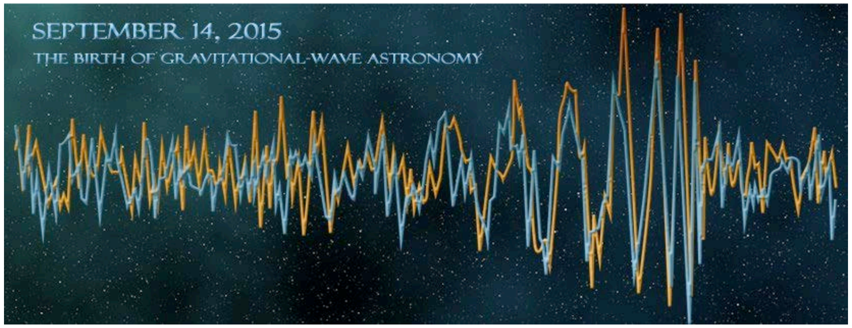
Gravitational Wave Astronomy



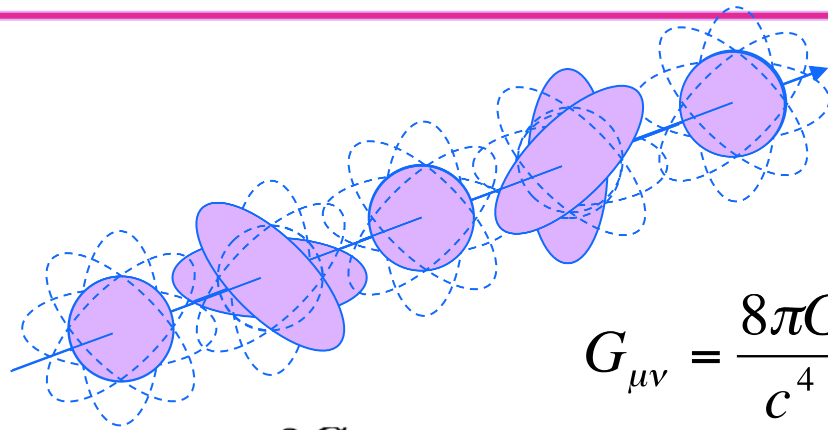
Gabriela González
Louisiana State University

(Results presented on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration)

November 7, 2020

Physikerinnentagung2020

Gravitational waves



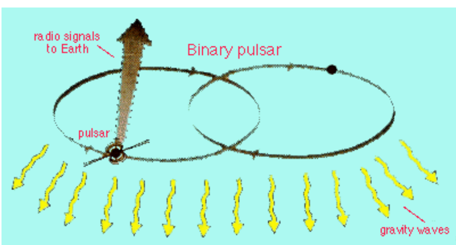
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

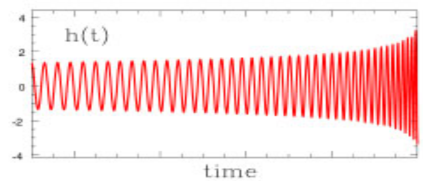
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} (= 0 \text{ in vacuum})$$

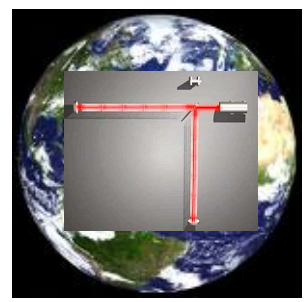
$$h_{\mu\nu} \sim \frac{2G}{c^4 r} \ddot{I}_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h = \frac{\Delta L}{L}$$

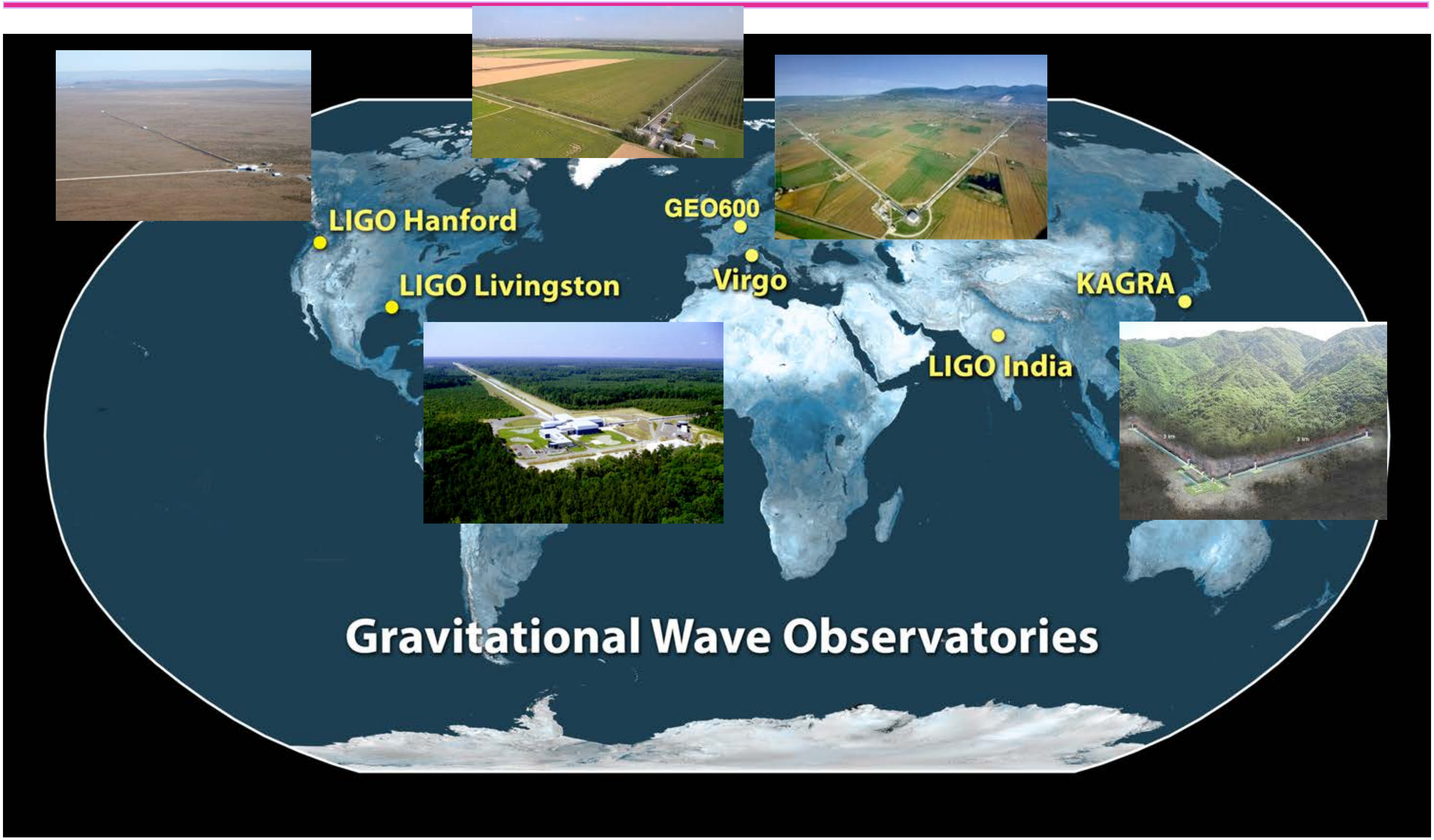






The first gravitational wave detected on September 14, 2015, produced by merging black holes 400 Mpc away had a peak amplitude $h \sim 10^{-21}$.

GW detectors network



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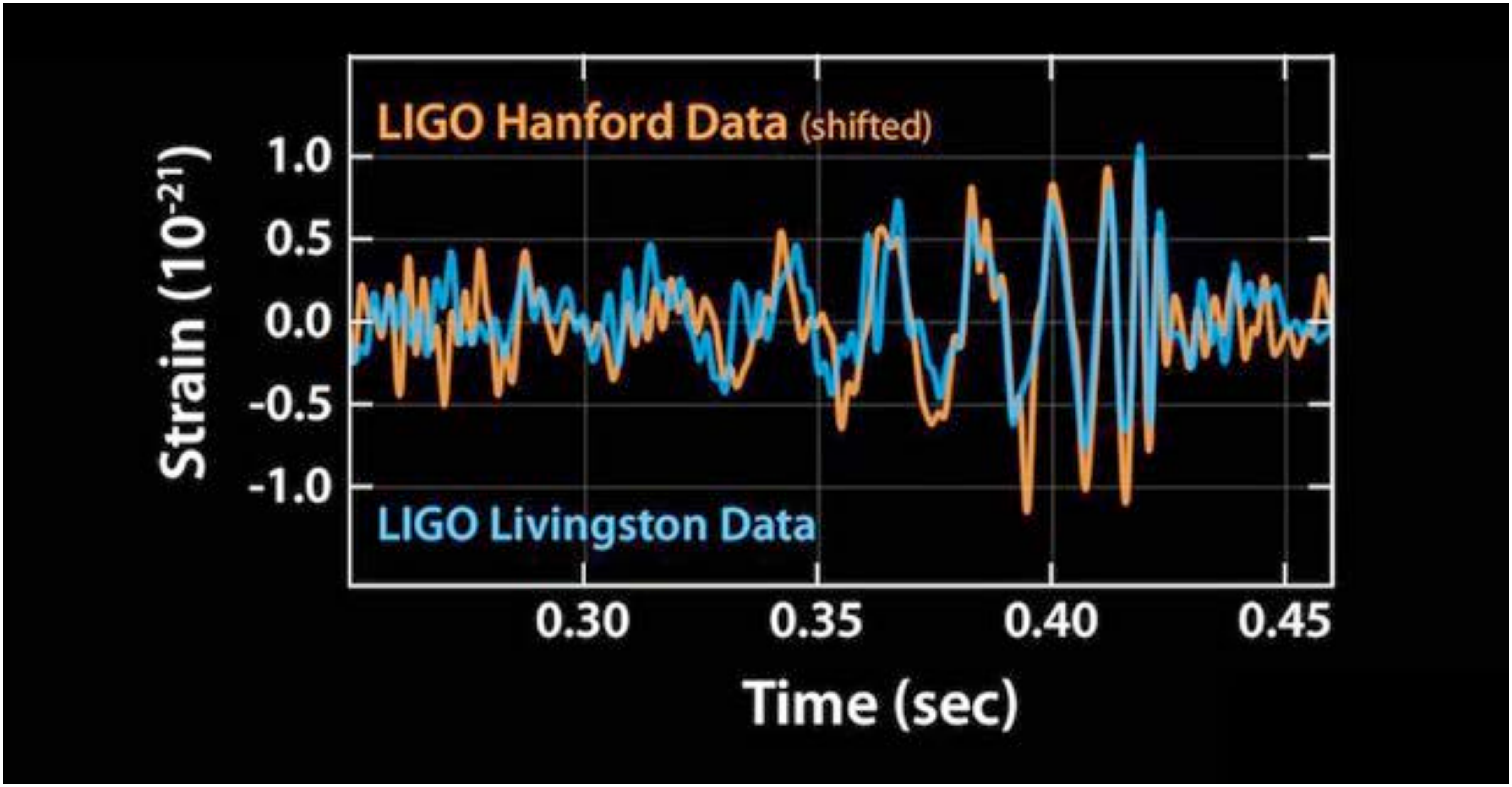
Sept 14 2015



