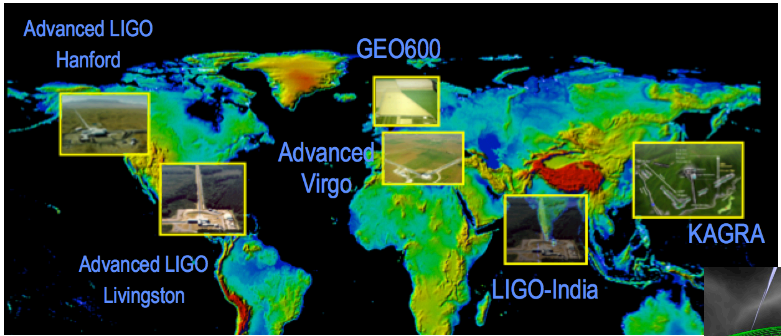
Searching for – and finding! gravitational waves

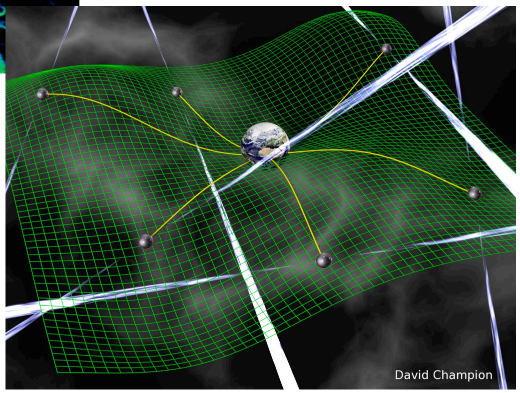
Gabriela González

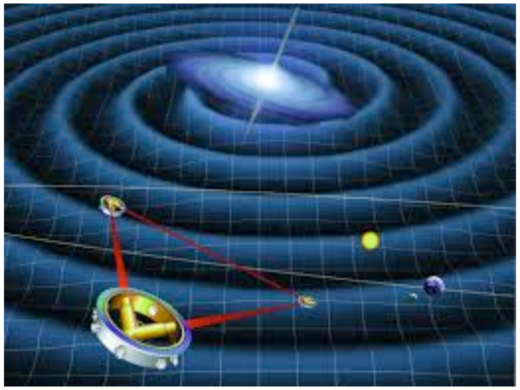
Louisiana State University

International School of Cosmic Ray Physics

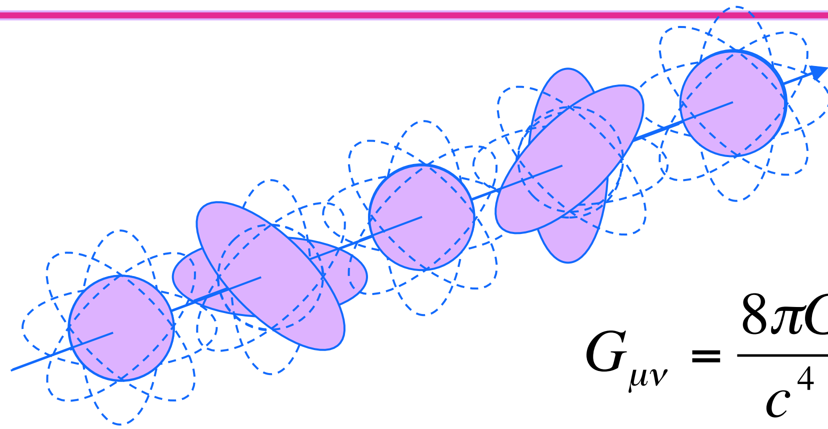
Erice, Italy, August 4-5, 2018







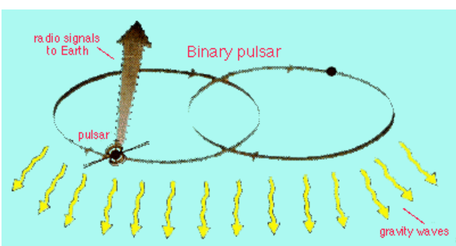
Gravitational waves

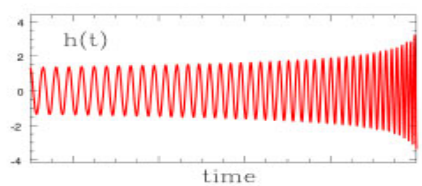


Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

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

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

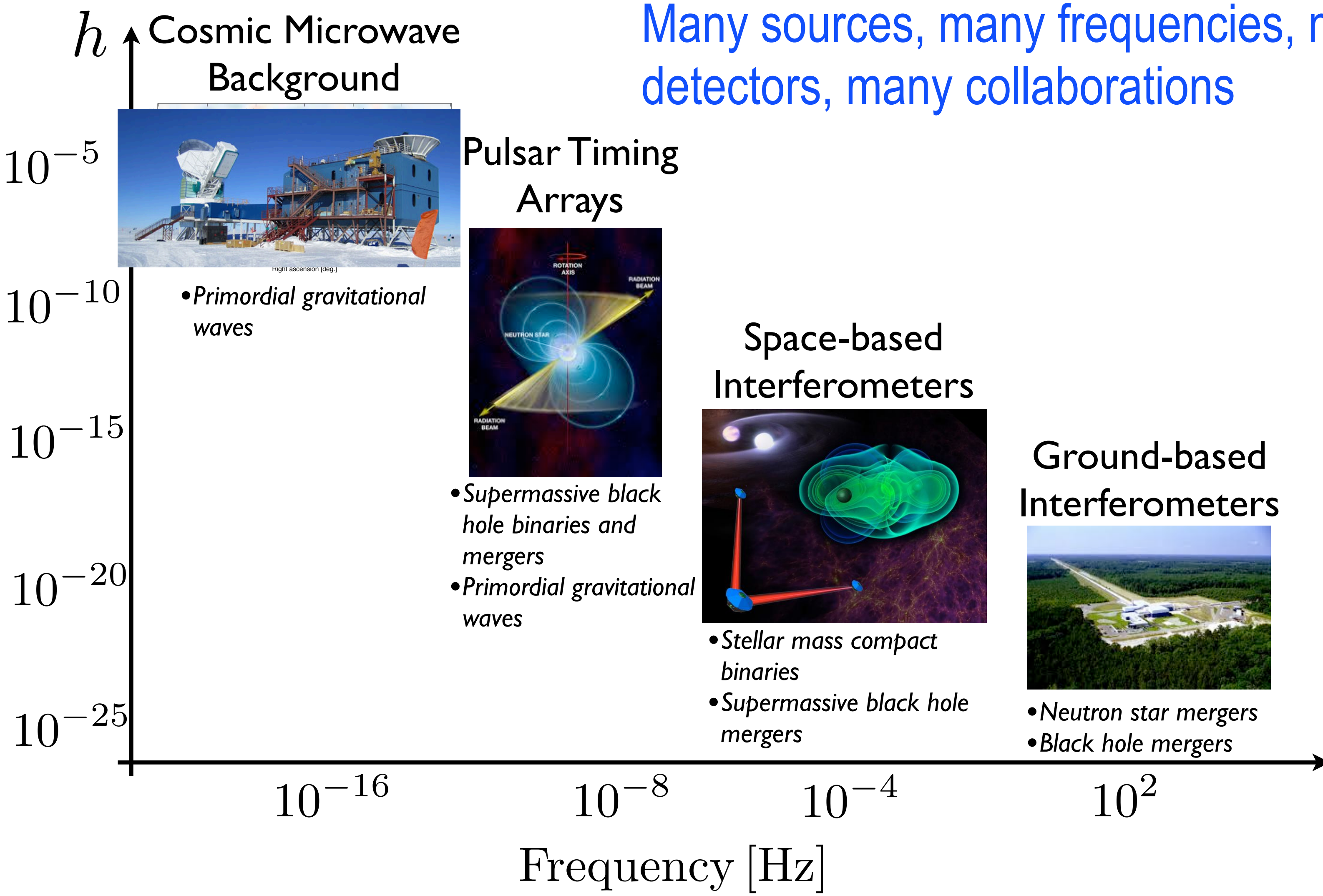




GWs from a NS-NS coalescence in the Virgo cluster has $h \sim 10^{-21}$ near Earth, and happens ~once every 50 years.

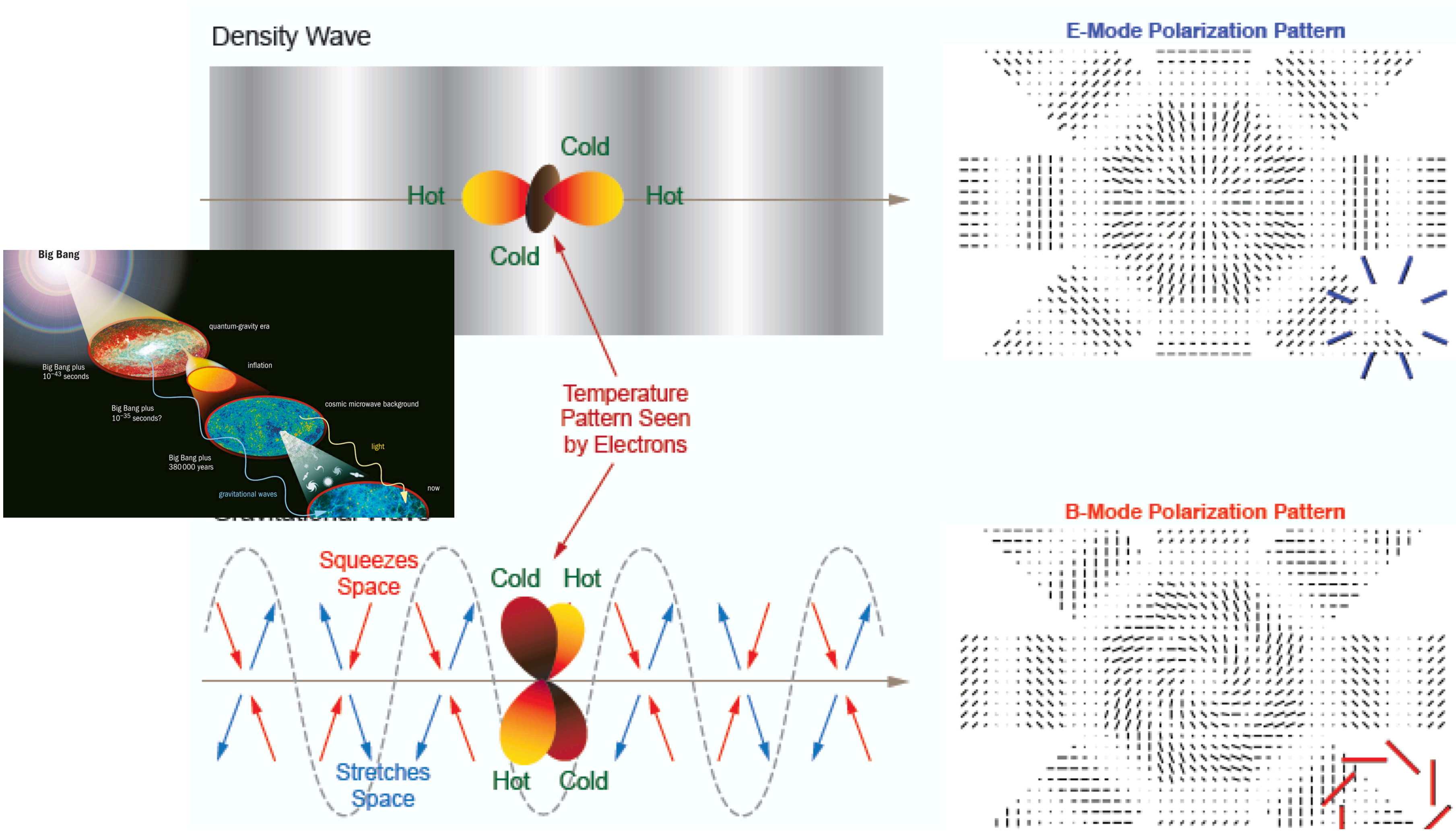
GW landscape

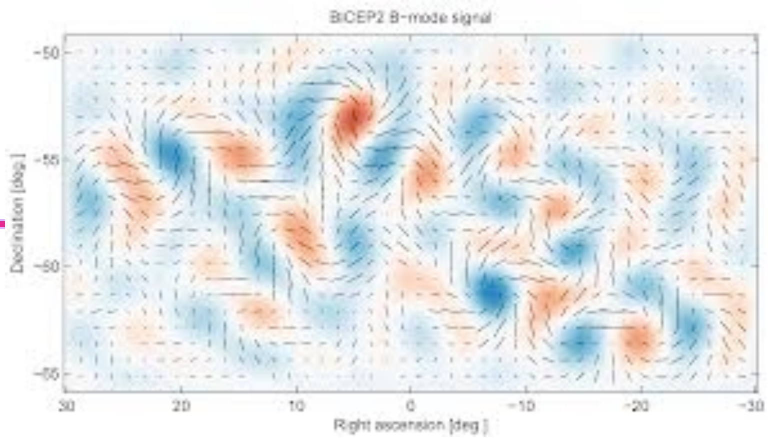
Many sources, many frequencies, many detectors, many collaborations

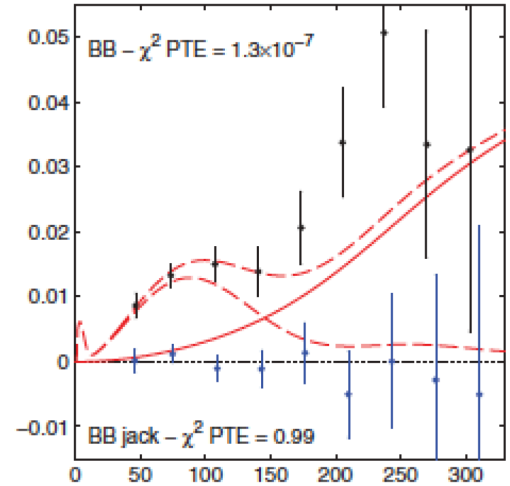


Credit: Nanograv/Bicep2

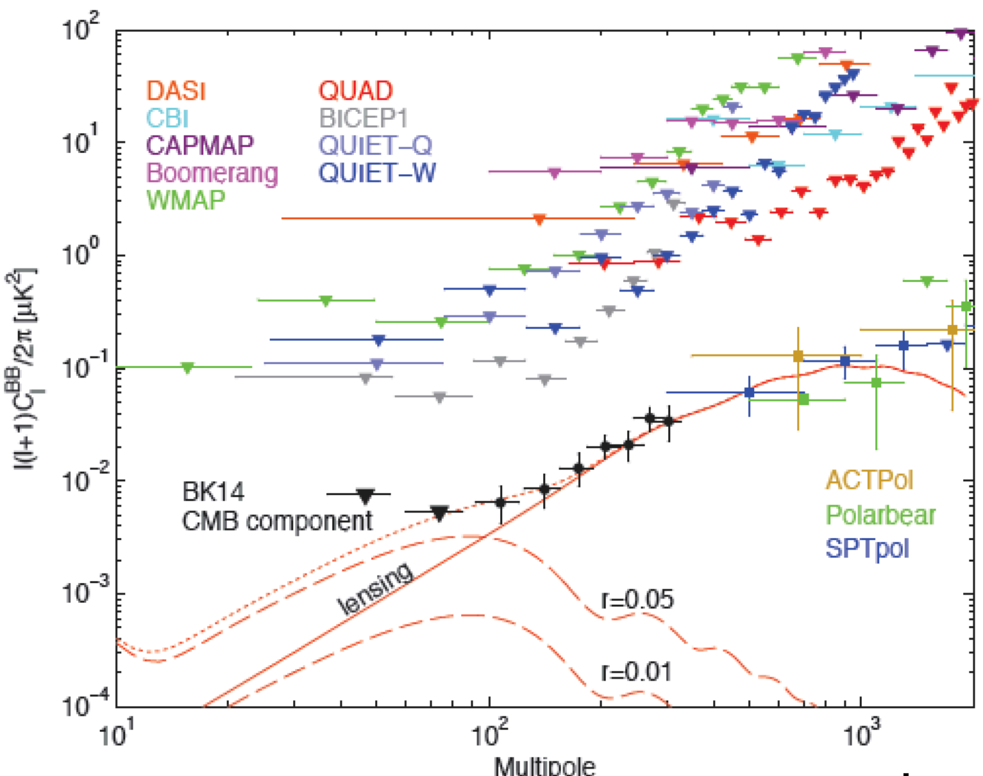
Primordial GWs: Cosmological Microwave Background







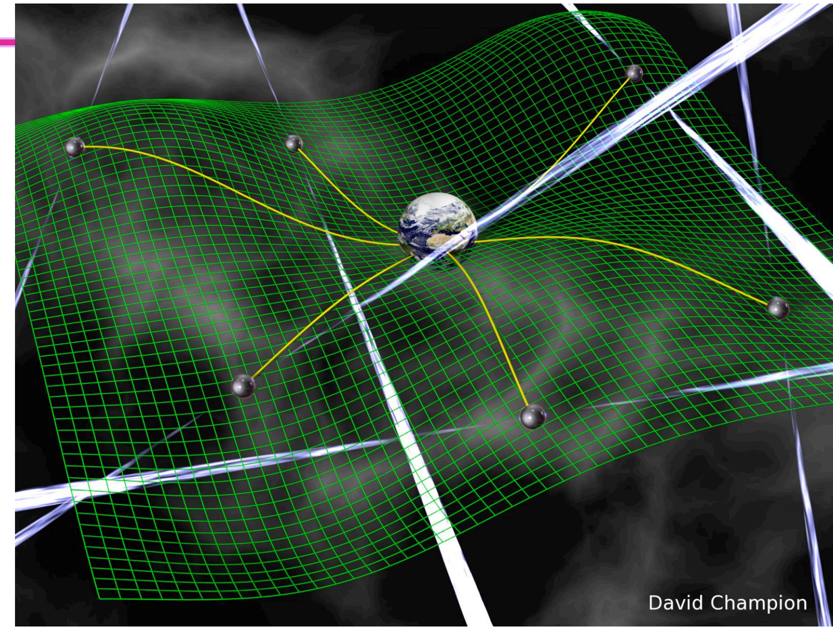
PRL 112, 241101 (2014)



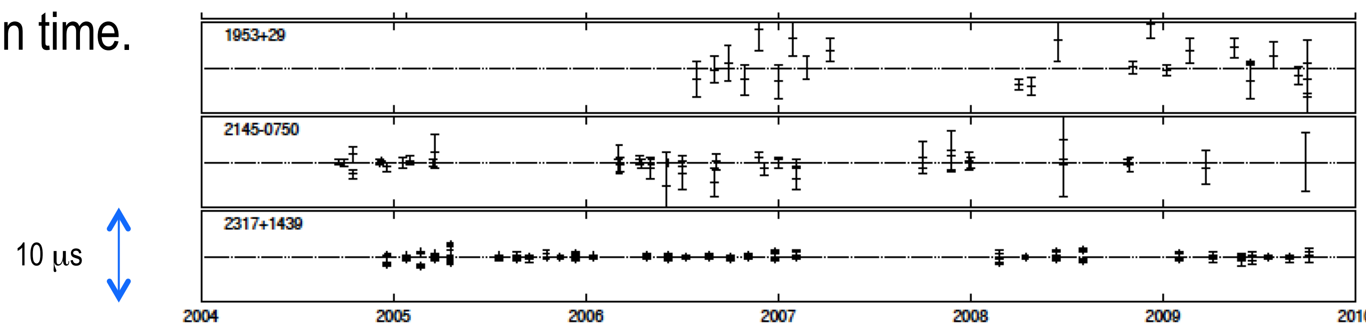
	arXiv	$\sigma(r)$
DASI	0409357	7.5
BICEP1 2yr	0906.1181	0.28
WMAP 7yr	1001.4538	1.1
QUIETQ	1012.3191	0.97
QUIETW	1207.5034	0.85
BICEP1 3yr	1310.1422	0.25
BICEP2	1403.3985	0.10
BK13/*Planck*	1502.00612	0.034
BK14/W/P	1510.09217	0.024
ABS	1801.01218	0.7

https://arxiv.org/abs/1807.02199

Pulsar timing



Measuring changes in phase of pulsar radio beams on Earth, we have a “galactic scale interferometer” measuring gravitational waves with periods of several years (nHz frequencies): mergers of super-massive black holes (galaxies!). They are limited by noise in the time of arrival of radio beams, number of pulsars and integration time.



Pulsar timing results

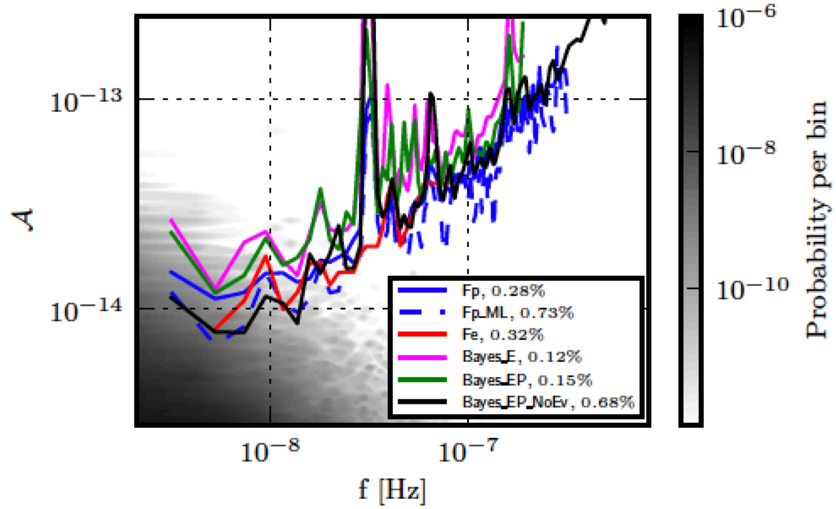
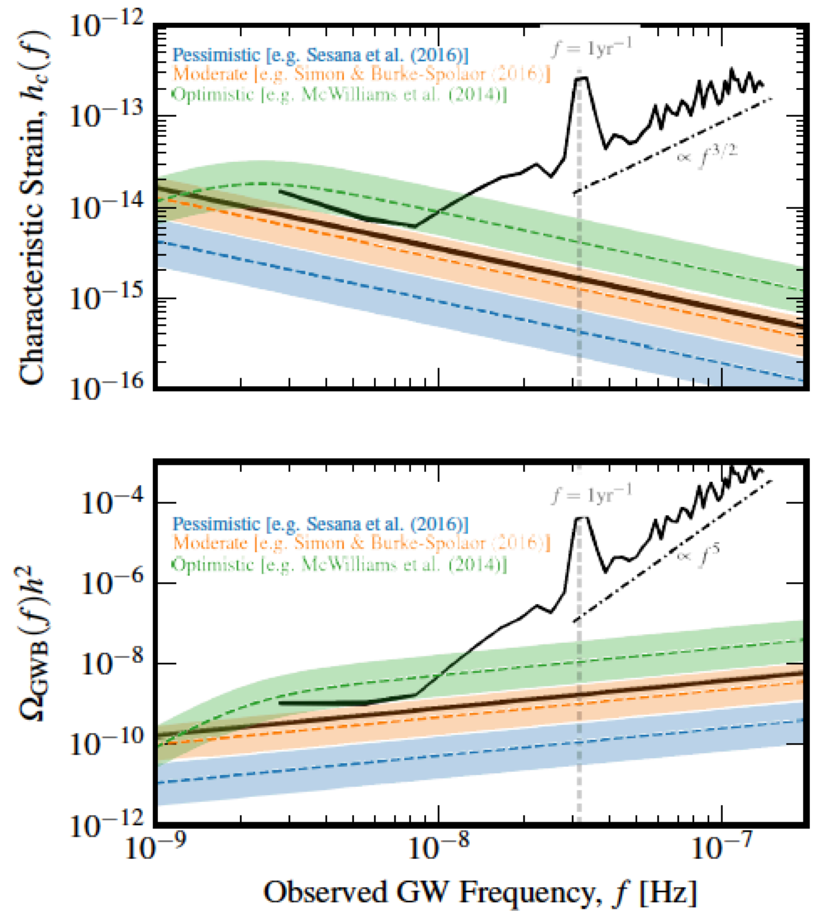


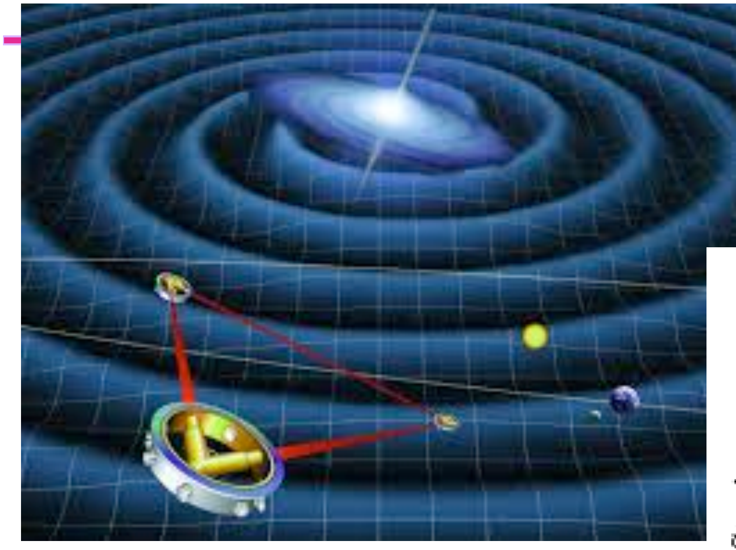
Figure 10. GW strain amplitude versus GW observed frequency. The coloured lines represent the different upper limits presented in this work. The shading gives the probability of detecting a SMBHB in a particular interval of strain and frequency. That detection probability increases towards lower frequencies and smaller values of strain (on the lower-left corner). In the legend, the percentage of detection probability is given for each of the upper limits.

