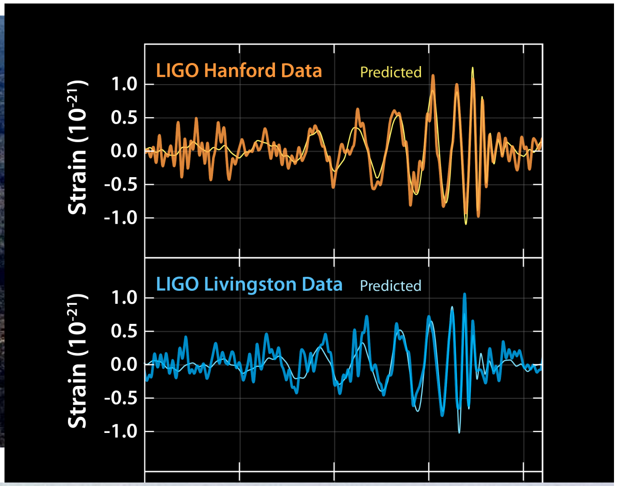
First Results from Advanced LIGO's Search for Gravitational Waves

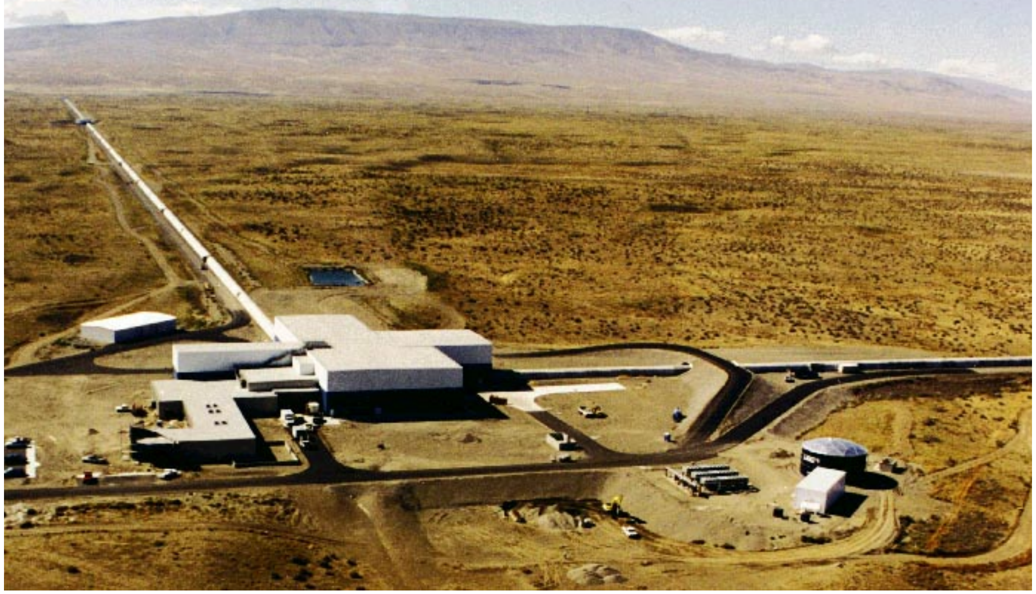
- Gravitational waves
- Advanced LIGO
- Compact Binary Coalescences
- GW150914
- What we can learn: physics and astrophysics

Alan Weinstein, Caltech

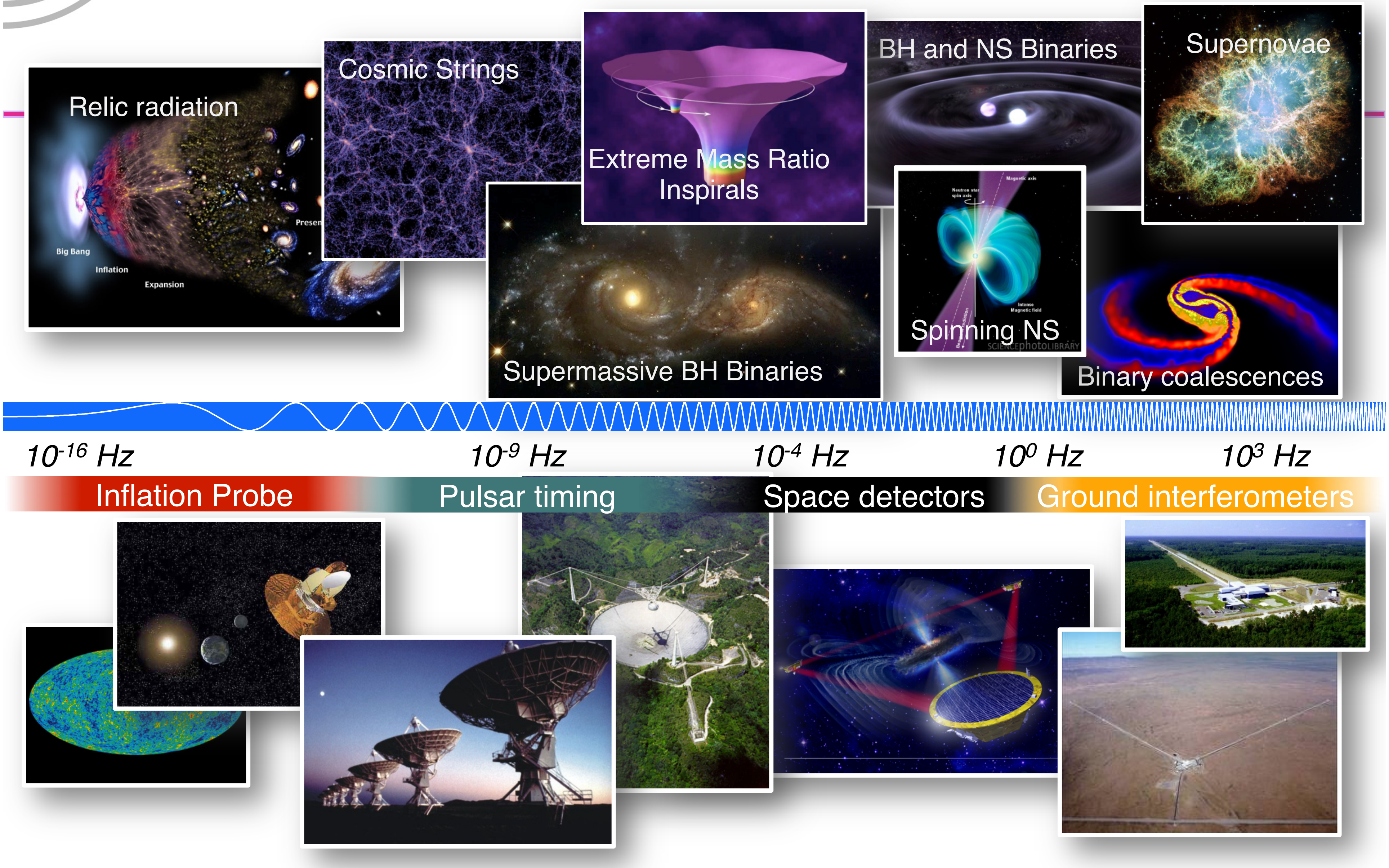
for the LIGO Scientific Collaboration

LIGO-G1600287





The GW Spectrum



Relic radiation

Cosmic Strings

Extreme Mass Ratio Inspirals

BH and NS Binaries

Supernovae

Spinning NS

Supermassive BH Binaries

Binary coalescences

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

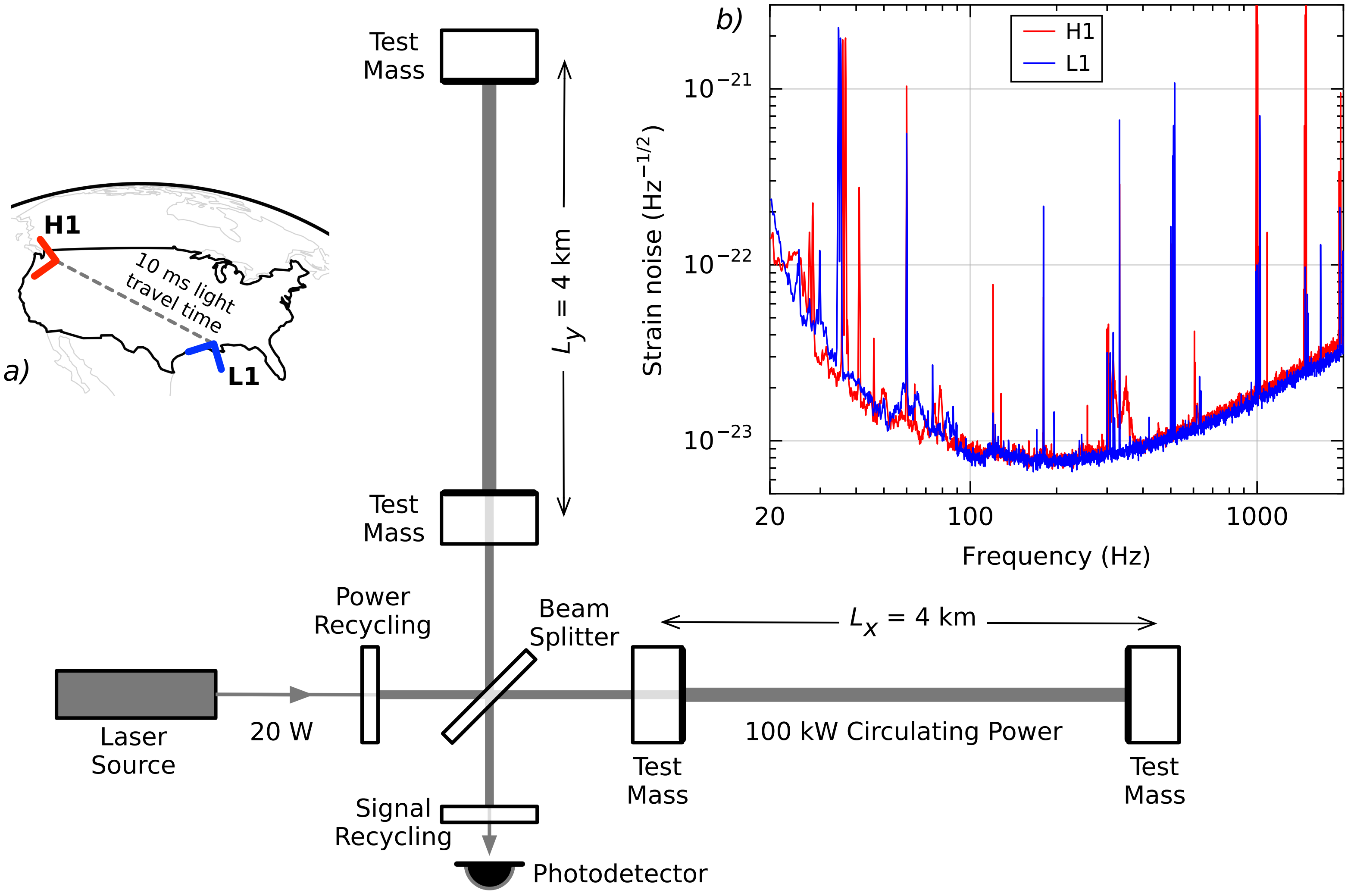
Inflation Probe

Pulsar timing

Space detectors

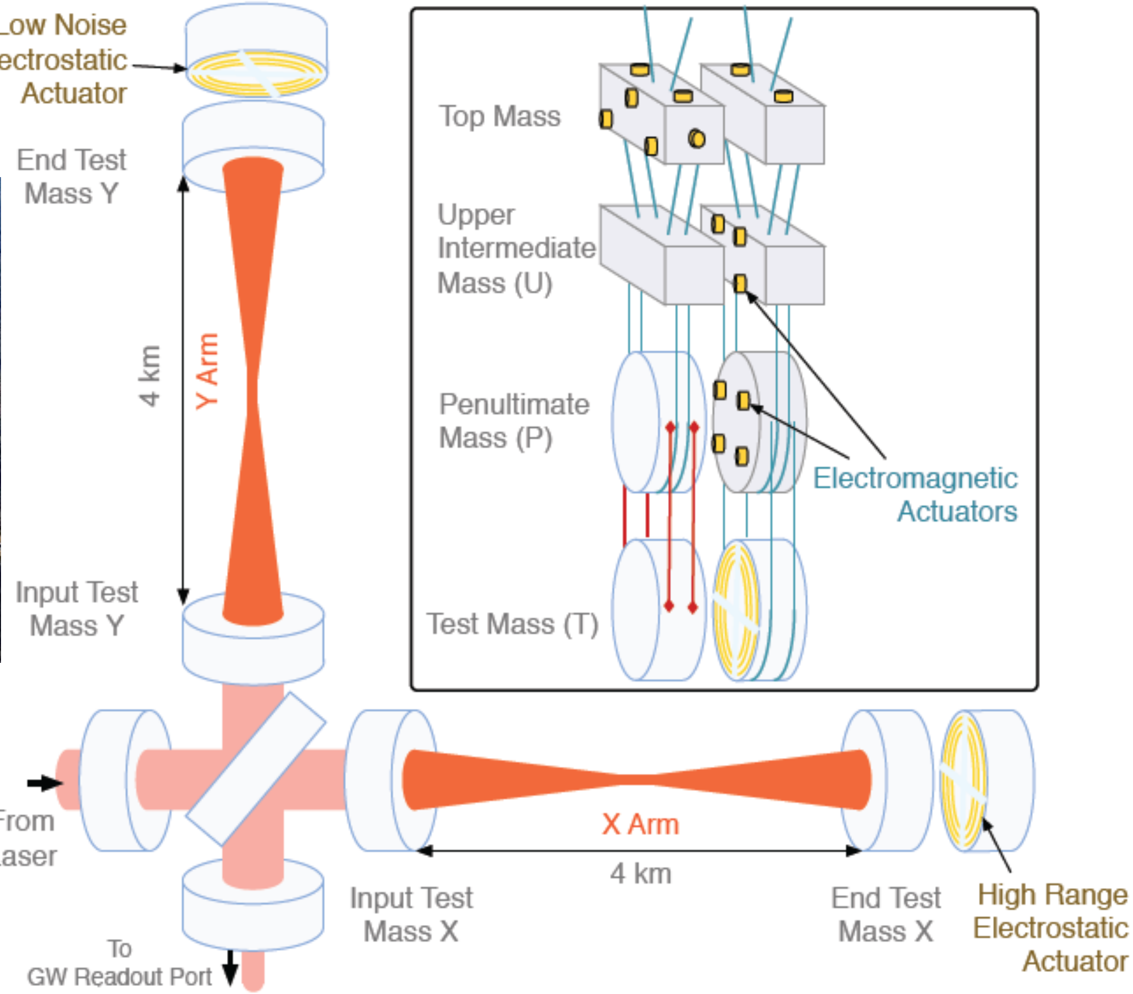
Ground interferometers

The Advanced LIGO detectors



https://dcc.ligo.org/LIGO-P1500237/public/main

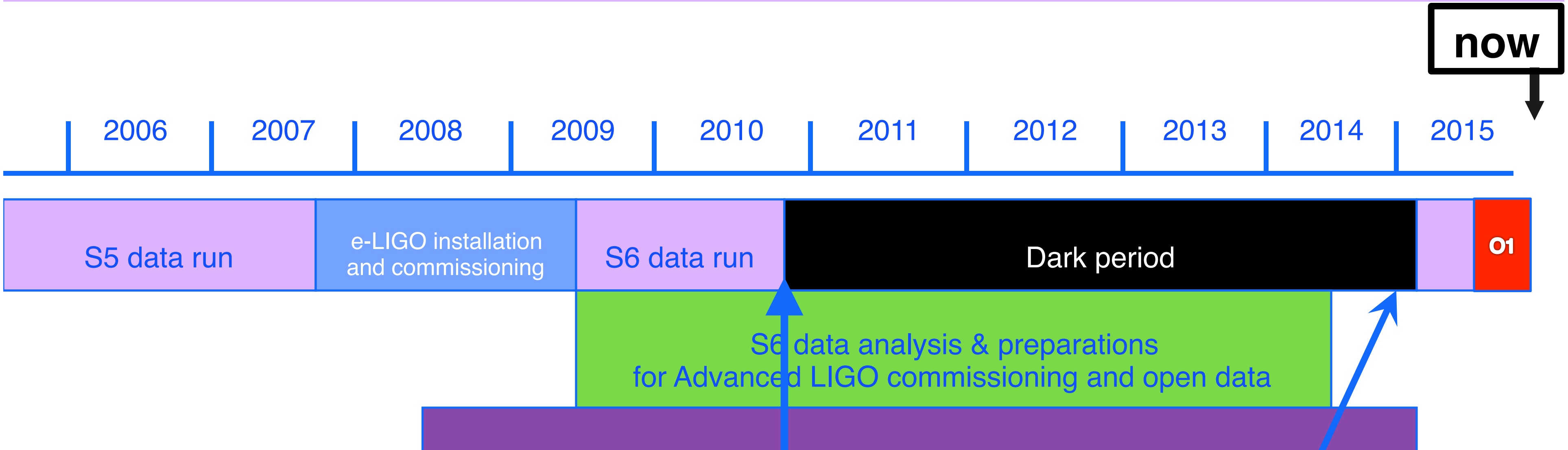
End mirror (“test mass”) quadruple-pendulum suspensions



photon calibrator

https://dcc.ligo.org/LIGO-P1500248/public/main

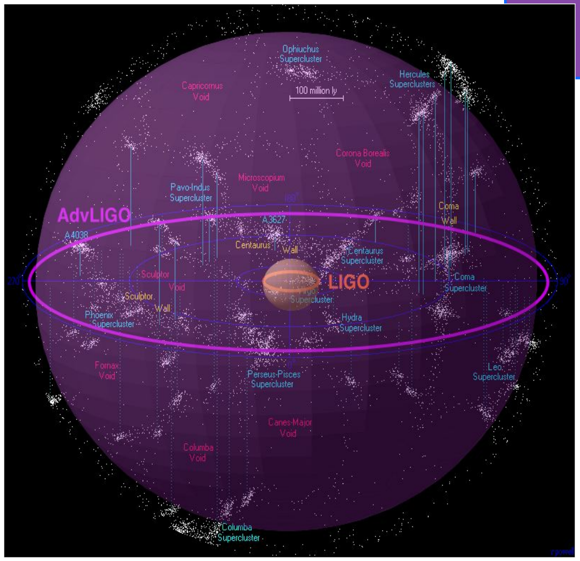
iLIGO → eLIGO → aLIGO



Advanced LIGO Project

Adv LIGO Installation begins

Commissioning & initial data With Advanced LIGO



Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!

LIGO Scientific Collaboration

Abilene Christian University
Albert-Einstein Institut
Andrews University
American University
California Institute of Technology
California State Univ., Fullerton
Canadian Inst. Th. Astrophysics
Carleton College
College of William and Mary
Columbia U. in the City of New York
Embry-Riddle Aeronautical Univ.
Eötvös Loránd University
Georgia Institute of Technology
Goddard Space Flight Center
Hobart & William Smith Colleges
ICTP-SAIFR
IndIGO
IAP-Russian Acad. of Sciences
Inst. Nacional Pesquisas Espaciais
Kenyon College
Korean Gravitational-Wave Group
Louisiana State University
Montana State University
Montclair State University
Moscow State University
National Tsinghua University
Northwestern University

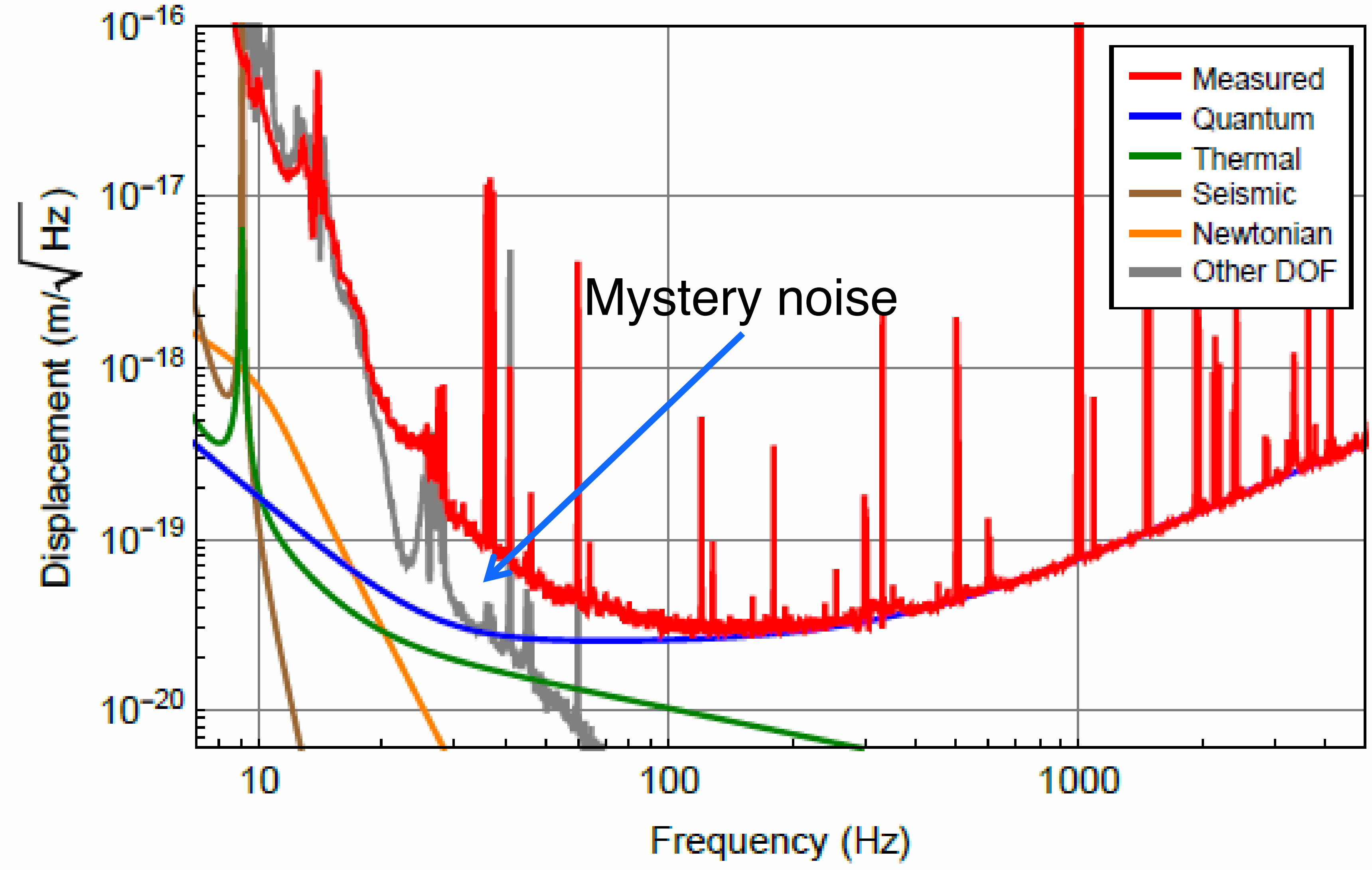
Penn State University
Rochester Institute of Technology
Sonoma State University
Southern Univ. and A&M College
Stanford University
Syracuse University
Szeged University
Texas Tech University
Trinity University
Tsinghua University
Universitat de les Illes Balears
University of Alabama in Huntsville
University of Brussels
University of Chicago
University of Florida
University of Maryland
University of Michigan
University of Minnesota
University of Mississippi
University of Oregon
University of Sannio
Univ. of Texas-Rio Grande Valley
University of Washington
University of Wisconsin-Milwaukee
Washington State University
West Virginia University
Whitman College

LIGO Laboratory: California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):
Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia

