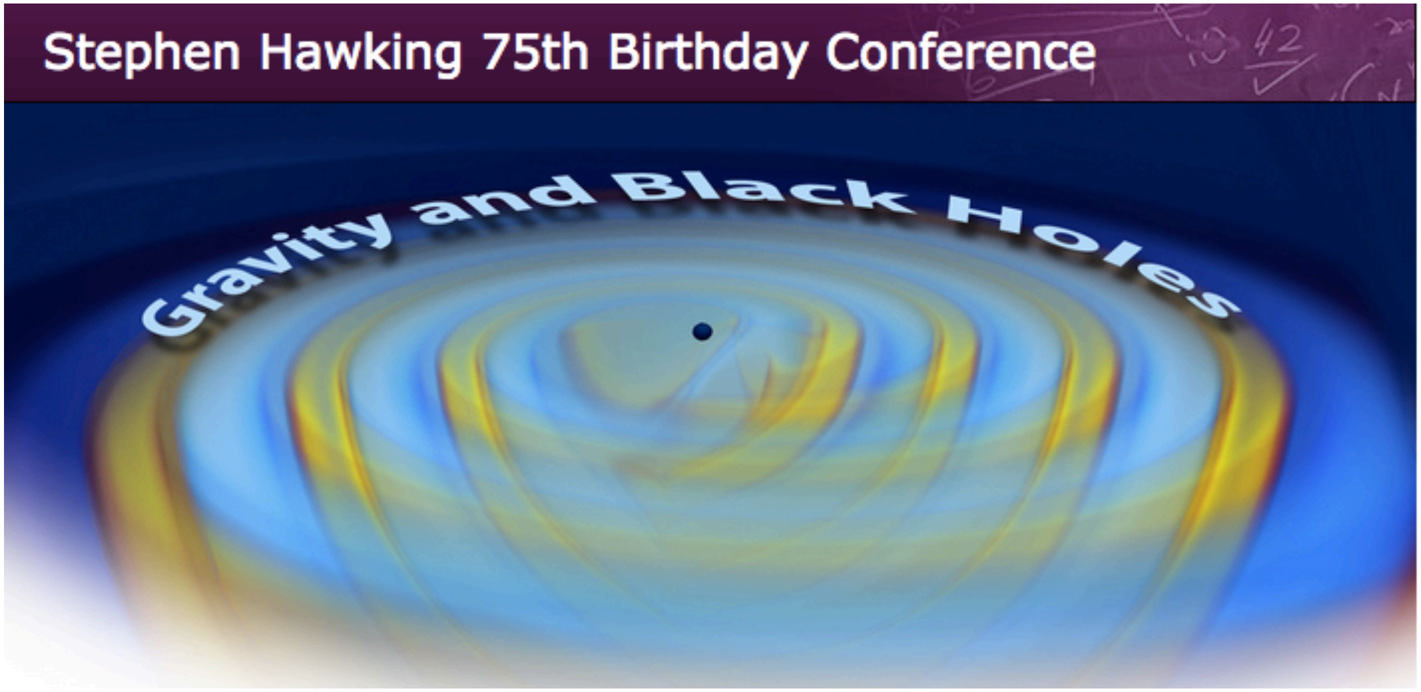
How to hear black holes and other cosmic sounds

Gabriela González
Louisiana State University

For the LIGO Scientific Collaboration and
the Virgo Collaboration



LIGO

“We” = LIGO Scientific Collaboration (and Virgo Collaboration)

LSC

TRINITY UNIVERSITY

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Andrews University

WASHINGTON STATE UNIVERSITY

CALIFORNIA STATE UNIVERSITY FULLERTON

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

SONOMA STATE UNIVERSITY

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MONTCLAIR STATE UNIVERSITY

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WHITMAN COLLEGE

AMERICAN UNIVERSITY WASHINGTON, DC

UNIVERSITY OF THE WEST of SCOTLAND UWS

TEXAS TECH UNIVERSITY

清華大學 Tsinghua University

R·I·T

UNIVERSITY OF STRATHCLYDE

Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE

MICHIGAN

Università degli Studi del Sannio

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique theorique

NASA GODDARD SPACE FLIGHT CENTER

ICTP SAIFR

THE UNIVERSITY OF WESTERN AUSTRALIA

PAH

UNIVERSITY OF CAMBRIDGE

MONASH University

SOUTHERN UNIVERSITY And Agricultural & Mechanical College

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

THE UNIVERSITY OF CHICAGO

MONTANA STATE UNIVERSITY

THE UNIVERSITY of MISSISSIPPI

THE UNIVERSITY OF ADELAIDE AUSTRALIA

Caltech

UNIVERSITY OF MINNESOTA

UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF MELBOURNE

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UIB Universitat de les Illes Balears

UNIVERSITY OF WASHINGTON

UTRGV

UNIVERSITY of WISCONSIN UWMILWAUKEE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

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Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU LOUISIANA STATE UNIVERSITY

ACIGA

University of Southampton

CHARLES STURT UNIVERSITY

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

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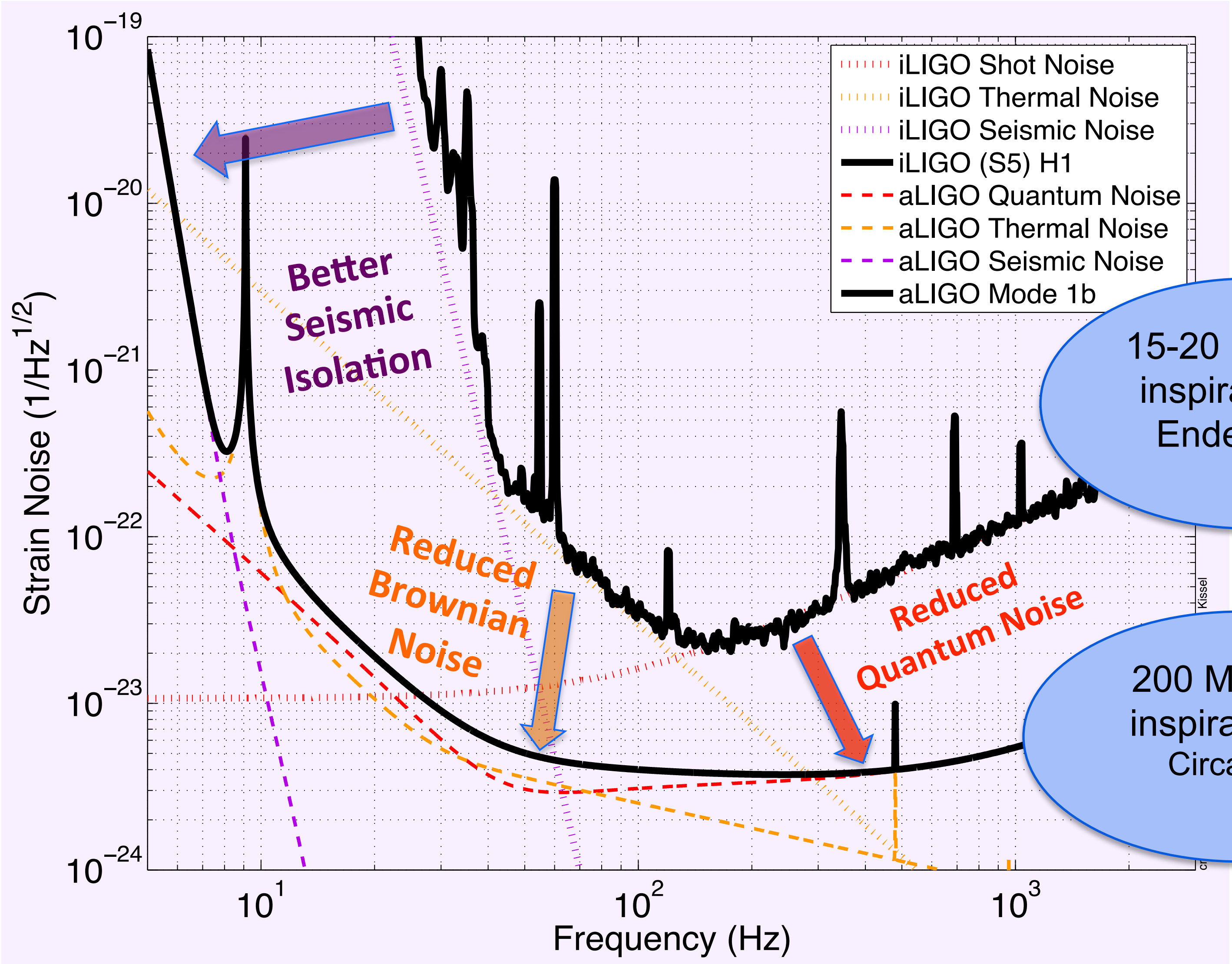
Science & Technology Facilities Council Rutherford Appleton Laboratory

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

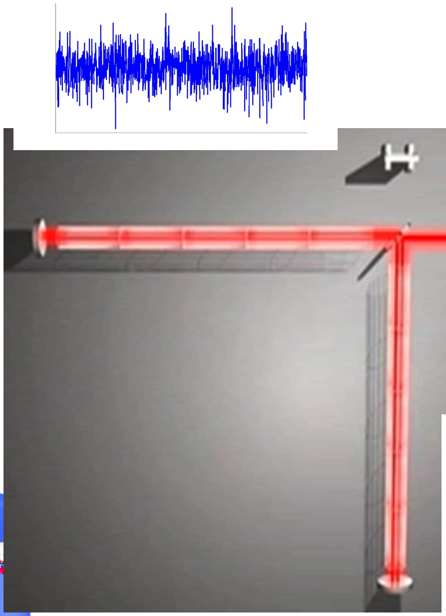


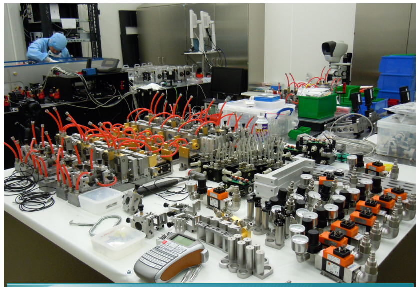
15-20 Mpc BNS inspiral range; Ended 2010

