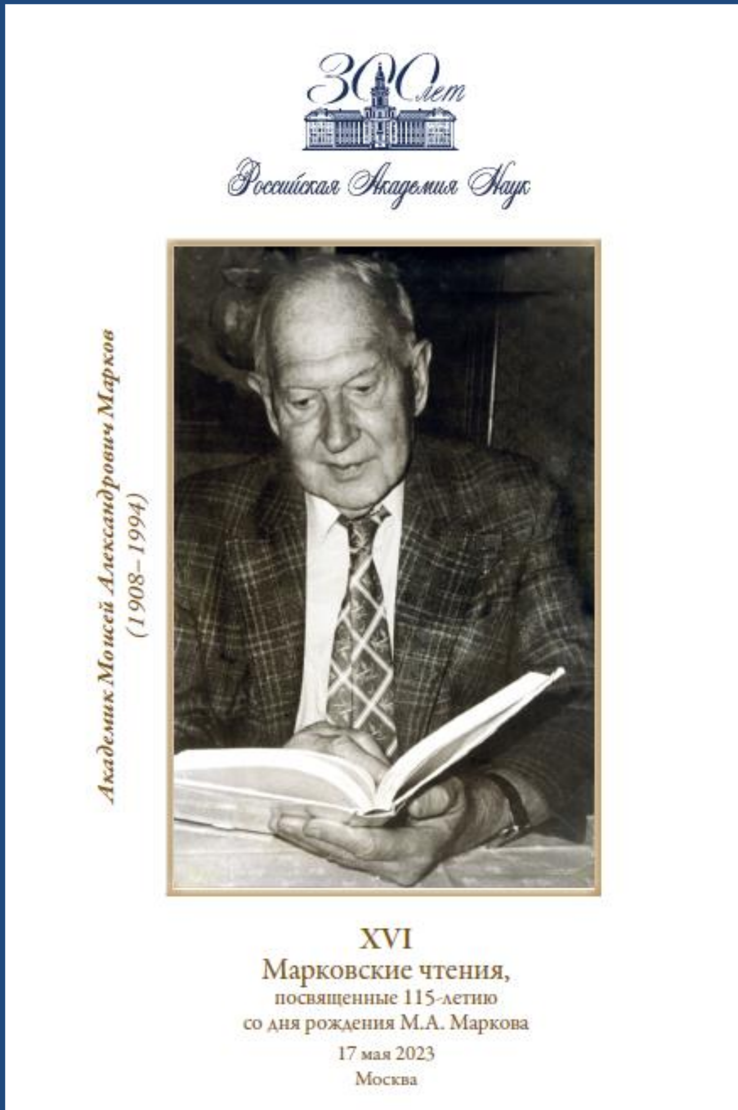


Астрофизические проявления первичных черных дыр

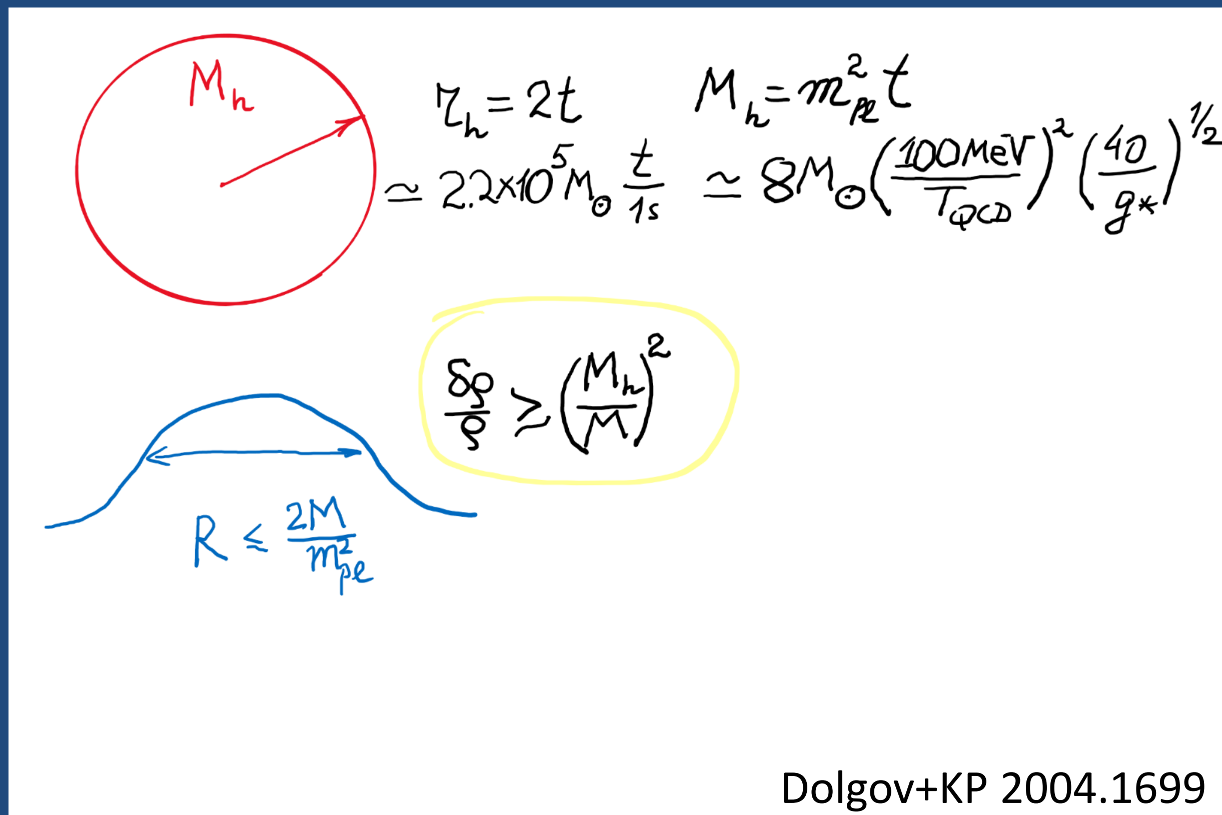
Константин Постнов
ГАИШ МГУ

Plan

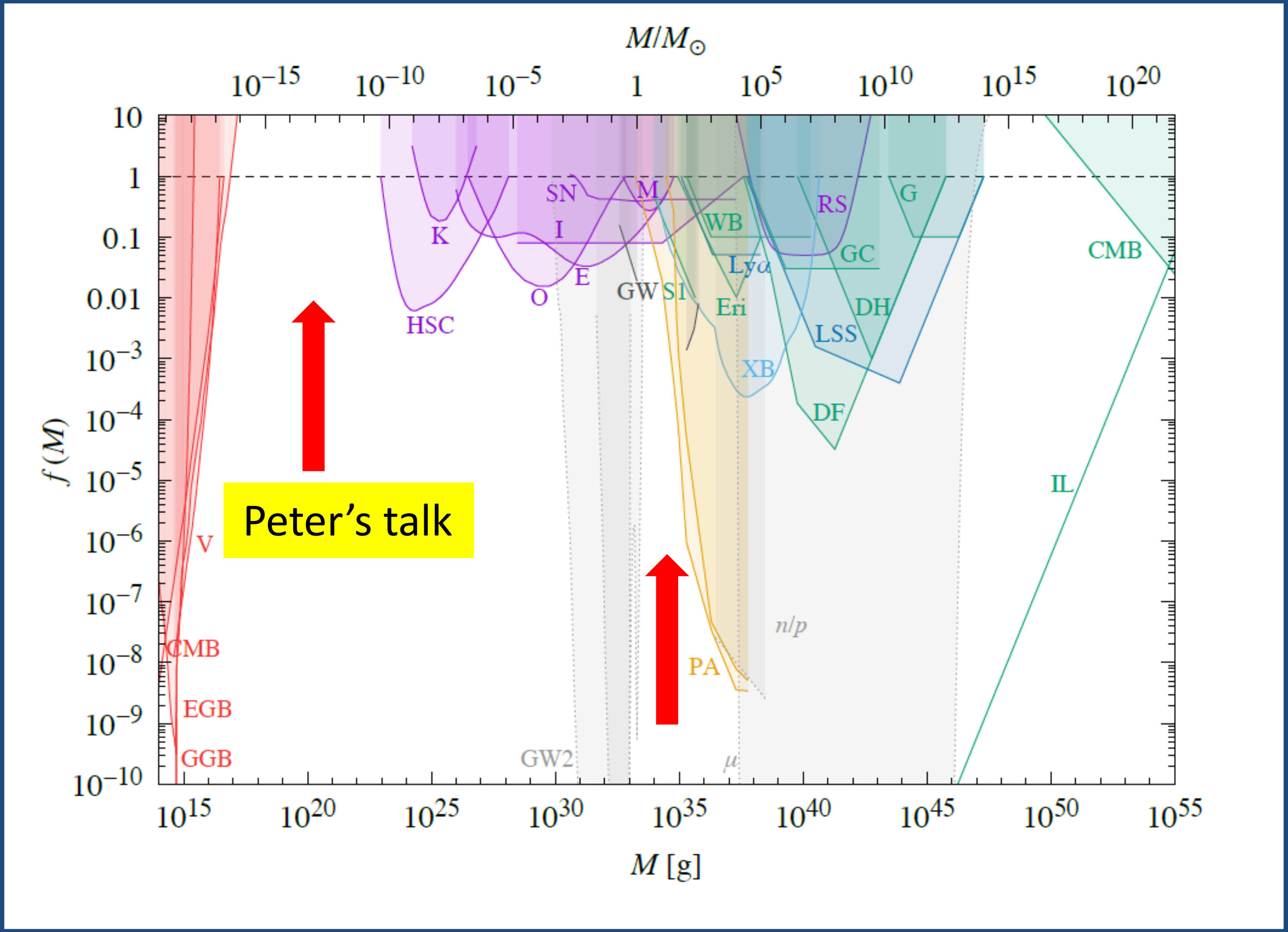
- Introduction
- PBH in LVK GWTC-3 data
- PBH as seeds of SMBH in early galaxies

PBH formation

Zeldovich, Novikov’67, Carr, Hawking’74….



PBH constraints (model-dependent)



Carr+ 2002.12778

Some PBH formation scenarios

- Primordial density fluctuations, $\delta>\delta_c\sim0.45$ (model-dependent)
- Collapse of scale-invariant fluctuations ➔ power-law mass spectra $dn/dM\sim M^{-\alpha}$, $\alpha=2(1+2w)/(1+w) = 2.5$ at RD ($w=1/3$)
- Inflationary models ➔ log-normal mass spectrum

$$\frac{dn}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_{max})\right]$$

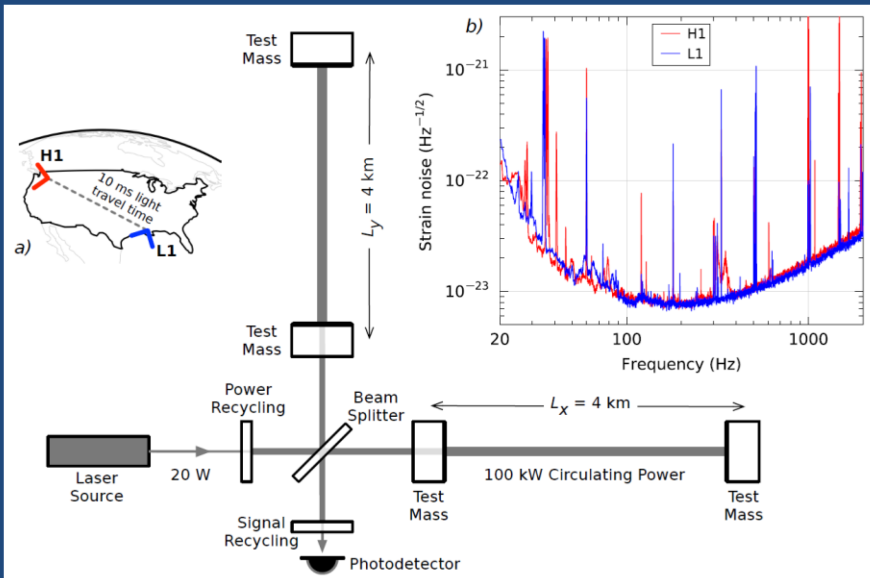
(Dolgov, Silk 1993)

- QCD phase transition at T=100-200 MeV:

