **"Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914"**
  Published in *Astrophys. J. Lett.* **826**, L13 (2016) -- **Open access article**

Data Release

GW150914 Data Release

LSC Observational and Instrument Publications

Link to collaboration authored Conference proceedings
Id

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Observational and LSC instrument papers

[Papers currently in LSC review]

25	S4/S3	CW	LSC, Kramer, Lyne	Phys. Rev. D 76 (2007) 042001	gr-qc/0702039	-	-	Upper Limits on Gravitational Wave Emission from 78 Radio Pulsars.
26	S4	CW	LSC	Phys. Rev. D 77 (2008) 022001	arXiv:0708.3818	-	-	All-sky search for periodic gravitational waves in LIGO S4 data
27	S4	CW	LSC	Phys. Rev. D 79 (2009) 022001	arXiv:0804.1747	-	-	The Einstein@Home search for periodic gravitational waves in LIGO S4 data
28	S4	Stochastic	LSC	Astrophys. J. 659 (2007) 918	astro-ph/0608606	-	-	Searching for Stochastic Background of Gravitational Waves with LIGO.
29	S4	Stochastic	LSC	Phys. Rev. D 76 (2007) 082003	astro-ph/0703234	-	-	Upper limit map of a background of gravitational waves.
30	S4	Stochastic	LSC, ALLEGRO	Phys. Rev. D 76 (2007) 022001	gr-qc/0703068	-	-	First Cross-Correlation Analysis of Interferometric and Resonant-Bar Gravitational-Wave Data for Stochastic Backgrounds.
31	S5	Bursts/Inspiral	LSC, Hurley	Astrophys. J. 681 (2008) 1419	arXiv:0711.1163	-	-	Implications for the Origin of GRB 070201 from LIGO Observations
32	S5	CW	LSC	Astrophys. J. Lett. 683 (2008) 45	arXiv:0805.4758	-	-	Beating the spin-down limit on gravitational wave emission from the Crab pulsar
33	S5	Bursts	LSC, Barthelmy,Gehrels, Hurley,Palmer	Phys. Rev. Lett. 101 (2008) 211102	arXiv:0808.2050	-	-	Search for Gravitational Wave Bursts from Soft Gamma Repeaters
34	S5	Detector	LSC	Rep. Prog. Phys. 72 (2009) 076901	arXiv:0711.3041	-	-	LIGO: The Laser Interferometer Gravitational-Wave Observatory
35	S5	CW	LSC	Phys. Rev. Lett.102 (2009) 111102	arXiv:0810.0283	-	-	All-sky LIGO Search for Periodic Gravitational Waves in the Early S5 Data
36	S5	CBC	LSC	Phys. Rev. D 79 (2009) 122001	arXiv:0901.0302	-	-	Search for Gravitational Waves from Low Mass Binary Coalescences in the First Year of LIGO's S5 Data
37	S4	Bursts	LSC	Phys Rev D 80 (2009) 062002	arXiv:0904.4718	-	-	First LIGO search for gravitational wave bursts from cosmic (super)strings
38	S5	Bursts	LSC	Phys Rev D 80 (2009) 102002	arXiv:0904.4910	-	-	Search for High Frequency Gravitational Wave Bursts in the First Calendar Year of LIGO's Fifth Science Run
39	S5	Bursts	LSC	Astrophys. J. 701 (2009) L68-L74	arXiv:0905.0005	-	-	Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm
40	S5	Bursts	LSC	Phys Rev D 80 (2009) 102001	arXiv:0905.0020	-	-	Search for gravitational-wave bursts in the first year of the fifth LIGO science run
41	S4	CBC	LSC	Phys. Rev. D 80 (2009) 062001	arXiv:0905.1654	-	-	Search for gravitational wave ringdowns from perturbed black holes in LIGO S4 data
42	S5	CW	LSC, Anderson	Phys. Rev. D 80 (2009) 042003	arXiv:0905.1705	-	-	Einstein@Home search for periodic gravitational waves in early S5 LIGO data
43	S5	CBC	LSC	Phys. Rev. D 80 (2009) 047101	arXiv:0905.3710	-	-	Search for Gravitational Waves from Low Mass Compact Binary Coalescence in 186 Days of LIGO's fifth Science Run
44	S5	Instrument	LSC	New J. Phys. 11 (2009) 073032	-	-	-	Observation of a kilogram-scale oscillator near its quantum ground state
45	S5/VSR1	Stochastic	LSC, Virgo	Nature 460 (2009) 990	arXiv:0910:5772	-	-	An upper limit on the stochastic gravitational-wave background of cosmological origin
46	S5/VSR1	Bursts	LSC, Virgo	Astrophys. J. 715 (2010) 1438	arXiv:0908.3824	-	-	Search for gravitational-wave bursts associated with gamma-ray bursts using data from LIGO Science Run 5 and Virgo Science Run 1
47	S5/VSR1	CW	LSC, Virgo	Astrophys. J. 713 (2010) 671	arXiv:0909.3583	-	-	Searches for gravitational waves from known pulsars with S5 LIGO data
48	S5/VSR1	CBC	LSC, Virgo	Astrophys. J. 715 (2010) 1453	arXiv:1001.0165	-	-	Search for gravitational-wave inspiral signals associated with short Gamma-Ray Bursts during LIGO's fifth and Virgo's first science run
49	S5/VSR1	Bursts	LSC, Virgo	Phys. Rev. D 81 (2010) 102001	arXiv:1002.1036	-	-	All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run
50	na	CBC	LSC, Virgo	Class. Quantum Grav. 27 (2010) 173001	arXiv:1003.2480	-	-	Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors
51	S5/VSR1	CBC	LSC, Virgo	non-journal companion to papers 50,52	arXiv:1003.2481	-	-	Sensitivity to Gravitational Waves from Compact Binary Coalescences Achieved during LIGO's Fifth and Virgo's First Science Run
52	S5/VSR1	CBC	LSC, Virgo	Phys. Rev. D 82 (2010) 102001	arXiv:1005.4655	-	-	Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1
53	S5	CW	LSC	Astrophys. J. 722 (2010) 1504	arXiv:1006.2535	-	-	First search for gravitational waves from the youngest known neutron star
54	S5	Instrument	LSC	Nucl. Instrum. Meth. A624 (2010) 223	arXiv:1007.3973	-	-	Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run
55	S5	Bursts	LSC	Phys. Rev. D83 (2011) 042001	arXiv:1011.1357	-	-	A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar
56	S5/VSR1/A5	Bursts	LSC, Virgo, external	Astrophys. J. 734 (2011) L35	arXiv:1011.4079	-	-	Search for Gravitational Wave Bursts from Six Magnetars
57	S5/VSR1	CBC	LSC, Virgo	Phys. Rev. D83 (2011) 122005	arXiv:1102.3781	-	-	Search for gravitational waves from binary black hole inspiral, merger and ringdown
58	VSR2	CW	LSC, Virgo	Astrophys. J. 737 (2011) 93	arXiv:1104.2712	-	-	Beating the spin-down limit on gravitational wave emission from the Vela pulsar
59	na	Instrum	LSC	Nature Physics 7 (2011) 962	-	-	Science summary	A gravitational wave observatory operating beyond the quantum shot-noise limit
60	S5	Stochastic	LSC, Virgo	Phys. Rev. Lett. 107 (2011) 271102	arXiv:1109.1809	-	Science summary	Directional limits on persistent gravitational waves using LIGO S5 science data
61	S6/VSR3	CBC/Bursts	LSC, Virgo	Astron Astrophys 539 (2012) A124	arXiv:1109.3498	-	Science summary	Implementation and testing of the first prompt search for gravitational wave transients with electromagnetic counterparts