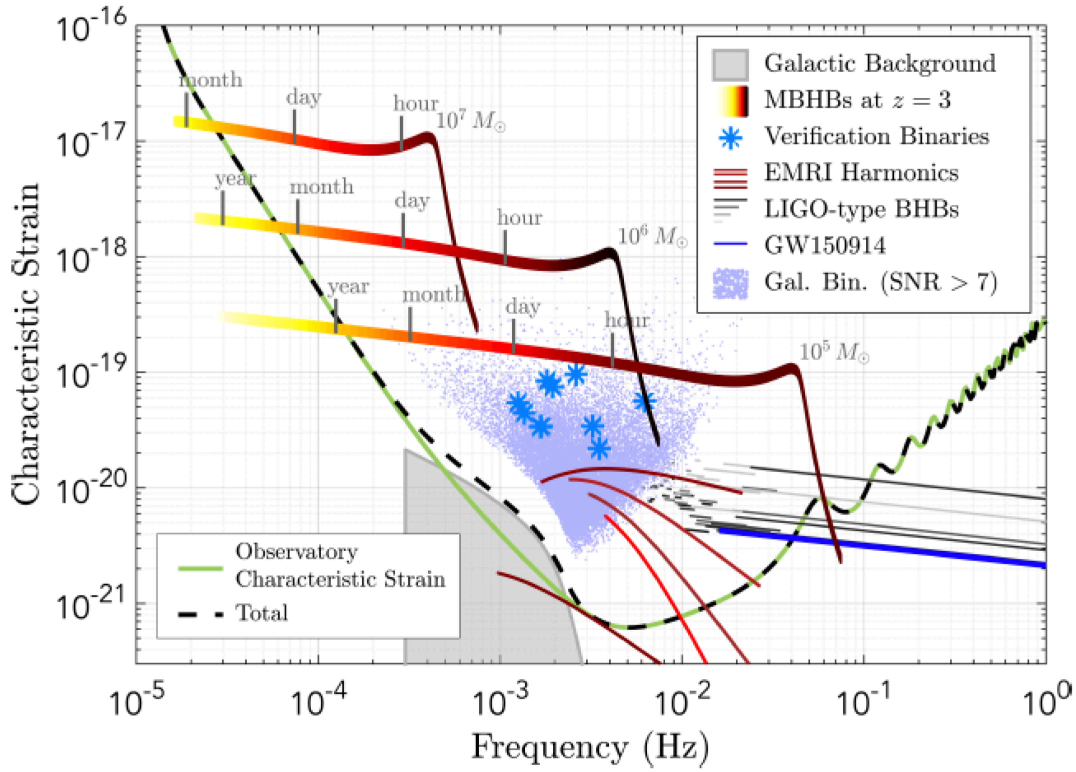


Babak et. al
MNRAS 455, 1665-1679, 2016

THE NANOGRAV COLLABORATION)
arXiv:1801.02617

Space-based detector: LISA

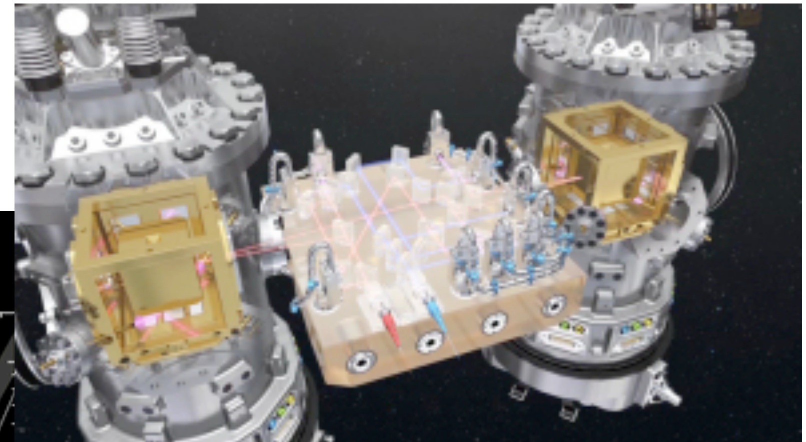


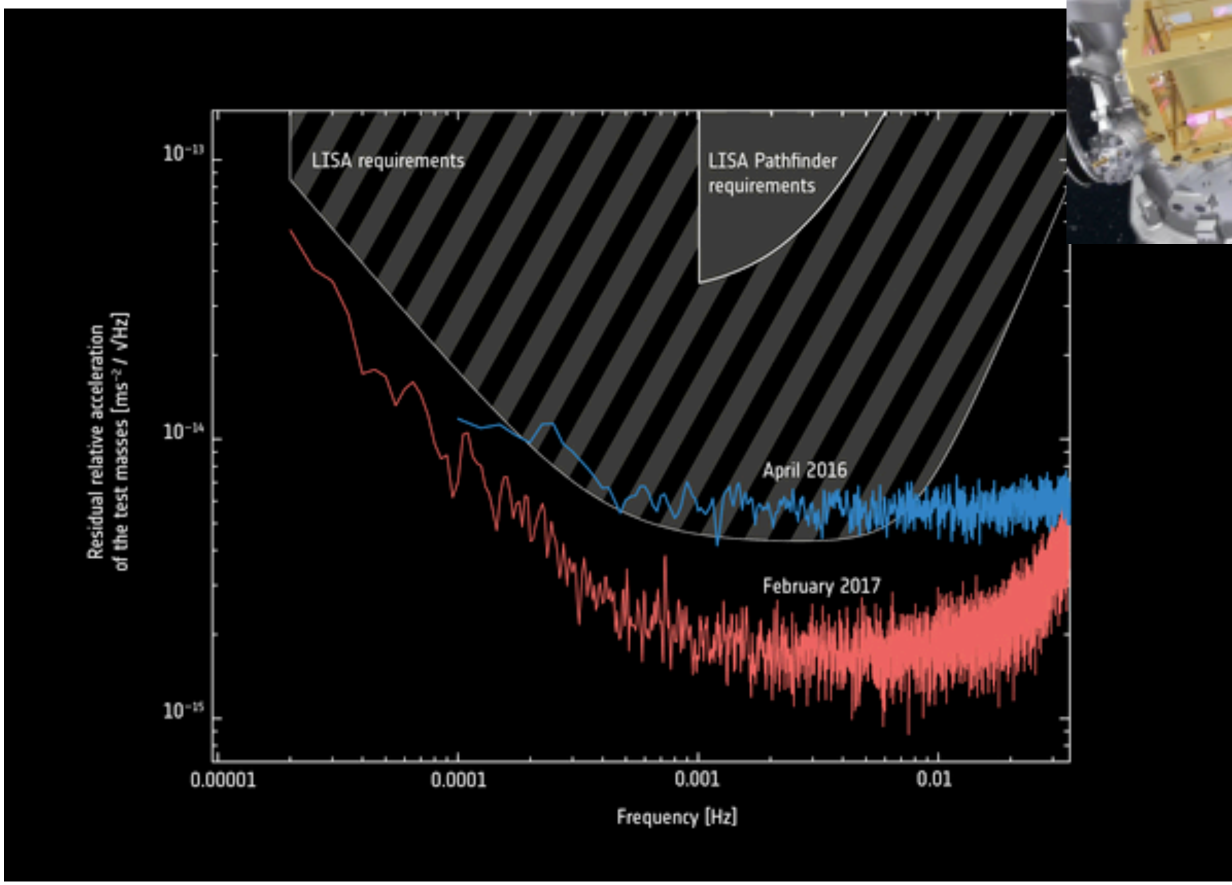


ESA large L3 mission,
launch date 2034,
Mission design call 2016

LISA L3 study
https://arxiv.org/abs/1702.00786

LISA Pathfinder
the quietest place in space

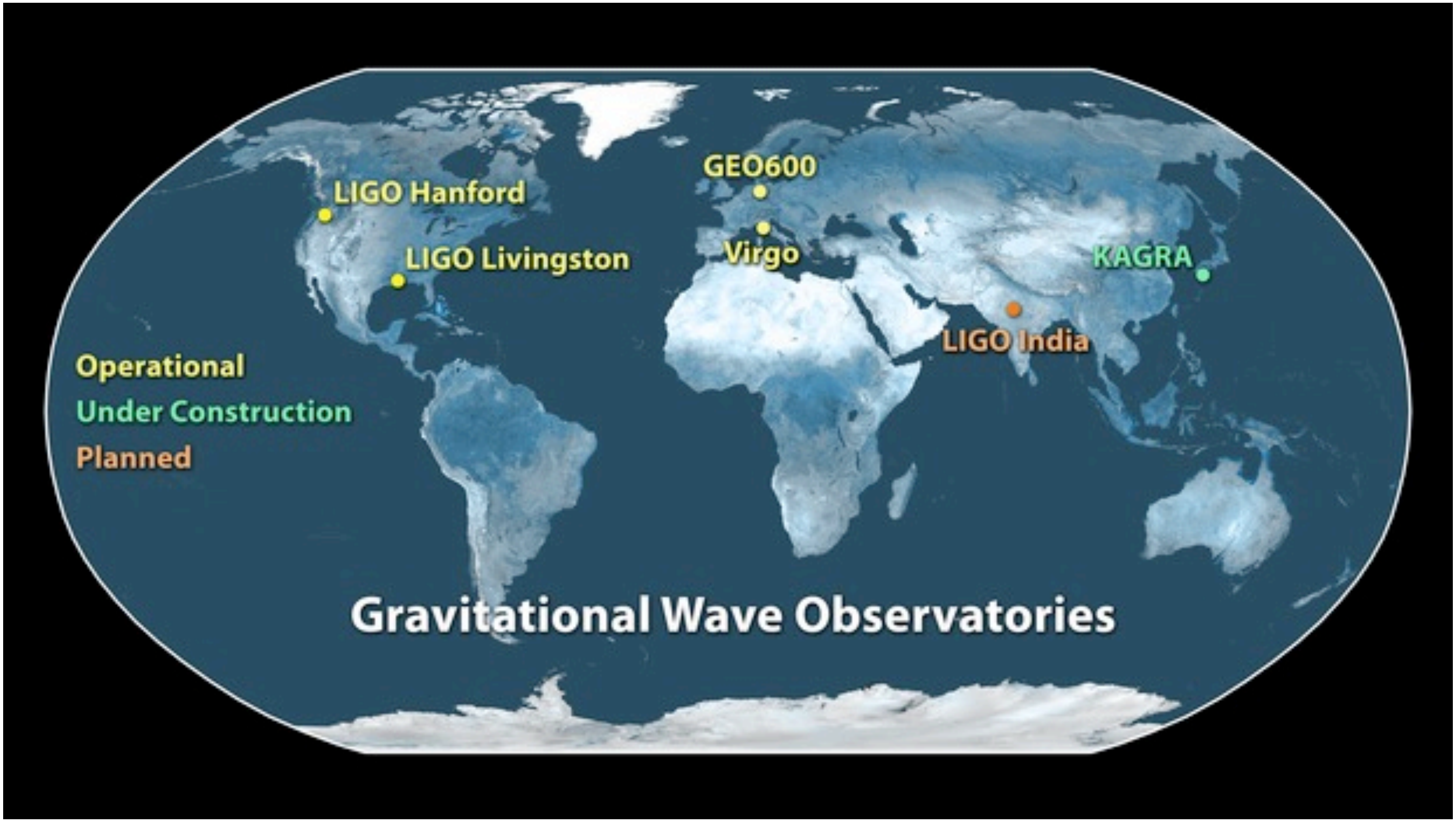




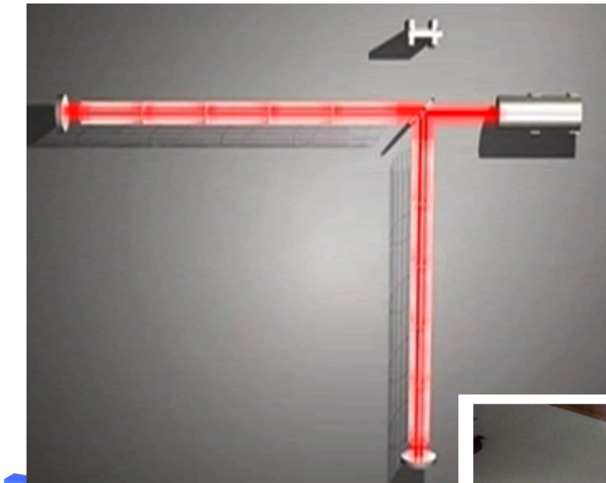
LISA Pathfinder performance analysis. *Credit: ESA/LISA Pathfinder Collaboration*

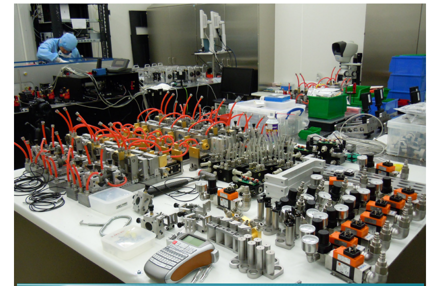

The LIGO Observatories
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms
10 ms
LIGO Livingston Observatory (LLO)
L1 : 4 km arms
NSF
•Adapted from "The Blue Marble: Land Surface, Ocean Colo nasa.gov
•NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow wa mmon (ocean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

Ground-based network

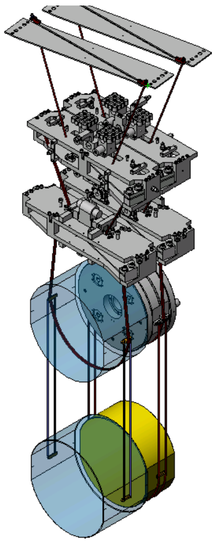


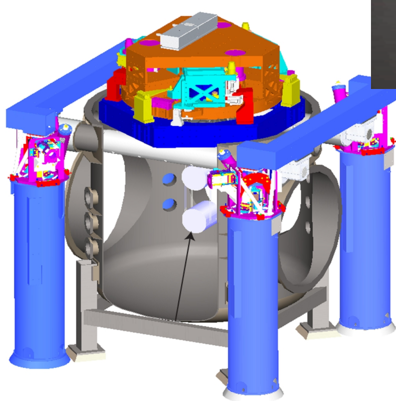
2008+:
Advanced LIGO detectors



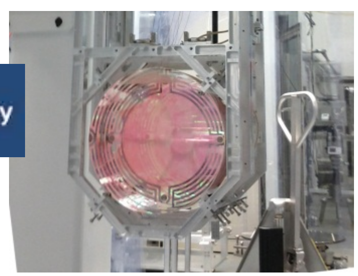


MAX-PLANCK-GESELLSCHAFT



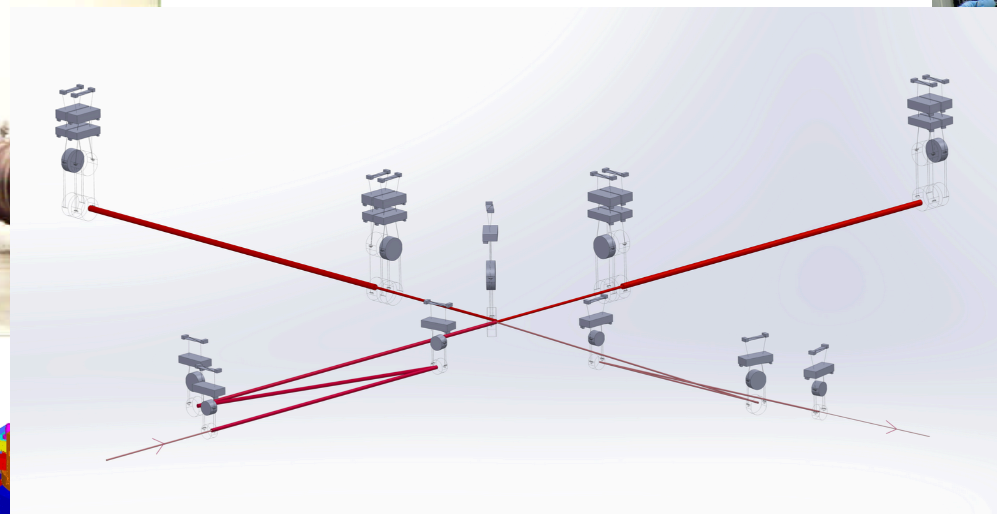


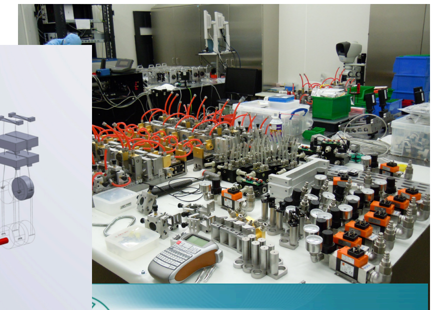
Science & Technology Facilities Council



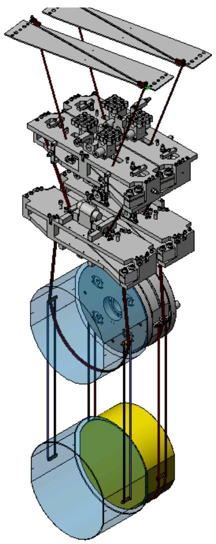
NSF

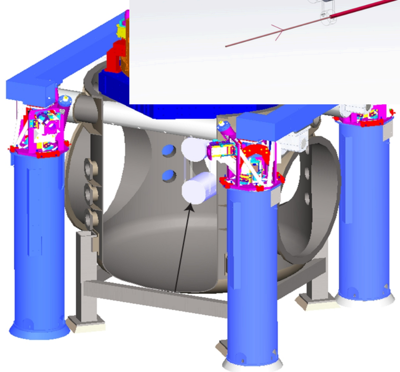
2008+:
Advanced LIGO detectors

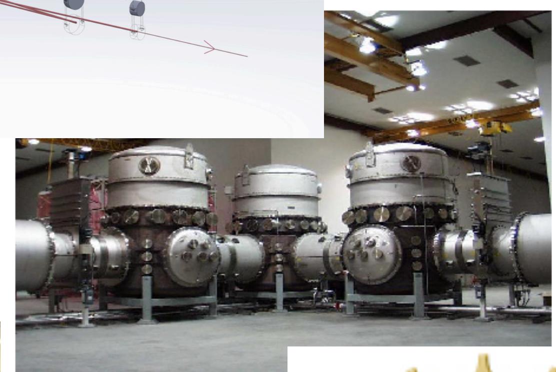




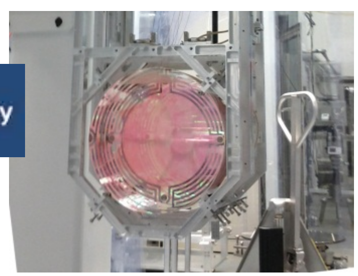
MAX-PLANCK-GESELLSCHAFT





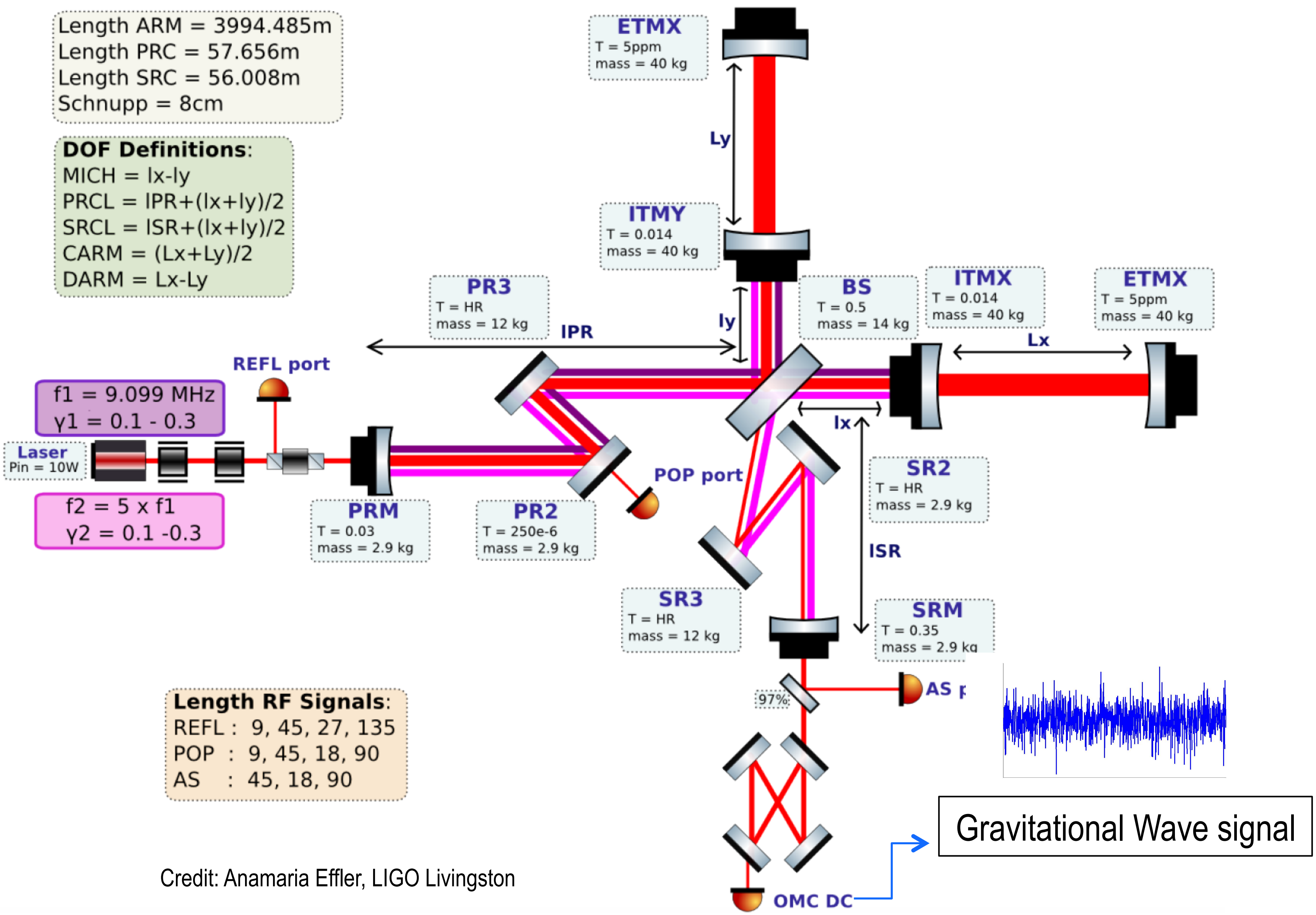


Science & Technology Facilities Council



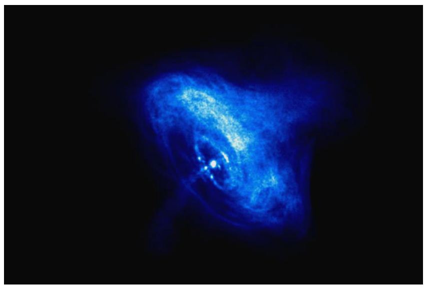
NSF

Advanced LIGO = (Servo Control)$^{N>>1}$

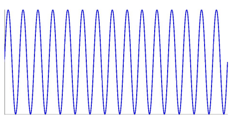


Credit: Anamaria Effler, LIGO Livingston

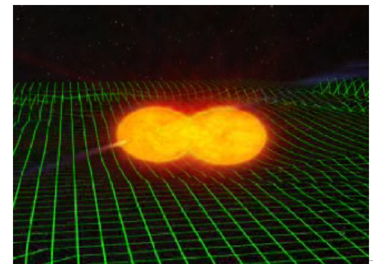
Searching for gravitational waves



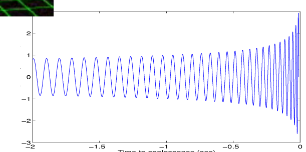
Crab pulsar (NASA, Chandra Observatory)



Periodic, continuous waves

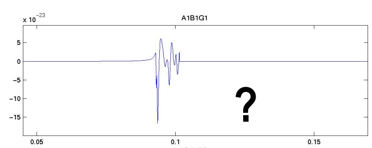


Credit: John Rowe



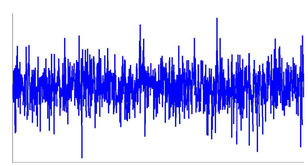
Binary systems with neutron stars and/or black holes

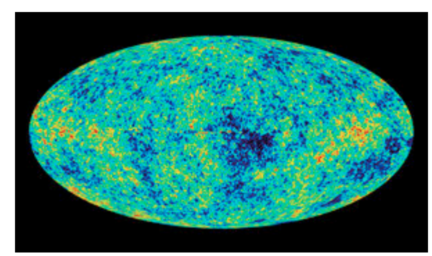
Short transients from supernova explosions or other sources



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

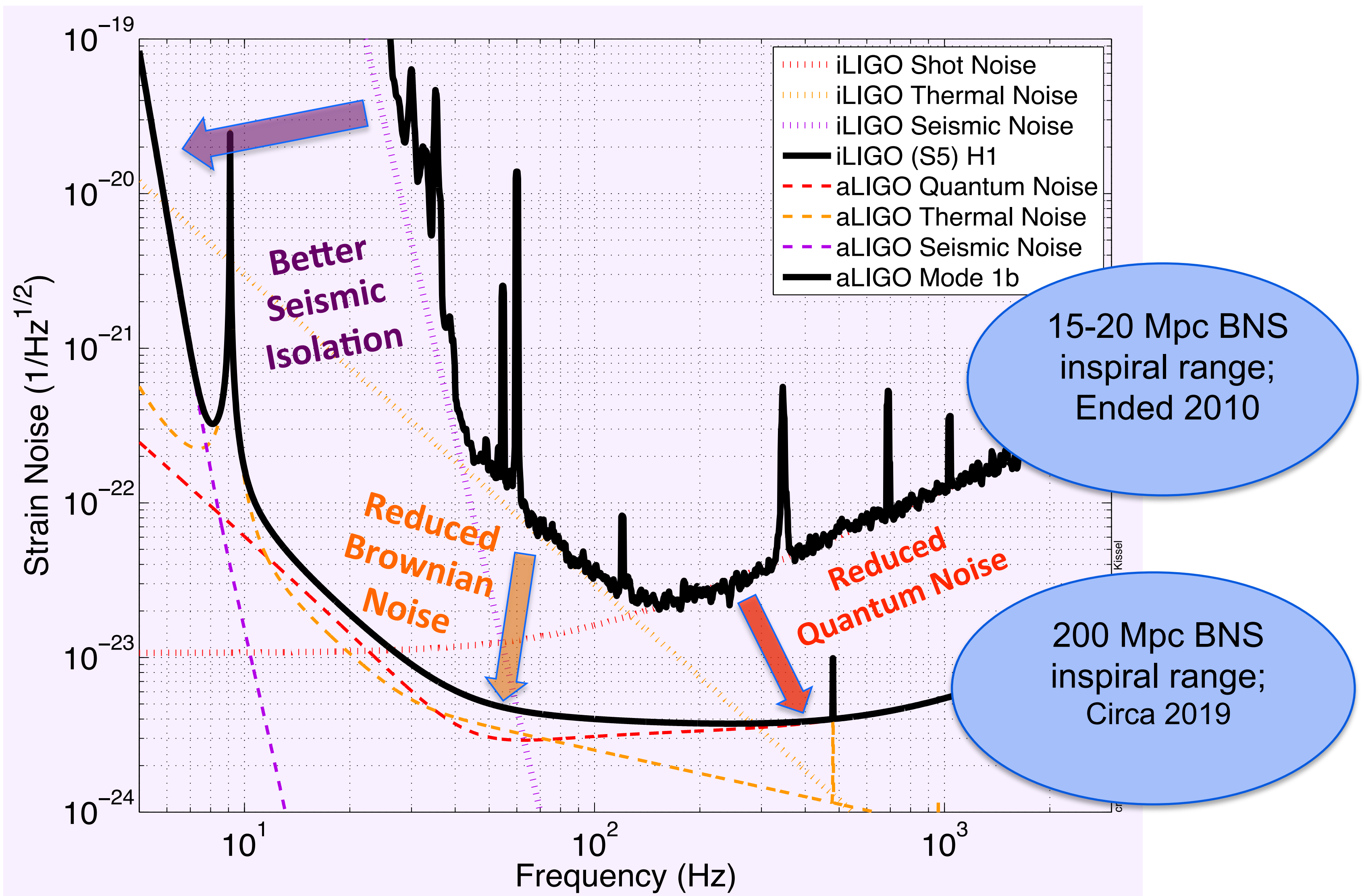
Stochastic background from many unresolved sources, or from the beginning of the Universe



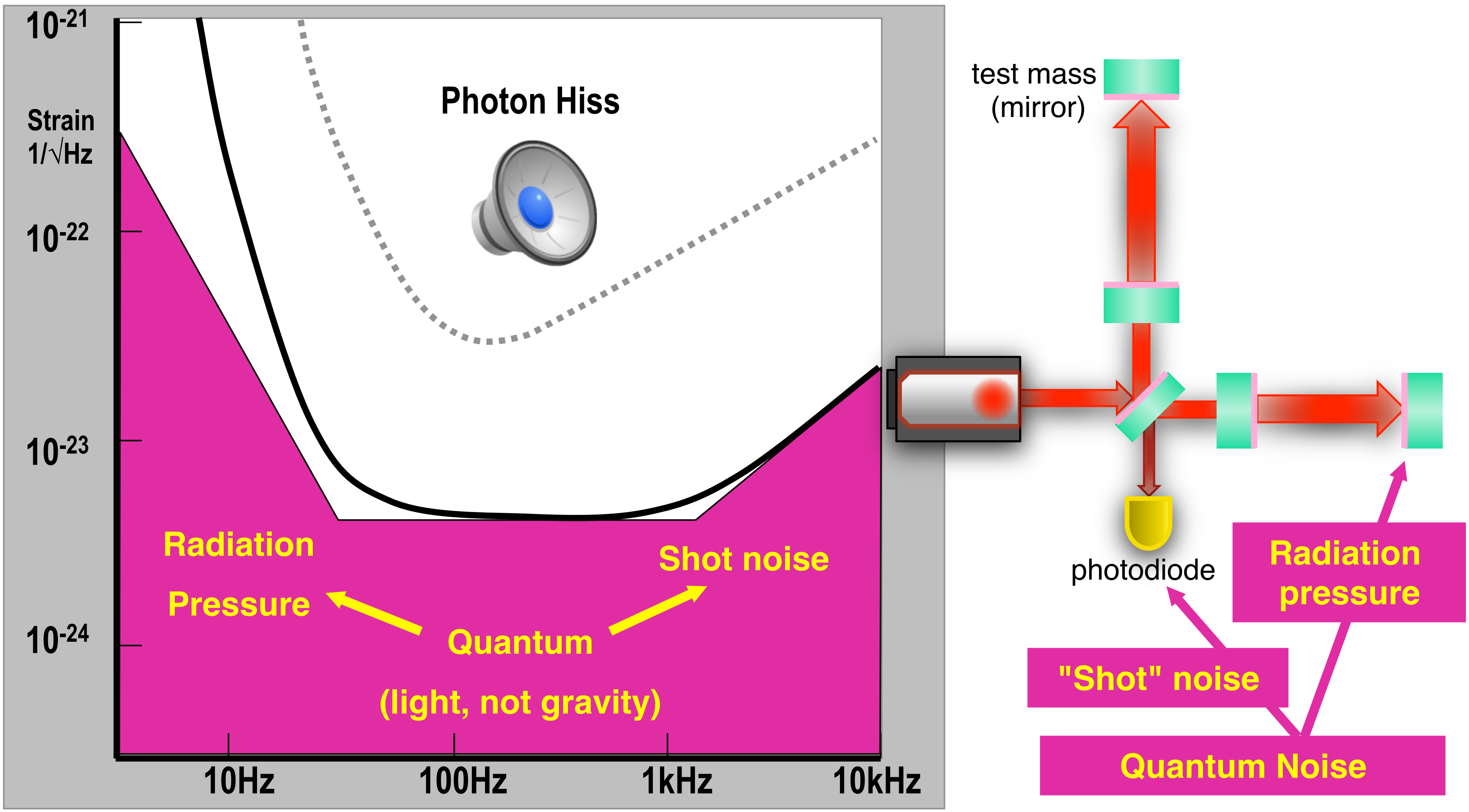


NASA, WMAP

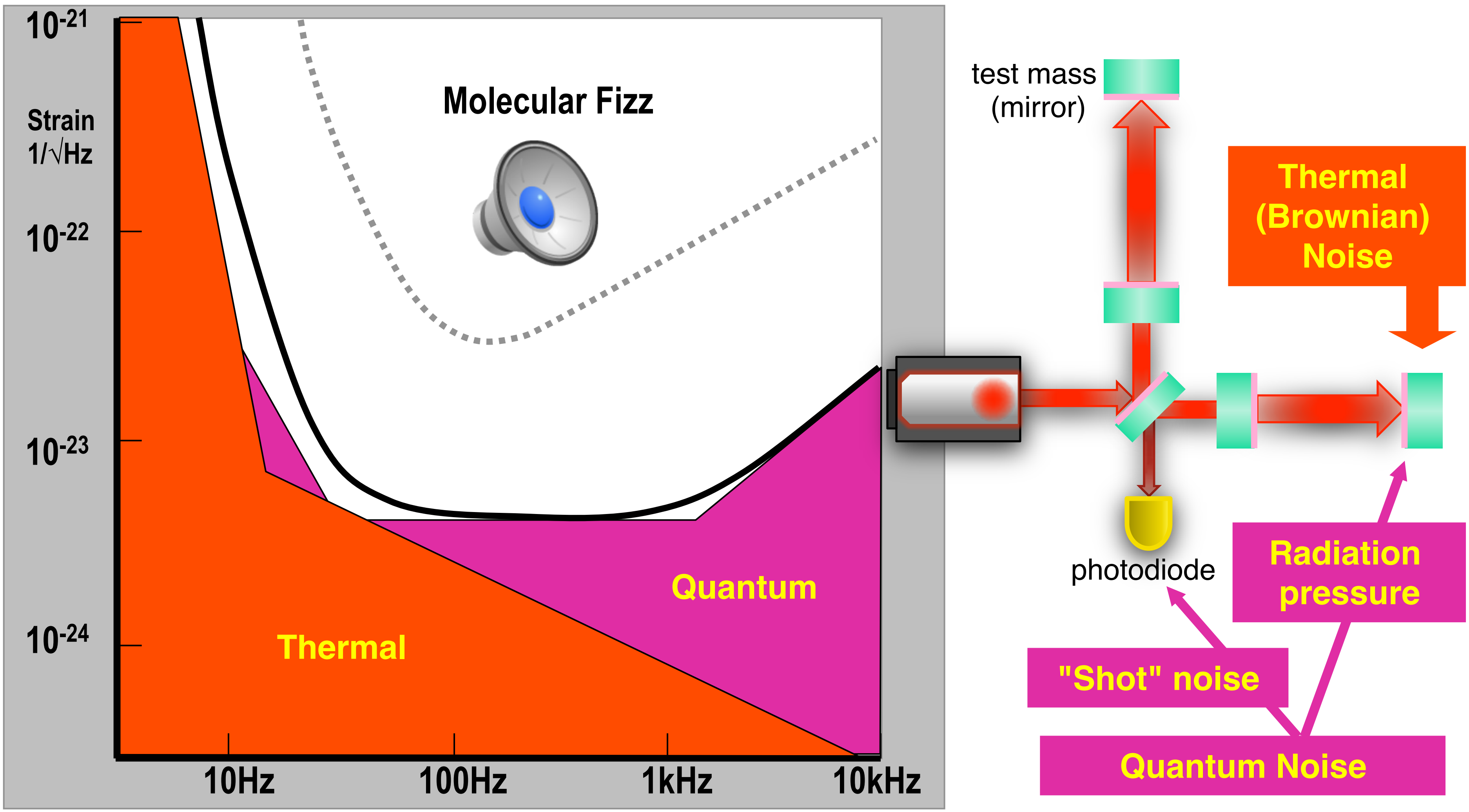
Initial (2001-2010) and advanced (2015+) LIGO



