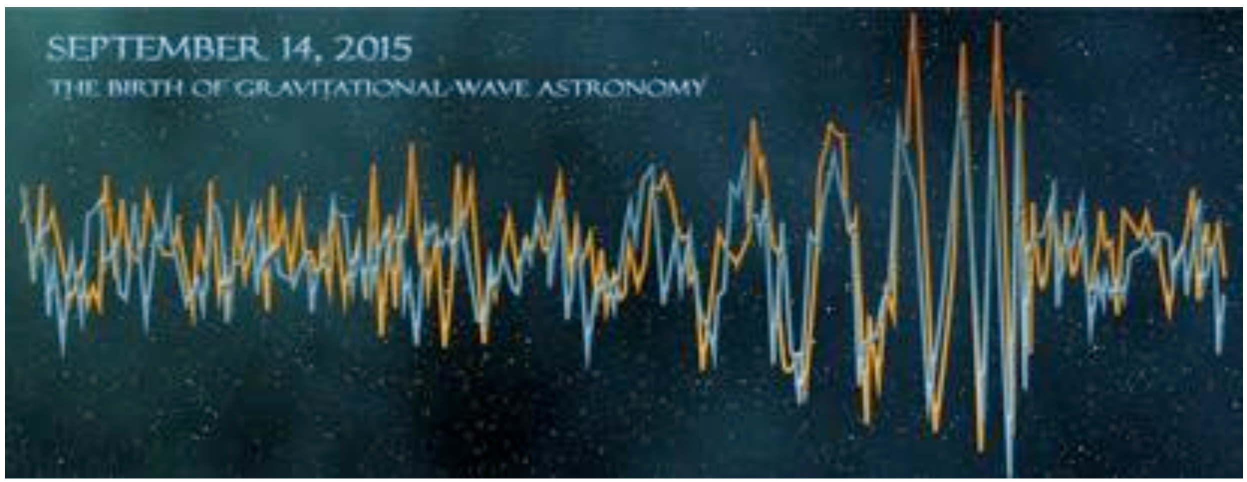
Gravitational-wave astronomy

Gabriela González

Louisiana State University

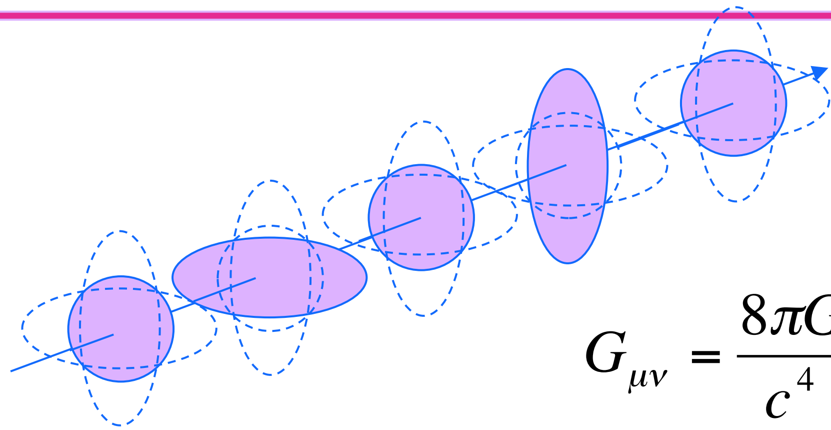
ESAC, July 12 2018



esac european space astronomy centre

esa

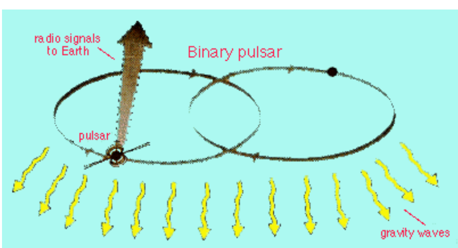
Gravitational waves

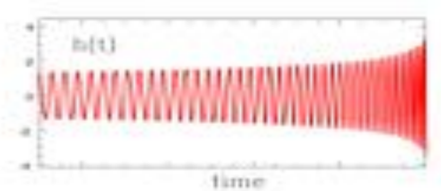


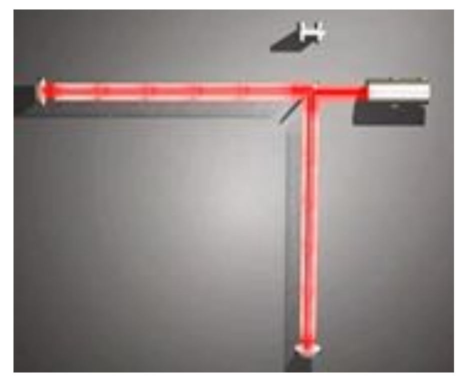
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

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

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

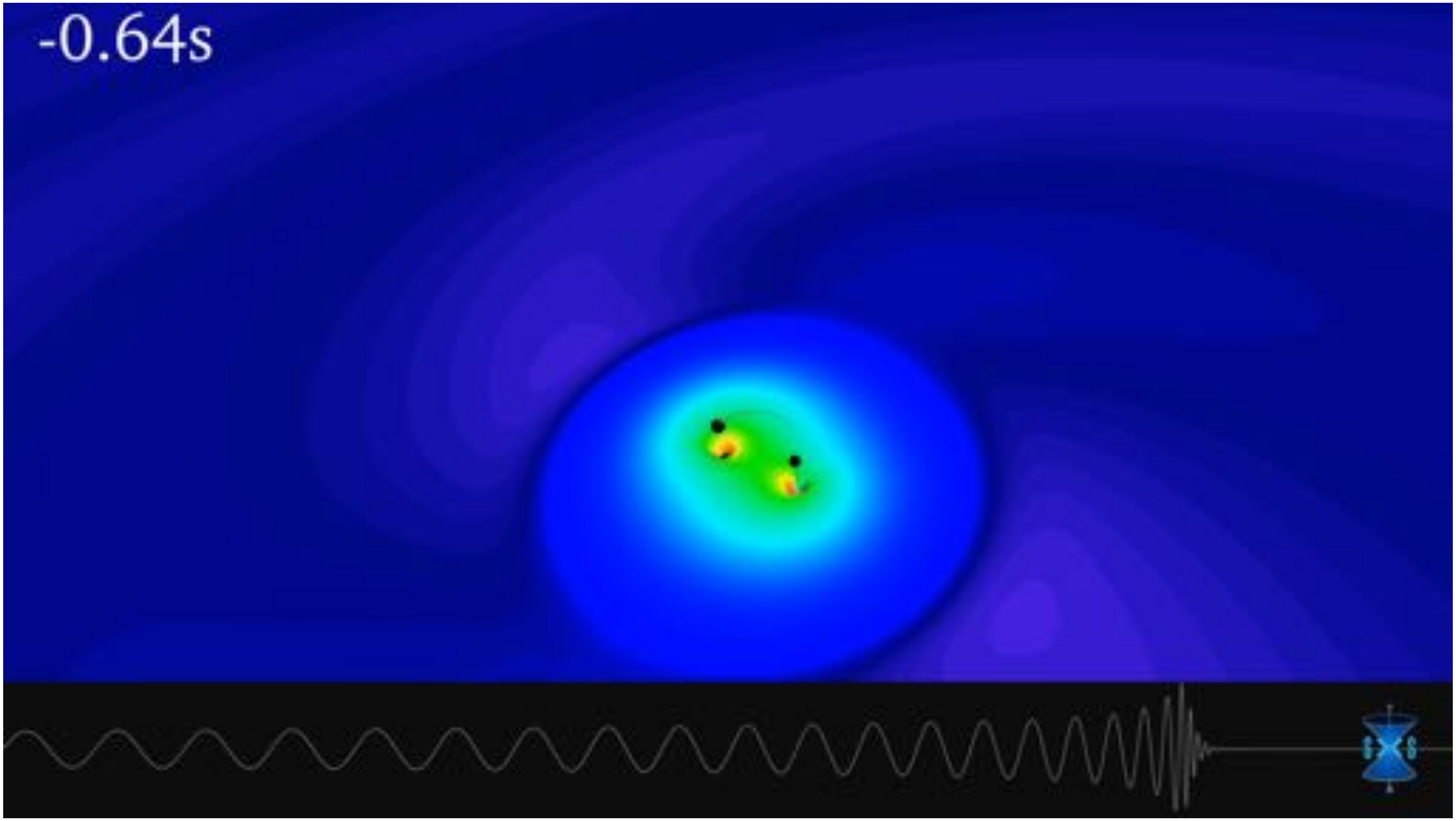






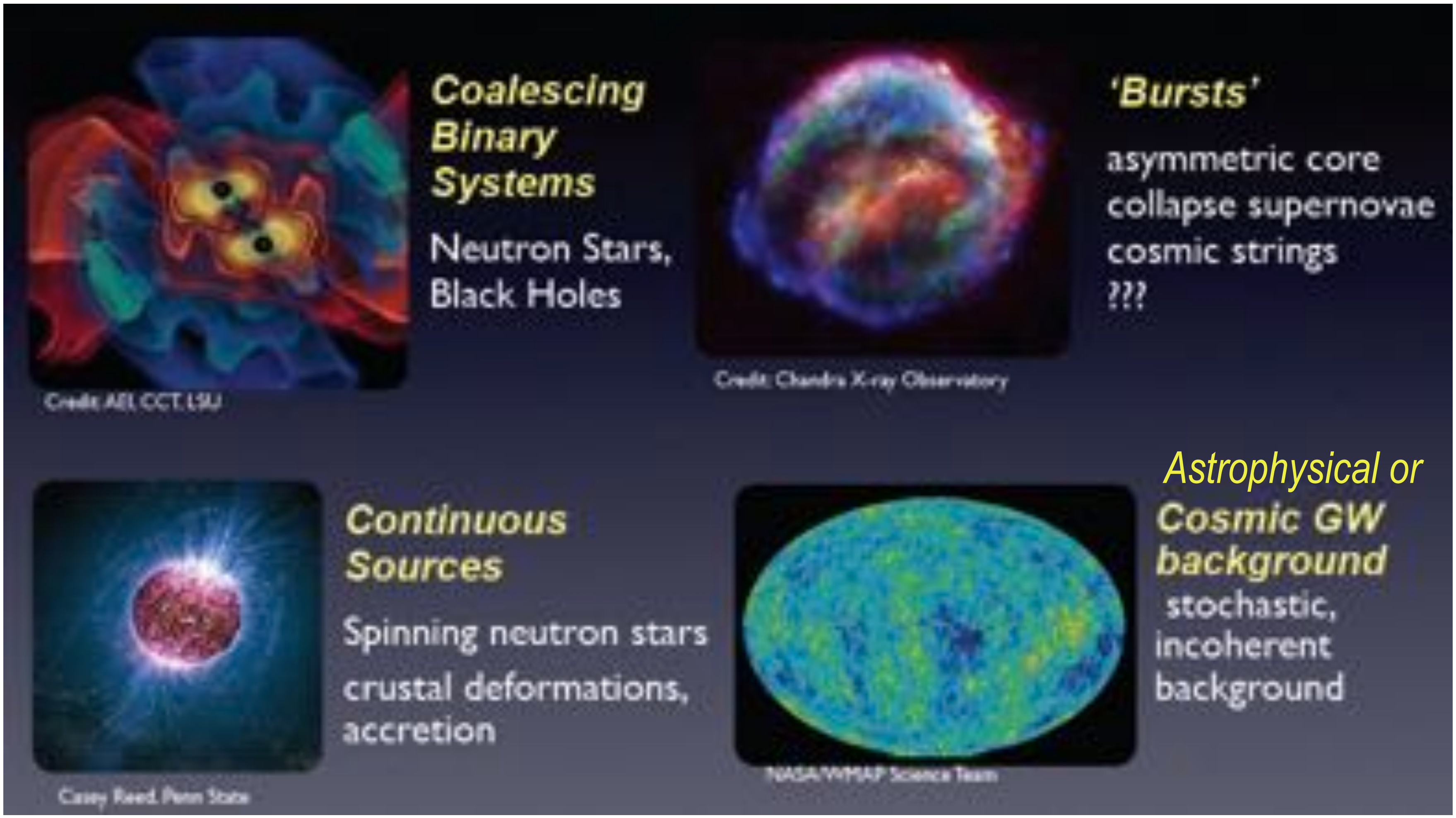
GWs from a NS-NS coalescence in the Virgo cluster (~16 MPc) has h ~ 10^{-21} near Earth, and happens ~once every 50 years.

Numerical simulations



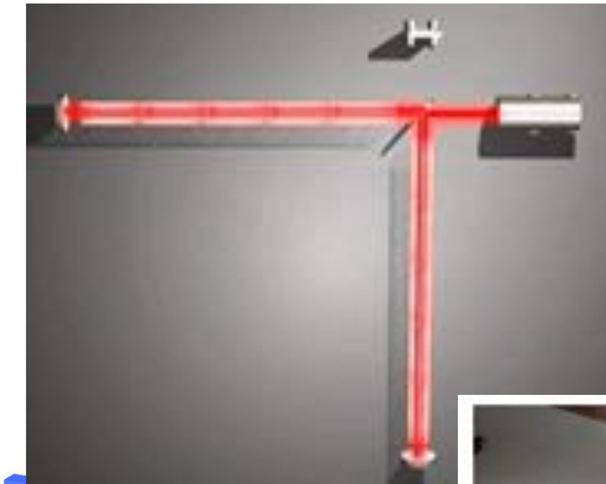
Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

Sources of gravitational waves

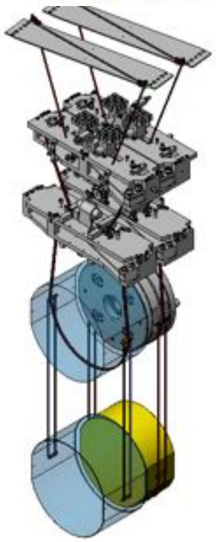


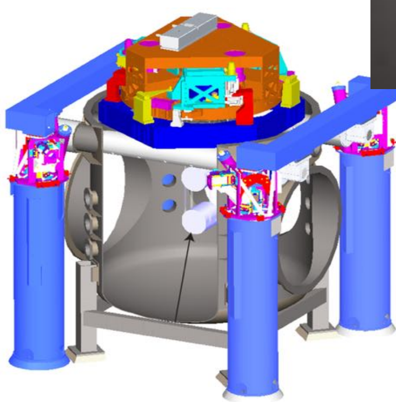
The LIGO Observatories
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms
10 ms
LIGO Livingston Observatory (LLO)
L1 : 4 km arms
Adapted from "The Blue Marble: Land Surface, Ocean Colo
nasa.gov
NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow wa
mmon (ocean
color, compositing, 3D globes, animation). Data and technical support: MODIS Land
n; MODIS
Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center
ensing Flagstaff
Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

