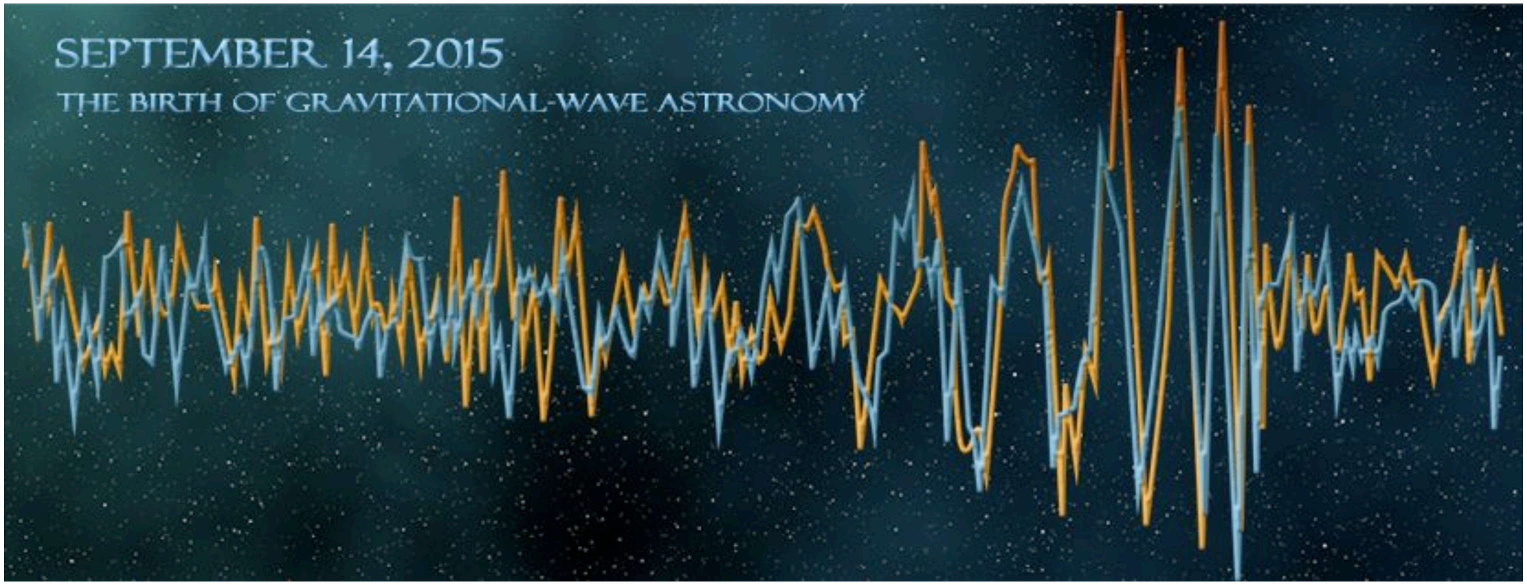
Searching for – and finding! gravitational waves

Gabriela González

Louisiana State University

For the LIGO Scientific Collaboration and
the Virgo Collaboration

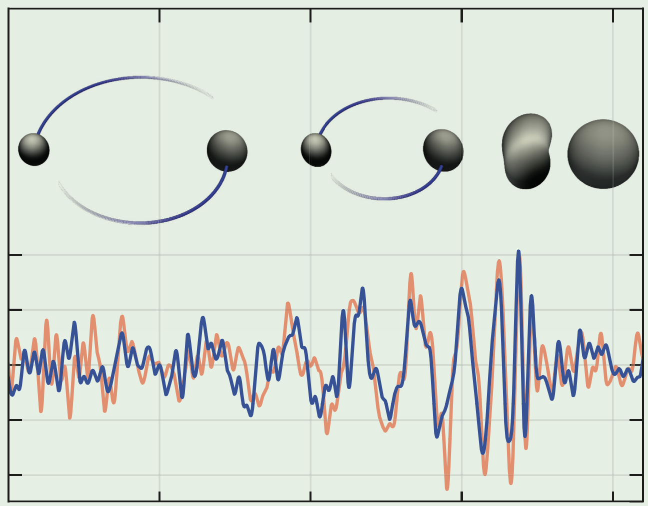


PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

(and papers.ligo.org)



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PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
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PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)

Binary Black Hole Mergers in the first Advanced LIGO Observing Run

https://dcc.ligo.org/LIGO-P1600088/public

LIGO

LSC

LIGO Scientific Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University Washington, DC
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of the West of Scotland UWS
Texas Tech University
清華大學 Tsinghua University
R·I·T
Stanford University
Max Planck Institute for Gravitational Physics Albert Einstein Institute
University of Strathclyde
Michigan
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CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique
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ICTP SAIFR
The University of Western Australia
PAH
ACU
Monash University
University of Cambridge
The University of Chicago
Montana State University
University of Minnesota
The University of Mississippi
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Columbia University in the City of New York
Caltech
Universitas Scientiarum Szegediensis
UIB Universitat de les Illes Balears
University of Birmingham
The University of Melbourne
Eötvös Loránd University
University of Washington
GEO 600
UTRGV
Carleton College
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Georgia Institute of Technology
Korean Gravitational-Wave Group
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Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

Einstein's gravity

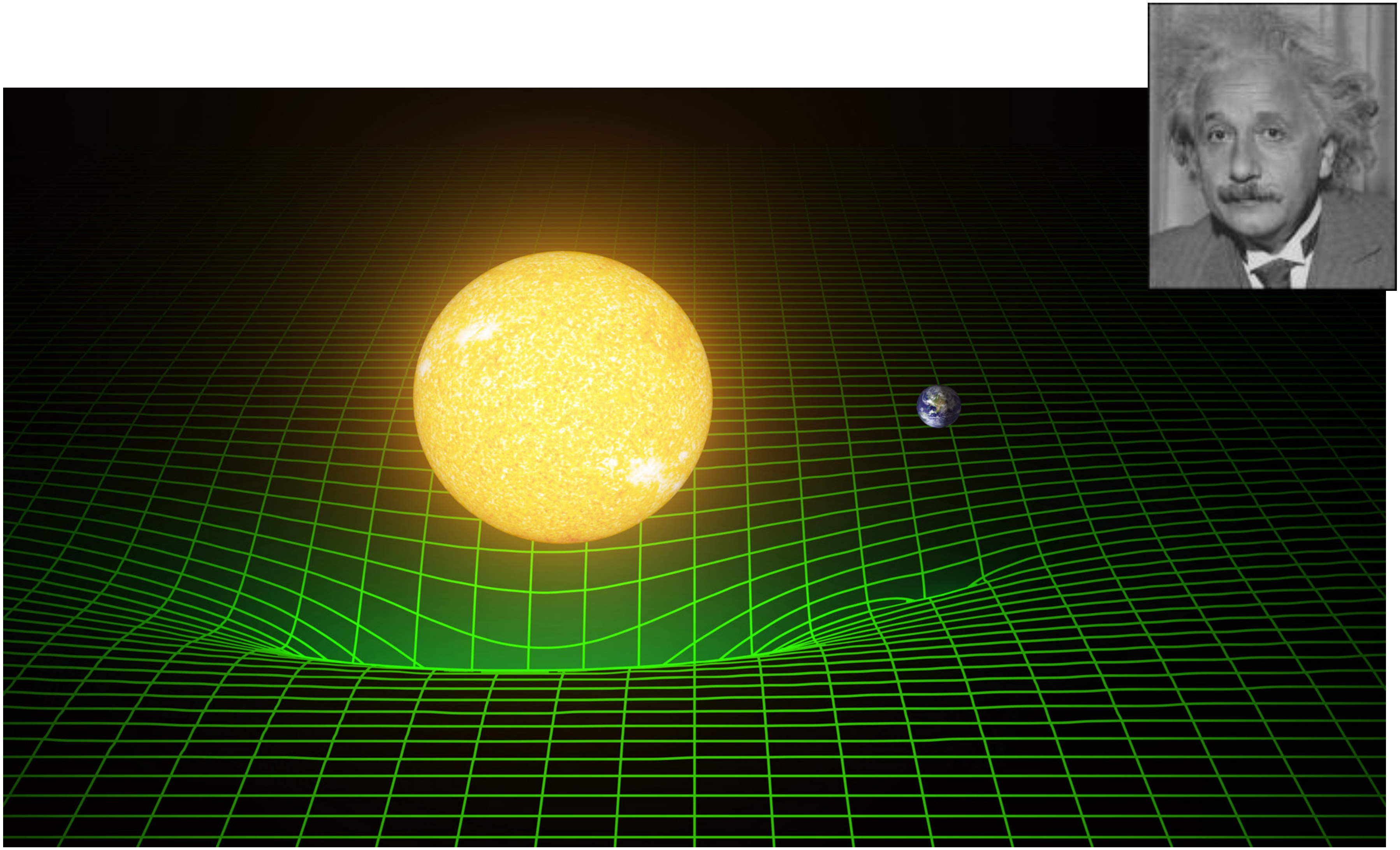
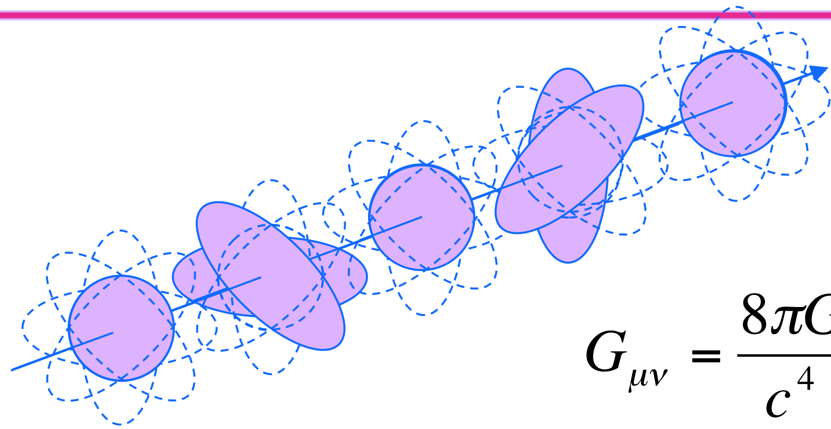


Image Credit: T. Pyle/Caltech/MIT/LIGO Lab

Gravitational waves

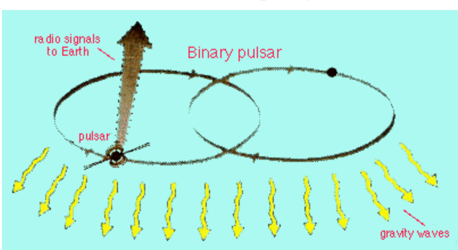


Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

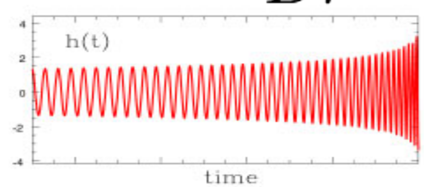
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} (= 0 \text{ in vacuum})$$

$$h_{\mu\nu} \sim \frac{2G}{c^4 r} \ddot{I}_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad h = 2\frac{\Delta L}{L}$$

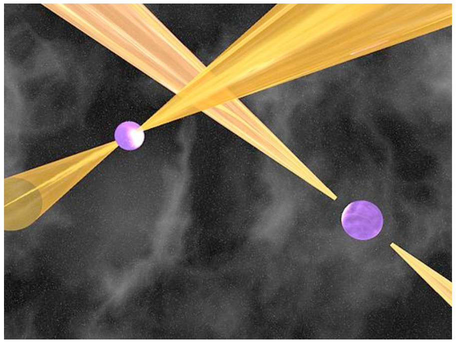


$$h_{\mu\nu} \sim \frac{R_1 R_2}{Dr}$$

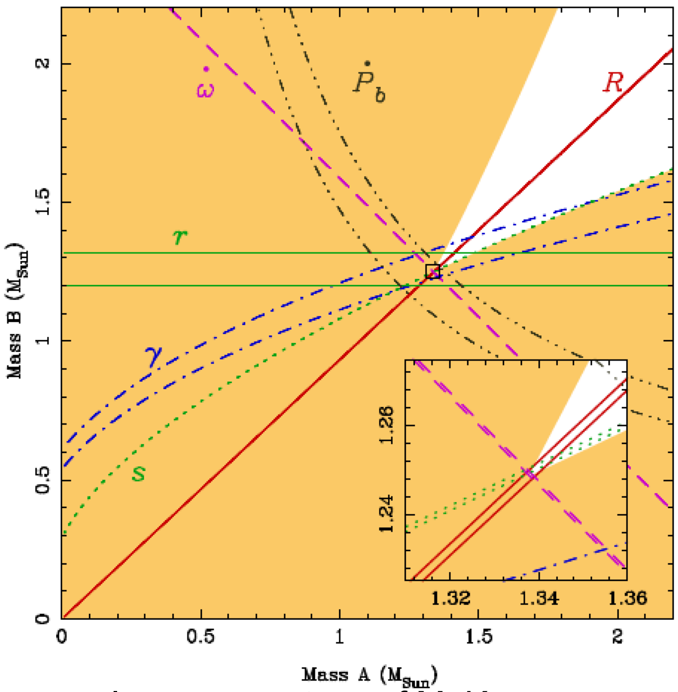


GWs from a NS-NS coalescence in the Virgo cluster has $h \sim 10^{-21}$ near Earth: change the distance between the Sun and the Earth by ~ one atomic diameter, and change 1km distance by ~10^{-18} m.

Gravitational Waves: a known quantity!