62	S5	CW	LSC, Virgo	Phys. Rev. D85 (2012) 022001	arXiv:1110.0208	-	Science summary	All-sky search for periodic gravitational waves in the full S5 LIGO data
63	S6/VSR2-3	CBC	LSC, Virgo	Phys. Rev D85 (2012) 082002	arXiv:1111.7314	P1100034	Science summary	Search for Gravitational Waves from Low Mass Compact Binary Coalescence in LIGO's Sixth Science Run and Virgo's Science Runs 2 and 3
64	S6/VSR2-3	CBC	LSC, Virgo	non-journal companion to paper 63	arXiv:1203.2674	T1100338	Science summary	Sensitivity Achieved by the LIGO and Virgo Gravitational Wave Detectors during LIGO's Sixth and Virgo's Second and Third Science Runs
65	S6/VSR3	CBC	LSC, Virgo	Astron Astrophys 541 (2012) A155	arXiv:1112.6005	P1100065	Science summary	First Low-Latency LIGO+Virgo Search for Binary Inspirals and their Electromagnetic Counterparts
66	S5/VSR1	Stochastic	LSC, Virgo	Phys. Rev. D 85 (2012) 122001	arXiv:1112.5004	P1000128	Science Summary	Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz
67	pre-S5	Bursts/CBC	LSC	Astrophys. J. 755 (2012) 2	arXiv:1201.4413	P1000097	Science summary	Implications for the Origin of GRB 051103 from LIGO Observations
68	S5/VSR1	Bursts	LSC, Virgo	Phys. Rev. D 85 (2012) 102004	arXiv:1201.5999	P1100068	Science summary	Search for Gravitational Waves from Intermediate Mass Binary Black Holes
69	S6/VSR2-3	Bursts	LSC, Virgo	Phys. Rev. D 85 (2012) 122007	arXiv:1202.2788	P1100118	Science summary	All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run
70	VSR1-3	DetChar	LSC, Virgo	Class. Quantum Grav. 29 (2012) 155002	arXiv:1203.5613	-	Science summary	Virgo data characterization and impact on gravitational wave searches
71	S6/VSR2-3	Bursts	LSC, Virgo, Swift	ApJS 203 (2012) 28	arXiv:1205.1124	P1100038	Science summary	Swift Follow-Up Observations Of Candidate Gravitational-Wave Transient Events
72	S6/VSR2-3	Bursts/CBC	LSC, Virgo, others	Astrophys. J. 760 (2012) 12	arXiv:1205.2216	P1000121	Science summary	Search for gravitational waves associated with gamma-ray bursts during LIGO science run 6 and Virgo science run 2 and 3
73	S5/VSR1	Bursts	LSC, Virgo, ANTARES	JCAP 1306 (2013) 008	arXiv:1205.3018	P1200006	Science summary	A first search for coincident gravitational waves and high energy neutrinos using LIGO, Virgo and ANTARES data from 2007
74	S5	CW	LSC, Virgo	Phys. Rev. D 87 (2013) 042001	arXiv:1207.7176	P1200026	Science summary	Einstein@Home all-sky search for periodic gravitational waves in LIGO S5 data
75	S6/VSR2-3	CBC	LSC, Virgo	Phys. Rev. D 87 (2013) 022002	arXiv:1209.6533	P1200024	Science summary	Search for Gravitational Waves from Binary Black Hole Inspiral, Merger and Ringdown in LIGO-Virgo Data from 2009-2010
76	na	Instrum	LSC	Nature Photonics 7 (2013) 613	arXiv:1310.0383	P1200041	Science summary	Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light
77	ADE	CBC/Bursts	LSC, Virgo	Living Rev. Relativity 19 (2016), 1	arXiv:1304.0670	P1200087	Science Summary	Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories
78	S6/VSR2-3	CBC	LSC, Virgo	Phys. Rev. D 88(2013) 062001	arXiv:1304.1775	P1200021	Science summary	Parameter estimation for compact binary coalescence signals with the first generation gravitational wave detector network
79	S6/VSR2,4	CW	LSC, Virgo	Astrophys. J. 785 (2014) 119	arXiv:1309.4027	P1200104	Science summary	Gravitational-waves from known pulsars: results from the initial detector era
80	S5	CW	LSC, Virgo	Phys. Rev. D 88(2013) 102022	arXiv:1309.6221	P1300037	Science summary	A directed search for continuous Gravitational Waves from the Galactic Center
81	S5	Stoch	LSC, Virgo	Phys. Rev. D 88(2013) 122004	arXiv:1309.6160	P1200093	Science summary	Search for long-lived gravitational-wave transients coincident with long gamma-ray bursts
82	S6/VSR3	Bursts	LSC, Virgo	ApJS 211 (2014) 7	arXiv:1310.2314	P1200171	Science summary	First Searches for Optical Counterparts to Gravitational-wave Candidate Events
83	S6/VSR3	Bursts	LSC, Virgo	Phys. Rev. Lett. 112 (2014) 131101	arXiv:1310.2384	P1300093	Science summary	Constraints on cosmic (super)strings from the LIGO-Virgo gravitational-wave detectors.
84	S5	CW	LSC, Virgo	Class. Quantum Grav. 31 (2014) 085014	arXiv:1311.2409	P1300071	Science summary	Application of a Hough search for continuous gravitational waves on data from the 5th LIGO science run
85	na	CBC/Bursts	LSC, Virgo, NINJA collaboration	Class. Quantum Grav. 31 (2014) 115004	arXiv:1401.0939	P1300199	Science summary	The NINJA-2 project: Detecting and characterizing gravitational waveforms modelled using numerical binary black hole simulations
86	VSR1	CW	LSC, Virgo	Class. Quantum Grav. 31 (2014) 165014	arXiv:1402.4974	P1300133	Science Summary	Implementation of an F-statistic all-sky search for continuous gravitational waves in Virgo VSR1 data
87	S5-6,VSR2-3	CBC	LSC, Virgo	Phys. Rev D 89 (2014) 102006	arXiv:1403.5306	P1300156	Science Summary	Search for gravitational wave ringdowns from perturbed intermediate mass black holes in LIGO-Virgo data from 2005-2010
88	S5-6,VSR1-3	CBC/Bursts	LSC, Virgo, IPN Collaboration	Phys. Rev. Lett. 113 (2014) 011102	arXiv:1403.6639	P1300226	Science Summary	Search for gravitational waves associated with gamma-ray bursts detected by the Interplanetary Network
89	S6,VSR2-3	Burst	LSC, Virgo	Phys. Rev D 89 (2014) 122003	arXiv:1404.2199	P1300158	Science Summary	Search for gravitational radiation from intermediate mass black hole binaries in data from the second LIGO-Virgo joint science run
90	S5-6,VSR1-4	Bursts	LSC, Virgo	Phys. Rev. D 89 (2014), 122004	arXiv:1405.1053	P1300086	Science Summary	Methods and results of a search for gravitational waves associated with gamma-ray bursts using the GEO600, LIGO, and Virgo detectors
91	S6,VSR2-3	CW	LSC, Virgo	Phys. Rev. D 90 (2014), 062010	arXiv:1405.7904	P1300048	Science Summary	First all-sky search for continuous gravitational waves from unknown sources in binary systems.
92	S6,VSR2-3	Stochastic	LSC, Virgo	Phys. Rev. Lett 113 (2014) 231101	arXiv:1406.4556	P1300154	Science Summary	Improved Upper Limits on the Stochastic Gravitational-Wave Background from 2009-2010 LIGO and Virgo Data
