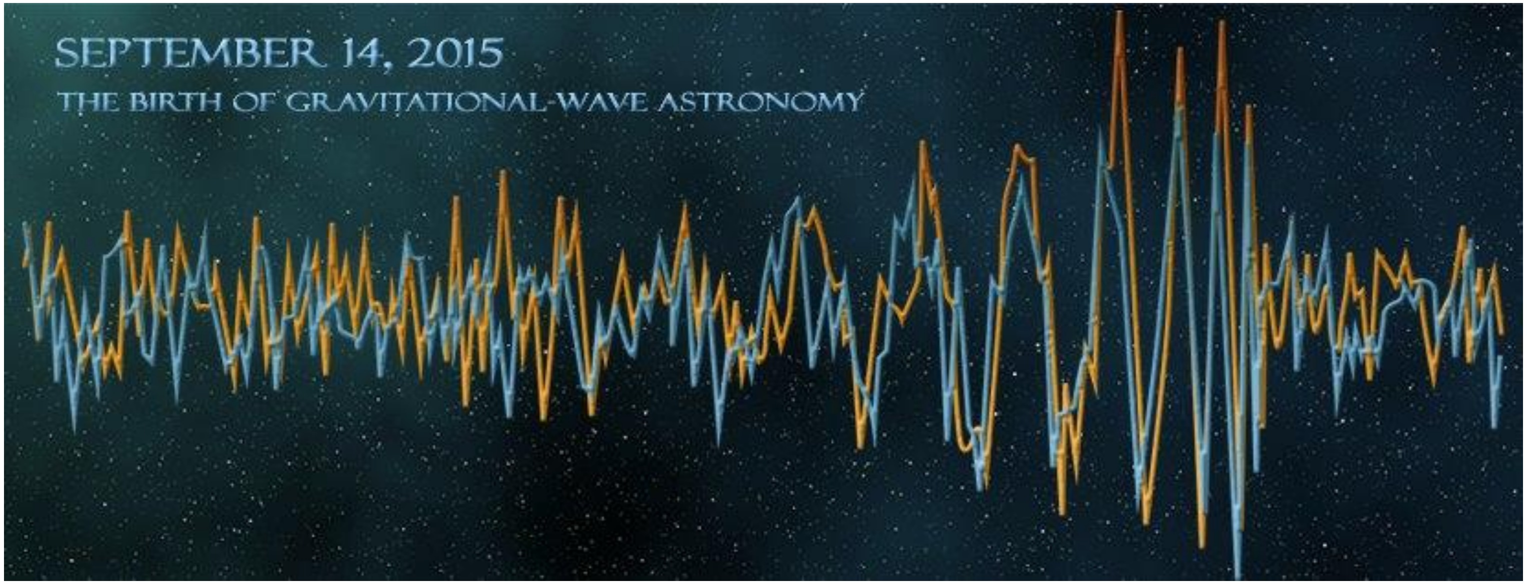
Searching for – and finding! gravitational waves

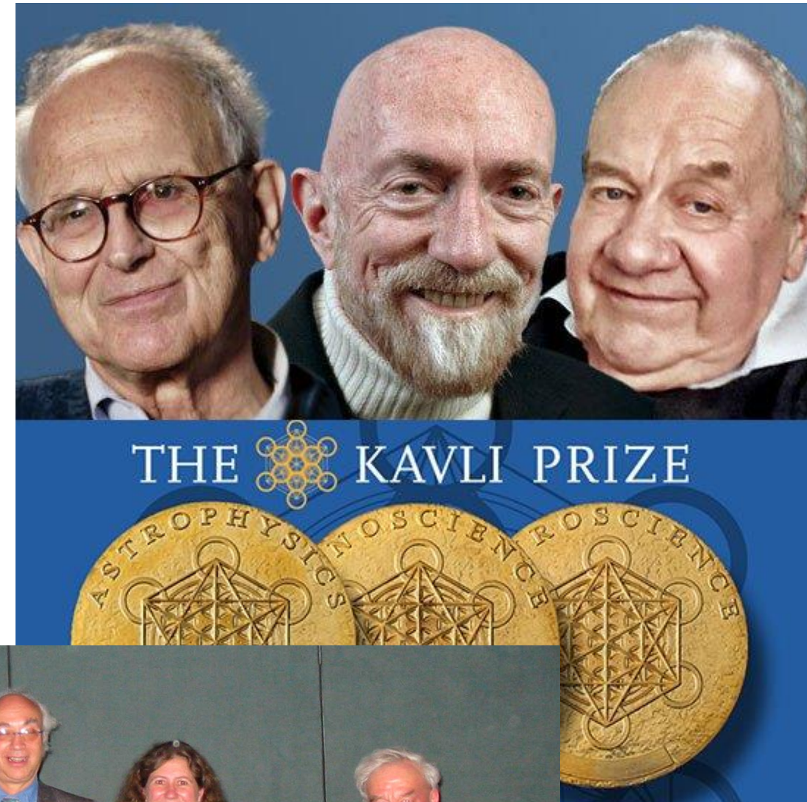
Gabriela González

Louisiana State University

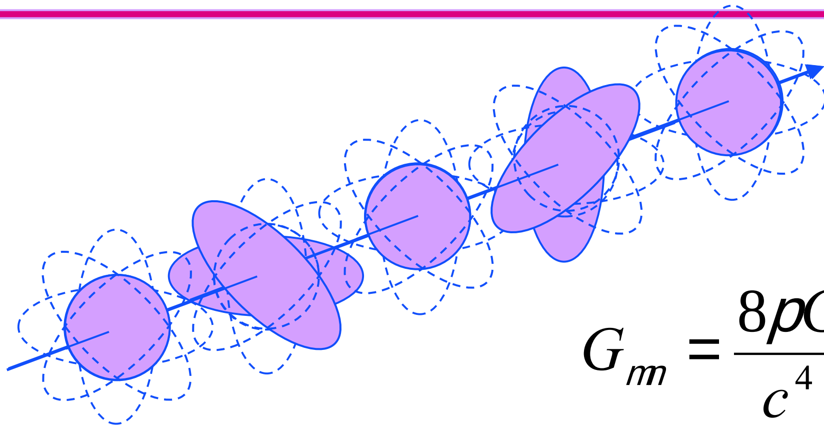
For the LIGO Scientific Collaboration and
the Virgo Collaboration



In memoriam
Ron Drever,1931-2017



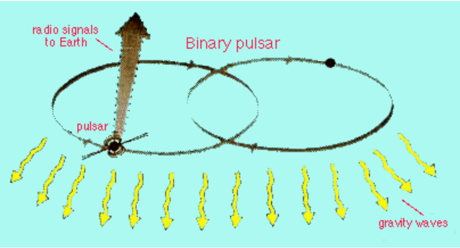
Gravitational waves



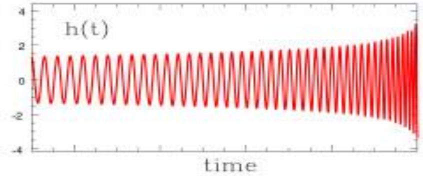
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

$$G_{m} = \frac{8pG}{c^4} T_{m} (= 0 \text{ in vacuum})$$

$$h_{\mu\nu} \sim \frac{2G}{c^4 r} \ddot{I}_{\mu\nu} \qquad g_{m} = h_{m} + h_{m} \qquad h = 2\frac{\Delta L}{L}$$

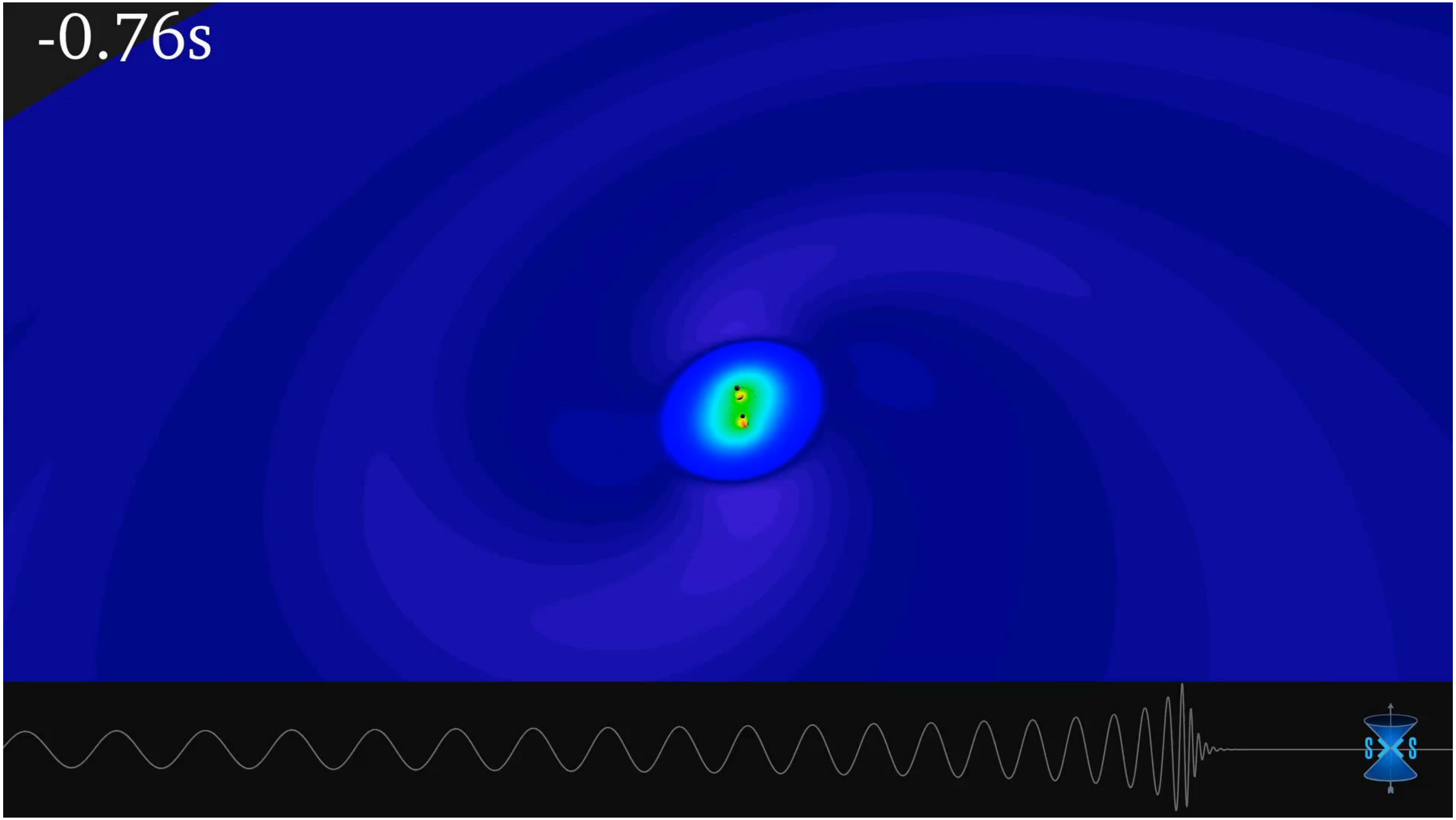


$$h_{\mu\nu} \sim \frac{R_1 R_2}{D r}$$



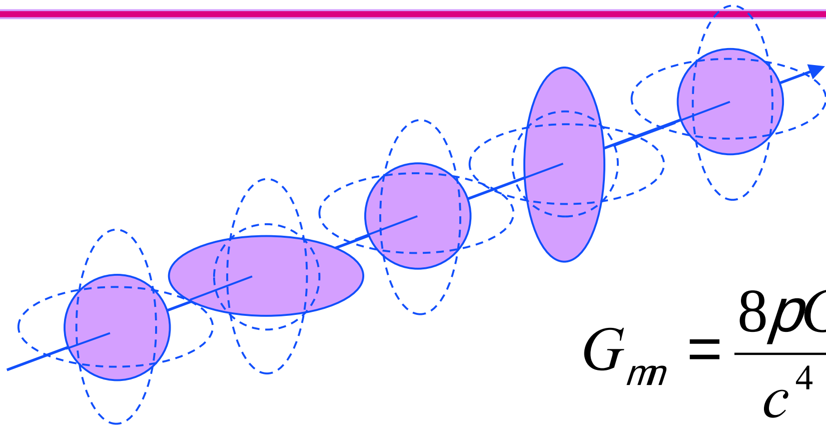
GWs from a NS-NS coalescence in the Virgo cluster has $h \sim 10^{-21}$ near Earth, and happens ~once every 50 years.

