Gravitational wave physics
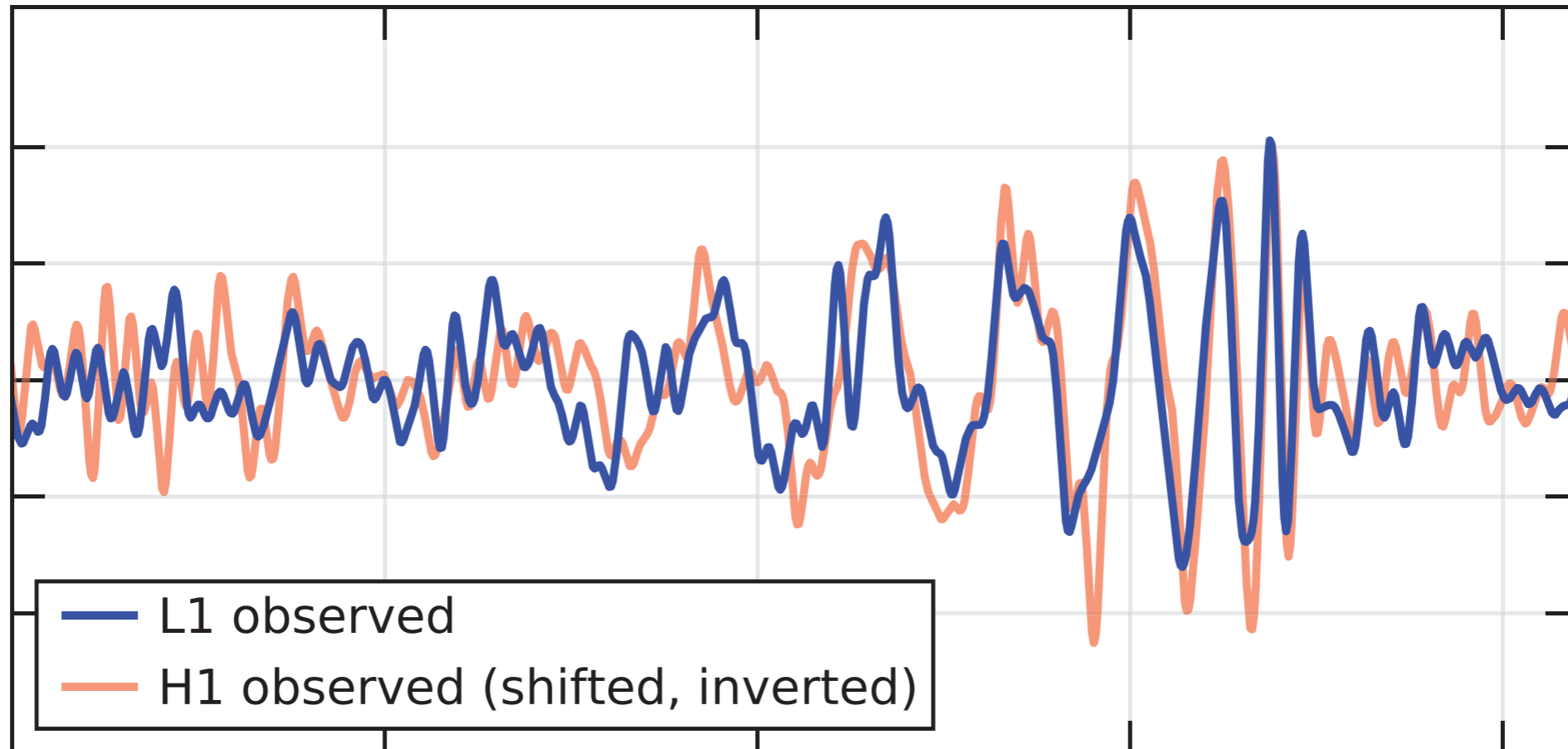
Aaron Zimmerman
University of Texas at Austin

SUSY2019
May 24, 2019

LIGO-G1901014

LIGO Scientific Collaboration

GRAVITATIONAL WAVES

Advanced LIGO and Virgo

Cascina, Italy
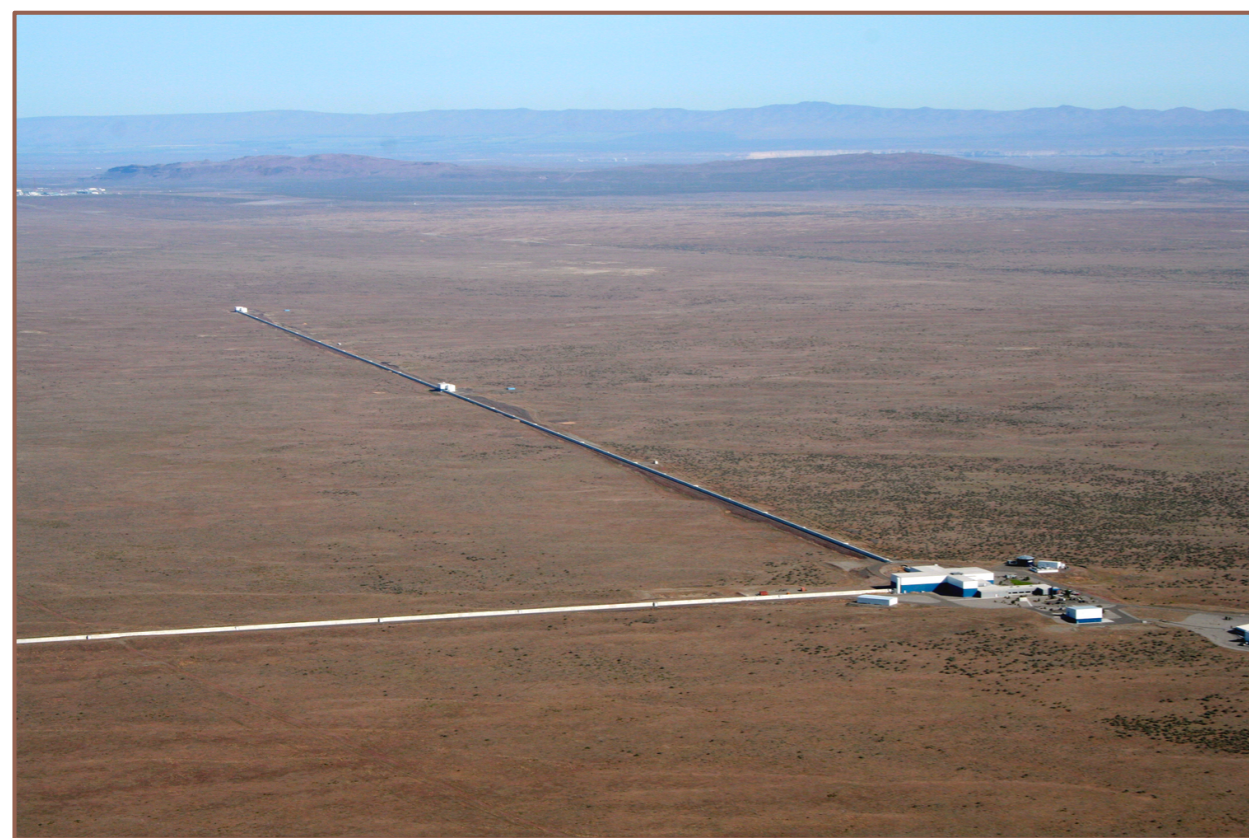
Hanford, WA

Livingston, LA

Photos courtesy LVC

A new window

A new window

Michelson perpendicular arm

$L_y = 4$ km

Laser

Input test mass

$L_x = 4$ km

End test mass

Output port

$\Delta L \sim 10^{-18}\mathrm{m}$

5

LVC PRL 116, 131103 (2016)

A new window

Credit: LIGO/T. Pyle

Michelson perpendicular arm

L_y = 4 km

Laser

Input test mass

L_x = 4 km

End test mass

Output port
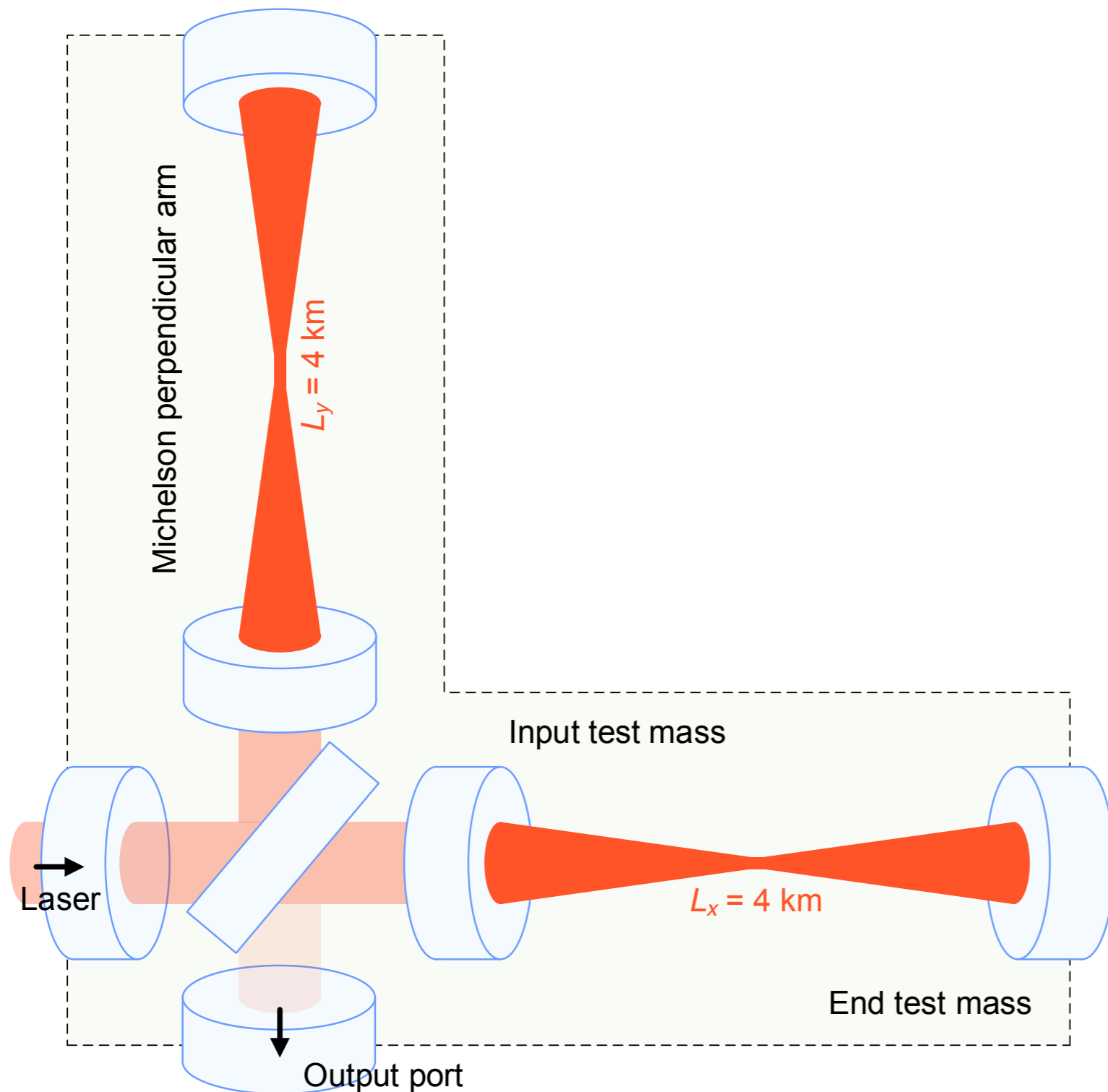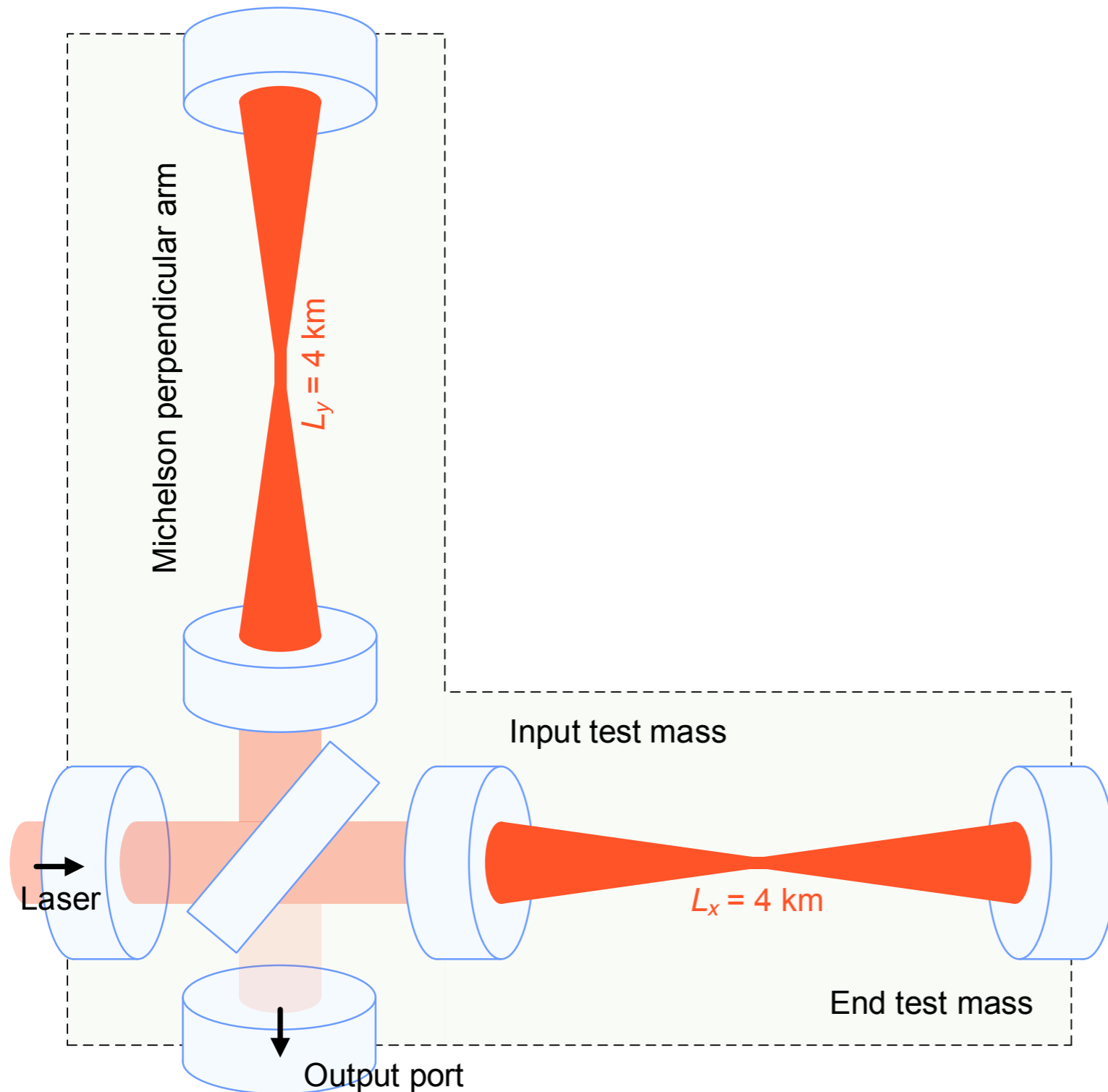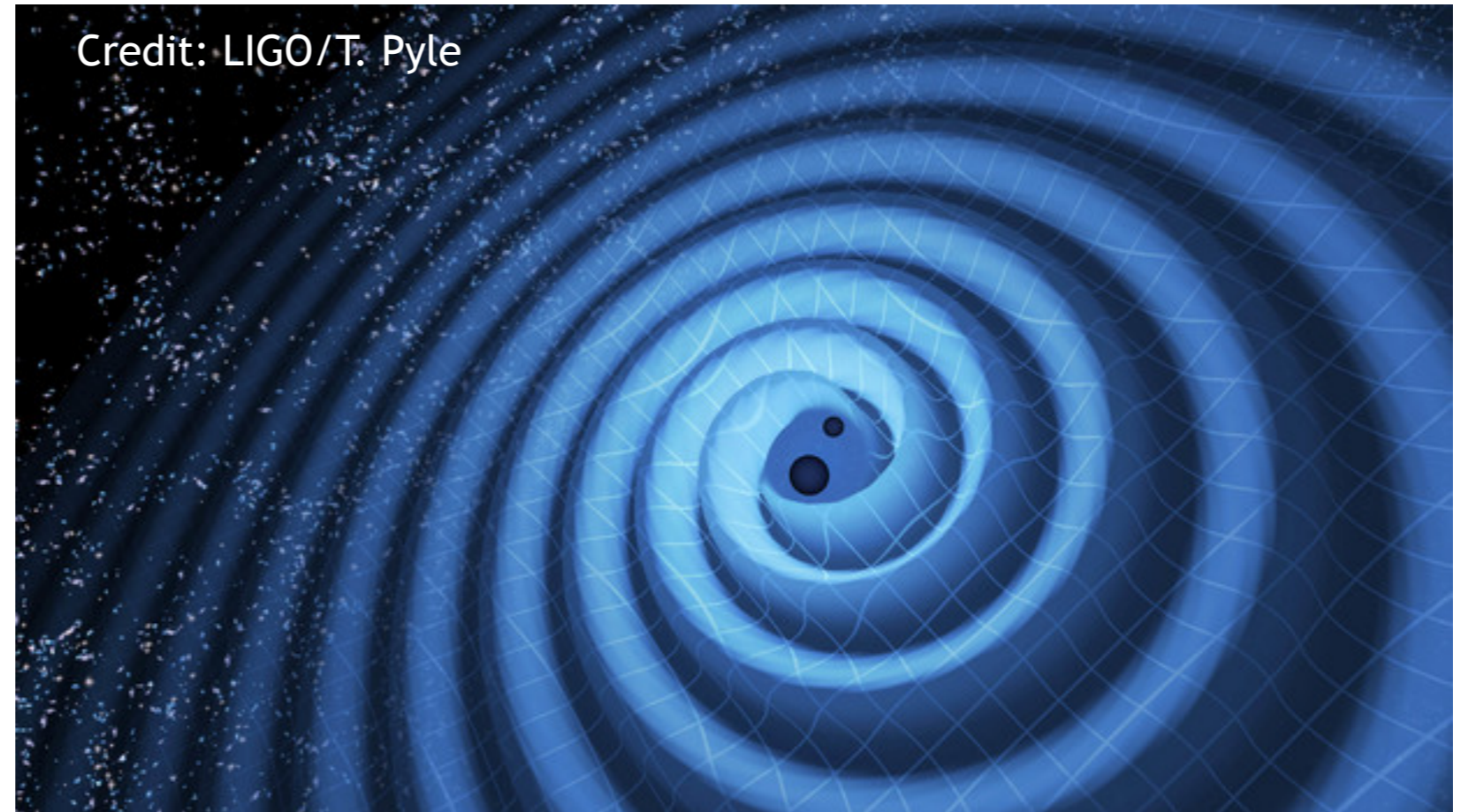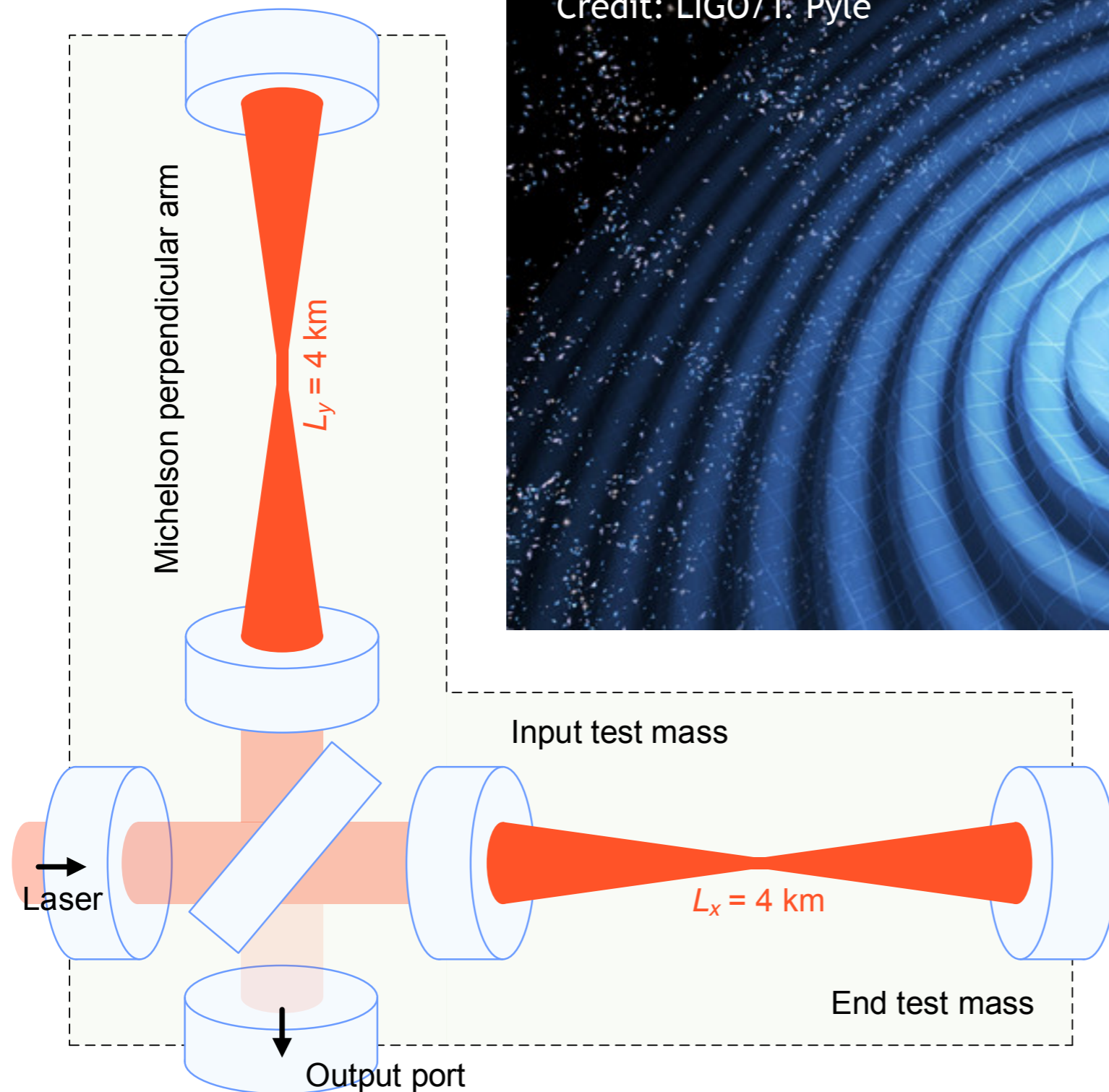
$$\Delta L \sim 10^{-18}\mathrm{m}$$

First detection: GW150914
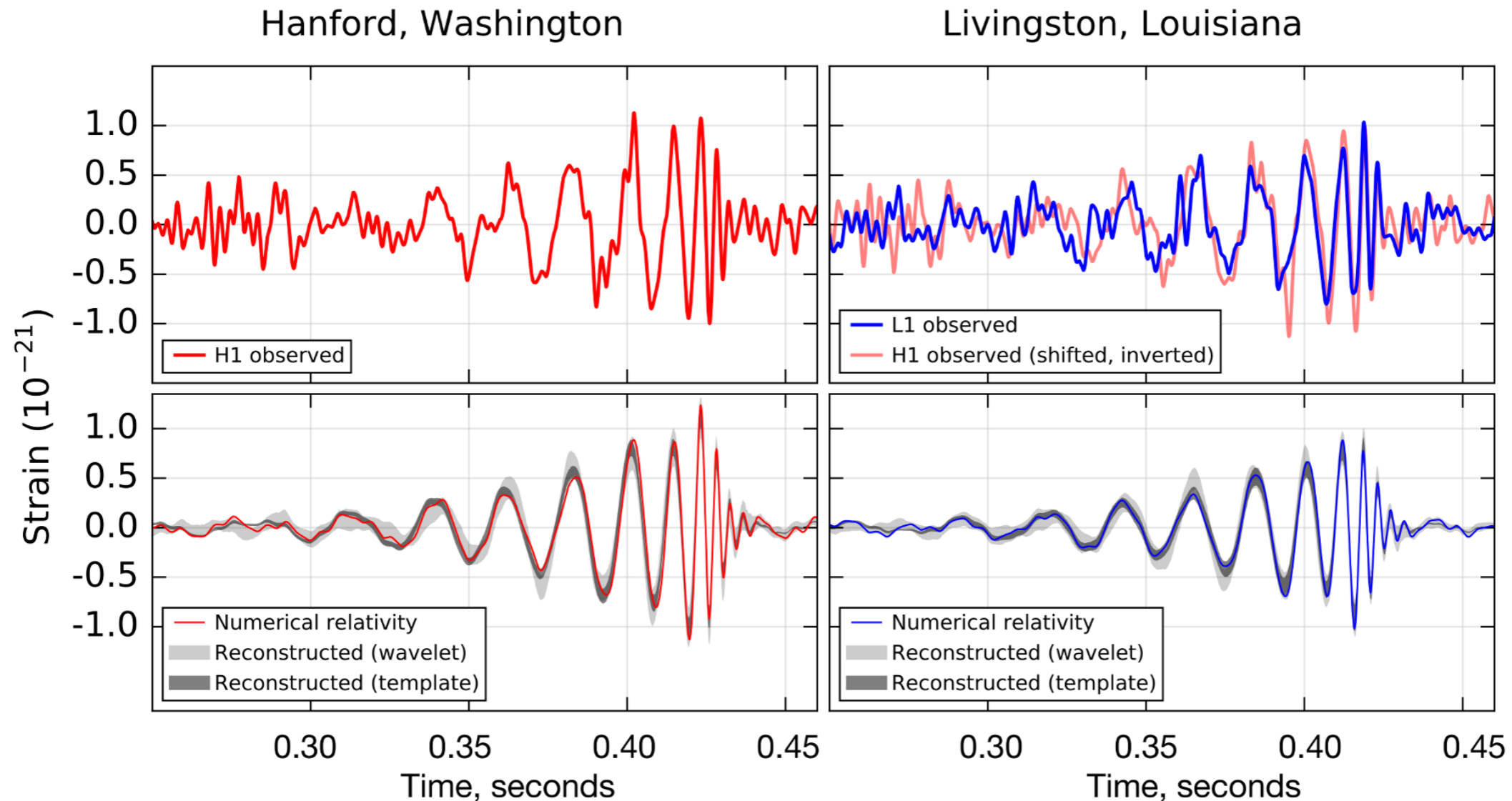
- Masses $\qquad m_1 = 36^{+5}_{-4} M_\odot \qquad m_2 = 29^{+4}_{-4} M_\odot$

- Peak luminosity $\qquad L \sim 10^{23} L_\odot \sim 10^{13} L_{\mathrm{MWG}}$

Binary black hole catalog

LVC arXiv:1811.12907

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GWTC-1: Catalog of detections