93	S5-6,VSR1-3	Burst	LSC, Virgo, IceCube	Phys. Rev. D 90 (2014) 102002	arXiv:1407.1042	P1400046	Science Summary	Multimessenger Search for Sources of Gravitational Waves and High-energy Neutrinos: Results for Initial LIGO-Virgo and IceCube.
94	S5	Stochastic	LSC, Virgo	Phys. Rev. D 91 (2015) 022003	arXiv:1410.6211	P1000112	Science Summary	Searching for stochastic gravitational waves using data from the two co-located LIGO Hanford detectors
95	S6	DetChar	LSC, Virgo	Class. Quantum Grav. 32 (2015) 105012	arXiv:1410.7764	P1000142	Science Summary	Characterization of the LIGO detectors during their sixth science run.
96	VSR4	CW	LSC, Virgo	Phys. Rev. D 91 (2015) 022004	arXiv:1410.8310	P1400045	Science Summary	Narrow-band search of continuous gravitational-wave signals from Crab and Vela pulsars in Virgo VSR4 data
97	S5	CW	LSC, Virgo	Phys. Rev. D 91 (2015) 062008	arXiv:1412.0605	P1400094	Science Summary	A directed search for gravitational waves from Scorpius X-1 with initial LIGO
98	--	Detector	LSC	Class. Quantum Grav. 32 (2015) 074001	arXiv:1411.4547	P1400177	Science Summary	Advanced LIGO
99	S6	CW	LSC, Virgo	Astrophys.J. 813 (2015) 1, 39	arXiv:1412.5942	P1400182	Science Summary	Searches for continuous gravitational waves from nine young supernova remnants
100	S6	CW	LSC, Virgo	Phys. Rev. D93, 042006 (2016)	arXiv:1510.03474	P1500034	Science Summary	A search of the Orion spur for continuous gravitational waves using a "loosely coherent" algorithm on data from LIGO interferometers
101	S6	CW	LSC, Virgo	Phys. Rev. D93, 042007 (2016)	arXiv:1510.03621	P1500030	Science Summary	First low frequency all-sky search for continuous gravitational wave signals
102	S6	Bursts	LSC, Virgo	Phys. Rev. D 93, 042005 (2016)	arXiv:1511.04398	P1400138	Science Summary	An all-sky search for long-duration gravitational wave transients with LIGO
103	O1	GW150914	LSC, Virgo	Phys. Rev. Lett. 116, 061102 (2016)	arXiv:1602.03837	P150914	Science Summary	Observation of Gravitational Waves from a Binary Black Hole Merger
104	O1	Instrument	LSC, Virgo	Phy. Rev. Lett. 116, 131103 (2016)	arXiv:1602.03838	P1500237	Science Summary	GW150914: The Advanced LIGO Detectors in the Era of First Discoveries
105	O1	CBC	LSC, Virgo	Phys. Rev. D 93, 122003 (2016)	arXiv:1602.03839	P1500269	Science Summary	GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
106	O1	CBC	LSC, Virgo	Phys. Rev. Lett. 116, 241102 (2016)	arXiv:1602.03840	P1500218	Science Summary	Properties of the binary black hole merger GW150914
107	O1	CBC	LSC, Virgo	Phys. Rev. Lett. 116, 221101 (2016)	arXiv:1602.03841	P1500213	Science Summary	Tests of general relativity with GW150914
108	O1	CBC	LSC, Virgo		arXiv:1602.03842	P1500217	Science Summary	The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
109	O1	Bursts	LSC, Virgo	Phys. Rev. D 93, 122004 (2016)	arXiv:1602.03843	P1500229	Science Summary	Observing gravitational-wave transient GW150914 with minimal assumptions
110	O1	DetChar	LSC, Virgo	Class.Quant.Grav. 33, 134001 (2016)	arXiv:1602.03844	P1500238	Science Summary	Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
111	O1	Instrument	LSC		arXiv:1602.03845	P1500248	Science Summary	Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
112	O1	CBC	LSC, Virgo	ApJL, 818, L22, 2016	arXiv:1602.03846	P1500262	Science Summary	Astrophysical Implications of the Binary Black-Hole Merger GW150914
113	O1	Stochastic	LSC, Virgo	Phys. Rev. Lett.116, 131102 (2015)	arXiv:1602.03847	P1500222	Science Summary	GW150914: Implications for the stochastic gravitational-wave background from binary black holes
114	O1	Bursts	LSC, Virgo, Antares, IceCube	Phys. Rev. D 93, 122010 (2016)	arXiv:1602.05411	P1500271	Science Summary	High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
115	O1	CBC, Bursts	LSC, Virgo, Various EM Partners	Astrophys.J. 826 (2016) no.1, L13	arXiv:1602.08492	P1500227	Science Summary	Localization and broadband follow-up of the gravitational-wave transient GW150914
116	S5,S6	Bursts	LSC, Virgo	Phys. Rev. D 93, 122008 (2016)	arXiv:1605.01707	P1400154	Science Summary	Search for Transient Gravitational Waves in Coincidence with Short Duration Radio Transients
117	S6	CW	LSC, Virgo	Phys. Rev. D 94, 042002 (2016)	arXiv:1605.03233	P1500219	Science Summary	Comprehensive All-sky Search for Periodic Gravitational Waves in the Sixth Science Run LIGO Data
118	S6	Bursts	LSC, Virgo		arXiv:1605.01785	P1400208	Science Summary	A First Targeted Search for Gravitational-Wave Bursts from Core-Collapse Supernovae in Data of First-Generation Laser Interferometer Detectors
119	O1	CBC	LSC, Virgo	Phys. Rev. X, 6, 041014 (2016)	arXiv:1606.01210	P1600048	Science Summary	An improved analysis of GW150914 using a fully spin-precessing waveform model
120	O1	CBC	LSC, Virgo	Phys. Rev. D 94, 064035 (2016)	arXiv:1606.01262	P1500263	Science Summary	Directly comparing GW150914 with numerical solutions of Einstein's equations for binary black hole coalescence
121	O1	GW151226	LSC, Virgo	Phys. Rev. Lett. 116, 241103 (2016)	arXiv:1606.04855	P151226	Science Summary	GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence
122	O1	CBC	LSC, Virgo	Phys. Rev. X 6, 041015 (2016)	arXiv:1606.04856	P1600088	Science Summary	Binary Black Hole Mergers in the first Advanced LIGO Observing Run
123	S6	CW	LSC, Virgo		arXiv:1606.09619	P1500156	Science Summary	Results of the deepest all-sky survey for continuous gravitational waves on LIGO S6 data running on the Einstein@Home volunteer distributed computing project
124	S6	CW	LSC, Virgo		arXiv:1607.02216	P1500225	Science Summary	Search for continuous gravitational waves from neutron stars in globular cluster NGC 6544
125	O1	CBC	LSC, Virgo		arXiv:1607.07456	P1600171	Science Summary	Upper limits on the rates of binary neutron star and black-hole neutron-star mergers from Advanced LIGOs first observing run
126	O1	CBC	LSC, Virgo	Annalen Phys. (2016)	arXiv:1608.01940	P1600161	Science Summary	The basic physics of the binary black hole merger GW150914
127	O1	CBC	LSC, Harms		arXiv:1607.08697	P1600143	Science Summary	Exploring the Sensitivity of Next Generation Gravitational Wave Detectors