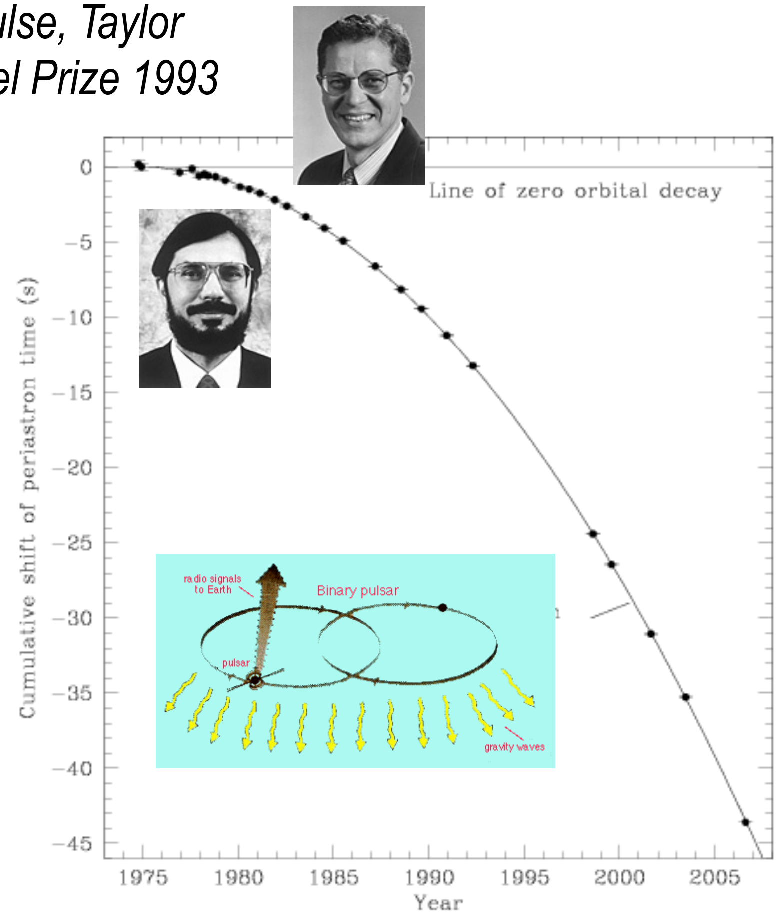


J0737-3039, or "double pulsar"



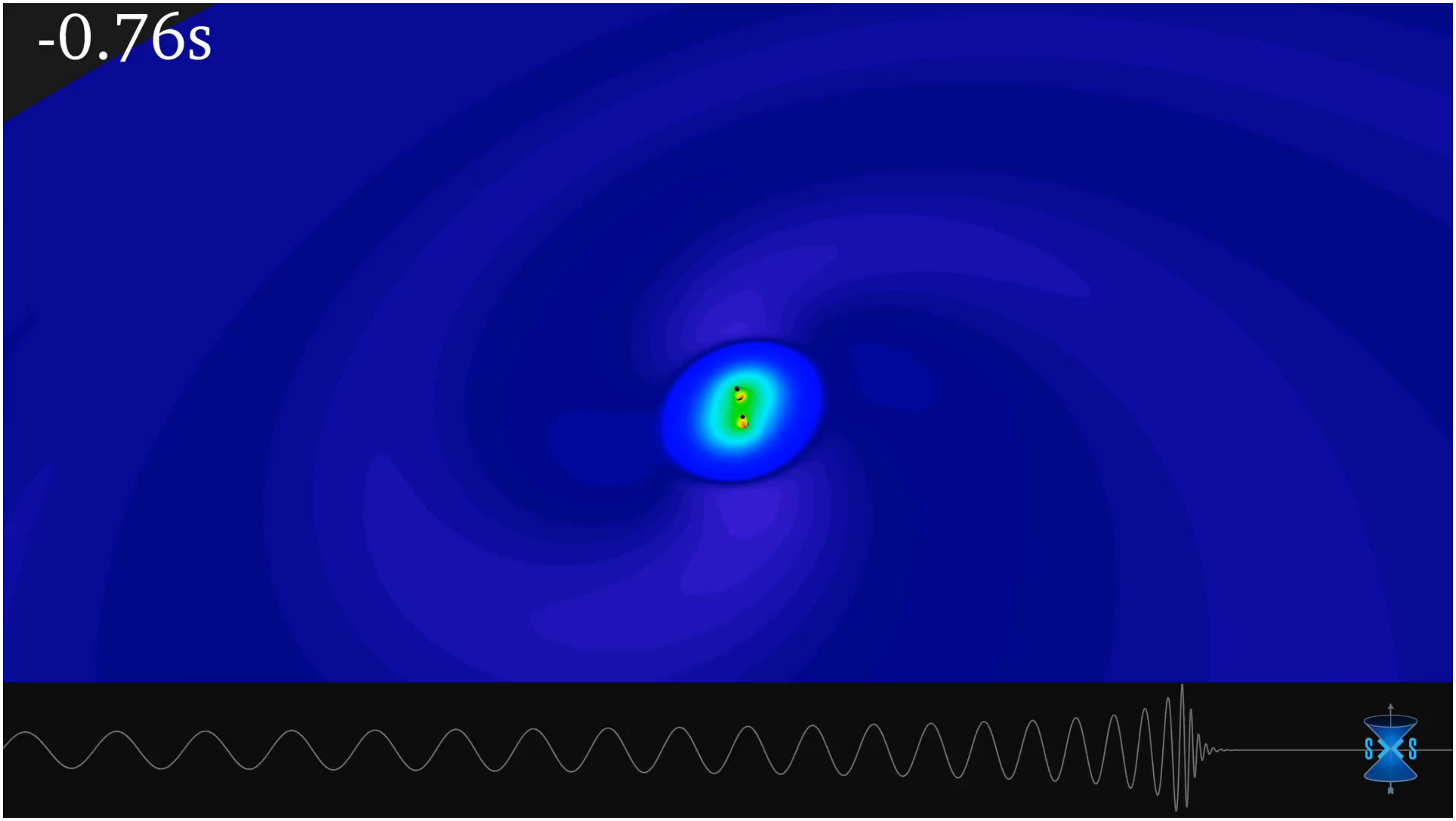
Images courtesy of M. Kramer.

Hulse, Taylor
Nobel Prize 1993



Weisberg, Nice & Taylor, 2010
(Courtesy Joel Weisberg)

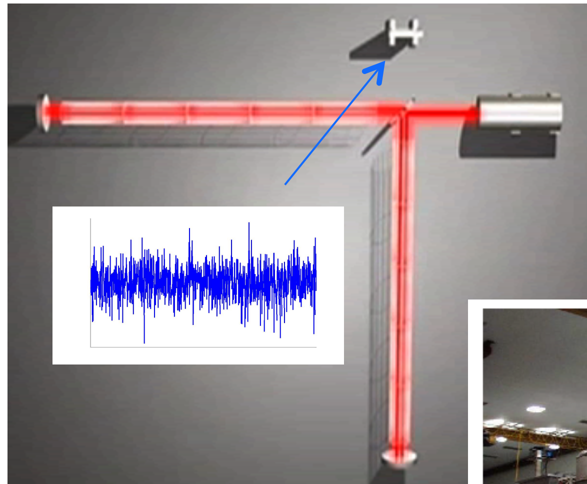
Einstein's gravity

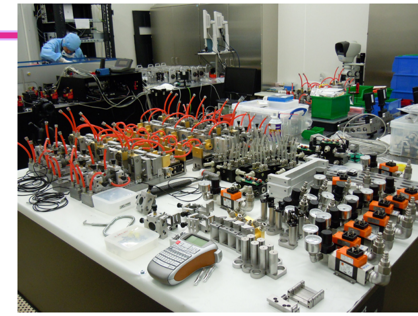


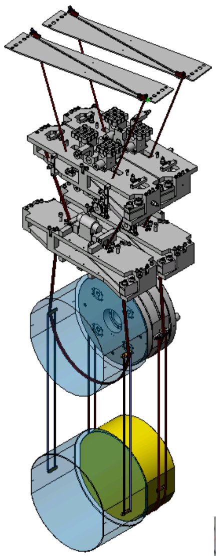
Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