Advanced LIGO Noise

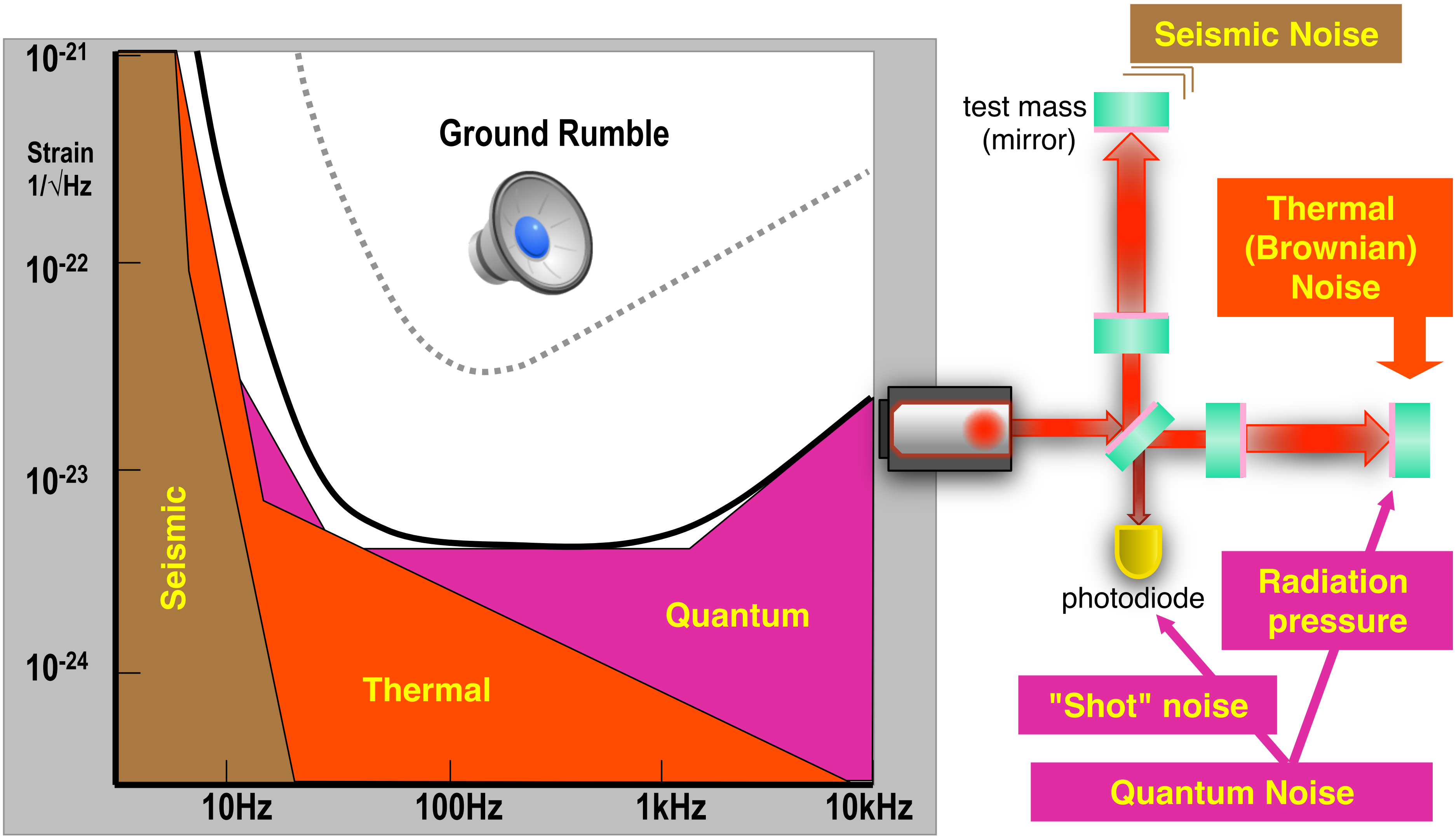


Advanced LIGO Noise



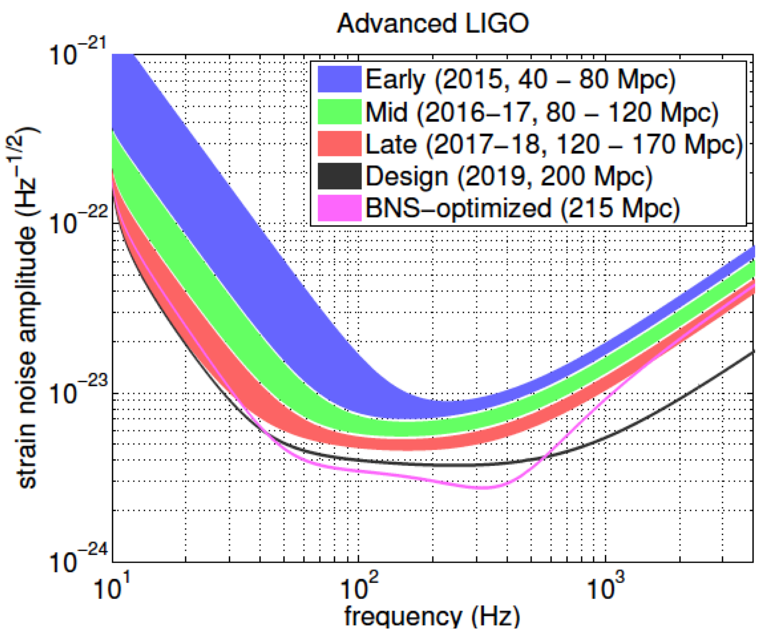
25 April 2016

Advanced LIGO Noise



25 April 2016

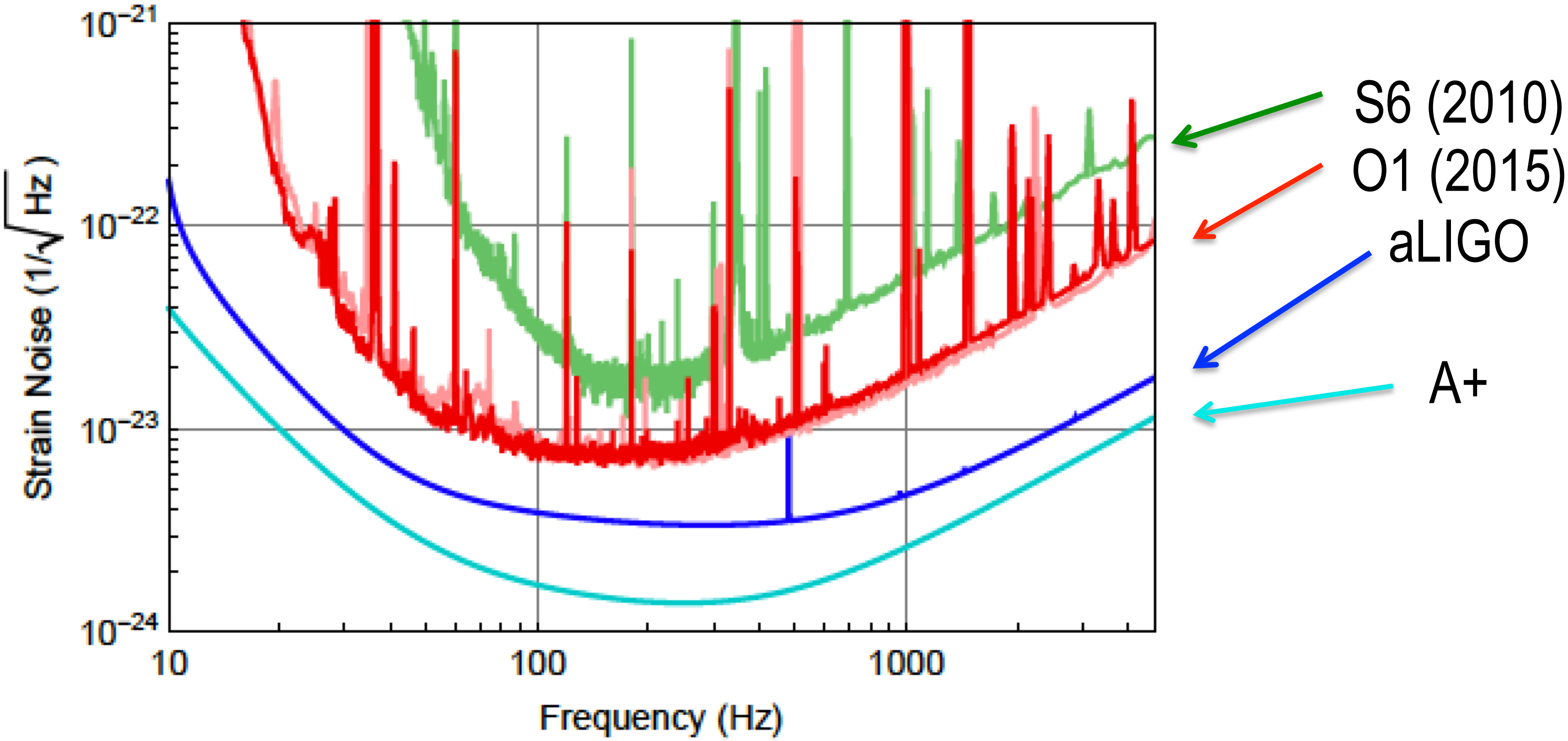
Projections, plans: 2013

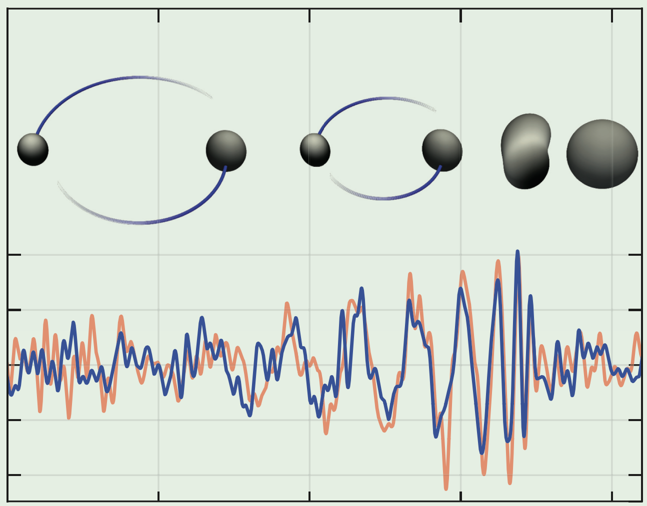


https://arxiv.org/abs/1304.0670v1

Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo
2015	3 months	40 – 60	–	40 – 80	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85
2019+	(per year)	105	40 – 80	200	65 – 130
2022+ (India)	(per year)	105	80	200	130

Sensitivity progress





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)

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Volume 116, Numbe

LIGO

LIGO Scientific Collaboration

LSC

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American University
Andrews University
Washington State University
California State University Fullerton
PennState
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology
Leland Stanford Junior University
The University of Sheffield
University of Maryland
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Texas Tech University
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Colorado State University
Charles Sturt University
NASA
Marshall Space Flight Center
CMI Chennai Mathematical Institute
東京大学 The University of Tokyo
ACIGA
ICTS International Centre for Theoretical Sciences, Tata Institute of Fundamental Research
University of Birmingham
Georgia Institute of Technology
Korean Gravitational Wave Group
Universität Hamburg — Der Forschung | Der Lehre | Der Bildung
The University of Melbourne
Embry-Riddle Aeronautical University
Villanova University
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University and Institute of Advanced Research — The Puri Foundation for Education in India
Swinburne University of Technology
The University of Mississippi
INPE
GEO 600
Max Planck Institute for Gravitational Physics, Albert Einstein Institute
Leibniz Universität Hannover
University of Zurich
IISER Thiruvananthapuram
CITA ICAT
King's College London
IISER Kolkata
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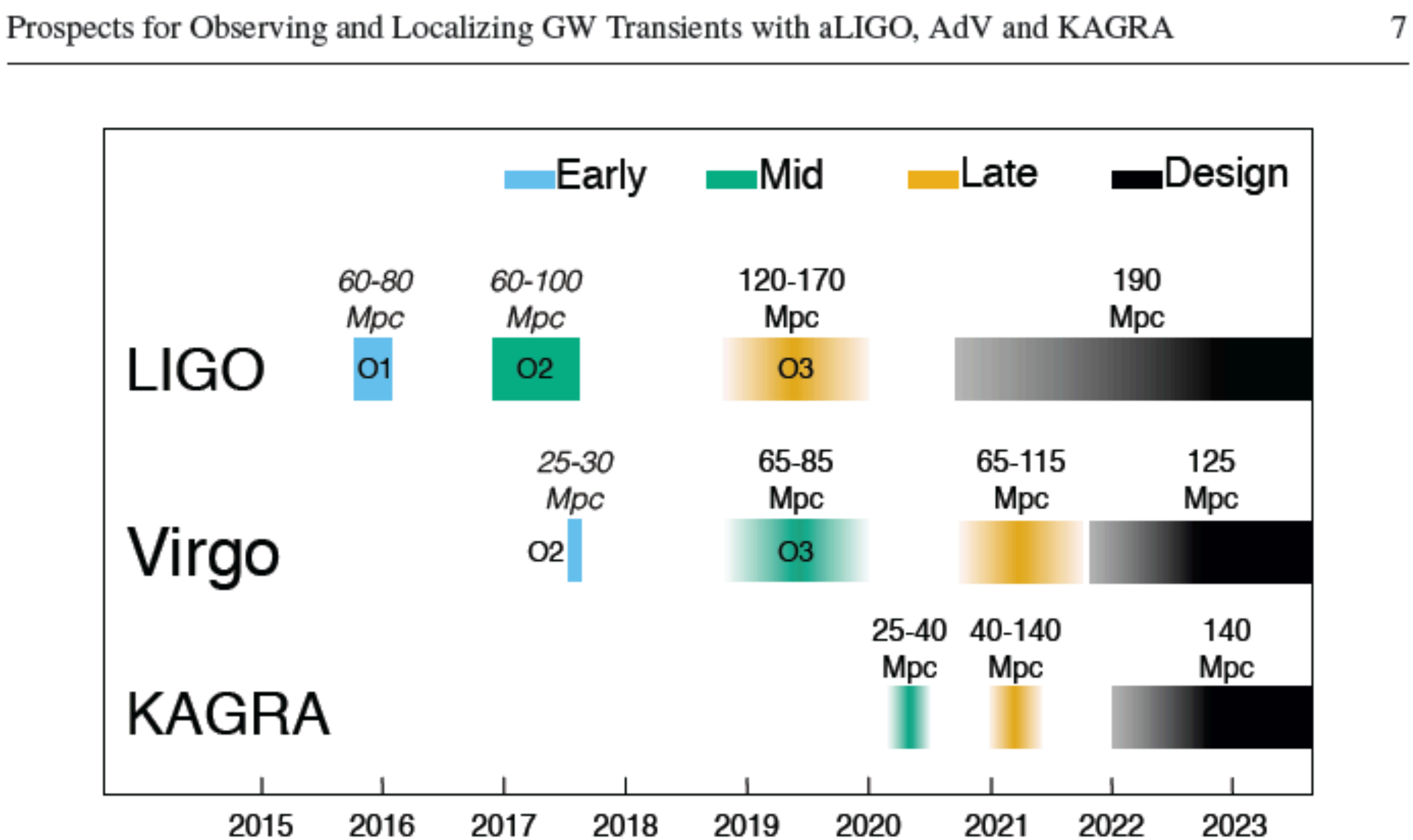
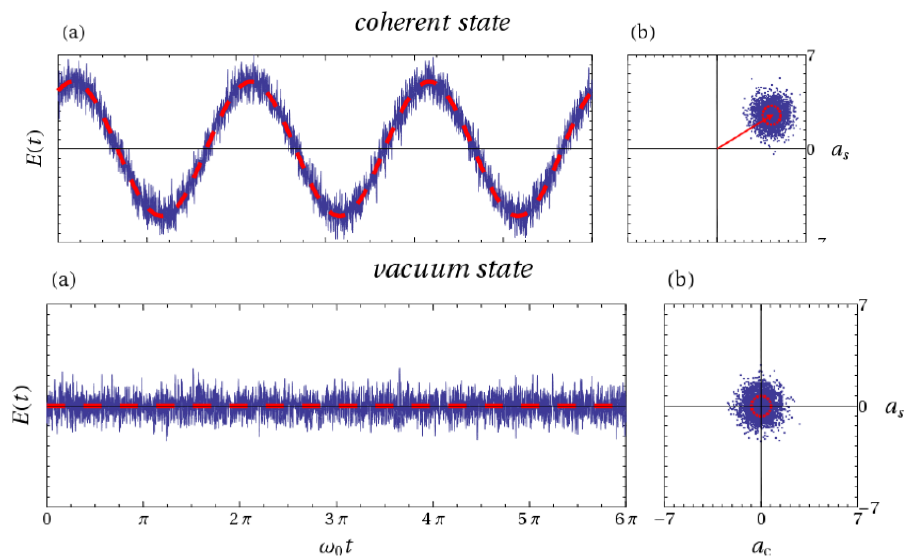
The next few years

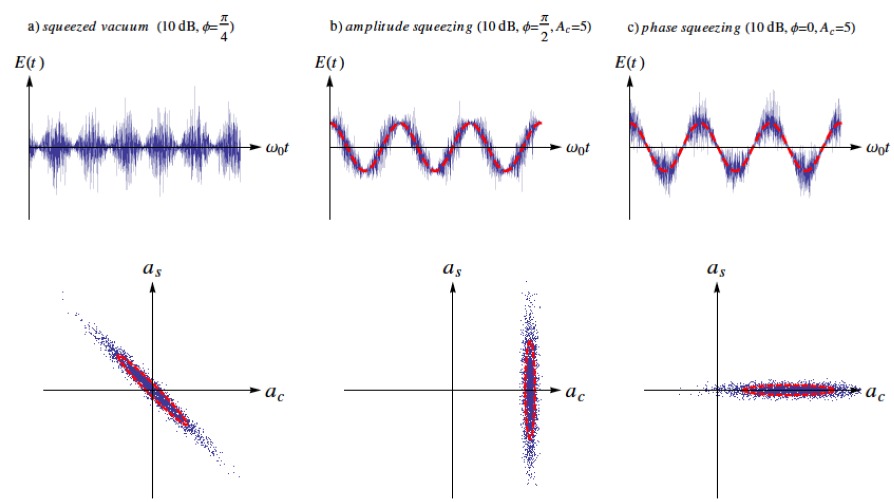


Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

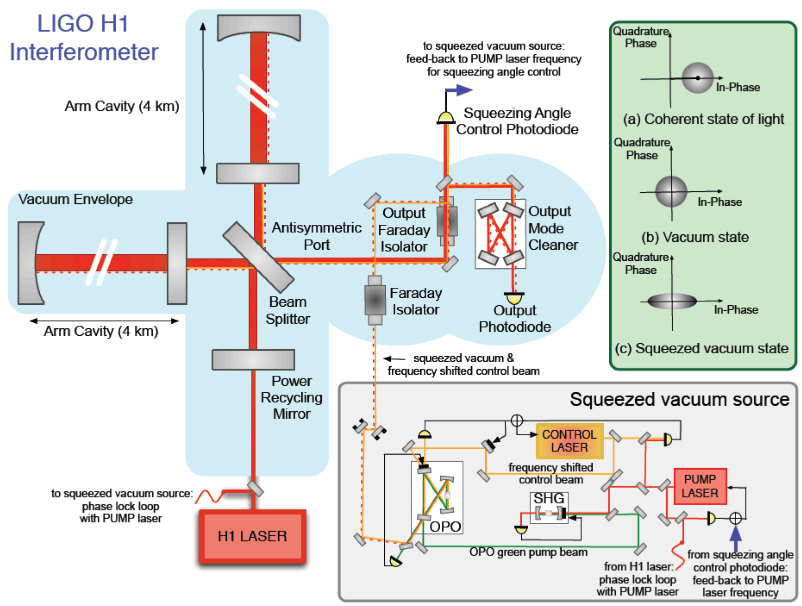
https://arxiv.org/abs/1304.0670

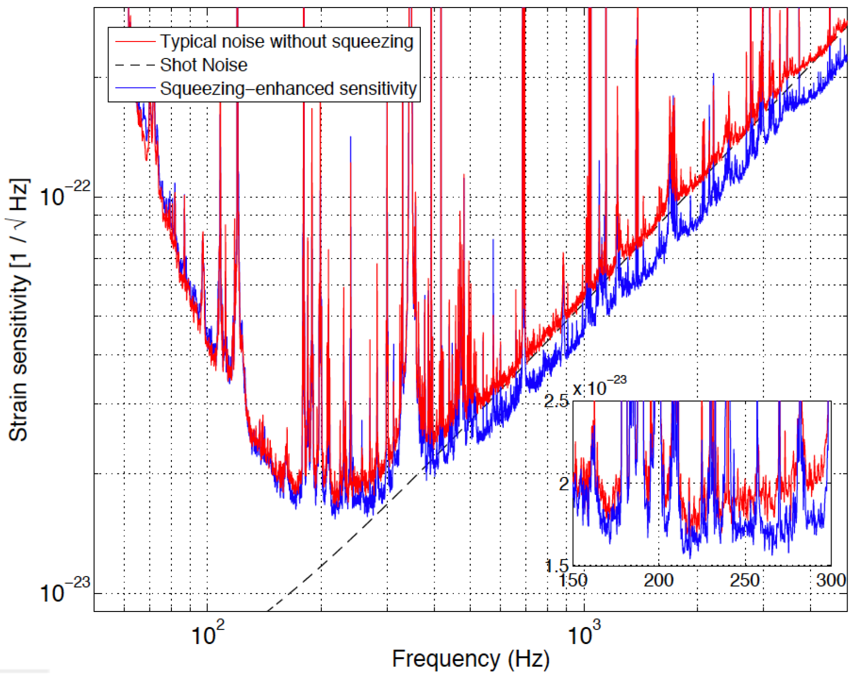
Shot noise: quantum noise!

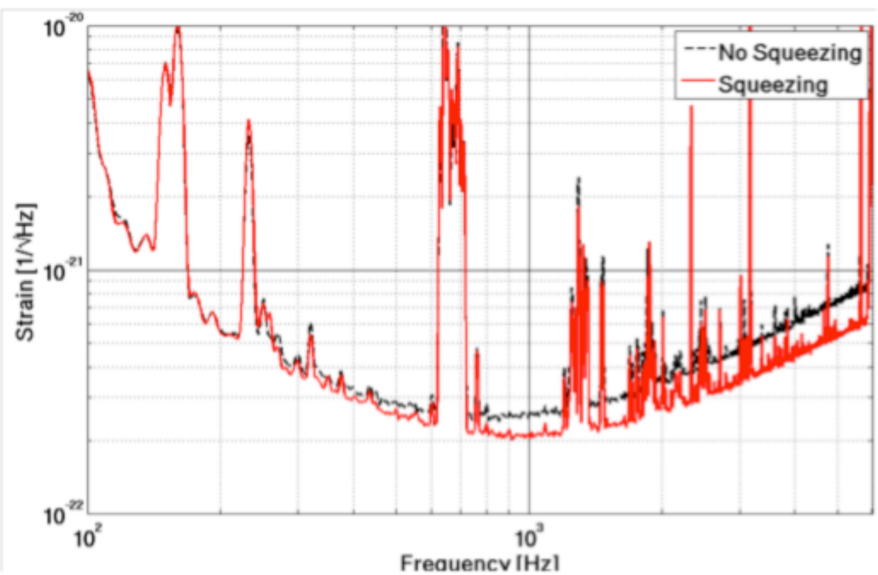




Squeezing en iLIGO and GEO600

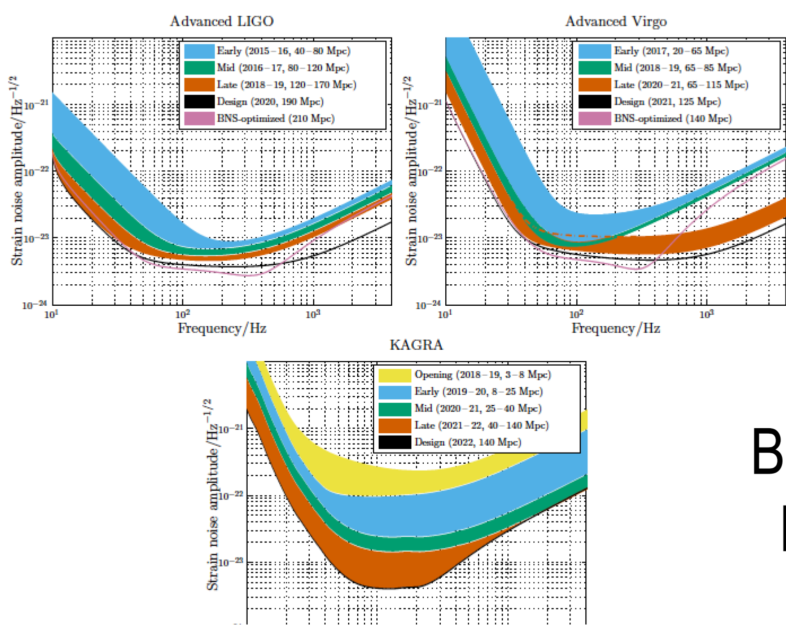






Projections, plans: 2018

Prospects for Observing and Localizing GW Transients with aLIGO, AdV and KAGRA 5



https://arxiv.org/abs/1304.0670v6

BNS coalescence rate: 320 – 4740 /Gpc^3/yr

BBH coalescence rate: 12 – 200 /Gpc^3/yr

Table 1 Plausible target detector sensitivities. The different phases match those in Fig. 1. We quote the range, the average distance to which a signal could be detected, for a $1.4M_\odot$+$1.4M_\odot$ binary neutron star (BNS) system and a $30M_\odot$+$30M_\odot$ binary black hole (BBH) system.

	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
Mid	80 – 120	775 – 1110	65 – 85	615 – 790	25 – 40	250 – 405
Late	120 – 170	1110 – 1490	65 – 115	610 – 1030	40 – 140	405 – 1270
Design	190	1640	125	1130	140	1270

Past, present and (near) future

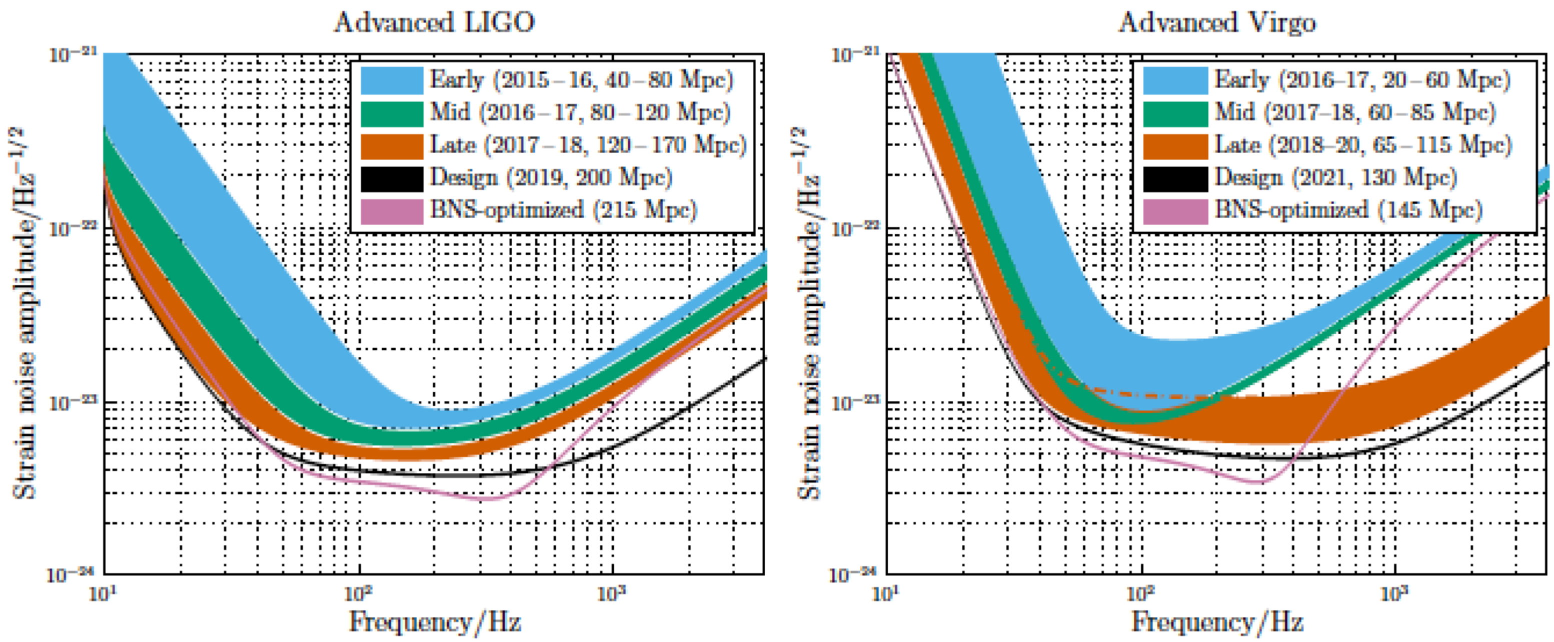
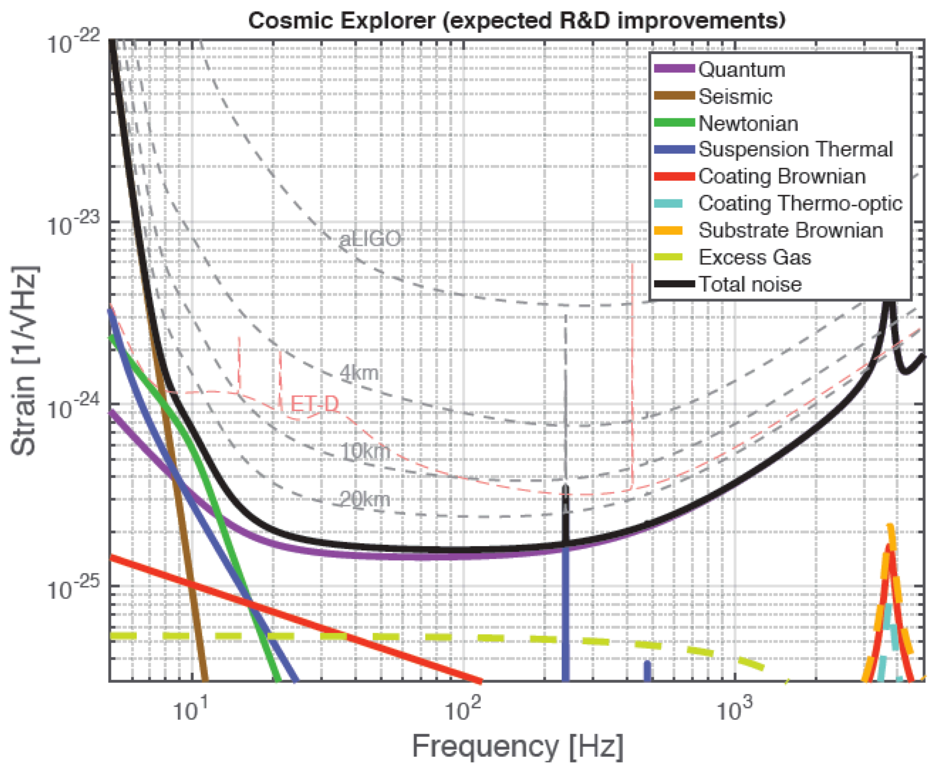


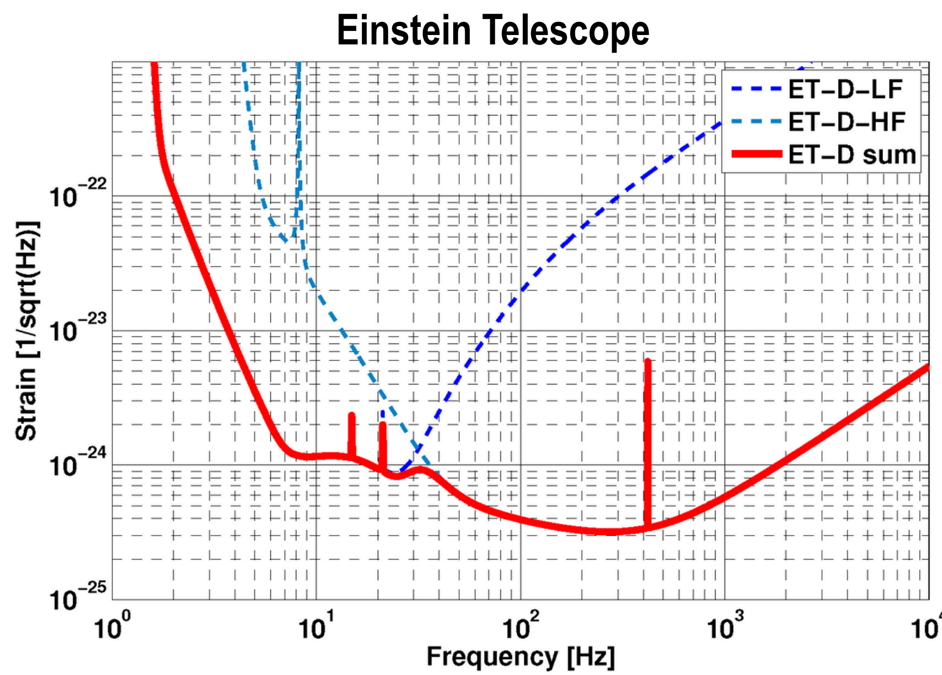
Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late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