A solution to Einstein's equations



Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

Gravitational waves



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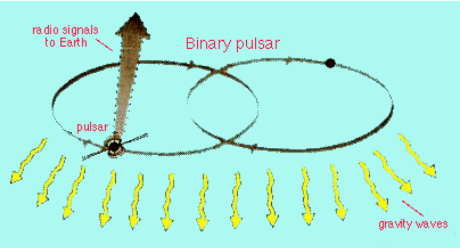
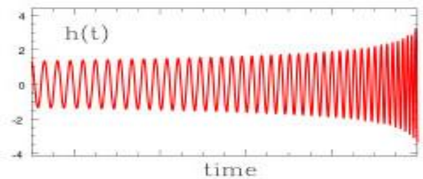
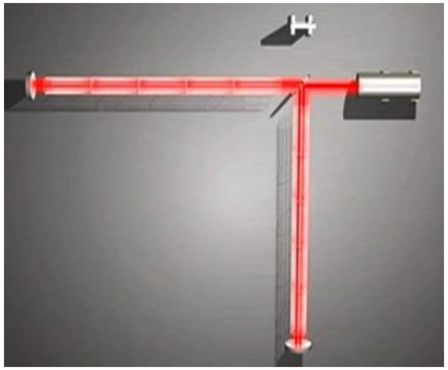


$$h_{\mu\nu} \sim \frac{R_1 R_2}{D r}$$

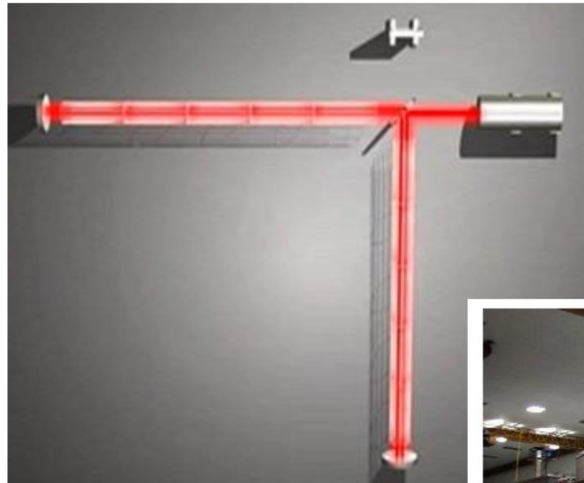


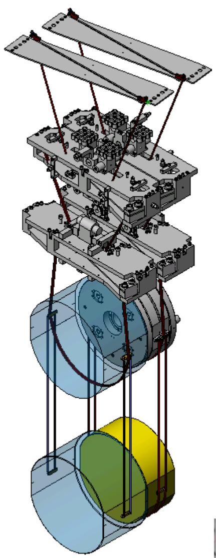


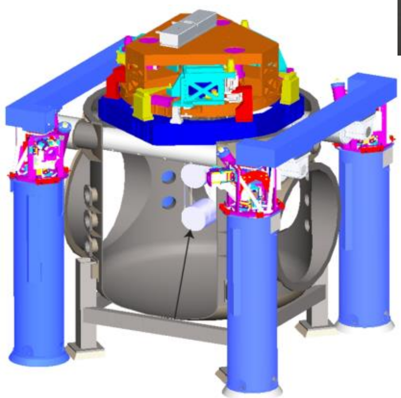
GWs from a NS-NS coalescence in the Virgo cluster has $h \sim 10^{-21}$ near Earth, and happens ~once every 50 years.

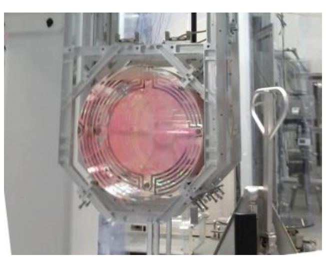
LIGO Detectors

Advanced LIGO detectors

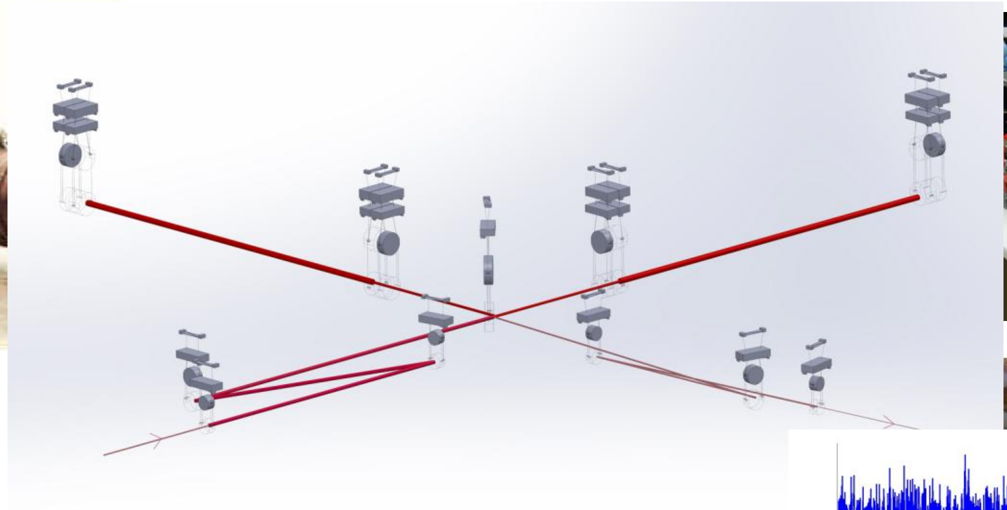


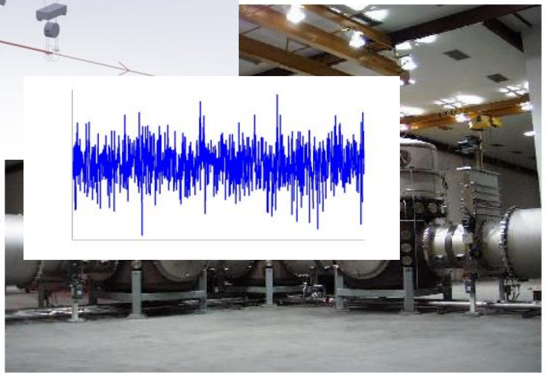


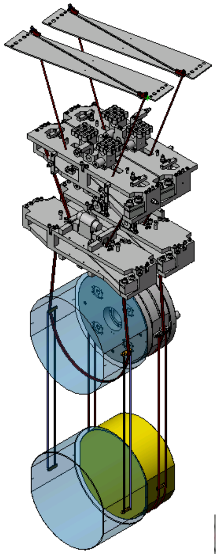


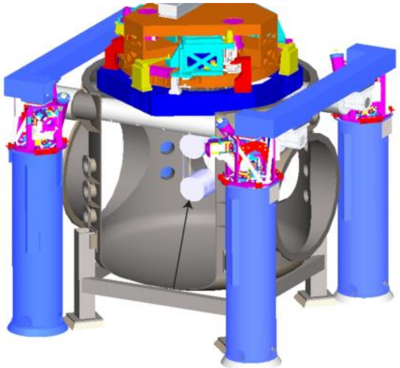


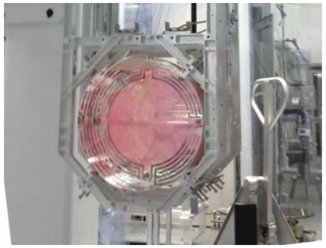
Advanced LIGO detectors



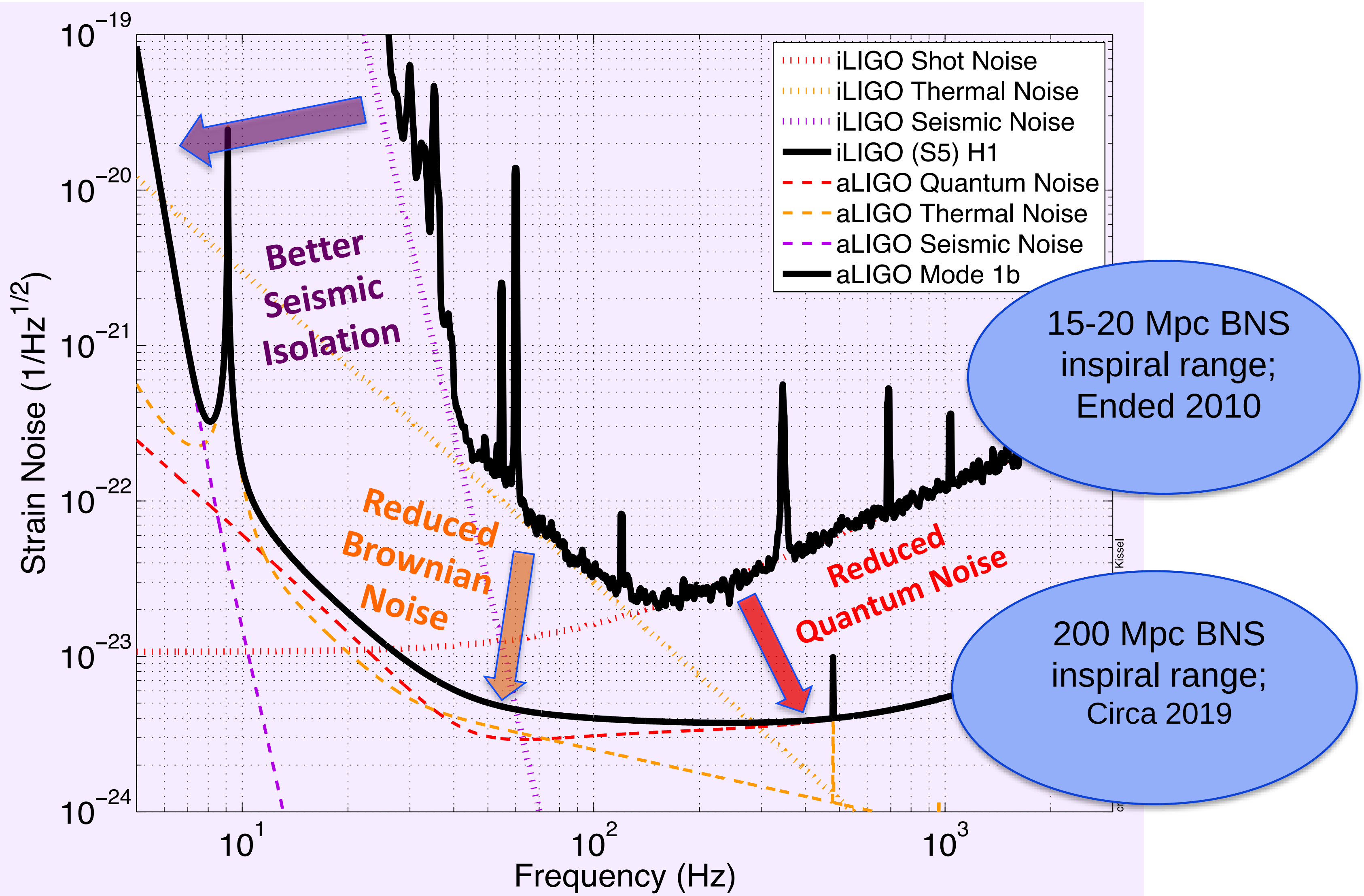




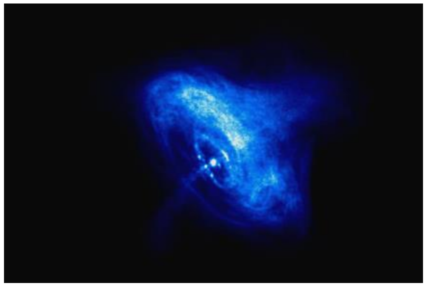




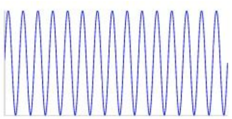
Initial (2001-2010) and advanced (2015+) LIGO



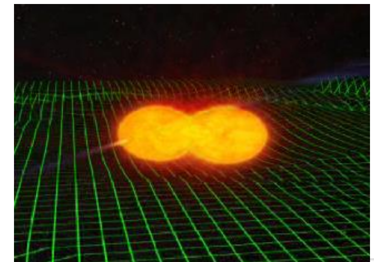
Searching for gravitational waves

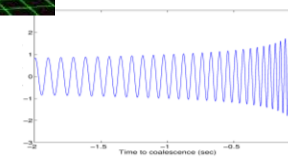


Crab pulsar (NASA, Chandra Observatory)



Periodic, continuous waves

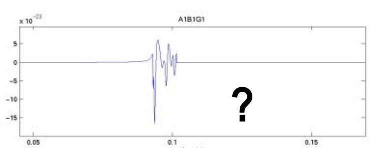




Credit: John Rowe

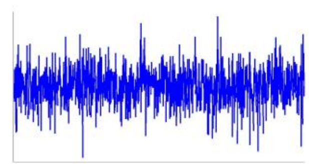
Binary systems with neutron stars and/or black holes

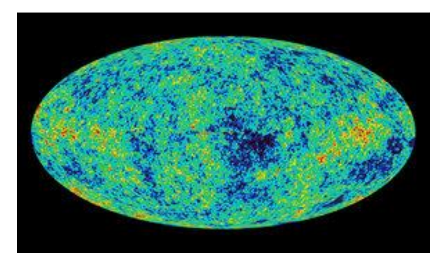
Short transients from supernova explosions or other sources



W49B composite;
X-ray: NASA/CXC/MIT/L.Lopez et al.;
Infrared: Palomar; Radio: NSF/NRAO/VLA

Stochastic background from many unresolved sources, or from the beginning of the Universe