200 Mpc BNS inspiral range; Circa 2019

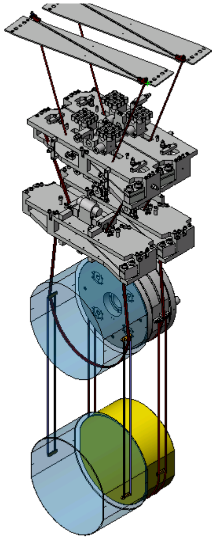
2008+:
Advanced LIGO detectors

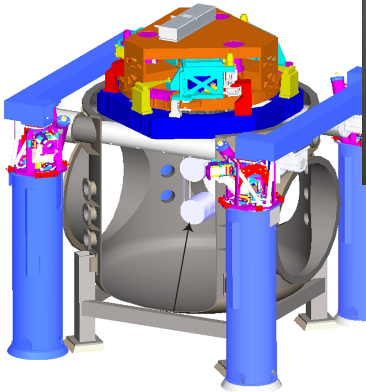
LIGO VIRGO

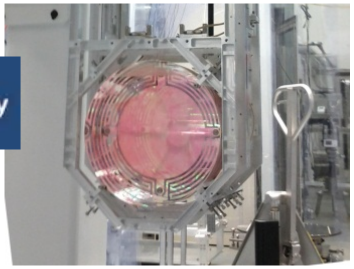




MAX-PLANCK-GESELLSCHAFT



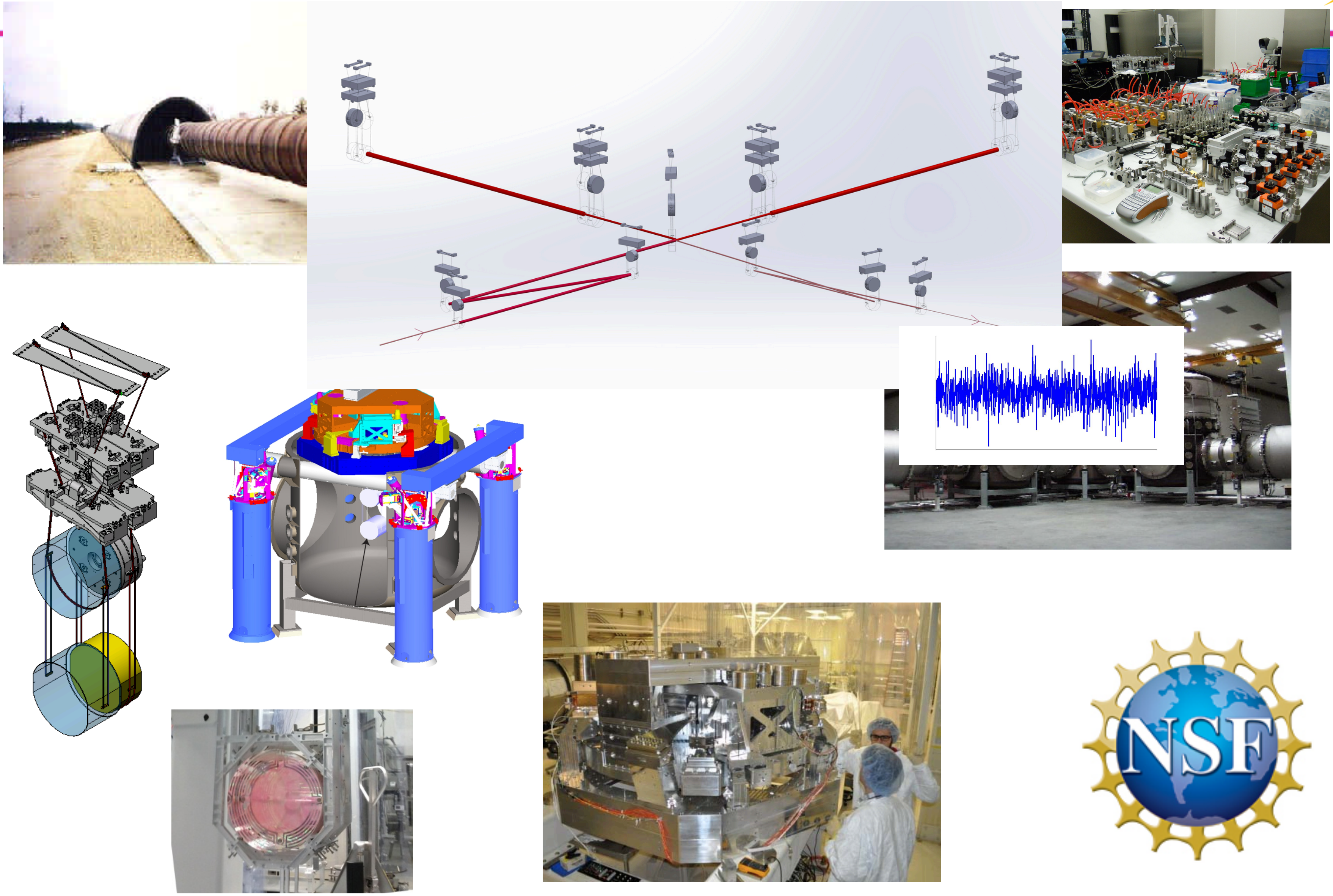




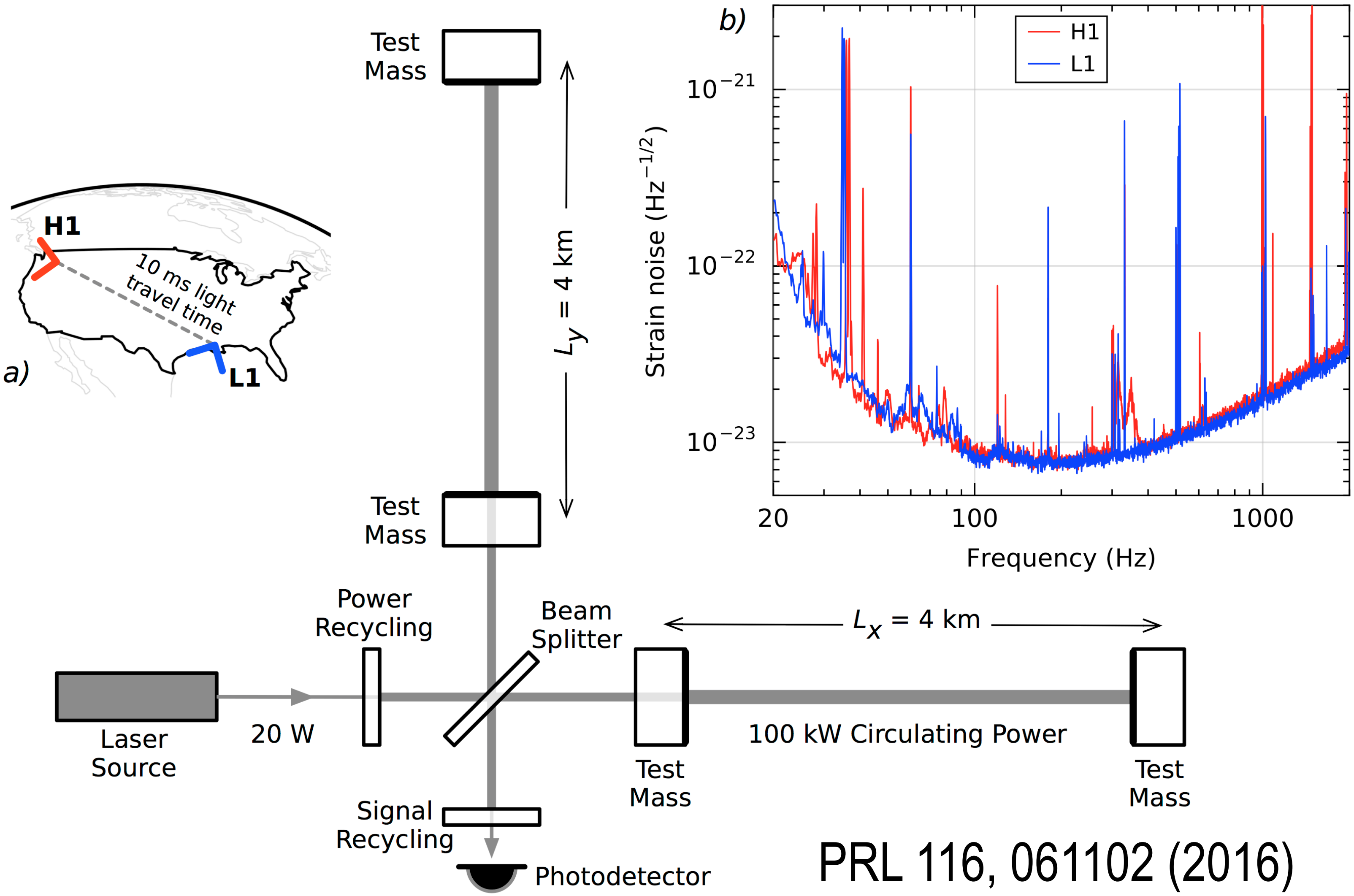
Science & Technology Facilities Council

NSF

Advanced LIGO detectors

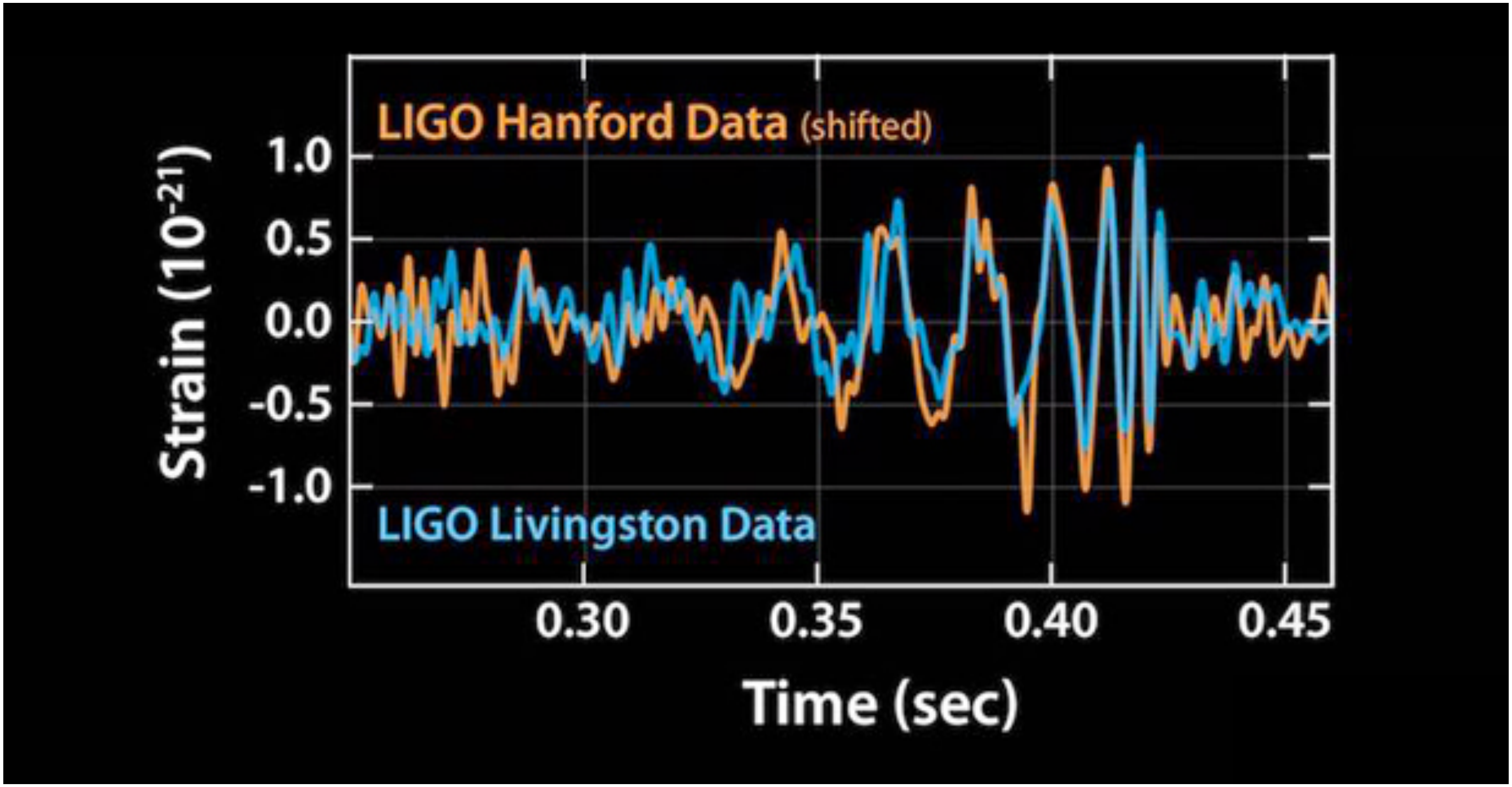


Advanced LIGO detectors
September 2015



PRL 116, 061102 (2016)

On Sept 14 2015…



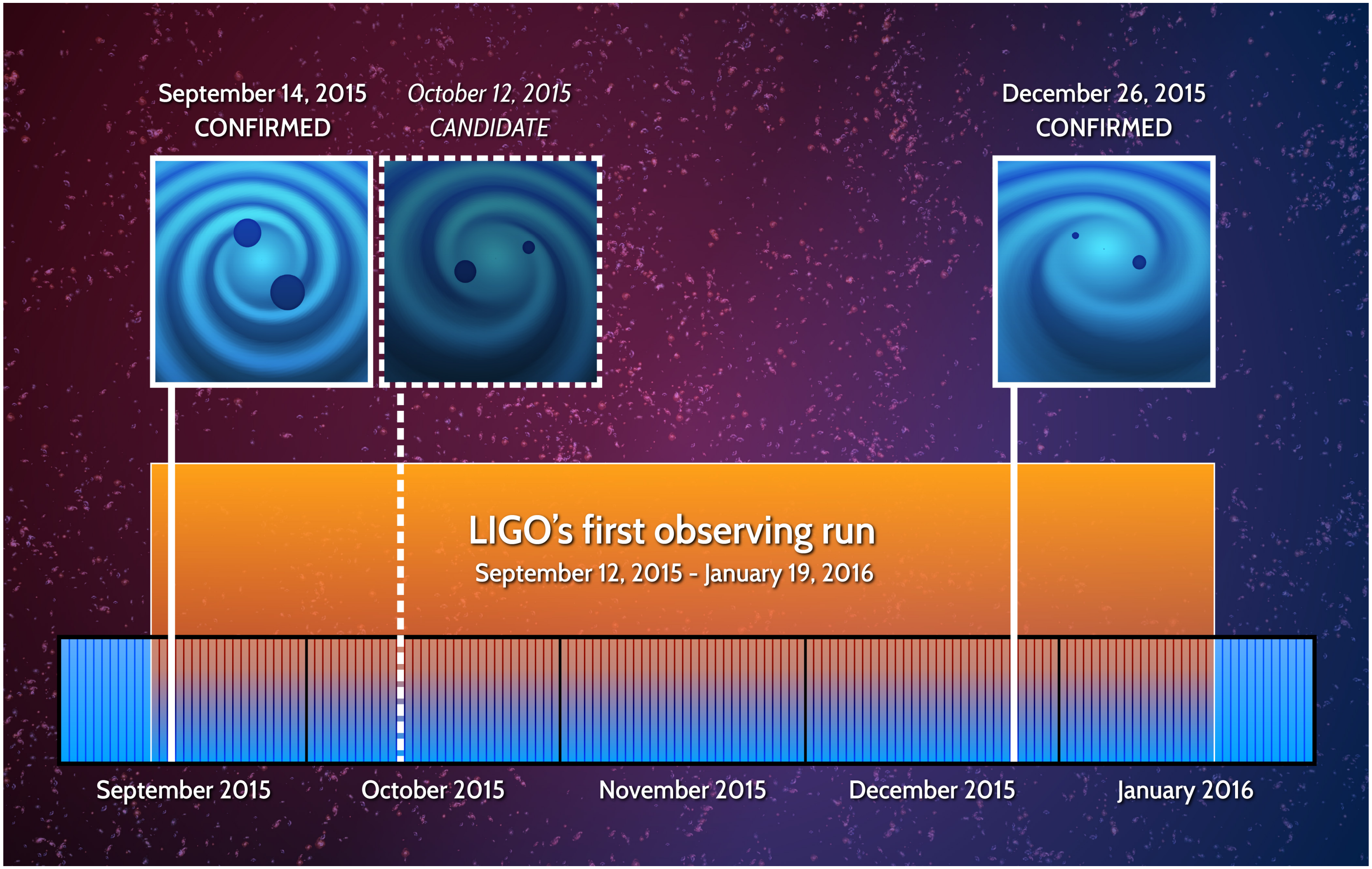
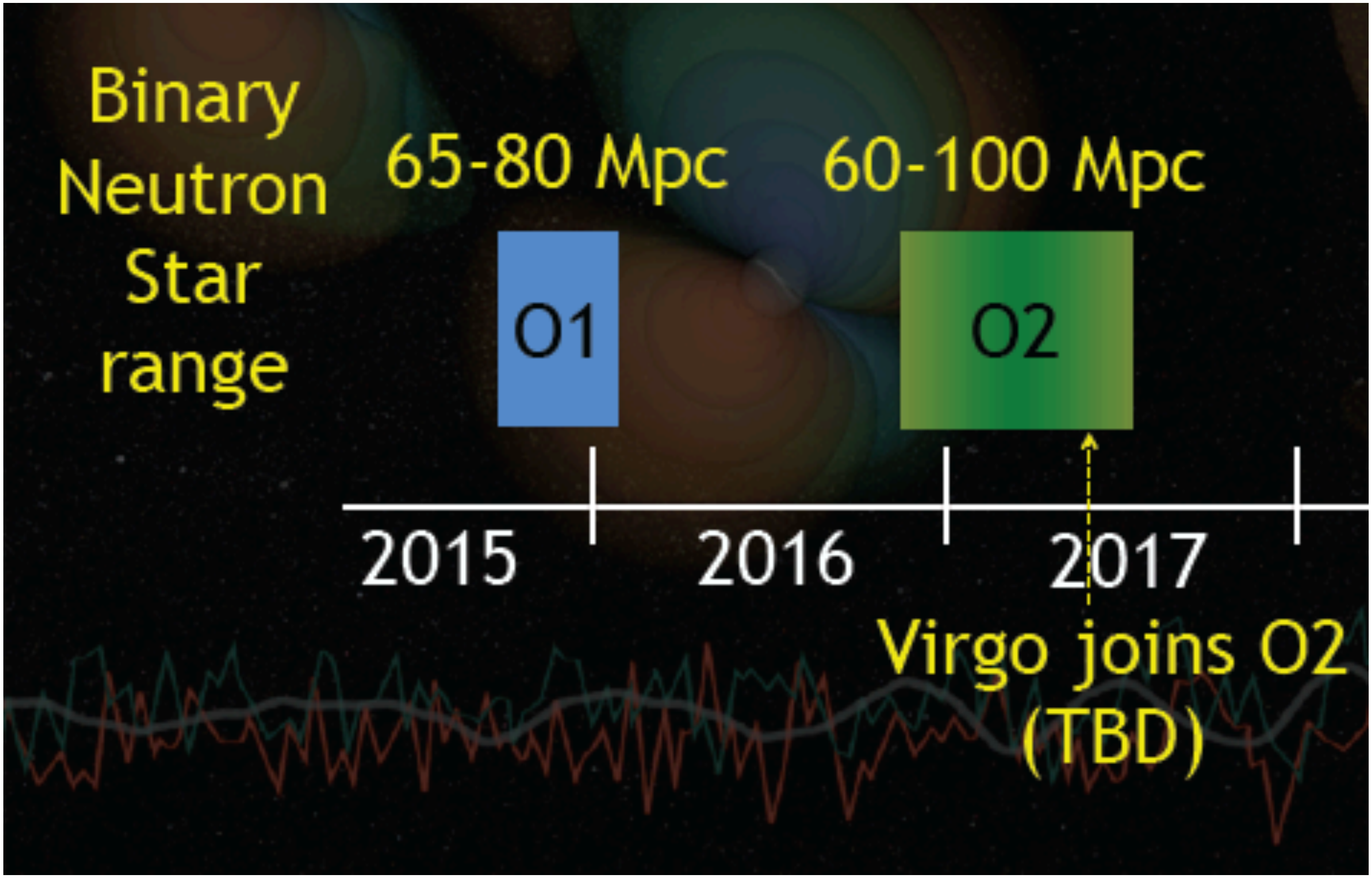
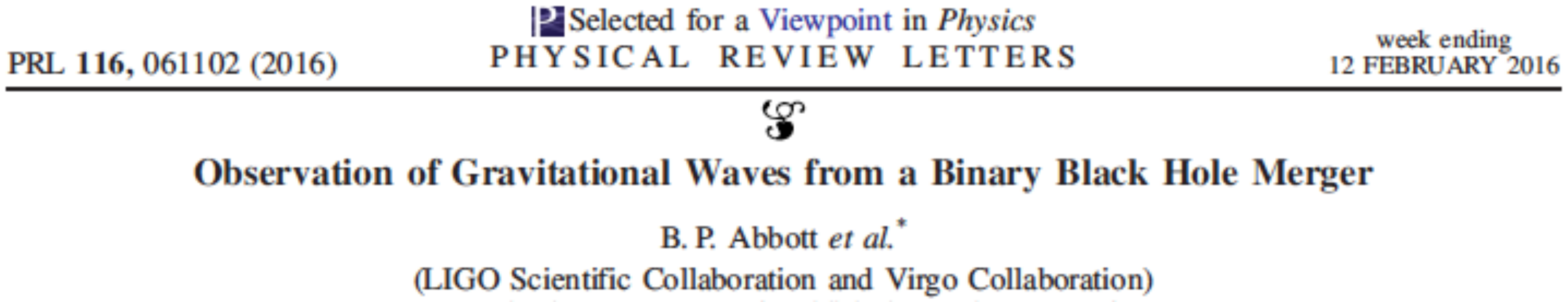


Image credit: LIGO

What happened since 2016?