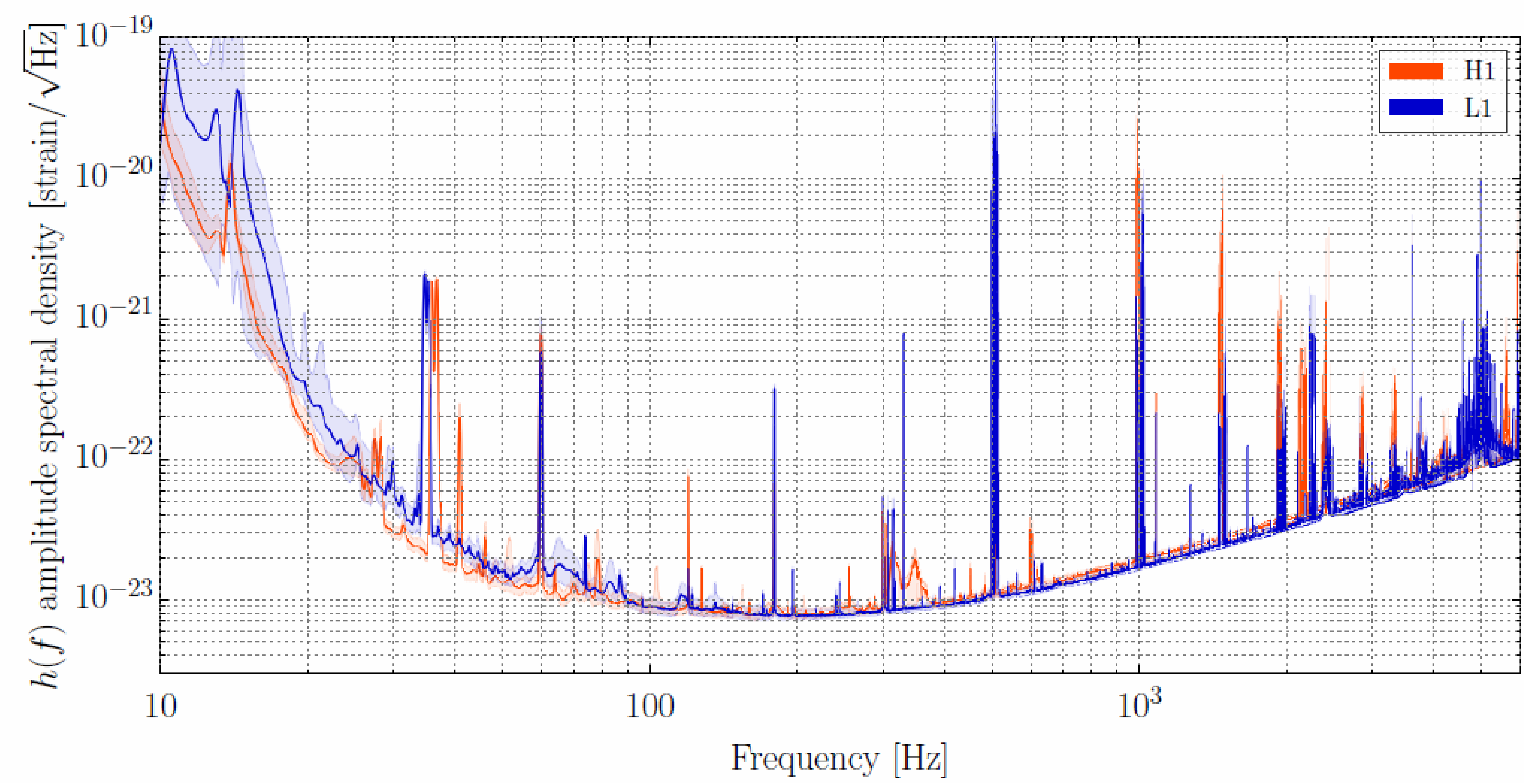
German/British Collaboration for the Detection of Gravitational Waves (GEO600):
Cardiff University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London, Rutherford Appleton Laboratory, University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield, University of Southampton, University of Strathclyde, University of the West of Scotland

Noise sources that limit performance during O1



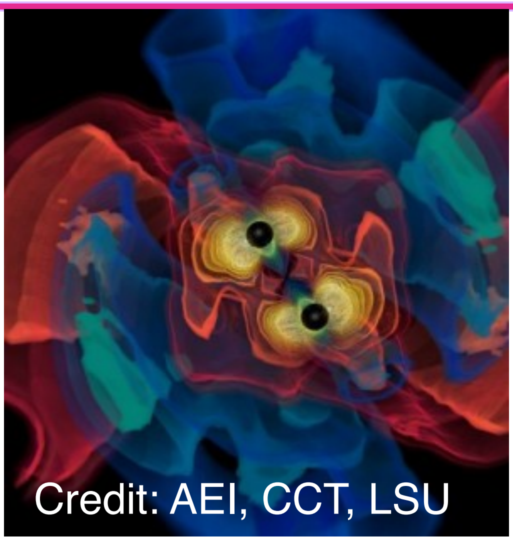
Mystery noise

Non-stationarity of the noise ASD



https://dcc.ligo.org/LIGO-P1500238/public/main

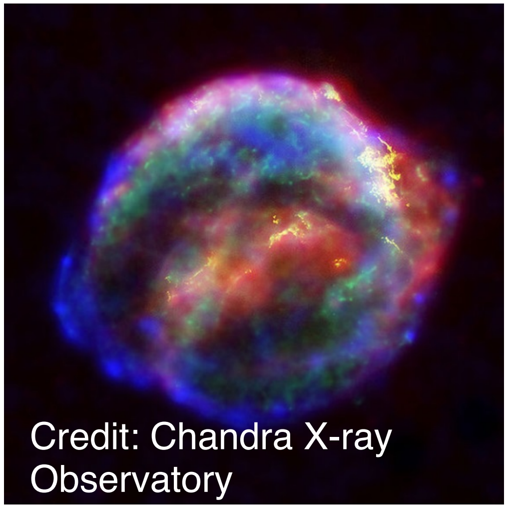
GW sources for ground-based detectors: The most energetic processes in the universe


Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

- (effectively) transient


Credit: Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient

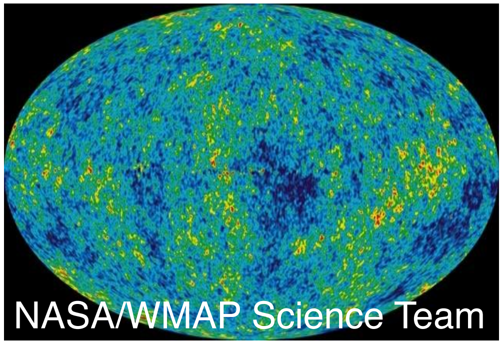
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class


Casey Reed, Penn State

Spinning neutron stars

- (effectively) monotonic waveform

- Long duration

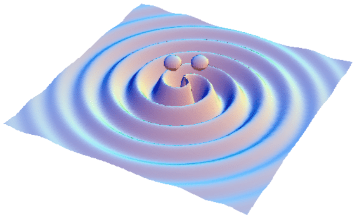

NASA/WMAP Science Team

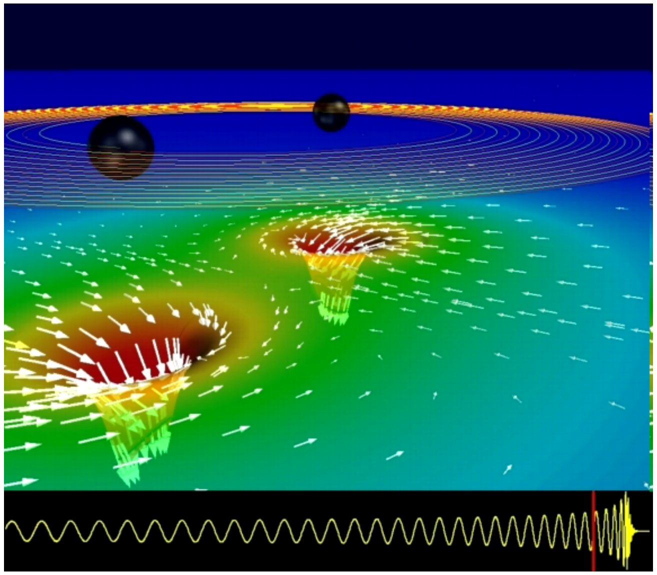
Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration

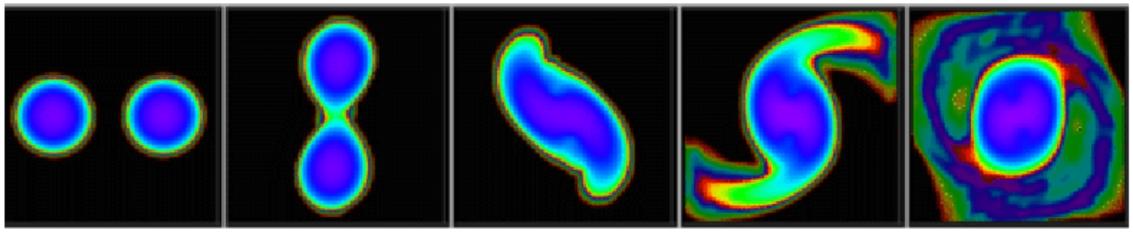
- Long duration, stochastic background

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





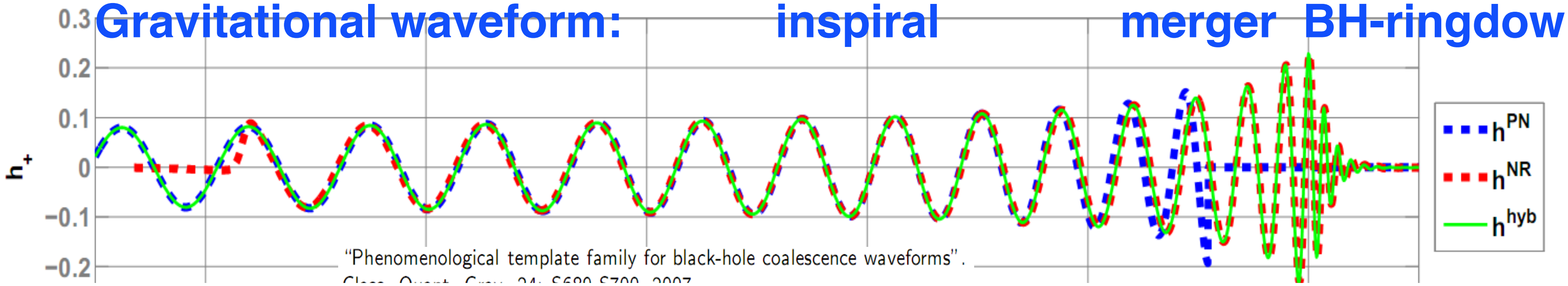
- Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Gravitational waveform: inspiral merger BH-ringdown

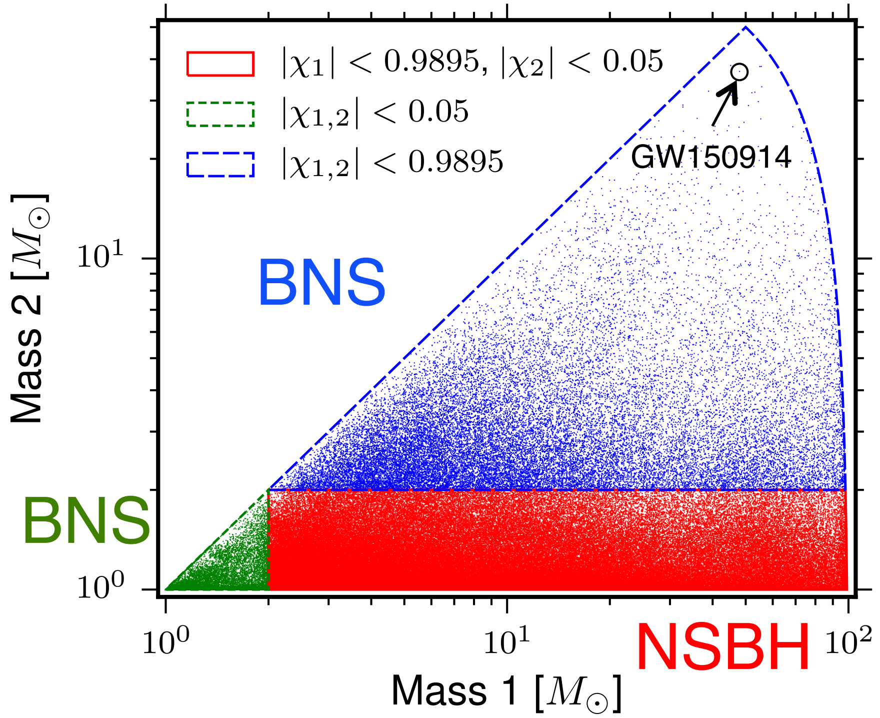


Waveform carries lots of information about binary masses, orbit, merger

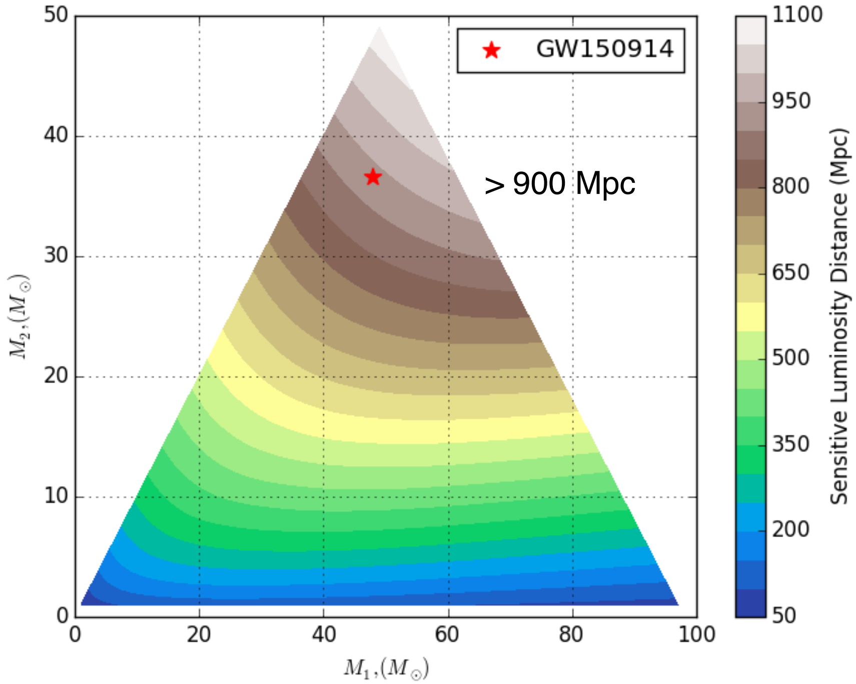
Search pipelines

- We need to sift through months of two-detector-coincident strain data h(t) to look for signals with durations from minutes to fractions of a second, above the detector noise.
- **Two different template-based searches for compact binary coalescence (CBC): BNS, NSBH,BBH**:
  - Low-latency (10's of seconds) – gstlal (gstreamer-based)
  - "Offline" - pyCBC (fft-based)
- **Two different searches for short-duration, unmodeled "bursts" of GW power in the time-frequency plane, with low latency:**
  - Coherent WaveBurst - cWB
  - Online LIGO Inference Burst – oLIB
- All make use of **two-detector coincidence in time and in signal morphology**.
- All estimate the background from accidental coincidence of instrumental noise triggers, using "time slides" or variations thereof.
- **All detected GW150914 with high significance above detector noise**

Template-based searches



Masses and (aligned) spins
Templates spaced for < 3%
loss of SNR: 250K templates.

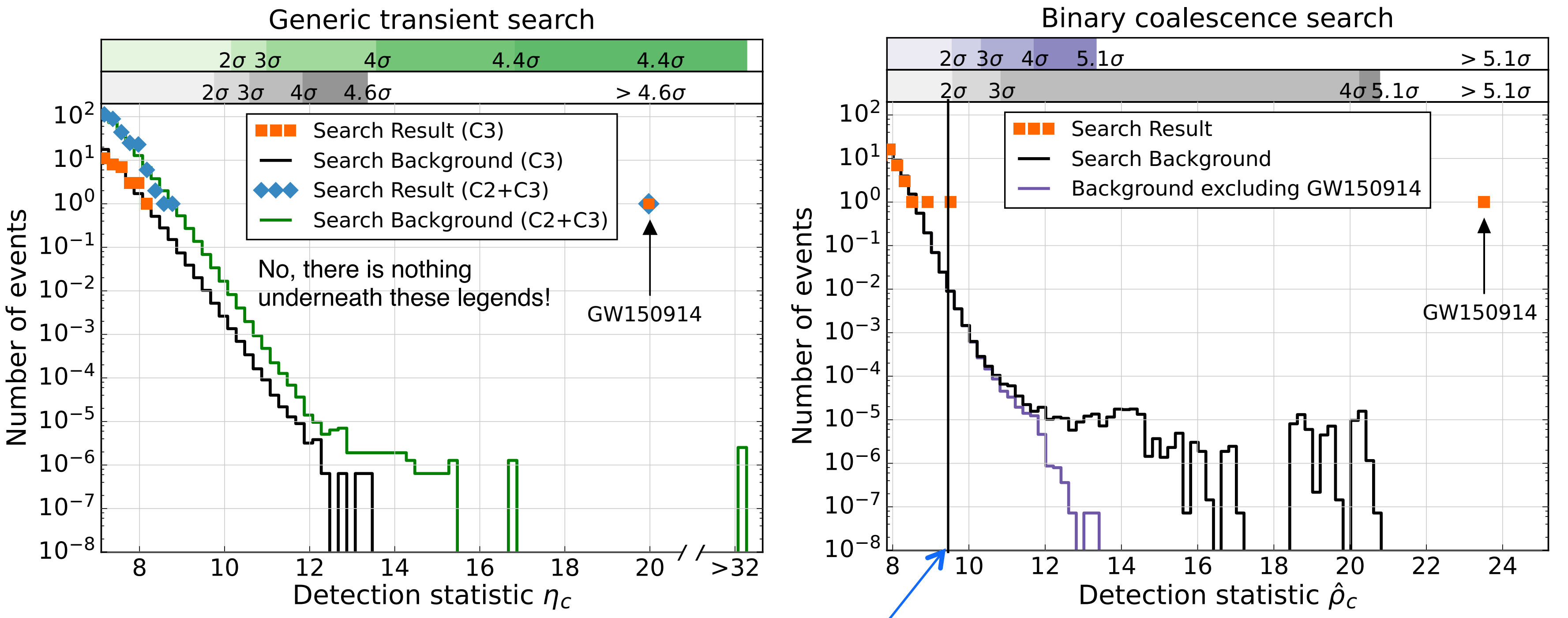


Sensitive distance in Mpc

https://dcc.ligo.org/LIGO-P1500269/public/main

Results of search over first 38 days of Observation run 1

(Sep 12 – Oct 20, 2015)



No, there is nothing underneath these legends!

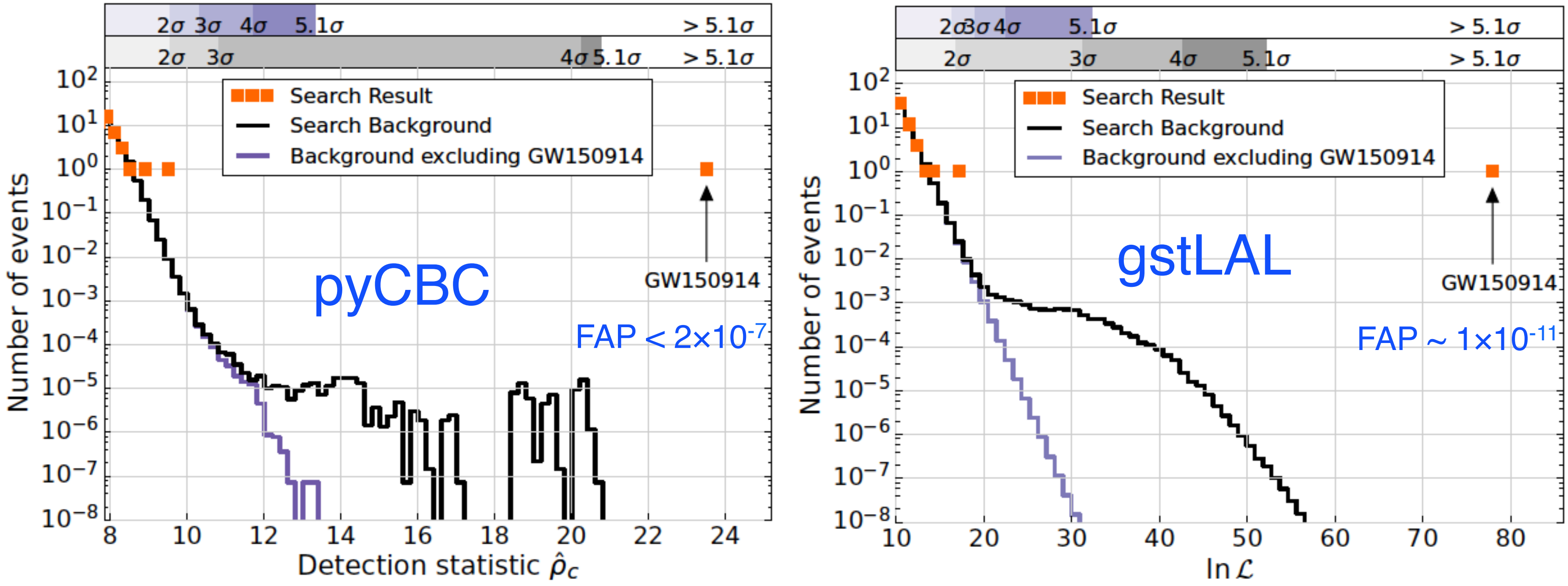
Is it likely that the first detected event should be so loud?

P(1 event with $\rho \geq 23.7$) = $(9.5/23.7)^3$ = 6%.

Are there fainter events? Yes, one! LVT151012, $\rho = 9.6$.

https://dcc.ligo.org/LIGO-P1500269/public/main

Both CBC pipelines detect signal with high significance

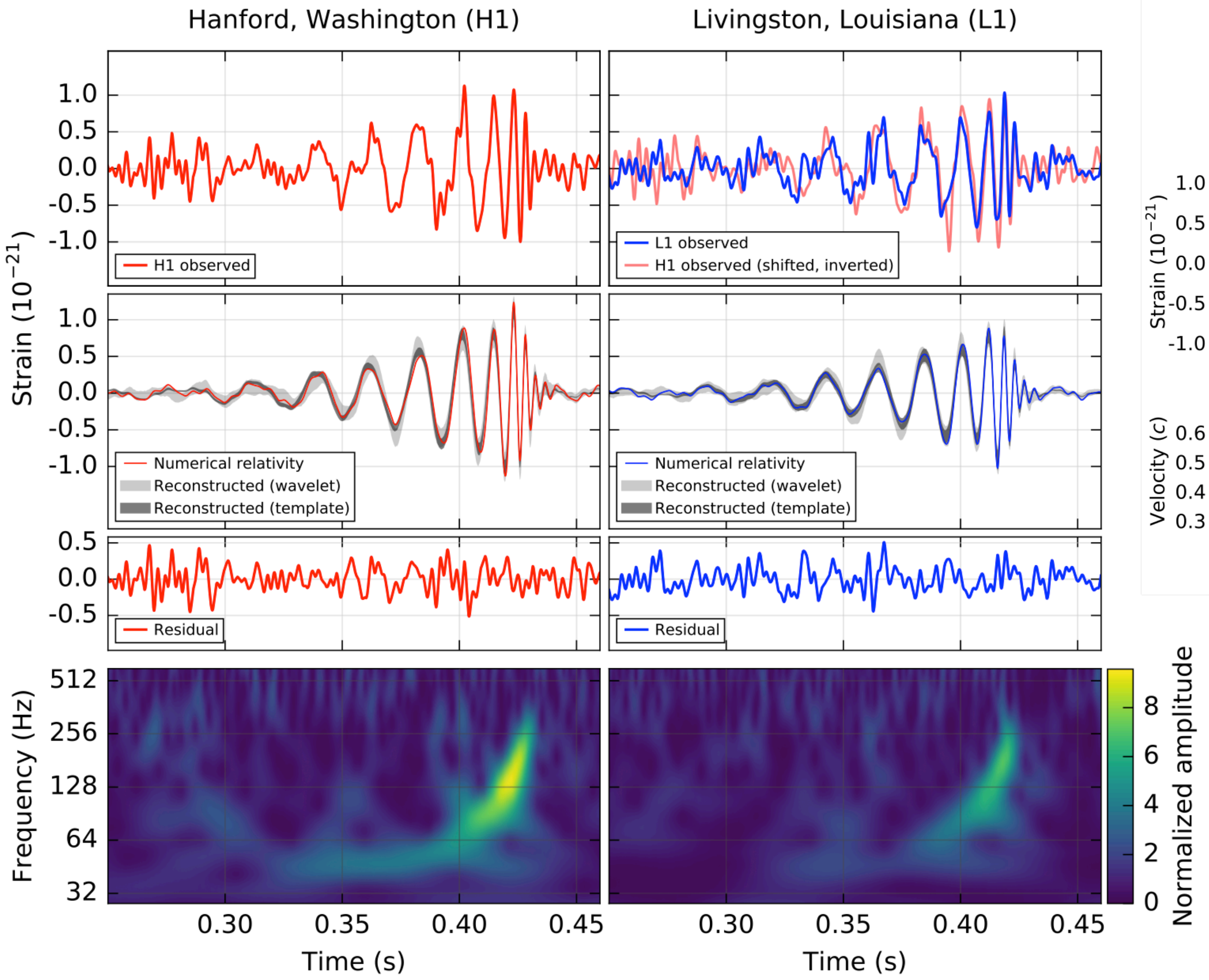


Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ (M$_\odot$)	m_1 (M$_\odot$)	m_2 (M$_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ $(> 5.1\,\sigma)$	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 $(2.1\,\sigma)$	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

