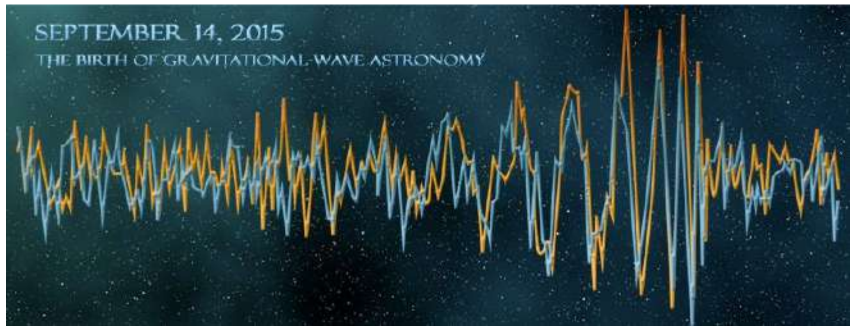
Gravitational Wave Astronomy

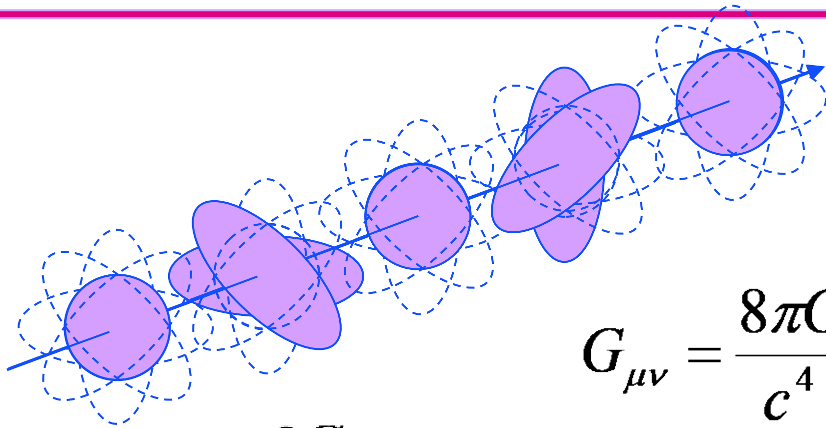


Gabriela González

Louisiana State University

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

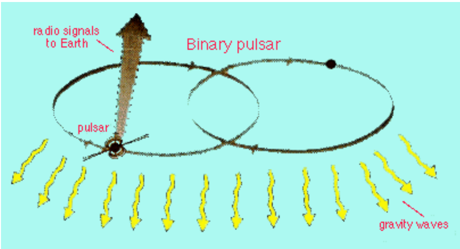
Gravitational waves

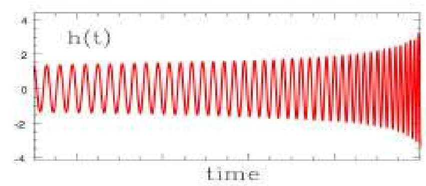


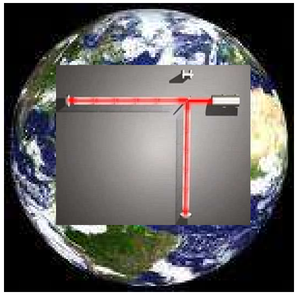
Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.

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

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



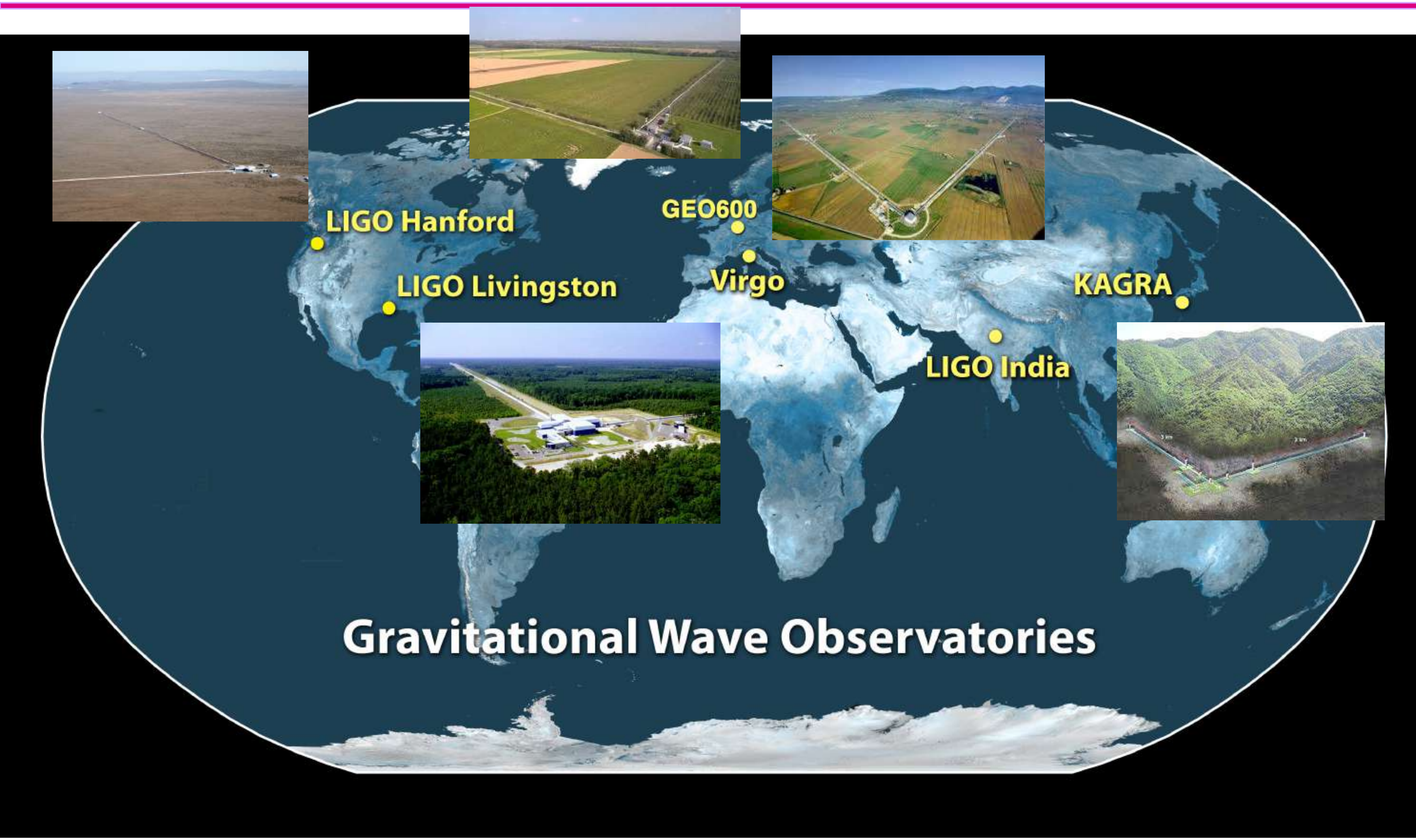




The first gravitational wave detected on September 14, 2015, produced by merging black holes 400 Mpc away had a peak amplitude $h \sim 10^{-21}$.

LSU

GW detectors network



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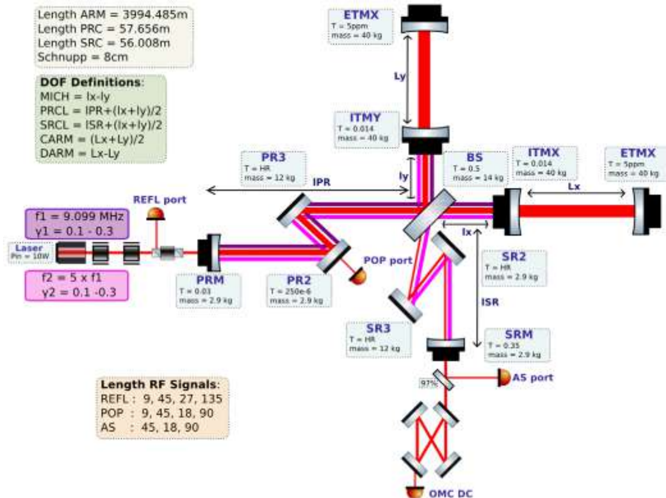
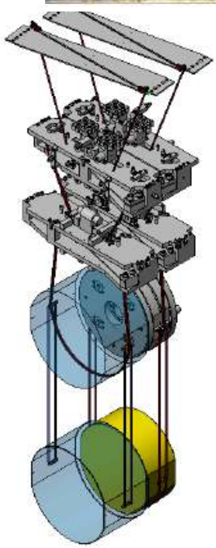
Advanced LIGO: complicated instruments!



