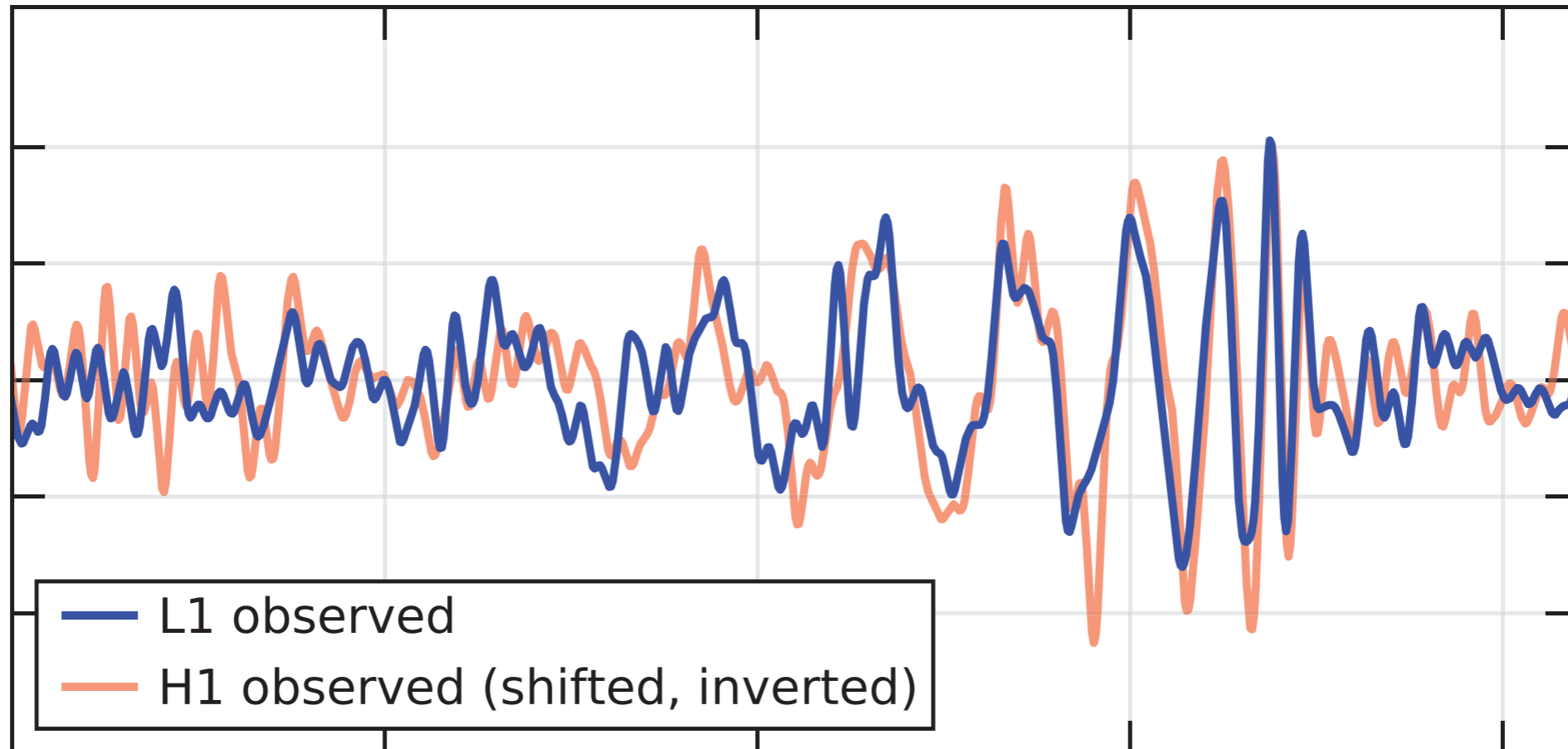


Gravitational wave physics



Aaron Zimmerman
University of Texas at Austin

SUSY2019
May 24, 2019



LIGO Scientific Collaboration



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Andrews University

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CALIFORNIA STATE UNIVERSITY FULLERTON

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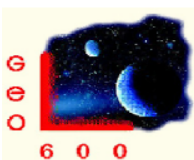
UTRGV

UNIVERSITY AND INSTITUTE OF ADVANCED RESEARCH THE PURI FOUNDATION FOR EDUCATION IN INDIA

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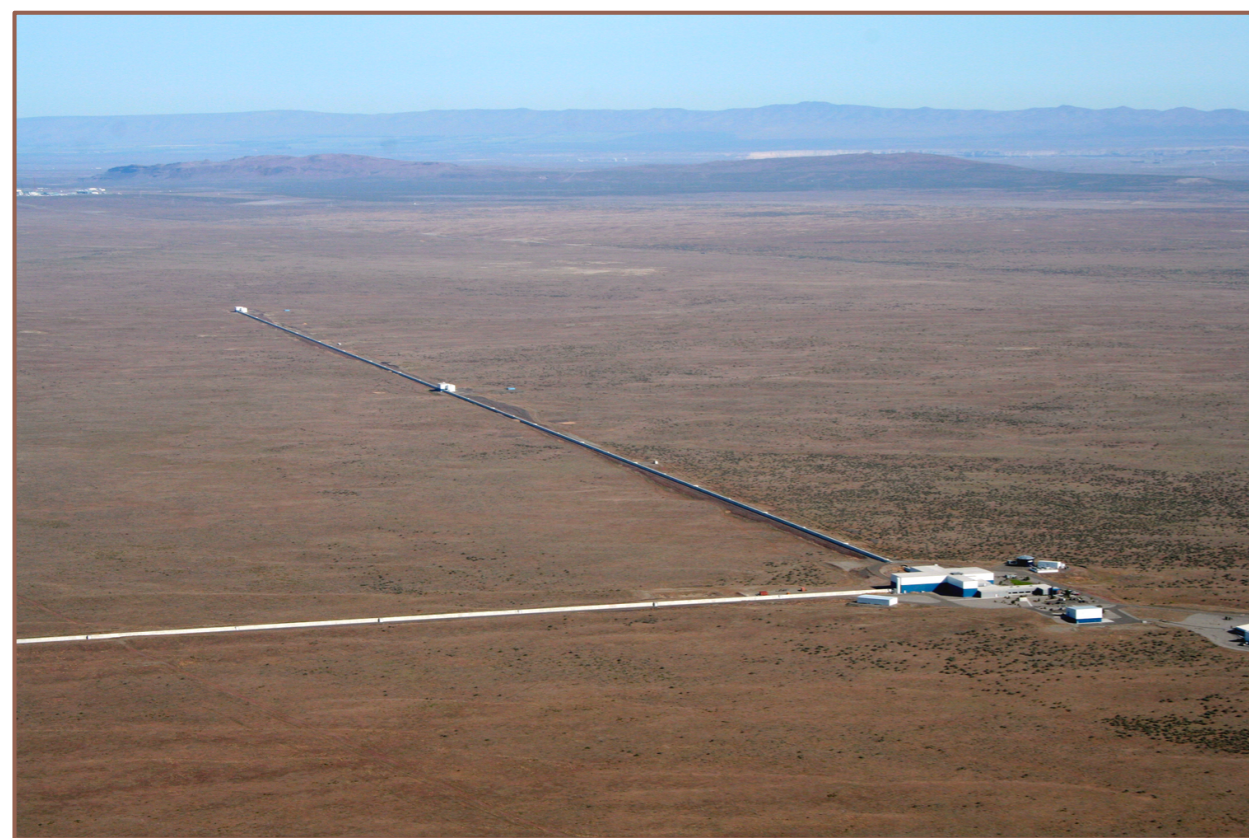
Goddard SPACE FLIGHT CENTER

GRAVITATIONAL WAVES

Advanced LIGO and Virgo



Cascina, Italy

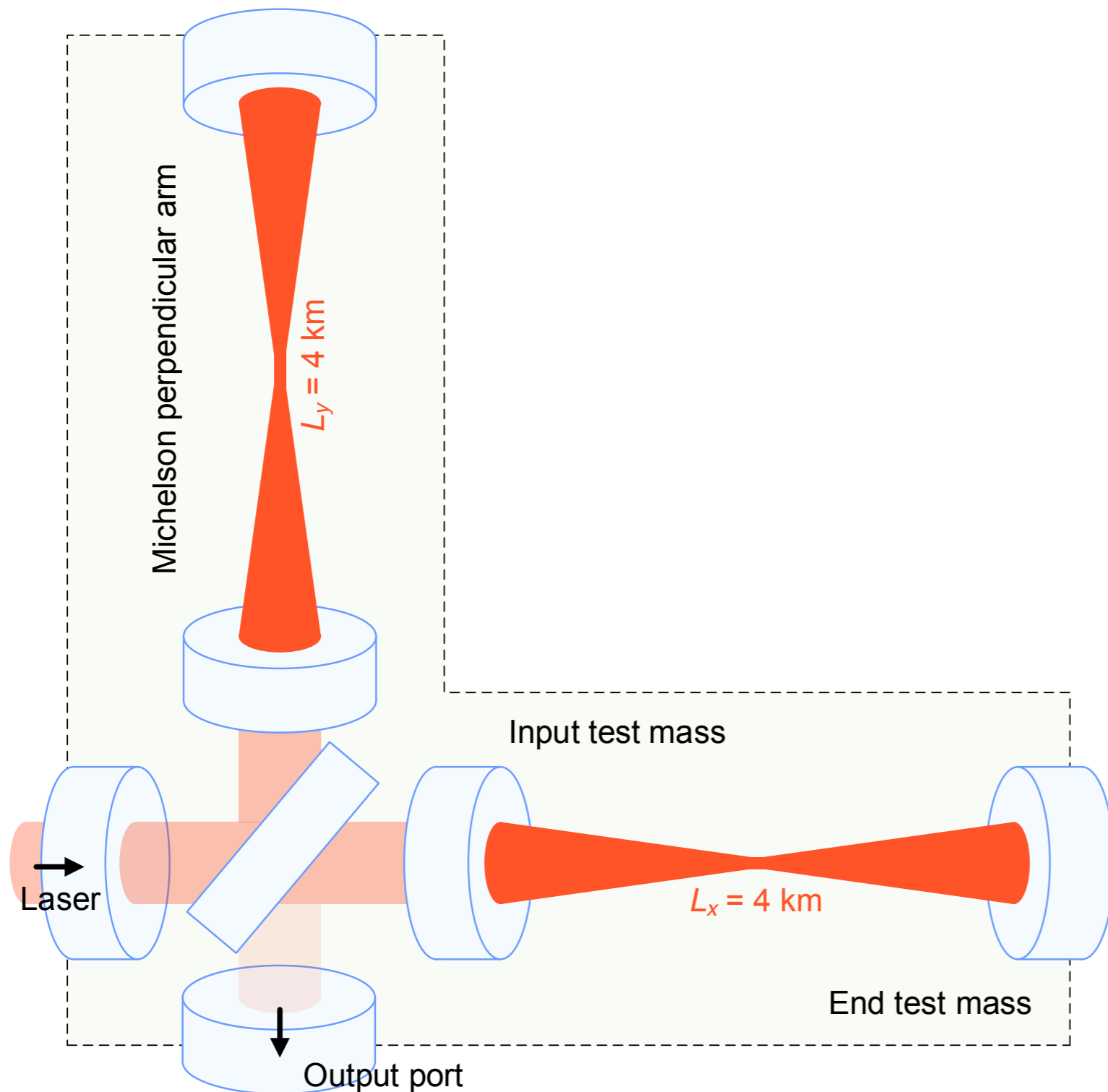


Hanford, WA

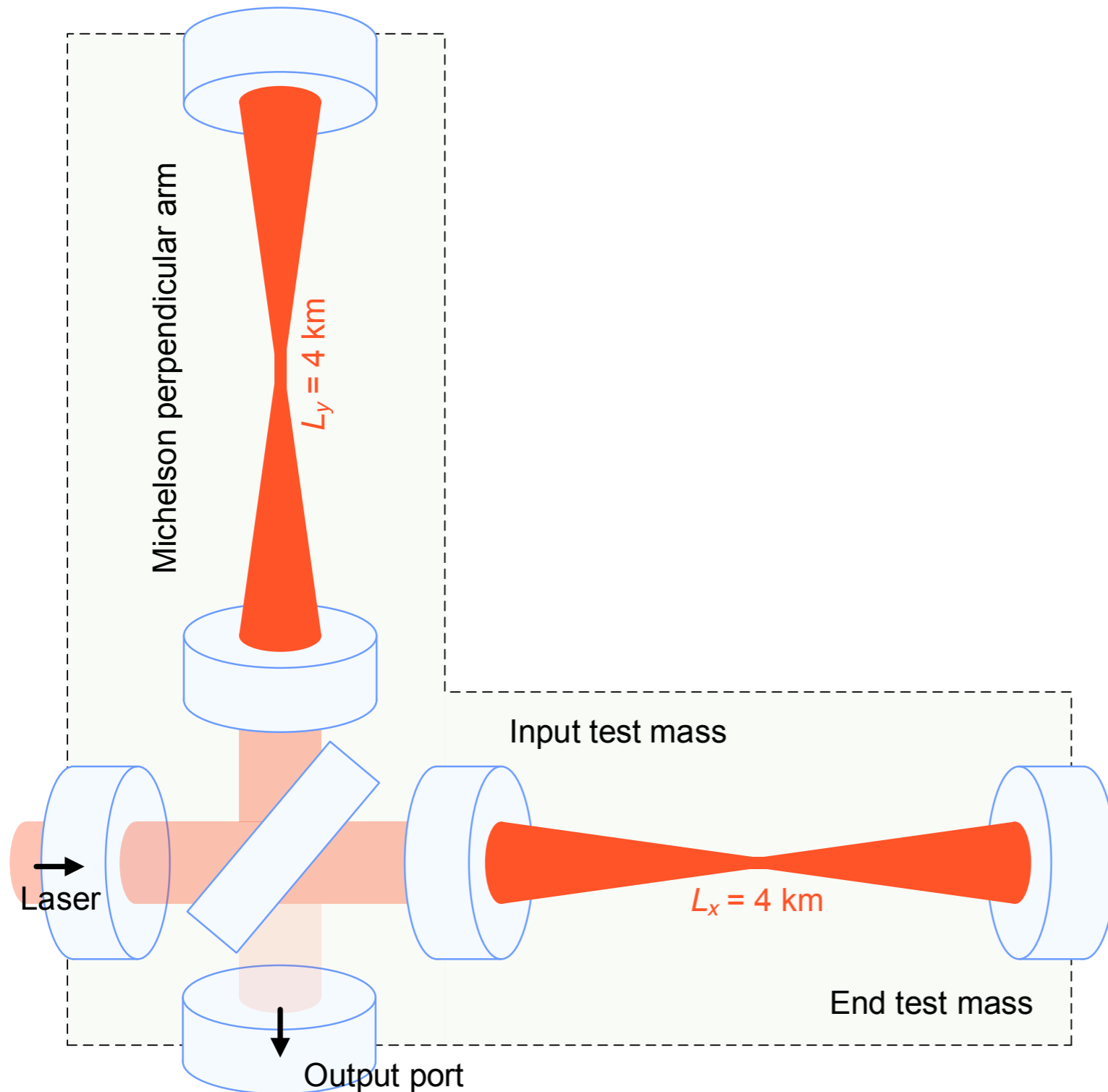


Livingston, LA

A new window

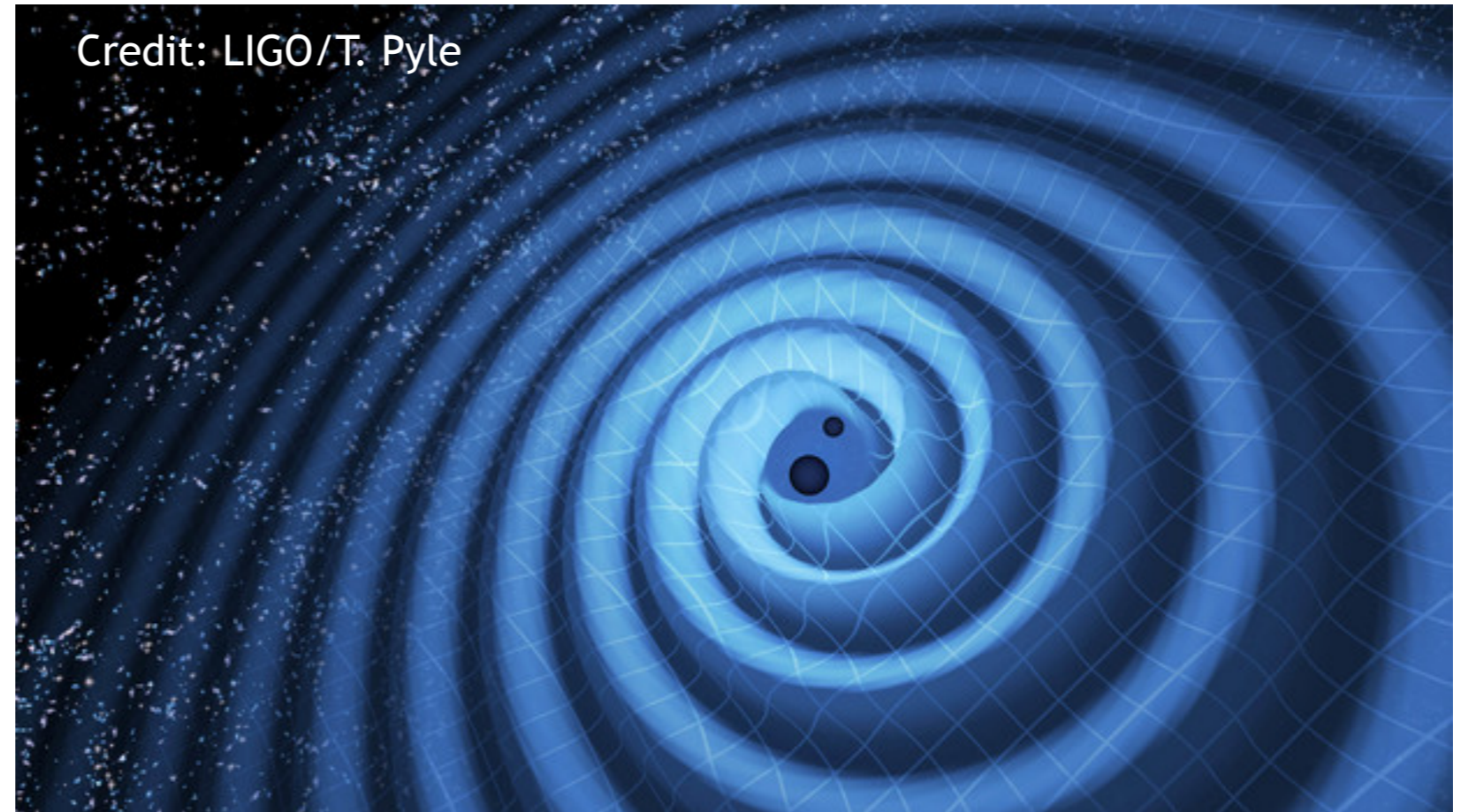
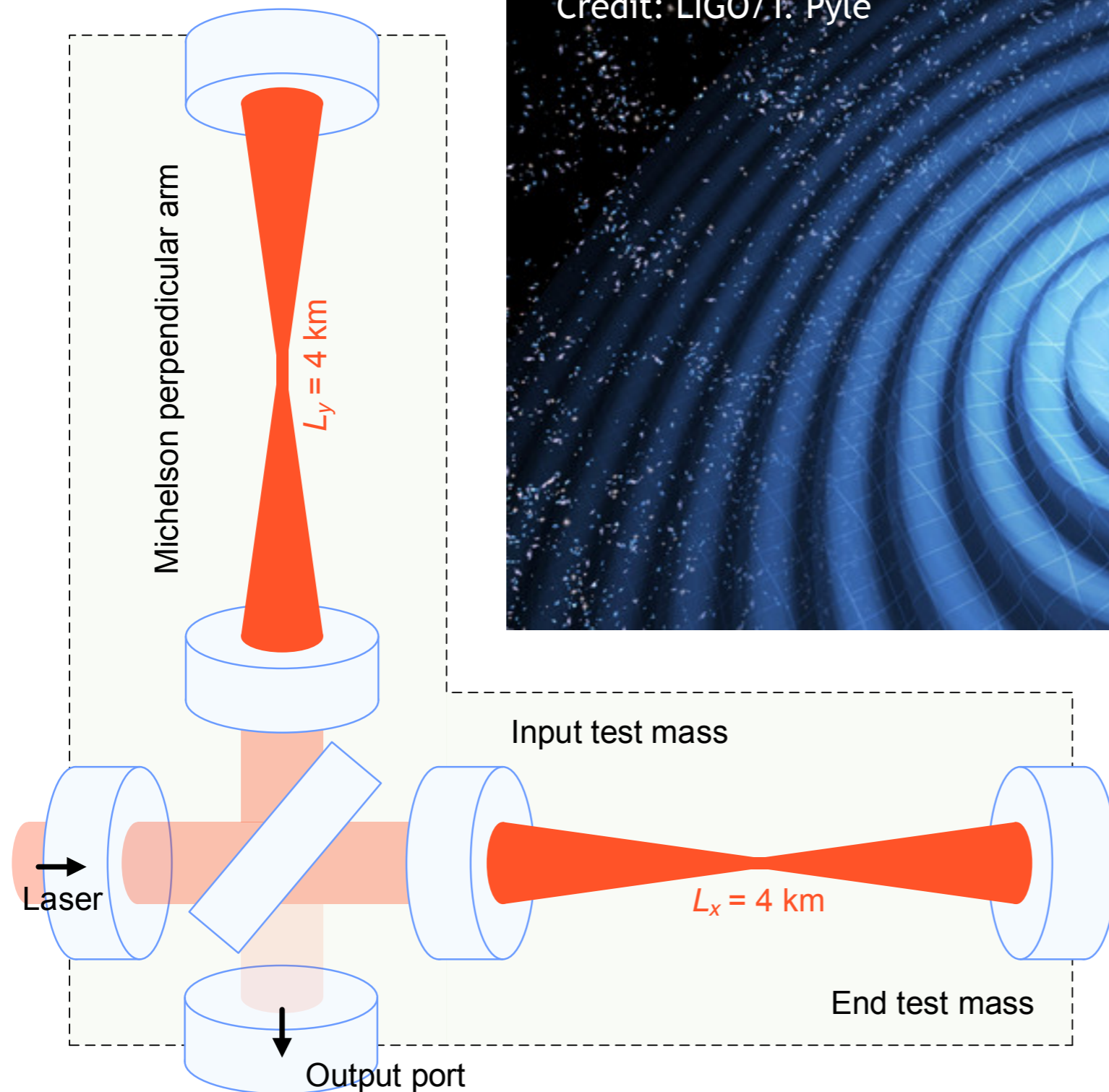