$$M \sim \left(\frac{m_{Pl}}{m_p}\right)^3 m_p \sim M_{Ch} \simeq 1 M_{\odot}$$

- Bubble collisions, cosmic strings …

I. PBH in GW observations



Laser interferometers

LIGO 1990-2017 ~690 MUSD

LIGO
Hanford
USA

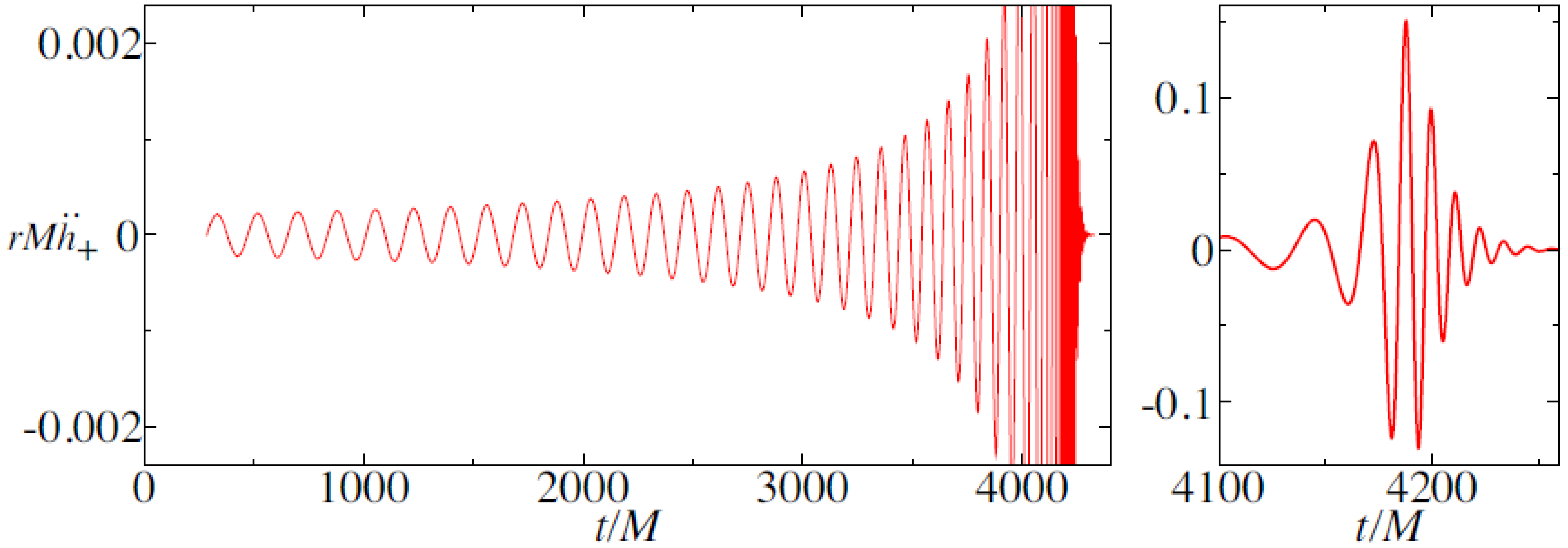
KAGRA
Kamioka
Japan

Virgo
Pisa
Italy

LIGO
Livingston
USA

Credit: LVC collab., Univ. of Tokyo

Chirp signal from coalescing binary system



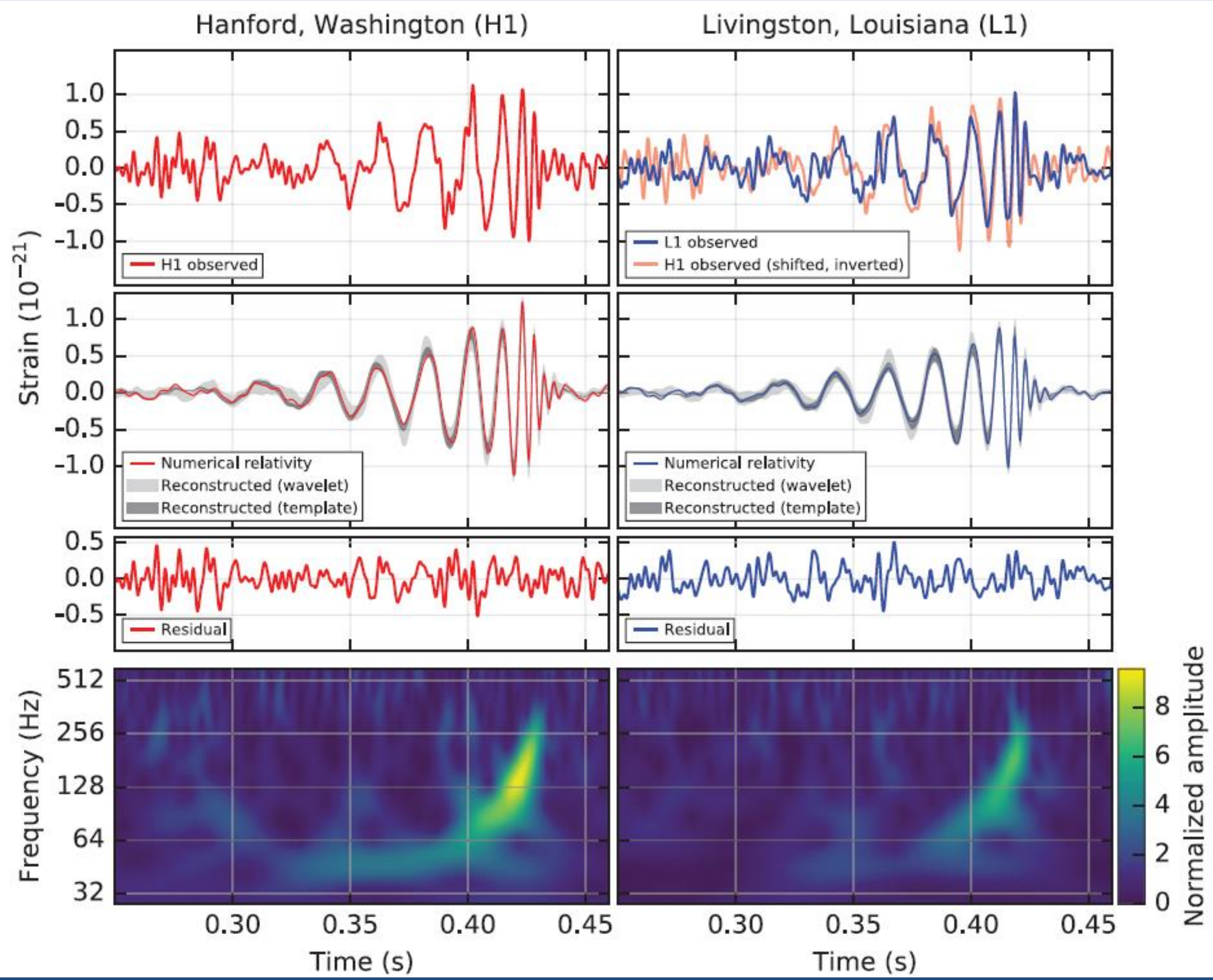
$$h_+ = h^{TT}_{\hat\theta\hat\theta} = \frac{2}{r}[\ddot{I}_{\hat\theta\hat\theta}(t-r)]^{TT} = -2(1+\cos^2\theta)\,\frac{\mu(M\Omega)^{2/3}}{r}\cos[2(\Omega t - \Omega r - \phi)]$$

$$h_\times = h^{TT}_{\hat\theta\hat\phi} = \frac{2}{r}[\ddot{I}_{\hat\theta\hat\phi}(t-r)]^{TT} = -4\cos\theta\,\frac{\mu(M\Omega)^{2/3}}{r}\sin[2(\Omega t - \Omega r - \phi)]\,.$$

GW150914

PRL 116, 061102 (2016)

35-350 Hz bandpass filter applied



Chirp signal from inspiraling binaries

- Chirp-mass determined inspiraling signal

$$M_{ch} = (\mu^3 M^2)^{1/5}$$

$$h \sim M_{ch}^{5/3} f^{2/3} / r$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right)^{3/5}$$