2008+:
Advanced LIGO detectors

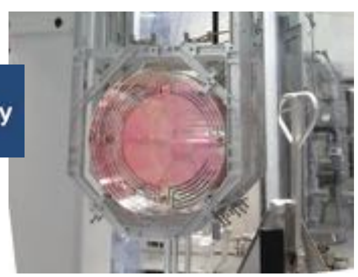


MAX-PLANCK-GESELLSCHAFT



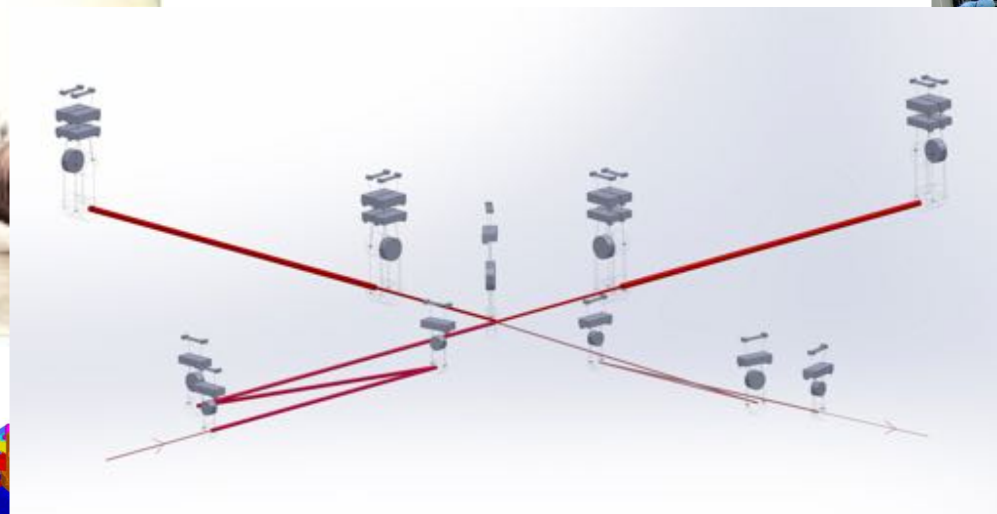


Science & Technology Facilities Council

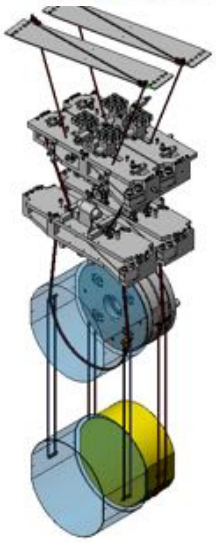


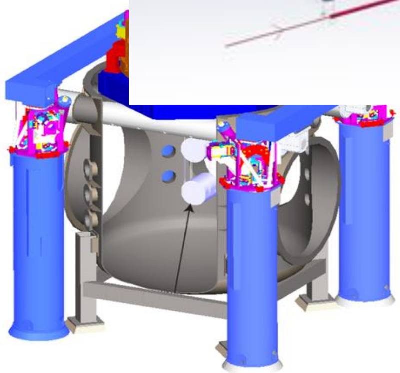
NSF

2008+:
Advanced LIGO detectors

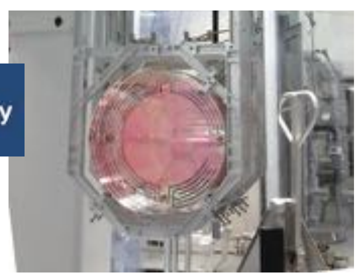


MAX-PLANCK-GESELLSCHAFT



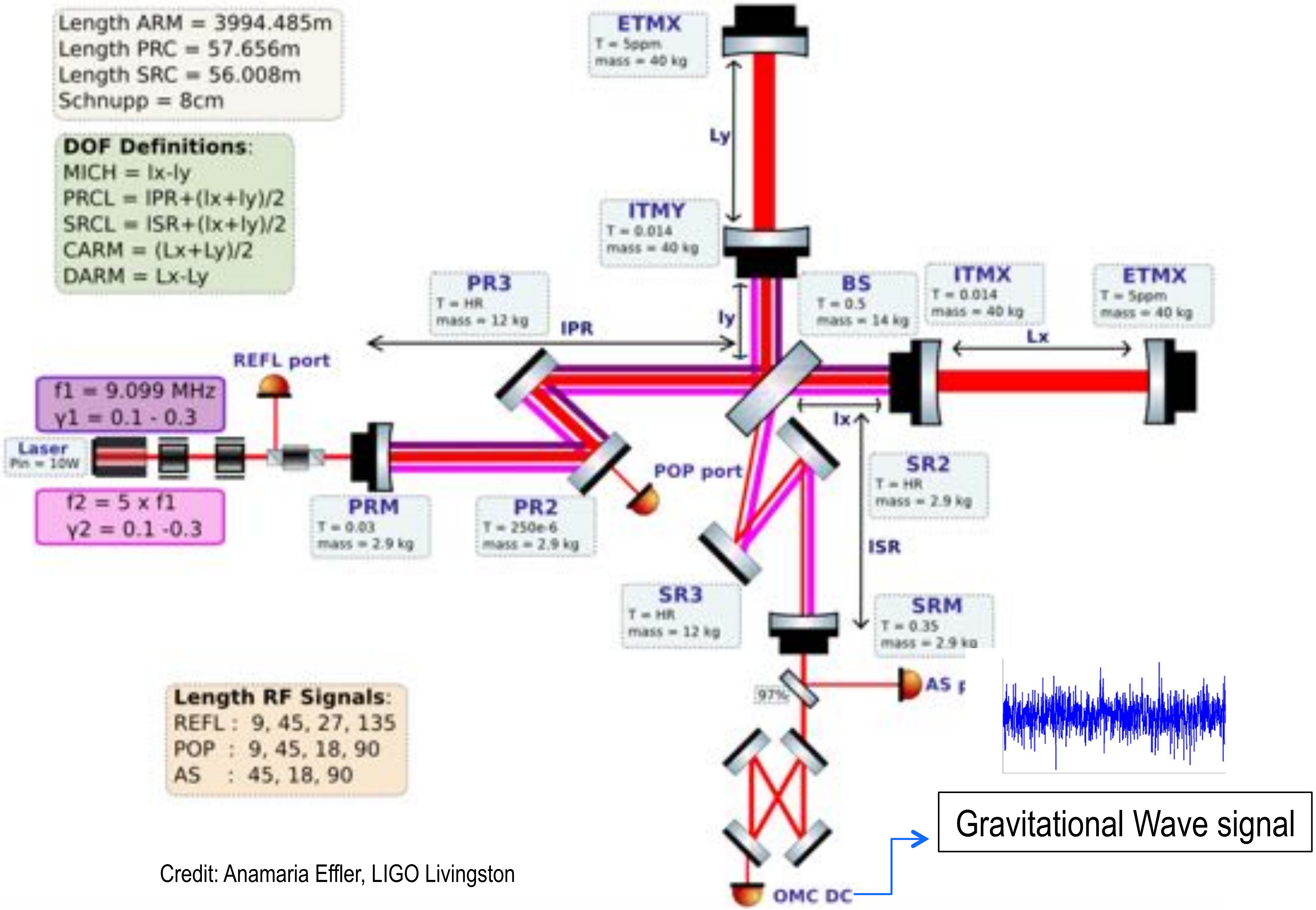


Science & Technology Facilities Council



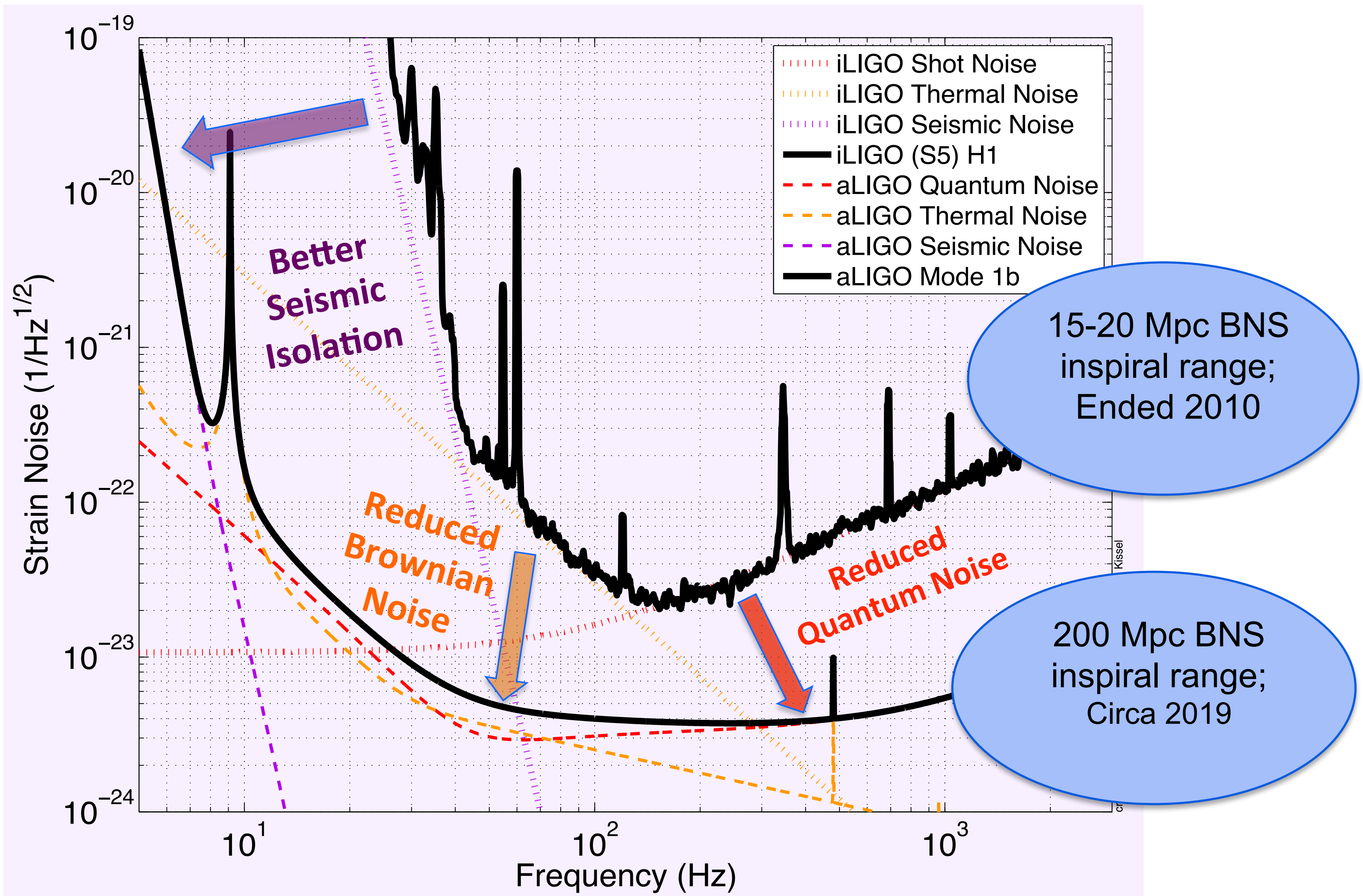
NSF

Advanced LIGO = Servo Control

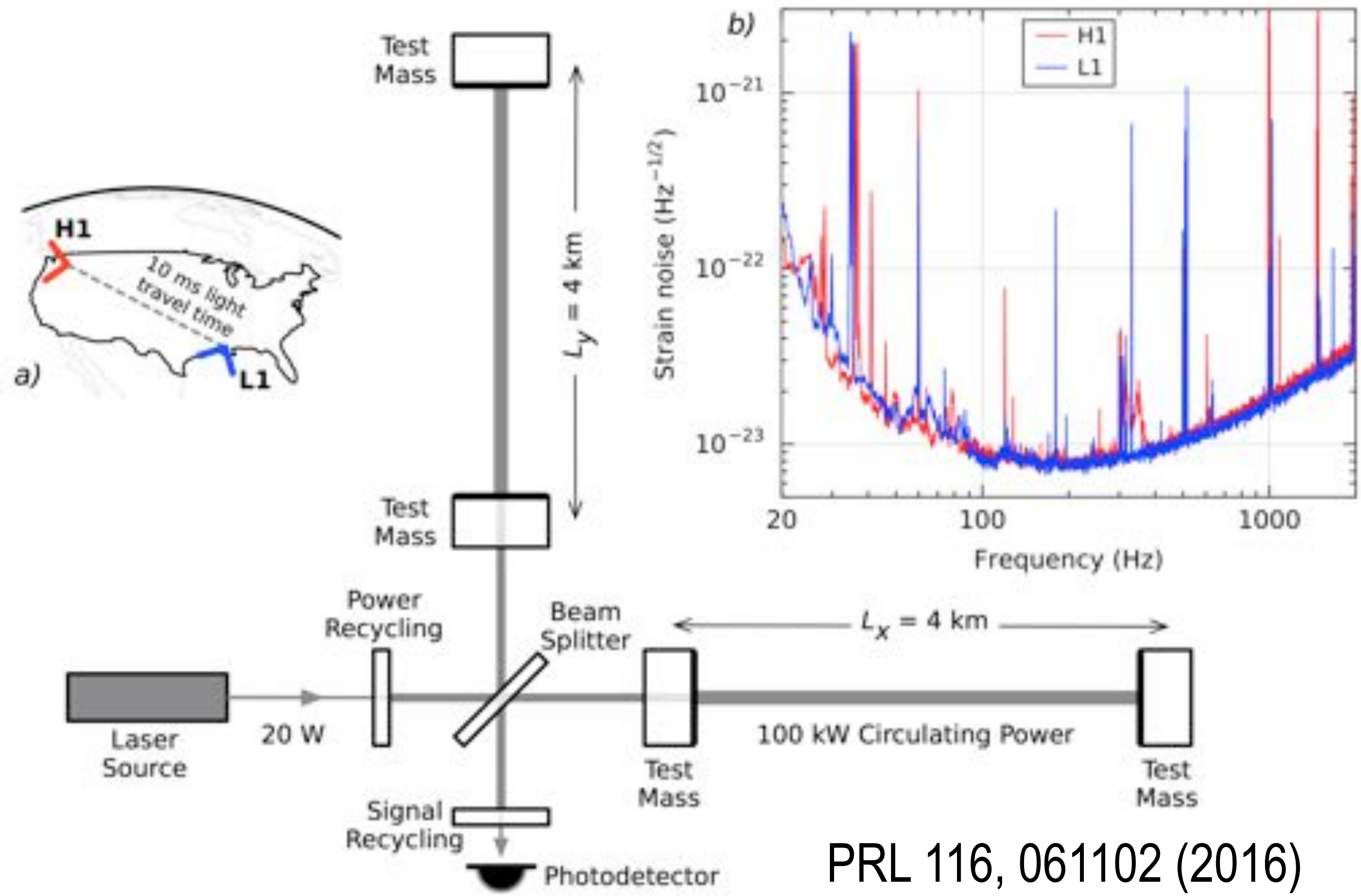


Credit: Anamaria Effler, LIGO Livingston

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



Advanced LIGO detectors
September 2015

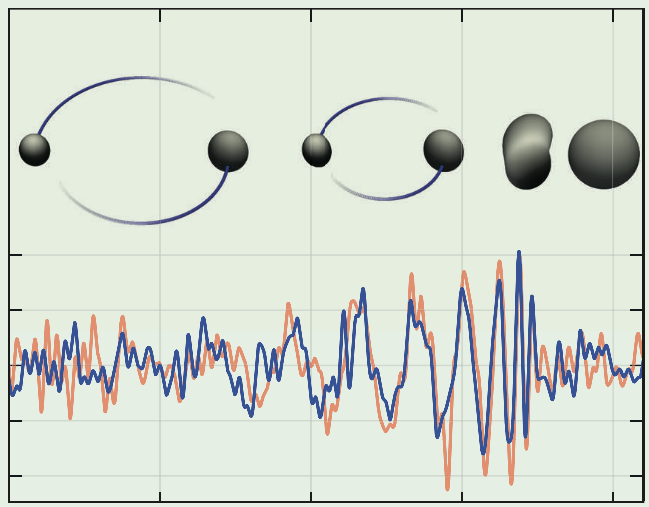


PRL 116, 061102 (2016)

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)