https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html

Open Data and publishing

- The LIGO Open Science Center (LOSC, losc.ligo.org) was created in response to a ruling by the National Science Board (NSB, policy-making body for NSF) that NSF-sponsored National Laboratories like LIGO must make their data public, to enhance advances in science.
- NASA has been doing this for many years.
- LOSC is patterned after NASA's HEASARC and LAMBDA (CMB) data archives.
- Open data is much more difficult for high energy physics (eg, LHC); they do only very limited data releases. It is much easier for LIGO: "strain h(t)" time series.
- Funding – NASA and other colleagues told us that we'll need at least $2M per year to do a good job. We requested $7M for 5 years, and got $700K for 2 years, and were told that in subsequent years, we must "fit it in your budget".
  - This pays for 3 part-time scientists, LSC reviewers.
- All data releases have a Digital Object Identifier (DOI; https://www.doi.org/).

Inspiration and direction: NASA's HEASARC and LAMBDA

http://heasarc.gsfc.nasa.gov/

Legacy Archive for Microwave Background Data Analysis

LAMBDA is a part of NASA's High Energy Astrophysics Science Archive Research Center (HEASARC). This site is a multi-mission NASA center of expertise for cosmic microwave background (CMB) radiation research; it provides CMB researchers with archive data from cosmology missions, software tools, and links to other sites of interest. As a resource for the CMB community, your suggestions are encouraged.

LAMBDA exists to serve the CMB research community, and the greater cosmological research community. In particular, LAMBDA:

- develops and maintains data archives
- develops and maintains data access and analysis tools
- offers scientific expertise on NASA's CMB missions
- carries out data-intensive processing of vital importance to NASA's CMB community
- conducts education and outreach efforts aimed at the general public.

There is no cost involved in the use of LAMBDA. However, if your research benefits from its use then we request that you include the following acknowledgement in your publications:

"We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA), part of the High Energy Astrophysics Science Archive Center (HEASARC). HEASARC/LAMBDA is a service of the Astrophysics Science Division at the NASA Goddard Space Flight Center."

https://losc.ligo.org

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

- Getting Started
- Tutorials
- Data
  - Events
  - Bulk Data
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Data Analysis Projects
- Acknowledgement

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
If you have LSC credentials, you may go to the development site

---

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

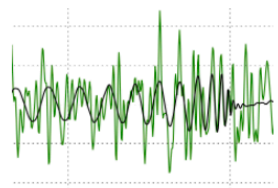
released 2016 June 15:
Candidate event of October 12, LVT151012: Chirp mass 15

released 2016 Feb 11:
Event of September 14, GW150914: Chirp mass 30

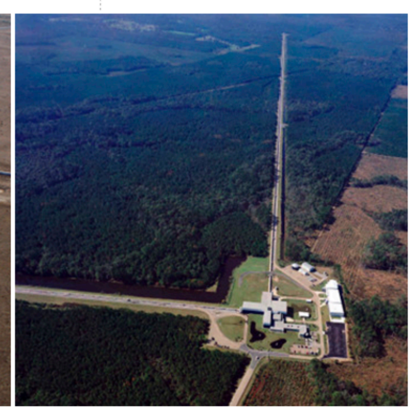
The LIGO Laboratory's Data Management Plan describes the scope and timing of LIGO data releases.

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



LIGO Hanford Observatory, Washington (image: C.Gray)



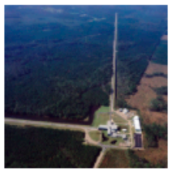
LIGO Livingston Observatory, Louisiana (image: J.Giaime)

The observatories are built and operated by the LIGO Laboratory (California Institute of Technology and Massachusetts Institute of Technology) with participation by the LIGO Scientific Collaboration, and are supported by the U.S. National Science Foundation.

Getting Started

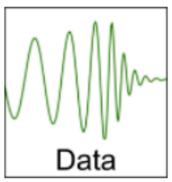
Welcome! The LIGO Open Science Center (LOSC) provides access to LIGO data, as well as documentation, tutorials, and online tools for finding and viewing data.

What's LIGO!?



The LIGO Scientific Collaboration Home Page provides a general introduction to LIGO.

Where's the data?

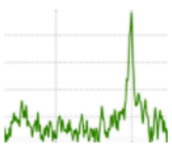


The Data Page allows you to download LIGO data.

The main data are a time series sampled at 4096 Hz.

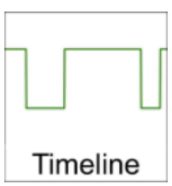
Data are calibrated so that gravitational wave signals have units of dimensionless strain (ΔL / L).

How do I work with LIGO data?



The Tutorials Page gives examples of how to work with LIGO data. If you are a student, this is a great place to start.

When was LIGO running?

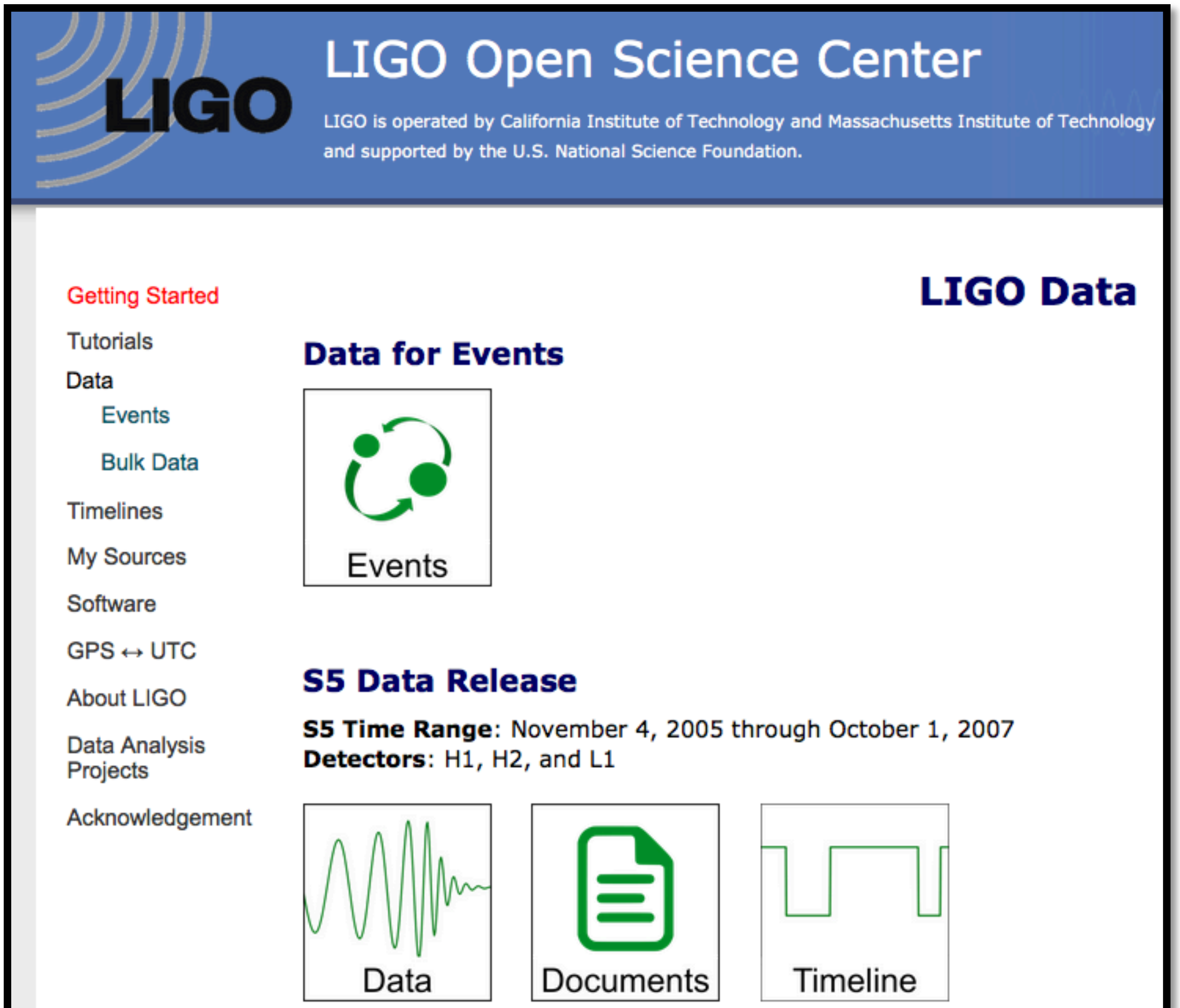


The Timeline Application shows times when LIGO was operating.