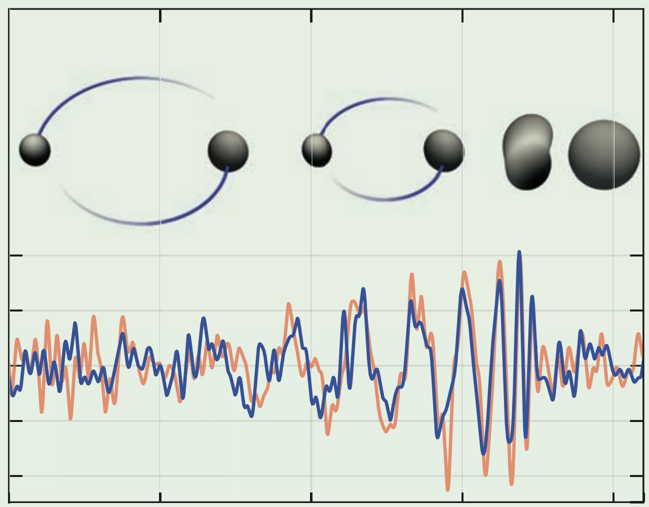
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

February 11, 2016: We did it!

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
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APS physics
Volume 116, Number 6

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LIGO

LIGO Scientific Collaboration

LSC

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American University Washington, DC
Andrews University
Bar-Ilan University
Bard College
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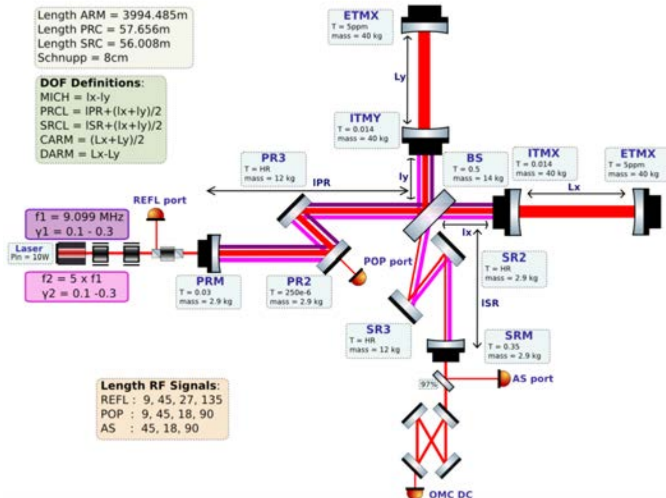
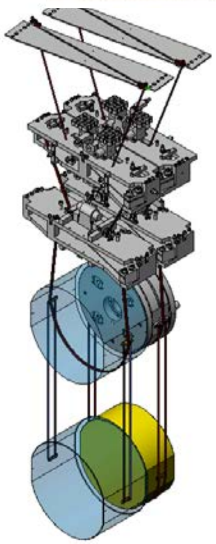
Texas The University of Texas at Austin
UTRGV
Universitat de les Illes Balears
東京大学 The University of Tokyo
The University of Utah
University of Washington
Bothell
Southampton
Universität Hamburg
IISER Kolkata
tifr
ICTS International Centre for Theoretical Sciences
UWM University of Wisconsin Milwaukee
University of Southern California
Villanova University
West Virginia University
Chennai Mathematical Institute
DCSEM
RRCAT
IIT Madras
KISTI 한국과학기술정보연구원 Korea Institute of Science and Technology Information
NIMS National Institute for Mathematical Sciences | South Korea
서울대학교 Seoul National University
UNIST
인제대학교 INJE UNIVERSITY
LISC LIGO–India Scientific Collaboration
IISER Pune
आई आई टी हैदराबाद IIT Hyderabad
IIT Bombay
IUCAA
KASI Korea Astronomy and Space Science Institute
Pusan National University
한양대학교 Hanyang University
Ewha Womans University
Korean Gravitational Wave Group

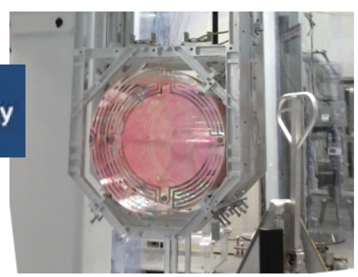
Advanced LIGO: complicated instruments!



MAX-PLANCK-GESELLSCHAFT



Science & Technology Facilities Council



NSF

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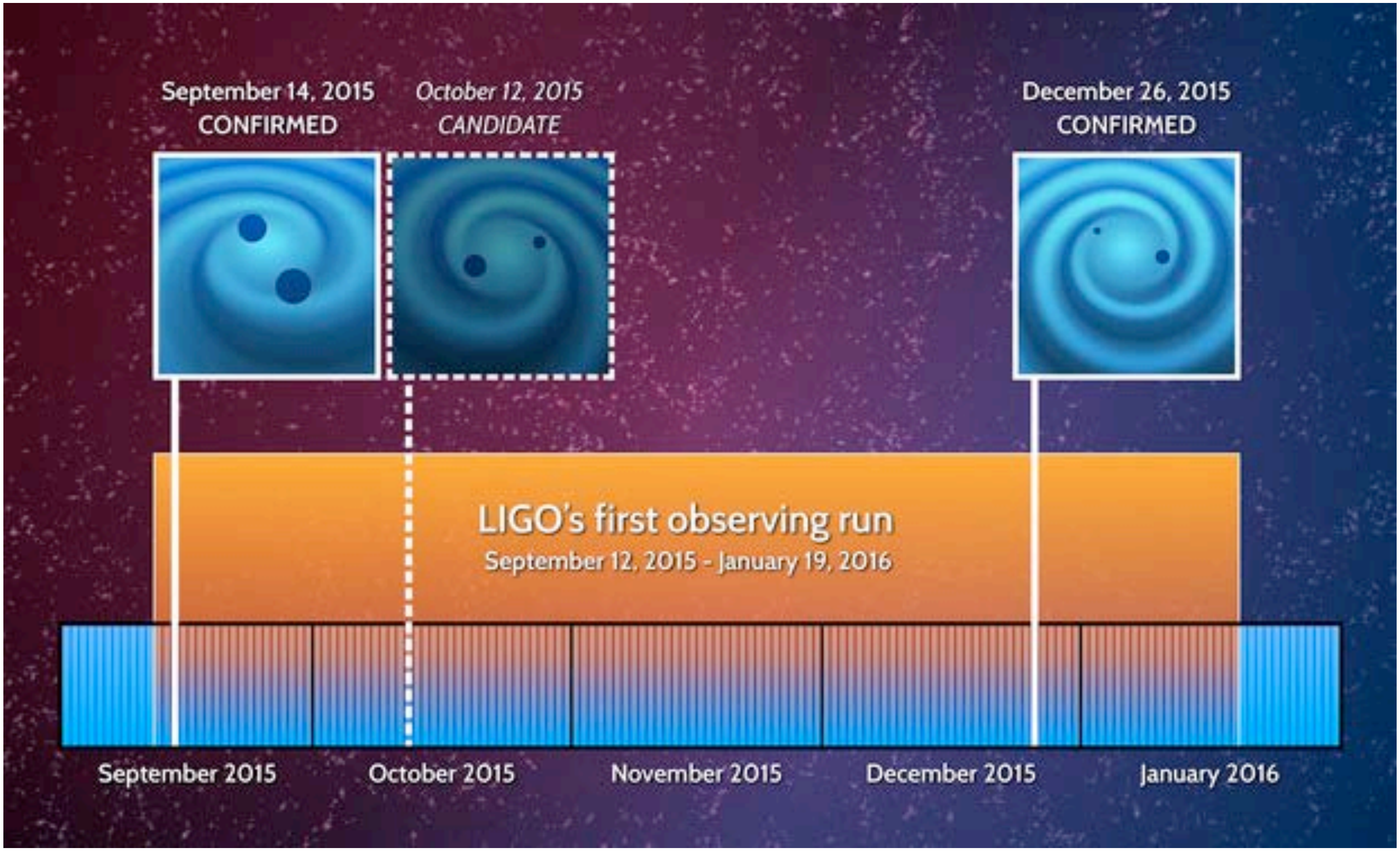
Not just one signal