A new window



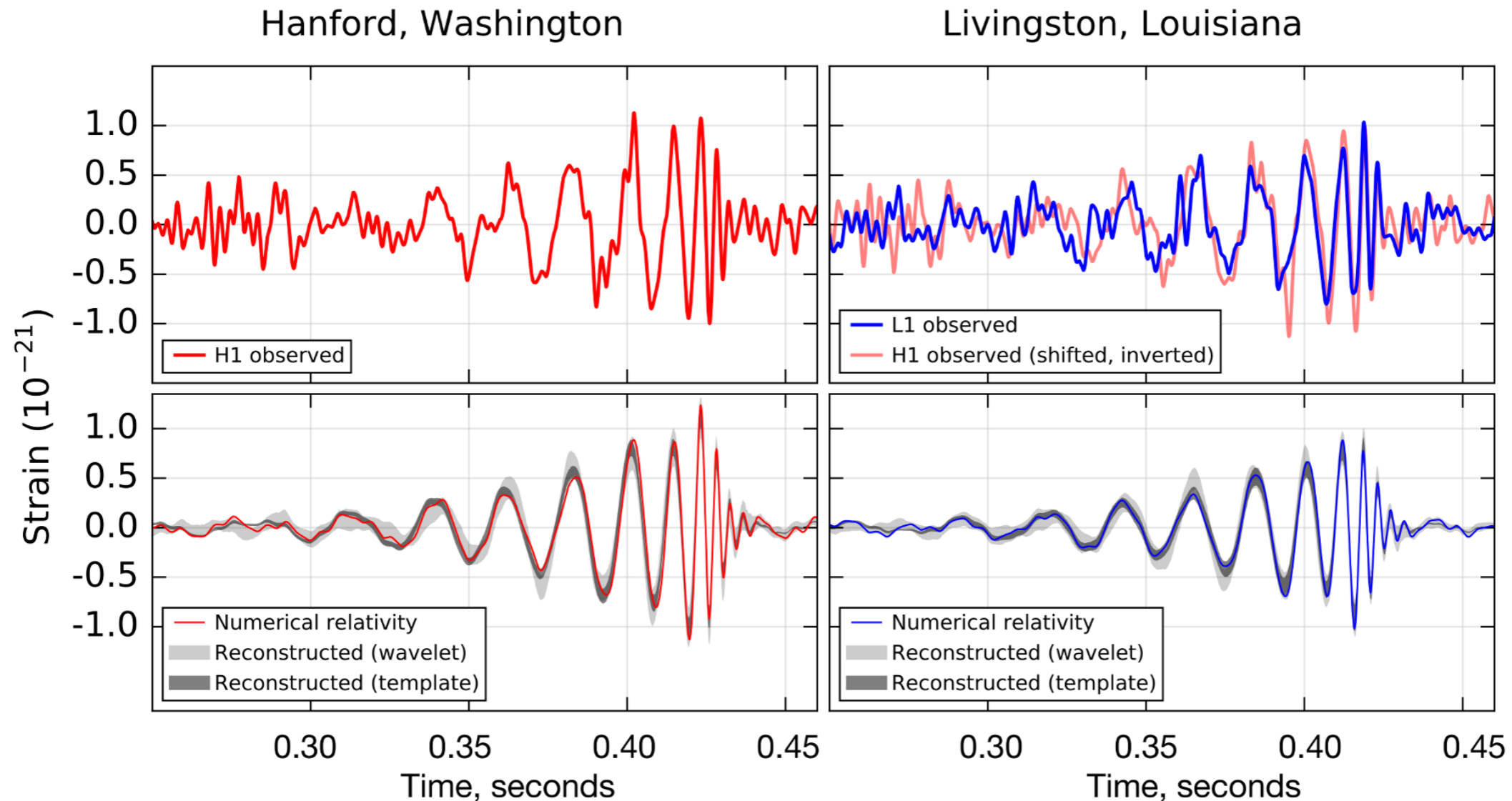
$$\Delta L \sim 10^{-18} \text{ m}$$

A new window



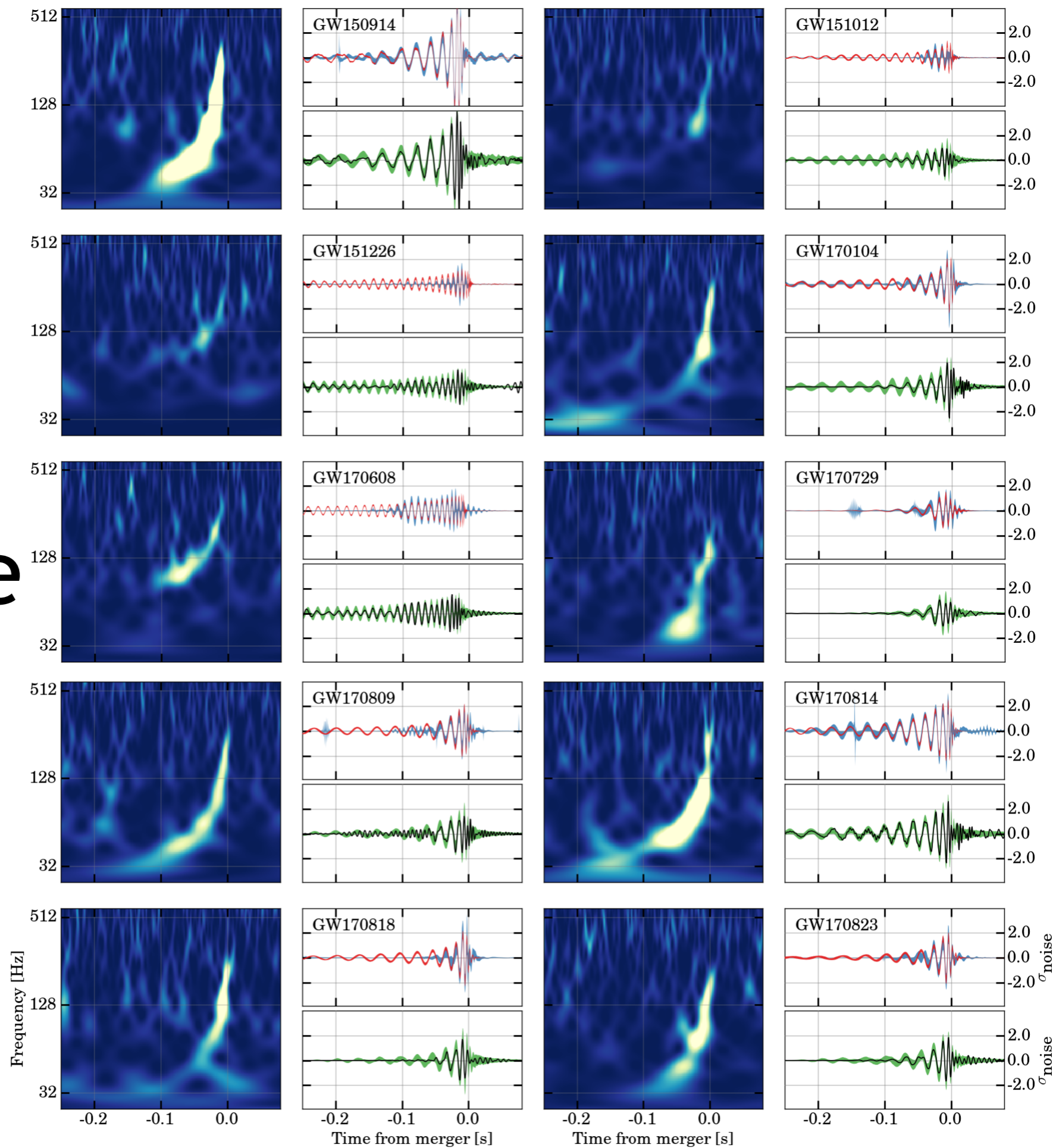
$$\Delta L \sim 10^{-18} \text{ m}$$

First detection: GW150914

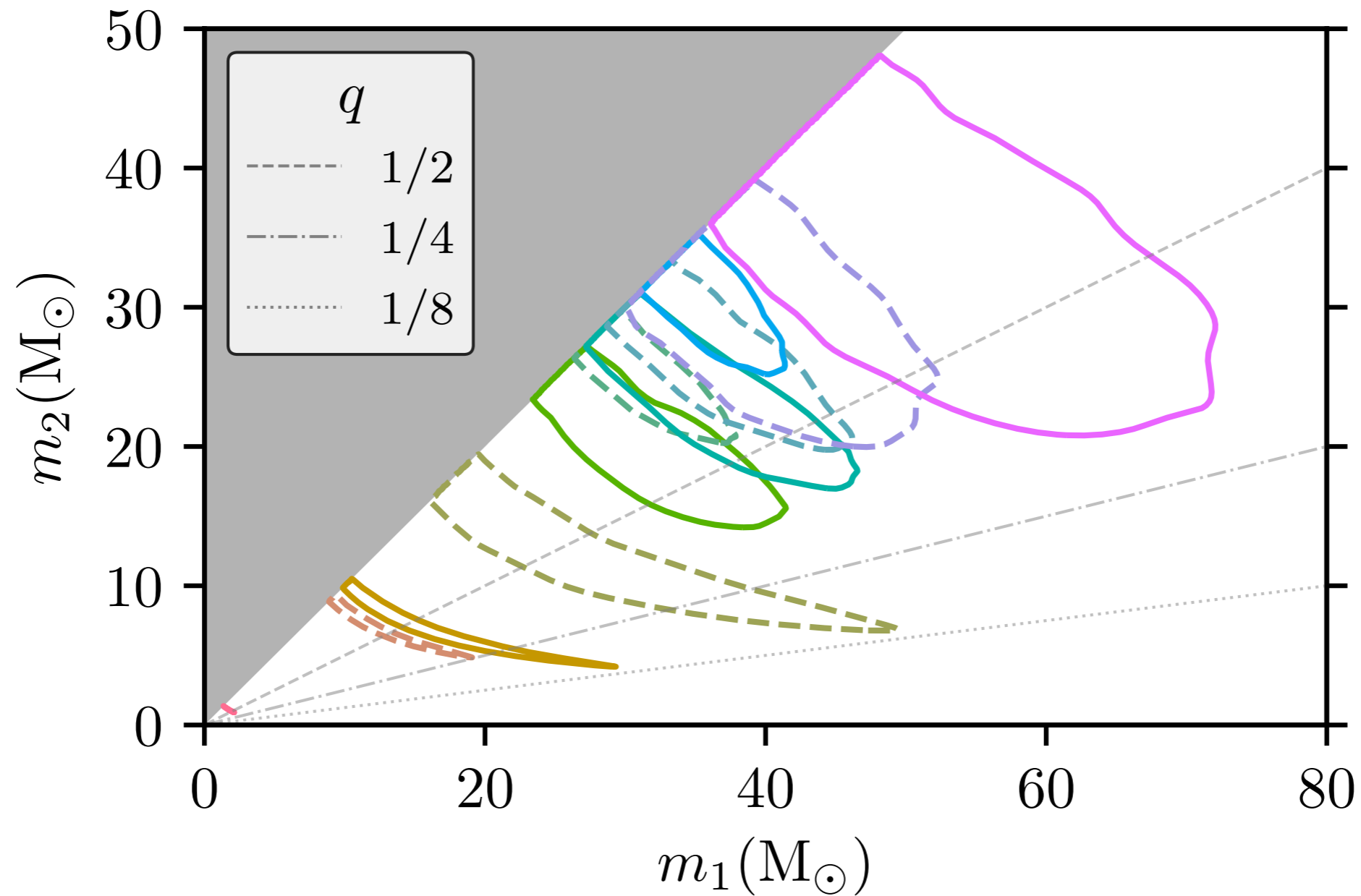


- **Masses** $m_1 = 36_{-4}^{+5} M_{\odot}$ $m_2 = 29_{-4}^{+4} M_{\odot}$
- **Peak luminosity** $L \sim 10^{23} L_{\odot} \sim 10^{13} L_{\text{MWG}}$

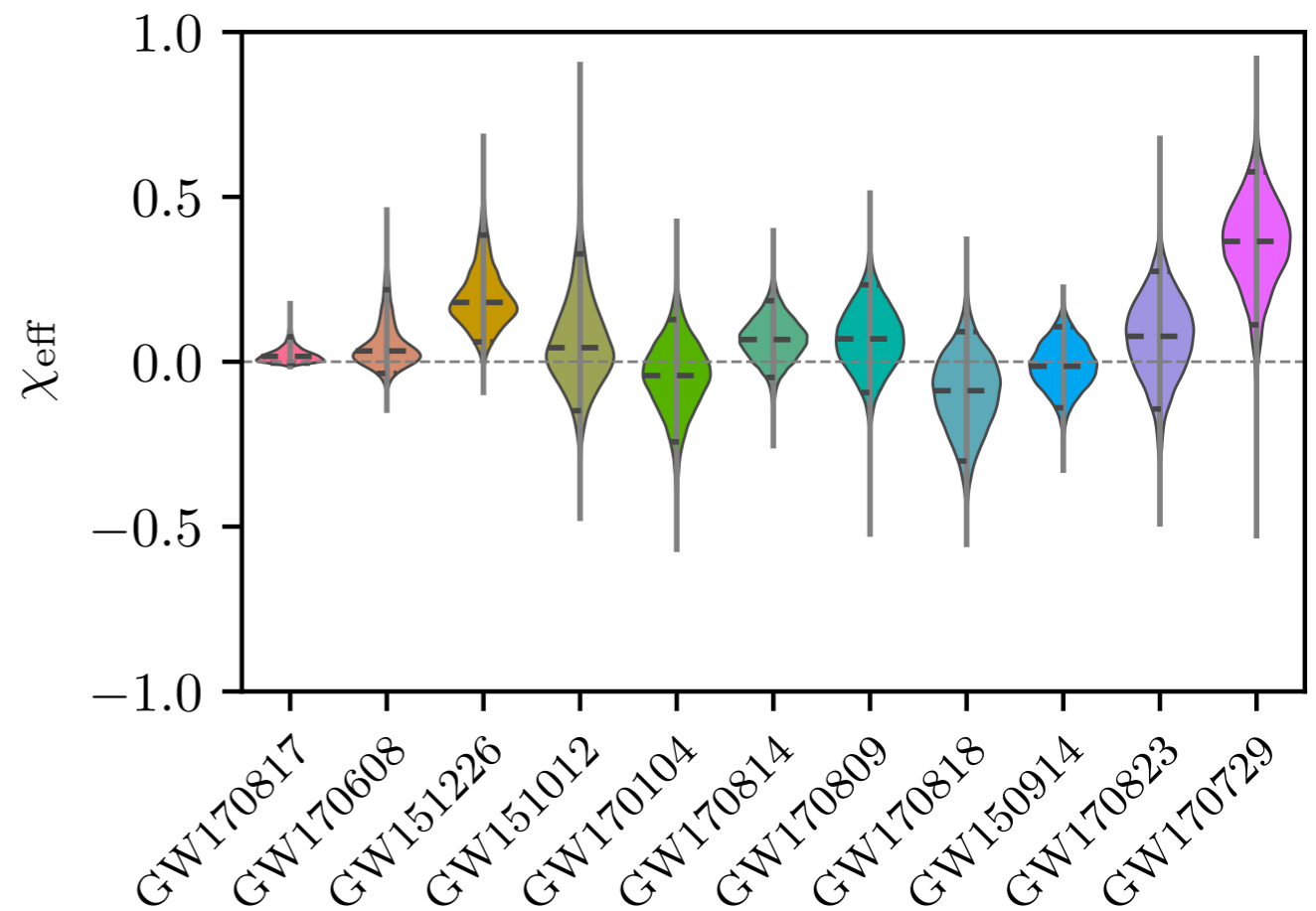
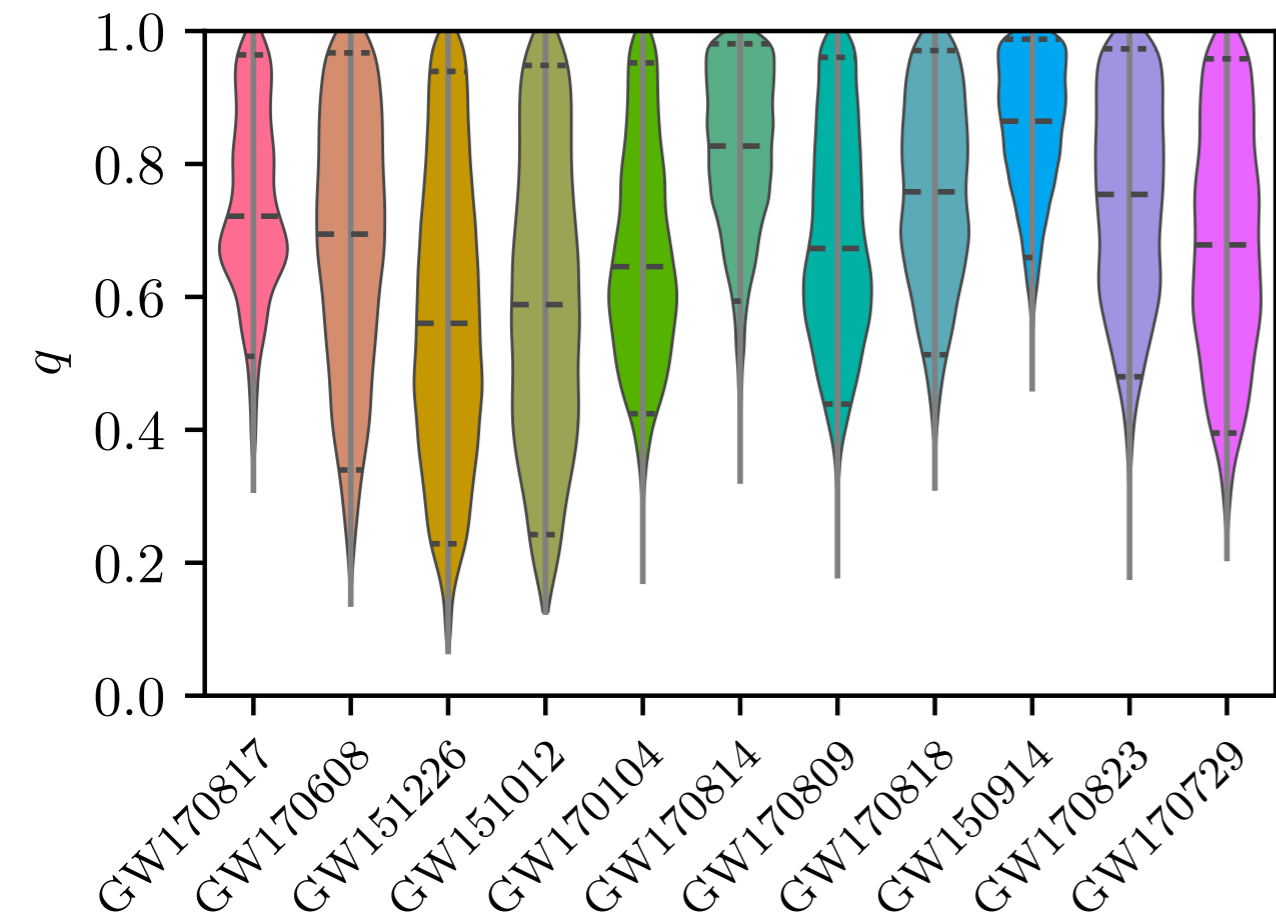
Binary black hole catalog



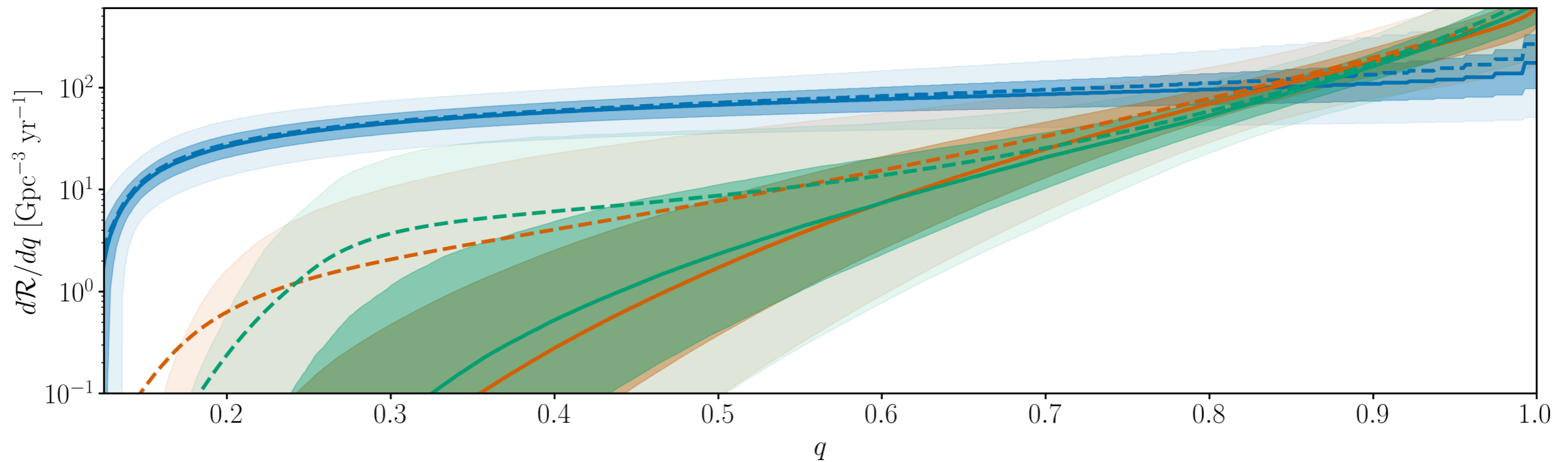
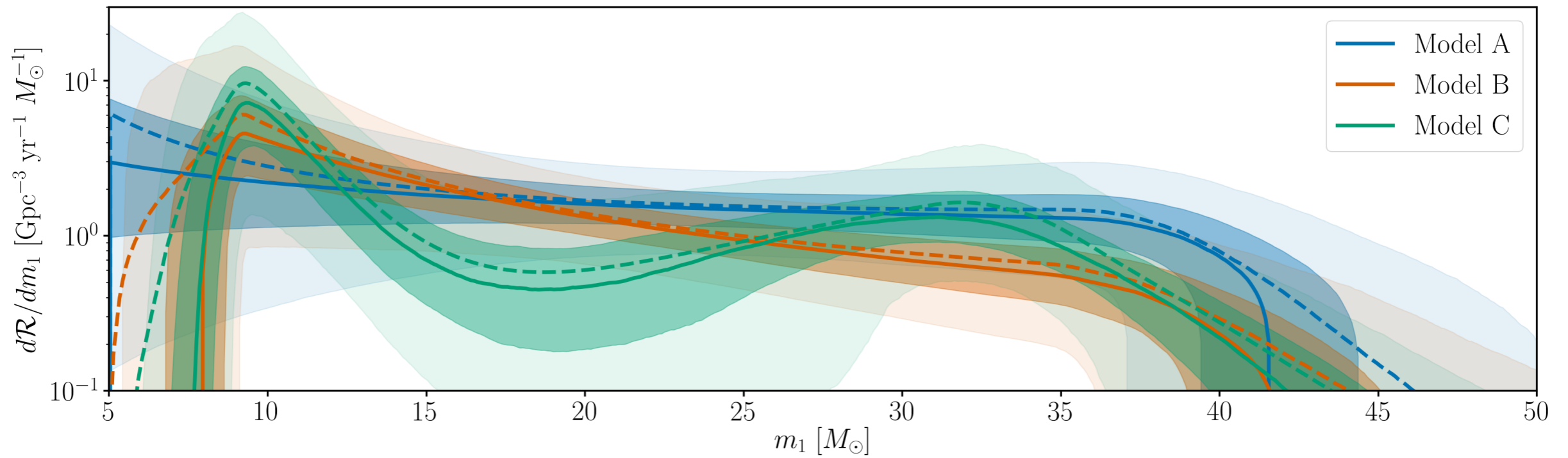
GWTC-1: Catalog of detections