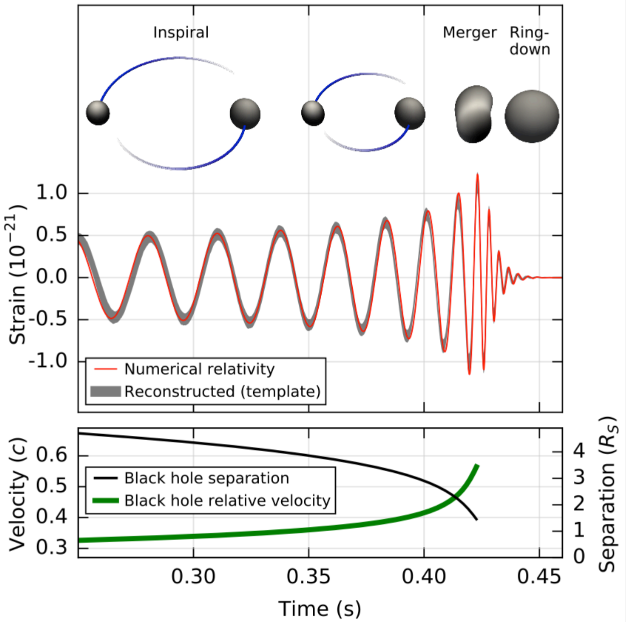
https://dcc.ligo.org/LIGO-P1500269/public/main

GW150914

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016
https://dcc.ligo.org/LIGO-P150914/public/main



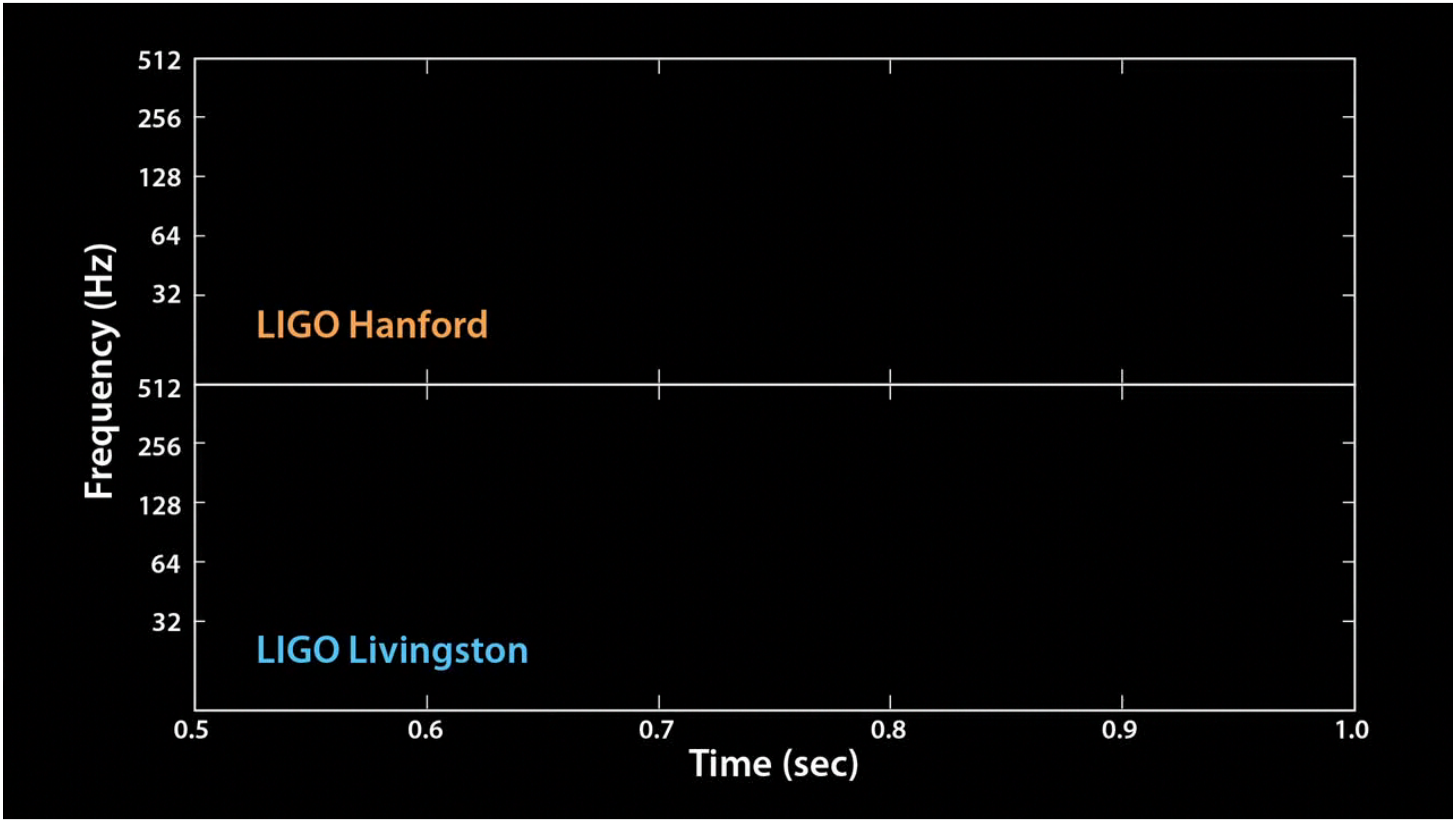
Whitened and band-passed [40-300] Hz



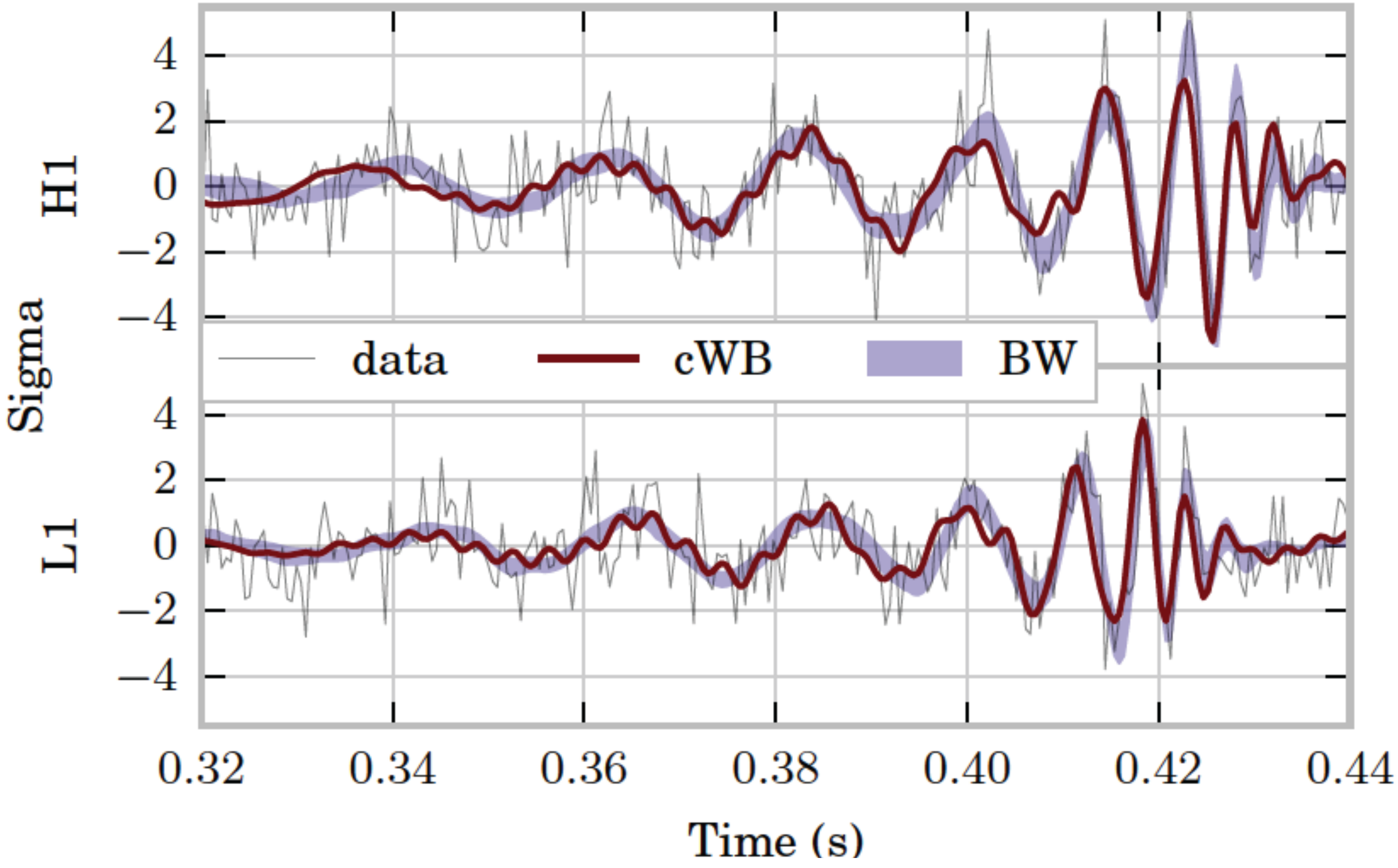
Reconstructed (no whitening)

Audio:
- filtered data
- freq-shifted data
- reconstructed & shifted

The sound of two black holes merging



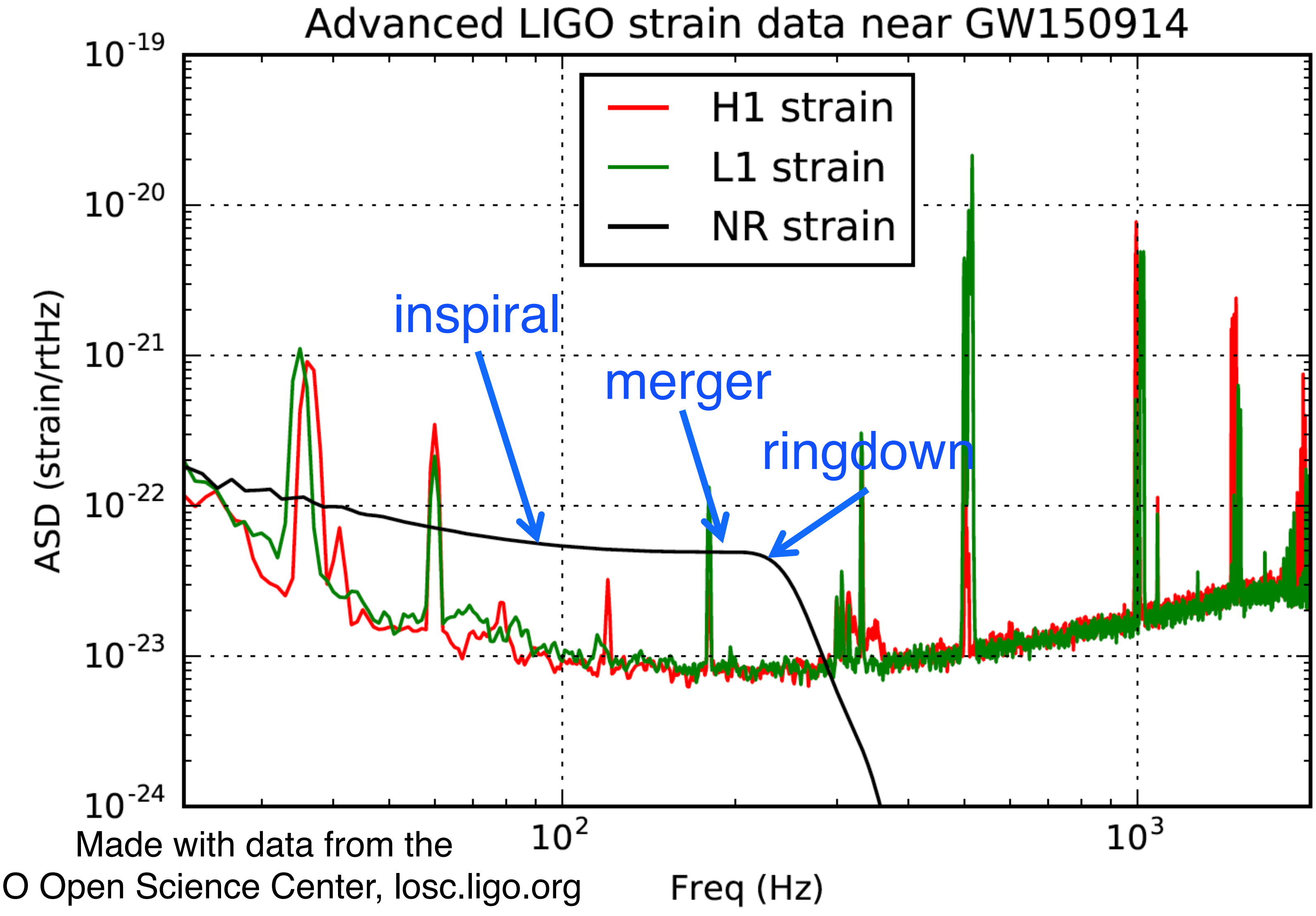
Unmodeled ("burst") signal reconstruction



Caltech LIGO: Jonah Kanner

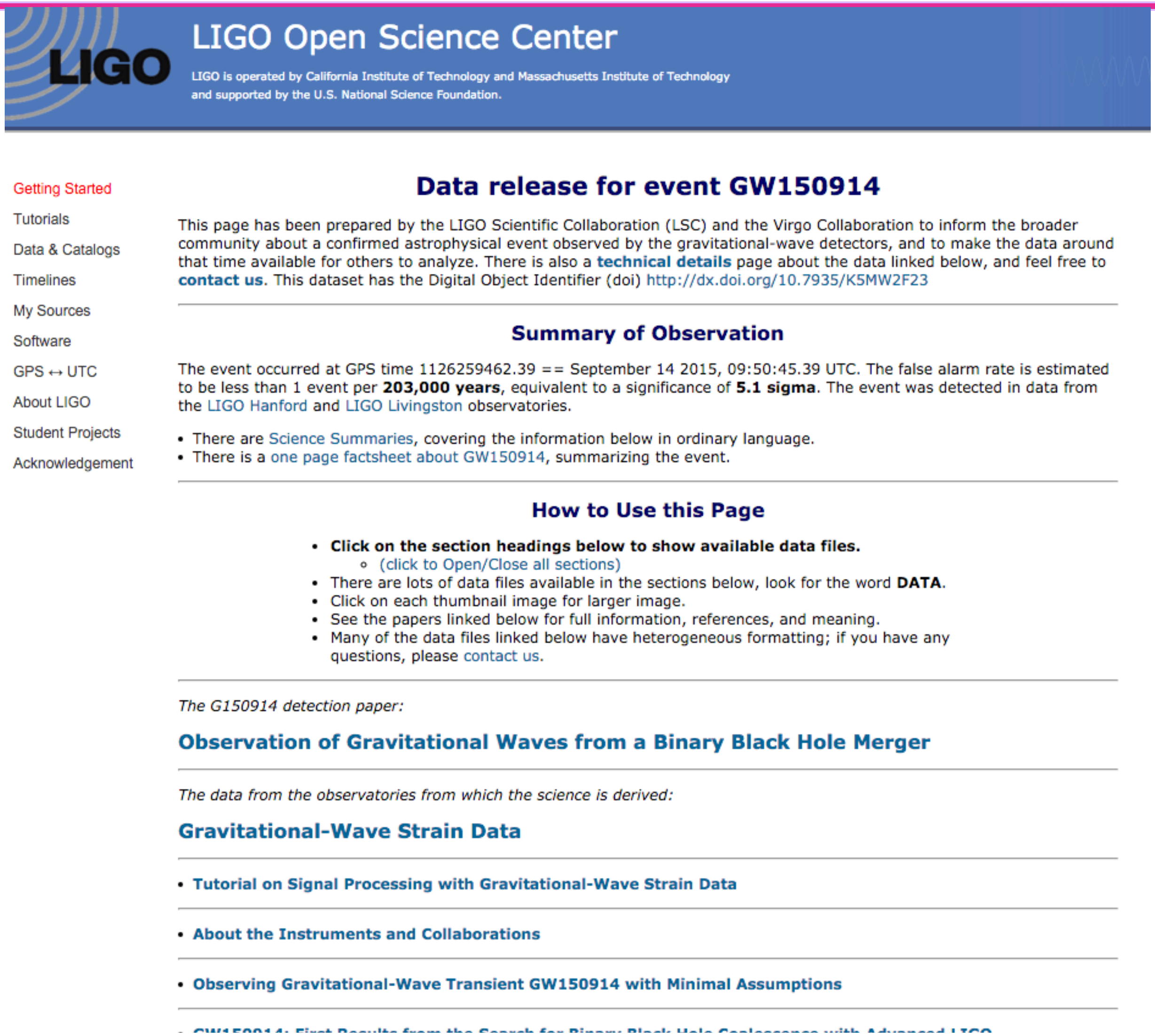
https://dcc.ligo.org/LIGO-P1500229/public/main

GW150914 in the frequency domain



Made with data from the
LIGO Open Science Center, losc.ligo.org

The LIGO Open Science Center
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 & Catalogs
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Student Projects
- Acknowledgement

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

Summary of Observation

The event occurred at GPS time 1126259462.39 == September 14 2015, 09:50:45.39 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.

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.

The G150914 detection paper:

Observation of Gravitational Waves from a Binary Black Hole Merger

The data from the observatories from which the science is derived:

Gravitational-Wave Strain Data

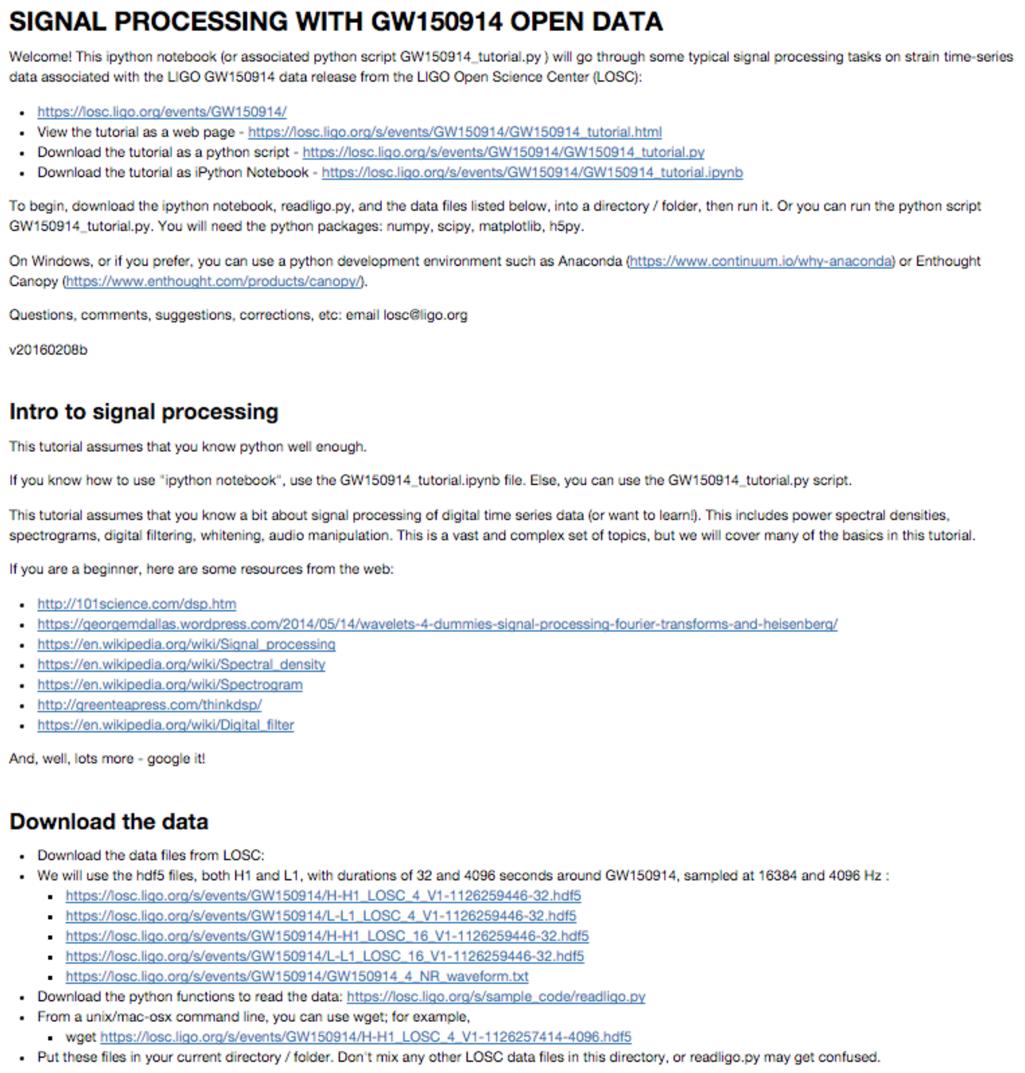
- **Tutorial on Signal Processing with Gravitational-Wave Strain Data**

- **About the Instruments and Collaborations**

- **Observing Gravitational-Wave Transient GW150914 with Minimal Assumptions**

- **GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO**

The LIGO Open Science Center
losc.ligo.org
Ipython notebook tutorial



SIGNAL PROCESSING WITH GW150914 OPEN DATA

Welcome! This ipython notebook (or associated python script GW150914_tutorial.py) will go through some typical signal processing tasks on strain time-series data associated with the LIGO GW150914 data release from the LIGO Open Science Center (LOSC):

- https://losc.ligo.org/events/GW150914/
- View the tutorial as a web page - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html
- Download the tutorial as a python script - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.py
- Download the tutorial as iPython Notebook - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.ipynb

To begin, download the ipython notebook, readligo.py, and the data files listed below, into a directory / folder, then run it. Or you can run the python script GW150914_tutorial.py. You will need the python packages: numpy, scipy, matplotlib, h5py.

On Windows, or if you prefer, you can use a python development environment such as Anaconda (https://www.continuum.io/why-anaconda) or Enthought Canopy (https://www.enthought.com/products/canopy/).

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

v20160208b

Intro to signal processing

This tutorial assumes that you know python well enough.

If you know how to use "ipython notebook", use the GW150914_tutorial.ipynb file. Else, you can use the GW150914_tutorial.py script.

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

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

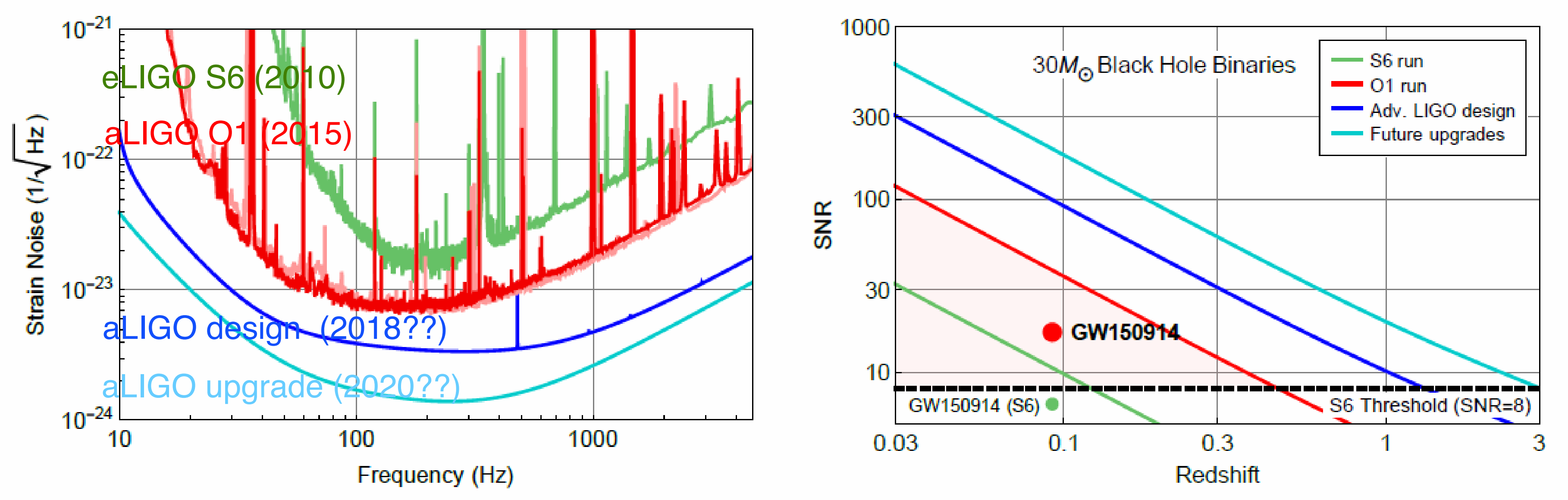
- http://101science.com/dsp.htm
- https://georgemdallas.wordpress.com/2014/05/14/wavelets-4-dummies-signal-processing-fourier-transforms-and-heisenberg/
- https://en.wikipedia.org/wiki/Signal_processing
- https://en.wikipedia.org/wiki/Spectral_density
- https://en.wikipedia.org/wiki/Spectrogram
- http://greenteapress.com/thinkdsp/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

And, well, lots more - google it!