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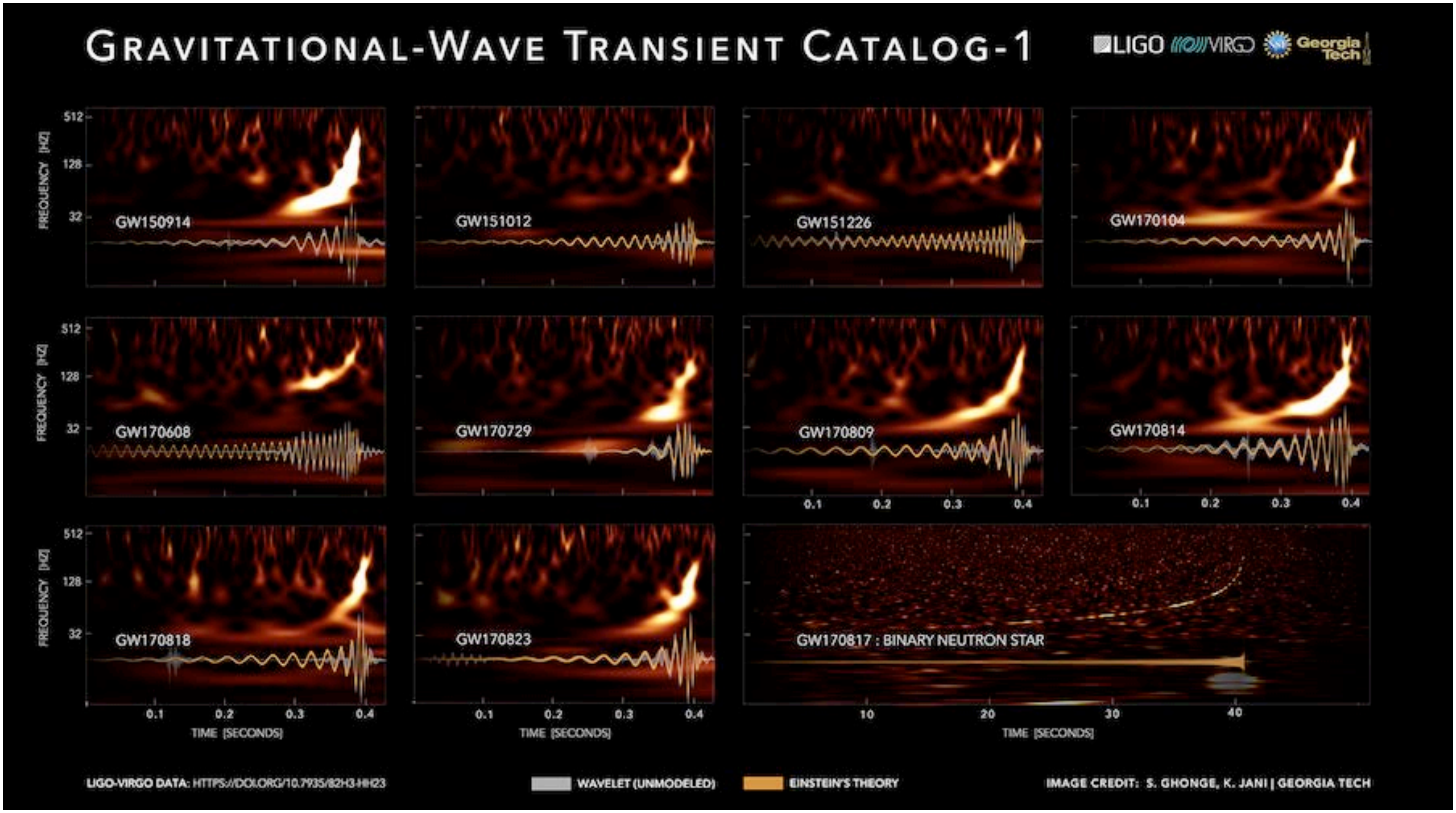
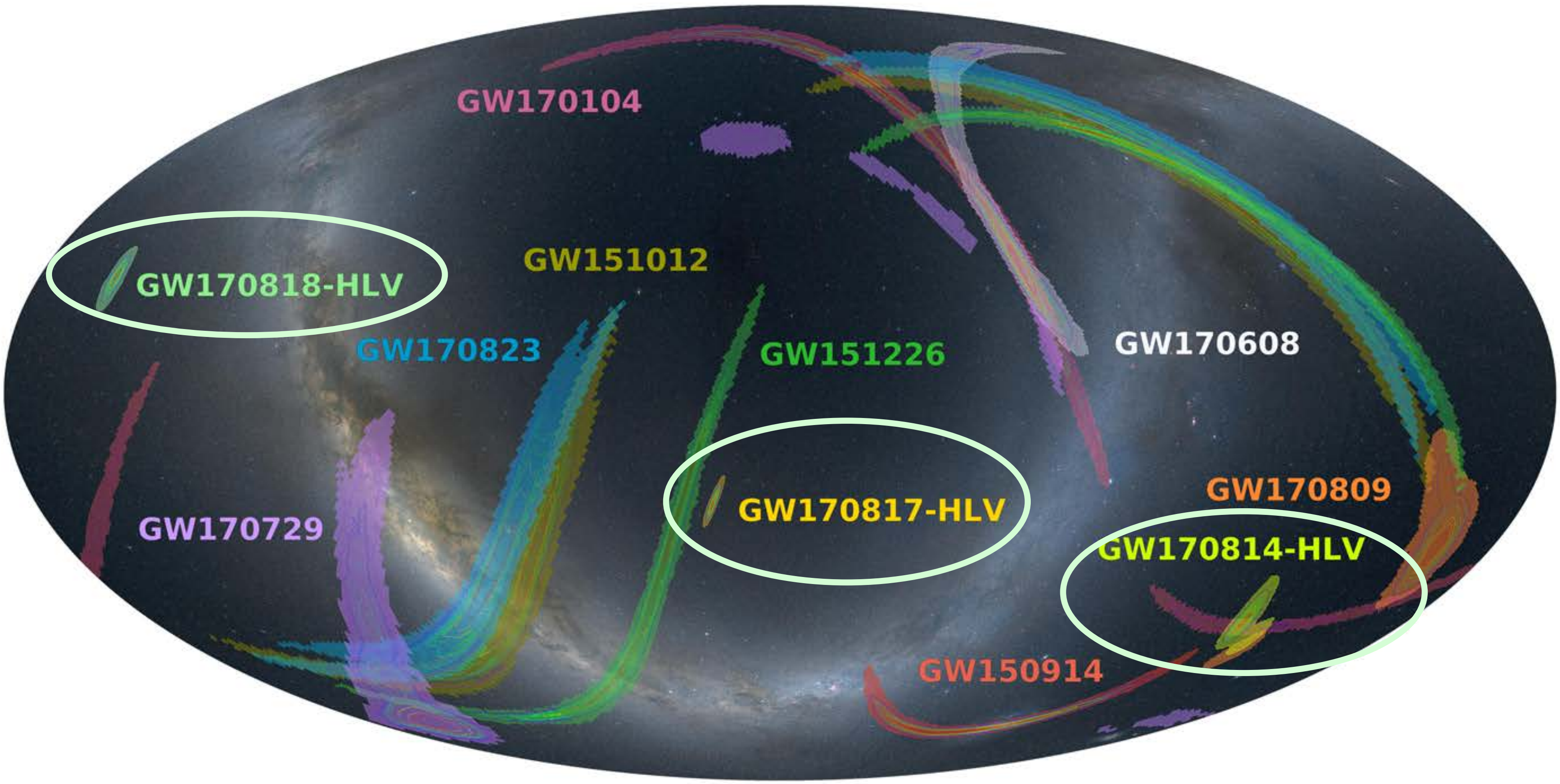
O1-O2 (2015-2017)

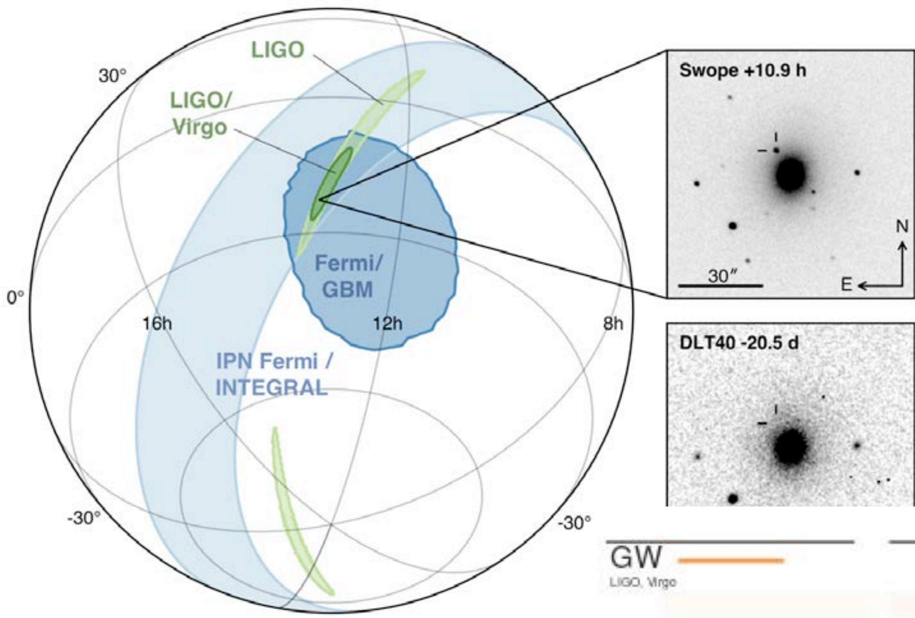


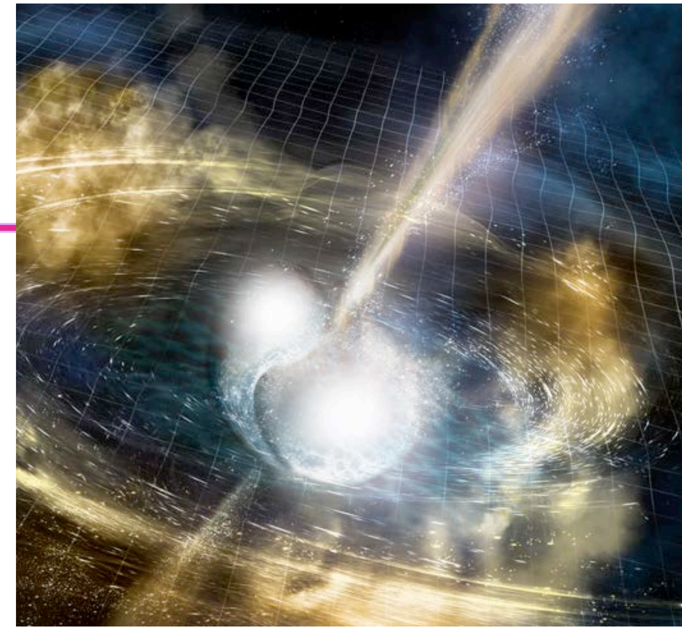
Phys. Rev. X **9**, 031040 (2019)

Where do GWs come from?