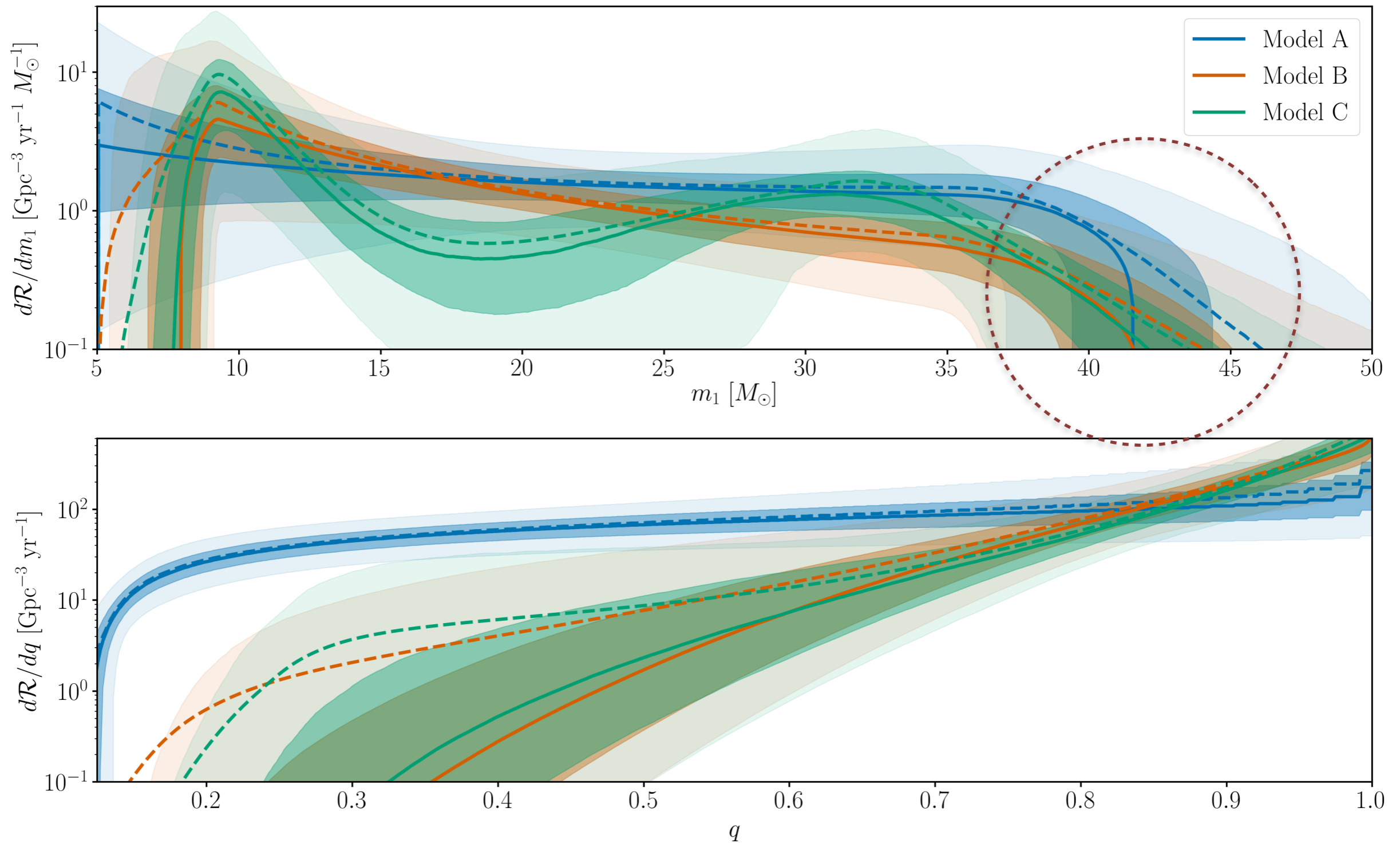
GWTC-1: Catalog of detections



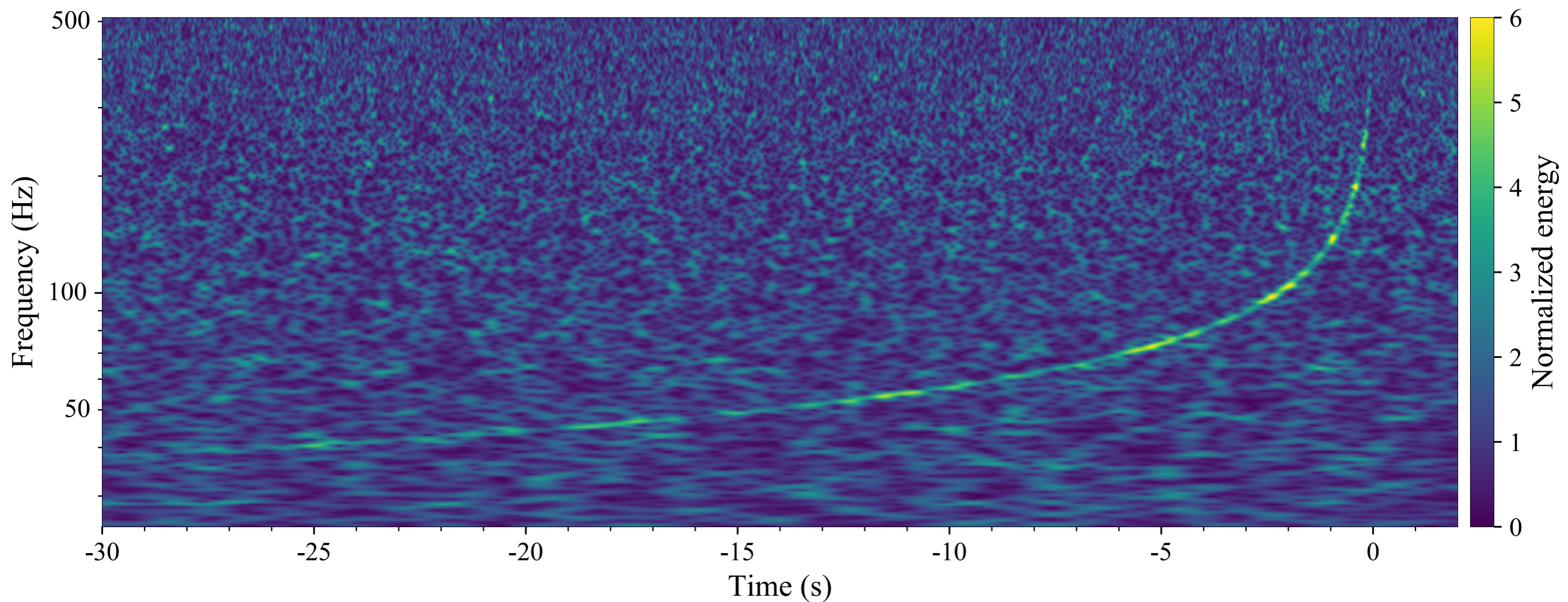
Astrophysics with GWs



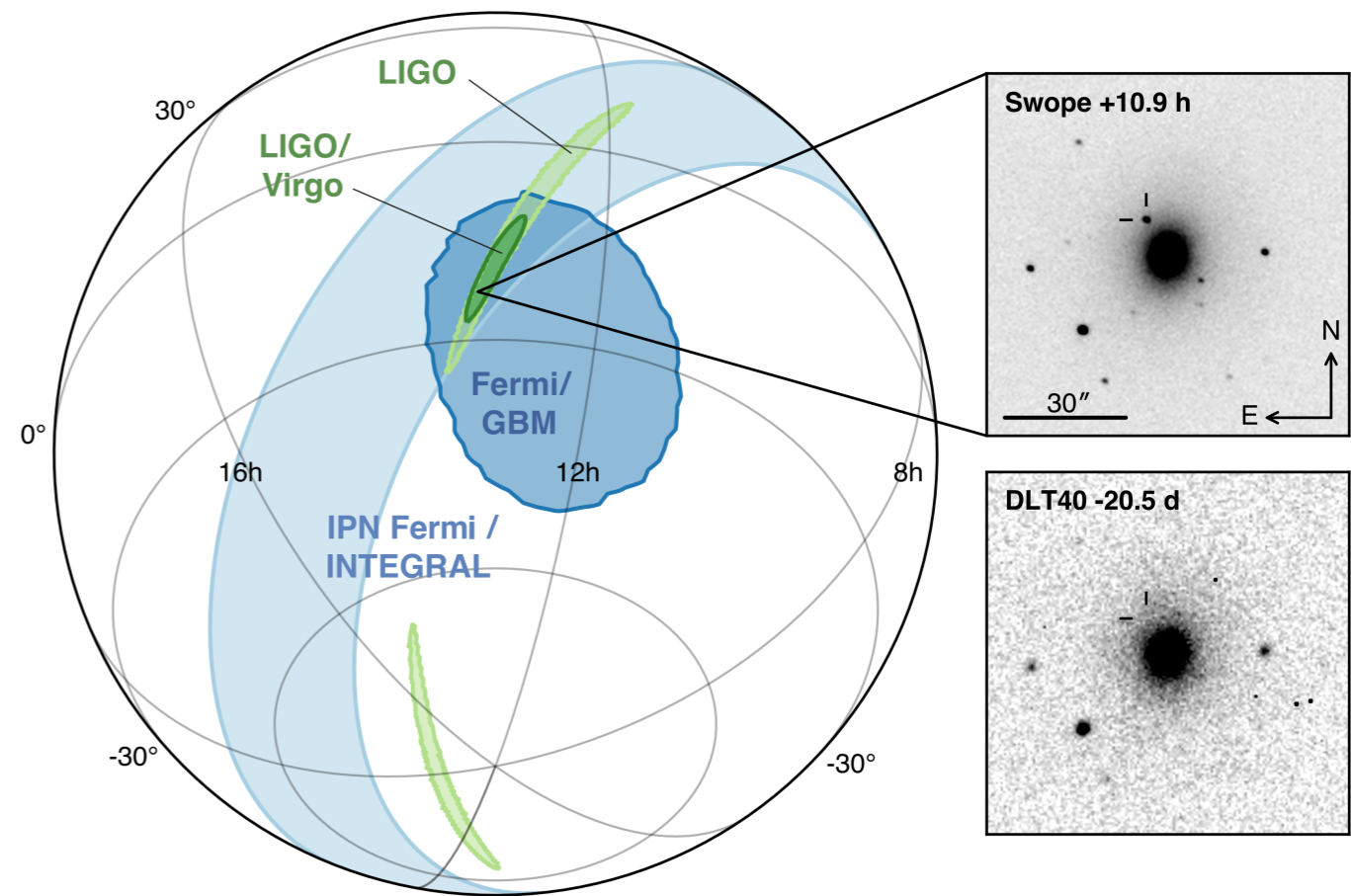
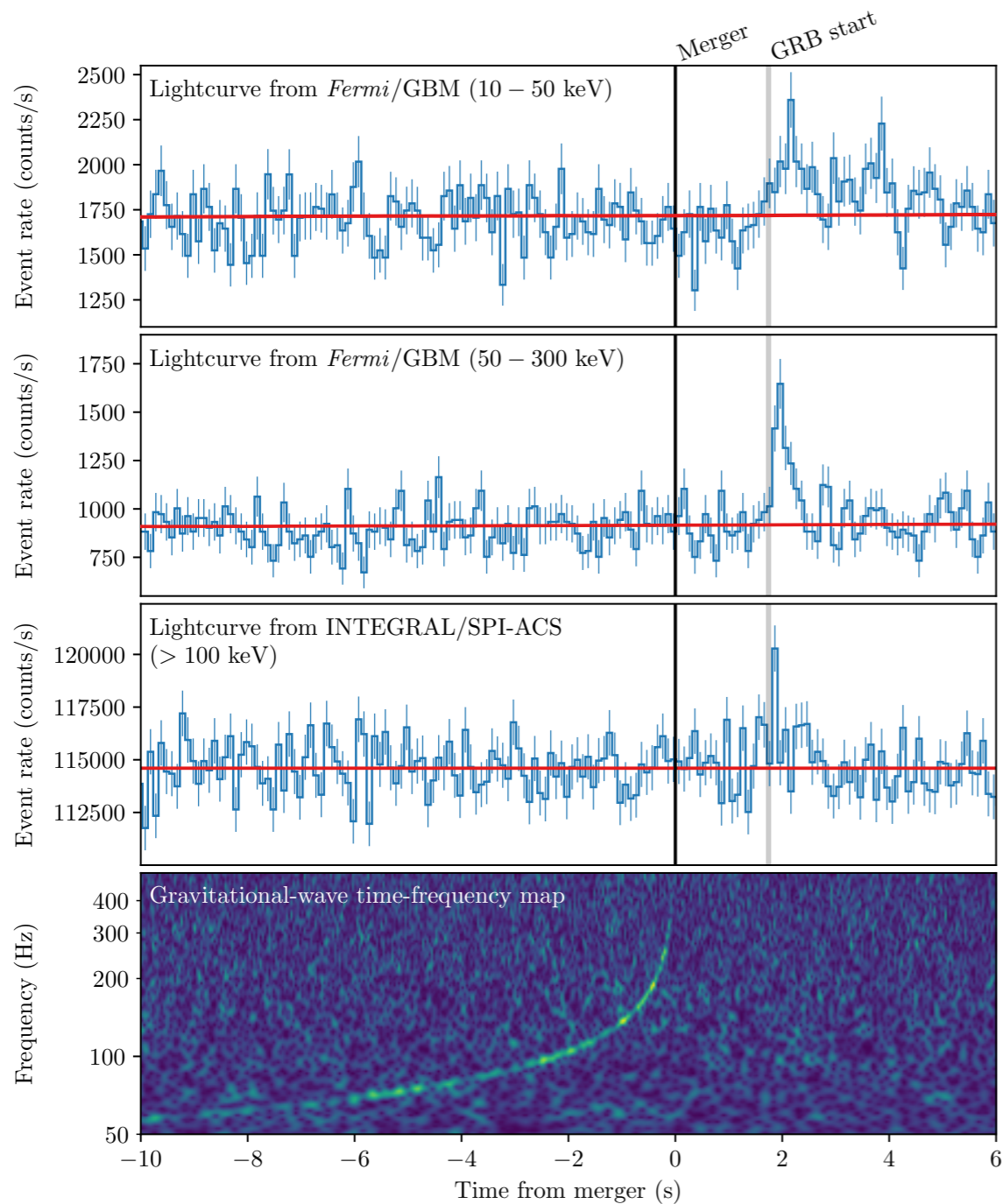
Astrophysics with GWs



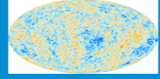





GW170817: A binary neutron star



Electromagnetic counterpart



The Origin of the Solar System Elements

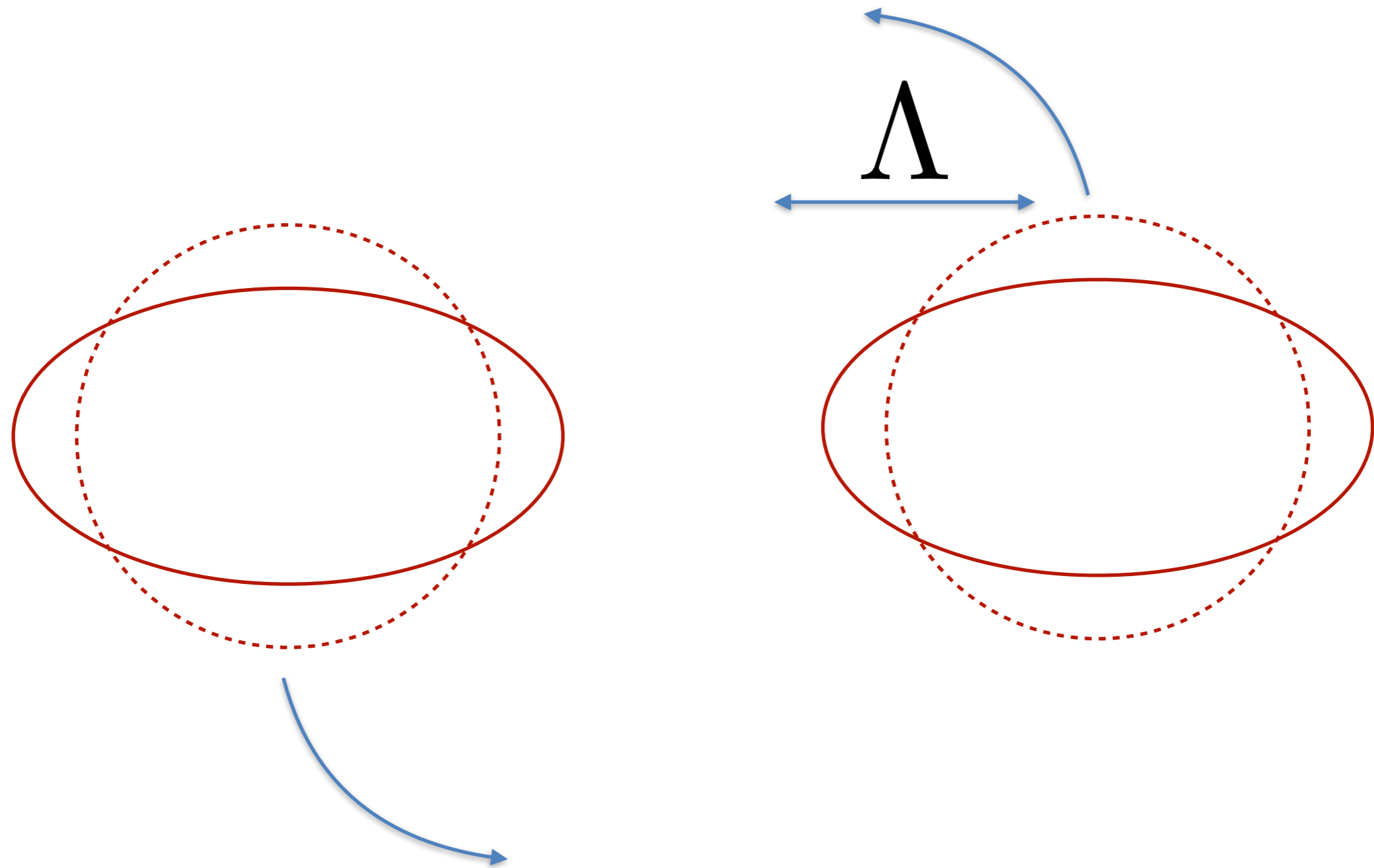
1 H	big bang fusion 						cosmic ray fission 						2 He						
3 Li	4 Be	merging neutron stars 						exploding massive stars 						5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars 						exploding white dwarfs 						13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn			
87 Fr	88 Ra																		
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
		89 Ac	90 Th	91 Pa	92 U														

Astronomical Image Credits:
ESA/NASA/AASNova

Graphic created by Jennifer Johnson

FUNDAMENTAL PHYSICS WITH GRAVITATIONAL WAVES

Nuclear physics with GW170817

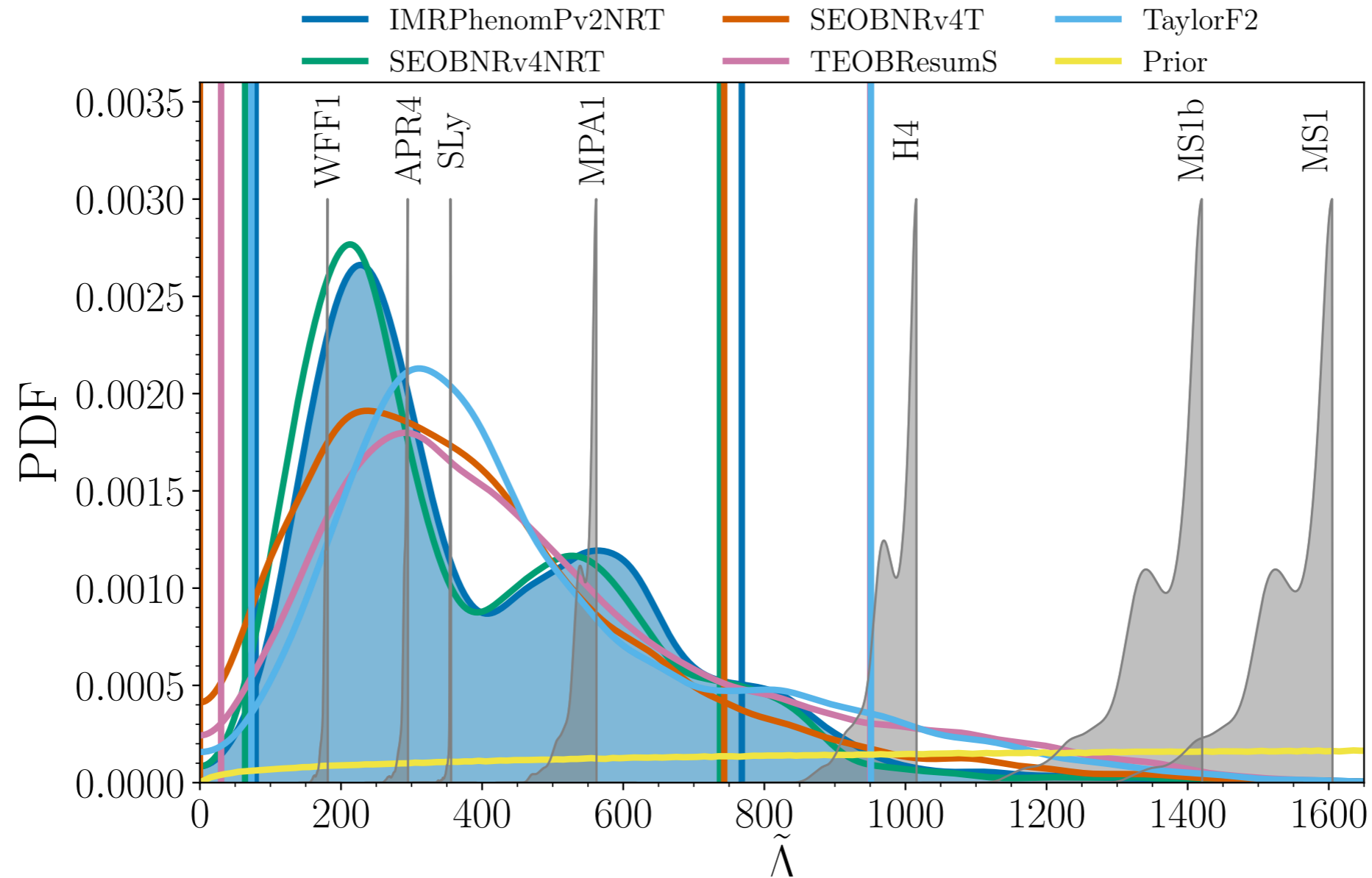


Flanagan and Hinderer, PRD (2008)

Hinderer ApJ (2008)

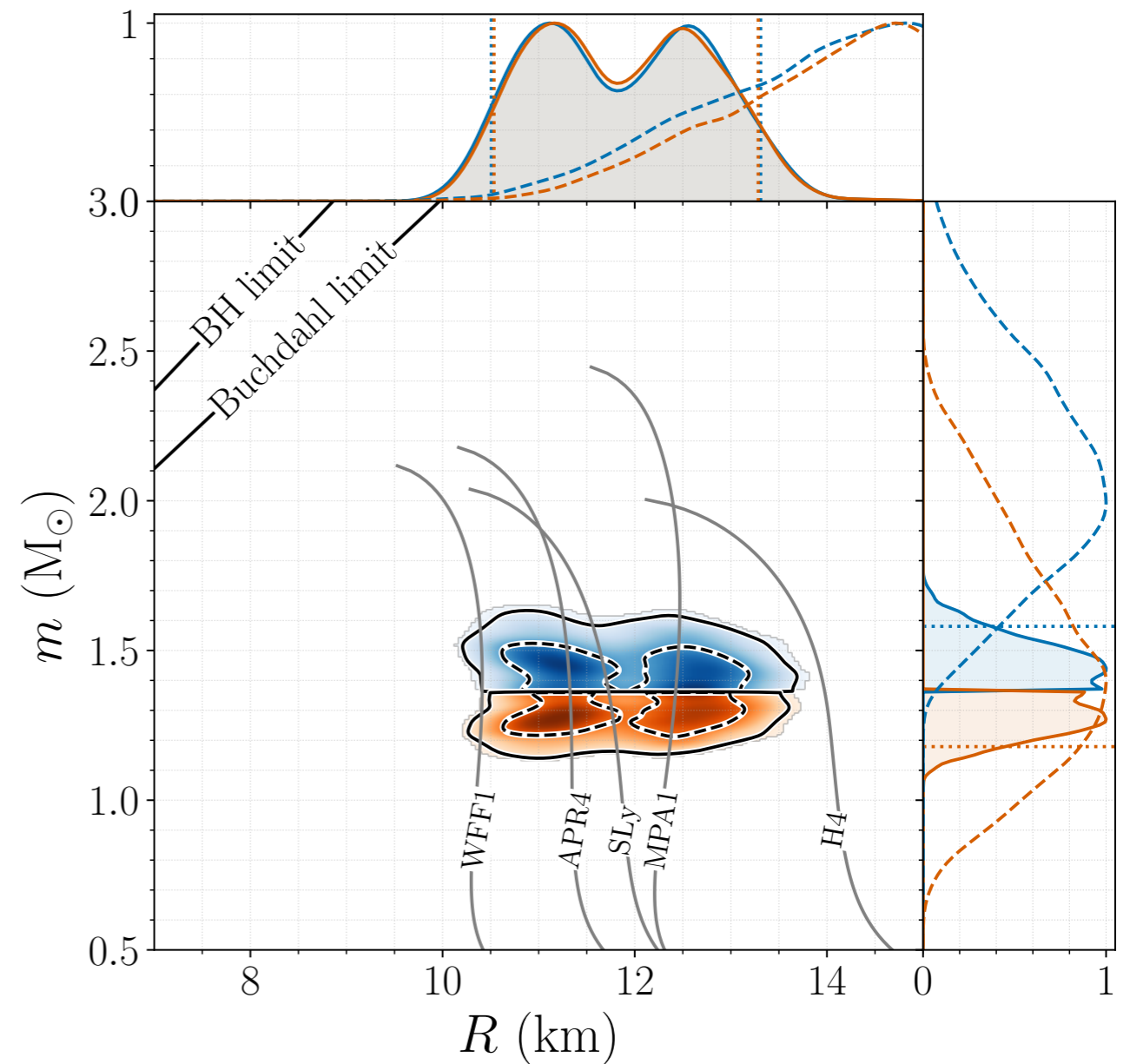
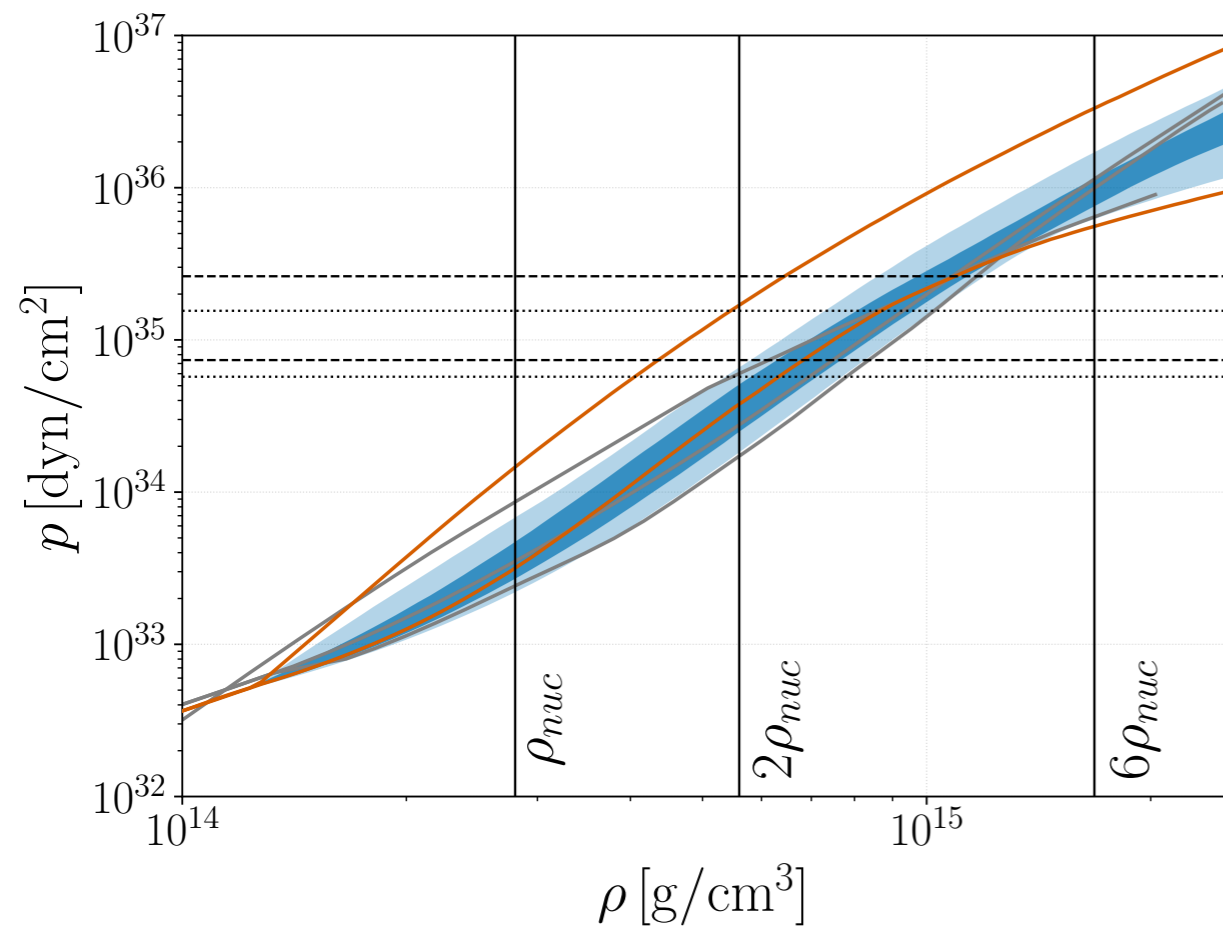
Hinderer, Lackey, Lang, Read PRD (2010)

Nuclear physics with GW170817



LVC PRL 119, 161101 (2017)
LVC PRX 9, 011001 (2019)
LVC arXiv:1811.12907

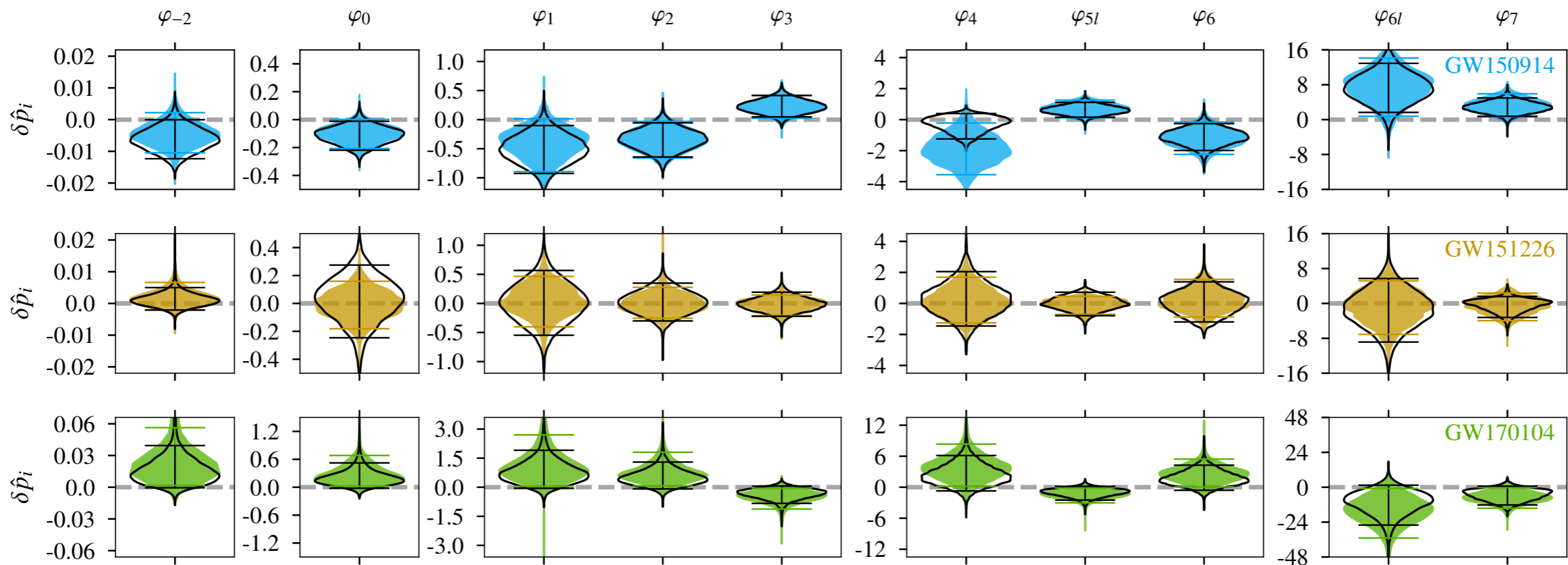
Nuclear physics with GW170817



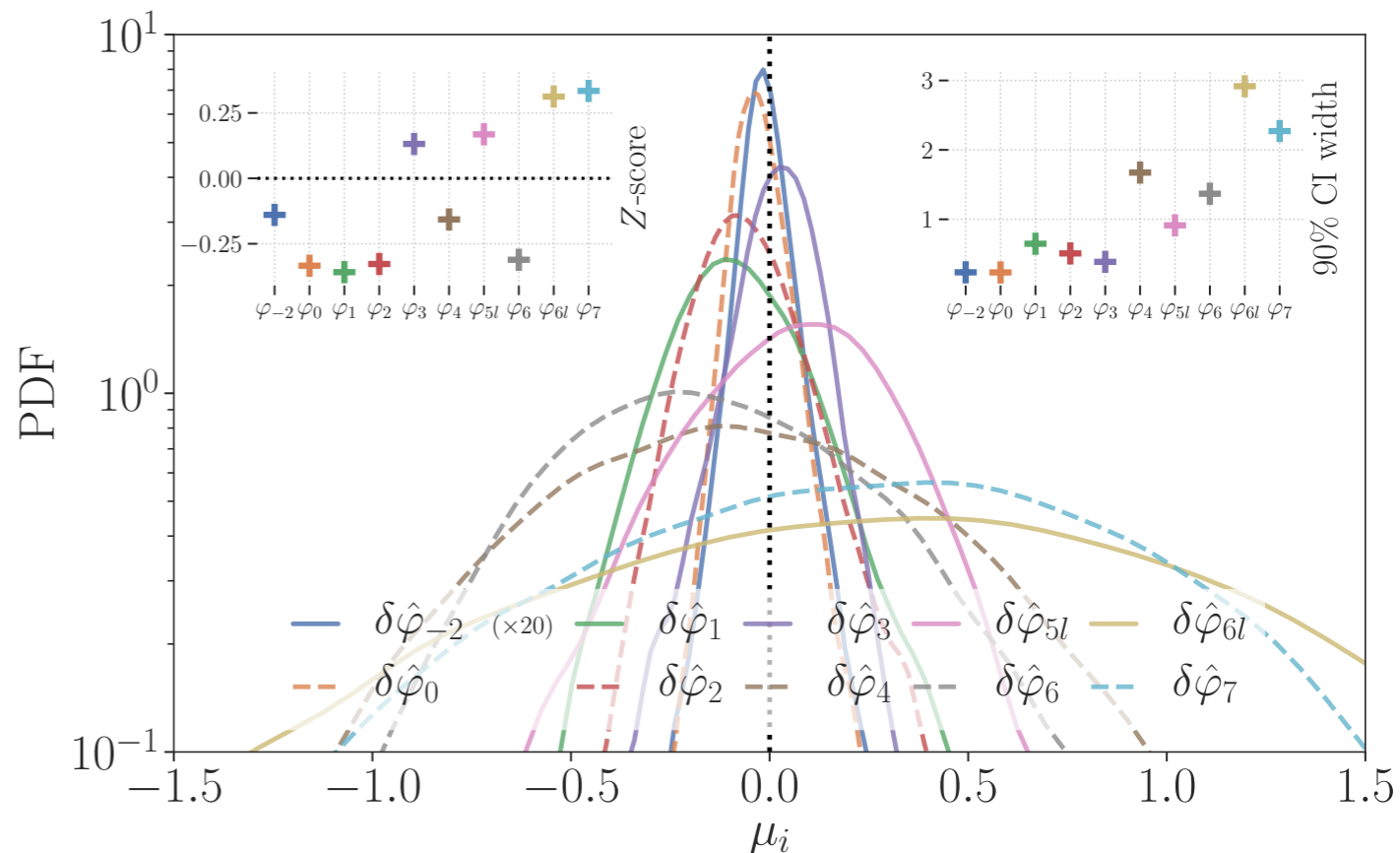
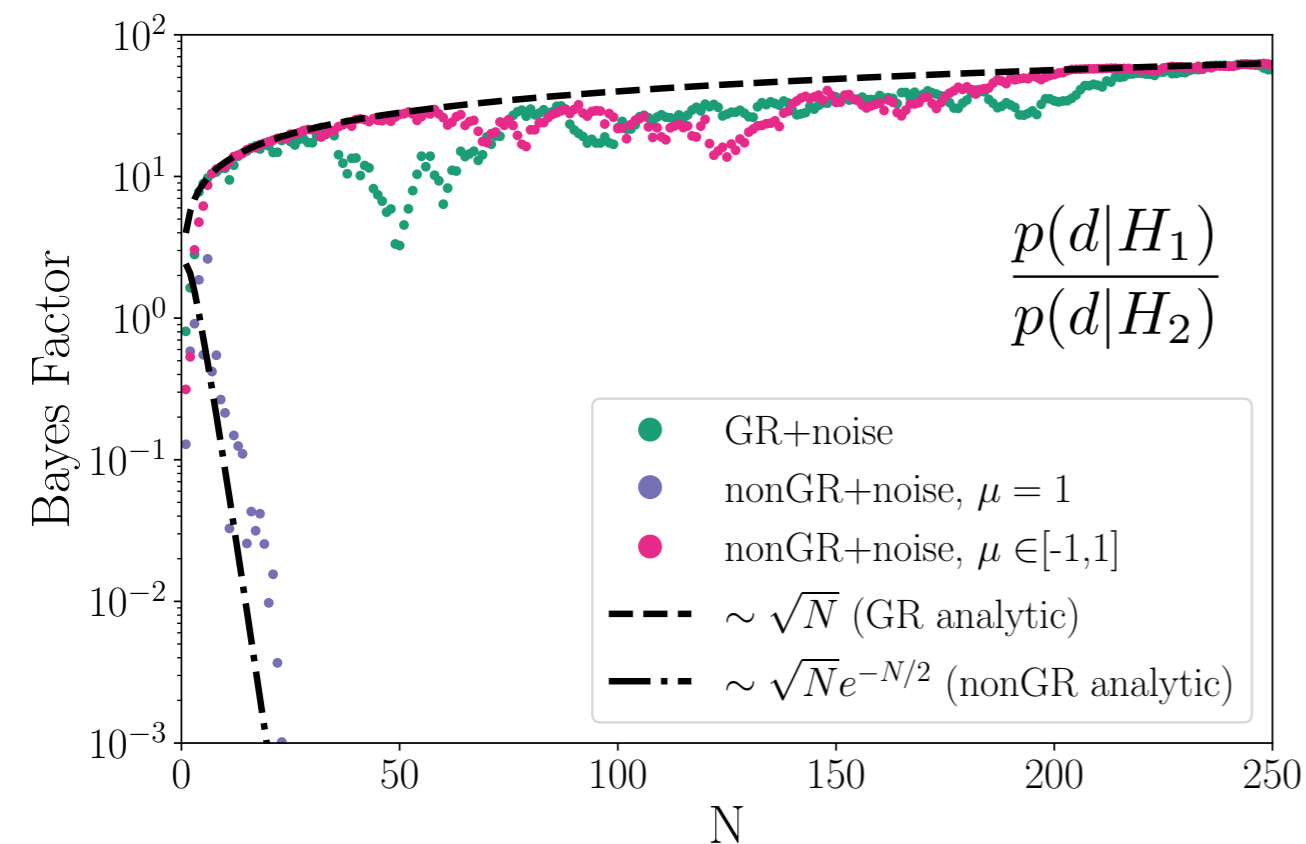
Tests of relativity: Constraining deviations