NASA, WMAP

LIGO Scientific Collaboration

Formed in 1997
1000+ members,
15 countries
www.ligo.org

Since 2007, taking and jointly analyzing data with the Virgo Collaboration

In 2013, we guessed Advanced LIGO (and Virgo) progress

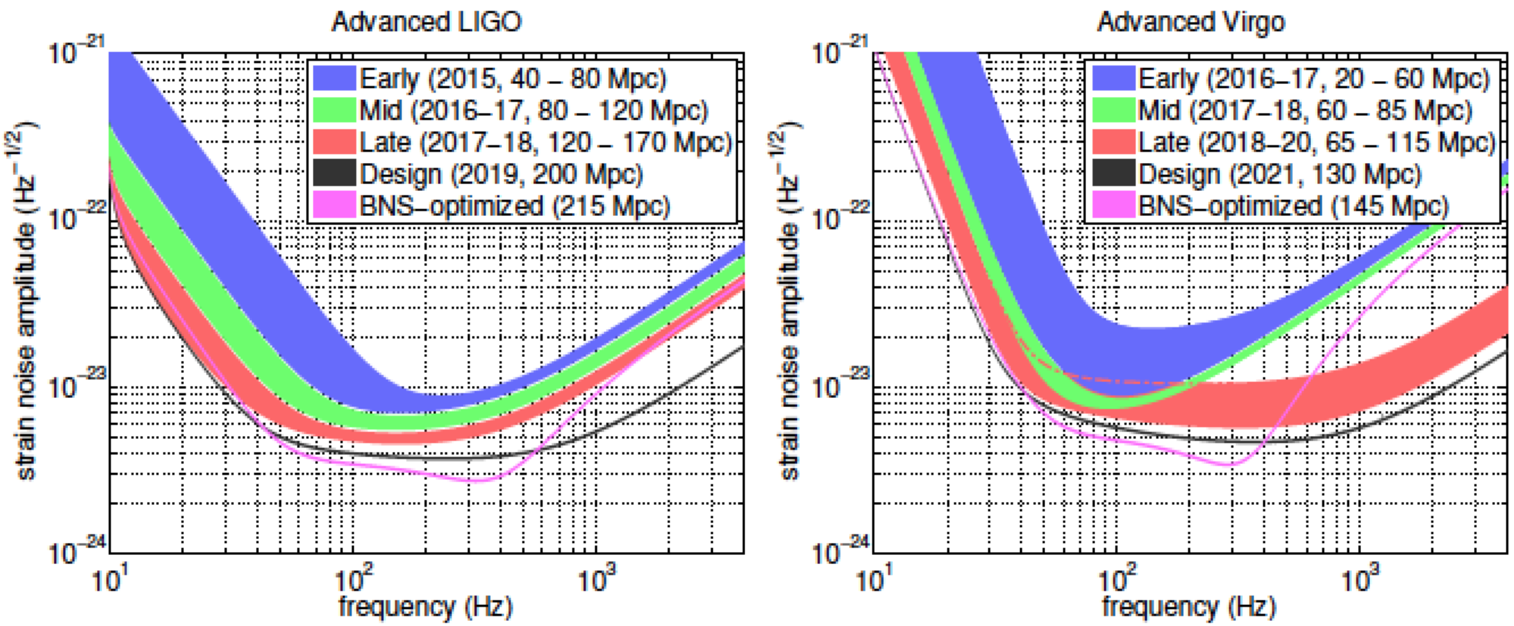
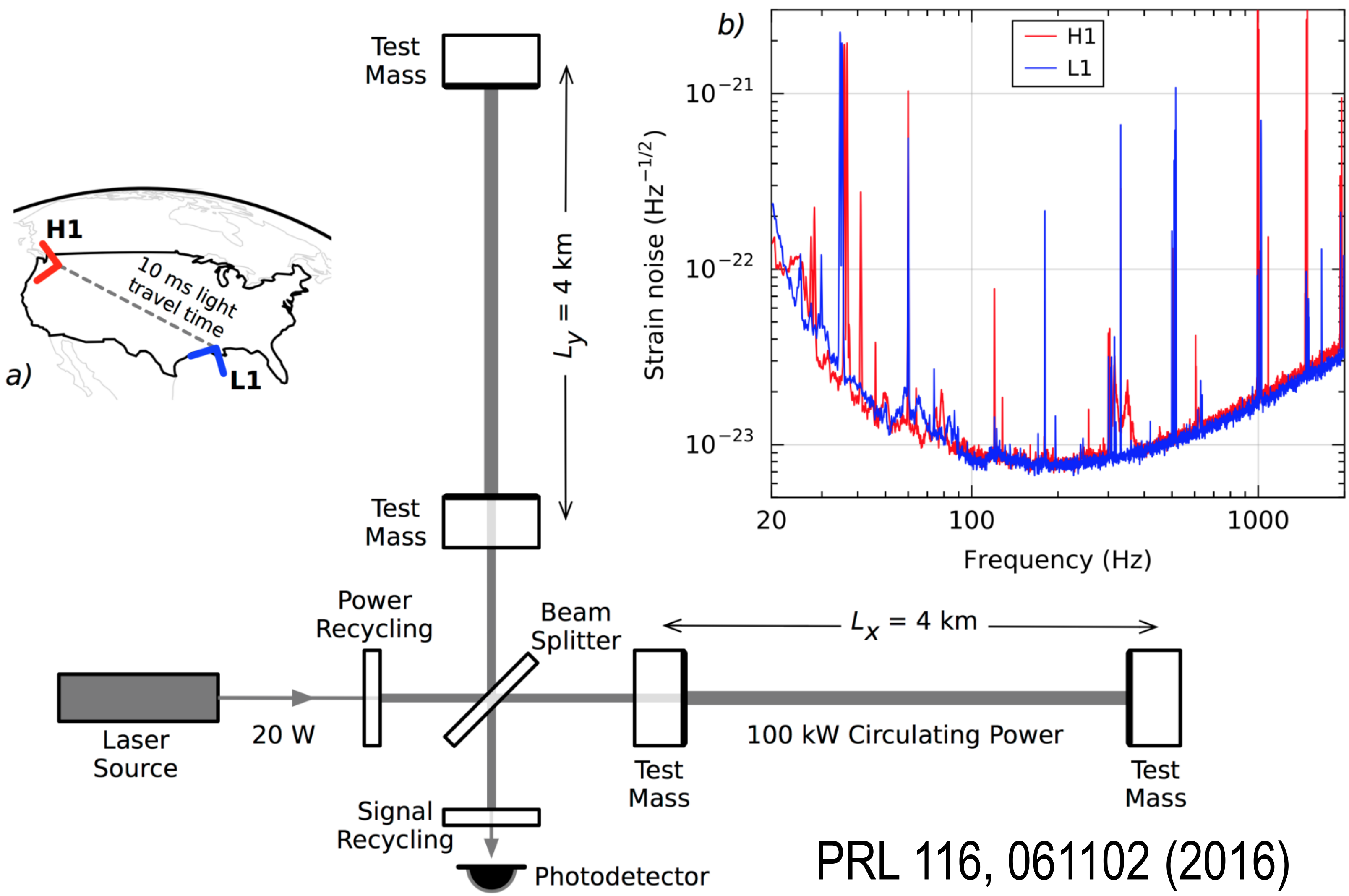


Figure 1: aLIGO (left) and AdV (right) target strain sensitivity as a function of frequency. The average distance to which binary neutron star (BNS) signals could be seen is given in Mpc. Current notions of the progression of sensitivity are given for early, middle, and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

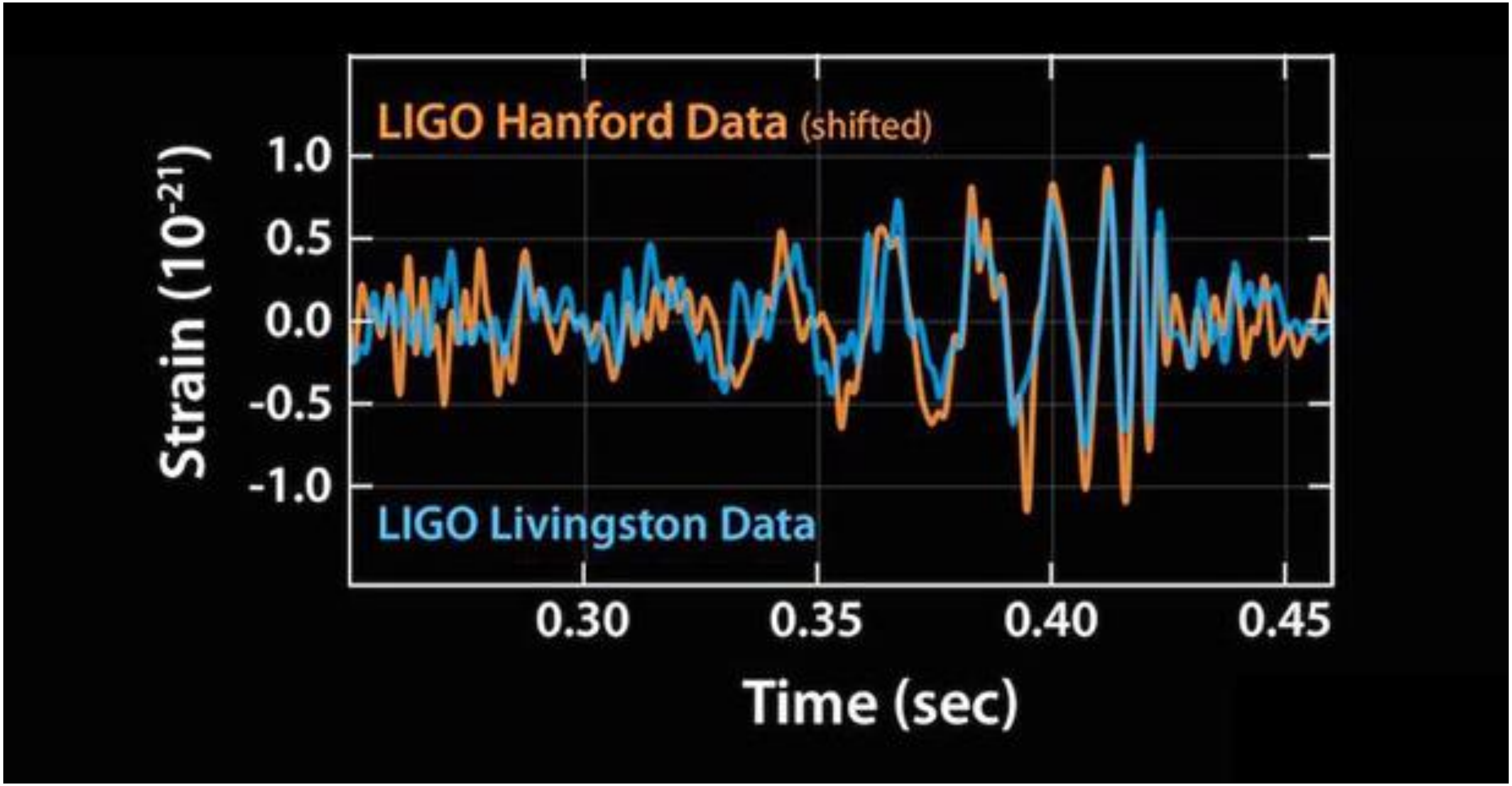
arXiv:1304.0670v1

Advanced LIGO detectors September 2015



PRL 116, 061102 (2016)