8
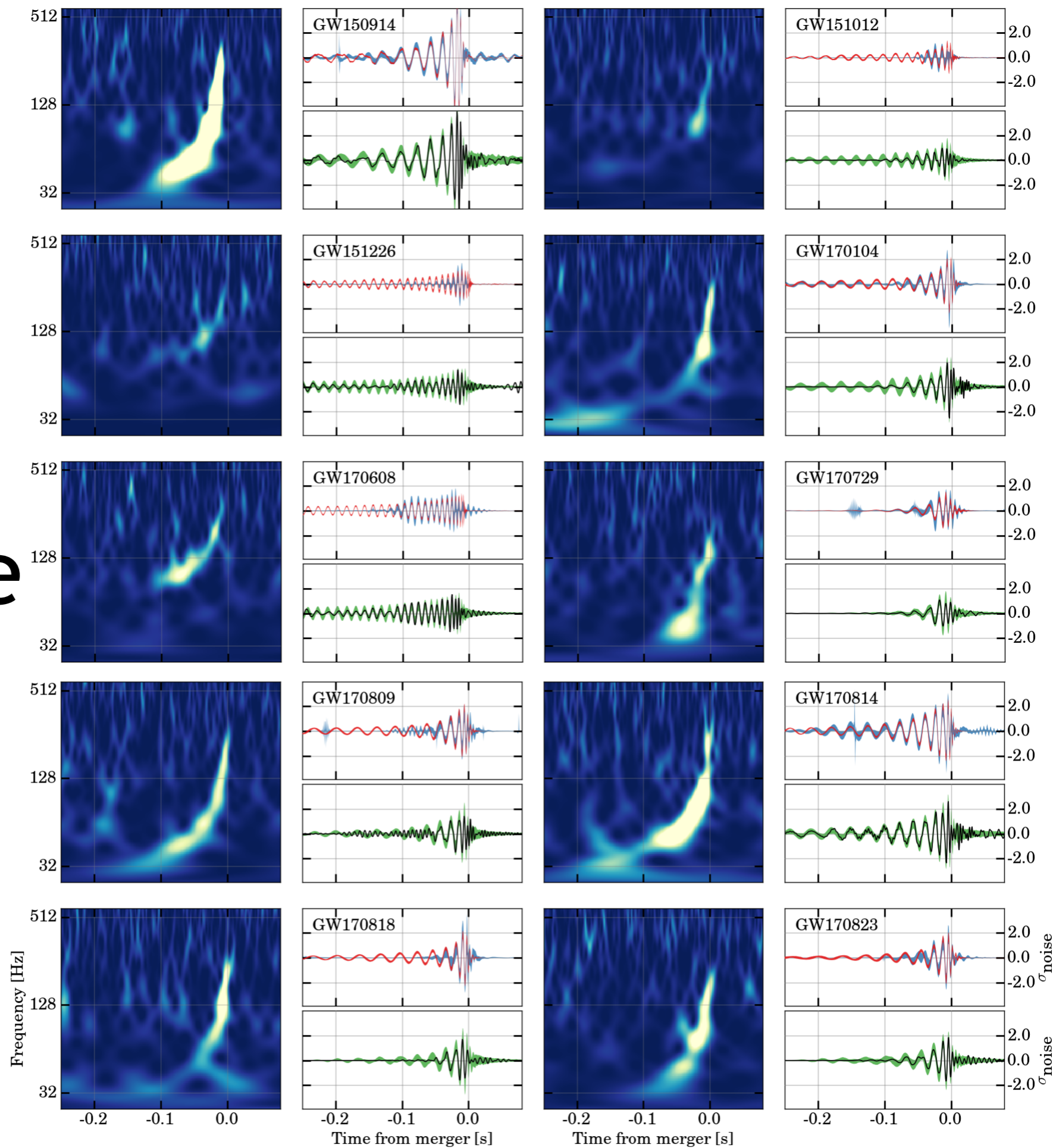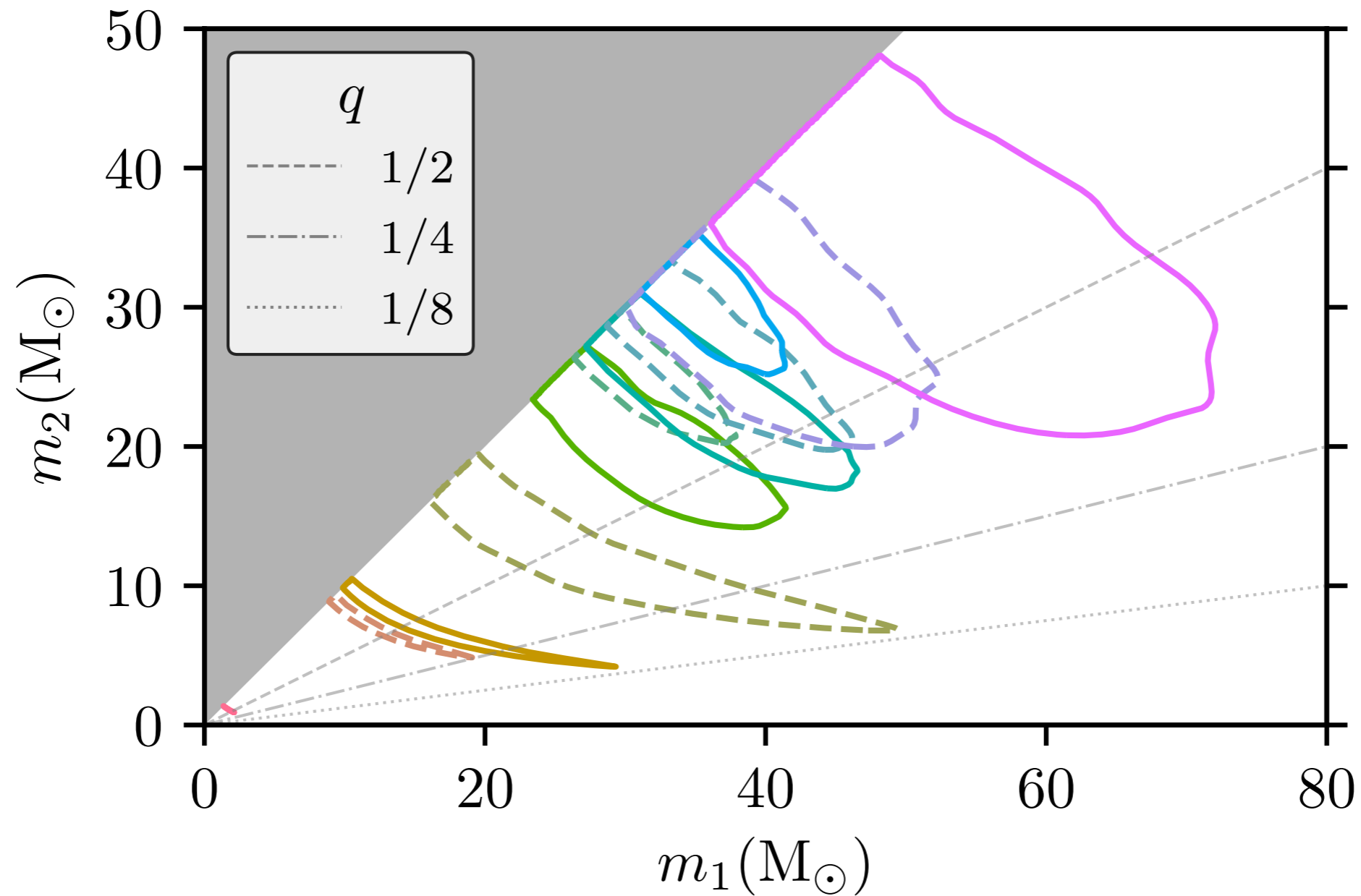
GWTC-1: Catalog of detections
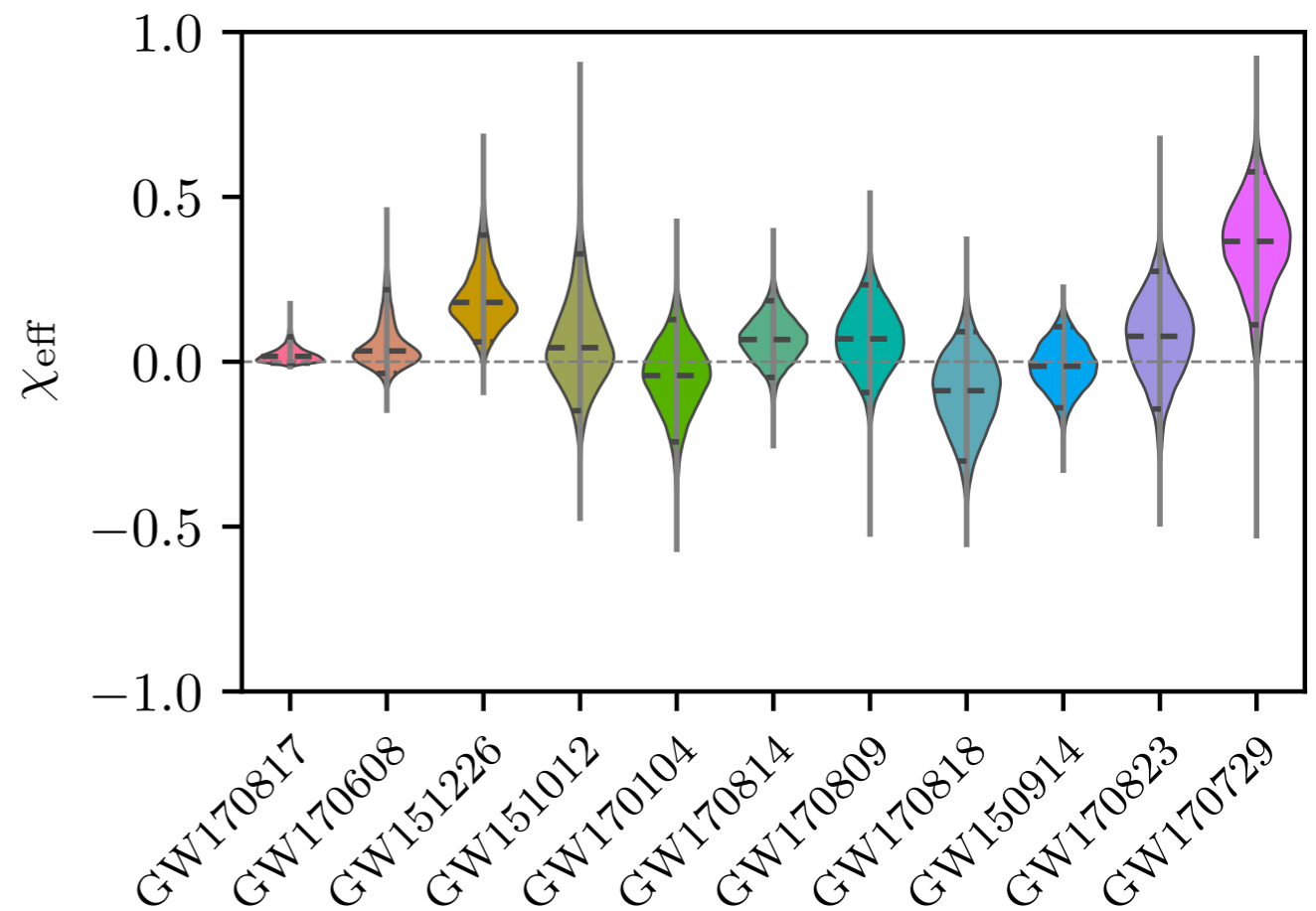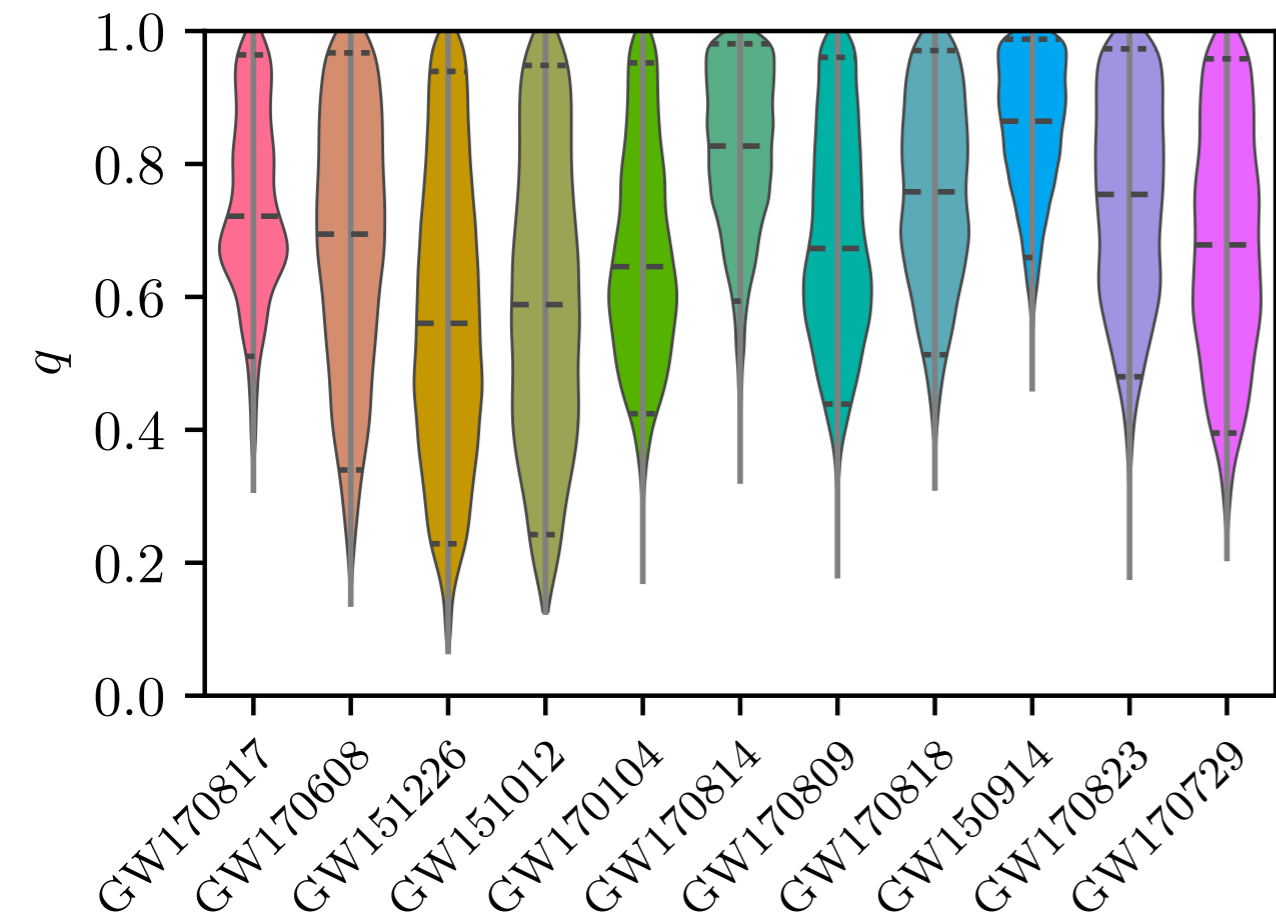
Astrophysics with GWs
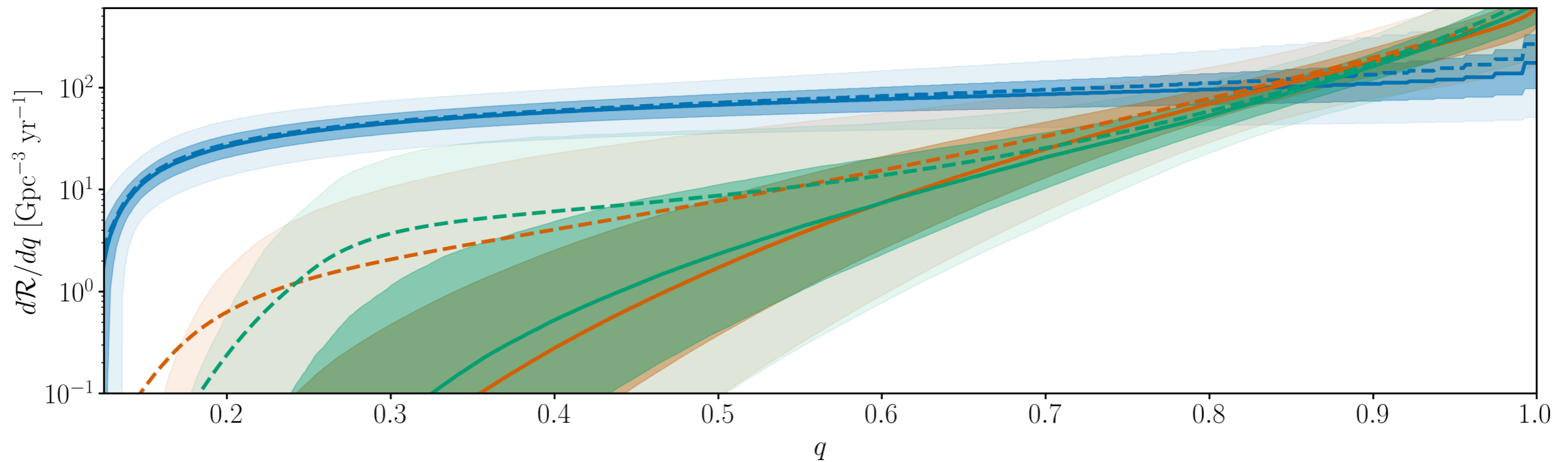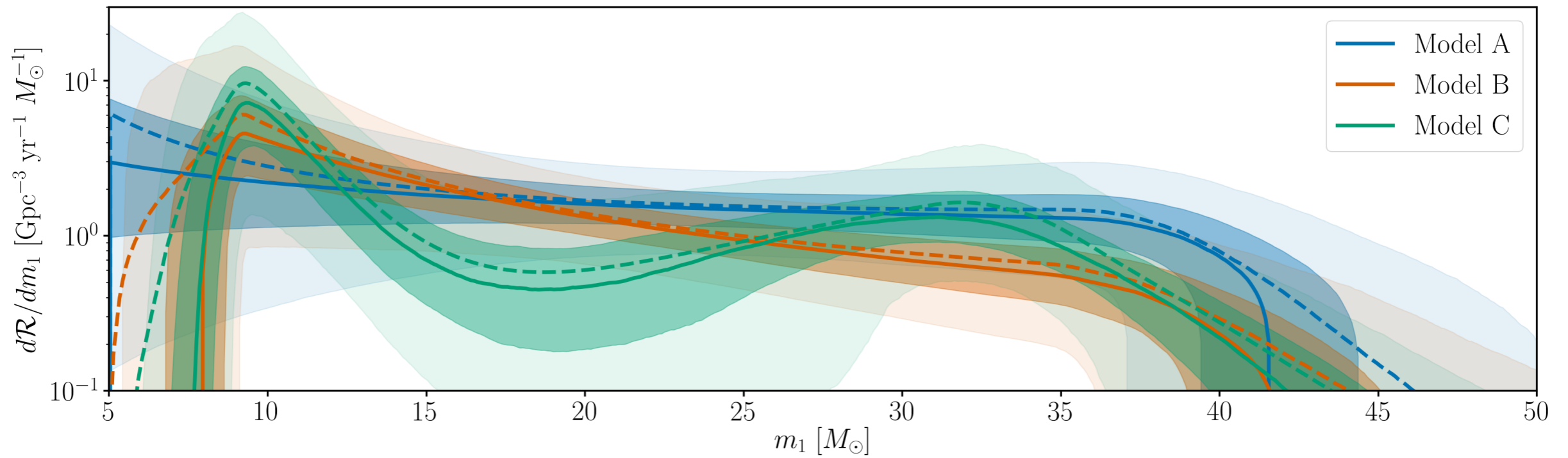
Astrophysics with GWs
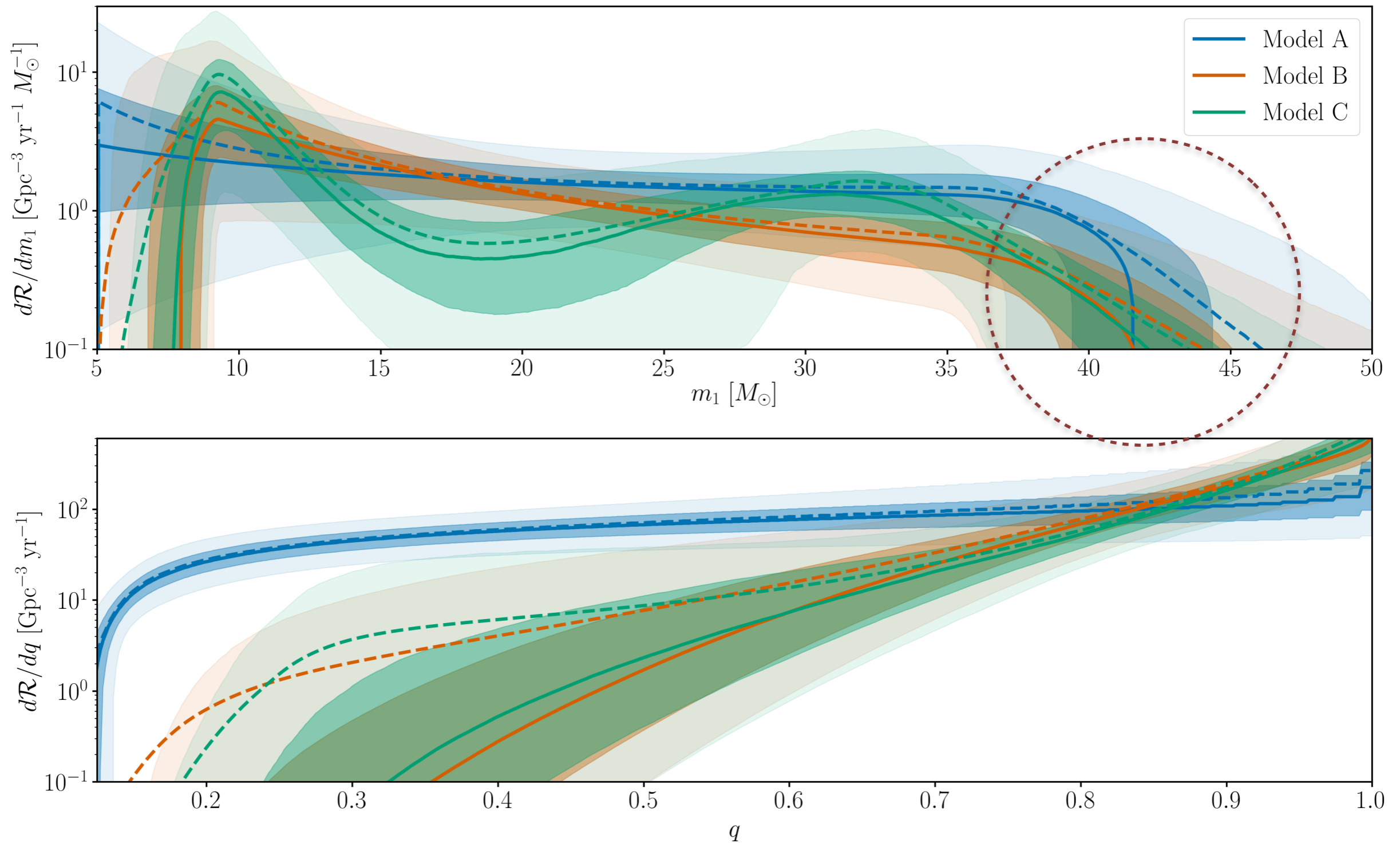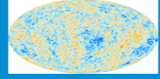
GW170817: A binary neutron star