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

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

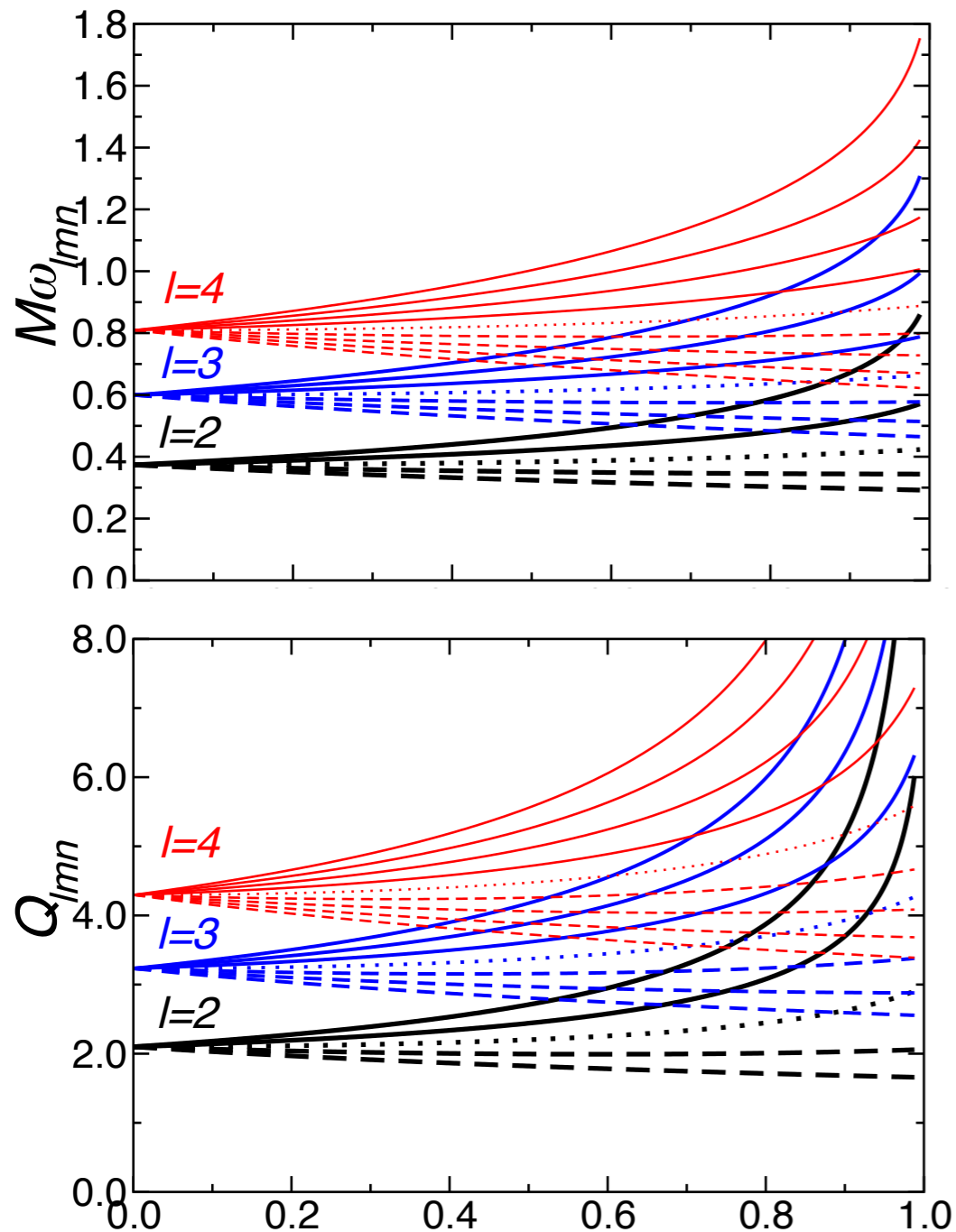


Combining events

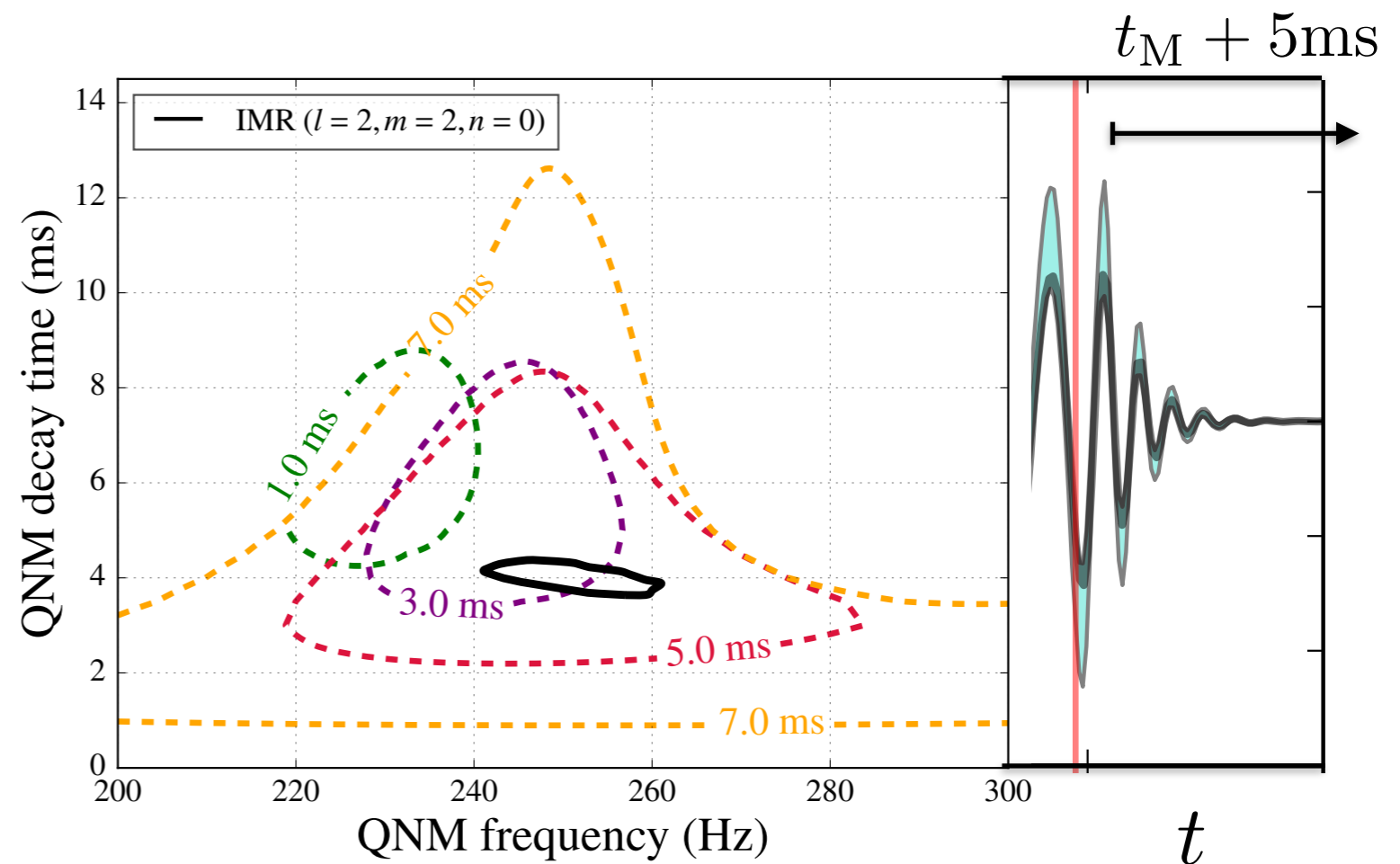


$$\delta\hat{\varphi}_i \sim \mathcal{N}(\mu_i, \sigma_i)$$

GW150914: Black hole ringdown

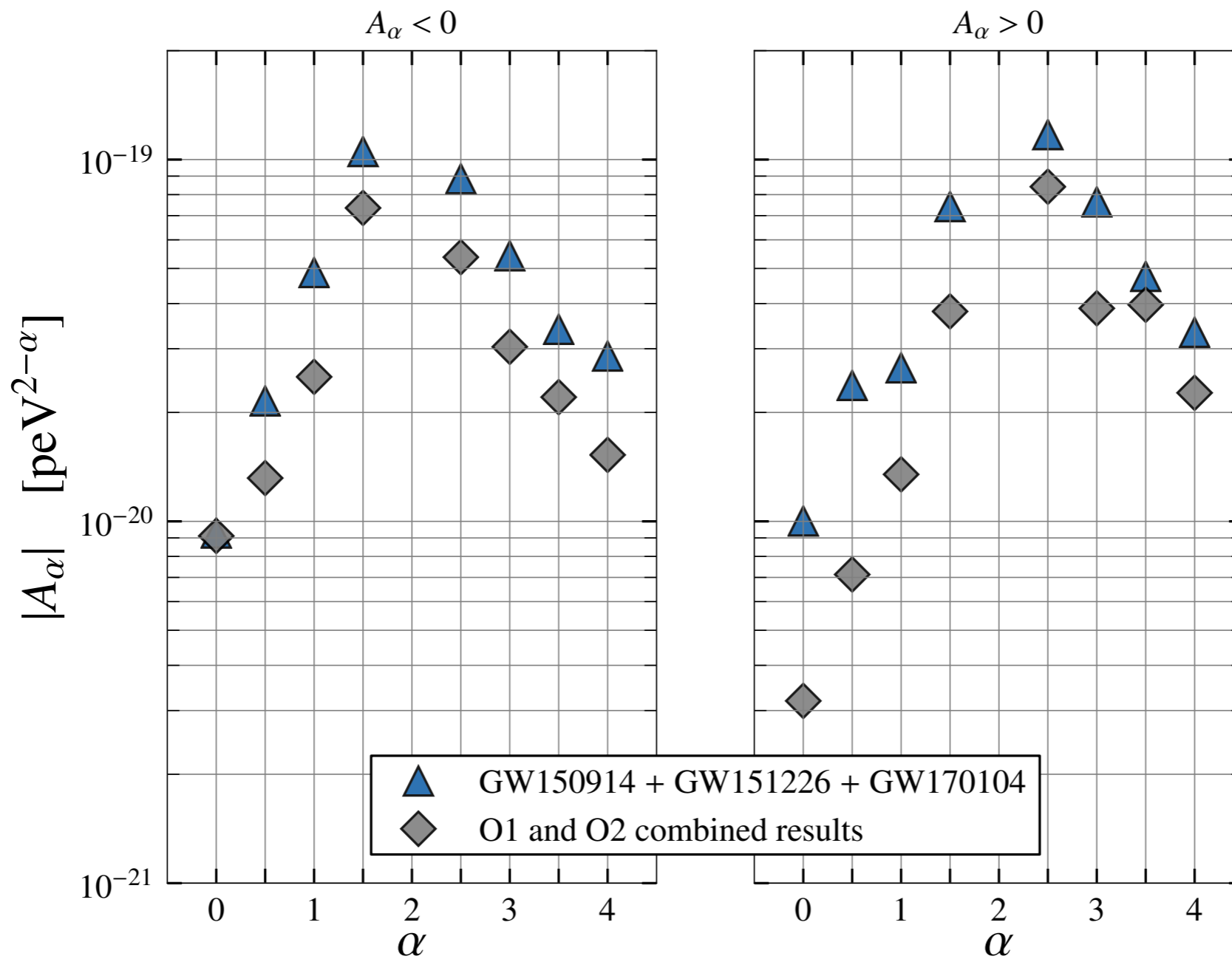


Berti, Cardoso, Starinets (2009)



LCV PRL 116, 221101 (2016)

Propagation of GWs

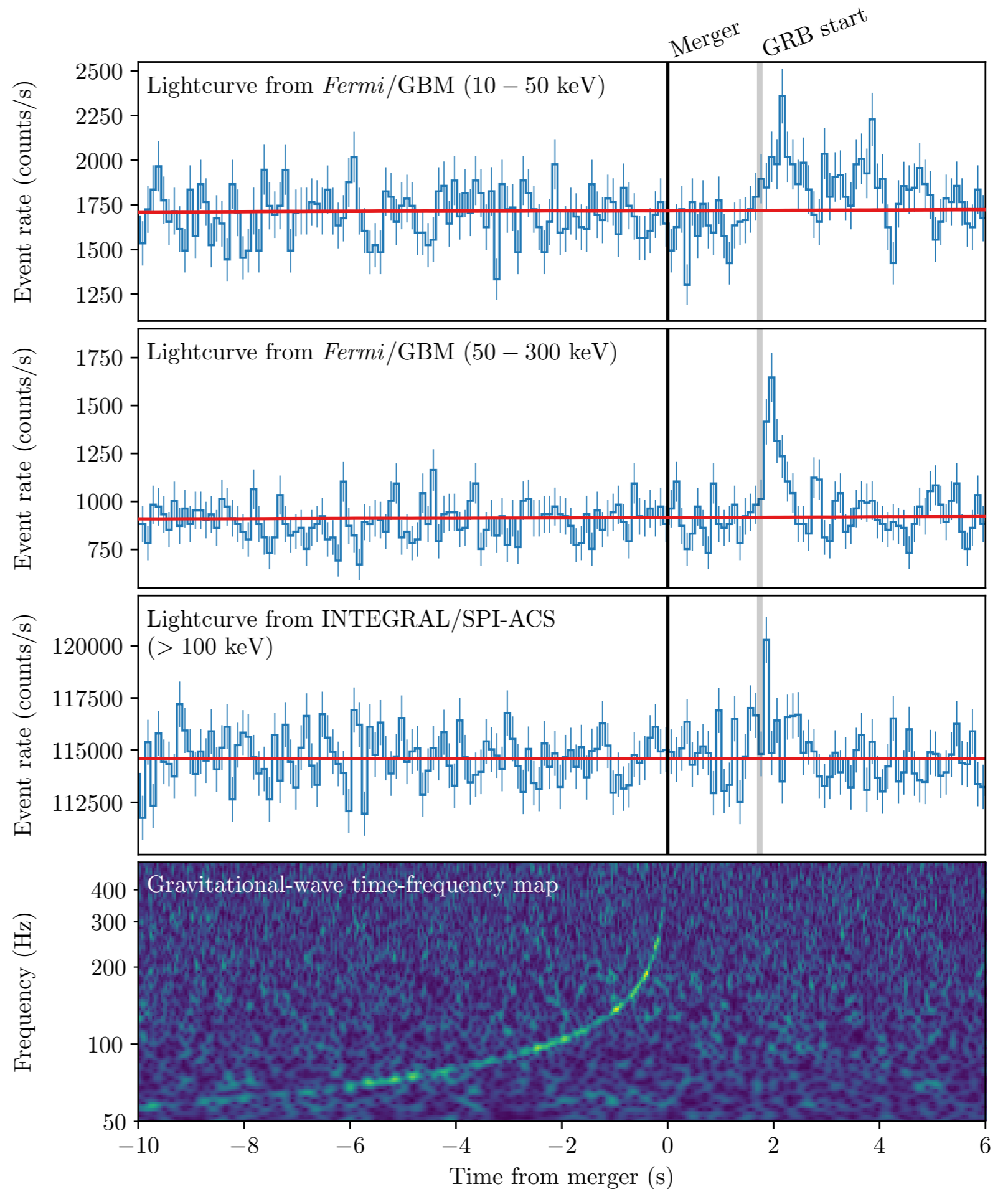


$$E^2 = p^2 c^2 + A p^\alpha c^\alpha$$

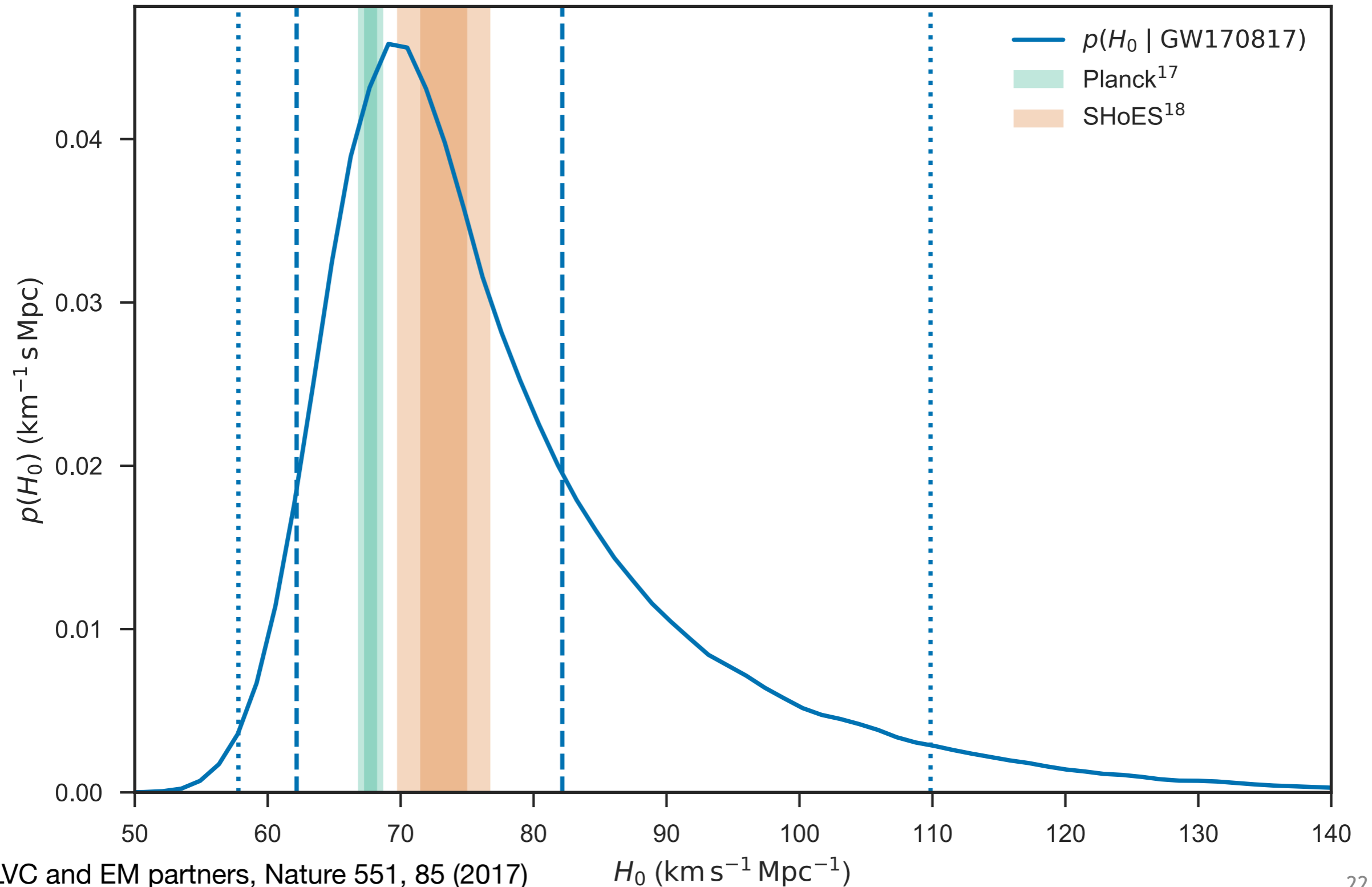
$$m_g \leq 5 \times 10^{-23} \text{ eV}/c^2$$

Speed of gravitational waves

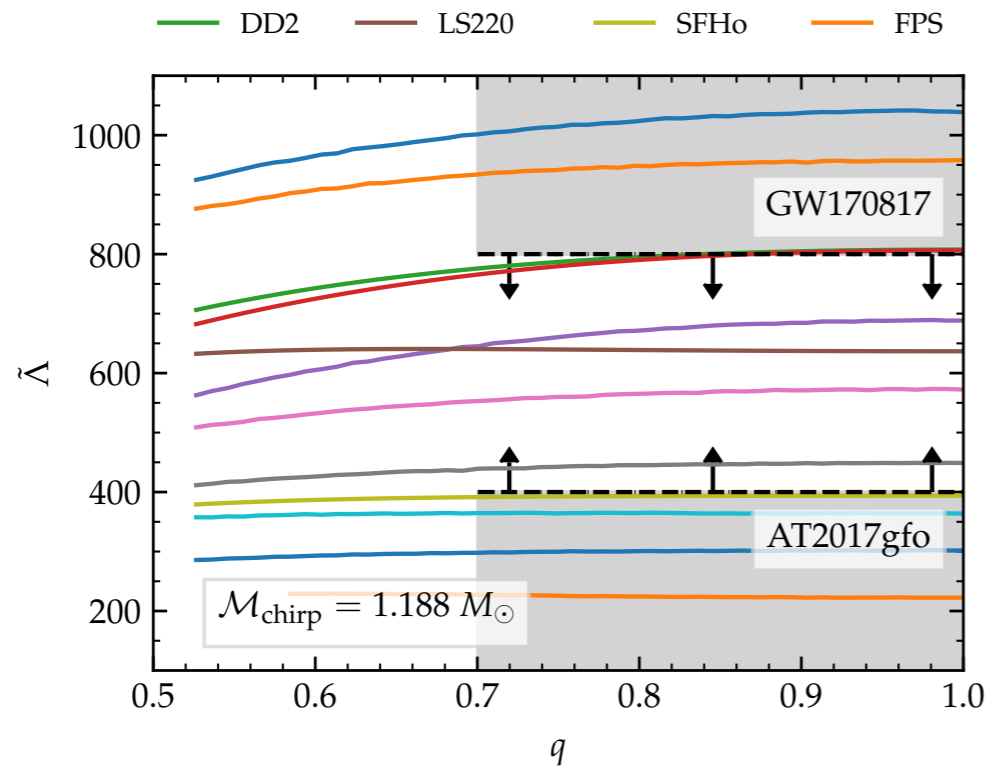
$$-3 \times 10^{-15} \leq \frac{\Delta v}{v} \leq +7 \times 10^{-16}$$



Standard siren cosmology

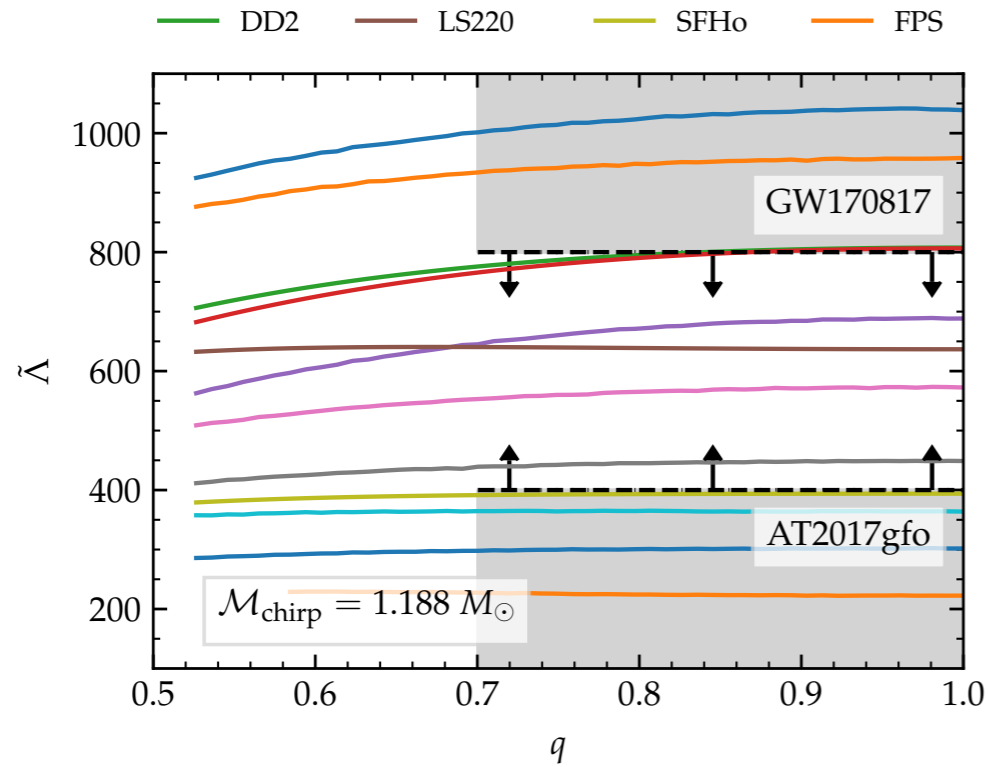


Other directions

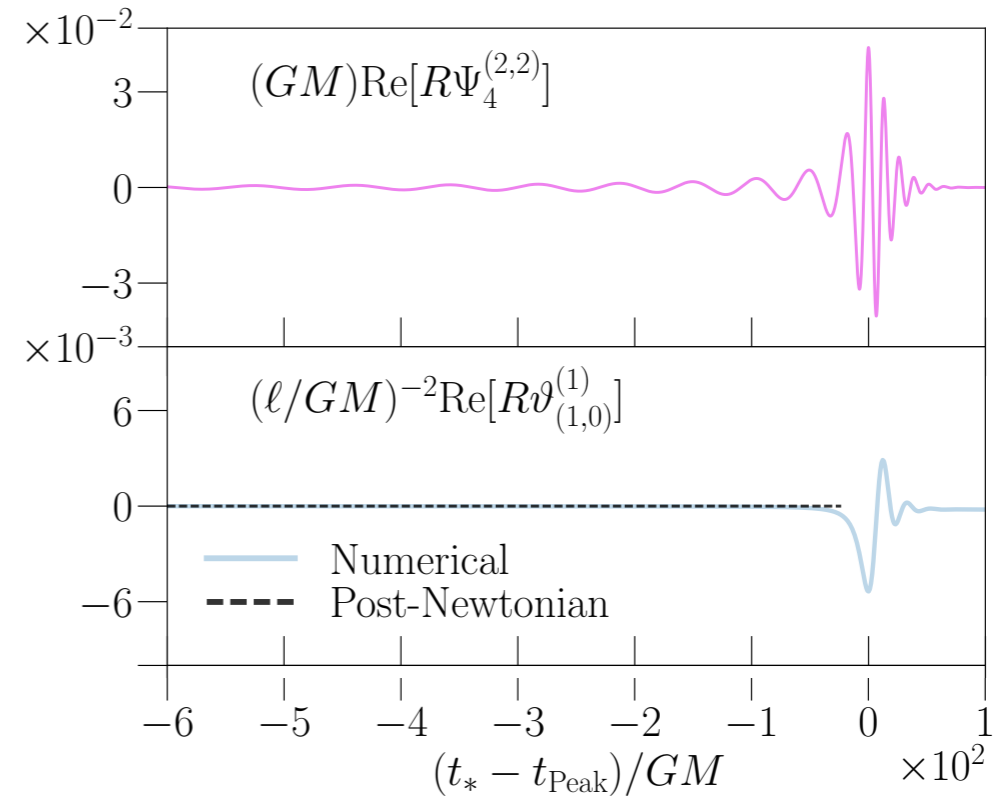


Radice, Perego, Zappa, ApJL 852:L29 (2018)