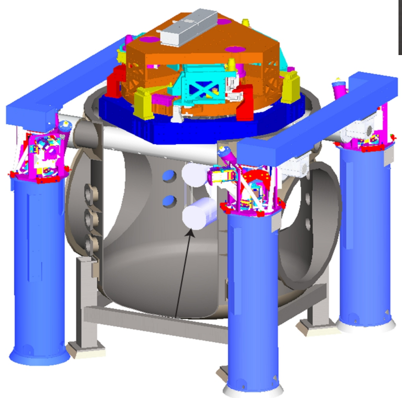
LIGO Detectors

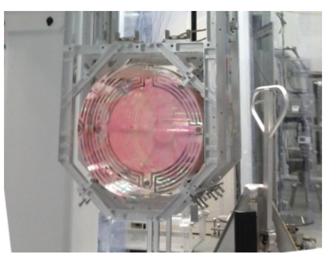
Advanced LIGO detectors



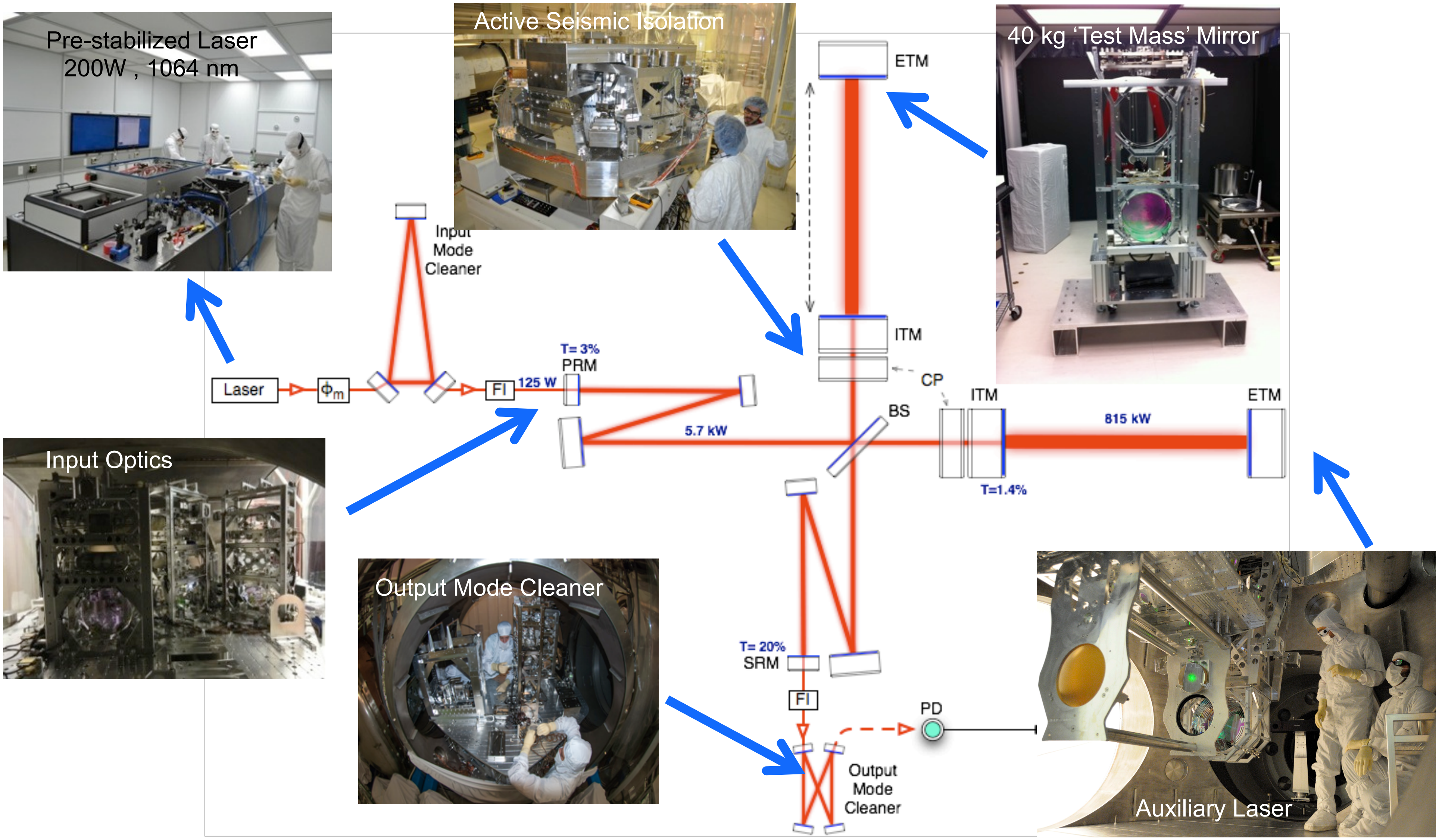




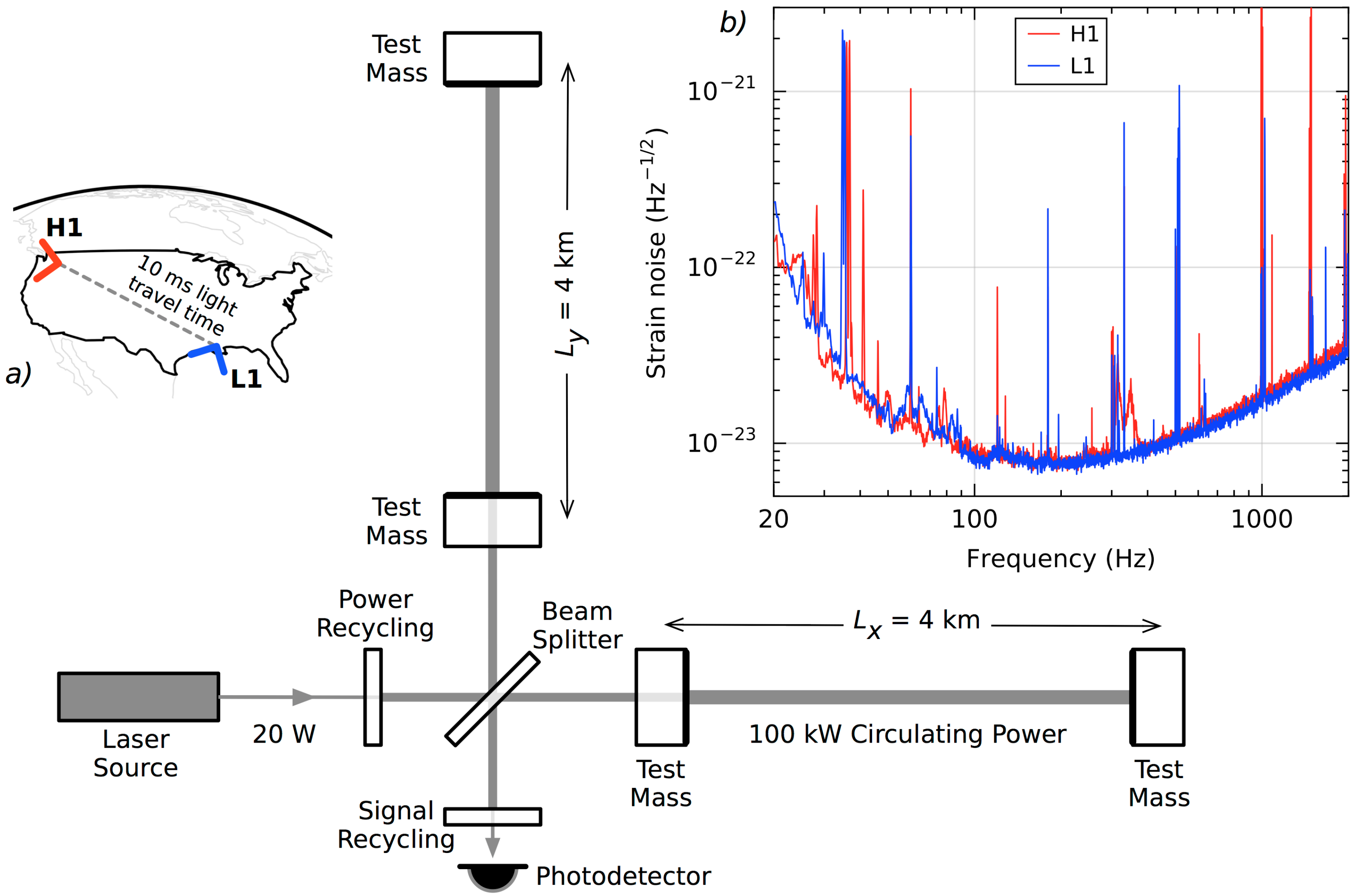




Advanced LIGO detectors



Advanced LIGO detectors September 2015



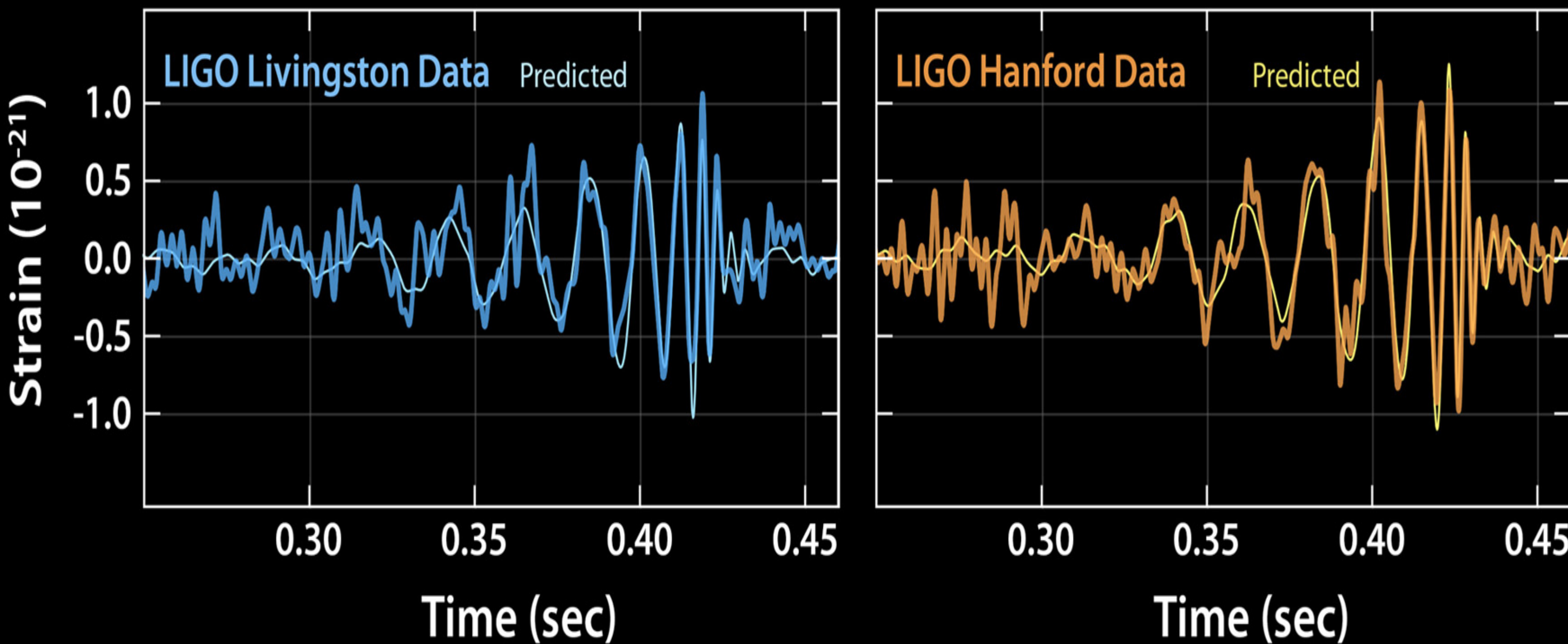
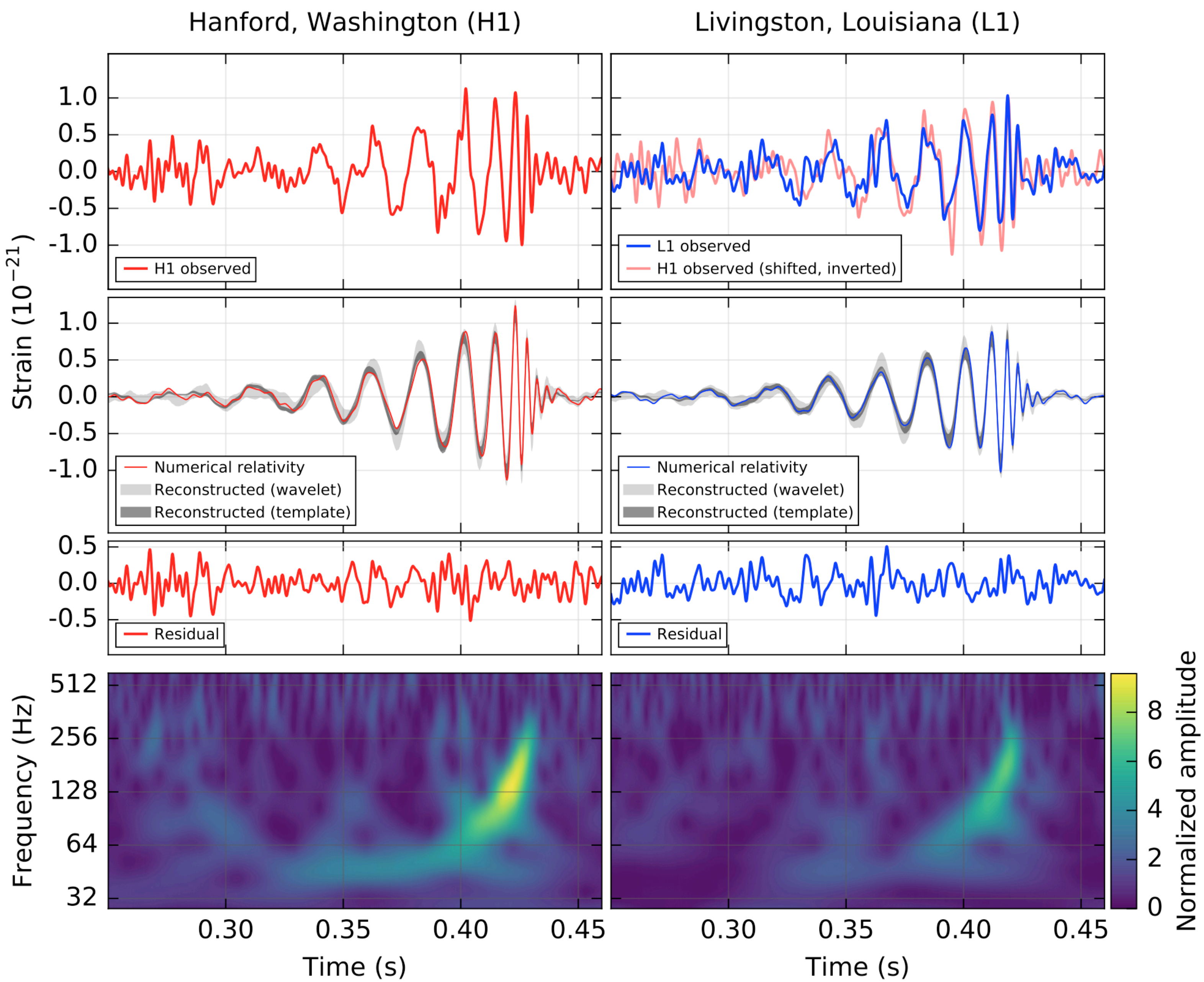
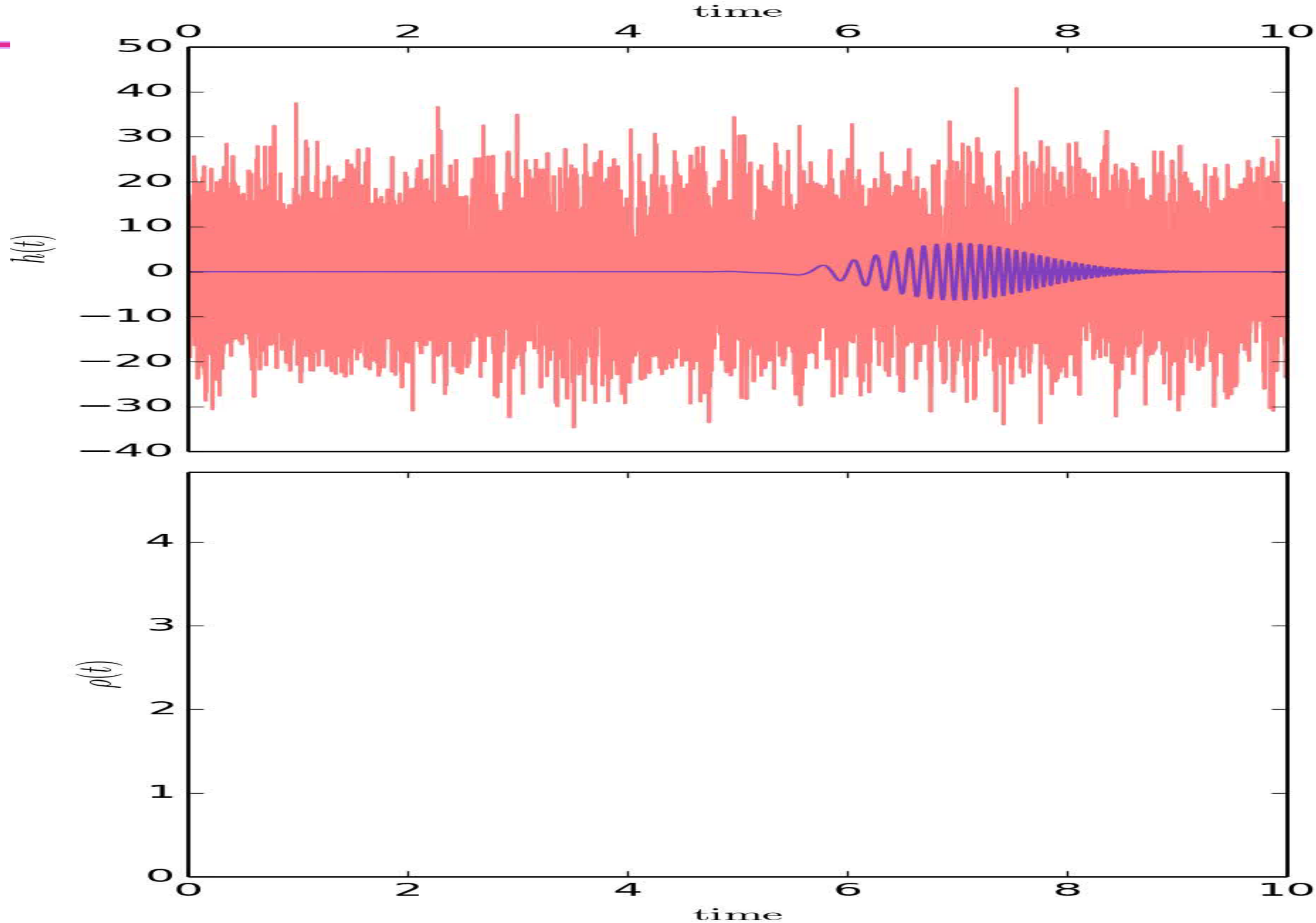