Credit: Alex Nitz/Max Planck Institute for Gravitational Physics/LIGO
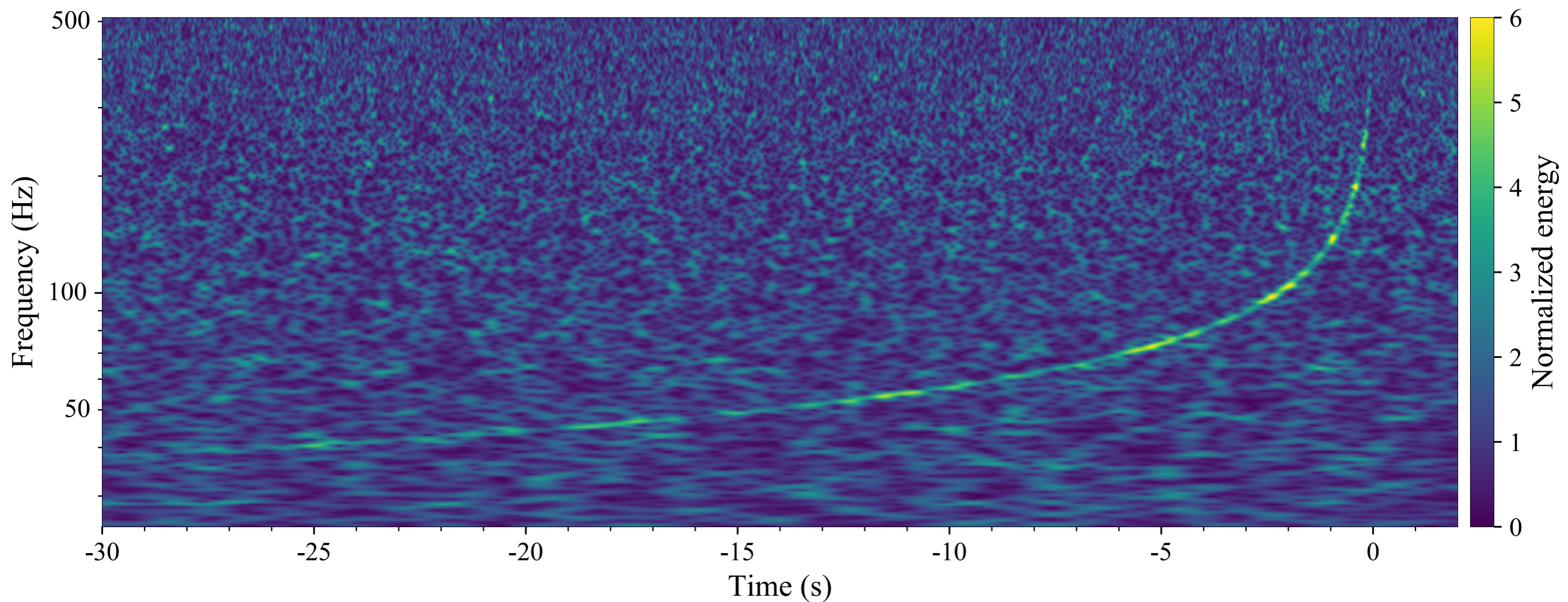
Electromagnetic counterpart
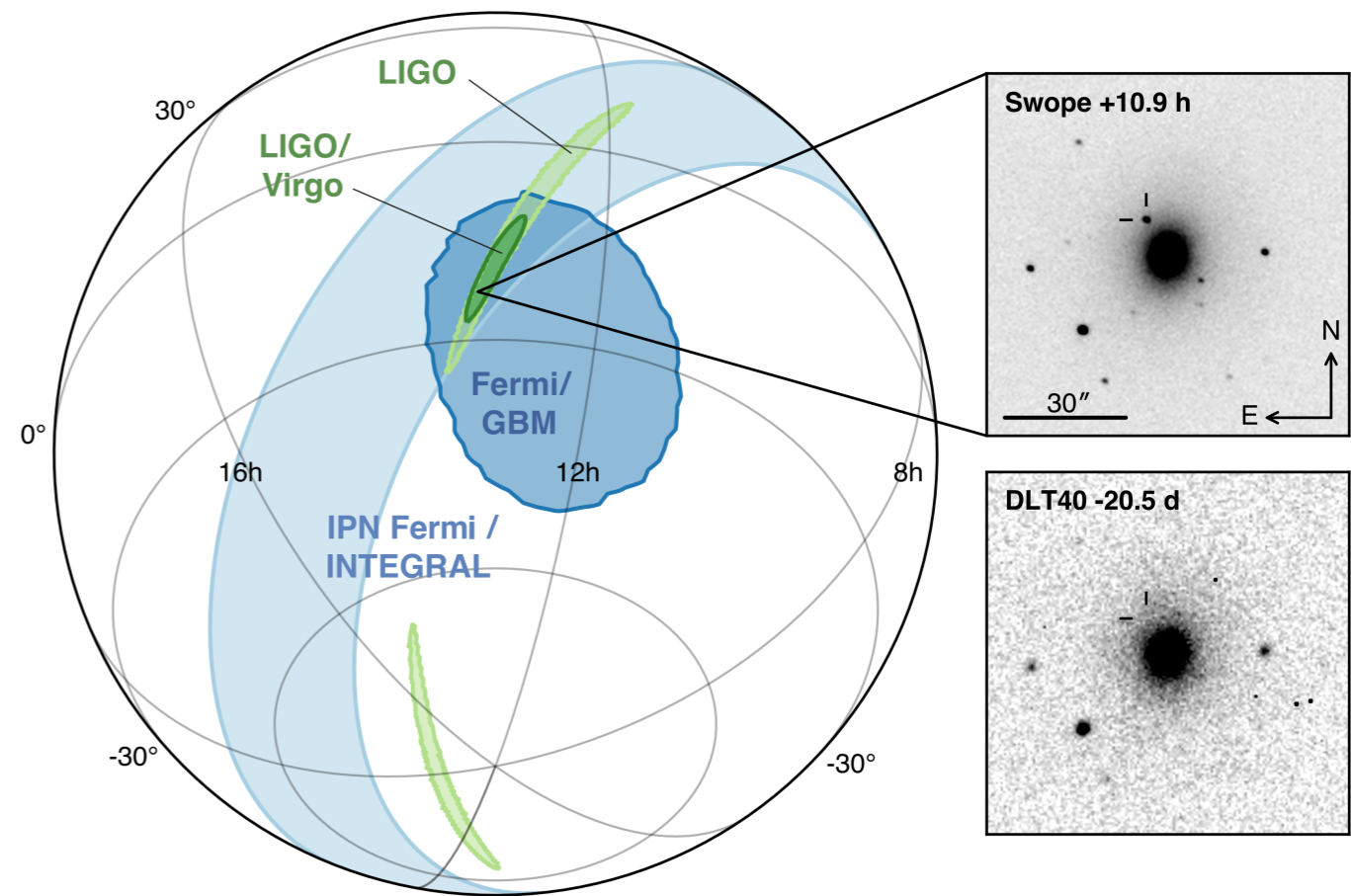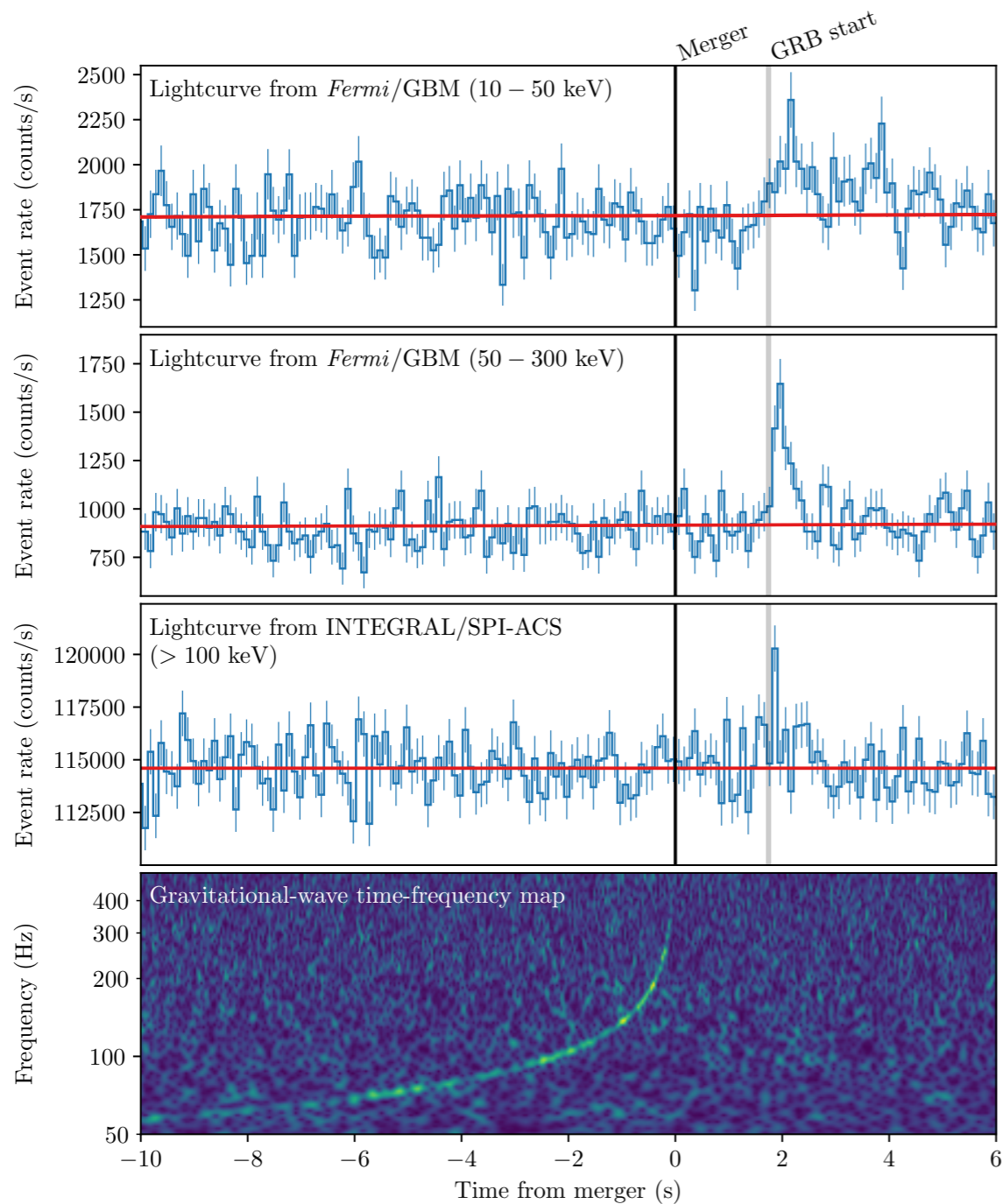
The Origin of the Solar System Elements

big bang fusion	cosmic ray fission	
merging neutron stars	exploding massive stars	
dying low mass stars	exploding white dwarfs	

Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova

FUNDAMENTAL PHYSICS WITH GRAVITATIONAL WAVES

Nuclear physics with GW170817

Λ
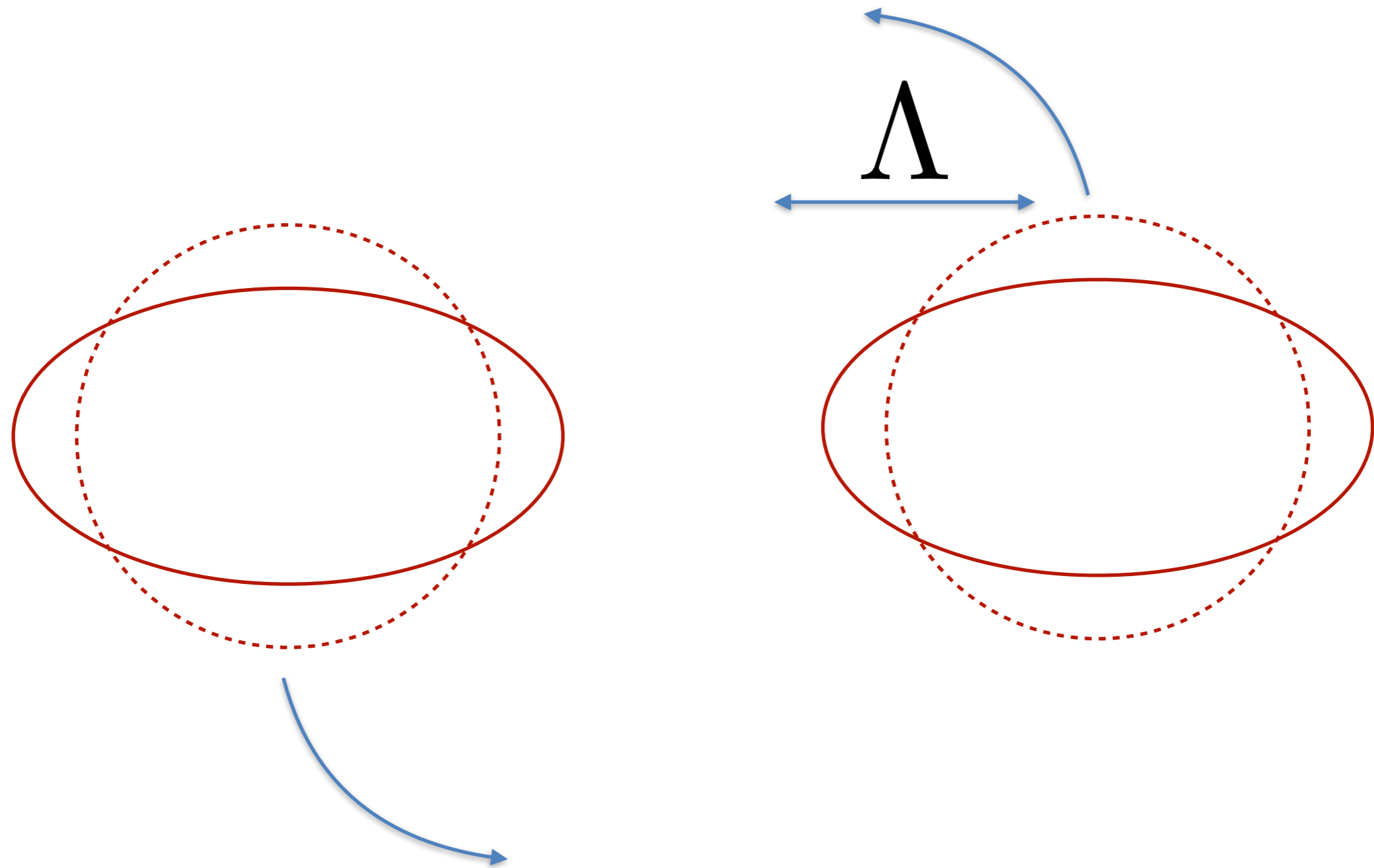
Flanagan and Hinderer, PRD (2008)
Hinderer ApJ (2008)
Hinderer, Lackey, Lang, Read PRD (2010)

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TEXAS

Nuclear physics with GW170817

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Nuclear physics with GW170817

Tests of relativity: Constraining deviations

$$h(f) = A(f, \vec{\theta})e^{i\Psi(f,\vec{\theta})}$$

$$\Psi = f^{-5/3}\sum_{i=0}^{7} p_i(\vec{\theta})f^{i/3} + (\text{log terms}) \qquad p_i \rightarrow p_i(1 + \delta\hat{p}_i)$$

Combining events

$$\frac{p(d|H_1)}{p(d|H_2)}$$

GR+noise
nonGR+noise, $\mu = 1$
nonGR+noise, $\mu \in [-1,1]$
$\sim \sqrt{N}$ (GR analytic)
$\sim \sqrt{N}e^{-N/2}$ (nonGR analytic)

$$\delta\hat{\varphi}_i \sim \mathcal{N}(\mu_i, \sigma_i)$$

AZ, Haster, Chatziioannou, arXiv: 1903.11008
Isi, Chatziioannou, Farr, arXiv: 1904.08011

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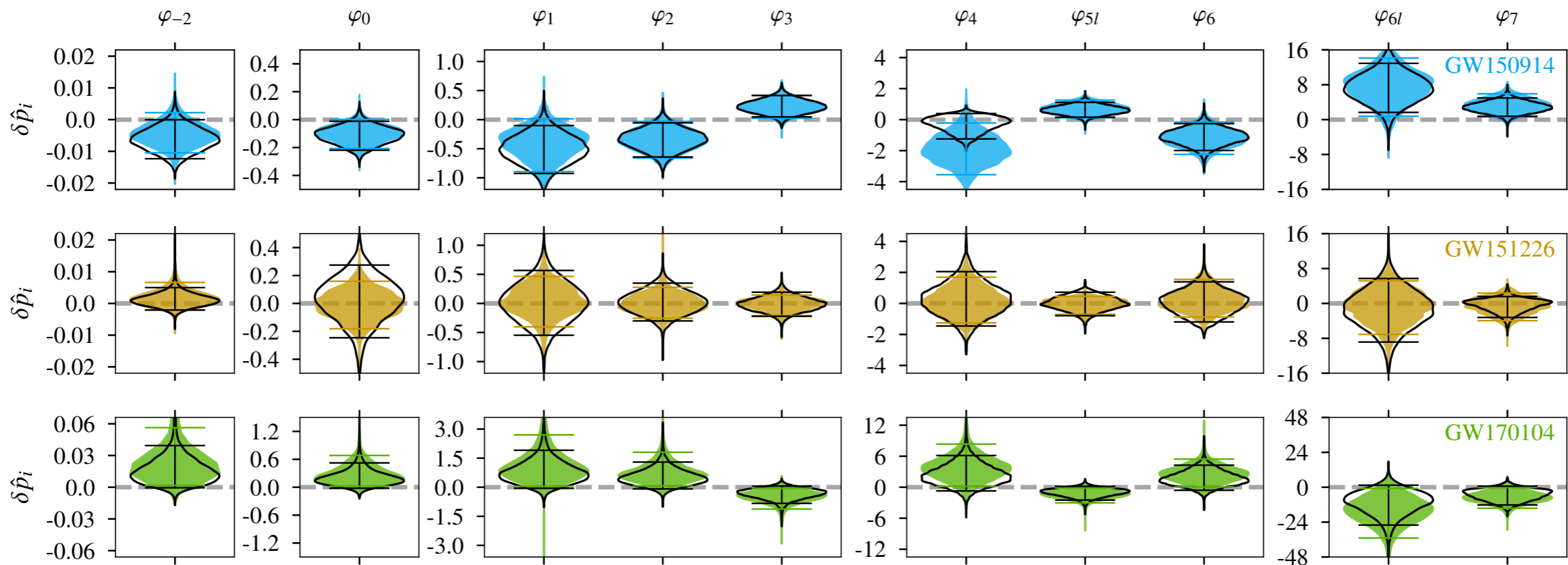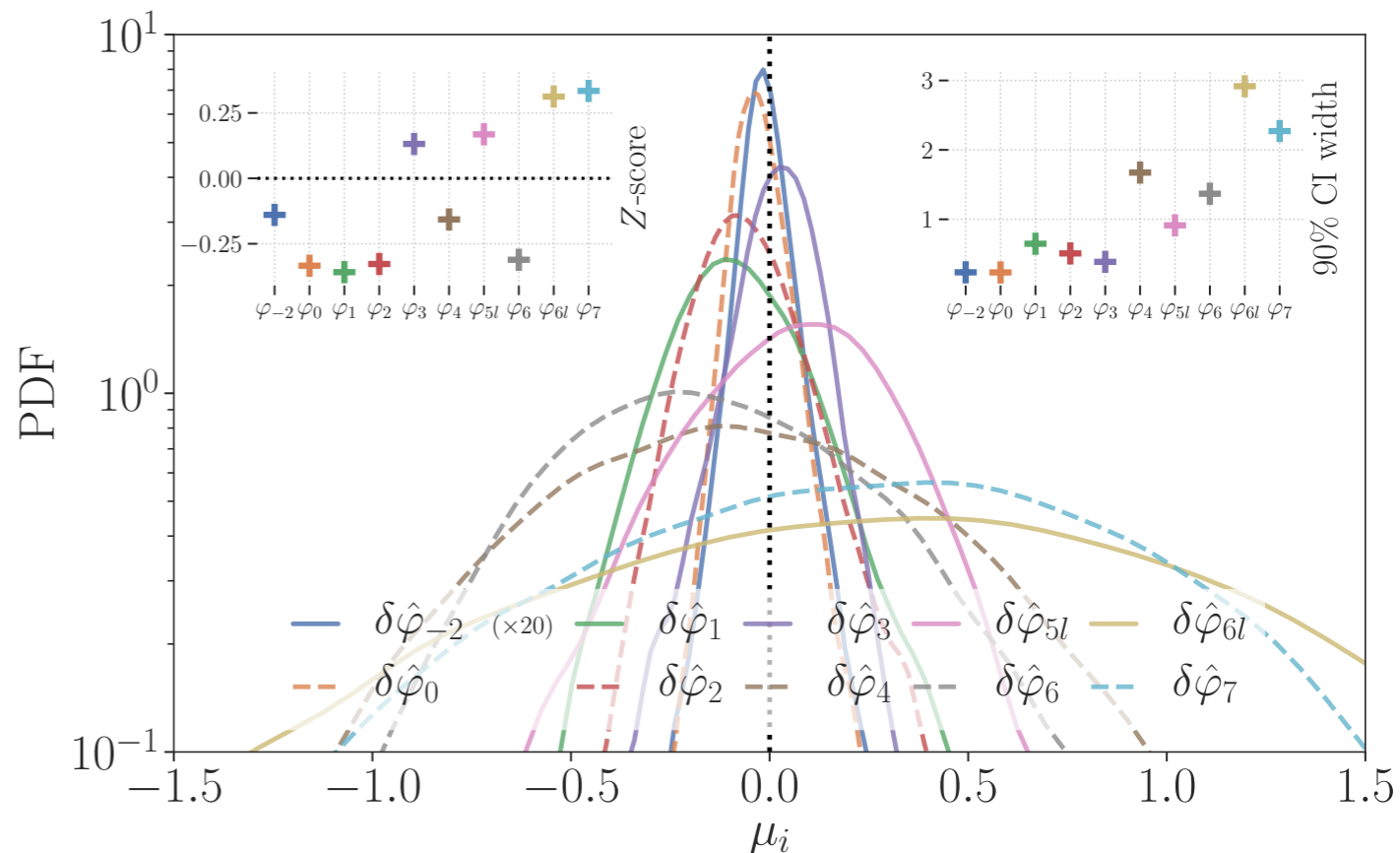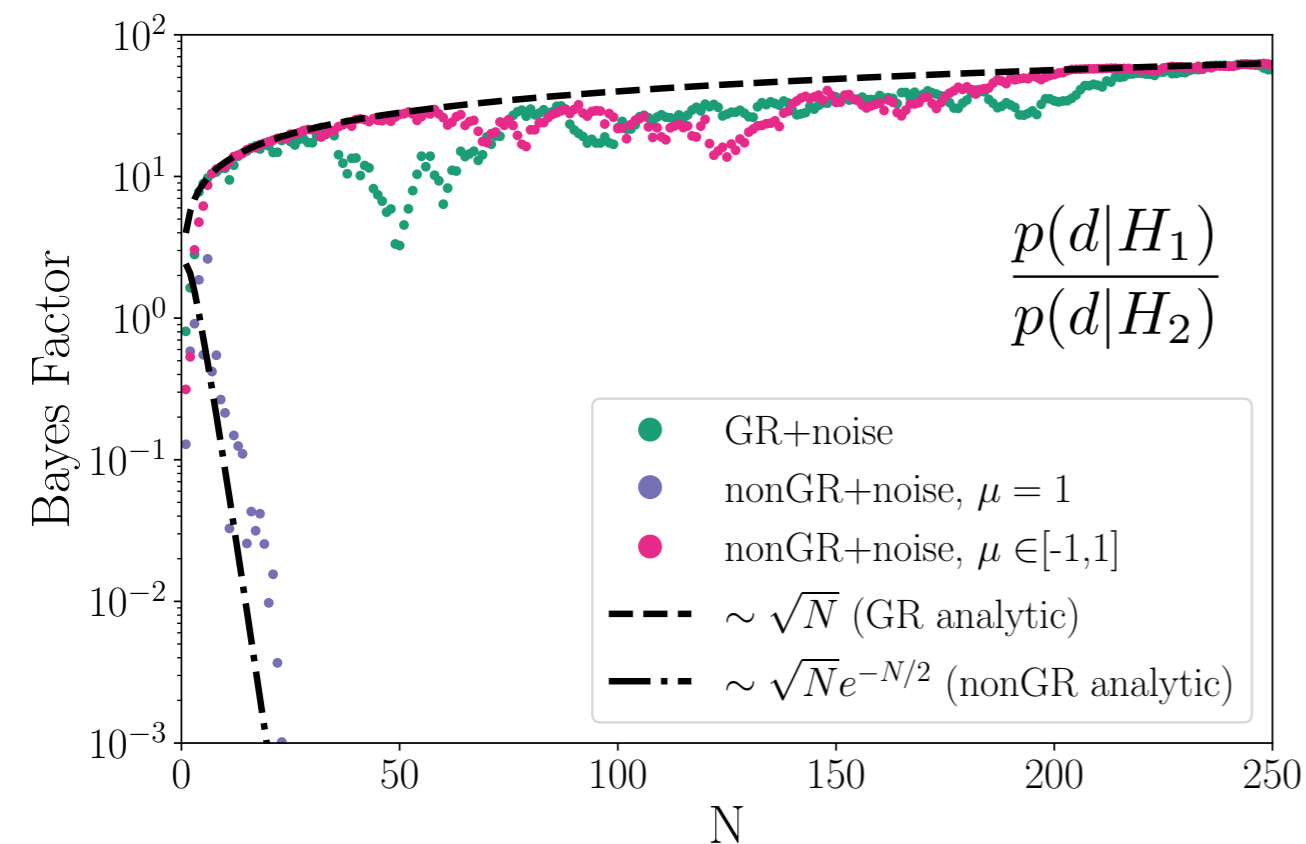
GW150914: Black hole ringdown
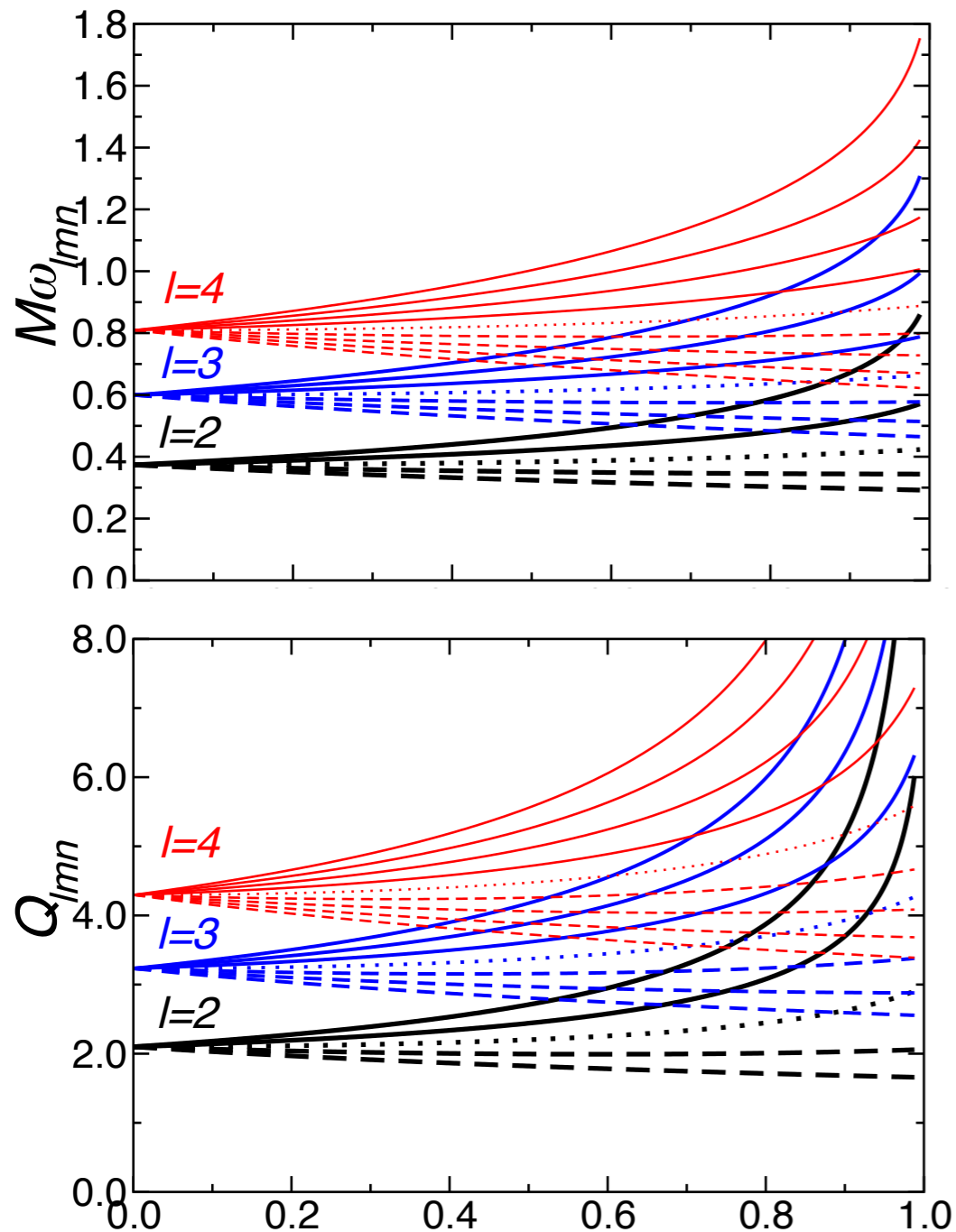
Berti, Cardoso, Starinets (2009)
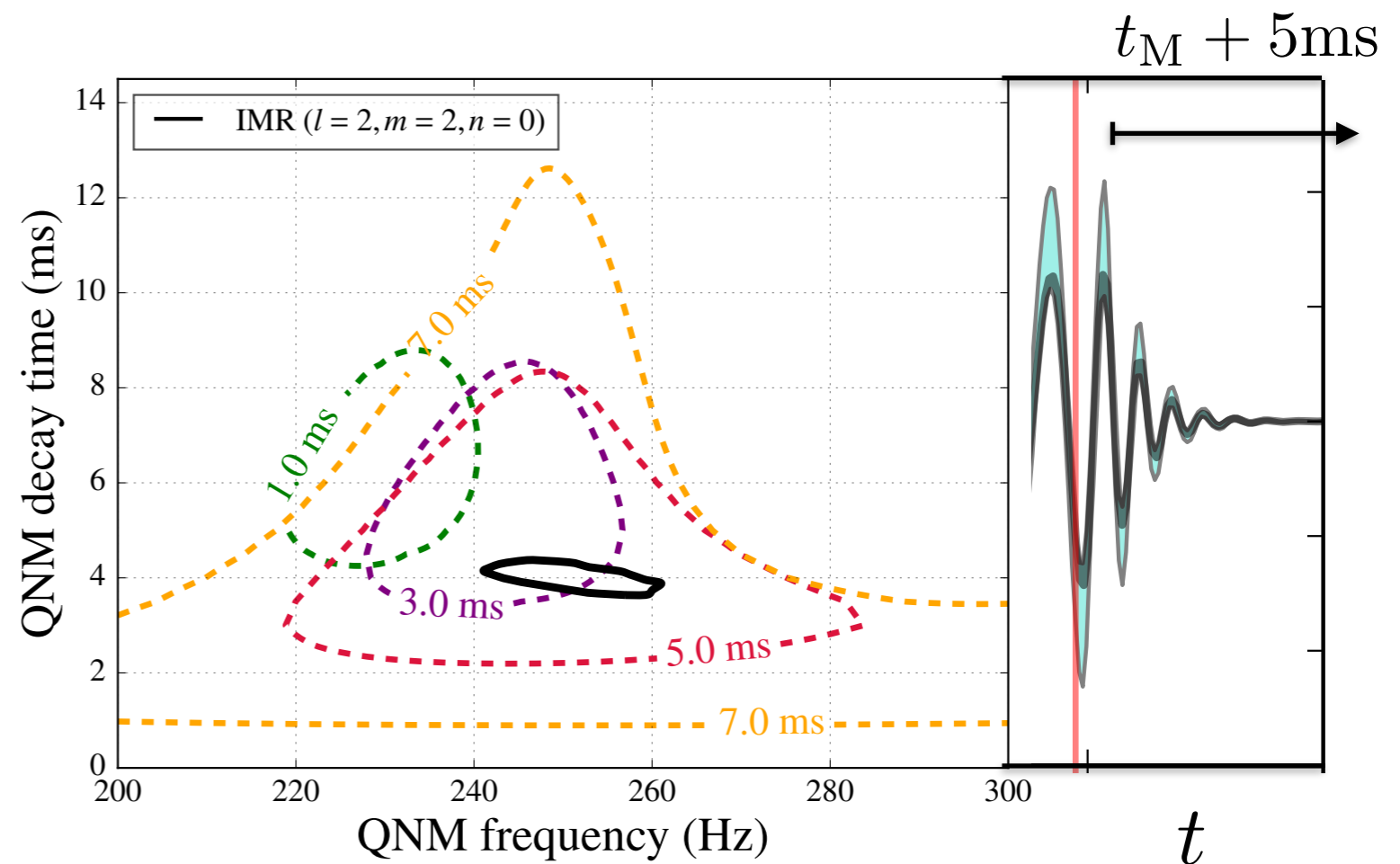
LCV PRL 116, 221101 (2016)