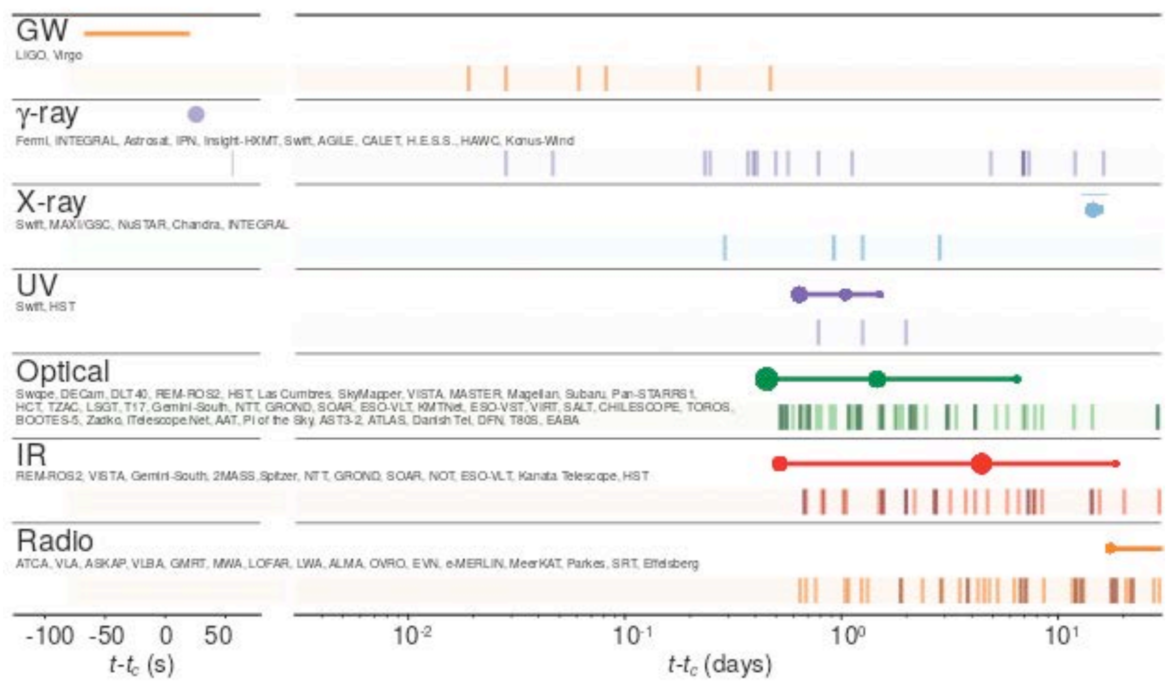


A kilonova rainbow





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



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

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Testing General Relativity

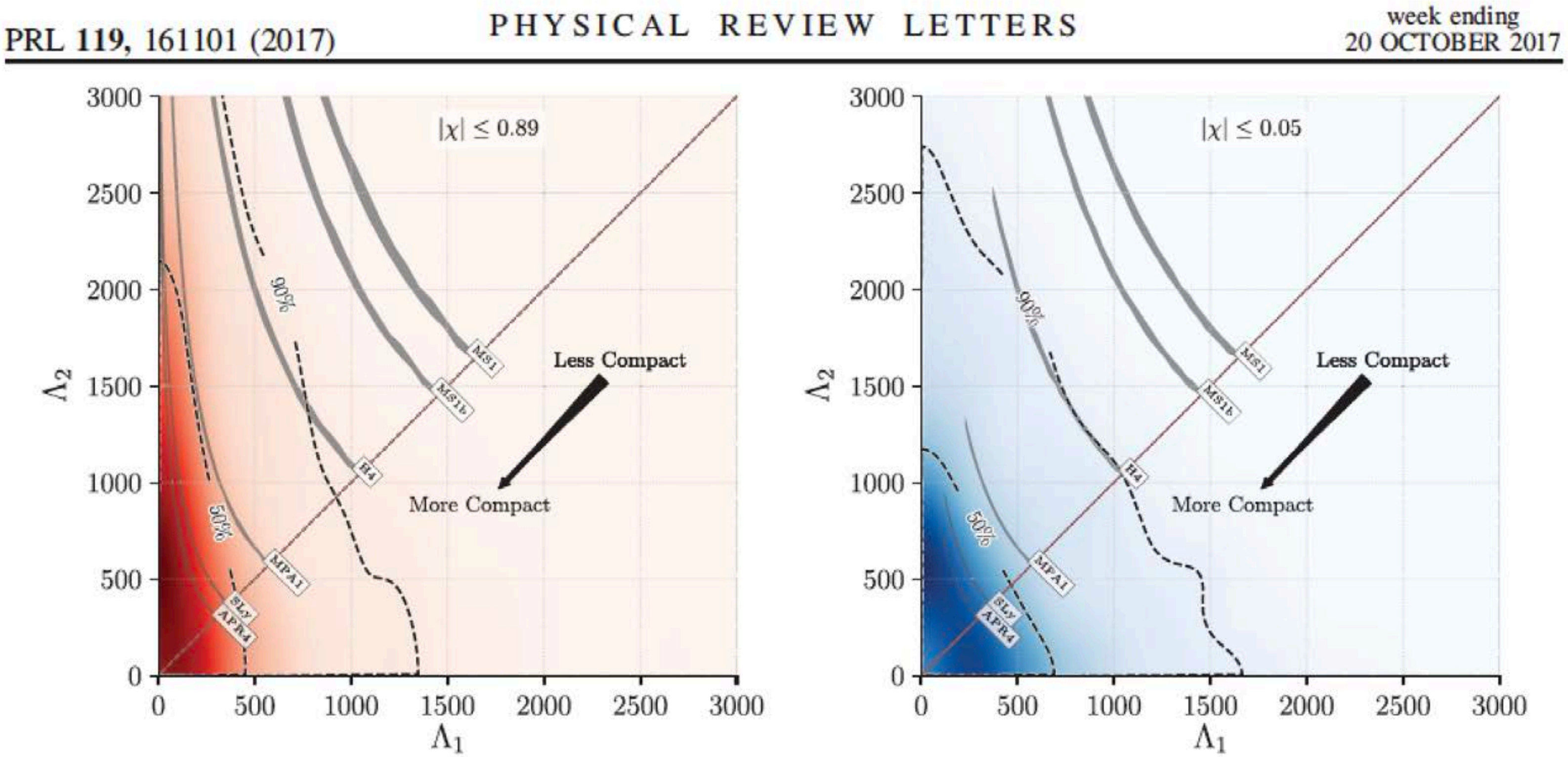
Phys. Rev. D **100**, 104036 (2019)

Event	Properties				SNR	GR tests performed				
	D_L [Mpc]	M_{tot} [$M_\odot$]	M_f [$M_\odot$]	a_f		RT	IMR	PI	PPI	MDR
GW150914[b]	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$25.3^{+0.1}_{-0.2}$	✓	✓	✓	✓	✓
GW151012[b]	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$9.2^{+0.3}_{-0.4}$	✓	–	–	✓	✓
GW151226[b,c]	440^{+180}_{-190}	$21.5^{+6.2}_{-1.5}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$12.4^{+0.2}_{-0.3}$	✓	–	✓	–	✓
GW170104	960^{+440}_{-420}	$51.3^{+5.3}_{-4.2}$	$49.1^{+5.2}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$14.0^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓
GW170608	320^{+120}_{-110}	$18.6^{+3.1}_{-0.7}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$15.6^{+0.2}_{-0.3}$	✓	–	✓	✓	✓
GW170729[d]	2760^{+1380}_{-1340}	$85.2^{+15.6}_{-11.1}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$10.8^{+0.4}_{-0.5}$	✓	✓	–	✓	✓
GW170809	990^{+320}_{-380}	$59.2^{+5.4}_{-3.9}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$12.7^{+0.2}_{-0.3}$	✓	✓	–	✓	✓
GW170814	580^{+160}_{-210}	$56.1^{+3.4}_{-2.7}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$17.8^{+0.3}_{-0.3}$	✓	✓	✓	✓	✓
GW170818	1020^{+430}_{-360}	$62.5^{+5.1}_{-4.0}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$11.9^{+0.3}_{-0.4}$	✓	✓	–	✓	✓
GW170823	1850^{+840}_{-840}	$68.9^{+9.9}_{-7.1}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$12.1^{+0.2}_{-0.3}$	✓	✓	–	✓	✓

- RT: If we subtract the best fit from data, are residuals inconsistent with instrumental noise?
- IMR: Are parameters obtained when fitting the inspiral phase different than those fitting the merger-ringdown phase?
- PI/PPI: If we parameterize the inspiral/post-inspiral phase, do we find deviations from the GR parameters?
- MDR: Do we have evidence of a modified dispersion relation (a.k.a. as graviton mass)?

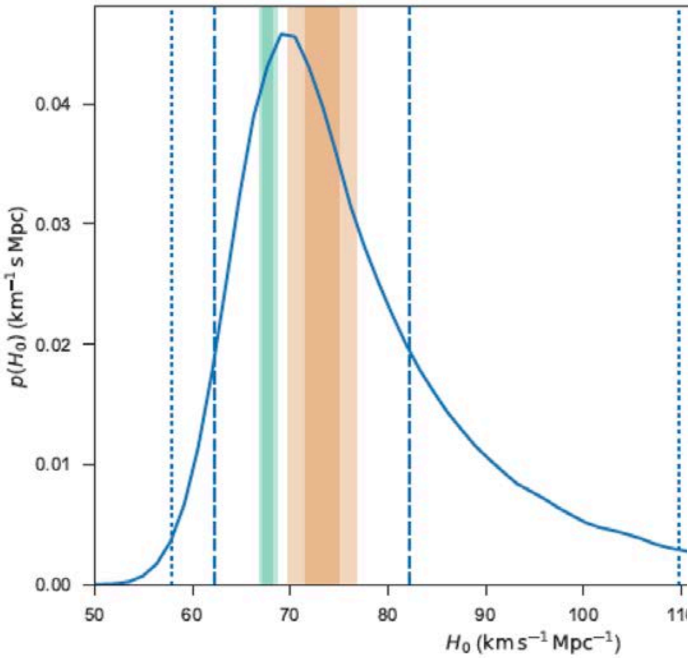
Ans: $m_g < 10^{-23}$ eV/c^2

Nuclear physics with GWs

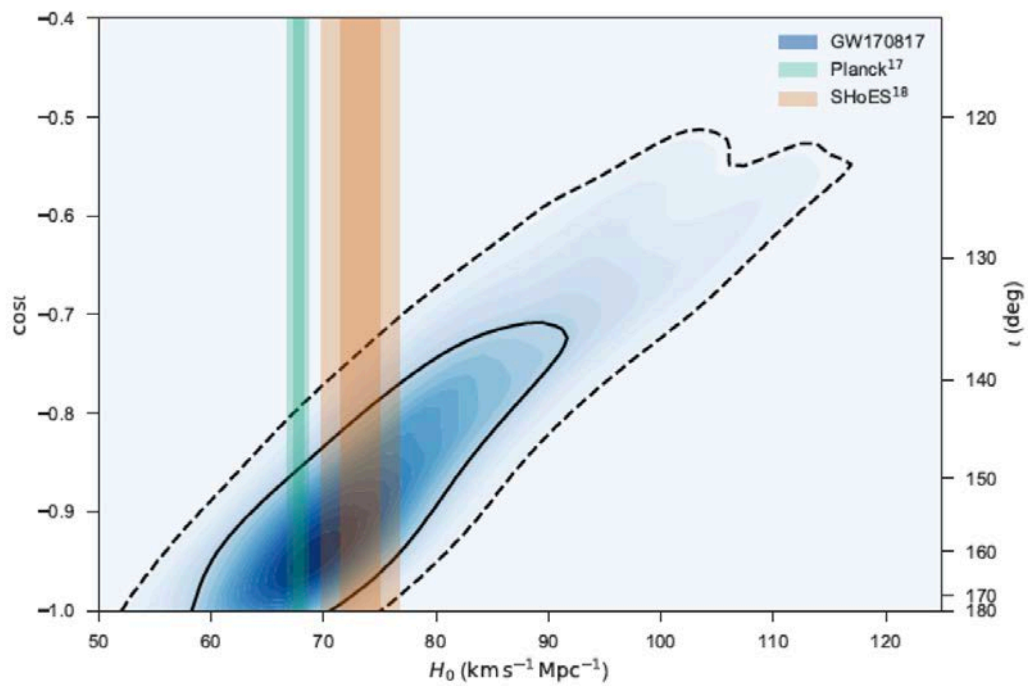


$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{m} \right)^5$$

Cosmology with GWs



Nature 551, 85 (2017)