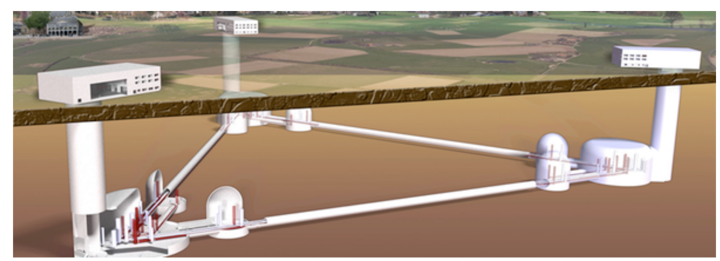
The future:
3rd generation detectors



Class. Quantum Grav. 34 (2017) 044001

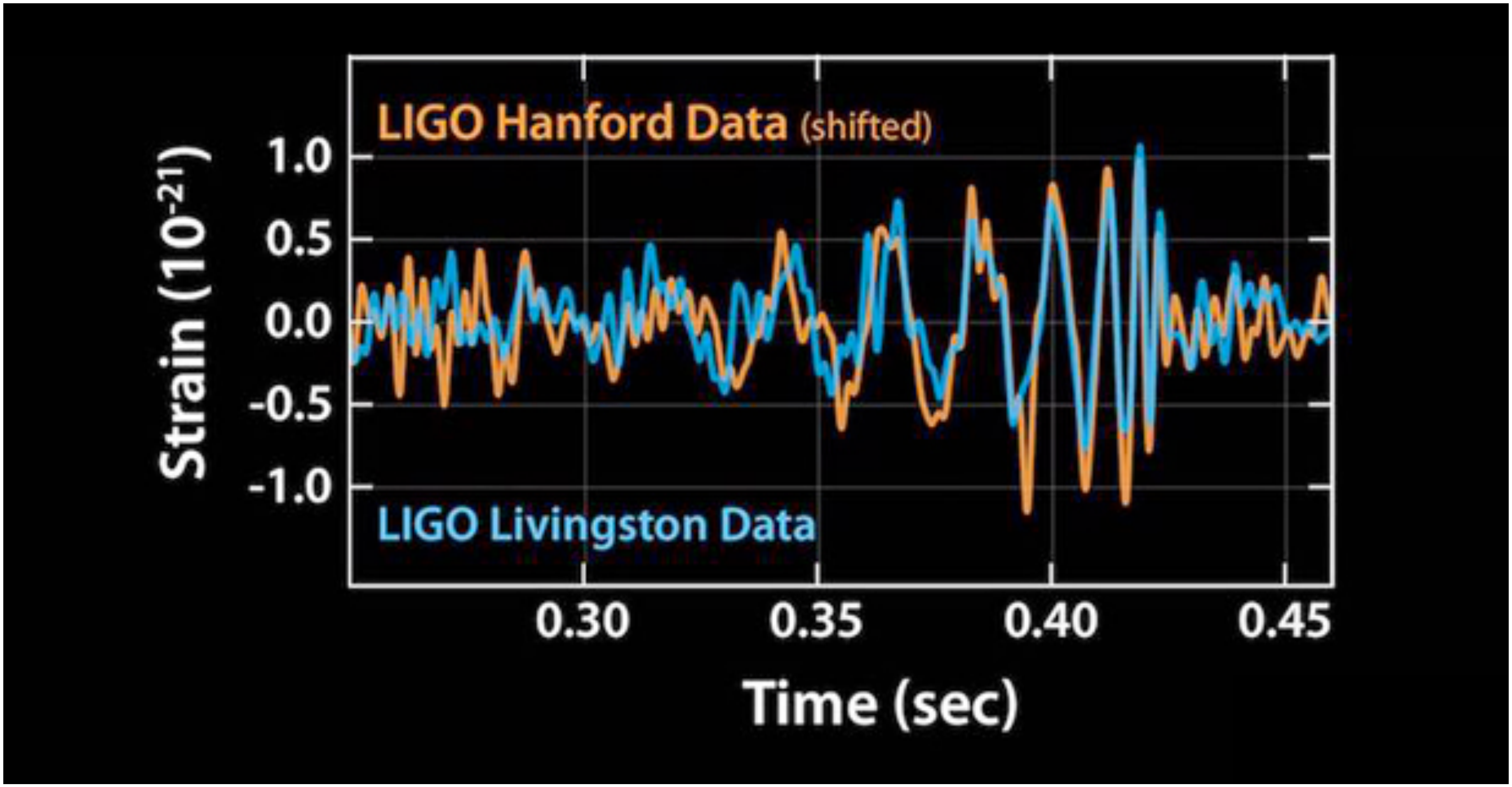


S.Hild et al., Classical and Quantum Gravity, 28 094013, 2011



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

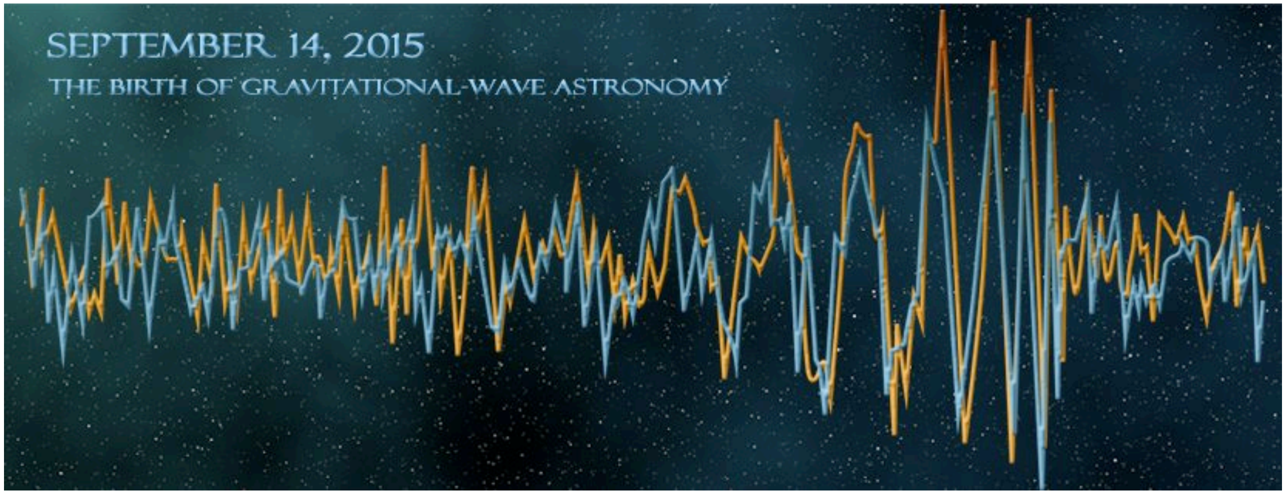
Tomorrow: GW astronomy



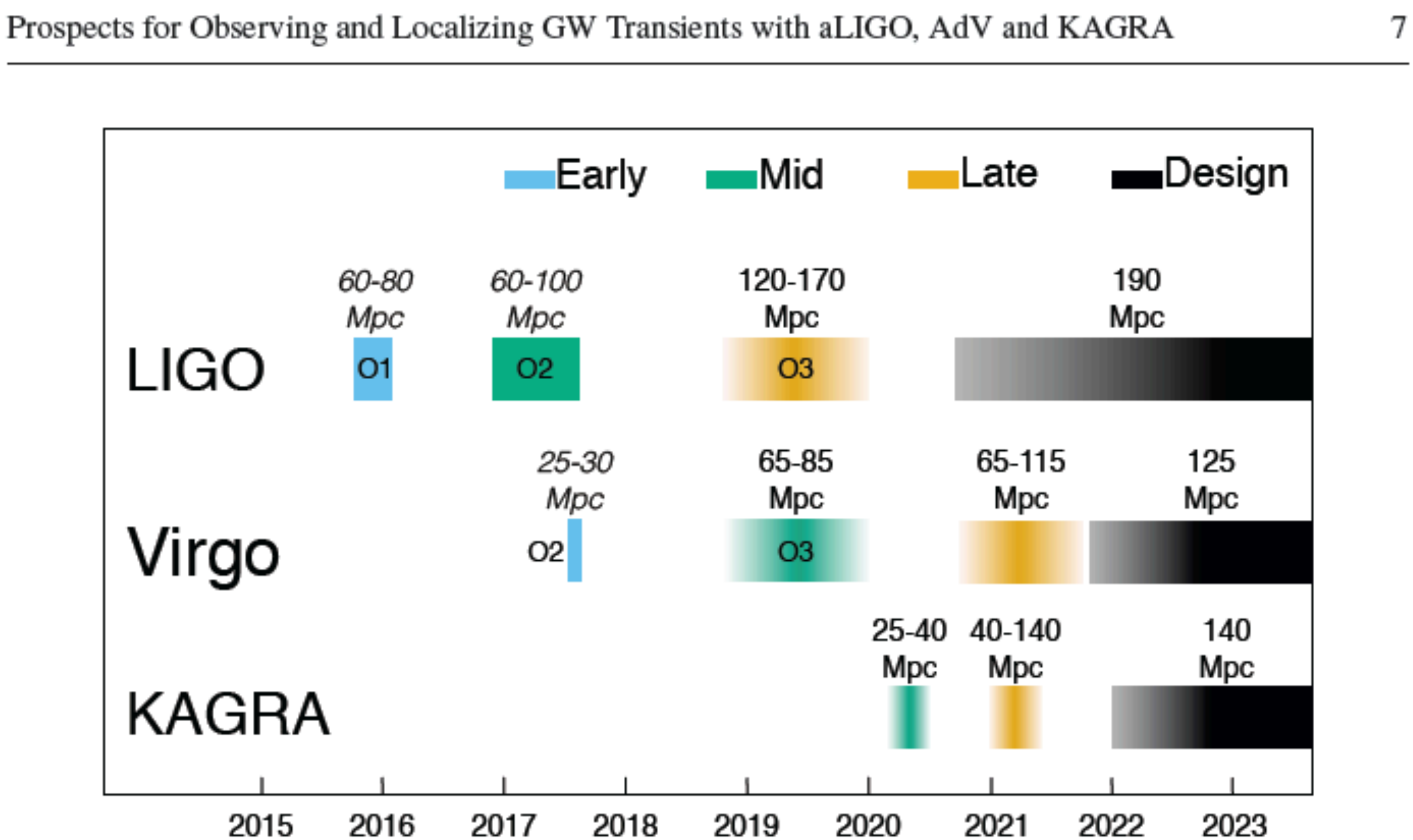
Searching for – and finding! gravitational waves

Gabriela González
Louisiana State University

International School of Cosmic Ray Physics
Erice, Italy, August 5, 2018



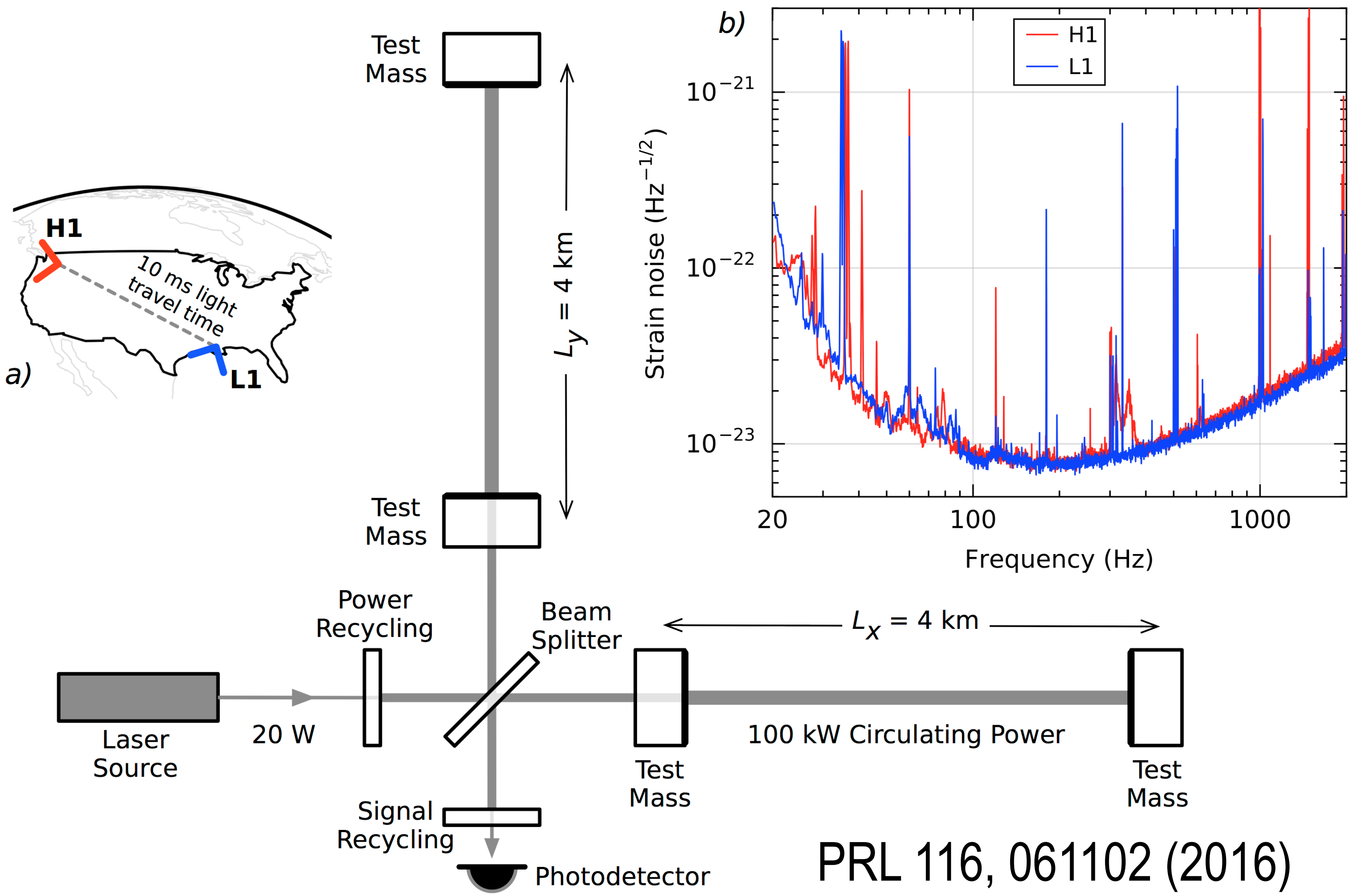
The next few years



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

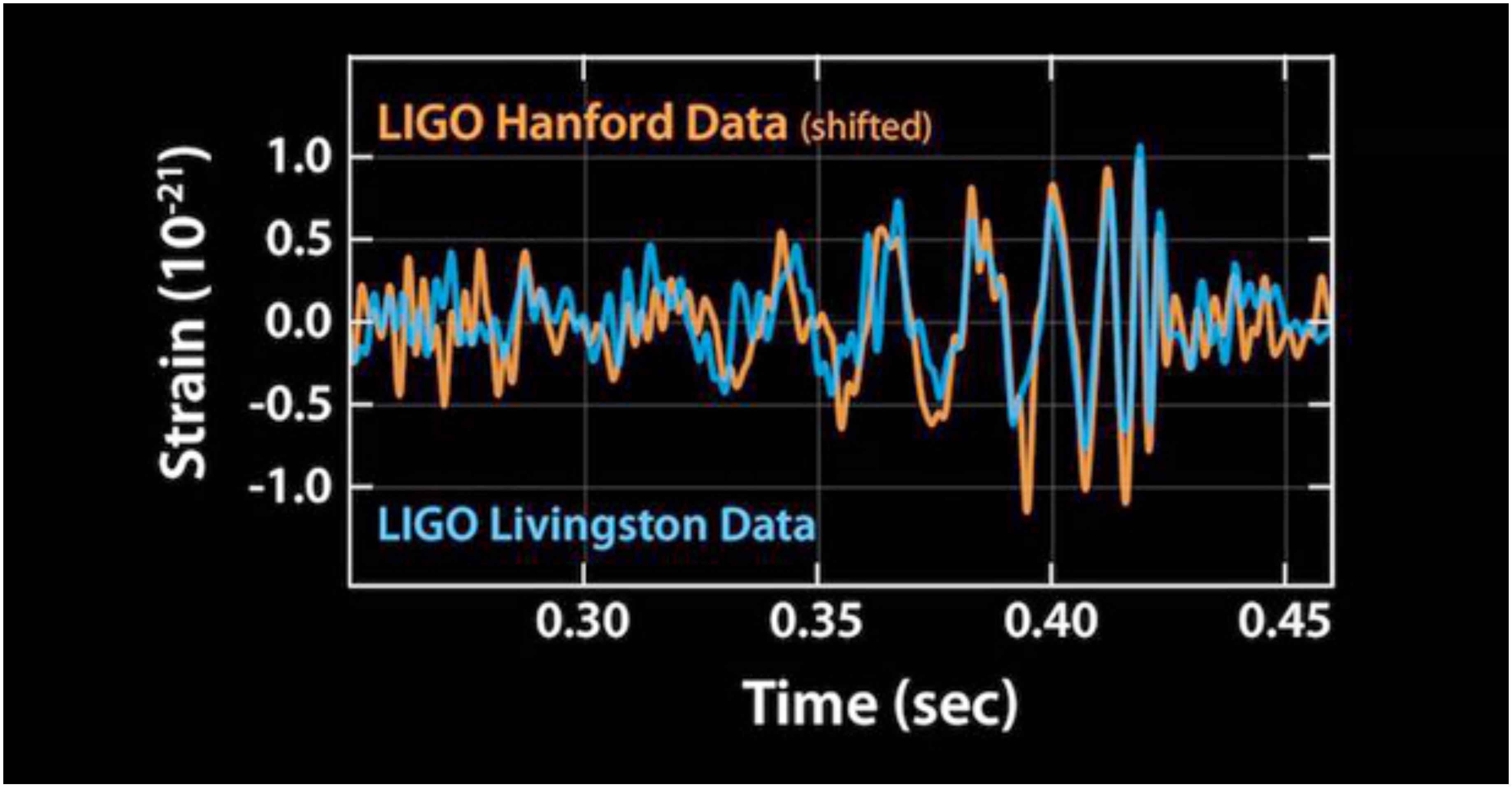
https://arxiv.org/abs/1304.0670

Advanced LIGO detectors September 2015



PRL 116, 061102 (2016)

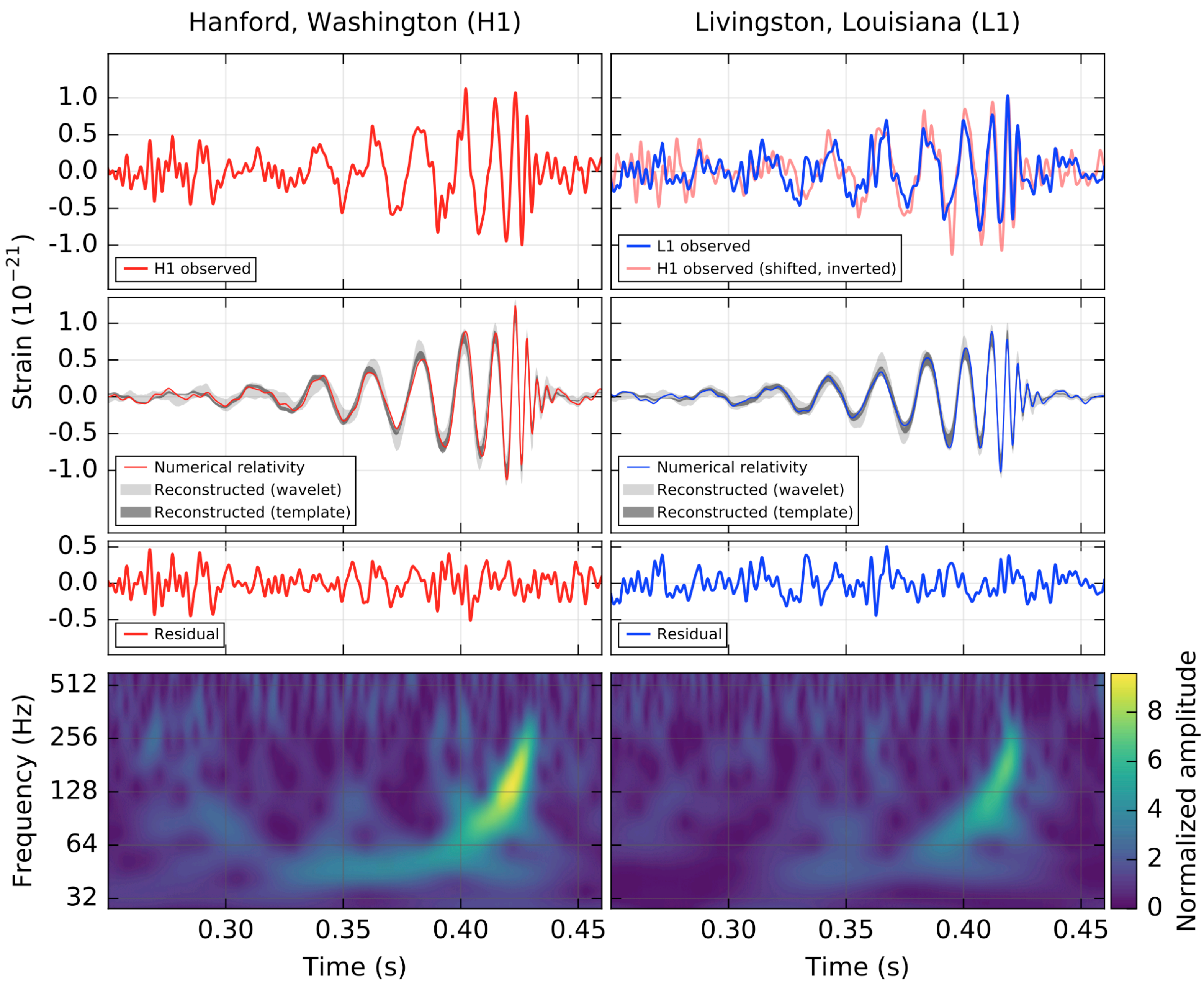
On Sept 14 2015…



11 de Febrero, 2016: ¡We did it!

International Day of Women and Girls in Science
11 February

PRL 116, 061102 (2016)



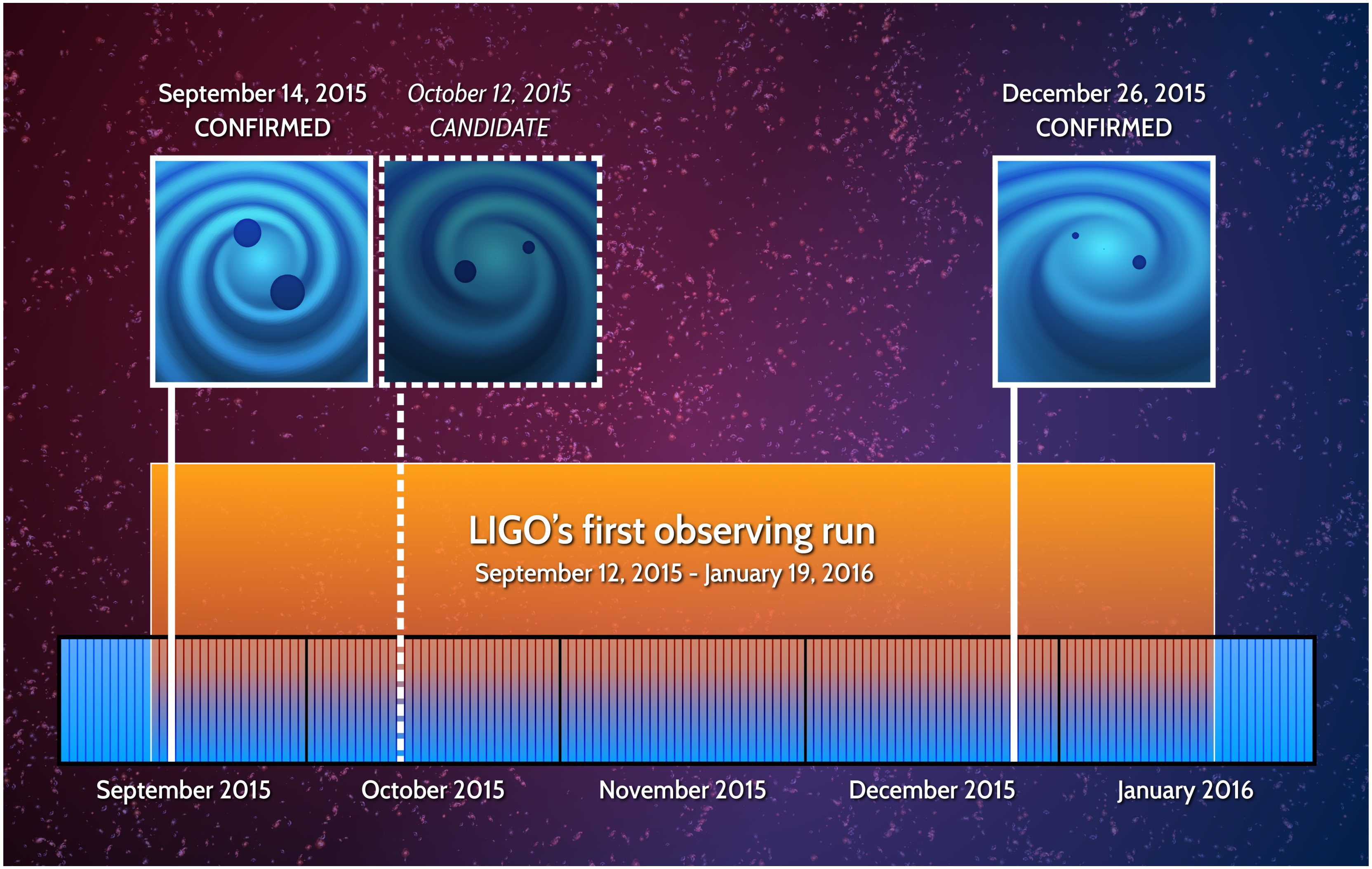
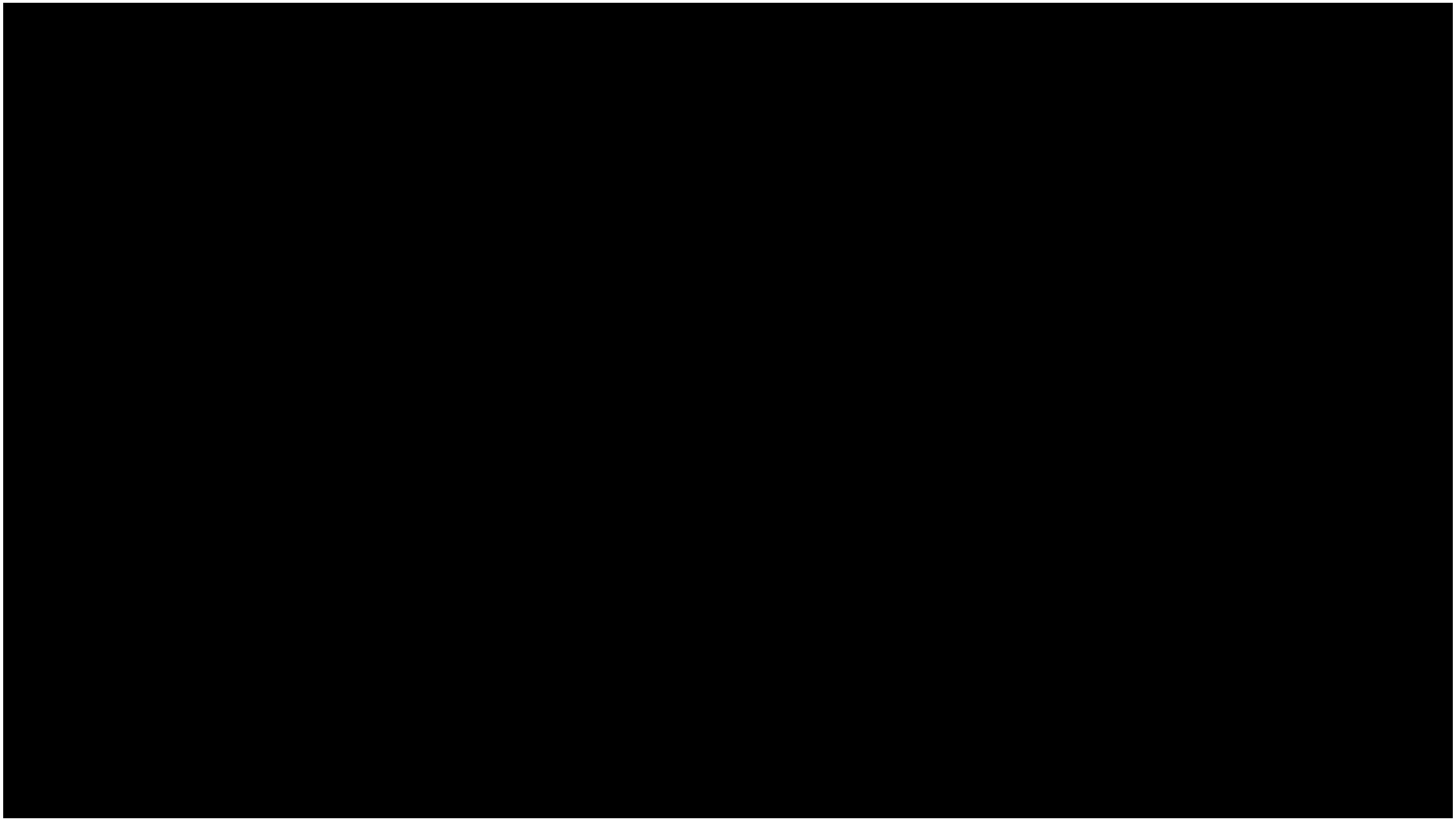
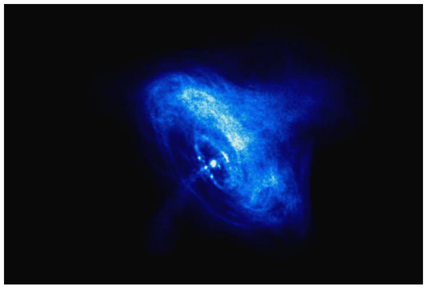


Image credit: LIGO

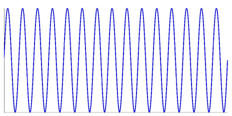
Gravity’s music



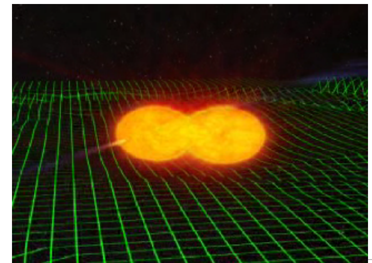
Searching for gravitational waves



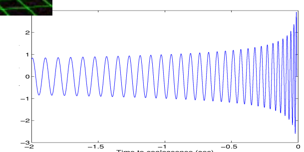
Crab pulsar (NASA, Chandra Observatory)



Periodic, continuous waves

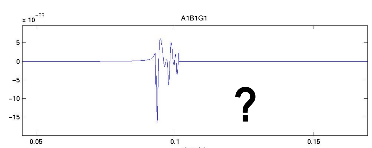


Credit: John Rowe



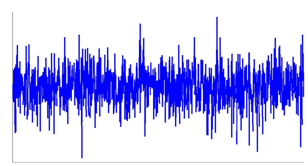
Binary systems with neutron stars and/or black holes

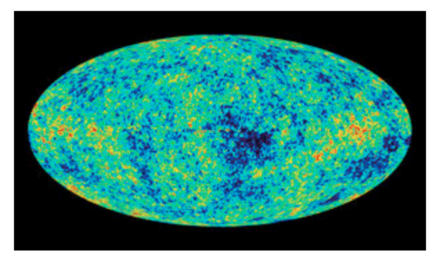
Short transients from supernova explosions or other sources



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

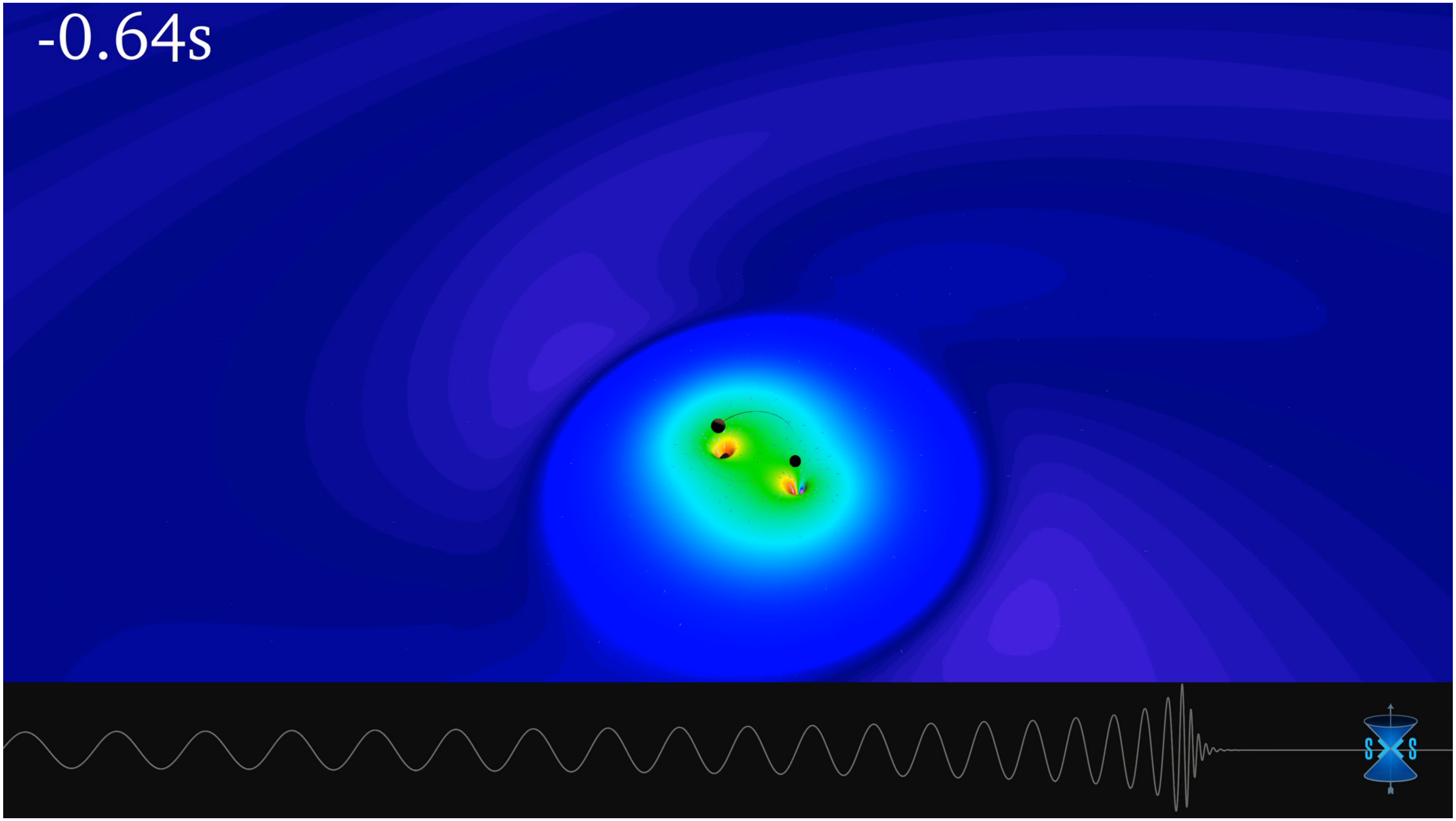
Stochastic background from many unresolved sources, or from the beginning of the Universe





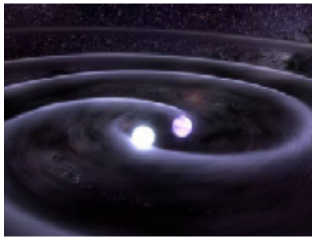
NASA, WMAP

A solution to Einstein's equations

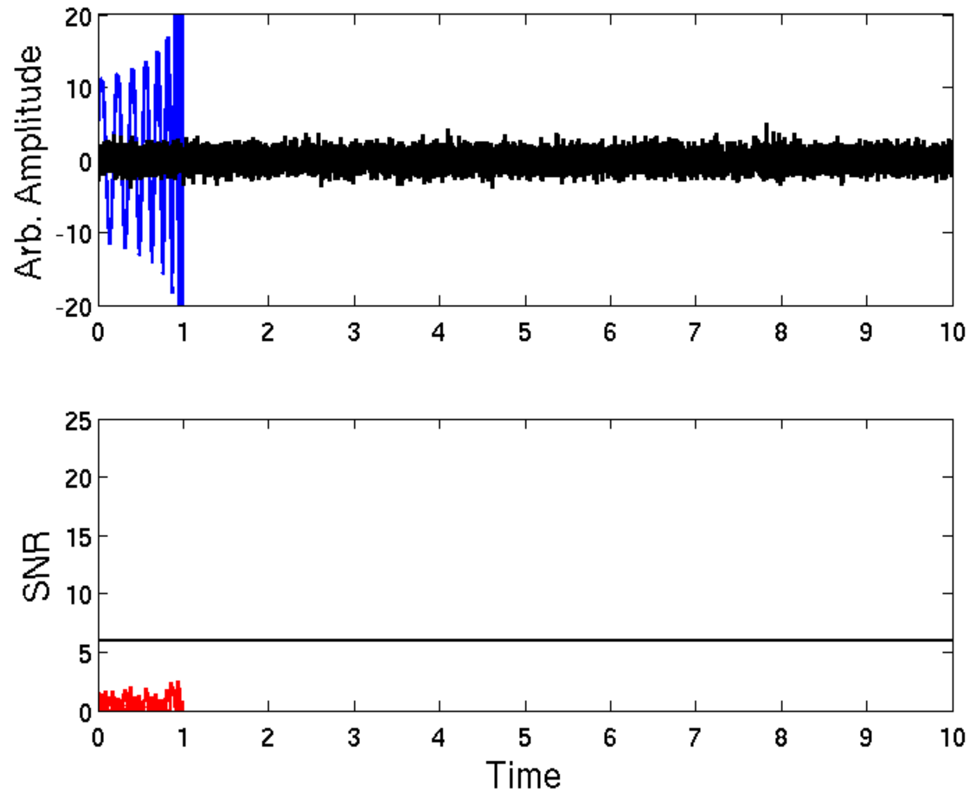


Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)