On Sept 14 2015…



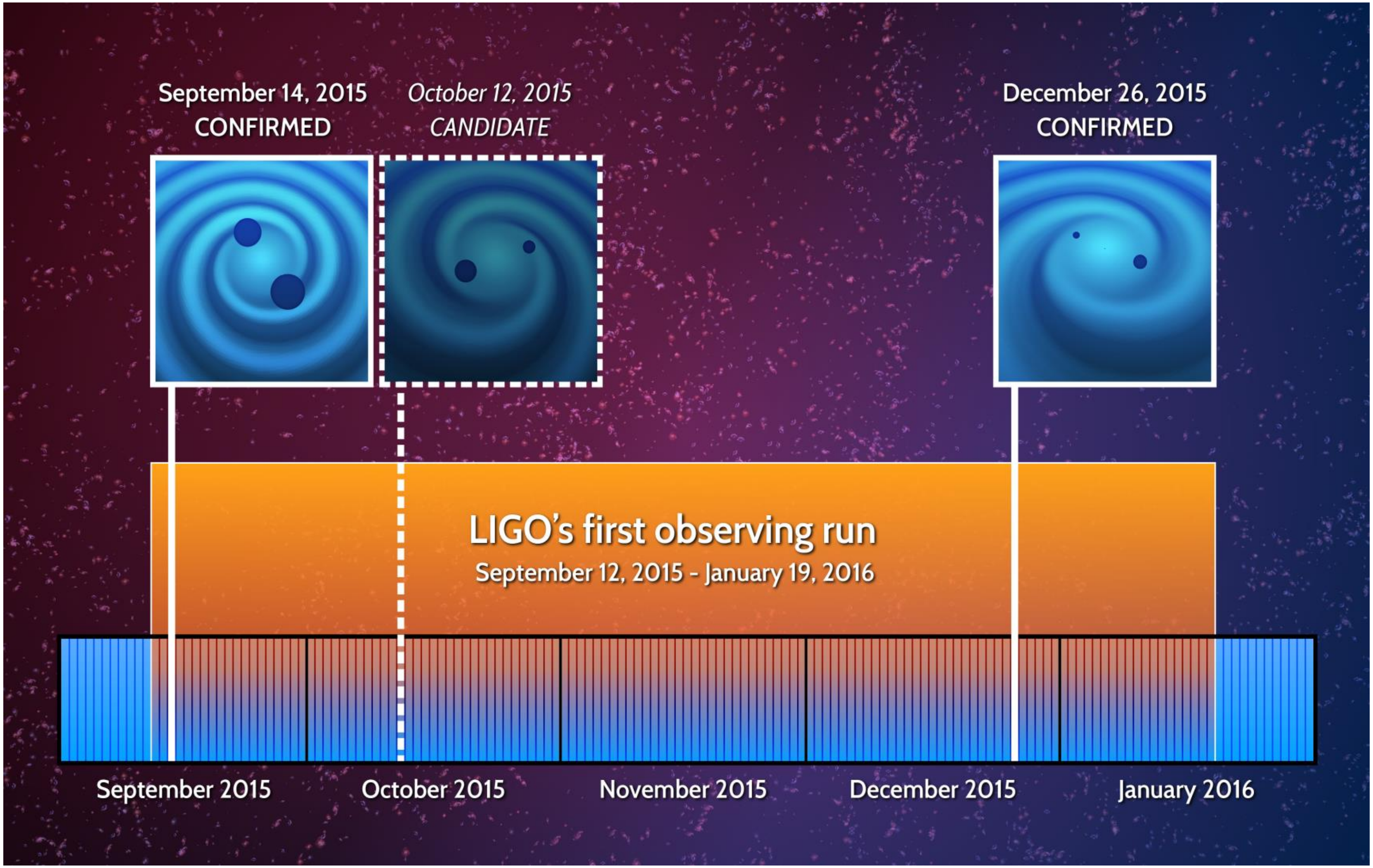


Image credit: LIGO

Filling in the black hole catalog

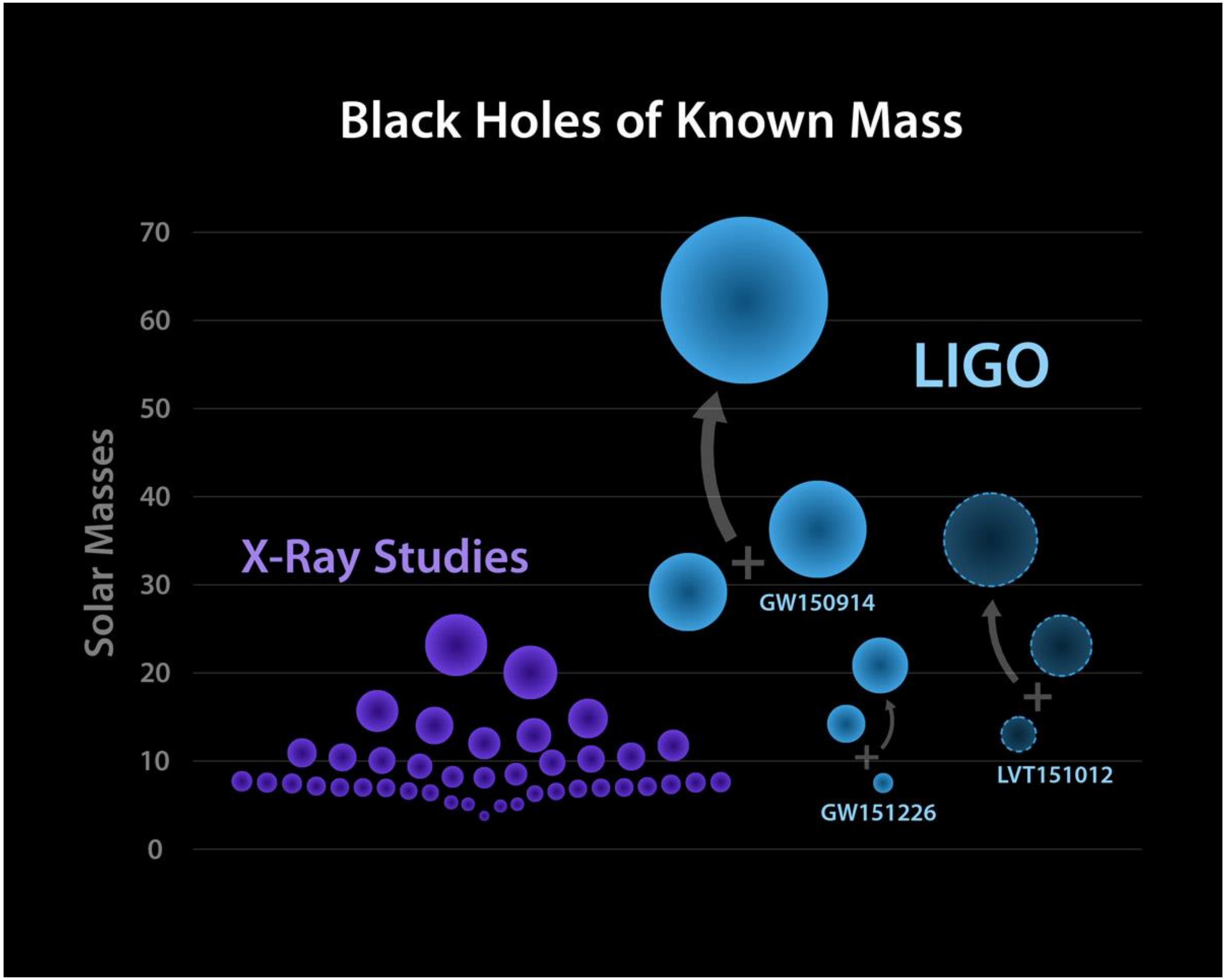
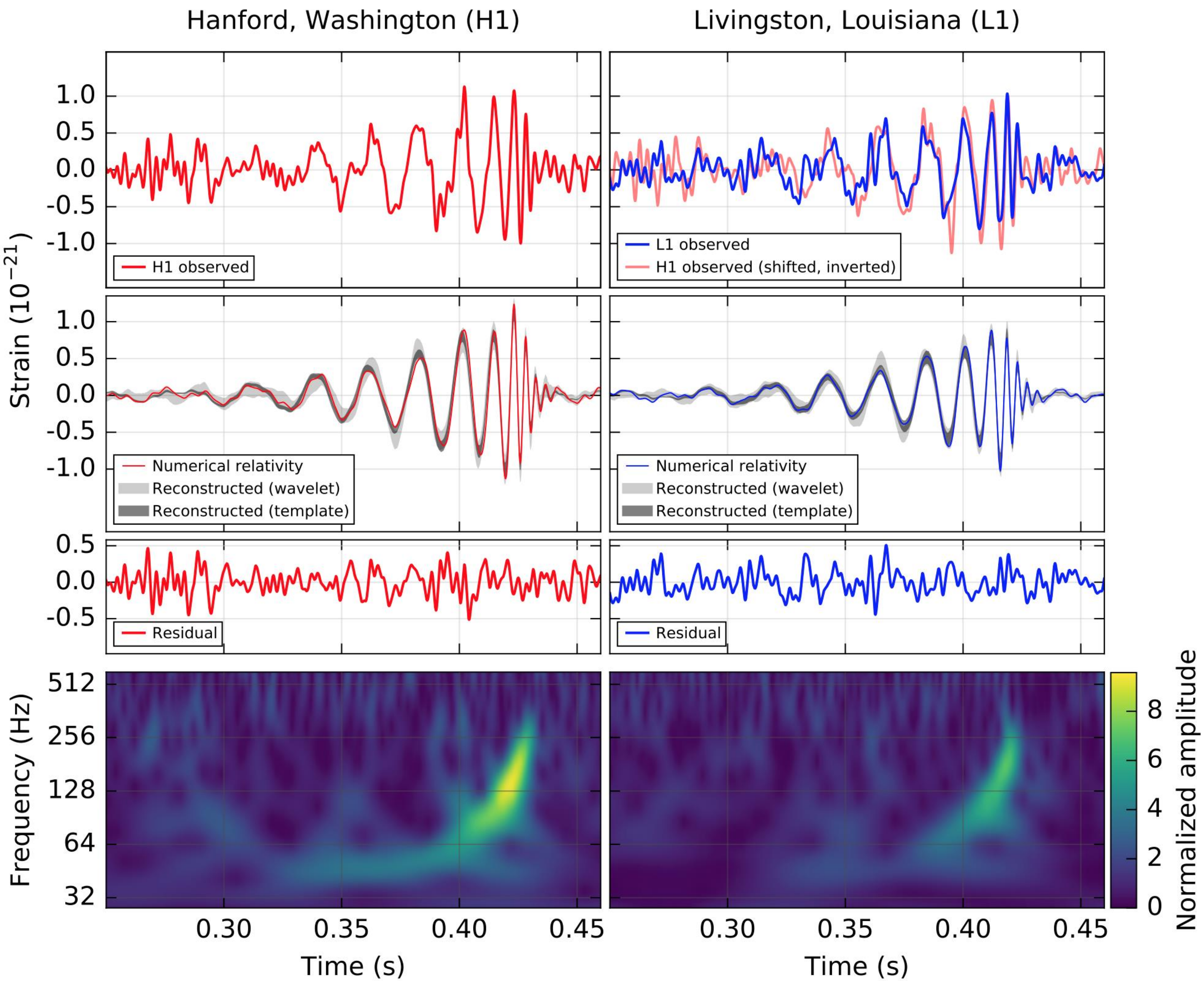
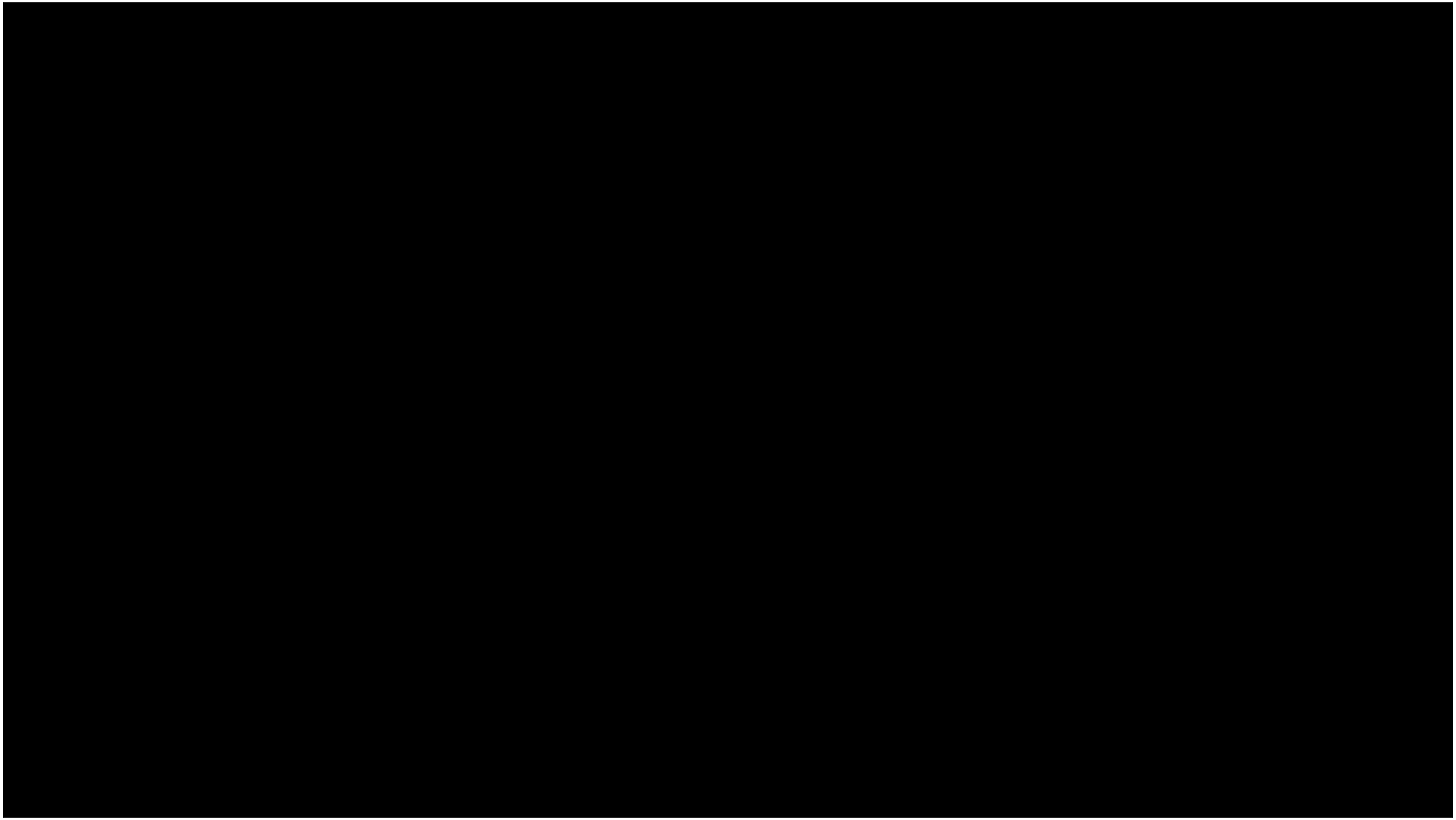


Image credit: LIGO

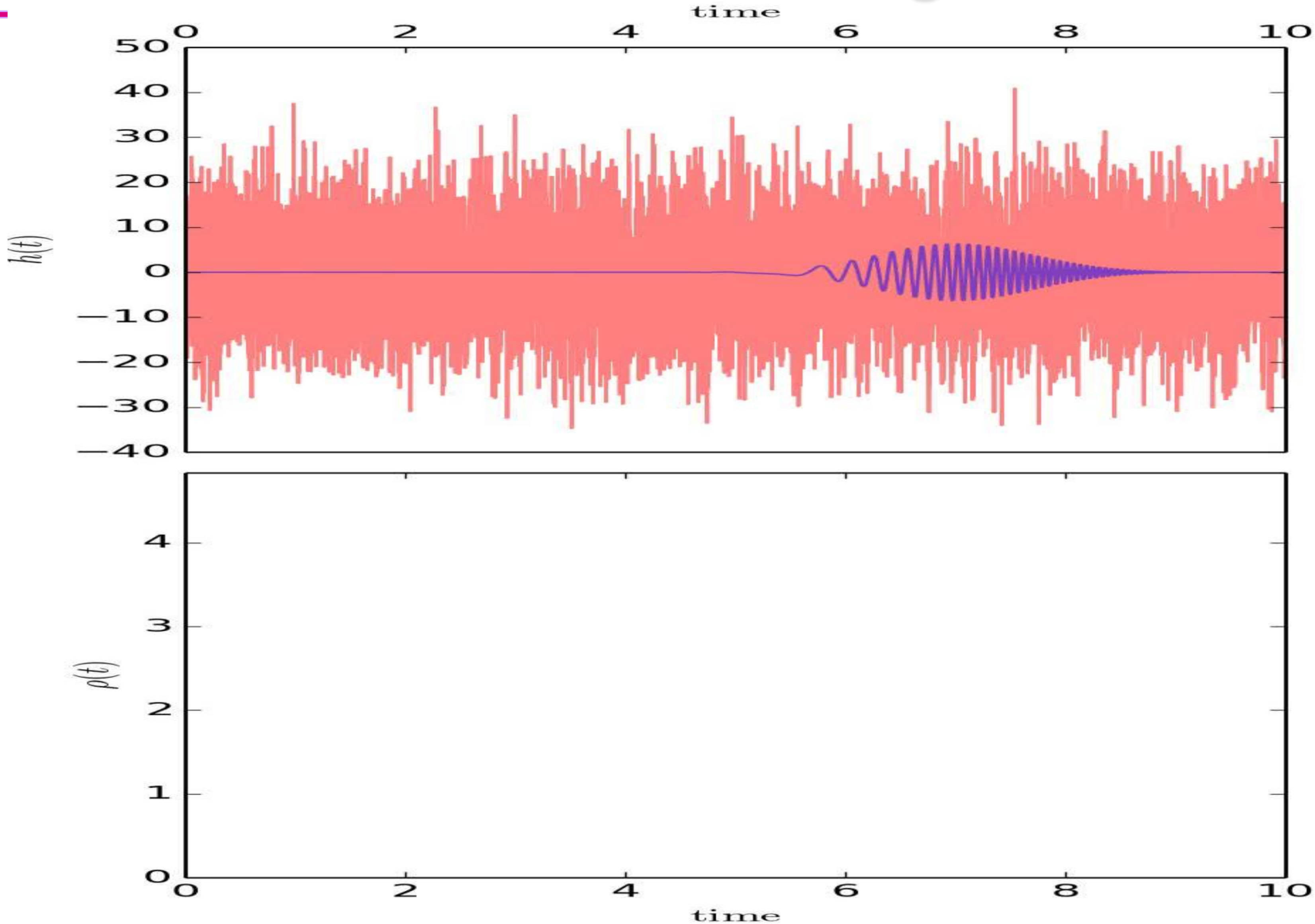
PRL 116, 061102 (2016)



