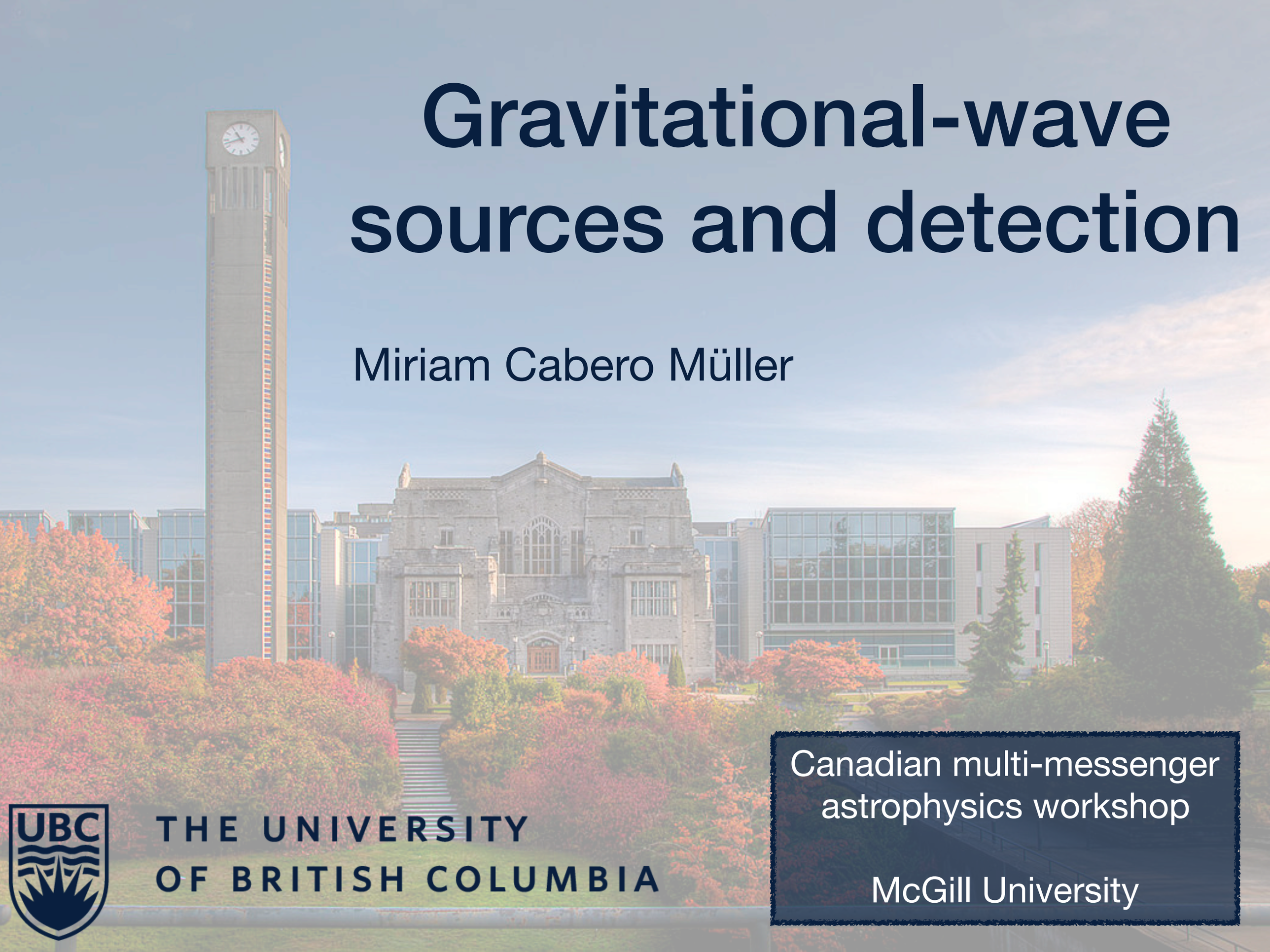
Gravitational-wave sources and detection

Miriam Cabero Müller



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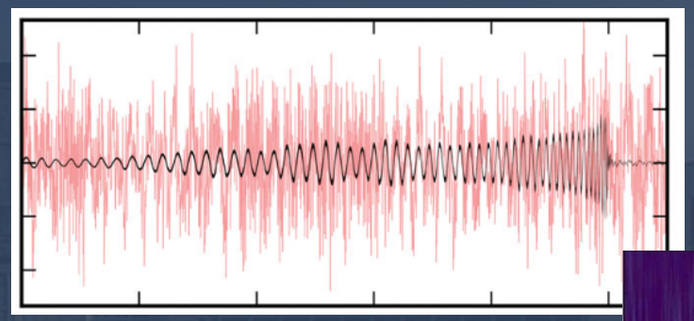
Canadian multi-messenger astrophysics workshop

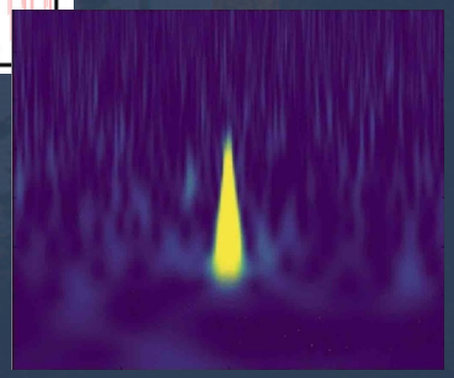
McGill University

Gravitational-wave detection

Advanced LIGO

Gravitational-wave searches and noise rejection





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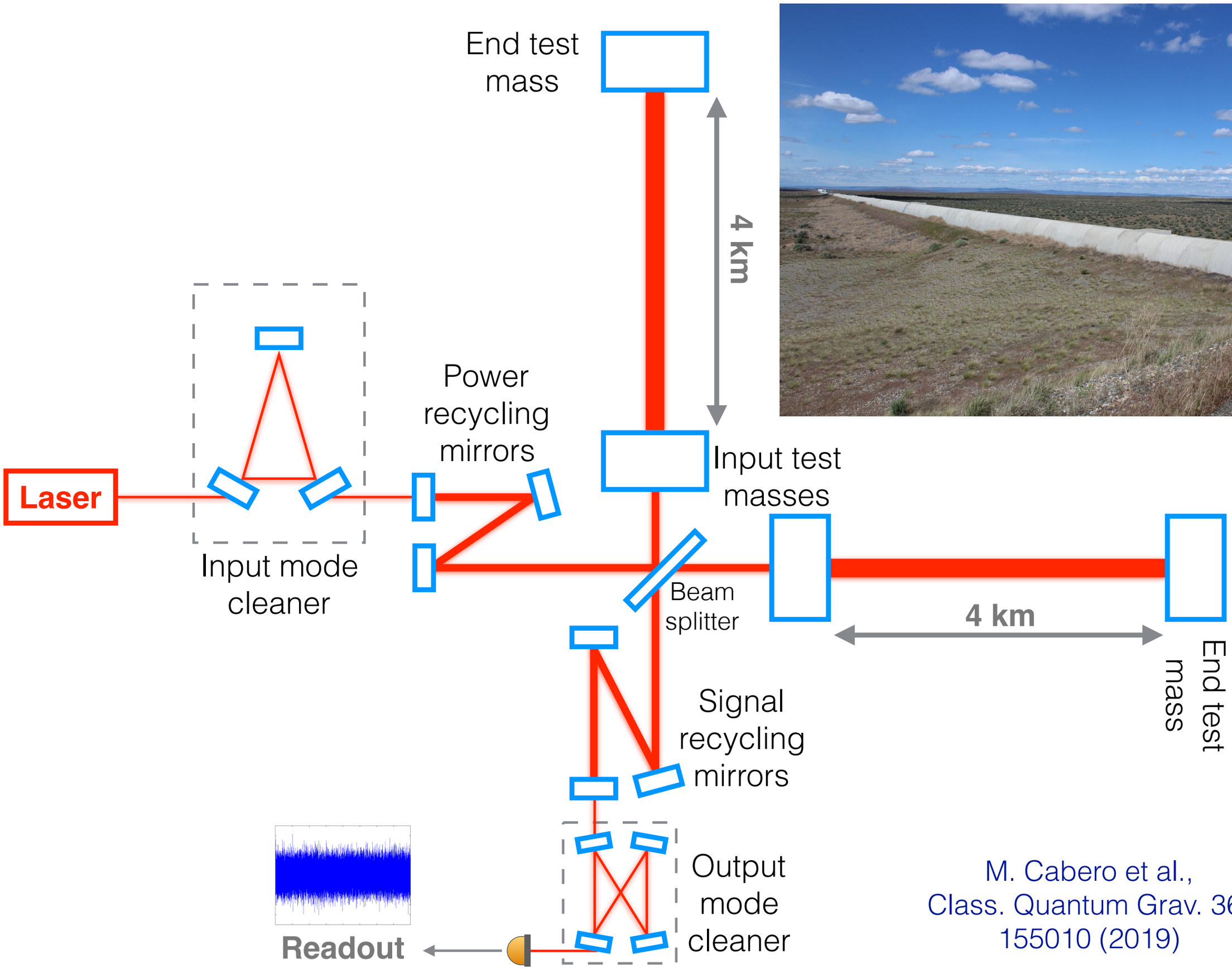
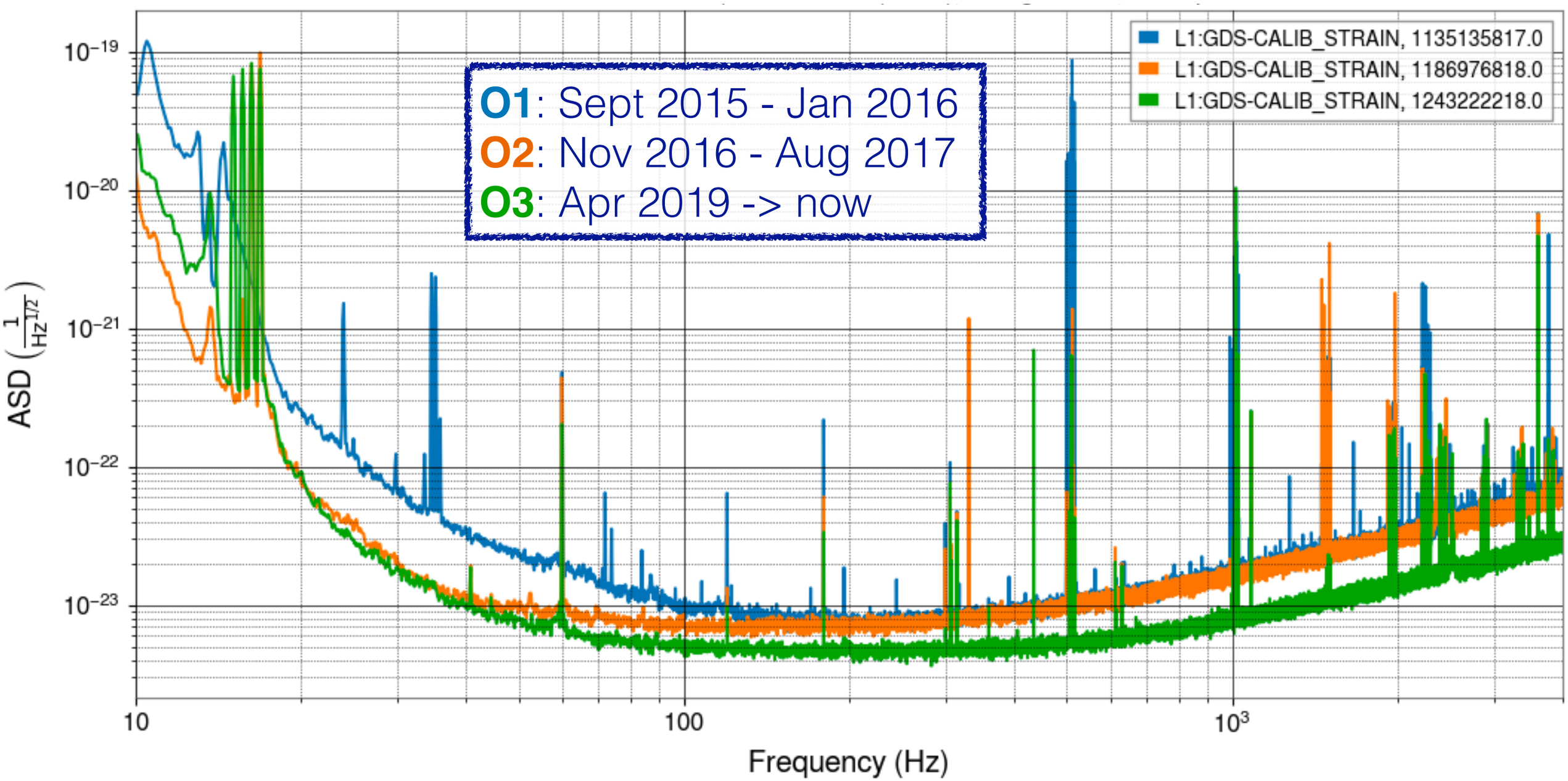
Advanced LIGO



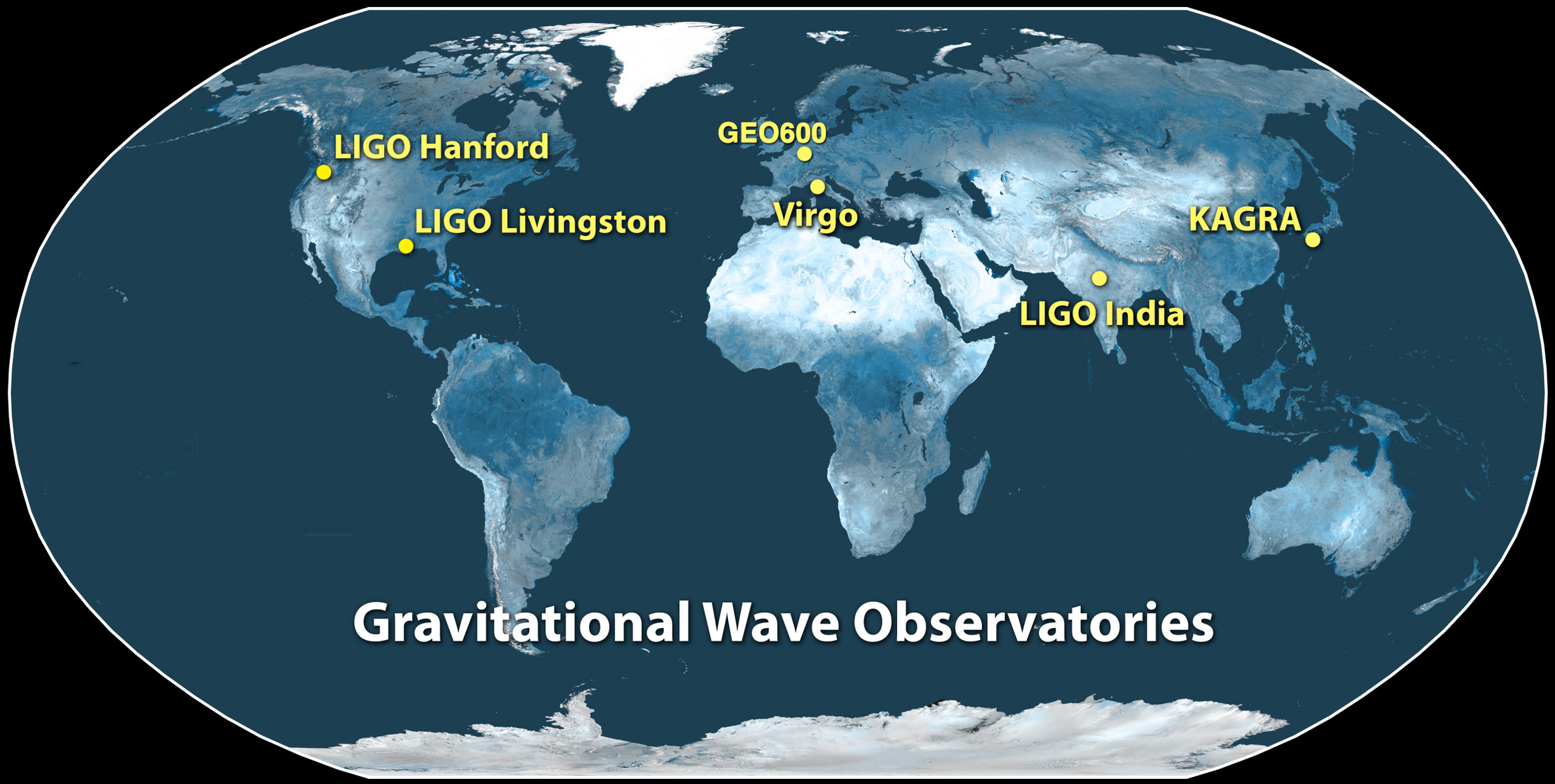
M. Cabero et al., Class. Quantum Grav. 36, 155010 (2019)