Published by
American Physical Society™
APS physics
Volume 116, Number 6

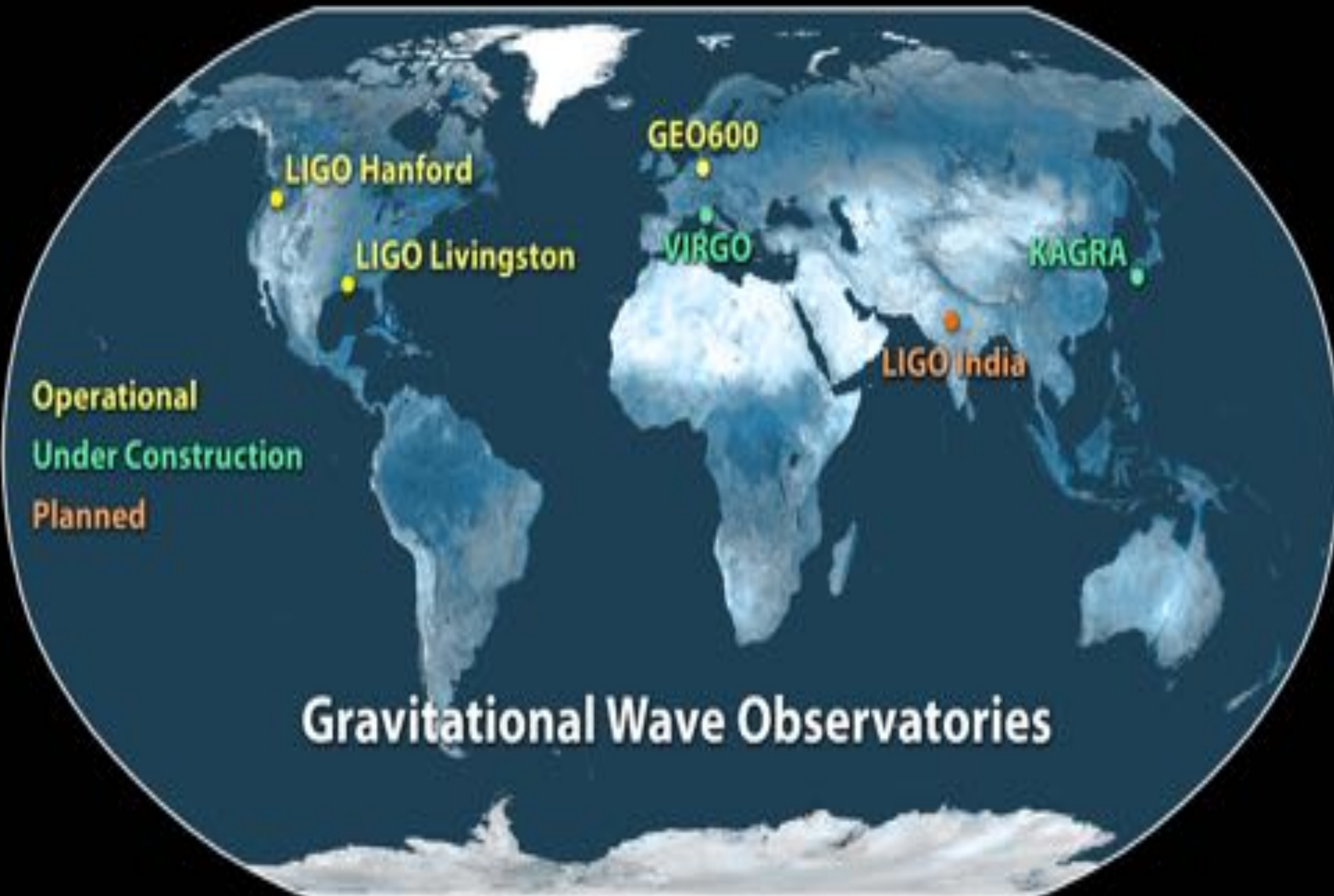


Image Credit: Caltech/MIT/LIGO Lab

LIGO Scientific Collaboration

LIGO

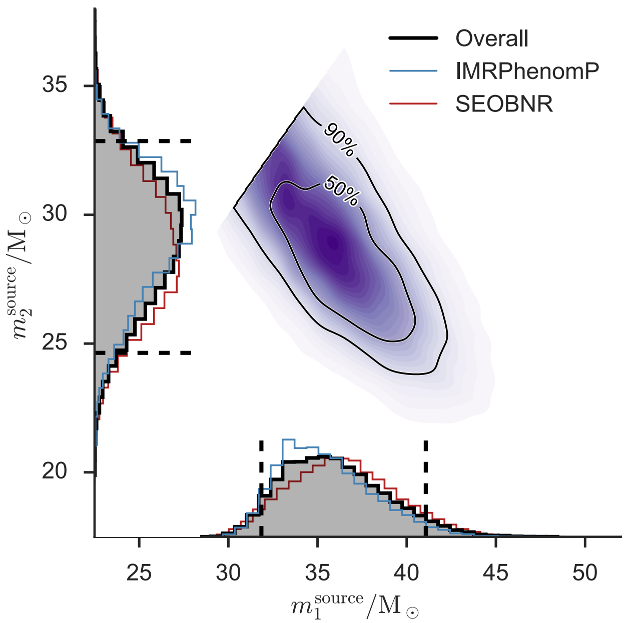
LSC

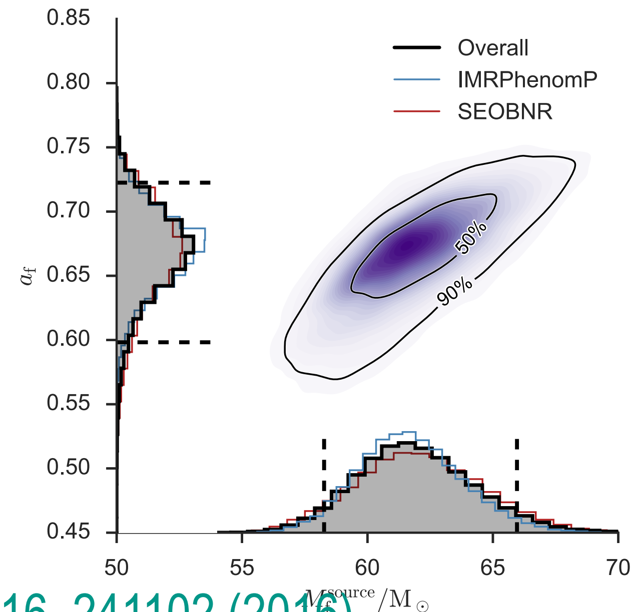
Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
Whitman College
American University Washington, DC
University of the West of Scotland UWS
Texas Tech University
Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics Albert Einstein Institute
University of Strathclyde
Michigan
CITA ICAT
Università degli Studi del Sannio
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
University of Cambridge
The University of Chicago
Montana State University
Southern University 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
GEO 600
UIB Universitat de les Illes Balears
University of Washington
UTRGV
UW Milwaukee University of Wisconsin
Syracuse University
Cardiff University Prifysgol Caerdydd
Northwestern
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
Science & Technology Facilities Council Rutherford Appleton Laboratory

Image credit: LIGO

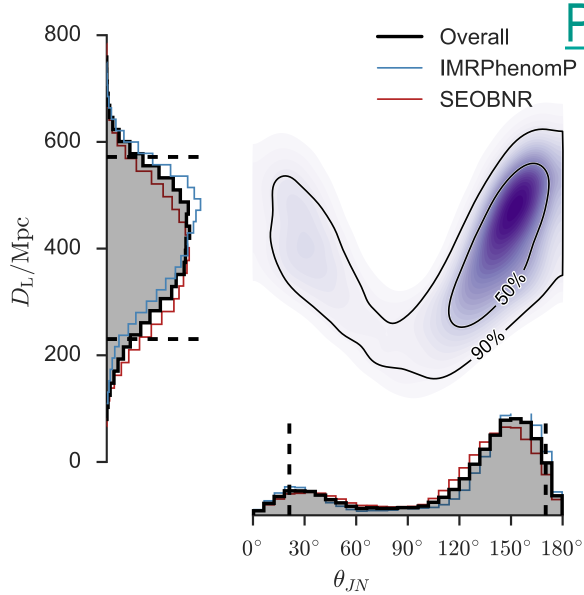
Gravity's music

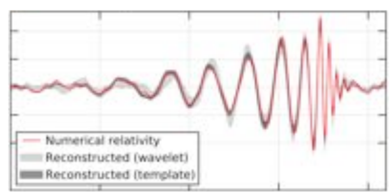
Finding parameters: GW150914

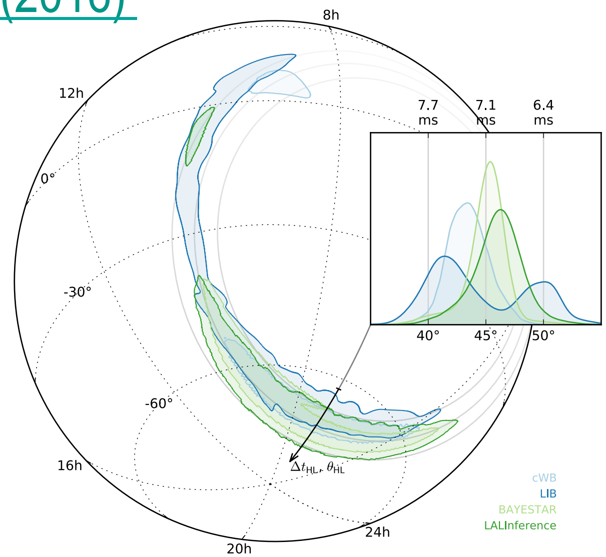




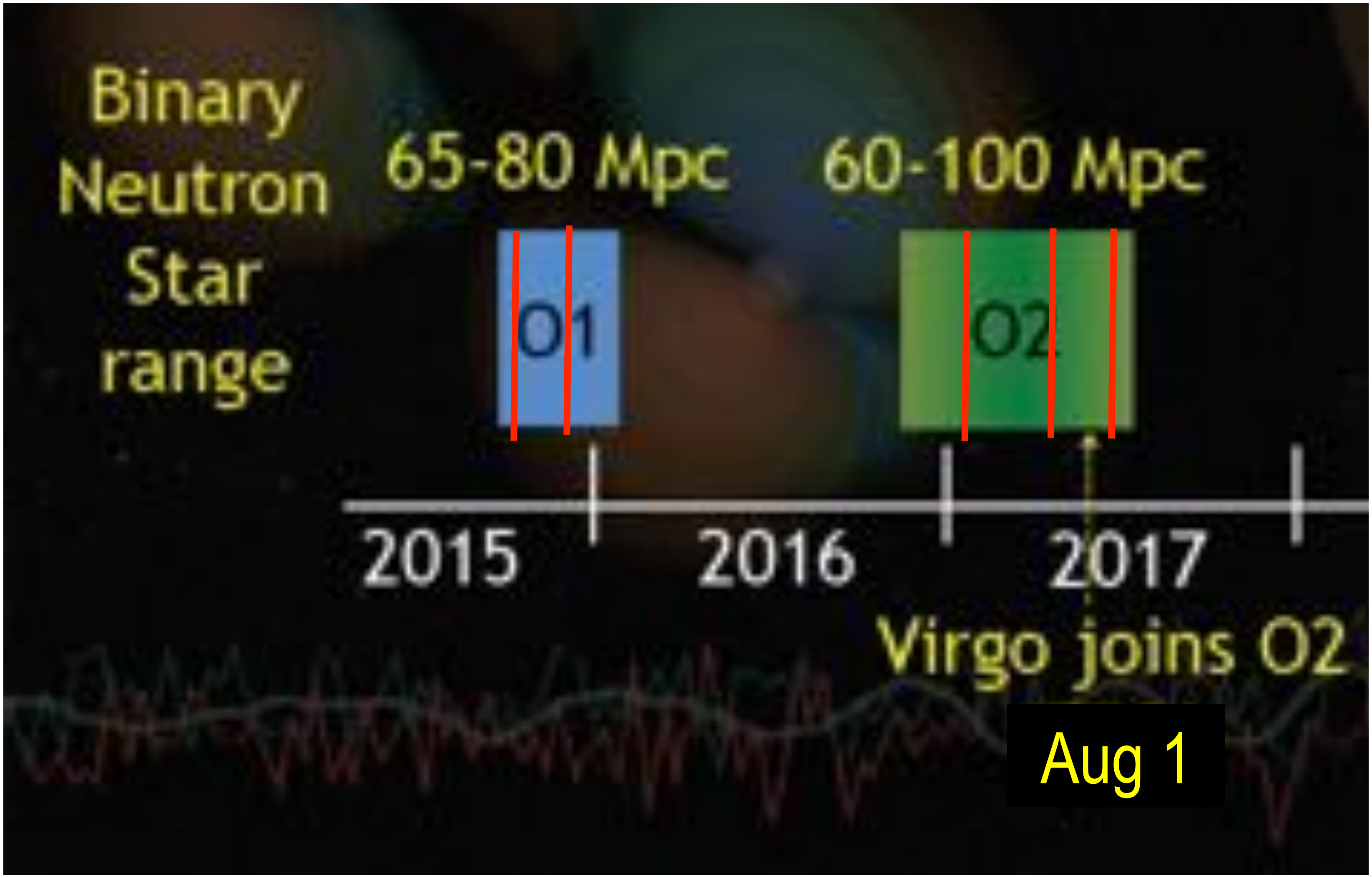
[Phys. Rev. Lett. 116, 241102 (2016)]