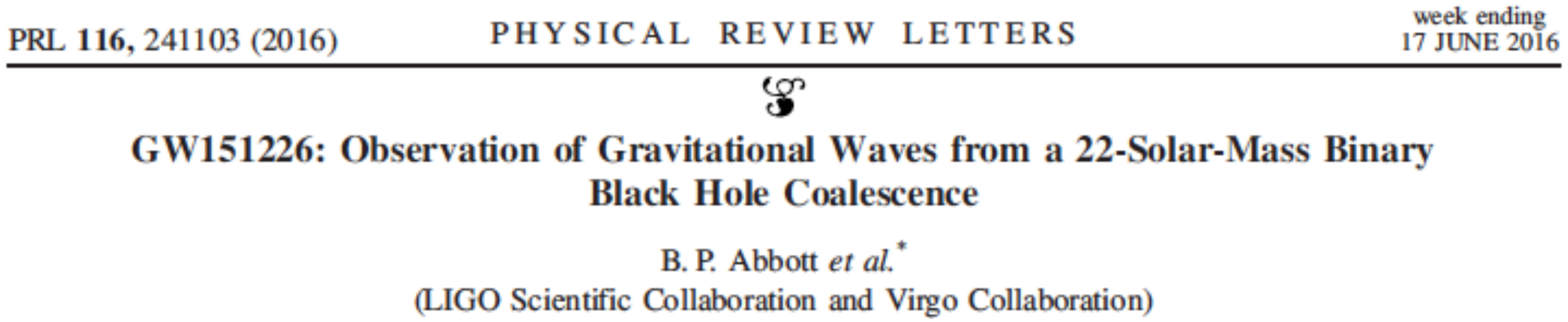
Selected for a Viewpoint in *Physics*

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)

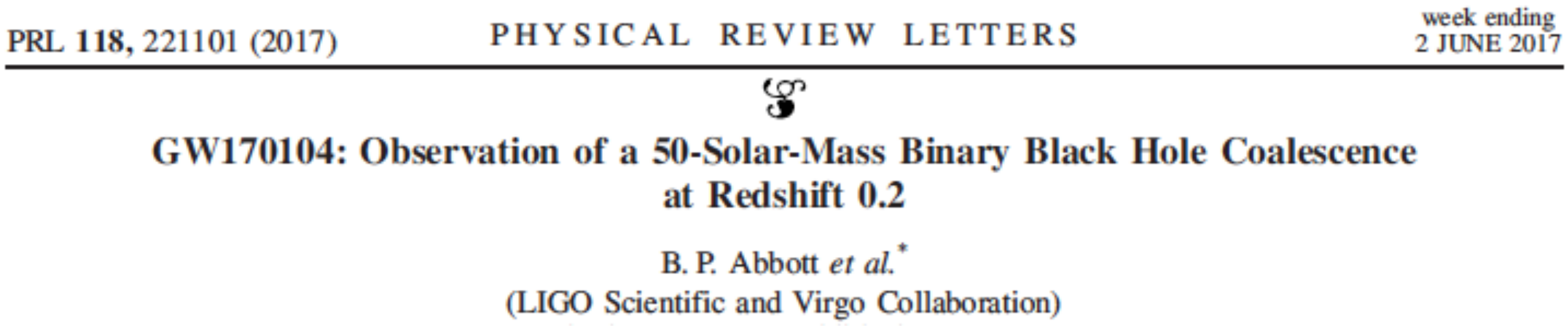


PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

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)

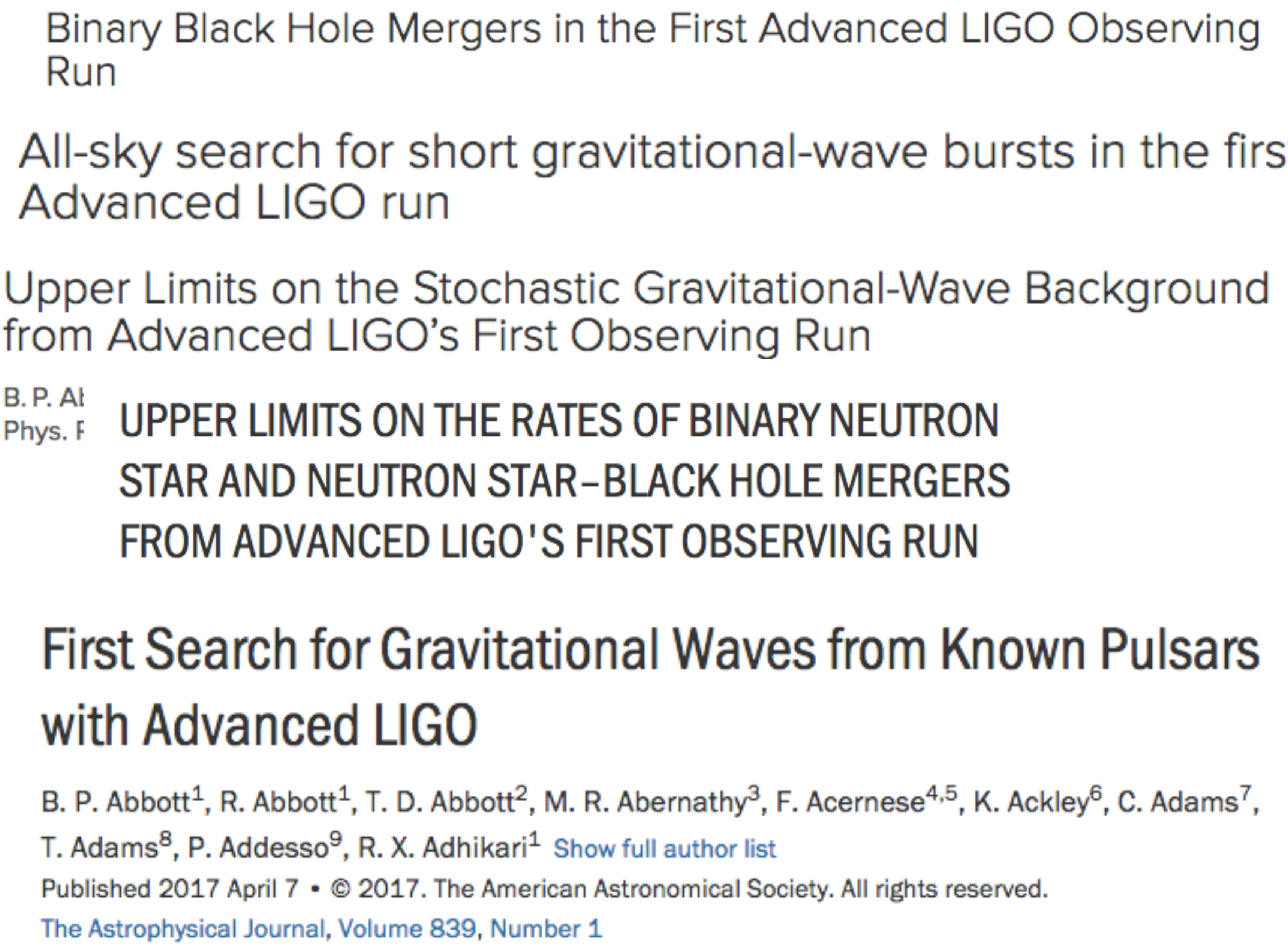


PRL **118,** 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott *et al.*[*]

(LIGO Scientific and Virgo Collaboration)



Binary Black Hole Mergers in the First Advanced LIGO Observing Run

All-sky search for short gravitational-wave bursts in the first Advanced LIGO run

Upper Limits on the Stochastic Gravitational-Wave Background from Advanced LIGO's First Observing Run

B. P. Ab

Phys. R

UPPER LIMITS ON THE RATES OF BINARY NEUTRON STAR AND NEUTRON STAR–BLACK HOLE MERGERS FROM ADVANCED LIGO'S FIRST OBSERVING RUN

First Search for Gravitational Waves from Known Pulsars with Advanced LIGO

B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. R. Abernathy[3], F. Acernese[4,5], K. Ackley[6], C. Adams[7], T. Adams[8], P. Addesso[9], R. X. Adhikari[1] Show full author list

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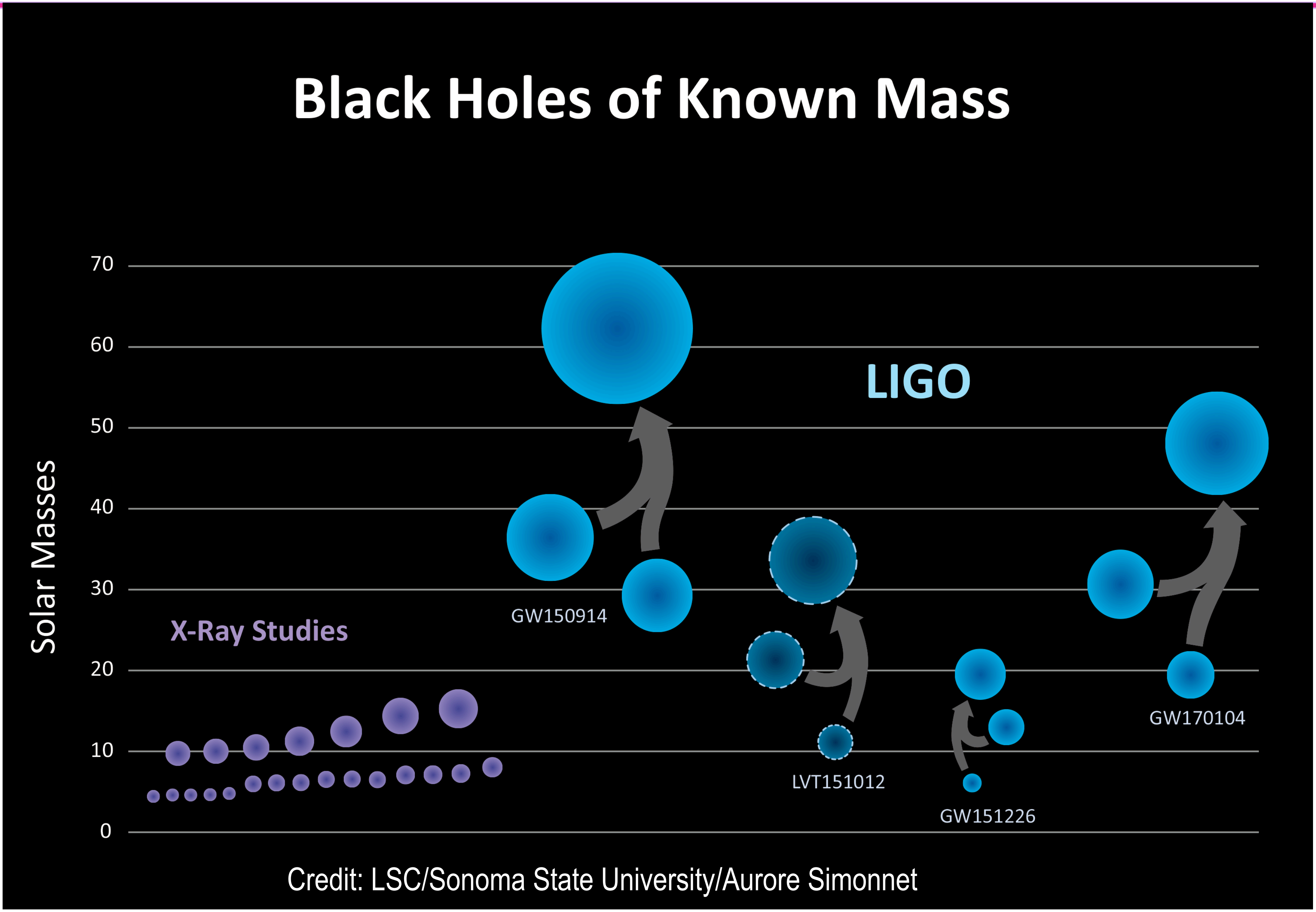
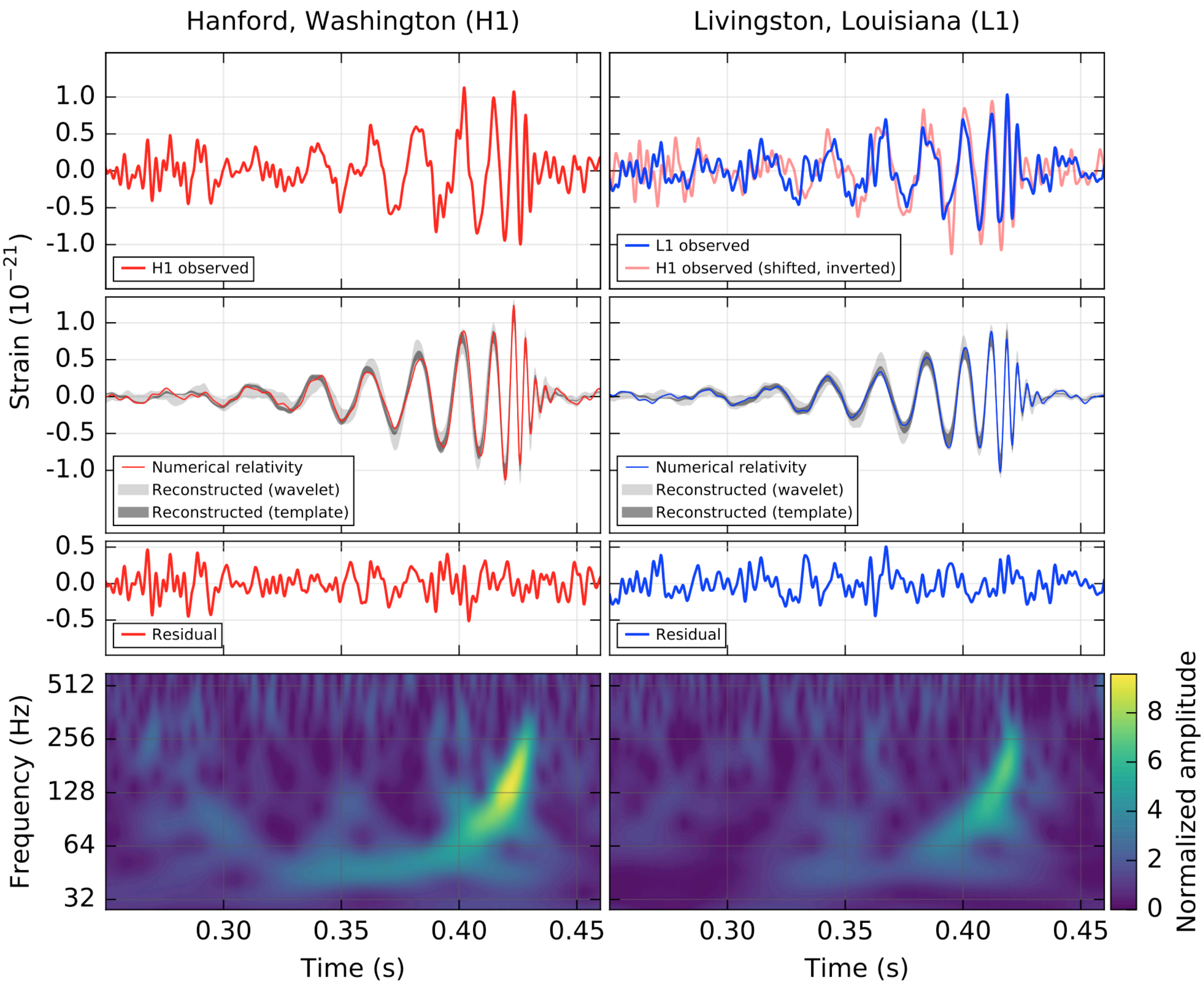
The Astrophysical Journal, Volume 839, Number 1