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Propagation of GWs
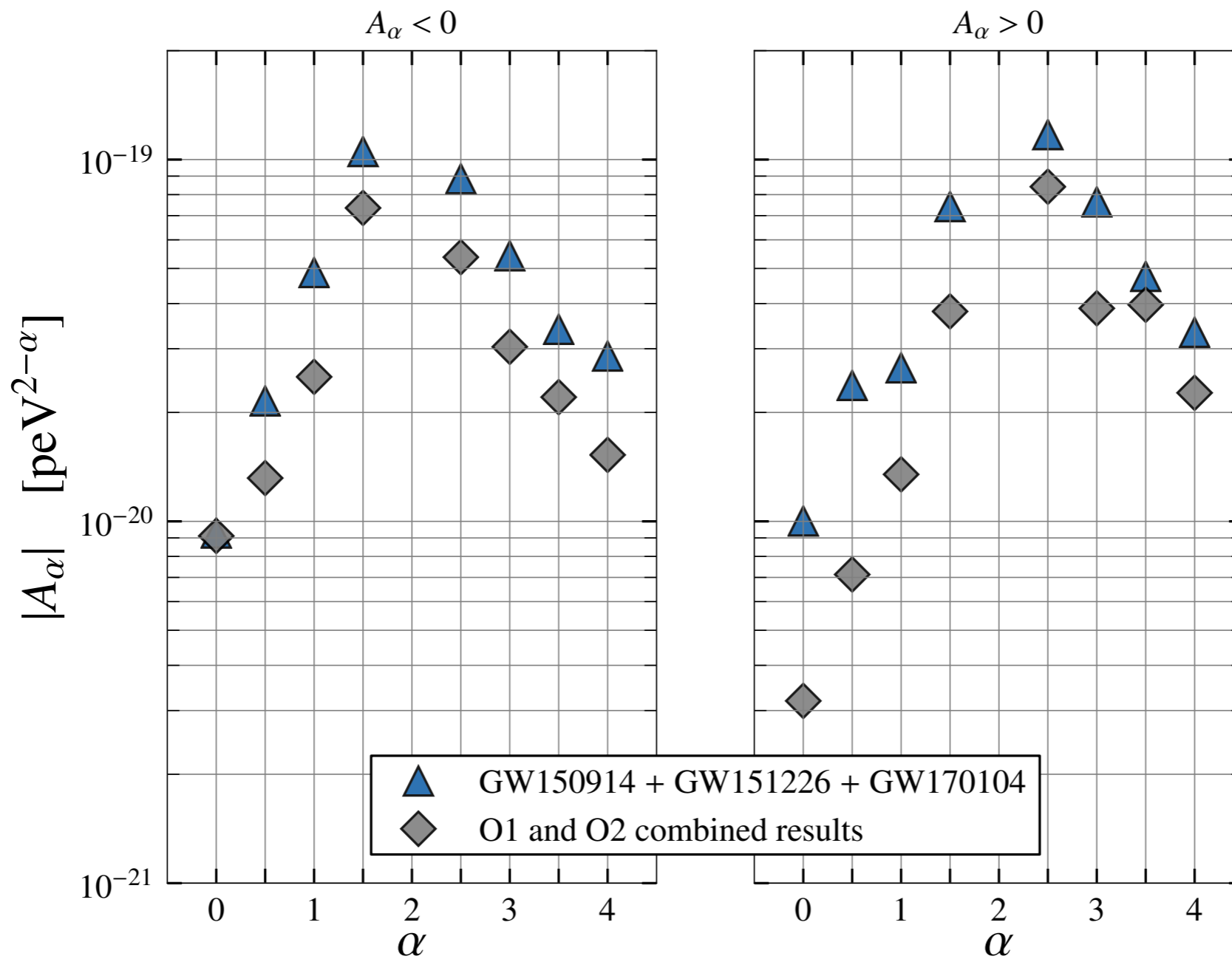
$$E^2 = p^2 c^2 + A p^\alpha c^\alpha \qquad m_g \leq 5 \times 10^{-23}\,\mathrm{eV}/c^2$$

Speed of gravitational waves

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v} \leq +7 \times 10^{-16}$$

LVC and Fermi/INTEGRAL, ApJ Lett 848, L13 (2017)
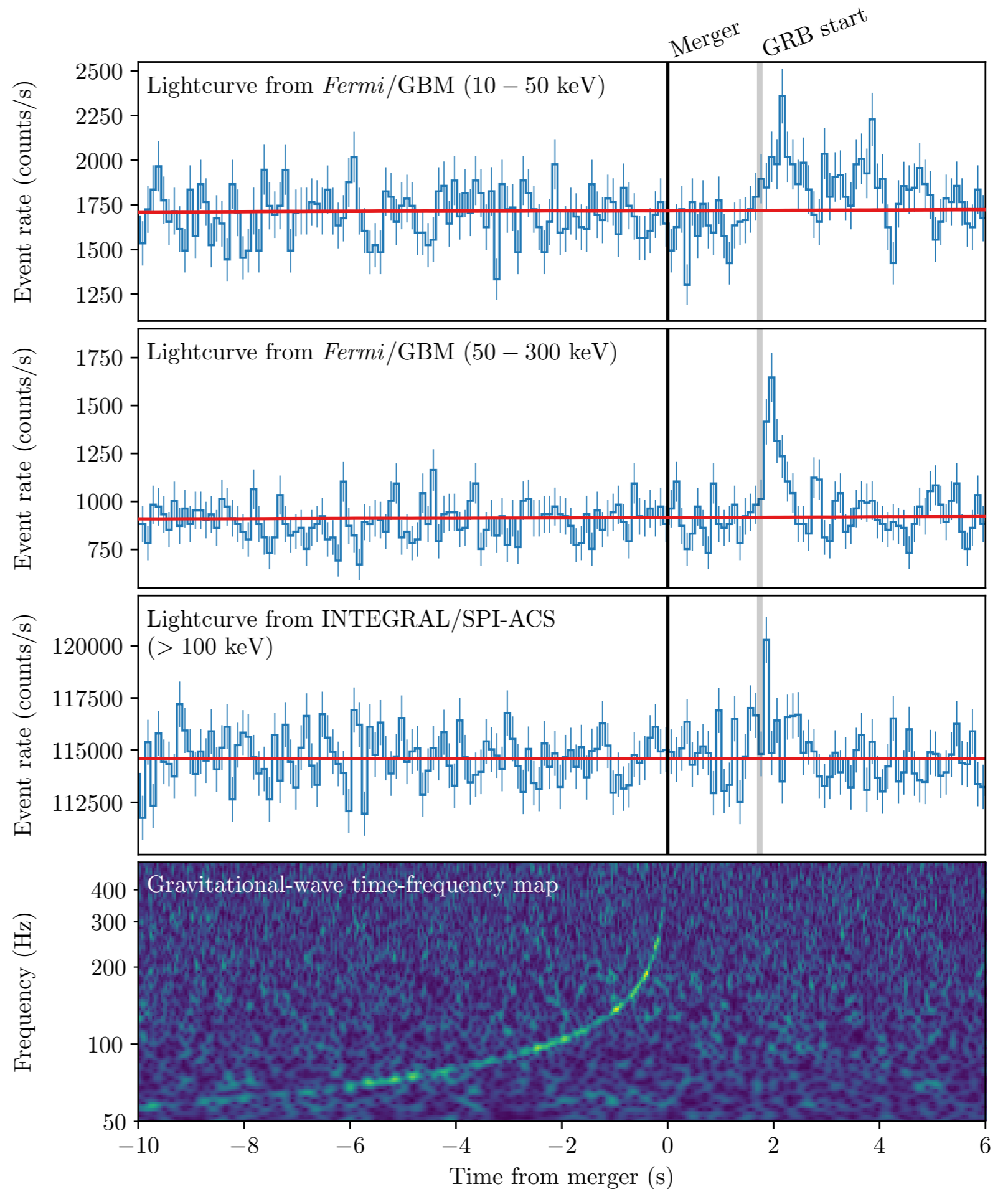
Standard siren cosmology

LVC and EM partners, Nature 551, 85 (2017)
LVC PRX 9, 011001 (2019)
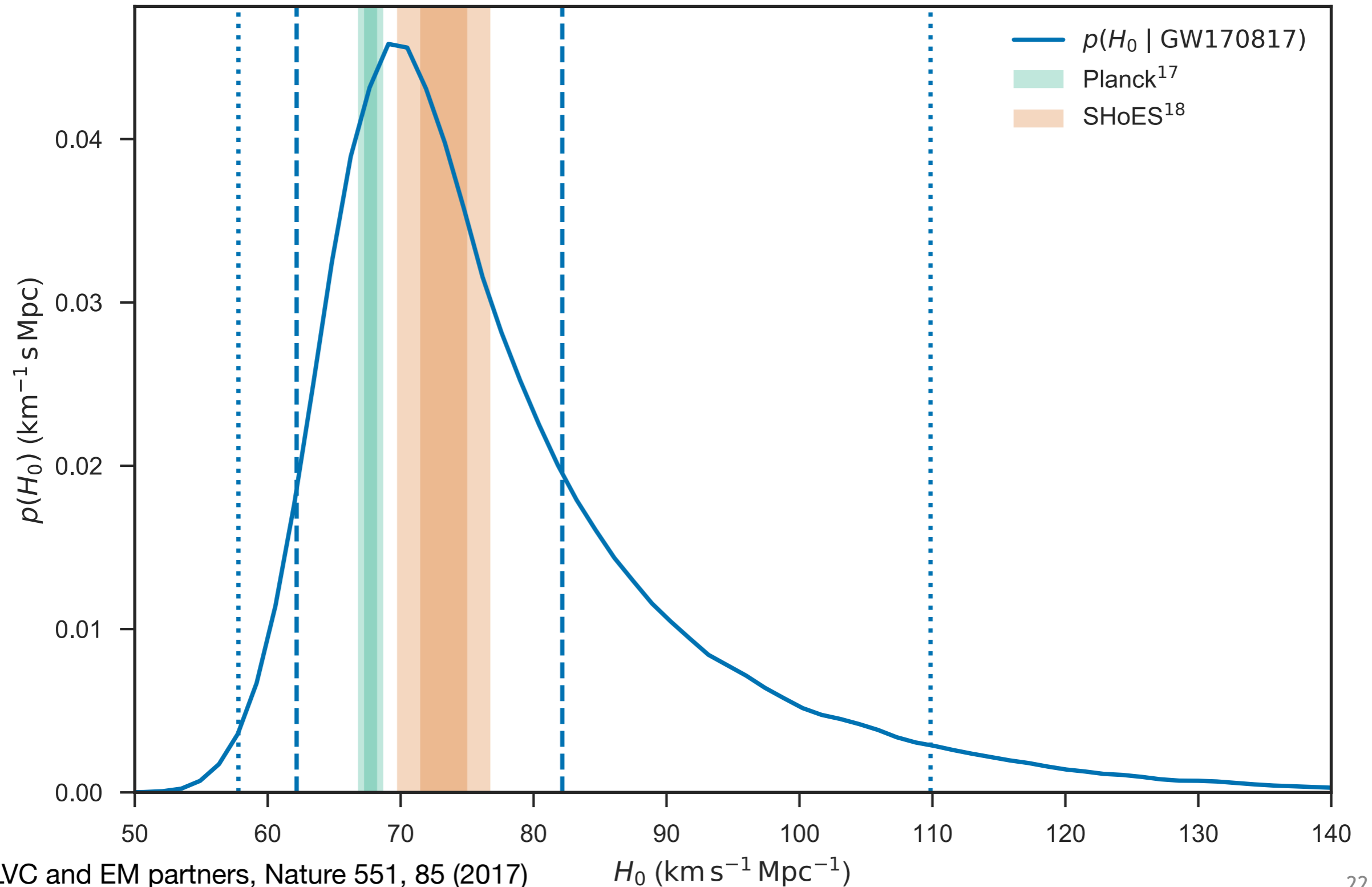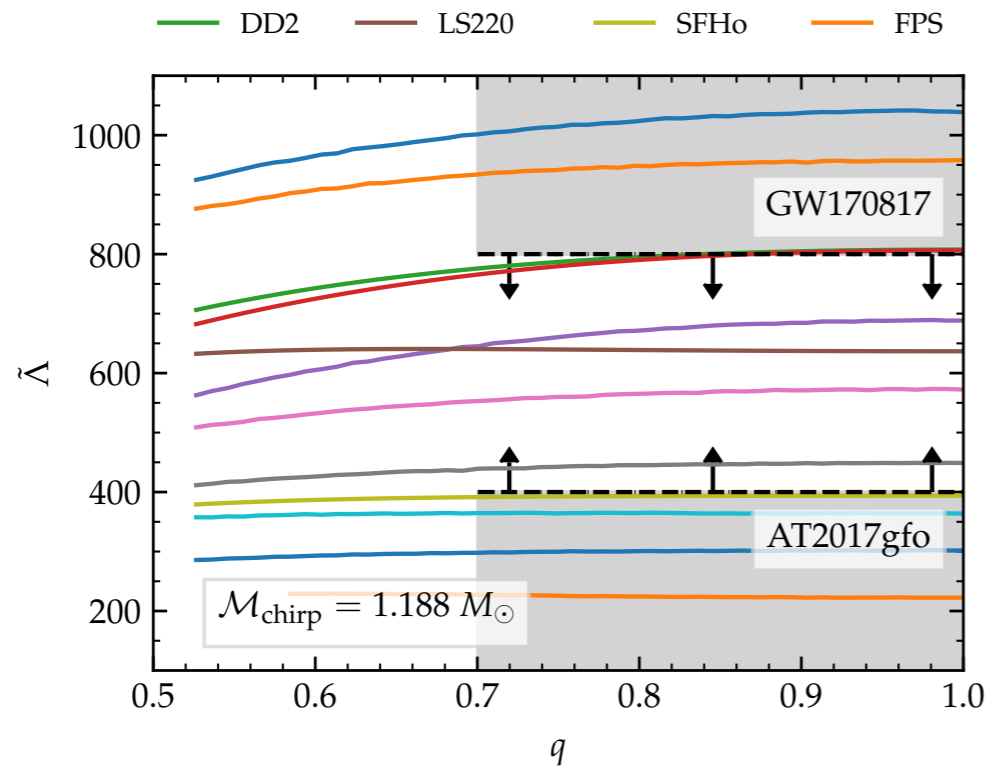
Other directions

Radice, Perego, Zappa, ApJL 852:L29 (2018)

Other directions
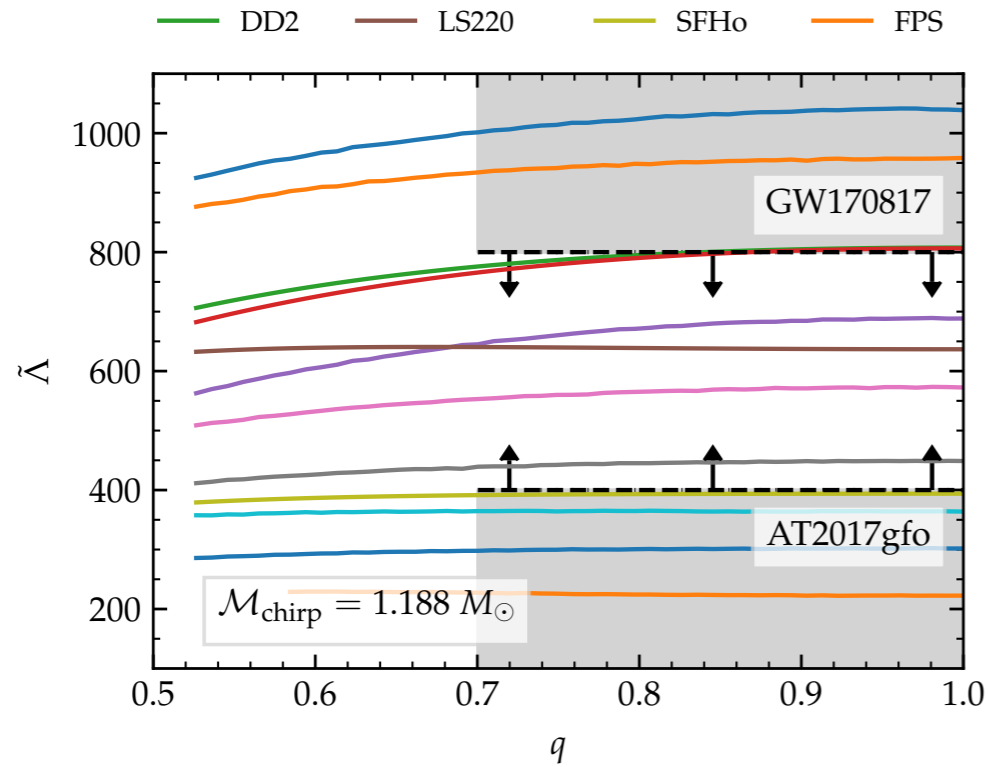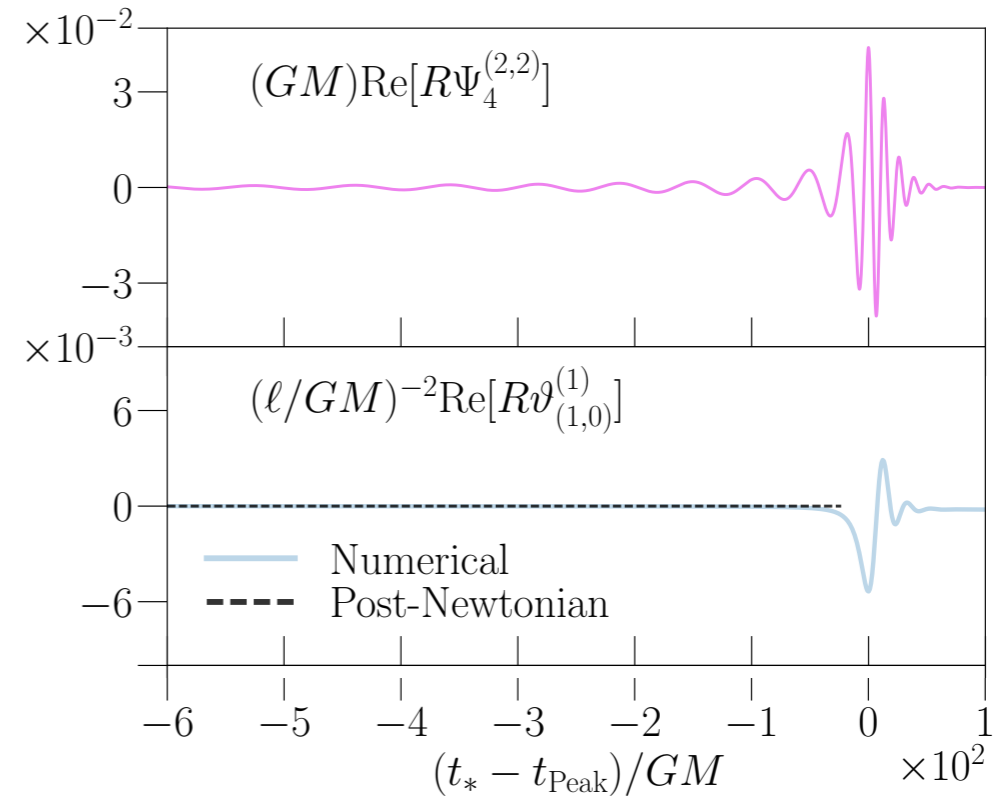
Radice, Perego, Zappa, ApJL 852:L29 (2018)

Okounkova et al. PRD (2017)

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Other directions

Radice, Perego, Zappa, ApJL 852:L29 (2018)

Okounkova et al. PRD (2017)

Cardoso, Pani arXiv:1904.05363

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Other directions

Radice, Perego, Zappa, ApJL 852:L29 (2018)

Okounkova et al. PRD (2017)

Cardoso, Pani arXiv:1904.05363

Arvanitaki et al. PRD (2017)
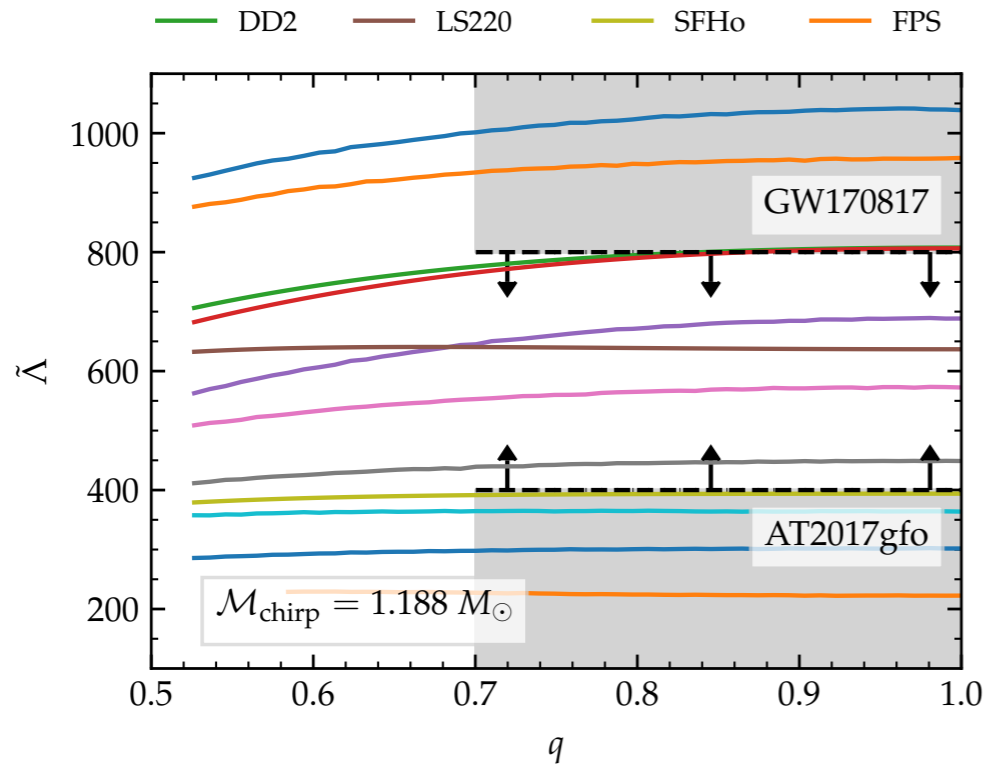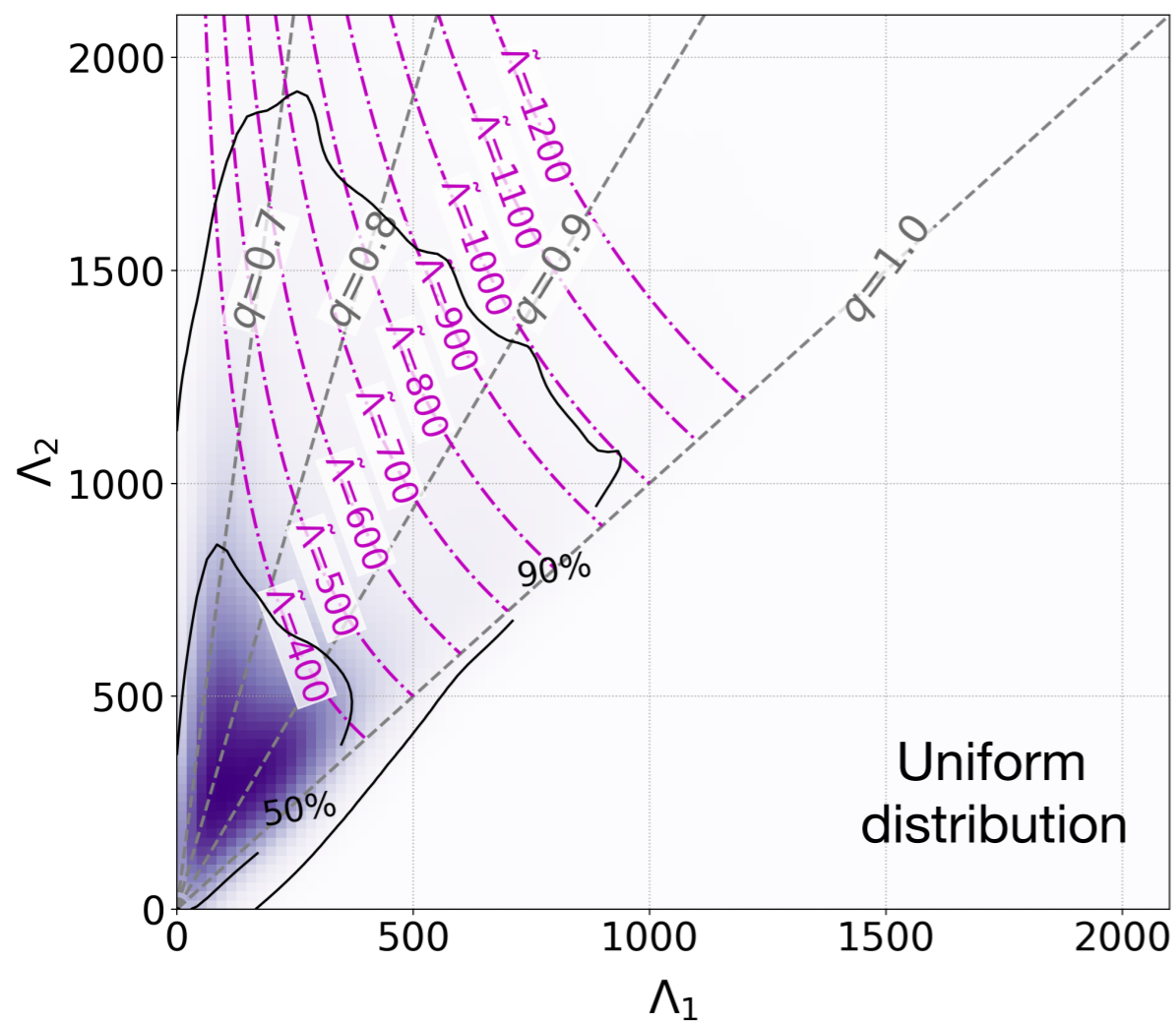
Open data analysis