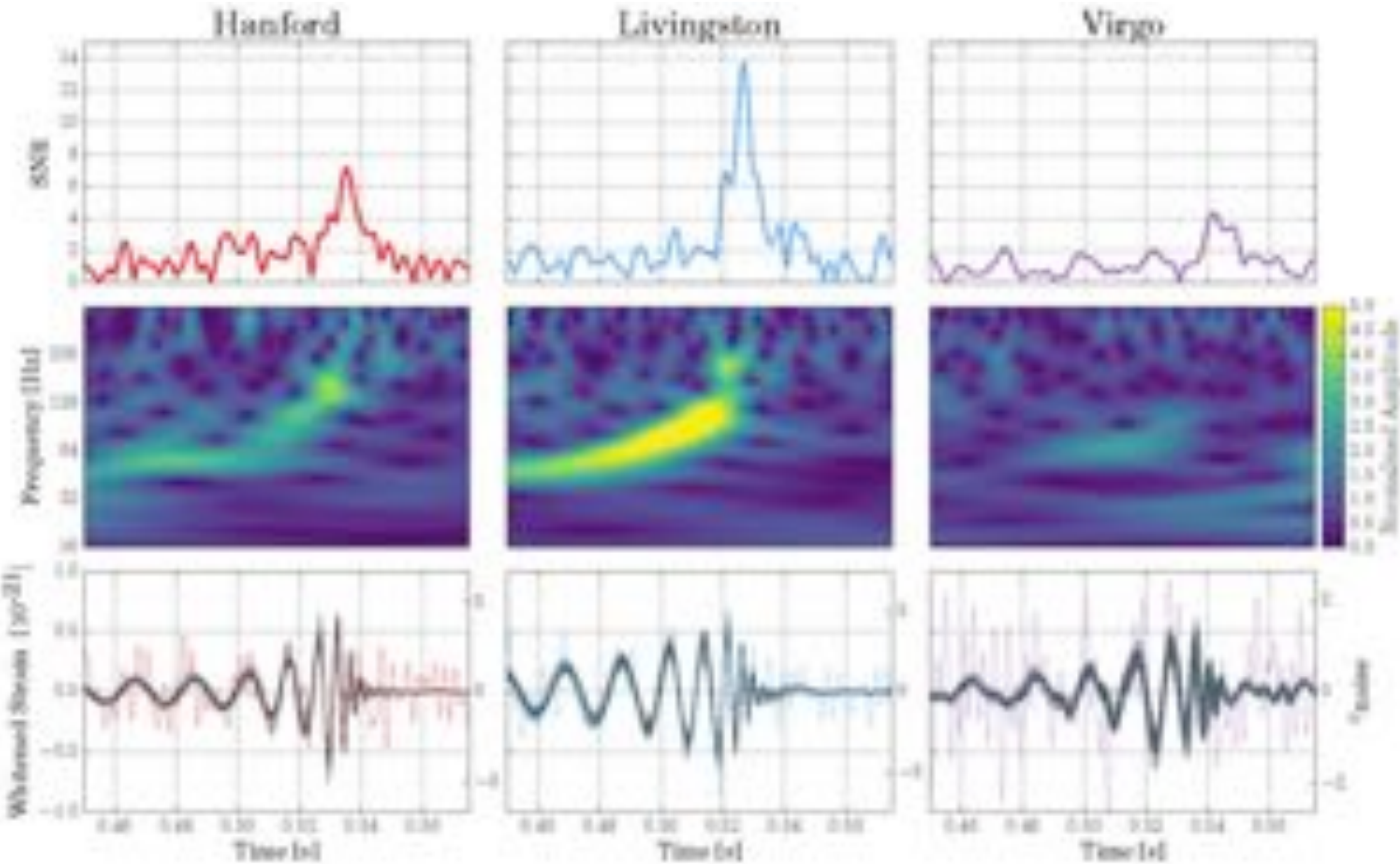




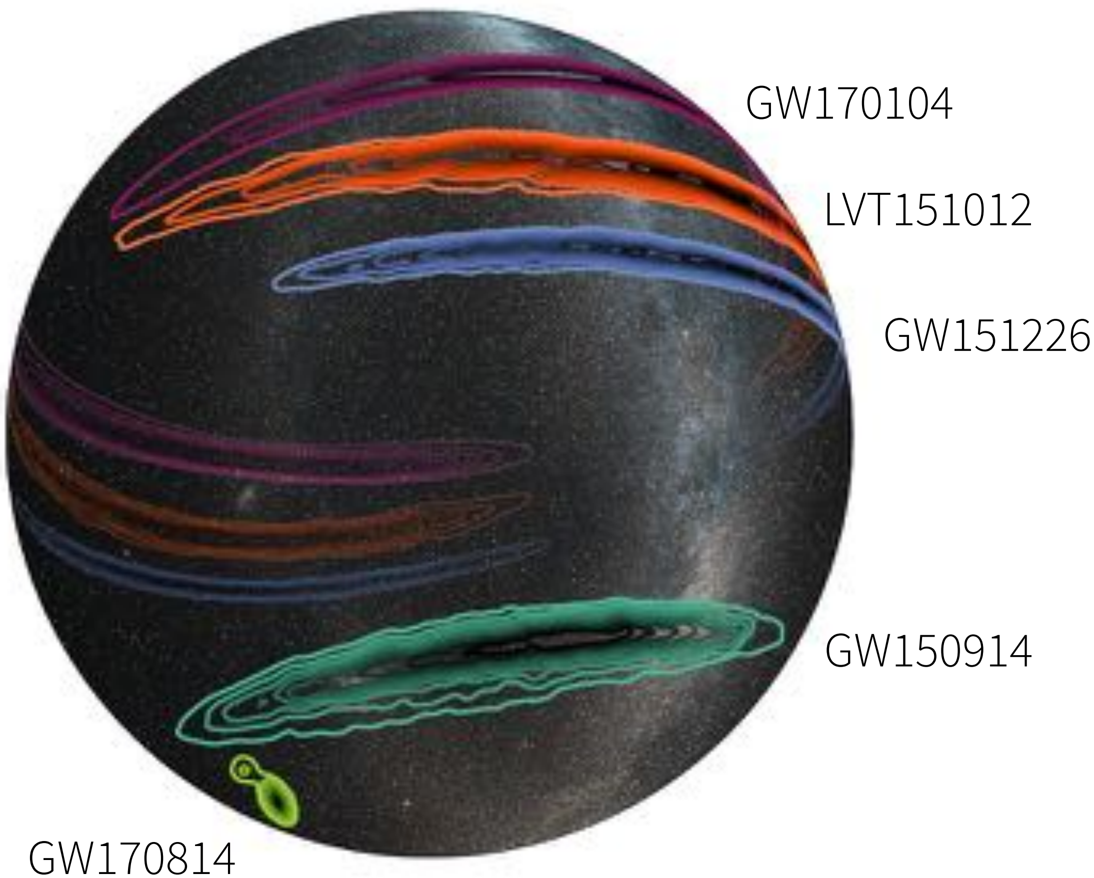
Nov 30, 2016: O2 started



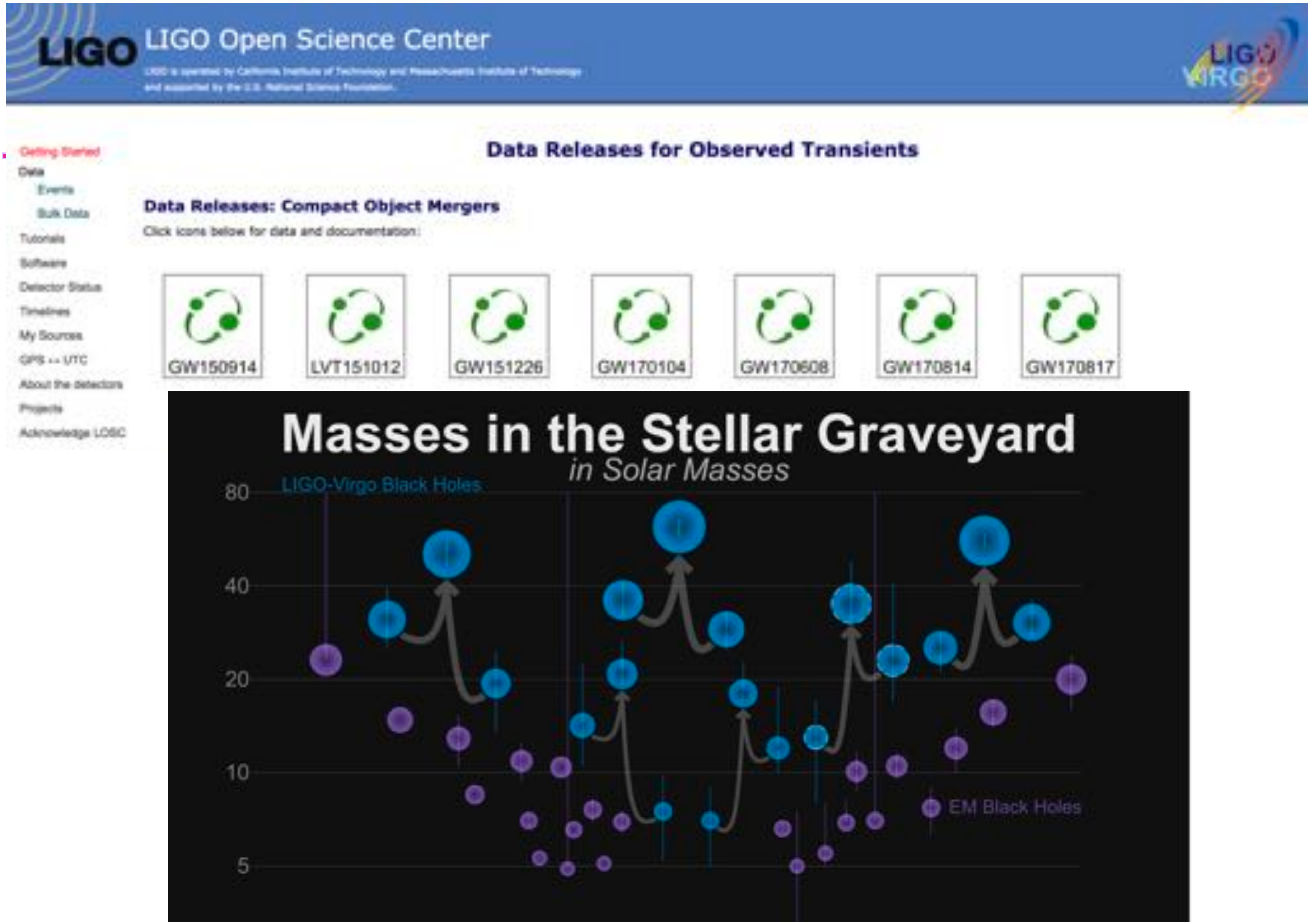
GW170814



Sky localization

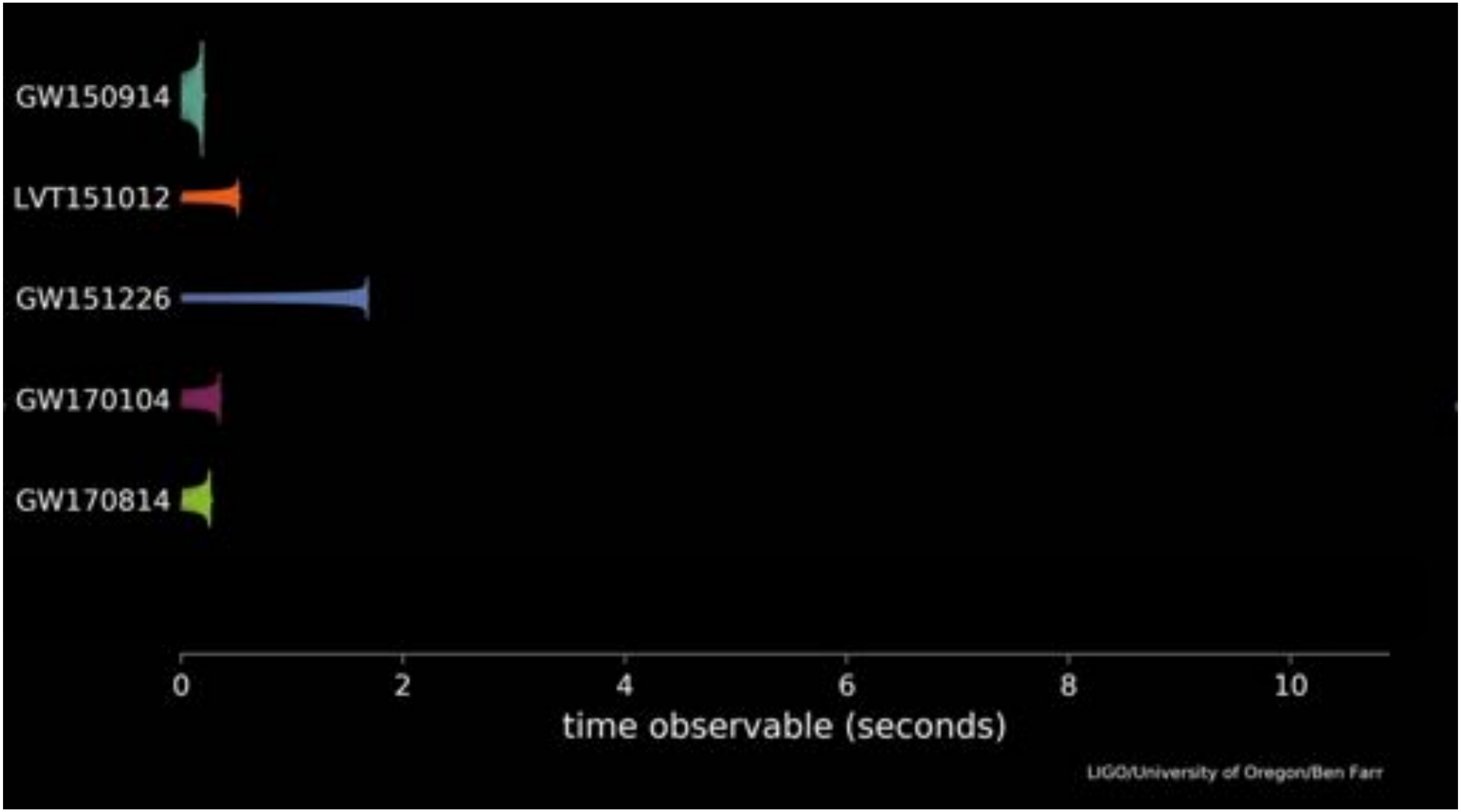


Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

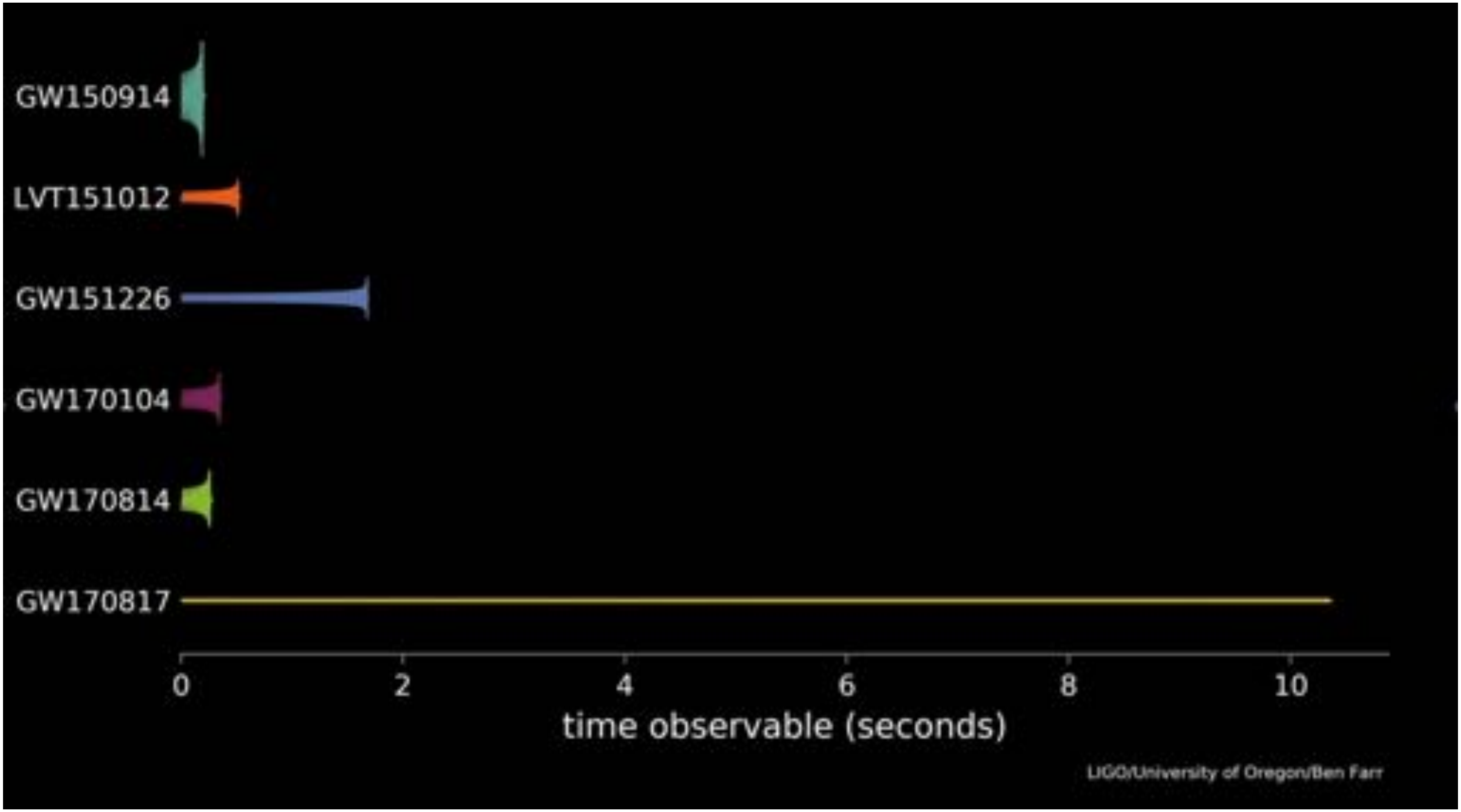


Credit: Visualization: LIGO/Frank Elavsky/Northwestern
EM Black Holes: https://stellarcollapse.org/sites/default/files/table.pdf | LIGO-Virgo Data: https://losc.ligo.org/events/