Download the data

- Download the data files from LOSC:
- We will use the hdf5 files, both H1 and L1, with durations of 32 and 4096 seconds around GW150914, sampled at 16384 and 4096 Hz :
  - https://losc.ligo.org/s/events/GW150914/H-H1_LOSC_4_V1-1126259446-32.hdf5
  - https://losc.ligo.org/s/events/GW150914/L-L1_LOSC_4_V1-1126259446-32.hdf5
  - https://losc.ligo.org/s/events/GW150914/H-H1_LOSC_16_V1-1126259446-32.hdf5
  - https://losc.ligo.org/s/events/GW150914/L-L1_LOSC_16_V1-1126259446-32.hdf5
  - https://losc.ligo.org/s/events/GW150914/GW150914_4_NR_waveform.txt
- Download the python functions to read the data: https://losc.ligo.org/s/sample_code/readligo.py
- From a unix/mac-osx command line, you can use wget; for example,
  - wget https://losc.ligo.org/s/events/GW150914/H-H1_LOSC_4_V1-1126257414-4096.hdf5
- Put these files in your current directory / folder. Don't mix any other LOSC data files in this directory, or readligo.py may get confused.

Could it have been found in the initial LIGO detectors?



With the S6 detector noise level, this event would have had SNR $\rho \sim 7$, insufficiently above the noise for detection.

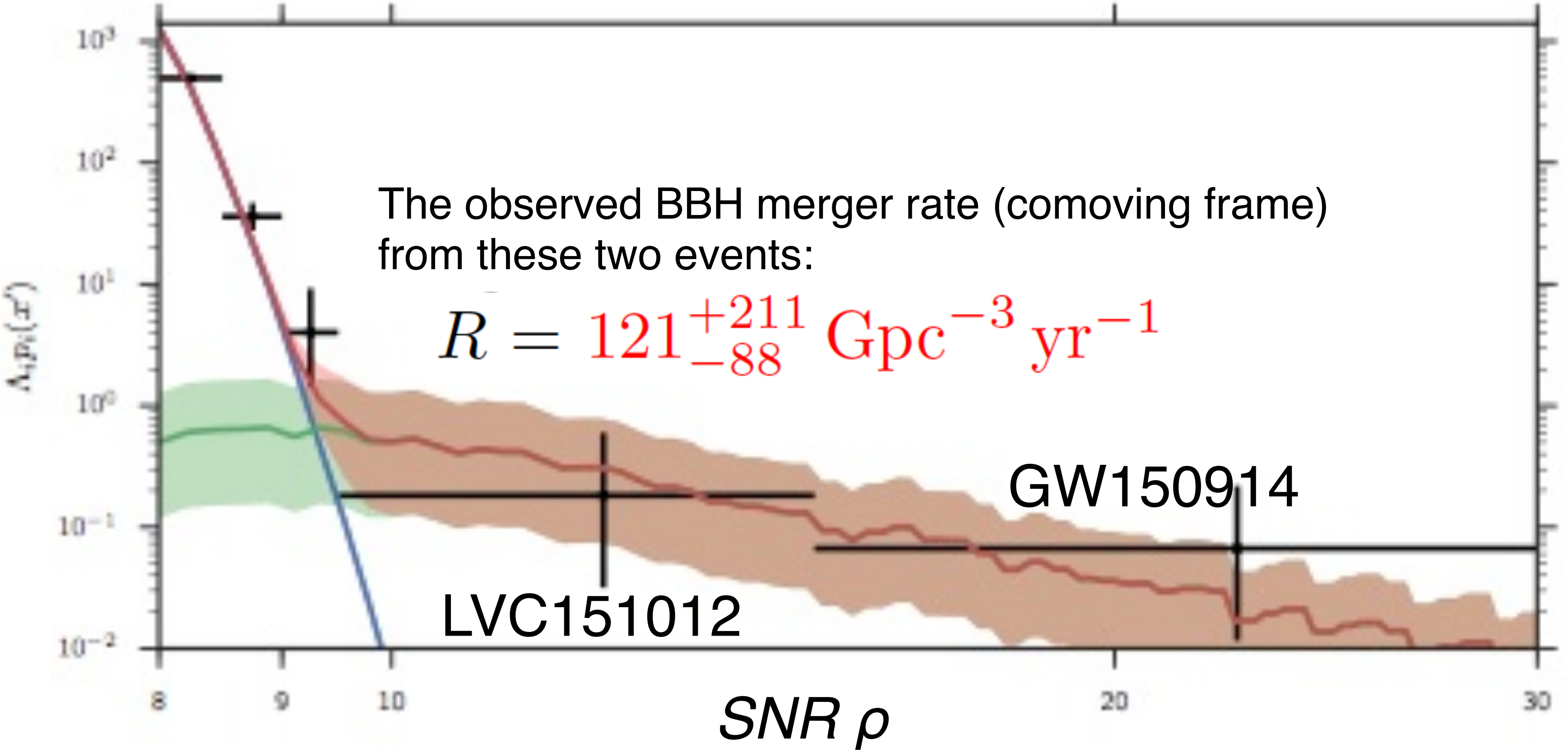
In aLIGO, the signal is very loud!, SNR $\rho \sim 24$.

Aren't sensitive detectors wonderful?

https://dcc.ligo.org/LIGO-P1500237/public/main

Observed BBH merger rate

https://dcc.ligo.org/LIGO-P1500217/public/main



The observed BBH merger rate (comoving frame) from these two events:

$$R = 121^{+211}_{-88}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Same ballpark as population synthesis models, CCSN rate, etc

iLIGO+eLIGO BBH rate upper limit: ~< 420 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

Aasi, J. et al. 2013, Phys. Rev. D, 87, 022002, arXiv:1209.6533

Are we SURE it’s not a rare instrumental noise fluctuation?

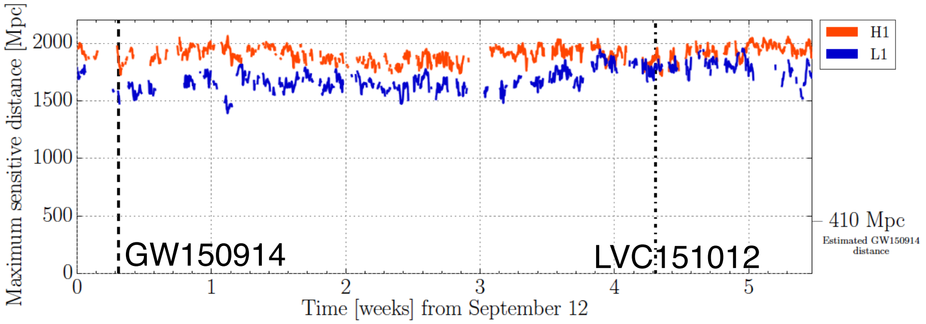
The detectors were behaving quite well, even though it was ER8, 4 days before the official start of O1.

- Stable sensitivity
- Stable instrumental noise trigger rate

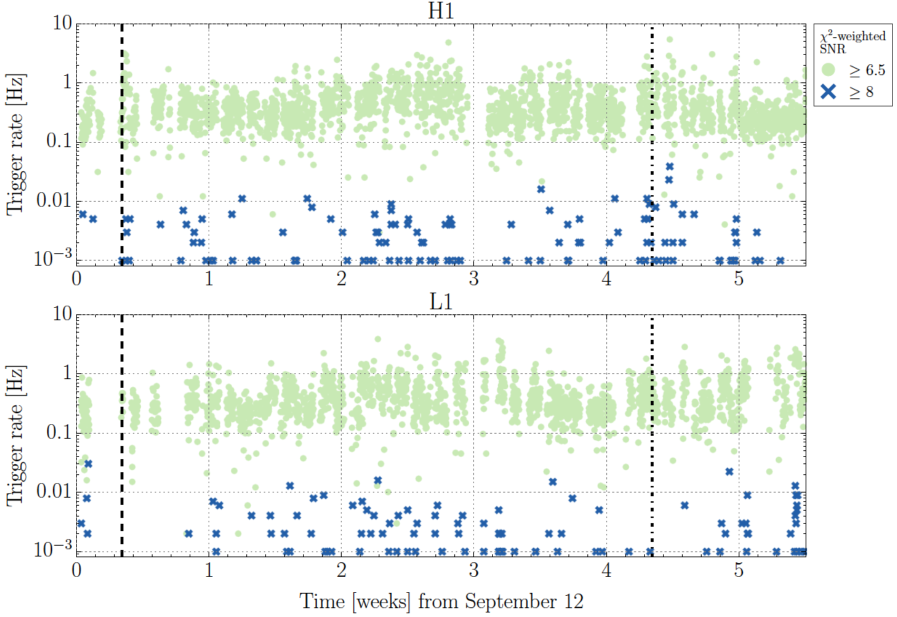
Physical environment monitors (seismometers, magnetometers, microphones, RF monitors, power line monitors, worldwide weather, cosmic ray detectors, etc…) show no anomalous behavior around GW150914.

https://dcc.ligo.org/LIGO-P1500238/public/main

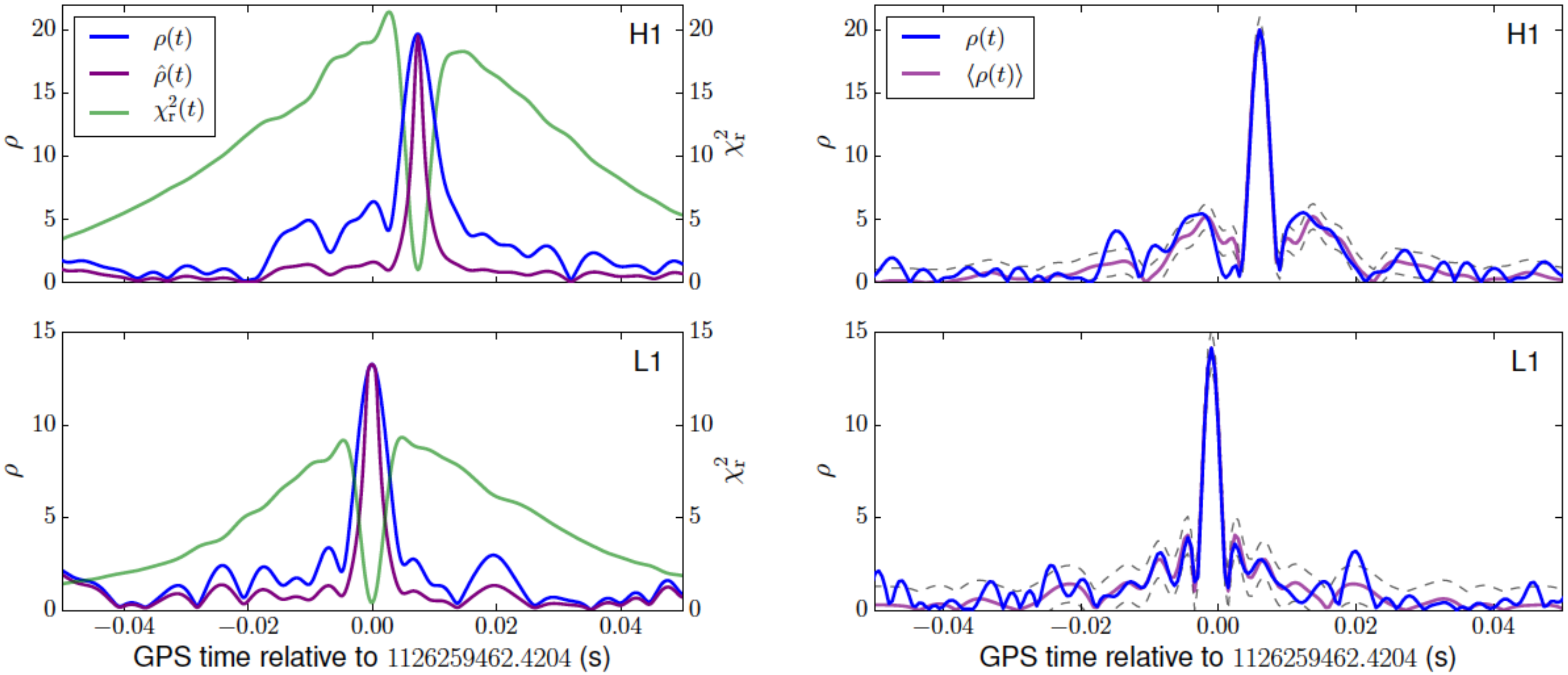
Stable sensitivity



Stable noise trigger rate



SNR time series and χ^2 time series

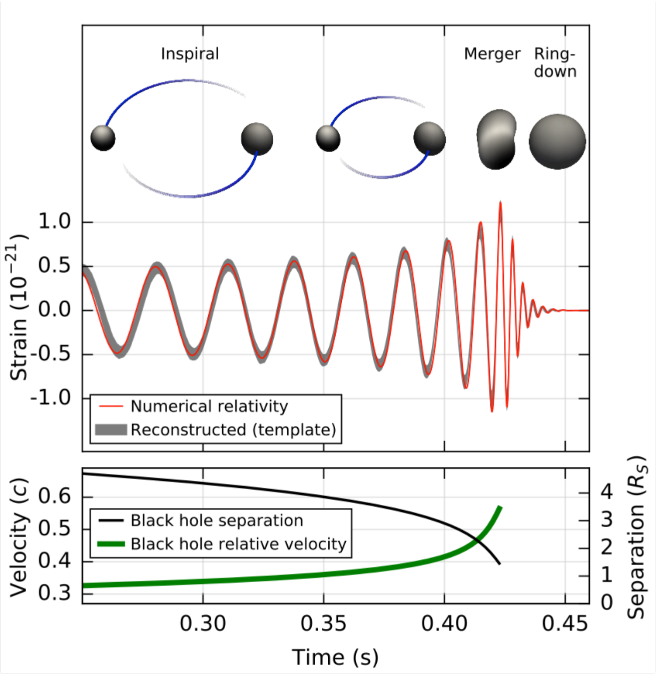


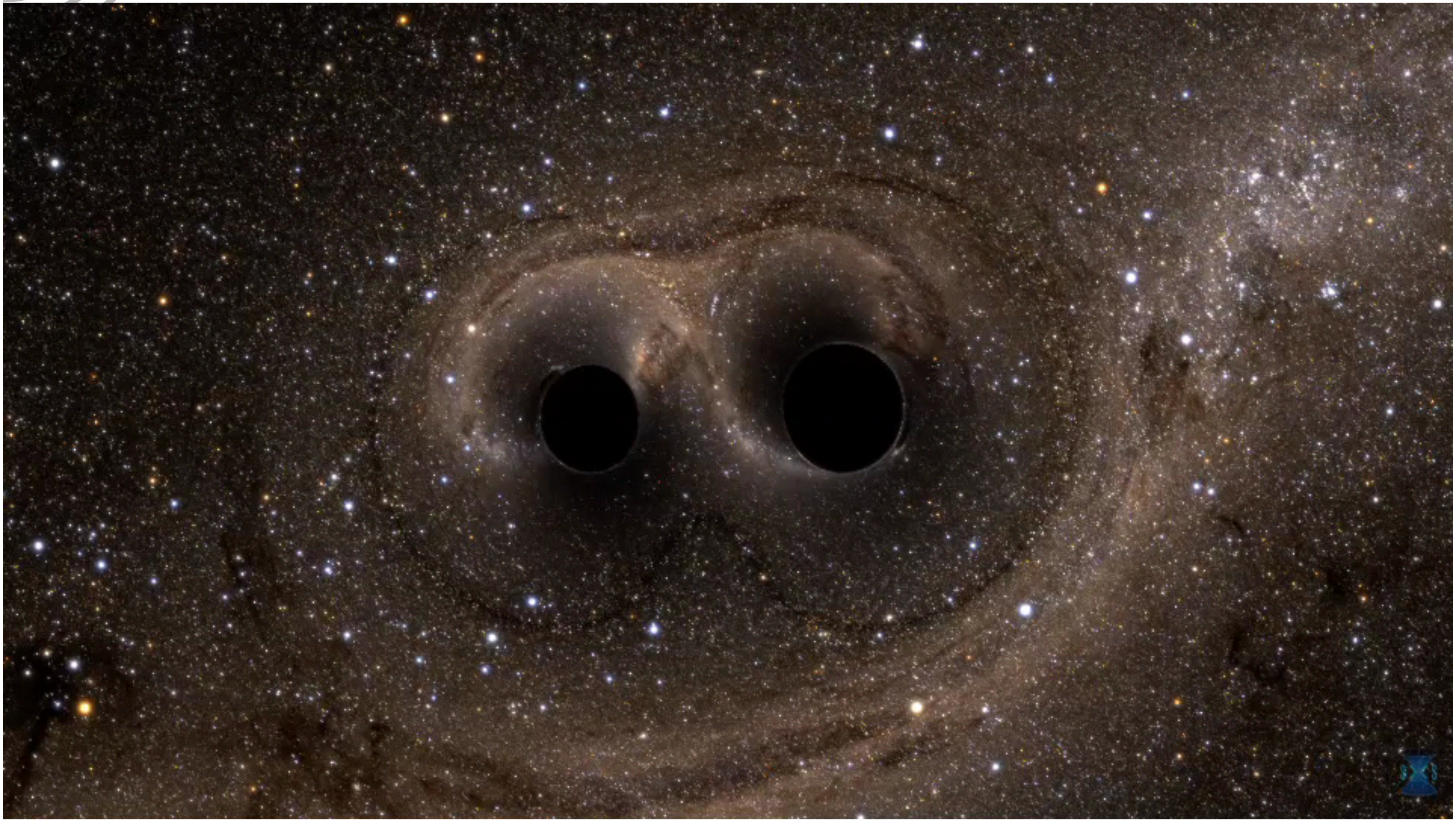
Signal ***ρ(t)*** is consistent with expectation ***<ρ(t)>***

https://dcc.ligo.org/LIGO-P1500238/public/main

What can we learn from one event?

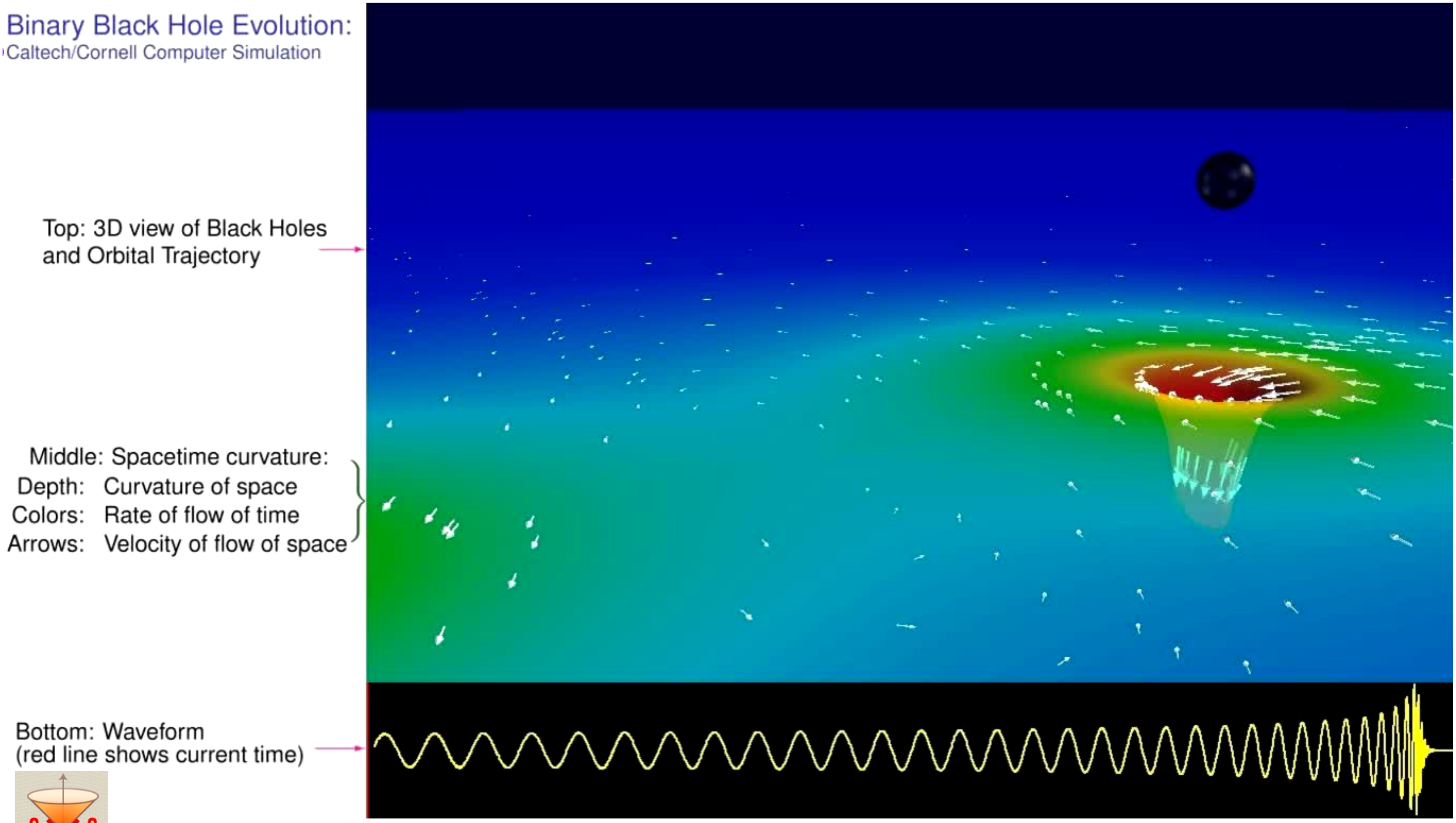
- Excellent **consistency between the observed waveform and the prediction from GR (numerical relativity)** tell us that we are seeing the inspiral of two black holes moving at 0.5c, merging into one BH, which subsequently rings down.
- Such high frequency chirps require extremely **compact orbiting objects of ~ stellar mass**.
- **Black holes (strongly-curved spacetime with event horizons) EXIST**, and emit waves of curved spacetime when perturbed.
  - » Previously, observations of high energy radiation from in-falling matter only told us that compact objects with strong gravity (and perhaps, with event horizons) were present.
- **Binary black holes exist**! Formation scenarios involving common evolution require the binary to survive two core-collapse supernovas.
  Other formation scenarios may be important!
- Two black holes merge into one, which rings down, consistent with **black hole perturbation theory**.
- **GR is tested, for the first time, in the strong (non-linear) and highly dynamical regime**.
- **Masses, spins, sky location, rates, formation mechanisms…**





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

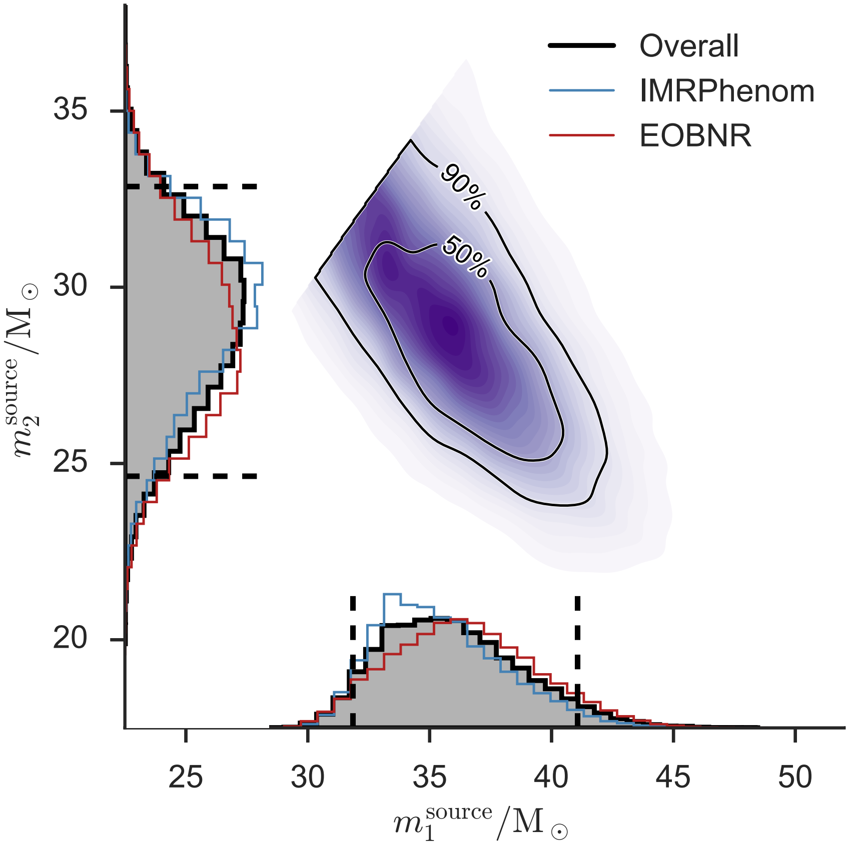
Binary black hole inspiral, merger, ringdown



http://www.black-holes.org/explore2.html

Binary Masses

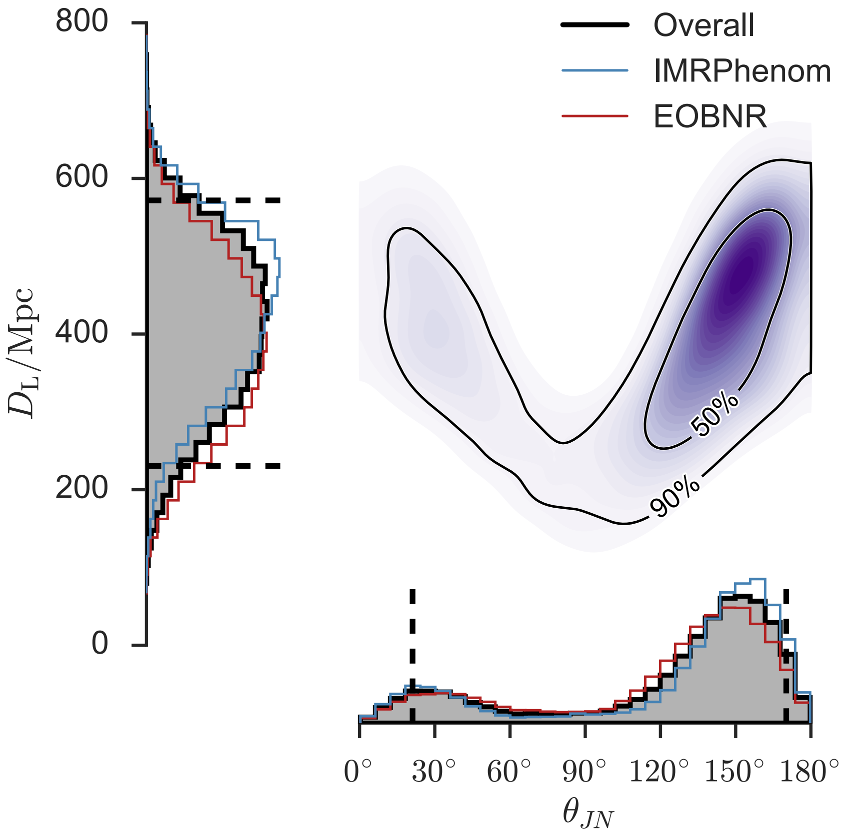
- Measurement of the masses is waveform-model dependent, but for these systems, the waveforms agree well.
- From the inspiral phase evolution $d\phi/dt$, we infer the chirp mass:
  $\mathcal{M}_c = m_{tot}\,\eta^{3/5}$; $\eta = m_1 m_2 / m^2_{tot}$
- From the merger frequency, we infer the total mass
  $m_{tot} = m_1 + m_2$.
- In this sweet spot, we measure both well, so we measure m_1 and m_2 reasonably well.



https://dcc.ligo.org/LIGO-P1500218/public/main

Luminosity distance

- Compact binary coalescence is a "standard siren", so we can infer the luminosity distance D_L.
- But, it depends on the orientation of the binary orbit wrt line of sight (θ_{JN}): face-on (louder) or edge-on (quieter).
- We can measure this by disentangling the two polarizations (+ and x).
- But this is difficult to do with only two almost-co-aligned detectors.
- Result: strong degeneracy, poor measurement of D_L.
- More detectors (coming!) will help!