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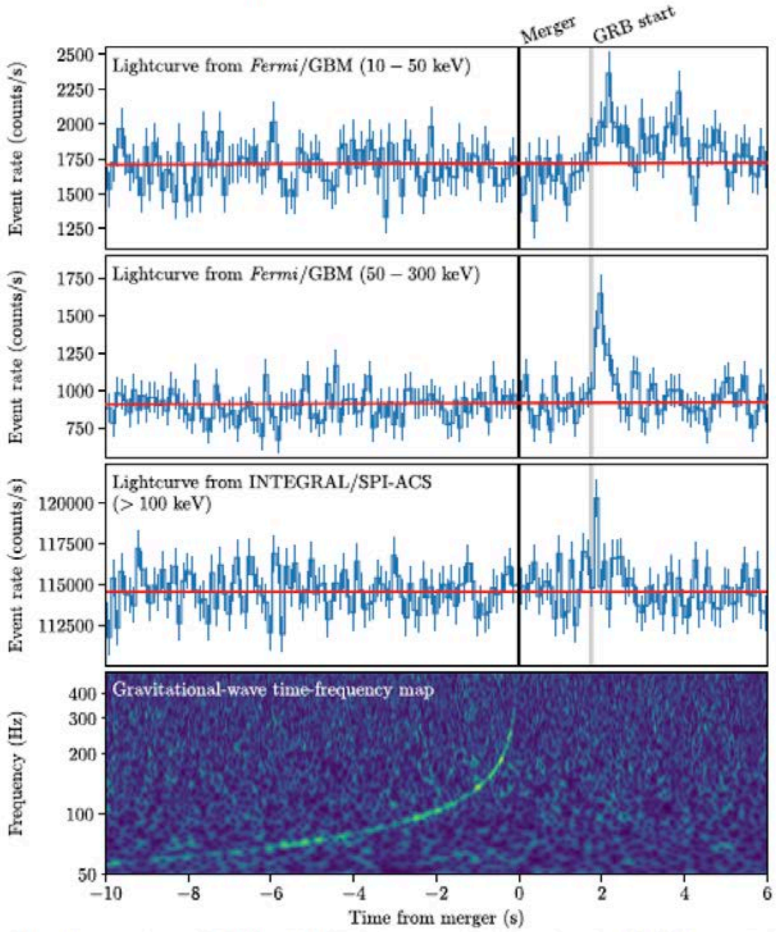
GW-GRB observation: Fundamental physics

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



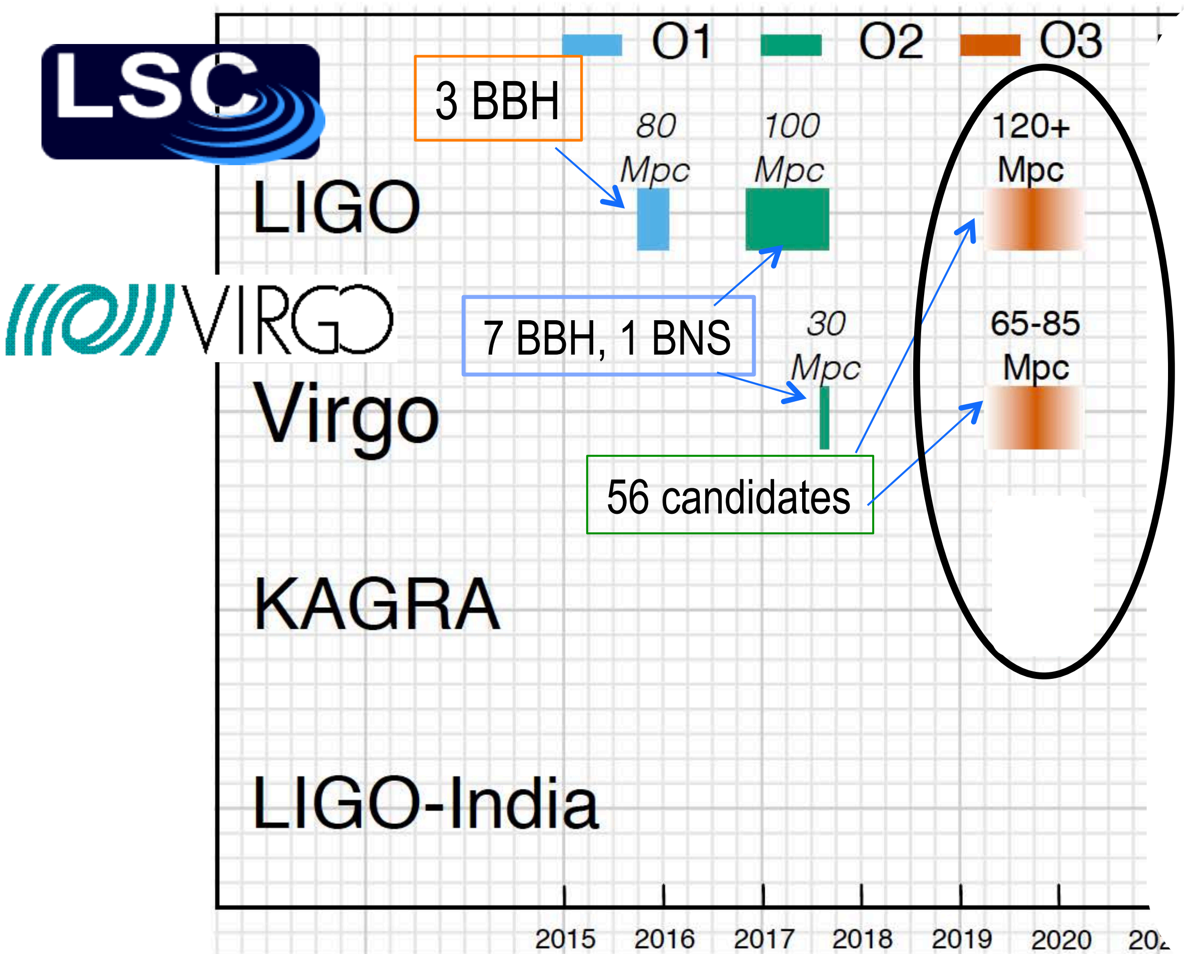
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}.$$

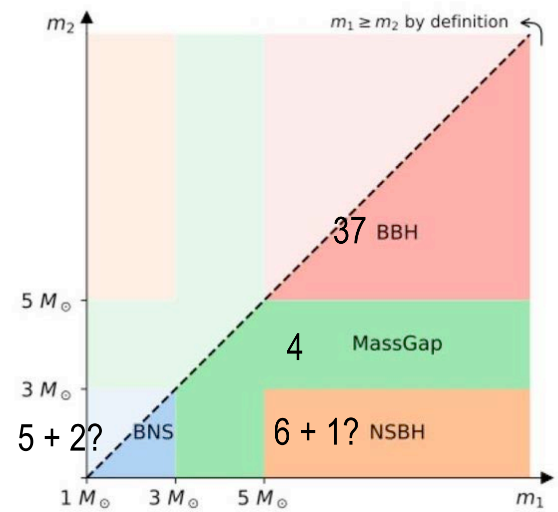
$$-2.6 \times 10^{-7} \leqslant \gamma_{\rm GW} - \gamma_{\rm EM} \leqslant 1.2 \times 10^{-6}. \qquad (4)$$