MAX-PLANCK-GESELLSCHAFT

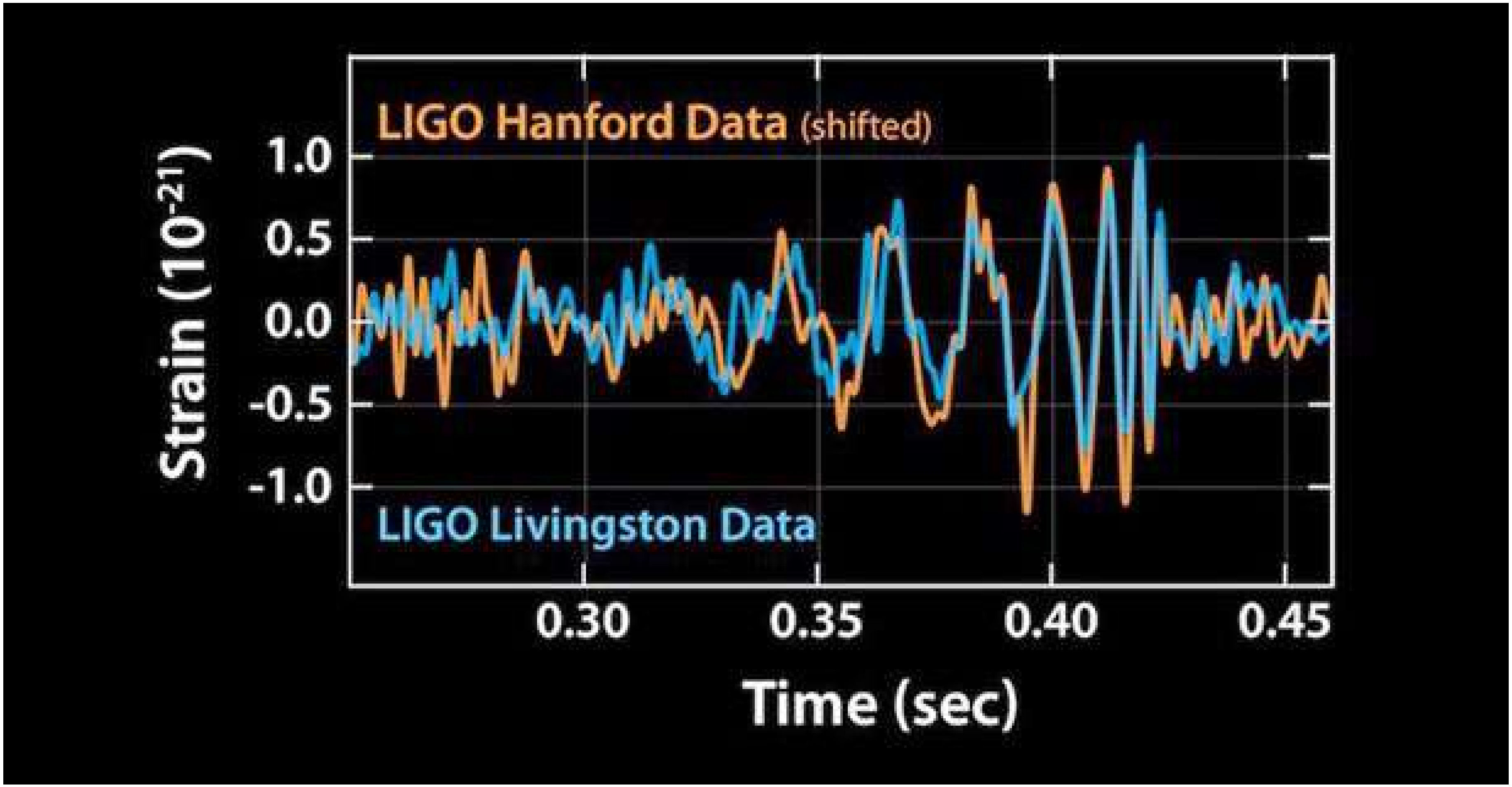


Science & Technology Facilities Council

NSF

LSU

Sept 14 2015

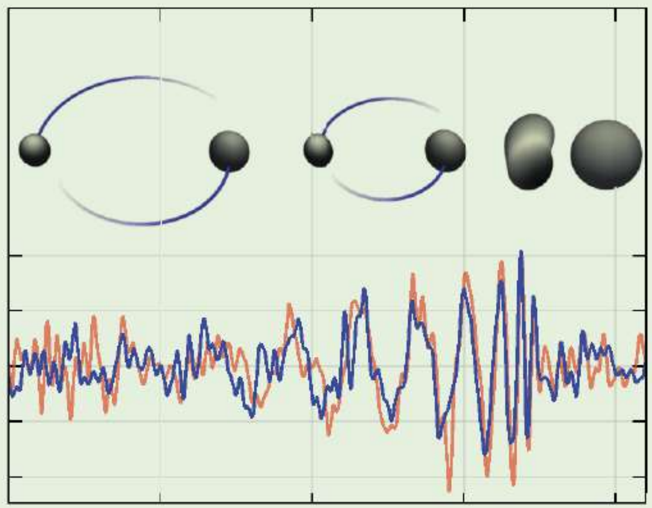


LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

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

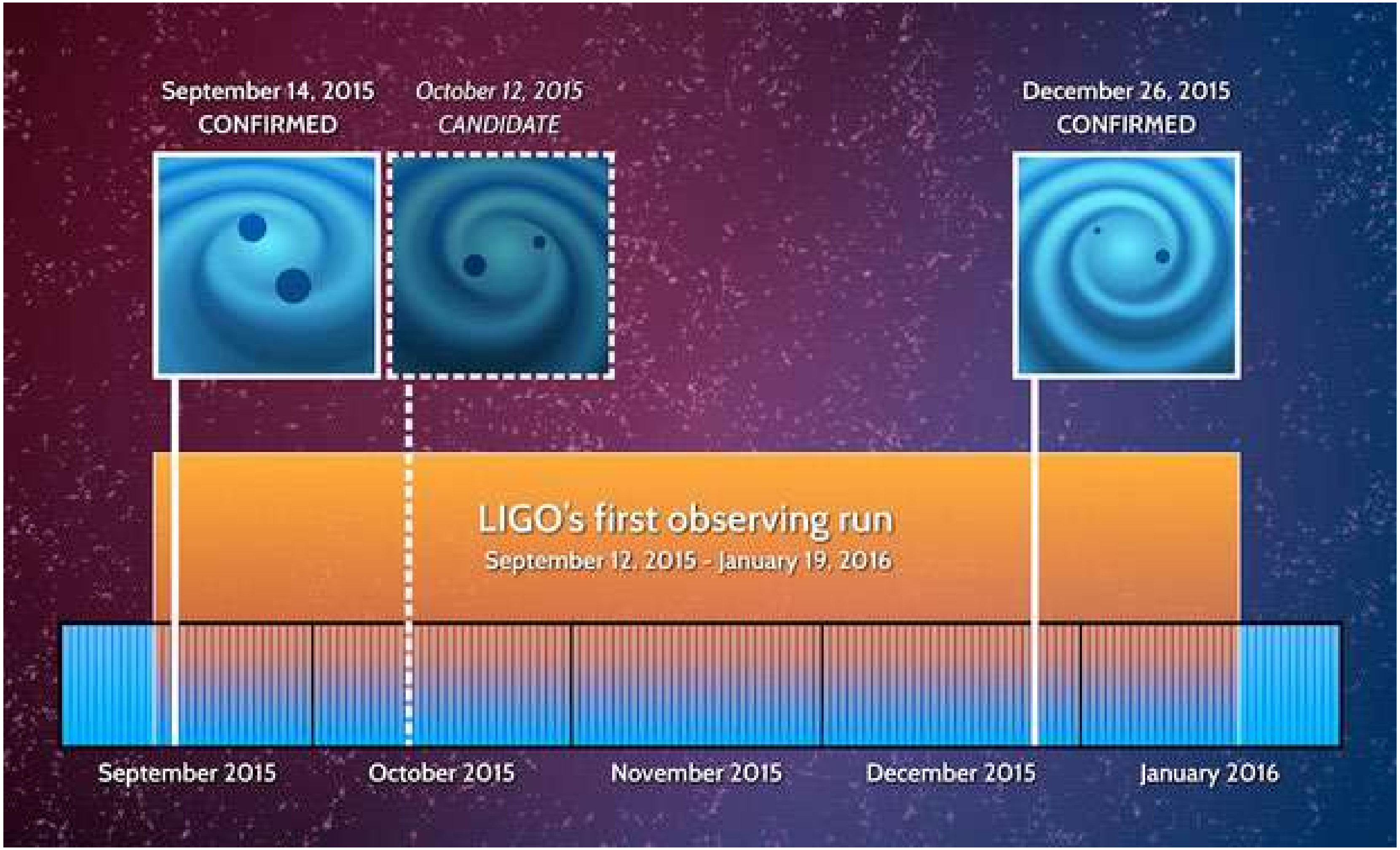
Observation of Gravitational Waves from a Binary Black Hole Merger

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

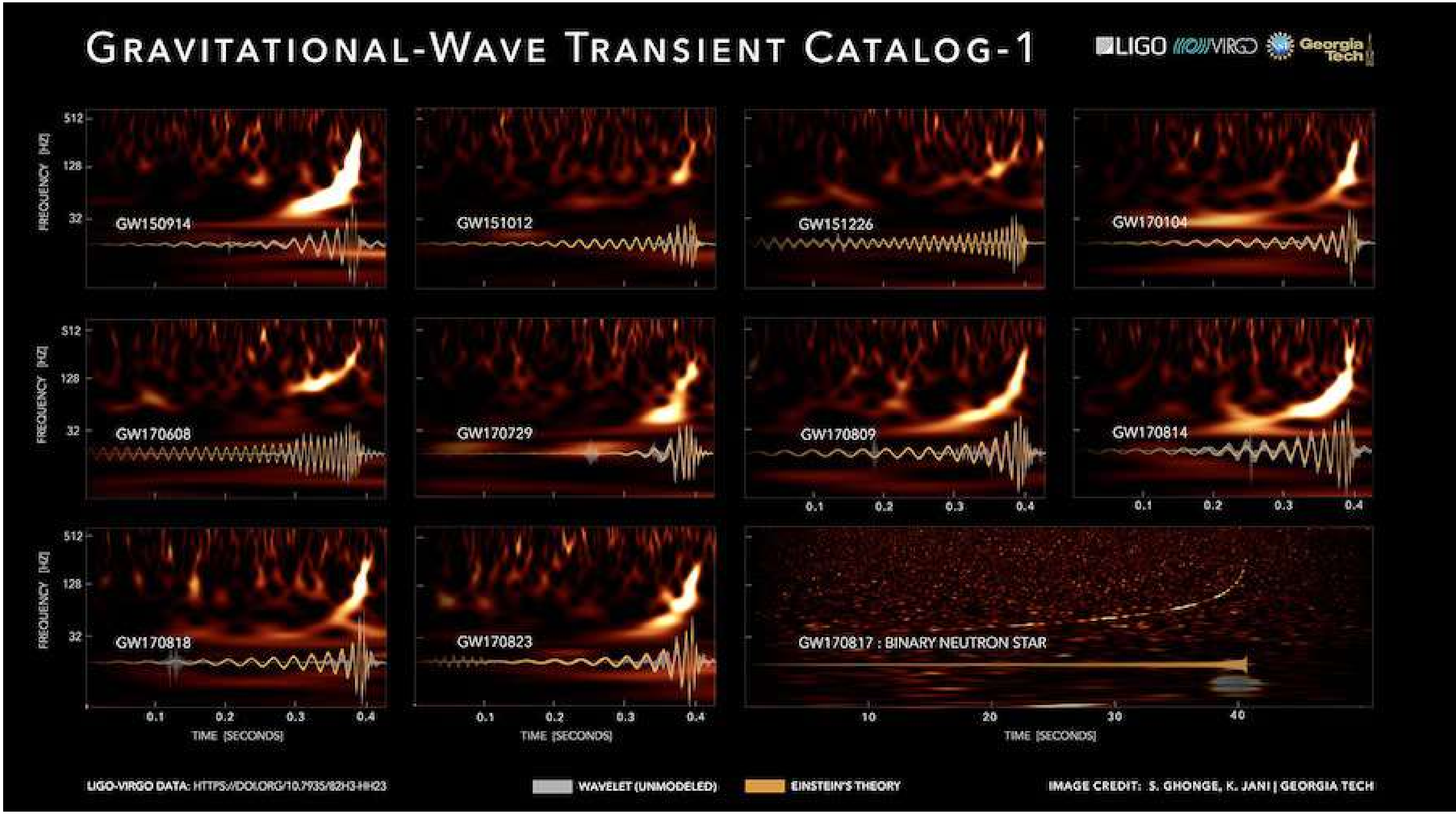


Published by
American Physical Society™
APS physics
Volume 116, Number 6

Not just one signal

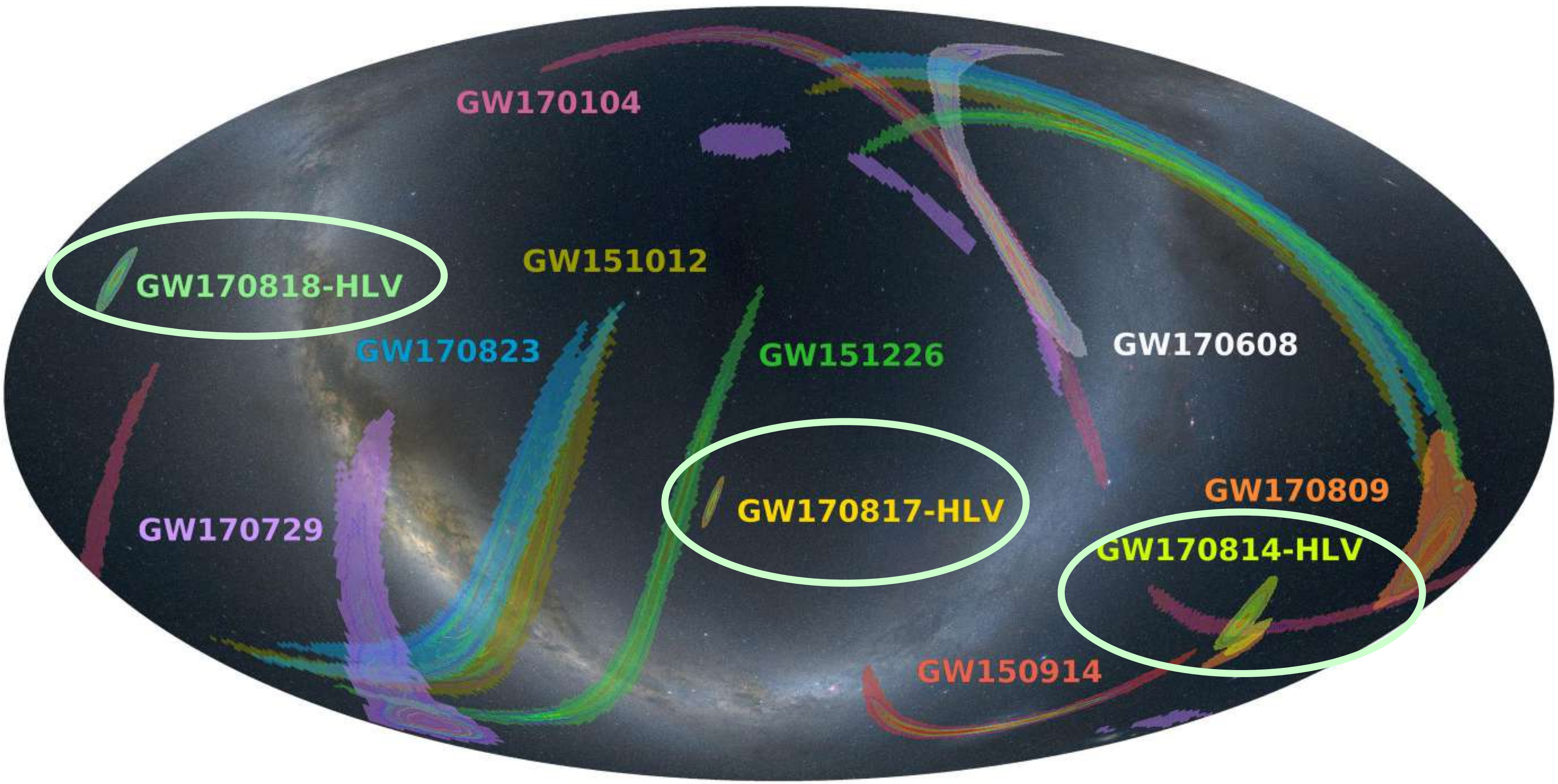


O1-O2 (2015-2017)

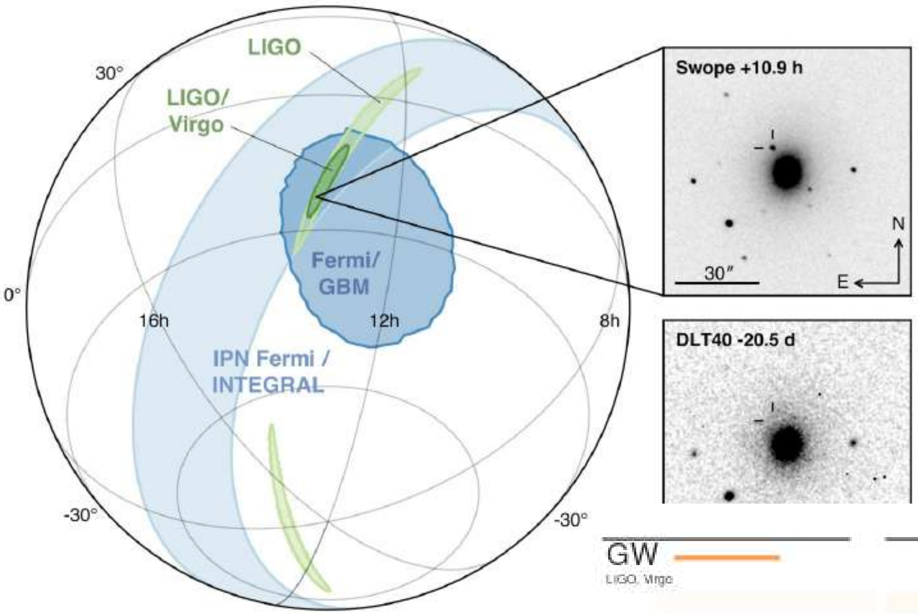


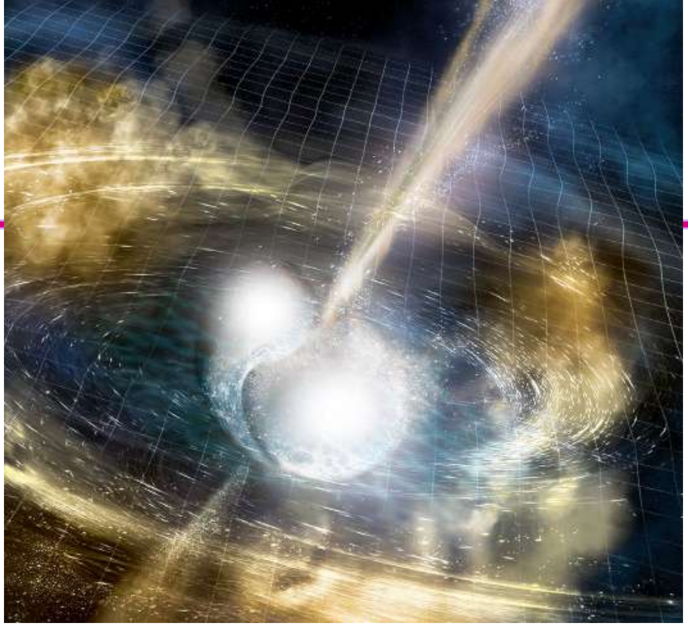
Phys. Rev. X **9**, 031040 (2019)

Where do GWs come from?