Advanced LIGO



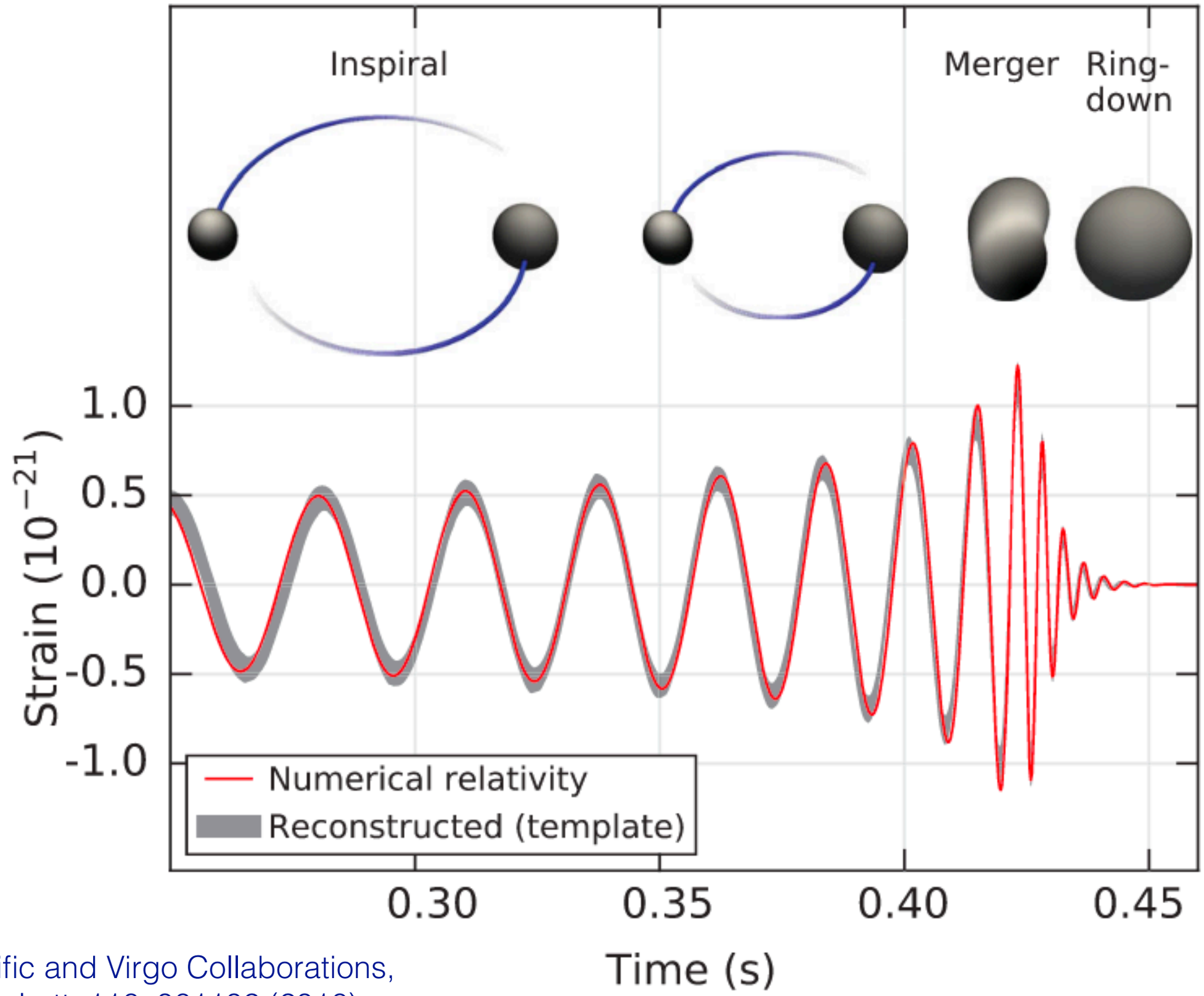
Made with ligoDV web: https://ldvw.ligo.caltech.edu/ldvw/view
(courtesy of Jess McIver)

Detector network



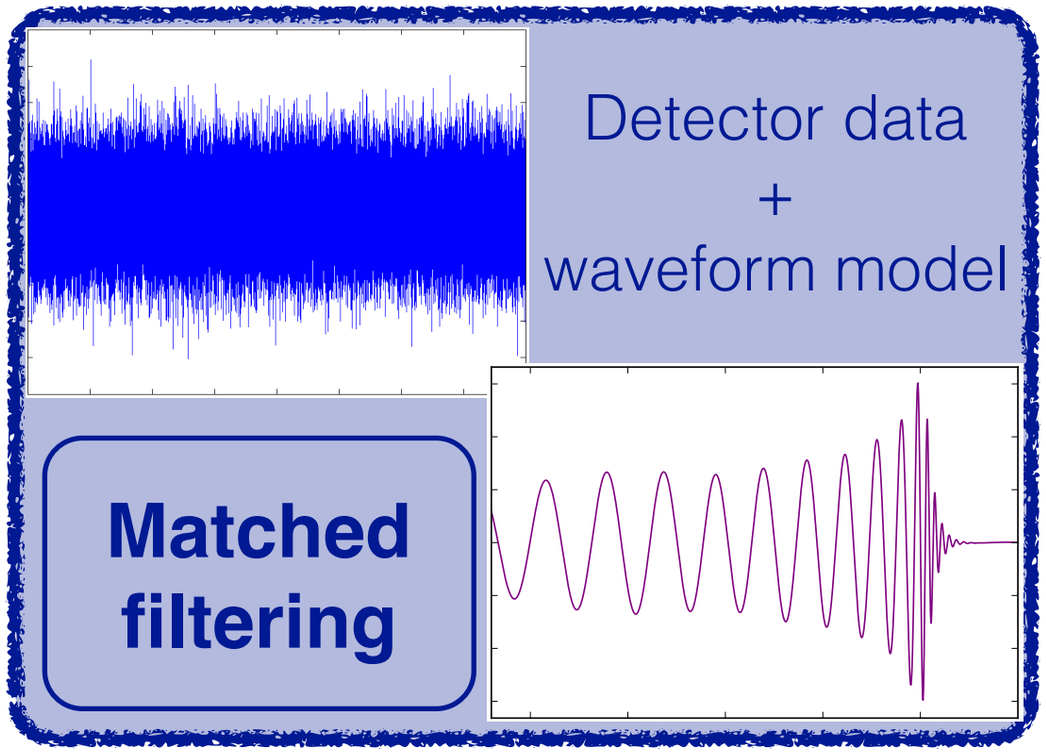
Caltech/MIT/LIGO Lab

Gravitational-wave searches

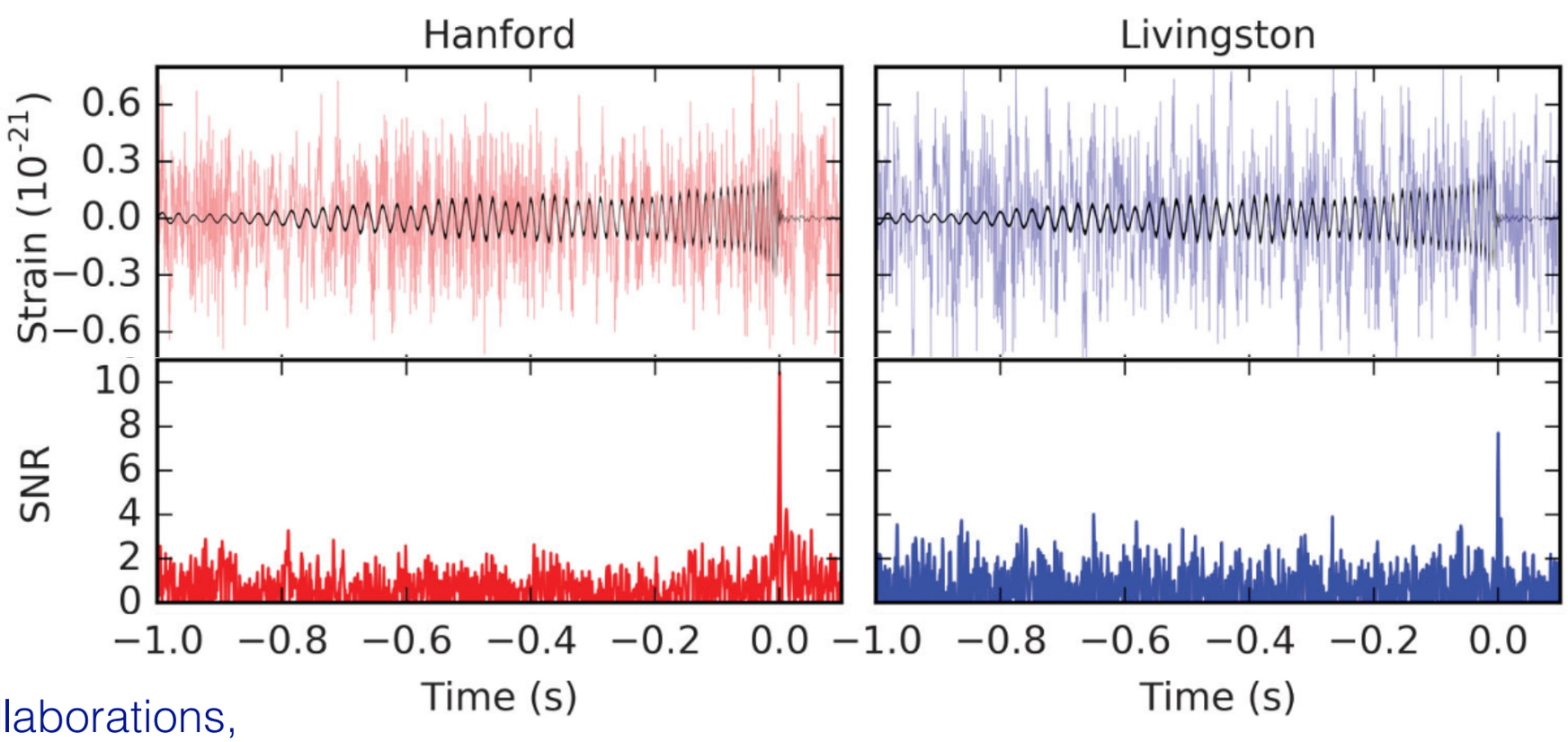


LIGO Scientific and Virgo Collaborations,
Phys. Rev. Lett. 116, 061102 (2016)

Gravitational-wave searches



Signal-to-noise ratio (SNR)



LIGO Scientific and Virgo Collaborations, Phys. Rev. Lett. 116, 241103 (2016)

Data quality noise rejection

Noise events reduce the significance of candidate events, hence reducing the sensitivity of the search

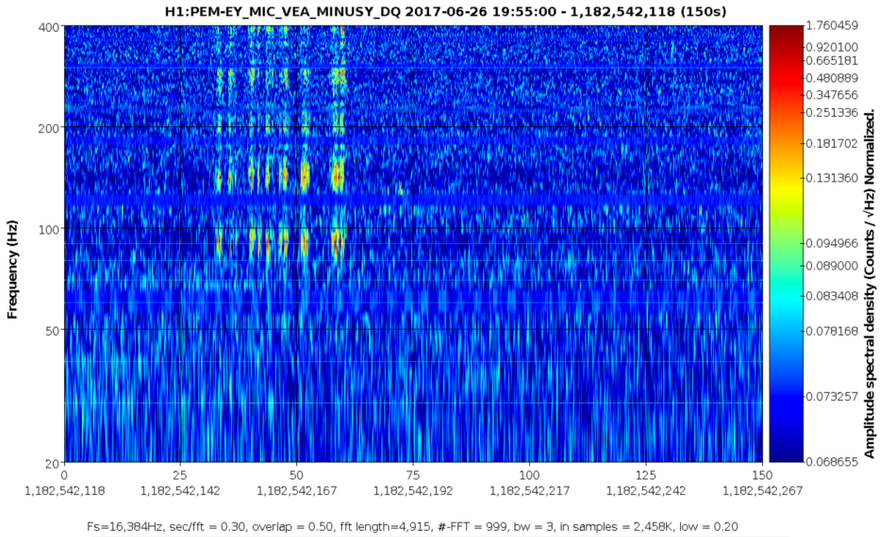
→

Data quality flags (for known noise sources)

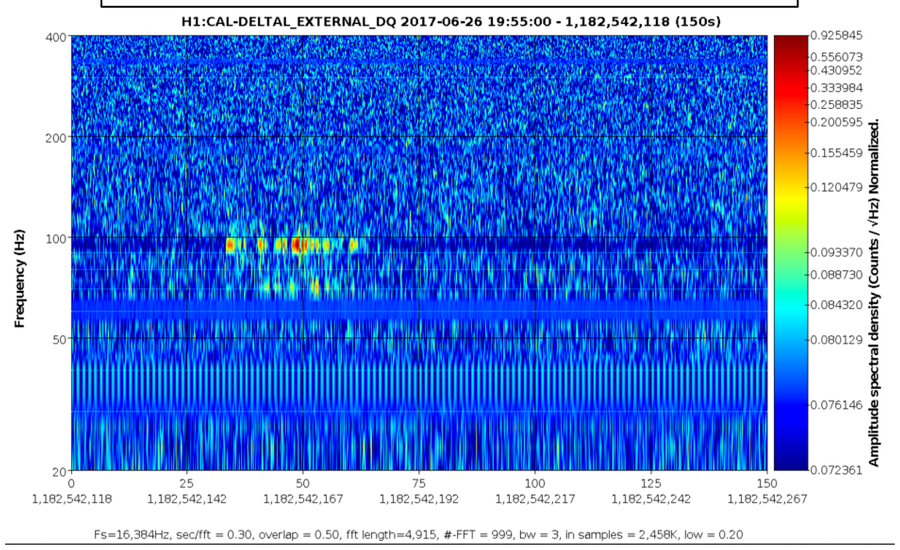
- Category 1 (**CAT1**): issue in the detector's performance, data badly contaminated.
- Category 2 (**CAT2**): instrumental or environmental noise transients of known origin.