Other directions

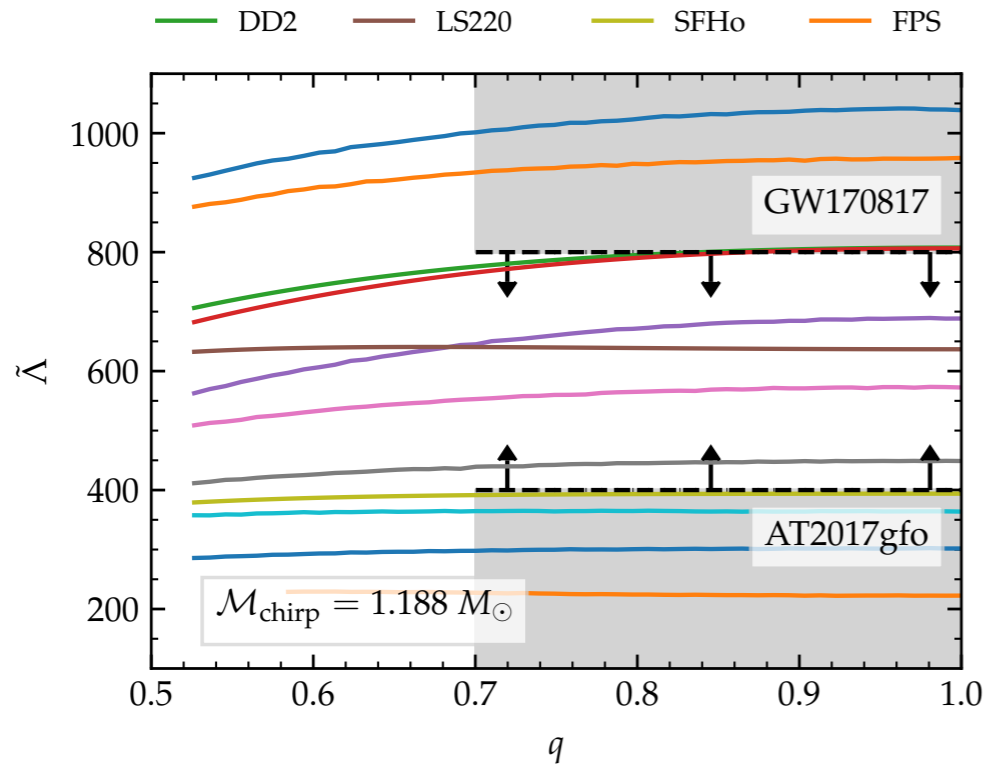


Radice, Perego, Zappa, ApJL 852:L29 (2018)

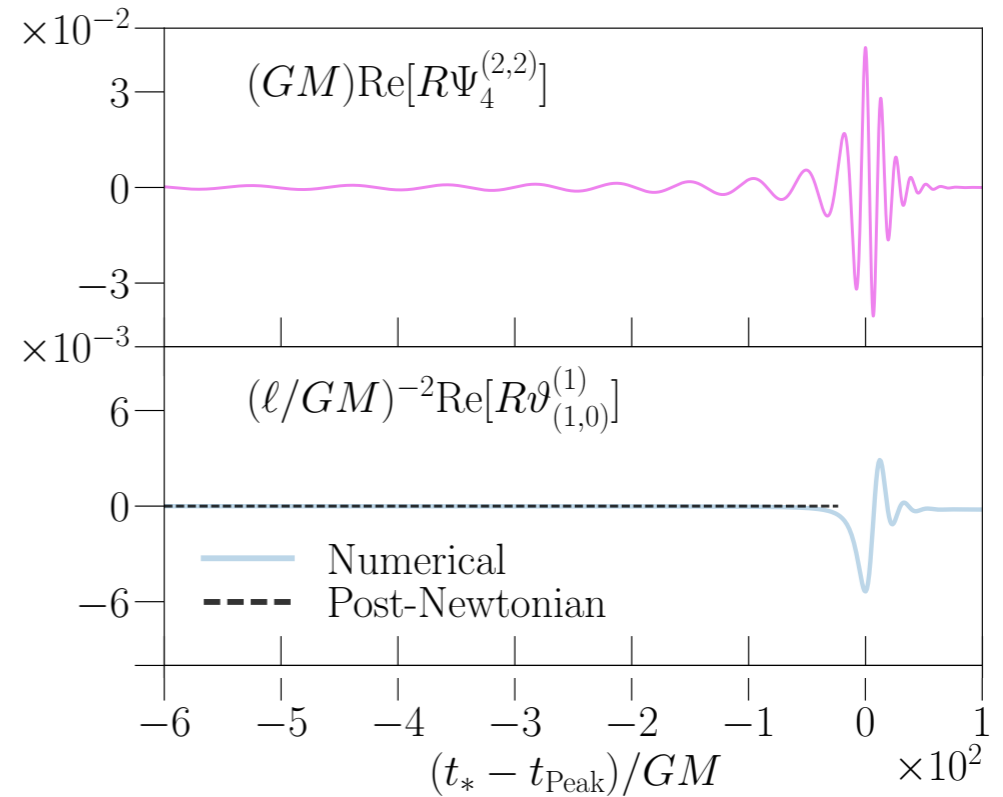


Okounkova et al. PRD (2017)

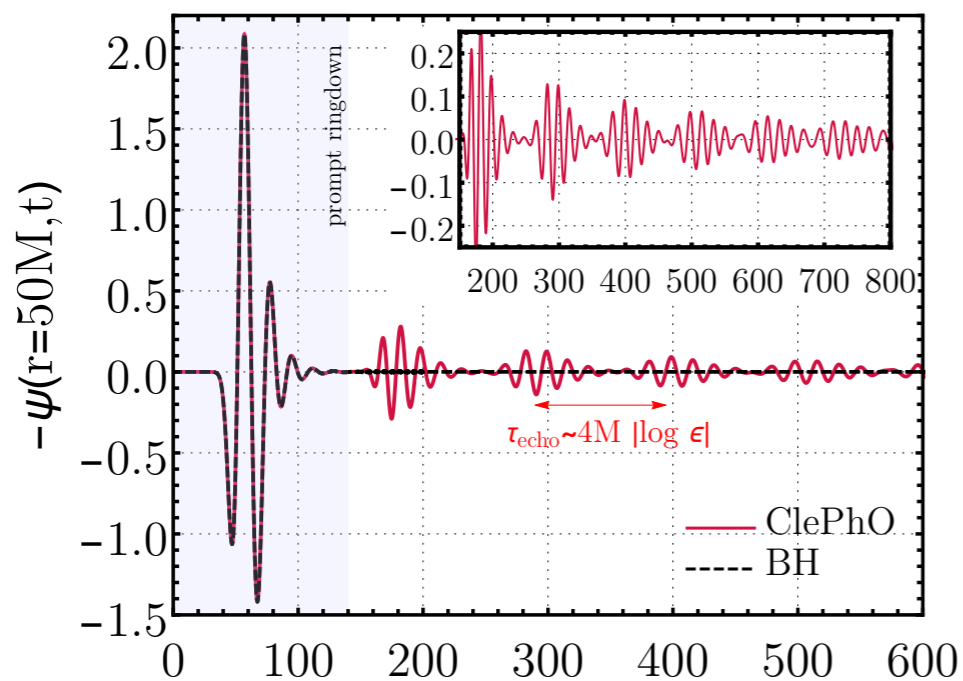
Other directions



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

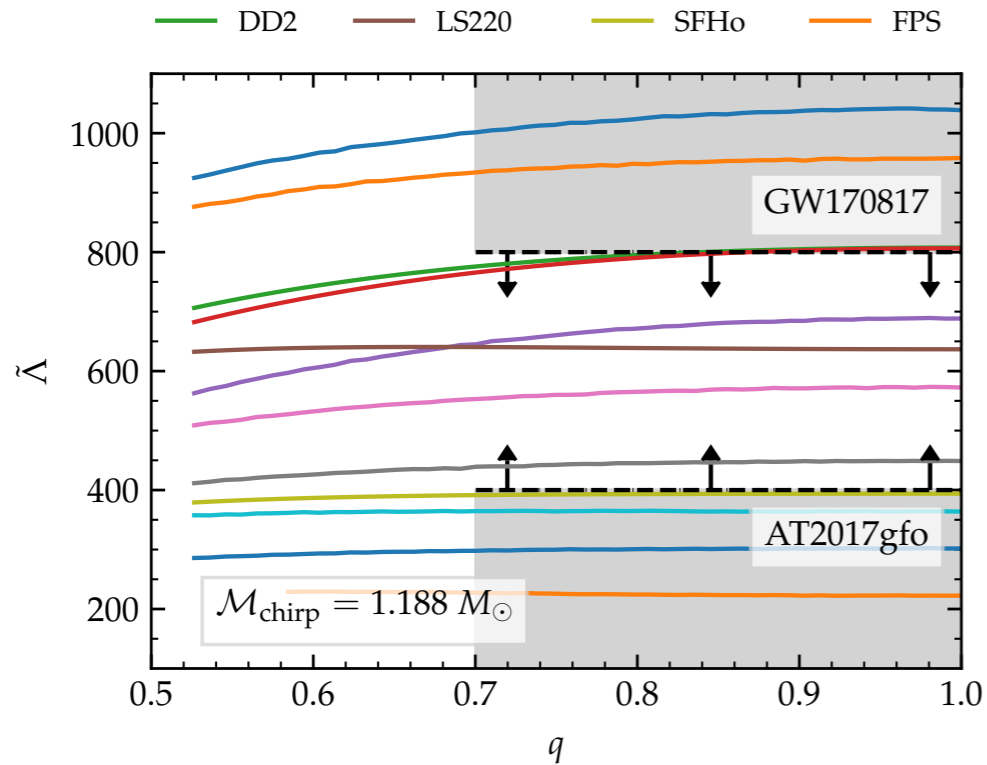


Okounkova et al. PRD (2017)

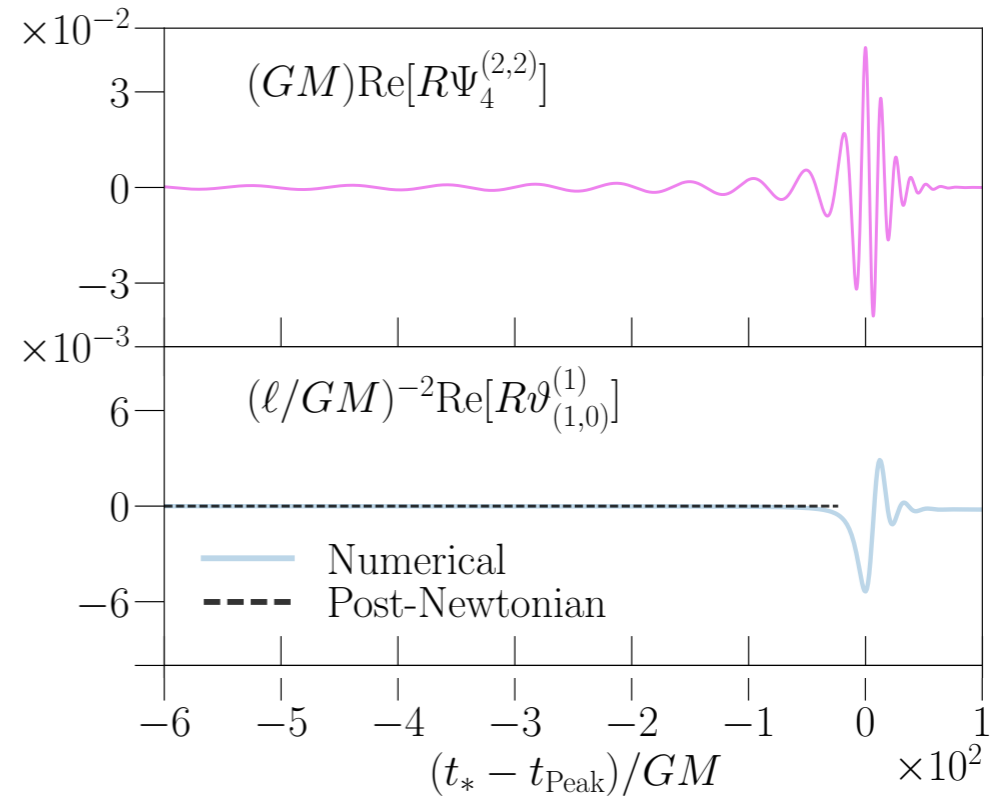


t/M Cardoso, Pani arXiv:1904.05363

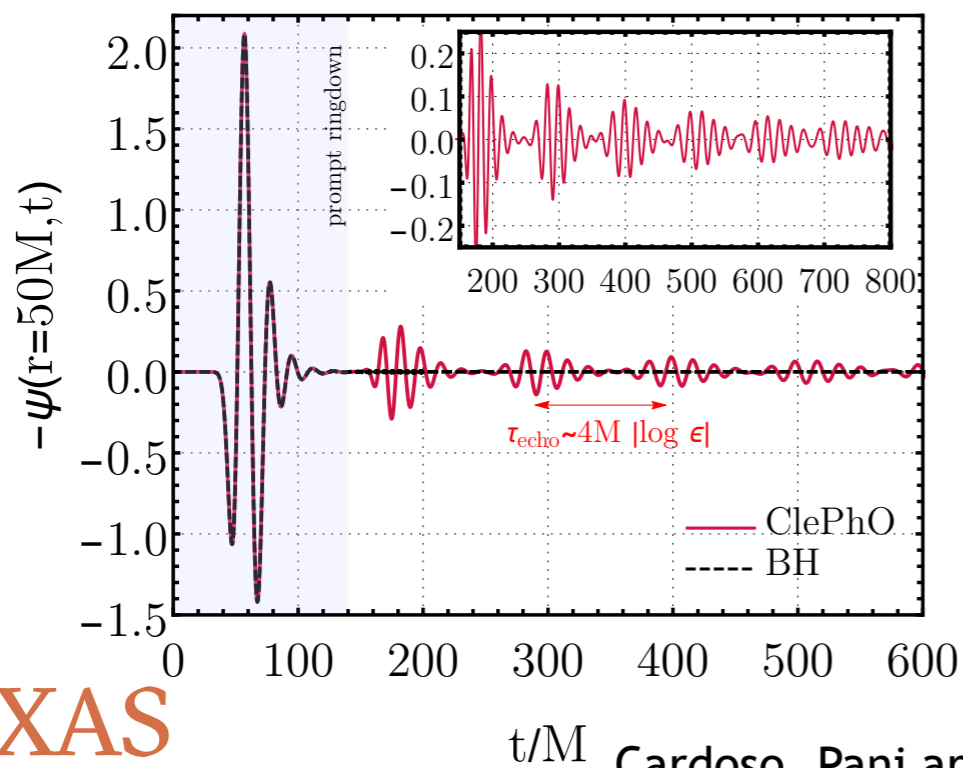
Other directions



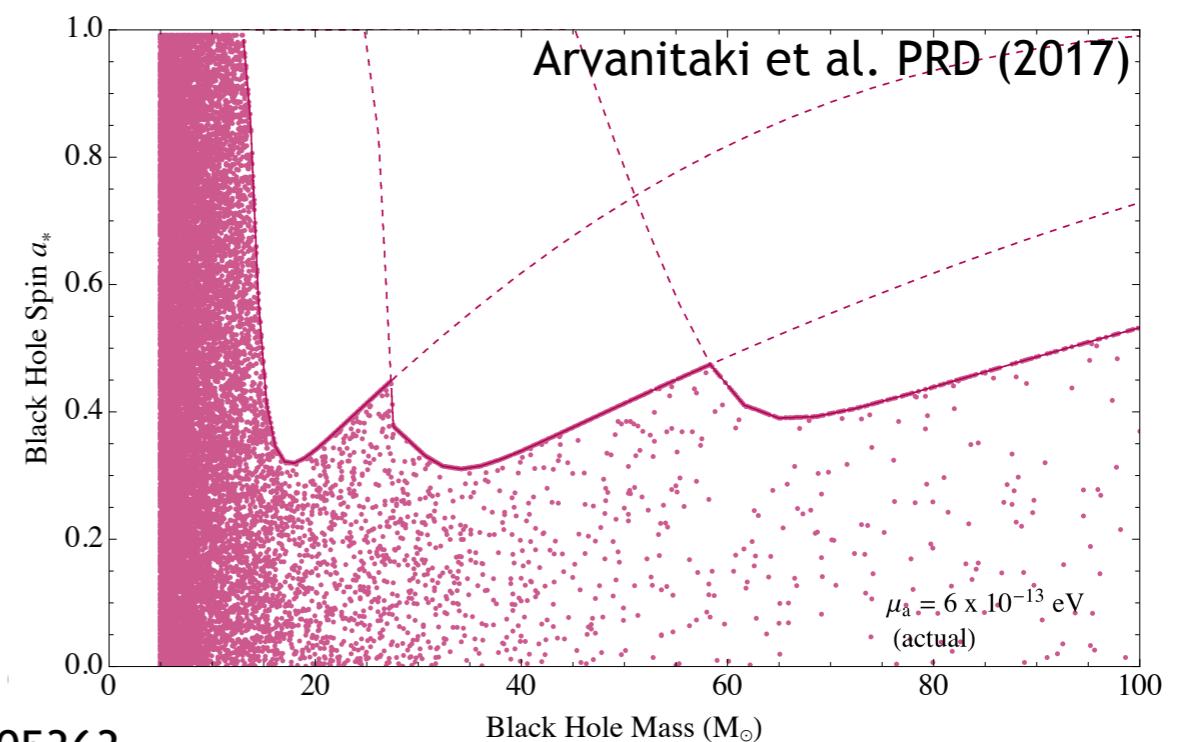
Radice, Perego, Zappa, ApJL 852:L29 (2018)



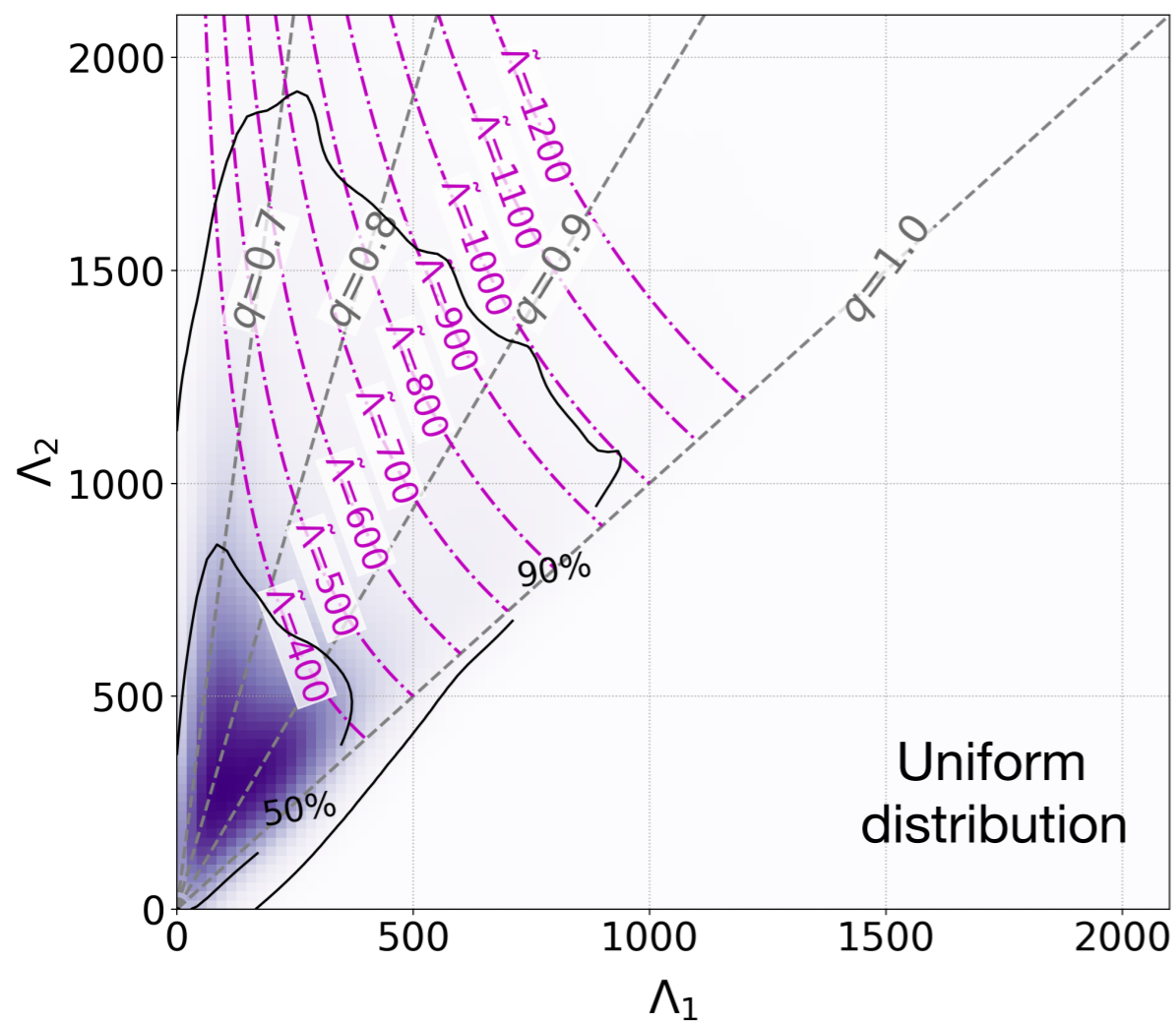
Okounkova et al. PRD (2017)



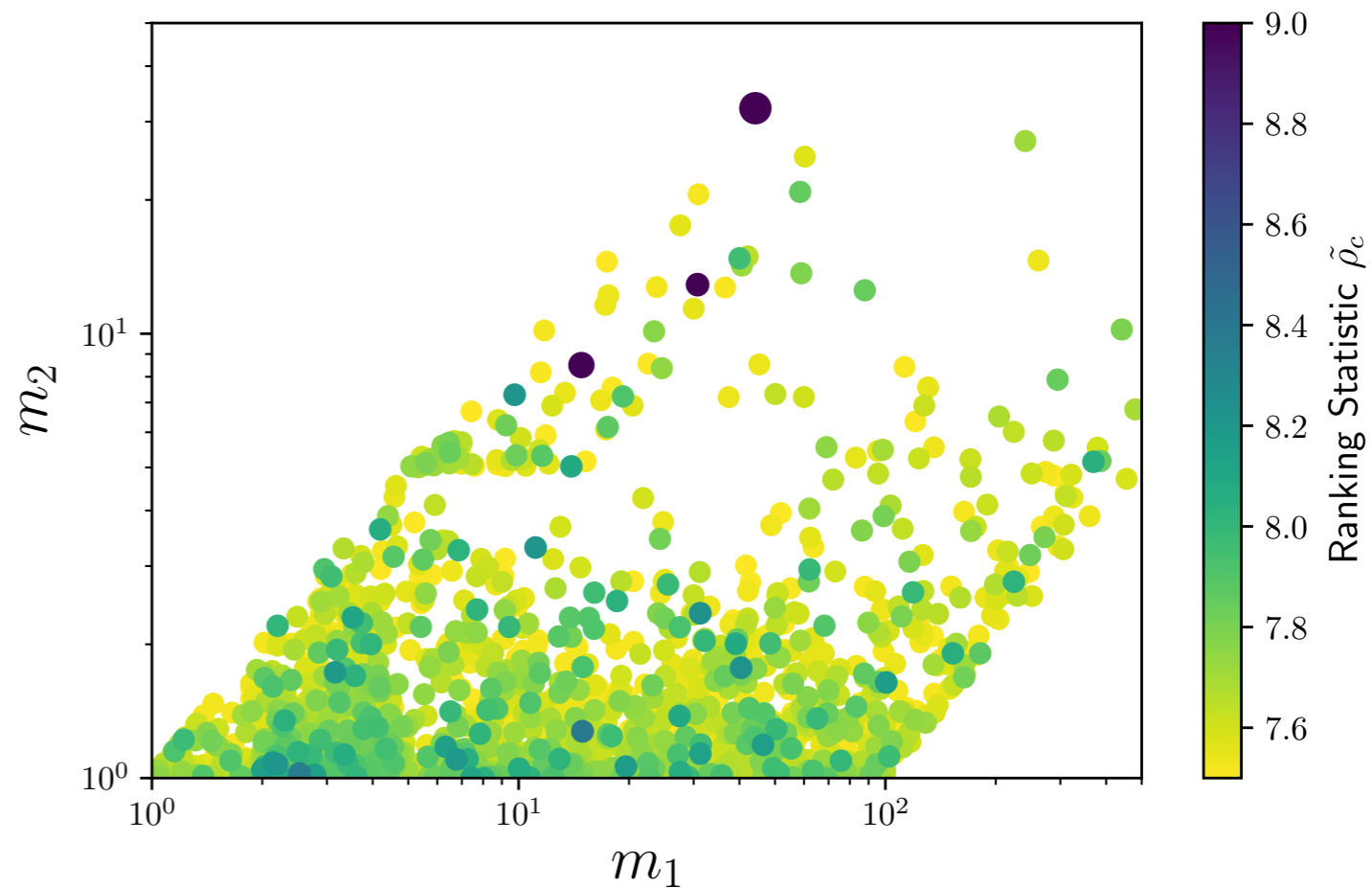
Cardoso, Pani arXiv:1904.05363



Open data analysis

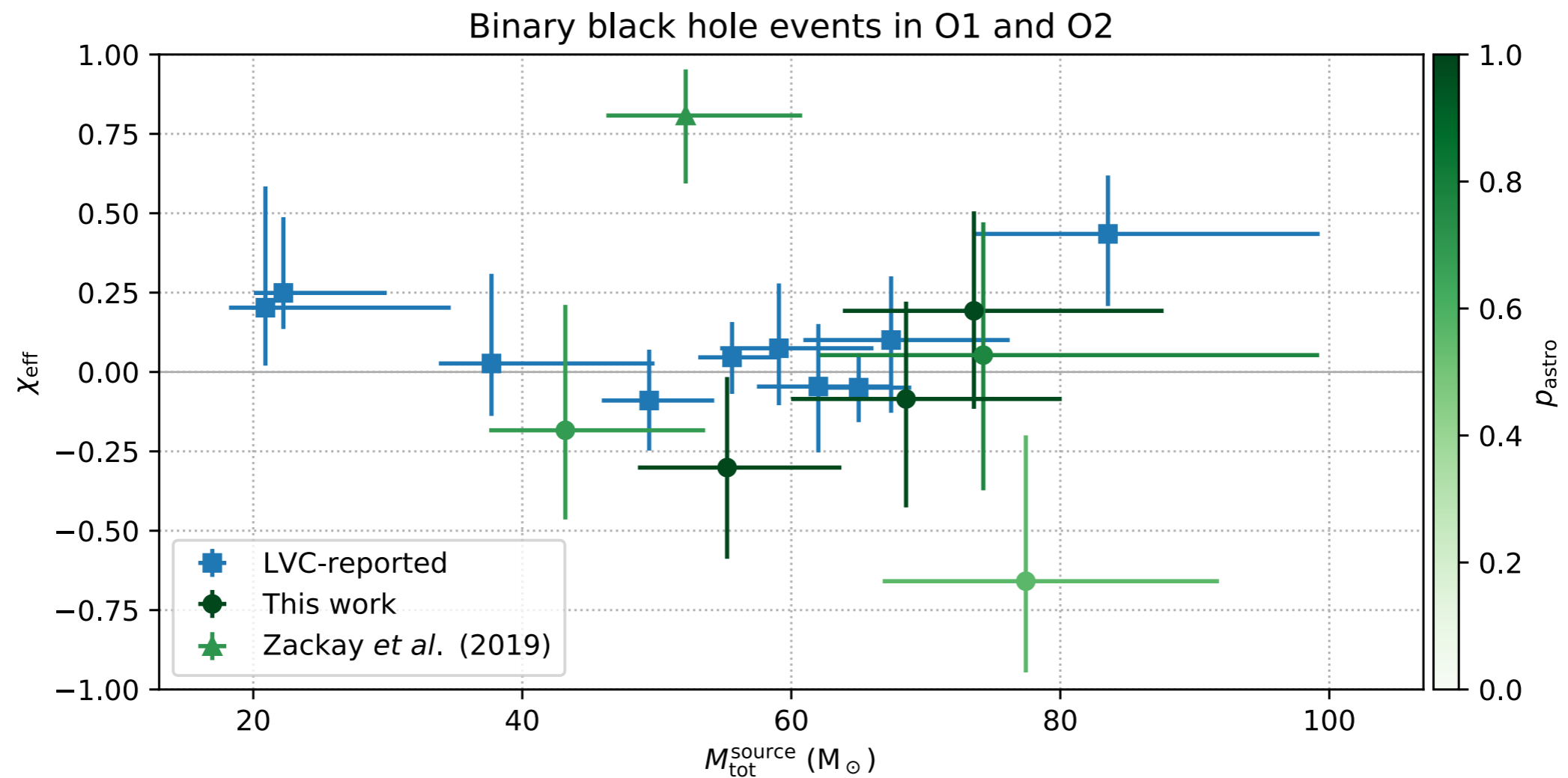


De et al. PRL (2018)