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

ApJL, 848:L13, 2017

More discoveries

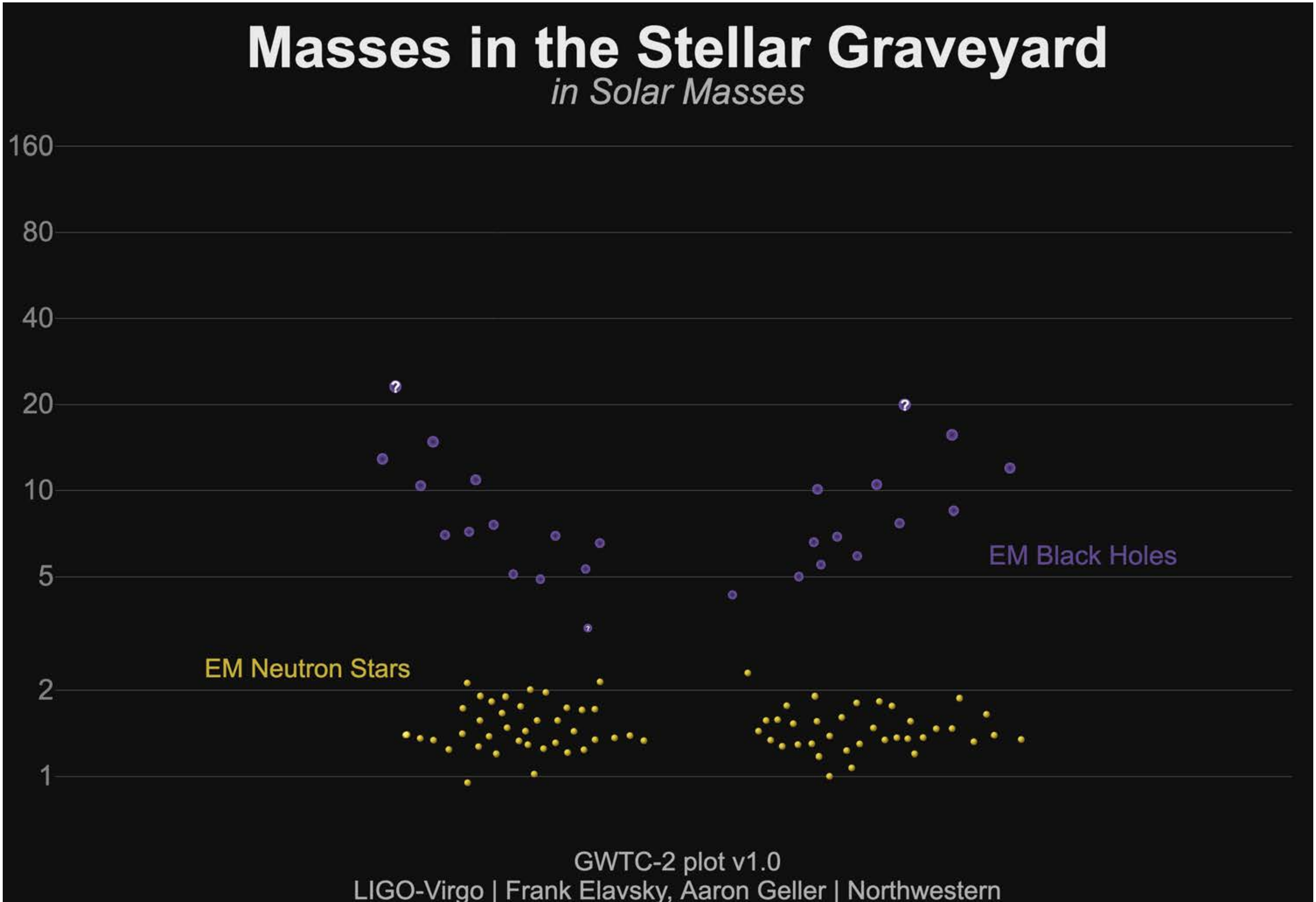




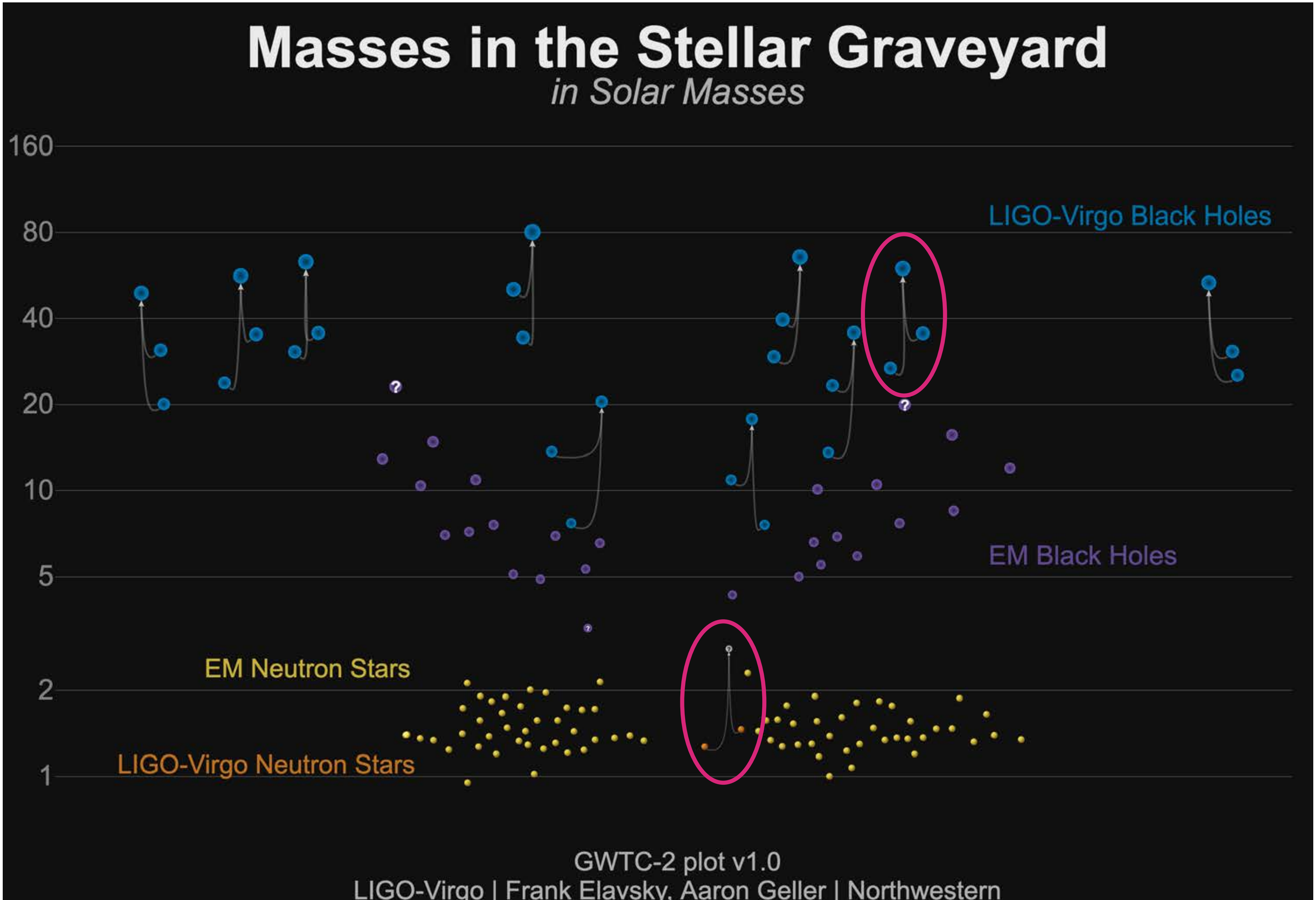
… and a (weak) different signal?

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

https://arxiv.org/abs/1304.0670



Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern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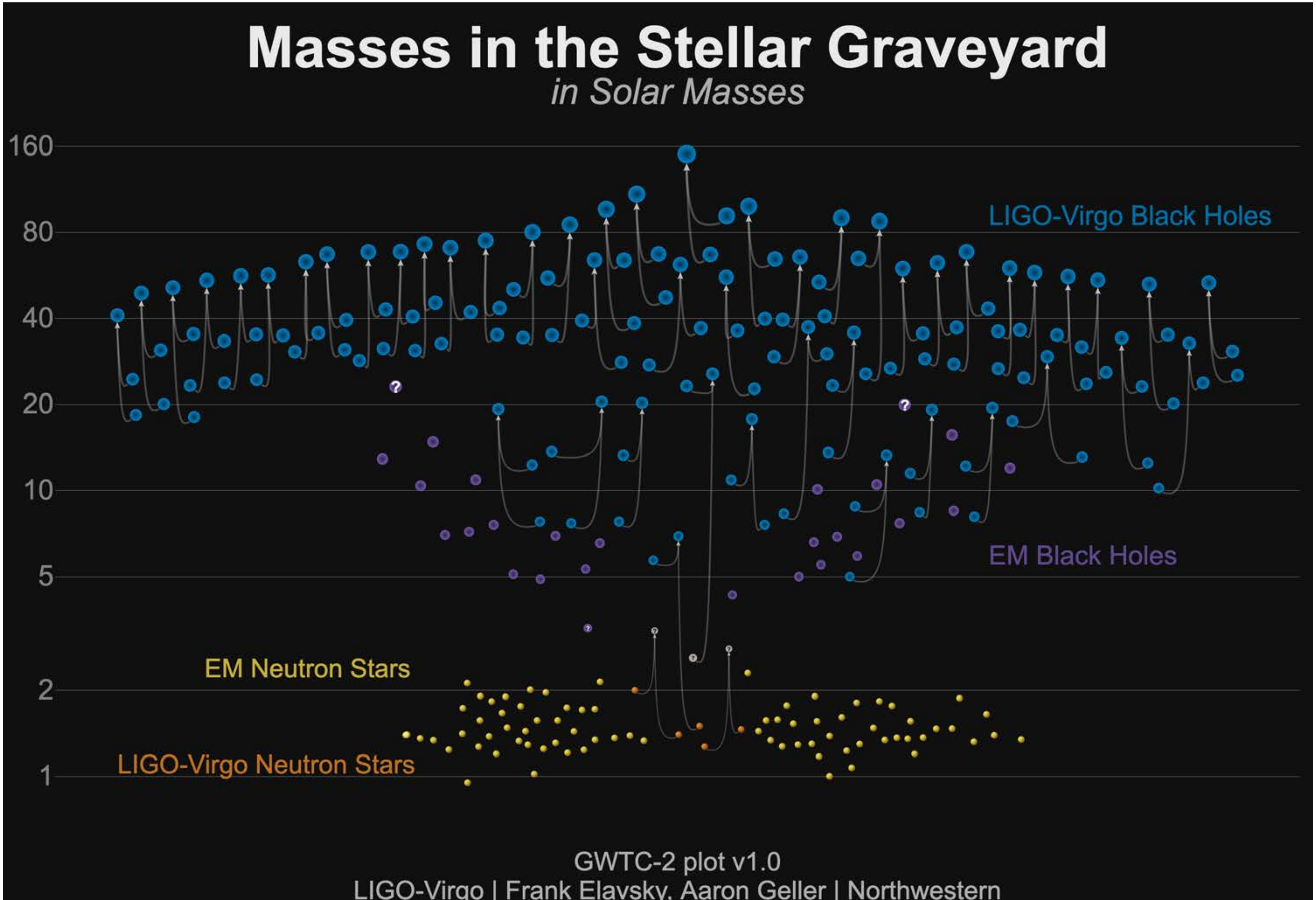
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern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LIGO-Virgo Black Holes
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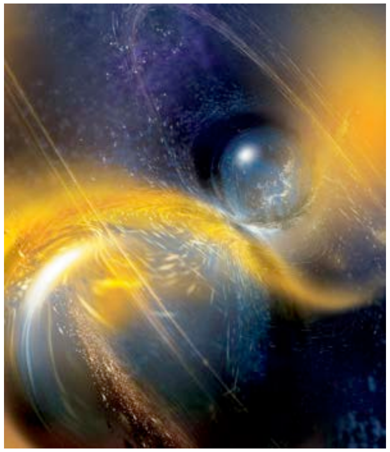
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Four special detections

Binary neutron star merger
(most massive NS pair known)
Astrophys. J. Lett. **892**, L3 (2020)



Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.

Asymmetric binary black hole merger
Phys. Rev. D 102, 043015

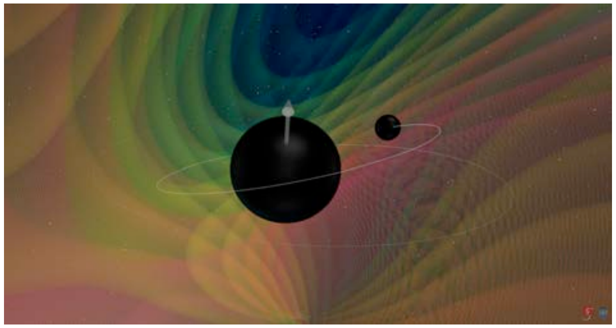
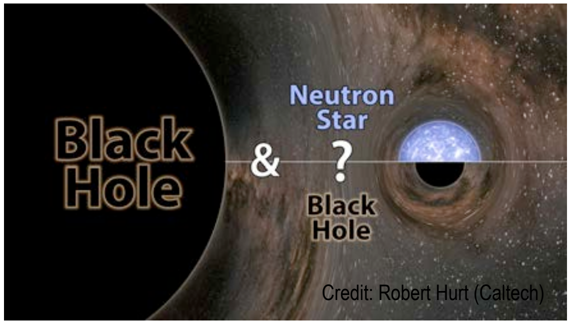


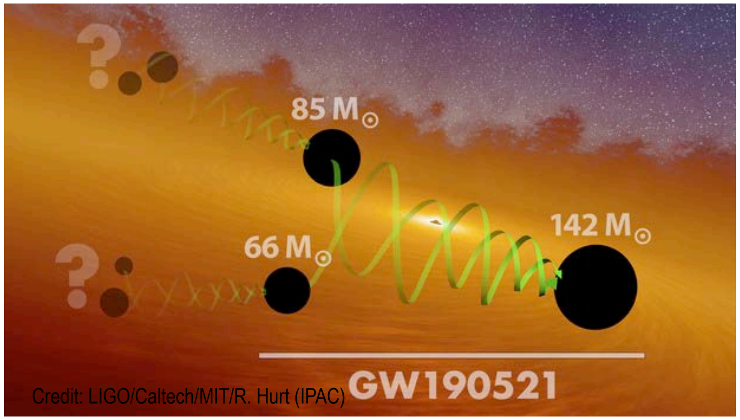
Image credit: N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes project]



Credit: Robert Hurt (Caltech)

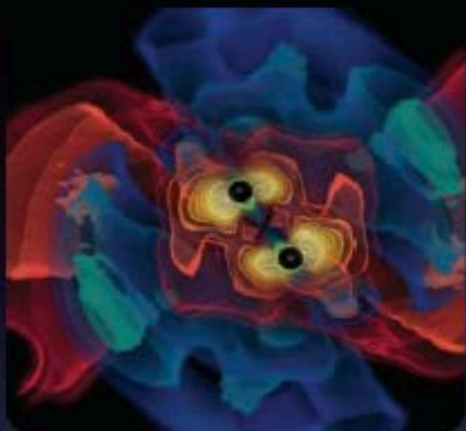
Mass gap: heavy neutron star or black hole?
Astrophys. J. Lett. **896**, L44 (2020)

Intermediate mass black hole
Phys. Rev. Lett. 125, 101102



Credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

Sources of gravitational waves: not just binary systems!