CAT2 examples

Possible raven pecks in EY microphone



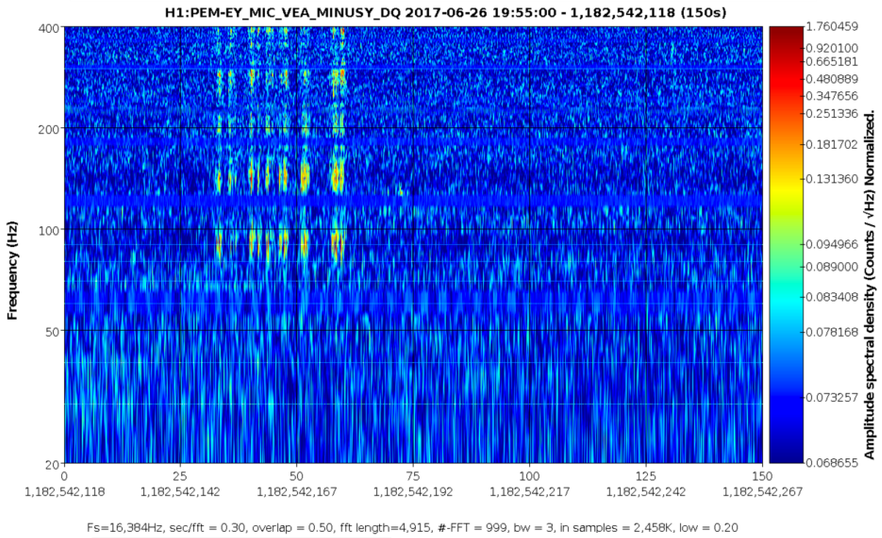
Coincident glitches in GW channel



https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=37630

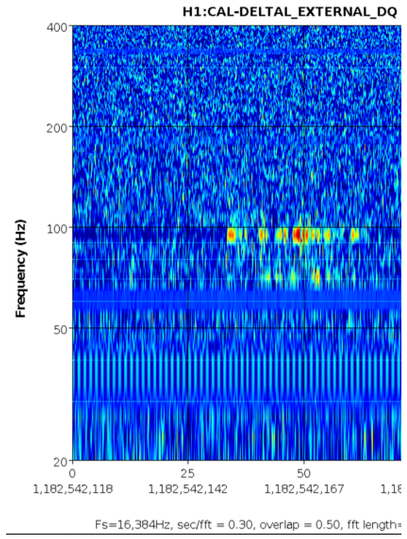
CAT2 examples

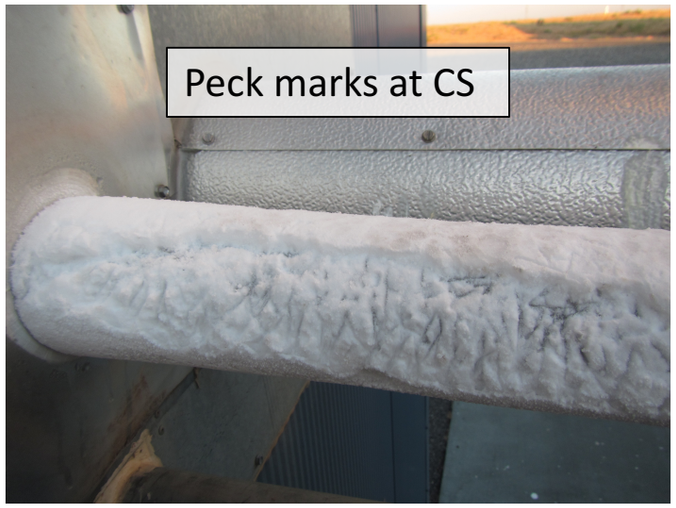
Possible raven pecks in EY microphone



https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=37630

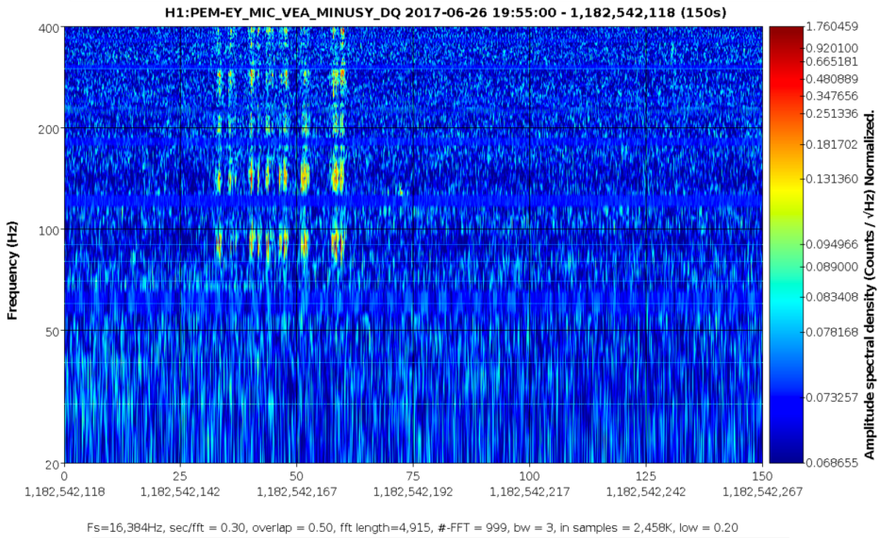
Coincident glitc



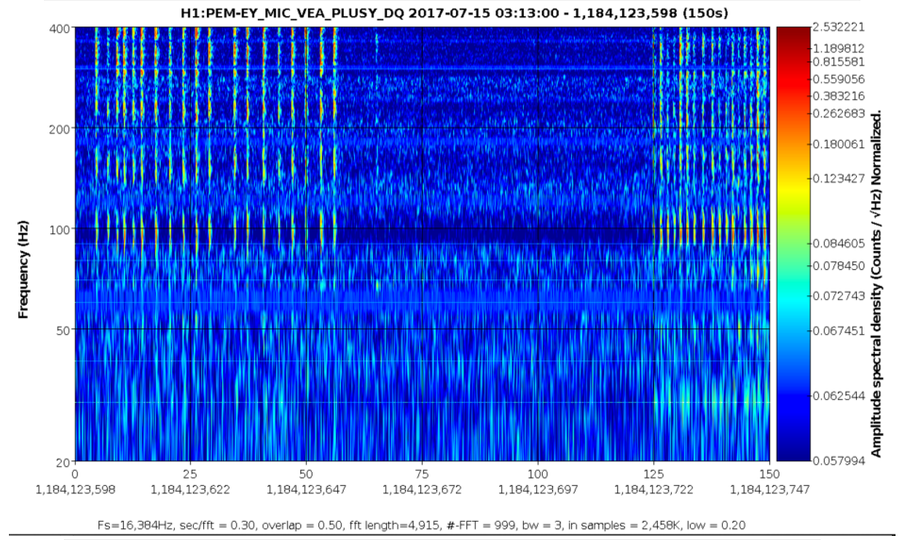


CAT2 examples

Possible raven pecks in EY microphone

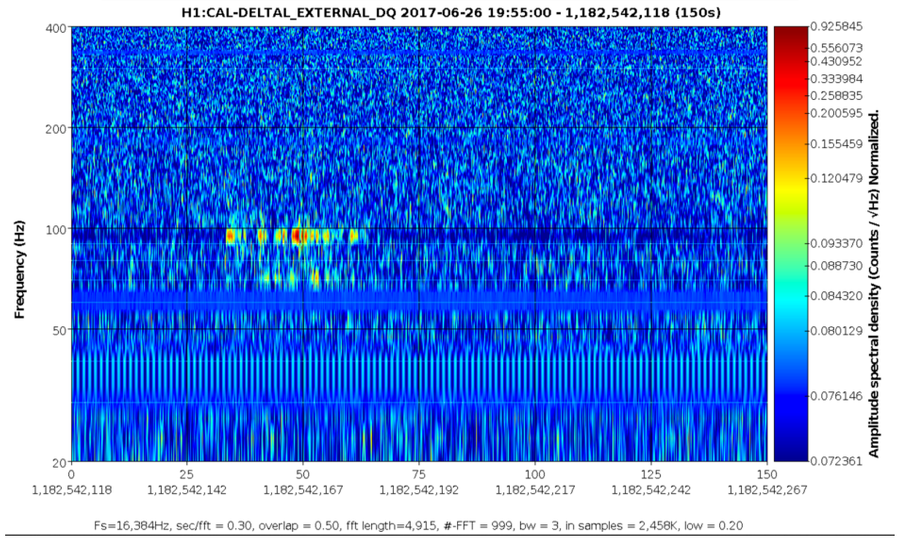


Immitation raven pecks in EY microphone

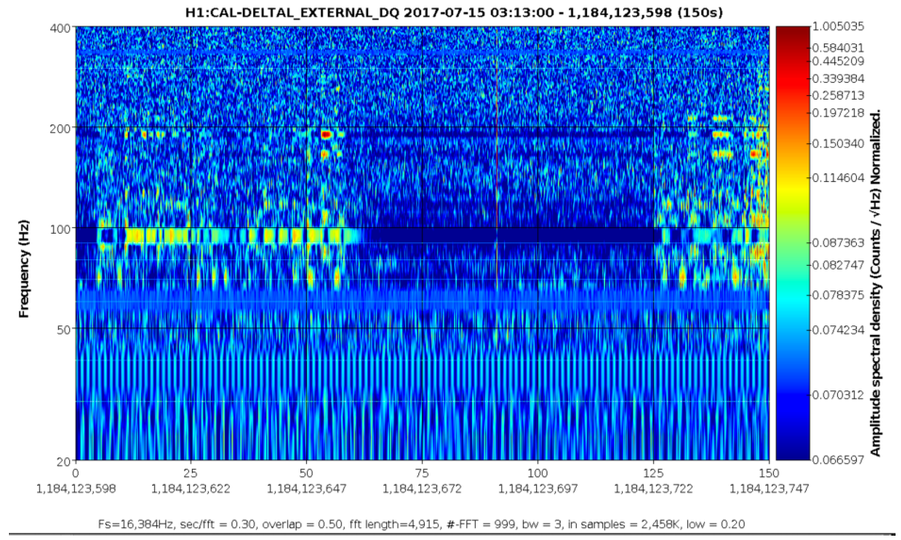


https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=37630

Coincident glitches in GW channel



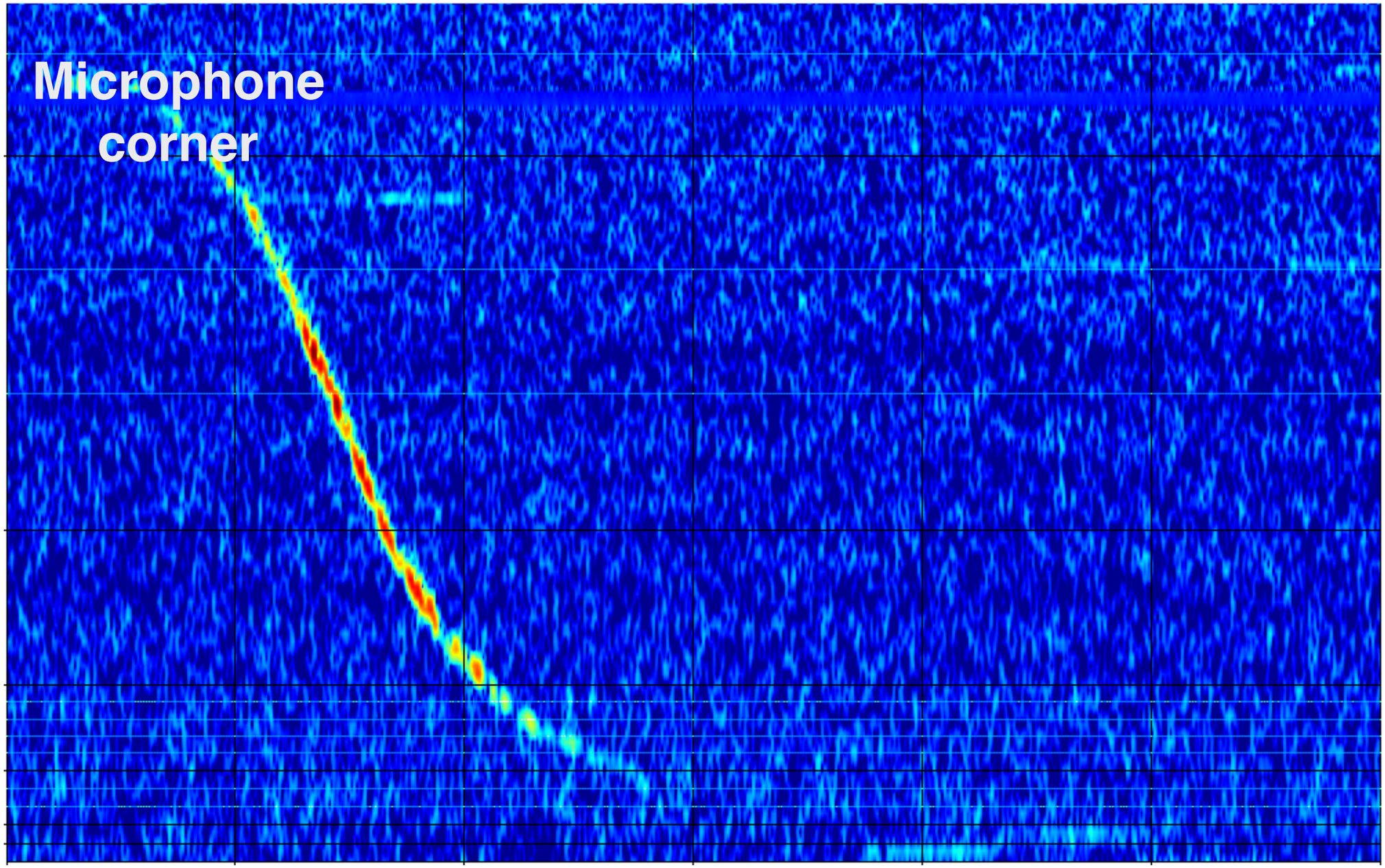
Coincident glitches in GW channel



Pep imitating raven

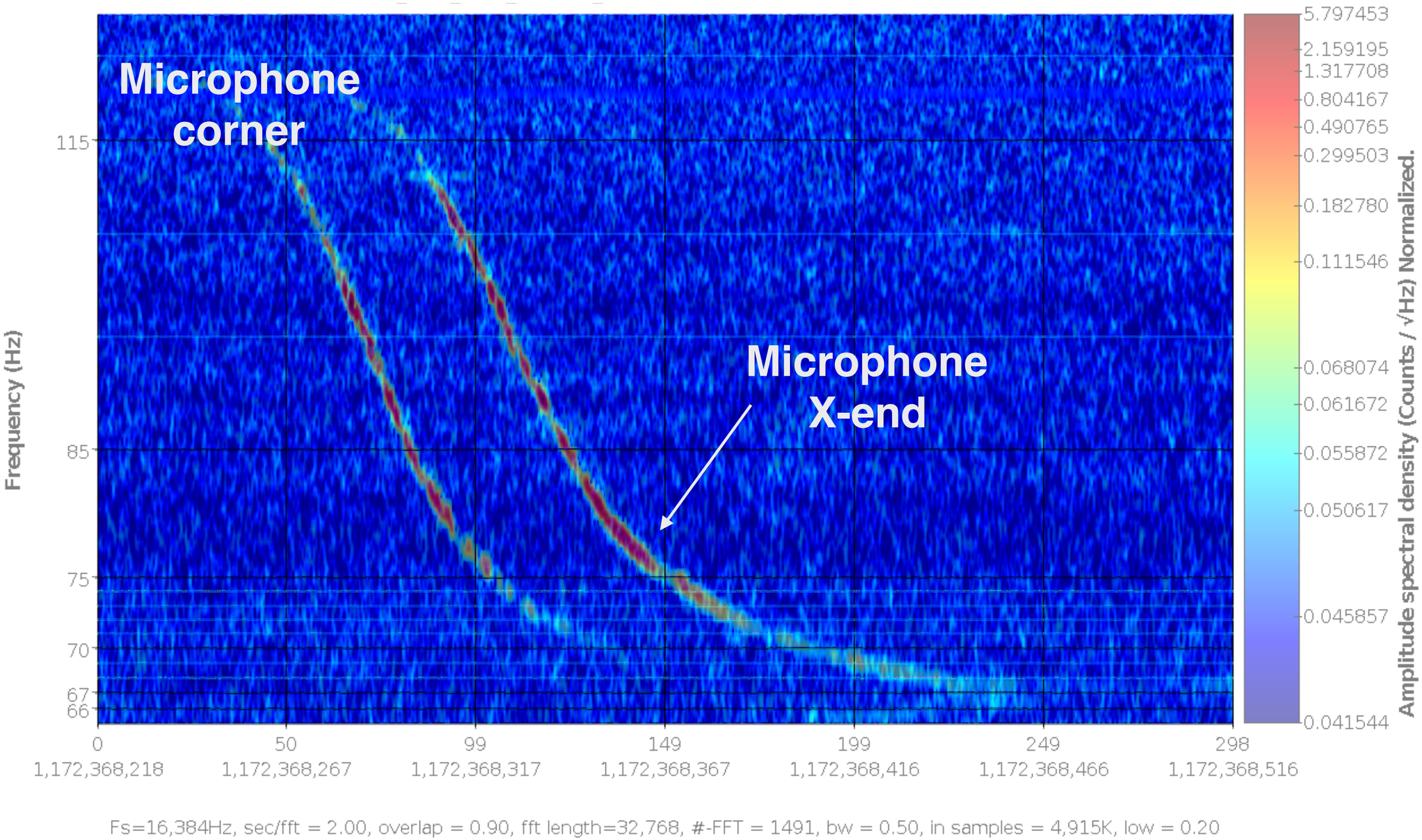
the ice is accumulating

CAT2 examples



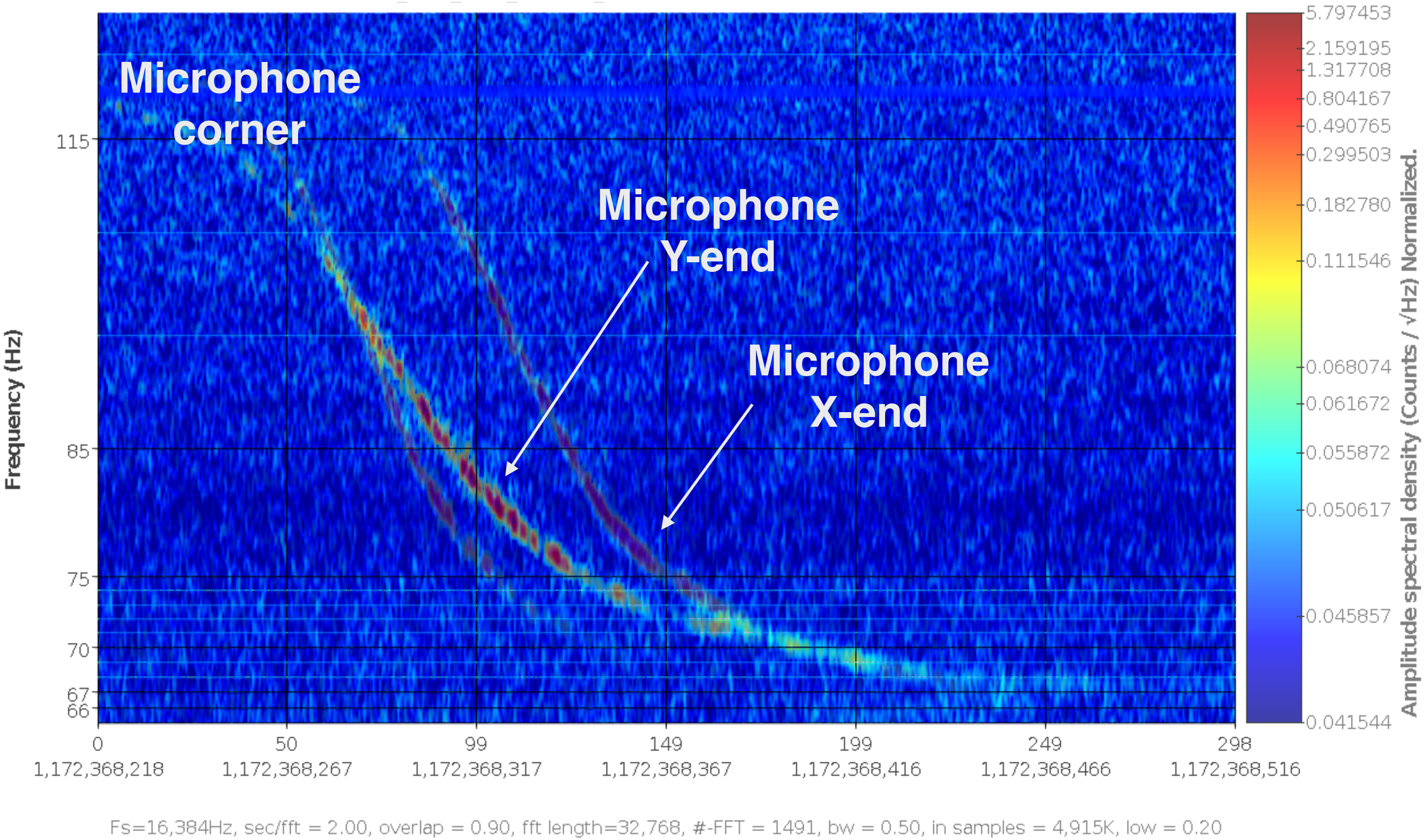
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=34547

CAT2 examples



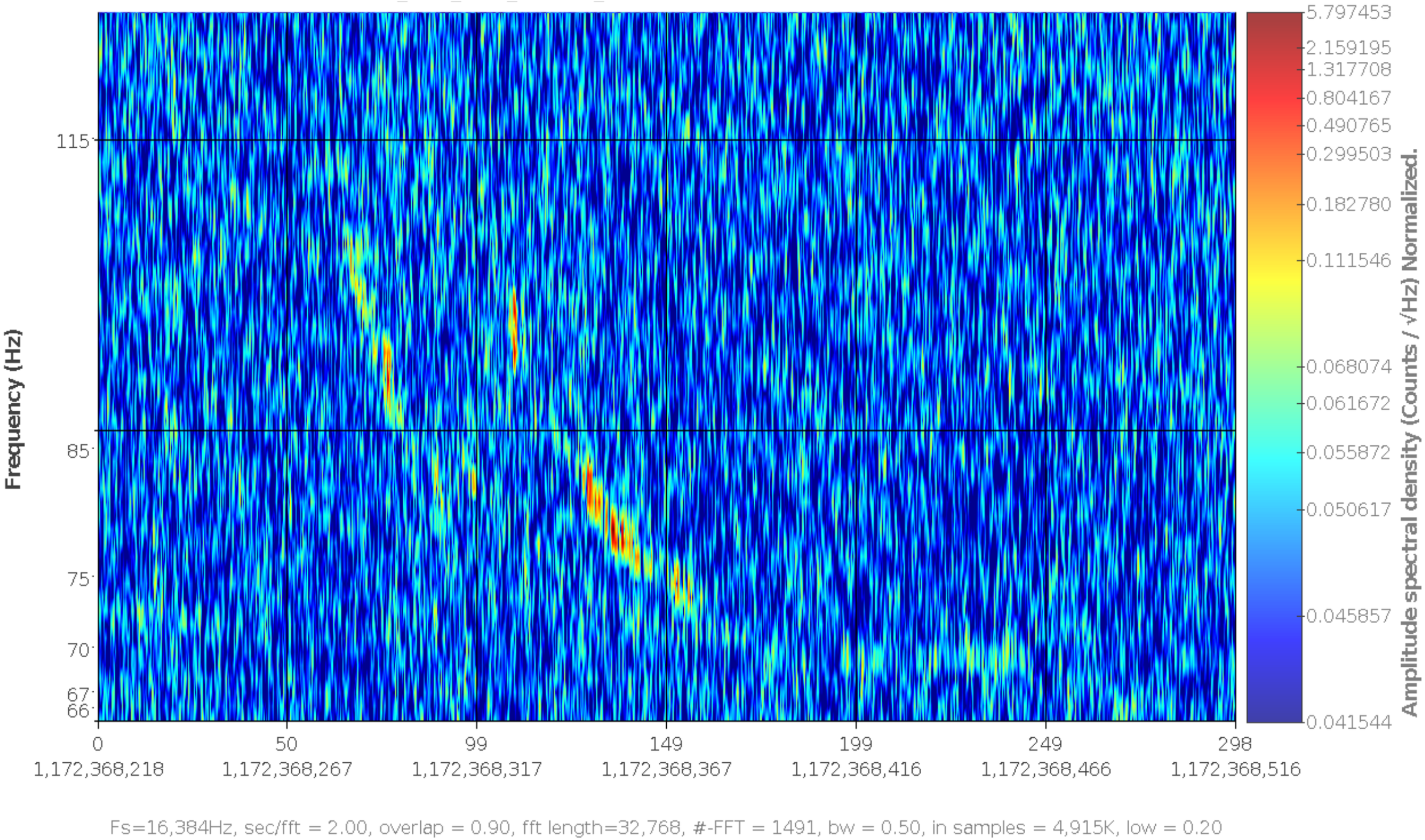
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=34547