De et al. PRL (2018)
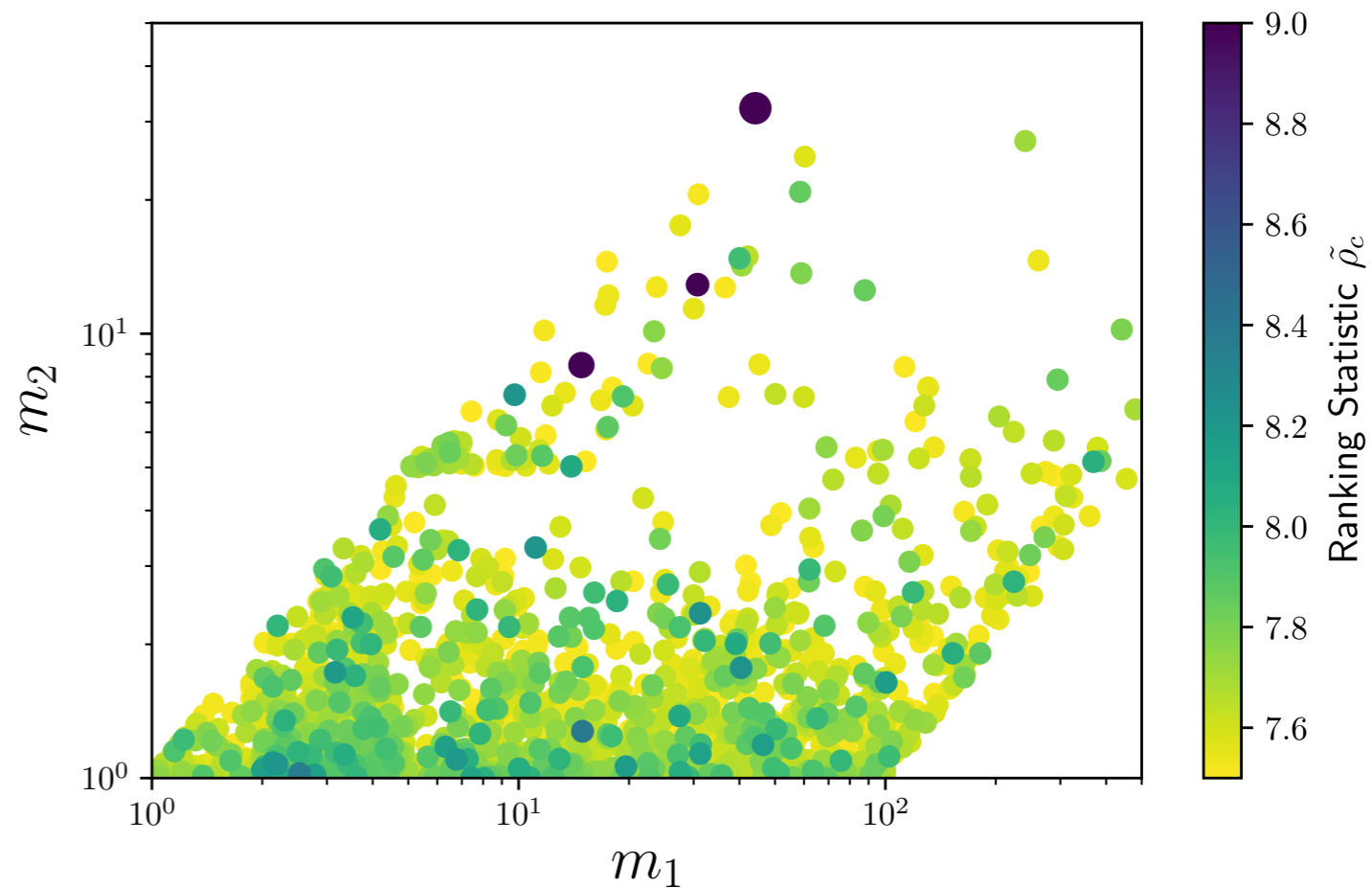
Nitz et al. ApJ (2019)

Open data analysis

Binary black hole events in O1 and O2
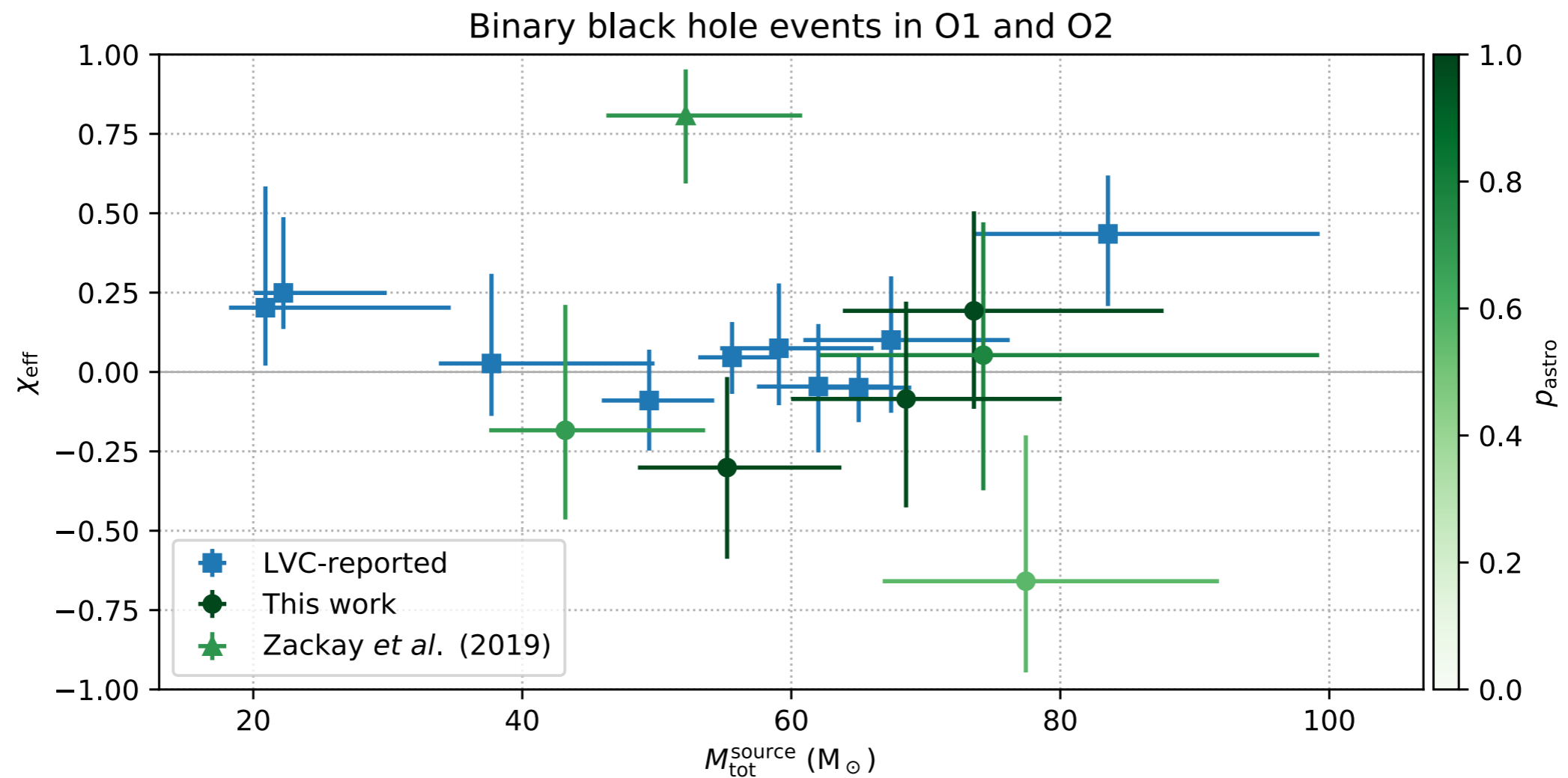
Venumadhav et al. arXiv: 1904.07214

THE PRESENT AND FUTURE

O3: Era of open alerts

- O3 started April 1st 2019
- 13 alerts (+2 retracted)
  - 9 likely BBH
  - 1 likely BNS
  - 1 maybe NSBH
  - 2 likely terrestrial (noise)

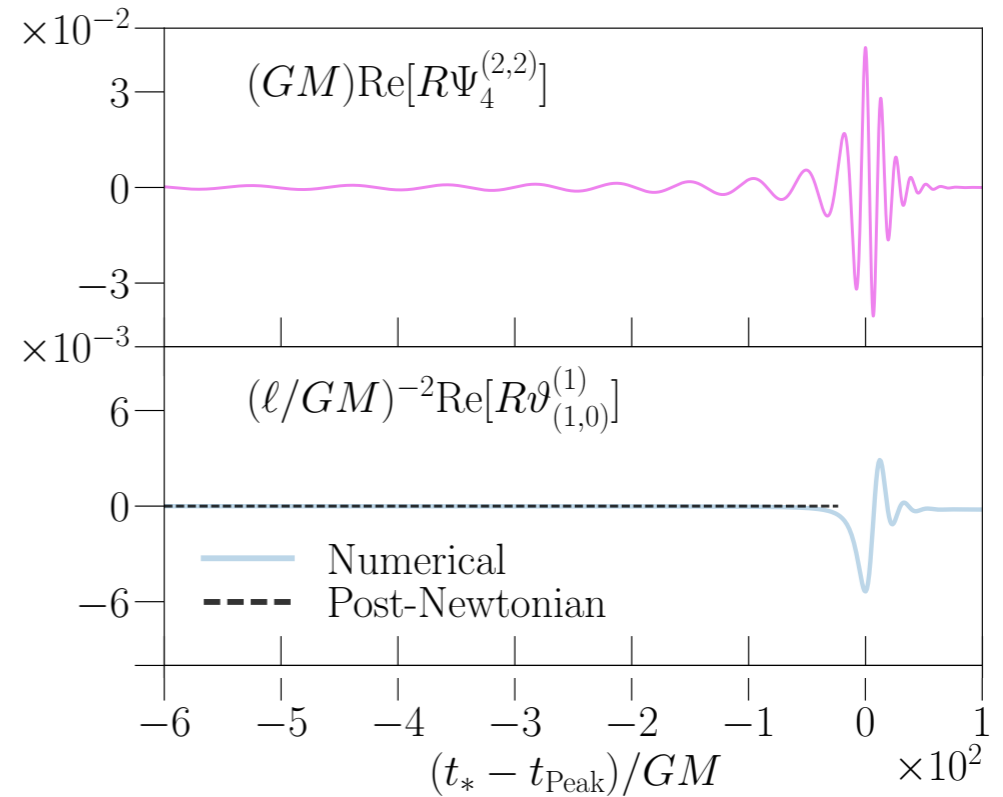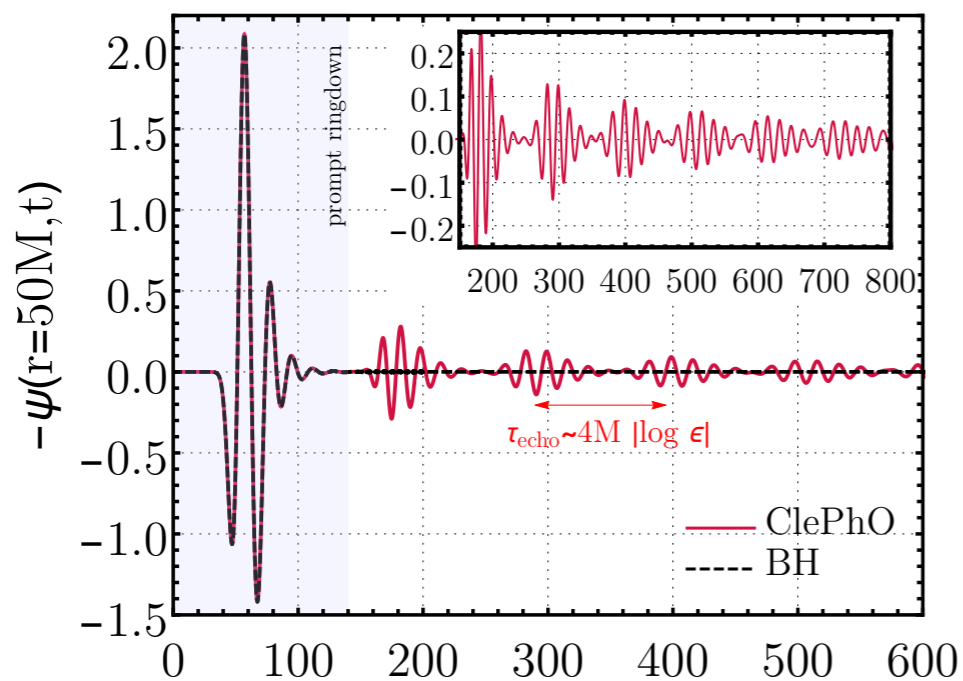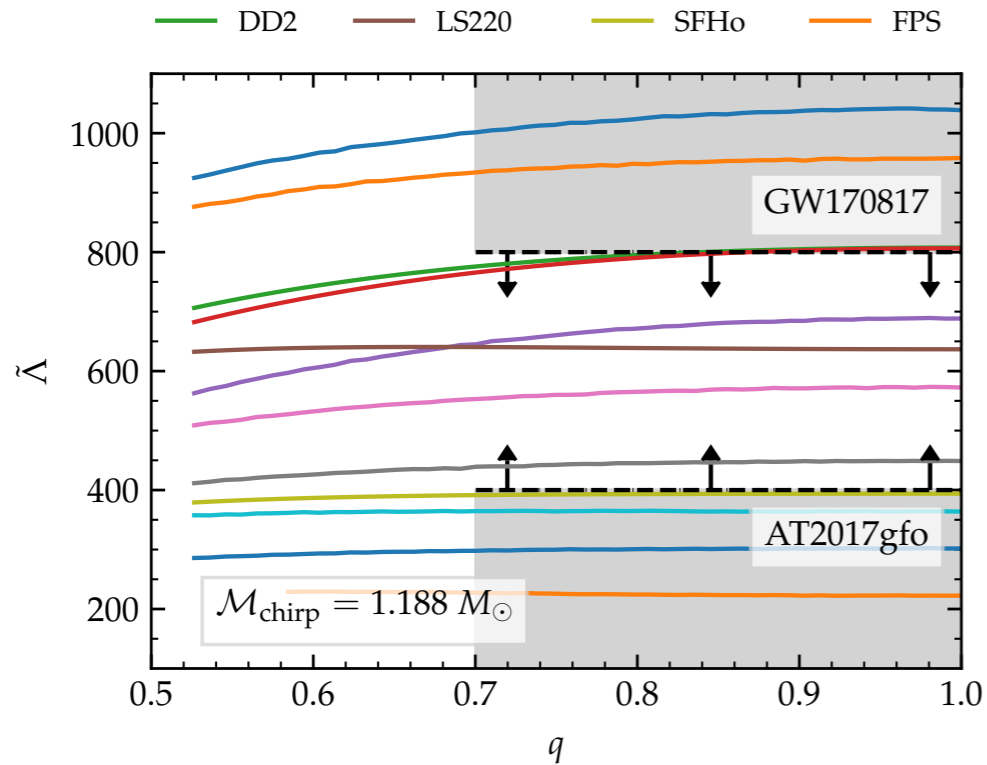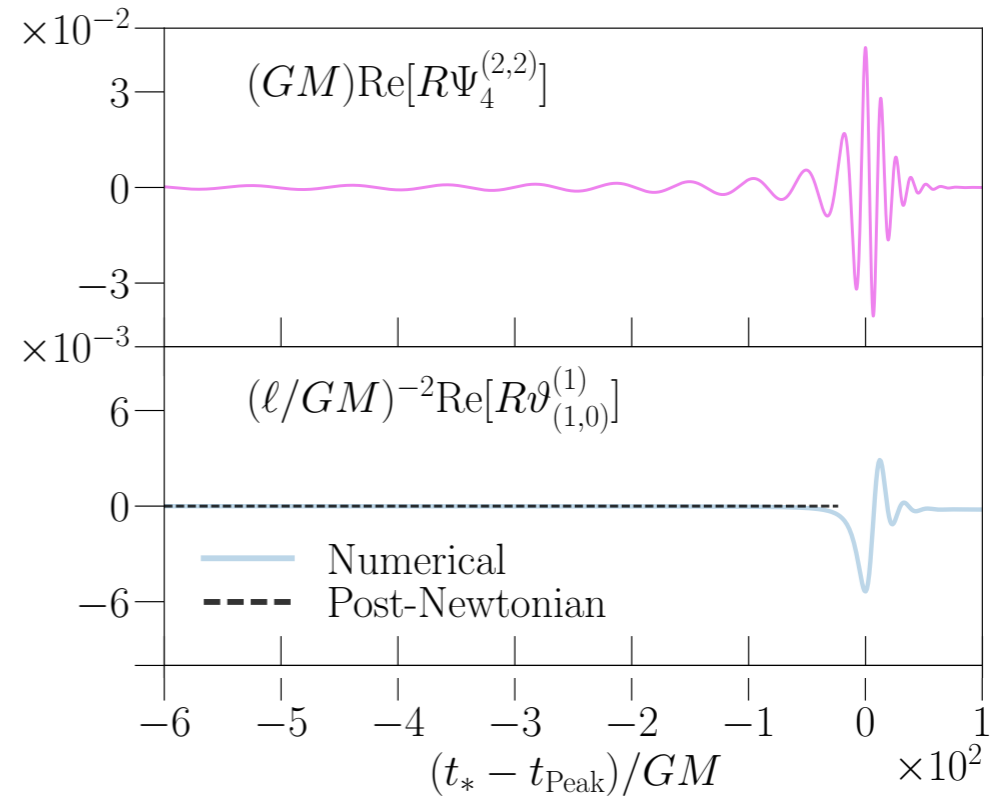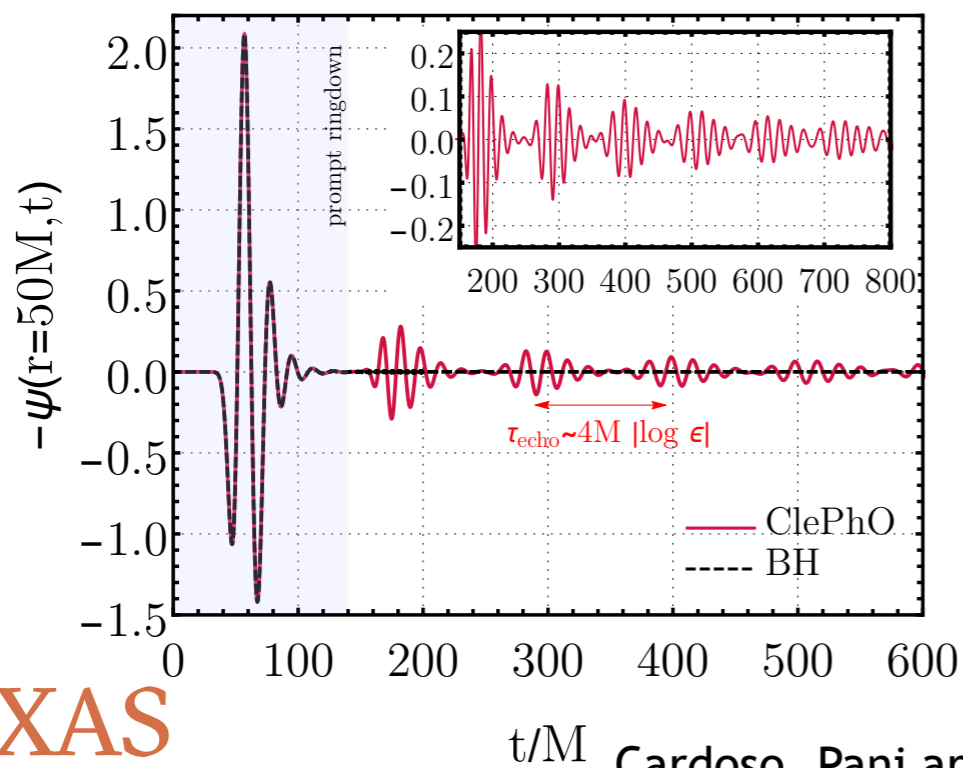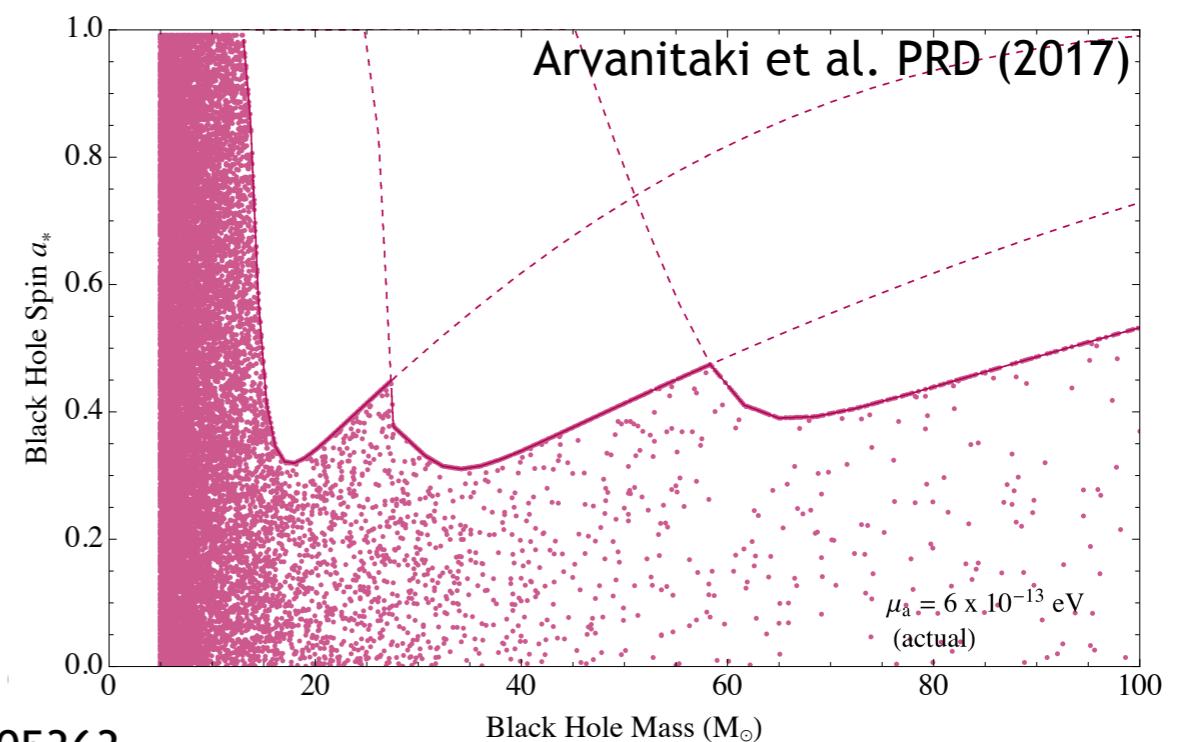| UID	Labels	FAR (Hz)	UTC Created
S190521r	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	2.373e-09	2019-05-17 05:51:23 UTC
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S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	2.141e-04	2019-04-05 16:01:56 UTC