Filling in the black hole catalog

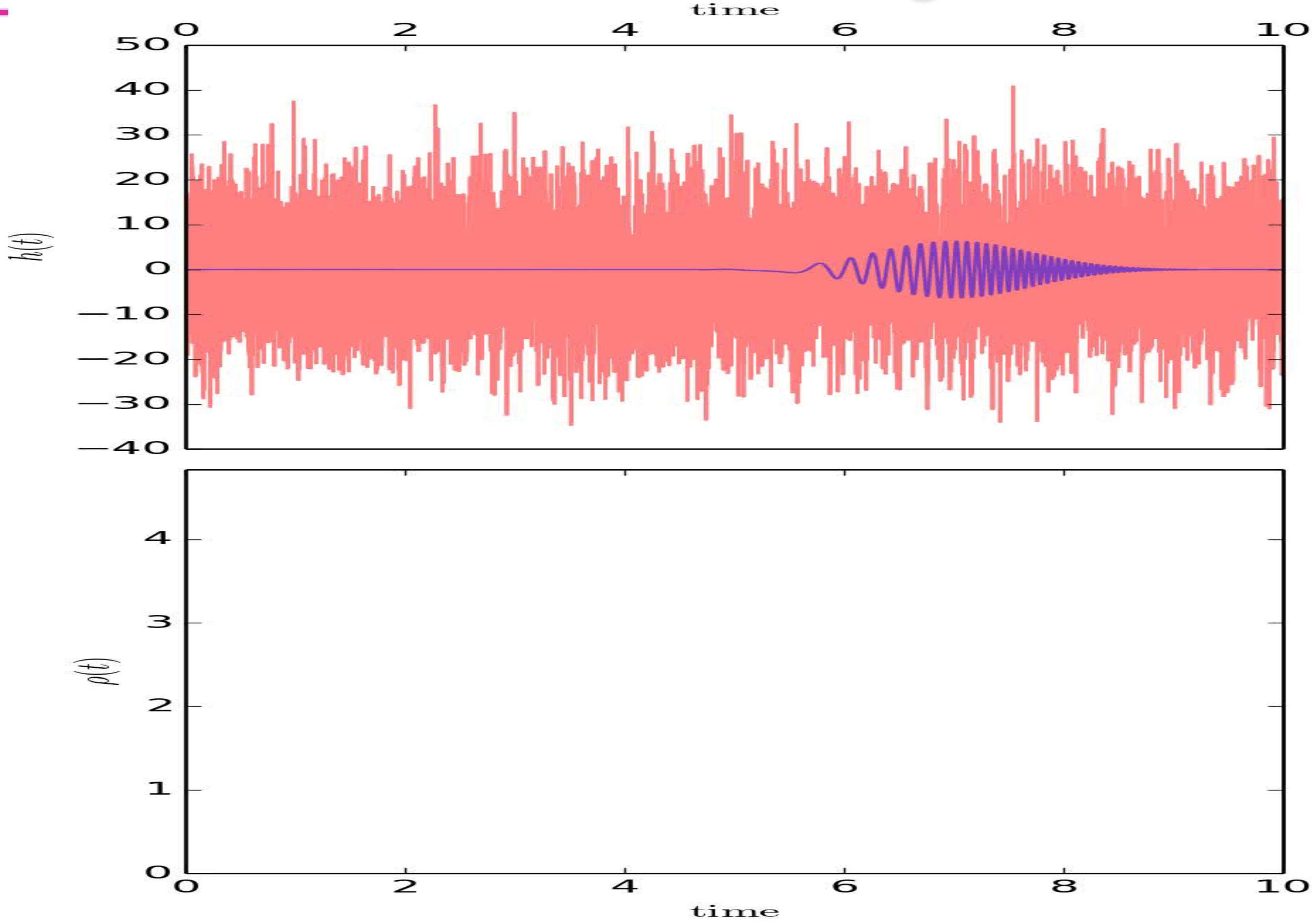


Credit: LSC/Sonoma State University/Aurore Simonnet

PRL 116, 061102 (2016)

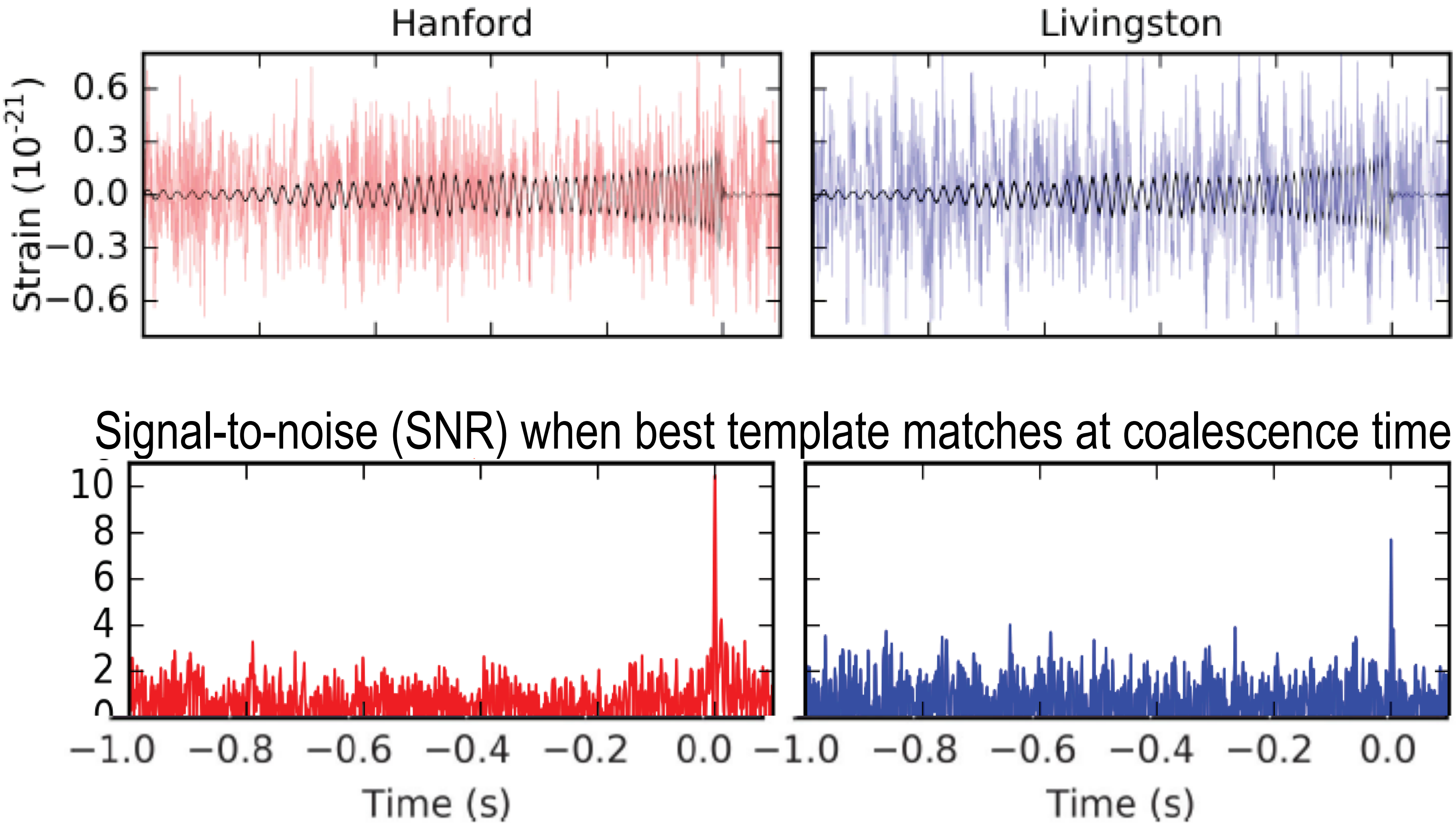


Searching for a specific waveform: matched filtering



GW151226

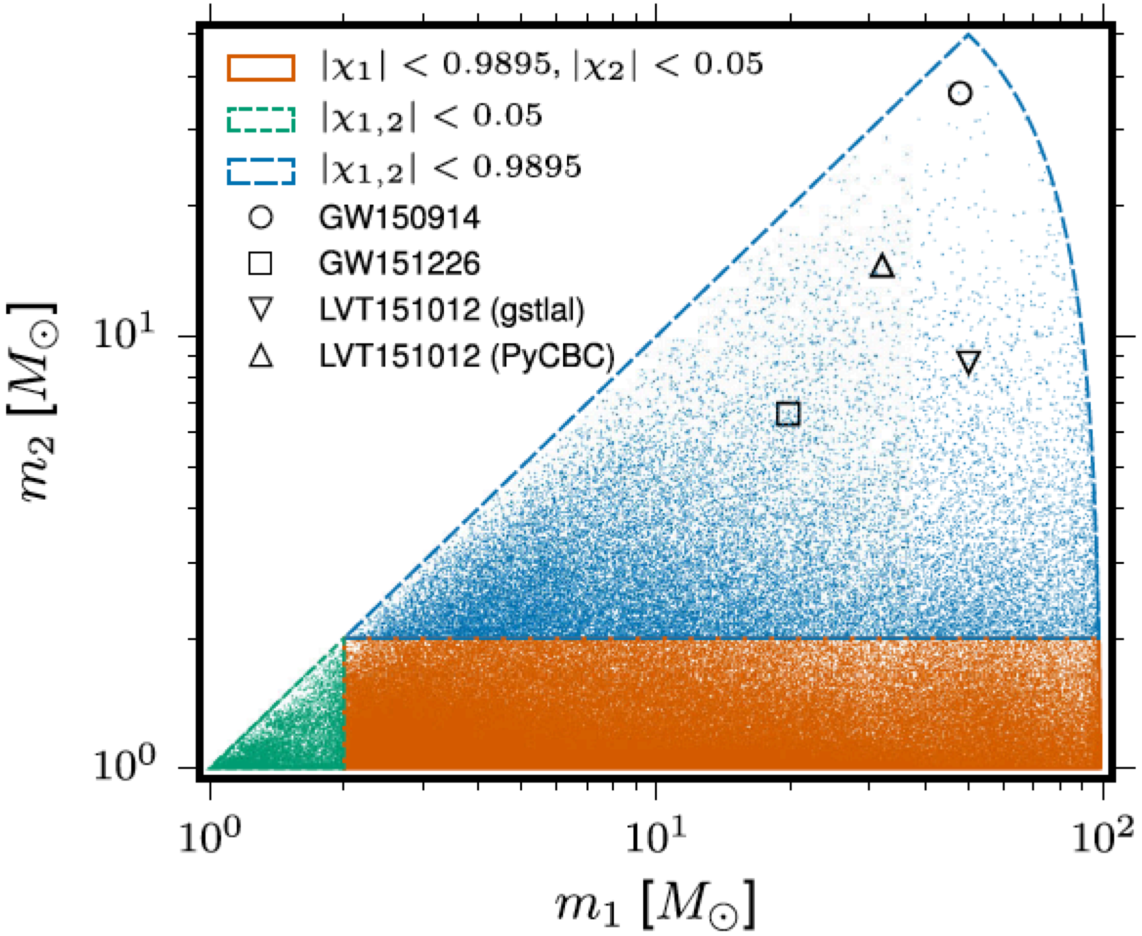
Filtered detector output and filtered best matching waveform