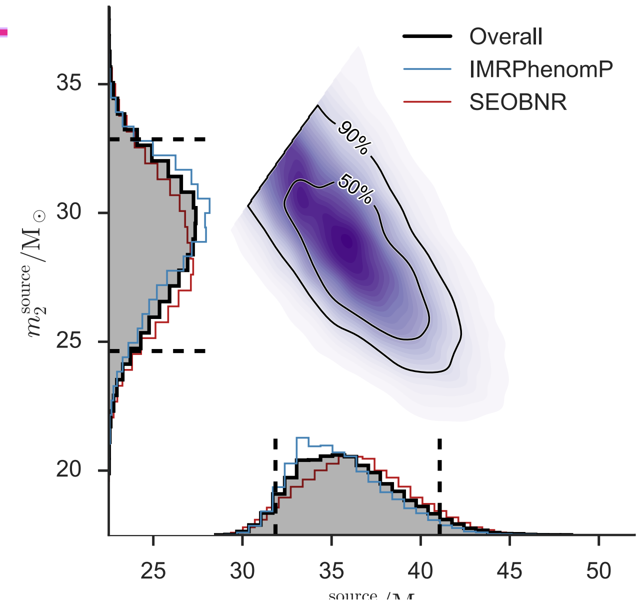
Image Credit: Caltech/MIT/LIGO Lab


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

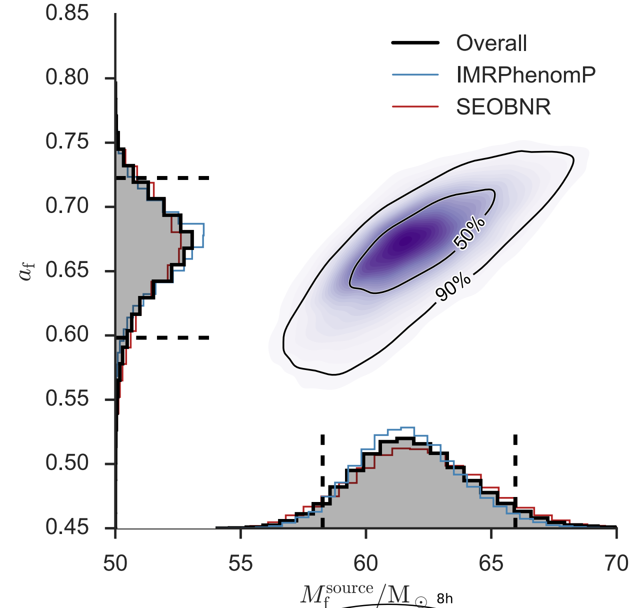
Searching for a specific waveform



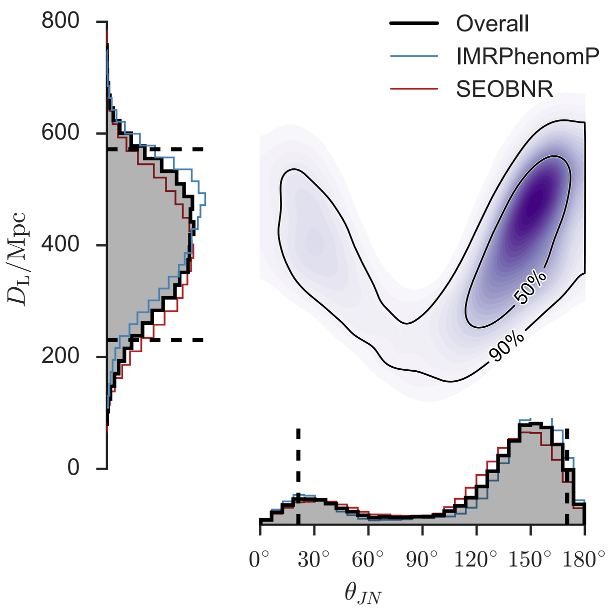
GW150914



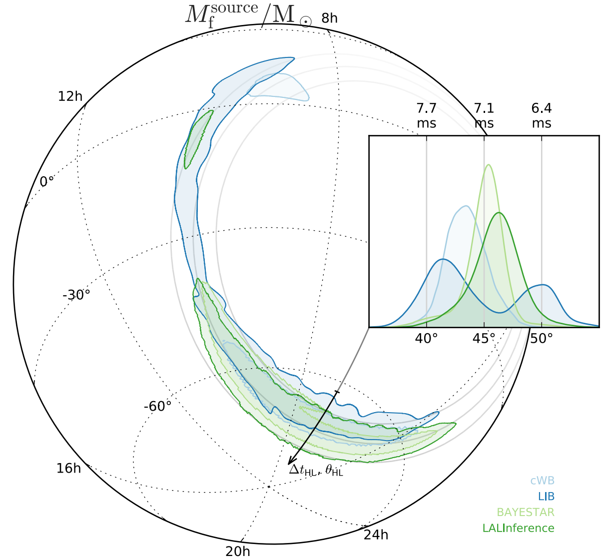
Overall
IMRPhenomP
SEOBNR
90%
50%
$m_2^{\rm source}/{\rm M}_\odot$
35
30
25
20
25
30
35
40
45
50



Overall
IMRPhenomP
SEOBNR
50%
90%
$a_{\rm f}$
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
50
55
60
65
70
$M_{\rm f}^{\rm source}/{\rm M}_\odot$



Overall
IMRPhenomP
SEOBNR
50%
90%
$D_{\rm L}/{\rm Mpc}$
800
600
400
200
0
0°
30°
60°
90°
120°
150°
180°
θ_{JN}



8h
12h
16h
20h
24h
0°
-30°
-60°
7.7 ms
7.1 ms
6.4 ms
40°
45°
50°
$\Delta t_{\rm HL}$, $\theta_{\rm HL}$
cWB
LIB
BAYESTAR
LALInference

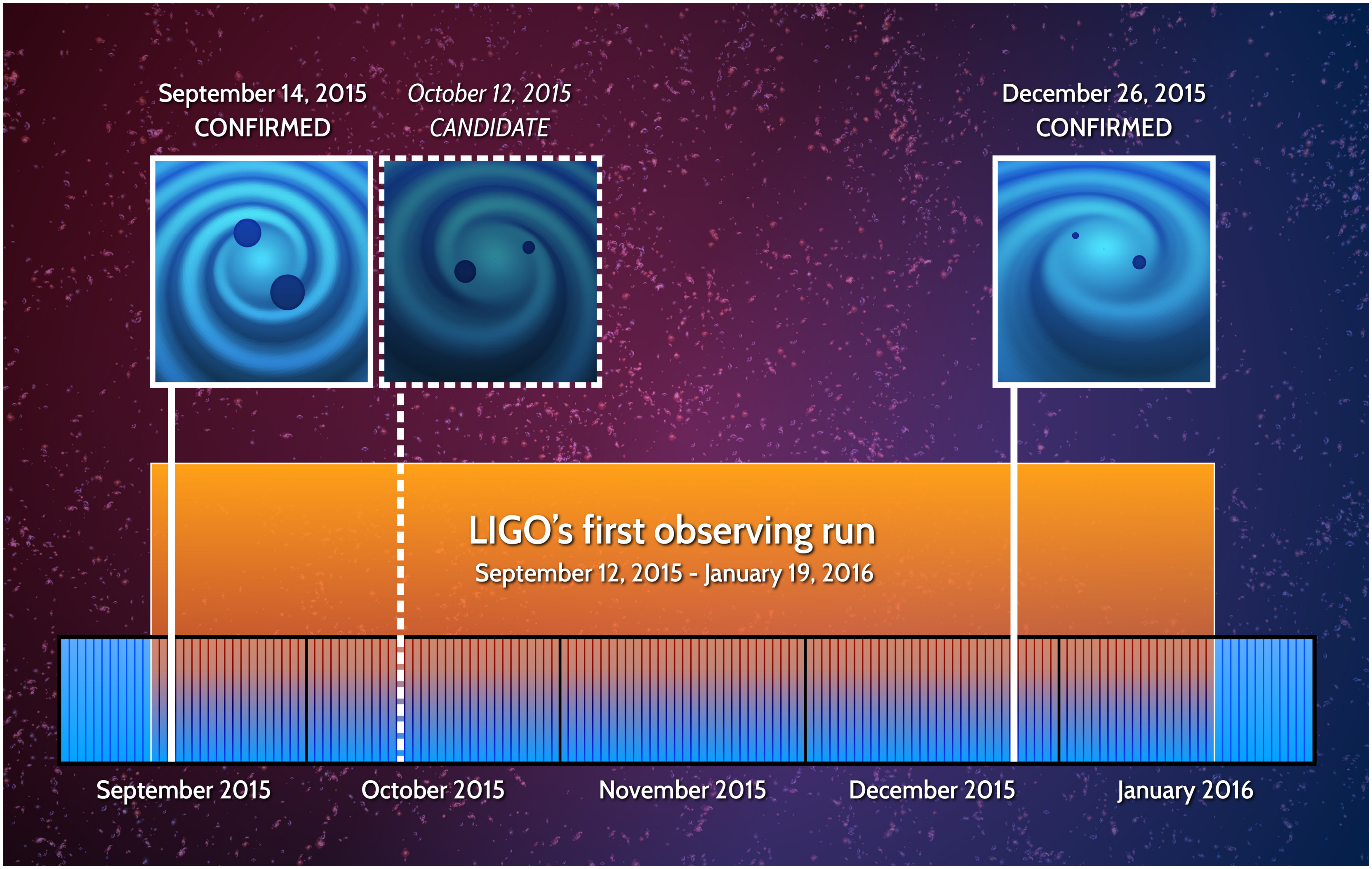
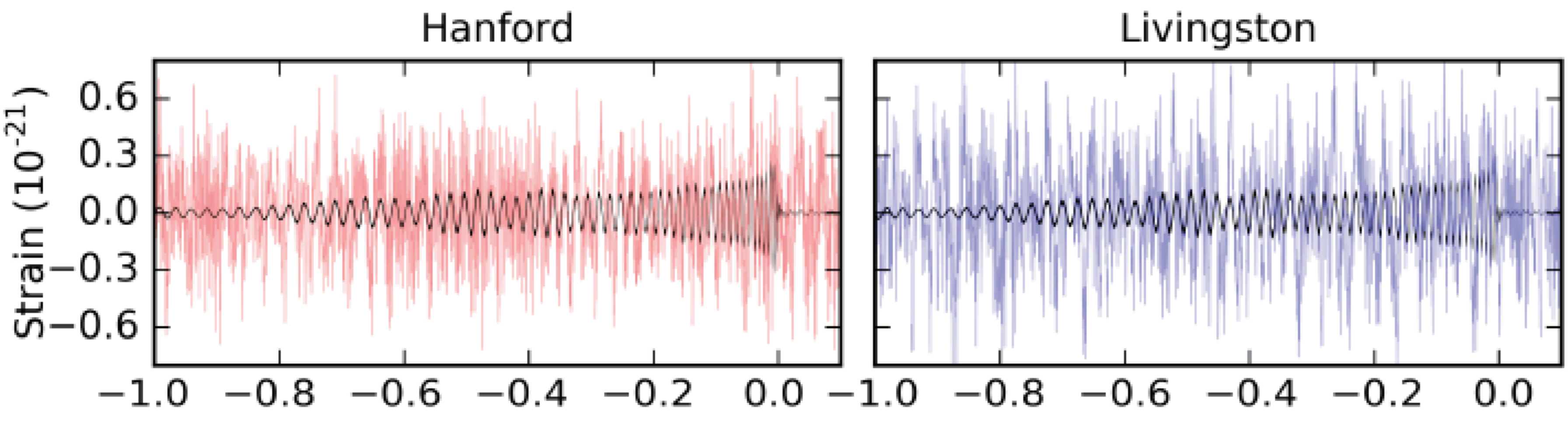
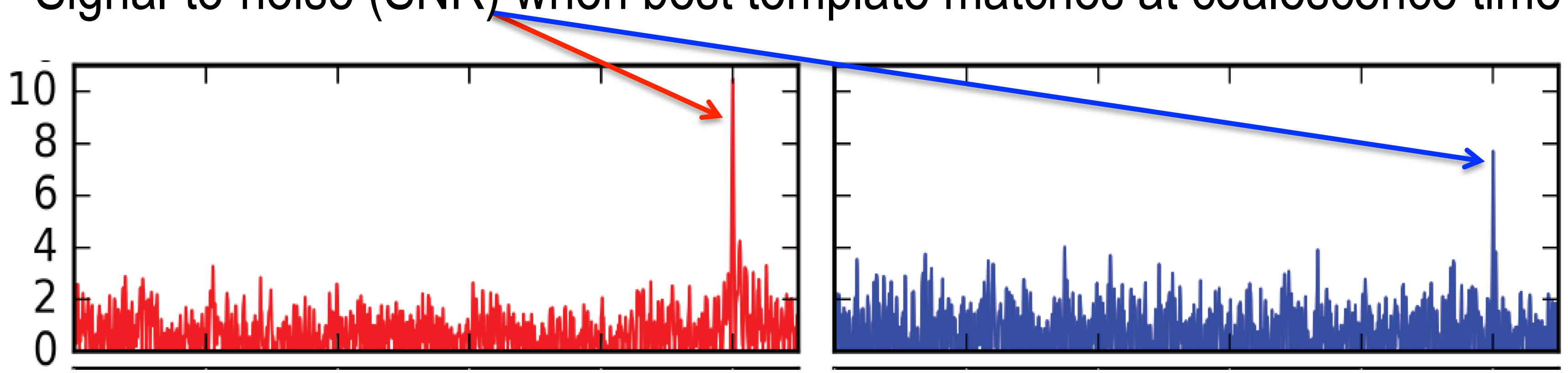