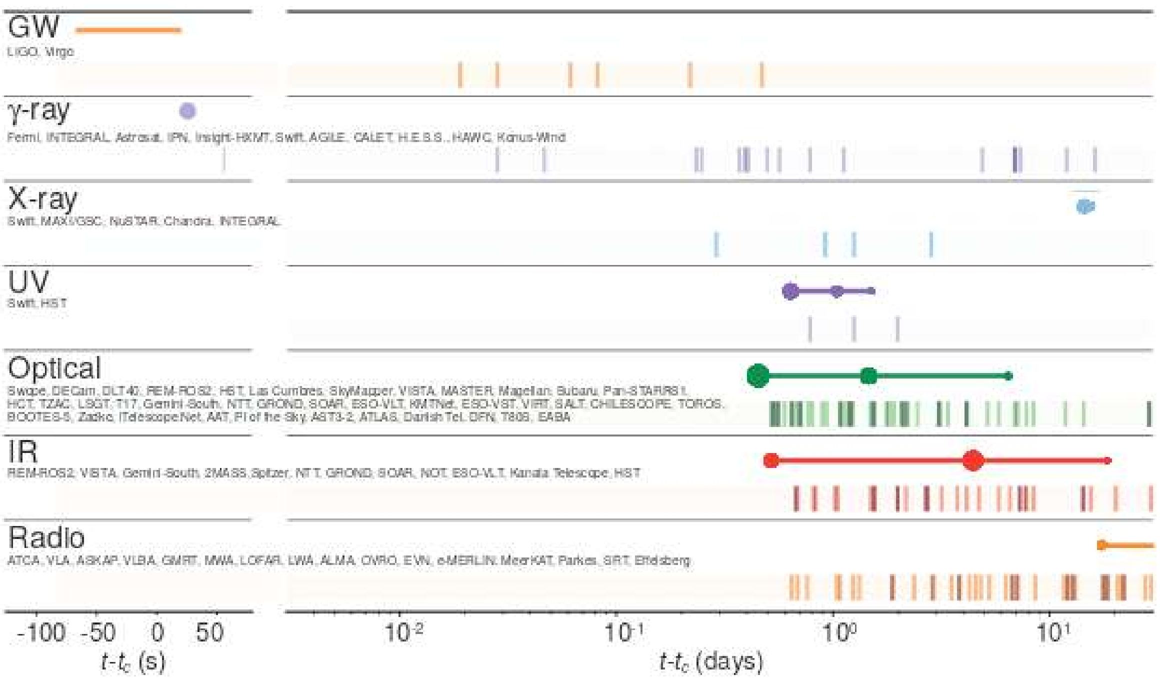
A kilonova rainbow





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

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



Testing General Relativity

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

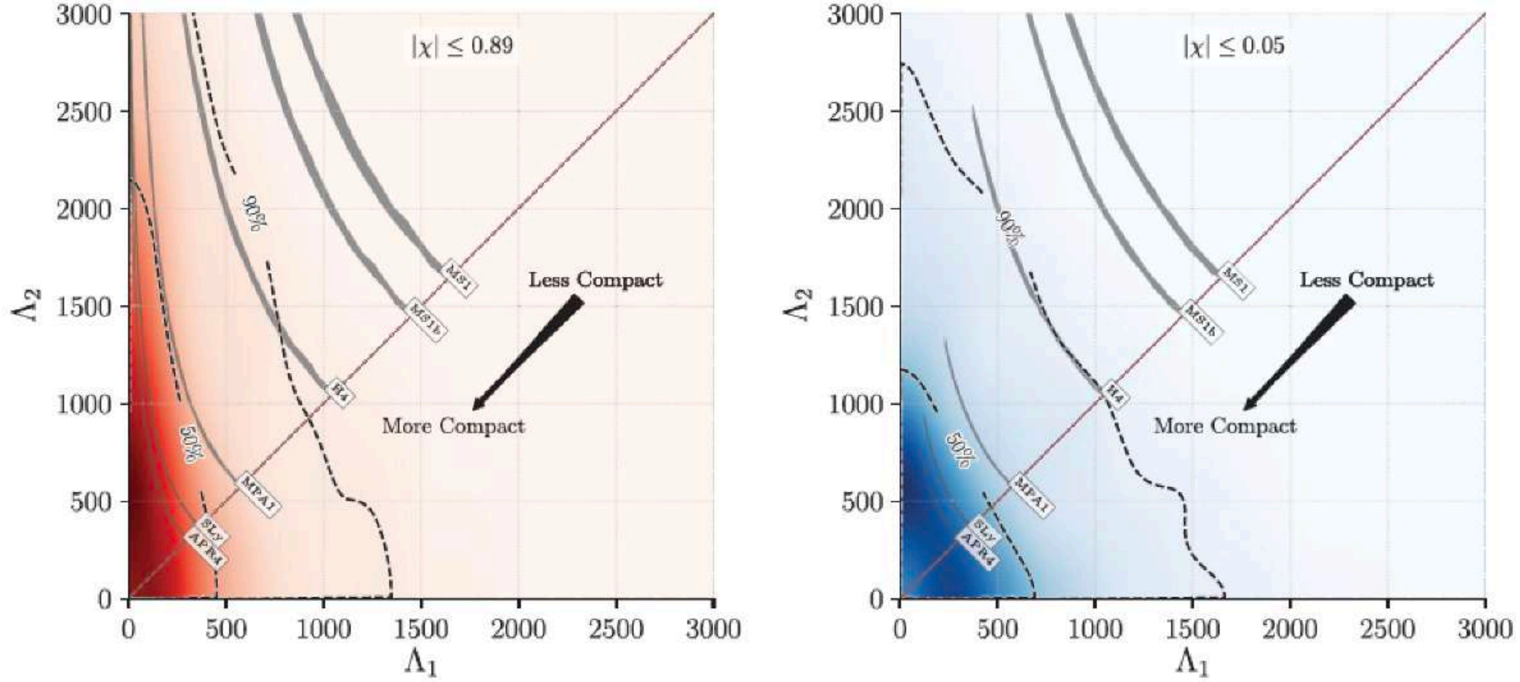
Event	Properties				SNR	GR tests performed				
	D_L [Mpc]	M_{tot} [$M_\odot$]	M_f [$M_\odot$]	a_f		RT	IMR	PI	PPI	MDR
GW150914[b]	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$25.3^{+0.1}_{-0.2}$	✓	✓	✓	✓	✓
GW151012[b]	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$9.2^{+0.3}_{-0.4}$	✓	–	–	✓	✓
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

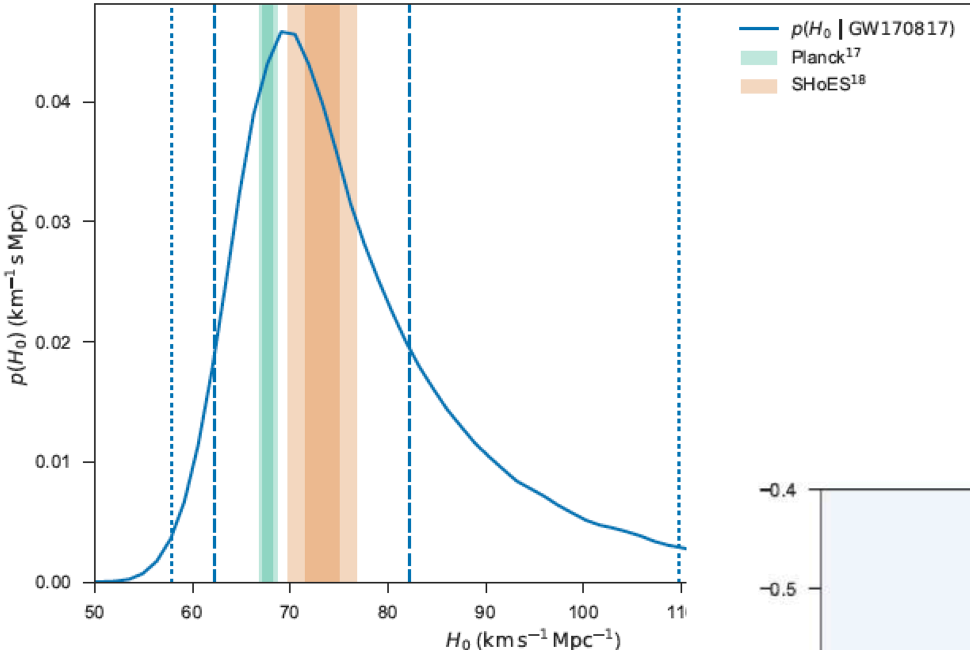
Nuclear physics with GWs

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

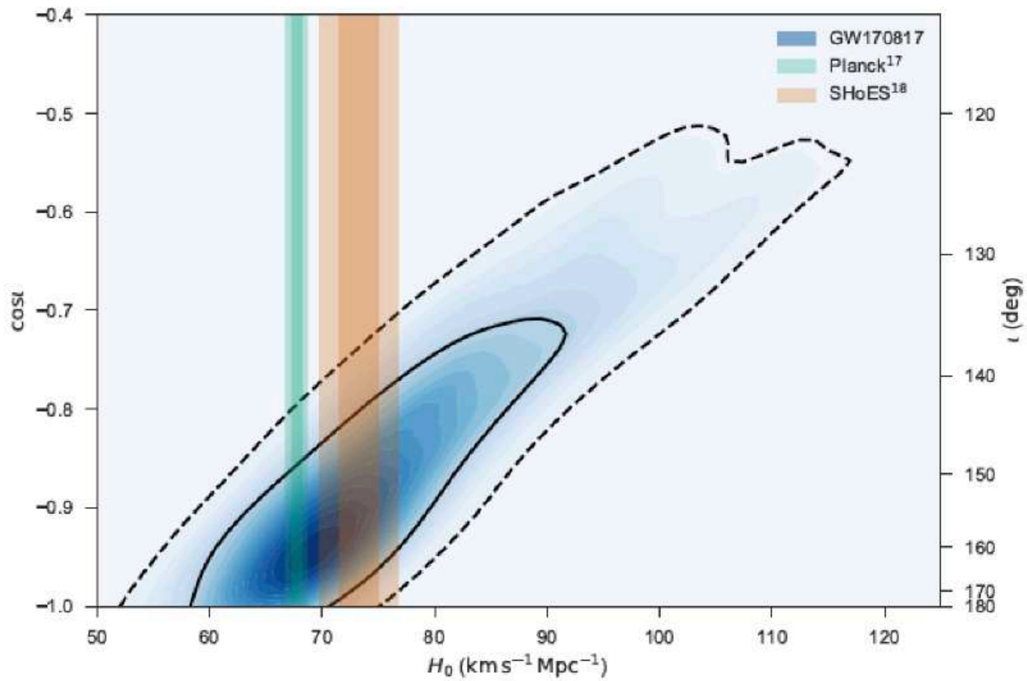


$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{m} \right)^5$$

Cosmology with GWs

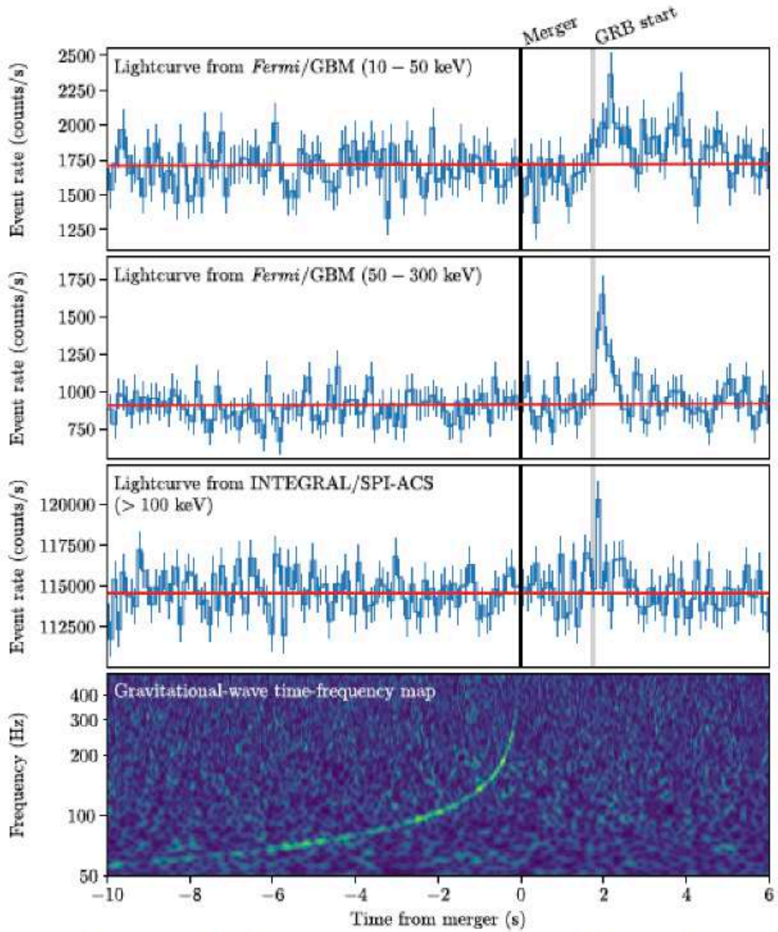


[Nature 551, 85 (2017)]