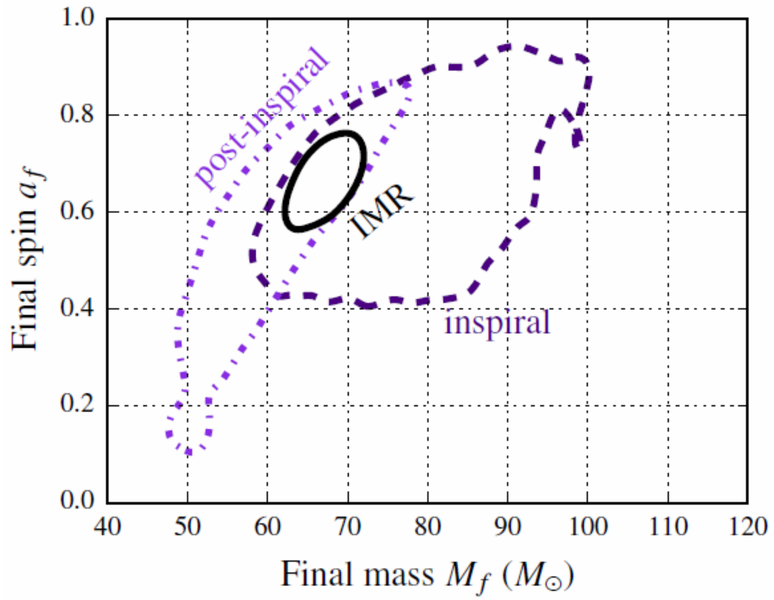


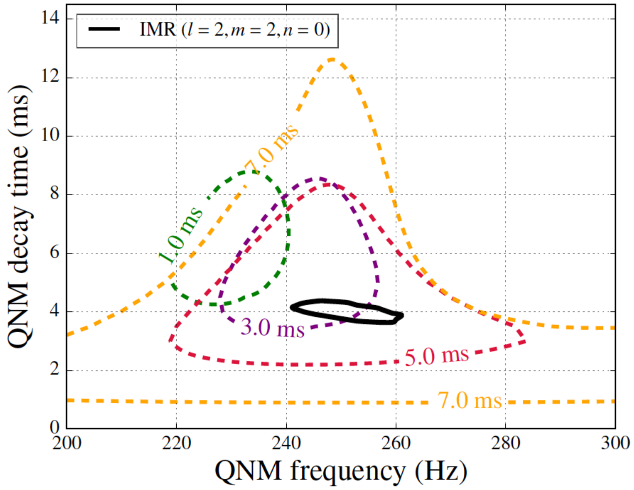
https://dcc.ligo.org/LIGO-P1500218/public/main

Final black hole mass and spin, total emitted energy & luminosity

- SNR of ringdown phase (at f ~ 300 Hz) is not high, so the extraction of the final black hole mass & spin are rather dependent on the model (GR template).
- Nonetheless, we robustly recover $m_{final} \approx m_1 + m_2 - (3\ M_\odot)$ with significant spin.
- $E_{GW} \approx 3\ M_\odot c^2 \approx 5\times10^{54}$ ergs, or ~4.5% of the total mass-energy of the system.
- Roughly 10^{80} gravitons.
- Peak luminosity $L_{GW} \sim 3.6\times10^{54}$ erg/s, briefly outshining the EM energy output of all the stars in the observable universe (by a factor ~ 50).

https://dcc.ligo.org/LIGO-P1500218/public/main

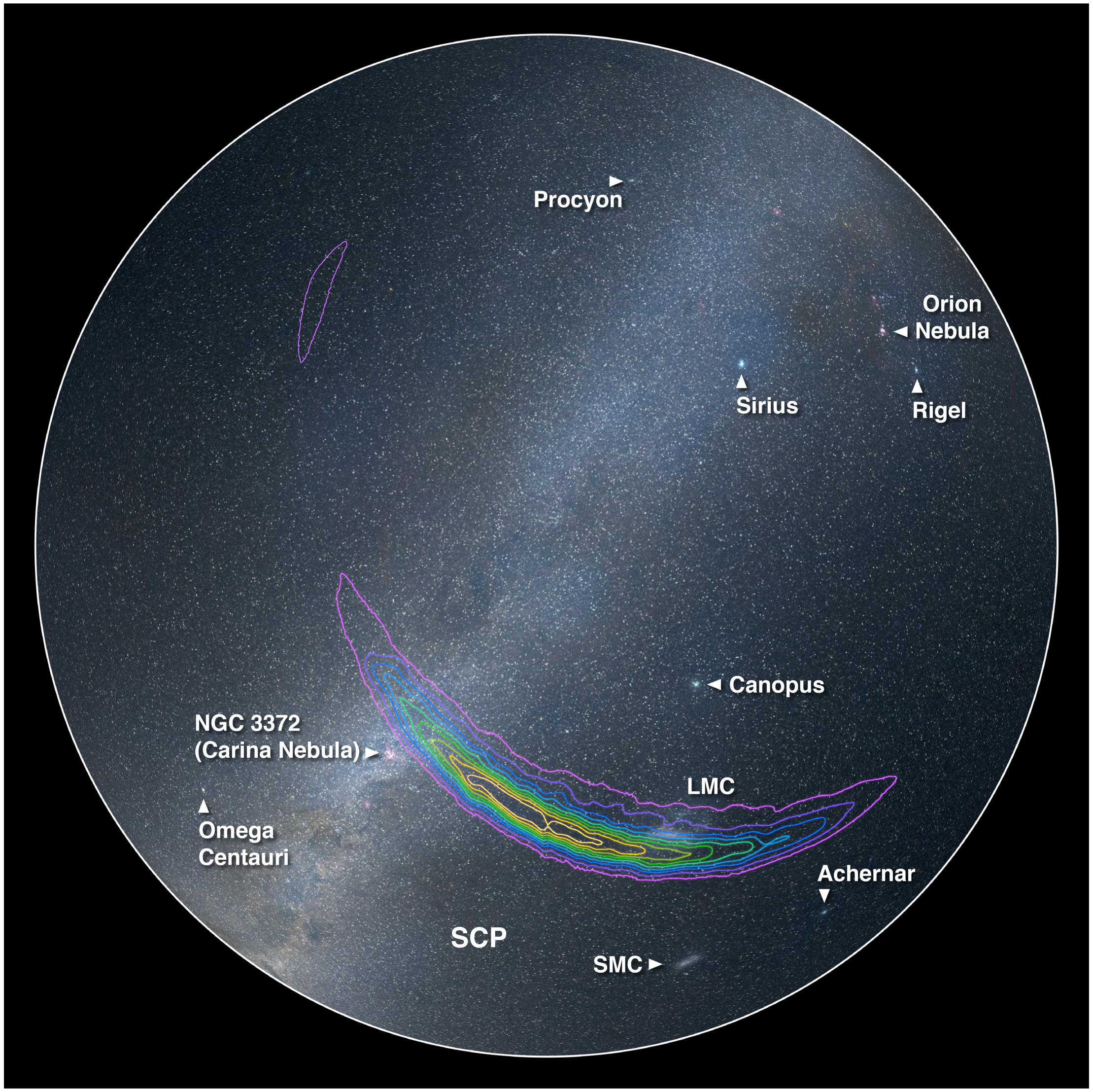




Source sky localization

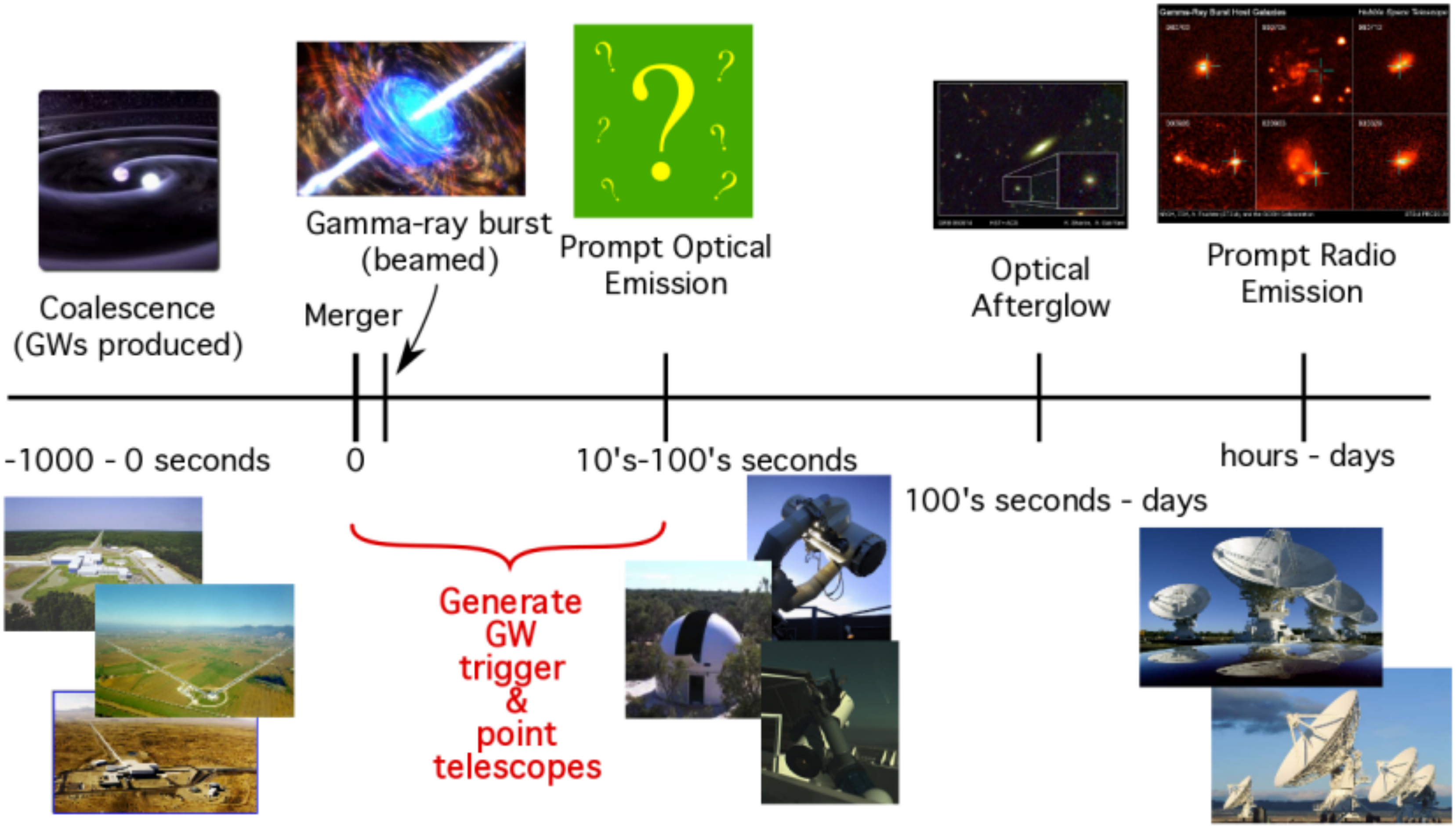
https://dcc.ligo.org/LIGO-P1500227/public/main

- Localization using timing (7 msec between H1 and L1) information (triangulation), plus amplitude and phase info.
- With only two detectors, localization is poor:
  140 deg^2 at 50% prob,
  590 deg^2 at 90% prob.
- Even though this is a BBH (EM-dim), we alerted partner astronomers, and
  ~20 different instruments imaged this region of the sky!
- Already on arXiv:
  Swift
  Fermi GBM
  Fermi LAT
  Pan-STARRS and PESSTO
  INTEGRAL
  DECam



Low-latency identification of transients for rapid (< ~100s) followup

EM counterparts to GW sources (if any) are short-lived and faint



Coalescence (GWs produced)

Gamma-ray burst (beamed)

Merger

Prompt Optical Emission

Optical Afterglow

Prompt Radio Emission

-1000 - 0 seconds

0

10's-100's seconds

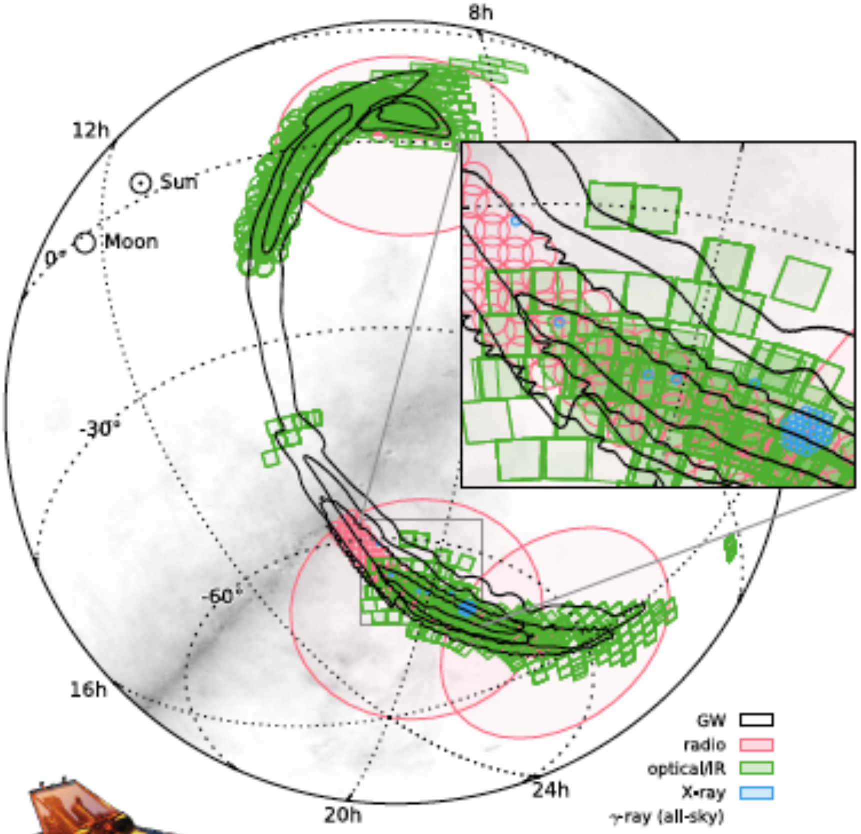
100's seconds - days

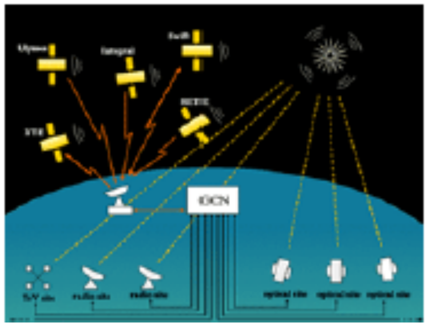
hours - days

Generate GW trigger & point telescopes

Localization and **broadband follow-up** of the first LIGO event

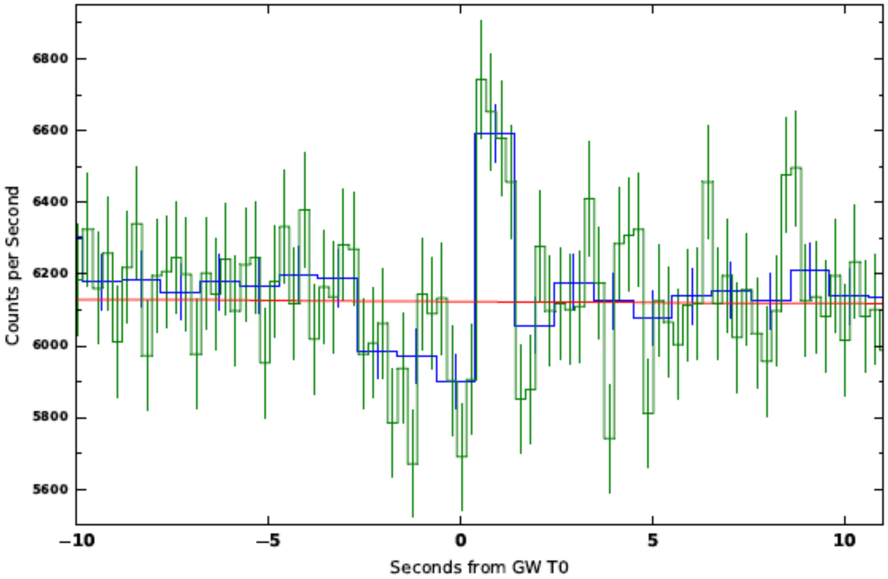
- Consortium between LIGO and 63 teams using ground and space facilities
- Gamma-ray, X-ray, optical, infrared, and radio wavelengths
- Key NASA contributions come from high-energy observational assets: ***Fermi***, ***Swift***, ***GCN network***

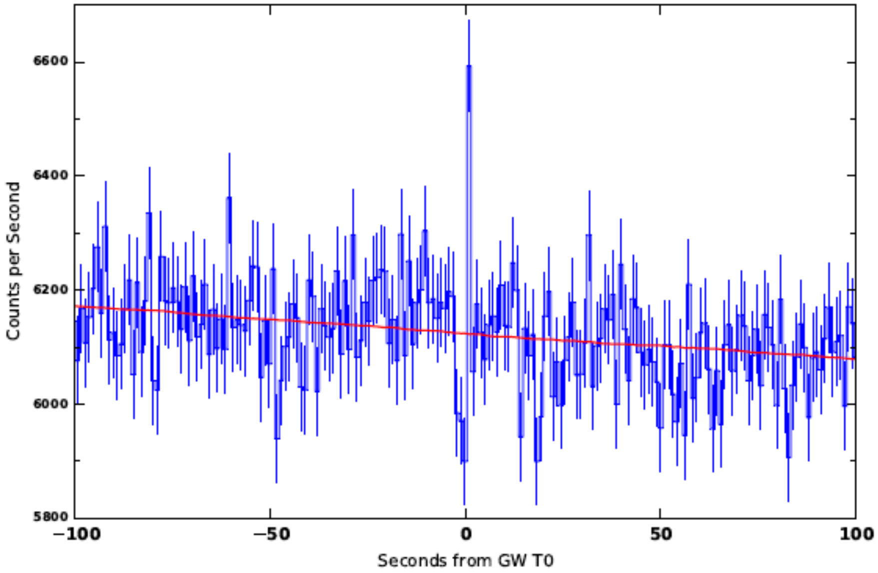


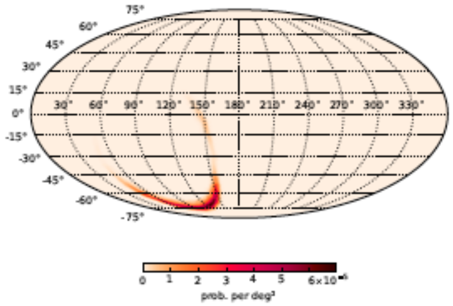


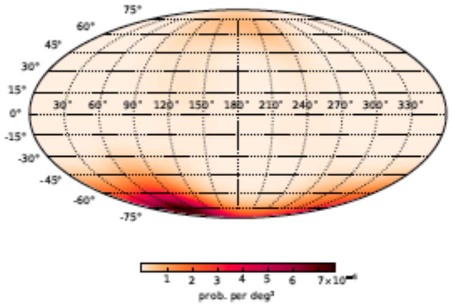
http://arxiv.org/abs/1602.08492

Fermi GBM around the time of the event



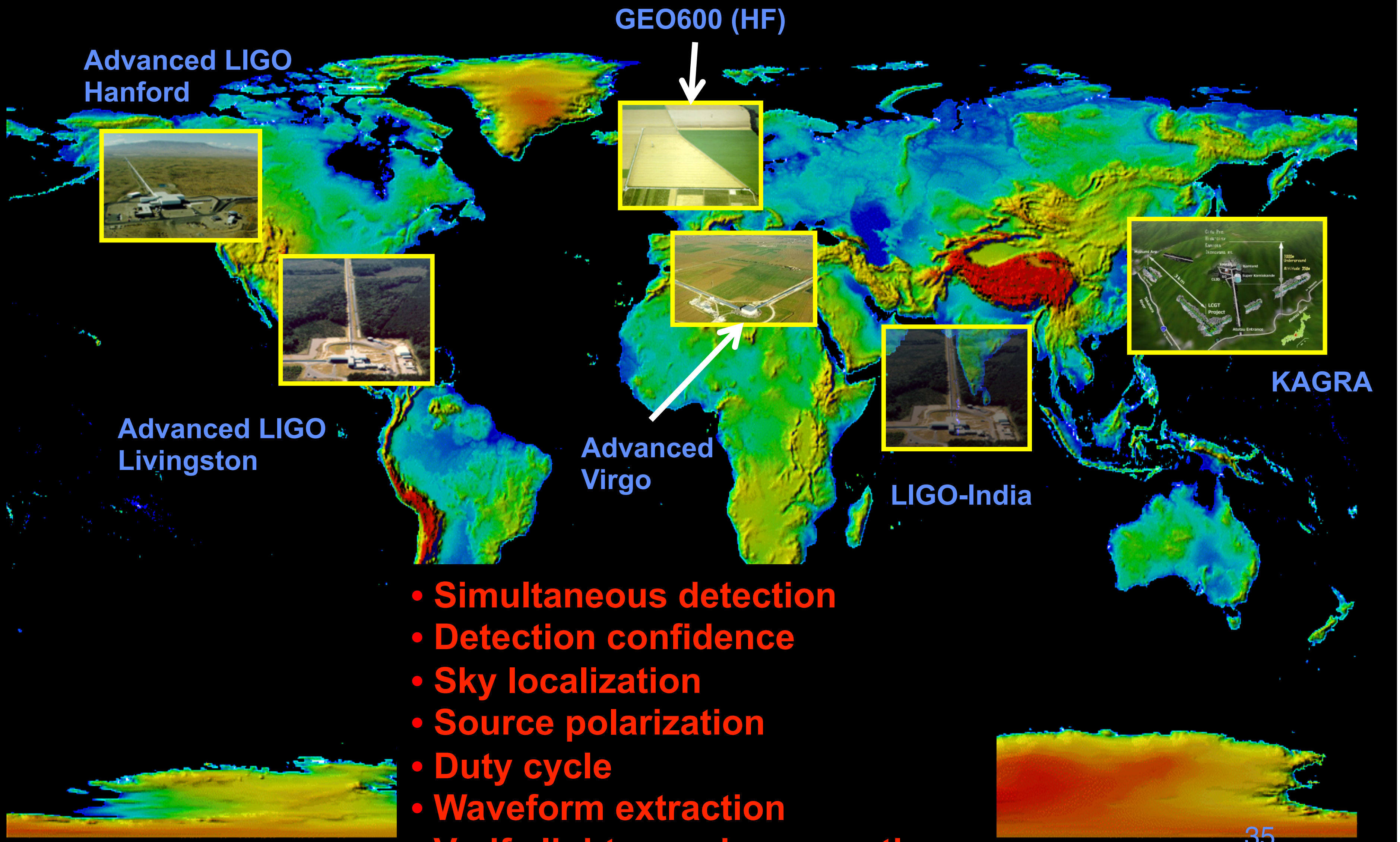






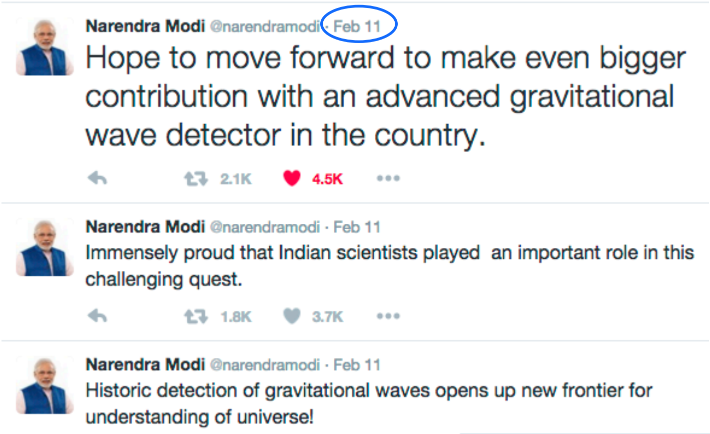
http://arxiv.org/abs/1602.03920

The Advanced GW Detector Network



- Simultaneous detection
- Detection confidence
- Sky localization
- Source polarization
- Duty cycle
- Waveform extraction
- Verify light speed propagation

LIGO India is a GO after 5 years of waiting on the Indian government!