Matched filtering in action

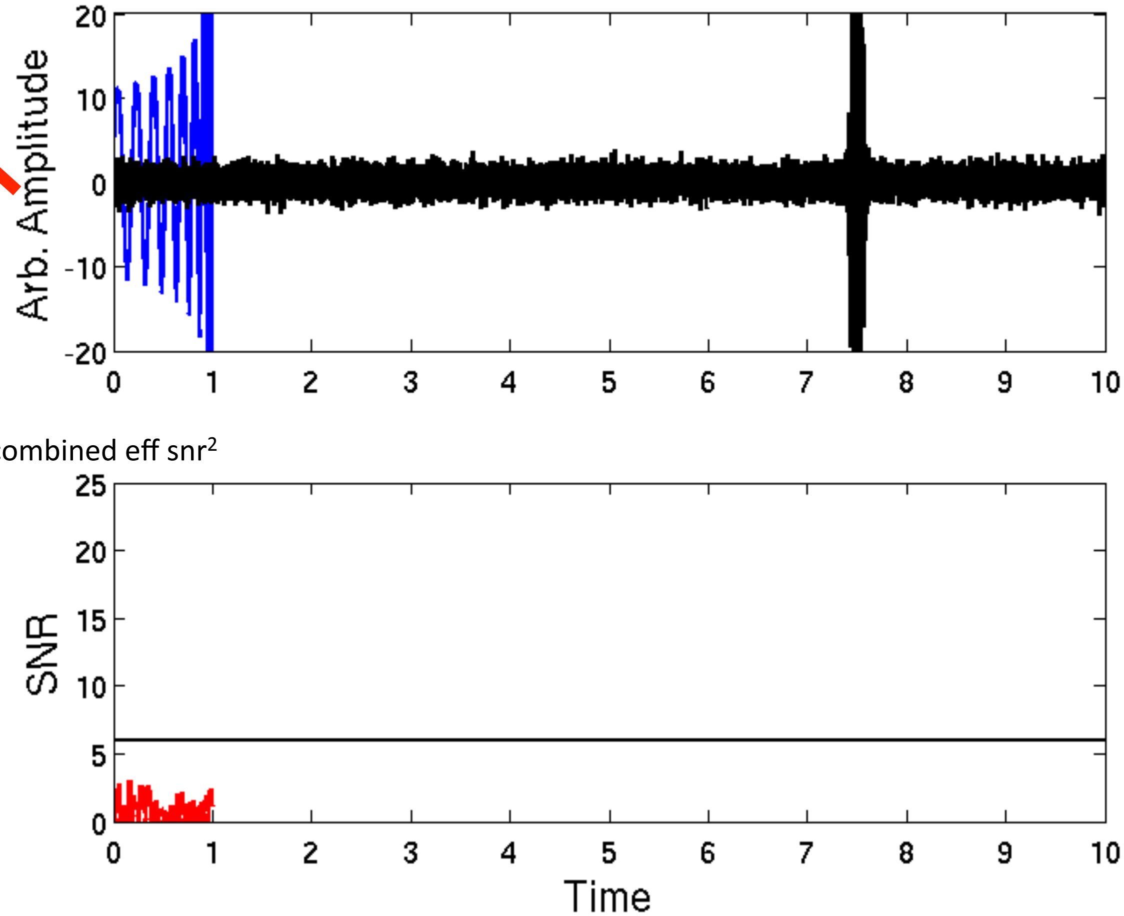


A signal with SNR 20 is not obvious in time series – but it is huge in matched filtering :



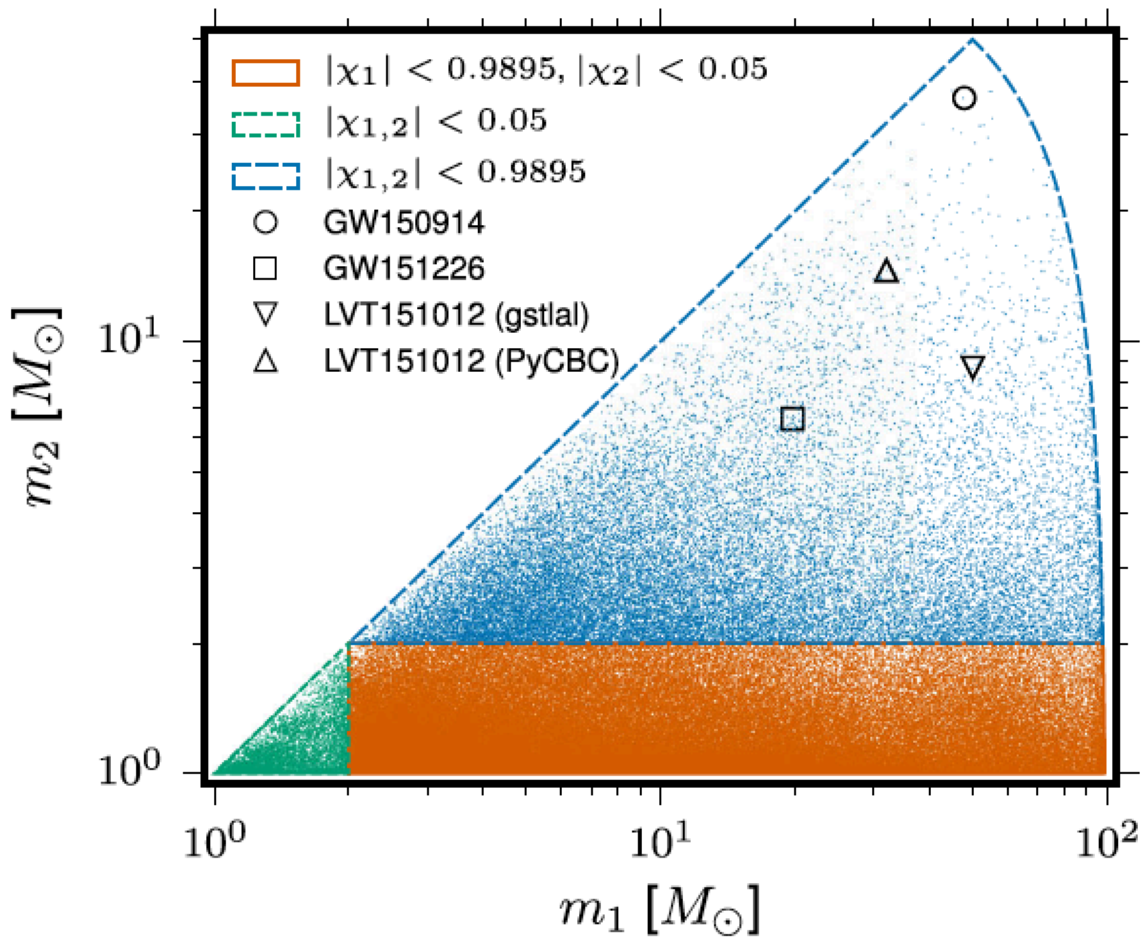
Animation by Chad Hanna

How to get misled by matched filtering in non-gaussian noise



Animation by Chad Hanna

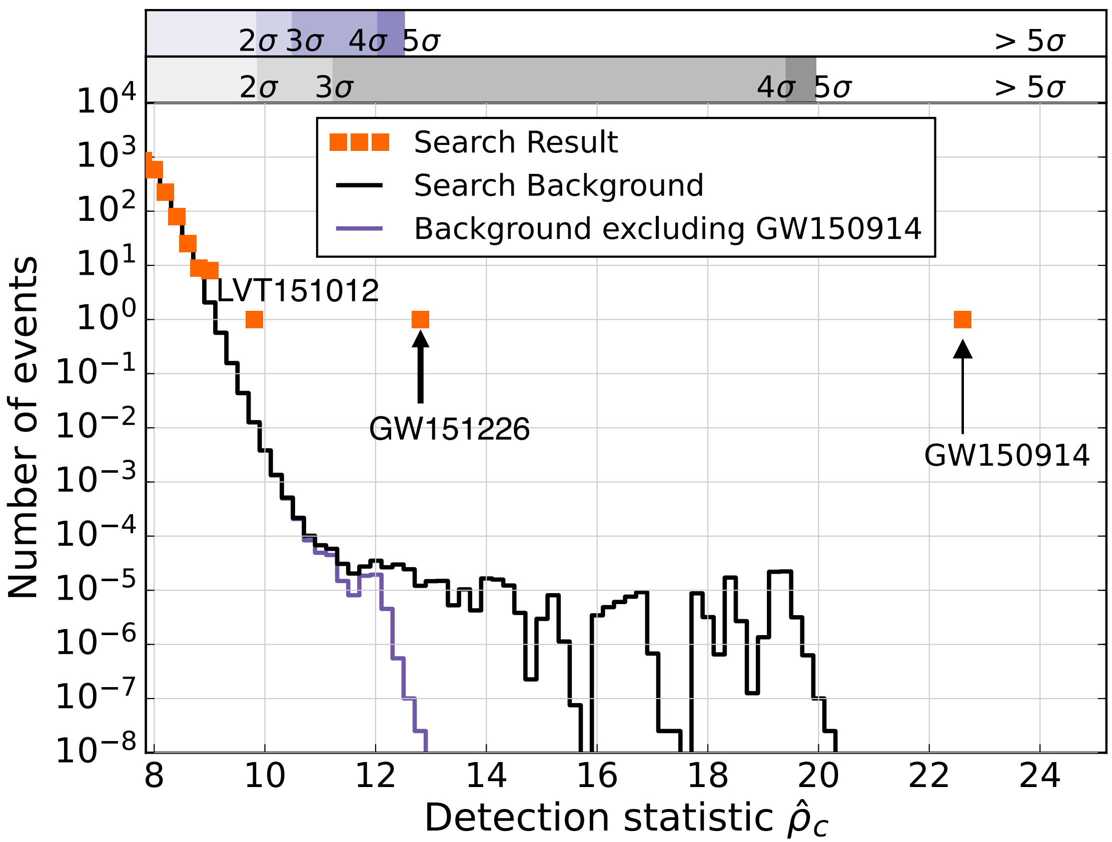
Searching and finding waveforms

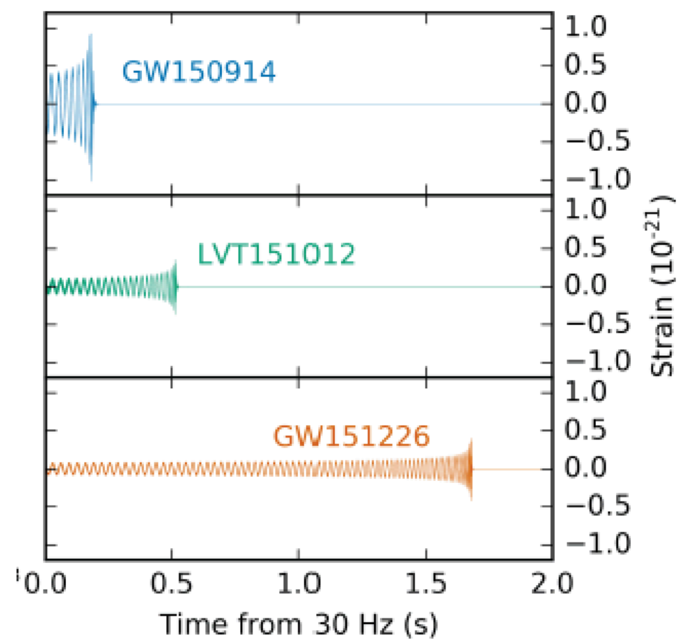


Phys. Rev. X 6, 041015 (2016))

O1 BBH search

Search for binary black holes systems with black holes larger than 2 $M_\odot$ and total mass less than 100 $M_\odot$, in O1 (Sep 12, 2015-Jan 19, 2016, ~48 days of coincident data)





Phys. Rev. X 6, 041015 (2016))

GW150914: also found as a "burst"

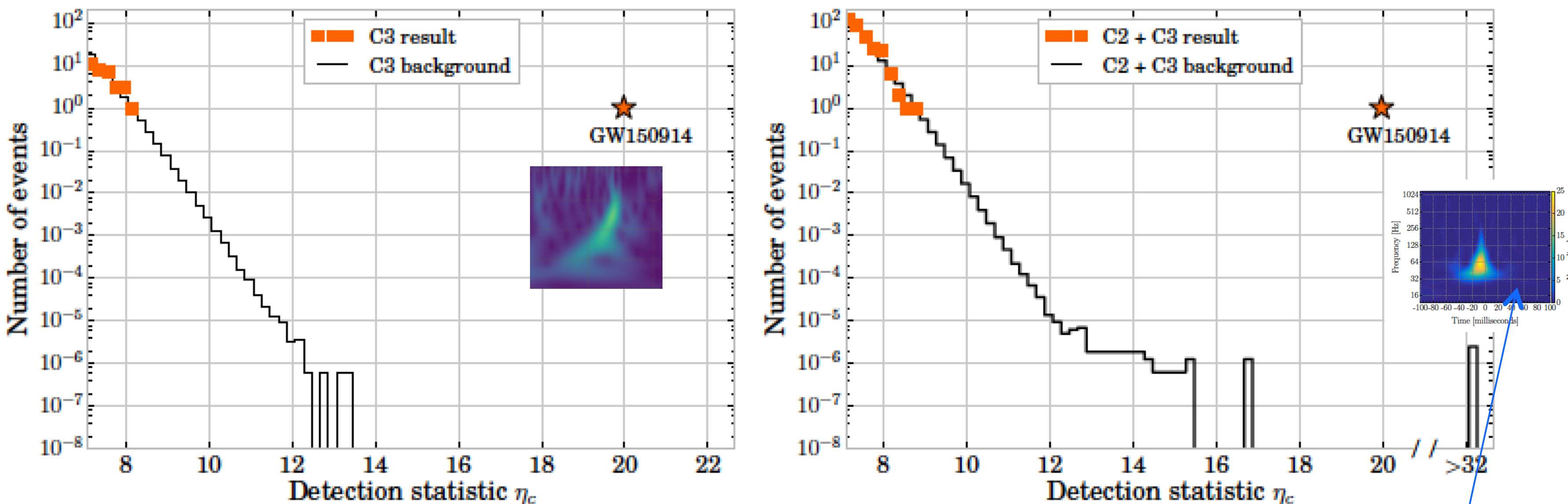


FIG. 2. Search results (in orange) and expected number of background events (black) in 16 day of the observation time as a function of the cWB detection statistic (bin size 0.2) for the $C3$ search class (left) and $C2 + C3$ search class (right). The black curve shows the total number of background events 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.

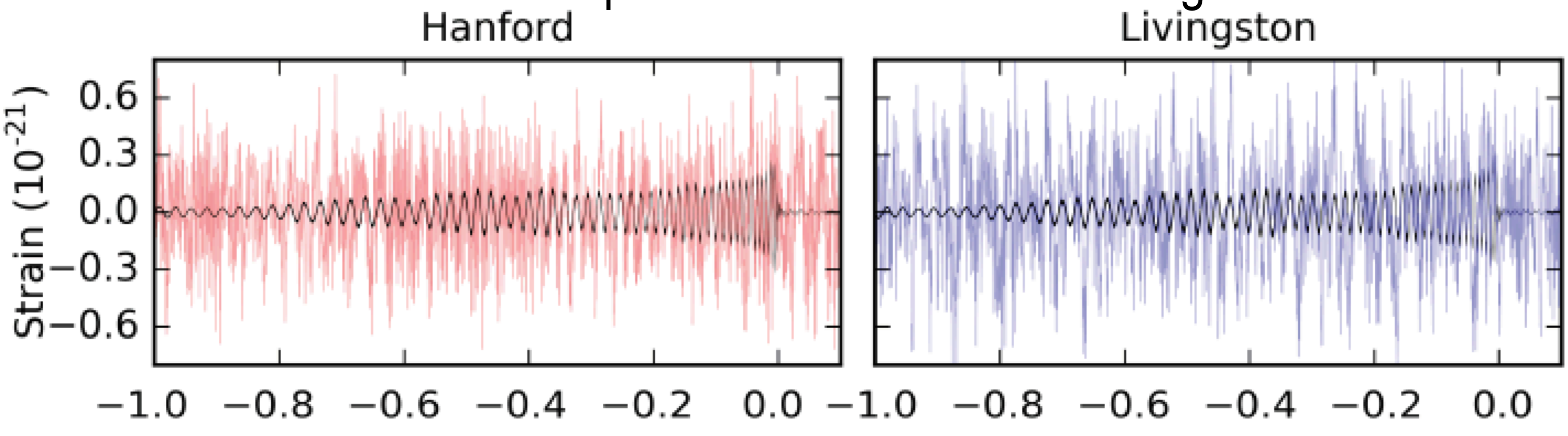
"blip glitch"

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

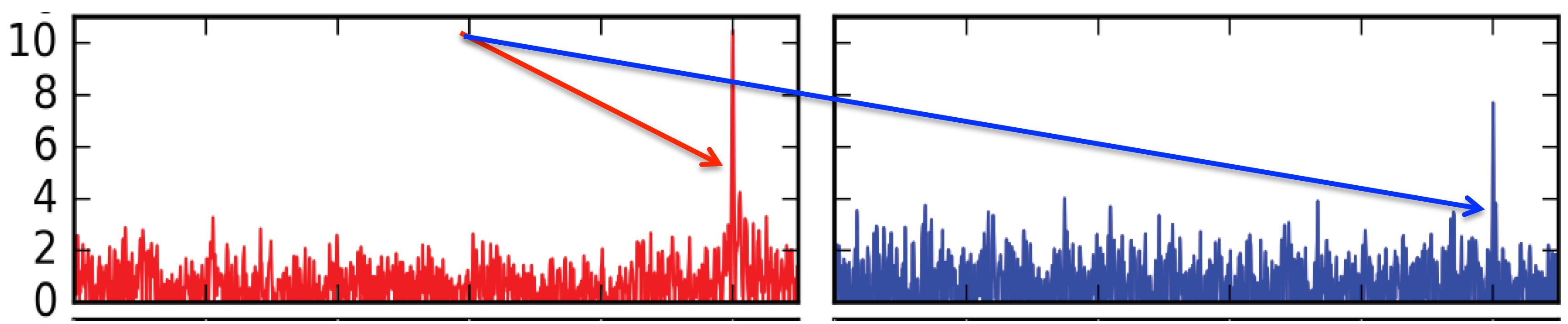
Phys. Rev. D **93**, 122004 (2016)

GW151226: not so obvious!

Filtered detector output and filtered best matching waveform

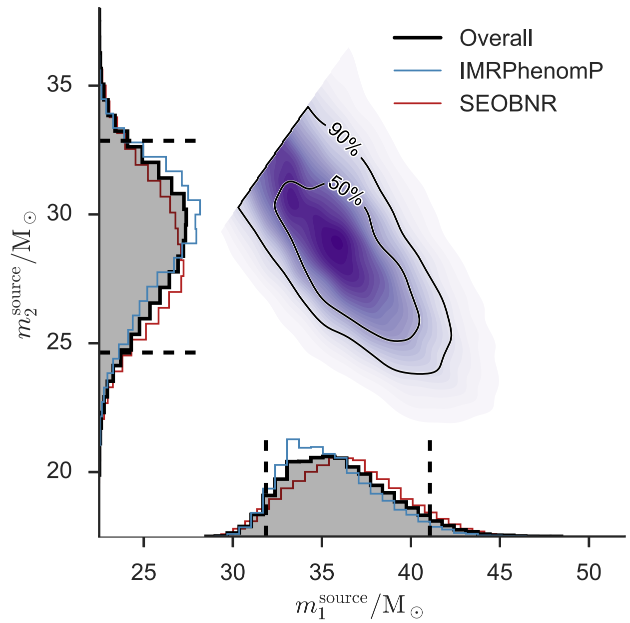


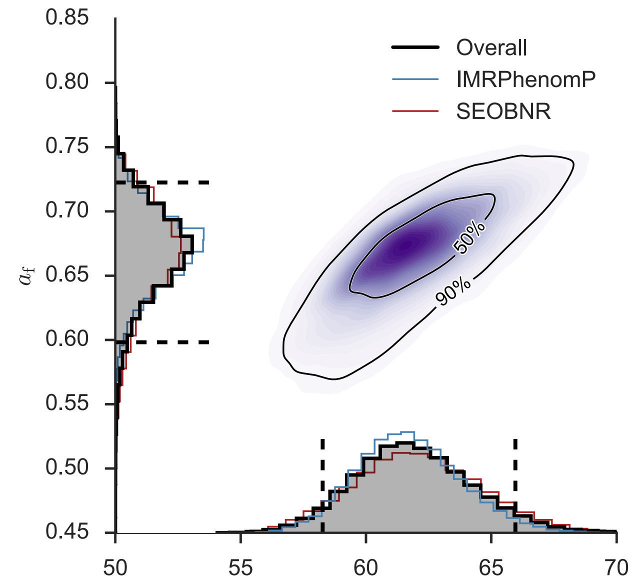
Signal-to-noise (SNR) when best template matches at coalescence time



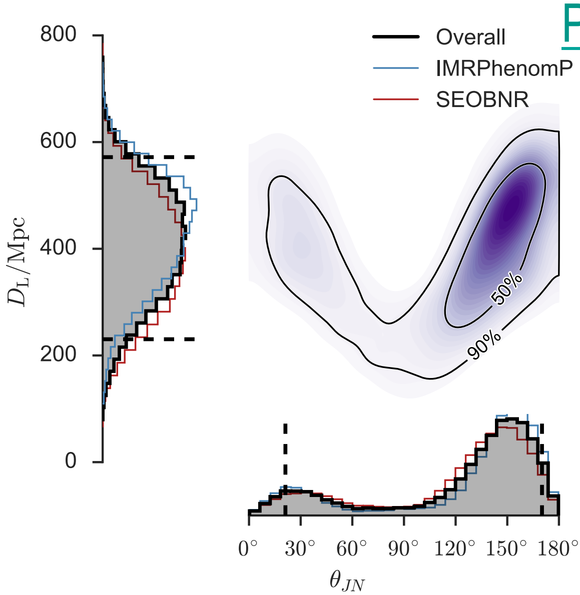
Phys. Rev. Lett. **116**, 241103 (2016)

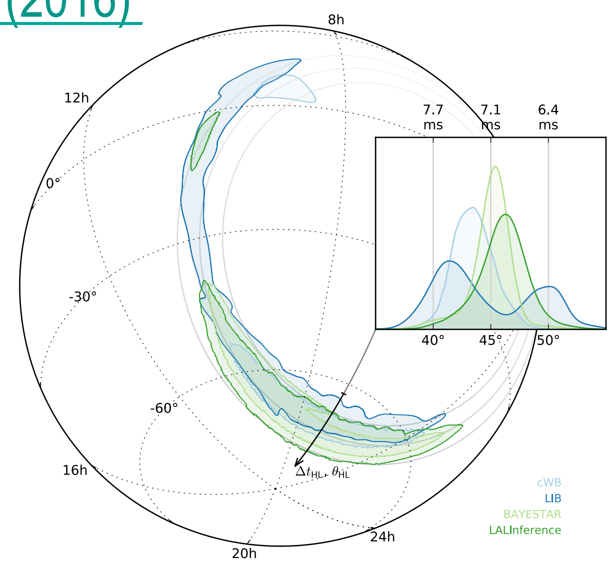
Finding parameters: GW150914





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





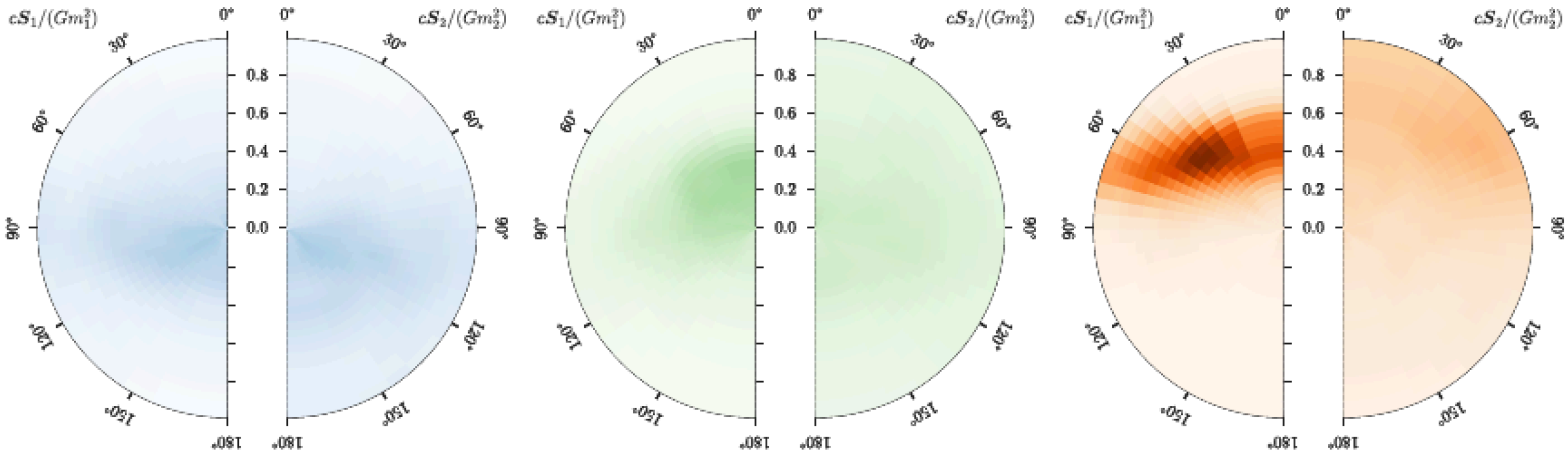
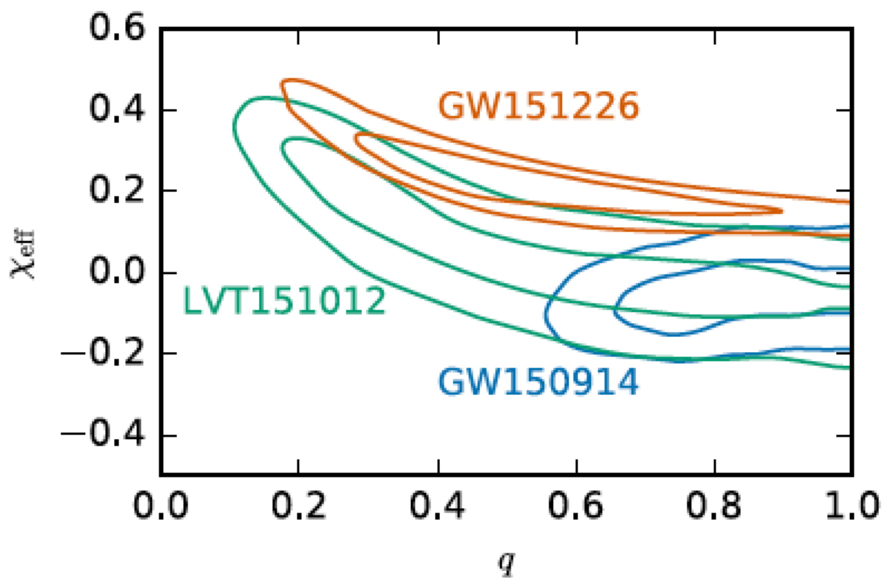
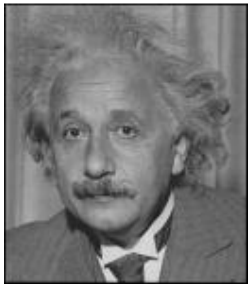


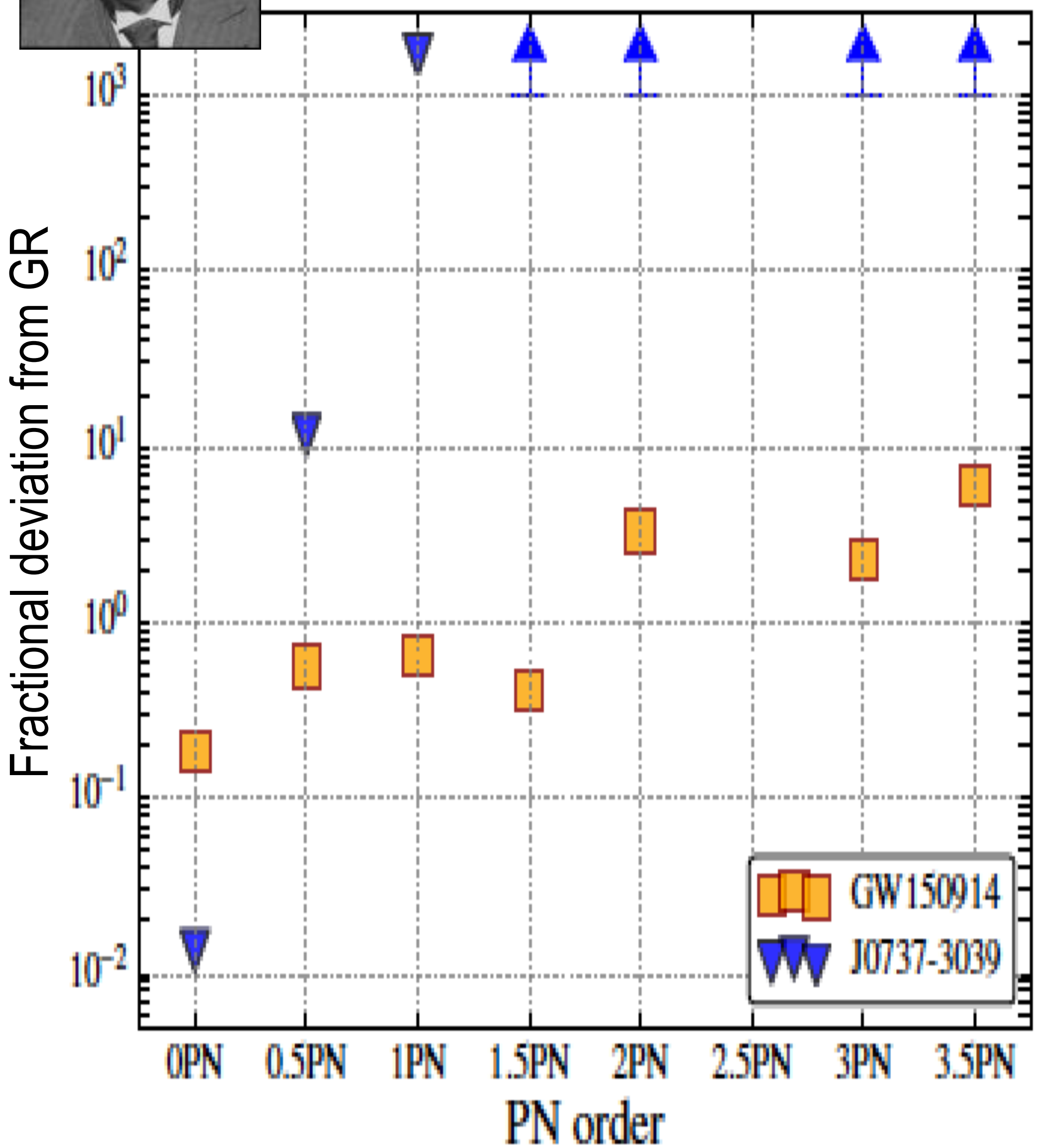
FIG. 5. Posterior probability distributions for the dimensionless component spins $cS_1/(Gm_1^2)$ and $cS_2/(Gm_2^2)$ relative to the normal to the orbital plane L, marginalized over the azimuthal angles. The bins are constructed linearly in spin magnitude and the cosine of the tilt angles, and therefore have equal prior probability. The left plot shows the distribution for GW150914, the middle plot is for LVT151012, and the right plot is for GW151226.



$$\chi_{\text{eff}} = \left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right) \cdot \left(\frac{\hat{\mathbf{L}}}{M}\right)$$