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

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

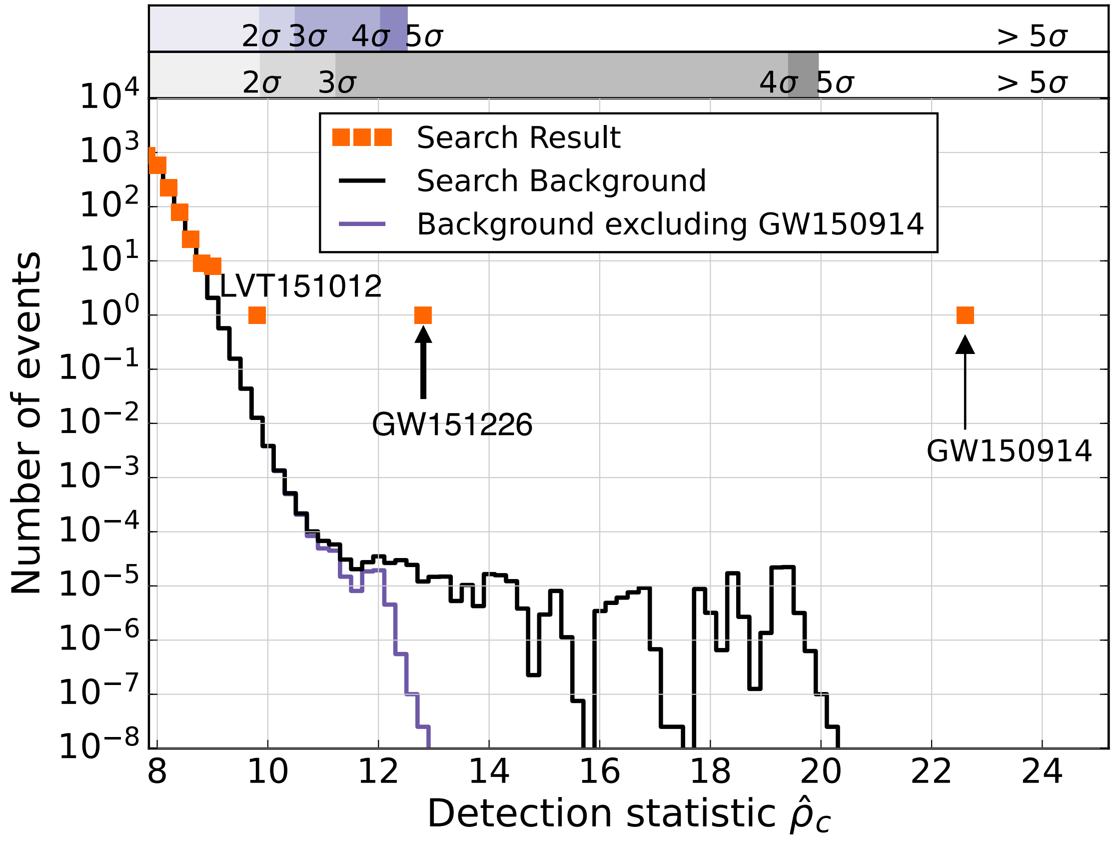
Searching and finding waveforms

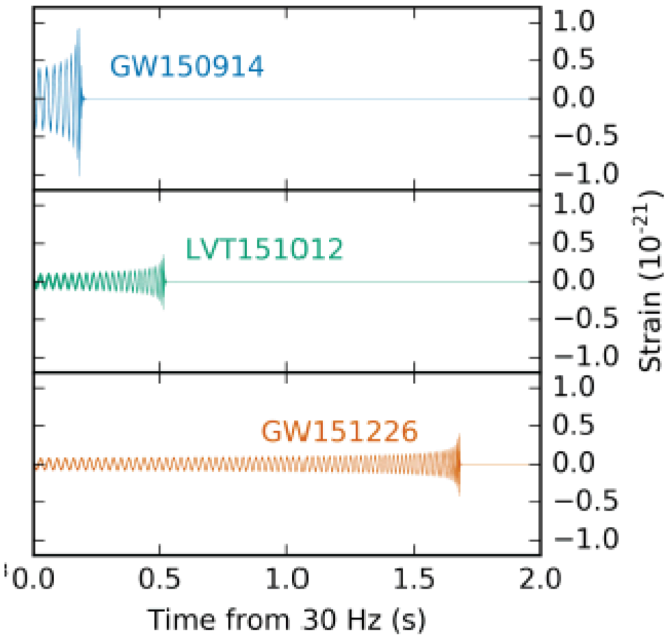


Phys. Rev. X 6, 041015 (2016))

O1 BBH search

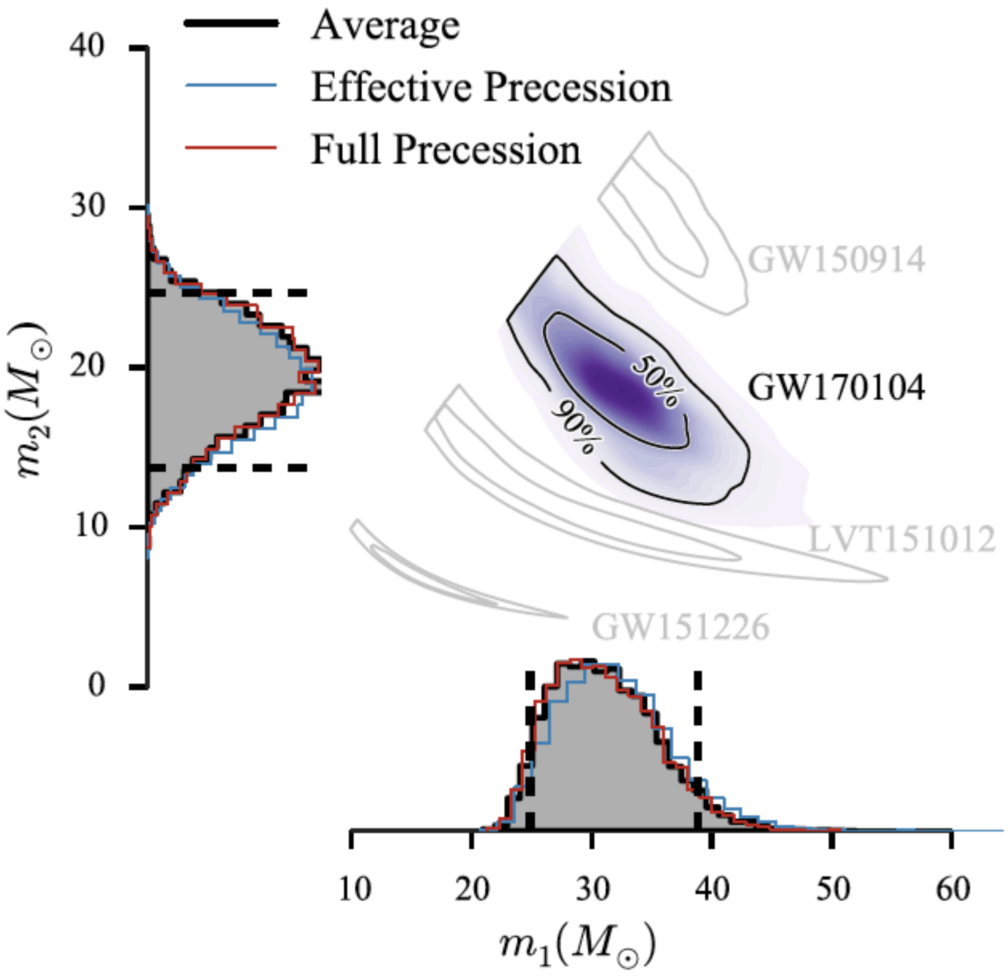
Search for binary black holes systems with black holes larger than 2 $M_\odot$ and total mass less than 100 $M_\odot$, in O1 (Sep 12, 2015-Jan 19, 2016, ~48 days of coincident data)





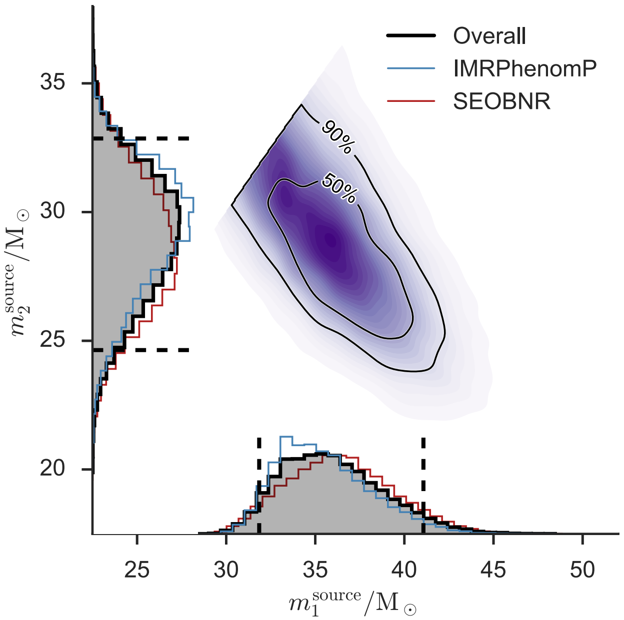
Phys. Rev. X 6, 041015 (2016))

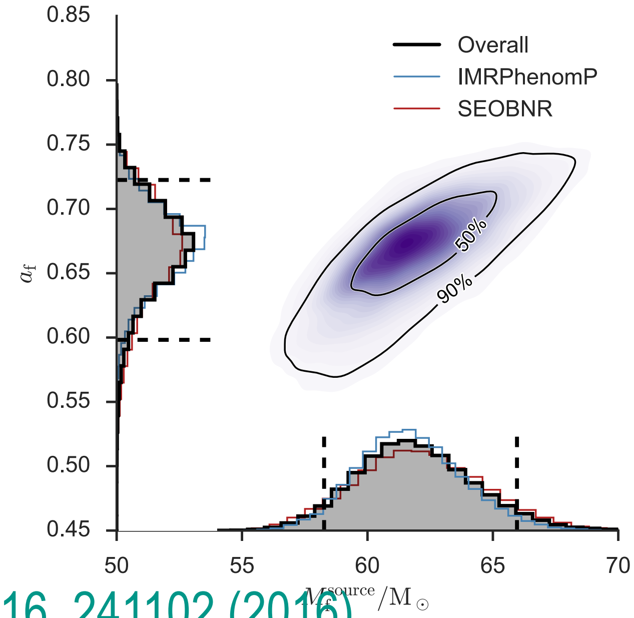
Finding parameters: masses



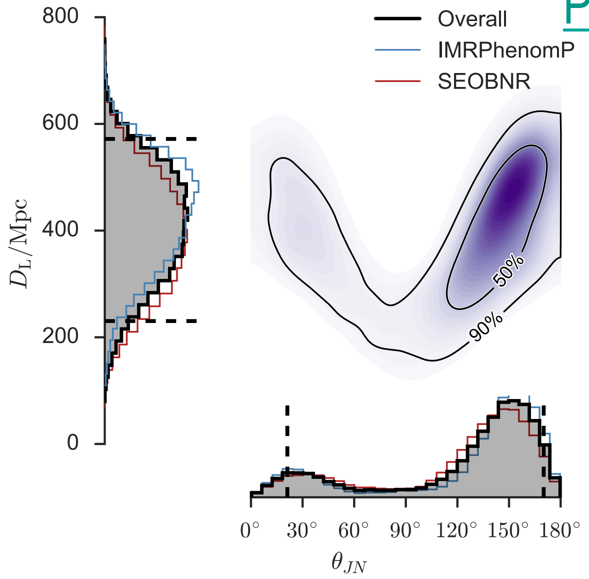
Phys. Rev. Lett. 118, 221101

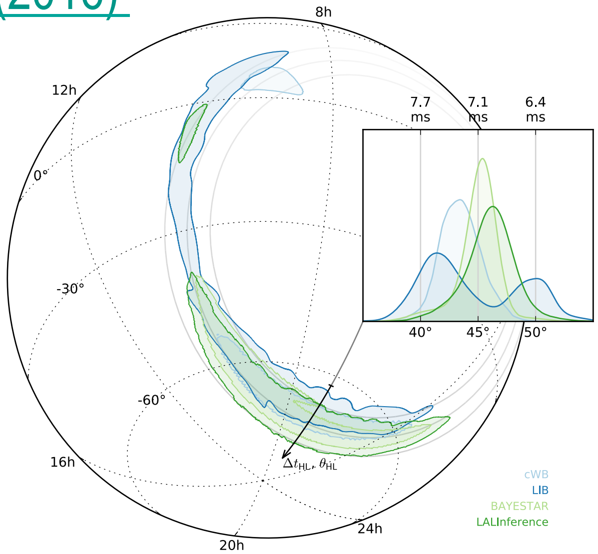
Finding parameters: GW150914





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





BINARY BLACK HOLE MERGERS IN THE FIRST … PHYS. REV. X **6**, 041015 (2016)

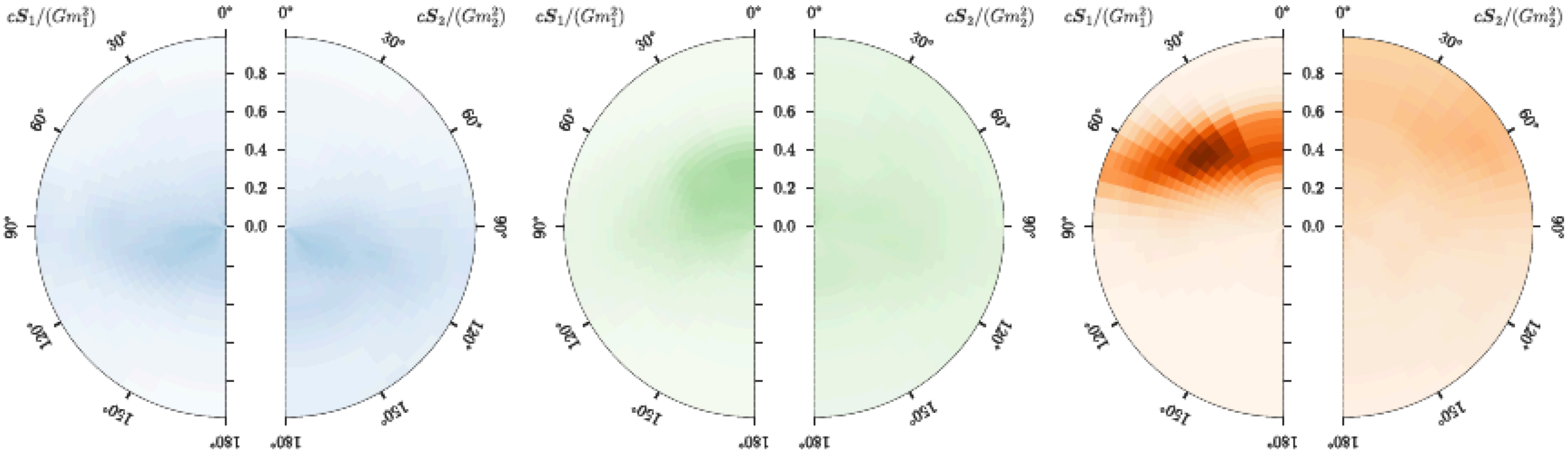
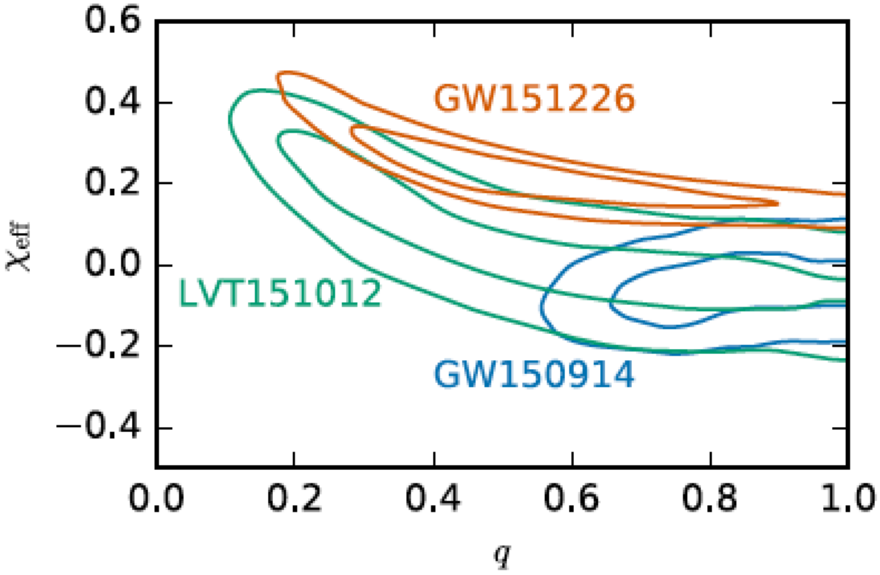


FIG. 5. Posterior probability distributions for the dimensionless component spins $cS_1/(Gm_1^2)$ and $cS_2/(Gm_2^2)$ relative to the normal to the orbital plane L, marginalized over the azimuthal angles. The bins are constructed linearly in spin magnitude and the cosine of the tilt angles, and therefore 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.