gracedb.ligo.org

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Looking ahead

5 detector network

Gravitational Wave Observatories
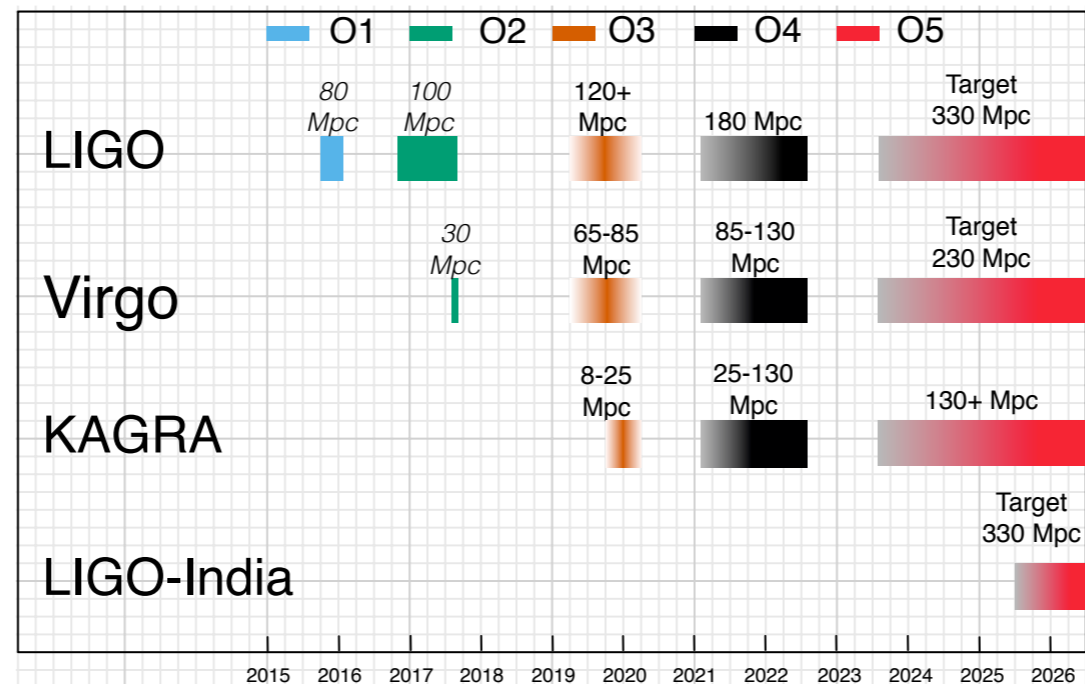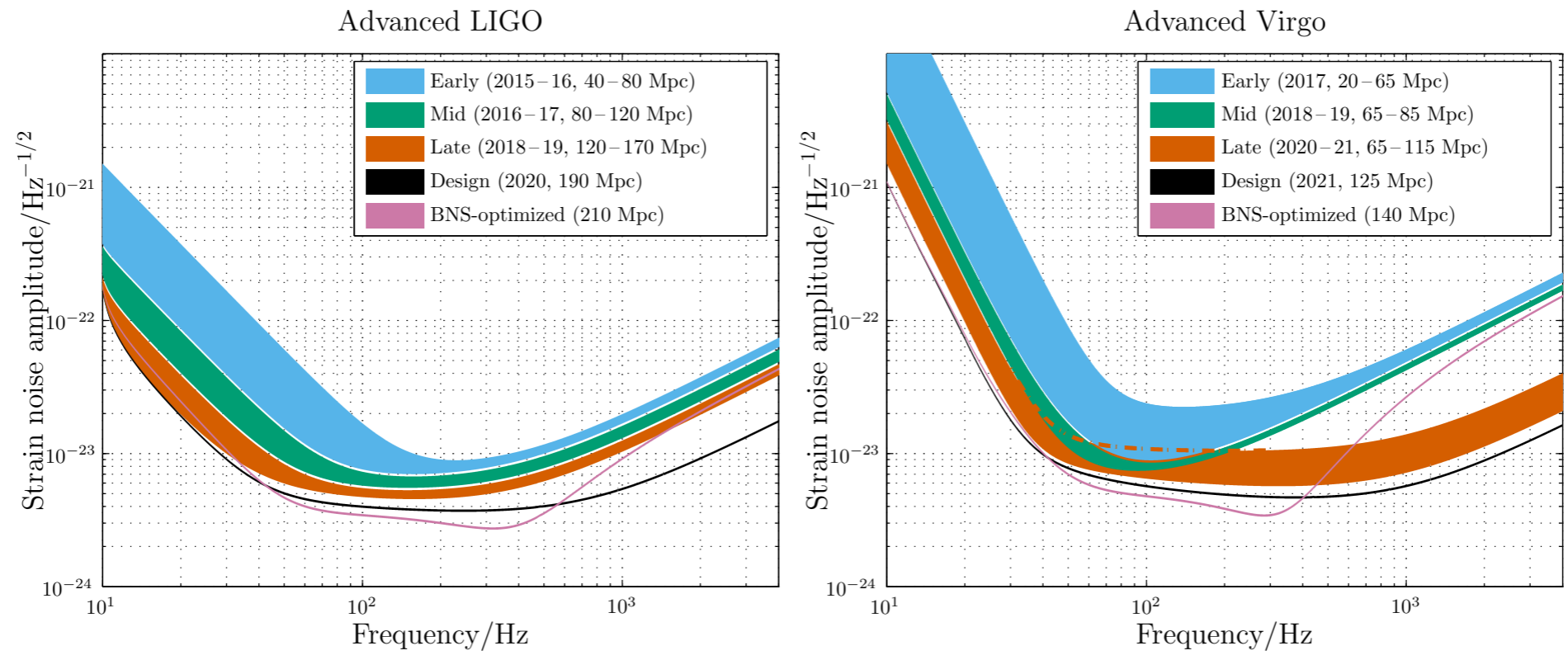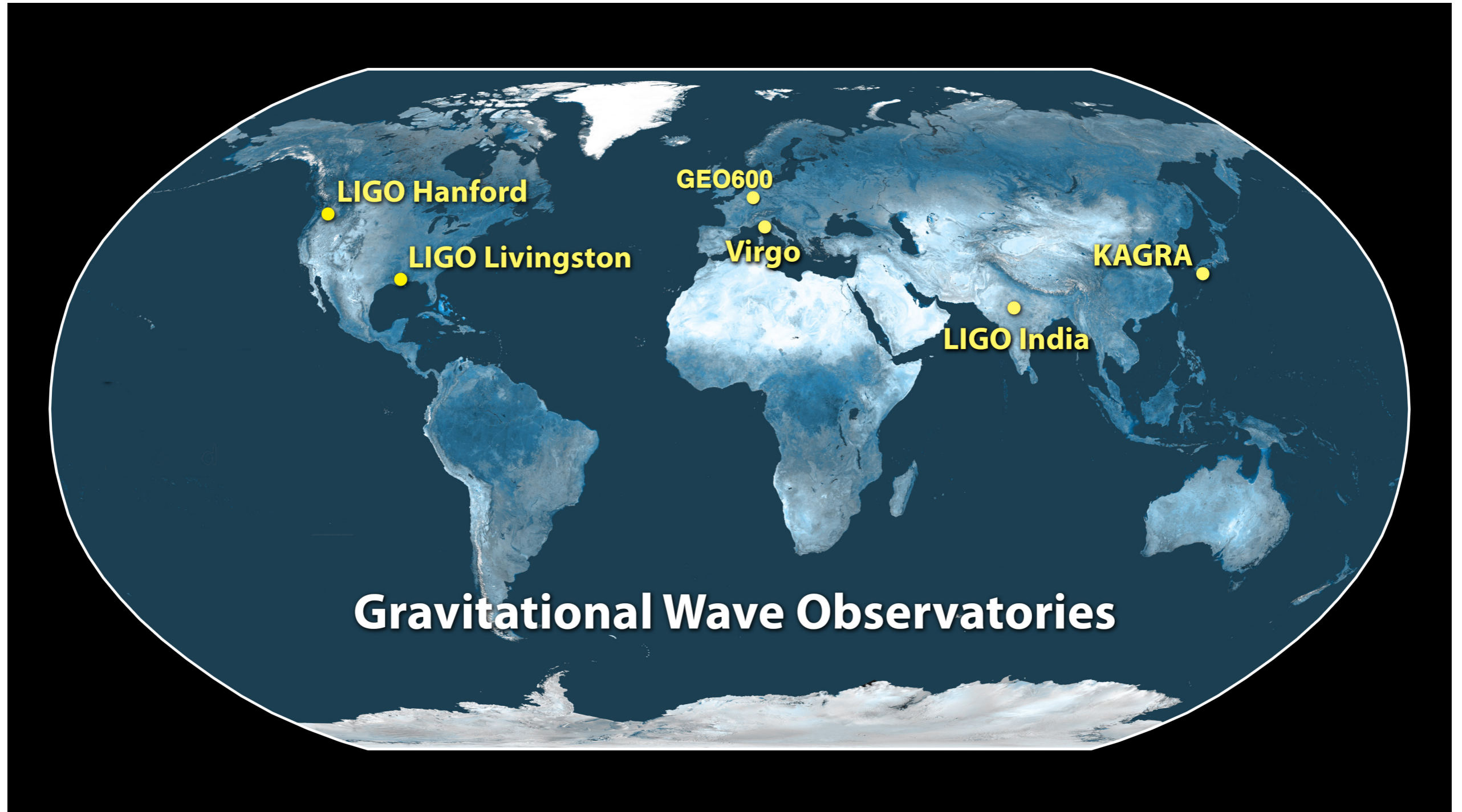
Next Generation Detectors

Einstein Telescope

Cosmic Explorer
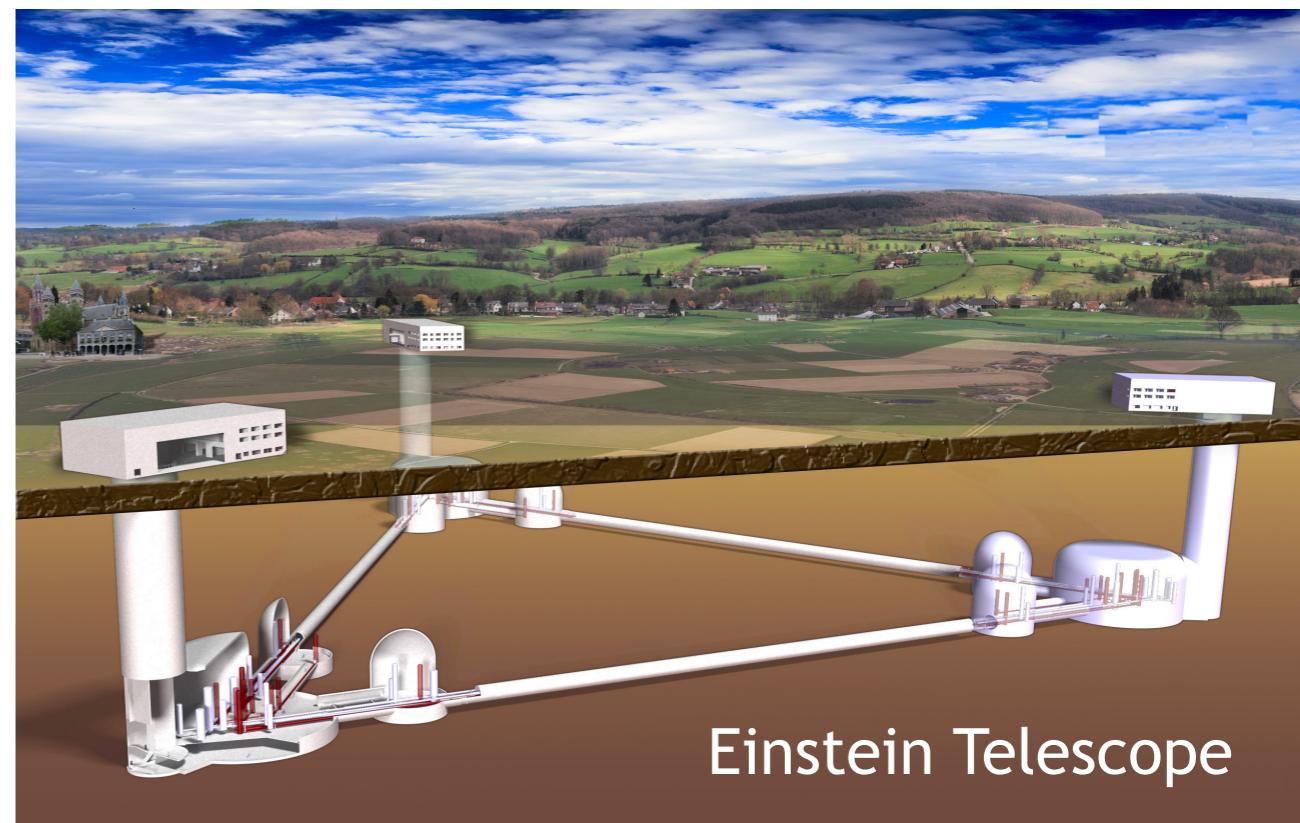
Next generation capabilities

Hall, Evans arXiv:1902.09485

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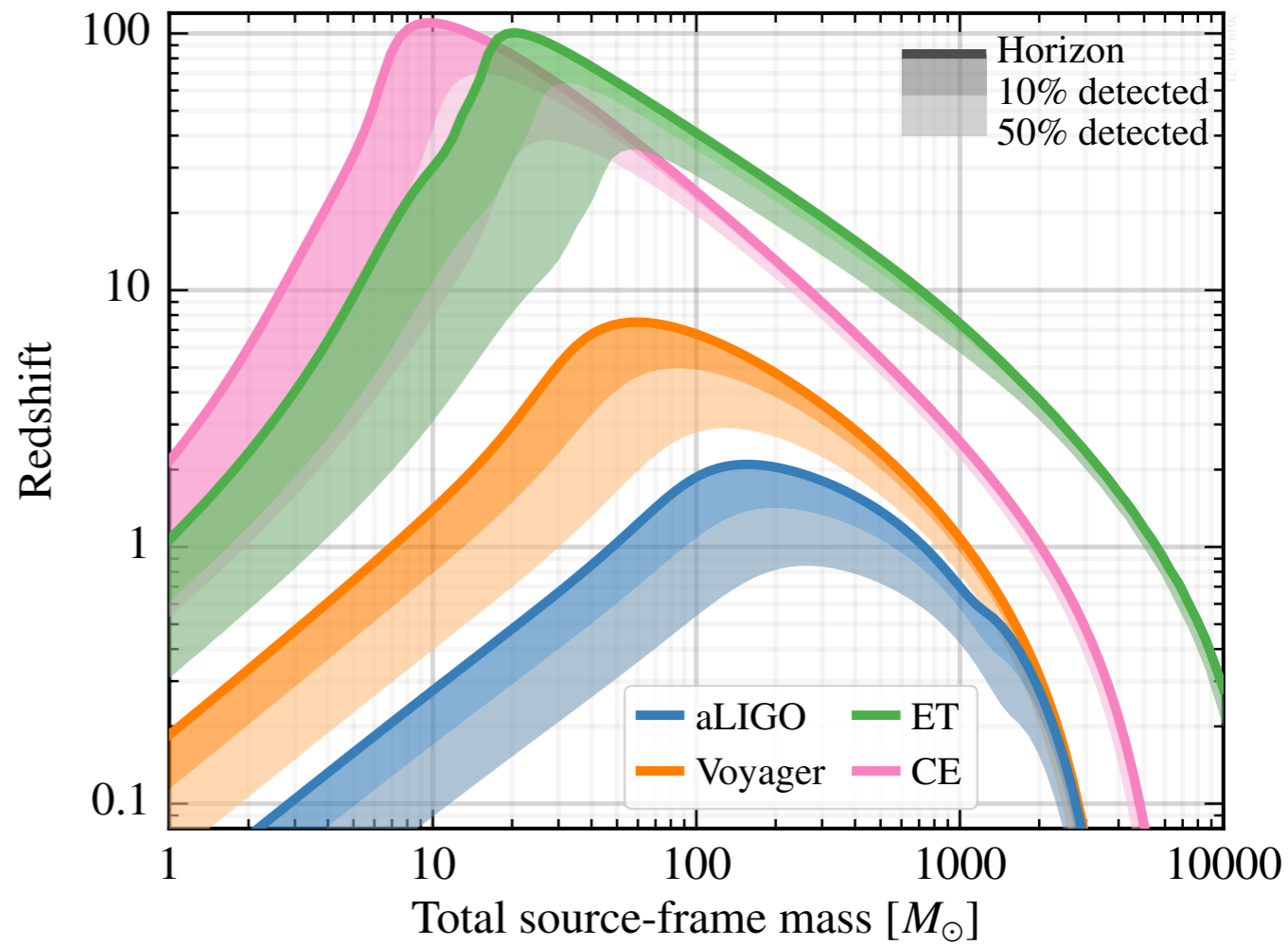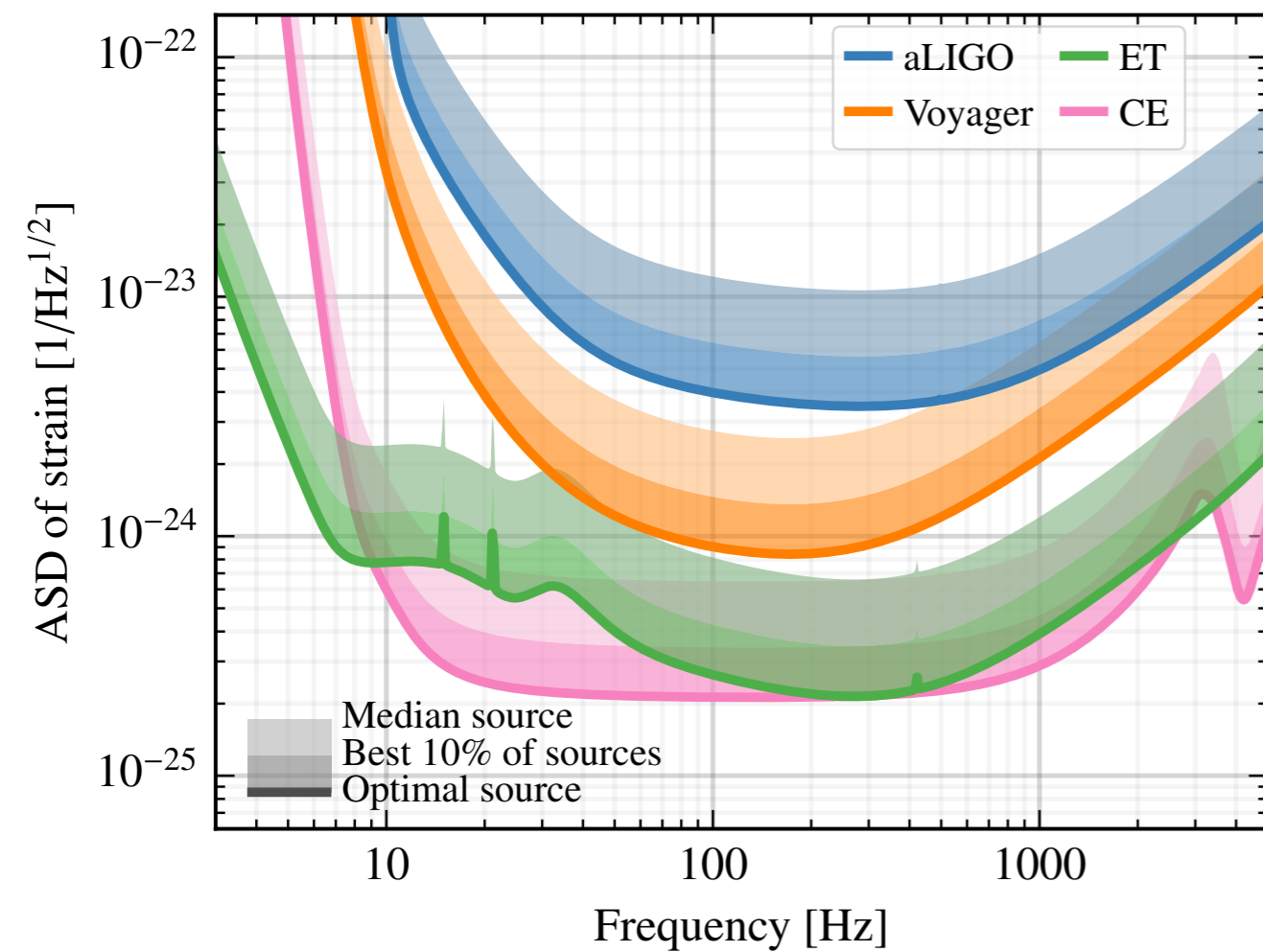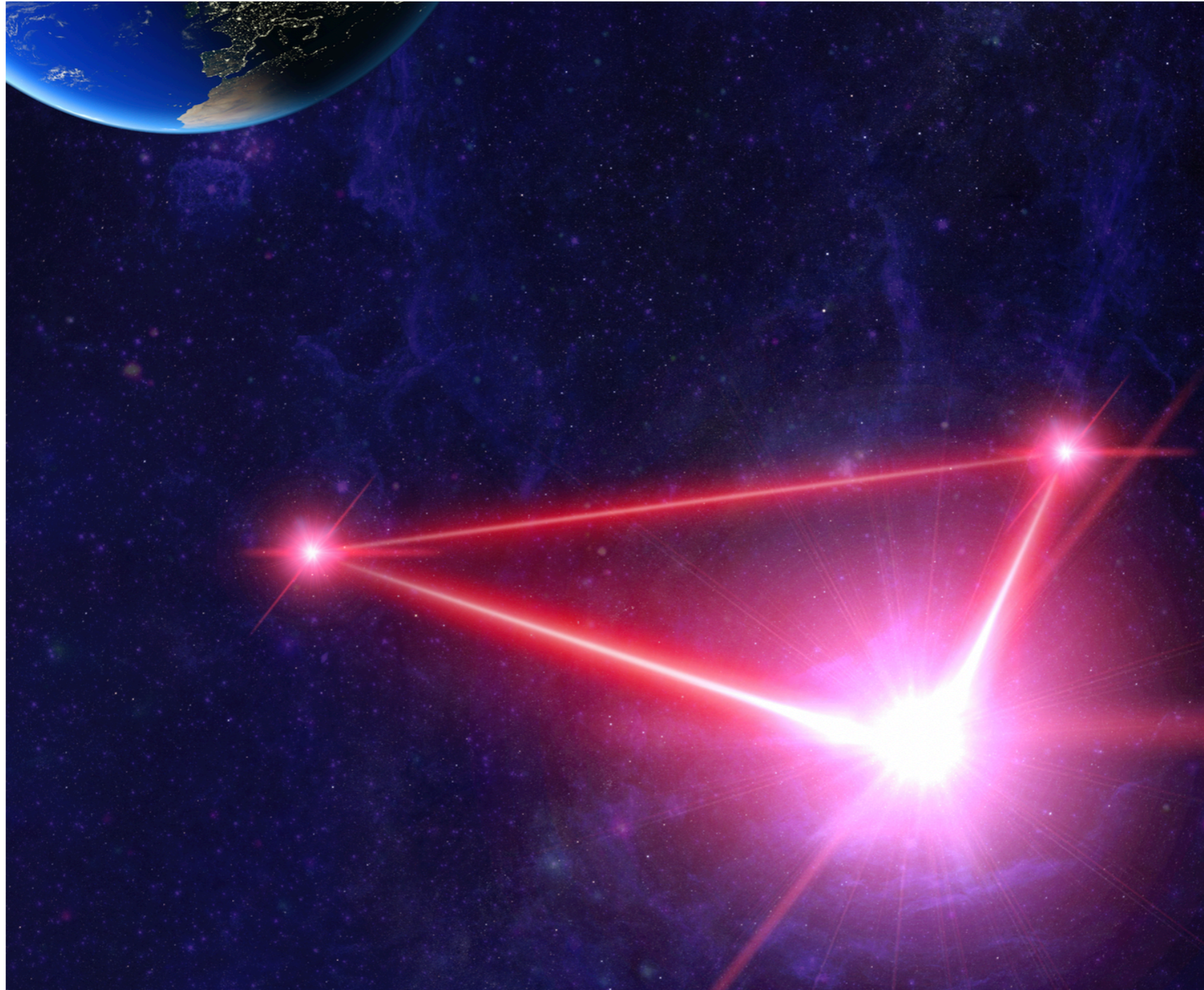
LISA

LISA
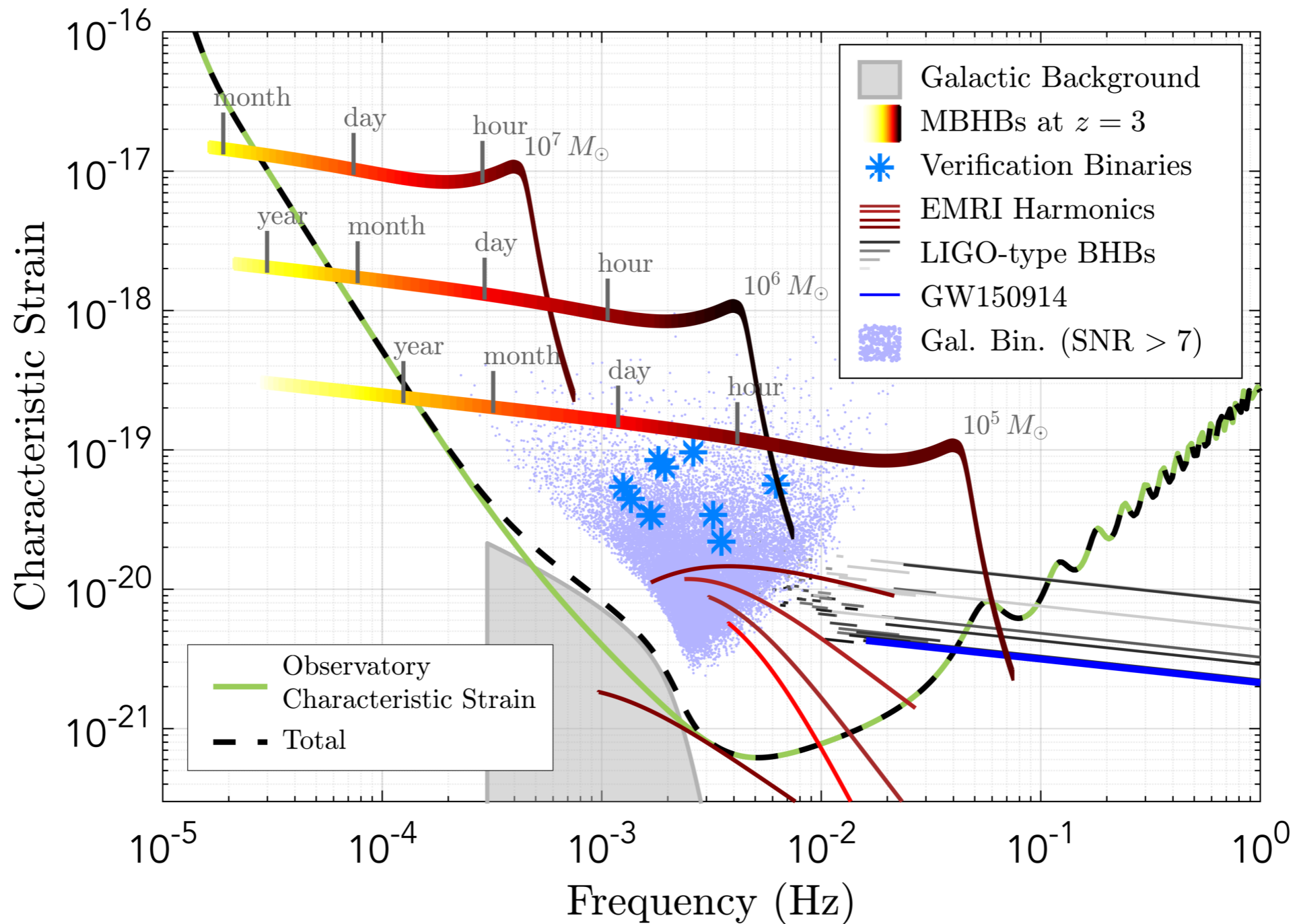
The future is bright (and loud)