CAT2 examples



https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=34547

CAT2 examples



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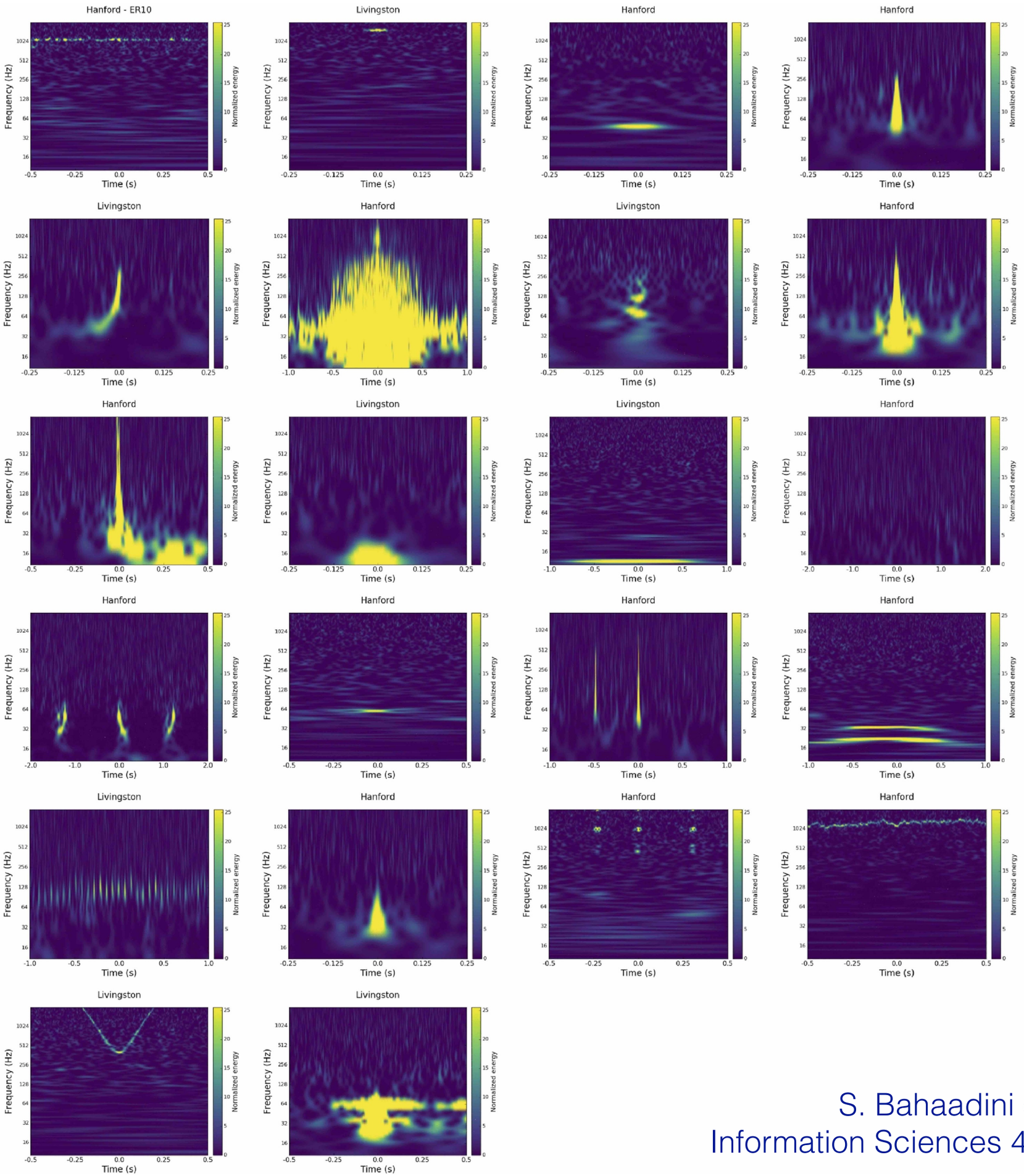
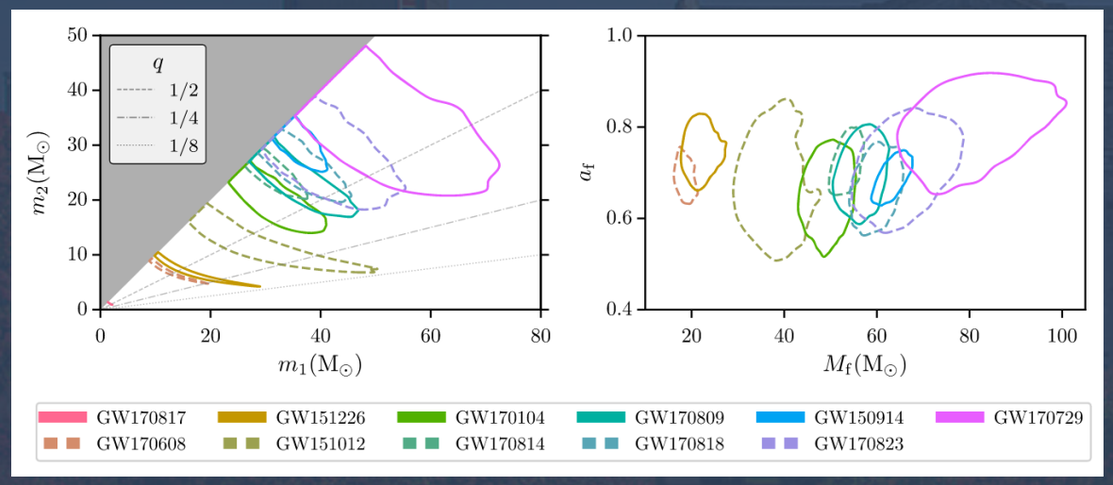


Noise transients from unknown sources (examples)

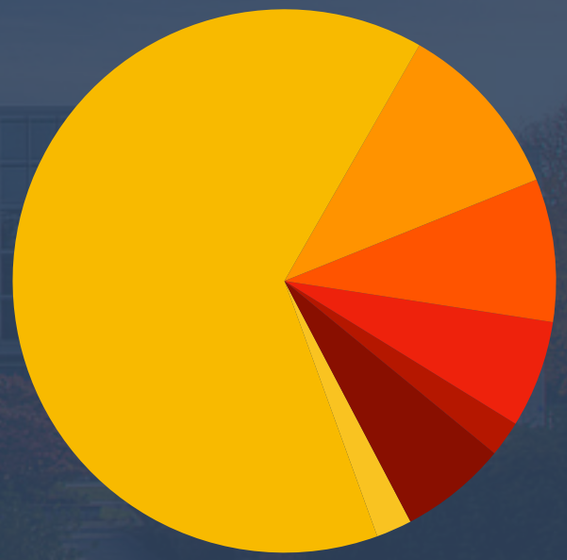
S. Bahaadini et al.,
Information Sciences 444, 172 (2018)

Gravitational-wave sources

O1-O2 & multi-messenger



O3 status



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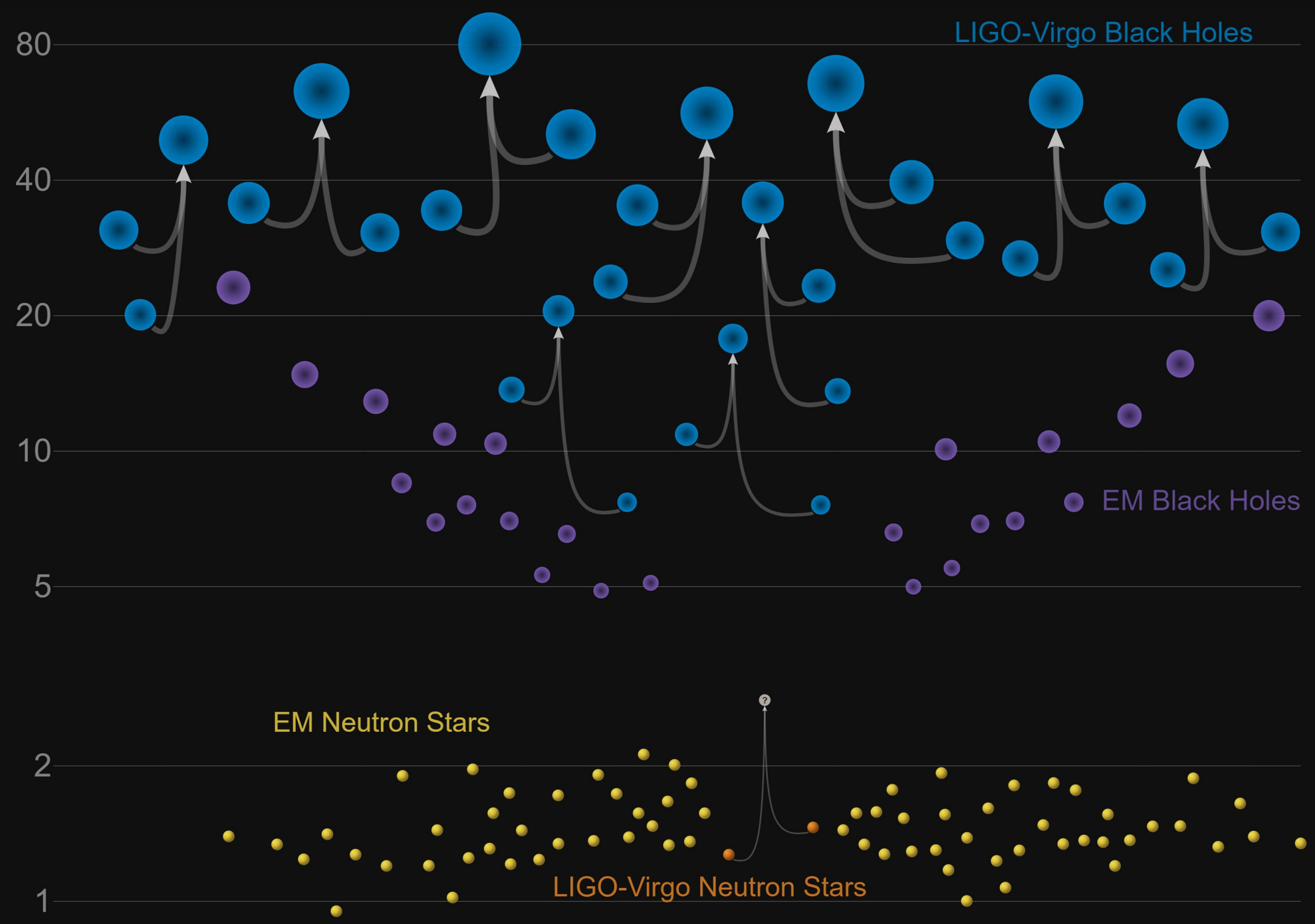
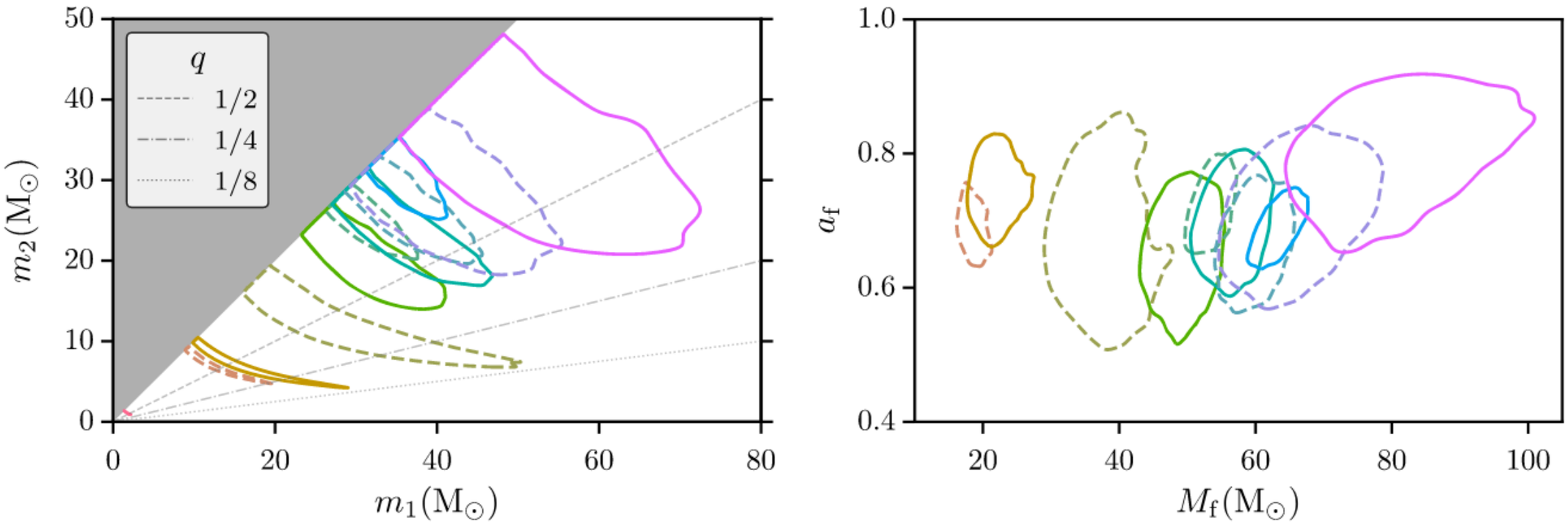
GW sources in O1-O2



LIGO-Virgo | Frank Elavsky | Northwestern

GWTC-1

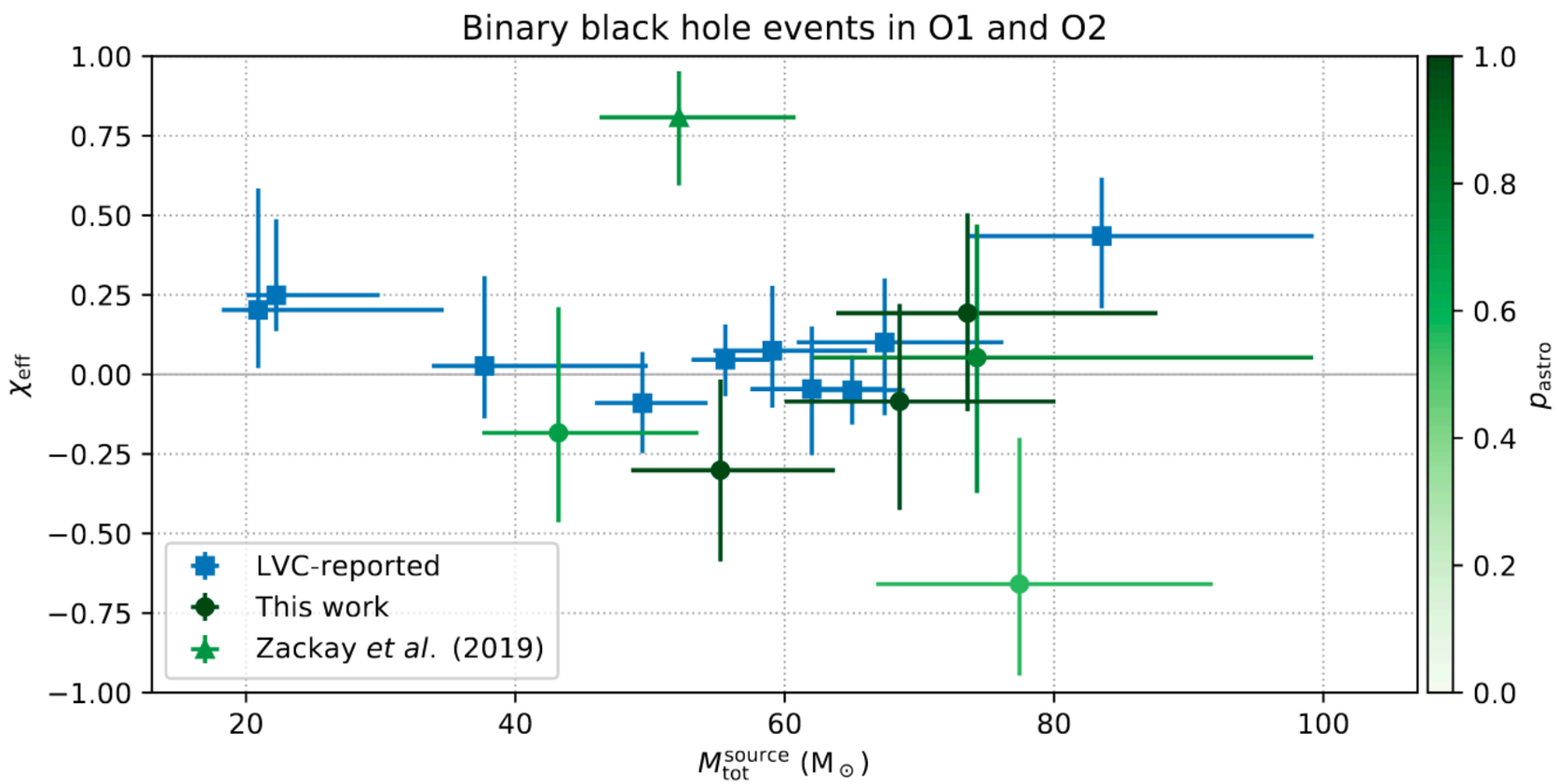
LIGO Scientific and Virgo Collaborations, Phys. Rev. X 9, 031040 (2019)