Nitz et al. ApJ (2019)

Open data analysis



Venumadhav *et al.* arXiv: 1904.07214

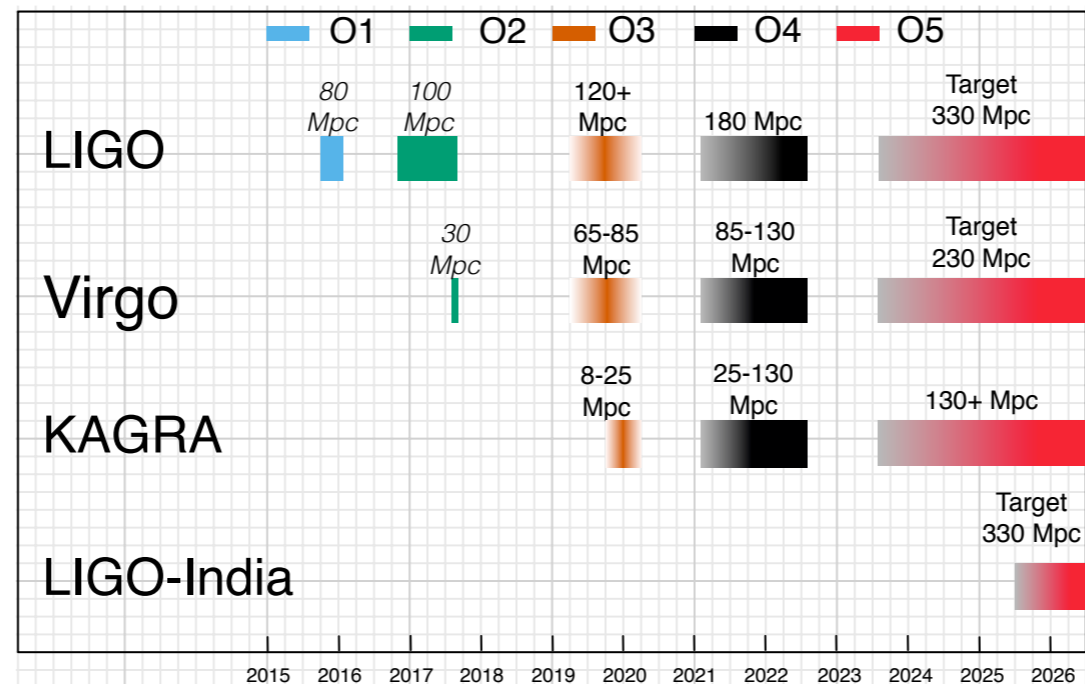
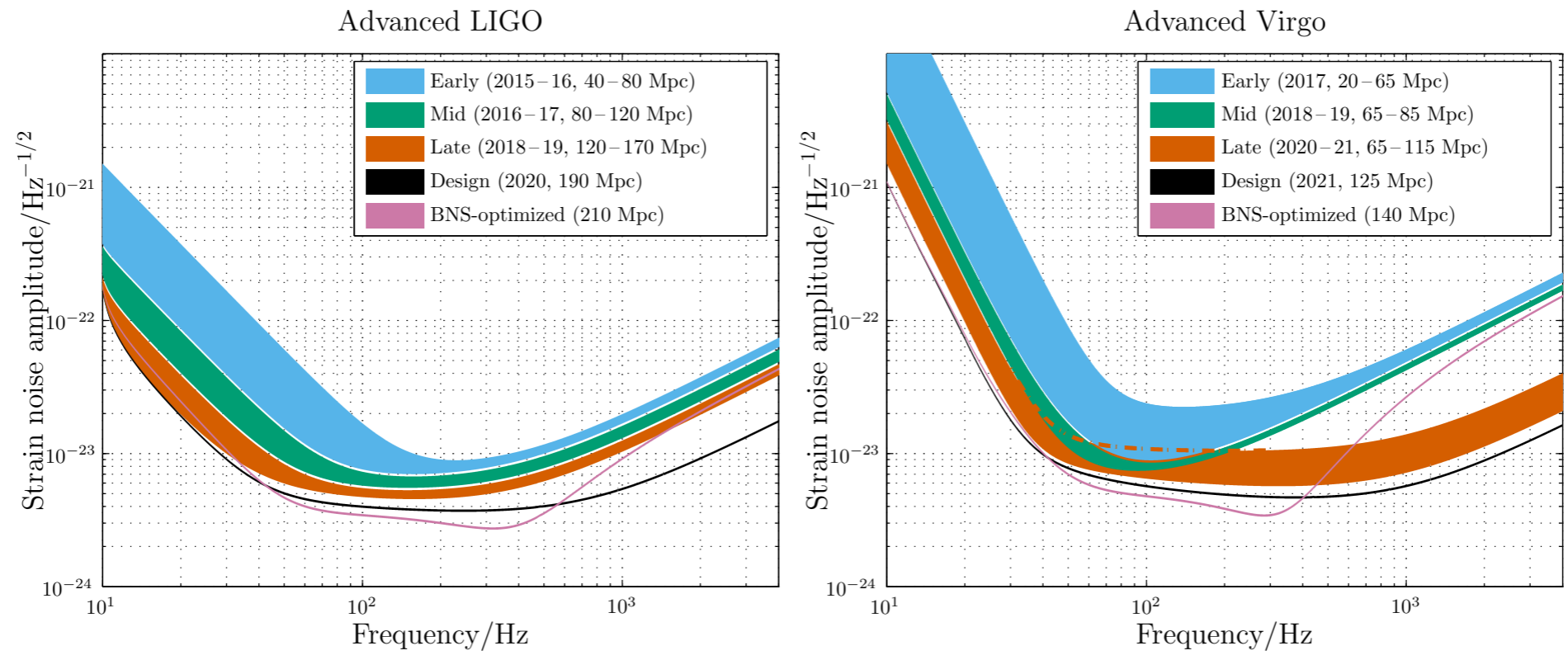
THE PRESENT AND FUTURE

O3: Era of open alerts

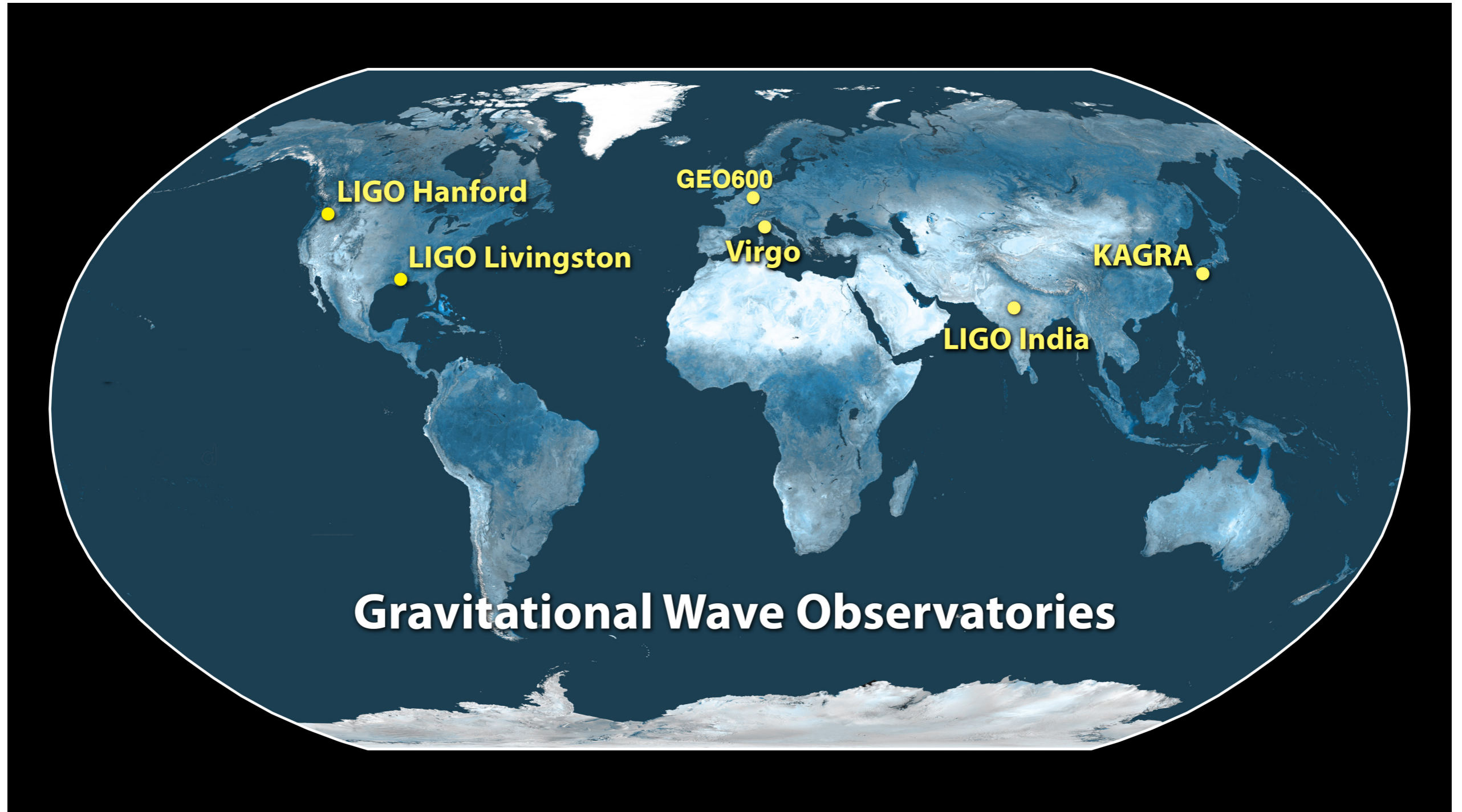
- O3 started April 1st 2019
- 13 alerts (+2 retracted)
 - 9 likely BBH
 - 1 likely BNS
 - 1 maybe NSBH
 - 2 likely terrestrial (noise)

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
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	3.734e-13	2019-05-13 20:54:48 UTC
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

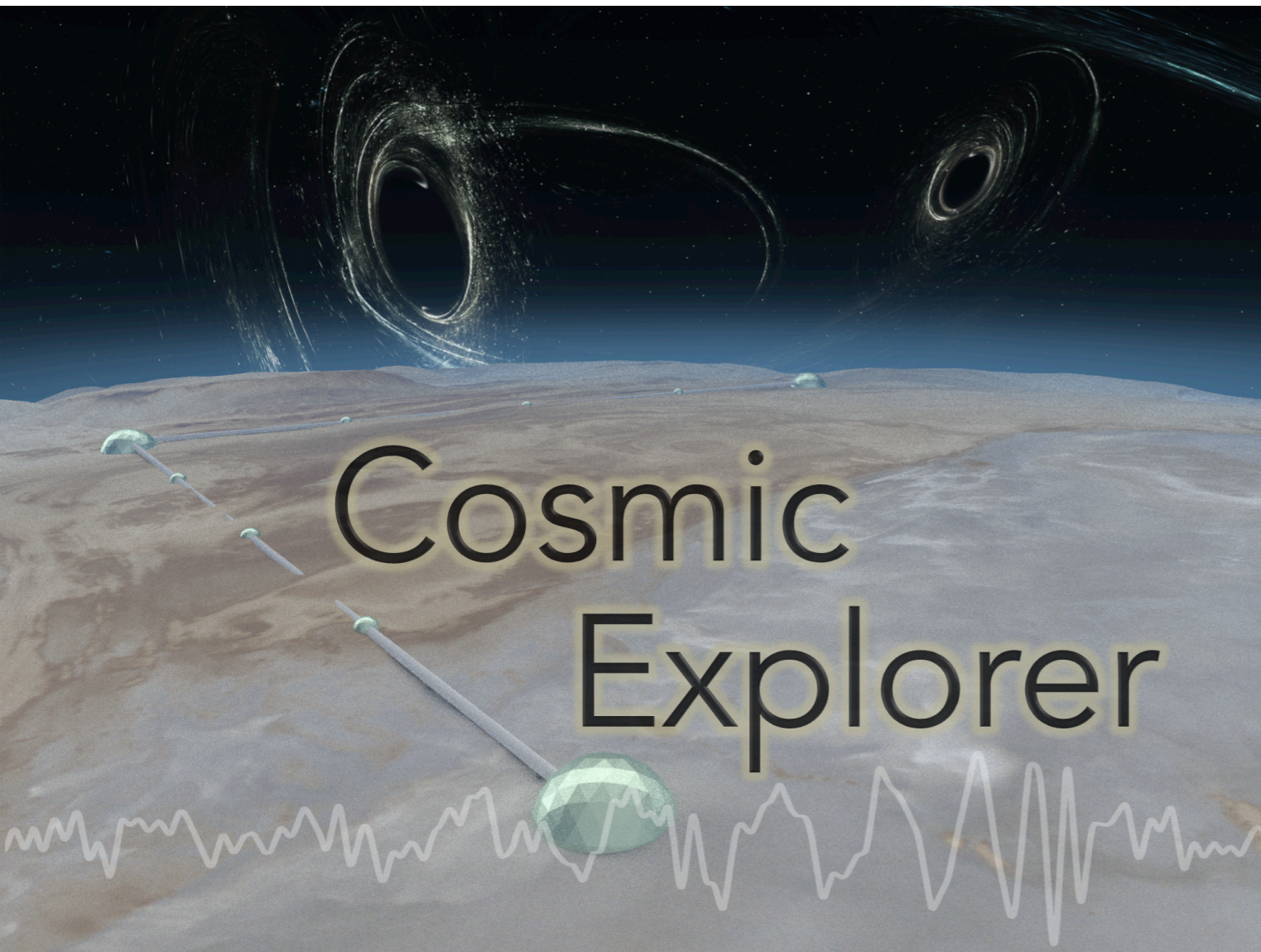
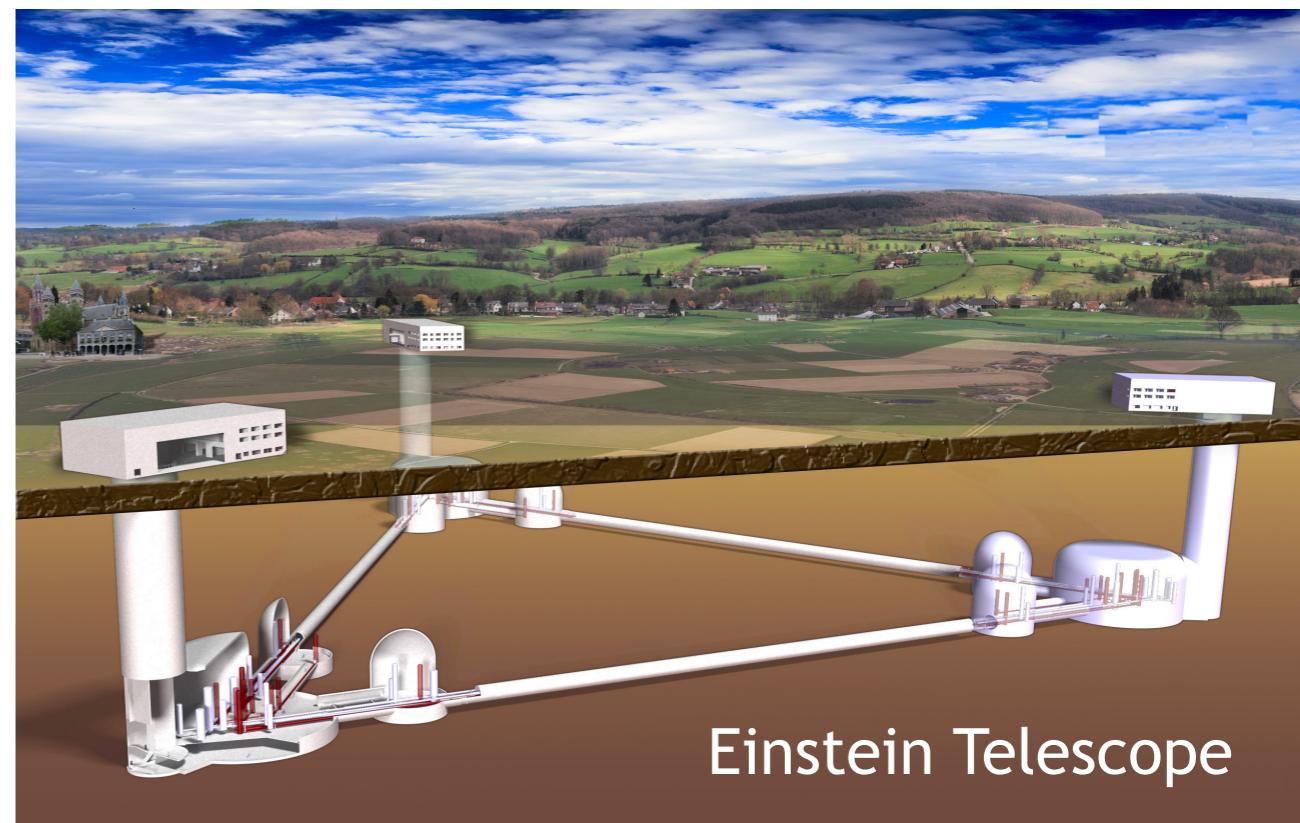
Looking ahead



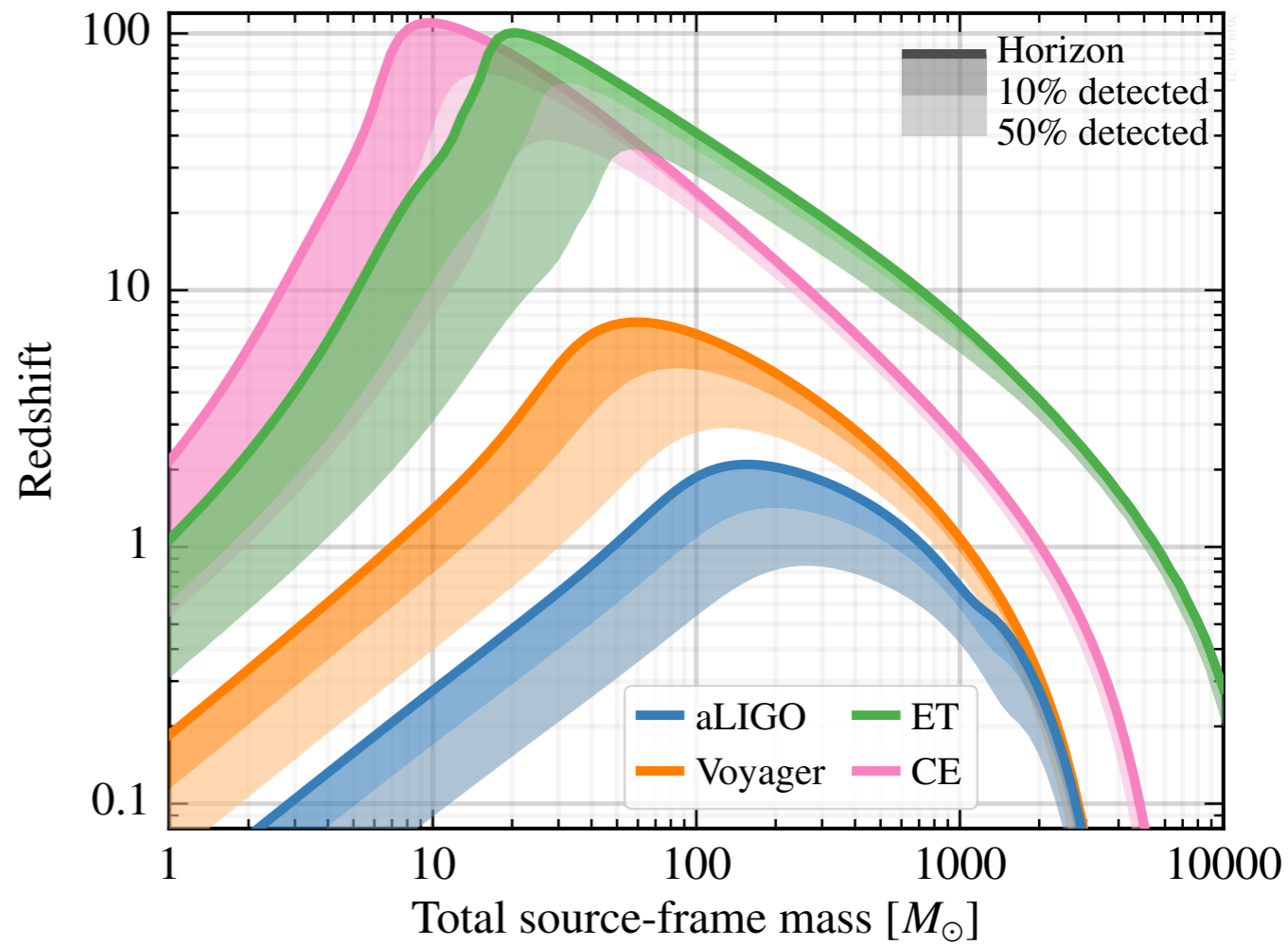
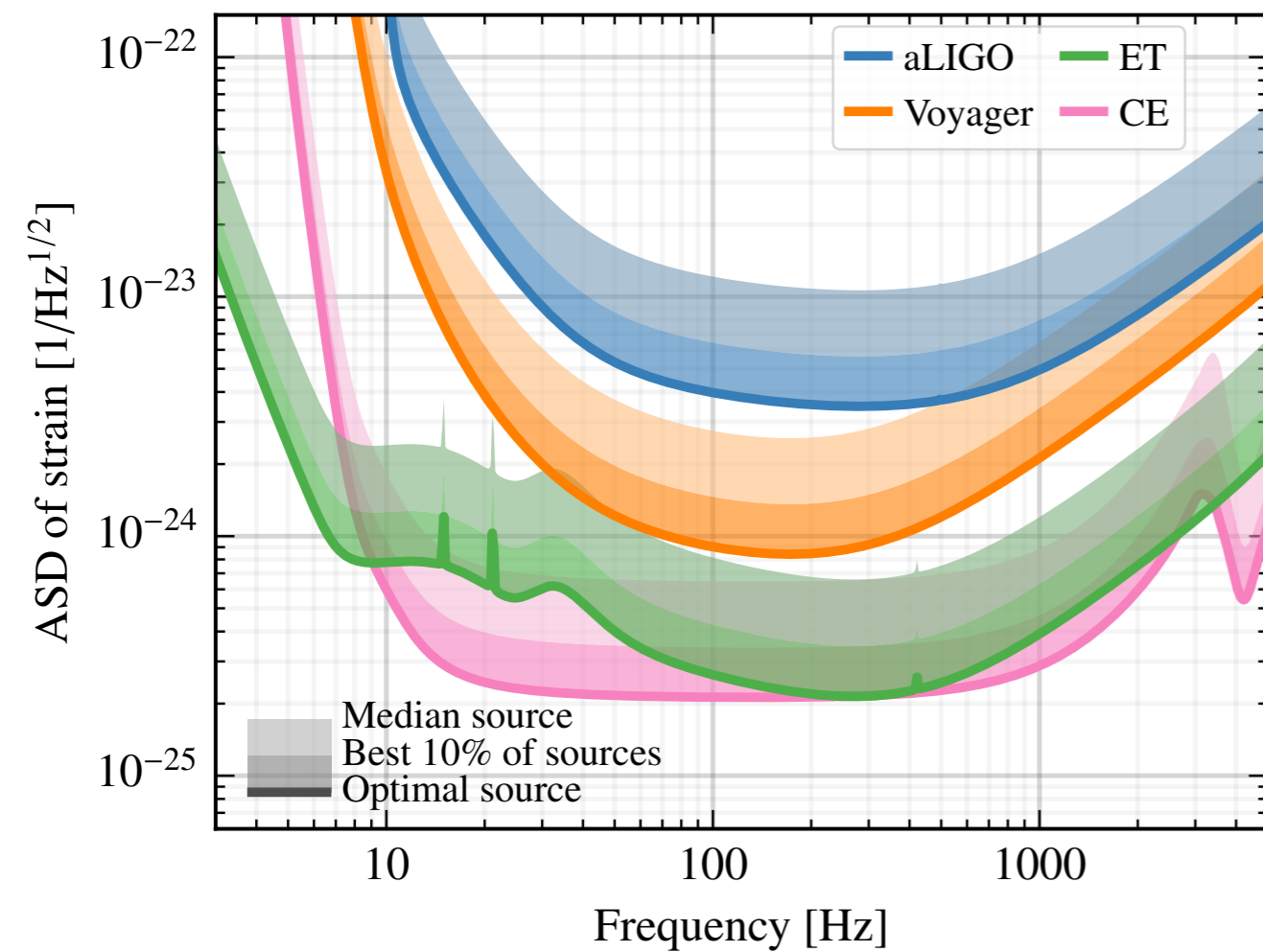
5 detector network