EXTRAS

Other searches

LVC arXiv:1903.02886

LVC arXiv:1903.01901

LVC arXiv:1905.03456

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Properties of the BBHs

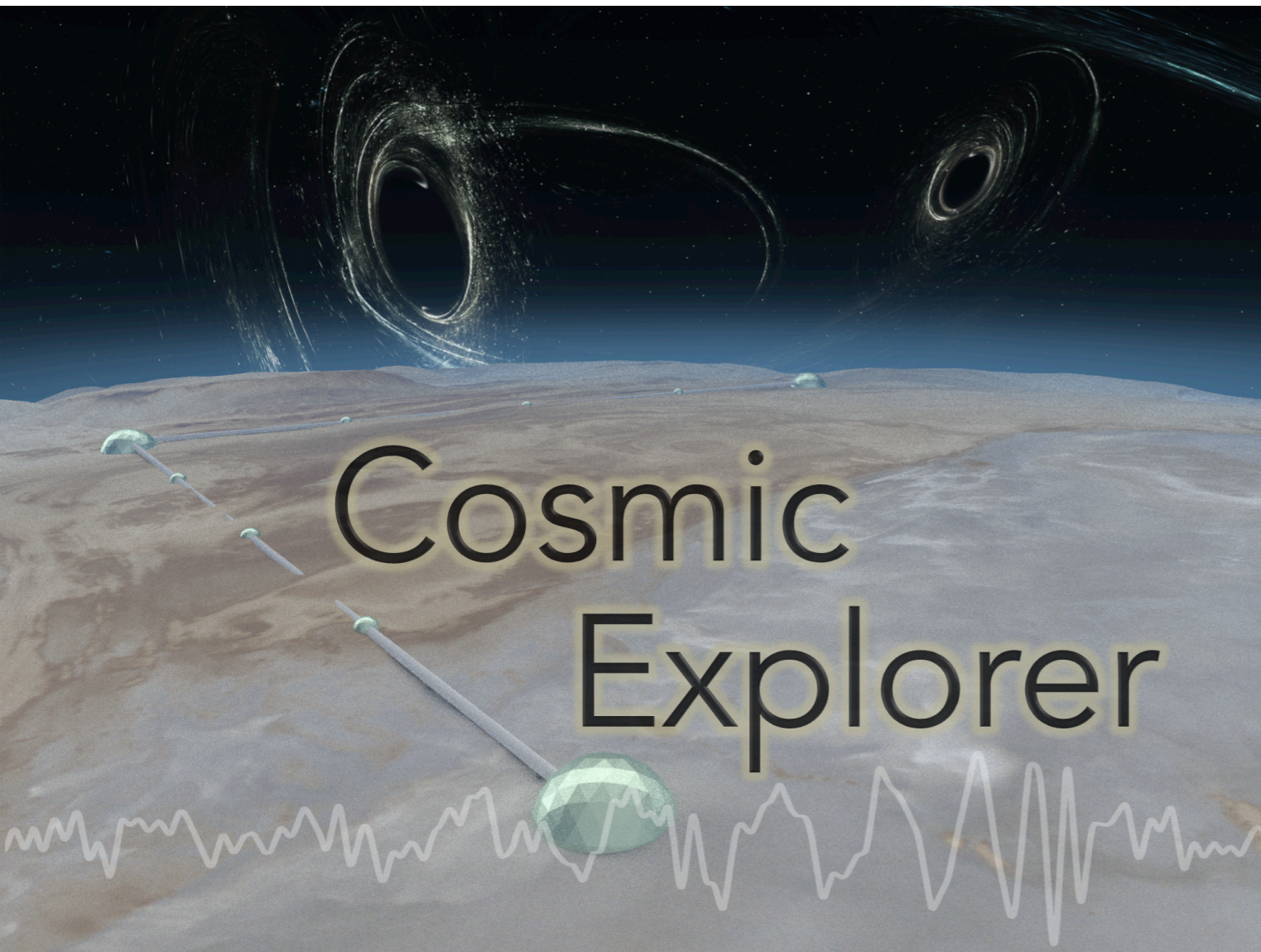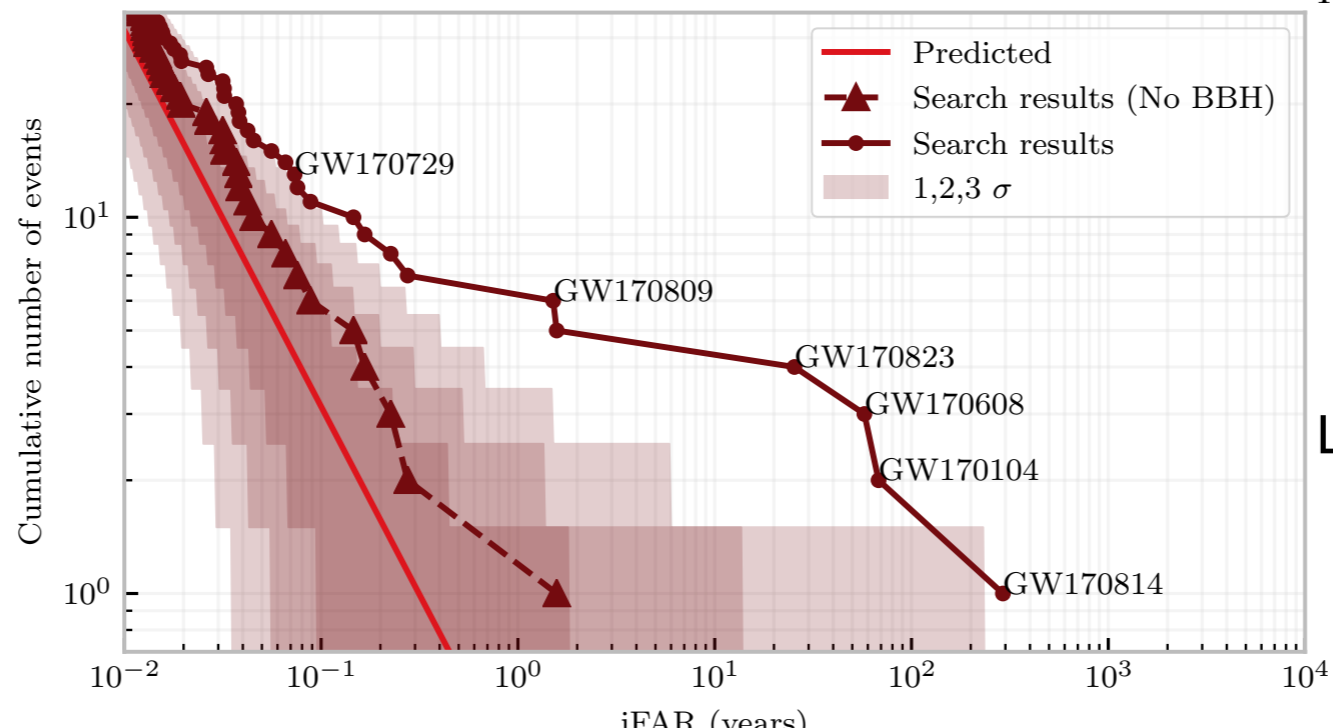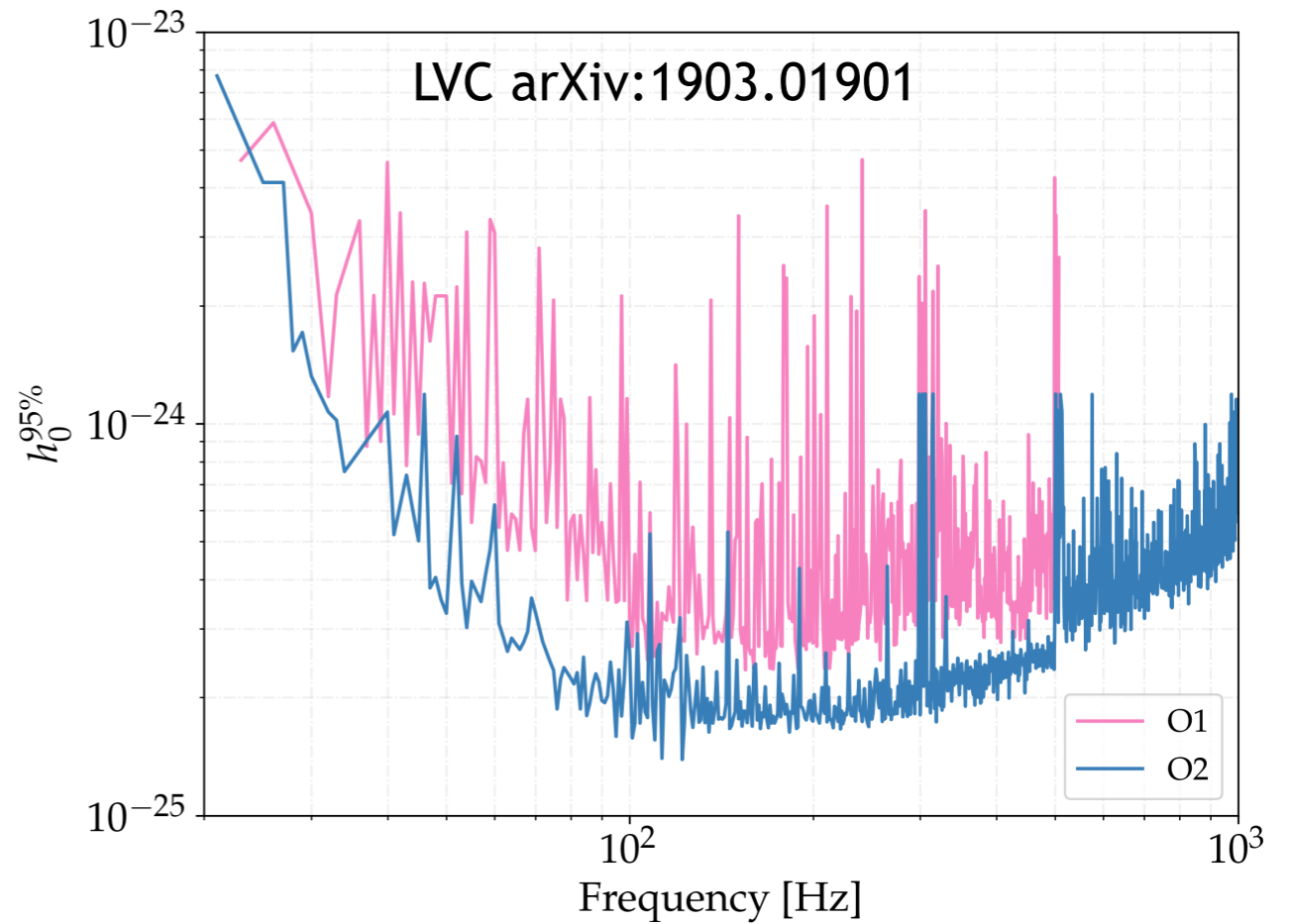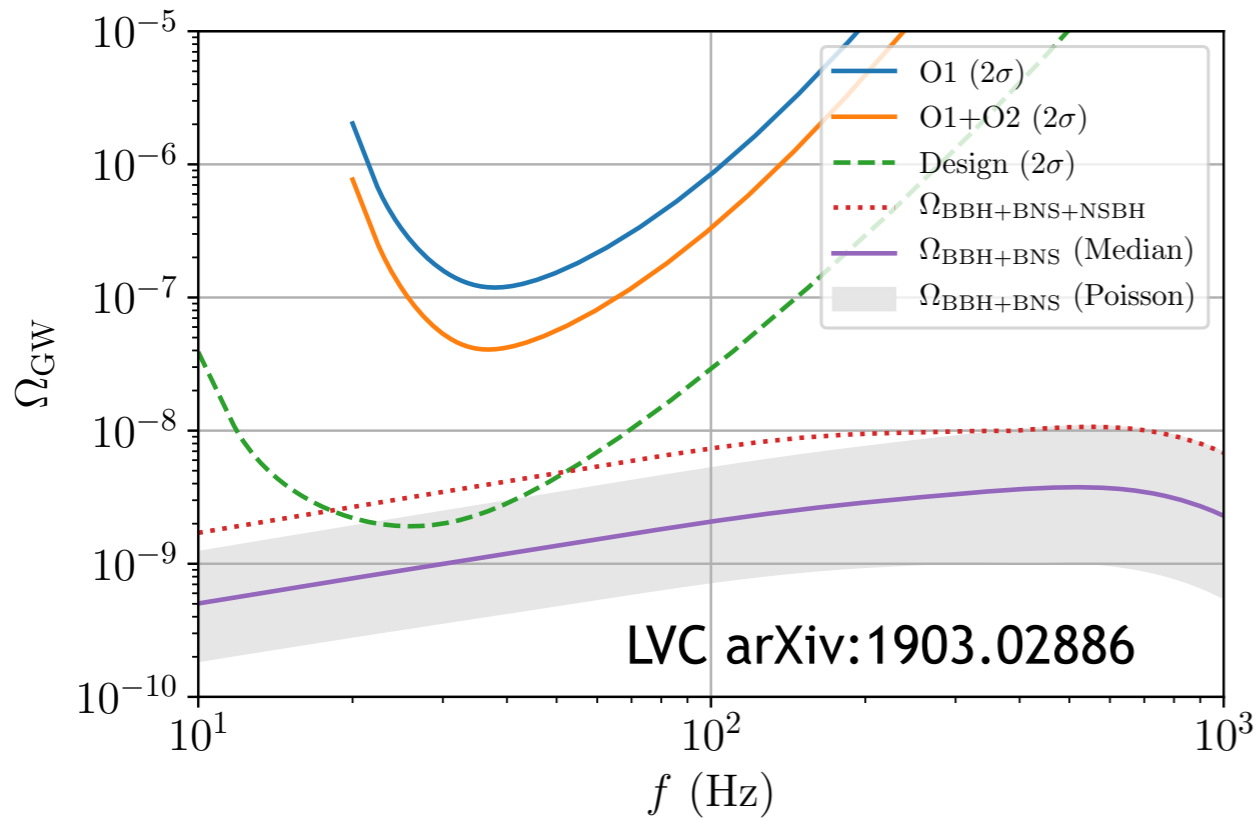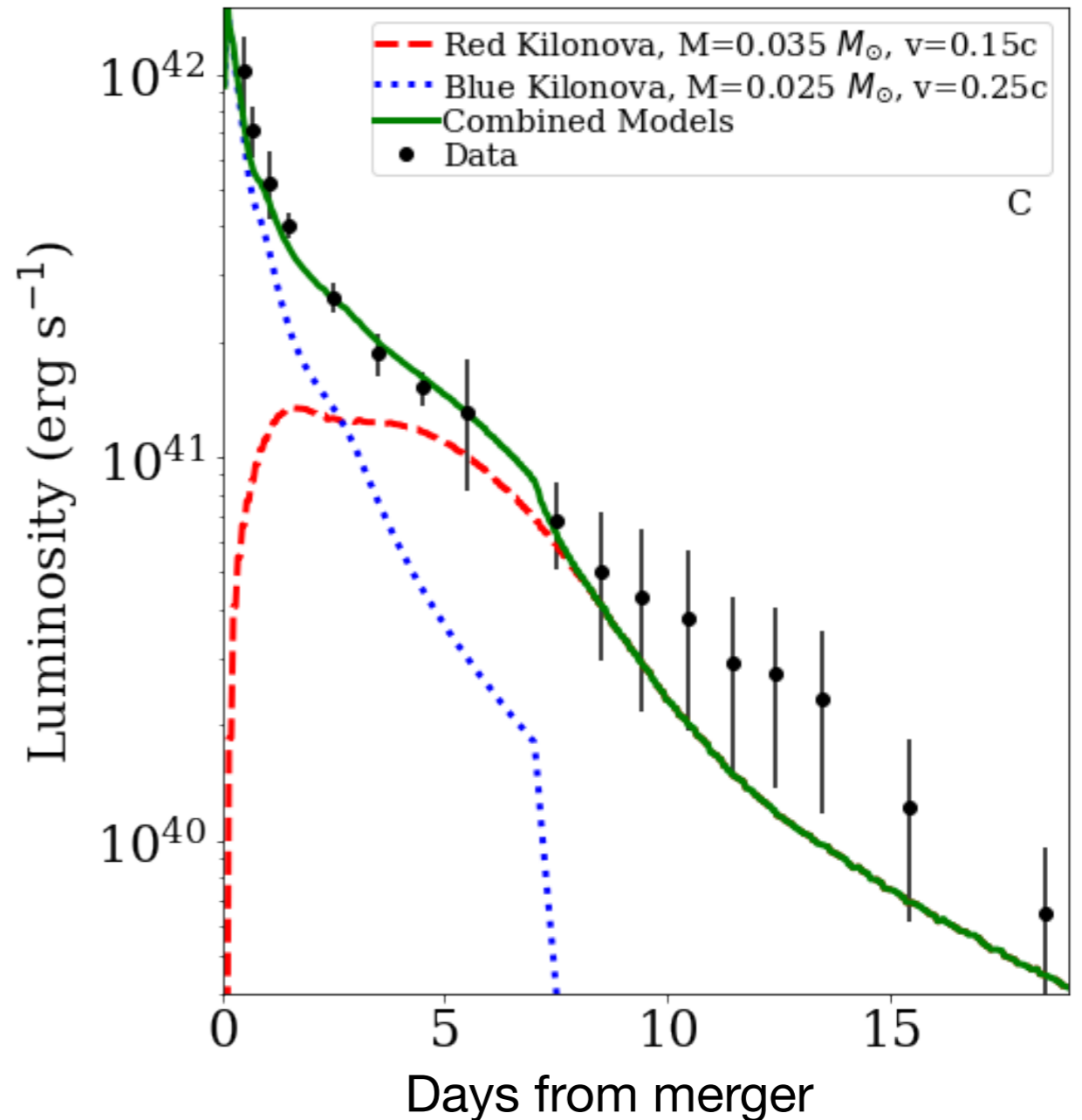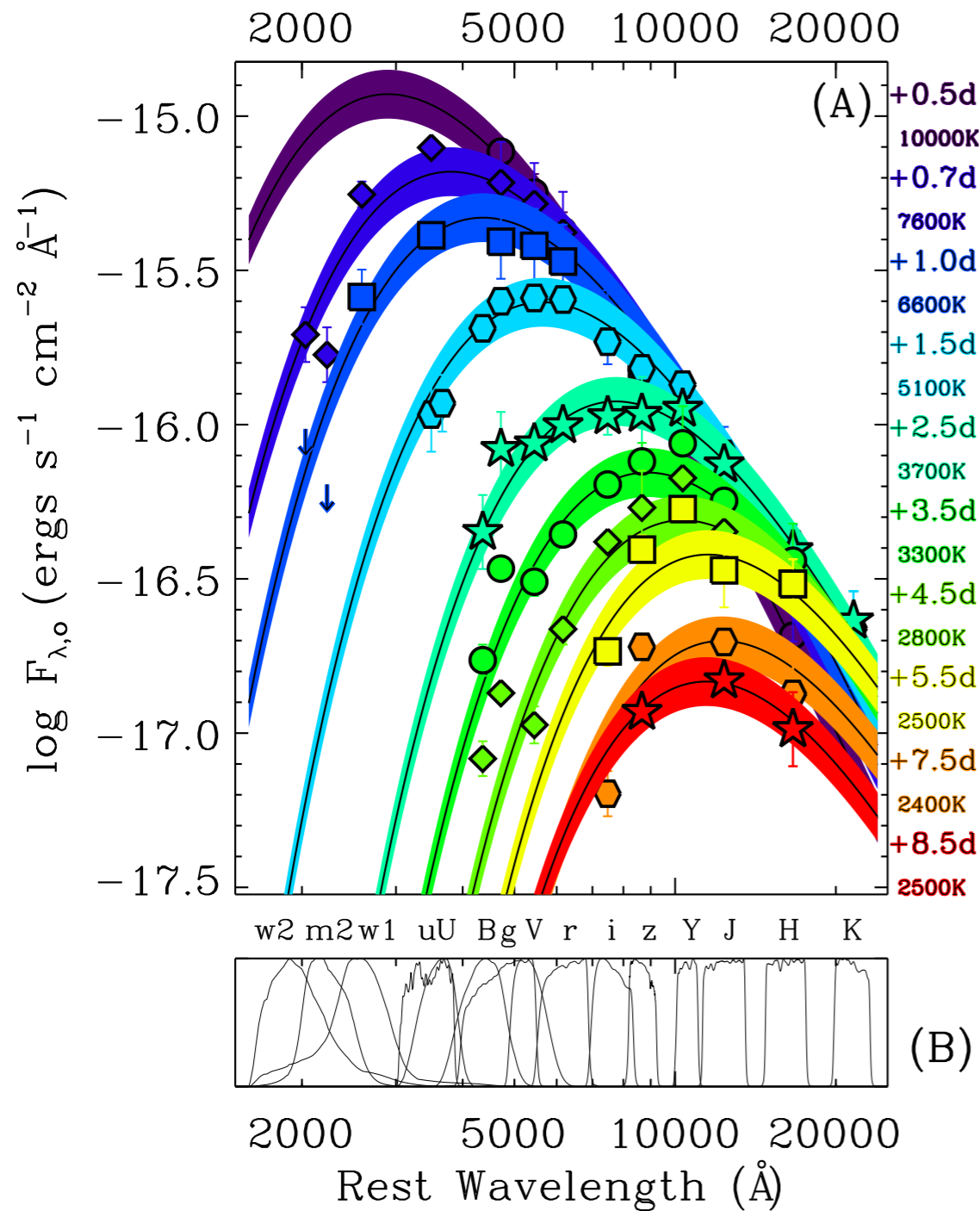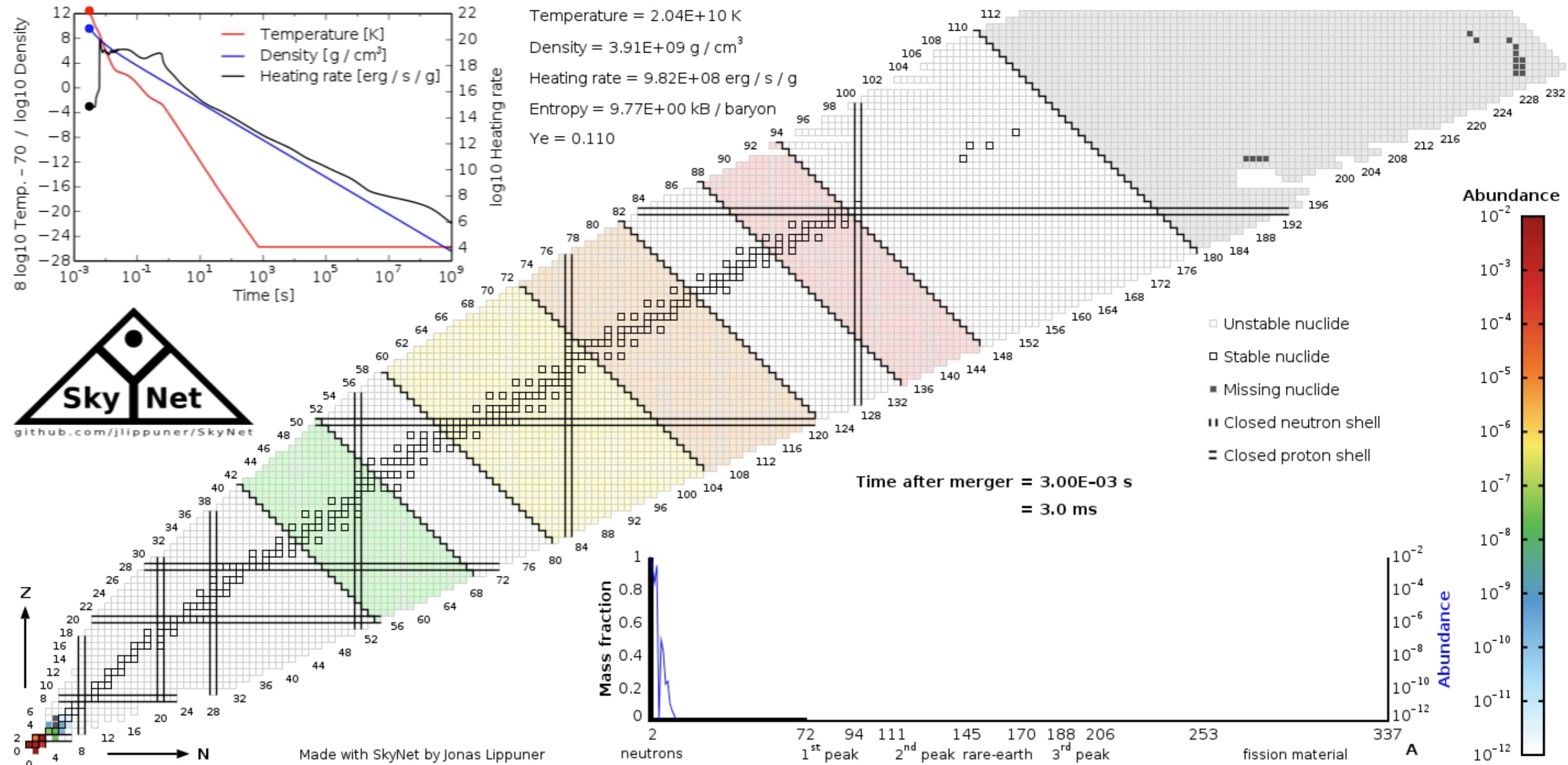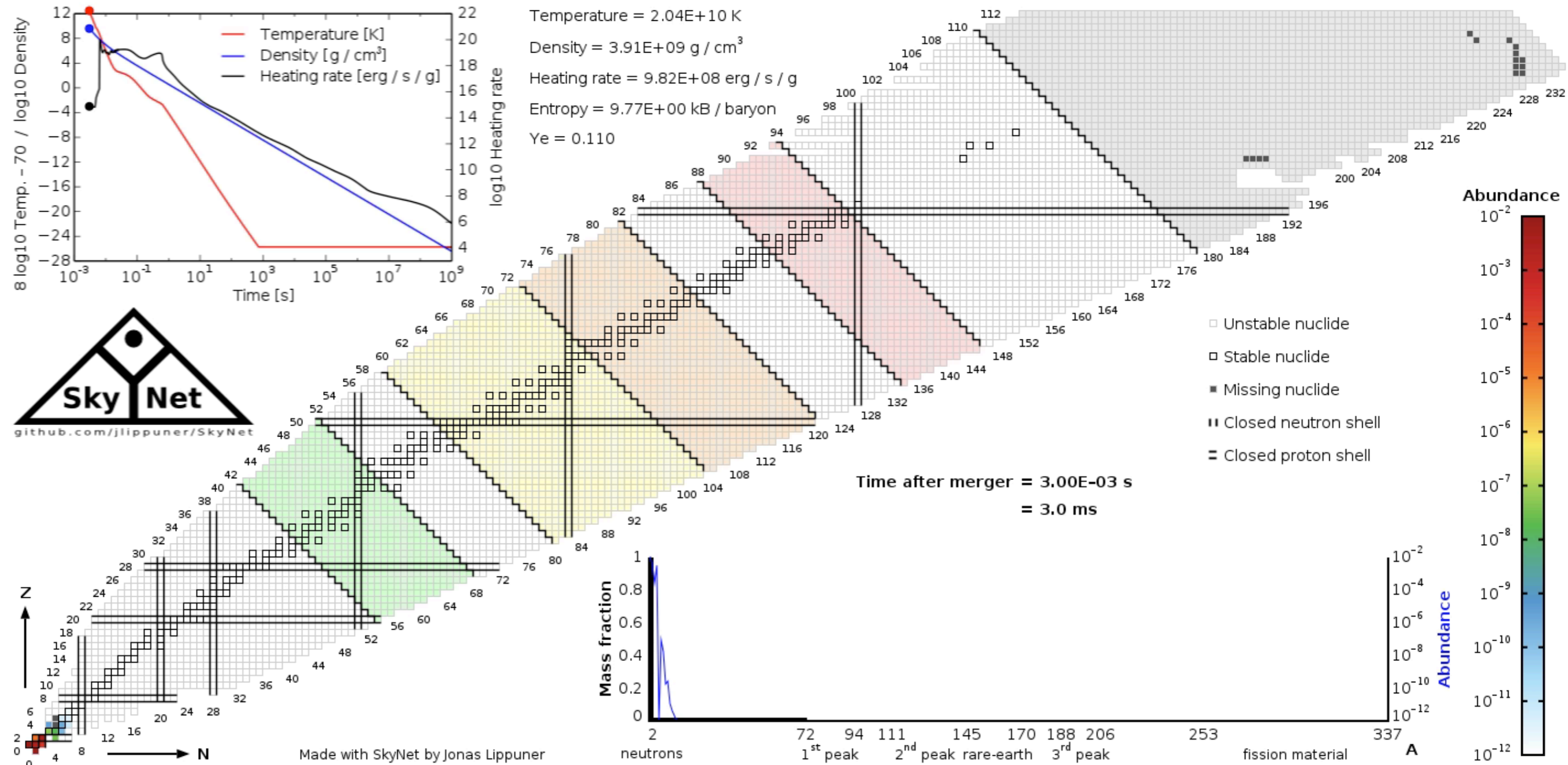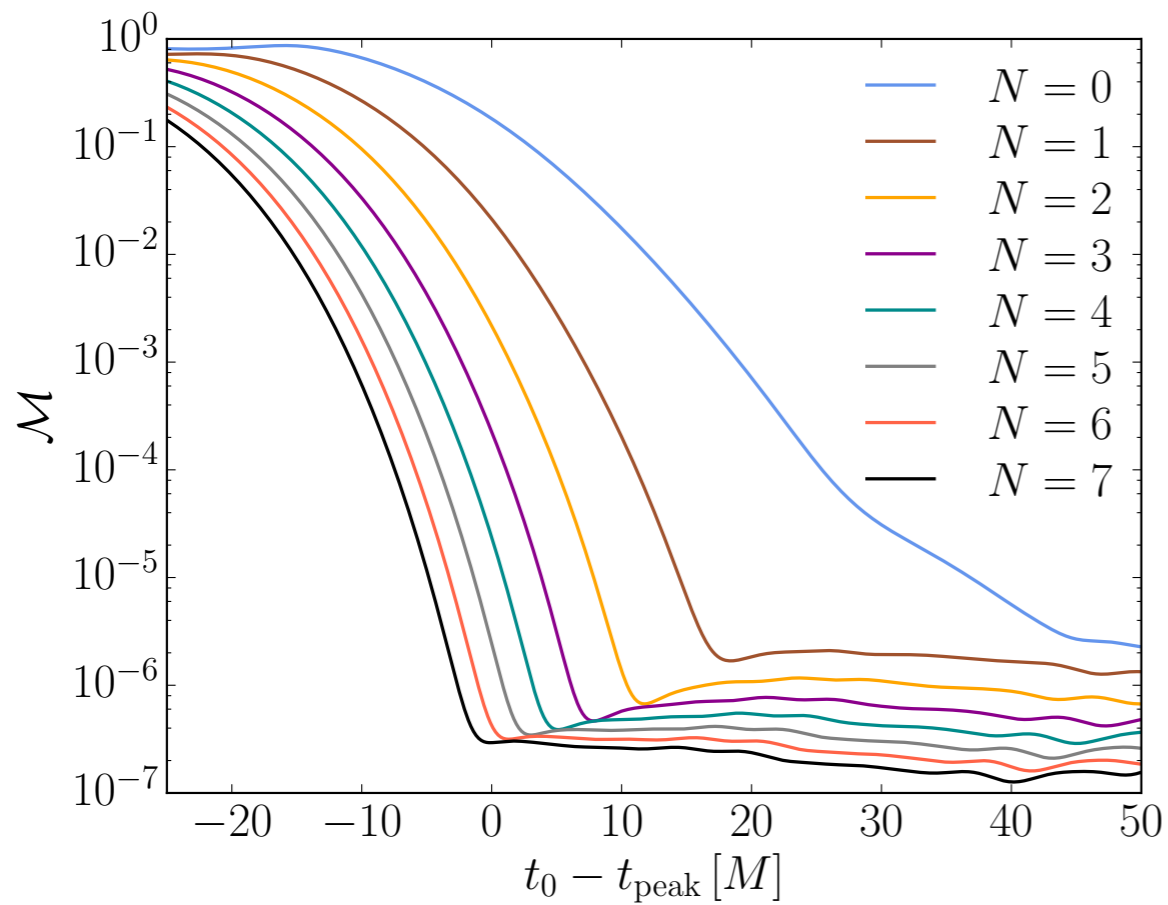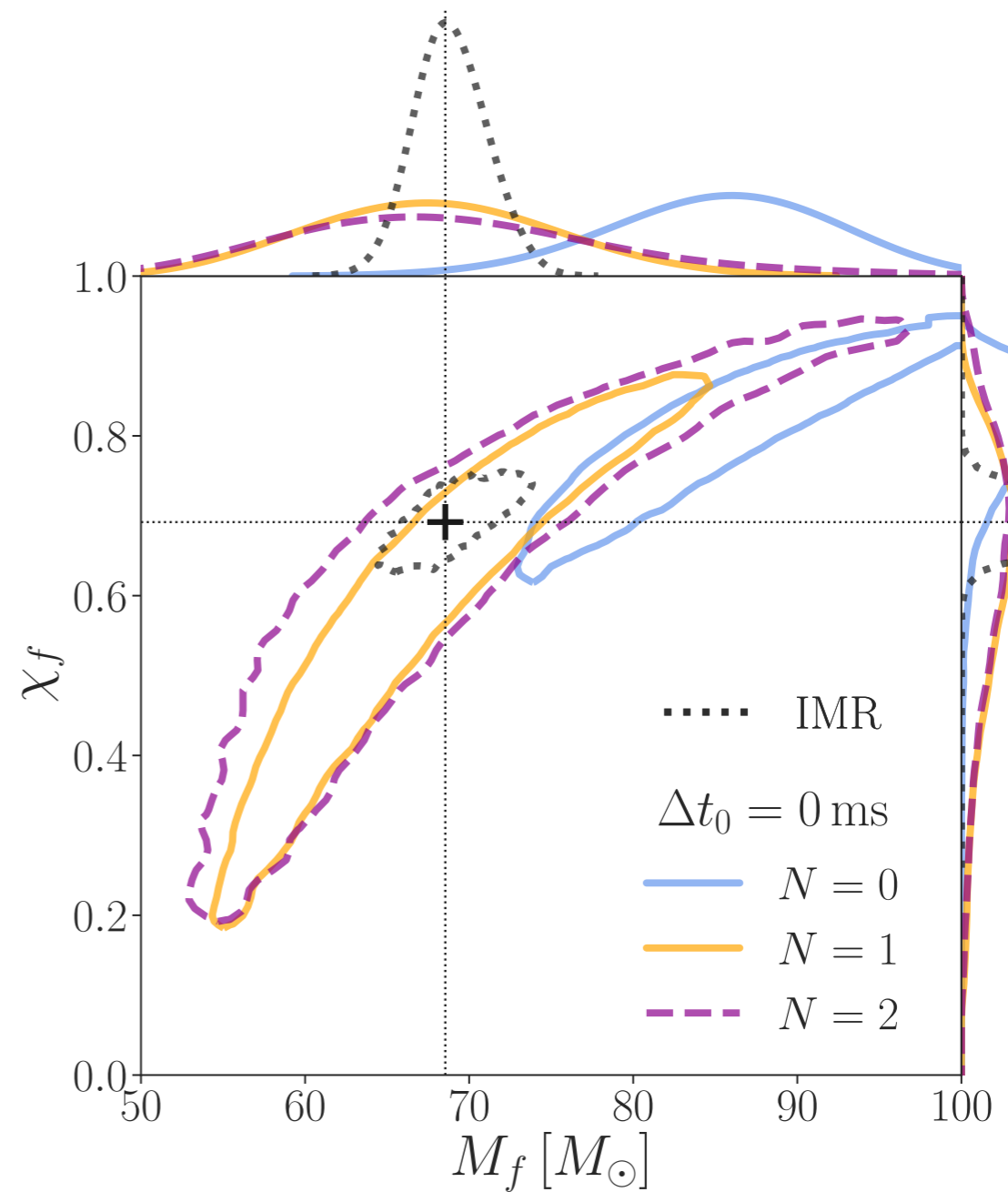| Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{rad}/(M_\odot c^2)$	$\ell_{peak}/(erg\,s^{-1})$	d_L/Mpc	z	$\Delta\Omega/deg^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Kilonova