GW-GRB observation: Fundamental physics

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



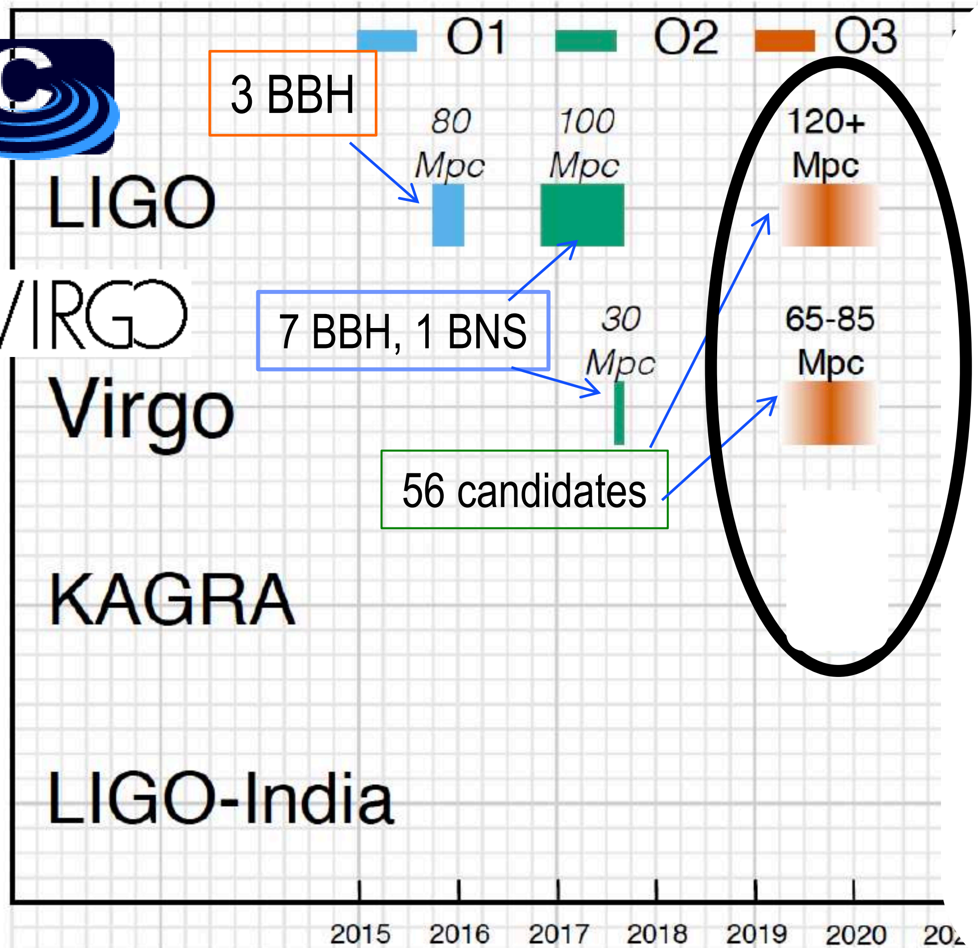
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

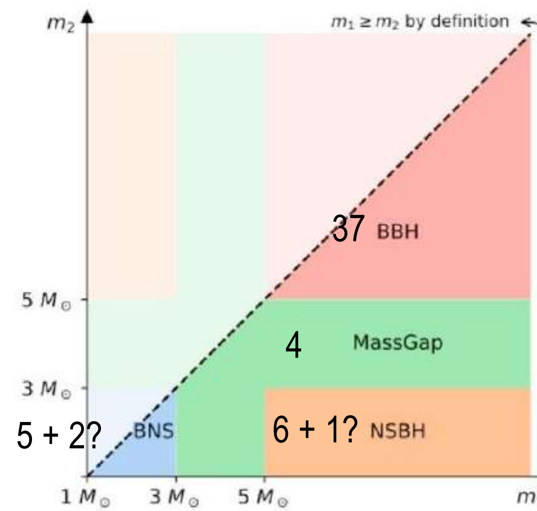
$$-2.6 \times 10^{-7} \leqslant \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leqslant 1.2 \times 10^{-6}. \qquad (4)$$

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

More discoveries





… and a (weak) different signal?

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

Living Reviews in Relativity **23**, 3 (2020)

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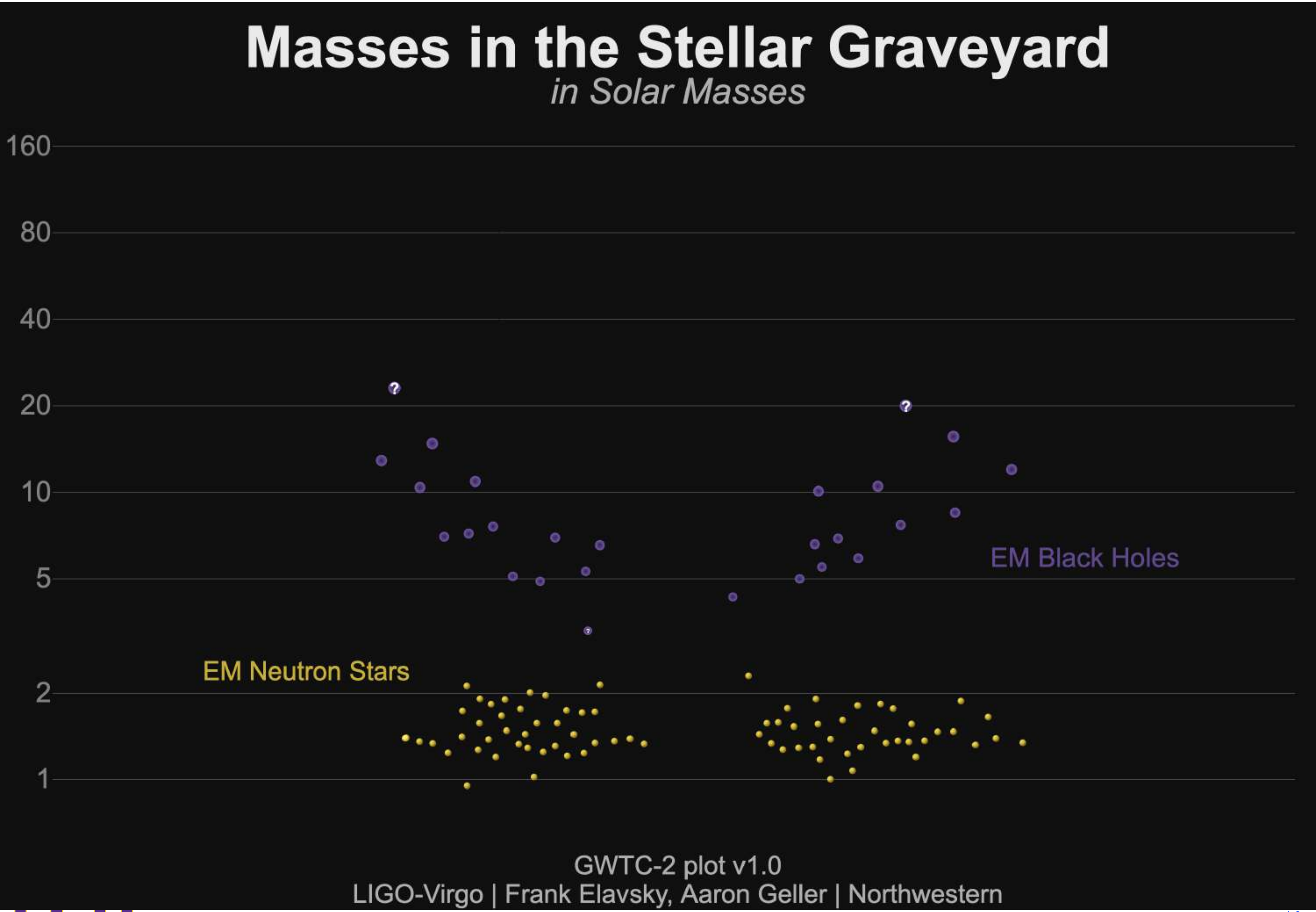
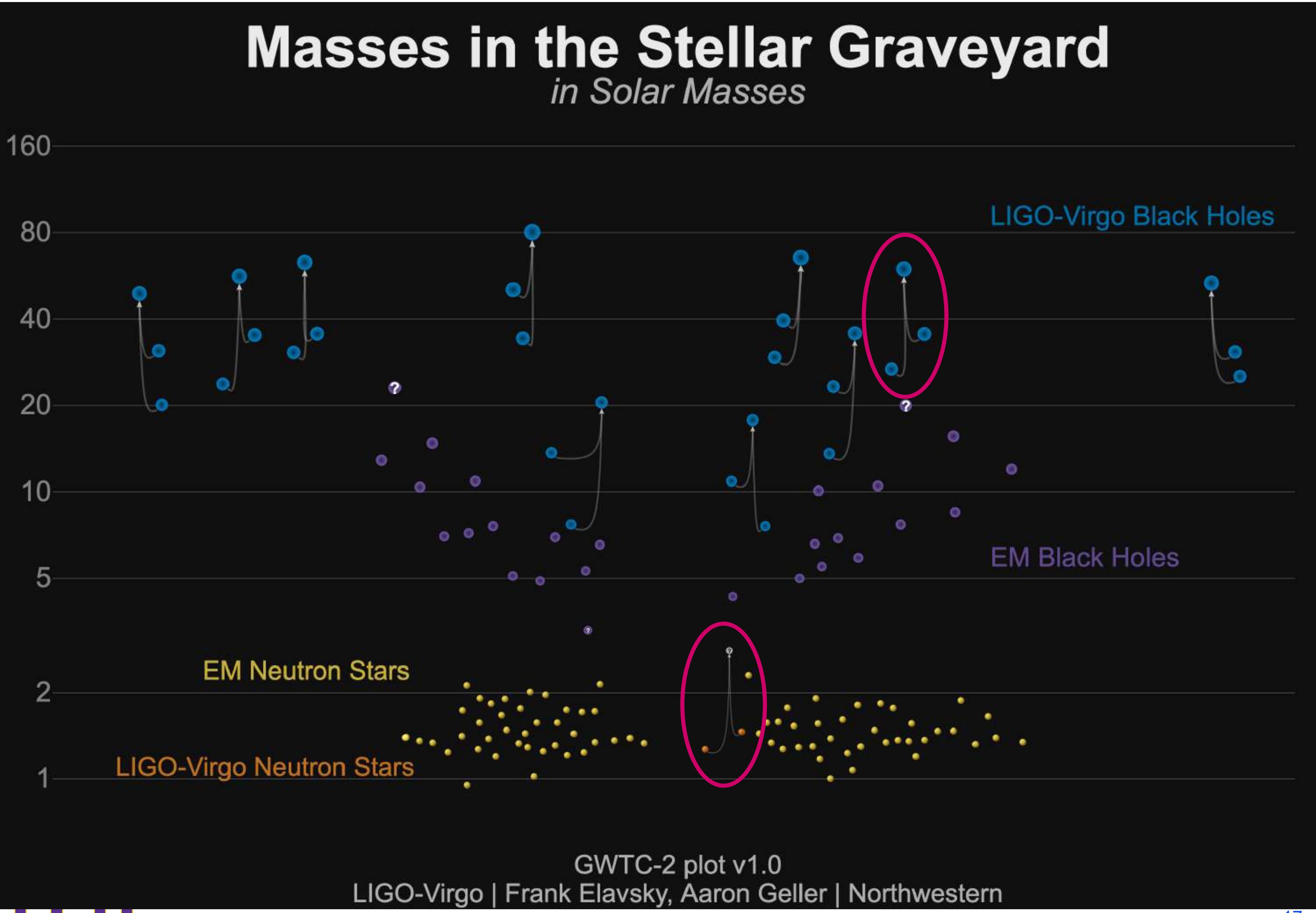