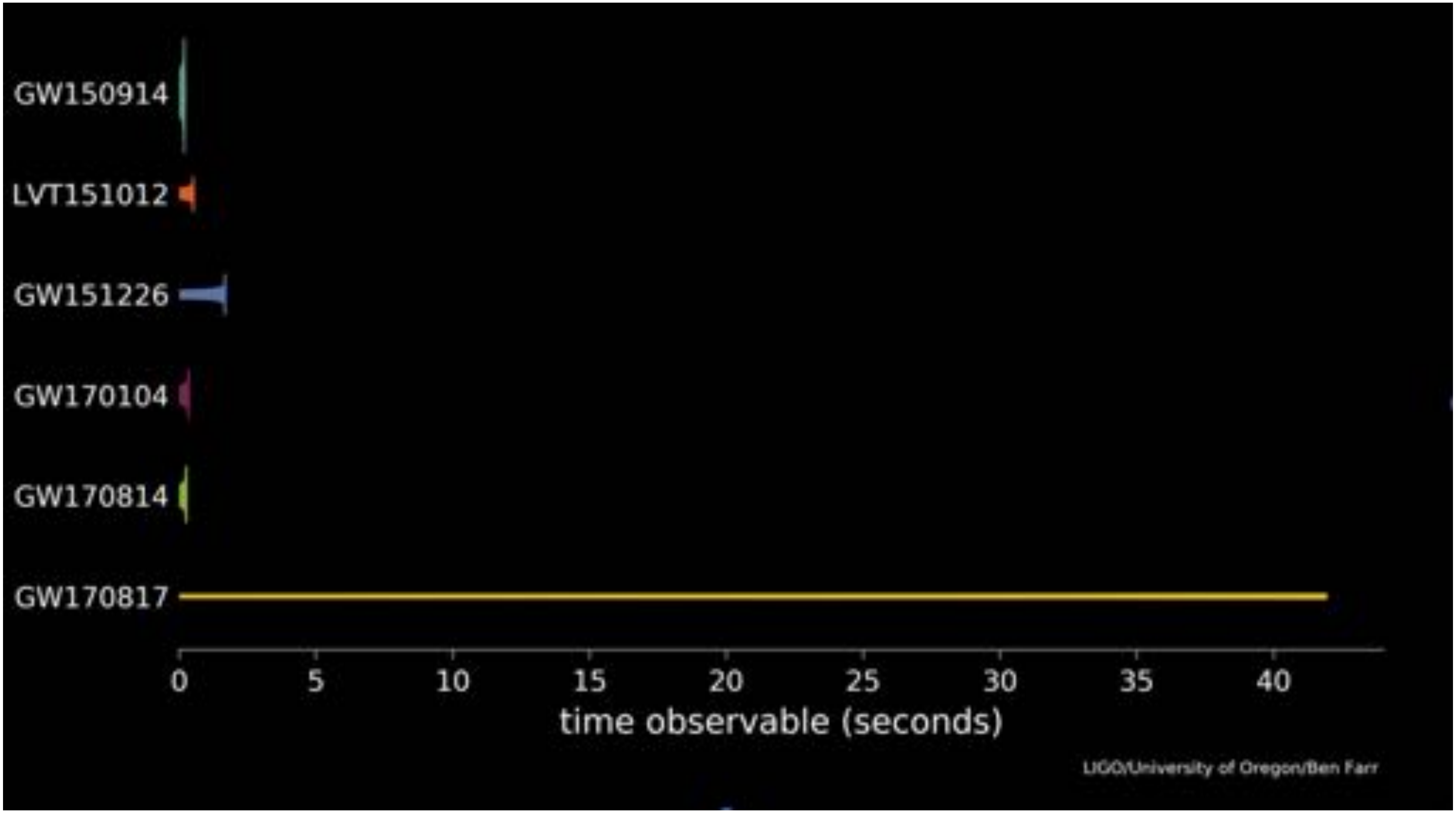
Gravitational waves from black holes



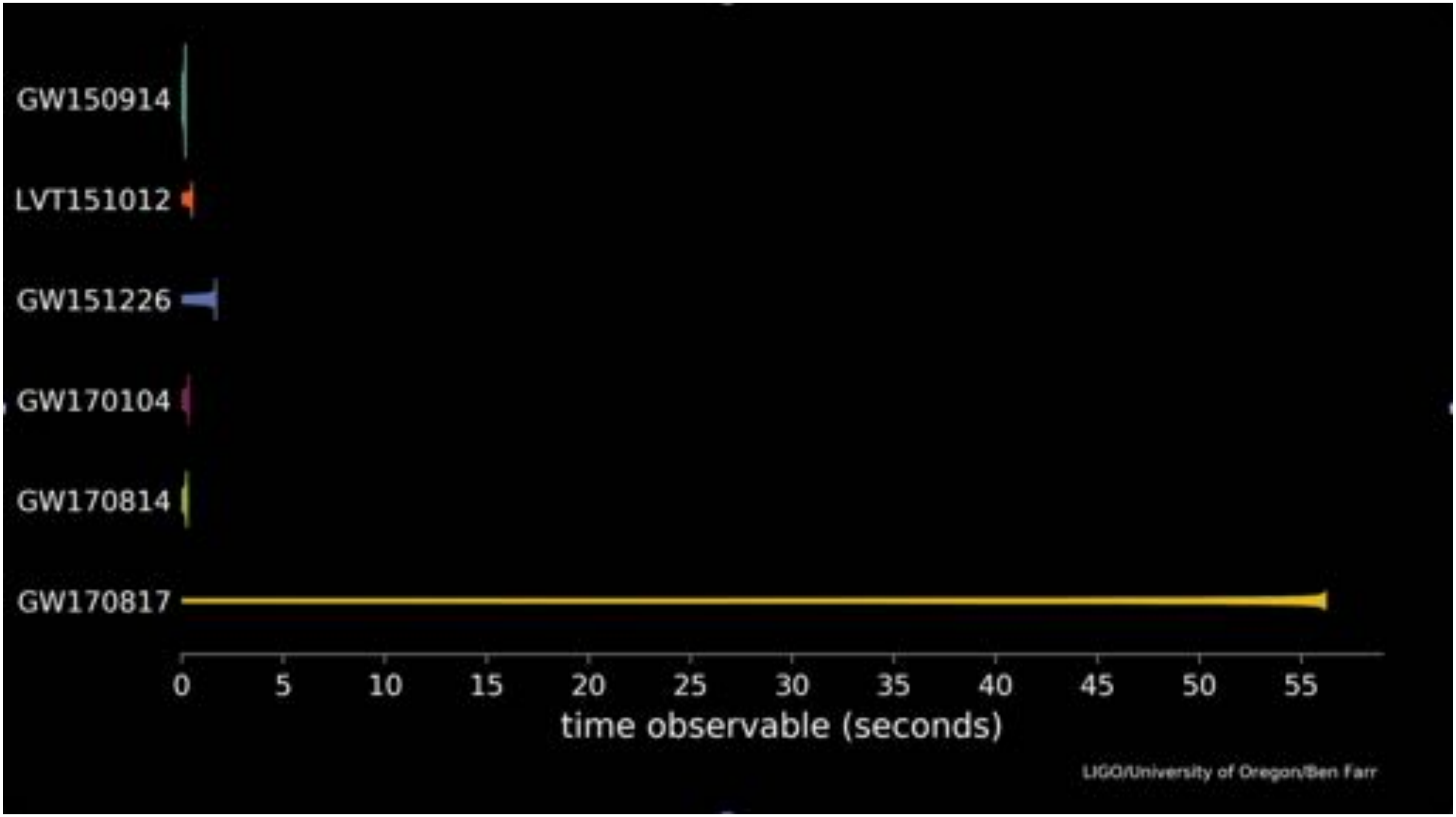
And on Aug 17, 2017…



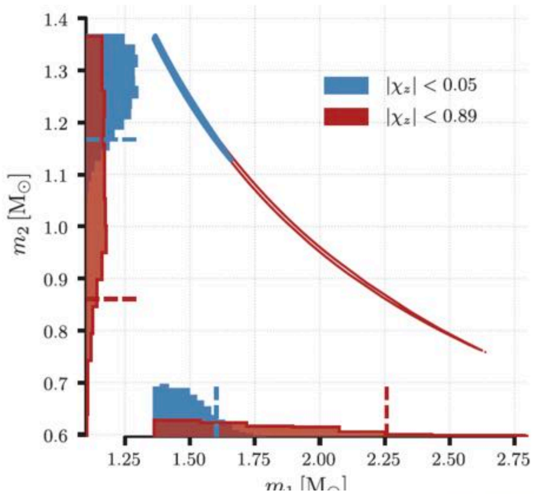
Gravitational waves : not just black holes!

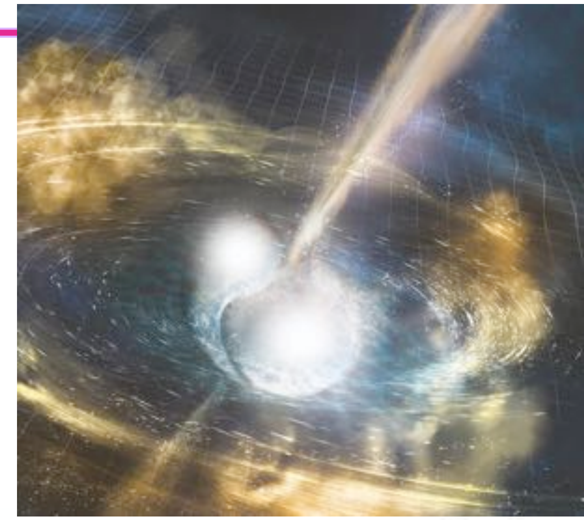


Gravitational waves : not just black holes!



GW170817



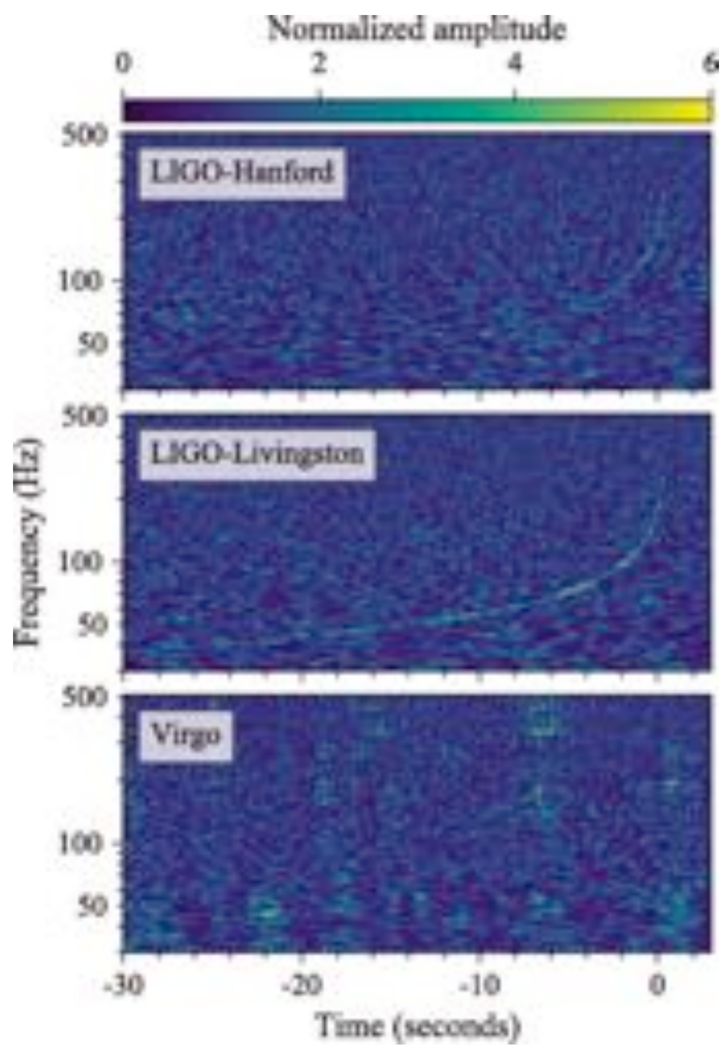


PRL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

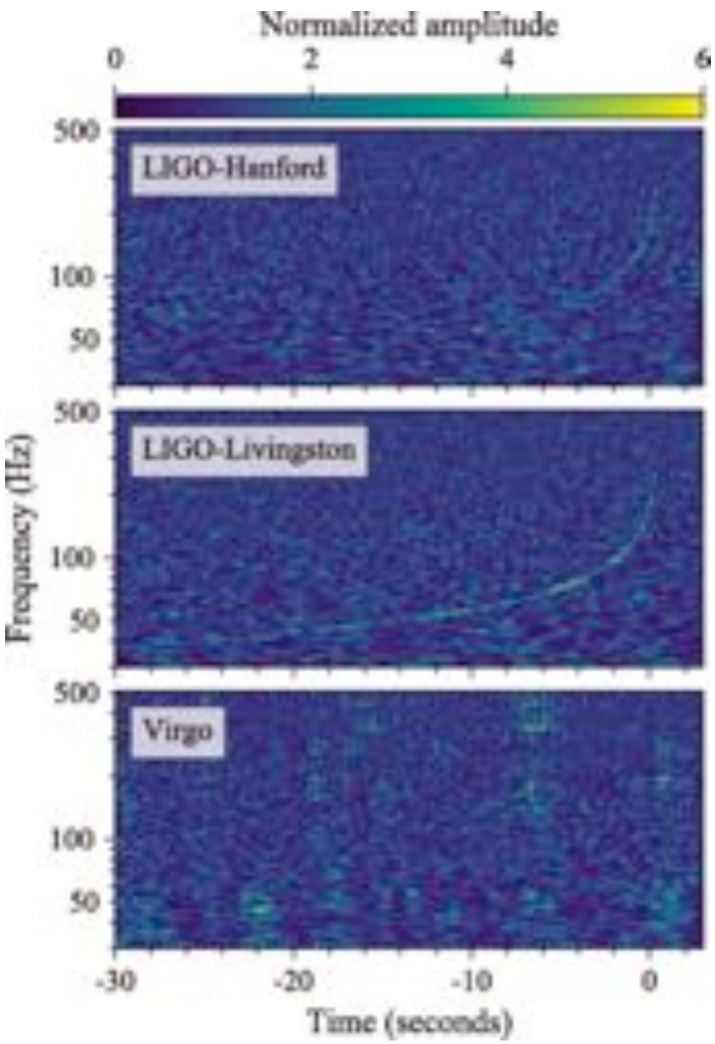
	Low-spin priors ($\lvert\chi\rvert \le 0.05$)	High-spin priors ($\lvert\chi\rvert \le 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\le 55°$	$\le 56°$

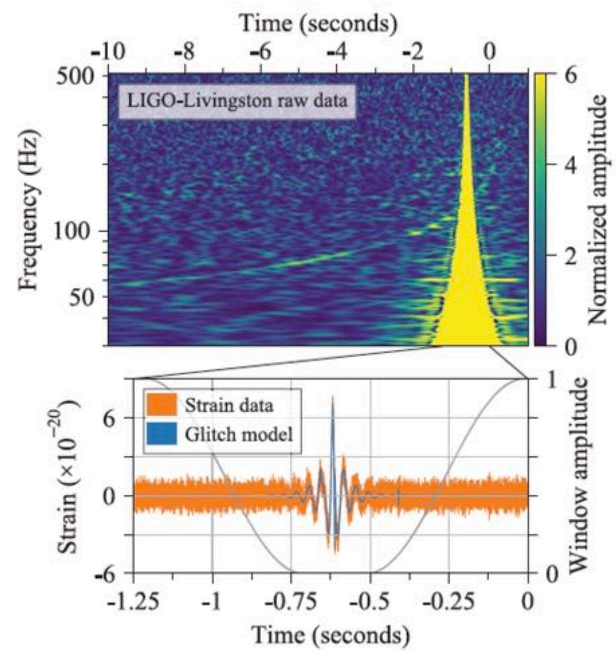
GW170817



[Phys. Rev. Lett. 119, 161101 (2017)]