Image credit: LIGO

Filtered detector output and filtered best matching waveform

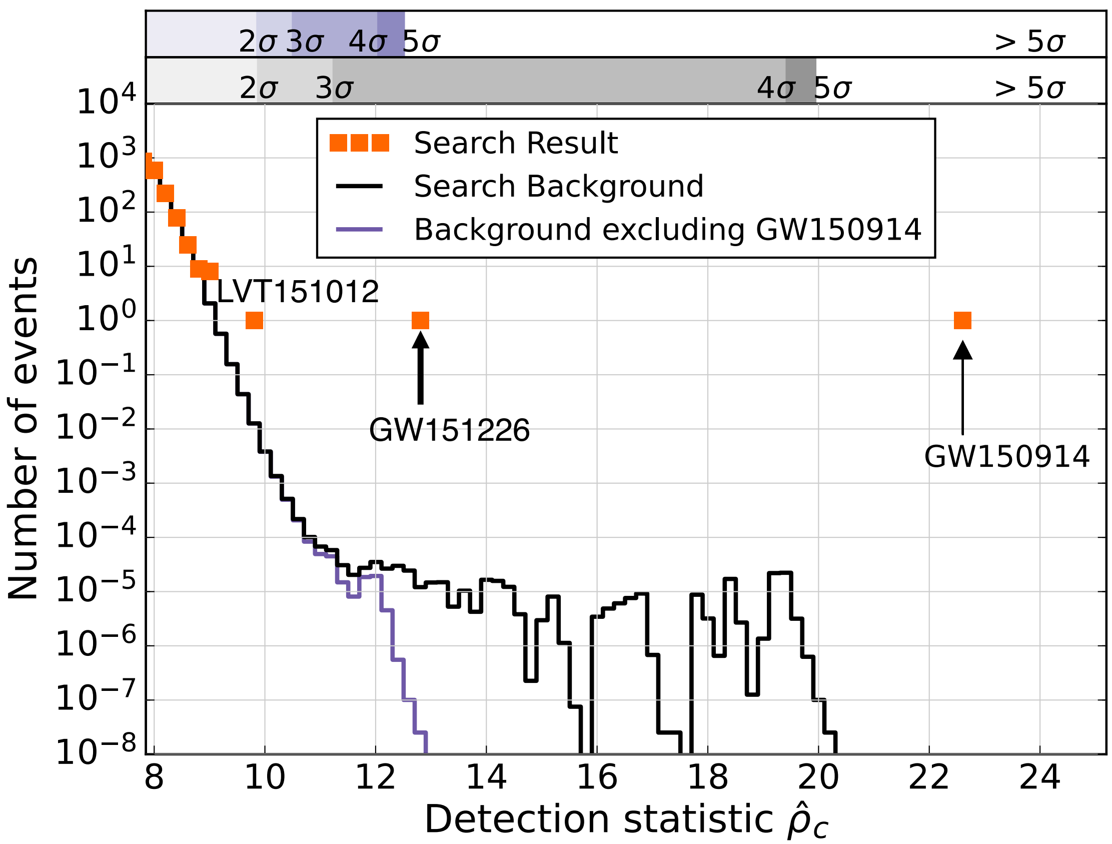


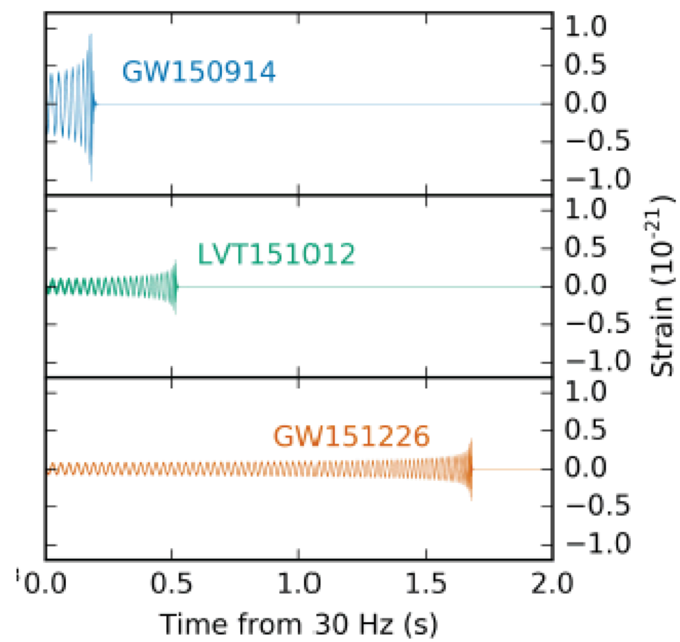
Signal-to-noise (SNR) when best template matches at coalescence time



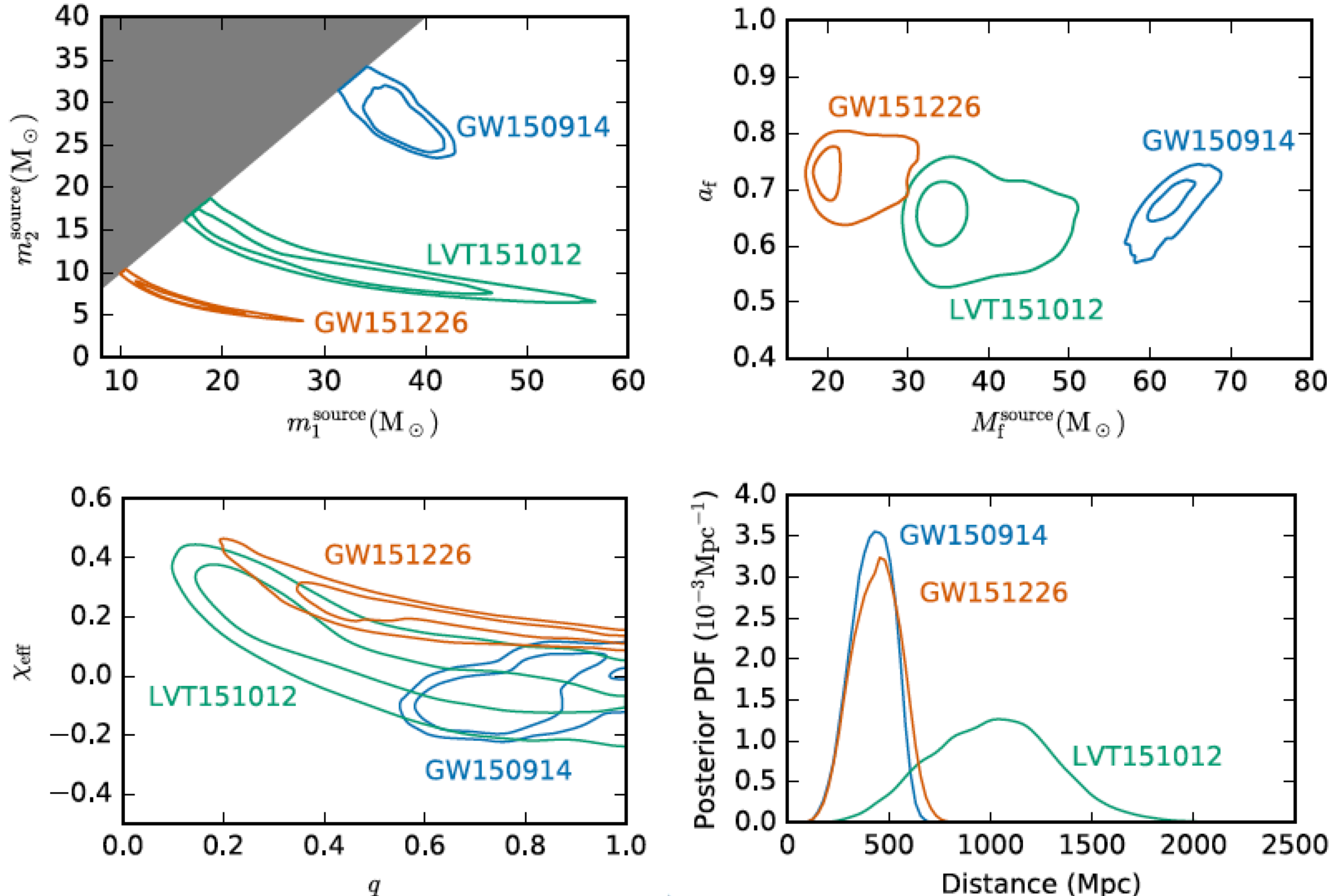
O1 BBH search

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)