See the Segments Page for notes about how to use Timeline.

Data Access

https://losc.ligo.org/data/



"Easy" point & click data downloads

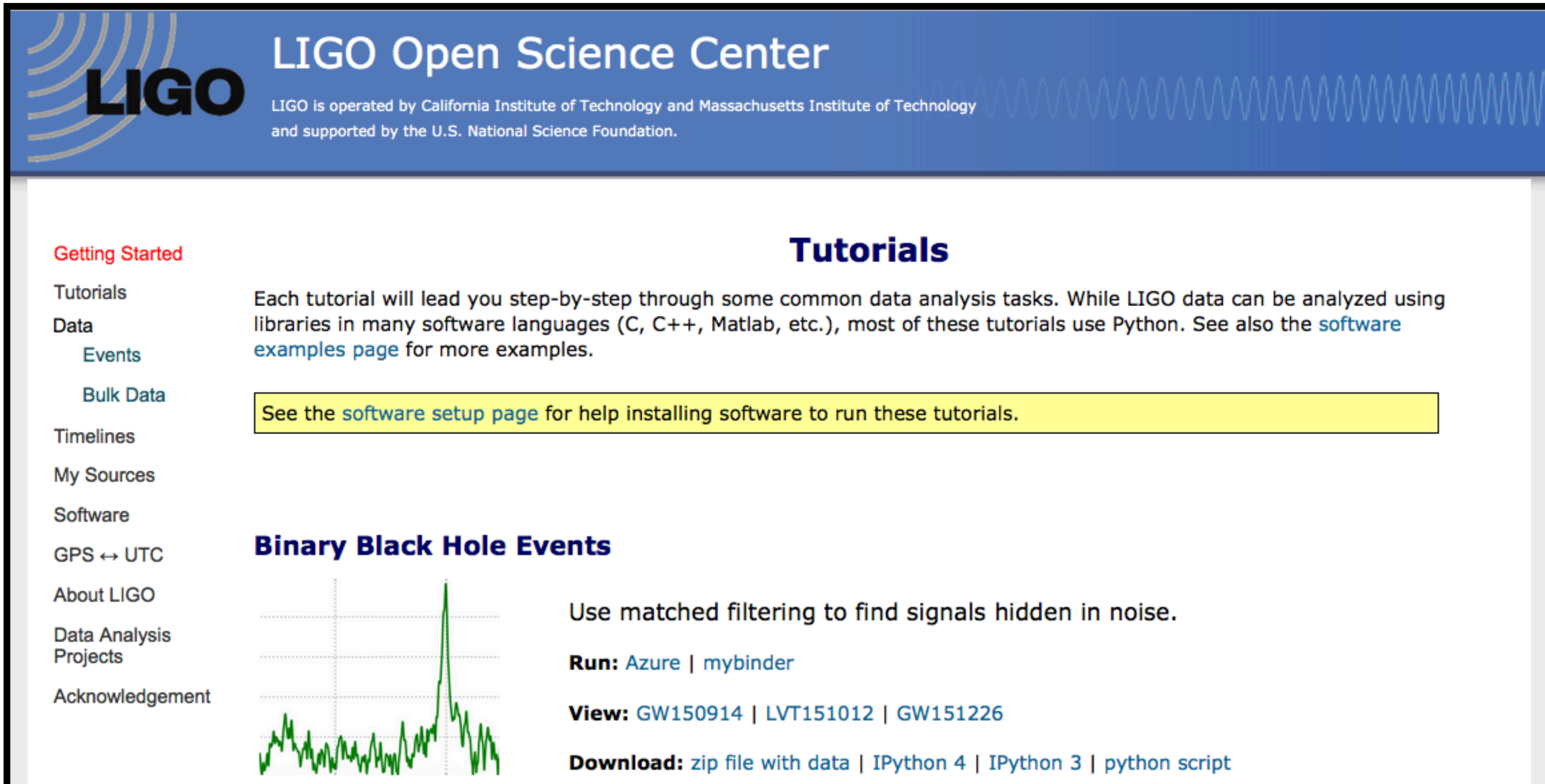
Includes:

- Documentation
- Data Quality
- Segments
- How to cite

Tutorials

https://losc.ligo.org/tutorials/

Examples use python to load data, make plots, find signals.
How to cite: click on "Acknowledgments"



LIGO Open Science Center

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Tutorials

Each tutorial will lead you step-by-step through some common data analysis tasks. While LIGO data can be analyzed using libraries in many software languages (C, C++, Matlab, etc.), most of these tutorials use Python. See also the software examples page for more examples.

See the software setup page for help installing software to run these tutorials.

Binary Black Hole Events

Use matched filtering to find signals hidden in noise.

Run: Azure | mybinder

View: GW150914 | LVT151012 | GW151226

Download: zip file with data | IPython 4 | IPython 3 | python script

Tutorials

https://losc.ligo.org/tutorials/

Three ways to access tutorials: Run, View, or Download

Run: Run tutorials in your browser with “binder” or “Microsoft Azure”

- Binder provides instant access, no log-in
- Microsoft Azure provides log-in feature to save work, create, & share new notebooks
- LOSC may be highlight in Microsoft Azure “roll-out”

View: See the tutorial as an HTML web page

Download: Download the code and run it on your own computer

Acknowledgement

How to acknowledge use of this data

If your research used data from one of the data releases, please cite as:

- LIGO Scientific Collaboration, "LIGO Open Science Center release of S5", 2014, DOI 10.7935/K5WD3XHR
- LIGO Scientific Collaboration, "LIGO Open Science Center release of S6", 2015, DOI 10.7935/K5RN35SD
- LIGO Scientific Collaboration, "LIGO Open Science Center release of GW150914", 2016, DOI 10.7935/K5MW2F23

and please include the statement "This research has made use of data, software and/or web tools obtained from the LIGO Open Science Center (https://losc.ligo.org), a service of LIGO Laboratory and the LIGO Scientific Collaboration. LIGO is funded by the U.S. National Science Foundation."

If you would also like to cite a published paper,

- M Vallisneri et al. "The LIGO Open Science Center", proceedings of the 10th LISA Symposium, University of Florida, Gainesville, May 18-23, 2014; also arxiv:1410.4839

Publications

We request that you let the LOSC team know if you publish (or intend to publish) a paper using data released from this site. If you would like, we may be able to review your work prior to publication, as we do for our colleagues in the LIGO Scientific Collaboration.

Credits

LOSC Development: The LOSC Team and The LIGO Scientific Collaboration

The data products made available through the LOSC web service are created and maintained by LIGO Lab and the LIGO Scientific Collaboration. The development of this web page was a team effort, with all members of the LOSC team making contributions in most areas. In addition to the team members listed below, a large number of individuals in the LIGO Scientific Collaboration have contributed content and advice. The LOSC team includes:

- Alan Weinstein: LOSC Director
- Roy Williams: LOSC Developer, web services and data base architecture
- Jonah Kanner: LOSC Developer, tutorials, documentation, data set curation
- Michele Vallisneri: LOSC Developer, data quality curation
- Branson Stephens: LOSC Developer, event database and web site architecture

Please send any comments, questions, or concerns to: losc@ligo.org

For general information on LIGO, see the About LIGO page.