GW170817

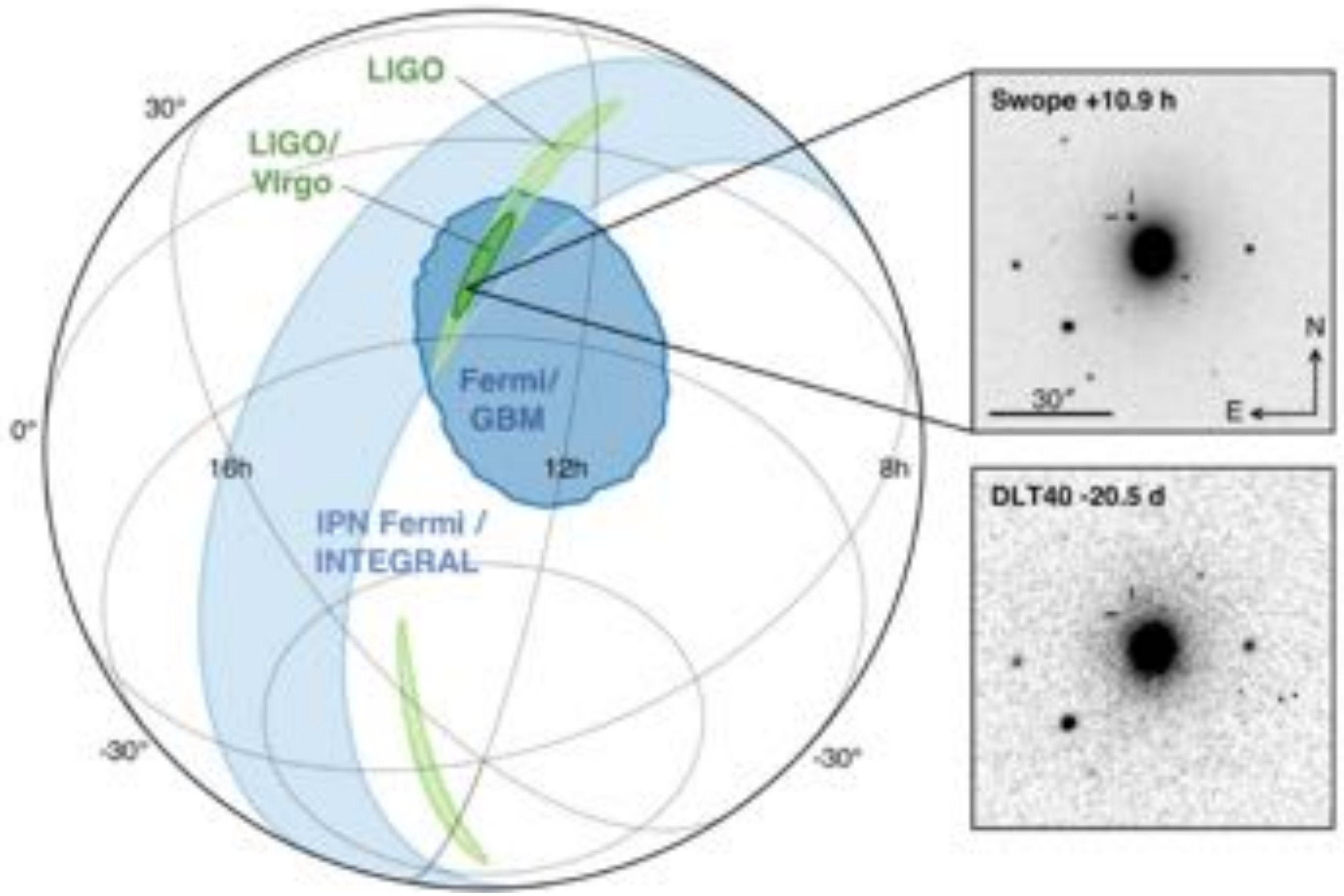


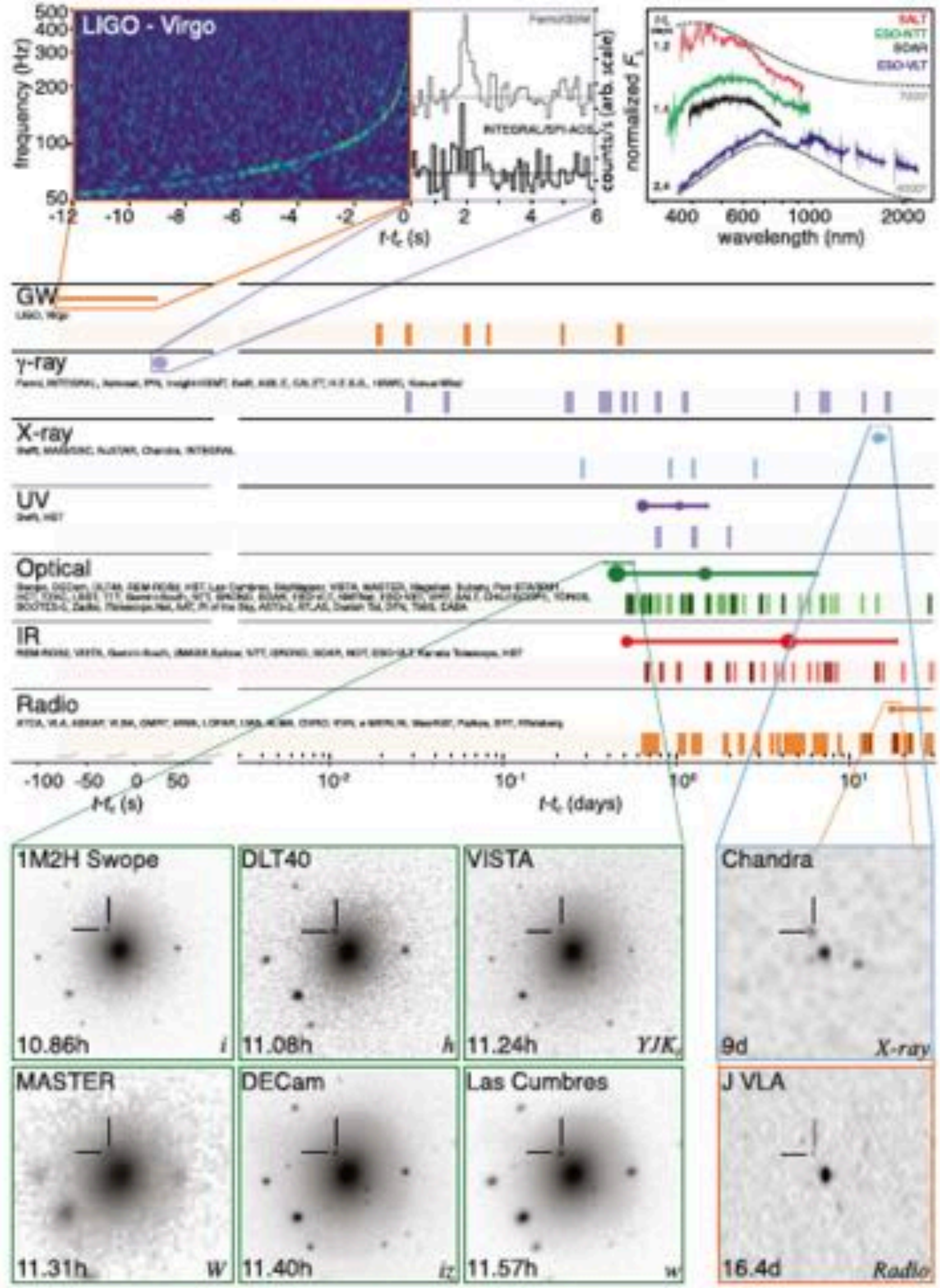


Phys. Rev. Lett. 119, 161101 (2017)

LIGO/Virgo localization: optical counterpart found!

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20




LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
$t-t_c$ (s)
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
400
600
1000
2000
wavelength (nm)
GW
γ-ray
X-ray
UV
Optical
IR
Radio
-100
-50
0
50
$t-t_c$ (s)
10^{-2}
10^{-1}
10^{0}
10^{1}
$t-t_c$ (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

Gravitational *and* Electromagnetic waves!

PRL 119, 161101 (2017)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

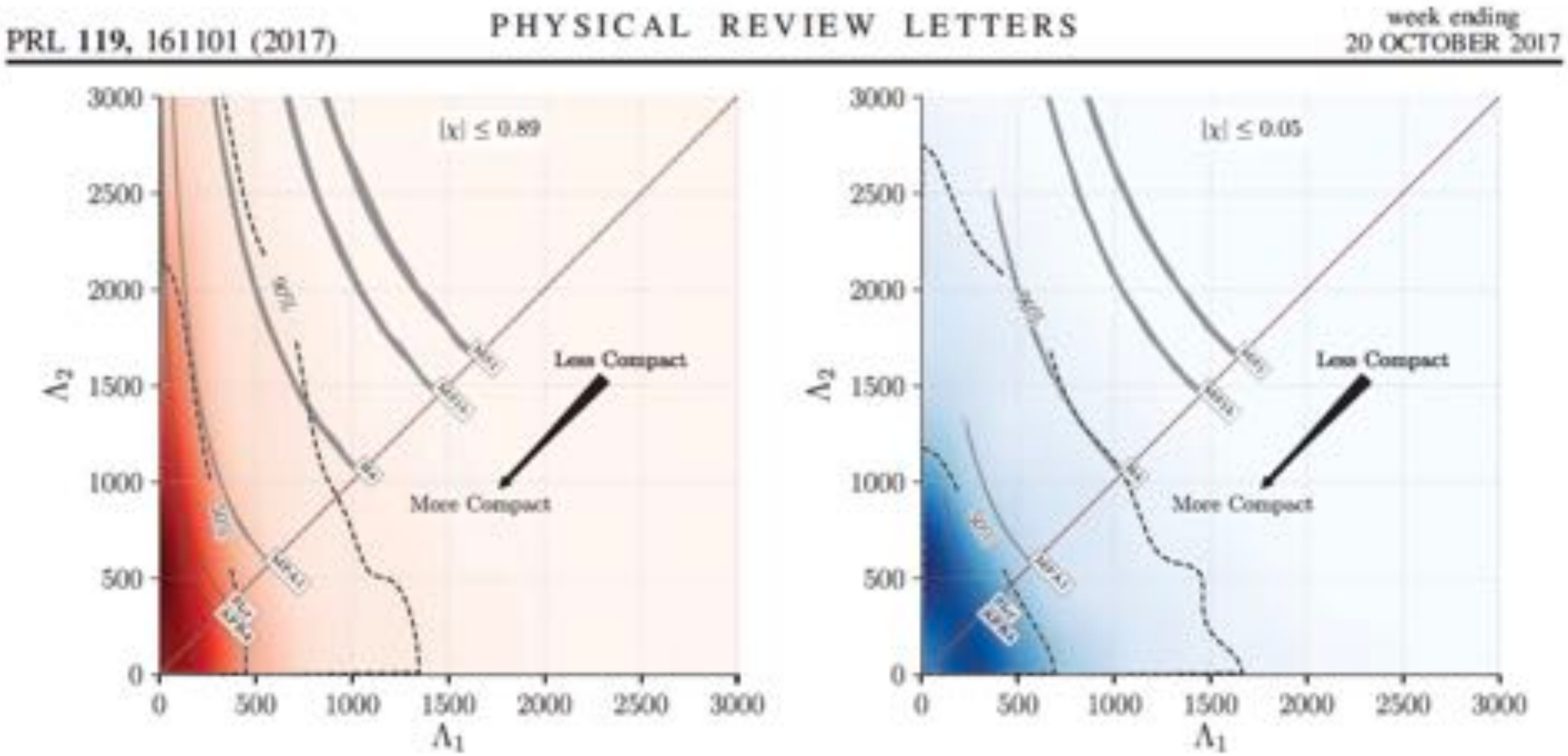
https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

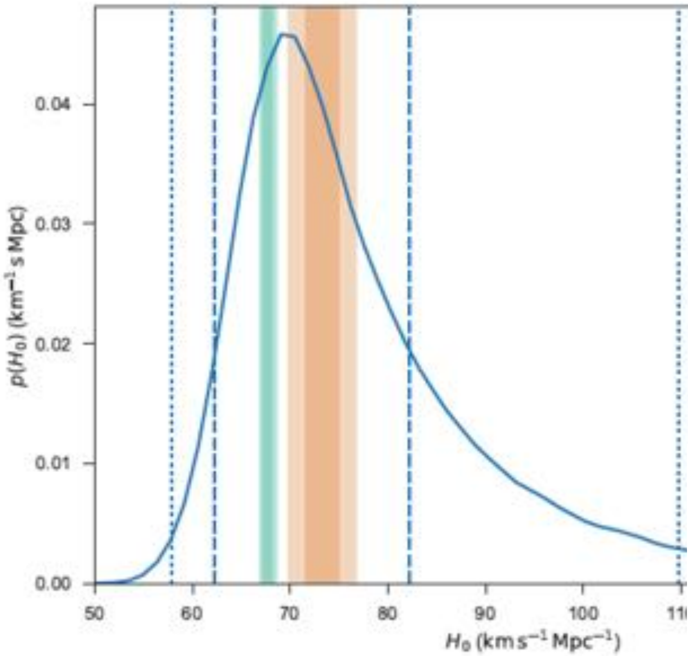
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Nuclear physics with GWs

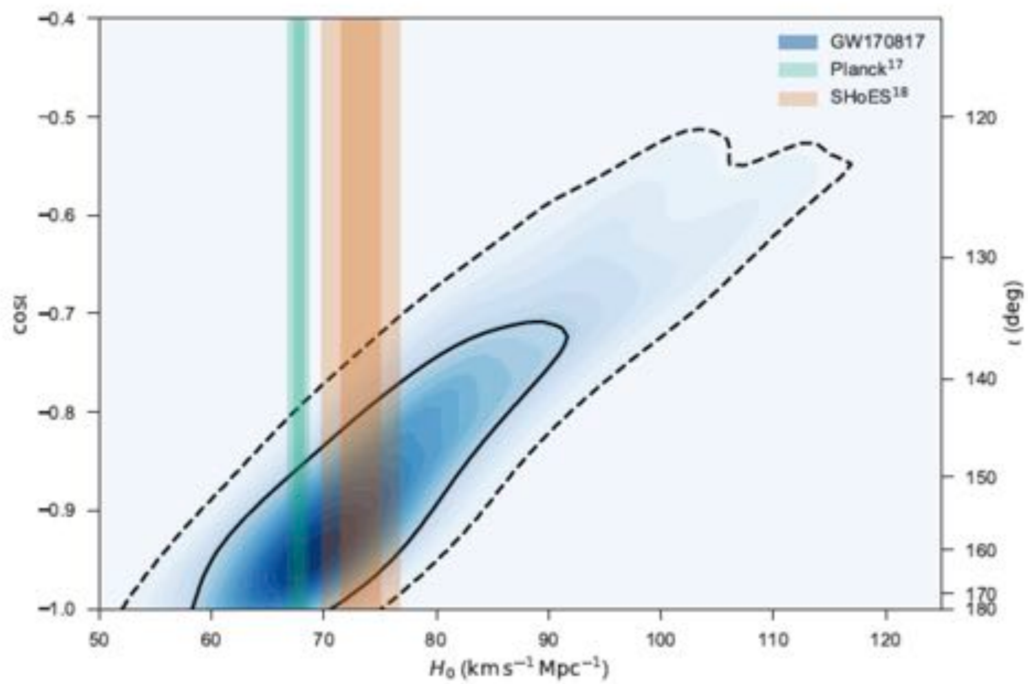


$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{m} \right)^5$$

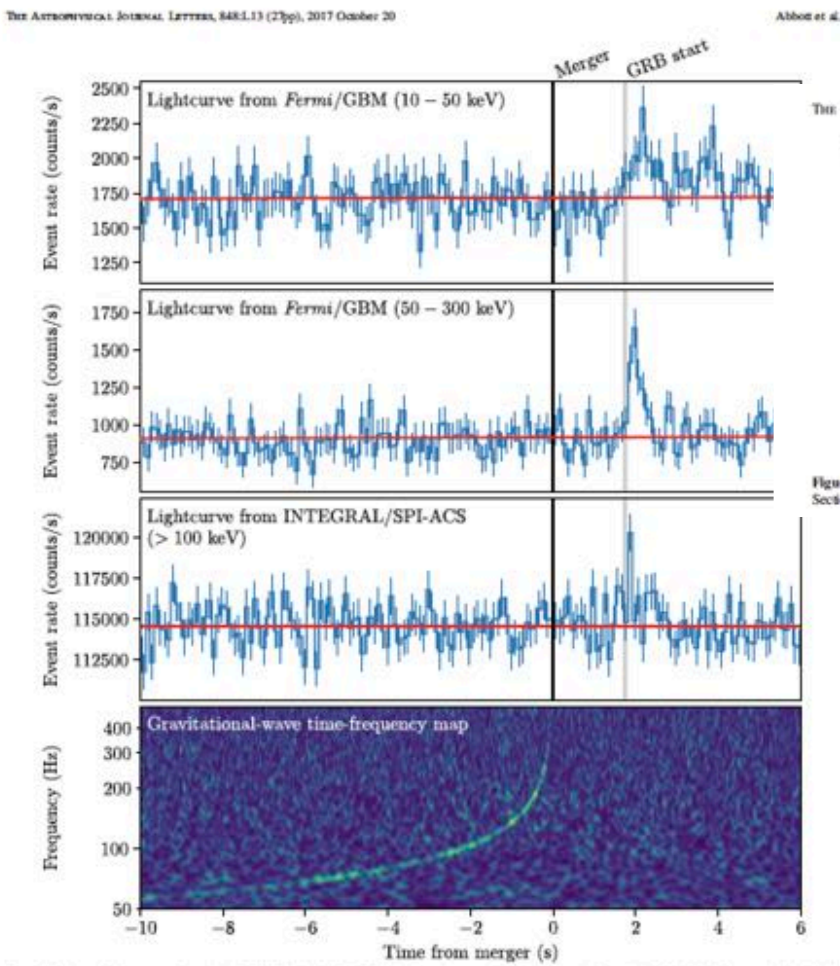
Cosmology with GWs



Nature 551, 85 (2017)