Parameters of the BBH systems



50% and 90% credible regions

Filling in the black hole catalog

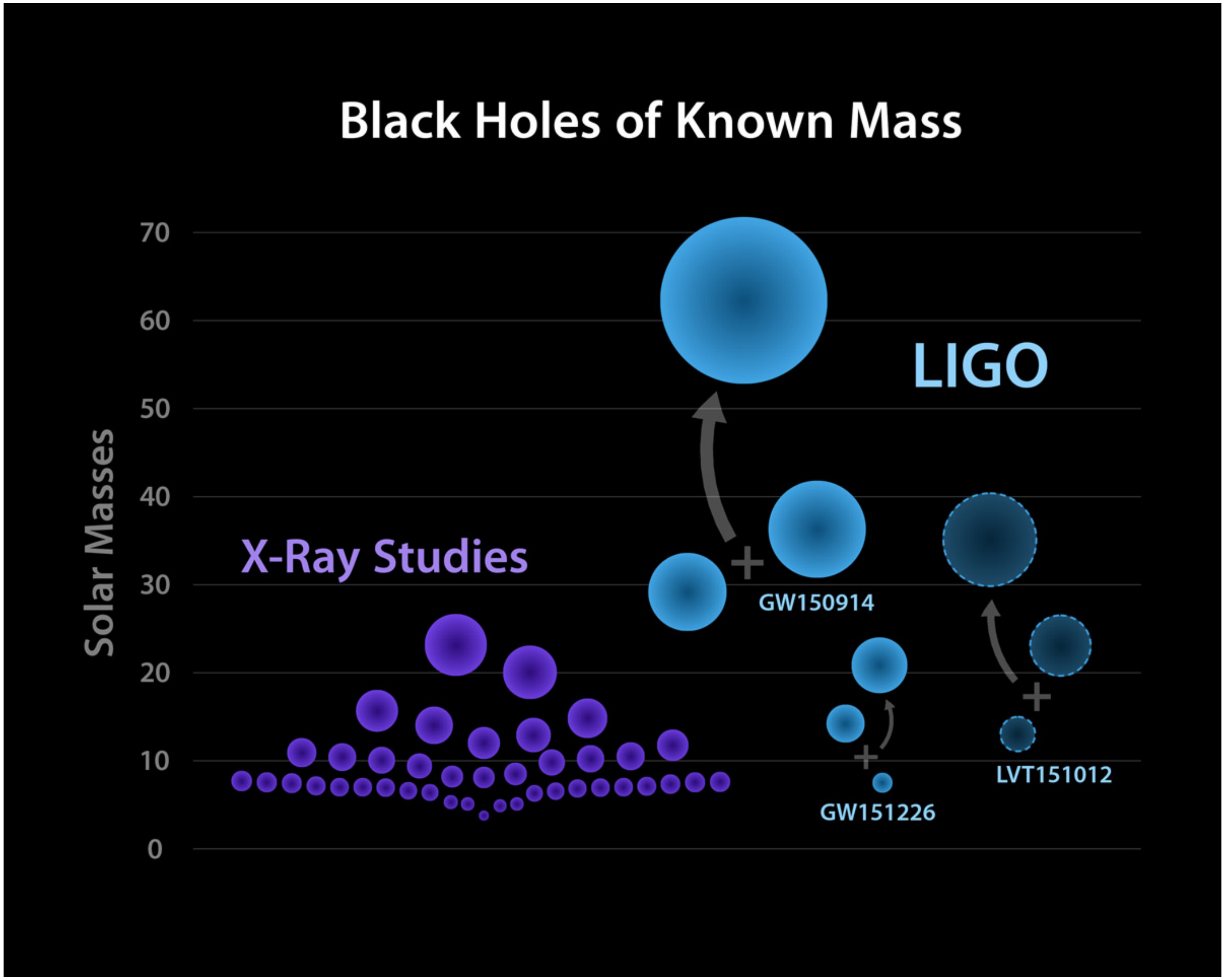


Image credit: LIGO

GW151226

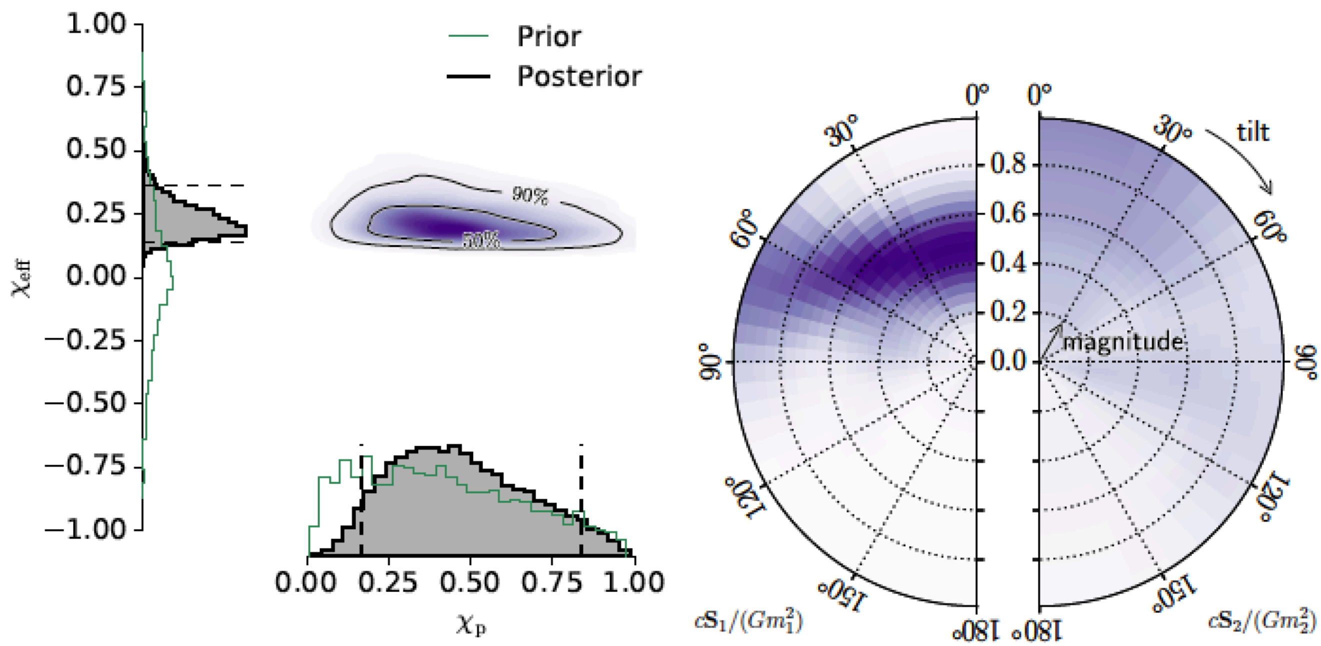
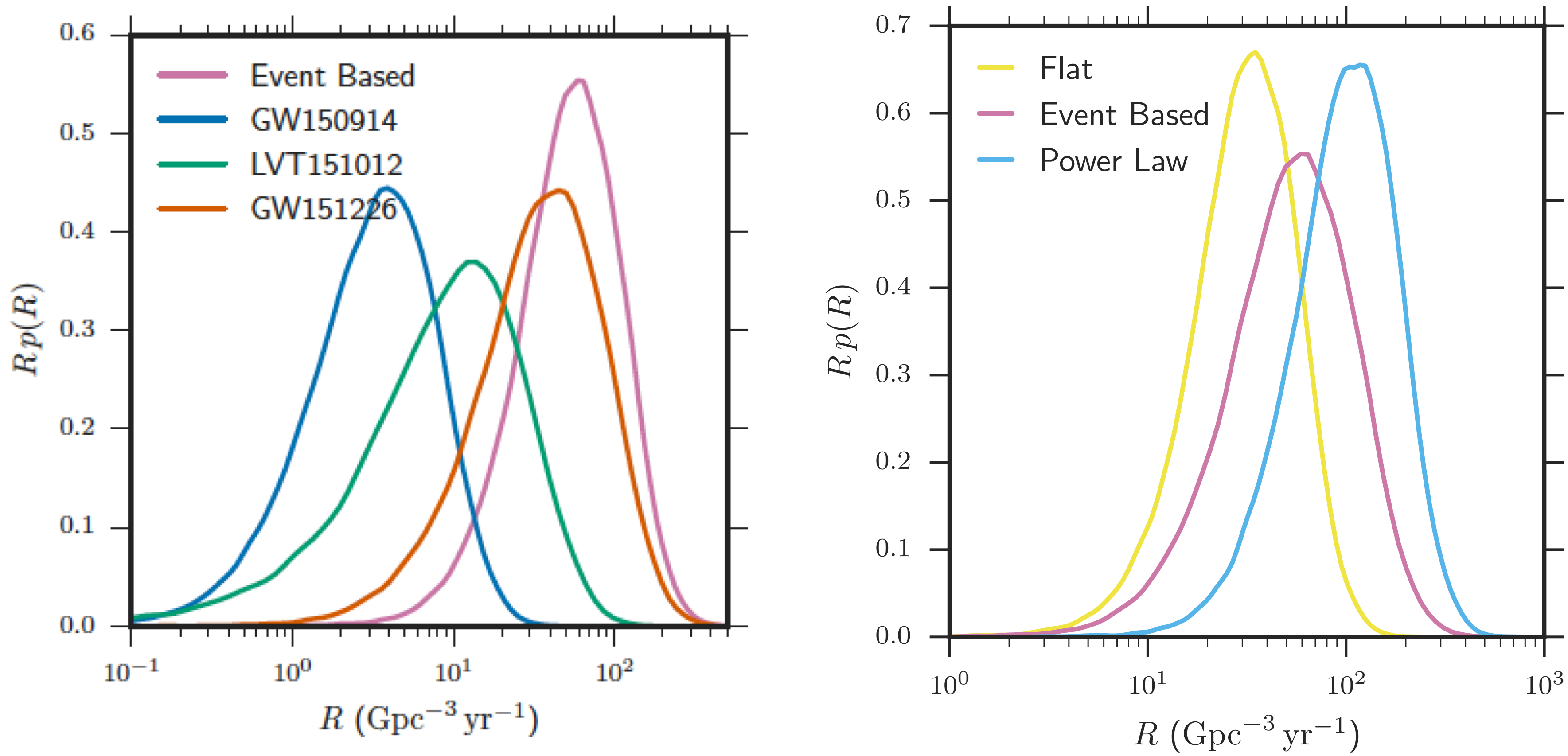


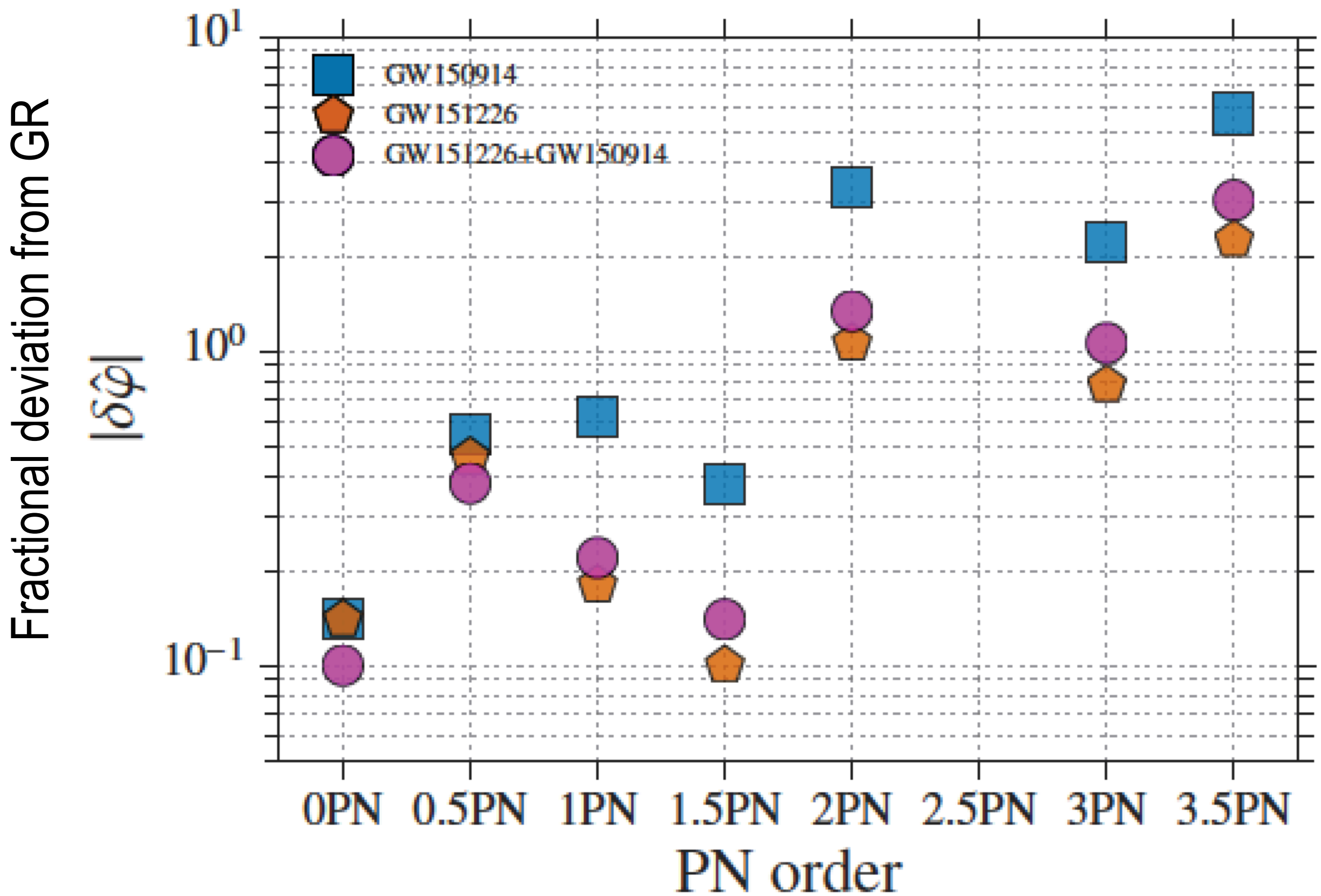
FIG. 4. *Left:* Posterior density function for the $\chi_{\rm p}$ and $\chi_{\rm eff}$ spin parameters (measured at 20 Hz) compared to their prior distributions. The 1-dimensional plot shows probability contours of the prior (green) and marginalized posterior density function (black) [60, 61]. The 2-dimensional plot shows the contours of the 50% and 90% credible regions plotted over a color-coded posterior density function. The dashed lines mark the 90% credible interval. *Right:* Posterior density function for the dimensionless component spins, $c\mathbf{S}_1/(Gm_1^2)$ and $c\mathbf{S}_2/(Gm_2^2)$, relative to the normal of the orbital plane $\hat{\mathbf{L}}$. $\mathbf{S}_i$ and m_i are the spin angular momenta and masses of the primary $(i = 1)$ and secondary $(i = 2)$ black holes, c is the speed of light and G is the gravitational constant. The posterior density functions are marginalized over the azimuthal angles. The bins are designed to have equal prior probability; they are constructed linearly in spin magnitudes and the cosine of the tilt angles $\cos^{-1}(\hat{\mathbf{S}}_i \cdot \hat{\mathbf{L}})$.

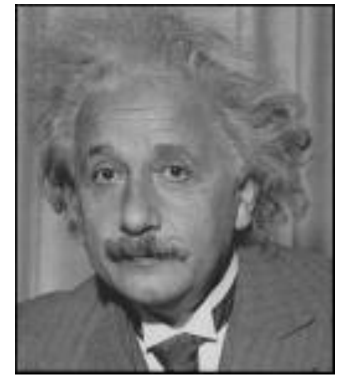
BBH merger rate



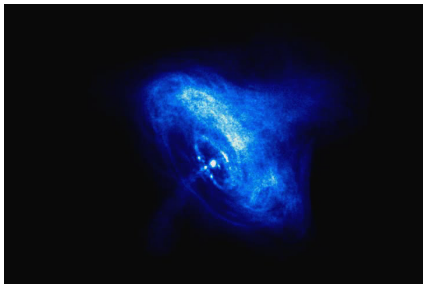
90% allowed range: [9-240] /Gpc^3/yr

Testing General Relativity

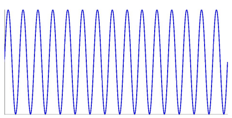




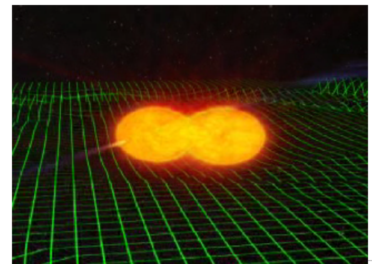
Sources of gravitational waves: not just black holes!



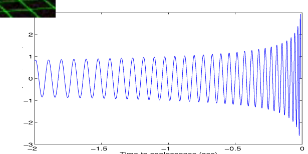
Crab pulsar (NASA, Chandra Observatory)



Periodic, continuous waves



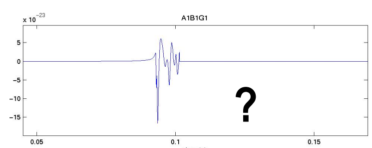
Credit: John Rowe



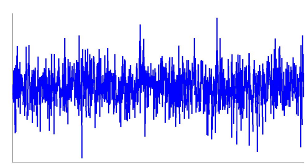
Binary systems with neutron stars, and/or black holes

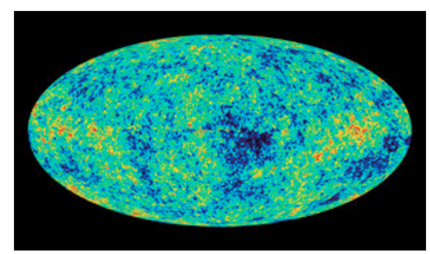
Short transients from supernova explosions or other sources

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

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

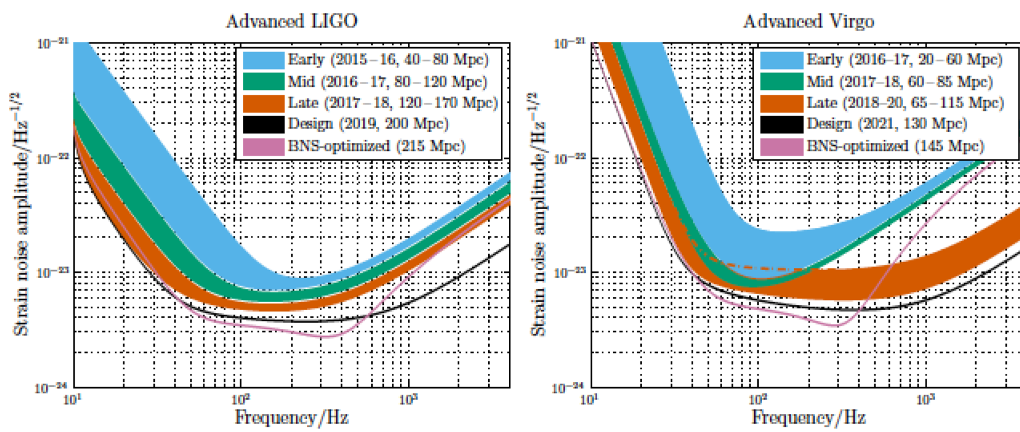


Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late 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.