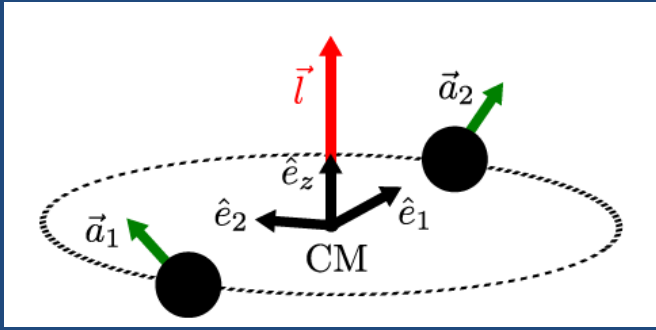
Parameters from GW observations

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$$

Chirp mass

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot\hat{L}_N}{M}$$

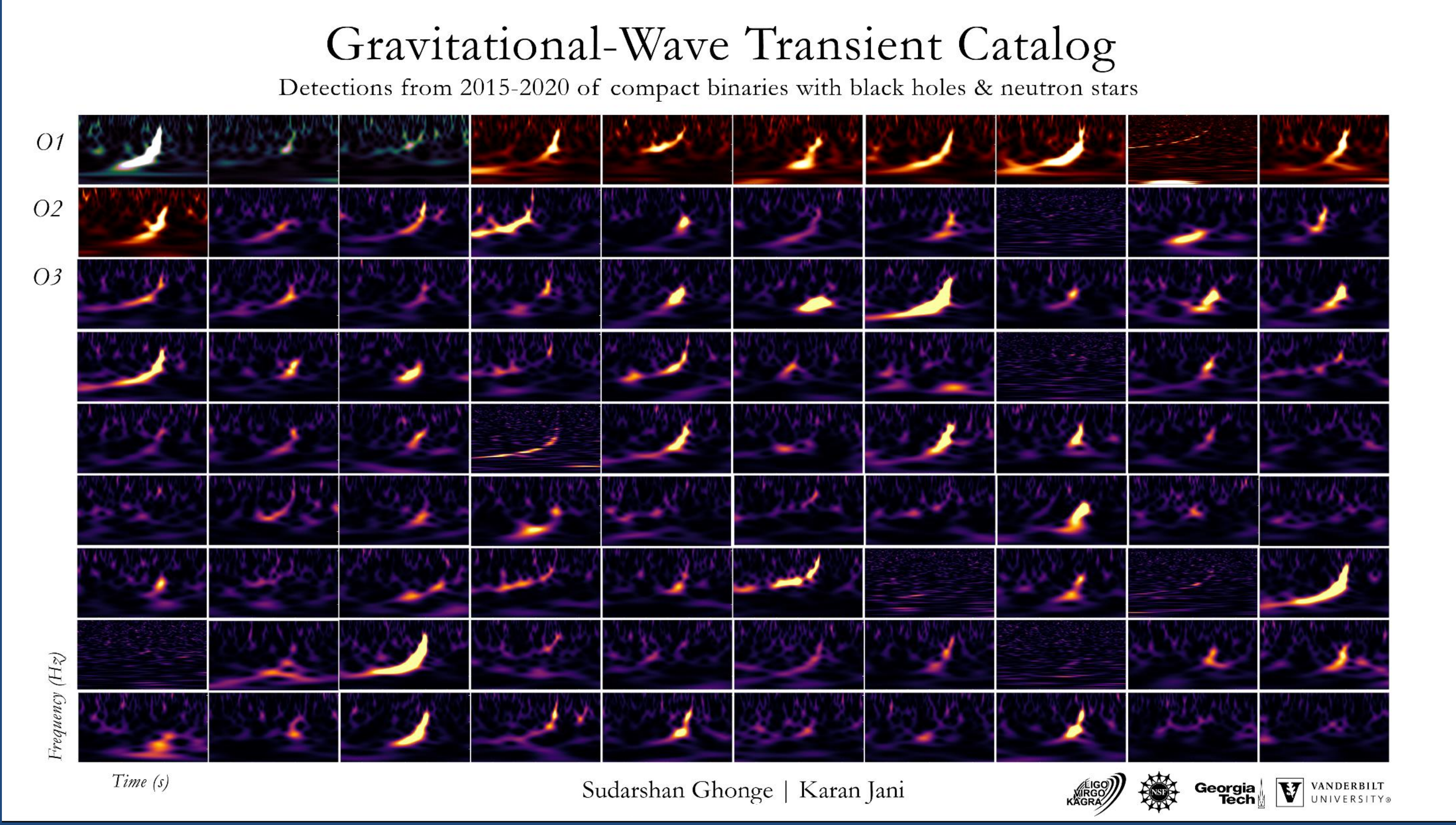
Effective spin

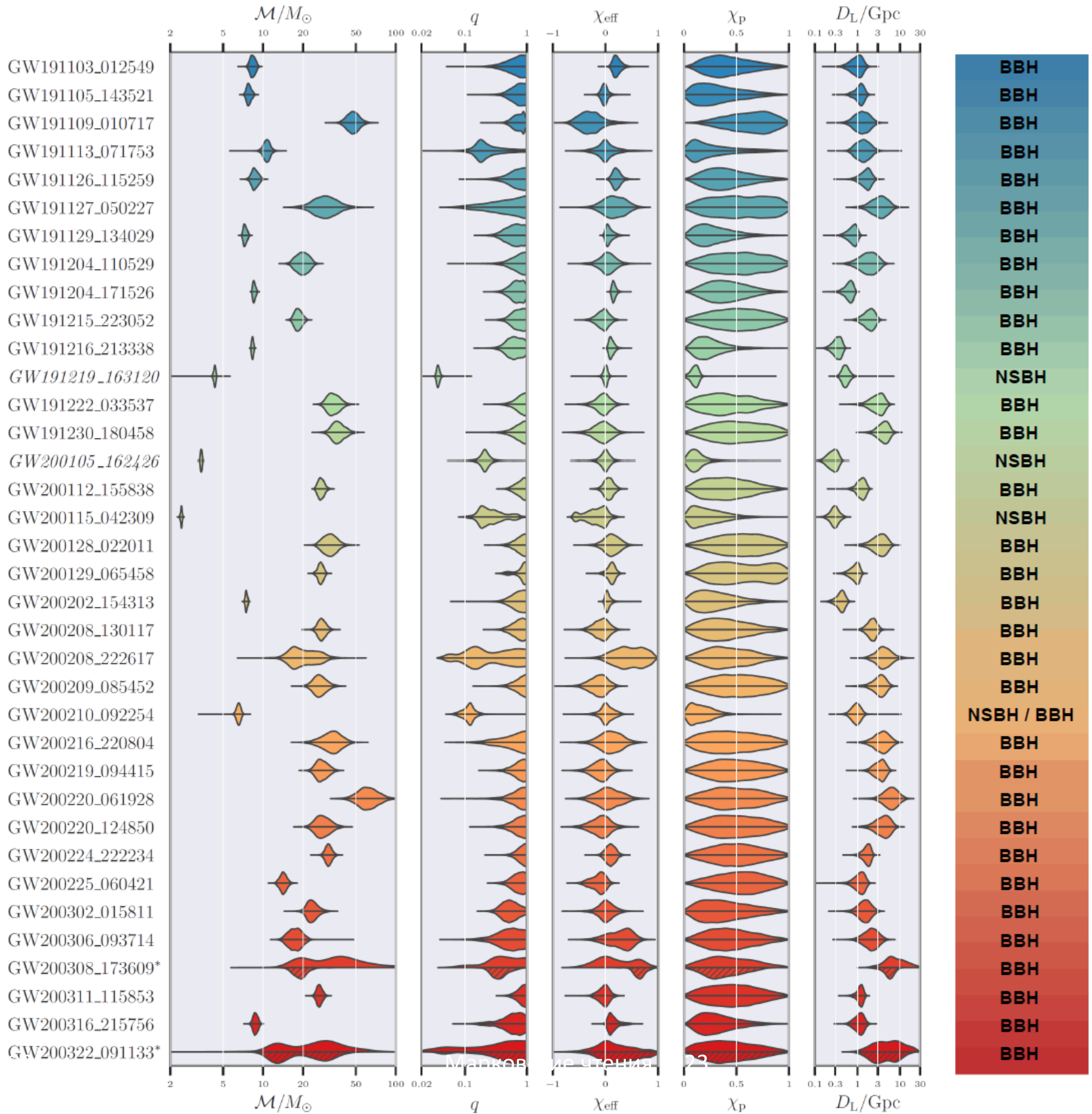


Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
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	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	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