Testing General Relativity



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

Binary pulsars tests:

$$\dot{P} \sim -10^{-14} - 10^{-12}$$

$$v/c \sim 2 \times 10^{-3}$$

BBH coalescence:

$$\dot{P} \sim -0.1 - 1.0$$

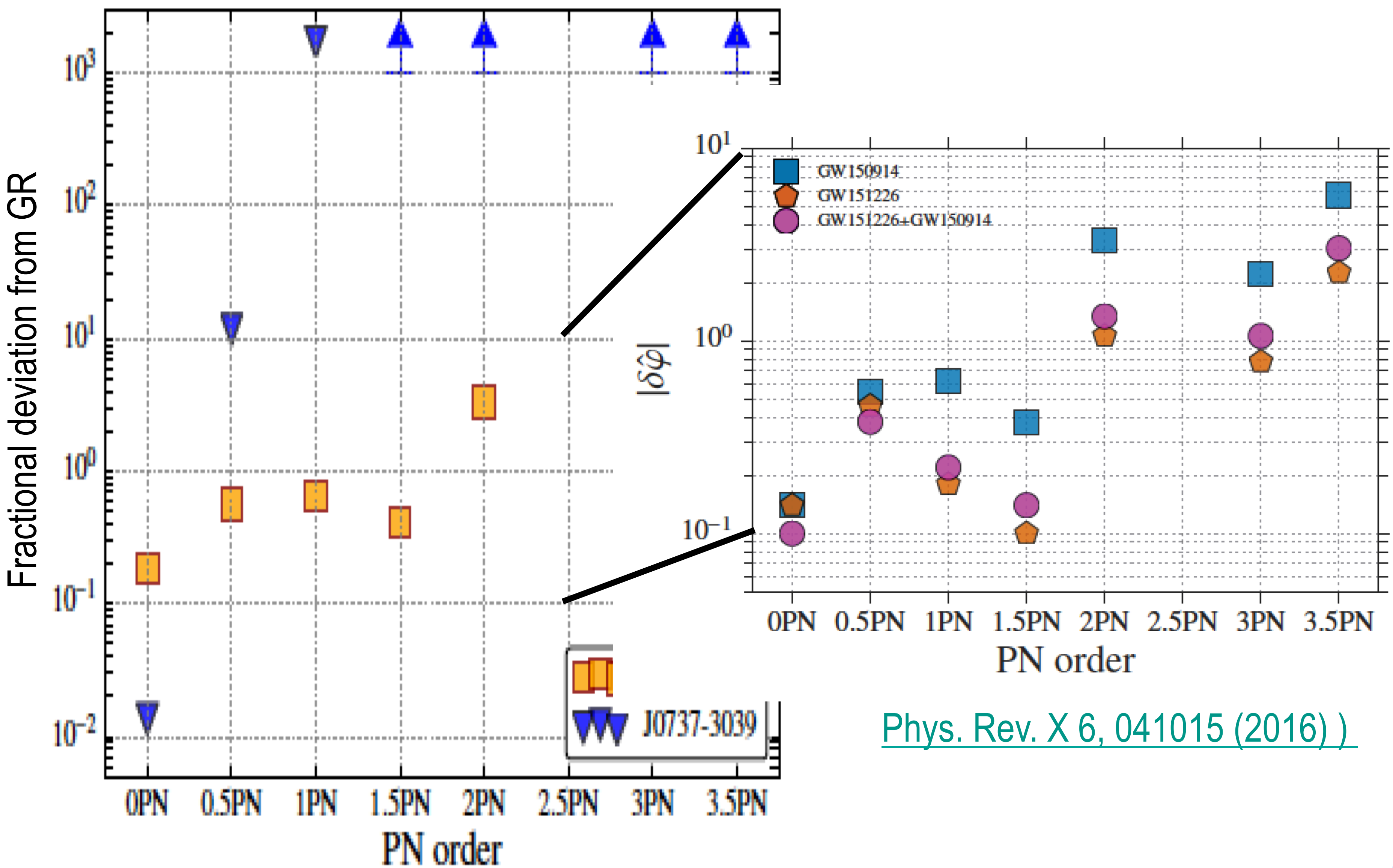
$$v/c \sim 0.5$$

$$\tilde{h}(f) = \mathcal{A}(f) e^{i\varphi(f)}$$

$$\varphi(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} + \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} + \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots$$

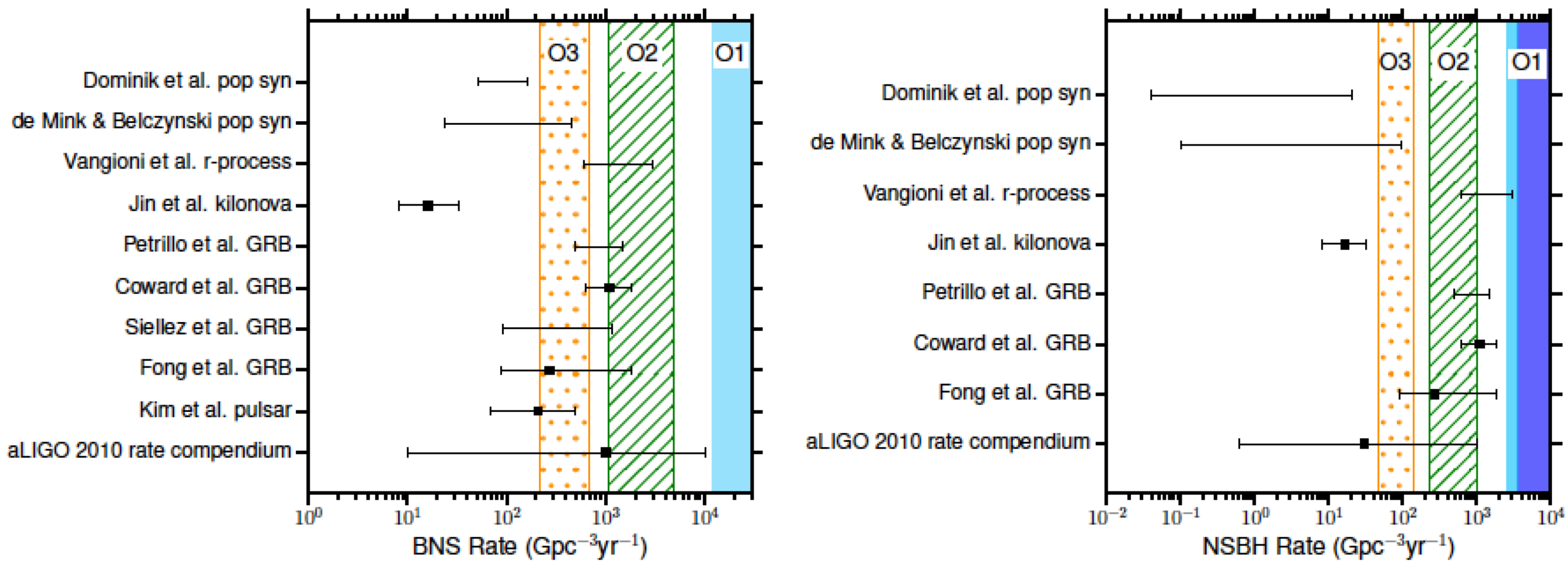
(Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

Testing General Relativity



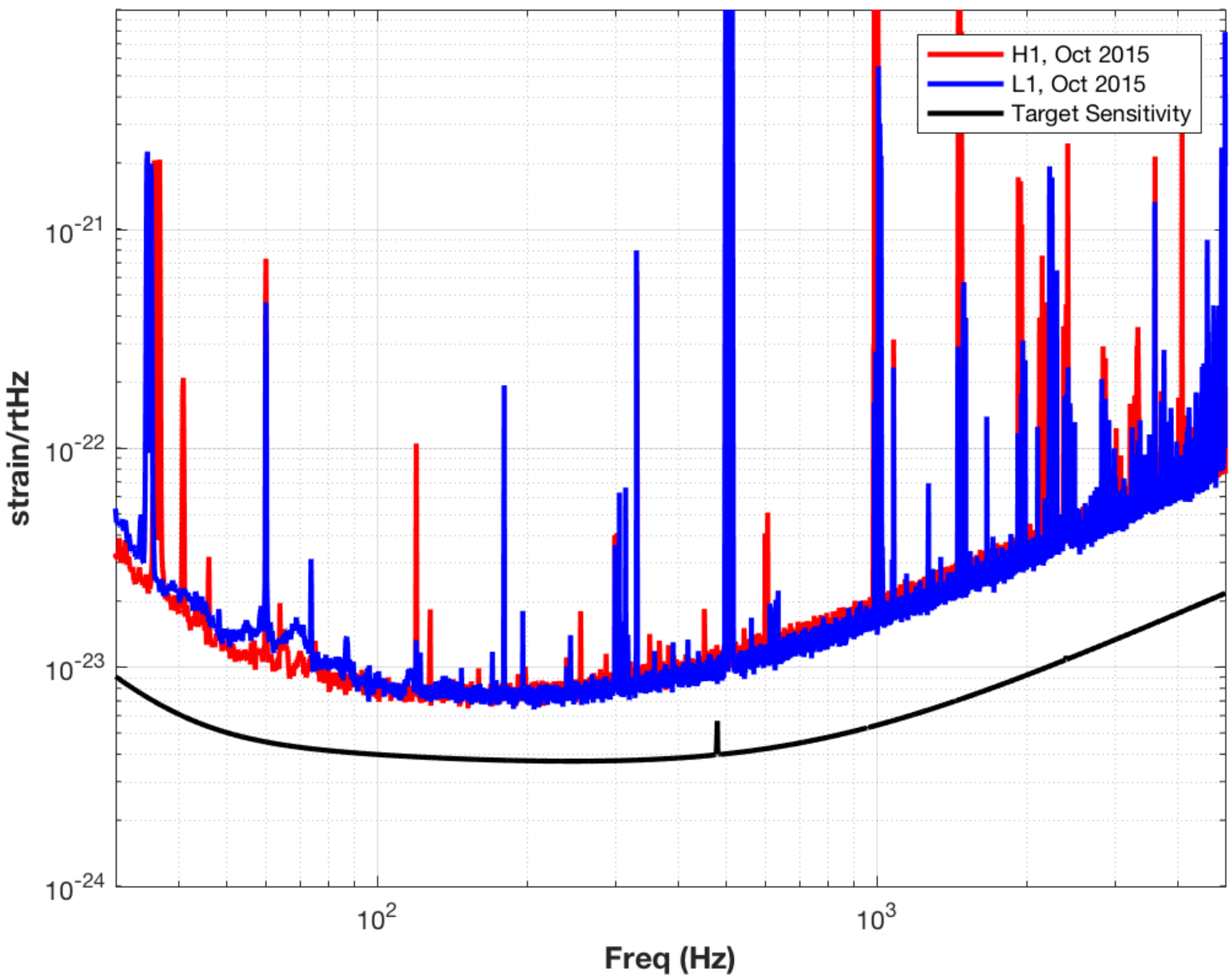
Phys. Rev. X 6, 041015 (2016))

BNS/NSBH (null) O1 searches

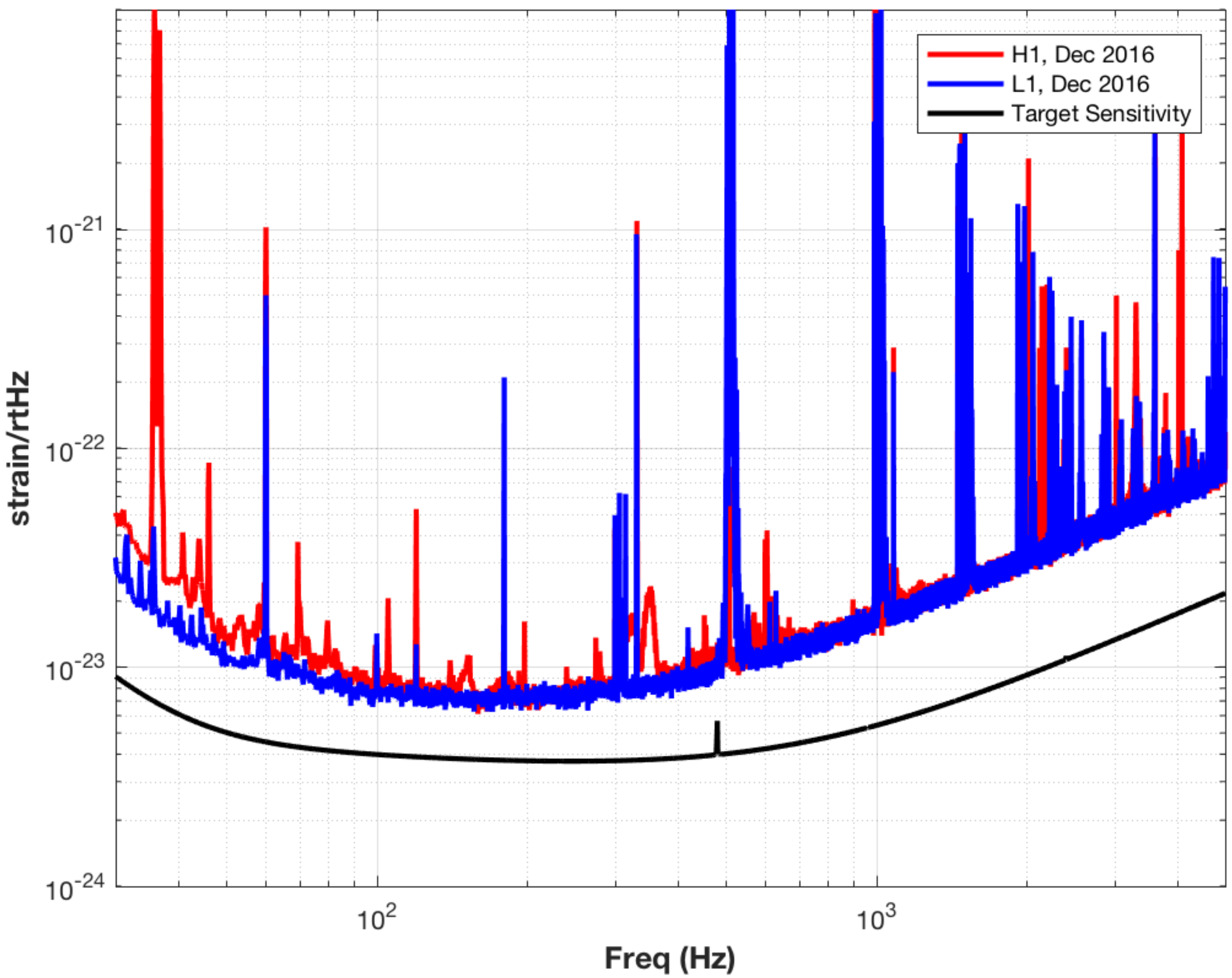


ApJL, L21 (2016)

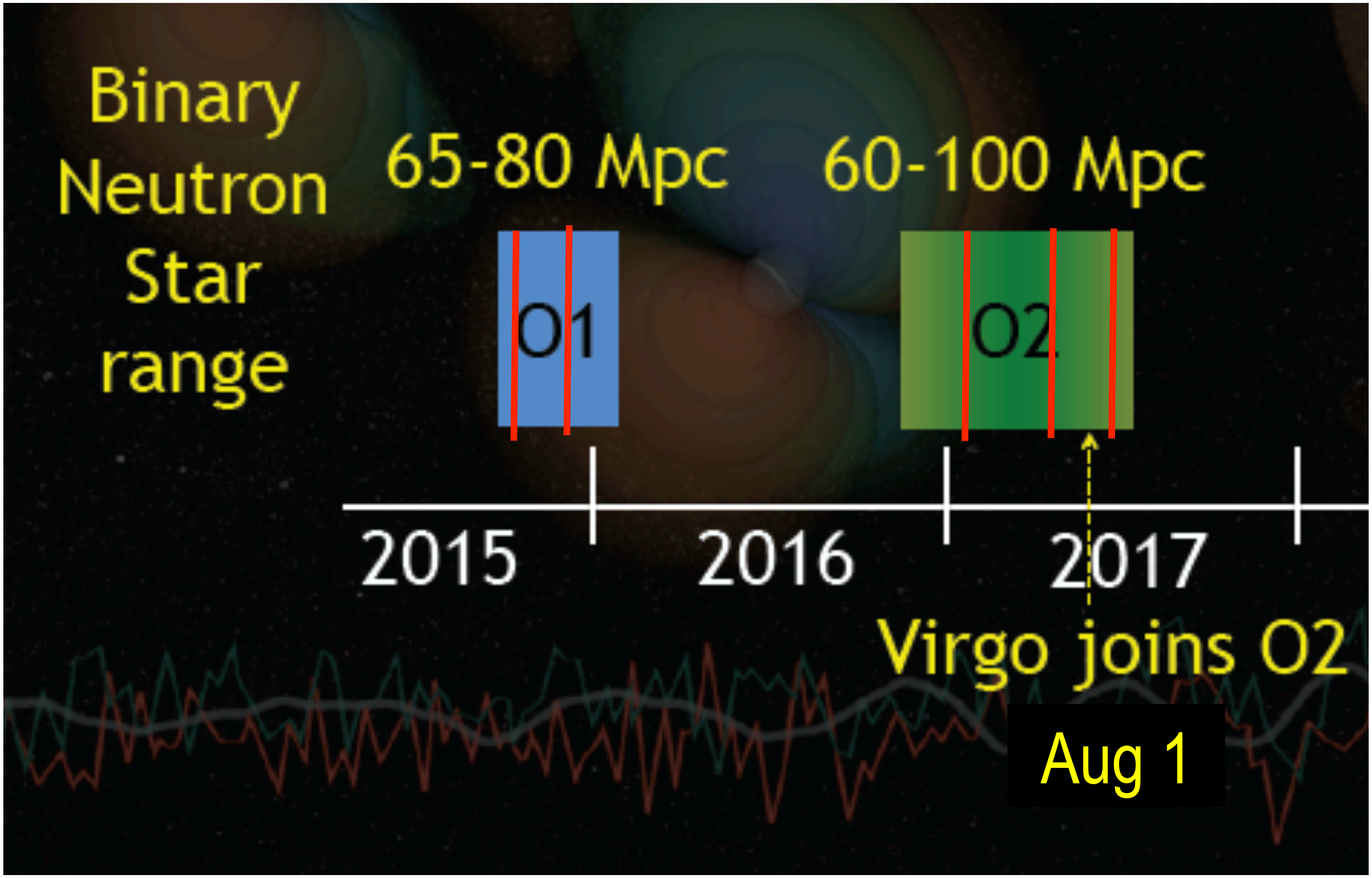
Noise where the signal hides: O1-O2



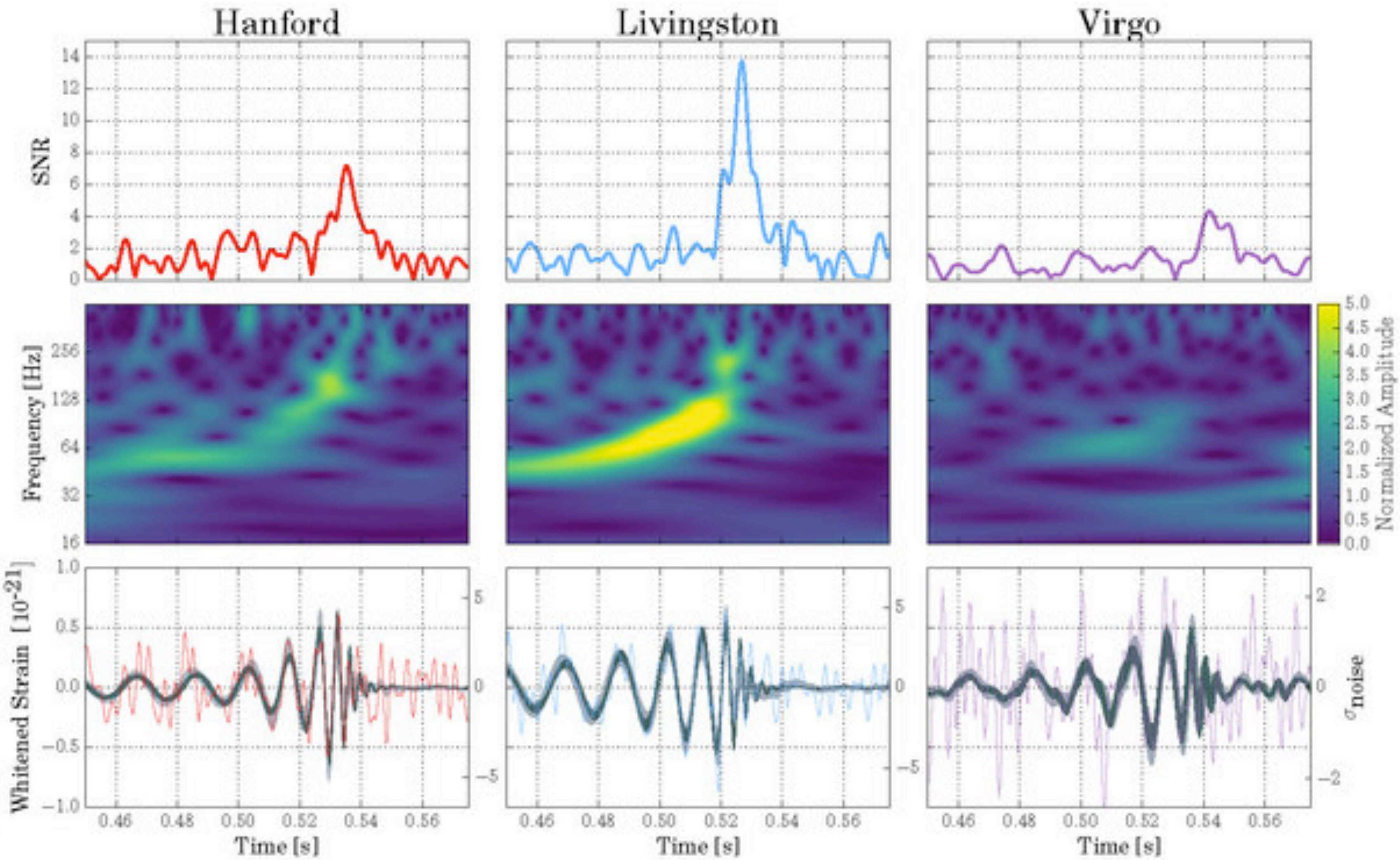
Noise where the signal hides: O1-O2



Second Observing run: started Nov 30, 2016

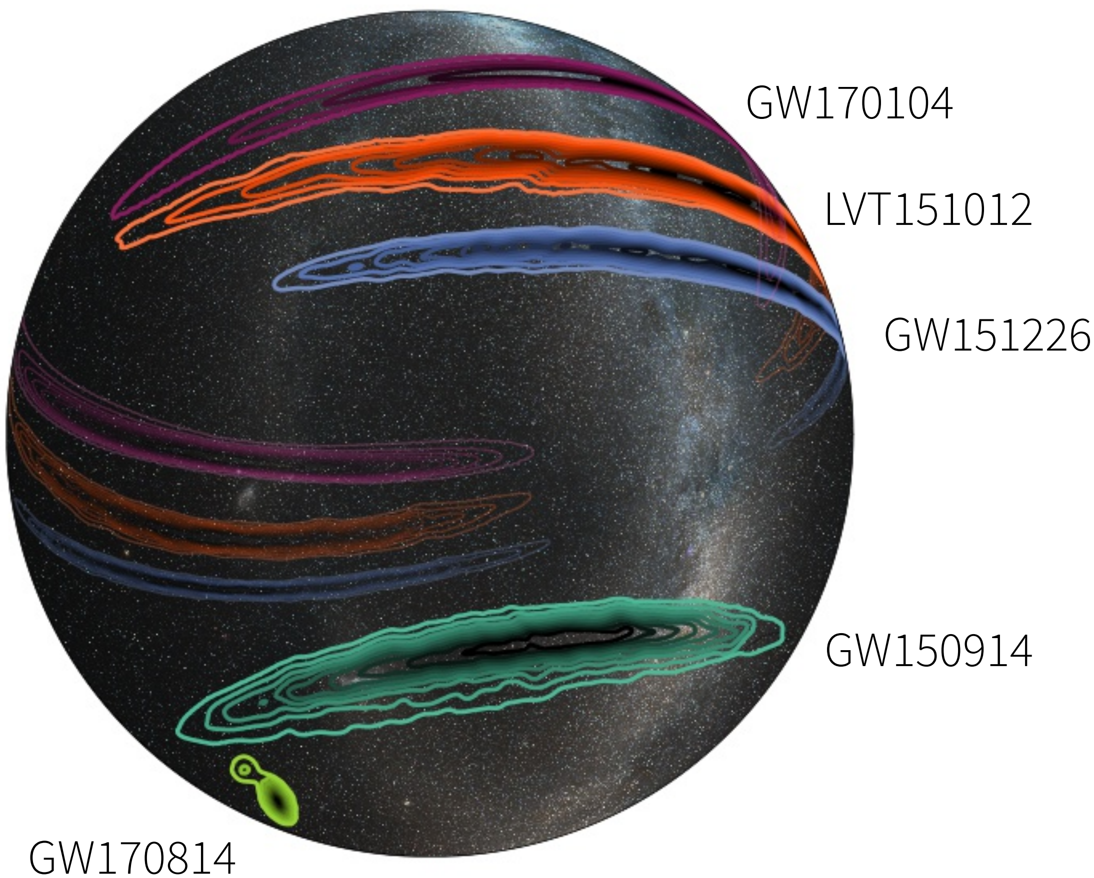


GW170814



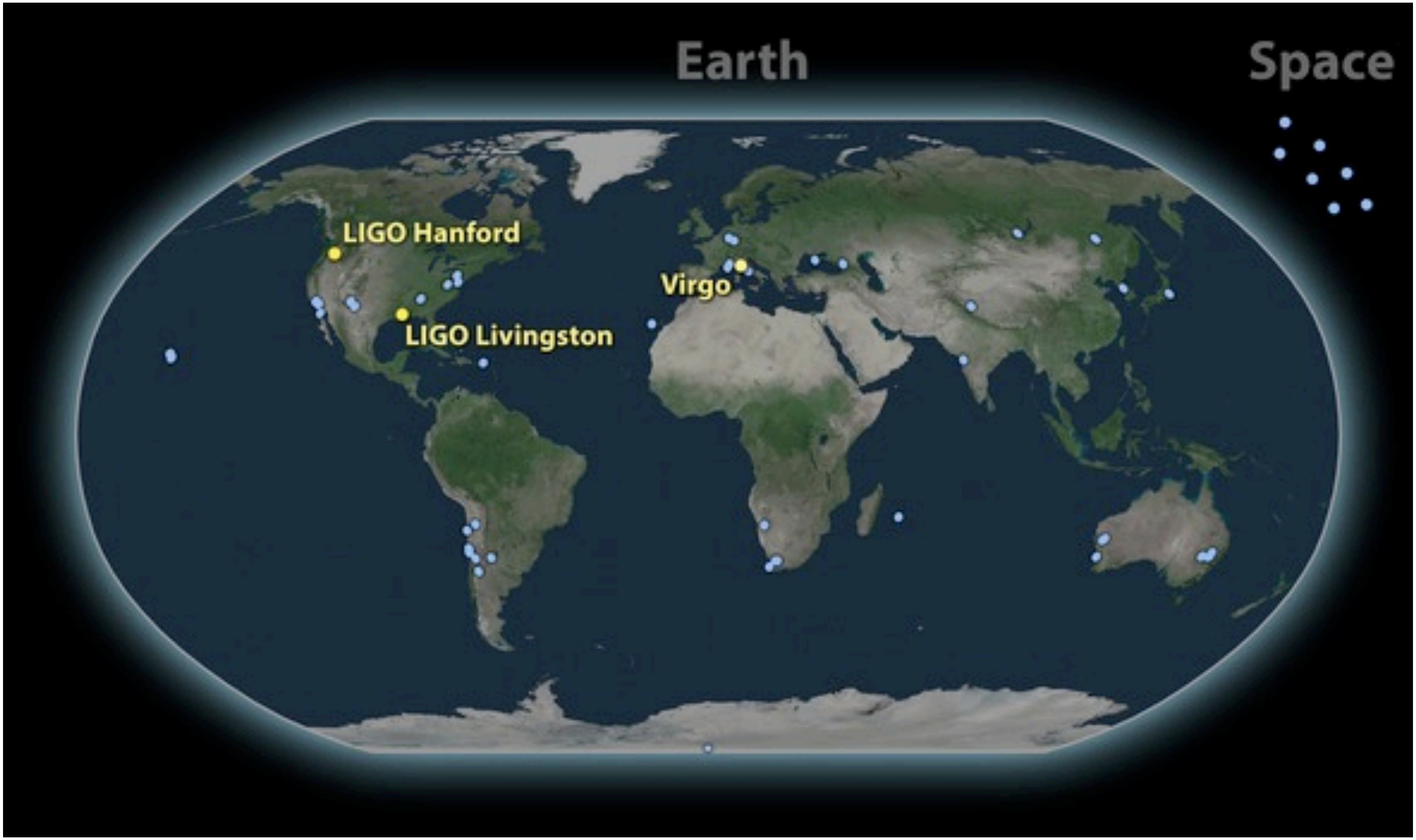
Phys. Rev. Lett. **119**, 141101 (2017)

Sky localization

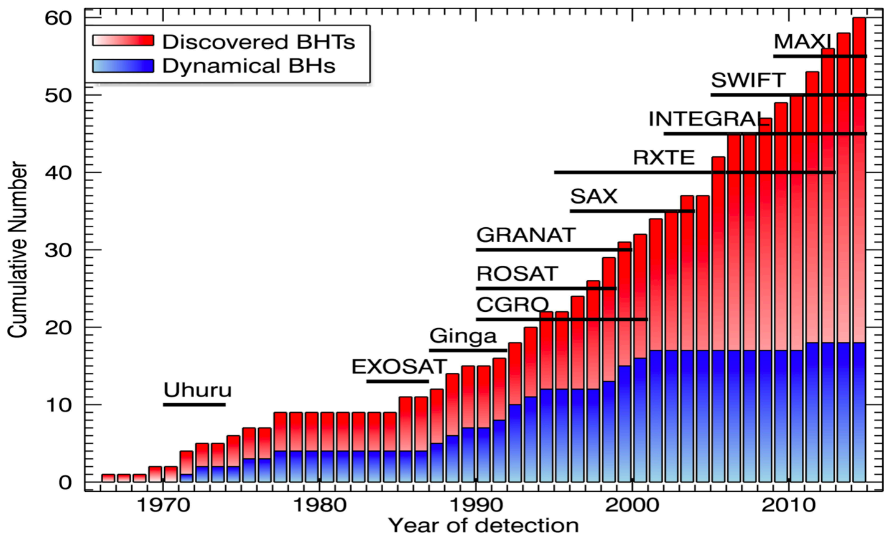


Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Multi-messenger astronomy



X-ray black holes



A&A 587, A61 (2016), Corral-Santana

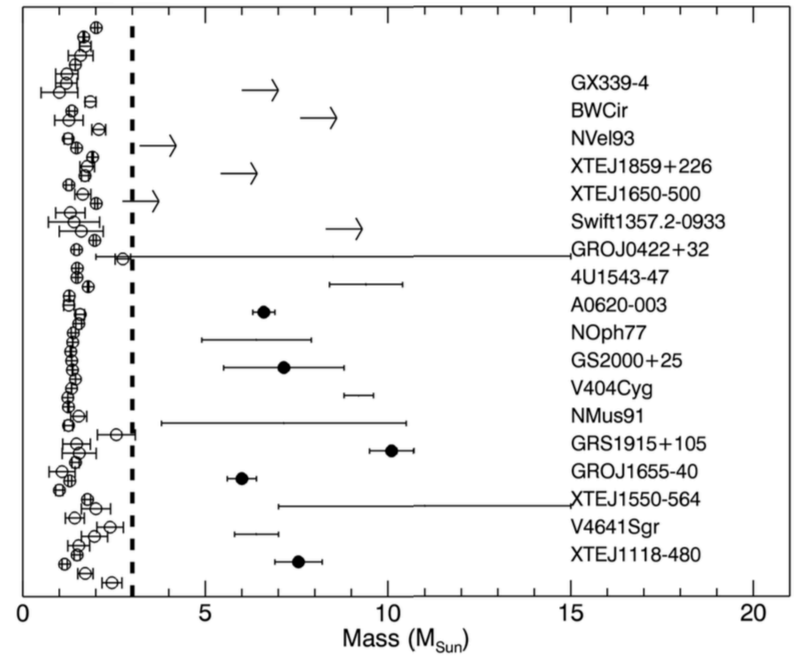
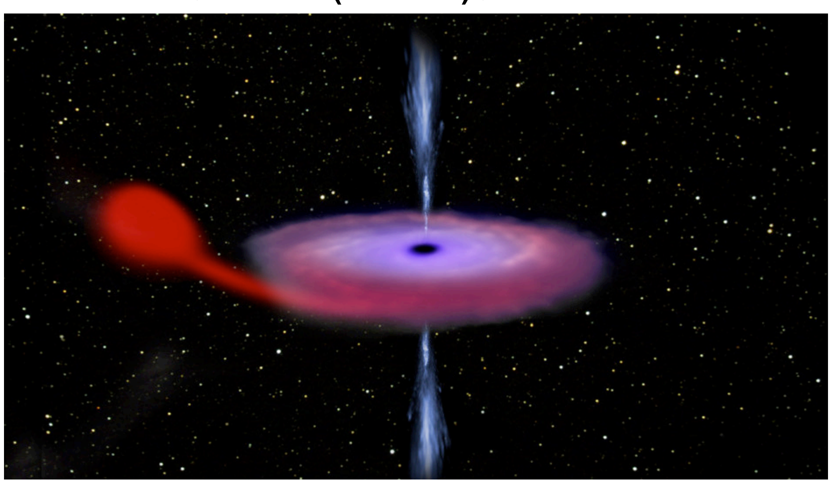


Fig. 8. Distribution of observed compact object masses. The vertical dashed line represents the maximum mass allowed for NS (Fryer & Kalogera 2001). Open circles below that limit represent the masses of the NS compiled by Lattimer & Prakash (2005), extended with updated data from Özel et al. (2012) and Antoniadis et al. (2013). The solid circles indicate reliable BH masses (adopting the values favoured by Casares & Jonker 2014), while arrows indicate lower limits based on mass functions and upper limits to the inclination.