Credit: AEI, CCT, LSU

Coalescing Binary Systems

Neutron Stars,
Black Holes

Credit: Chandra X-ray Observatory

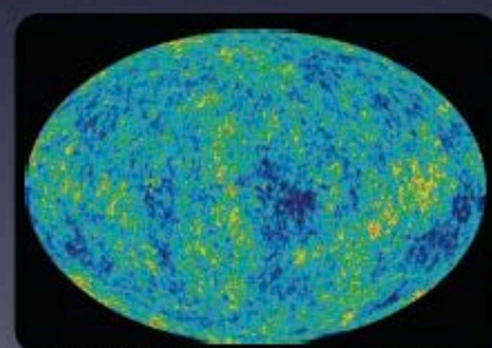
'Bursts'

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

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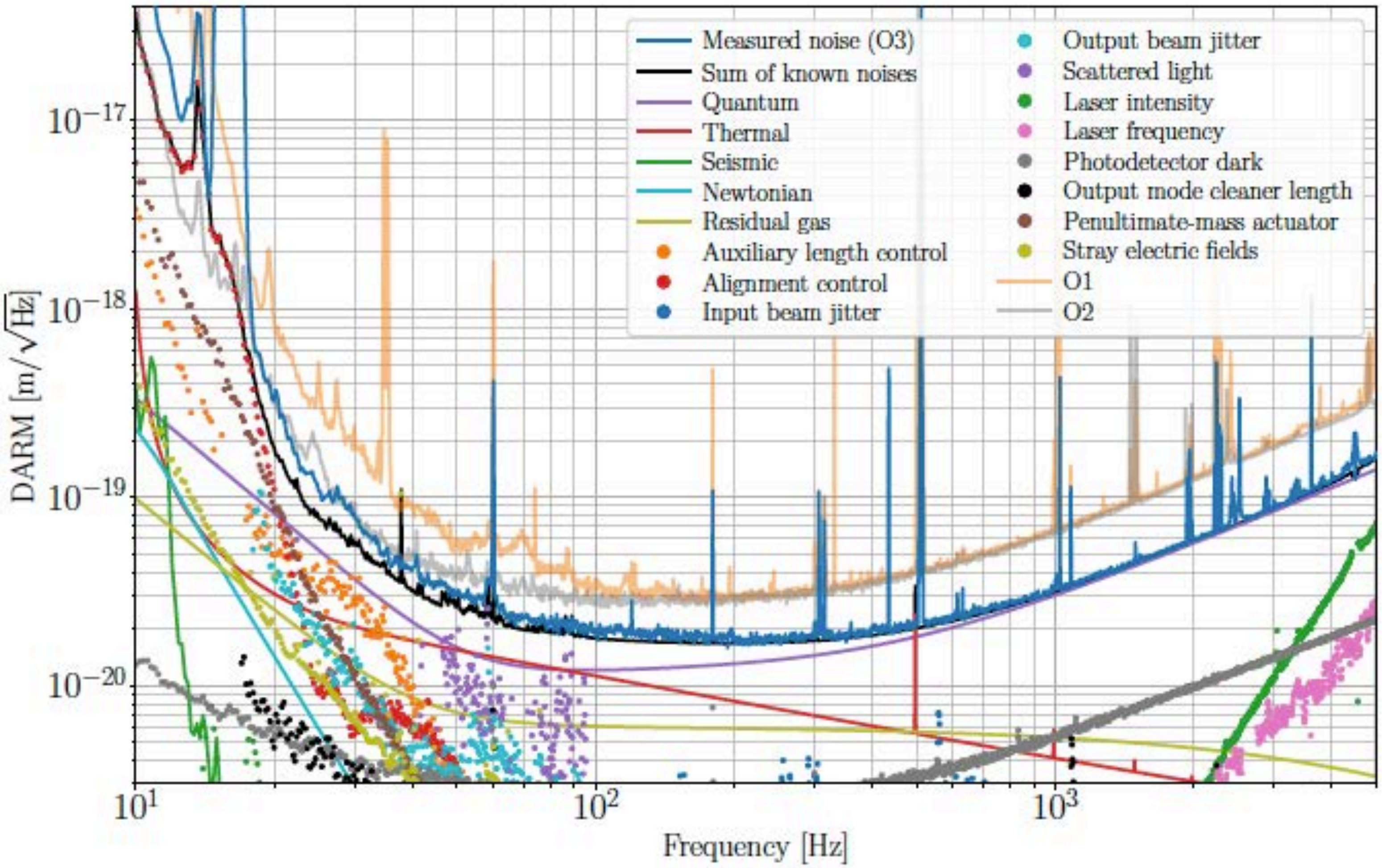
Reducing the noise, increasing the rate of detections

LIGO Livingston Detector



https://arxiv.org/abs/2008.01301

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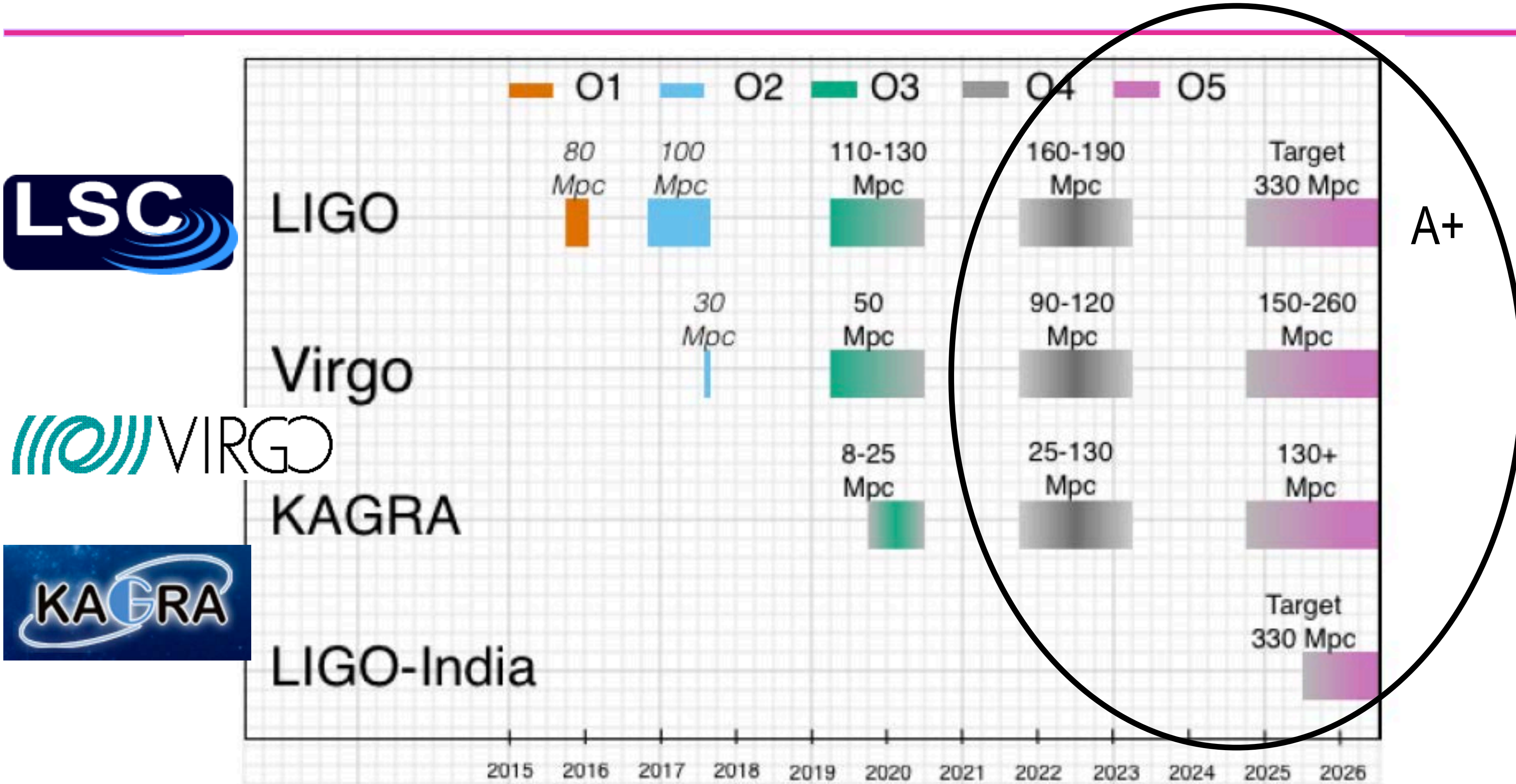
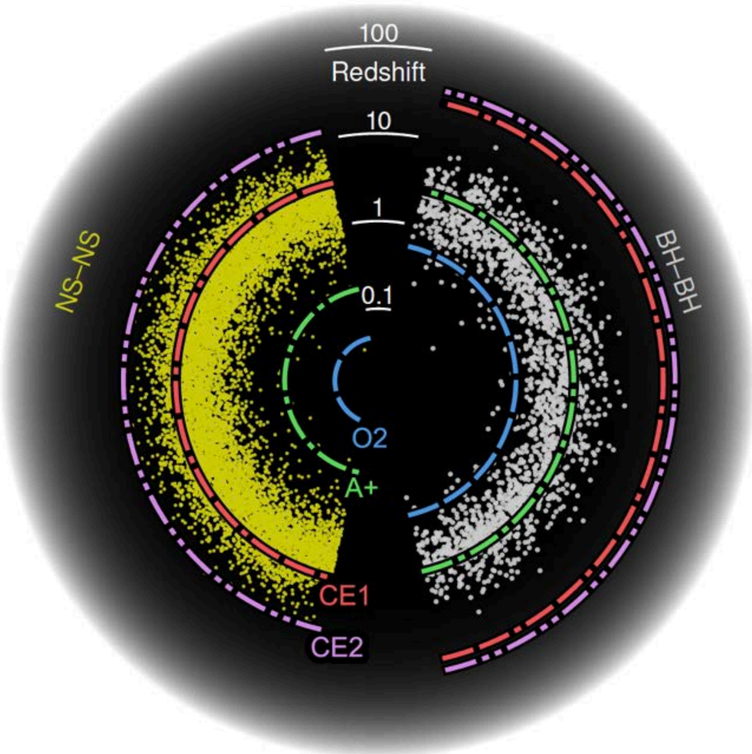
The next few years