Narendra Modi @narendramodi · Feb 11

Hope to move forward to make even bigger contribution with an advanced gravitational wave detector in the country.

2.1K 4.5K

Narendra Modi @narendramodi · Feb 11

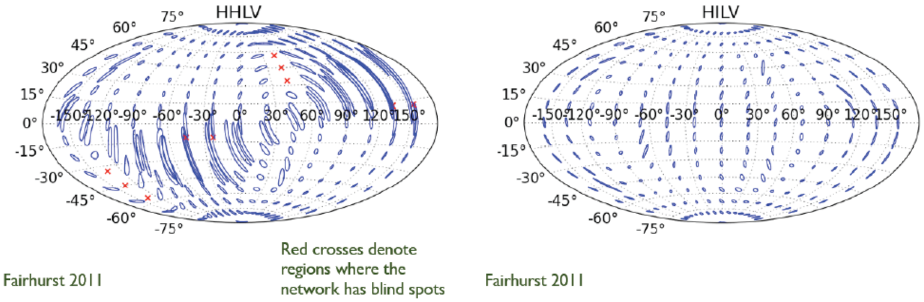
Immensely proud that Indian scientists played an important role in this challenging quest.

1.8K 3.7K

Narendra Modi @narendramodi · Feb 11

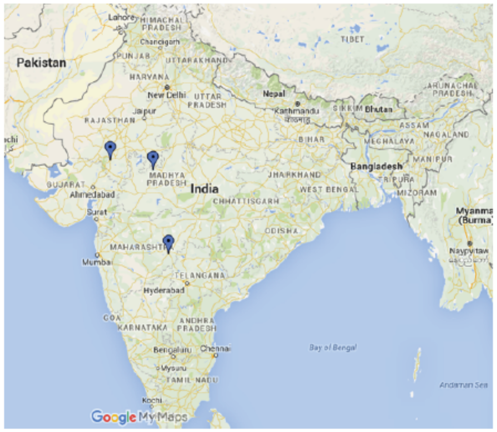
Historic detection of gravitational waves opens up new frontier for understanding of universe!

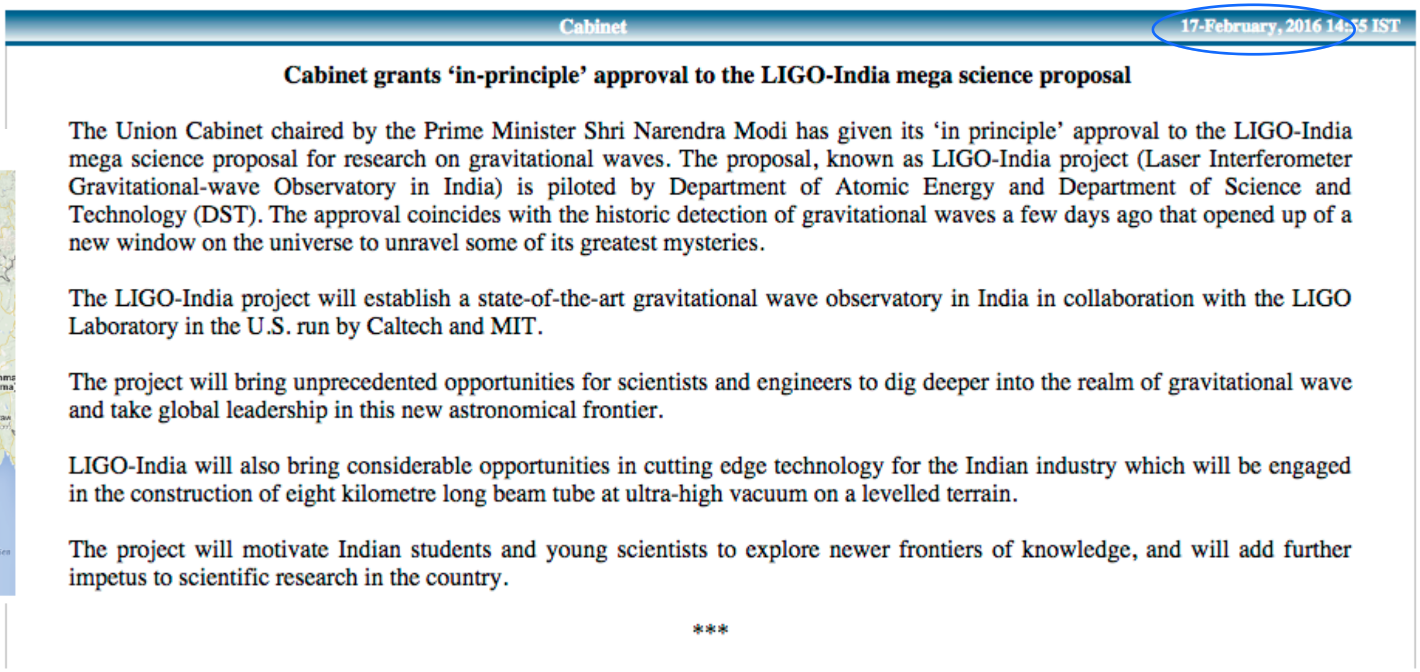
1.9K 3.7K



LIGO+Virgo only

With LIGO-India





Cabinet 17-February, 2016 14:55 IST

Cabinet grants 'in-principle' approval to the LIGO-India mega science proposal

The Union Cabinet chaired by the Prime Minister Shri Narendra Modi has given its 'in principle' approval to the LIGO-India mega science proposal for research on gravitational waves. The proposal, known as LIGO-India project (Laser Interferometer Gravitational-wave Observatory in India) is piloted by Department of Atomic Energy and Department of Science and Technology (DST). The approval coincides with the historic detection of gravitational waves a few days ago that opened up of a new window on the universe to unravel some of its greatest mysteries.

The LIGO-India project will establish a state-of-the-art gravitational wave observatory in India in collaboration with the LIGO Laboratory in the U.S. run by Caltech and MIT.

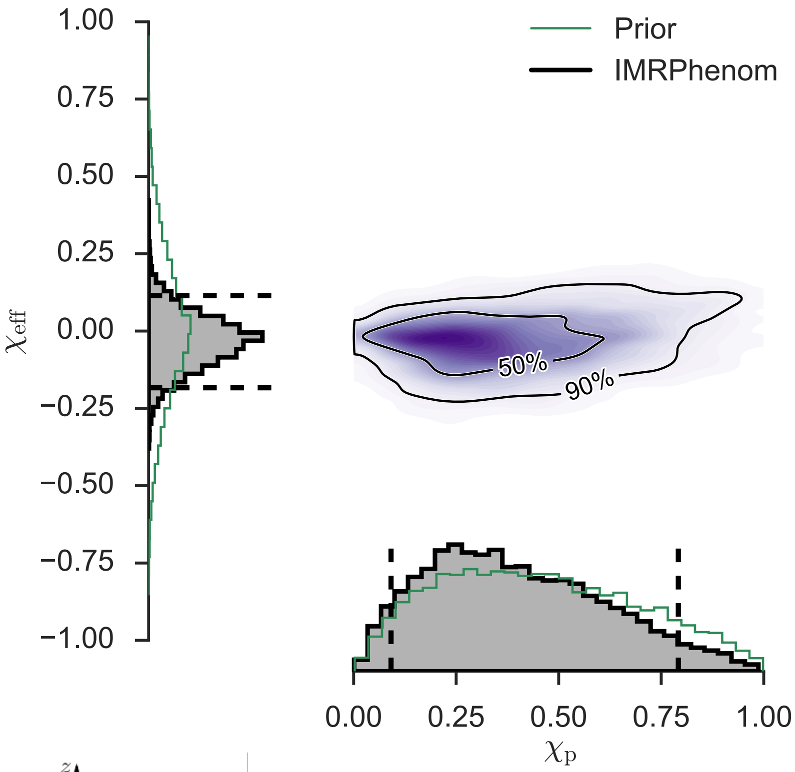
The project will bring unprecedented opportunities for scientists and engineers to dig deeper into the realm of gravitational wave and take global leadership in this new astronomical frontier.

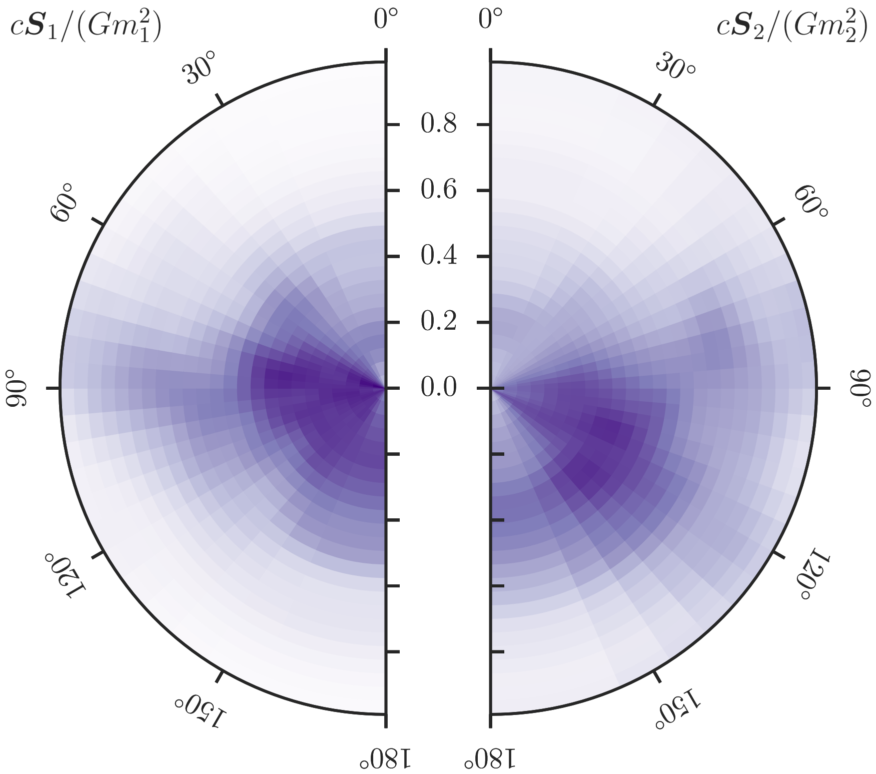
LIGO-India will also bring considerable opportunities in cutting edge technology for the Indian industry which will be engaged in the construction of eight kilometre long beam tube at ultra-high vacuum on a levelled terrain.

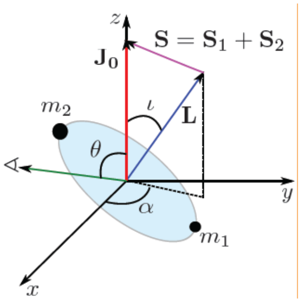
The project will motivate Indian students and young scientists to explore newer frontiers of knowledge, and will add further impetus to scientific research in the country.

***

BH spins – aligned with orbital angular momentum, and precessing spin



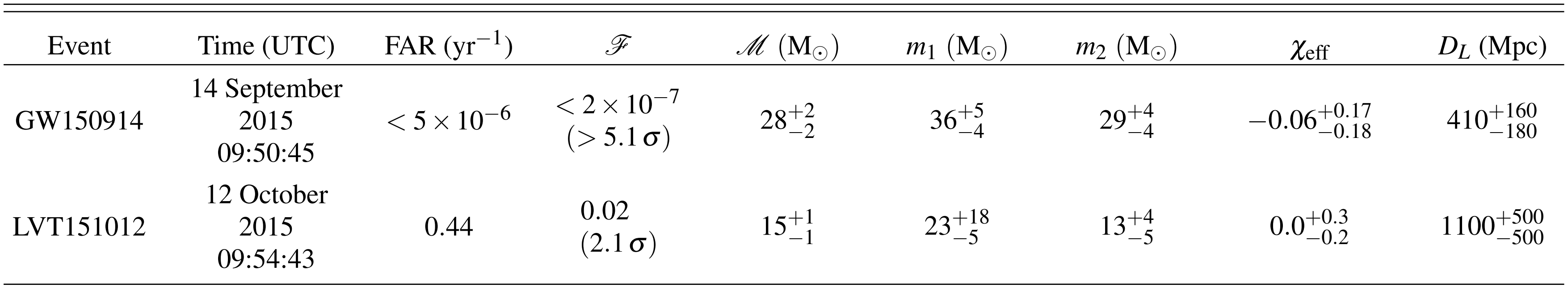




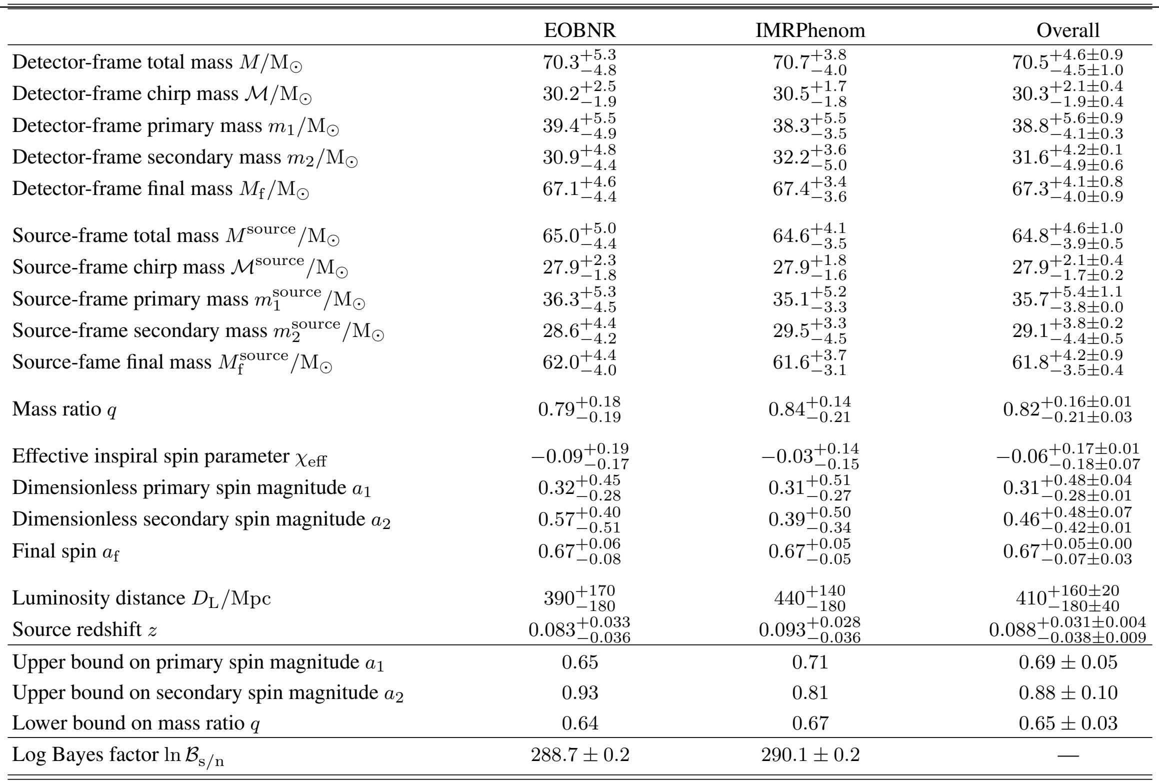
https://dcc.ligo.org/LIGO-P1500218/public/main

Parameters of two loudest events

https://dcc.ligo.org/LIGO-P1500218/public/main

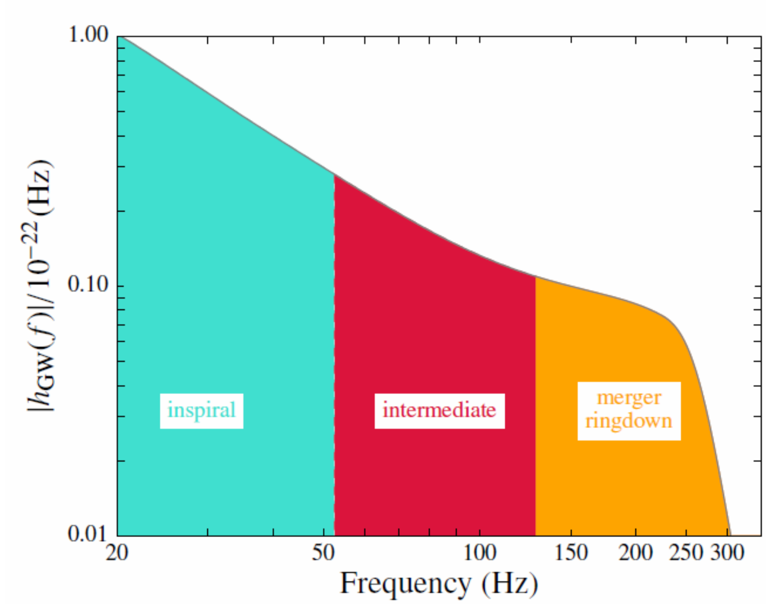


Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($\mathrm{M}_\odot$)	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

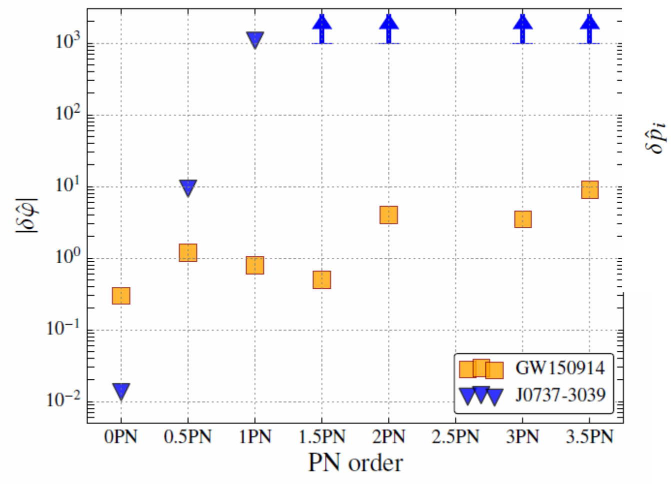


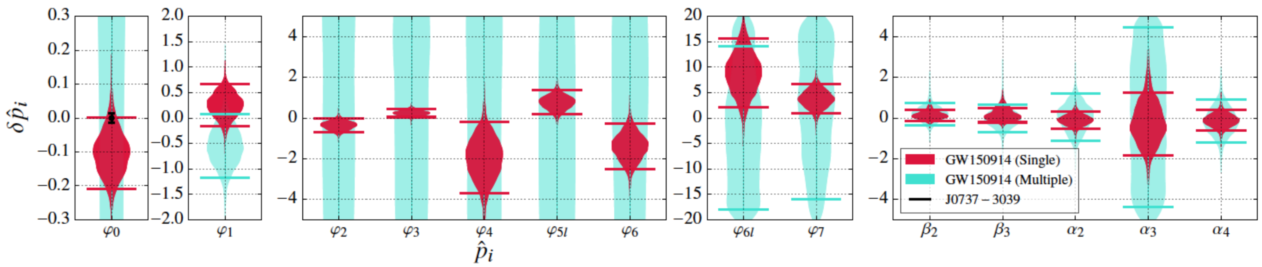
	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_{\mathrm{f}}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_{eff}	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_{f}	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\mathrm{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

Tests of consistency with predictions from General Relativity



waveform regime			median		GR quantile		$\log_{10} B^{\mathrm{GR}}_{\mathrm{model}}$	
	parameter	f−dependence	single	multiple	single	multiple	single	multiple
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.3^{+3.0}_{-3.2}$	0.94	0.30	1.9 ± 0.2	3.7 ± 0.6
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$0.3^{+0.4}_{-0.4}$	$-0.5^{+0.6}_{-0.6}$	0.16	0.93	1.6 ± 0.2	
	$\delta\hat{\varphi}_2$	f^{-1}	$-0.4^{+0.3}_{-0.4}$	$-1.6^{+18.8}_{-16.6}$	0.96	0.56	1.2 ± 0.2	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	$0.2^{+0.2}_{-0.2}$	$2.0^{+13.4}_{-13.9}$	0.02	0.42	1.2 ± 0.2	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	$-1.9^{+1.6}_{-1.7}$	$-1.9^{+19.3}_{-16.4}$	0.98	0.56	0.3 ± 0.2	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.5}_{-0.6}$	$-1.4^{+18.6}_{-16.9}$	0.01	0.55	0.7 ± 0.4	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	$-1.4^{+1.1}_{-1.1}$	$1.2^{+16.8}_{-18.9}$	0.99	0.47	0.4 ± 0.2	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	$8.9^{+6.8}_{-6.8}$	$-1.9^{+19.1}_{-16.1}$	0.02	0.57	-0.3 ± 0.2	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	$3.8^{+2.9}_{-2.9}$	$3.2^{+15.1}_{-19.2}$	0.02	0.41	-0.0 ± 0.2	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	$0.1^{+0.4}_{-0.3}$	$0.2^{+0.6}_{-0.5}$	0.24	0.28	1.4 ± 0.2	2.3 ± 0.2
	$\delta\hat{\beta}_3$	f^{-3}	$0.1^{+0.6}_{-0.3}$	$-0.0^{+0.8}_{-0.7}$	0.31	0.56	1.2 ± 0.4	
merger-ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	$-0.1^{+0.4}_{-0.4}$	$0.0^{+1.0}_{-1.2}$	0.68	0.50	1.2 ± 0.2	2.1 ± 0.4
	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.3^{+1.9}_{-1.5}$	$0.0^{+4.4}_{-4.4}$	0.60	0.51	0.7 ± 0.2	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af+b)$	$-0.1^{+0.5}_{-0.5}$	$-0.1^{+1.1}_{-1.0}$	0.68	0.62	1.1 ± 0.2	





https://dcc.ligo.org/LIGO-P1500213/public/main

Mass of the graviton

A graviton mass

$$E^2 = p^2c^2 + m_g^2c^4$$

and associated Compton wavelength

$$\lambda_g = h/(m_g c)$$

results in frequency-dependent velocity

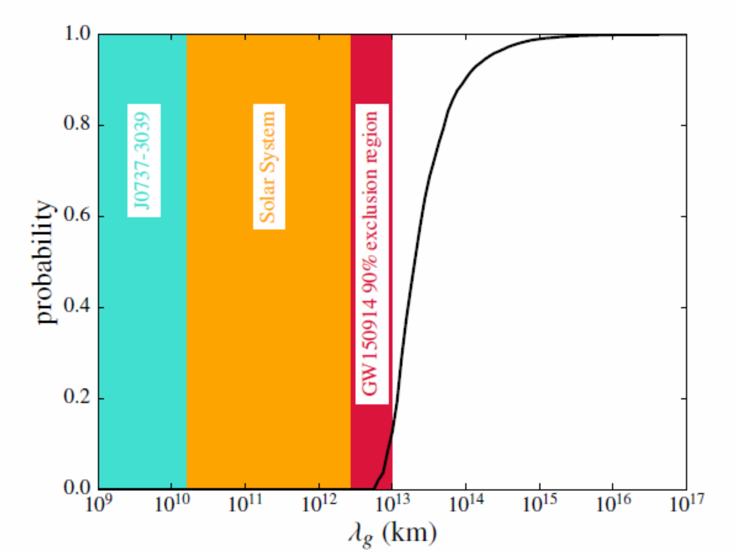
$$v_g^2/c^2 \equiv c^2p^2/E^2 = 1 - h^2c^2/(\lambda_g^2 E^2)$$

and dispersion causes distortion of the phase evolution of the waveform (wrt massless theory)

$$\Phi_{\mathrm{MG}}(f) = -(\pi D c)/[\lambda_g^2(1+z)f]$$

Agreement of observed waveform with theory allows us to set the bound:

$$m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV/c^2}\ \text{at 90\% confidence}$$