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern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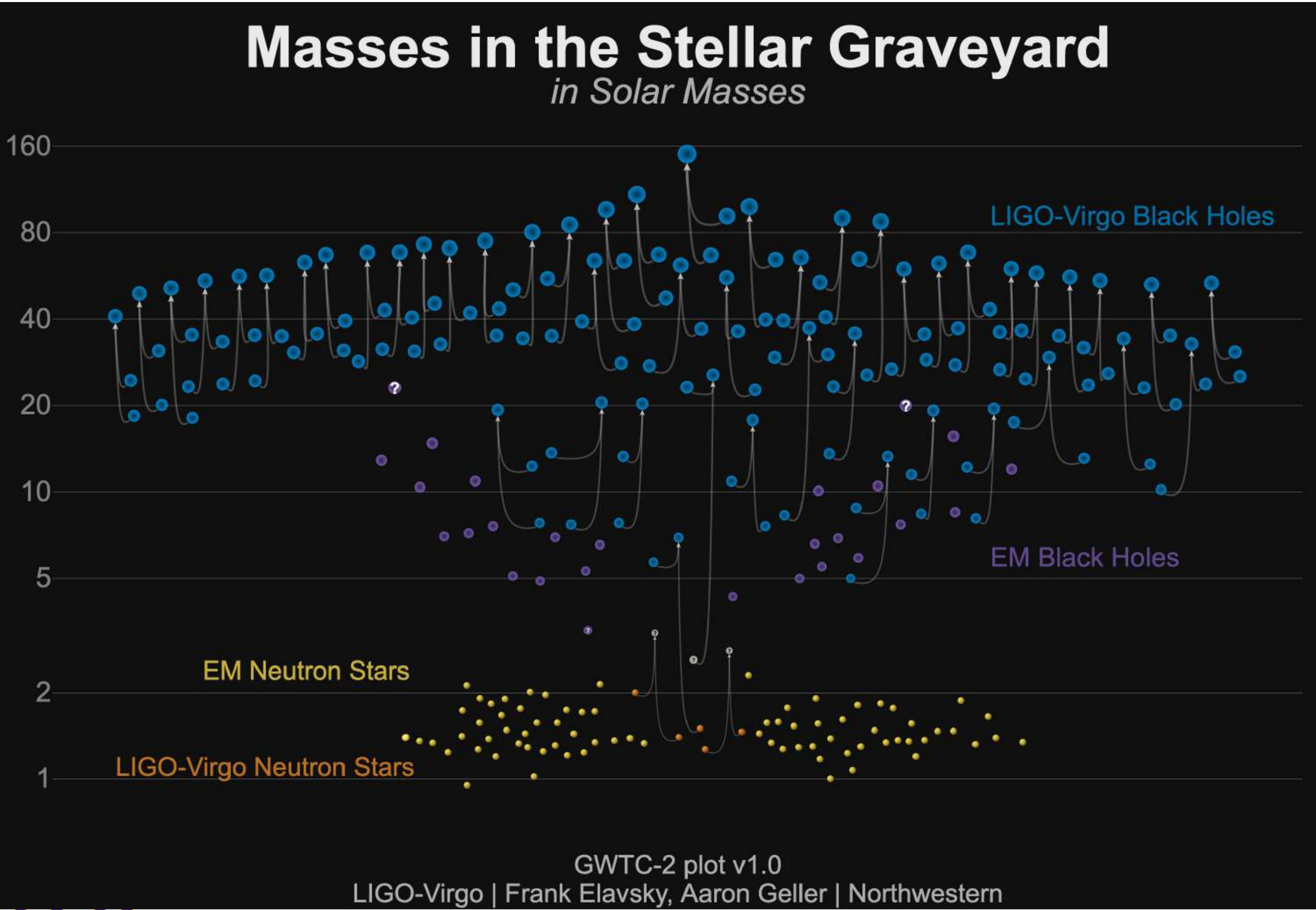
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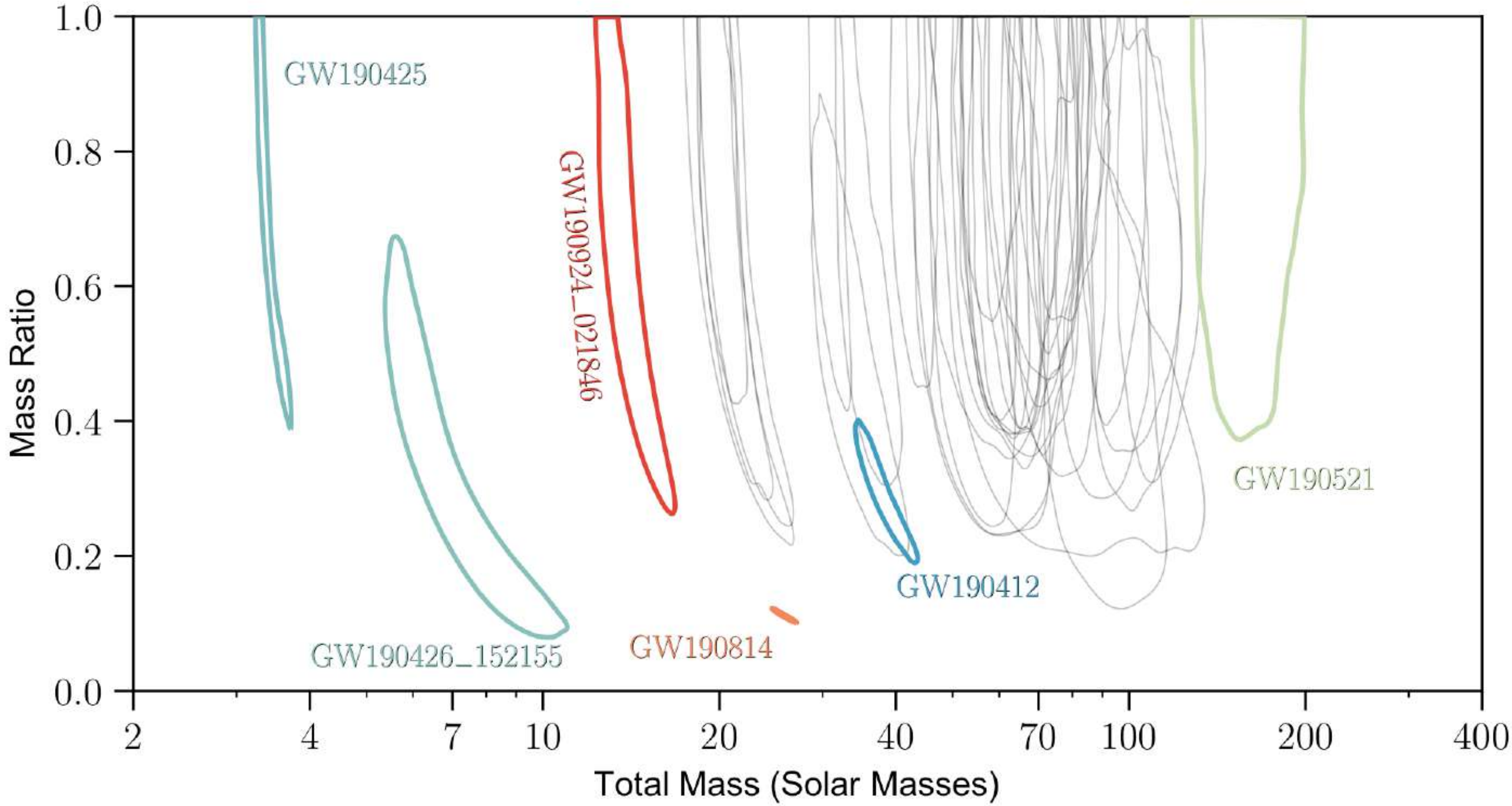
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GWTC-2 catalog (O3a): 39 events



http://arxiv.org/abs/2010.14527

https://www.gw-openscience.org

https://pnp.ligo.org/ppcomm/Papers.html

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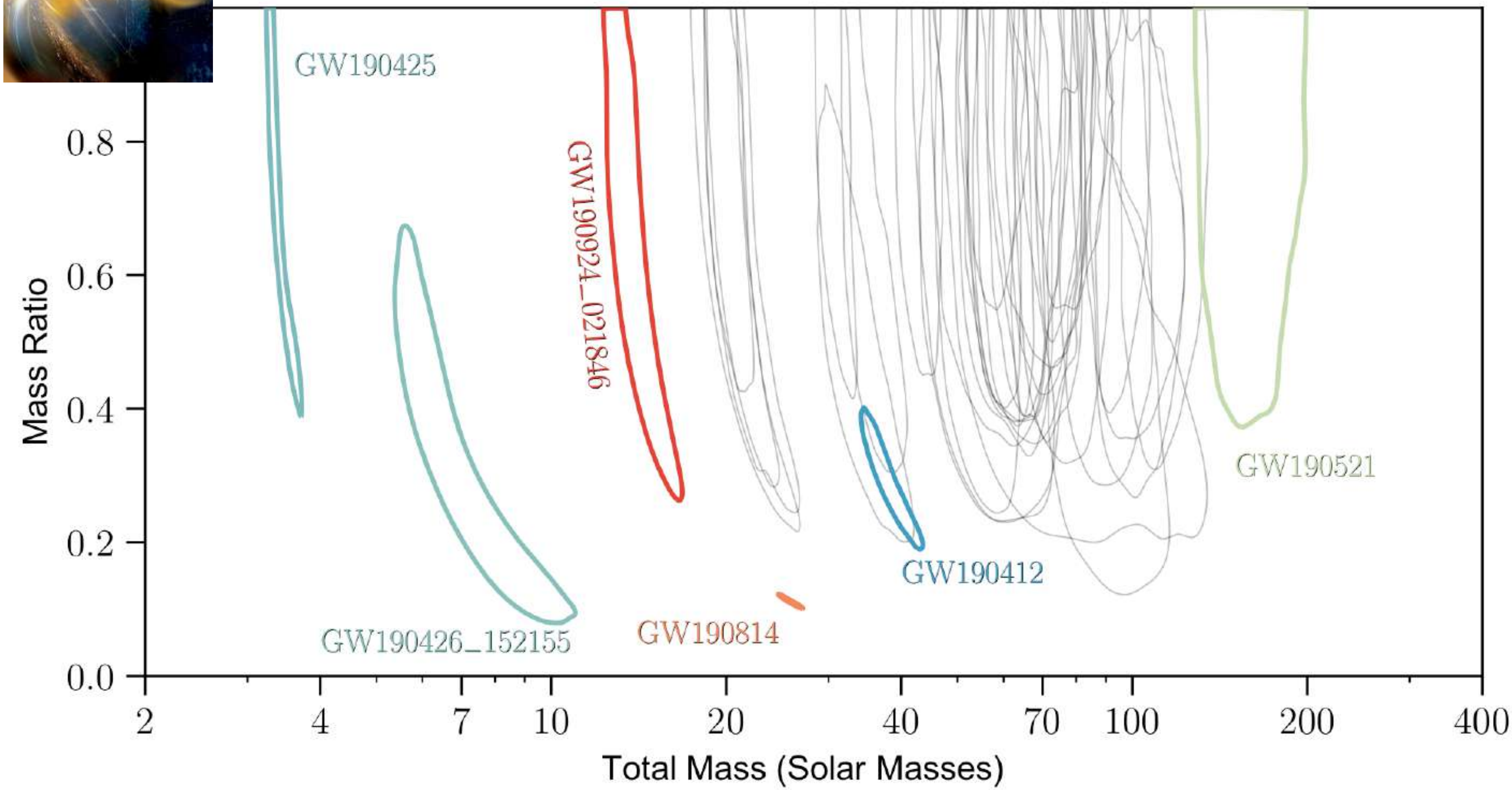
GW190425: Another BNS merger

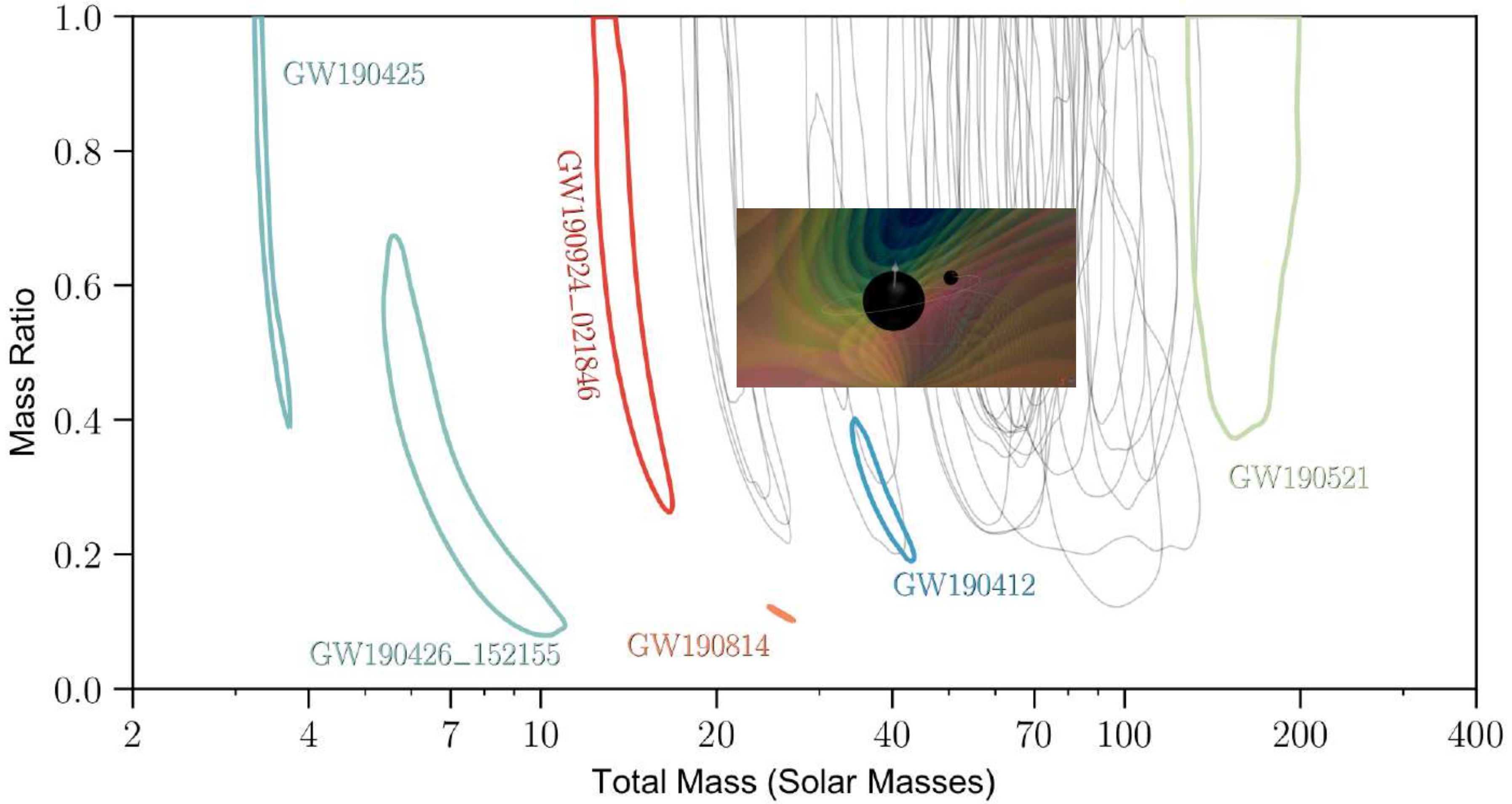


http://arxiv.org/abs/2010.14527

Astrophys. J. Lett. **892**, L3 (2020)