Gravity’s music

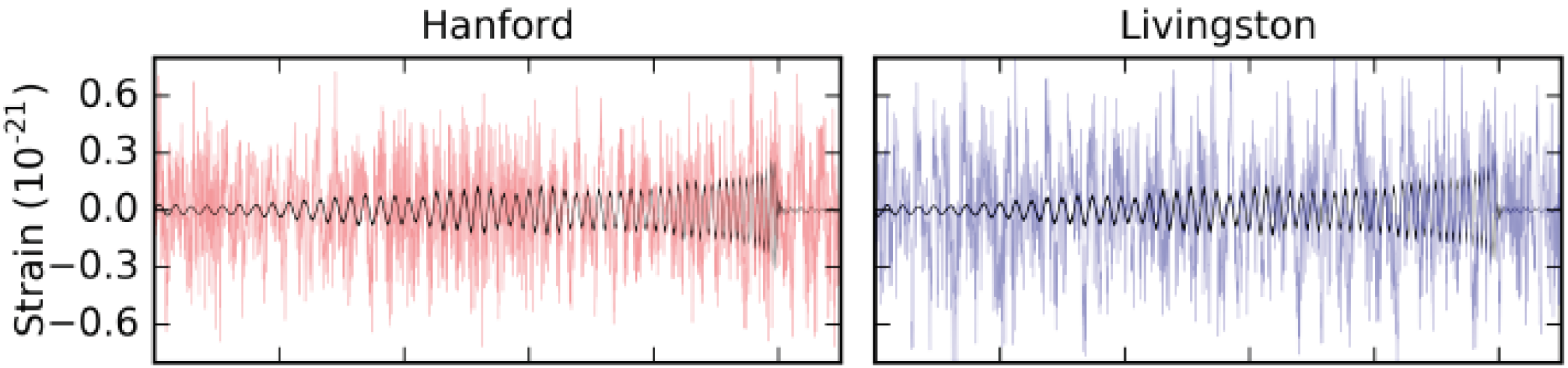


Searching for a specific waveform: matched filtering

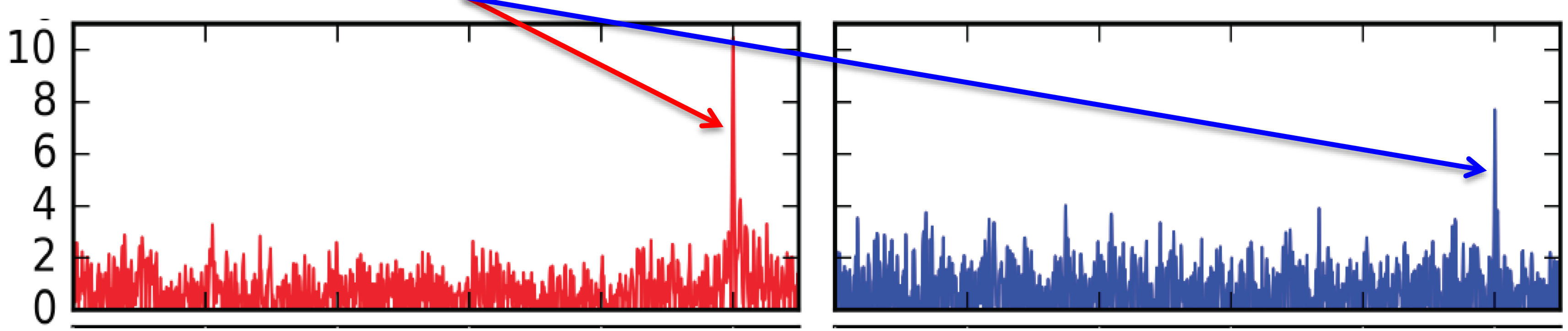


GW151226

Filtered detector output and filtered best matching waveform



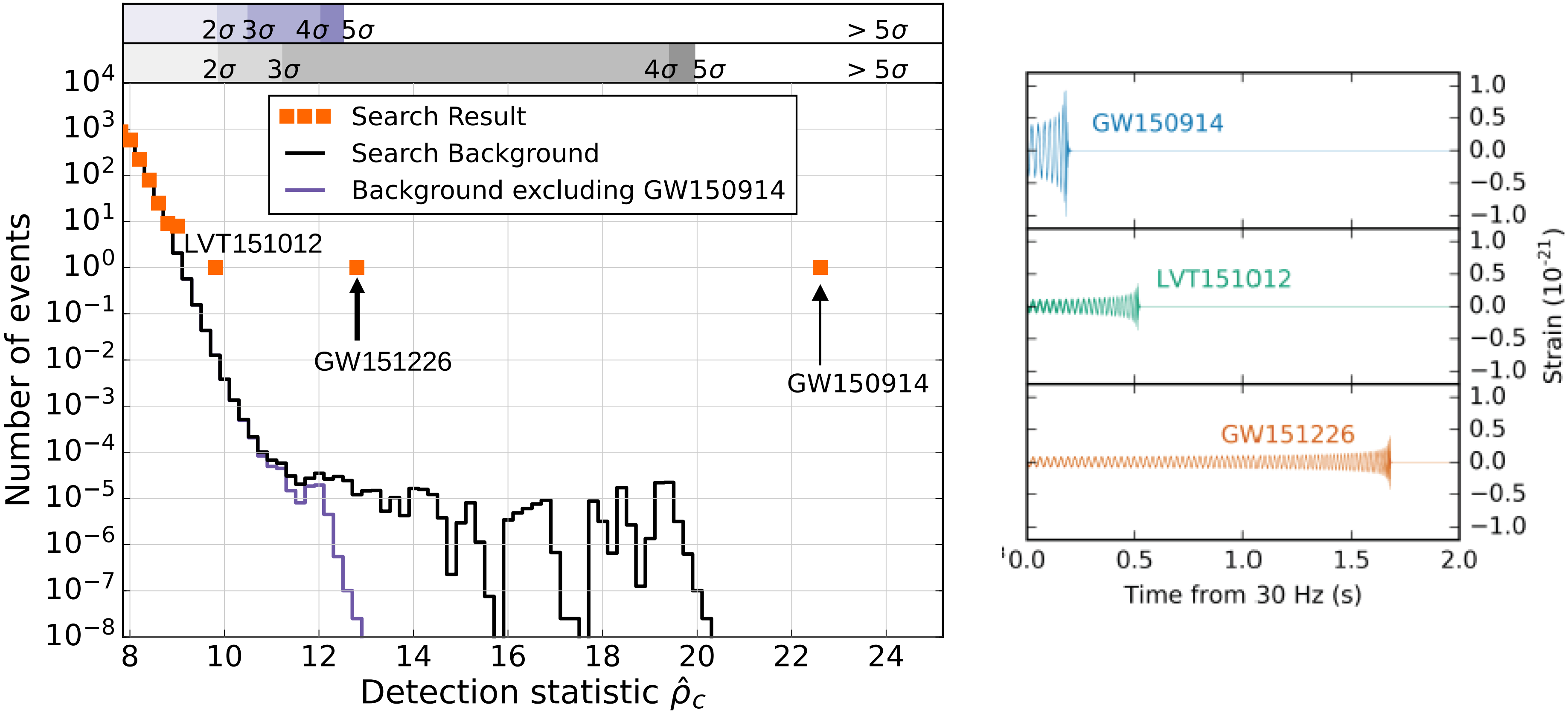
Signal-to-noise (SNR) when best template matches at coalescence time



Phys. Rev. Lett. **116**, 241103 (2016)

O1 BBH search

Search for binary black holes systems with black holes larger than 2 $M_{\odot}$ and total mass less than100 $M_{\odot}$, in O1 (Sep 12, 2015-Jan 19, 2016, ~48 days of coincident data)



arXiv:1606.04856v2, to appear in PRX

GW150914: also found as a "burst"

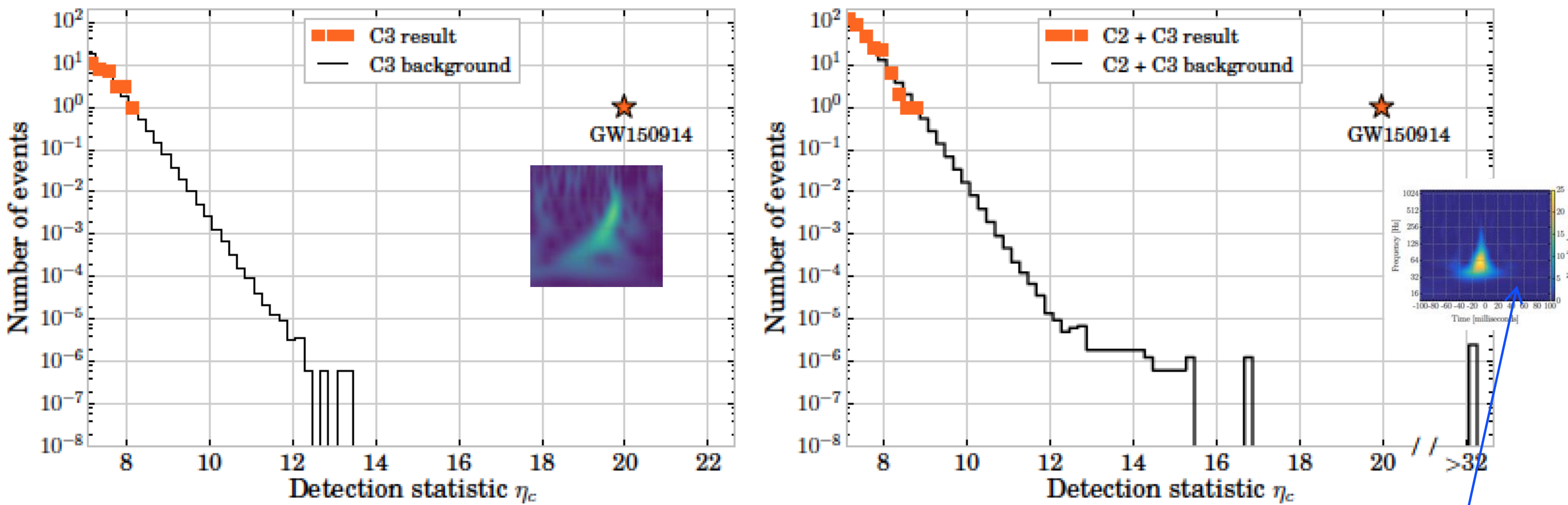


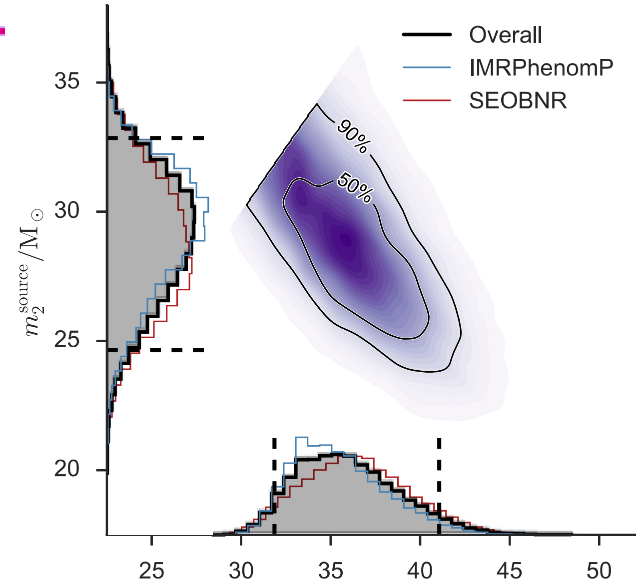
FIG. 2. Search results (in orange) and expected number of background events (black) in 16 day of the observation time as a function of the cWB detection statistic (bin size 0.2) for the $C3$ search class (left) and $C2 + C3$ search class (right). The black curve shows the total number of background events found in 67 400 years of data, rescaled to 16 days of observation time. The orange star represents GW150914, found in the $C3$ search class.