$\lambda_g > 10^{13}$ km

https://dcc.ligo.org/LIGO-P1500213/public/main

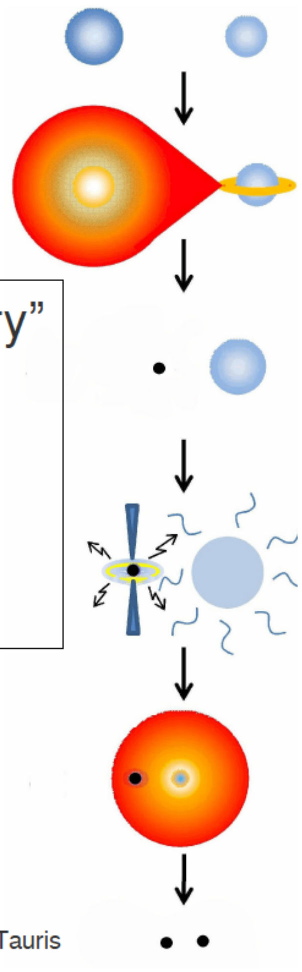
Formation mechanisms

- How do massive binary black hole systems form?
- Common envelope evolution of isolated binaries: two massive stars survive successive CCSNe
- Dynamical capture of isolated black holes in N-body exchange interactions.
- Even the most massive stars (60-100 $M_\odot$) can only produce black holes with mass > 20 $M_\odot$ only in low-metalicity environments ($\sim 0.1\ Z_\odot$).
- https://dcc.ligo.org/LIGO-P1500262/public/main

Formation channels

https://dcc.ligo.org/LIGO-P1500262/public/main

Isolated binary



"ordinary"
or
rapid
rotation
or
PopIII

Fig. after Tauris

Dynamical formation

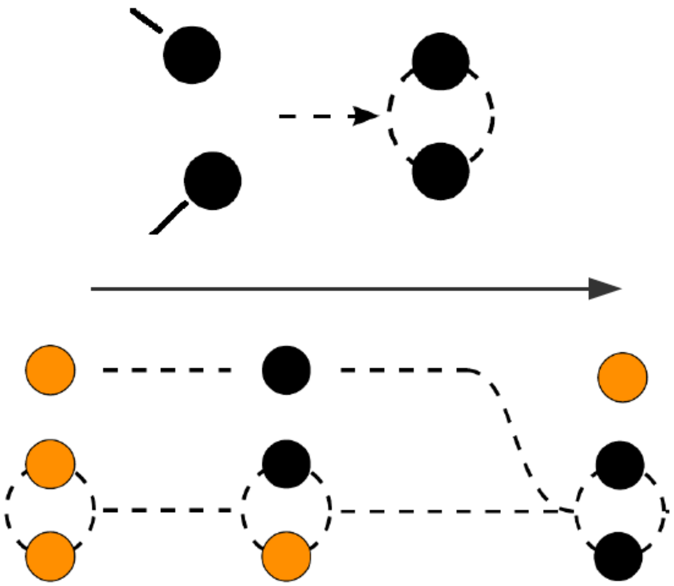


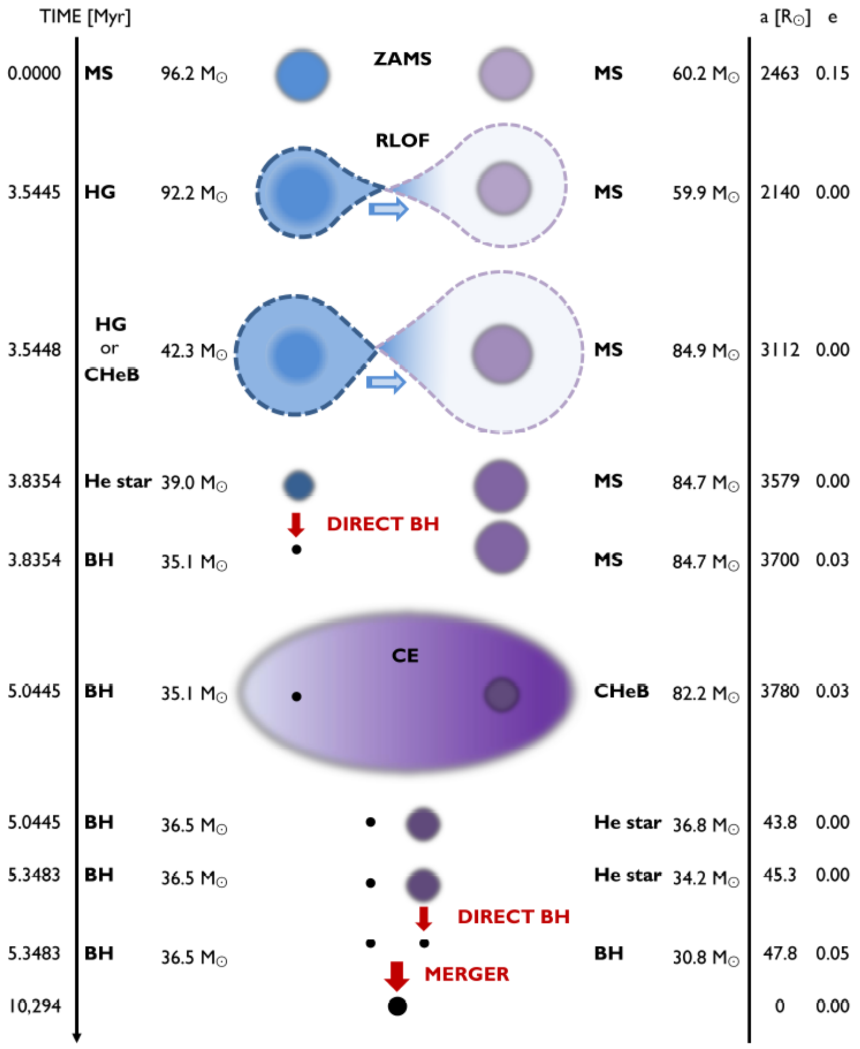
Fig. after Ziosi

Globular/young clusters/gal. nuclei

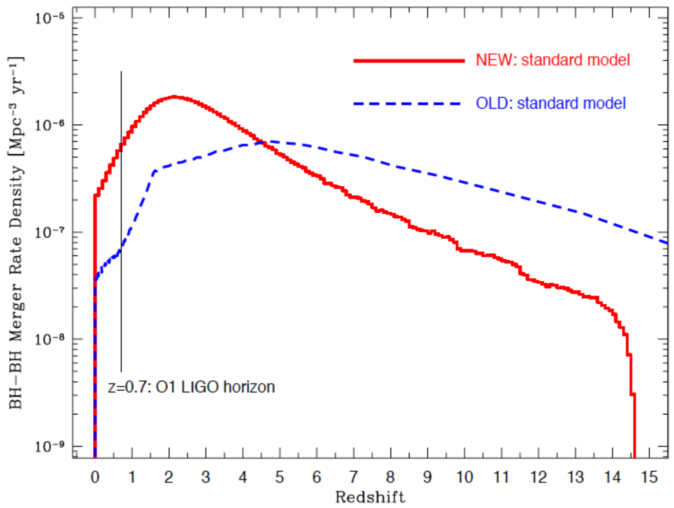
Radboud Universiteit Nijmegen

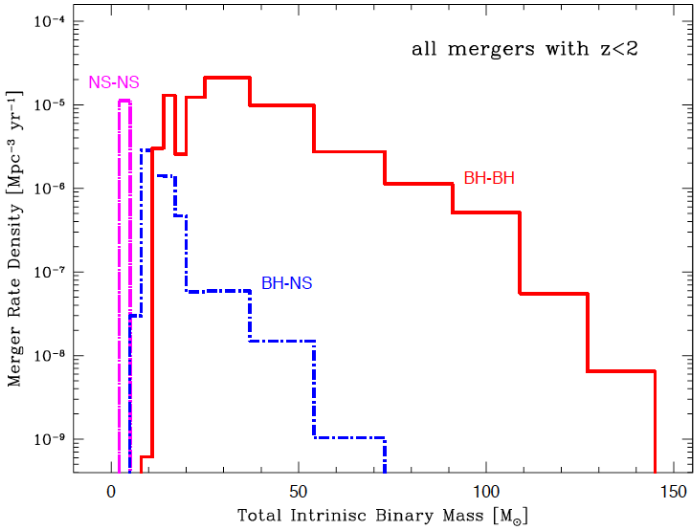
“Classic” evolutionary scenario

Belczynski et al, arXiv:1602.04531



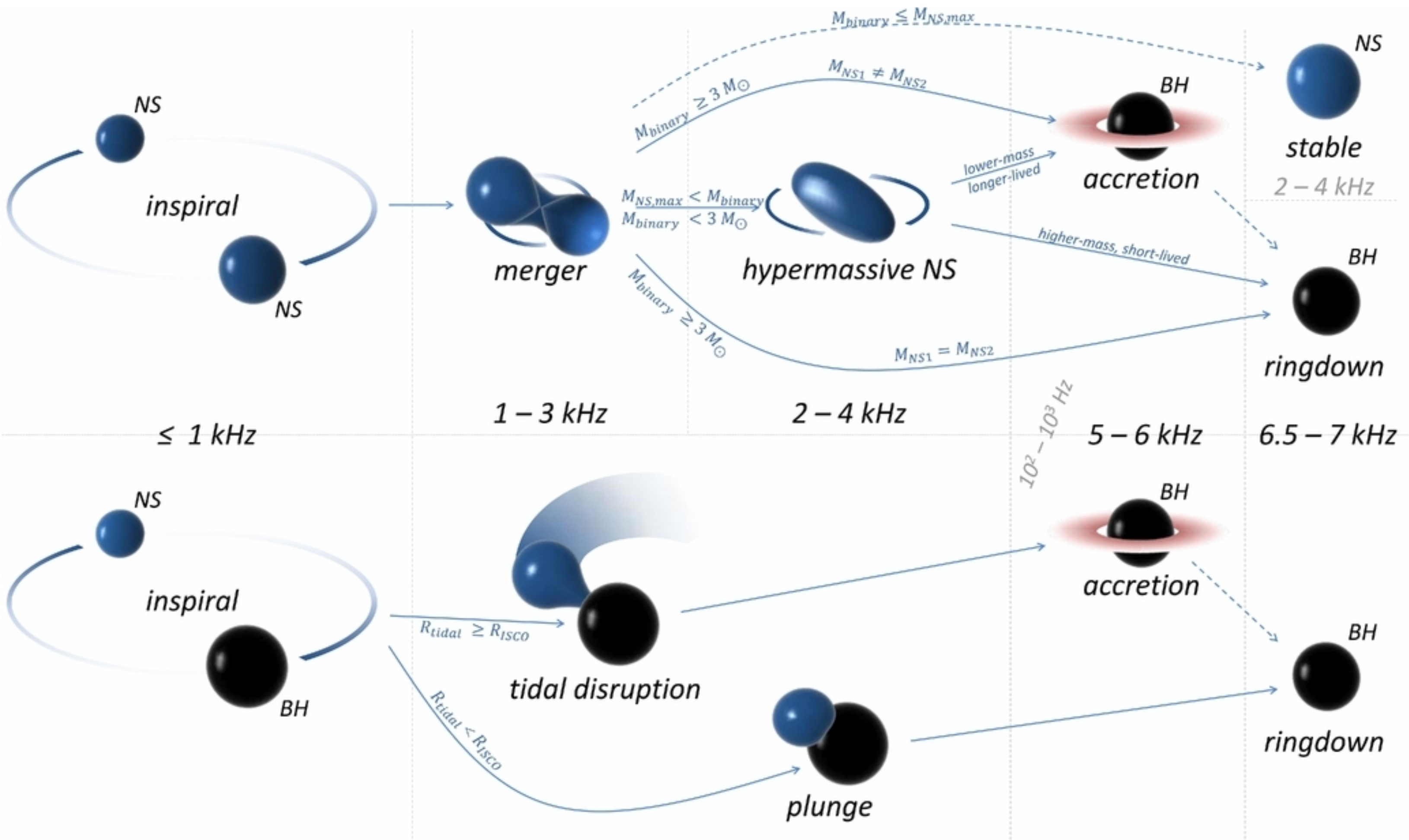
TIME [Myr]						a [$R_\odot$]	e
0.0000	MS	96.2 $M_\odot$	ZAMS	MS	60.2 $M_\odot$	2463	0.15
3.5445	HG	92.2 $M_\odot$	RLOF	MS	59.9 $M_\odot$	2140	0.00
3.5448	HG or CHeB	42.3 $M_\odot$		MS	84.9 $M_\odot$	3112	0.00
3.8354	He star	39.0 $M_\odot$		MS	84.7 $M_\odot$	3579	0.00
			DIRECT BH				
3.8354	BH	35.1 $M_\odot$		MS	84.7 $M_\odot$	3700	0.03
5.0445	BH	35.1 $M_\odot$	CE	CHeB	82.2 $M_\odot$	3780	0.03
5.0445	BH	36.5 $M_\odot$		He star	36.8 $M_\odot$	43.8	0.00
5.3483	BH	36.5 $M_\odot$		He star	34.2 $M_\odot$	45.3	0.00
			DIRECT BH				
5.3483	BH	36.5 $M_\odot$		BH	30.8 $M_\odot$	47.8	0.05
			MERGER				
10,294						0	0.00





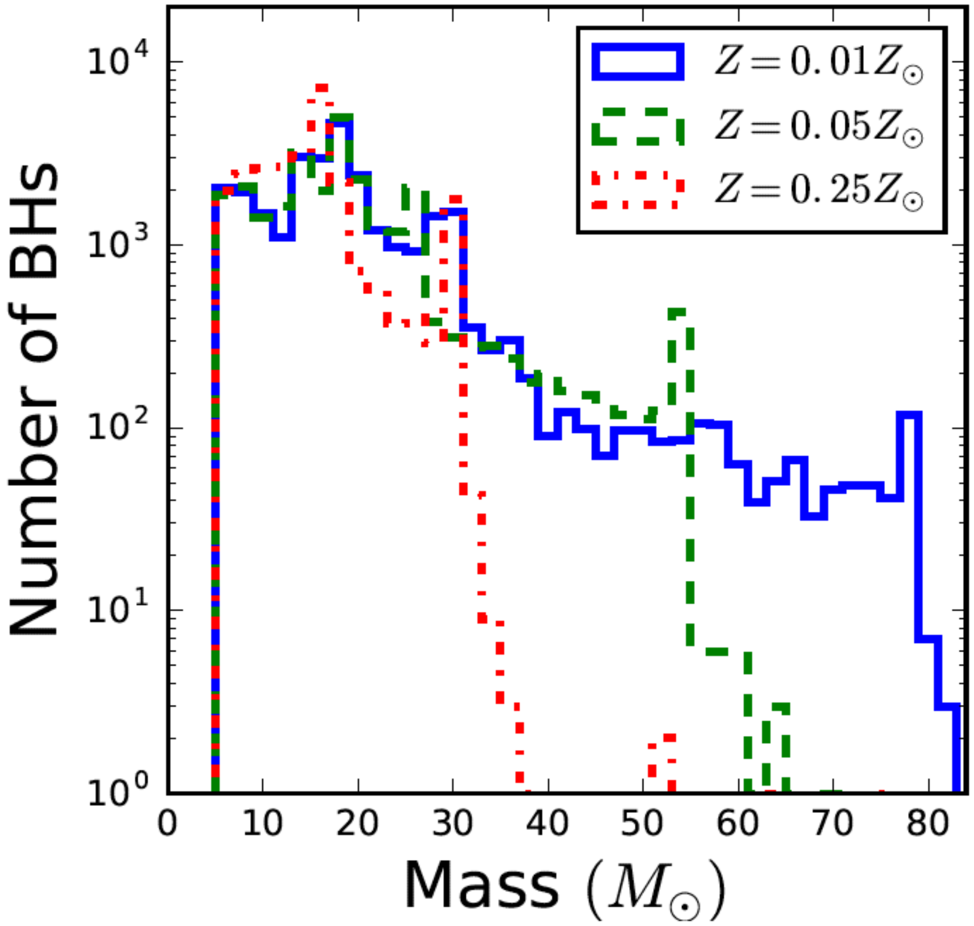
And in the end … binary mergers

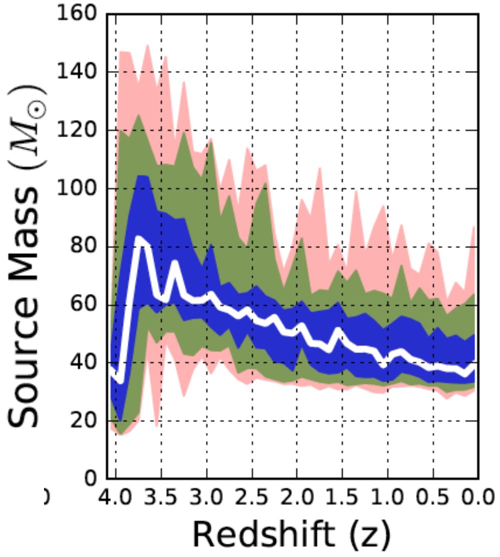
Figure 1 from I Bartos et al 2013 Class. Quantum Grav. 30 123001

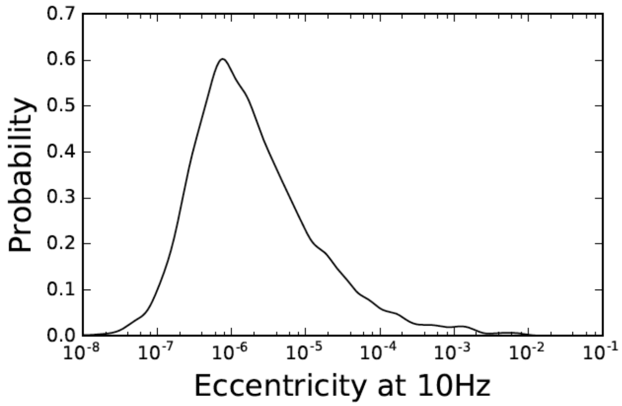


BBH Mergers from Globular Clusters

C. Rodriguez et al, arXiv:1602.02444

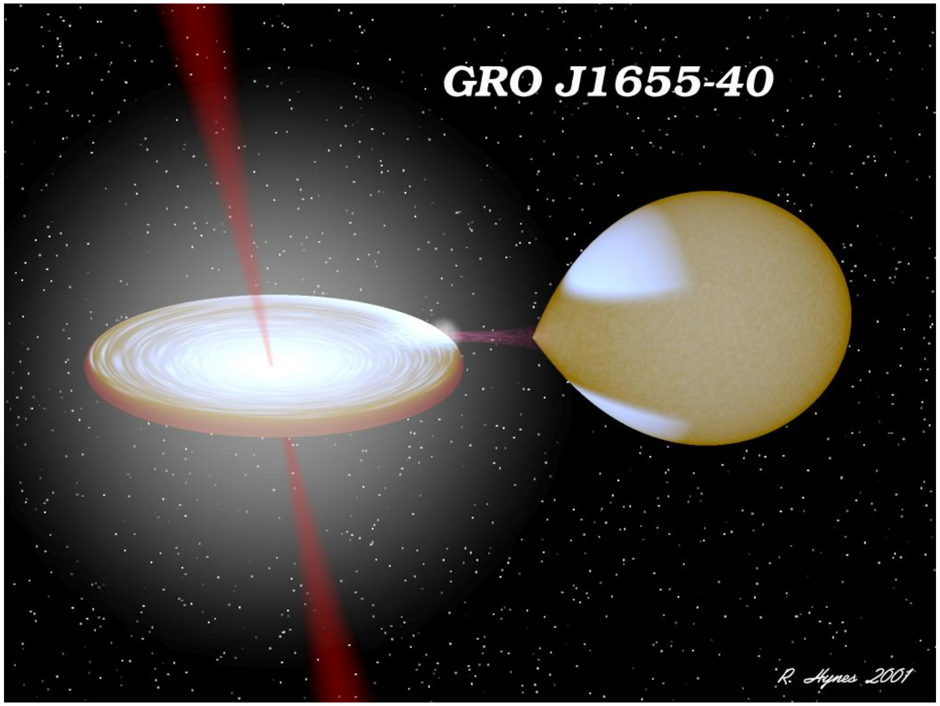




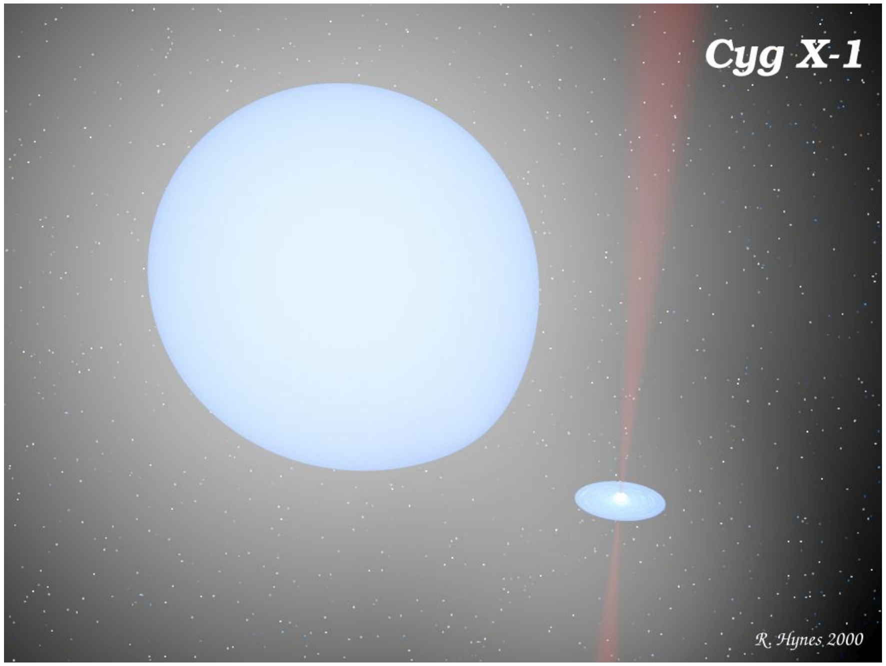


Progenitors of compact binaries

- LMXB



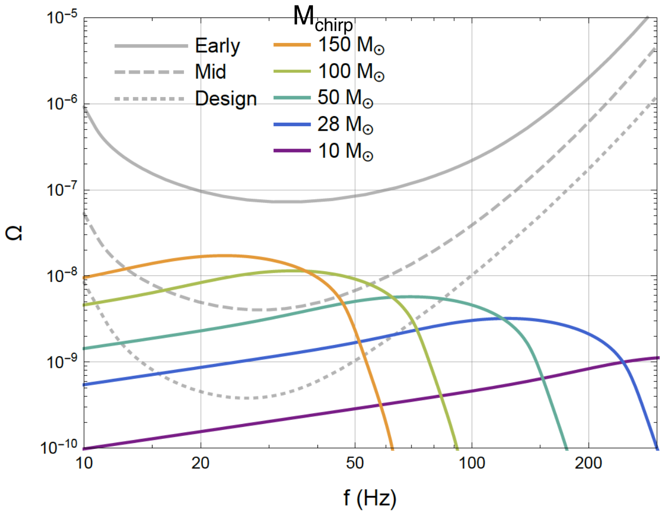
HMXB

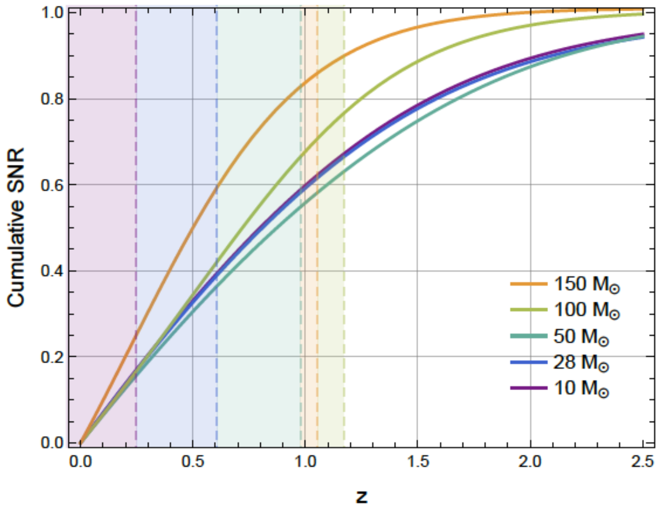


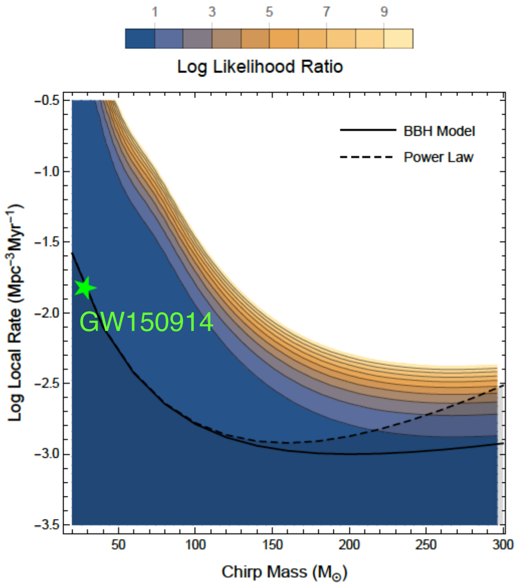
http://www.phys.lsu.edu/~rih/binsim/gallery.html

Contribution to a stochastic astrophysical background

- In addition to individual *foreground* events, we expect a *stochastic background* of many unresolved, distant events from all directions at essentially all times (“popcorn noise”).
- There will be a (redshifted) cutoff frequency, depending on the average chirp mass of the systems that dominate this background.
- For low mass systems, foreground events account for only a small fraction of the total SNR in the stochastic signal.
- The background associated with events like GW150914 may be marginally detectable (at SNR ~ 3) with Advanced LIGO after three years of observation.
- However, the cutoff frequency distribution will be indistinguishable from a simple power-law.