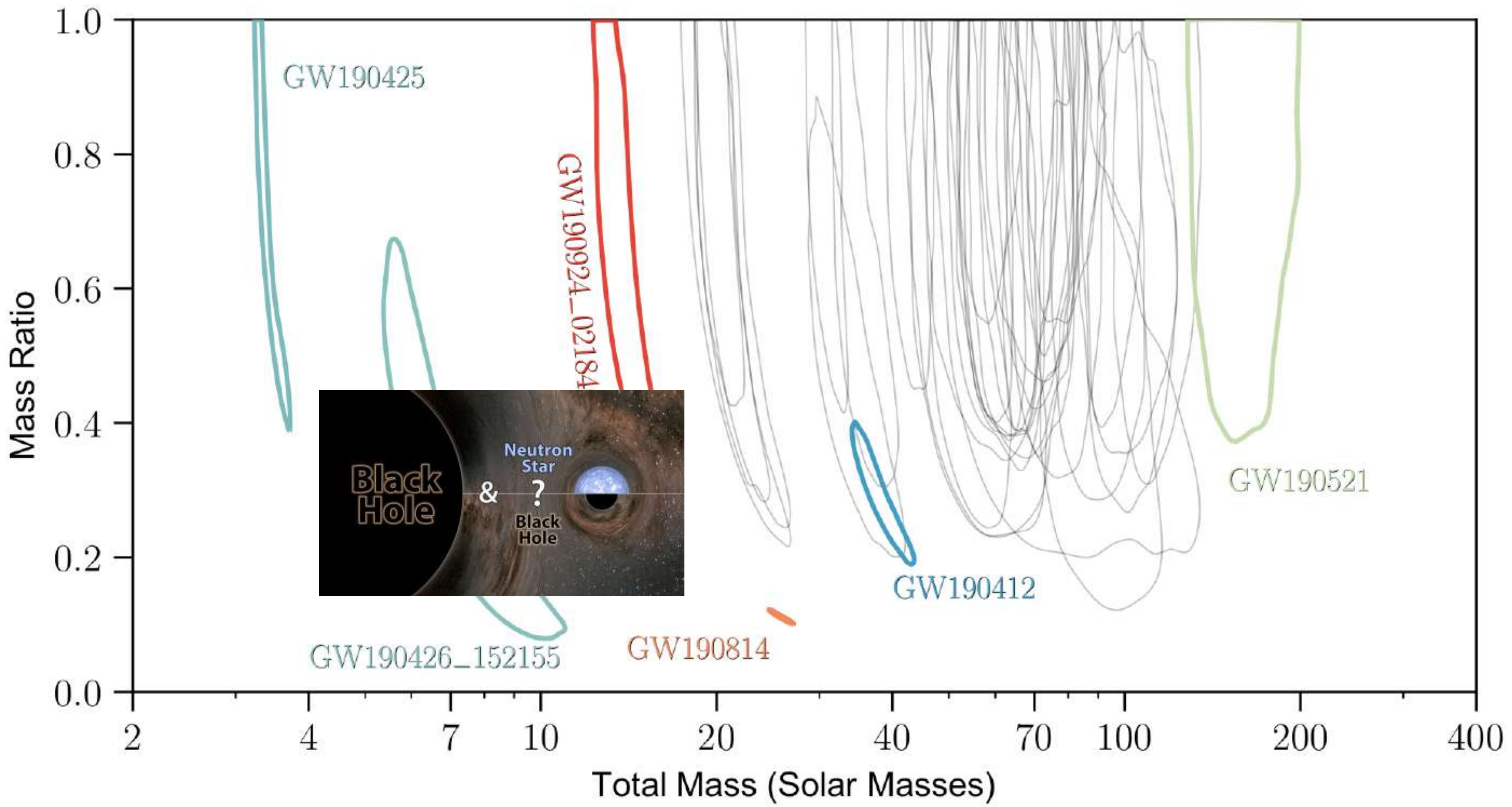
LSU

GW190412: Asymmetric mases



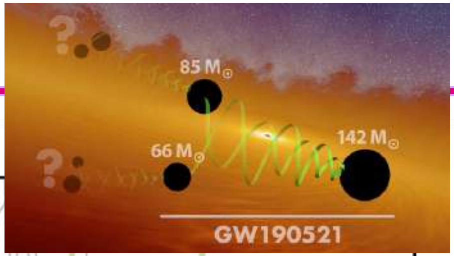
[Phys. Rev. D **102**, 043015 (2020)](http://arxiv.org/abs/2010.14527)
http://arxiv.org/abs/2010.14527

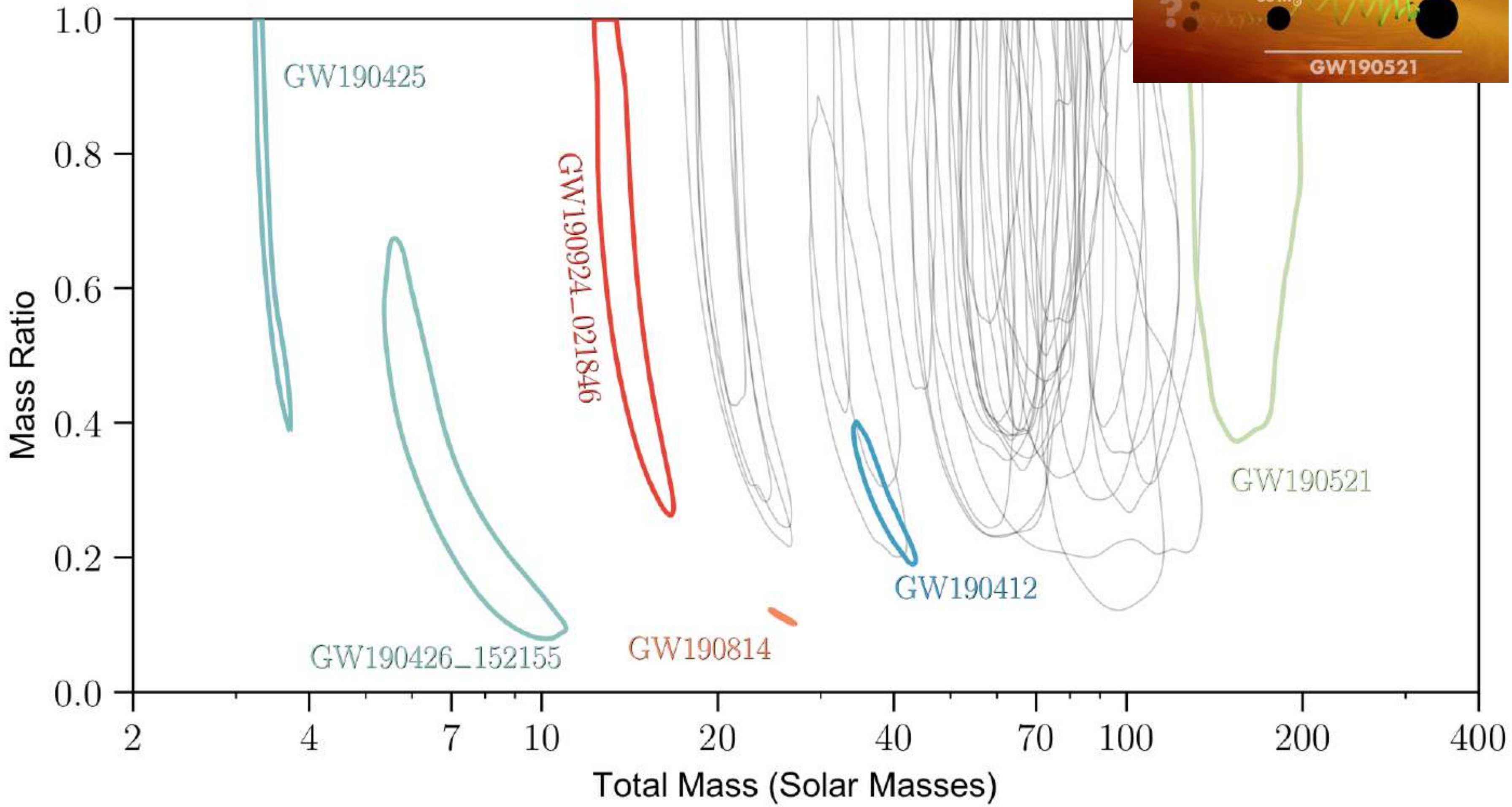
GW190814: Even more asymmetric masses



Astrophys. J. Lett. **896**, L44 (2020)
http://arxiv.org/abs/2010.14527

GW190521: Largest black hole masses





Phys. Rev. Lett. **125**, 101102 (2020)
http://arxiv.org/abs/2010.14527

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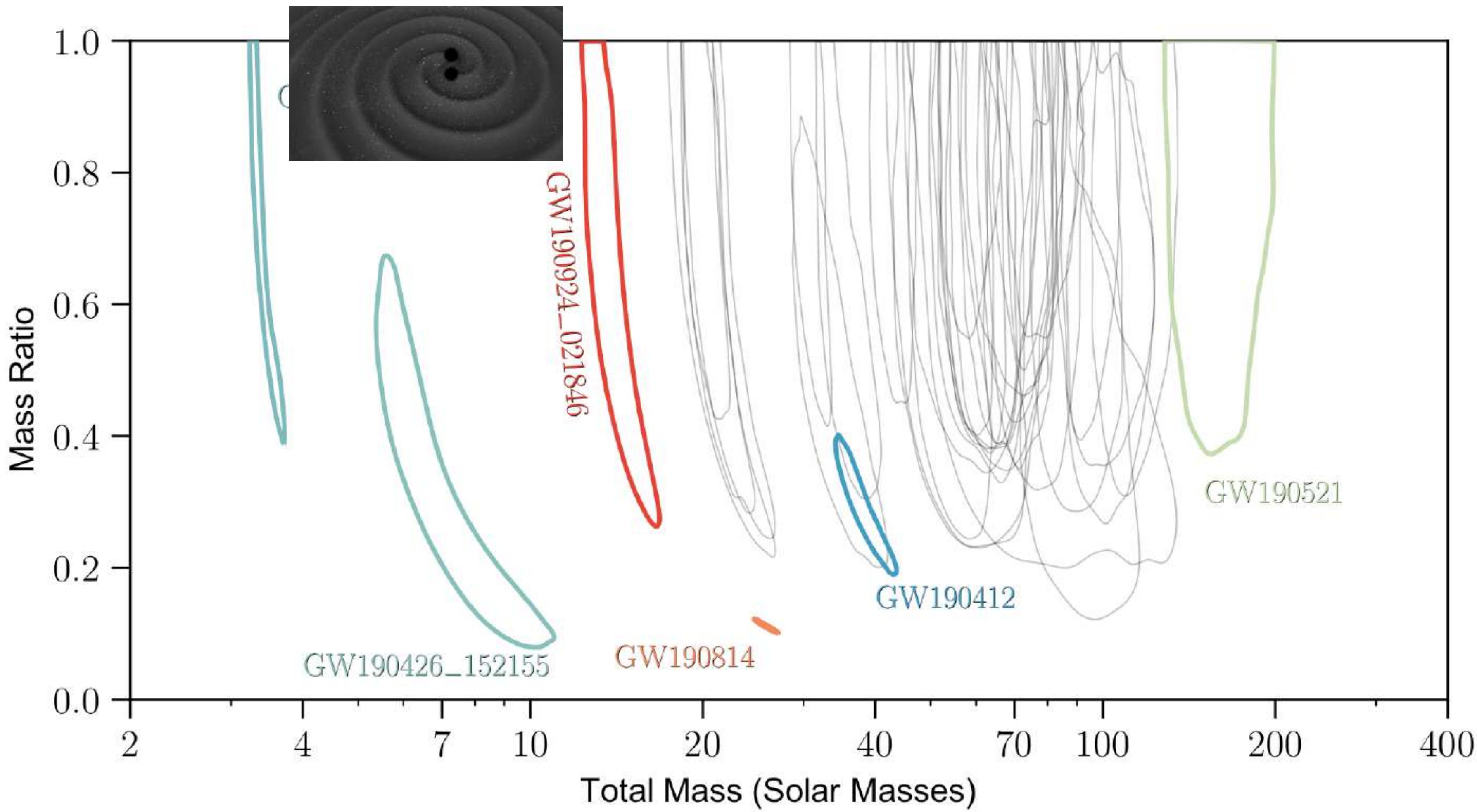
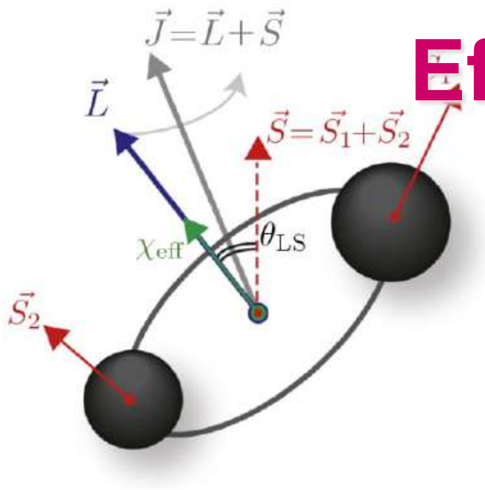
GW190924_021846: Smallest black hole masses