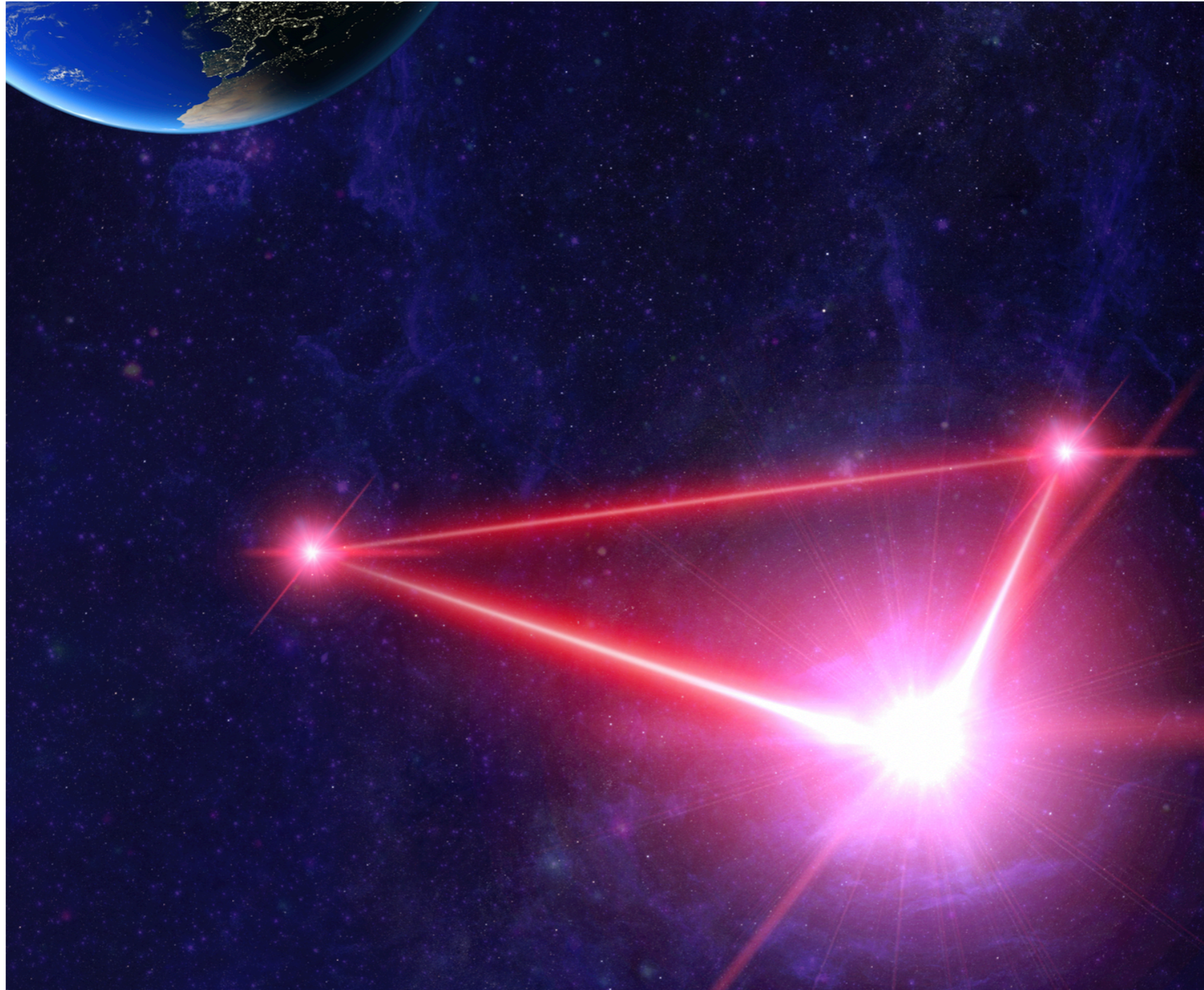
Next Generation Detectors



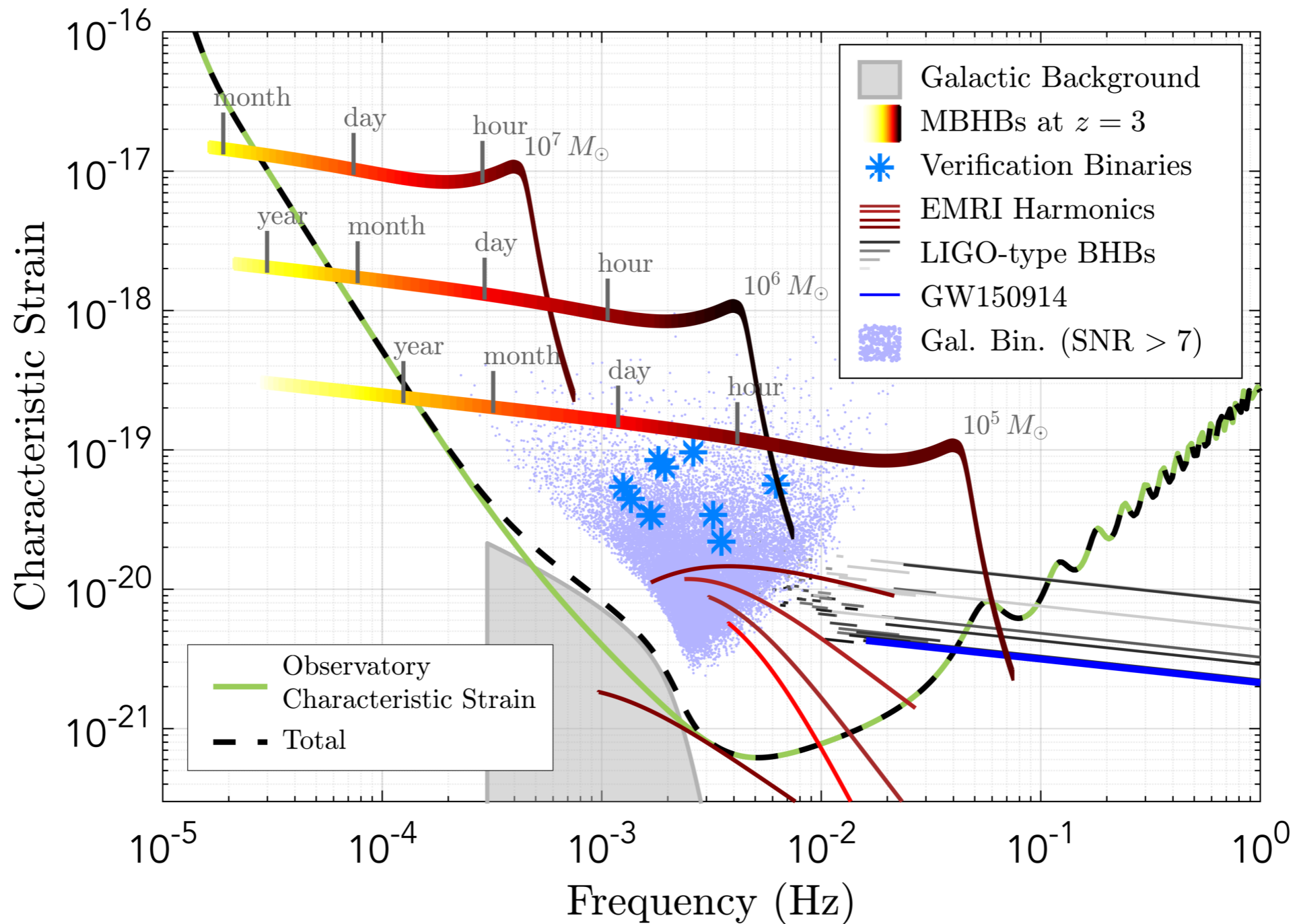
Next generation capabilities



LISA



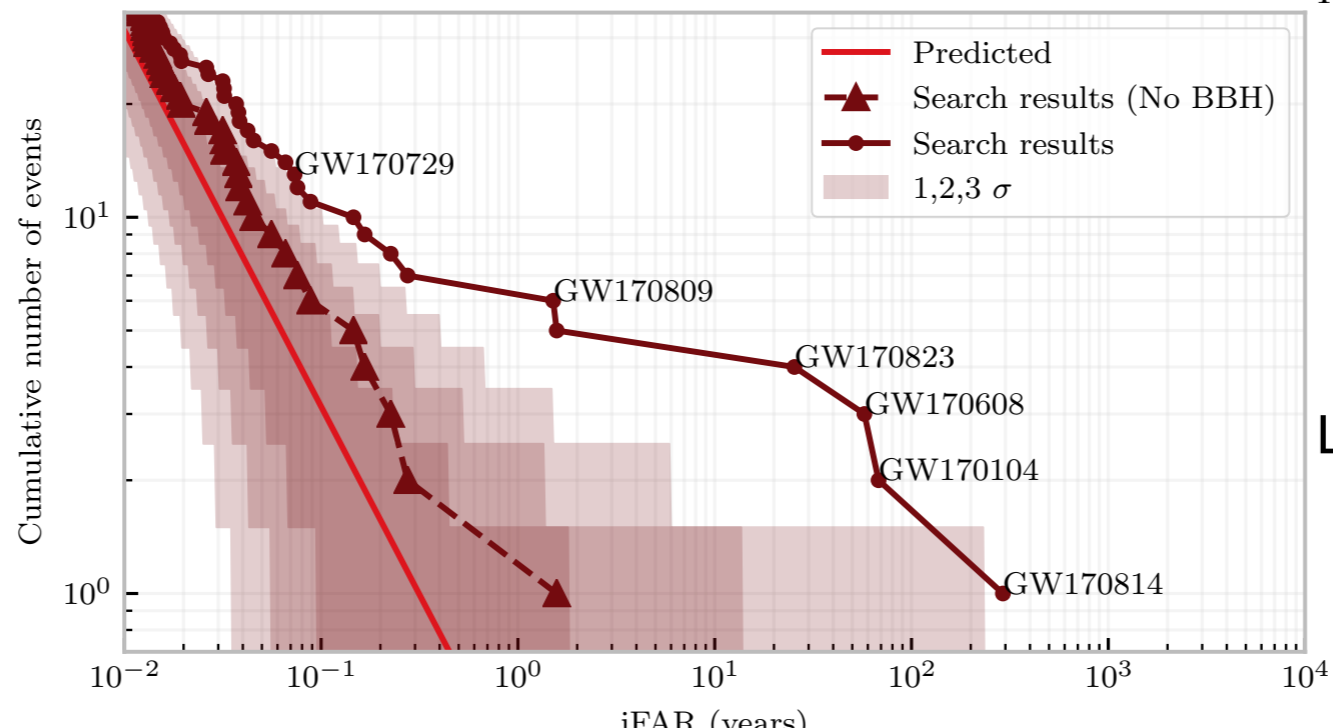
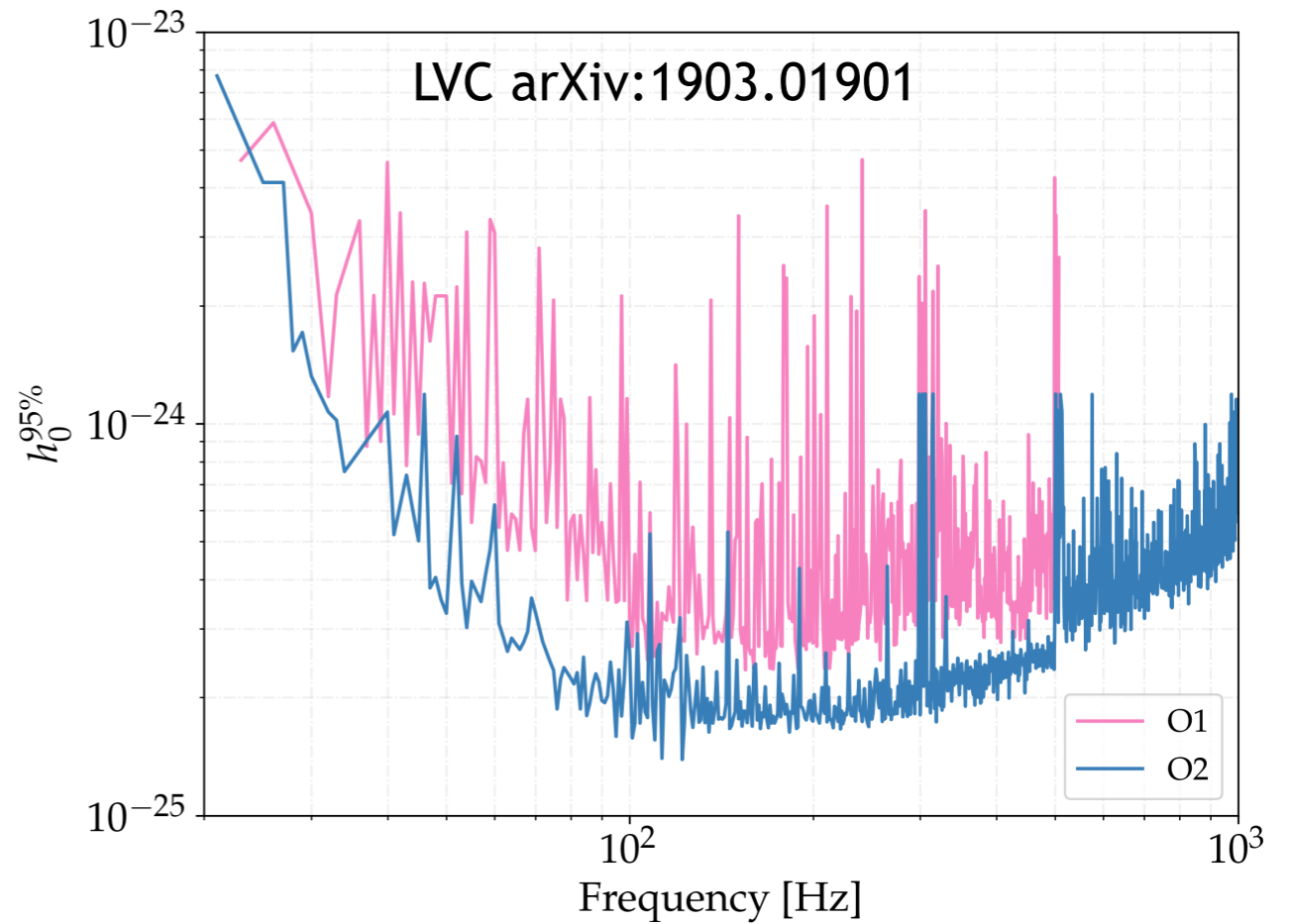
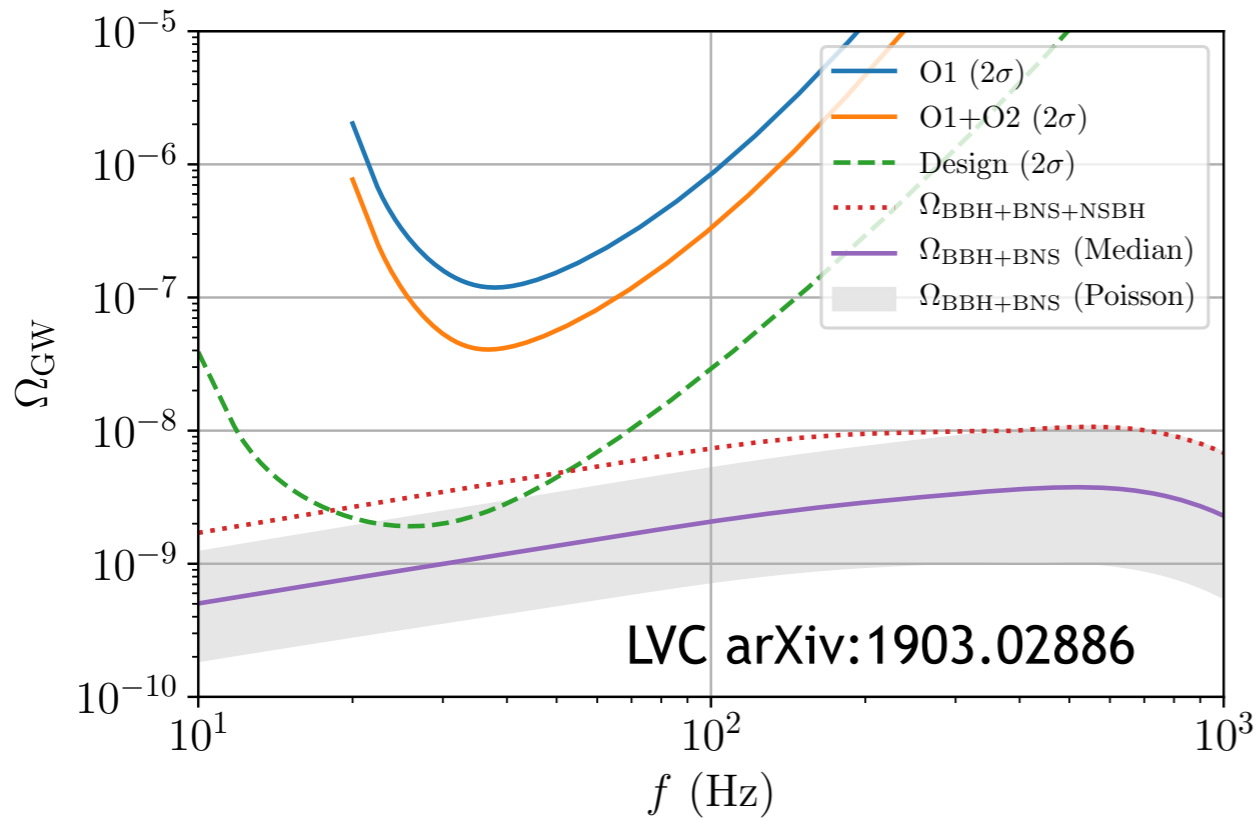
LISA



**The future is bright
(and loud)**

EXTRAS

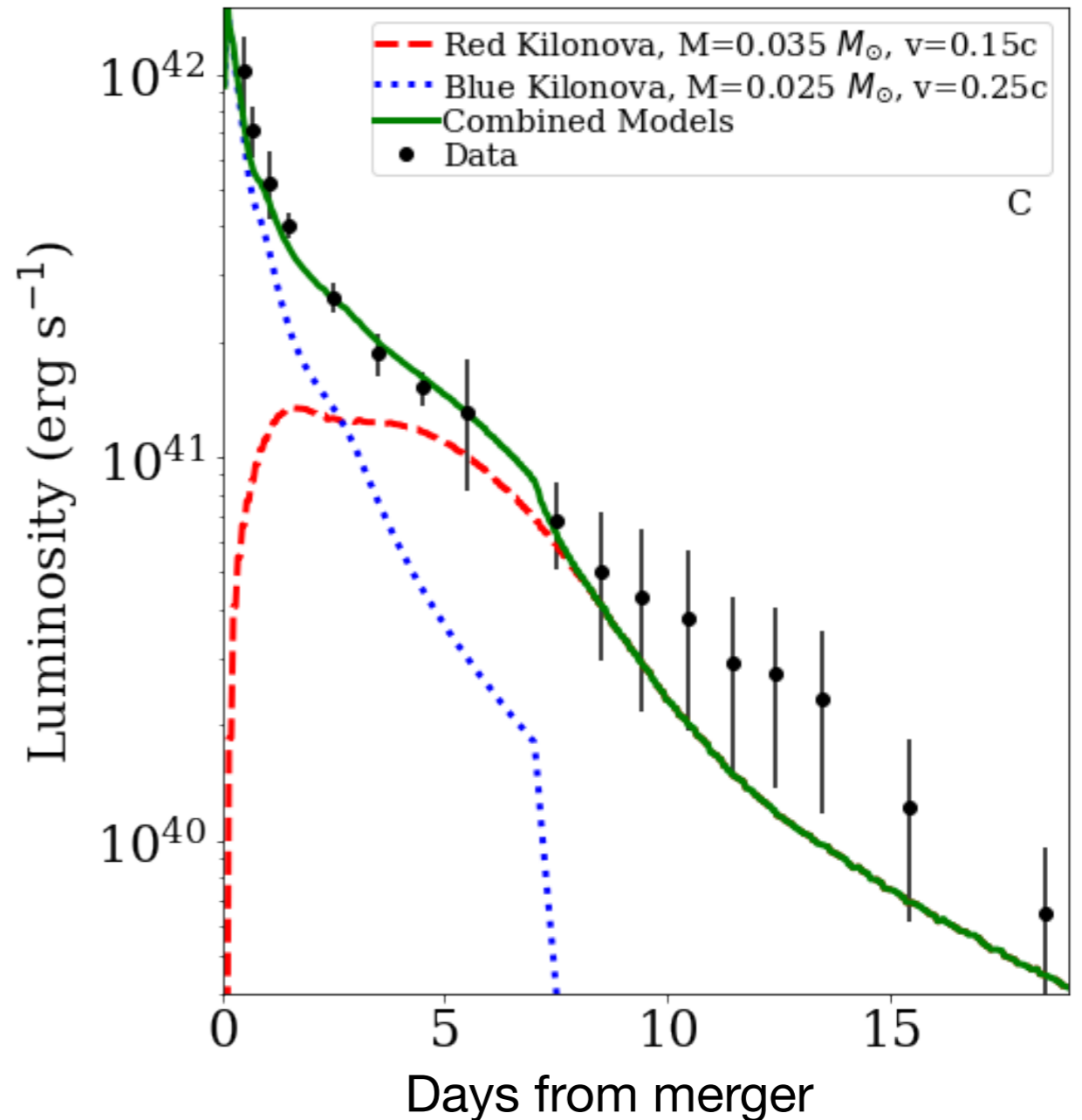
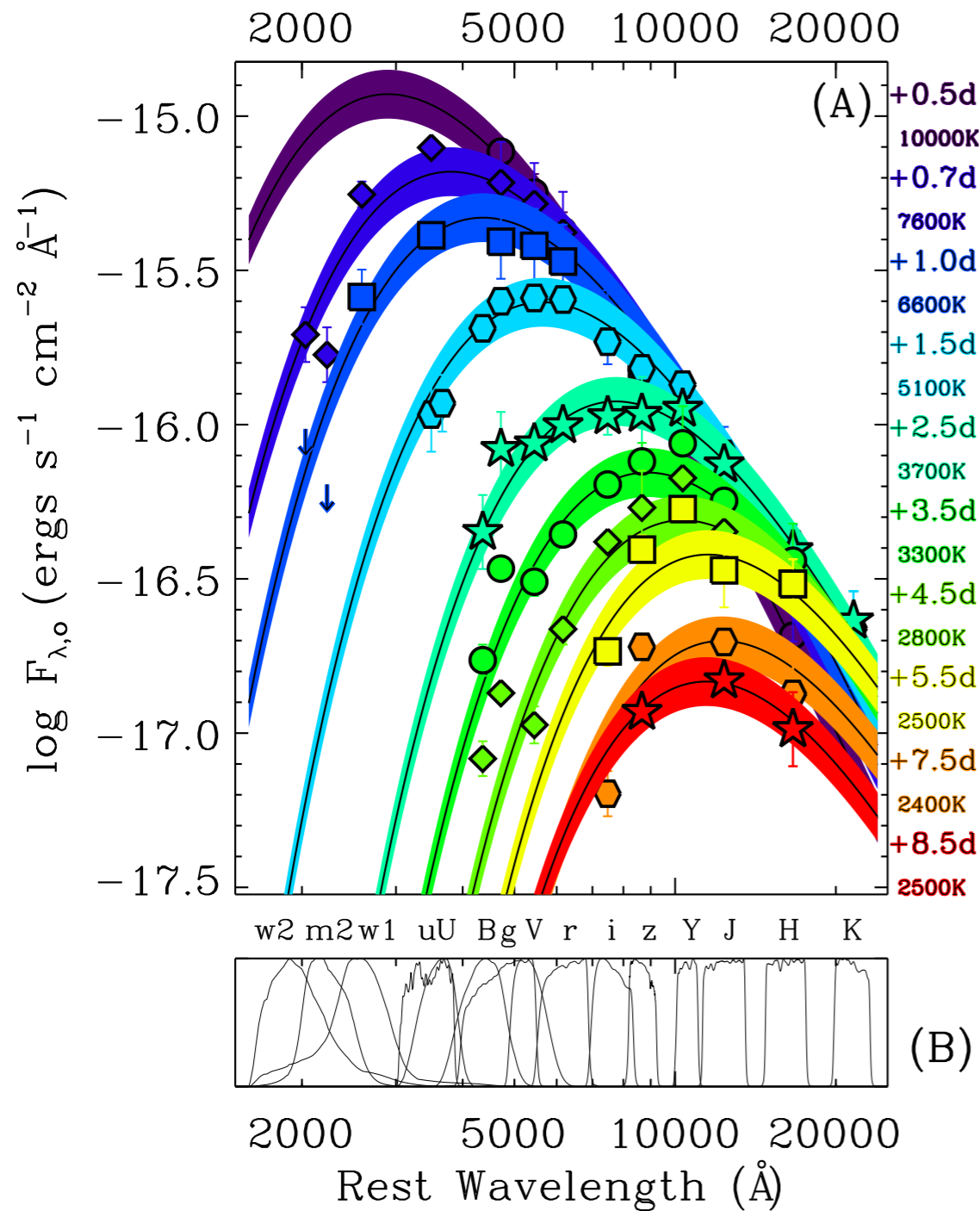
Other searches