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.

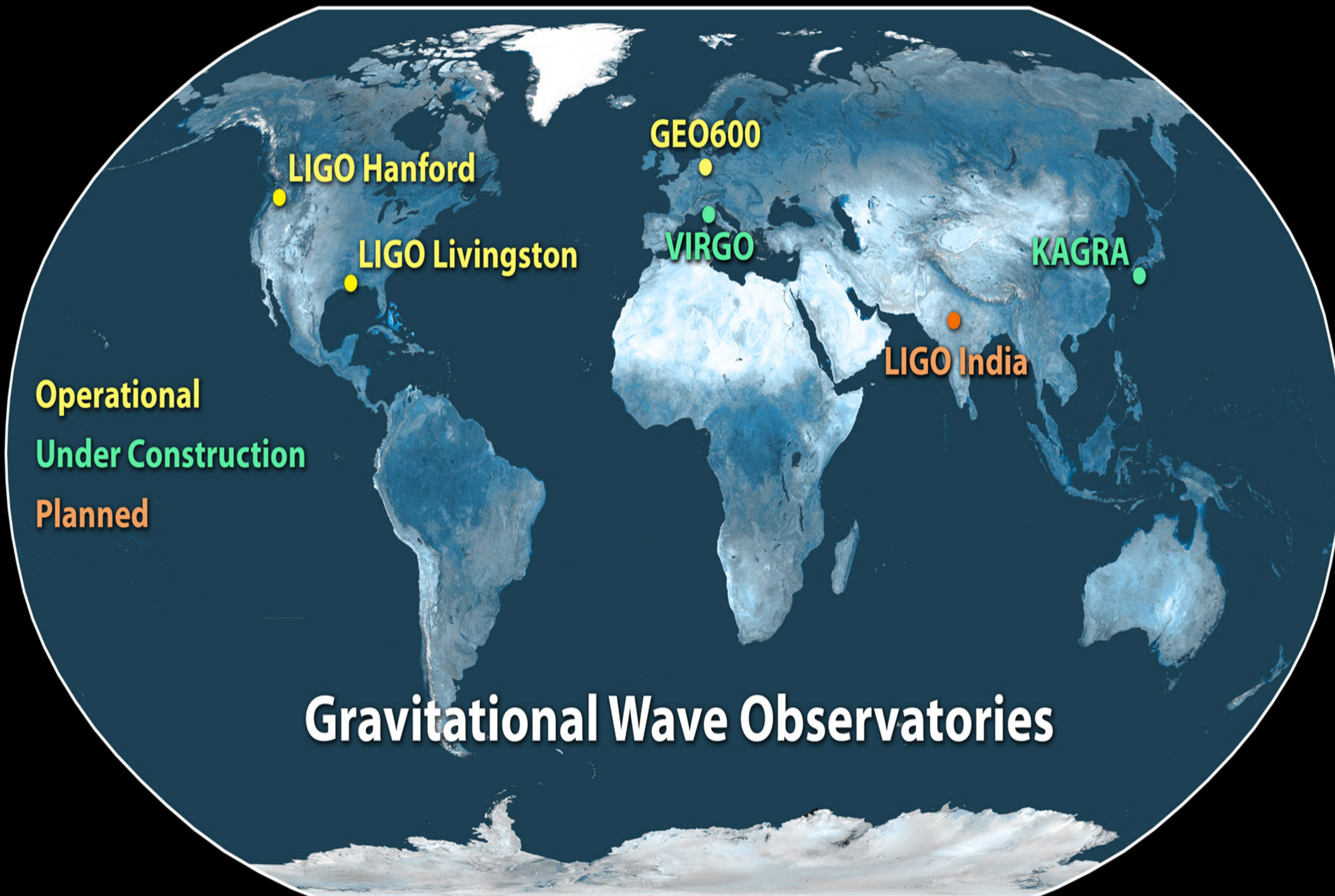
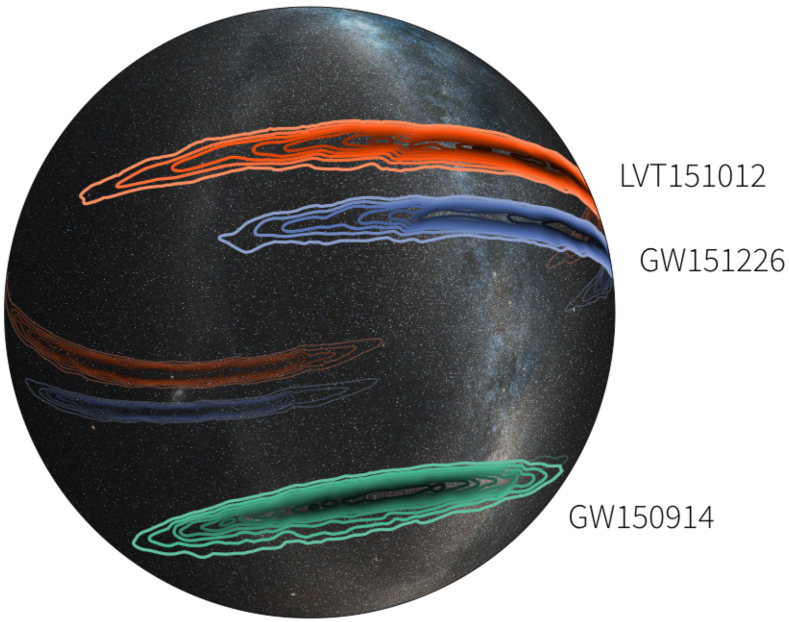


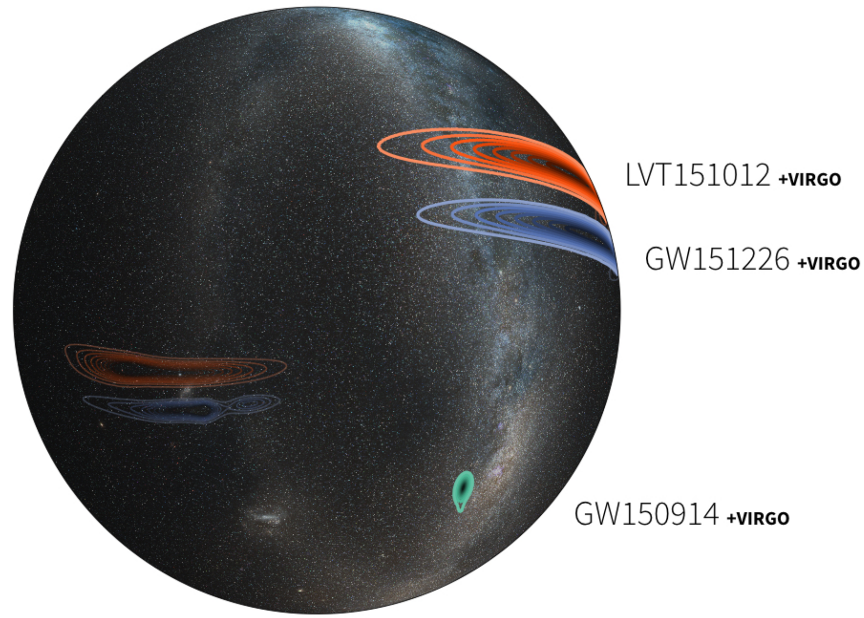
Image Credit: Caltech/MIT/LIGO Lab

Sky localization: more detectors needed!

Actual estimates



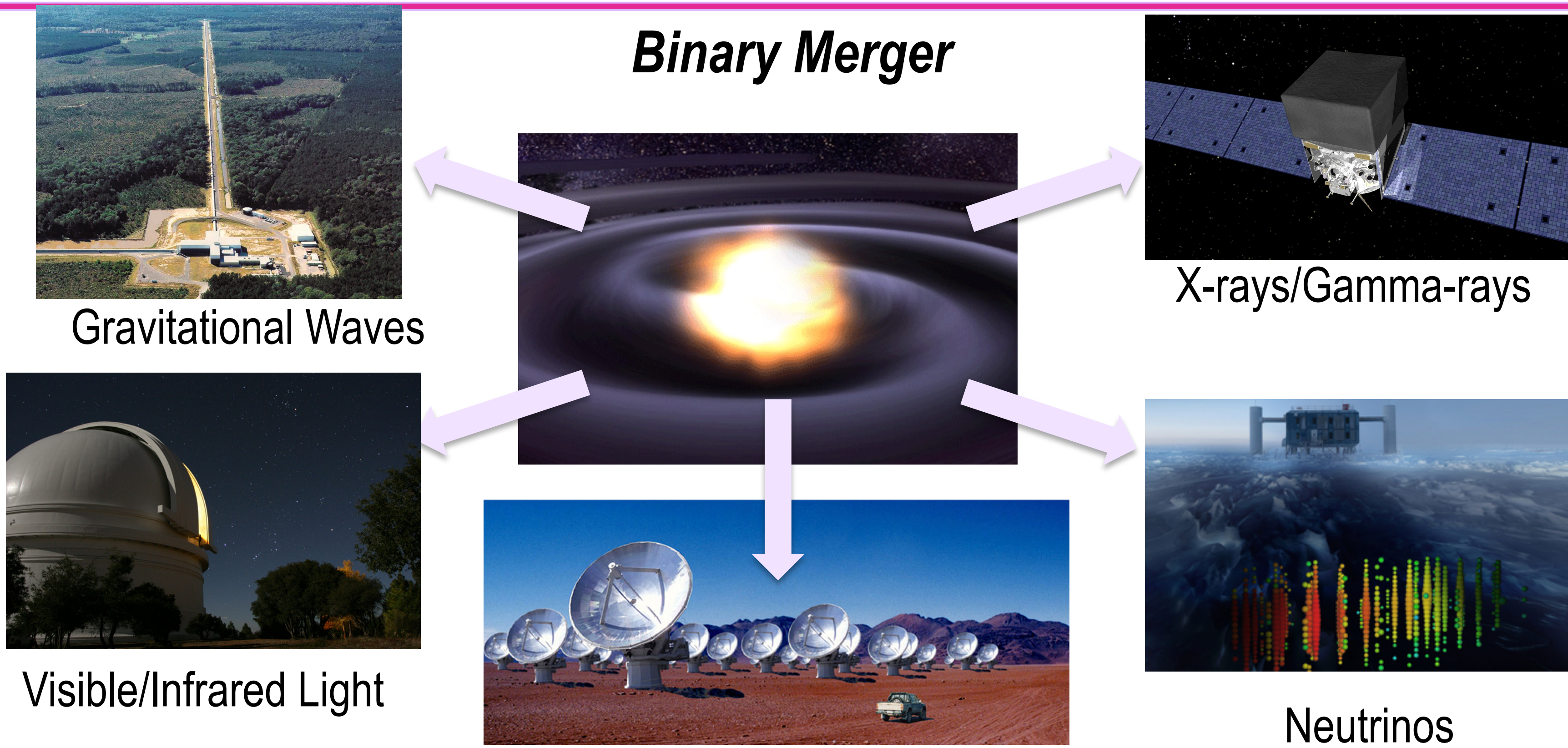
Simulated estimates with Virgo



3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (green), and GW151226 (blue), and the candidate LVT151012 (red). The outer contour for each represents the 90 percent confidence region while the innermost contour is the 10 percent region.