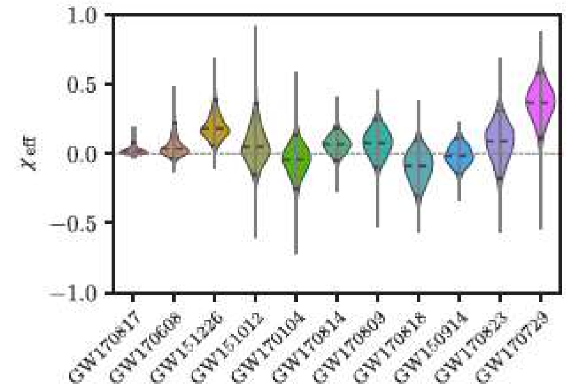


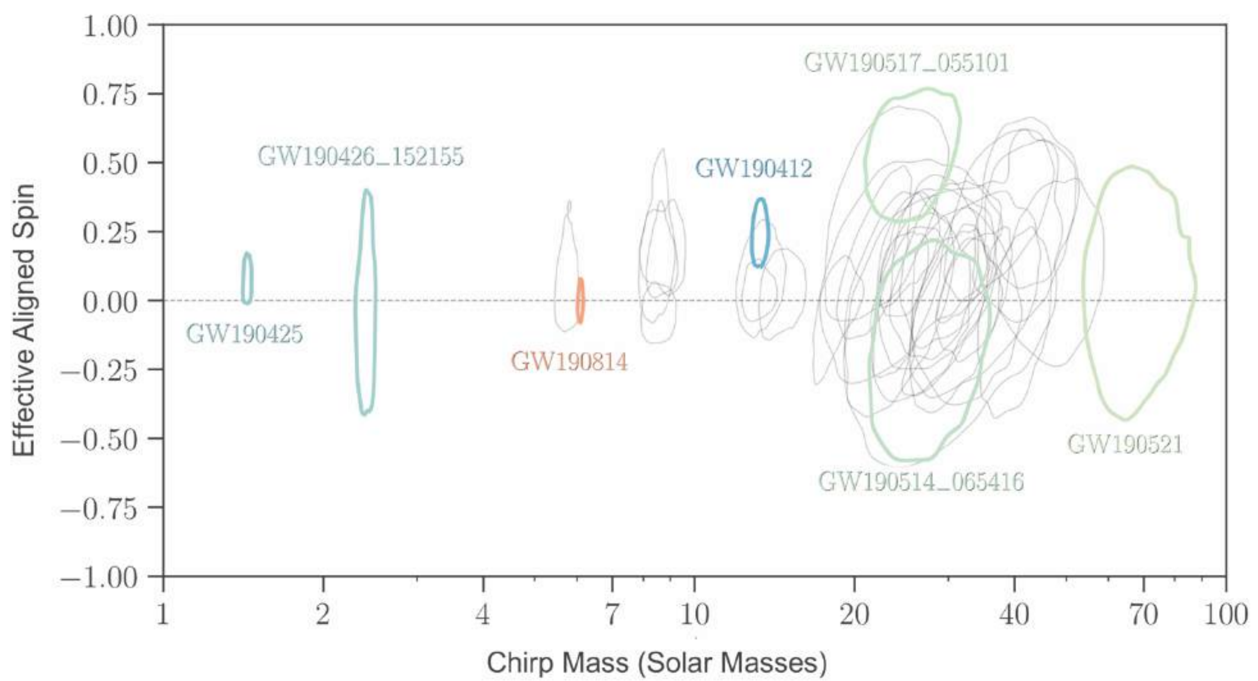
http://arxiv.org/abs/2010.14527
https://pnp.ligo.org/ppcomm/Papers.html

Effective Aligned Spin



Credit: Carl Rodriguez





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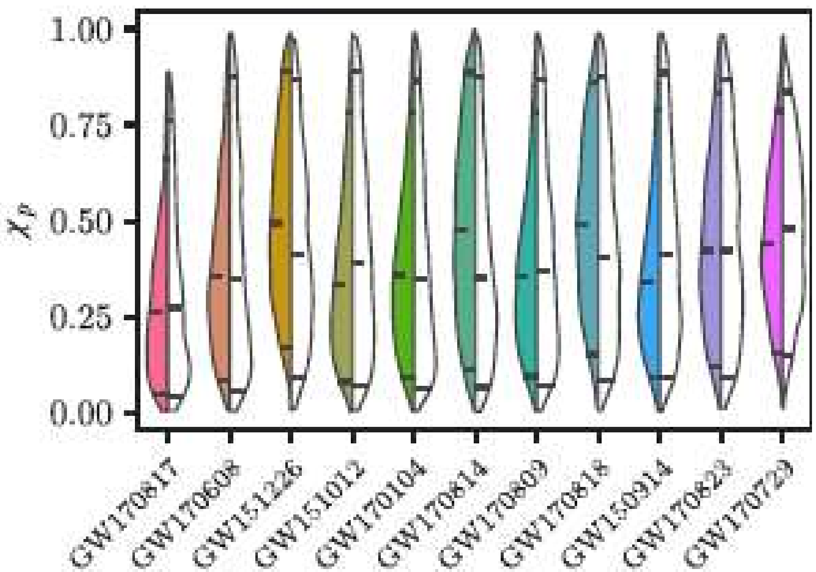
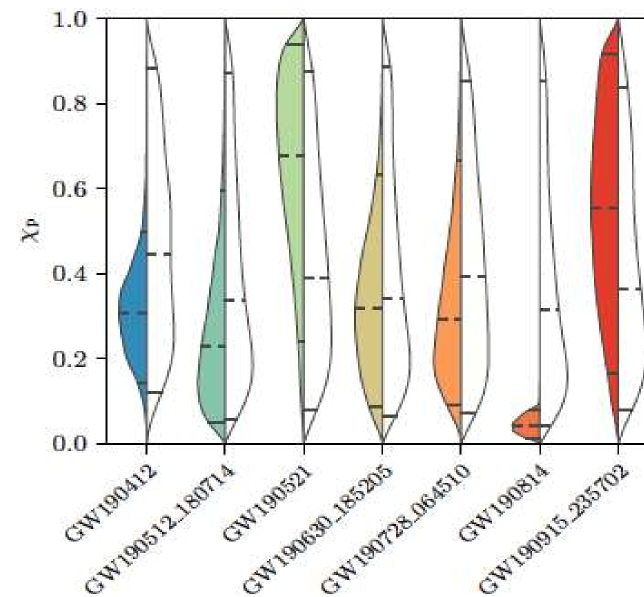
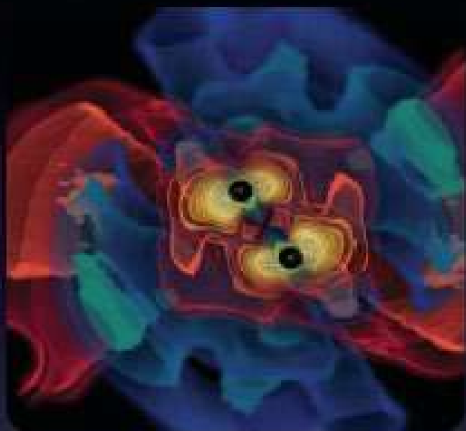
Effective Precession Spin

Credit:
LIGO/Caltech/MIT/Son
ma State (Aurore
Simmonnet)





Sources of gravitational waves: not just binary systems!


Credit: AEI, CCT, LSU

Coalescing Binary Systems

Neutron Stars, Black Holes


Credit: Chandra X-ray Observatory

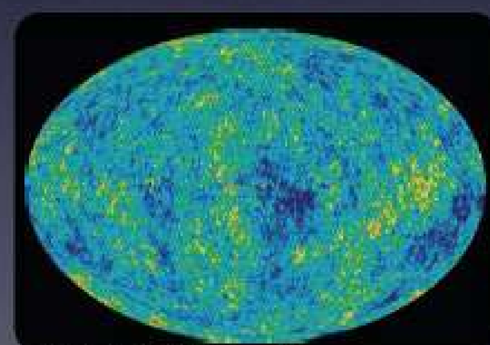
'Bursts'

asymmetric core collapse supernovae
cosmic strings
???