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.

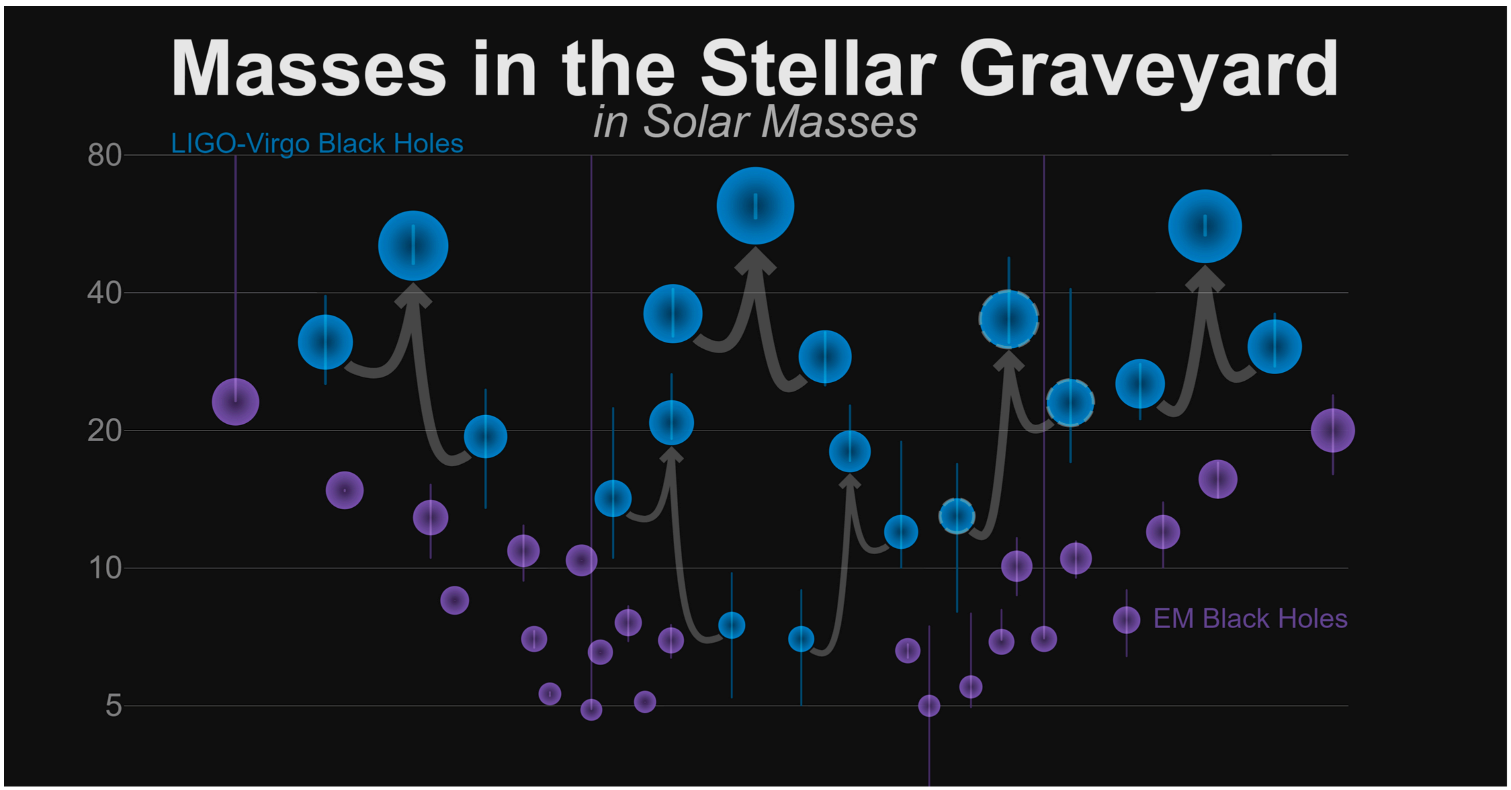
- Getting Started
- Data
  - Events
  - Bulk Data
- Tutorials
- Software
- Detector Status
- Timelines
- My Sources
- GPS ↔ UTC
- About the detectors
- Projects
- Acknowledge LOSC

Data Releases for Observed Transients

Data Releases: Compact Object Mergers

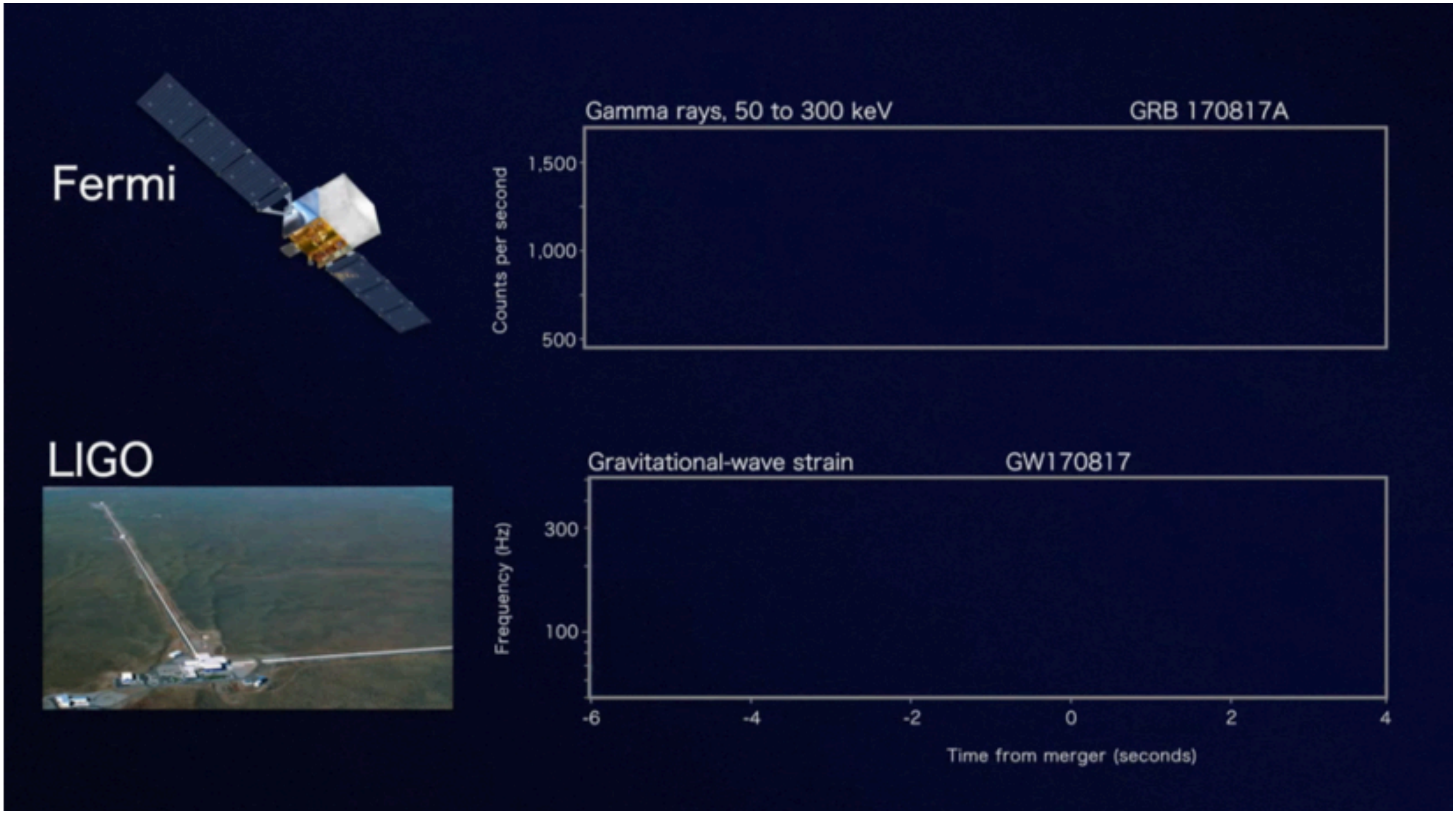
Click icons below for data and documentation:

GW150914 | LVT151012 | GW151226 | GW170104 | GW170608 | GW170814 | GW170817

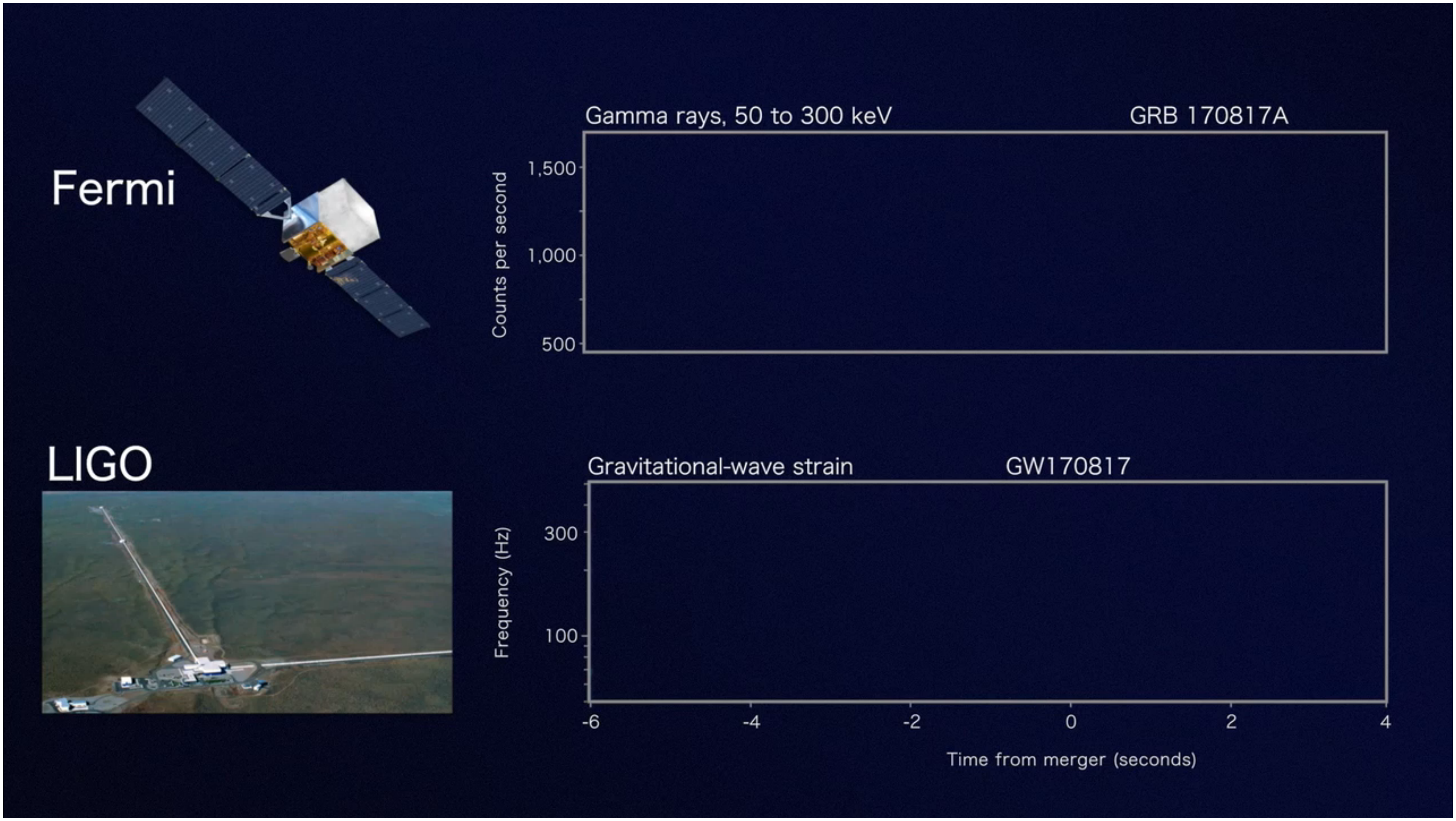


Credit: Visualization: LIGO/Frank Elavsky/Northwestern
EM Black Holes: https://stellarcollapse.org/sites/default/files/table.pdf | LIGO-Virgo Data: https://losc.ligo.org/events/

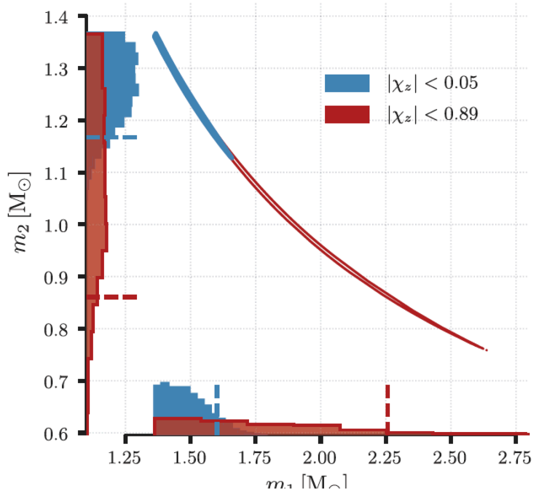
August 17, 2017

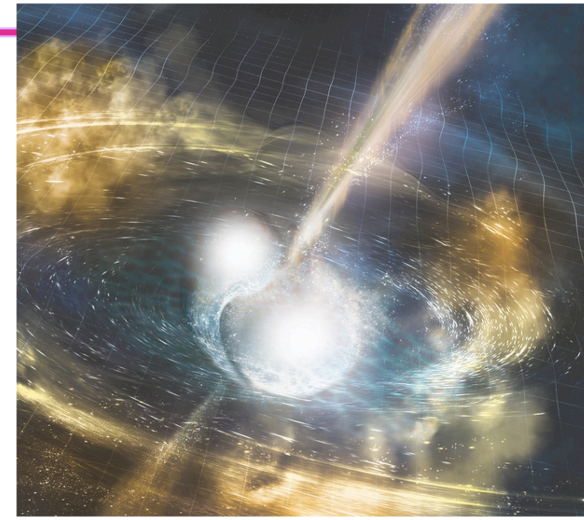


August 17, 2017



GW170817



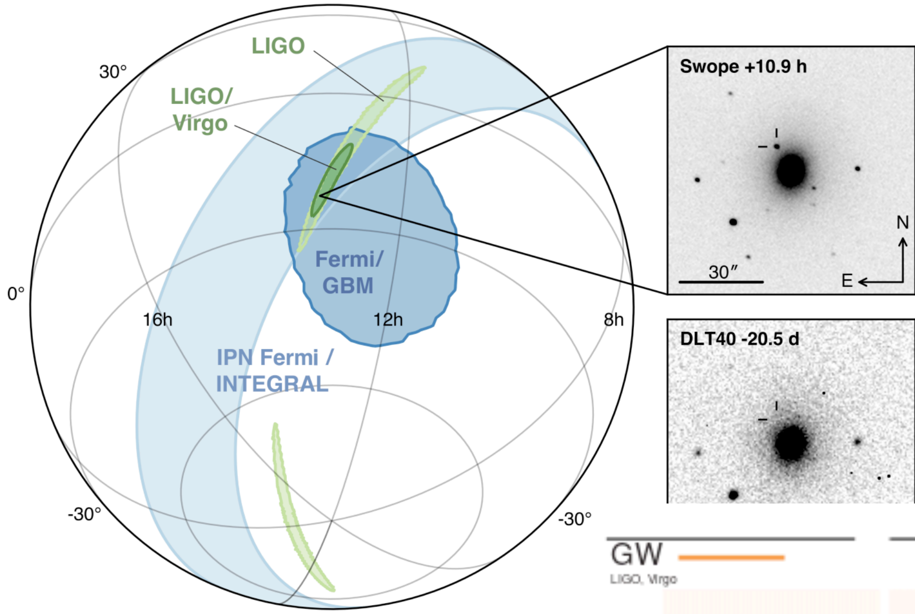


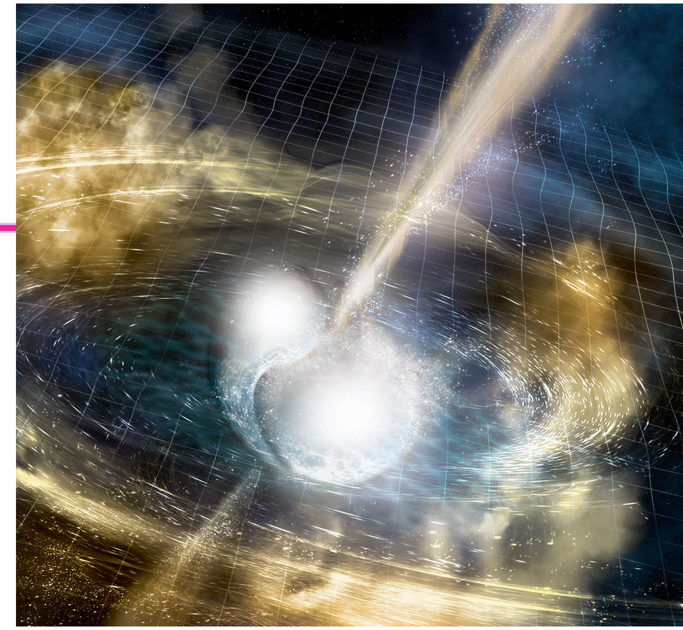
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

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.

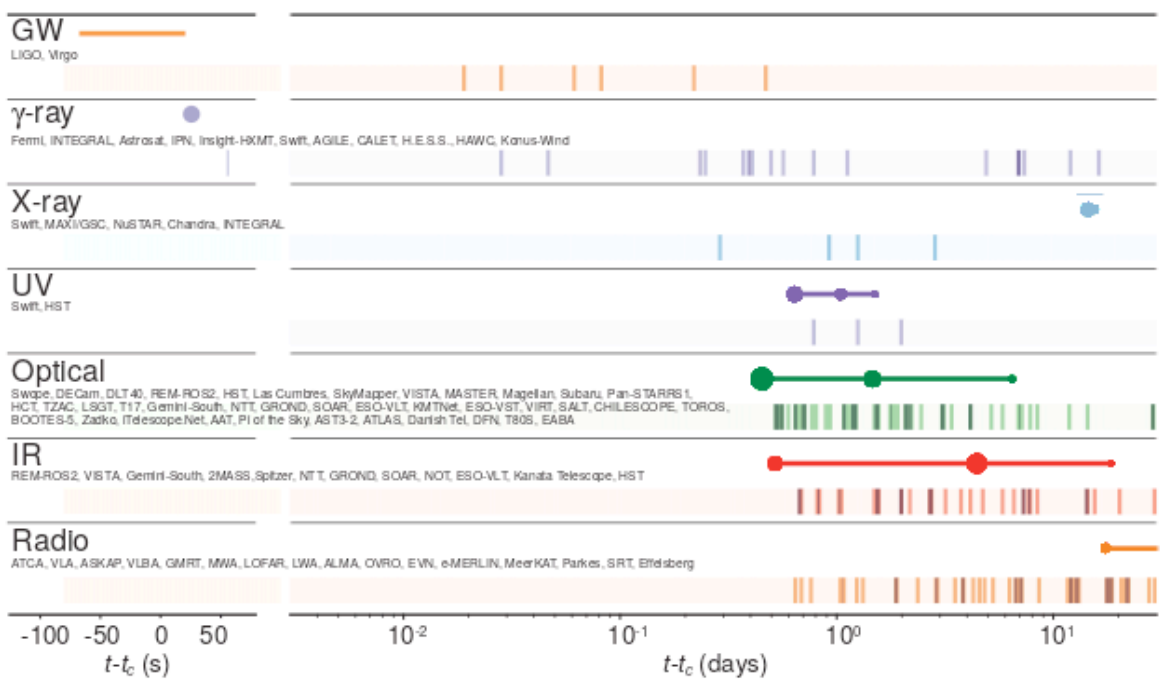
	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	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	$\leq 55°$	$\leq 56°$

A kilonova rainbow





Credit: NSF/LIGO/Sonoma State University/A. Simonnet



Astrophys. J. Lett. 848, L12 (2017)

Gravitational *and* Electromagnetic waves!

Selected for a Viewpoint in *Physics*
PRL 119, 161101 (2017) 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)

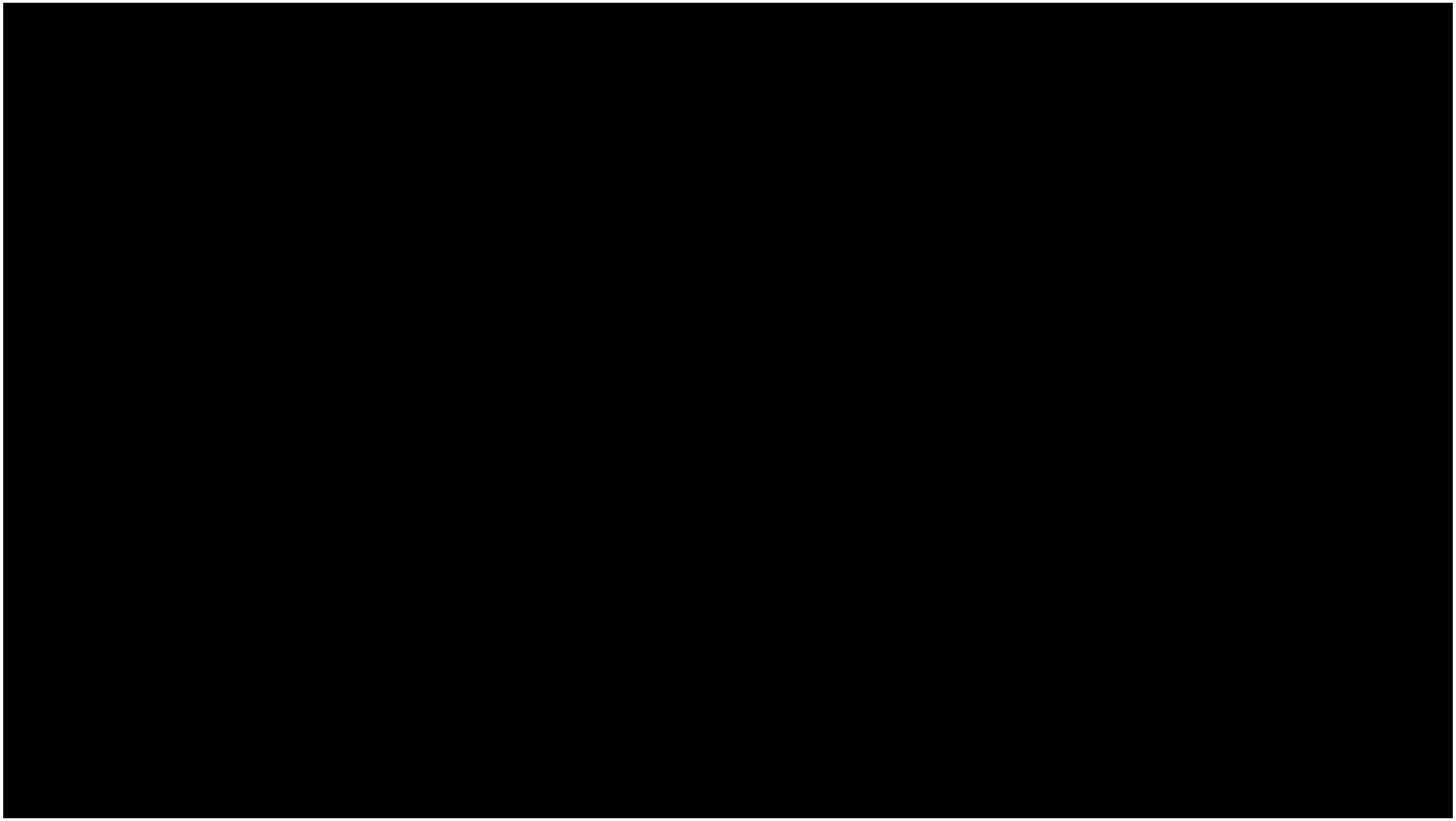
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

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.)

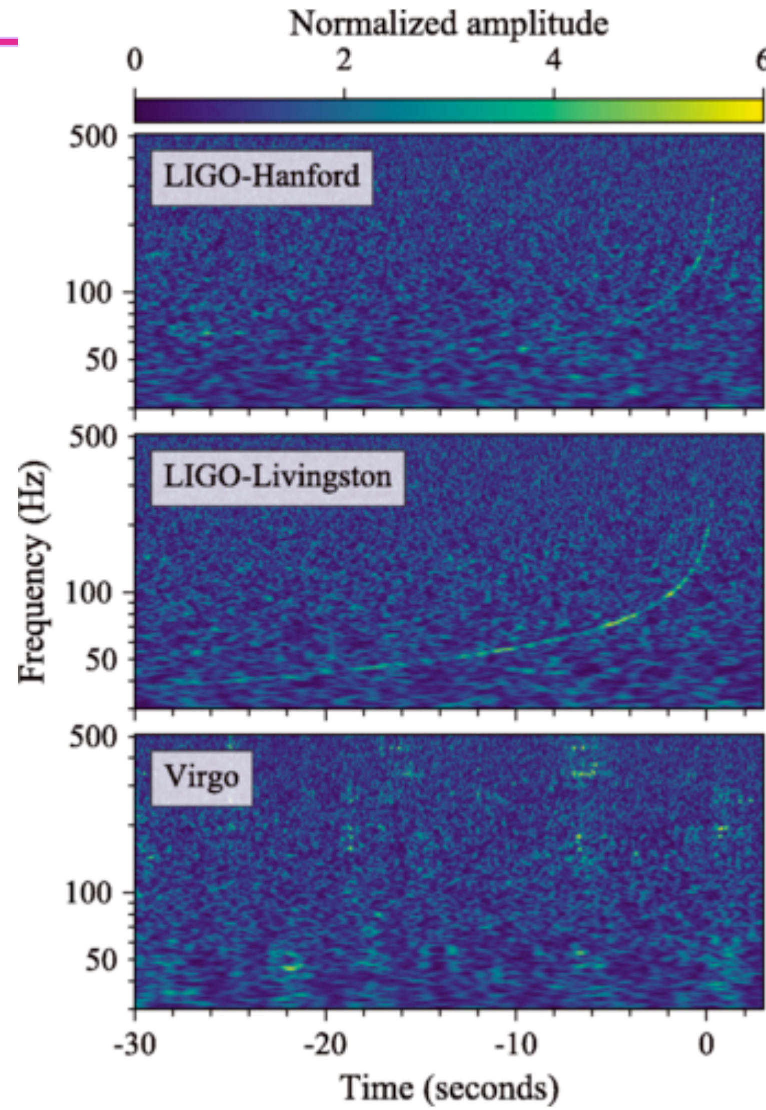
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Binary Neutron Star merger: the movie



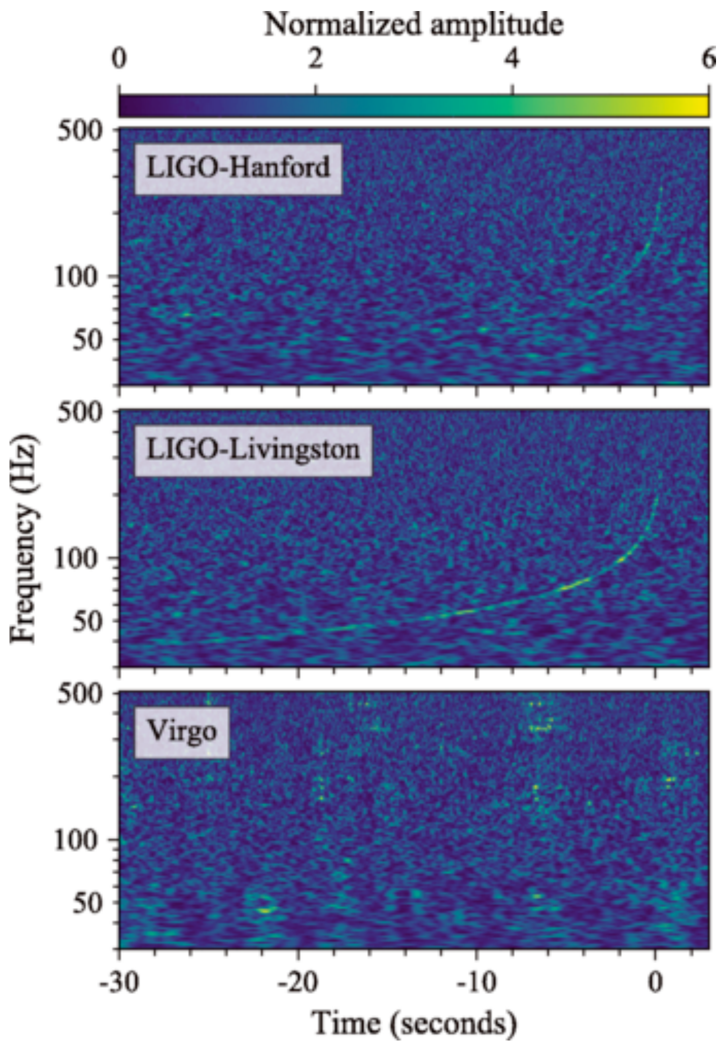
Credit: NASA/Goddard Space Flight Center

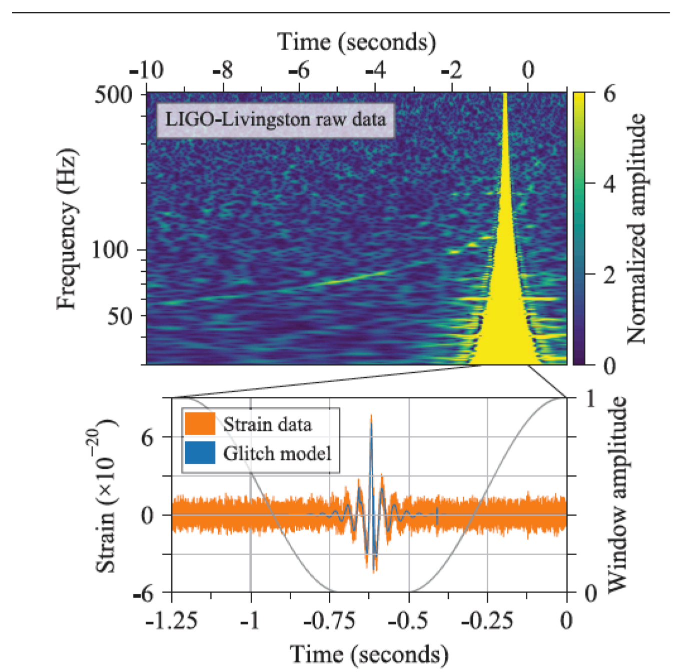
GW170817



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

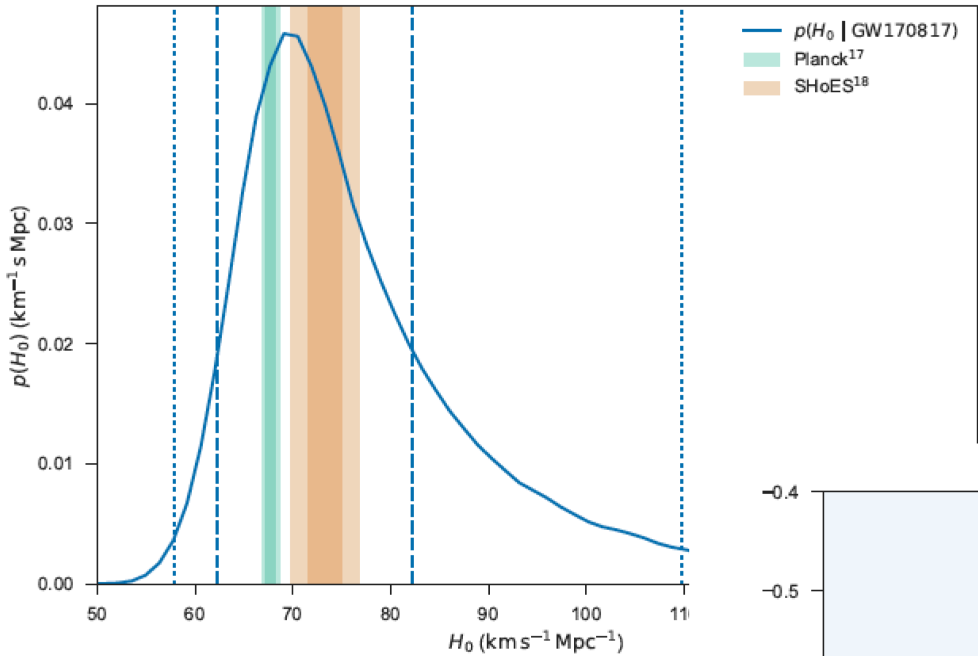
GW170817



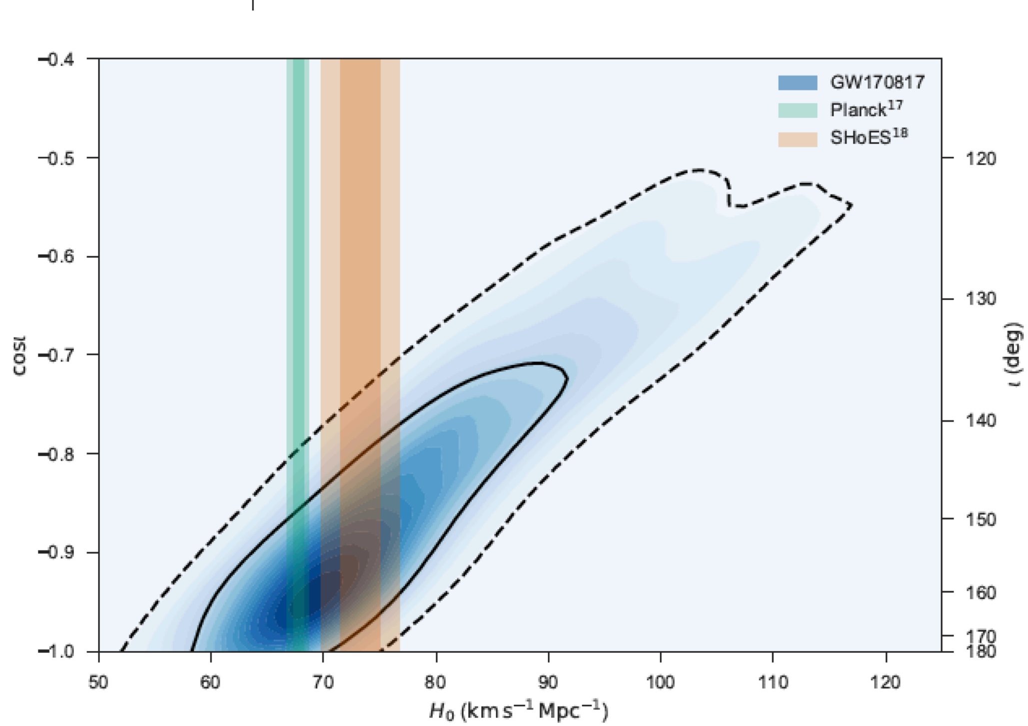


Phys. Rev. Lett. 119, 161101 (2017)