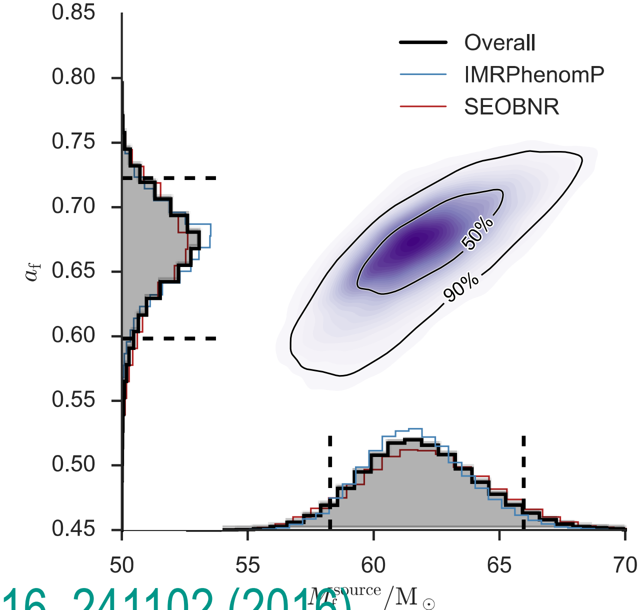
"blip glitch"

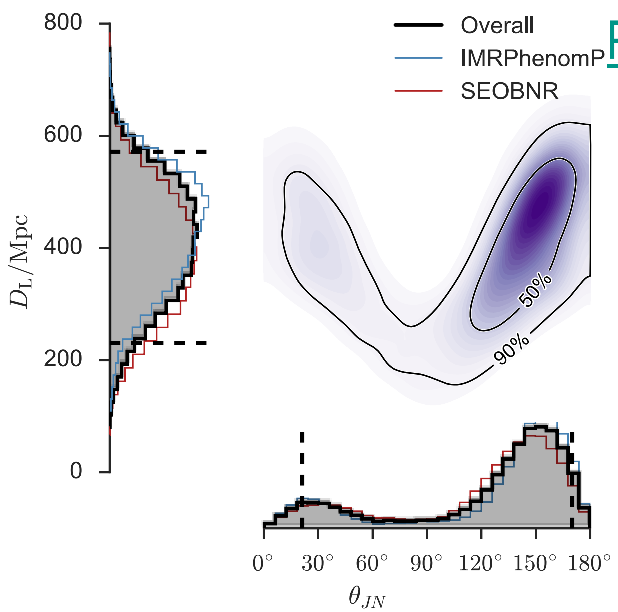
Classical and Quantum Gravity **33**, 134001 (2016)

Phys. Rev. D **93**, 122004 (2016)

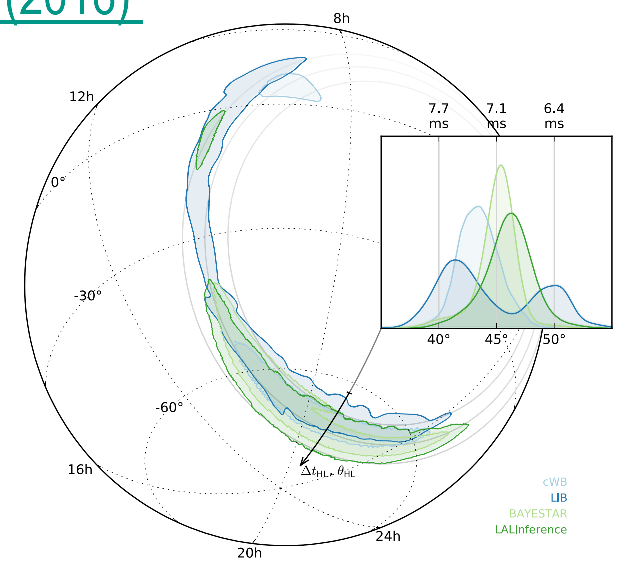
GW150914



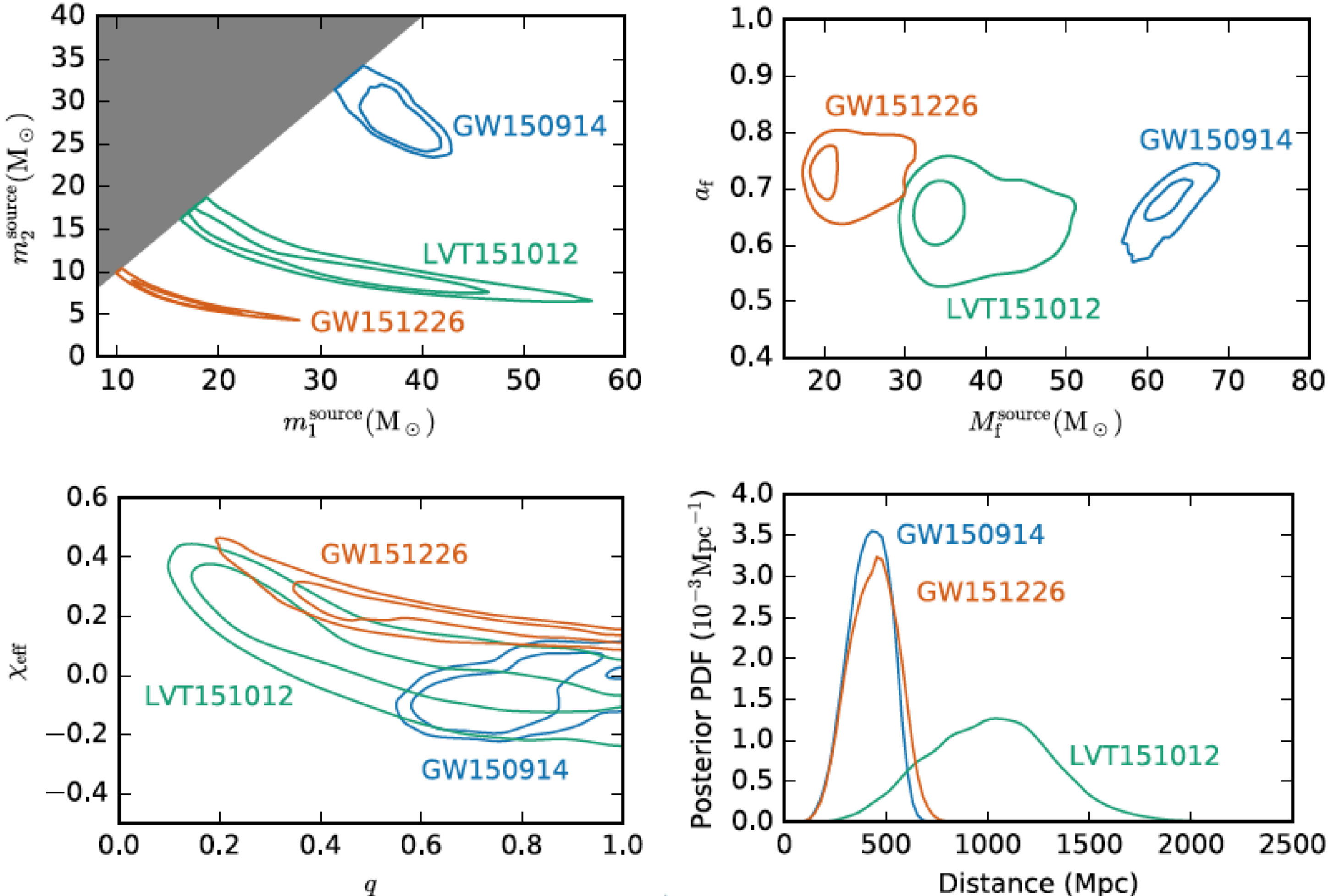




Phys. Rev. Lett. 116, 241102 (2016)



Parameters of the BBH systems

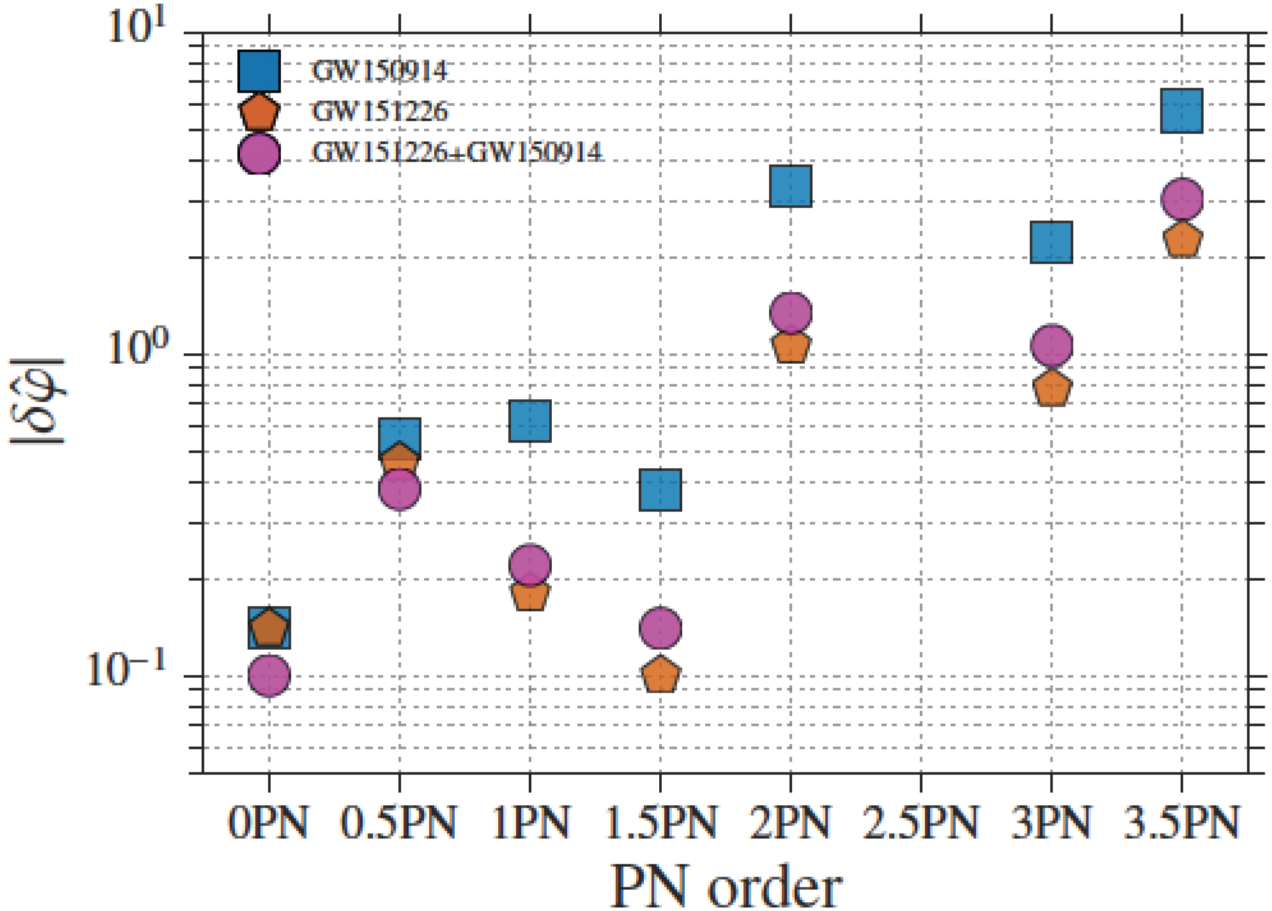


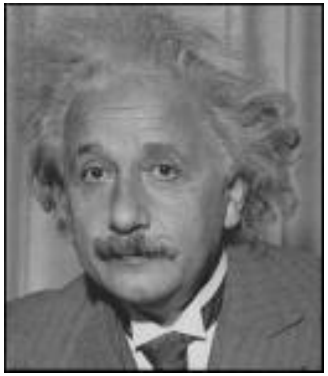
50% and 90% credible regions

[Phys. Rev. D 93, 122003 (2016)]

Testing General Relativity

Fractional deviation from GR





Phys. Rev. Lett. 116, 221101 (2016)

BNS/NSBH (null) O1 searches

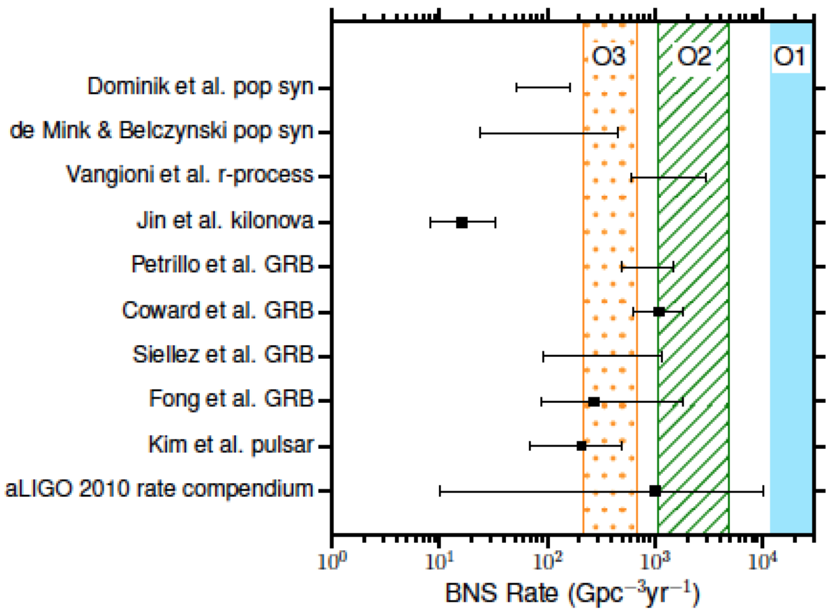


Figure 6. A comparison of the O1 90% upper limit on the BNS merger rate to other rates discussed in the text (Abadie

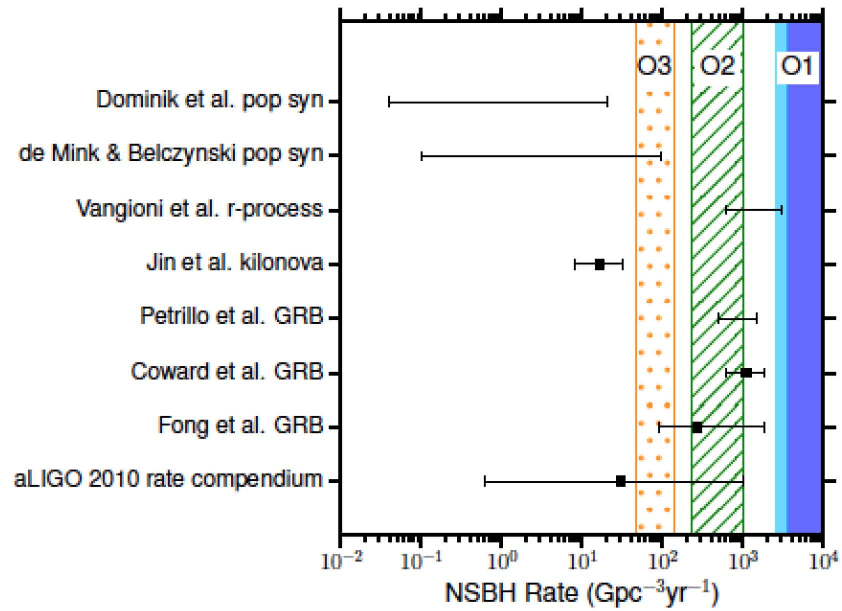


Figure 7. A comparison of the O1 90% upper limit on the NSBH merger rate to other rates discussed in the text (Abadie