Casey Reed, Penn State

Continuous Sources

Spinning neutron stars
crustal deformations, accretion


NASA/WMAP Science Team

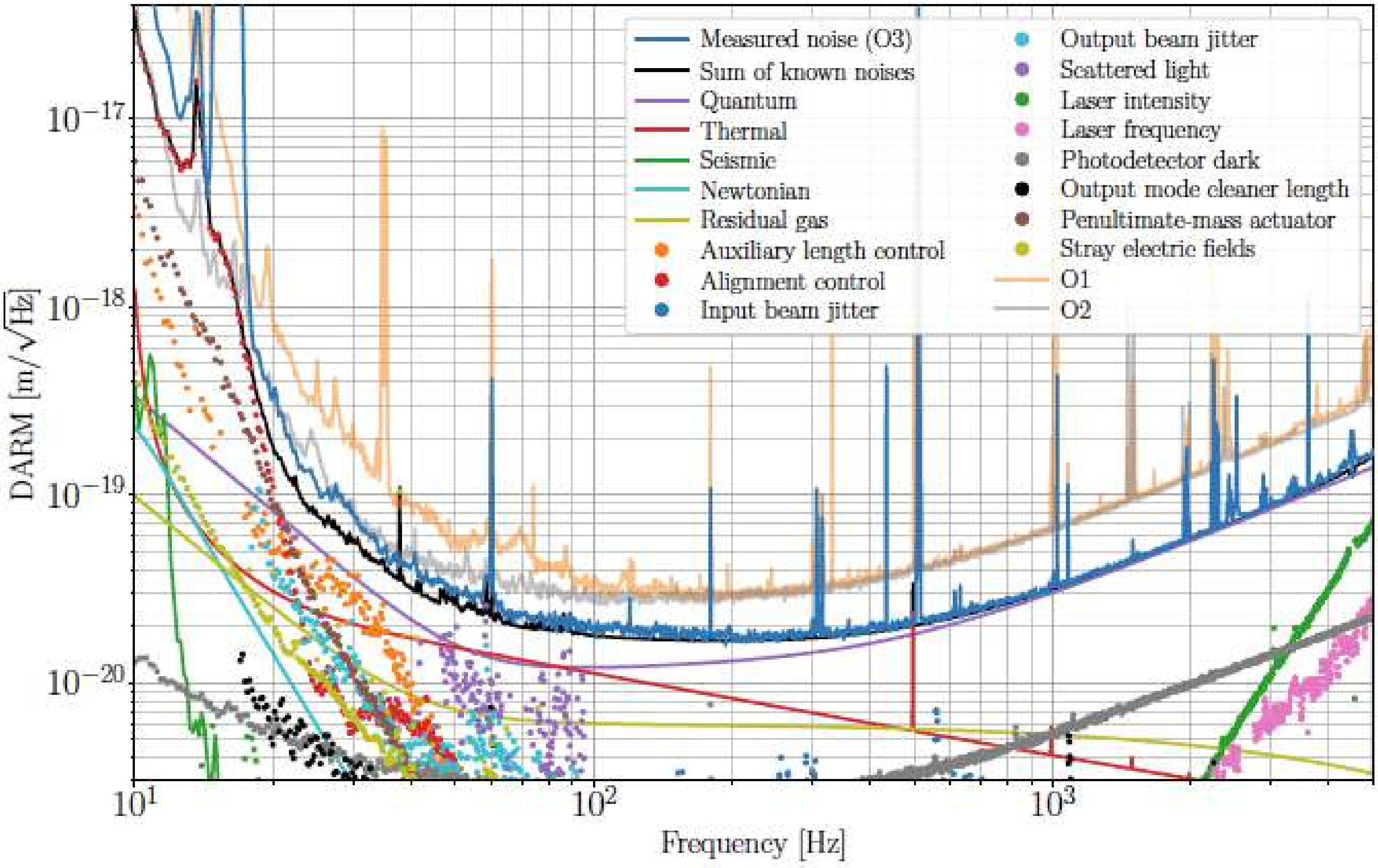
Astrophysical or

Cosmic GW background

stochastic, incoherent background

Reducing the noise, increasing the rate of detections

LIGO Livingston Detector



https://arxiv.org/abs/2008.01301

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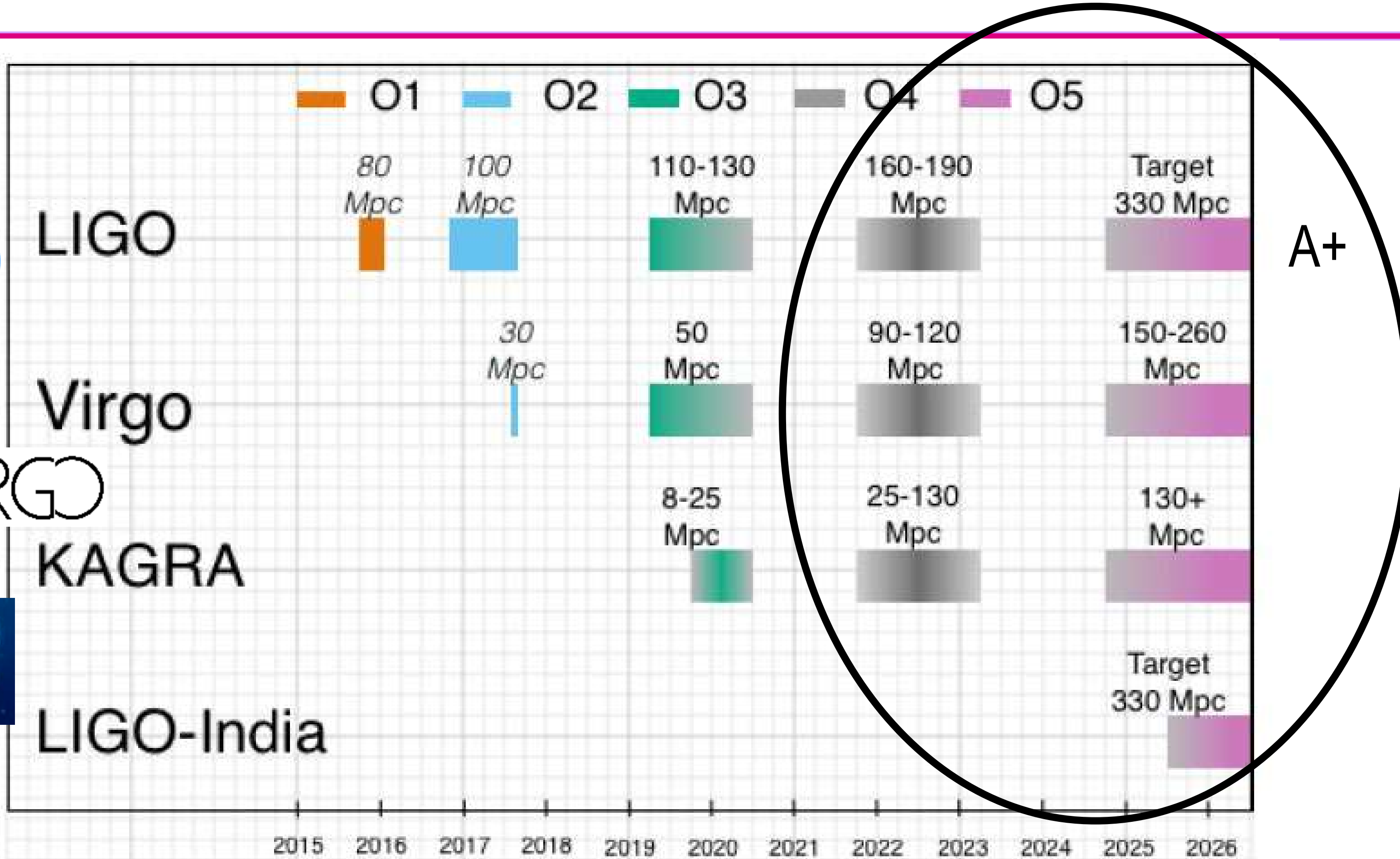
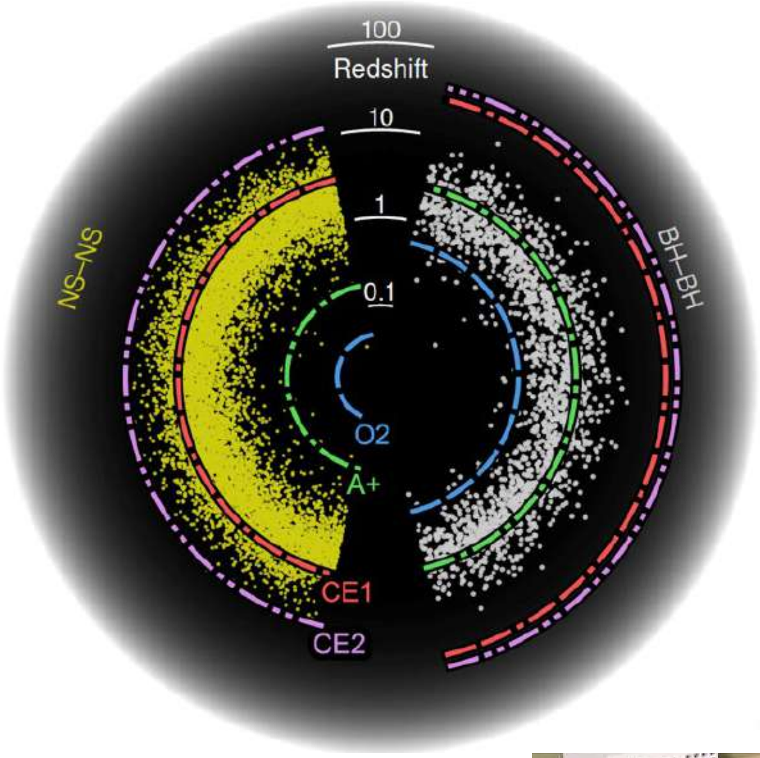
The next few years

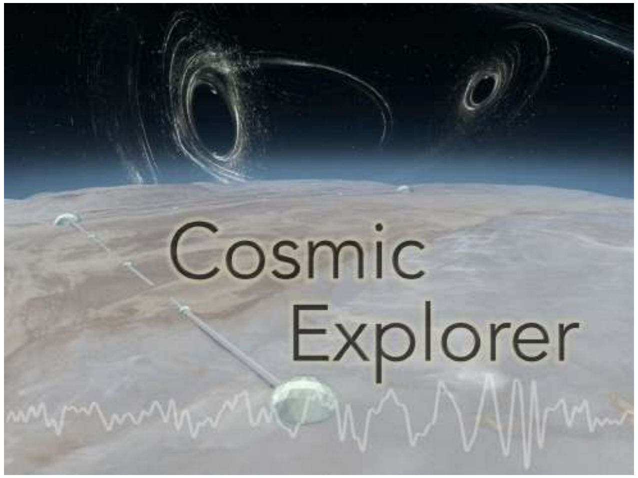


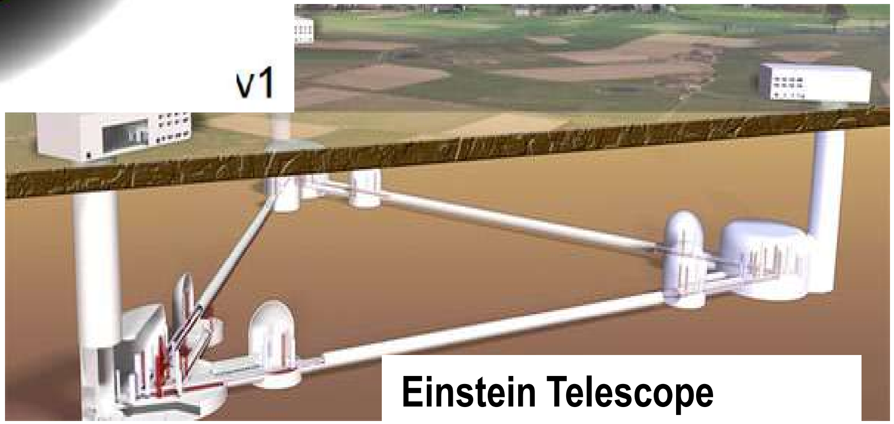
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

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

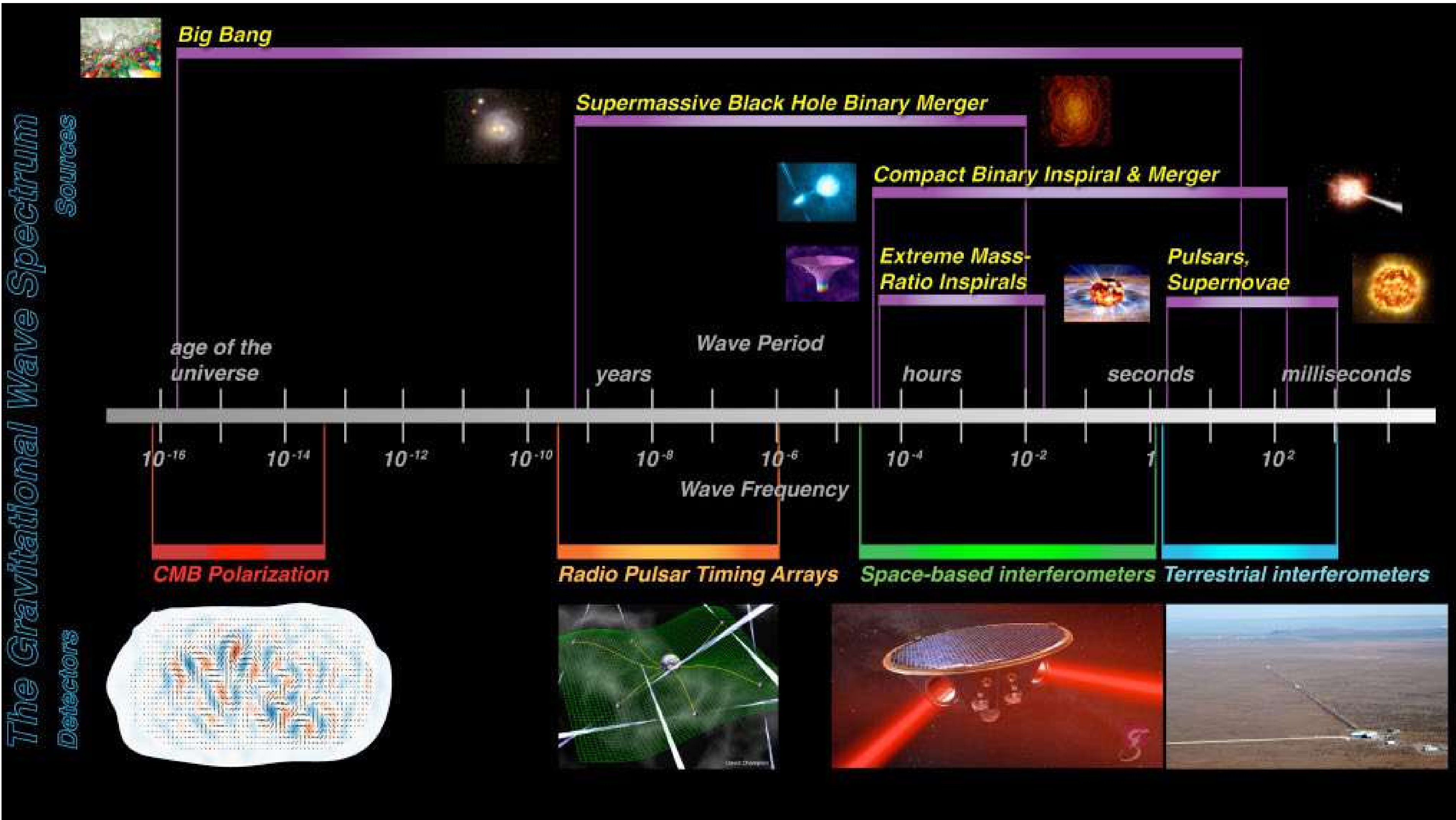
Third Generation Detectors (Ground based)







Different wavelengths need different instruments



The era of GW astronomy is here!

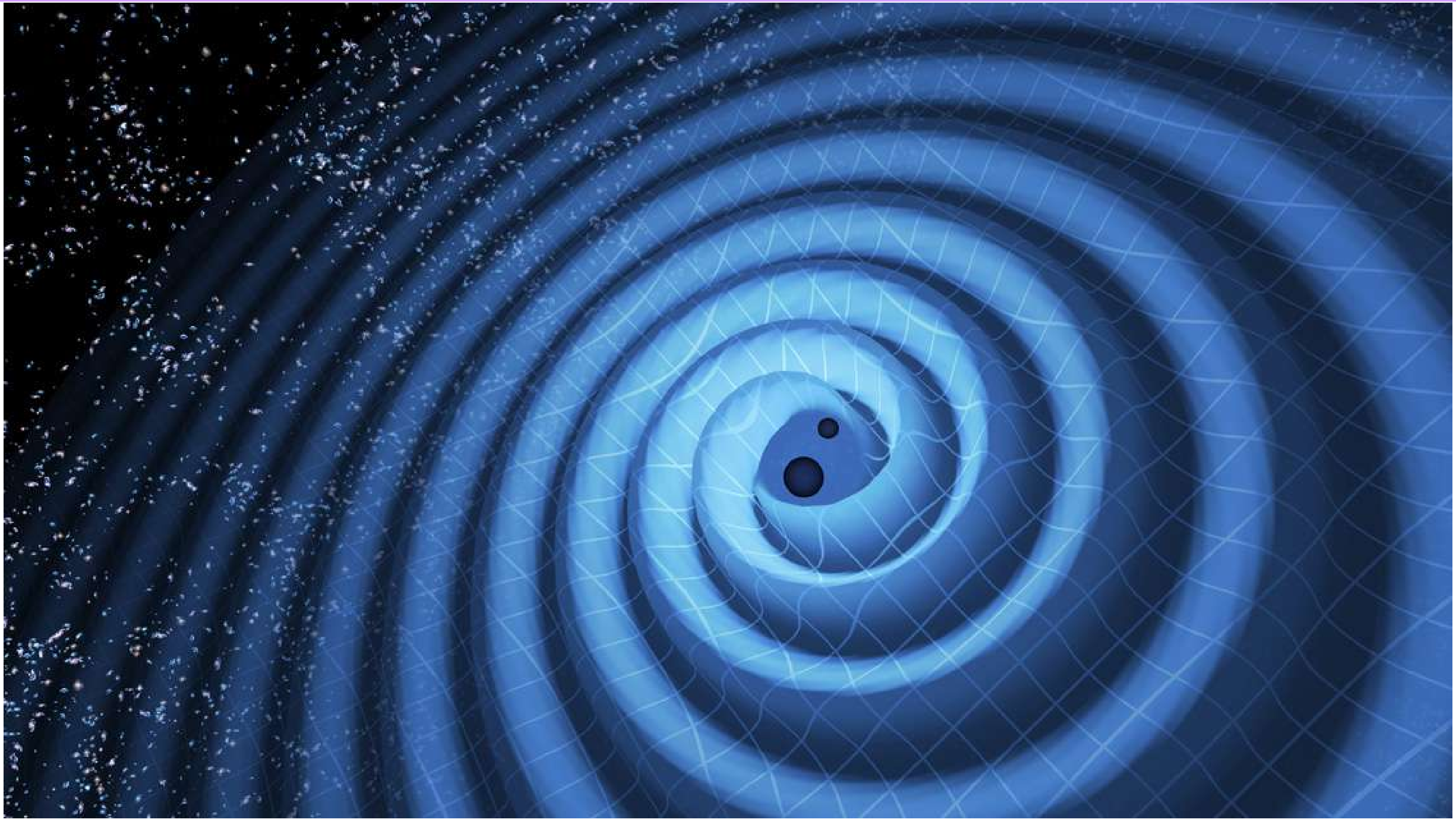


Image credit: LIGO/T. Pyle

www.ligo.org