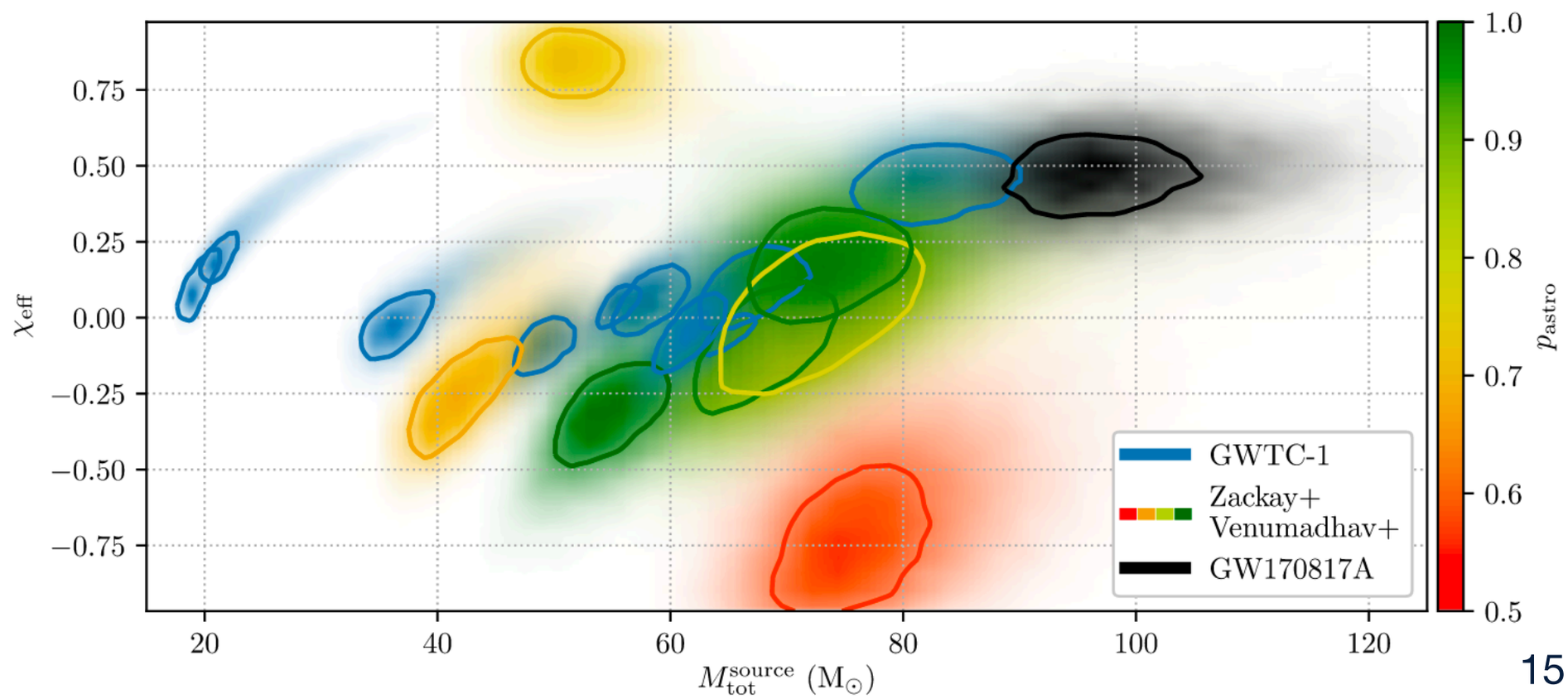
GW170817 GW151226 GW170104 GW170809 GW150914 GW170729
GW170608 GW151012 GW170814 GW170818 GW170823

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_eff	$M_f/M_\odot$	a_f	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	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	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

Independent analyses (IAS)

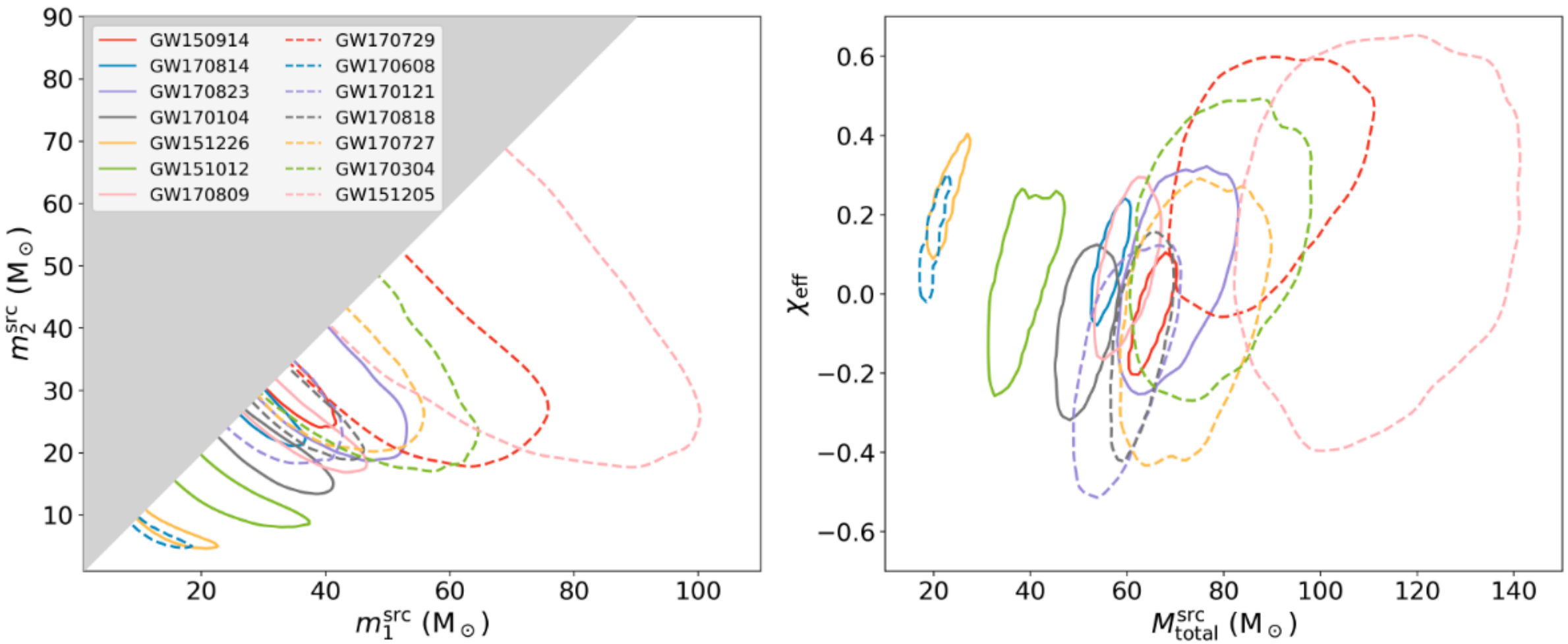


T. Venumadhav et al., arXiv:1904.07214



B. Zackay et al., arXiv:1910.09528

Independent analyses (2-OGC)



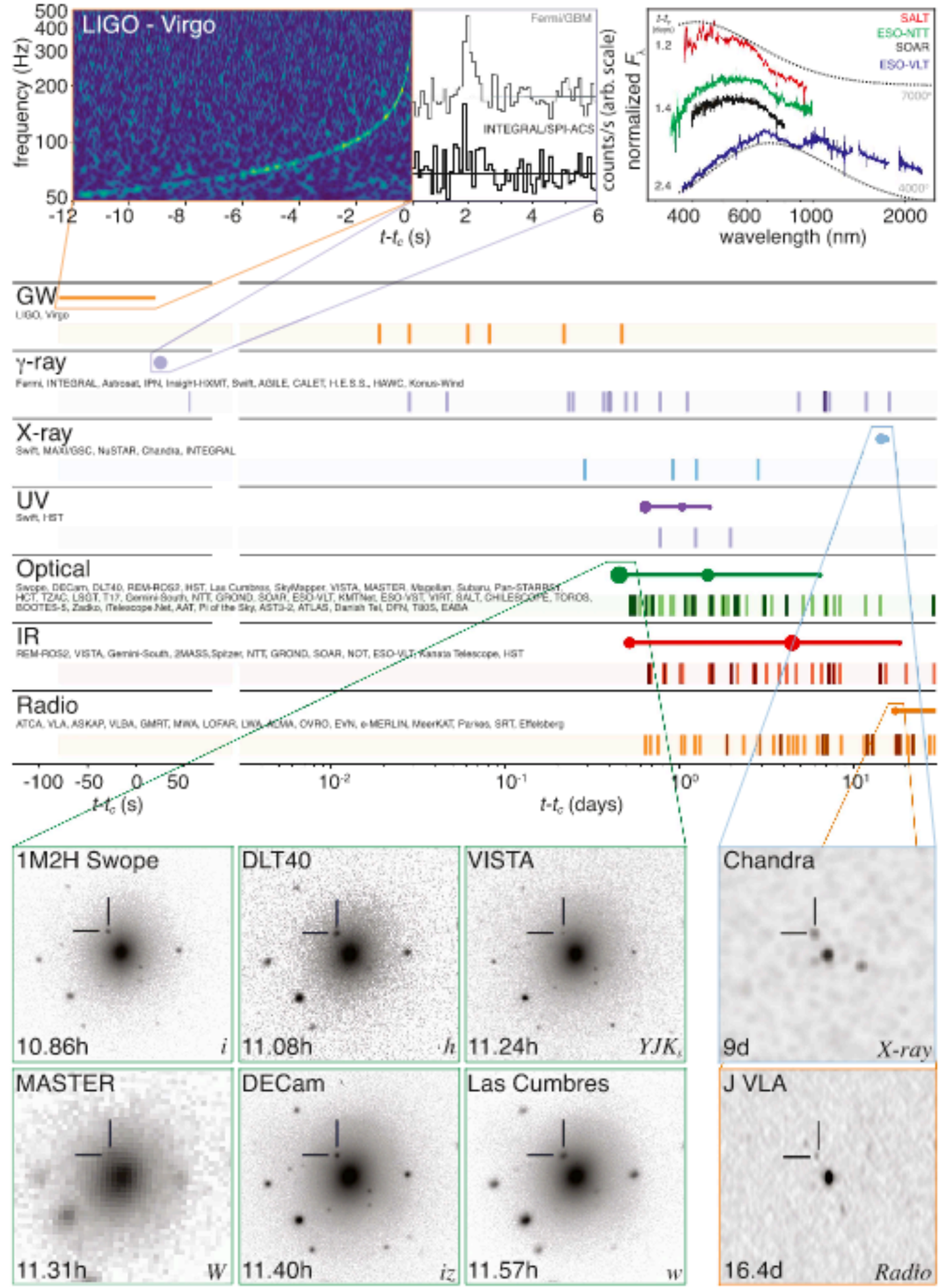
A. H. Nitz et al.,
arXiv:1910.05331

Independent analyses (2-OGC)

Date designation	GPS time	$p_{\rm astro}$	FAR^{-1} (y)	Det.	$\tilde{\Lambda}_{\rm BBH}$	ρ_H	ρ_L	ρ_V	$m_1^{\rm src}$	$m_2^{\rm src}$	$\chi_{\rm eff}$	D_L (Mpc)	
150914+09:50:45UTC	1126259462.43	> 0.999	> 10000	HL	111.71	19.7	13.4	-	$35.4^{+5.3}_{-3.2}$	$29.8^{+3.1}_{-4.7}$	$-0.04^{+0.11}_{-0.13}$	470^{+140}_{-190}	LVC
170814+10:30:43UTC	1186741861.53	> 0.999	> 10000	HL	61.58	9.3	13.8	-	$30.4^{+5.6}_{-2.7}$	$25.8^{+2.6}_{-4}$	$0.08^{+0.12}_{-0.12}$	580^{+130}_{-190}	LVC
170823+13:13:58UTC	1187529256.52	> 0.999	> 10000	HL	59.43	6.3	9.2	-	$40^{+11.7}_{-7.1}$	$28.8^{+6.8}_{-7.9}$	$0.05^{+0.21}_{-0.22}$	1750^{+850}_{-820}	LVC
170104+10:11:58UTC	1167559936.60	> 0.999	> 10000	HL	47.32	9.1	9.9	-	$31.6^{+7.8}_{-6.3}$	$19.2^{+5}_{-4.1}$	$-0.08^{+0.16}_{-0.18}$	920^{+420}_{-400}	LVC
151226+03:38:53UTC	1135136350.65	> 0.999	> 10000	HL	40.58	10.7	7.4	-	$13.9^{+7.9}_{-3.3}$	$7.6^{+2.2}_{-2.3}$	$0.209^{+0.177}_{-0.077}$	460^{+160}_{-180}	LVC
151012+09:54:43UTC	1128678900.45	> 0.999	> 10000	HL	20.25	7.0	6.7	-	$22.4^{+13.4}_{-4.8}$	$13.8^{+3.7}_{-4.8}$	$-0.00^{+0.25}_{-0.16}$	990^{+470}_{-460}	LVC
170809+08:28:21UTC	1186302519.76	> 0.999	8300[a]	HL	43.34	6.6	10.7	-	$35.2^{+9.5}_{-5.9}$	$23.9^{+5.1}_{-5.3}$	$0.06^{+0.18}_{-0.16}$	980^{+310}_{-390}	LVC
170729+18:56:29UTC	1185389807.33	> 0.999	4000	HL	19.16	7.5	7.1	-	55^{+18}_{-13}	32^{+13}_{-10}	$0.31^{+0.22}_{-0.29}$	2300^{+1600}_{-1300}	LVC
170608+02:01:16UTC	1180922494.49	> 0.999	> 910	HL	55.12	12.5	8.7	-	$11.6^{+6.7}_{-2.1}$	$7.4^{+1.6}_{-2.3}$	$0.088^{+0.213}_{-0.073}$	310^{+130}_{-110}	LVC
170121+21:25:36UTC	1169069154.58	> 0.999	210[a]	HL	23.86	5.1	8.9	-	$33^{+9.2}_{-5.3}$	$25.7^{+5.3}_{-6.1}$	$-0.17^{+0.24}_{-0.26}$	1150^{+950}_{-650}	IAS
170818+02:25:09UTC	1187058327.09	> 0.999	5.1[a]	HL	21.42	4.4	9.4	-	$36^{+8.2}_{-5.3}$	$26.2^{+4.8}_{-5.7}$	$-0.11^{+0.20}_{-0.23}$	980^{+430}_{-340}	LVC
170727+01:04:30UTC	1185152688.03	0.994	180	HL	15.84	4.5	6.9	-	$41.6^{+12.8}_{-7.9}$	$30.4^{+7.9}_{-8.2}$	$-0.05^{+0.25}_{-0.30}$	2200^{+1500}_{-1100}	2-OGC
170304+16:37:53UTC	1172680691.37	0.70	2.5	HL	11.61	4.6	7.1	-	$44.9^{+17.6}_{-9.4}$	$31.8^{+9.5}_{-11.6}$	$0.11^{+0.29}_{-0.27}$	2300^{+1600}_{-1200}	2-OGC
151205+19:55:25UTC	1133380542.42	0.53	.61	HL	10.97	5.8	4.8	-	67^{+28}_{-17}	42^{+16}_{-19}	$0.14^{+0.40}_{-0.38}$	3000^{+2400}_{-1600}	2-OGC
151217+03:47:49UTC	1134359286.35	0.26	.15	HL	9.61	6.7	5.6	-	46^{+13}_{-26}	$8.2^{+5.1}_{-1.7}$	$0.70^{+0.15}_{-0.50}$	1000^{+660}_{-440}	
170201+11:03:12UTC	1169982210.74	0.24	.16	HL	9.26	6.0	5.6	-	48^{+13}_{-23}	$13.1^{+8.6}_{-3.7}$	$0.44^{+0.28}_{-0.54}$	1530^{+1360}_{-770}	
170425+05:53:34UTC	1177134832.19	0.21	.2	HL	9.42	5.1	5.8	-	45^{+21}_{-11}	30^{+11}_{-11}	$-0.06^{+0.28}_{-0.32}$	2600^{+2000}_{-1300}	IAS
151216+09:24:16UTC	1134293073.19	0.18	.1	HL	9.25	5.9	5.5	-	41^{+15}_{-17}	$14.4^{+7}_{-6.3}$	$0.51^{+0.21}_{-0.57}$	1620^{+1140}_{-910}	IAS
170202+13:56:57UTC	1170079035.73	0.13	.06	HL	8.37	5.0	6.6	-	33^{+17}_{-11}	$13.8^{+7}_{-4.8}$	$-0.06^{+0.27}_{-0.32}$	1220^{+980}_{-640}	IAS
170104+21:58:40UTC	1167602338.72	0.12	.03	HL	8.80	5.6	5.4	-	98^{+49}_{-40}	44^{+30}_{-33}	$0.25^{+0.50}_{-0.49}$	4600^{+4300}_{-3100}	
170220+11:36:24UTC	1171625802.53	0.10	.05	HL	8.43	4.4	5.2	-	69^{+37}_{-25}	31^{+22}_{-14}	$0.28^{+0.33}_{-0.37}$	3600^{+3700}_{-2100}	
170123+20:16:42UTC	1169237820.55	0.08	.04	HL	7.97	5.0	5.3	-	44^{+23}_{-12}	28^{+13}_{-13}	$-0.12^{+0.31}_{-0.35}$	2800^{+2800}_{-1600}	
151011+19:27:49UTC	1128626886.61	0.08	.12	HL	8.45	4.9	6.6	-	51^{+18}_{-12}	31^{+12}_{-12}	$0.09^{+0.29}_{-0.27}$	1560^{+1090}_{-740}	
151216+18:49:30UTC	1134326987.60	0.07	.03	HL	8.14	6.1	6.0	-	$19.7^{+6.4}_{-7.4}$	$3.25^{+1.32}_{-0.58}$	$-0.03^{+0.24}_{-0.49}$	500^{+280}_{-250}	
170721+05:55:13UTC	1184651731.37	0.06	.04	HL	7.76	6.6	5.1	-	$31.7^{+9.3}_{-6.1}$	$21.4^{+5.3}_{-5.6}$	$-0.06^{+0.25}_{-0.29}$	1160^{+750}_{-520}	
170403+23:06:11UTC	1175295989.23	0.03	.07	HL	7.26	5.2	5.2	-	53^{+23}_{-13}	35^{+13}_{-15}	$-0.20^{+0.35}_{-0.37}$	2500^{+2100}_{-1300}	
170629+04:13:55UTC	1182744853.11	0.02	.06	HL	6.72	6.6	4.8	-	49^{+20}_{-30}	$7.3^{+4.6}_{-2.6}$	$0.73^{+0.15}_{-0.98}$	1880^{+1450}_{-940}	
170620+01:14:02UTC	1181956460.10	0.02	.04	HL	6.18	5.7	5.1	-	$29.4^{+13.2}_{-6.8}$	$17.9^{+5.4}_{-5.5}$	$0.05^{+0.25}_{-0.25}$	1710^{+1300}_{-850}	
170801+23:28:19UTC	1185665317.35	-	.04	LV	8.59	-	6.9	4.3	$23.9^{+12.6}_{-6.6}$	$12.4^{+4.7}_{-4}$	$-0.09^{+0.25}_{-0.24}$	1070^{+920}_{-580}	
170818+09:34:45UTC[b]	1187084103.28	-	.04	HV	8.40	6.5	-	4.4	55^{+59}_{-28}	23^{+43}_{-15}	$0.06^{+0.48}_{-0.45}$	3100^{+1700}_{-1900}	