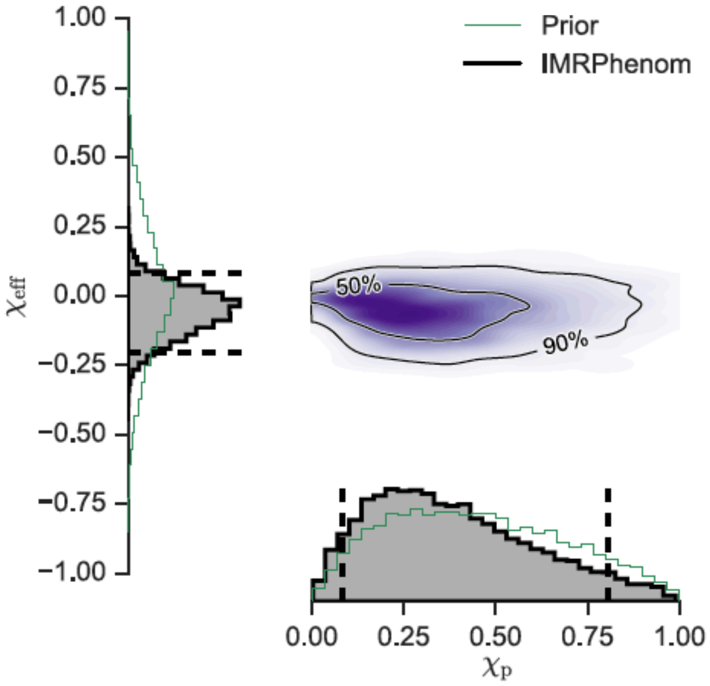
$$\chi_{\rm eff} = \left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right) \cdot \left(\frac{\hat{\mathbf{L}}}{M}\right)$$

Black hole spins

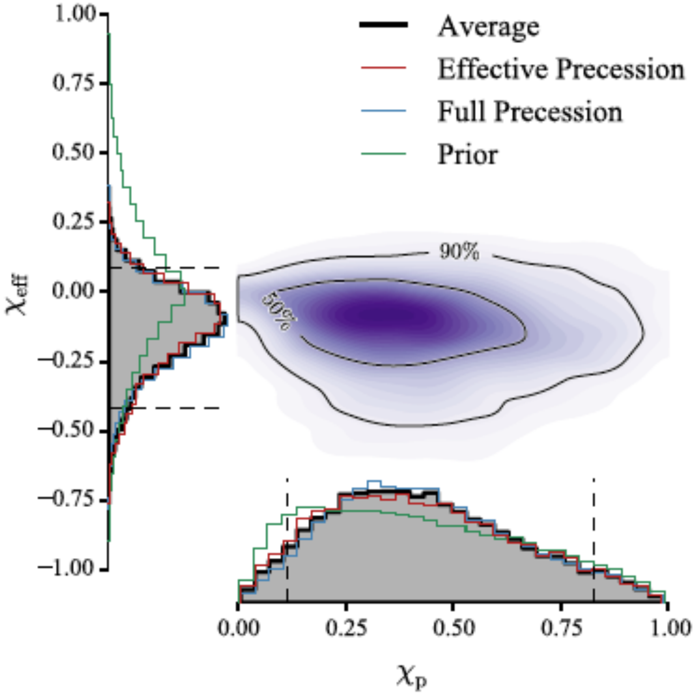
$$\chi_{\rm eff} = \left(\frac{\mathbf{S}_1}{m_1}+\frac{\mathbf{S}_2}{m_2}\right)\cdot\left(\frac{\hat{\mathbf{L}}}{M}\right)$$

$$\chi_p = \frac{c}{B_1 G m_1^2}\max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0,$$

$$B_1 = 2+3q/2 \text{ and } B_2 = 2+3/(2q),$$



GW150914
Phys. Rev. Lett. 116, 241102



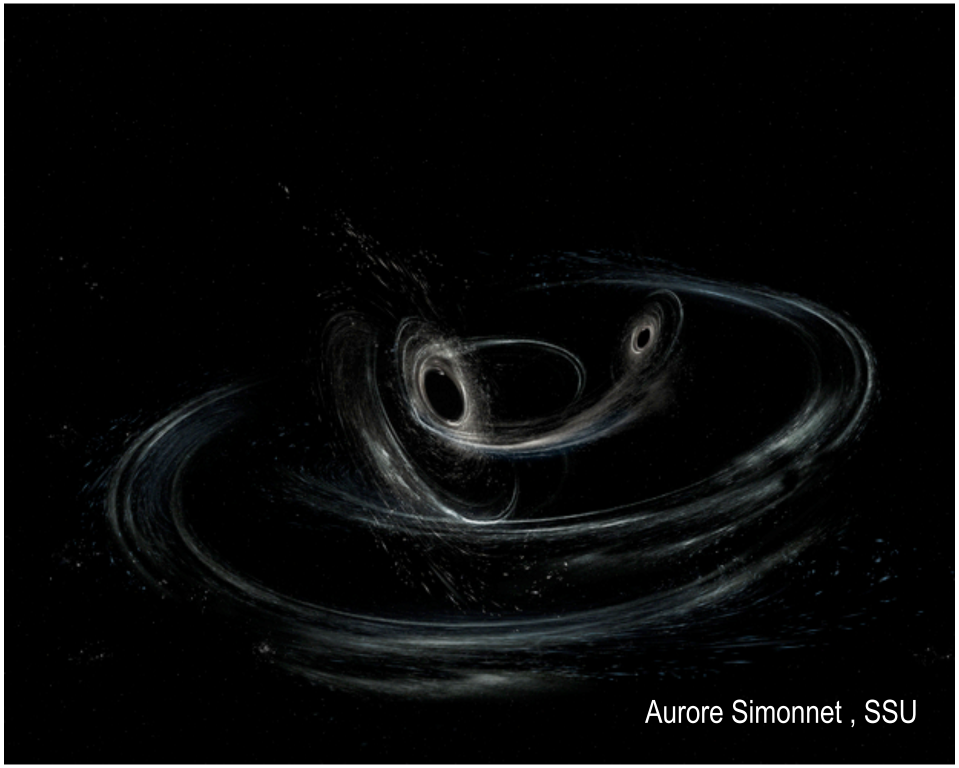
GW170104
Phys.Rev.Lett 118, 221101 (2017)

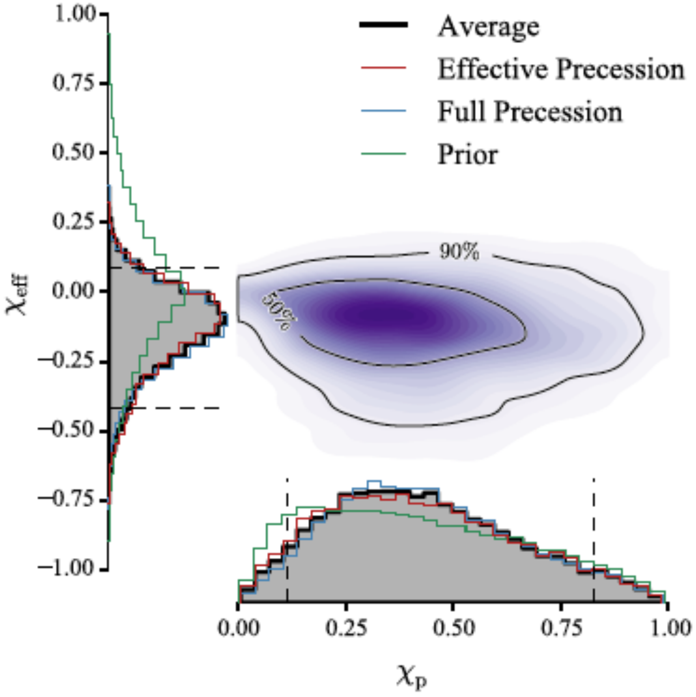
Black hole spins

$$\chi_{\mathrm{eff}} = \left(\frac{\mathbf{S}_1}{m_1} + \frac{\mathbf{S}_2}{m_2}\right) \cdot \left(\frac{\hat{\mathbf{L}}}{M}\right)$$

$$\chi_p = \frac{c}{B_1 G m_1^2} \max(B_1 S_{1\perp}, B_2 S_{2\perp}) > 0,$$

$$B_1 = 2 + 3q/2 \text{ and } B_2 = 2 + 3/(2q),$$


Aurore Simonnet , SSU



GW170104
Phys.Rev.Lett 118, 221101 (2017)

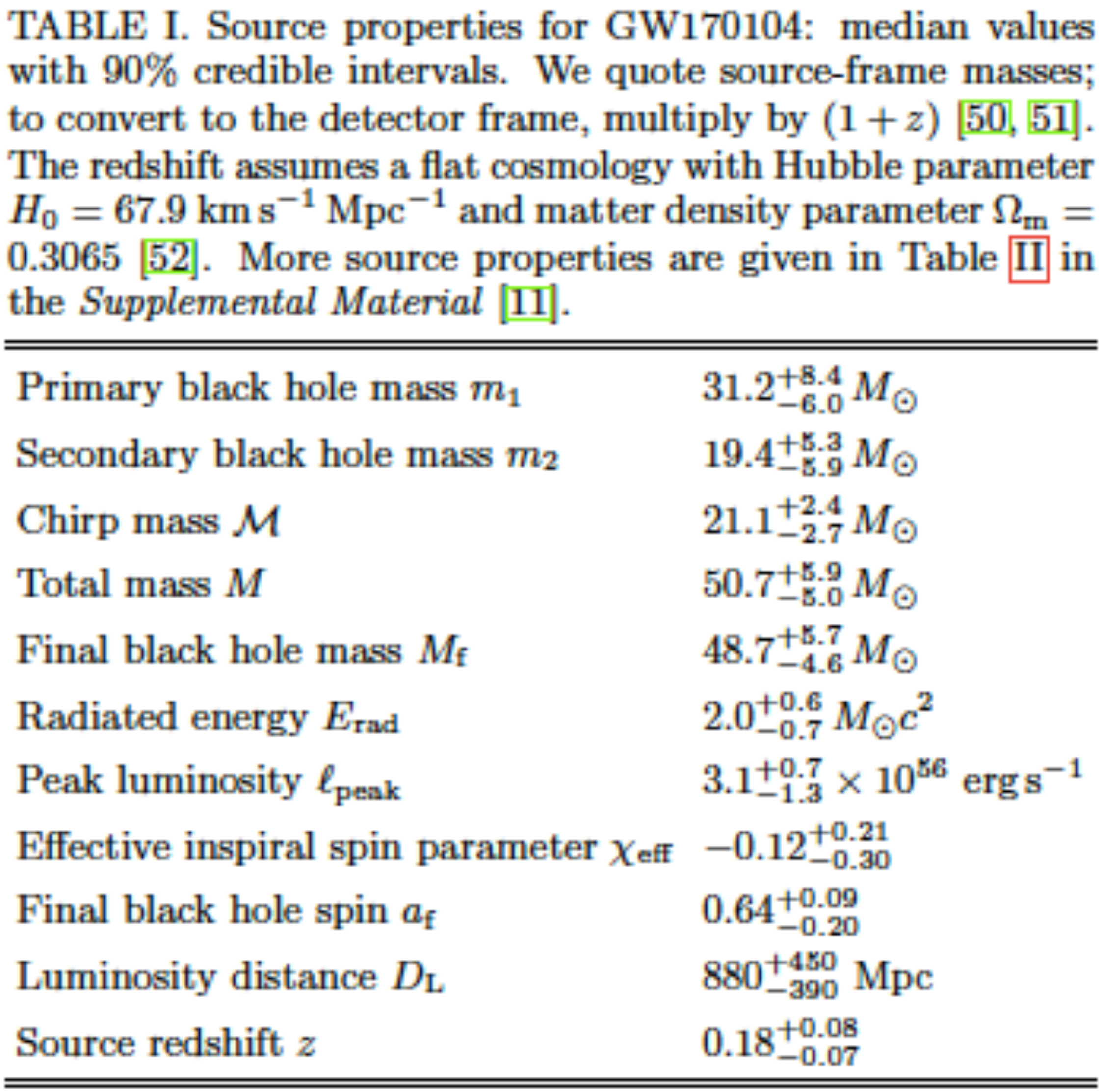
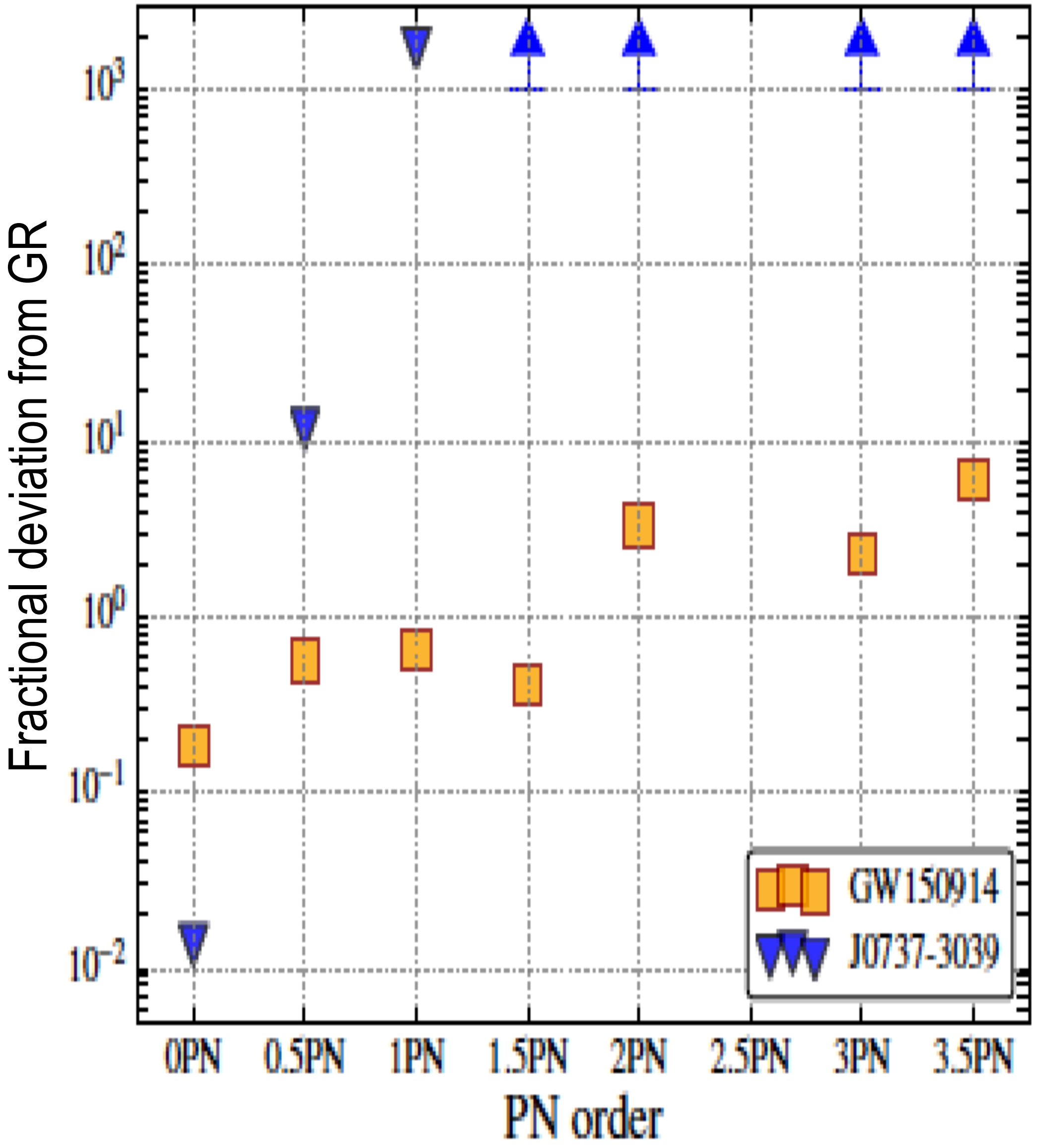


TABLE I. Source properties for GW170104: median values with 90% credible intervals. We quote source-frame masses; to convert to the detector frame, multiply by $(1+z)$ [50, 51]. The redshift assumes a flat cosmology with Hubble parameter $H_0 = 67.9\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and matter density parameter $\Omega_{\mathrm{m}} = 0.3065$ [52]. More source properties are given in Table II in the *Supplemental Material* [11].