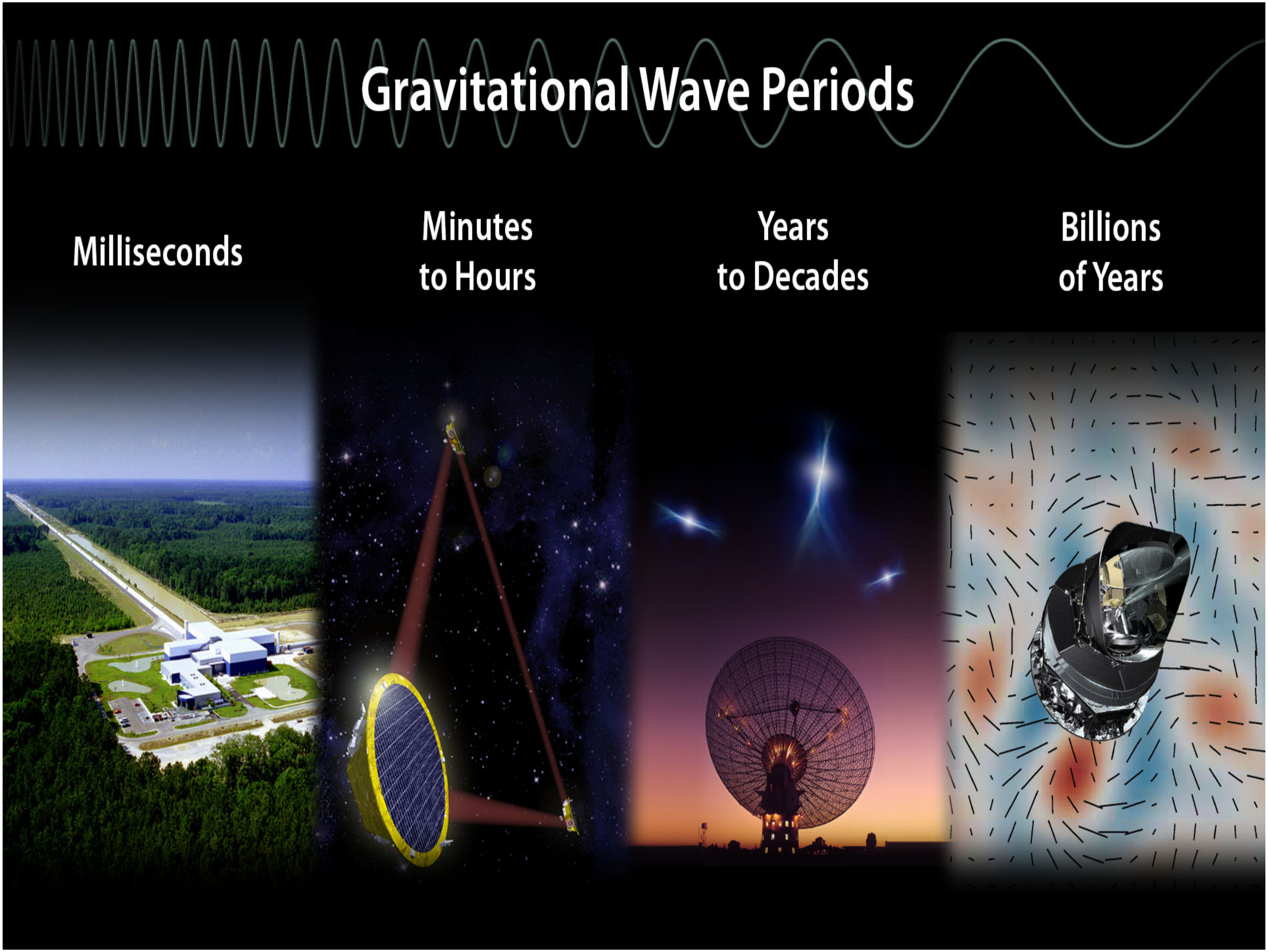
Image credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

Multi-messenger Astronomy with Gravitational Waves

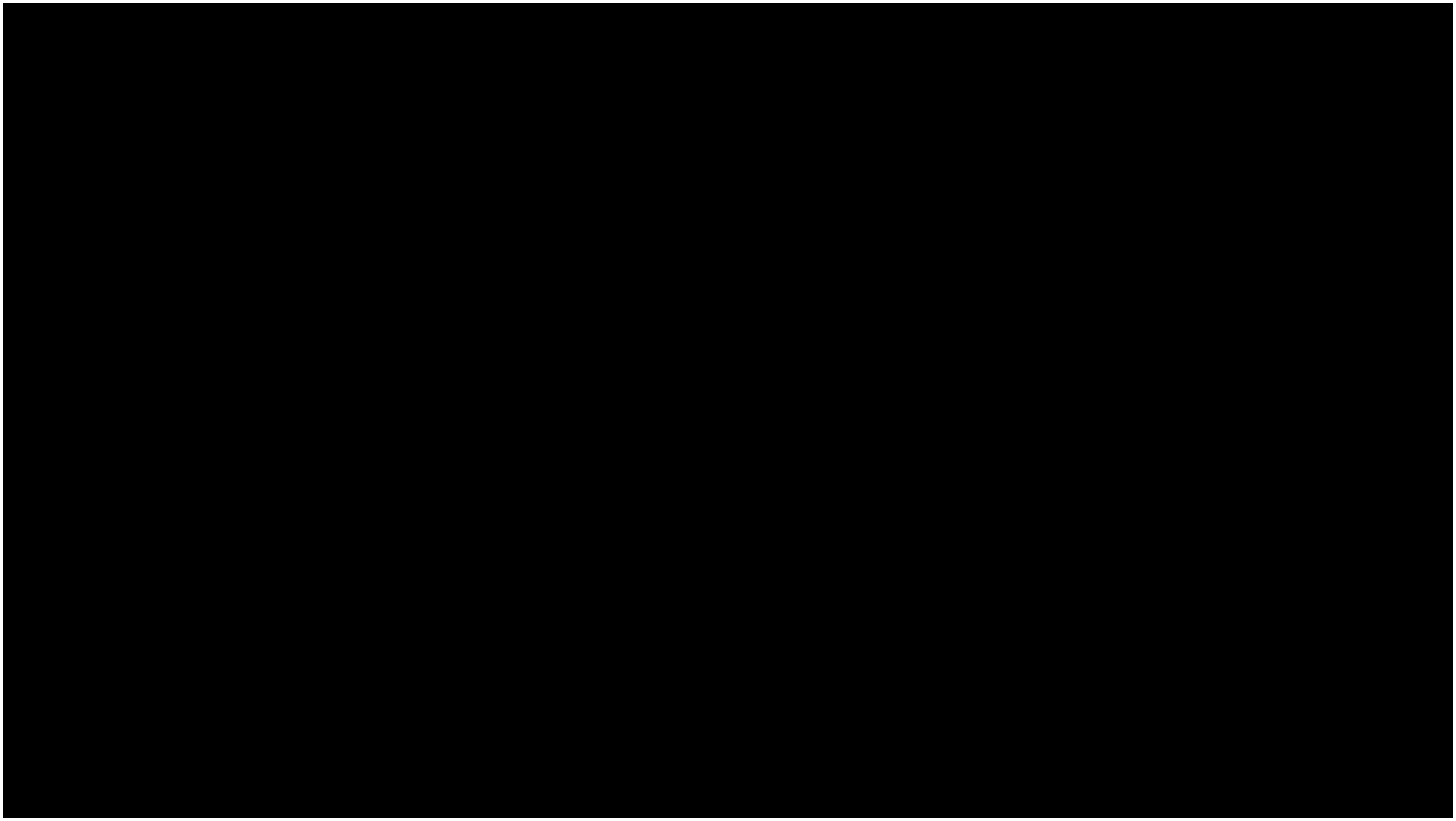


LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

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

Gravity's music



Thanks!

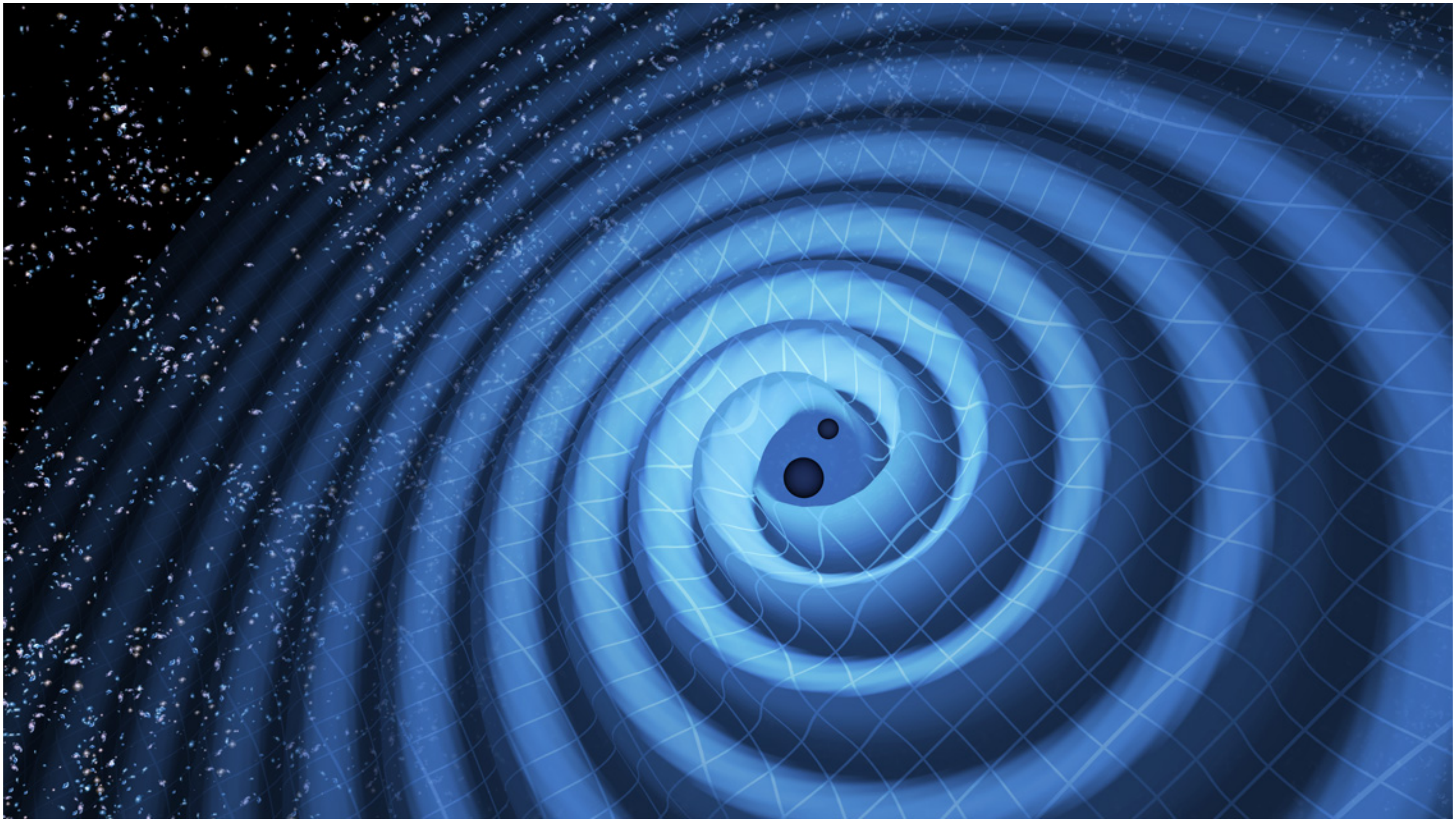


Image credit: LIGO/T. Pyle

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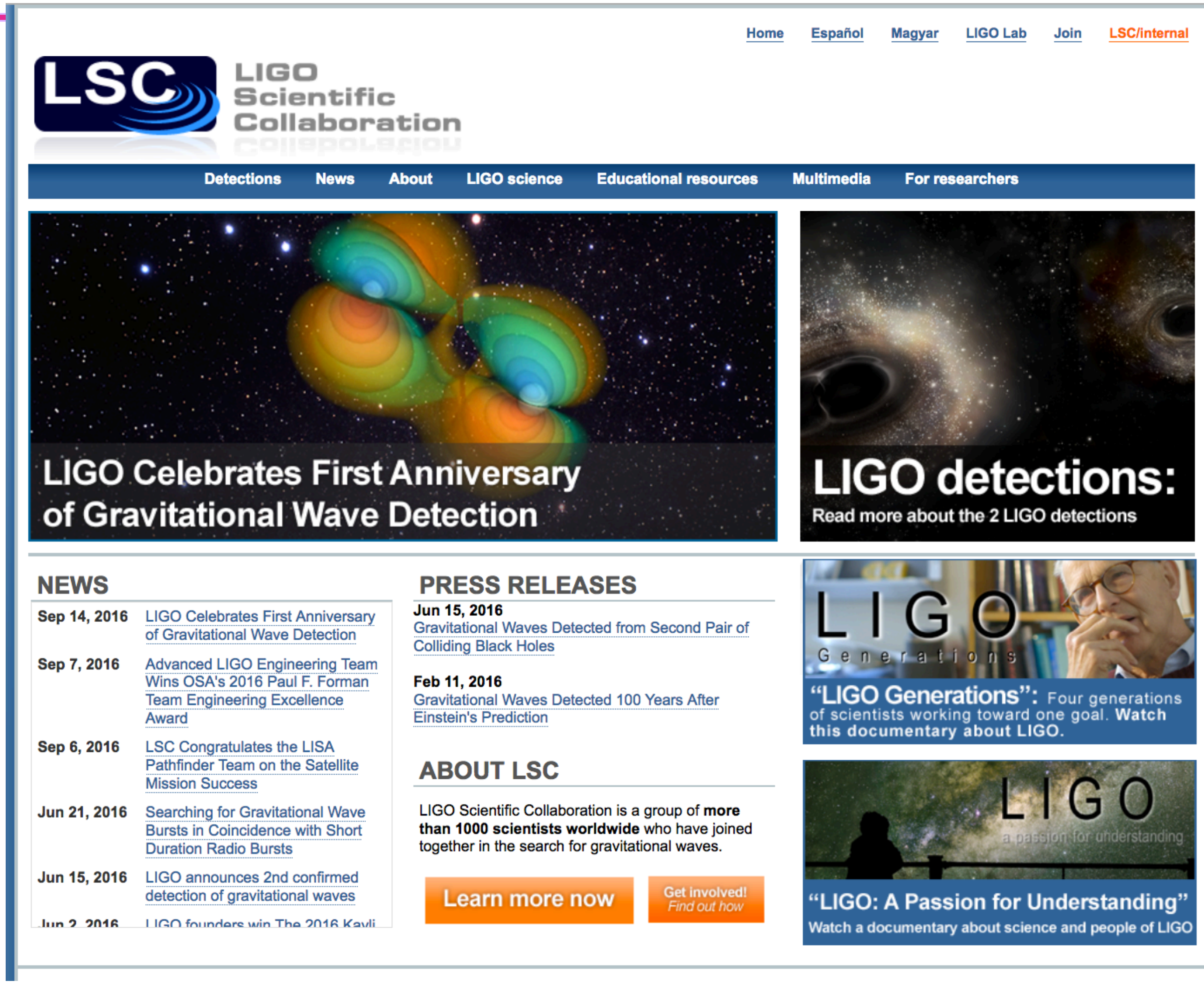
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a passion for understanding
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