1811.12907

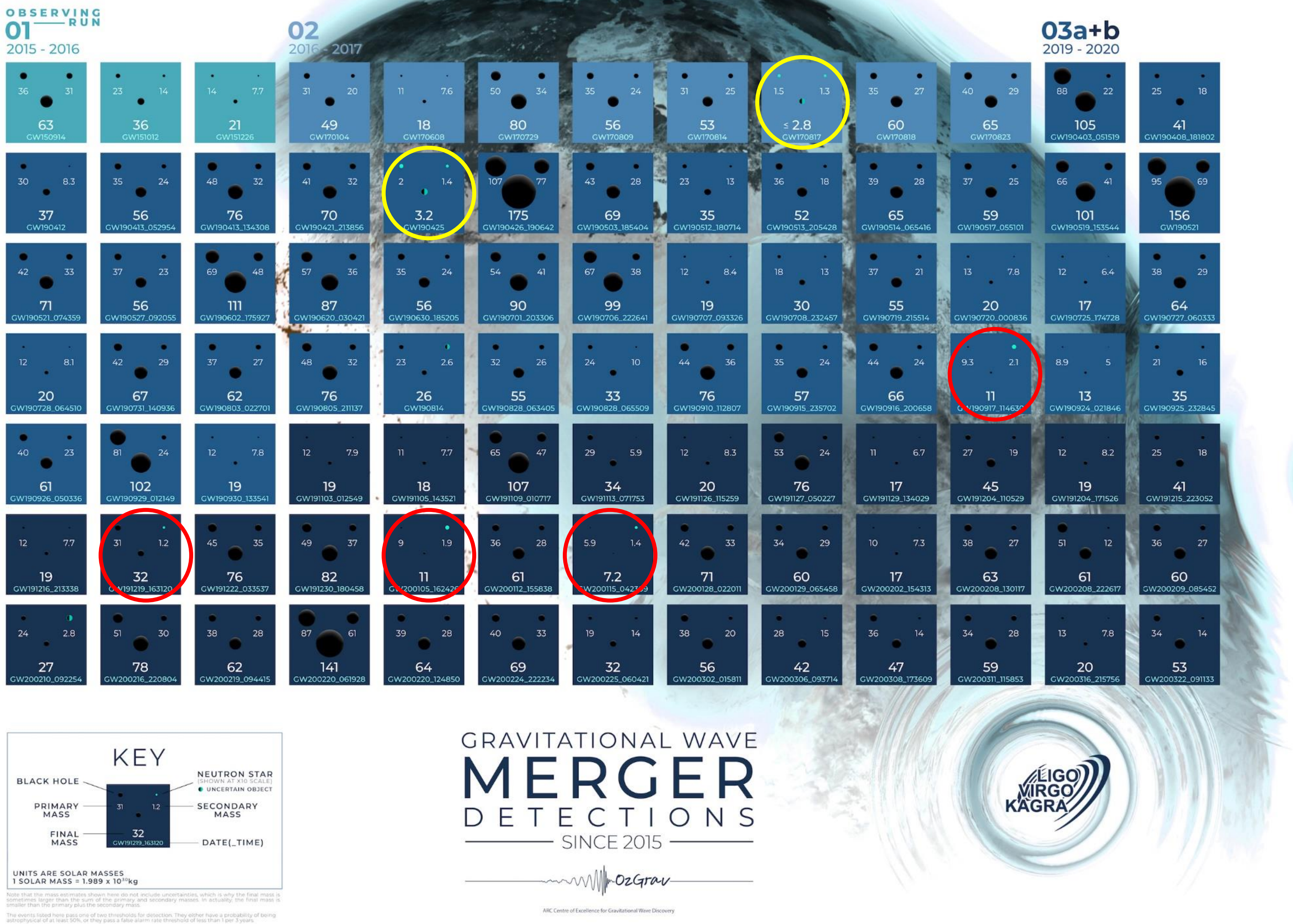
Coalescing binaries LIGO/Virgo





$\mathcal{M}/M_\odot$
q
$\chi_{\rm eff}$
$\chi_{\rm p}$
$D_{\rm L}/{\rm Gpc}$
GW191103_012549 BBH
GW191105_143521 BBH
GW191109_010717 BBH
GW191113_071753 BBH
GW191126_115259 BBH
GW191127_050227 BBH
GW191129_134029 BBH
GW191204_110529 BBH
GW191204_171526 BBH
GW191215_223052 BBH
GW191216_213338 BBH
GW191219_163120 NSBH
GW191222_033537 BBH
GW191230_180458 BBH
GW200105_162426 NSBH
GW200112_155838 BBH
GW200115_042309 NSBH
GW200128_022011 BBH
GW200129_065458 BBH
GW200202_154313 BBH
GW200208_130117 BBH
GW200208_222617 BBH
GW200209_085452 BBH
GW200210_092254 NSBH / BBH
GW200216_220804 BBH
GW200219_094415 BBH
GW200220_061928 BBH
GW200220_124850 BBH
GW200224_222234 BBH
GW200225_060421 BBH
GW200302_015811 BBH
GW200306_093714 BBH
GW200308_173609* BBH
GW200311_115853 BBH
GW200316_215756 BBH
GW200322_091133* BBH