BINARY BLACK HOLE SIGNALS IN LIGO OPEN DATA

Version 1.41, 2016 July 18

Welcome! This IPython notebook (or associated python script LOSC_Event_tutorial.py) will go through some typical signal processing tasks o series data associated with the LIGO Event data releases from the LIGO Open Science Center (LOSC):

- Find events at https://losc.ligo.org/events/.
- View the tutorial as a web page, for GW150914.
- Run this tutorial with Binder using the link on the tutorials page.
- If you are running this tutorial on your own computer, see the Download section below.
- This notebook works with nbformat version 4. If you are running version 3, pick it up from the tutorials page.
- After setting the desired "eventname" below, you can just run the full notebook.

Please note that the results obtained here will not match precisely with numbers in o due to various subtleties in the analysis that are discussed further down.

Questions, comments, suggestions, corrections, etc: email losc@ligo.caltech.edu

Table of Contents

Intro to signal processing

This tutorial assumes that you are comfortable with python.

This tutorial also assumes that you know a bit about signal processing of digital time series data (or want to learn!). This includes power specti spectrograms, digital filtering, whitening, audio manipulation. This is a vast and complex set of topics, but we will cover many of the basics in

If you are a beginner, here are some resources from the web:

- http://101science.com/dsp.htm
- https://www.coursera.org/course/dsp
- https://georgemdallas.wordpress.com/2014/05/14/wavelets-4-dummies-signal-processing-fourier-transforms-and-heisenberg/
- https://en.wikipedia.org/wiki/Signal_processing
- https://en.wikipedia.org/wiki/Spectral_density
- https://en.wikipedia.org/wiki/Spectrogram
- http://greenteapress.com/thinkdsp/
- https://en.wikipedia.org/wiki/Digital_filter

And, well, lots more on the web!

Download the data on a computer with a python installation

If you are using a pre-configured setup (eg, in binder), great! You don't have to download or set up anything.

Otherwise, to begin, get the necessary files, by downloading the zip file and unpacking it into single directory:

- LOSC_Event_tutorial.zip

This zip file contains:

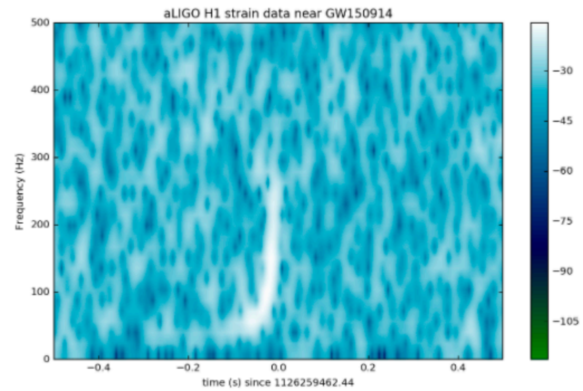
- this IPython notebook LOSC_Event_tutorial.ipynb, and LOSC_Event_tutorial.py code.
- python code for reading LOSC data files: readligo.py.
- the event data files (32s sampled at 4096 Hz, in hdf5 format, for both LIGO detectors).

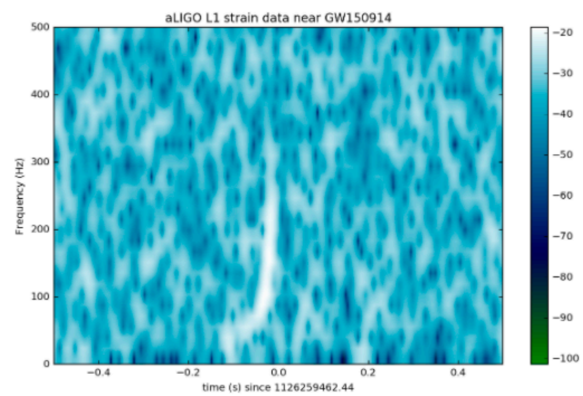
In [12]:
```
if make_plots:
    #  plot the whitened data, zooming in on the signal region:

    # pick a shorter FTT time interval, like 1/16 of a second:
    NFFT = int(fs/16.0)
    # and with a lot of overlap, to resolve short-time features:
    NOVL = int(NFFT*15/16.0)
    # choose a window that minimizes "spectral leakage"
    # (https://en.wikipedia.org/wiki/Spectral_leakage)
    window = np.blackman(NFFT)

    # Plot the H1 whitened spectrogram around the signal
    plt.figure(figsize=(10,6))
    spec_H1, freqs, bins, im = plt.specgram(strain_H1_whiten[indxt], NFFT=NFFT, Fs=fs, window=window,
                                            noverlap=NOVL, cmap=spec_cmap, xextent=[-deltat,deltat])
    plt.xlabel('time (s) since '+str(tevent))
    plt.ylabel('Frequency (Hz)')
    plt.colorbar()
    plt.axis([-0.5, 0.5, 0, 500])
    plt.title('aLIGO H1 strain data near '+eventname)
    plt.savefig(eventname+'_H1_spectrogram_whitened.'+plottype)

    # Plot the L1 whitened spectrogram around the signal
    plt.figure(figsize=(10,6))
    spec_H1, freqs, bins, im = plt.specgram(strain_L1_whiten[indxt], NFFT=NFFT, Fs=fs, window=window,
                                            noverlap=NOVL, cmap=spec_cmap, xextent=[-deltat,deltat])
    plt.xlabel('time (s) since '+str(tevent))
    plt.ylabel('Frequency (Hz)')
    plt.colorbar()
    plt.axis([-0.5, 0.5, 0, 500])
    plt.title('aLIGO L1 strain data near '+eventname)
    plt.savefig(eventname+'_L1_spectrogram_whitened.'+plottype)
```

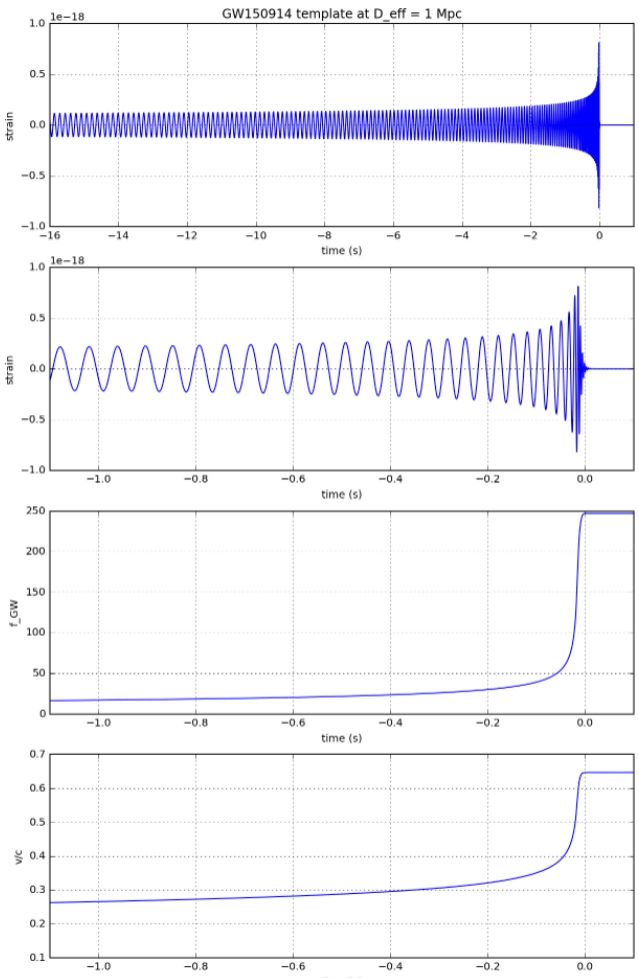




Loud (high SNR) signals may be visible in these spectrograms. Compact object mergers show a characteristic "chirp" as the signal rises in f can't see anything, try event GW150914, by changing the

```
    plt.subplot(4,1,4)
    plt.plot(ttime,voverc)
    plt.xlim([-1.1,0.1])
    plt.grid()
    plt.xlabel('time (s)')
    plt.ylabel('v/c')
    #plt.title(eventname+' template v/c')
    plt.savefig(eventname+'_template.'+plottype)
```