Cosmology with GWs

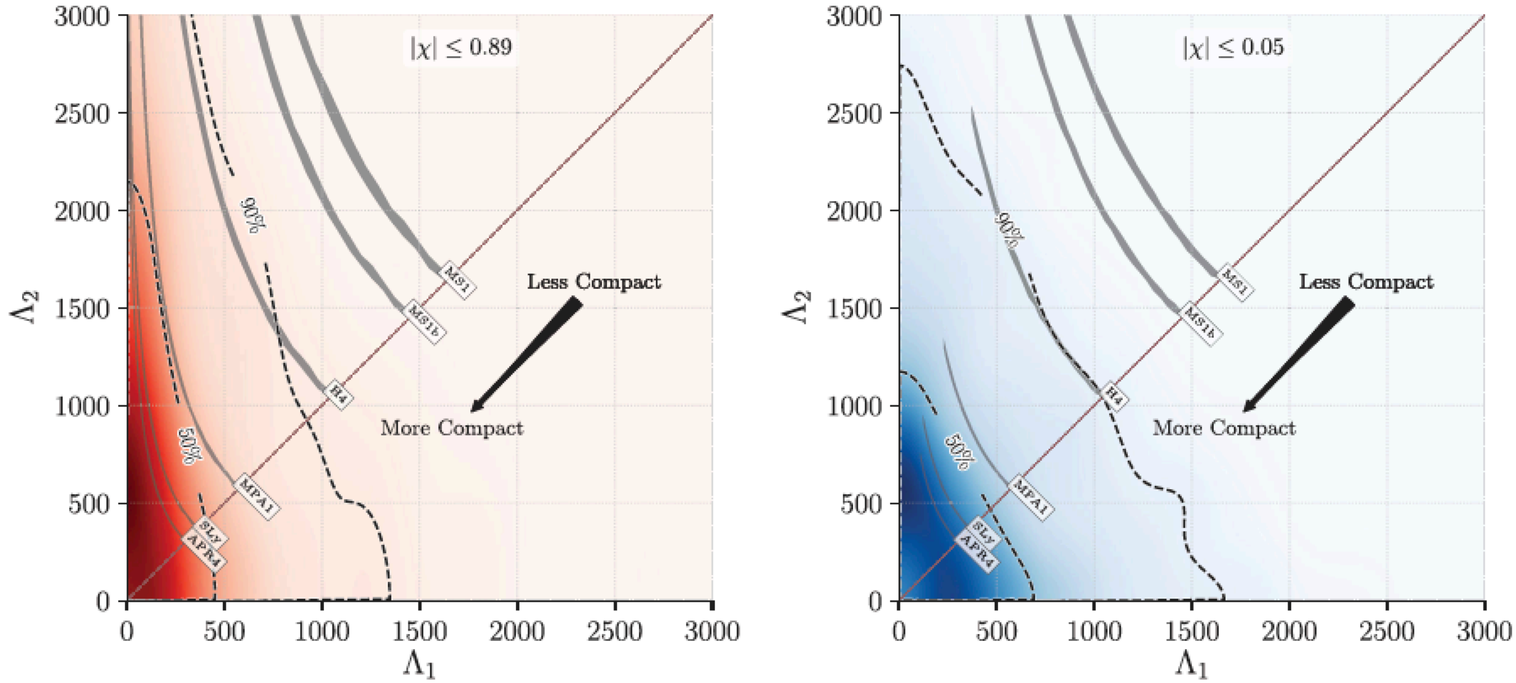


[Nature 551, 85 (2017)]()



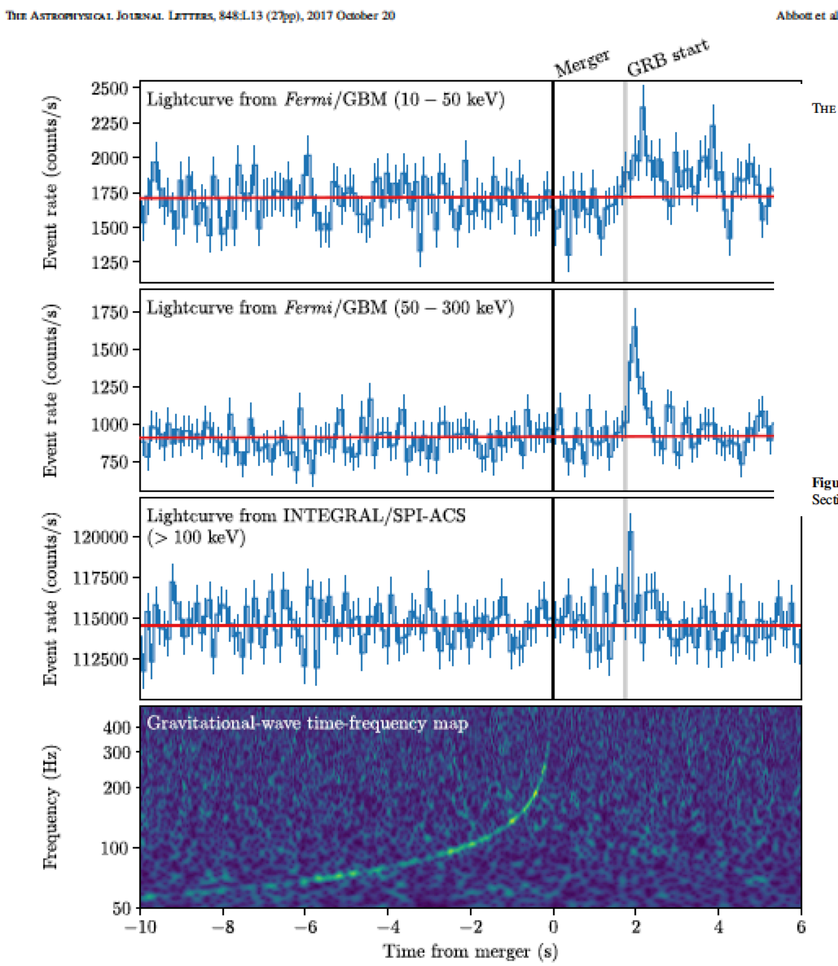
Nuclear physics with GWs

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



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

GW-GRB joint observation: sGRB models



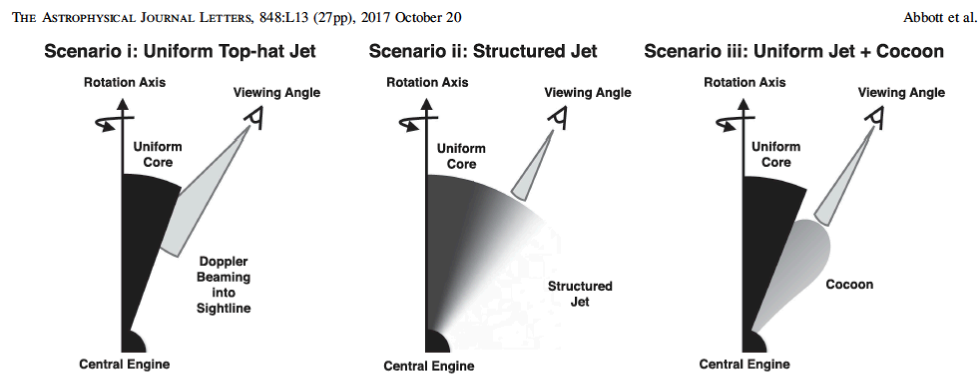
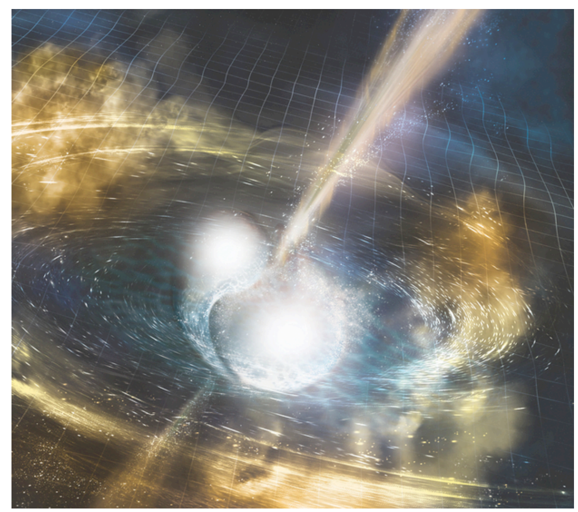


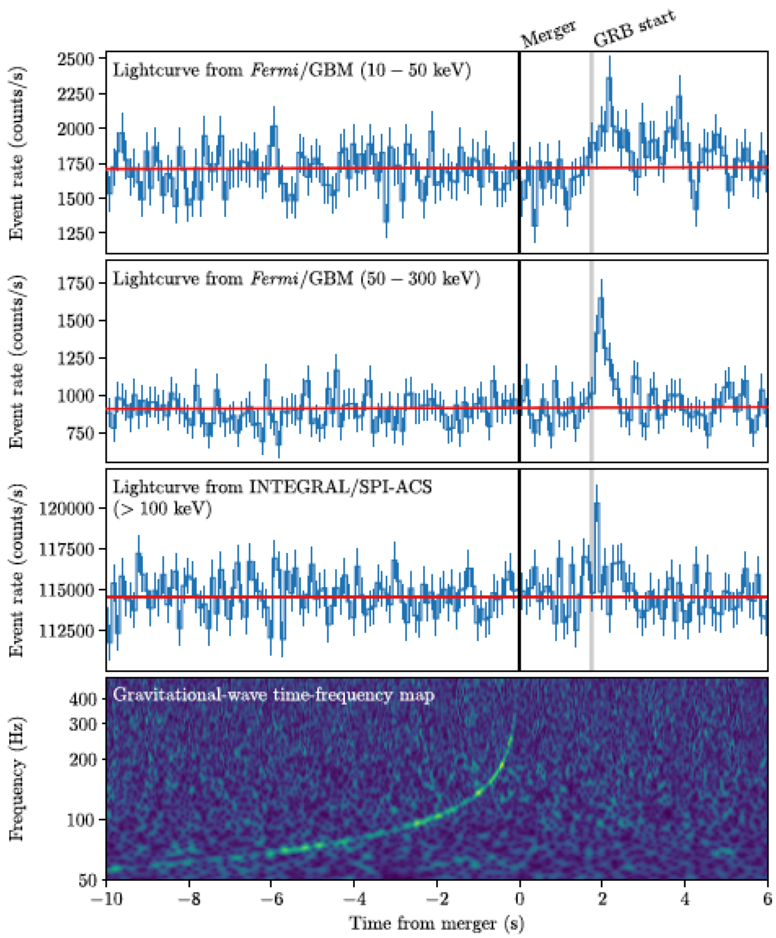
Figure 5. Three potential jet viewing geometries and jet profiles that could explain the observed properties of GRB 170817A, as described by scenarios (i)–(iii) in Section 6.2.



ApJL, 848:L13, 2017

GW-GRB observation: Fundamental physics

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



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

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

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

We (and our jewelry) are made of star dust

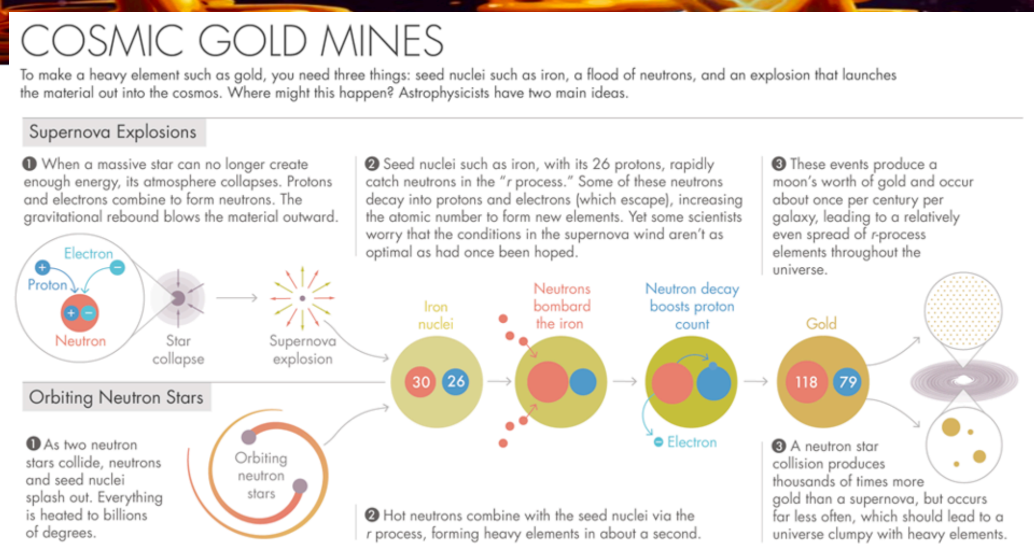
SCIENCE

The Mysterious Origin of Our Galaxy's Gold

After long believing that exploding stars forged the coveted metal, researchers are now divided over which extraordinary cosmic event is truly responsible.

JOSHUA SOKOL AND QUANTA MAR 27, 2017

The Atlantic

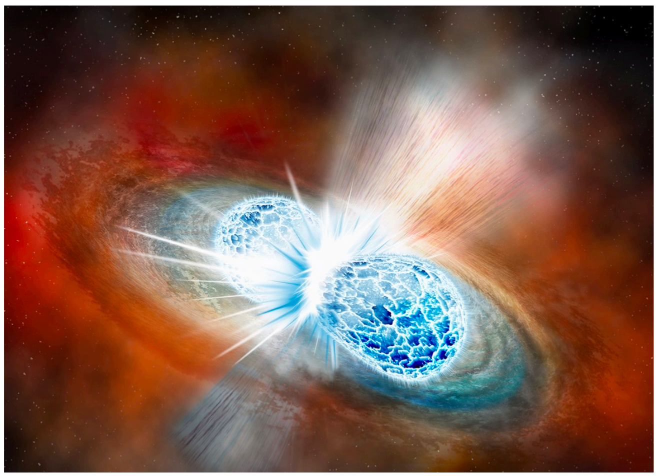


We (and our jewelry) are star dust …

BUSINESS INSIDER

Astronomers just proved the incredible origin of nearly all gold, platinum, and silver in the universe

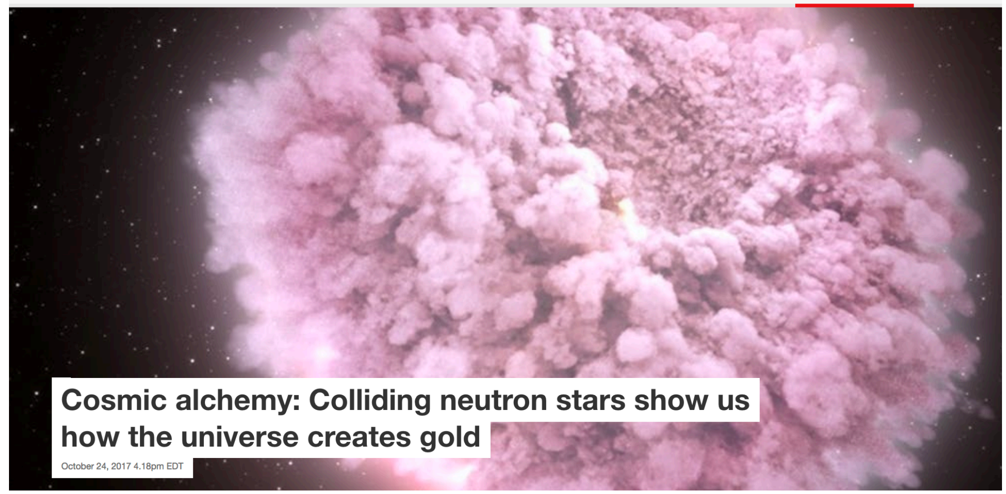
Dave Mosher Oct. 16, 2017, 10:35 AM



THE CONVERSATION

Academic rigor, journalistic flair

Arts + Culture Economy + Business Education Environment + Energy Ethics + Religion Health + Medicine Politics + Society Science + Technology

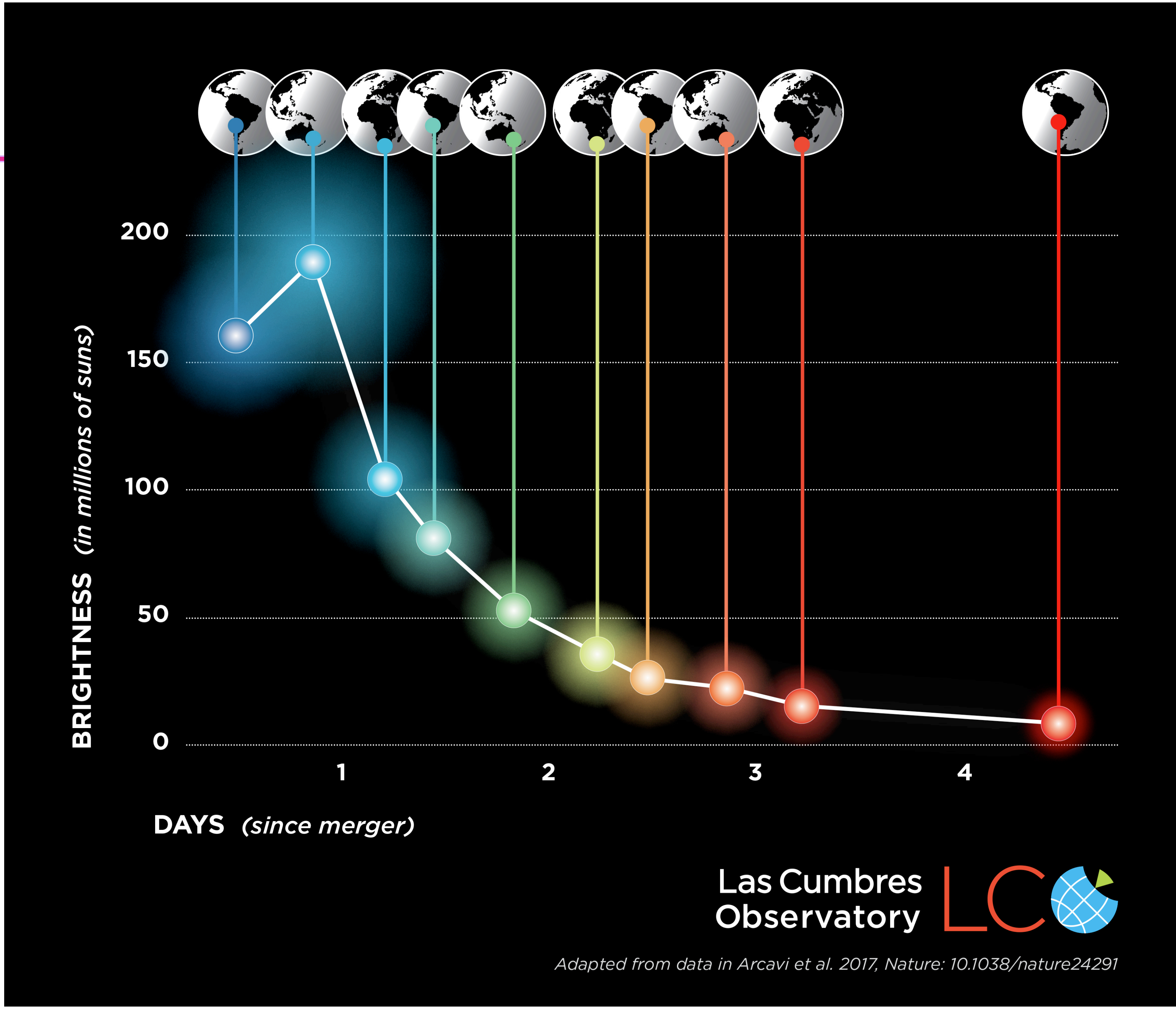


nature

International journal of science

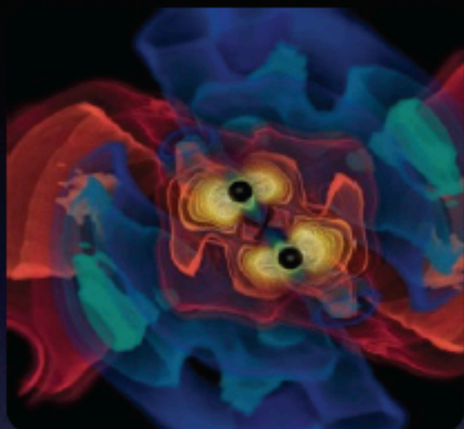
News & Views | Published: 15 October 2017

Gravitational waves: A golden binary



200
150
100
50
0
BRIGHTNESS (in millions of suns)
1
2
3
4
DAYS (since merger)
Las Cumbres Observatory
LCO
Adapted from data in Arcavi et al. 2017, Nature: 10.1038/nature24291

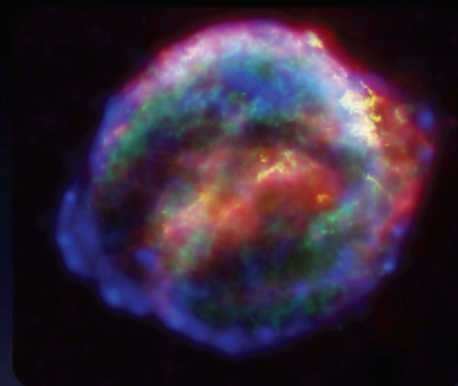
Other gravitational waves to come...



Credit: AEI, CCT, LSU

Coalescing Binary Systems

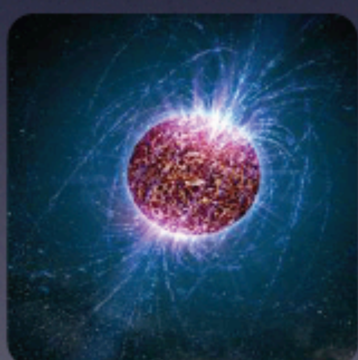
Neutron Stars,
Black Holes



Credit: Chandra X-ray Observatory

'Bursts'

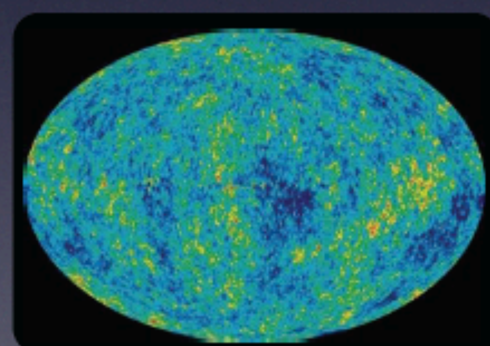
asymmetric core collapse supernovae
cosmic strings
???



Casey Reed, Penn State

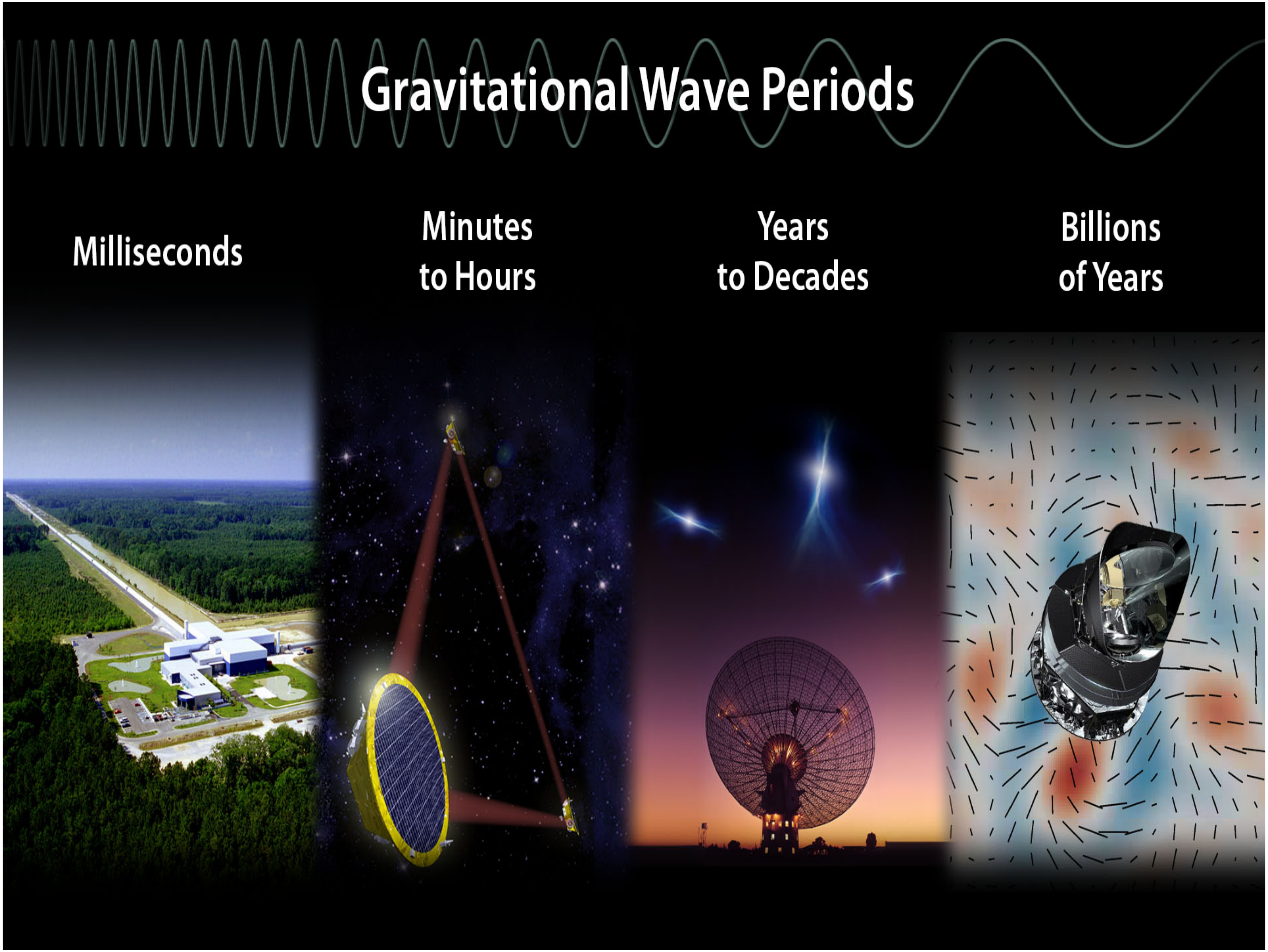
Continuous Sources

Spinning neutron stars
crustal deformations, accretion



NASA/WMAP Science Team

Astrophysical or
Cosmic GW background
stochastic, incoherent background


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

The era of GW astronomy here!

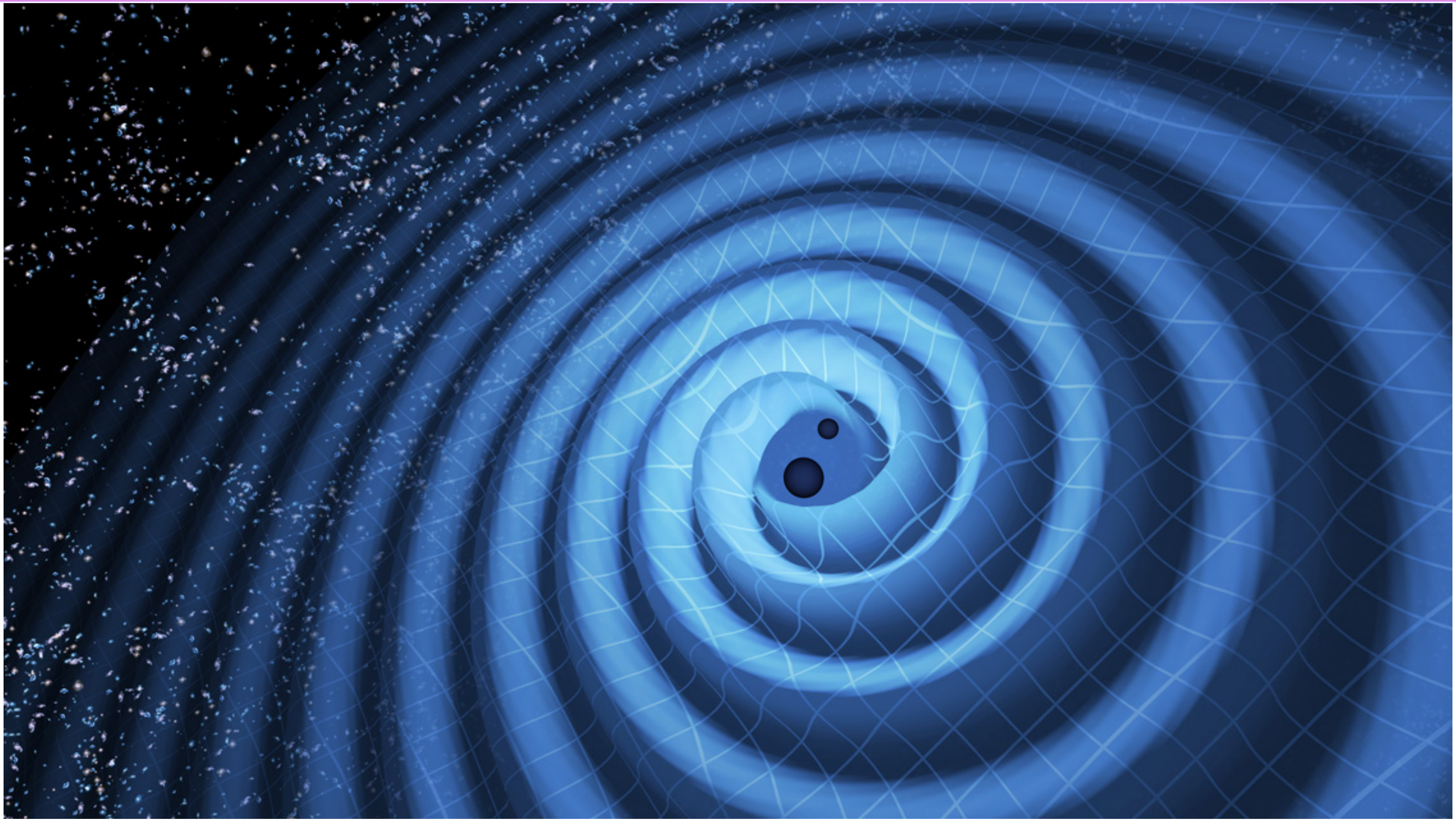


Image credit: LIGO/T. Pyle

www.ligo.org

gonzalez@lsu.edu