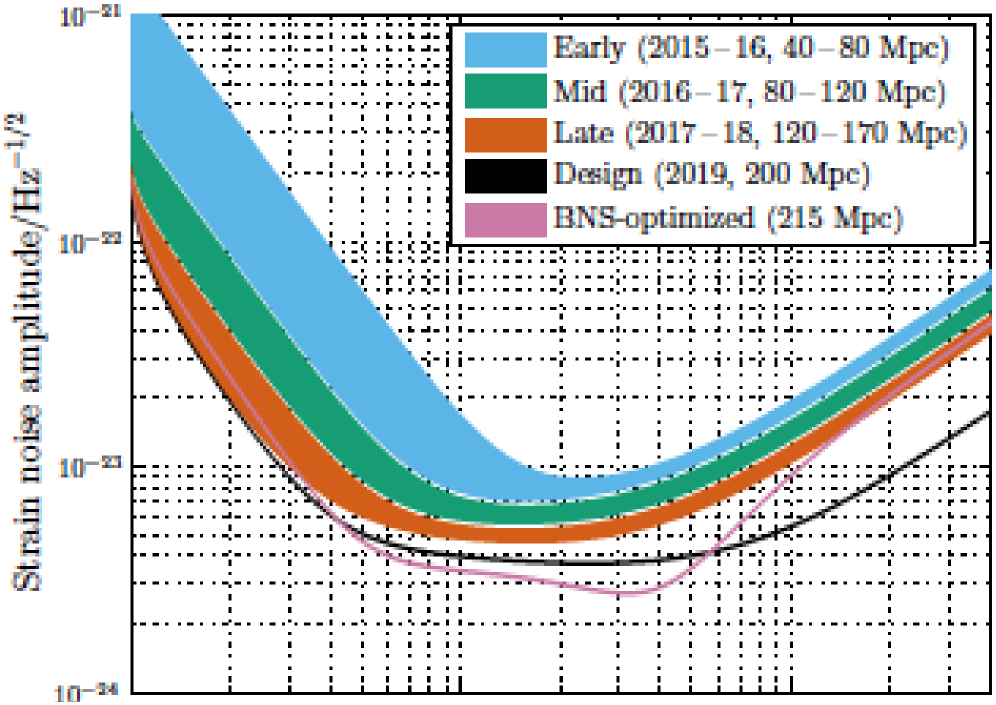
arXiv:1607.07456v1, accepted by ApJL

Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

LIVING REVIEWS *in relativity*

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
(The full author list and affiliations are given at the end of paper.)
email: lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it



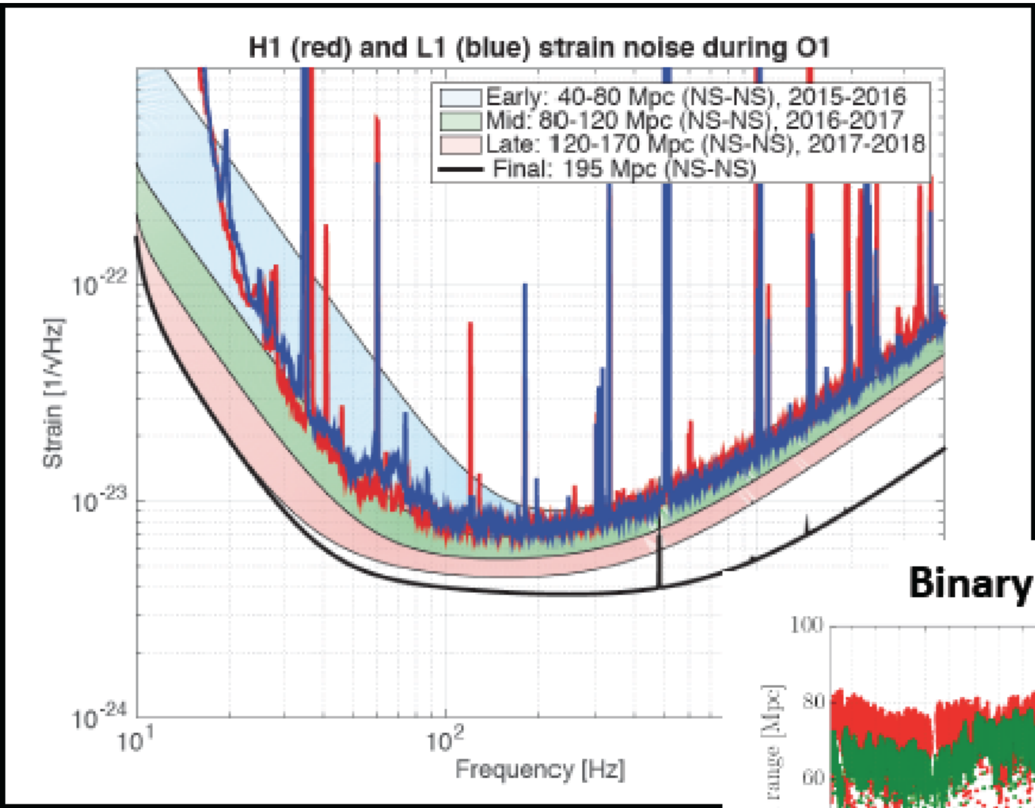
2015 – 2016 (O1) A four-month run (beginning 18 September 2015 and ending 12 January 2016) with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).

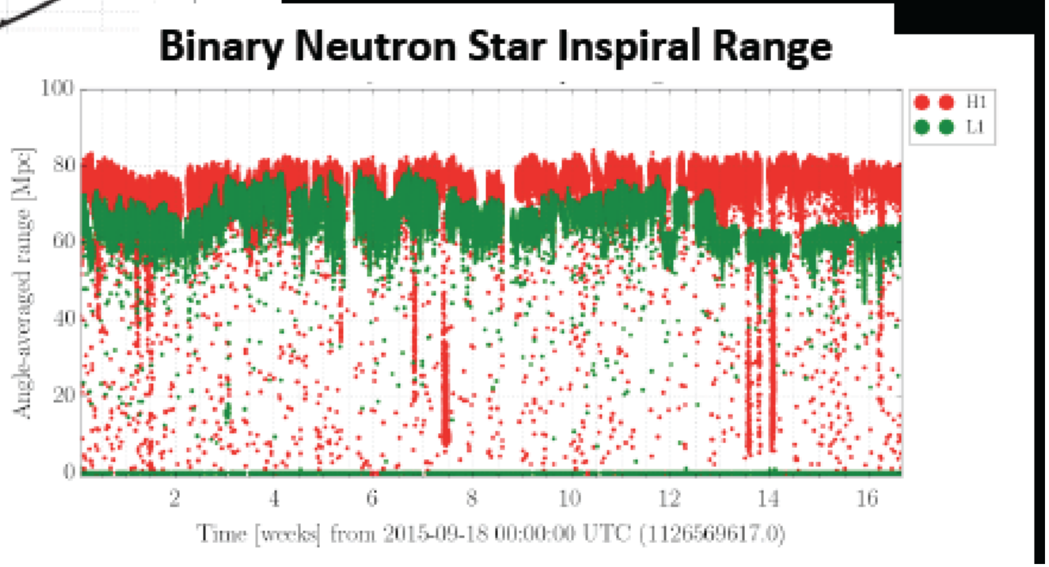
2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

2017 – 2018 (O3) A nine-month run with H1L1 at 120 – 170 Mpc and V1 at 60 – 85 Mpc.

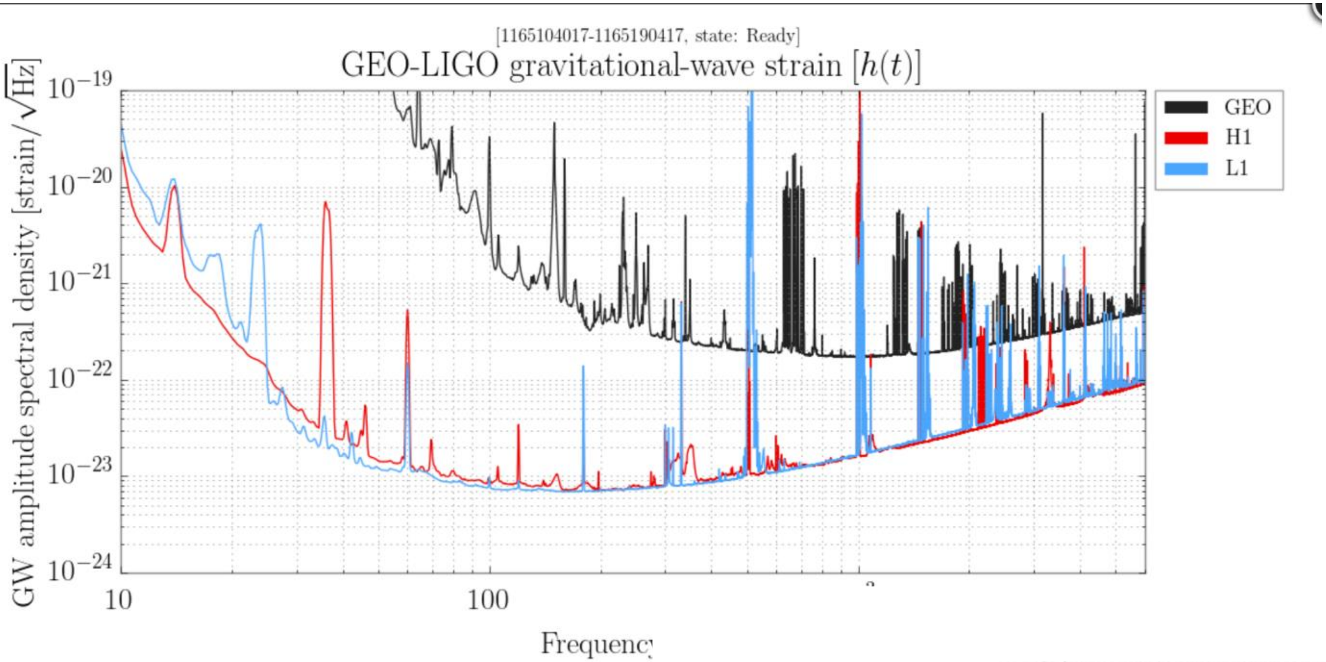
2019+ Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.

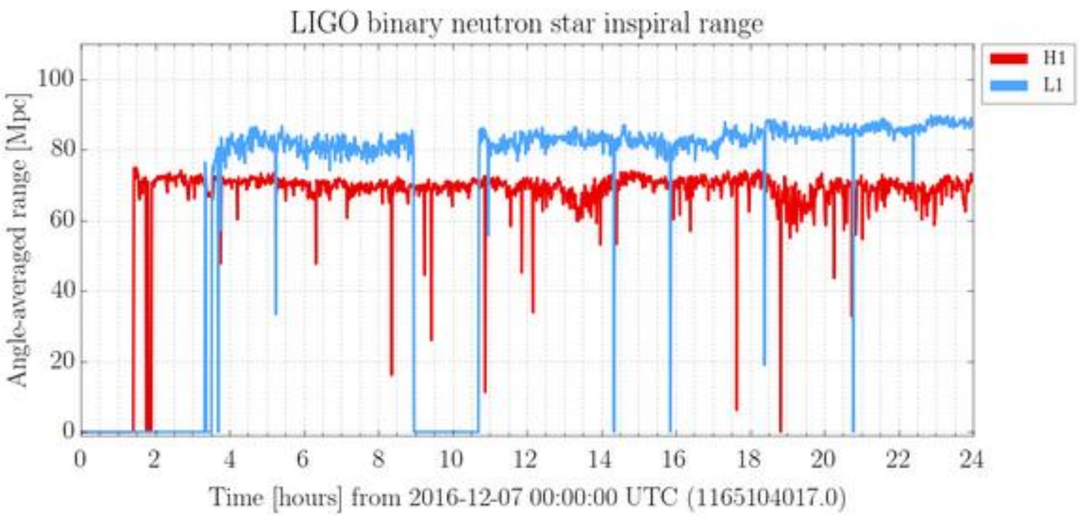
Advanced LIGO detectors in O1





O2 in progress!