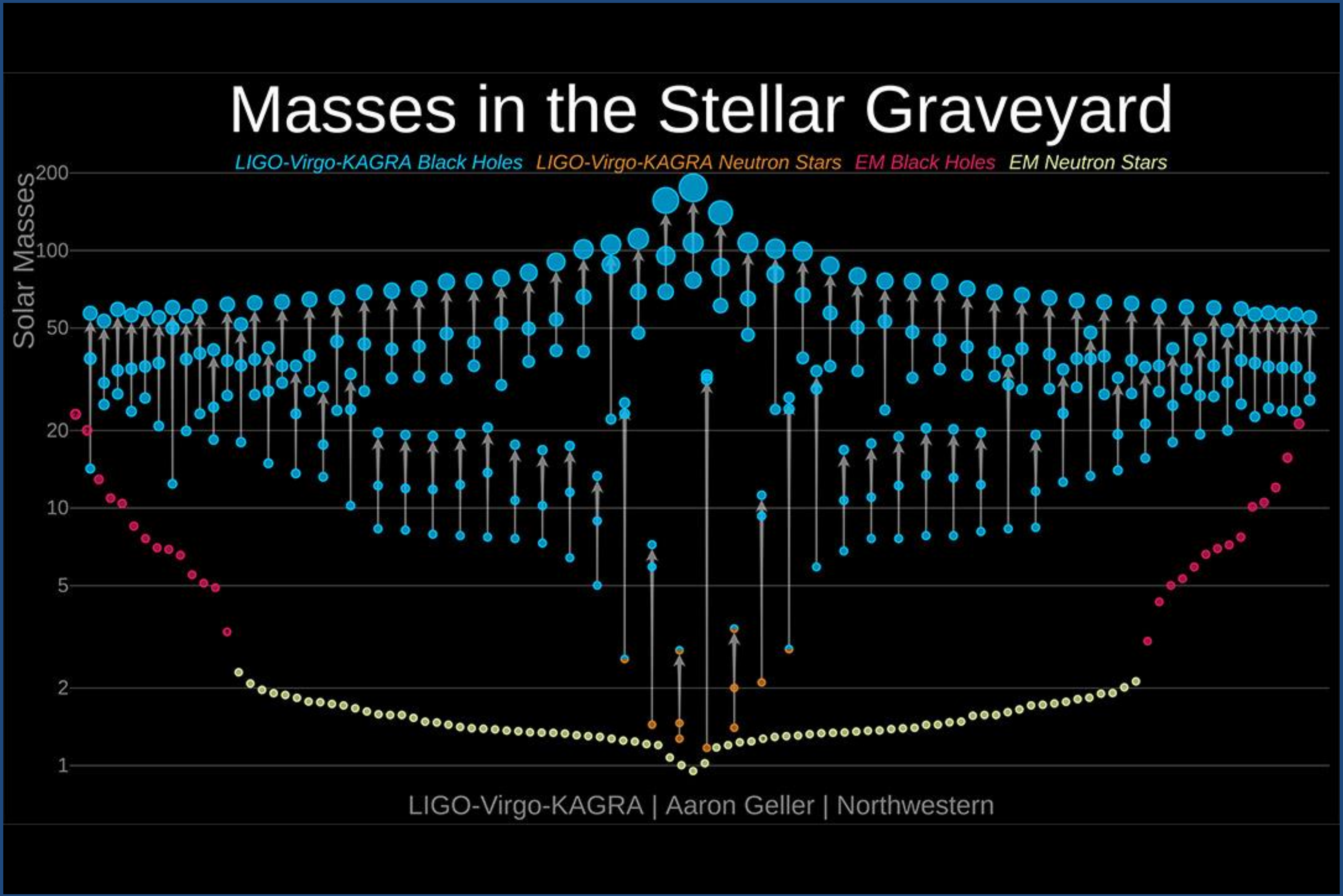
LIGO



OBSERVING RUN
O1
2015 - 2016
O2
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤ 2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 190917_11463
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 200105_16242
36 28 61 GW200112_155838
5.9 1.4 7.2 W200115_042
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
KEY
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
31 1.2 32 GW191219_163120
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^30 kg
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery
LIGO VIRGO KAGRA

Statistical properties: summary

- O1+O2+O3: 91 robust (S/N>8) detections
- Isotropic on the sky (2207.05792)
- Signal properties in agreement with GR up to a few % accuracy
- 2 NS+NS mergings, EM from GW 170817
- 4 BH+NS candidates. No electromagnetic signals.


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Exceptional BHBH mergers

- GW 190814, M_1=26 , q=0.112, M_2=2.6 in lower mass gap? NS? Strange quark star? Outlier population? Formation from a triple star? Formation in AGN disk? Primordial BH?
- GW190521 $m_1 = 85^{+21}_{-14}\,\mathrm{M}_\odot$ $m_2 = 66^{+17}_{-18}\,\mathrm{M}_\odot$n upper mass gap (60-120), large effective spin $\chi_{1,2} \sim 0.1\text{–}0.9)$

  (Or even $m_1 = 168^{+15}_{-61}\,\mathrm{M}_\odot$ $m_2 = 66^{+33}_{-3}\,\mathrm{M}_\odot$??)

Repeated meggers in stellar clusters or AGN disks?? Primordial BH?

- GW190412 $m_1 = 30.1^{+4.6}_{-5.3}\,\mathrm{M}_\odot$ $m_2 = 8.3^{+1.6}_{-0.9}\,\mathrm{M}_\odot$ high spin $\chi_1 = 0.44^{+0.16}_{-0.22}$

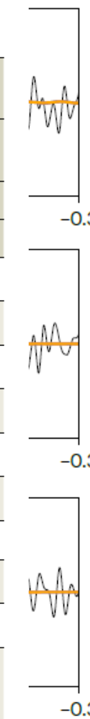
➔ Hierarchical merger?

GW190521 as hyperbolic encounter of non-spinning BHs?

Table 1 | Source parameters of GW190521 with median values and 90% credible intervals quoted and natural logarithms reported