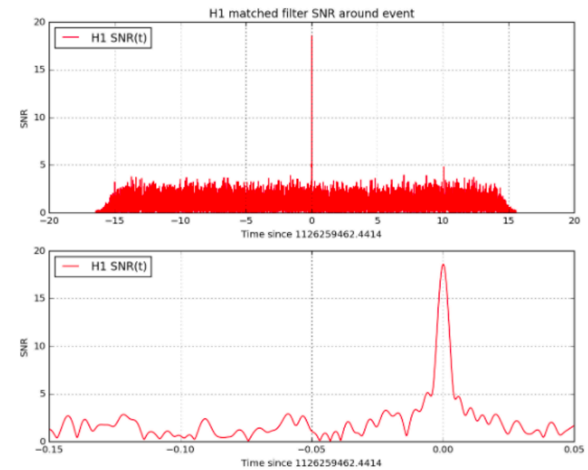
```
Properties of waveform template in GW150914_4_template.hdf5
Waveform family = lalsim.SEOBNRv2
Masses = 41.74, 29.24 Msun
Mtot = 70.98 Msun, mfinal = 67.43 Msun
Spins = 0.35, -0.77
Freq at inband, peak = 43.05, 169.84 Hz
Time at inband, peak = -0.08, -0.02 s
Duration (s) inband-peak = 0.06 s
N_cycles inband-peak = 4
v/c at peak = 0.57
Radius of final BH = 199 km
```

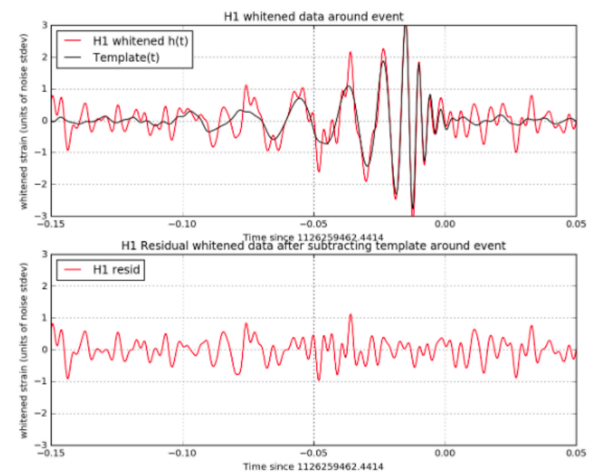


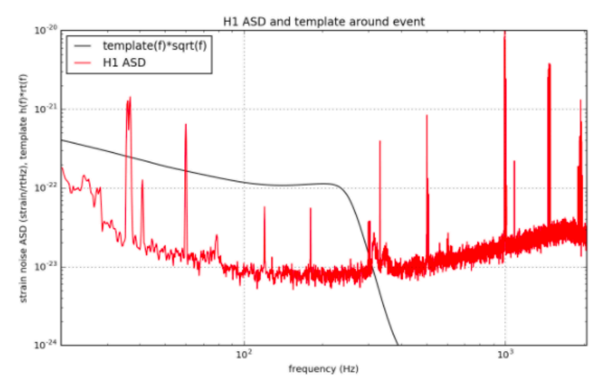
Matched filtering to find the signal

```
    plt.legend(loc='upper left')
    plt.title(det+' ASD and template around event')
    plt.savefig(eventname+"_"+det+"_matchfreq."+plottype)
```

```
For detector H1, maximum at 1126259462.4414 with SNR = 18.6, D_eff = 805.83, horizon = 1873.7 Mpc
For detector L1, maximum at 1126259462.4343 with SNR = 13.3, D_eff = 979.07, horizon = 1623.6 Mpc
```

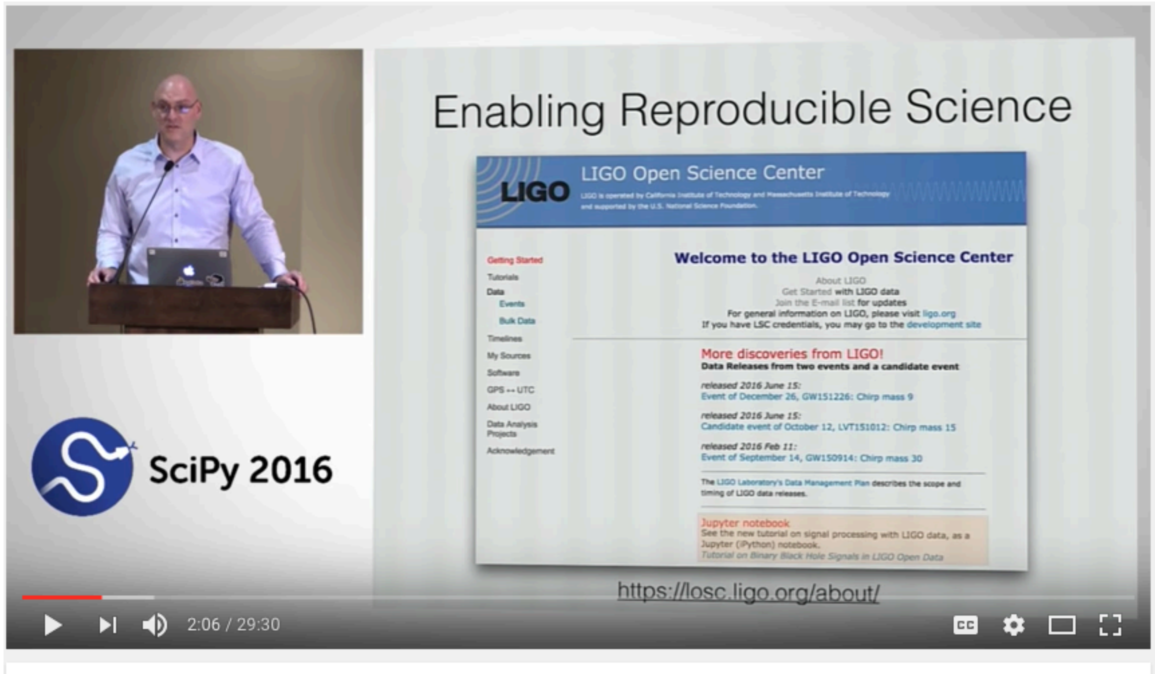






LOSC for Outreach

- Open Data
- Open Code
  - Jupyter notebook for data analysis
- Open Computing
  - notebooks.azure.com (all in browser)



https://www.youtube.com/watch?v=Ejh0ftSjk6g&t=1m53s

"The Jupyter notebook is enabling **reproducible science**, this is something near and dear to our hearts. The LIGO collaboration, which recently discovered the first experimental signatures of gravitational waves, has been publishing all of their analysis at this website, the LIGO Open Science Center, as Jupyter notebooks. So anyone can download the data with the notebooks, and there's even a live Binder service, so people can run those notebooks without installing anything."