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0}\,M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9}\,M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7}\,M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0}\,M_\odot$
Final black hole mass M_{f}	$48.7^{+5.7}_{-4.6}\,M_\odot$
Radiated energy E_{rad}	$2.0^{+0.6}_{-0.7}\,M_\odot c^2$
Peak luminosity ℓ_{peak}	$3.1^{+0.7}_{-1.3} \times 10^{56}\ \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter χ_{eff}	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_{f}	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_{L}	$880^{+450}_{-390}\ \mathrm{Mpc}$
Source redshift z	$0.18^{+0.08}_{-0.07}$

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:

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

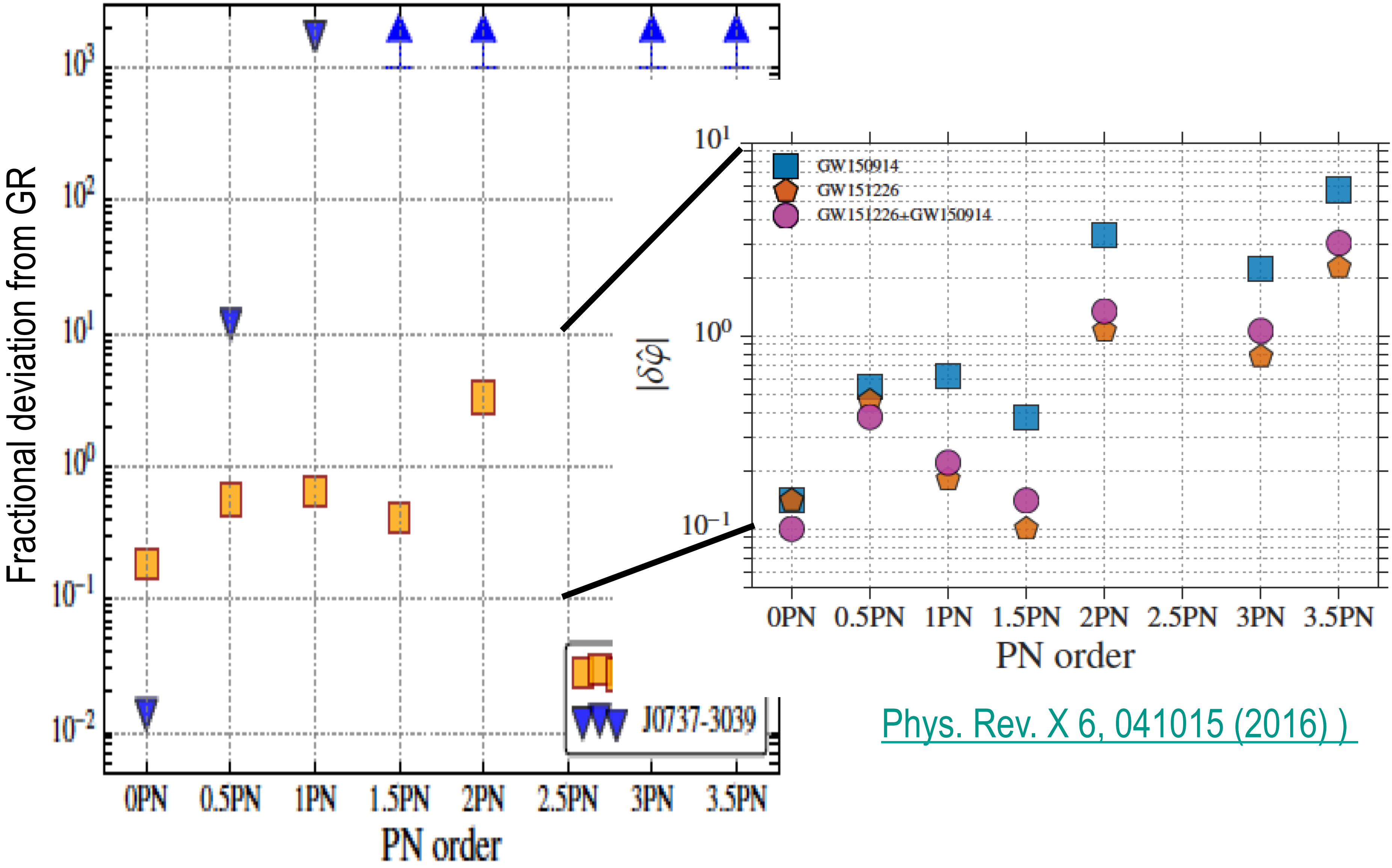
$$v/c \sim 0.5$$

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

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

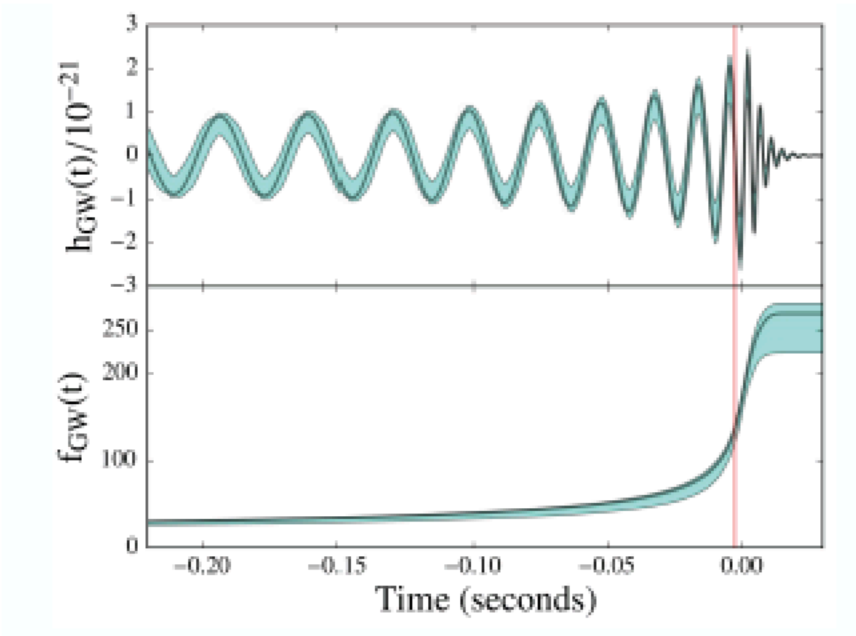
(Arun et al. 06 , Mishra et al. 10,
Yunes & Pretorius 09, Li et al. 12)

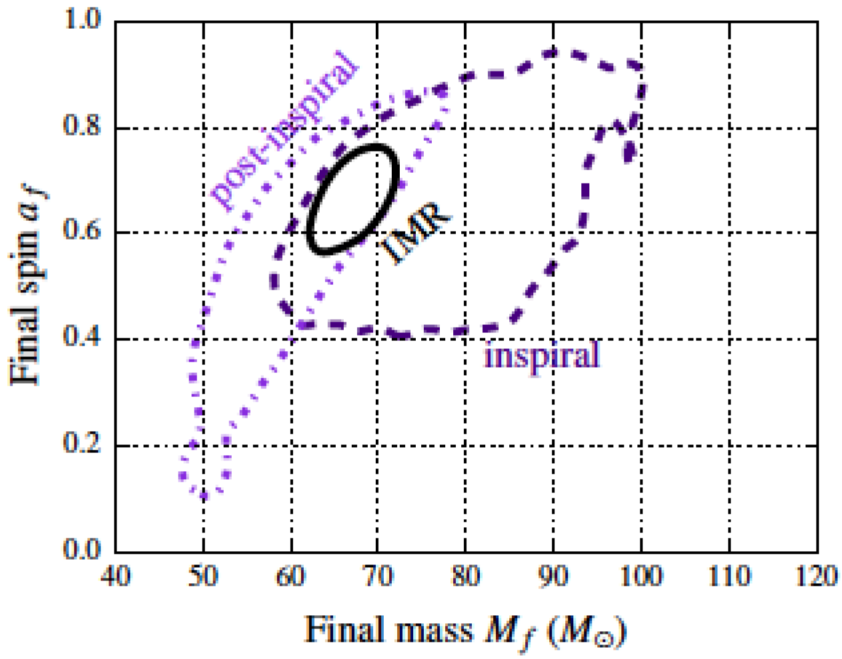
Testing General Relativity



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

Inspiral vs merger-ringdown

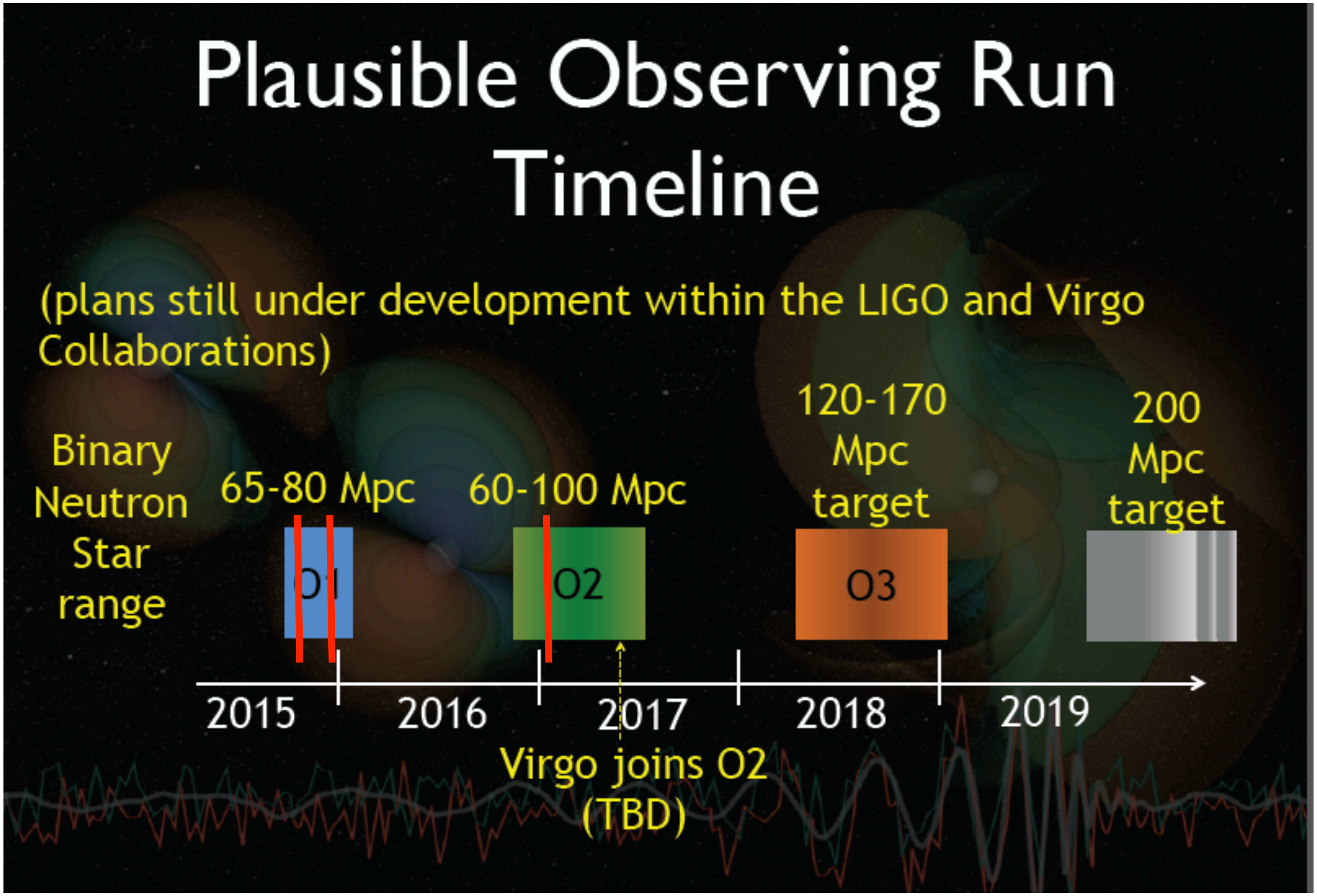




Phys. Rev. Lett. 116, 221101 (2016)

Test done in frequency domain with approximations of GR waveforms

What happened since 2016?
What will happen in the next few years?