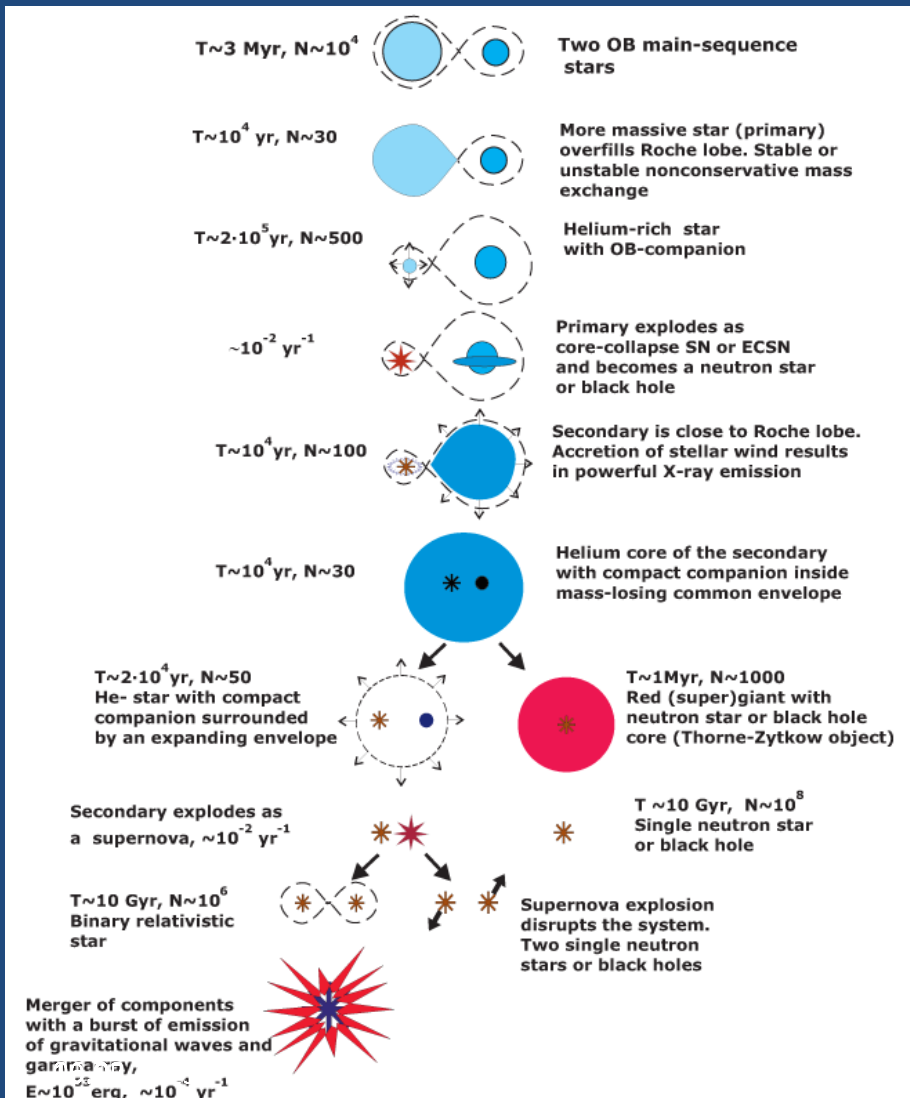
Reference[a]	This paper					LVK[4]	Gayathri et al.[15]	Romero-Shaw et al.[16]
Waveform	TEOBResumS[30,31]	TEOBResumS[30,31]	TEOBResumSP[44b]	NRSur7dq4 (ref.[42])	NRSur7dq4 (ref.[42])	NRSur7dq4 (ref.[42])	NR[47]	SEOBNRE[52]
E_0 prior	Unconstrained (UE_0)	Constrained (CE_0)	–	–	–	–	–	
Multipoles	$(\ell,\|m\|)=(2,2)$	$(\ell,\|m\|)=(2,2)$	$(\ell,\|m\|)=(2,2)$	$(\ell,\|m\|)=(2,2)$	$\ell\leq4$	$\ell\leq4$	–	–
$m_1\,(M_\odot)$	85^{+88}_{-22}	81^{+62}_{-25}	90^{+19}_{-14}	102^{+35}_{-23}	84^{+17}_{-12}	85^{+21}_{-14}	102^{+7}_{-11}	92^{+26}_{-16}
$m_2\,(M_\odot)$	59^{+18}_{-37}	52^{+32}_{-32}	66^{+10}_{-8}	64^{+19}_{-25}	71^{+16}_{-18}	66^{+17}_{-18}	102^{+7}_{-11}	69^{+18}_{-19}
$M_{source}\,(M_\odot)$[c]	151^{+73}_{-51}	130^{+75}_{-43}	156^{+25}_{-15}	164^{+40}_{-23}	153^{+29}_{-19}	150^{+29}_{-17}	–	–
$m_2/m_1\leq1$	$0.69^{+0.27}_{-0.52}$	$0.63^{+0.31}_{-0.43}$	$0.73^{+0.21}_{-0.15}$	$0.62^{+0.32}_{-0.30}$	$0.86^{+0.12}_{-0.30}$	$0.79^{+0.19}_{-0.29}$	–	–
χ_{eff}[d]	–	–	$-0.05^{+0.09}_{-0.12}$	$0.01^{+0.24}_{-0.26}$	$-0.03^{+0.25}_{-0.26}$	$0.08^{+0.27}_{-0.36}$	0	$0.0^{+0.2}_{-0.2}$
χ_p[e]	–	–	$0.72^{+0.16}_{-0.22}$	$0.71^{+0.22}_{-0.36}$	$0.79^{+0.16}_{-0.40}$	$0.68^{+0.25}_{-0.37}$	0.7	–
Eccentricity	–	–	–	–	–	–	0.67	0.11[f]
E_0/M	$1.014^{+0.009}_{-0.012}$	$1.014^{+0.010}_{-0.012}$	–	–	–	–	–	–
p^0_φ	$4.18^{+0.50}_{-0.62}$	$4.24^{+0.57}_{-0.37}$	–	–	–	–	–	–
Luminosity distance D_L (Gpc)	$4.7^{+4.8}_{-2.7}$	$6.1^{+3.3}_{-3.7}$	$4.5^{+1.2}_{-1.2}$	$3.9^{+2.3}_{-1.9}$	$4.8^{+2.3}_{-2.2}$	$5.3^{+2.4}_{-2.6}$	$1.84^{+1.07}_{-0.054}$	$4.1^{+1.8}_{-1.8}$
SNR_{max}	15.2	15.4	14.7	14.7	14.6	15.4	–	–
$\log(L)_{max}$	123.2	123.0	106.0	107.0	105.6	–	–	–
$\log B^{signal}_{noise}$	84.00±0.18	83.30±0.18	72.95±0.08	74.76±0.11	74.86±0.11	–	–	–