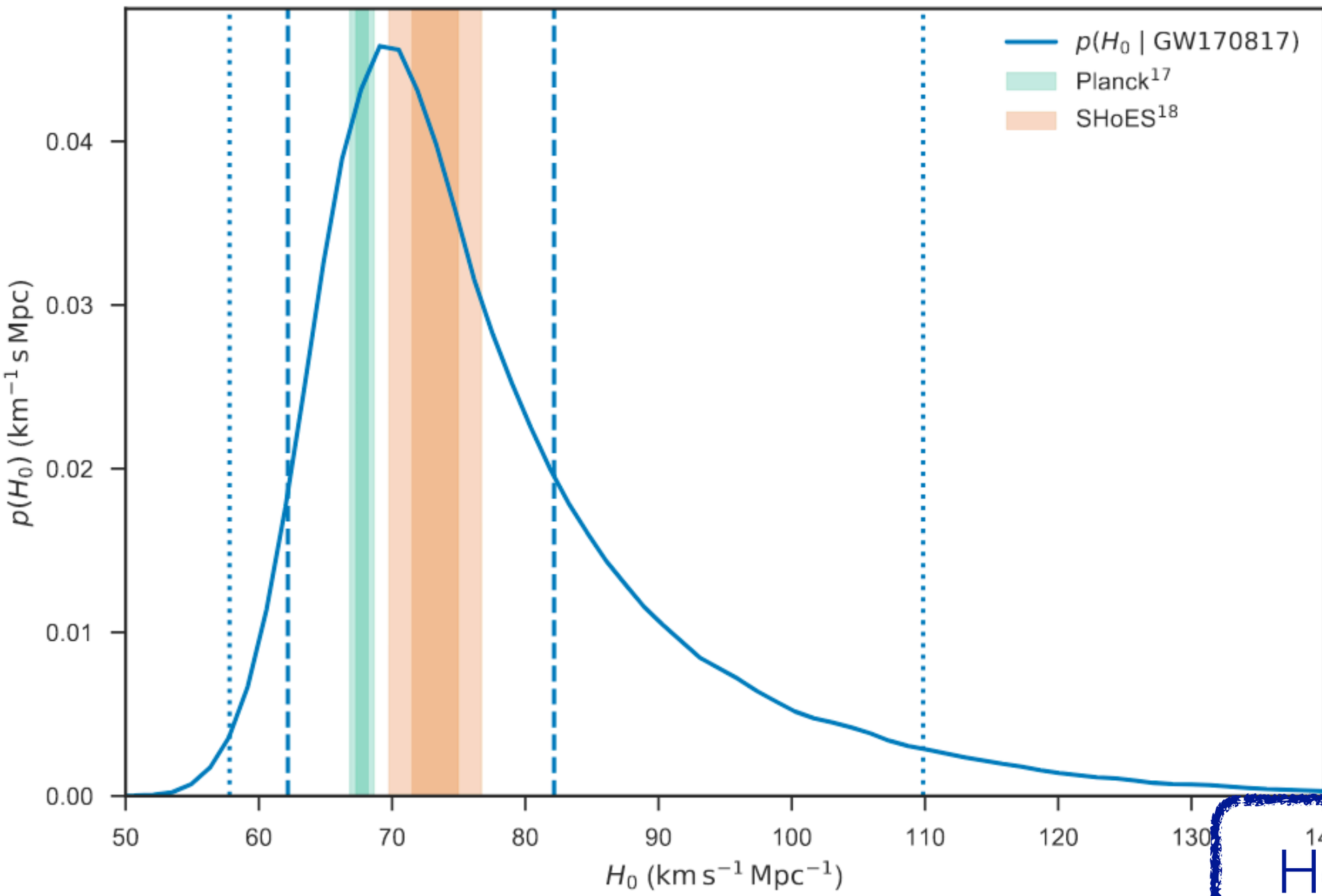
Multi-messenger astronomy with GW170817

See talks by Maria Drout and Daryl Haggard later today



LIGO Scientific and Virgo Collaborations, Astroph. J. Lett. 848:L12 (2017)

Hubble constant



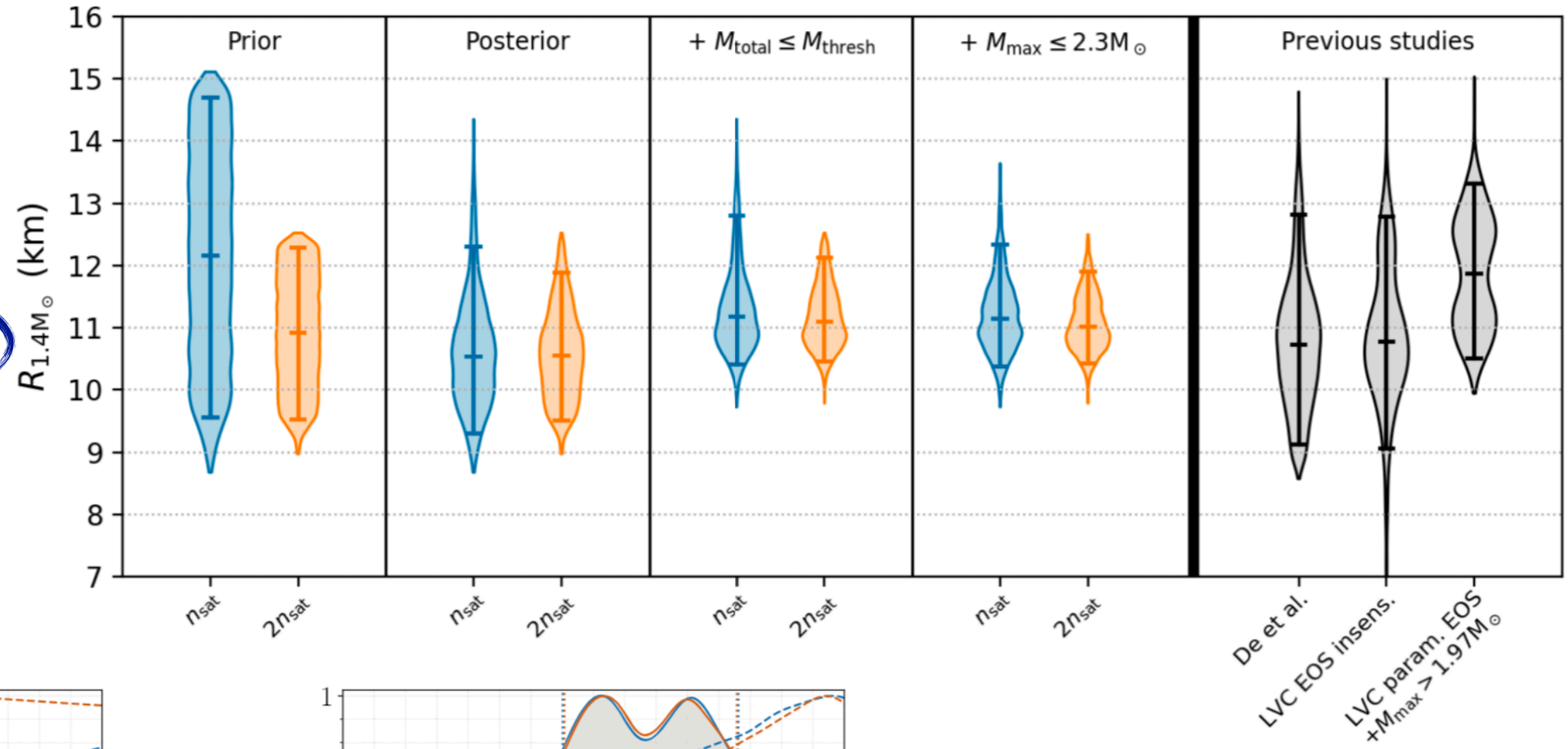
Host galaxy:
NGC 4993

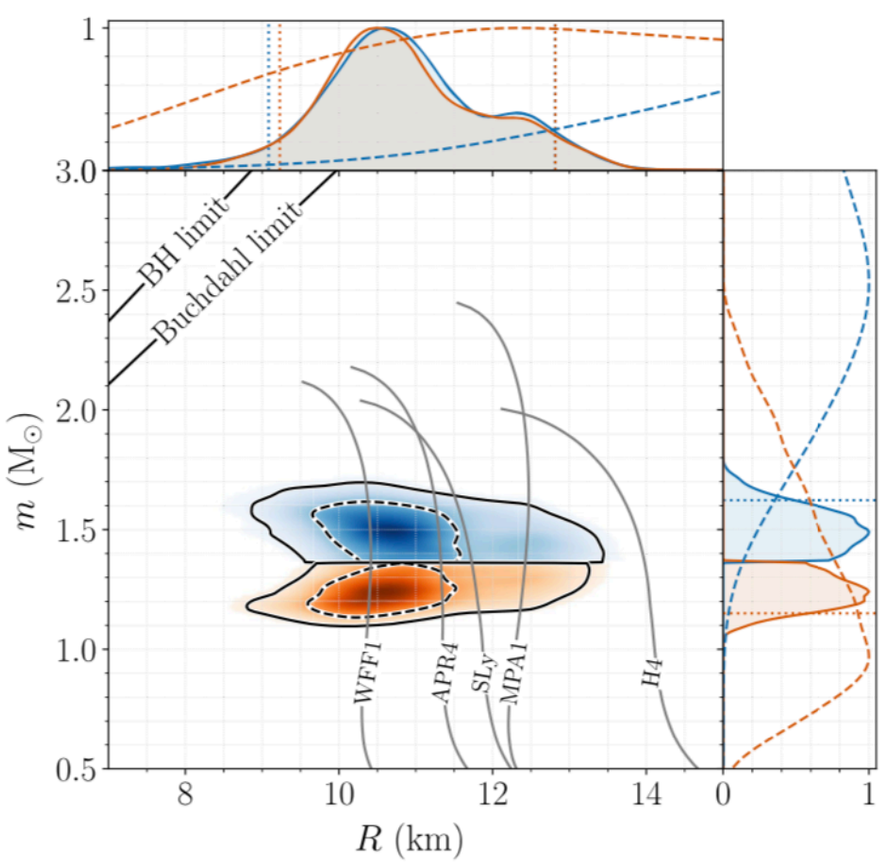
LIGO Scientific and Virgo Collaborations,
Nature 551, 85-88 (2017)

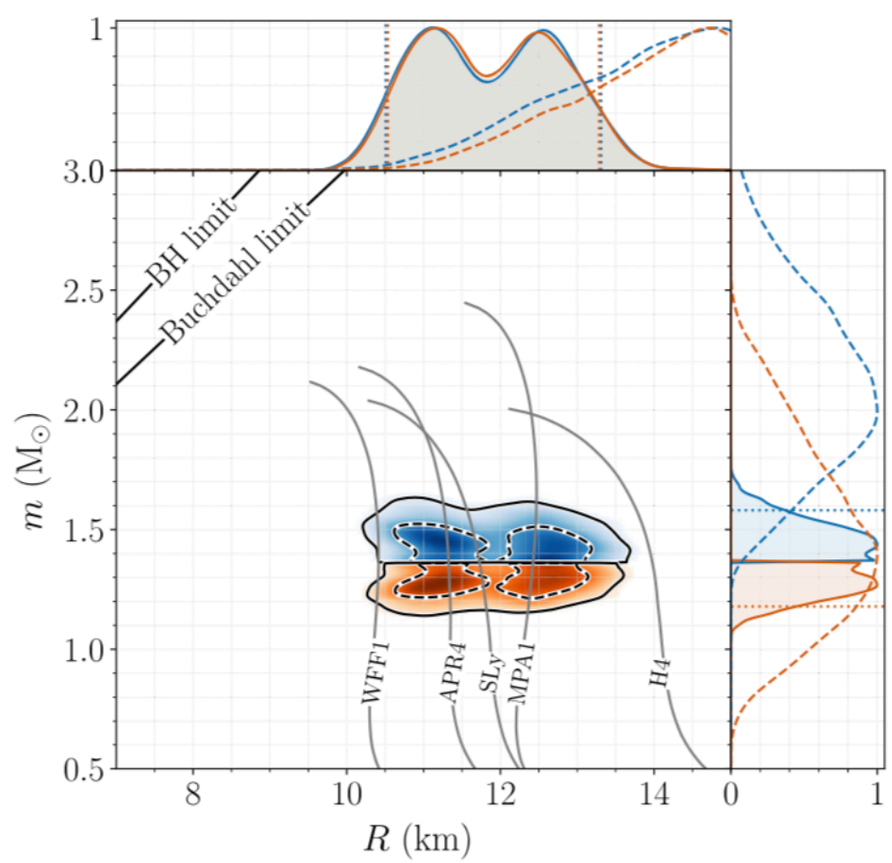
Neutron star radii

C. Capano et al., arXiv:1908.10352 (2019)

$$R_{1.4M_\odot} = 11.0^{+0.9}_{-0.6}\ km$$



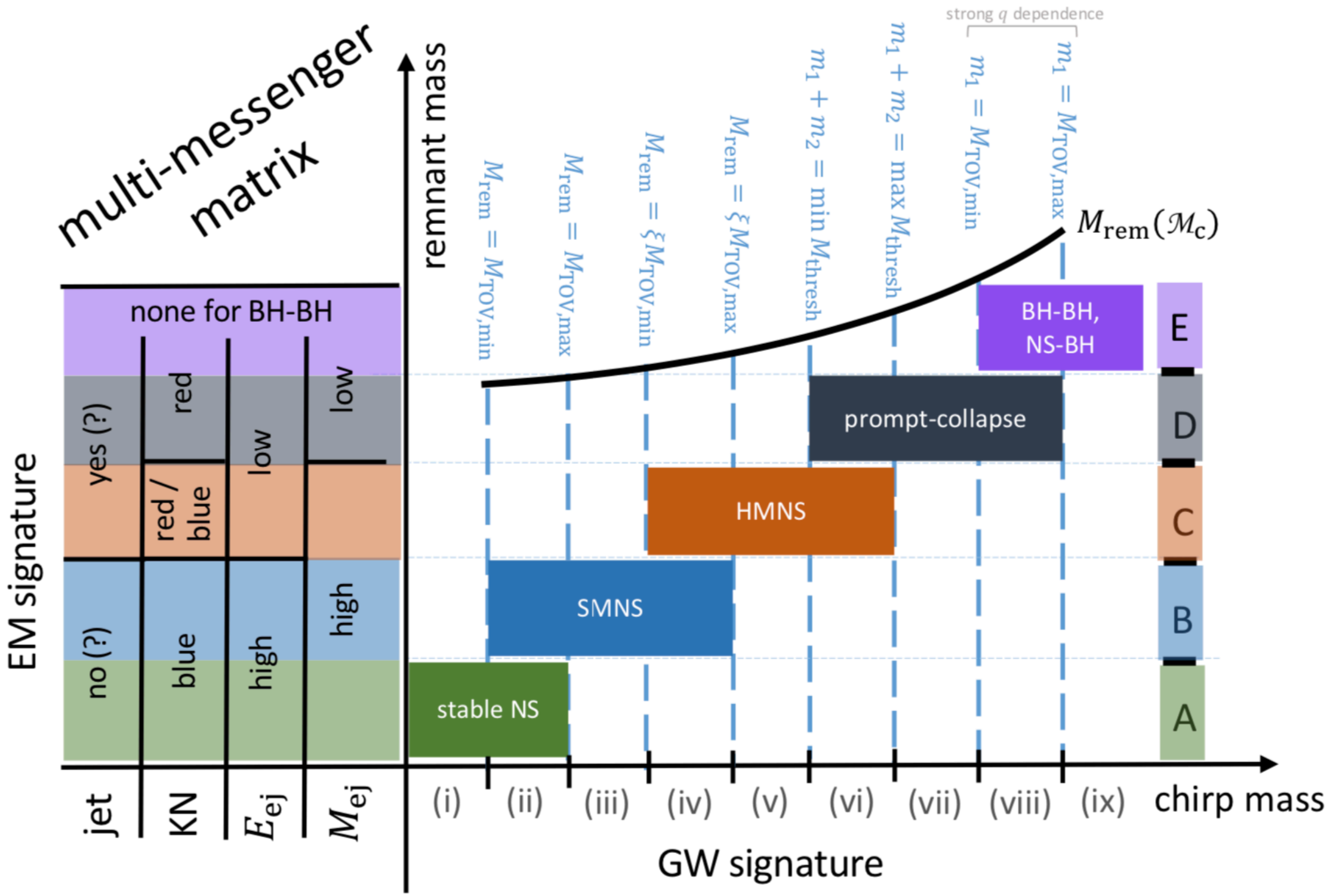




LIGO Scientific and Virgo Collaborations, Phys. Rev. Lett. 121, 161101 (2018)

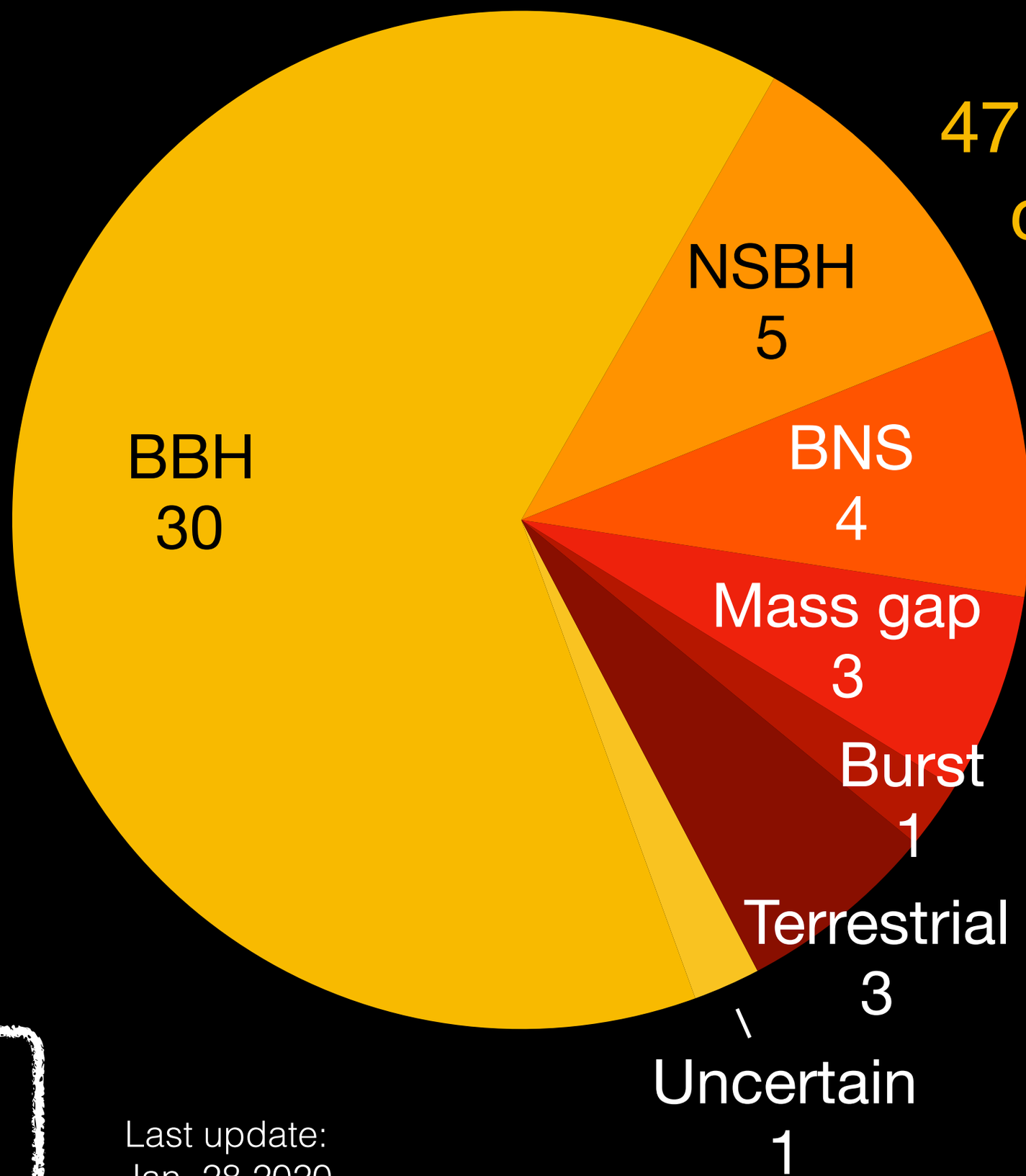
Host galaxy: NGC 4993

Multi-messenger matrix



B. Margalit et al., arXiv:1904.11995 (2019)

O3 status (GraceDB)