GW-GRB joint observation: sGRB models



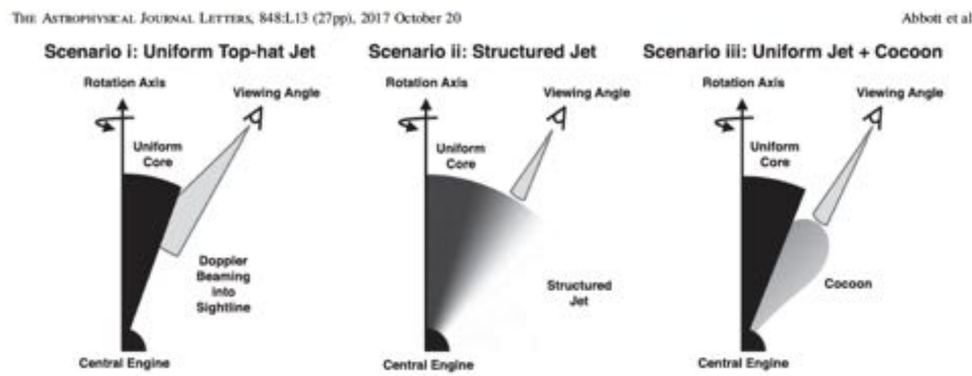
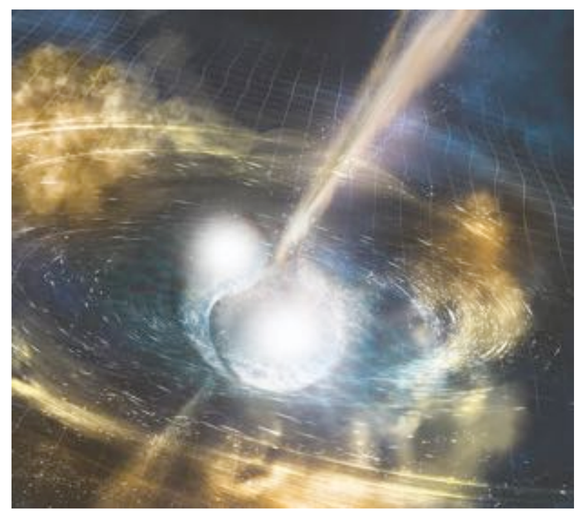


Figure 5. Three potential jet viewing geometries and jet profiles that could explain the observed properties of GRB 170817A, as described by scenarios (i)–(iii) in Section 6.2.



ApJL, 848:L13, 2017

arXiv:1805.02870

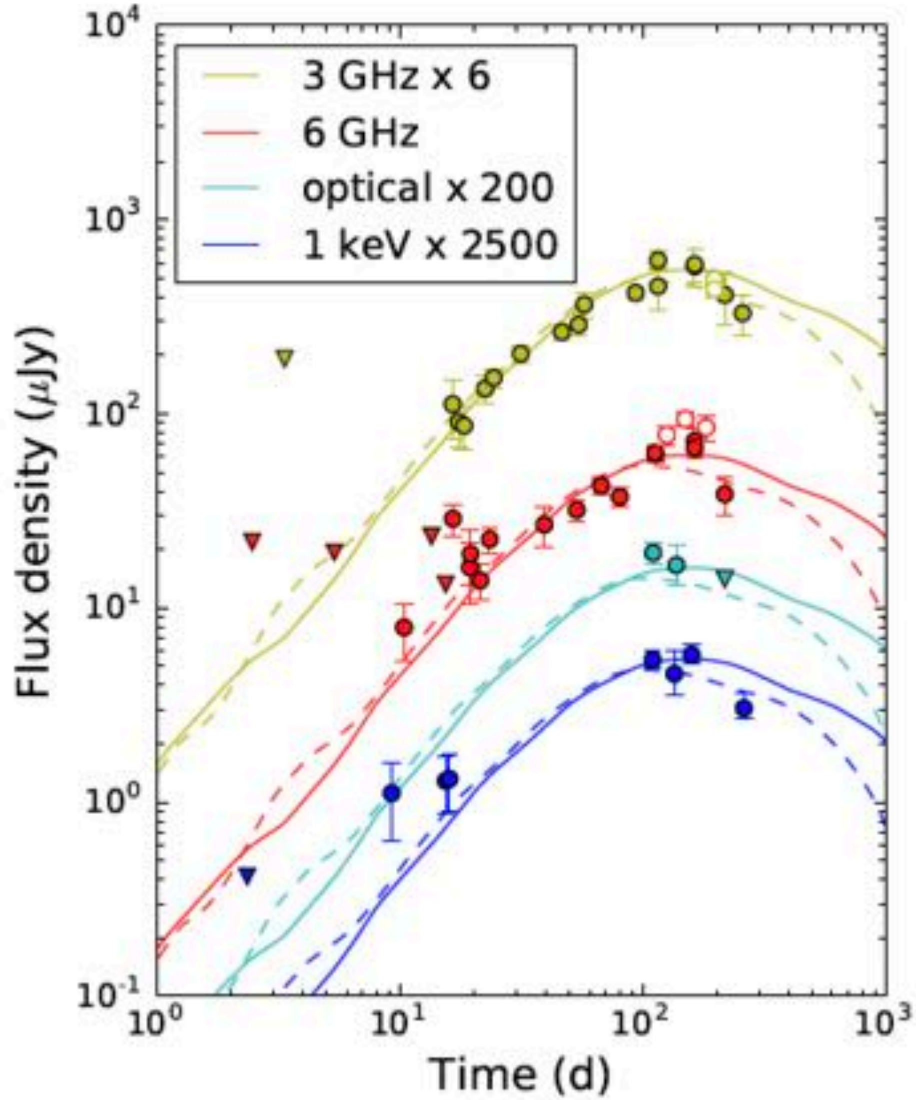
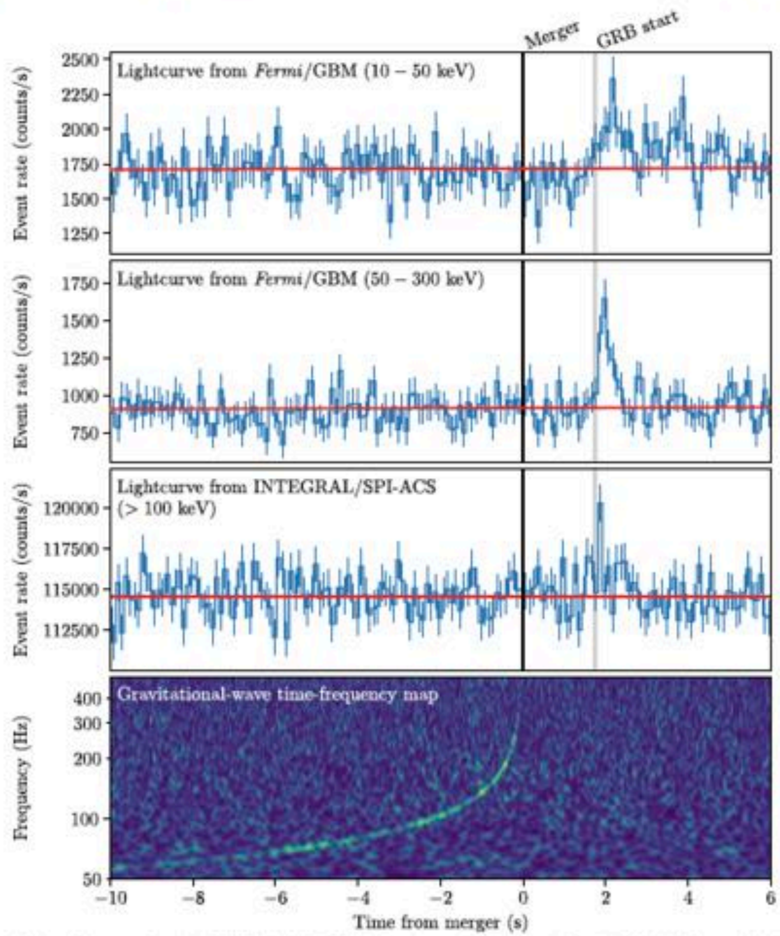


Figure 1. Up-to-date X-ray, optical, and radio light curves of *GW170817* (solid circles; open circles are the new data presented in Dobie et al. 2018). The data are clearly indicative of a decline at $\gtrsim 200$ days. Also shown are our structured jet models from Margutti et al. (2018); see Xie et al. (2018) for full details of the simulations. Both jets have an ultra-relativistic core with $E_{K,jet} = 6 \times 10^{52}$ erg within an opening angle $\theta_{jet} = 9°$. The solid lines are for a model with $n = 10^{-5}$ cm^{-3}, $\theta_{obs} = 17°$, $\epsilon_e = 0.1$, and $\epsilon_B = 0.0005$, while the dashed lines are for $n = 10^{-4}$ cm^{-3}, $\theta_{obs} = 20°$, $\epsilon_e = 0.02$, and $\epsilon_B = 0.001$. Our new radio, optical, and X-ray observations continue to support these models.

GW-GRB observation: Fundamental physics

The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20 Abbott et al.



$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

$$-2.6 \times 10^{-7} \leqslant \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leqslant 1.2 \times 10^{-6}. \qquad (4)$$

The best absolute bound on γ_{EM} is $\gamma_{\mathrm{EM}} - 1 = (2.1 \pm 2.3) \times 10^{-5}$, from the measurement of the Shapiro delay (at radio wavelengths) with the Cassini spacecraft (Bertotti et al. 2003).

ApJL, 848:L13, 2017

Past, present and (near) future

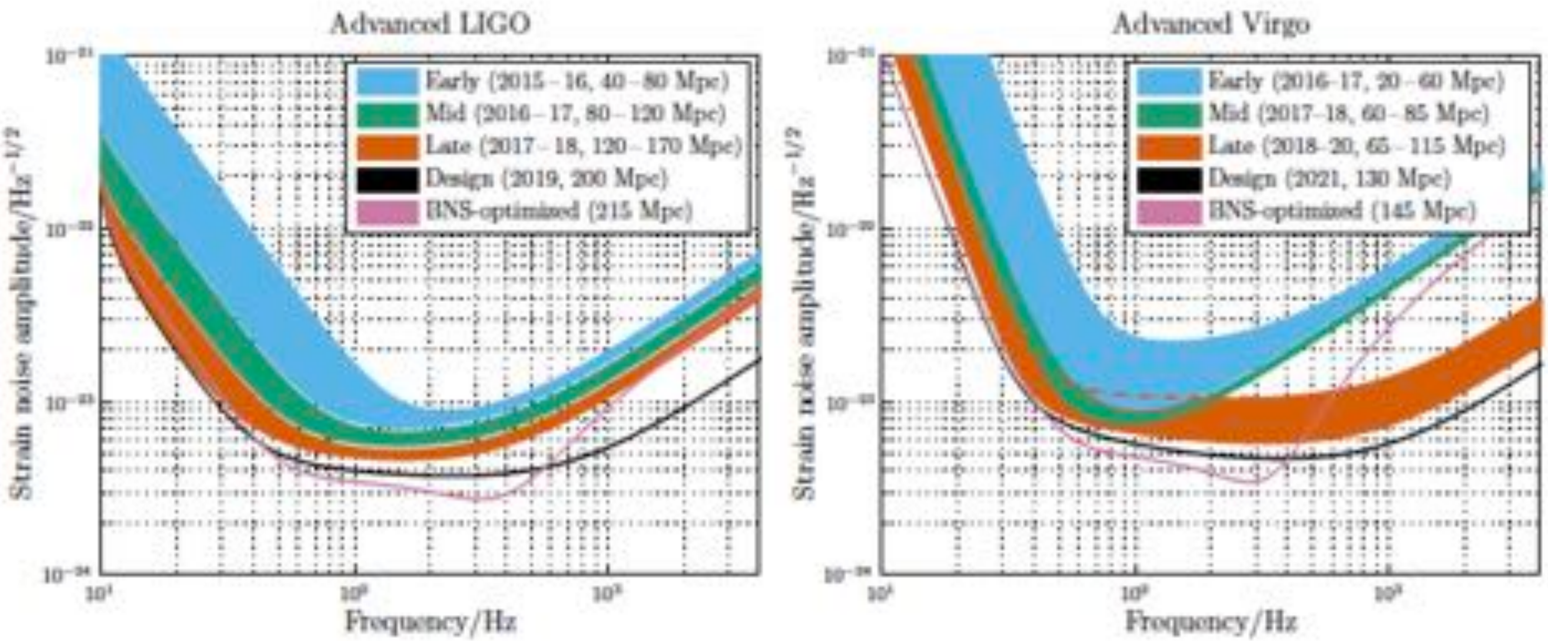
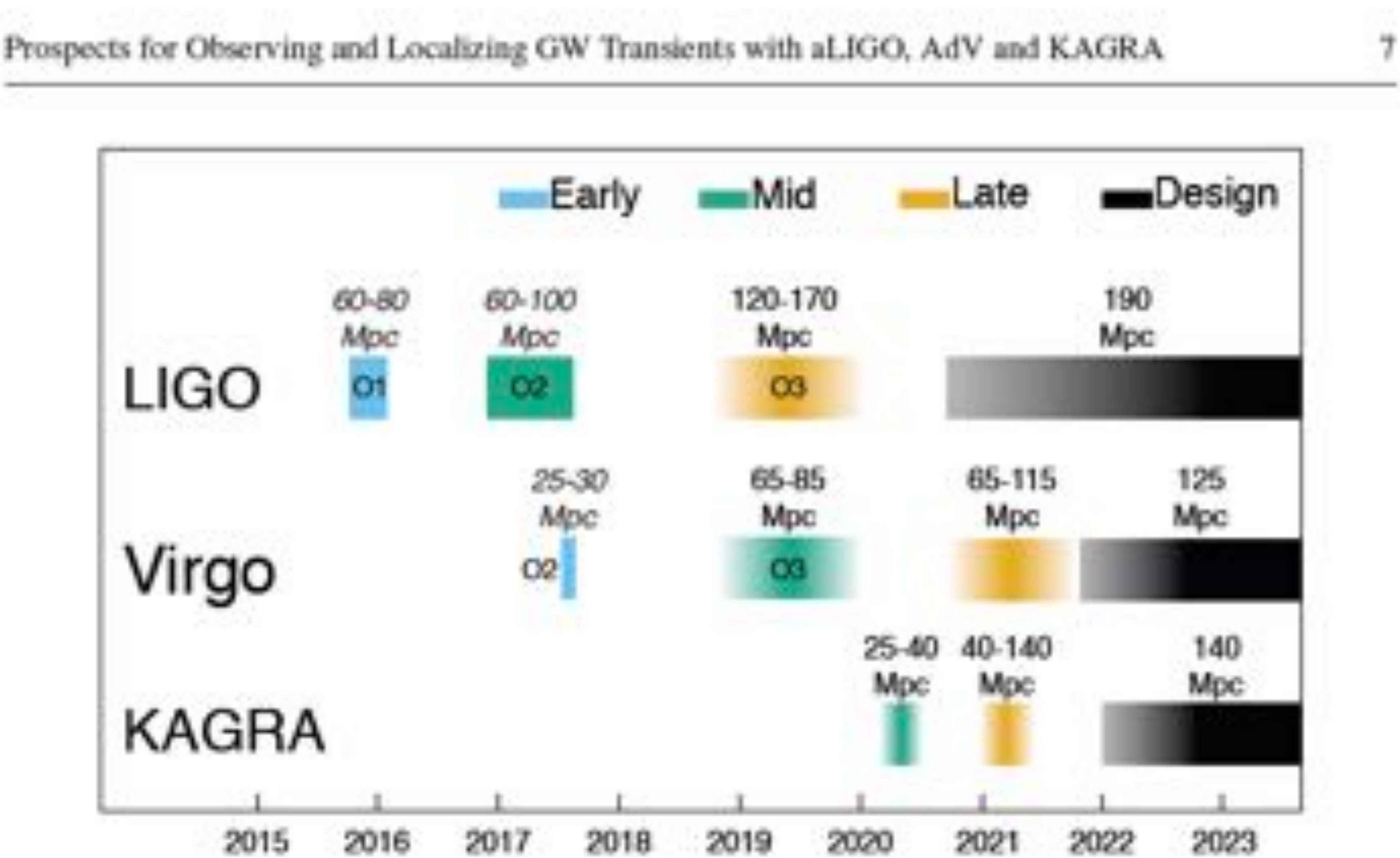


Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late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

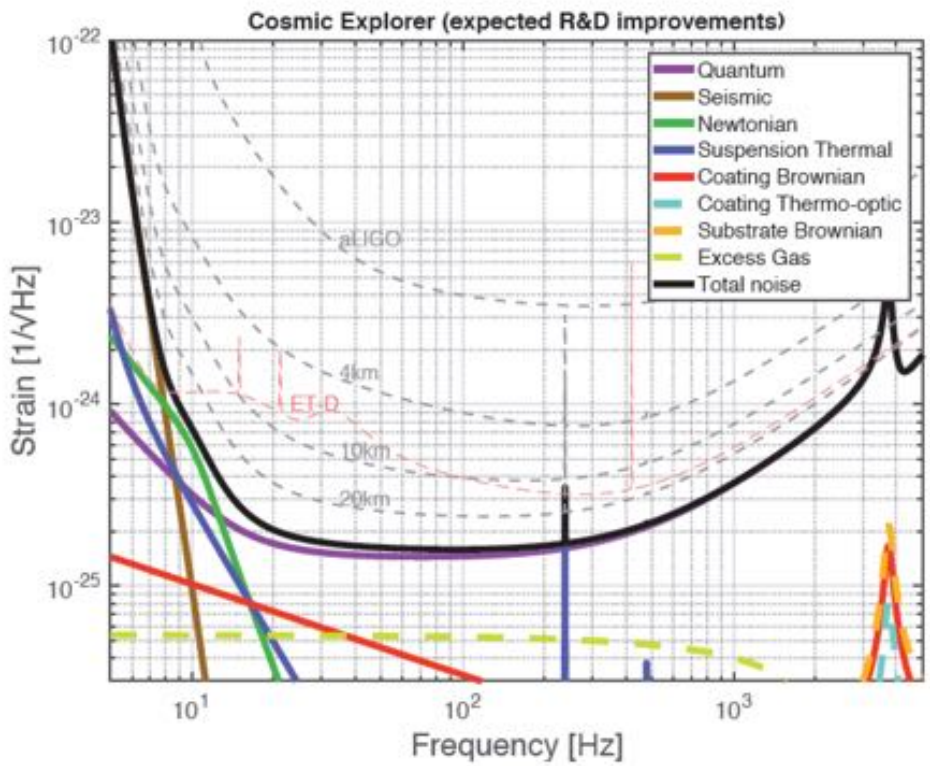
Living Rev. Relativity 19 (2016), 1

The next few years

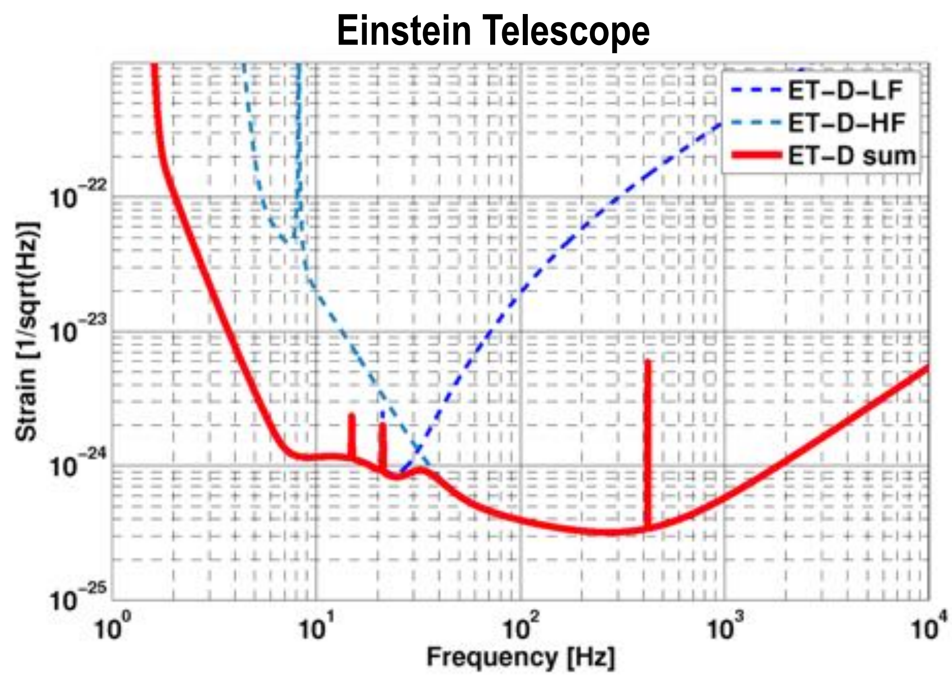


https://arxiv.org/abs/1304.0670

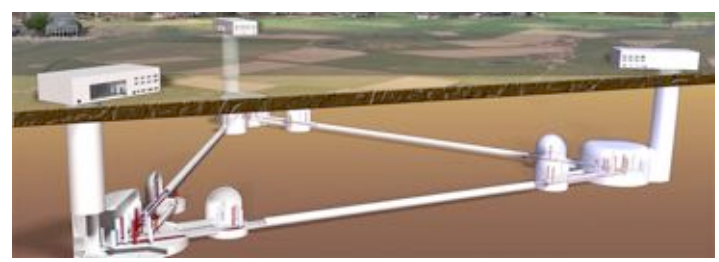
The (farther) future: 3rd generation detectors



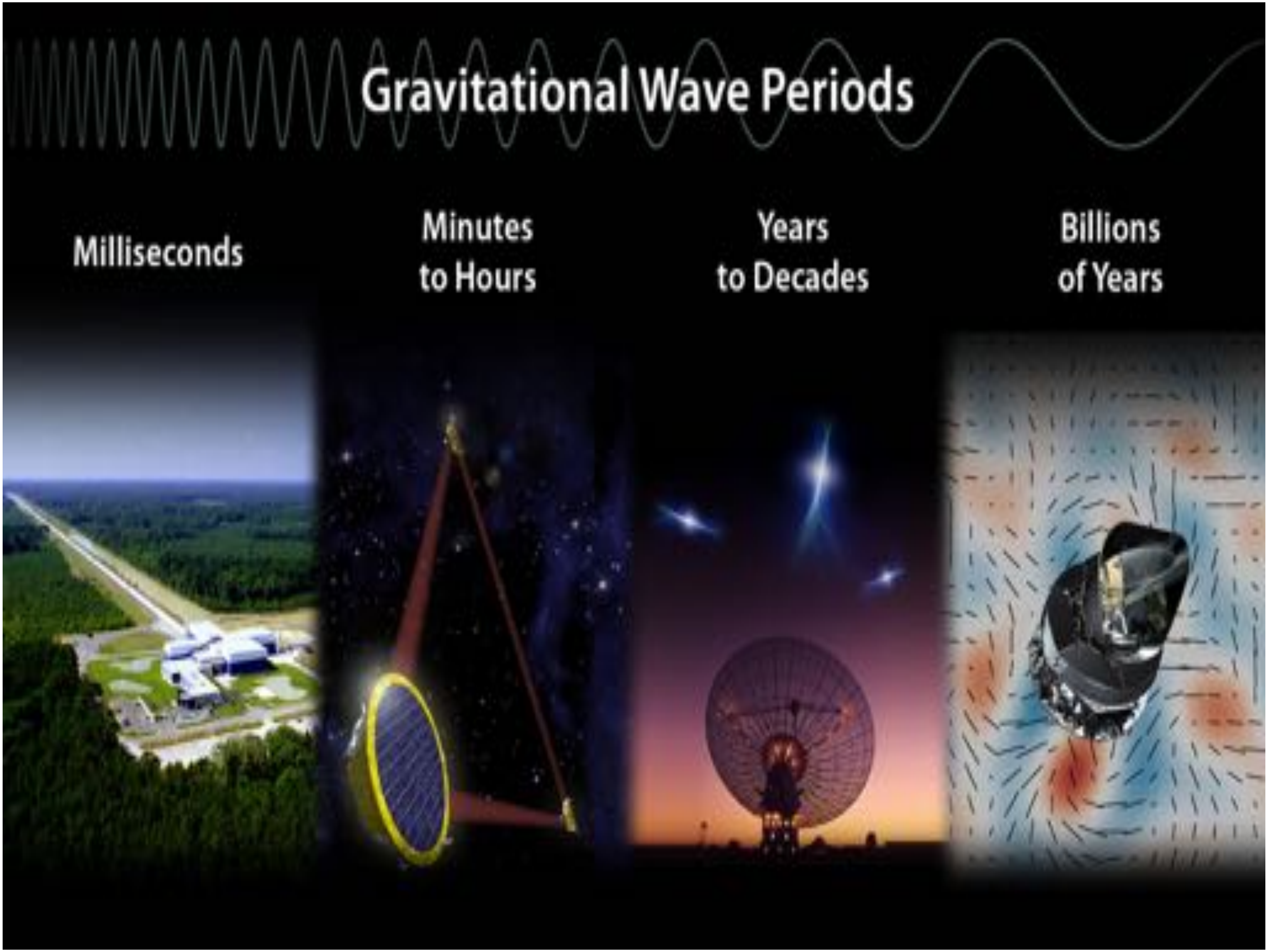
Class. Quantum Grav. 34 (2017) 044001



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



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


Gravitational Wave Periods
Milliseconds
Minutes
to Hours
Years
to Decades
Billions
of Years

The era of GW astronomy is here!

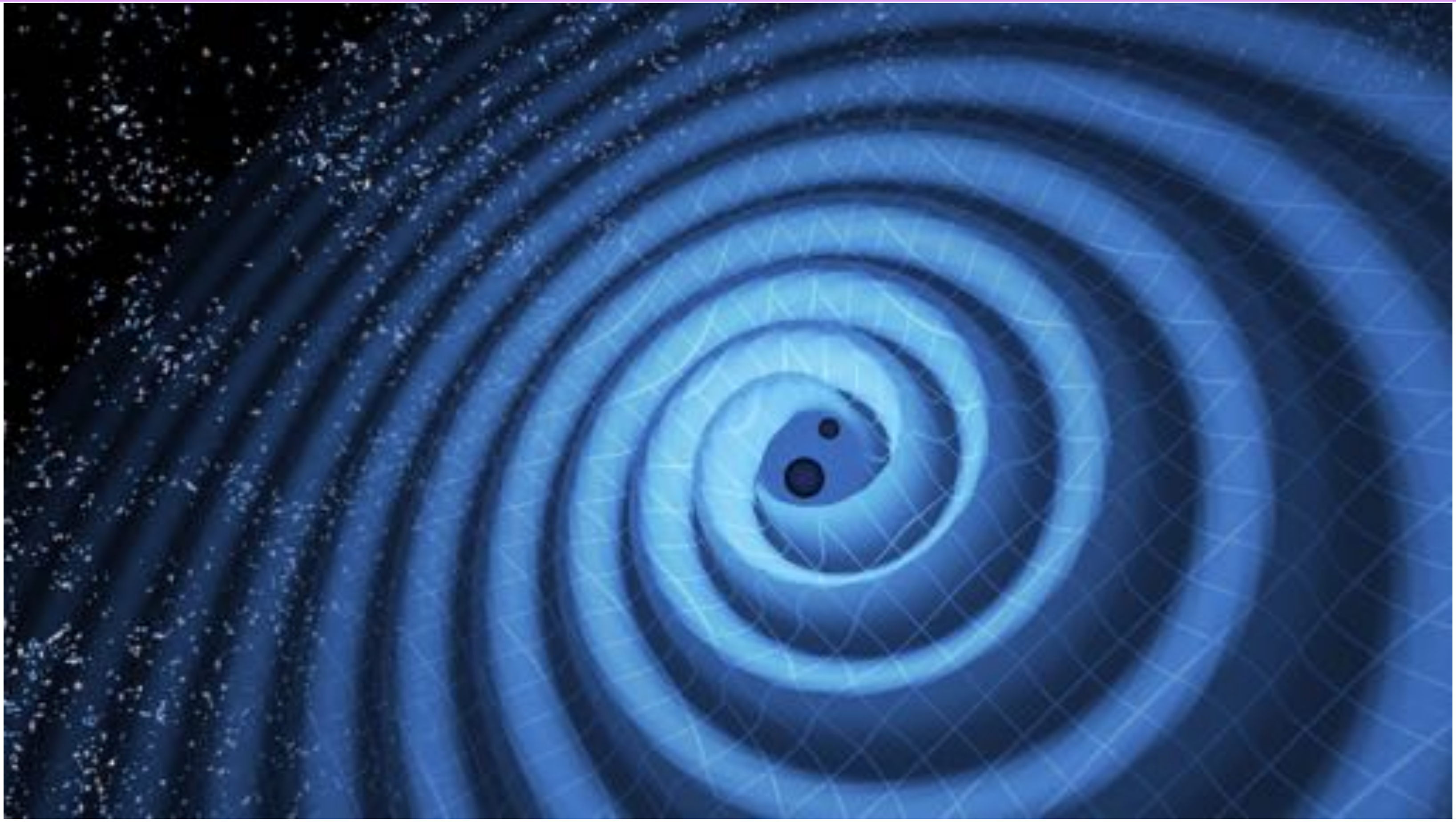


Image credit: LIGO/T. Pyle

www.ligo.org

gonzalez@lsu.edu