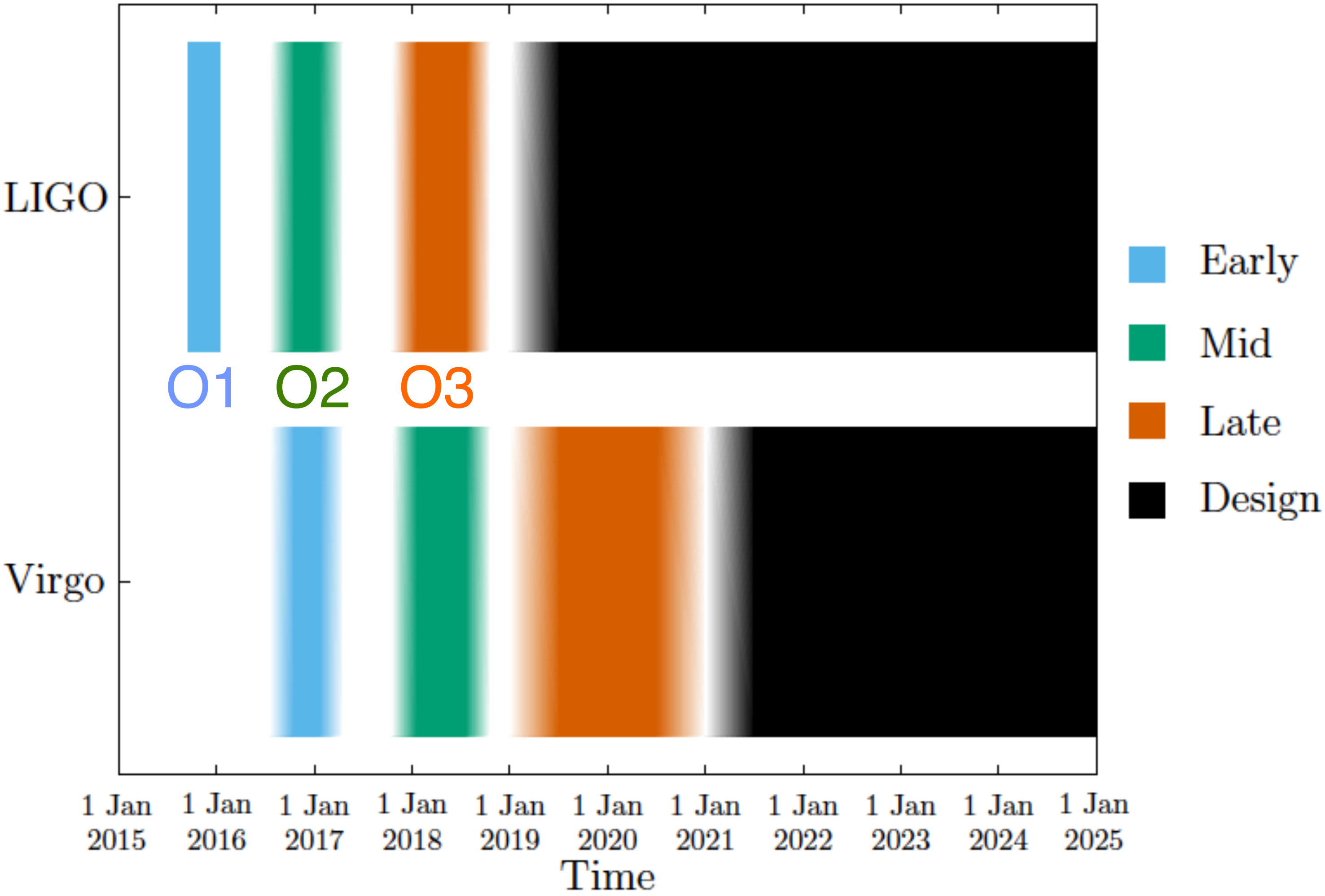






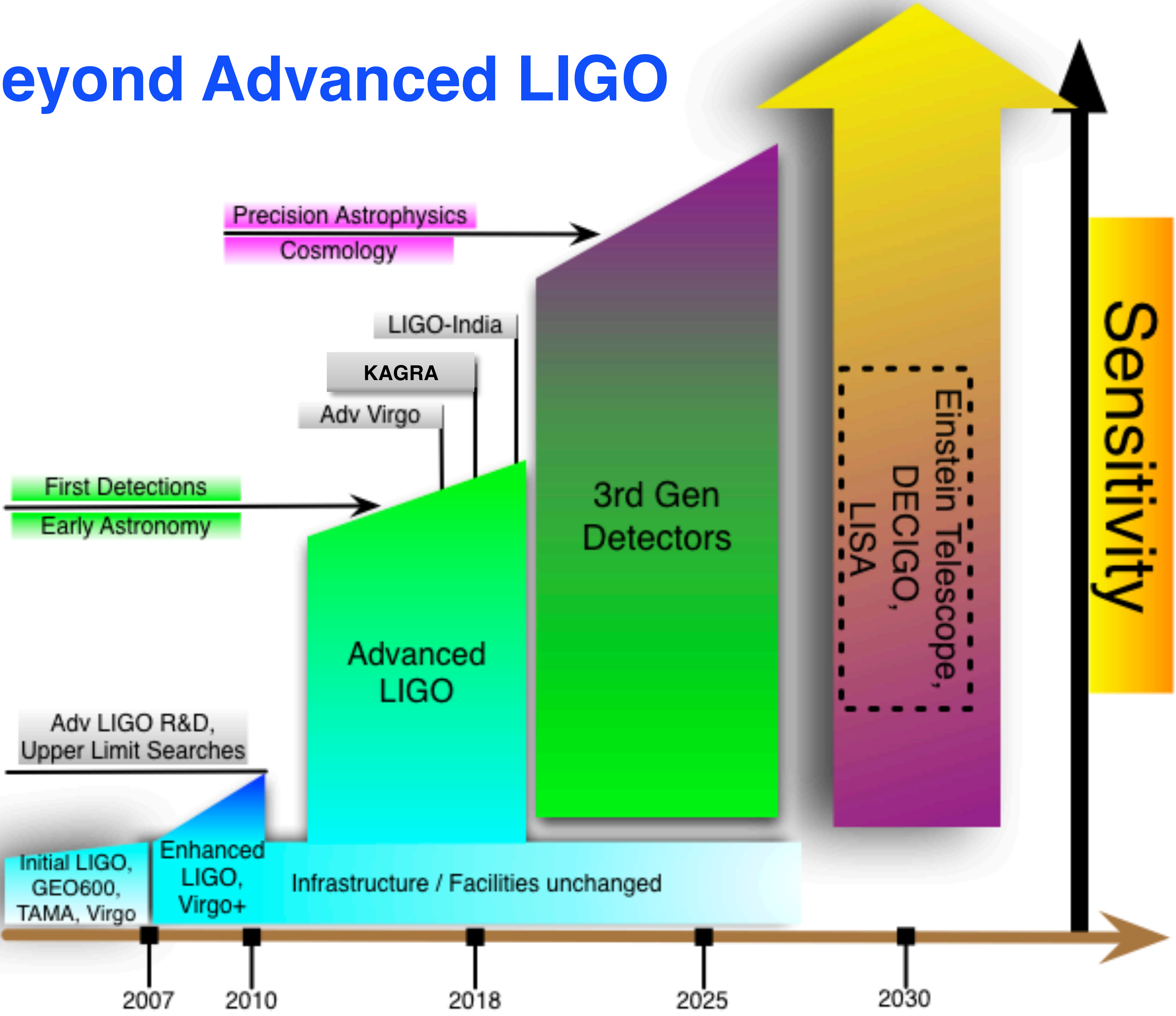
https://dcc.ligo.org/LIGO-P1500222/public/main ; Tom Callister, in prep

near-term future – very preliminary plan

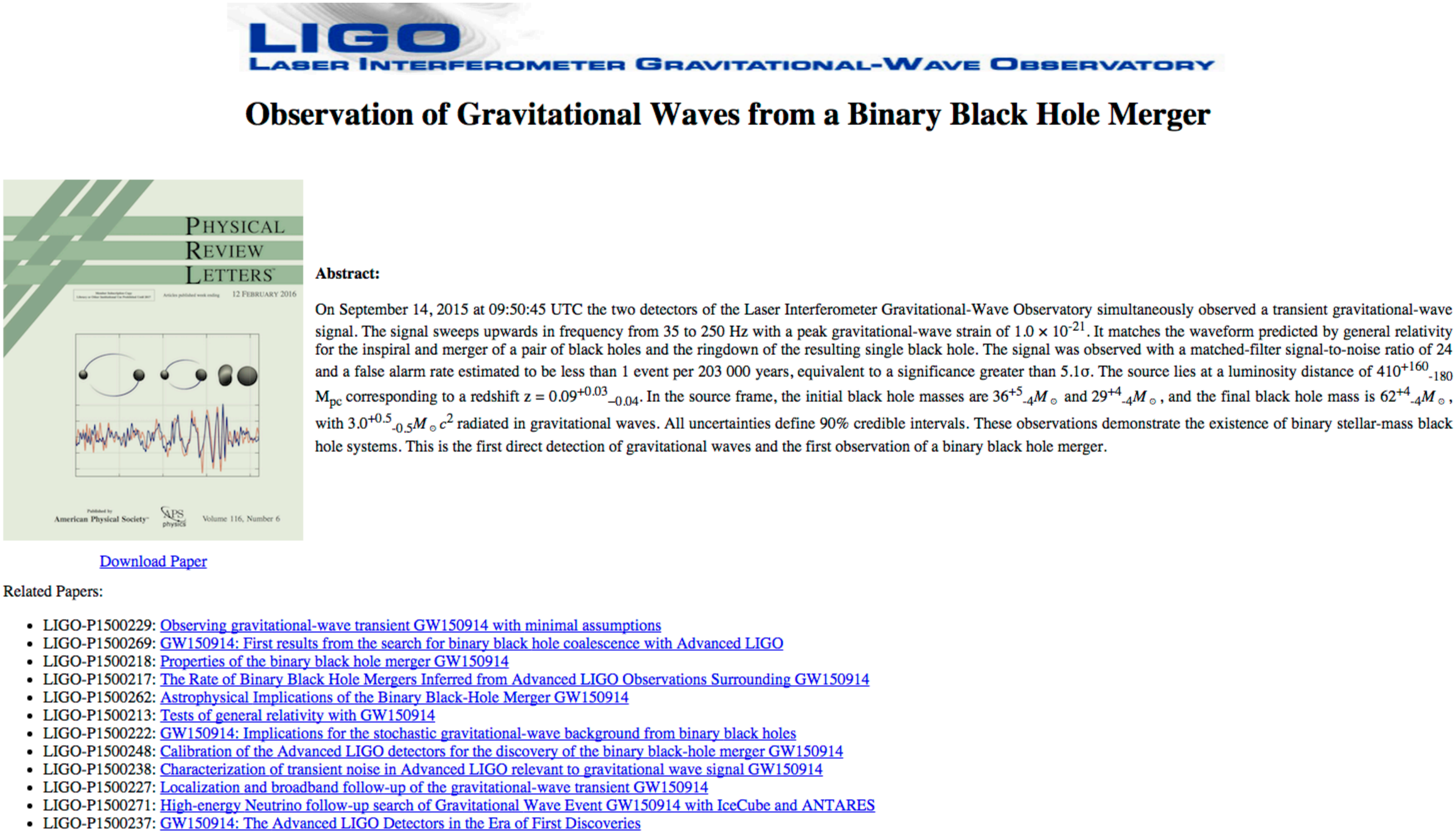


http://relativity.livingreviews.org/Articles/lrr-2016-1/

Beyond Advanced LIGO



More info: papers.ligo.org
(much more to come!)



LIGO

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Observation of Gravitational Waves from a Binary Black Hole Merger

Abstract:

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} $\mathrm{M_{pc}}$ corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

Download Paper

Related Papers:

- LIGO-P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions
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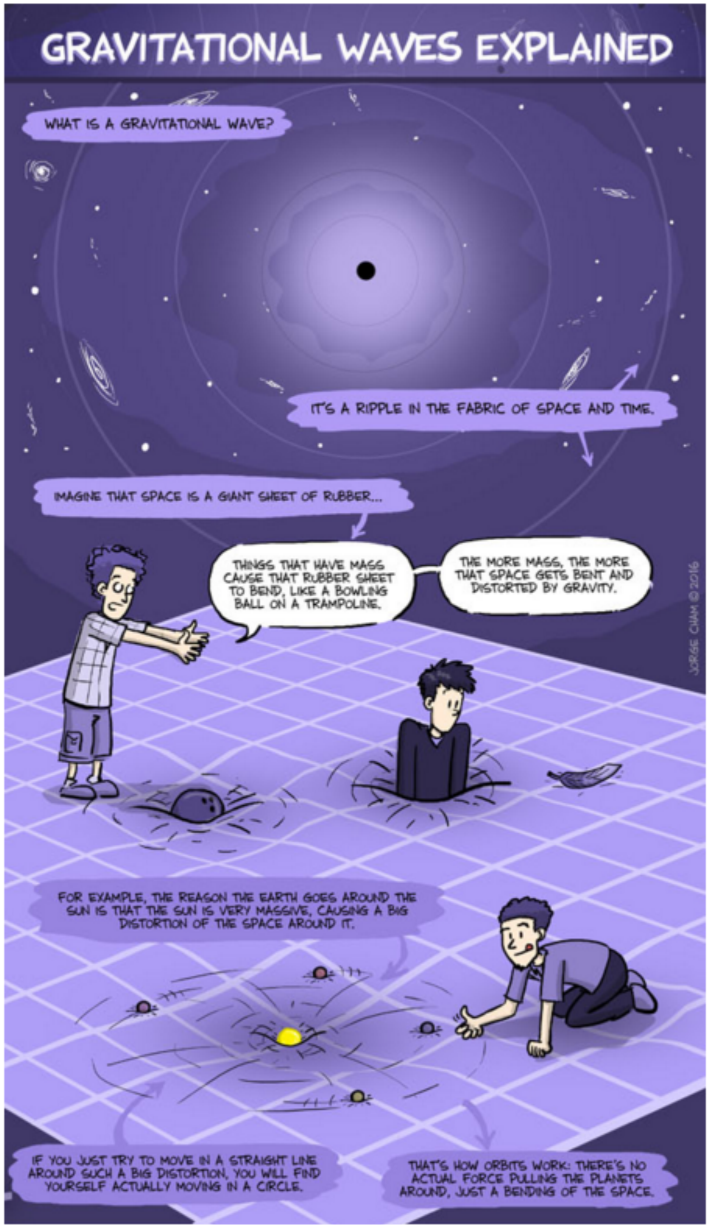
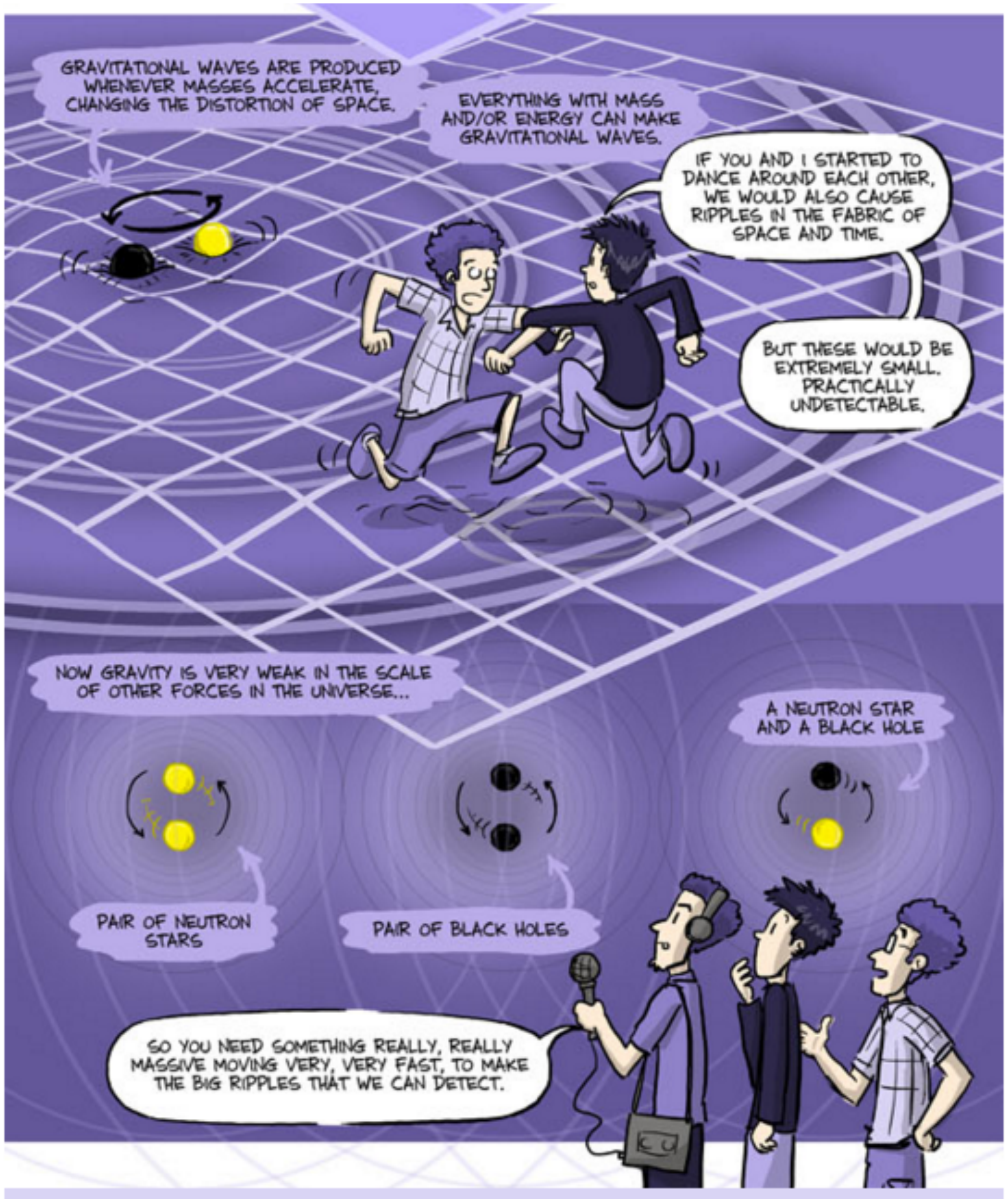
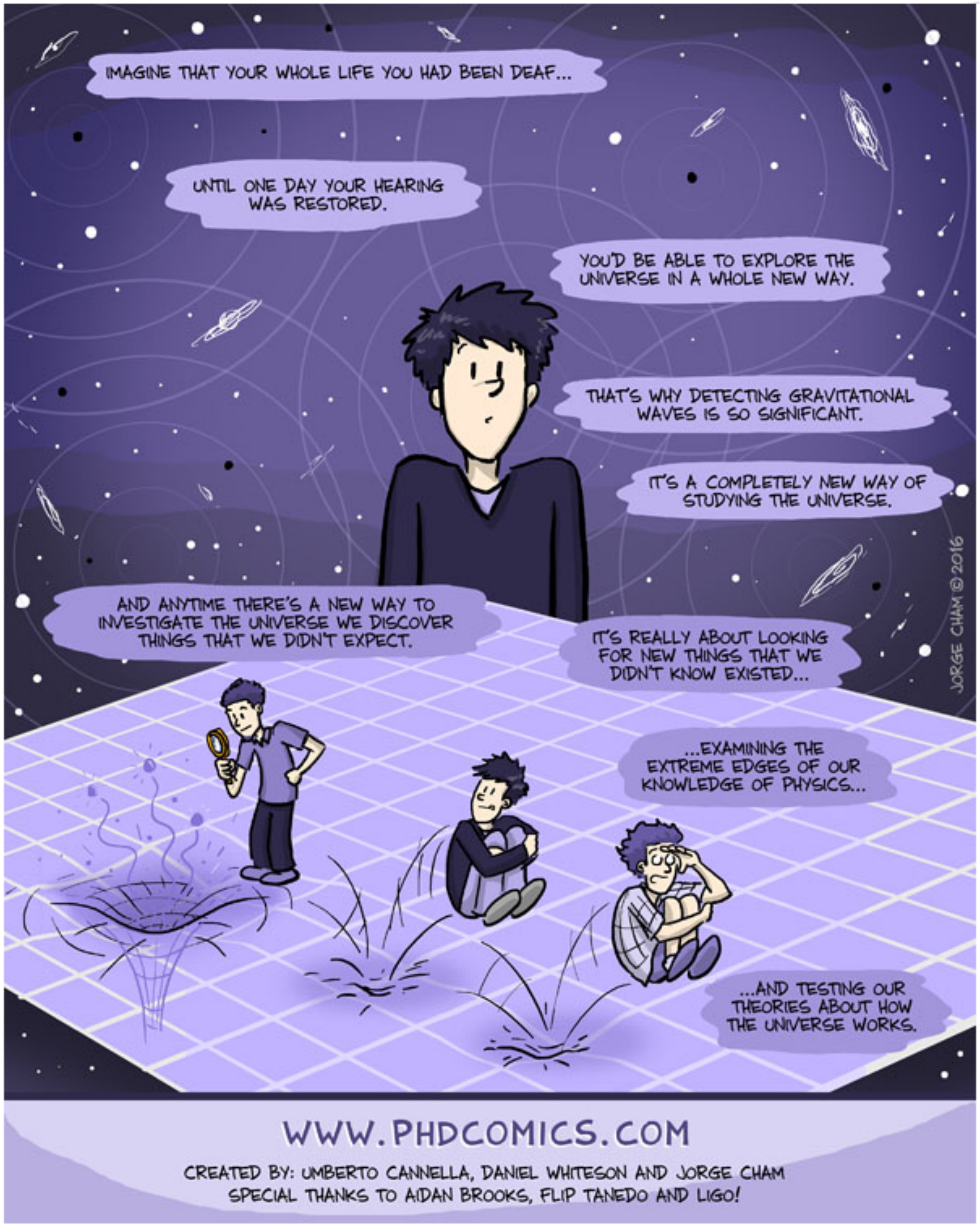
- LIGO-P1500217: The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
- LIGO-P1500262: Astrophysical Implications of the Binary Black-Hole Merger GW150914
- LIGO-P1500213: Tests of general relativity with GW150914
- LIGO-P1500222: GW150914: Implications for the stochastic gravitational-wave background from binary black holes
- LIGO-P1500248: Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
- LIGO-P1500238: Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
- LIGO-P1500227: Localization and broadband follow-up of the gravitational-wave transient GW150914
- LIGO-P1500271: High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
- LIGO-P1500237: GW150914: The Advanced LIGO Detectors in the Era of First Discoveries

If none of this was comprehensible… see http://phdcomics.com/comics.php?f=1853 (over 1 million page views!)






IMAGINE THAT YOUR WHOLE LIFE YOU HAD BEEN DEAF...
UNTIL ONE DAY YOUR HEARING WAS RESTORED.
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IT'S A COMPLETELY NEW WAY OF STUDYING THE UNIVERSE.
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IT'S REALLY ABOUT LOOKING FOR NEW THINGS THAT WE DIDN'T KNOW EXISTED...
...EXAMINING THE EXTREME EDGES OF OUR KNOWLEDGE OF PHYSICS...
...AND TESTING OUR THEORIES ABOUT HOW THE UNIVERSE WORKS.
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SPECIAL THANKS TO AIDAN BROOKS, FLIP TANEDO AND LIGO!

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Gravitational Wave Detection is HARD!

PRECISION Gravitational Wave science is HARDER!

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The advanced GW detector era has begun!

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- **unique tests of General Relativity in the strong-field, highly non-linear and dynamical regime;**
- **joint observations and discoveries with EM and neutrino telescopes;**
- **and a rich new branch of astrophysics.**

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