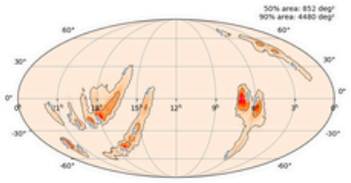
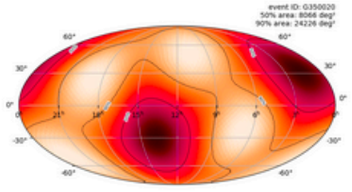
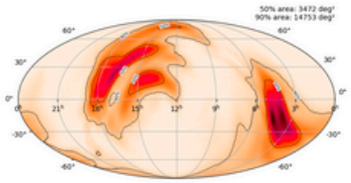
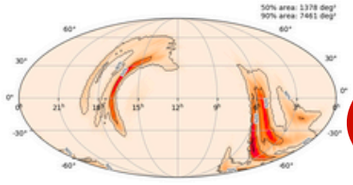


47 un-retracted candidates

22 retracted candidates

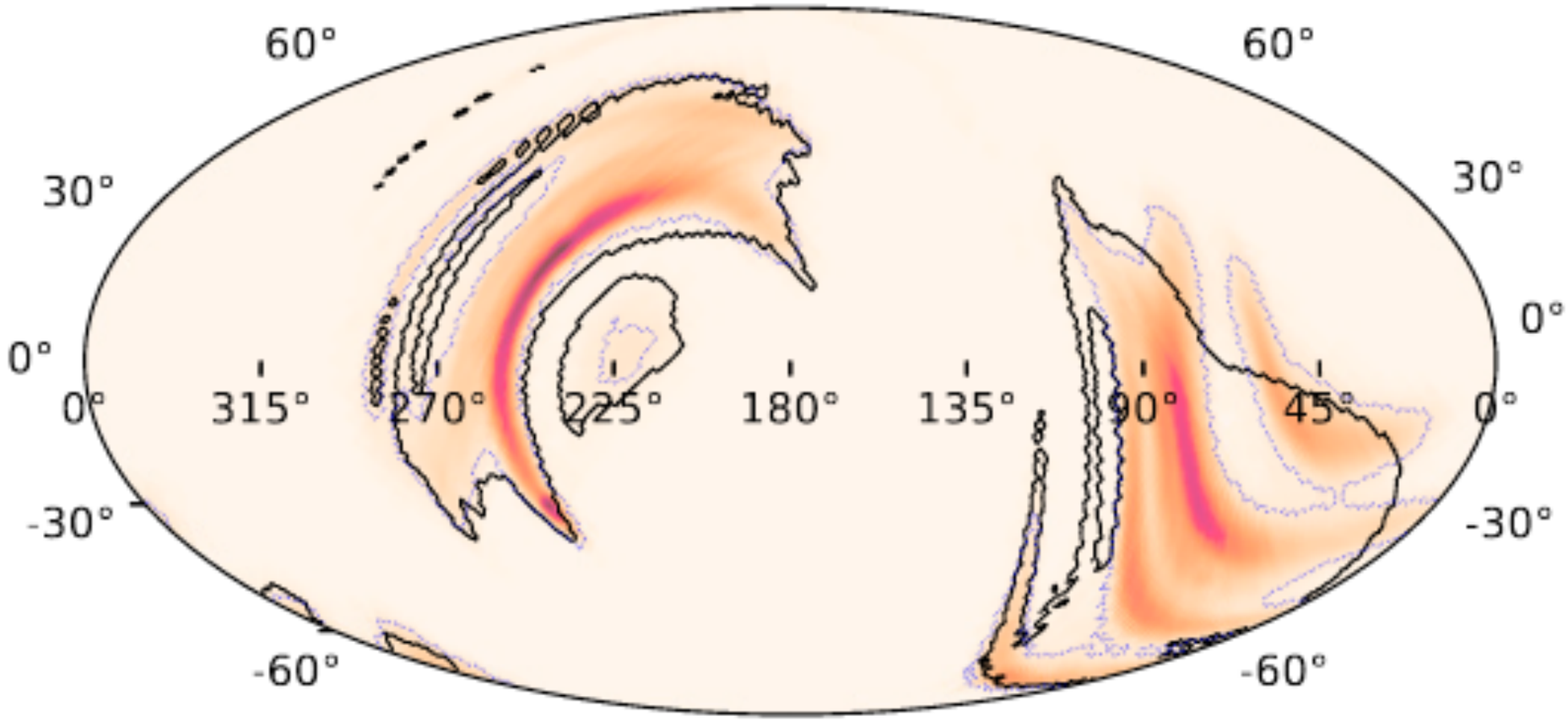
Last update:
Jan. 28 2020

BNS candidates in O3

HLV S191213g	BNS (77%), Terrestrial (23%)	Dec. 13, 2019 04:34:08 UTC	GCN Circulars Notices | VOE		1.1197 per year
L S190910h	BNS (61%), Terrestrial (39%)	Sept. 10, 2019 08:29:58 UTC	GCN Circulars Notices | VOE		1.1312 per year
LV S190901ap	BNS (86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE		1 per 4.5093 years
LV S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years

GW190425

LIGO Scientific and Virgo Collaborations, arXiv:2001.01761 (2020)



	Low-spin prior ($\chi < 0.05$)	High-spin prior ($\chi < 0.89$)
Primary mass m_1	$1.62-1.88\,M_\odot$	$1.61-2.52\,M_\odot$
Secondary mass m_2	$1.45-1.69\,M_\odot$	$1.12-1.68\,M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}\,M_\odot$	$1.44^{+0.02}_{-0.02}\,M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}\,M_\odot$	$1.4873^{+0.0008}_{-0.0006}\,M_\odot$
Mass ratio m_2/m_1	$0.8-1.0$	$0.4-1.0$
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}\,M_\odot$	$3.4^{+0.3}_{-0.1}\,M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.013^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	161^{+67}_{-73} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 600	≤ 1100

GW190425

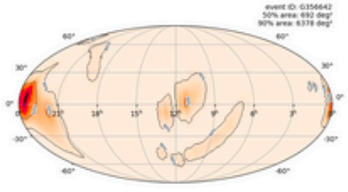
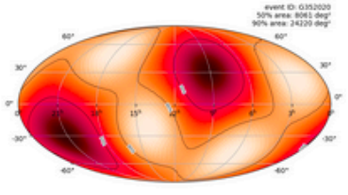
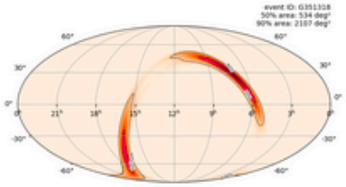
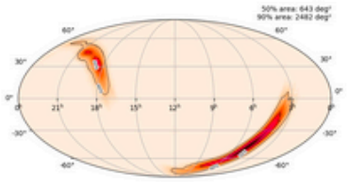
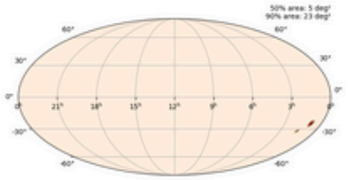
LIGO Scientific and Virgo Collaborations, arXiv:2001.01761 (2020)

GW170817

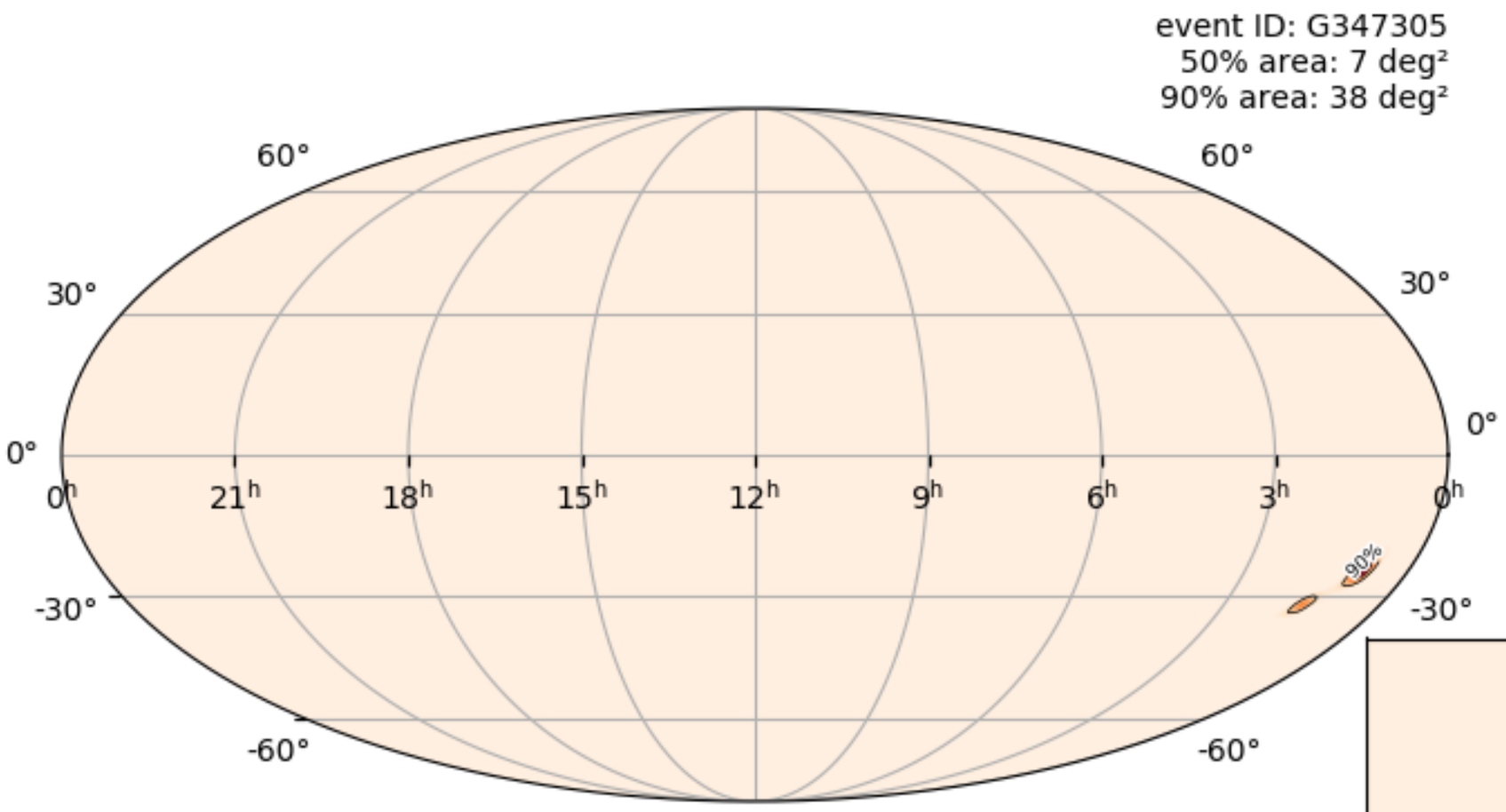
	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

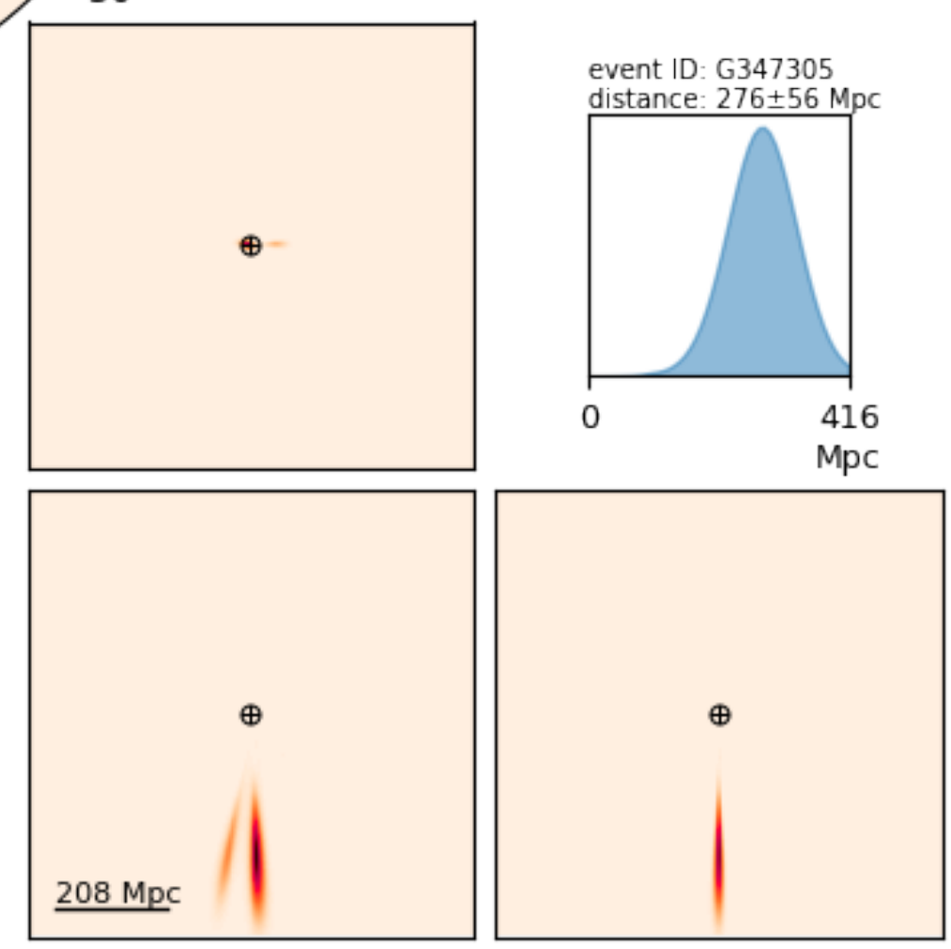
	Low-spin prior ($\chi < 0.05$)	High-spin prior ($\chi < 0.89$)
Primary mass m_1	$1.62 - 1.88\, M_\odot$	$1.61 - 2.52\, M_\odot$
Secondary mass m_2	$1.45 - 1.69\, M_\odot$	$1.12 - 1.68\, M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}\, M_\odot$	$1.44^{+0.02}_{-0.02}\, M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}\, M_\odot$	$1.4873^{+0.0008}_{-0.0006}\, M_\odot$
Mass ratio m_2/m_1	$0.8 - 1.0$	$0.4 - 1.0$
Total mass $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}\, M_\odot$	$3.4^{+0.3}_{-0.1}\, M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.013^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	161^{+67}_{-73} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 600	≤ 1100

NSBH candidates in O3

HLV S191205ah	NSBH (93%), Terrestrial (7%)	Dec. 5, 2019 21:52:08 UTC	GCN Circulars Notices | VOE		1 per 2.5383 years
L S190930t	NSBH (74%), Terrestrial (26%)	Sept. 30, 2019 14:34:07 UTC	GCN Circulars Notices | VOE		1 per 2.0536 years
HL S190923y	NSBH (68%), Terrestrial (32%)	Sept. 23, 2019 12:55:59 UTC	GCN Circulars Notices | VOE		1.5094 per year
HL S190910d	NSBH (98%), Terrestrial (2%)	Sept. 10, 2019 01:26:19 UTC	GCN Circulars Notices | VOE		1 per 8.5248 years
HLV S190814bv	NSBH (>99%)	Aug. 14, 2019 21:10:39 UTC	GCN Circulars Notices | VOE		1 per 1.559e+25 years

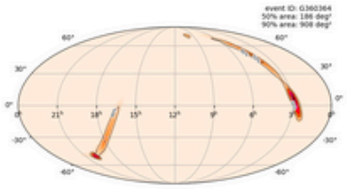
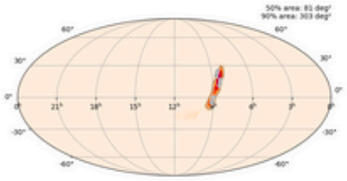
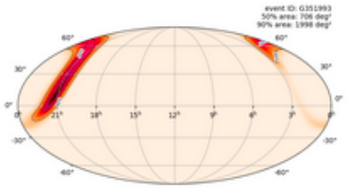
NSBH candidates in O3