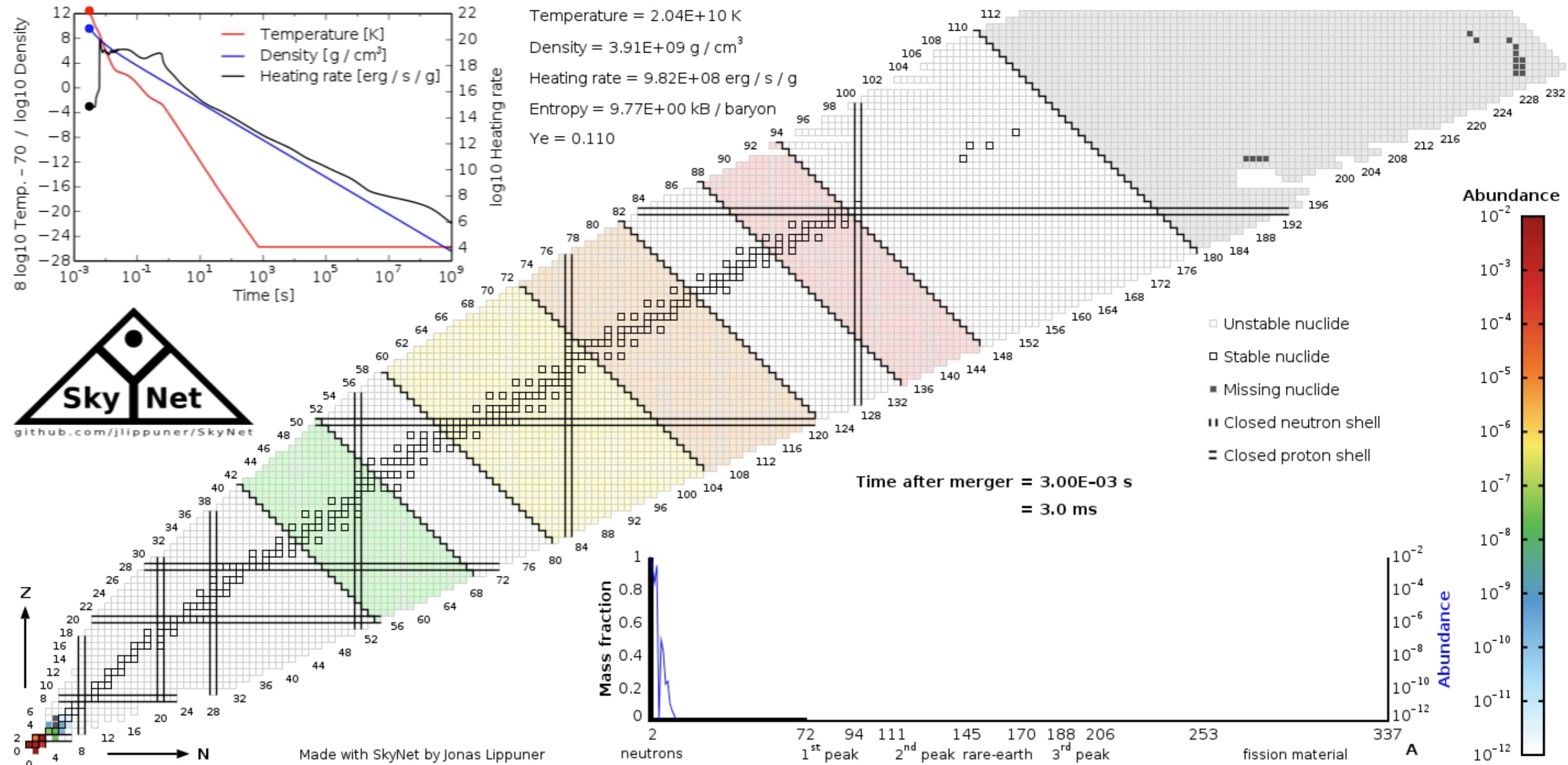
Properties of the BBHs

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

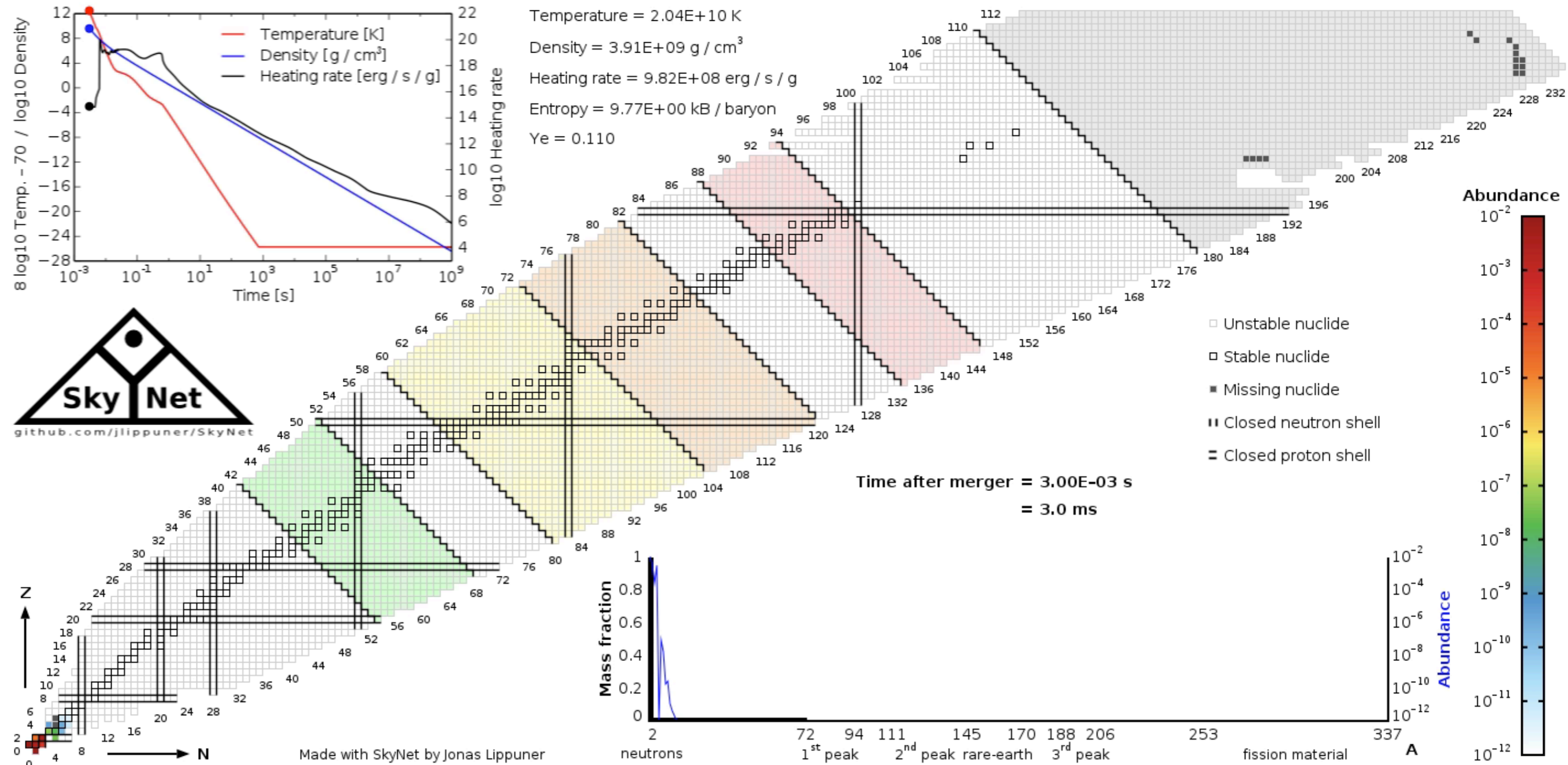
Kilonova



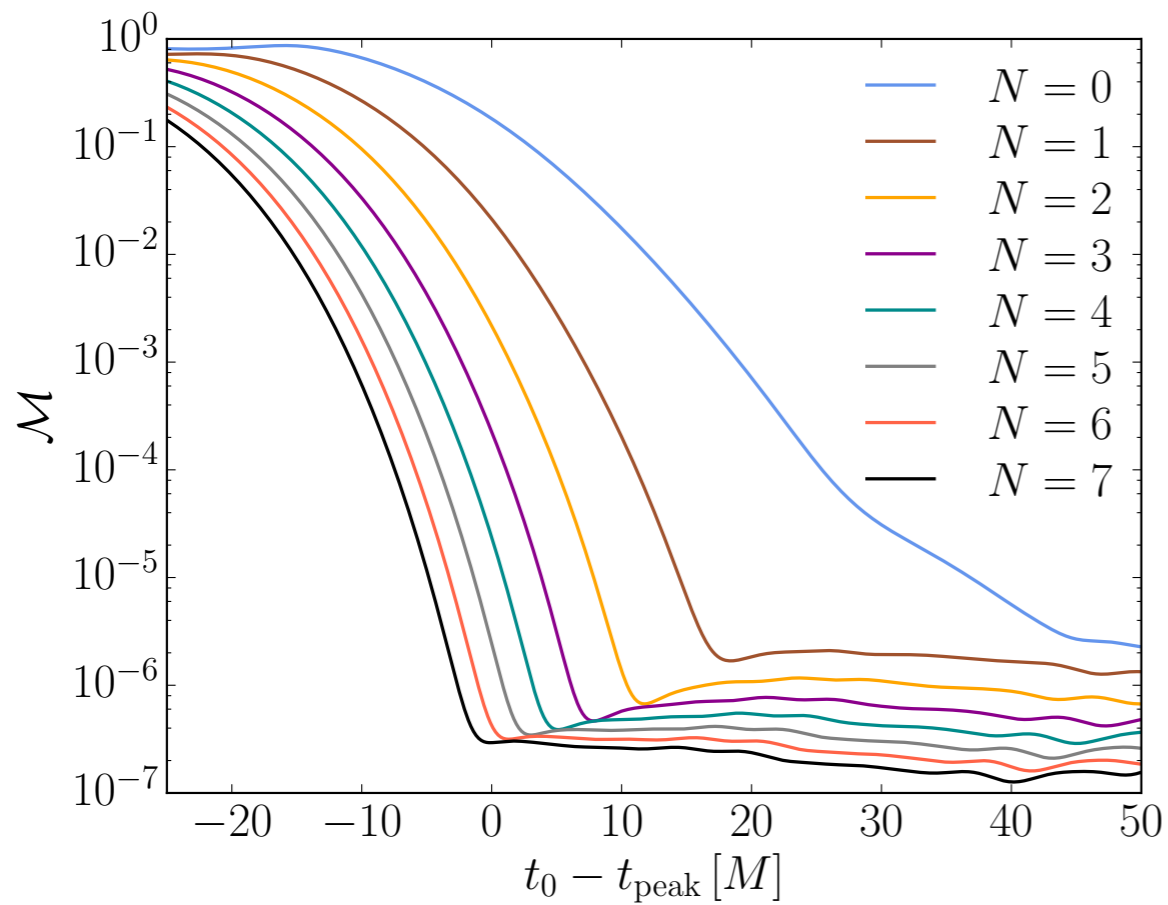
r-process nucleosynthesis



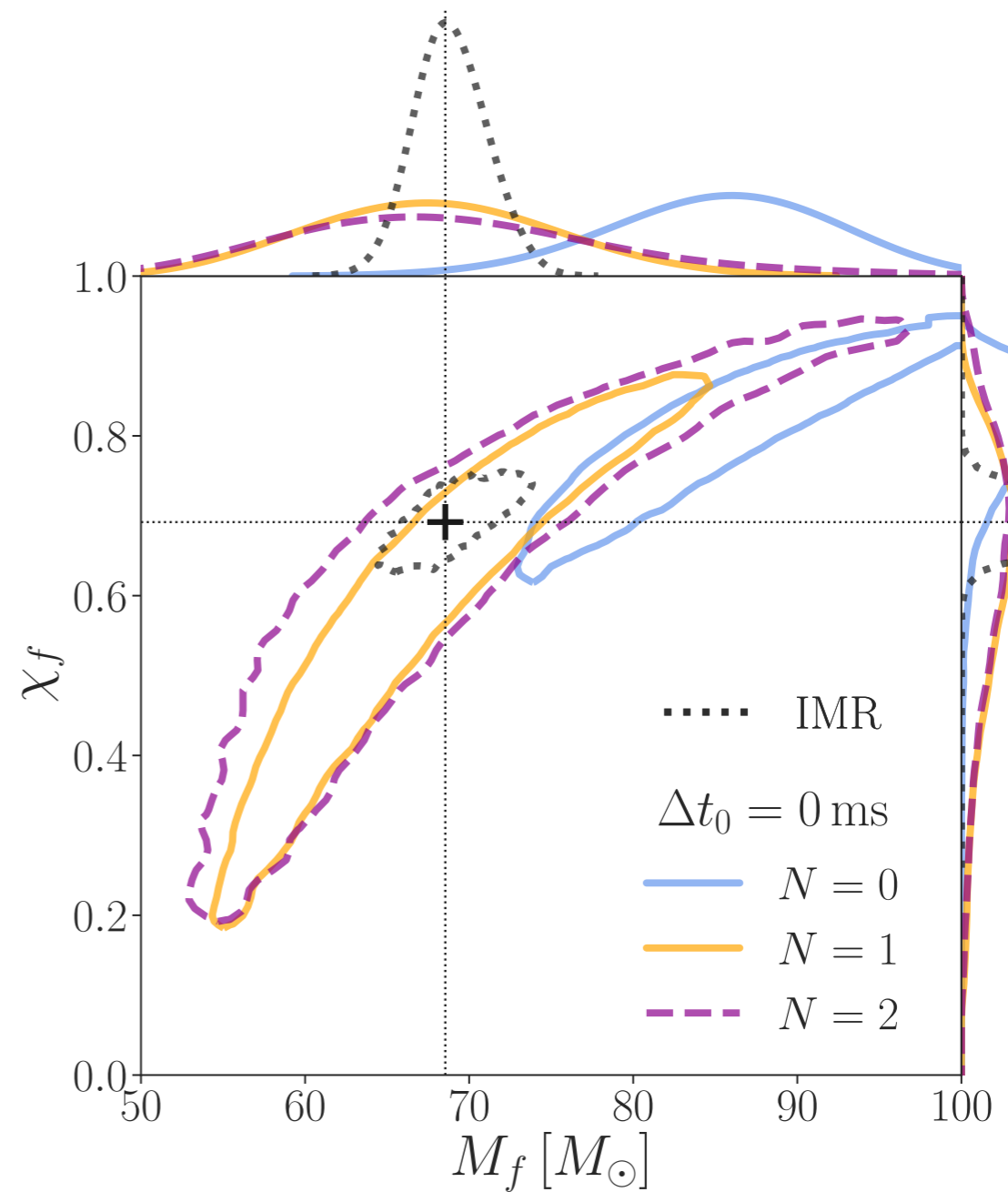
r-process nucleosynthesis



Ringdown with overtones

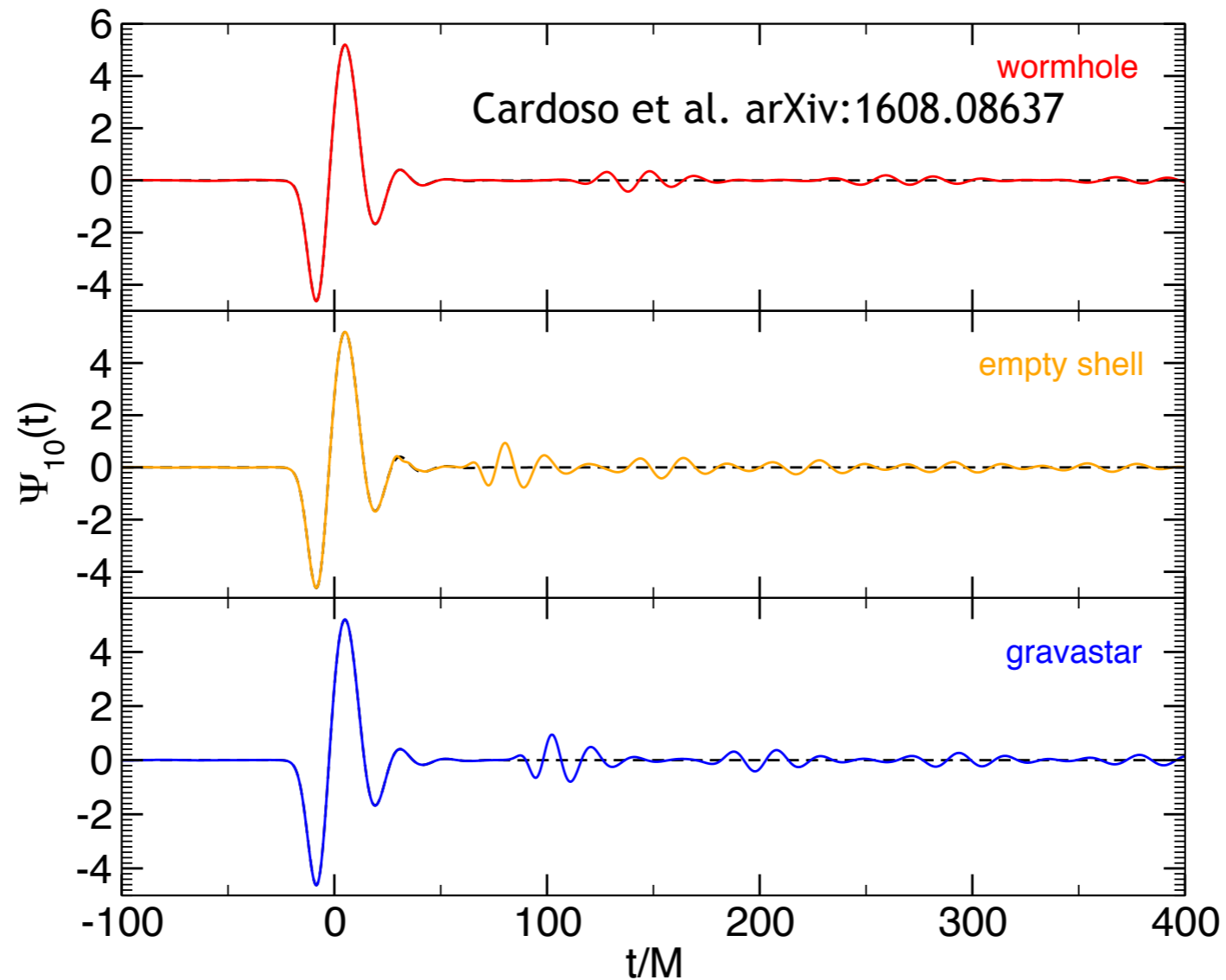


Giesler et al. arXiv: 1903.08284



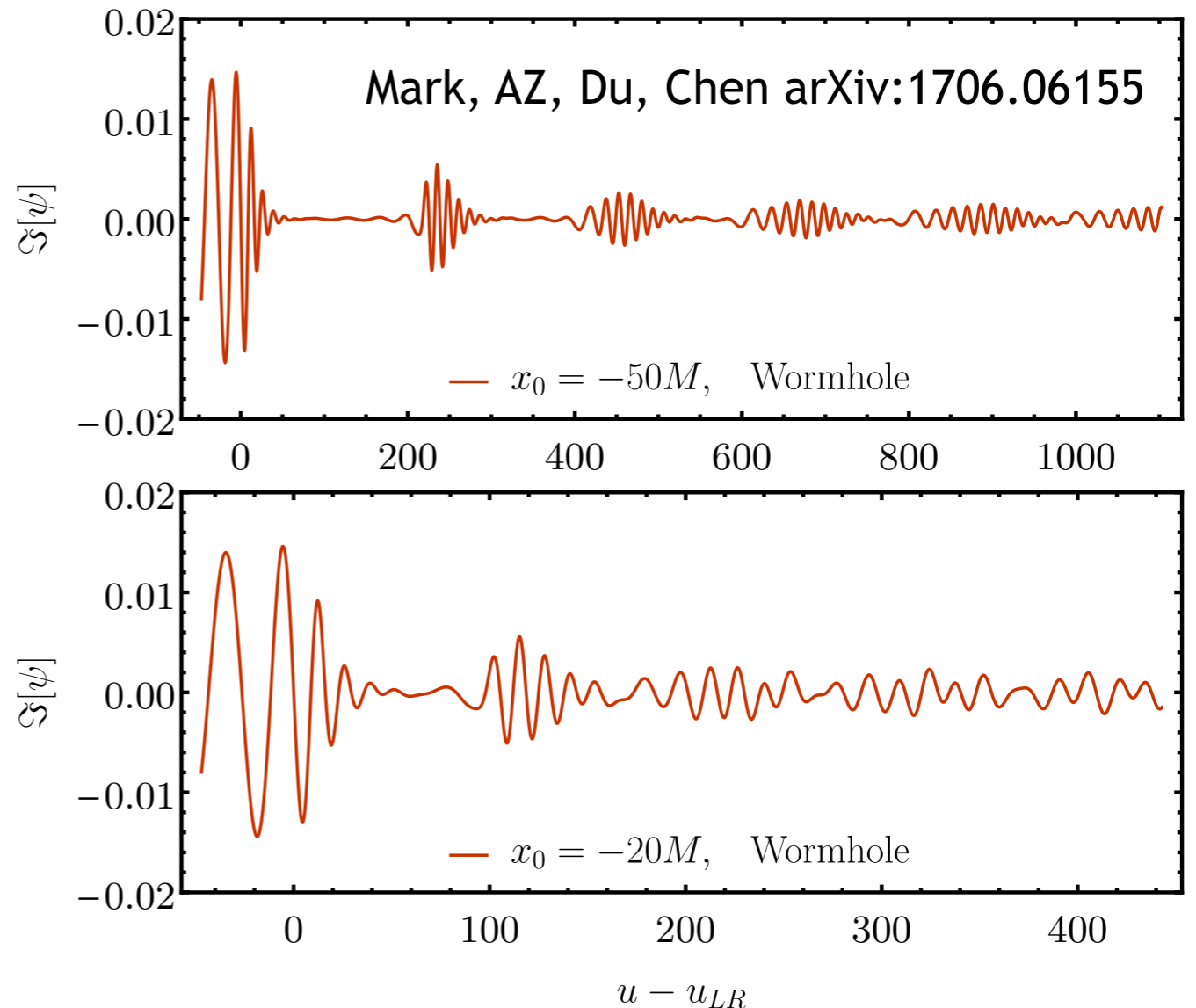
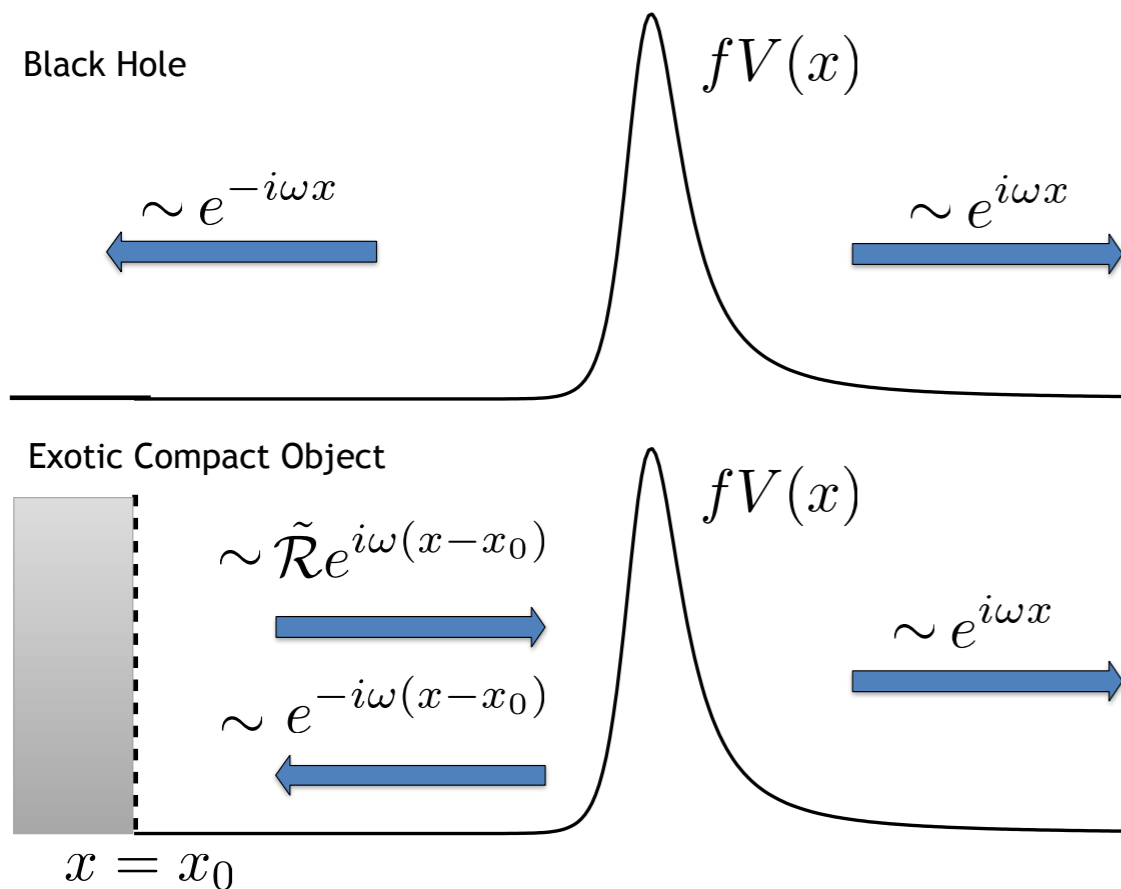
Isi et al. arXiv:1905.00869

Echoes from exotic compact objects



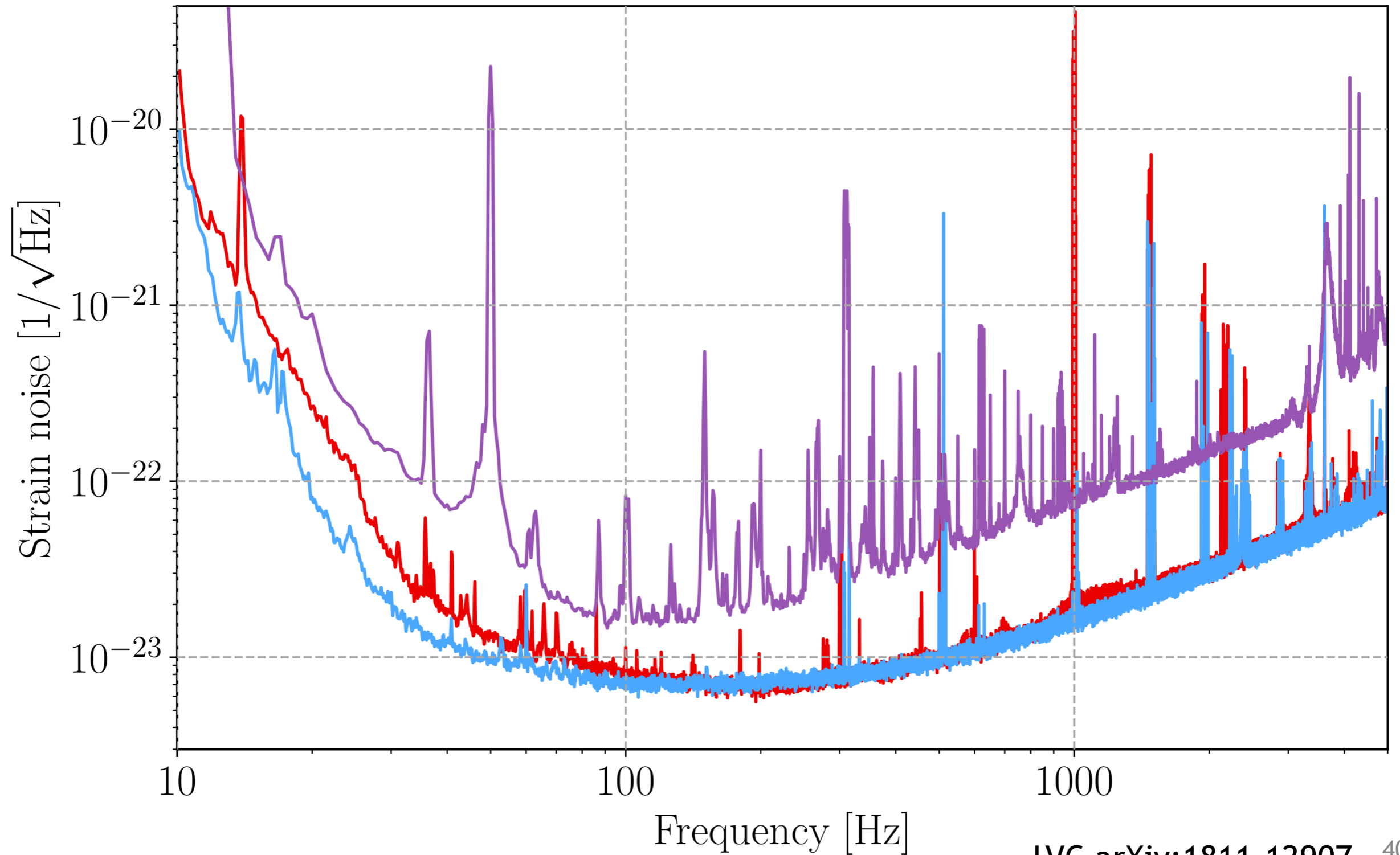
For a recent review see Cardoso and Pani arXiv:1904.05363

Echoes from exotic compact objects

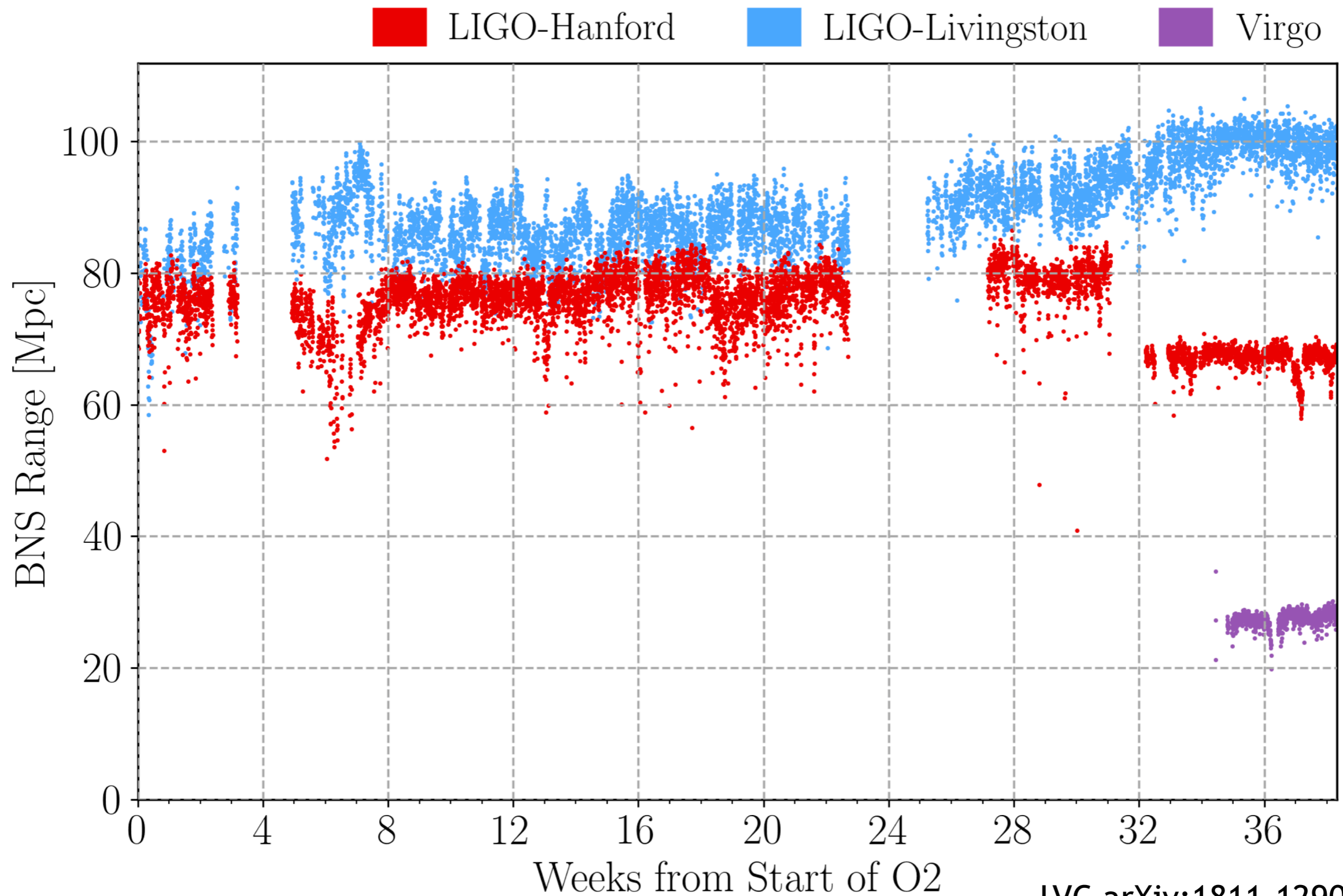


For a recent review see Cardoso and Pani arXiv:1904.05363

Detector sensitivity O2



Detector sensitivity O2



Detector sensitivity 03

[1239148818-1239235218, state: Observing]

GEO-LIGO-Virgo gravitational-wave strain