[a]Results of other analyses[4,15,16] are included for reference [b]Spin results obtained at a reference frequency of 5 Hz [c]Total mass in the frame of the source [d]Effective spin along the orbital angular momentum [e]Effective precessing spin[4] [f]Lower limit at 10 Hz



 Gamba+'22, Nat. Ast.

Principal sources: compact binary coalescences



Evolution of massive binaries

Tutukov, Yungelson 1993

Lipunov, Postnov, Prokhorov 1997

.....

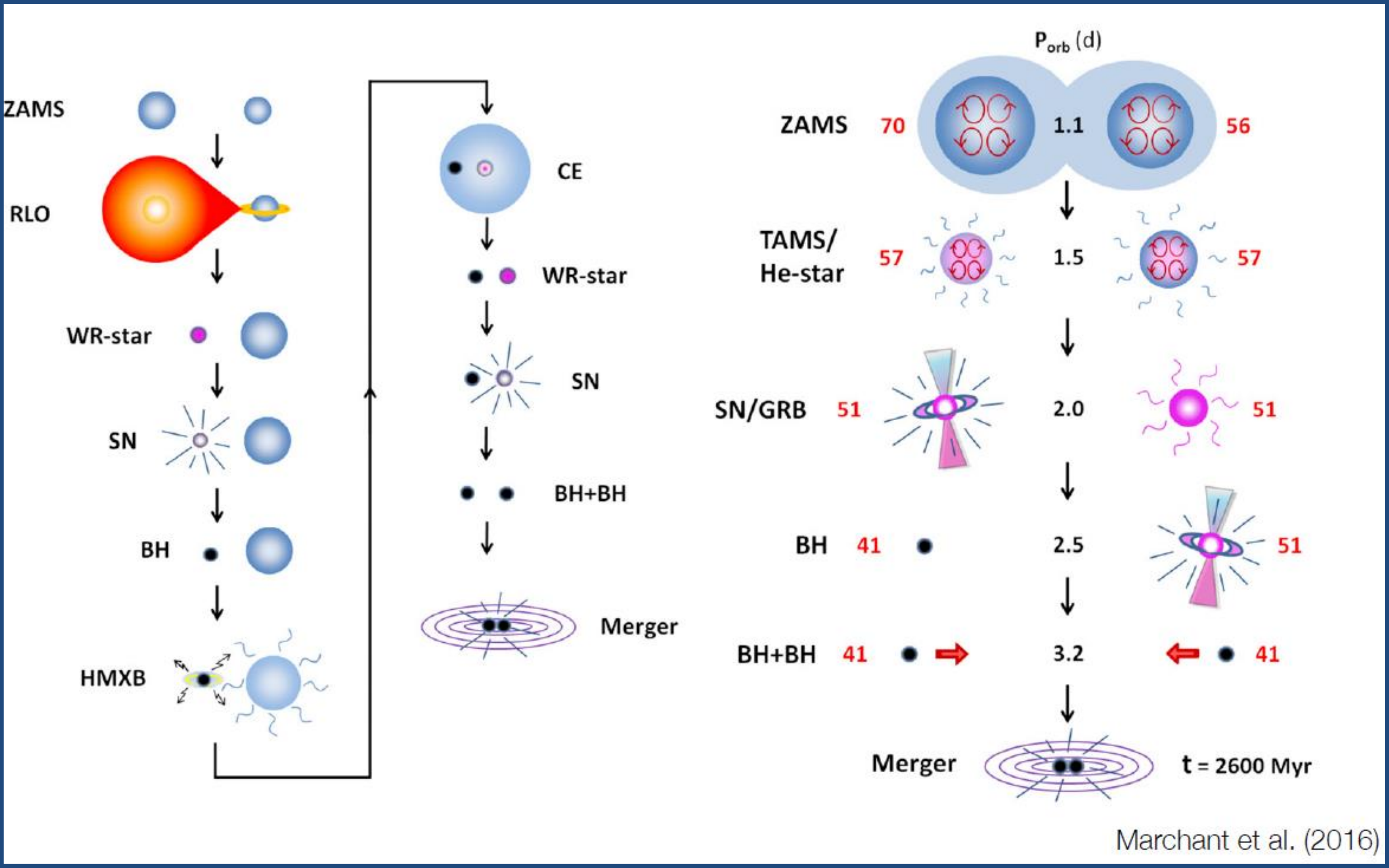
Other scenarios:

Dynamical interactions in stellar clusters

Exotica (primordial BHs)

...