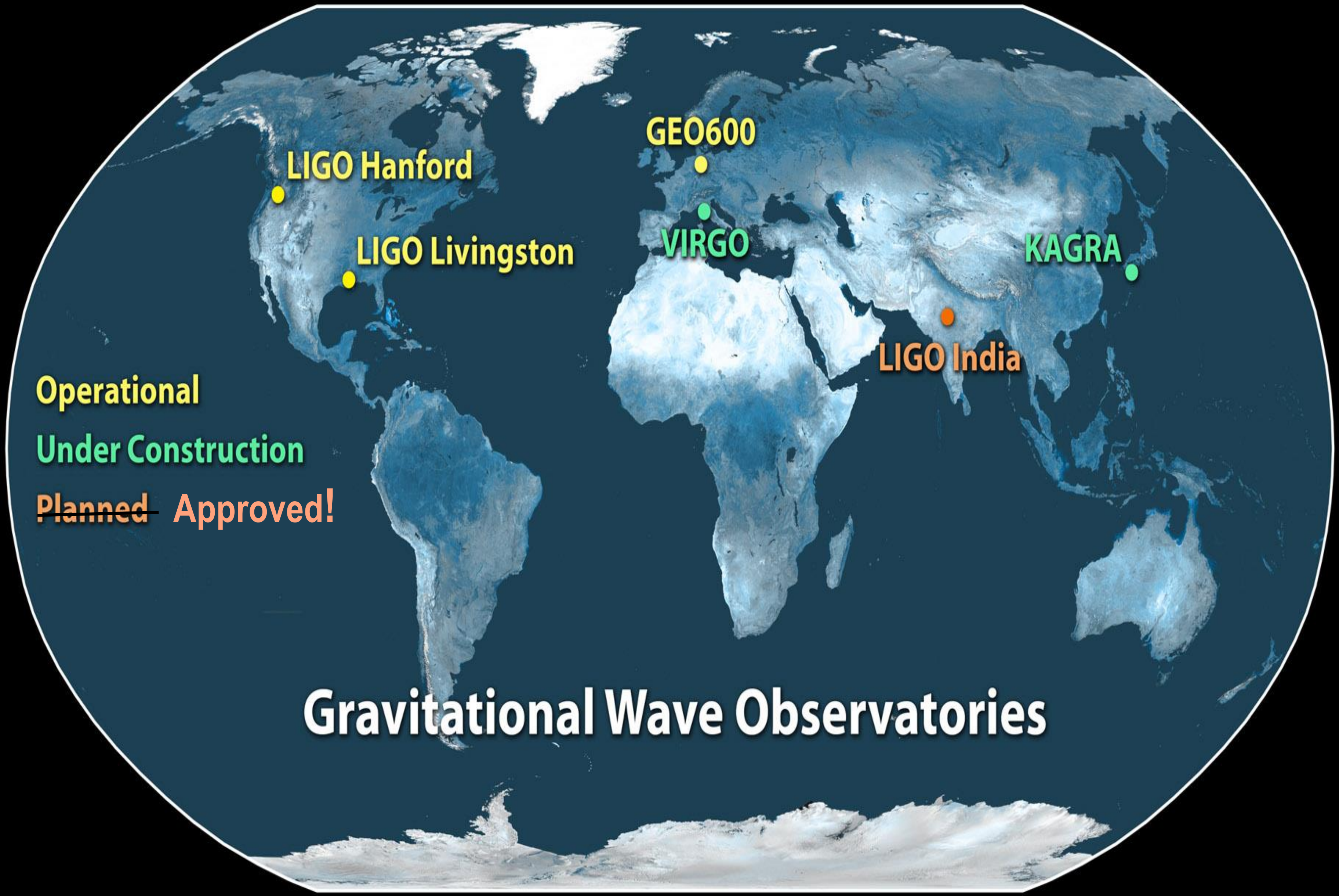
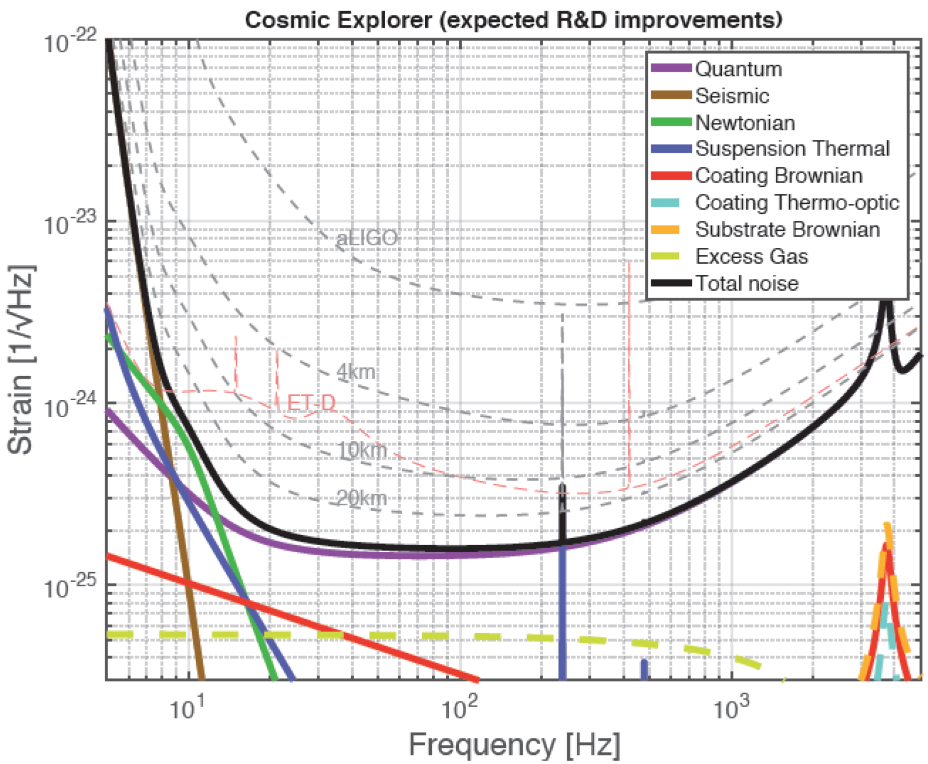
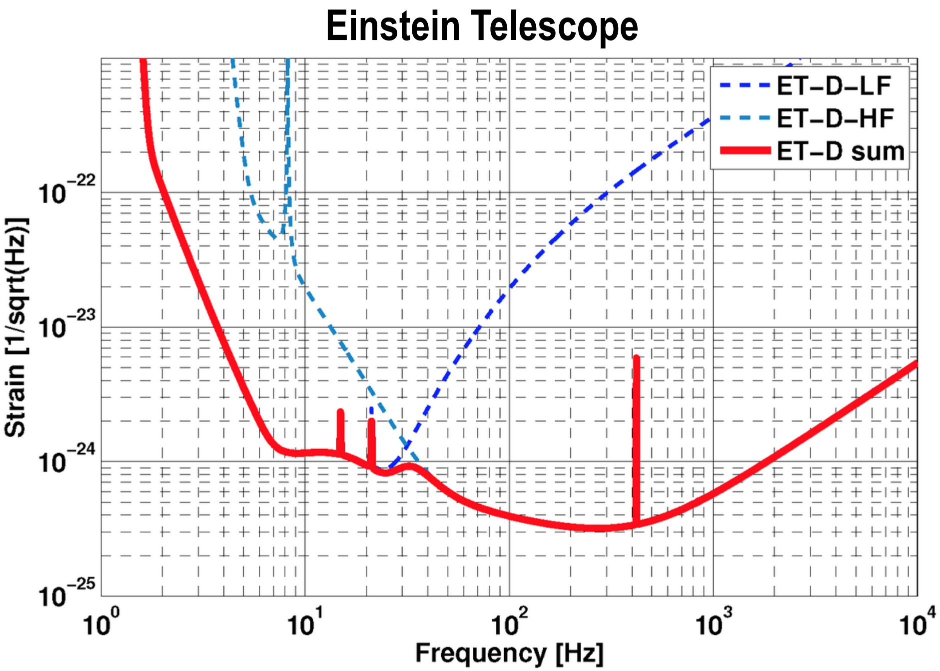


Image Credit: Caltech/MIT/LIGO Lab

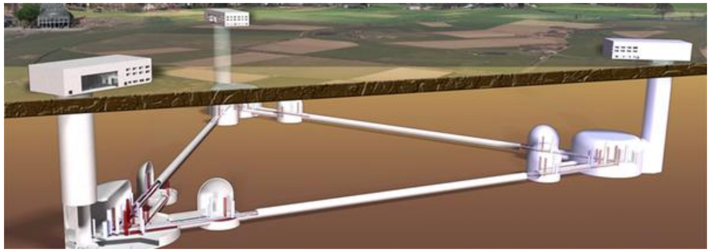
The future: 3rd generation detectors



arXiv:1607.08697



S.Hild et al., Classical and Quantum Gravity, 28 094013, 2011

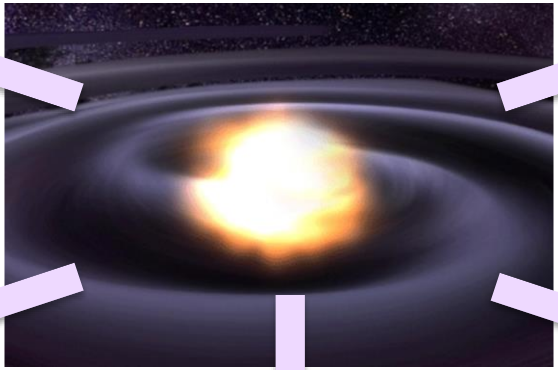


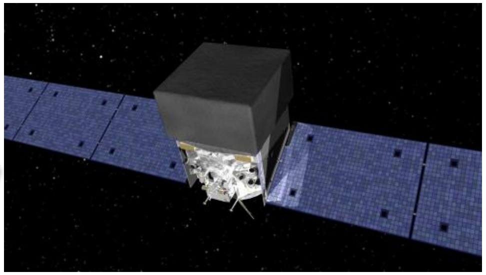
http://www.et-gw.eu/

Multi-messenger Astronomy with Gravitational Waves

Binary Merger

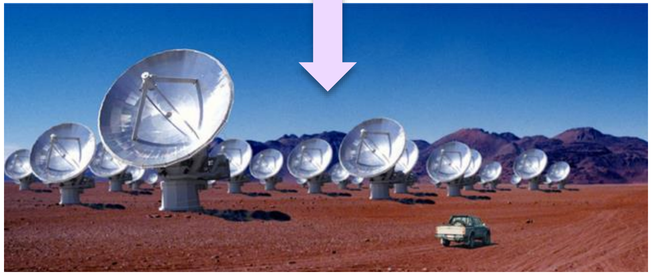
Gravitational Waves

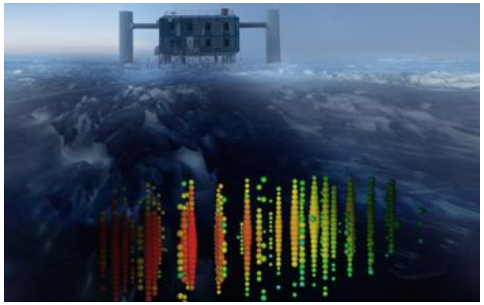




X-rays/Gamma-rays

Visible/Infrared Light





Neutrinos

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

Gravitational Wave Periods

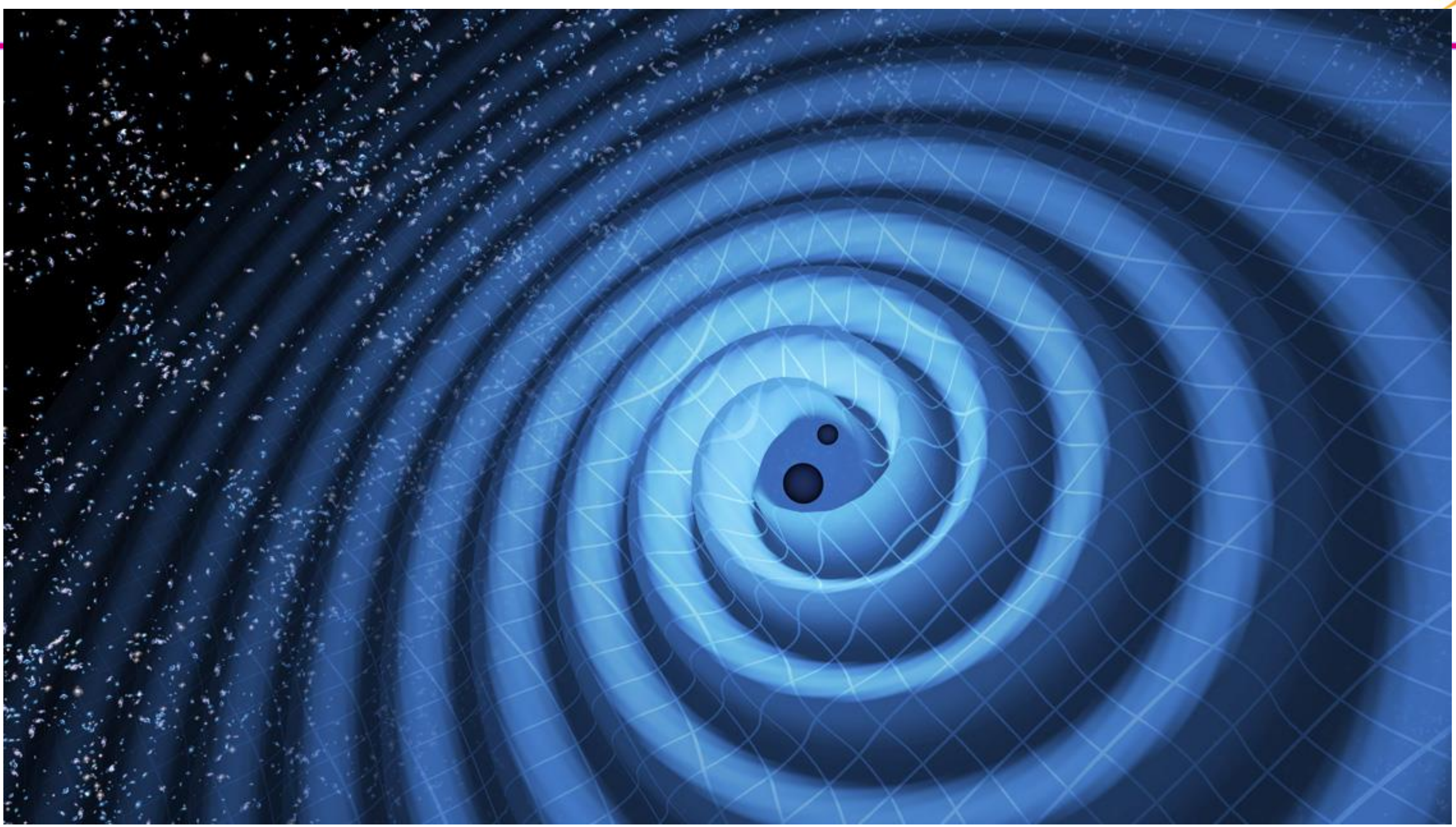
Milliseconds

Minutes
to Hours

Years
to Decades

Billions
of Years

Thanks!



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