Drout et al, Science (2017)

Kilpatrick et al, Science (2017)

r-process nucleosynthesis

Temperature = 2.04E+10 K

Density = 3.91E+09 g / cm³

Heating rate = 9.82E+08 erg / s / g

Entropy = 9.77E+00 kB / baryon

Ye = 0.110

Time after merger = 3.00E-03 s
= 3.0 ms

Made with SkyNet by Jonas Lippuner

Credit: Jonas Lippuner

r-process nucleosynthesis

Made with SkyNet by Jonas Lippuner

Credit: Jonas Lippuner
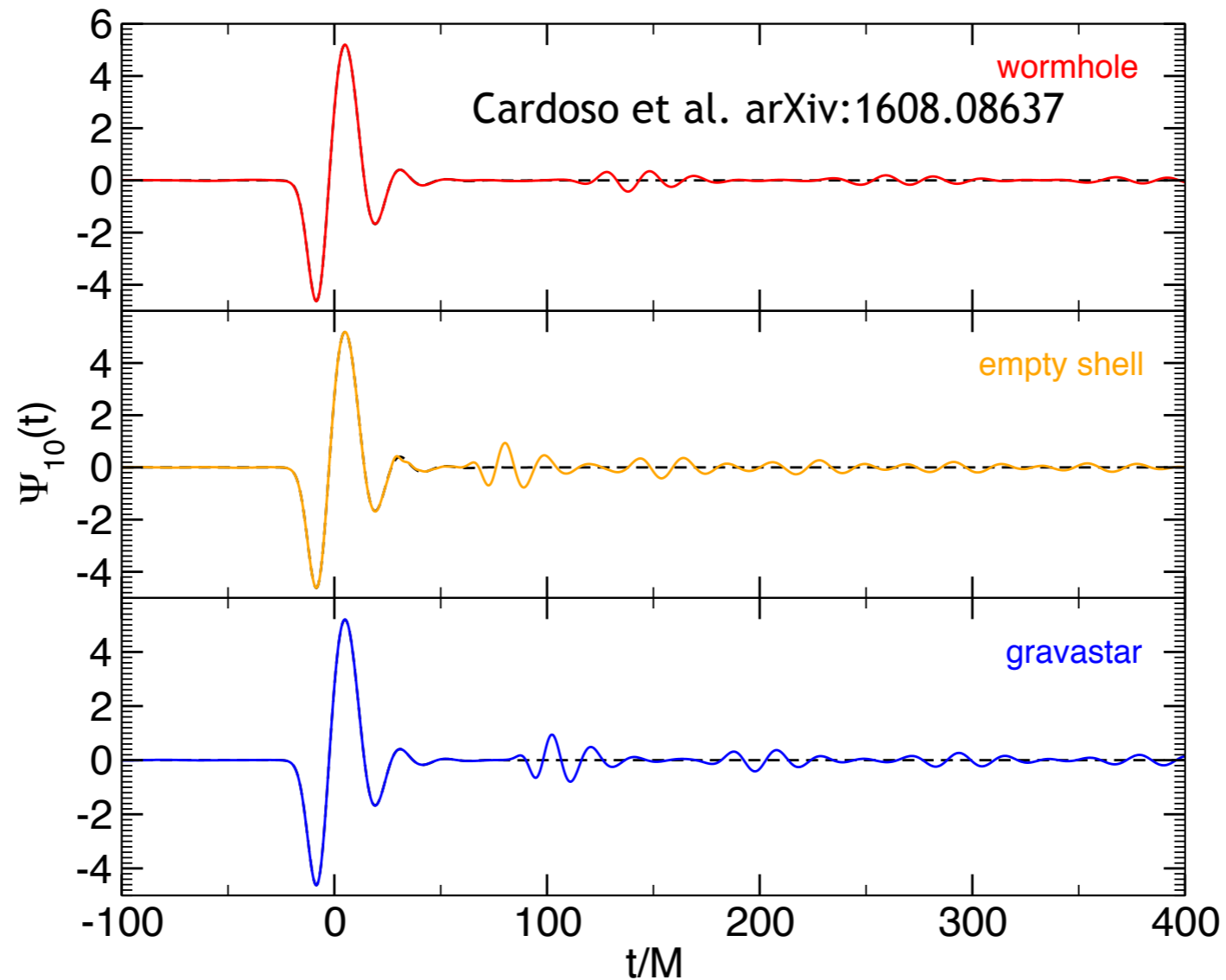
Ringdown with overtones
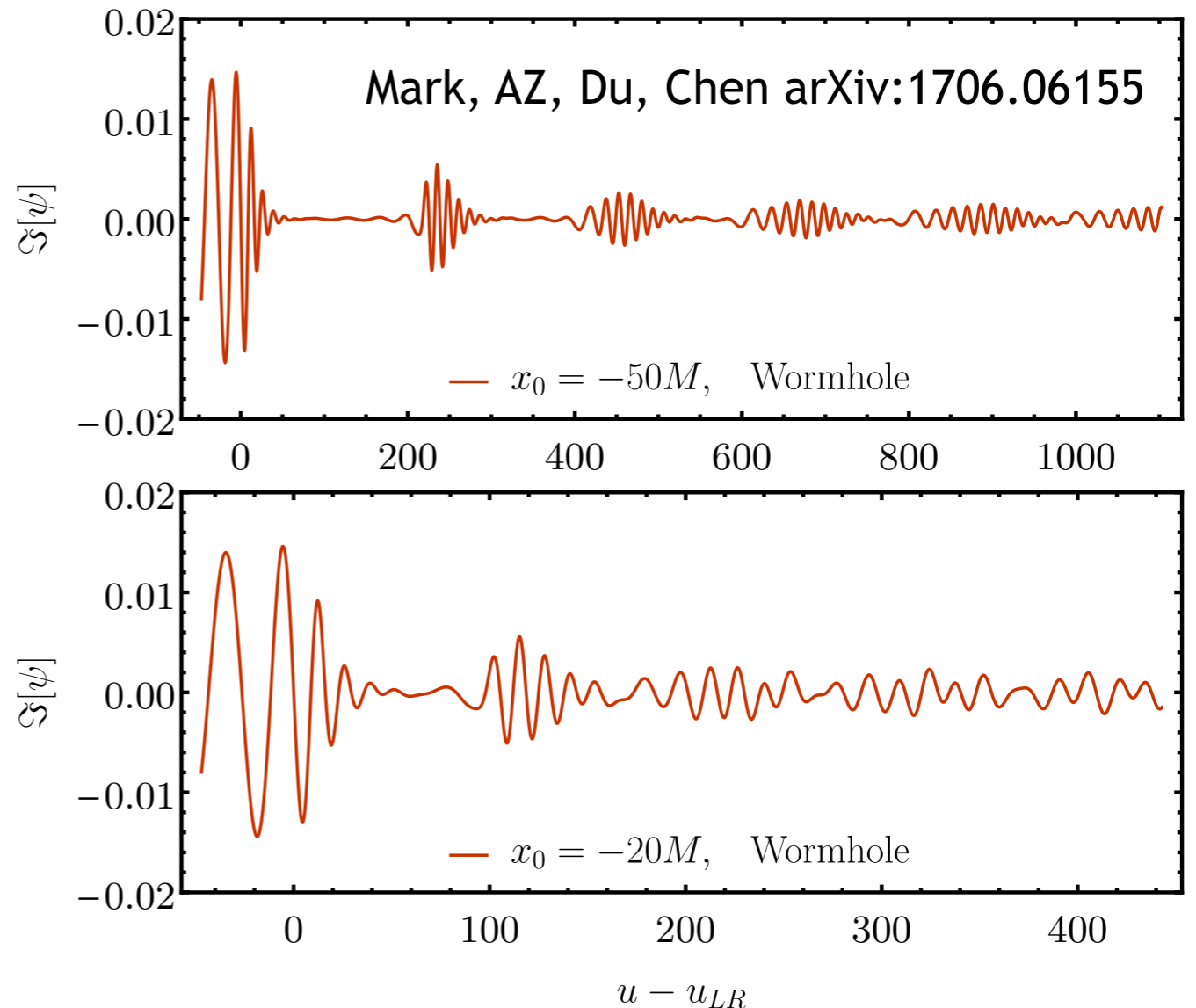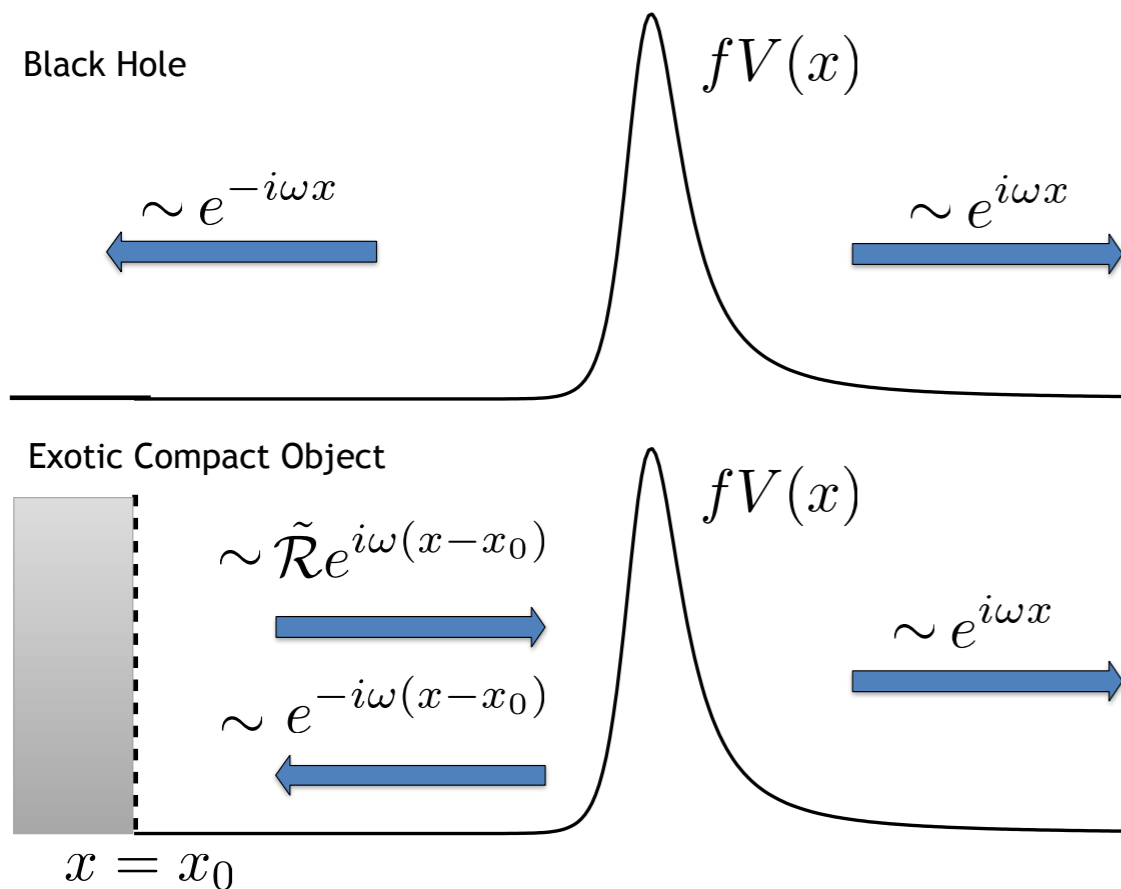

Giesler et al. arXiv: 1903.08284

Isi et al. arXiv:1905.00869
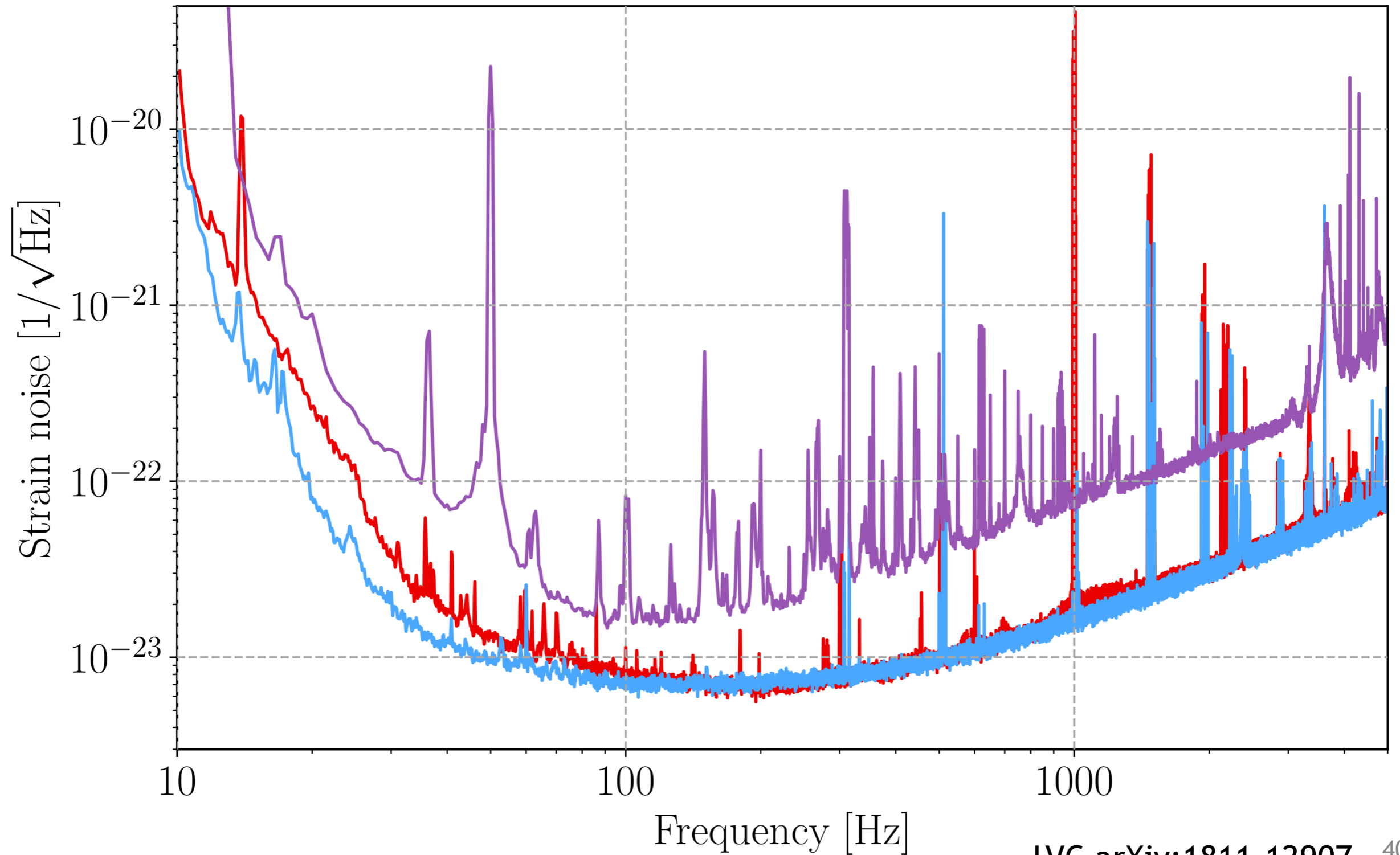
Echoes from exotic compact objects

For a recent review see Cardoso and Pani arXiv:1904.05363
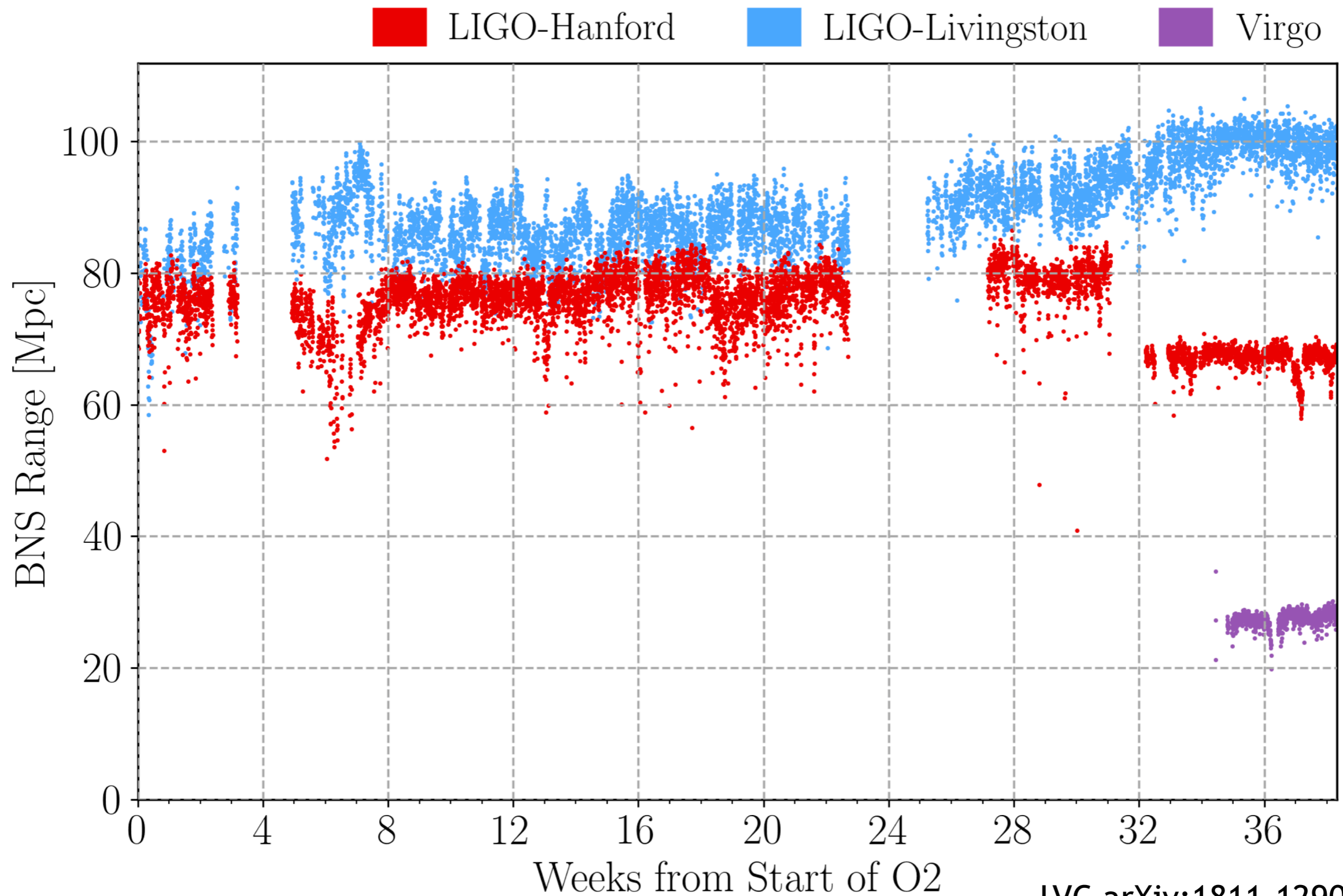
Echoes from exotic compact objects

For a recent review see Cardoso and Pani arXiv:1904.05363

Detector sensitivity O2

Detector sensitivity O2

LVC arXiv:1811.12907

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Detector sensitivity O3