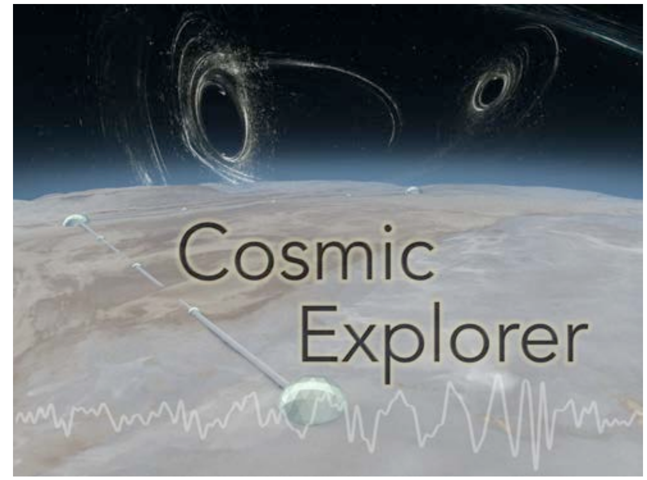


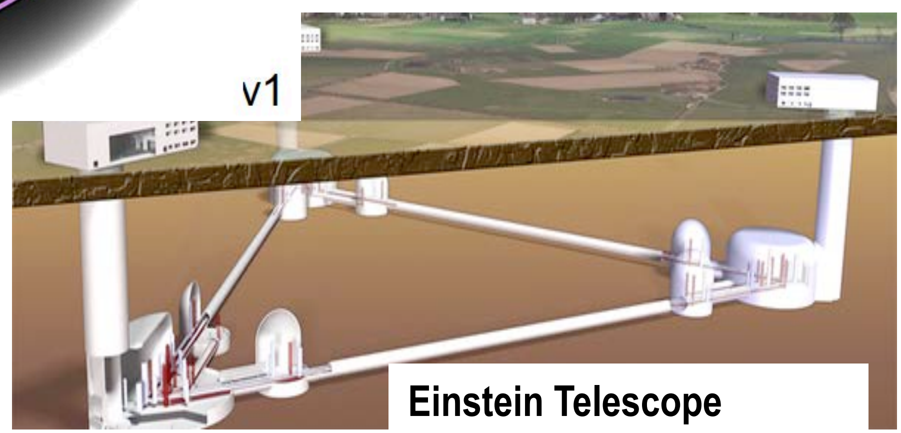
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

https://arxiv.org/abs/1304.0670 (last updated September 2019)

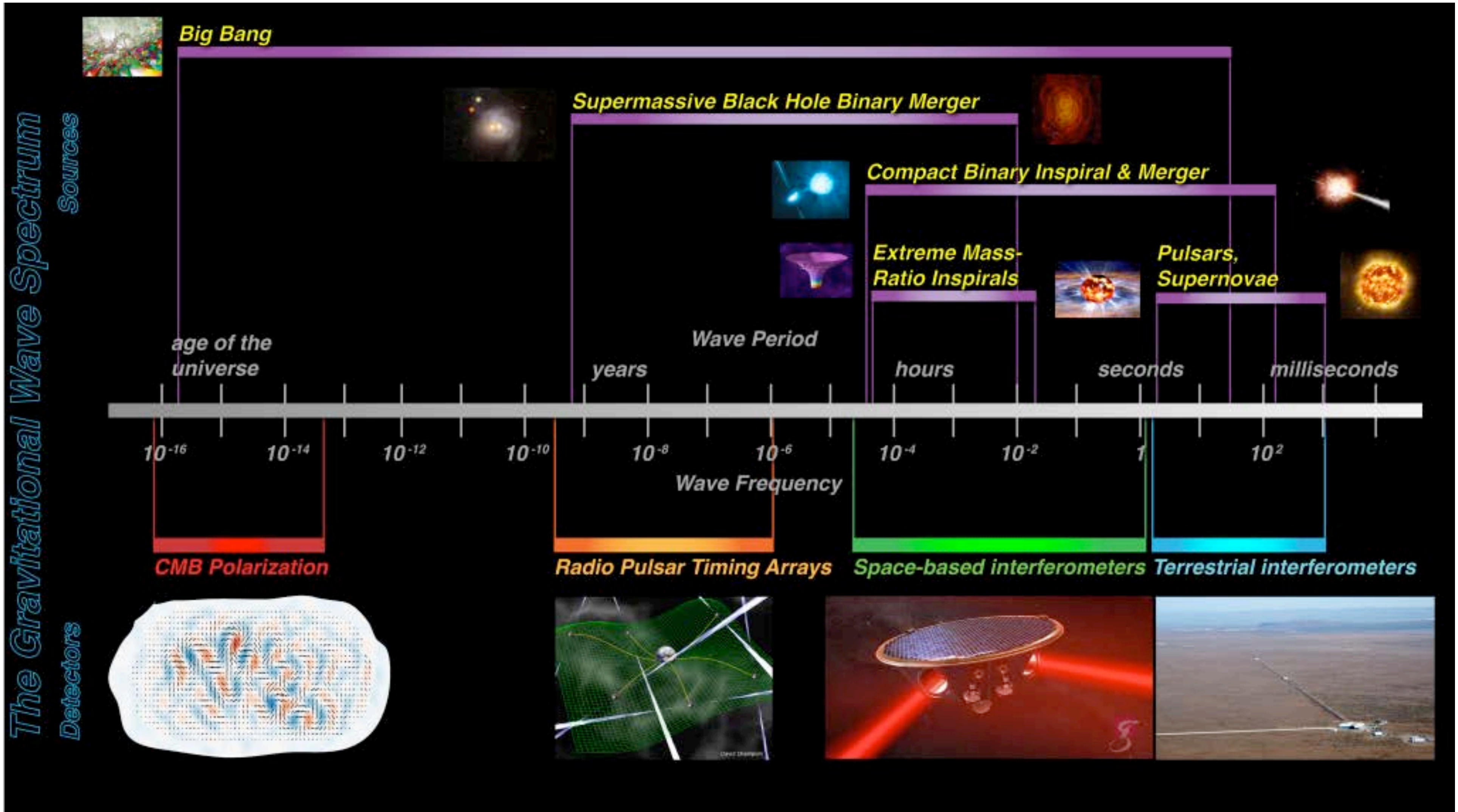
Third Generation Detectors (Ground based)







Different wavelengths need different instruments



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The era of GW astronomy is here!

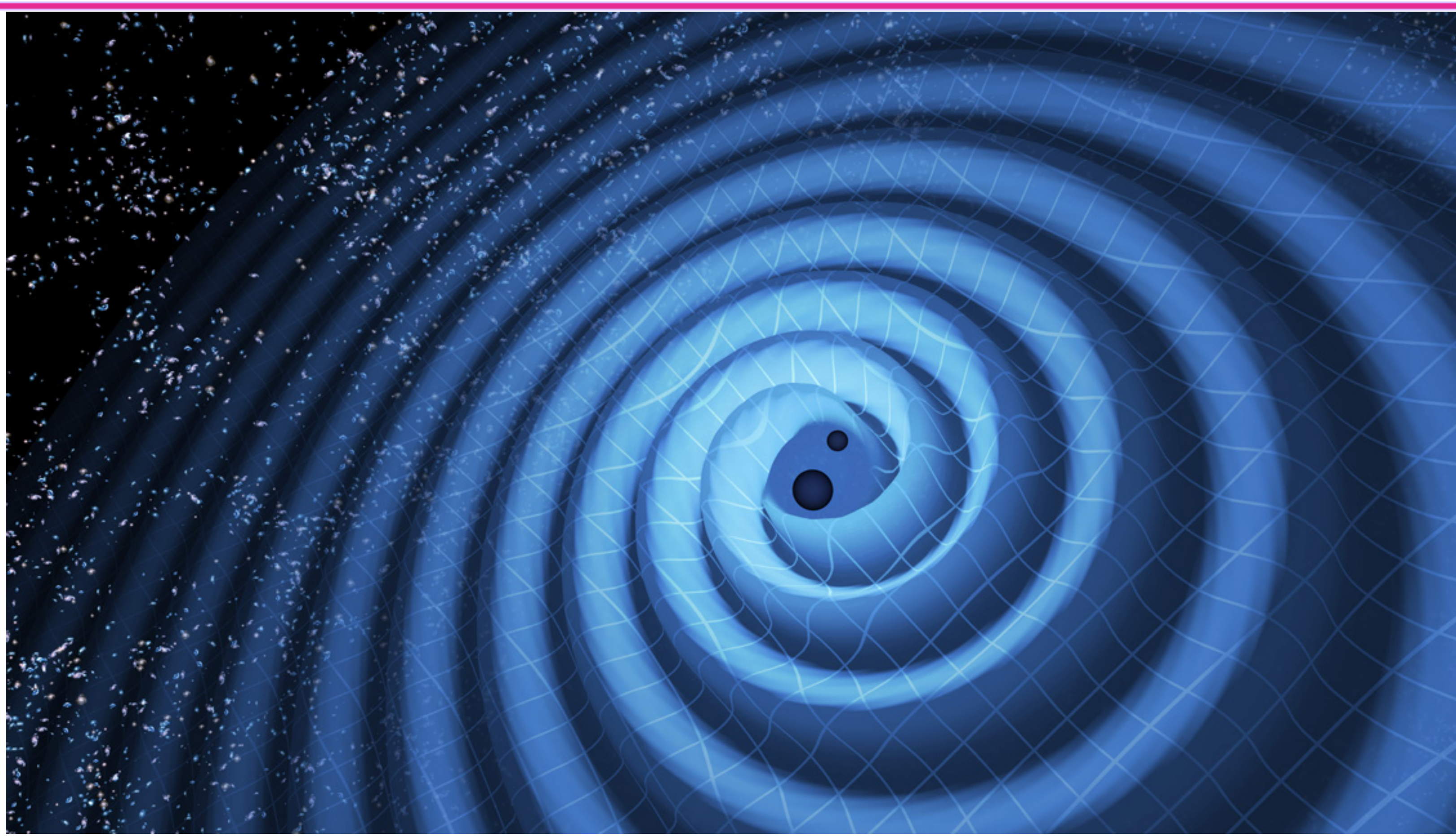

Image credit: LIGO/T. Pyle

www.ligo.org

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