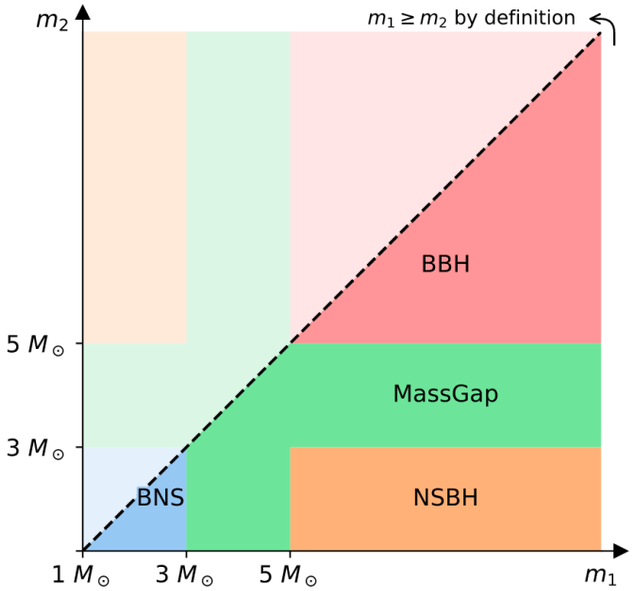




See talk by Nicholas Vieira on EM follow-up later today

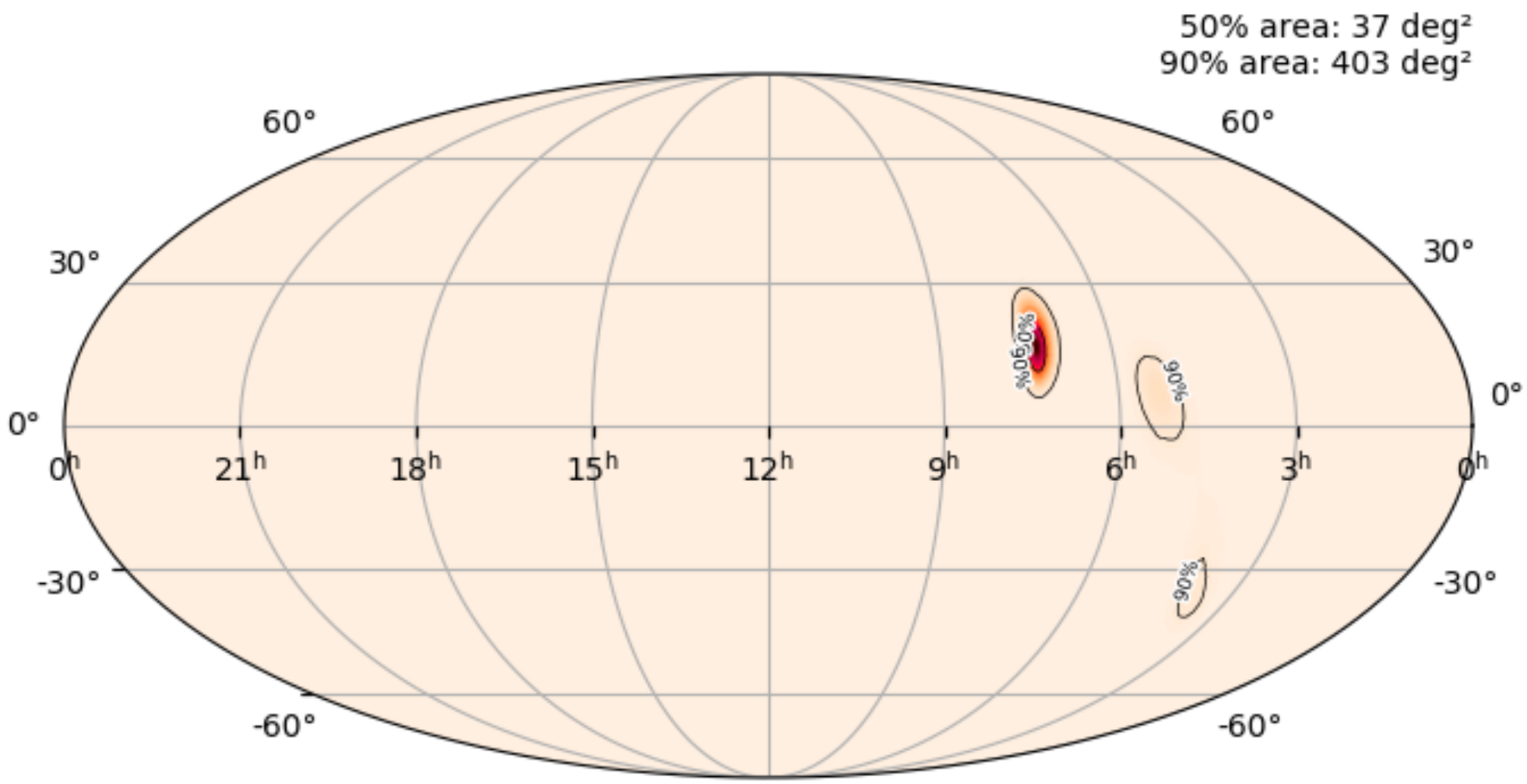
Mass gap candidates in O3

HLV S200115j	MassGap (>99%)	Jan. 15, 2020 04:23:09 UTC	GCN Circulars Notices | VOE		1 per 1513 years
HLV S190924h	MassGap (>99%)	Sept. 24, 2019 02:18:46 UTC	GCN Circulars Notices | VOE		1 per 3.5493e+10 years
HL S190930s	MassGap (95%), Terrestrial (5%)	Sept. 30, 2019 13:35:41 UTC	GCN Circulars Notices | VOE		1 per 10.534 years

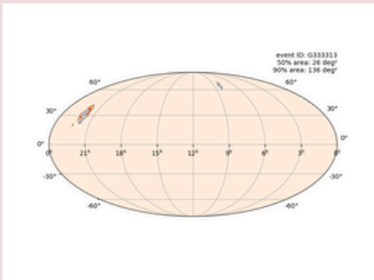


Burst candidate in O3

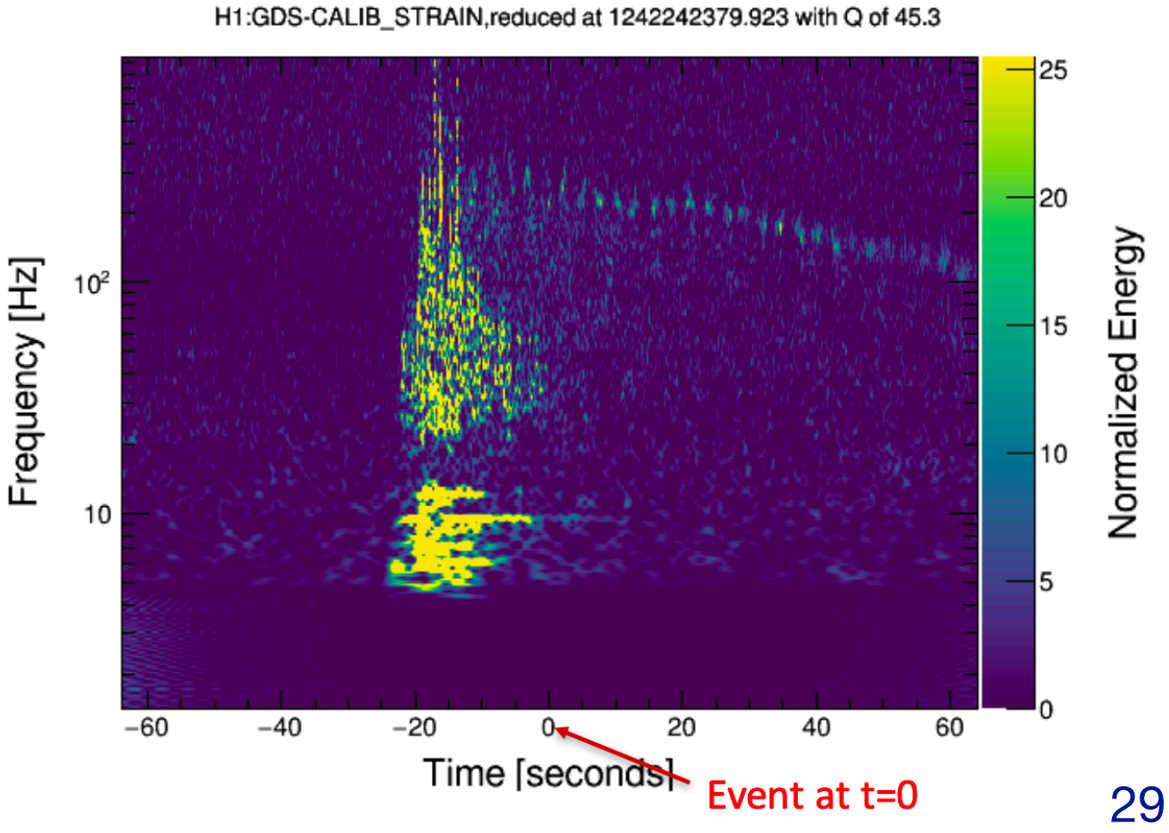
S200114f
HLV: FAR 1 per 25 years



Example retraction: S190518bb

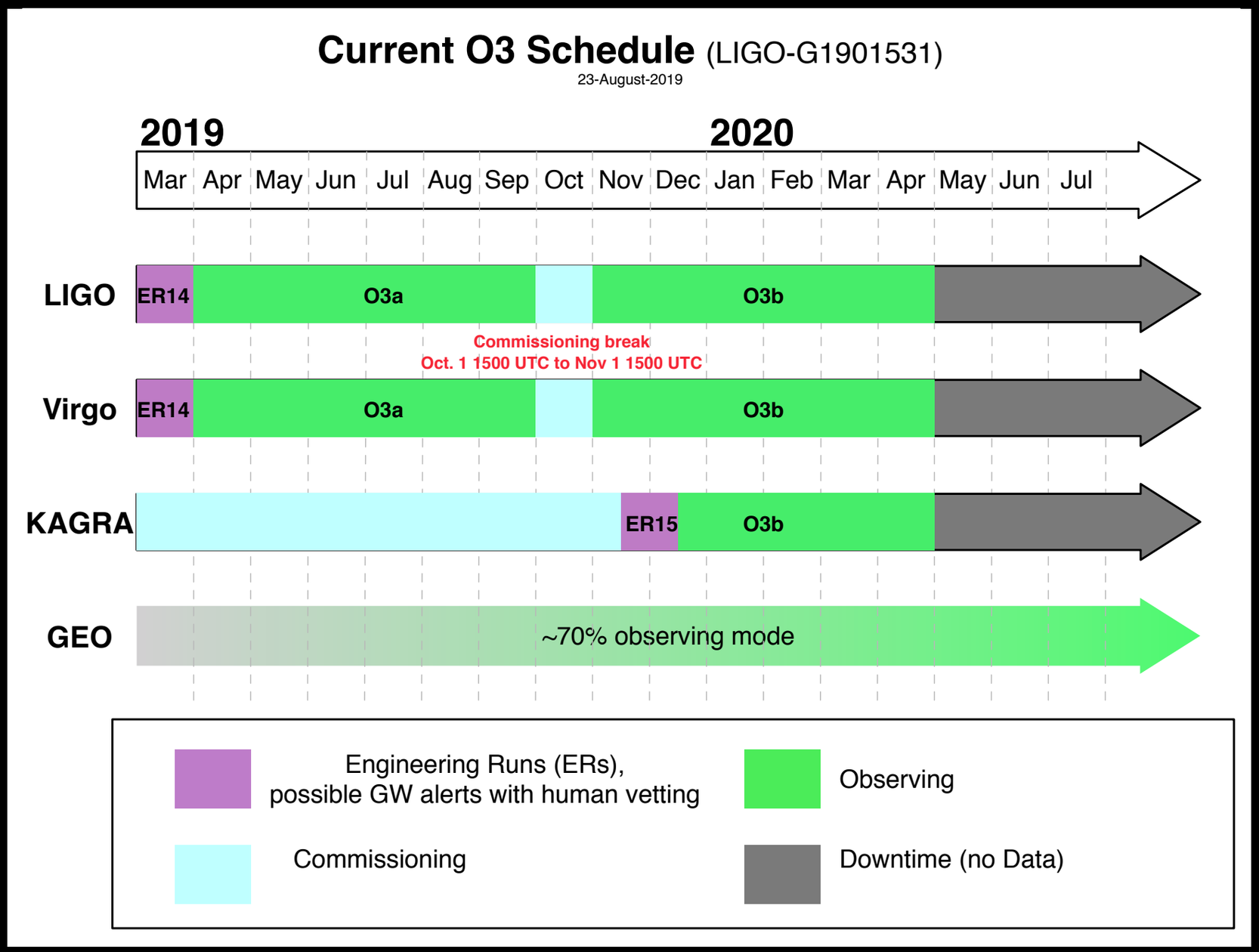
S190518bb	BNS (75%), Terrestrial (25%)	May 18, 2019 19:19:19 UTC	GCN Circulars Notices | VOE		1 per 3.1557 years	RETRACTED

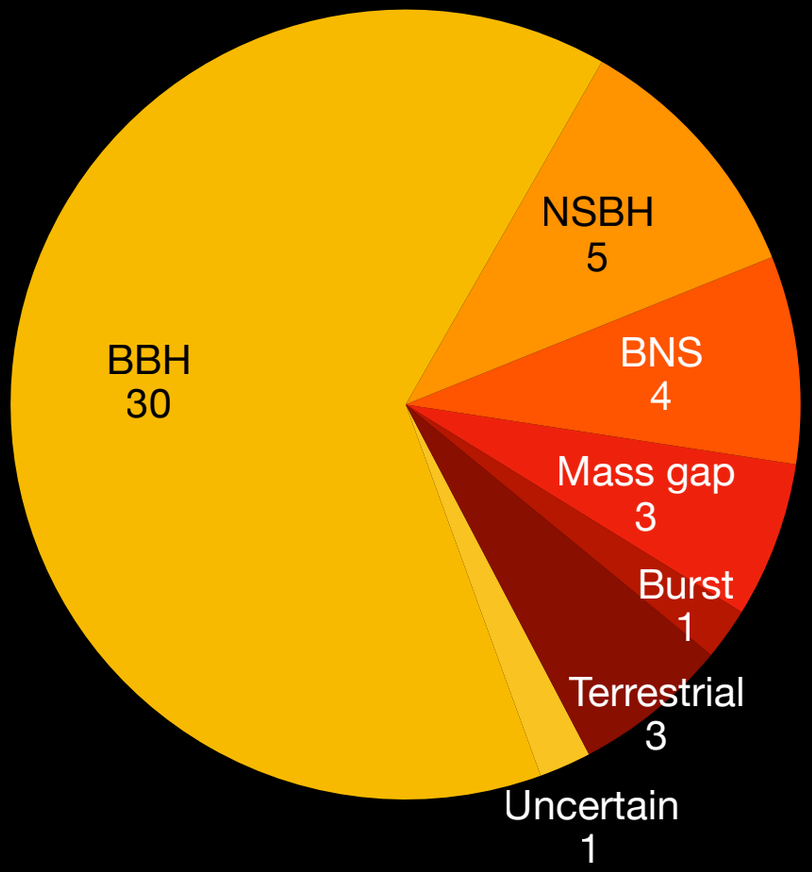
```
//////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  24591
SUBJECT: LIGO/Virgo S190518bb: Retraction of GW compact binary merger candidate
DATE:    19/05/18 20:08:37 GMT
FROM:    Geoffrey Mo at LIGO  <geoffrey.mo@ligo.org>

 The LIGO Scientific Collaboration and the Virgo Collaboration report:

The trigger S190518bb is no longer considered to be a gravitational
wave signal.

The data in LIGO-Hanford was highly non-stationary leading up to the
reported trigger time.
//////////////////////////////////////////////////////////////////////
```



LIGO DCC: G1900994

O3 status (GraceDB)





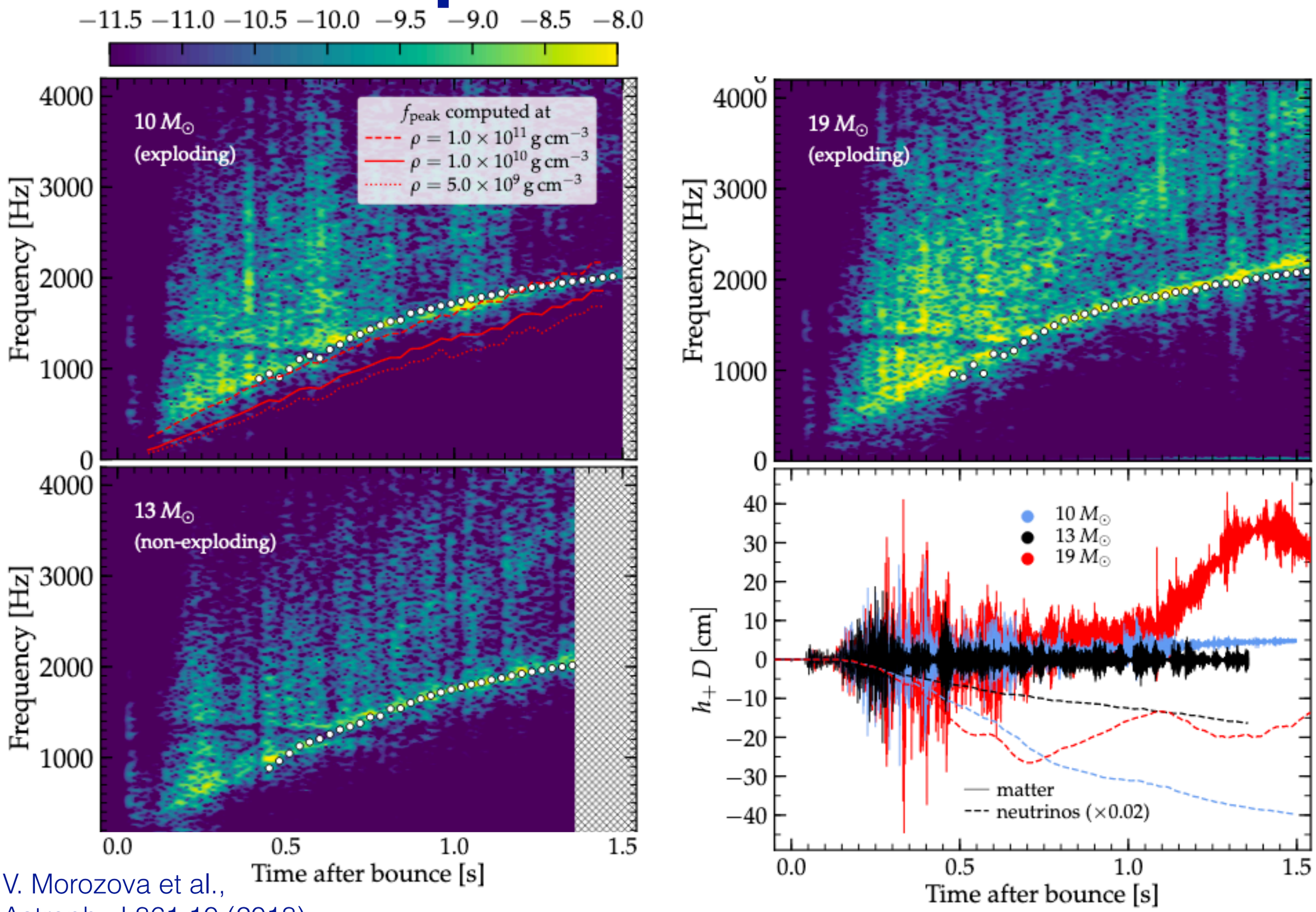
Thank you

THE UNIVERSITY OF BRITISH COLUMBIA

Canadian multi-messenger astrophysics workshop

McGill University

Supernova GWs



V. Morozova et al., Astroph. J 861:10 (2018)