Plausible Observing Run Timeline

(plans still under development within the LIGO and Virgo Collaborations)

Gravitational Wave Observatories

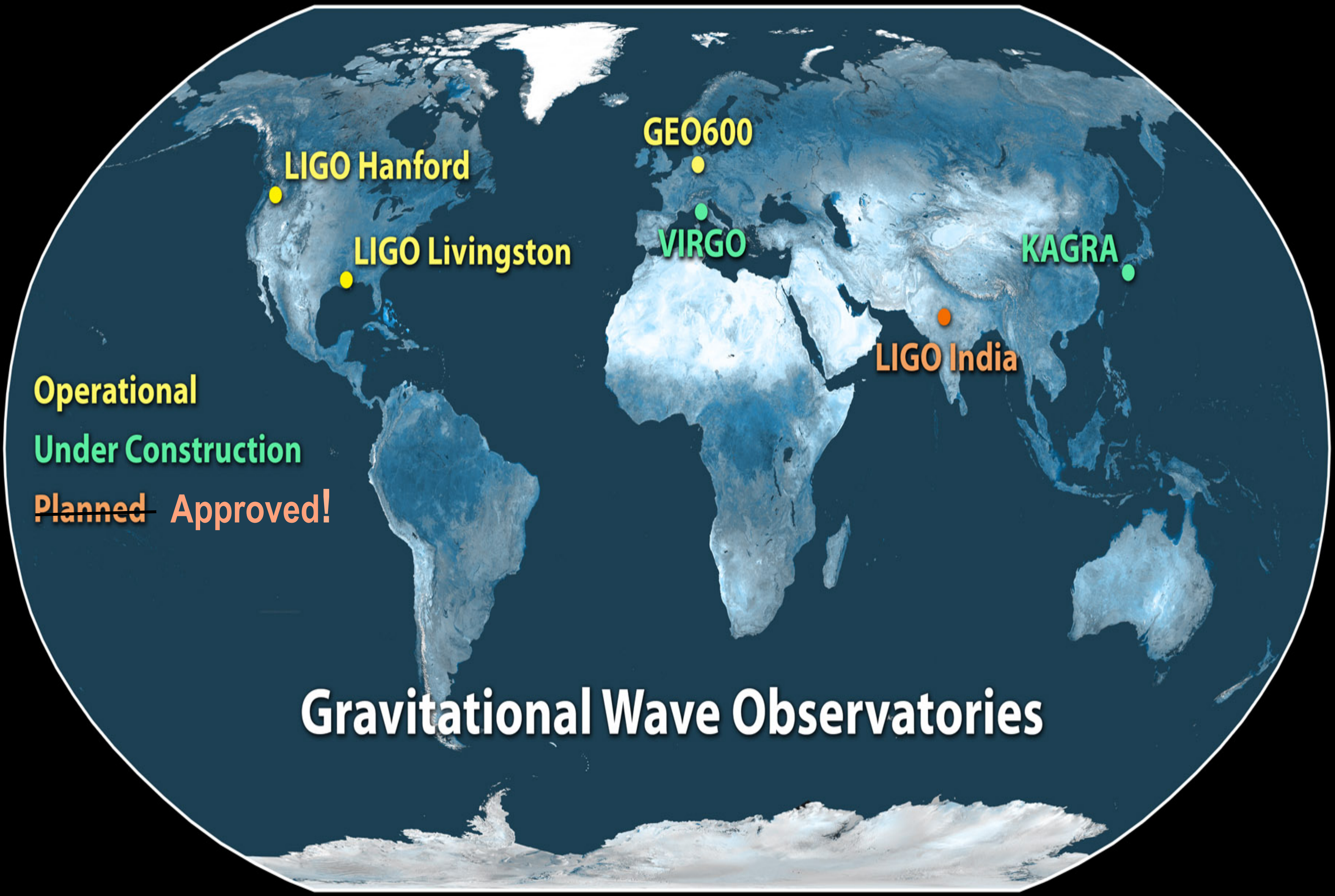
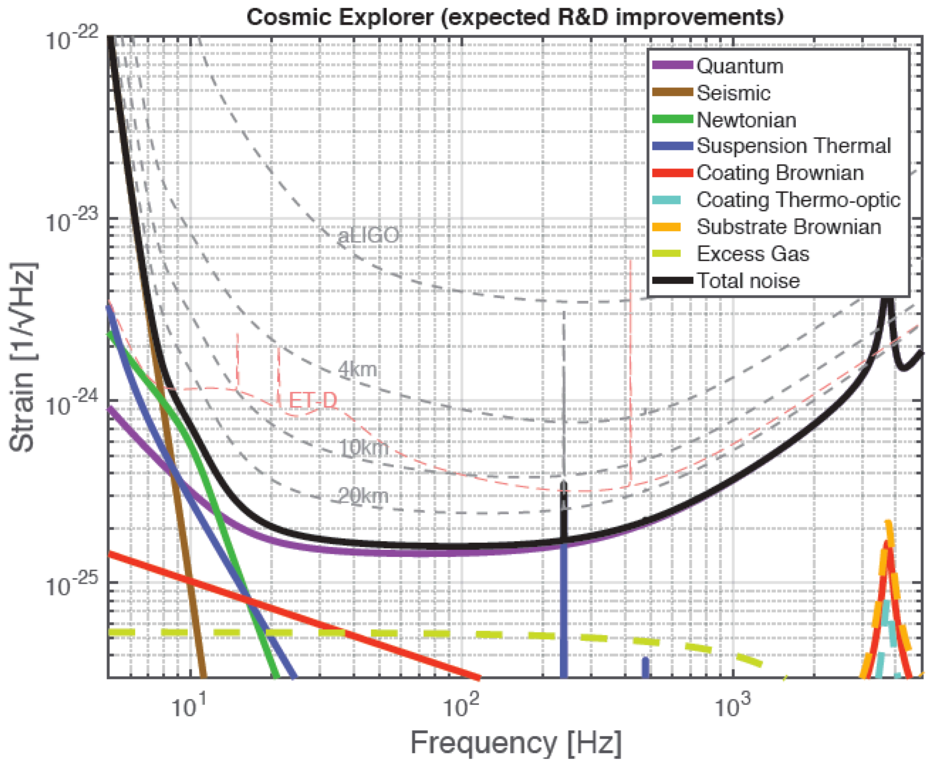
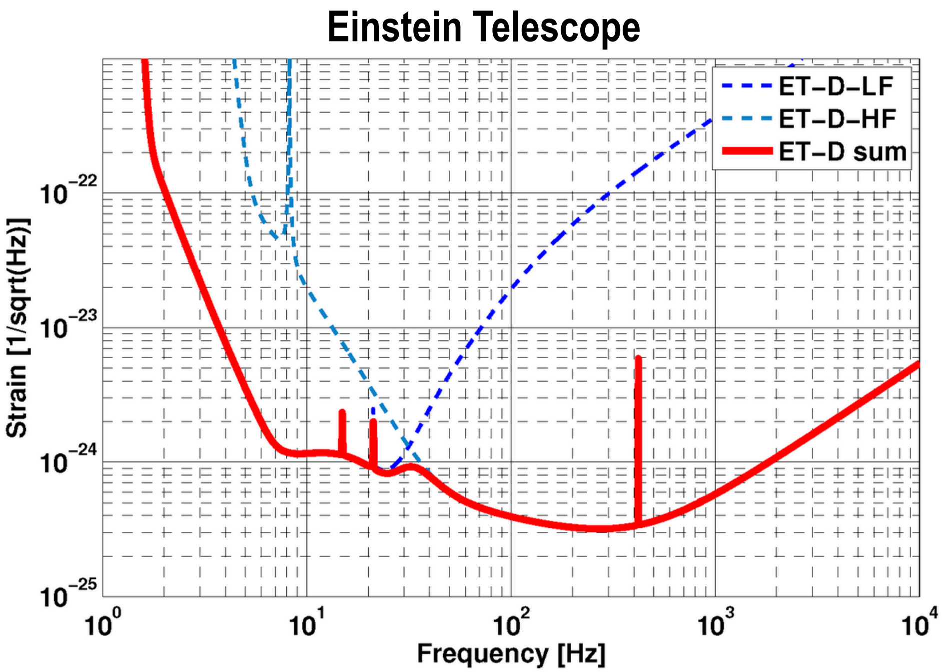


Image Credit: Caltech/MIT/LIGO Lab

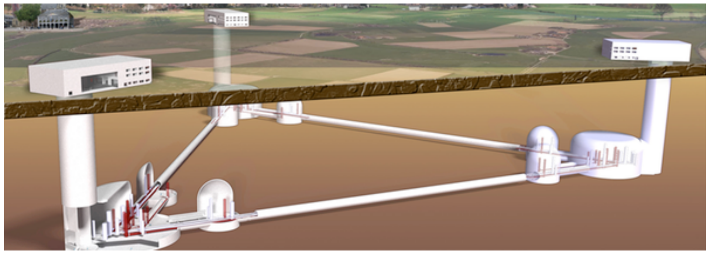
The future:
3^{rd} generation detectors



arXiv:1607.08697



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

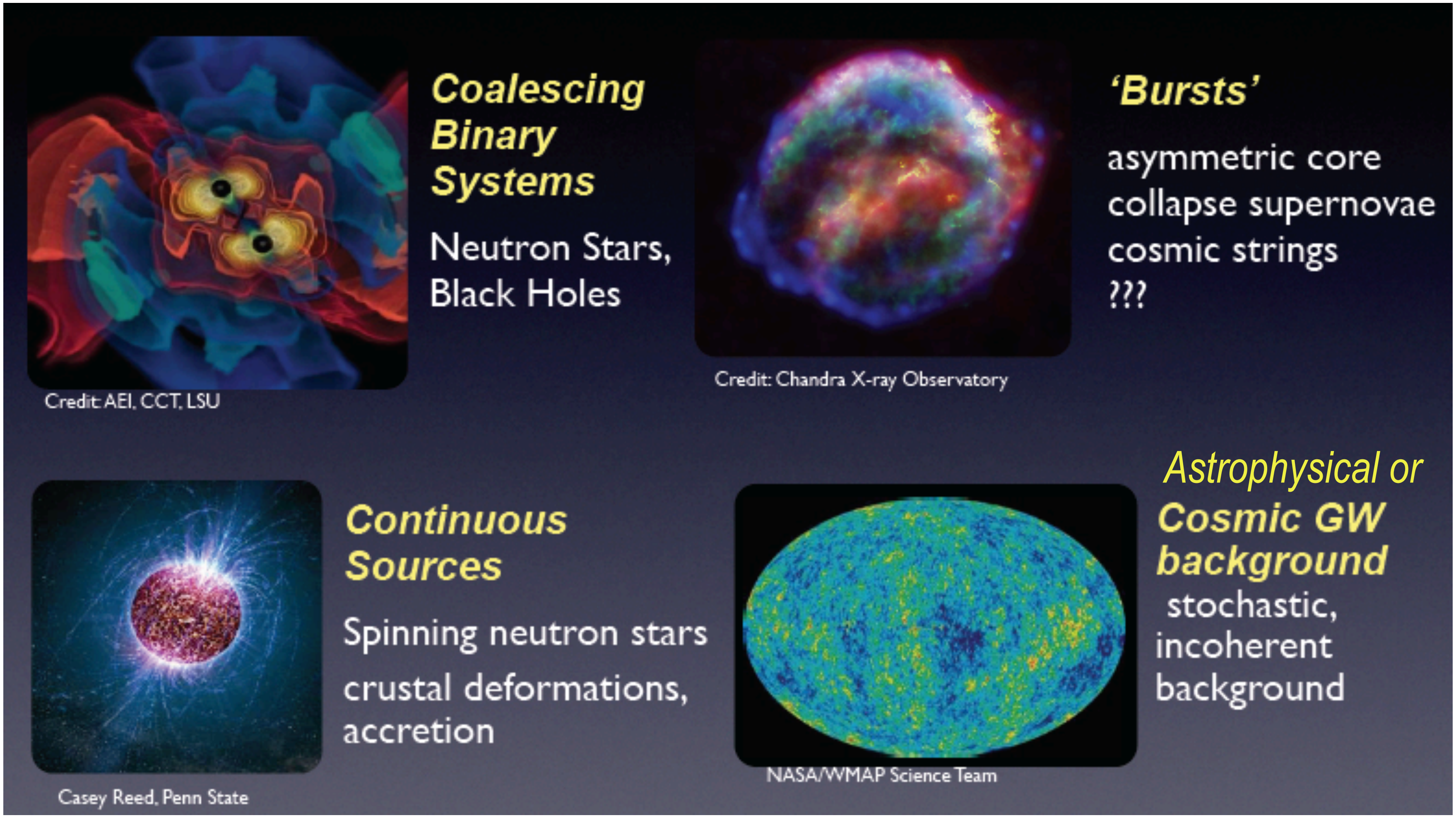


http://www.et-gw.eu/

Gravity’s symphony: first two notes

Credit: LIGO

Sources of gravitational waves: not just black holes!



Coalescing Binary Systems

Neutron Stars,
Black Holes

Credit: AEI, CCT, LSU

'Bursts'

asymmetric core collapse supernovae
cosmic strings
???

Credit: Chandra X-ray Observatory

Continuous Sources

Spinning neutron stars

crustal deformations, accretion

Casey Reed, Penn State

Astrophysical or
Cosmic GW background

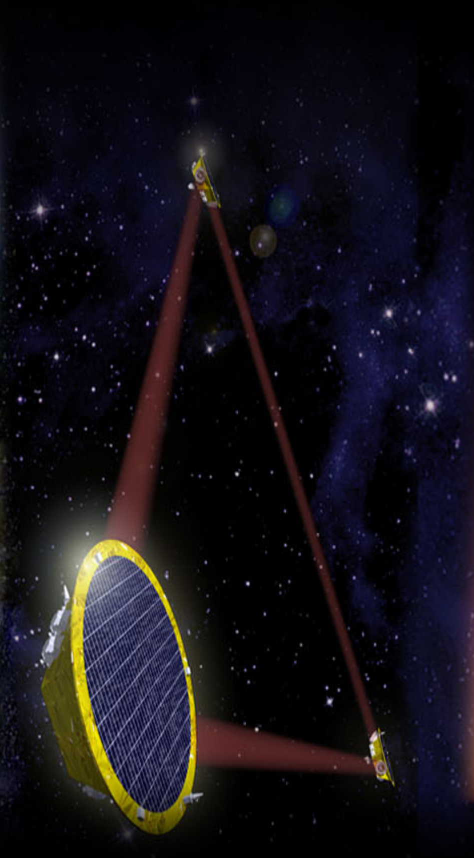
stochastic, incoherent background

NASA/WMAP Science Team

Gravitational Wave Periods

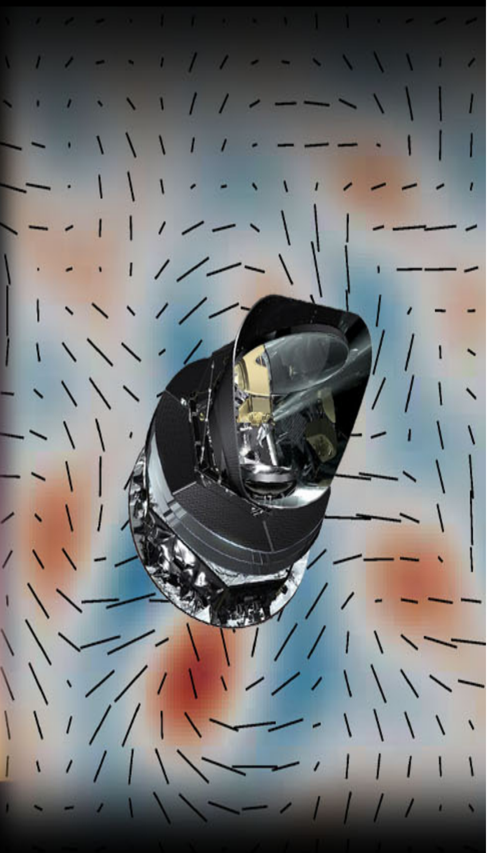
Milliseconds

Minutes
to Hours



Years
to Decades

Billions
of Years



Gravitational-wave astronomy: this is just the beginning!