-- Brian Granger

*** also in azure.com**

LOSC Usage

Track web site usage through Google Analytics

- See stats in LOSC Q2 report: https://dcc.ligo.org/LIGO-P1600244
- Would welcome help interpreting these numbers

From e-mails, we know users include:

students, teachers, citizen scientists, professional scientists, and artists

2. Web Server Activity

Number of users at the LOSC website, peaking at 1600 on the day of the release of GW151226, the second detection.

Data archiving

- LIGO Laboratory is of course obliged to archive its ~petabytes of data for the NSF, over the long term.
- LOSC piggybacks off of a larger Laboratory effort, which maintains a public Data Management Plan, updated regularly: https://dcc.ligo.org/M1000066/public
- The LIGO Data group (lead: Stuart Anderson) keeps abreast of technology advancement.
- But of course, no one can predict what will happen to data archiving technologies over the coming decades … not to mention funding...

Open Data – the dangers

- LOSC's biggest fear: users finding fake signals that we routinely inject into the data for testing and calibration. Much effort goes into documenting these.
- A growing list of student projects, PhD theses using these data. Many have been focused on finding and fully documenting the fake signals in the data.
- As noted above, Public release of data adds complexity to the collaboration publication policy: random passers-by can use our open data to write papers about what they find (signals!?),
  but LSC members *cannot* (until a long waiting period has elapsed).
- In early December 2016, a group in Waterloo posted a paper on ArXiv:
  "Echoes from the Abyss" (https://arxiv.org/abs/1612.00266)
  using LOSC-released data
  - If the authors are right, this is the most significant scientific discovery since the discovery of GWs (actually, much more significant!).
  - But, they almost certainly are NOT right.

https://losc.ligo.org/projects/

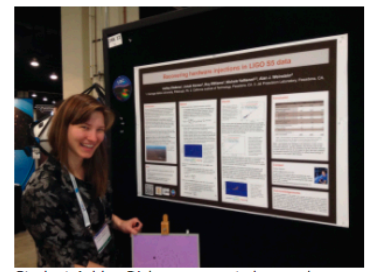
LIGO

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

Data Analysis Projects with LOSC data

The LOSC can be a great resource for education and outreach. The tutorials provide an introduction to both data access and basic data anlysis techniques, so new students can quickly begin work. Some examples of past projects are shown on this page. For more project ideas, contact the the LOSC team.


Student Ashley Disbrow presents her work at the 2014 American Astronomical Society meeting in Washington, DC.

2016

Pioneer Academics student projects
Projects mentored by Eric Myers
Final papers: Zhehao Lu | Minqi Fu | Jinghong Liang | William Li

Echoes from the Abyss: Evidence for Planck-scale structure at black hole horizons
Jahed Abedi, Hannah Dykaar, Niayesh Afshordi
arXiv:1612.00266

Modified LIGO data analysis notebook
Valentin Baillard
Azure | mybinder | github

Physics From Planet Earth homework problems
Joe Amato and Enrique (Kiko) Galvez
See Gravitational Radiation 2 and Gravitational Radiation 3

Non-Gaussian noise and data analysis of laser interferometric gravitational wave detectors
Takahiro Yamamoto, Ph.D. Thesis
See JGW-P1605355

Understanding the LIGO GW150914 event
P. Naselsky, A. D. Jackson, Hao Liu
See arxiv:1604.06211

Gravitational Wave Detection in the Introductory Lab
Lior M. Burko
Georgia Gwinnett College,
See arxiv:1602.04666

2014

Searching for Compact Binaries in LIGO Data
Shannon Wang
Date Completed: September 2014
Report: Paper

Recovering S5 Burst Injections
Alexander Cole
Date Completed: May 2014
Presentation: Paper | Slides

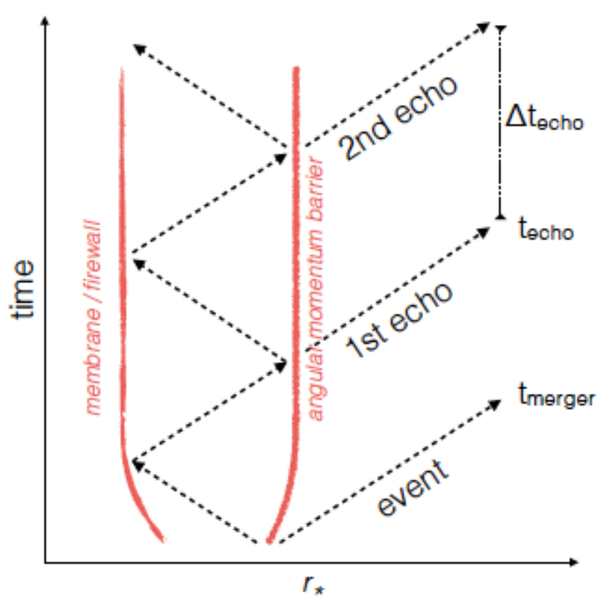
General Relativity and Quantum Cosmology

Echoes from the Abyss: Evidence for Planck-scale structure at black hole horizons

Jahed Abedi, Hannah Dykaar, Niayesh Afshordi

(Submitted on 1 Dec 2016)

In classical General Relativity (GR), an observer falling into an astrophysical black hole is not expected to experience anything dramatic as she crosses the event horizon. However, tentative resolutions to problems in quantum gravity, such as the cosmological constant problem, or the black hole information paradox, invoke significant departures from classicality in the vicinity of the horizon. It was recently pointed out that such near-horizon structures can lead to late-time echoes in the black hole merger gravitational wave signals that are otherwise indistinguishable from GR. We search for observational signatures of these echoes in the gravitational wave data released by advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), following the three black hole merger events GW150914, GW151226, and LVT151012. In particular, we look for repeating damped echoes with time-delays of $8M \log M$ (+spin corrections, in Planck units), corresponding to Planck-scale departures from GR near their respective horizons. Accounting for the "look elsewhere" effect due to uncertainty in the echo template, we find tentative evidence for Planck-scale structure near black hole horizons at 2.9σ significance level (corresponding to false detection probability of 1 in 270). Future data releases from LIGO collaboration, along with more physical echo templates, will definitively confirm (or rule out) this finding, providing possible empirical evidence for alternatives to classical black holes, such as in *firewall* or *fuzzball* paradigms.



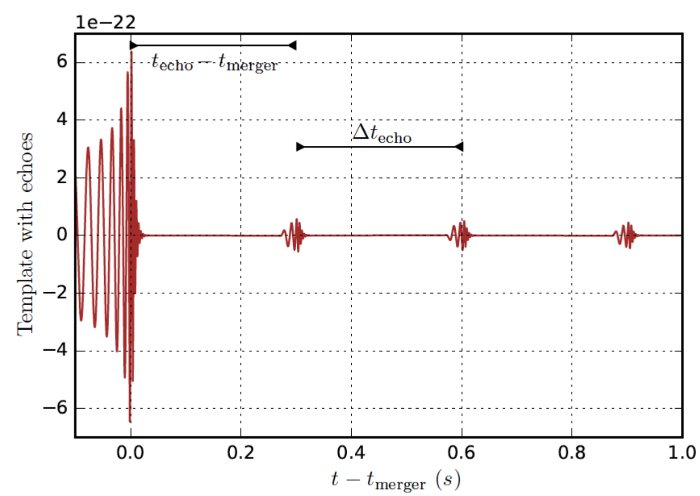


FIG. 2: LIGO original template for GW150914, along with our best fit template for the echoes.

Thank you for your attention!

Questions?