Simplest scenario: BH+BH from massive star evolution

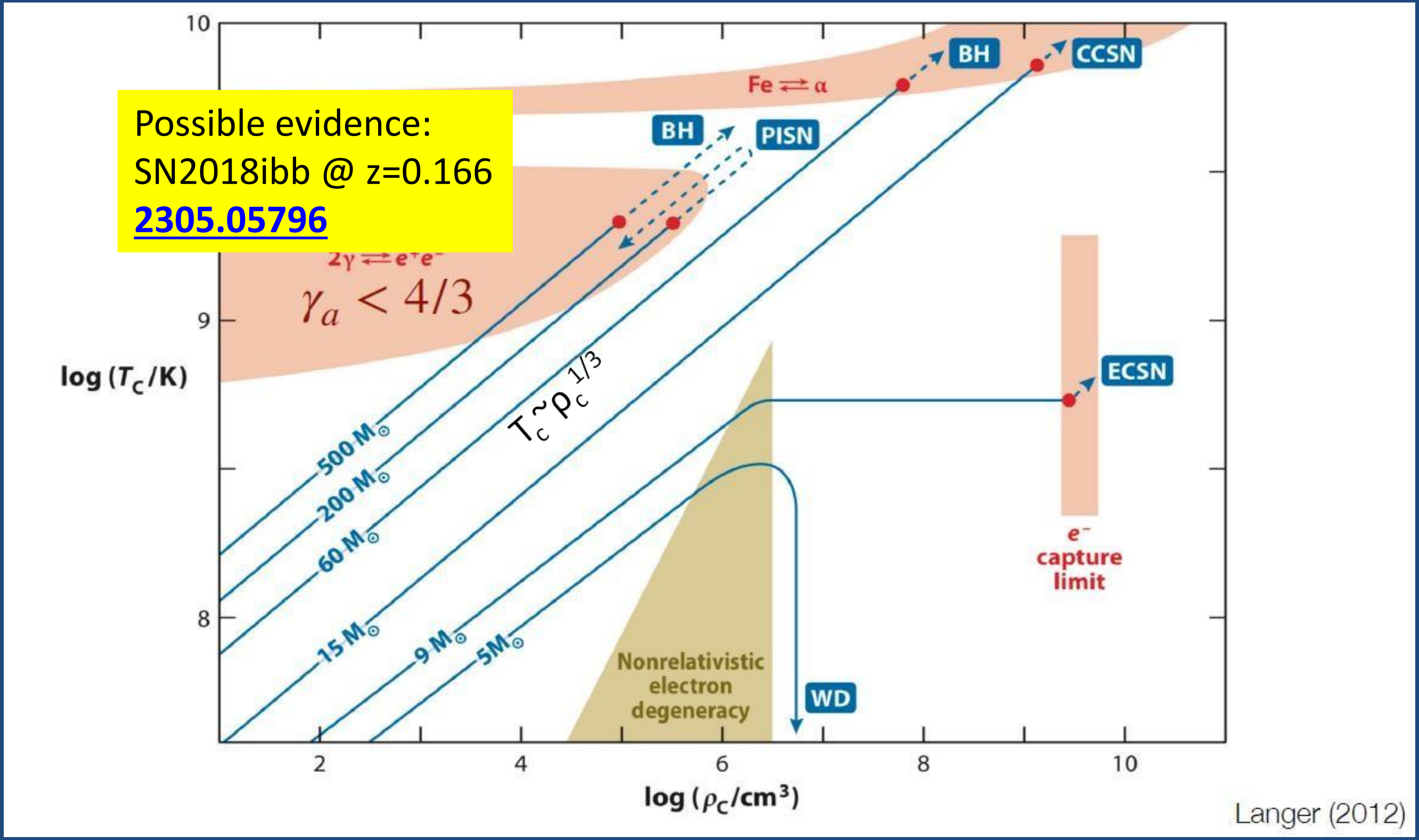


Astrophysical issues:
BH from stellar collapses, binary BH formation

- Mass loss from massive stars
- BH mass gaps (2.5-5, 60-130 M_{sun})
- BH kicks
- BH spins
- …

BH formation from stars

Possible evidence:
SN2018ibb @ z=0.166
2305.05796



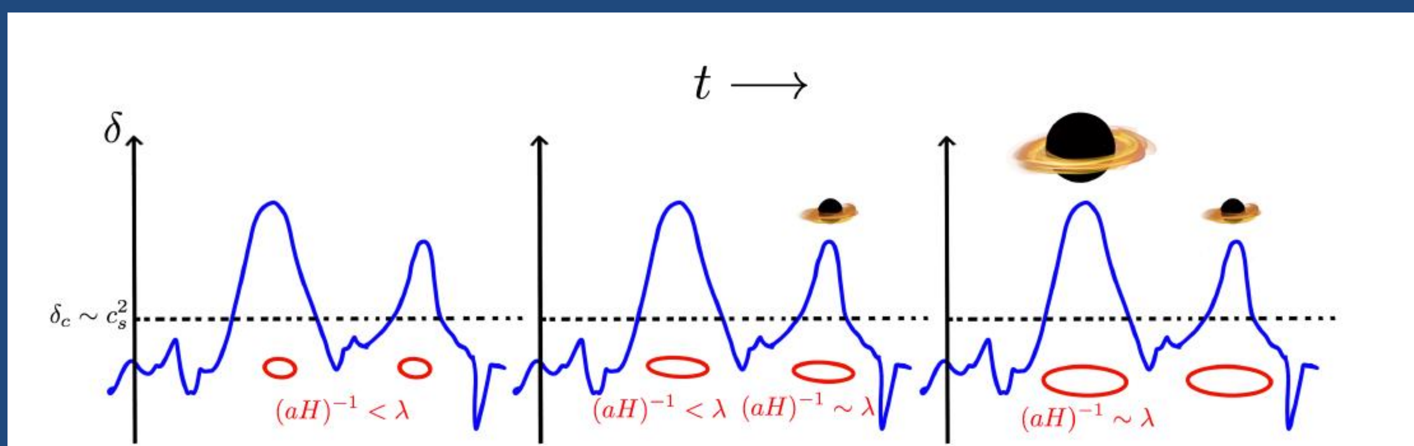
Possible astrophysical explanations of most massive LIGO binaries

- GW measurement uncertainty (straddling the gap: 2009.05742)
- Dynamical formation in dense stellar cluster (signs of large pre-merging eccentricity: 2009.04771), repeated mergers (3: 2009.05065, 7: 2010:0616)
- Population III stars (BH mass up to 75 $M_{\odot}$: 2009.06585; up to 150 $M_{\odot}$:2009.06922, 2009.11447; direct collapse 90 → 90 for small convection overshooting: 2010:07616)
- Accretion growth in dense molecular clouds (2009.11326)
- Standard low-Z binary evolution with direct collapse (BH mass up to 90 $M_{\odot}$: 2009.13526)
- Addition of additional nuclear energy (DM?) to avoid PISN (M_{BH}~120 $M_{\odot}$: 2010.00245)
- Stellar merger of low-Z stars to avoid mass gap (2010.00705)
- Stellar physics of PISN (shifting the gap to 92-110 $M_{\odot}$: 2010.02242)

Other scenarios

Dynamical capture in dens stellar clusters (can produce BH with $M>50\ M_{\odot}$ and non-parallel BH spins)

- “Exotic” scenarios – primordial BH (Zeldovich,Novikov 1967…Carr 1975… Dolgov&Silk 1993…)



LIGO BH+BH: Could they be PBH?

- Stellar-mass primordial black holes:
  - Can be formed in the early Universe in different models (Zeldiovich, Novikov'67,Carr, Hawking'74)
  - Can be in binaries (Nakamura+'97)
  - Can naturally explain observed BH+BH rate (Bird+'16, Blinnikov+'16, Sasaki+'16…)
  - Can substantially contribute to dark matter
  - Can be seeds for growth of SMBH in galactic centers

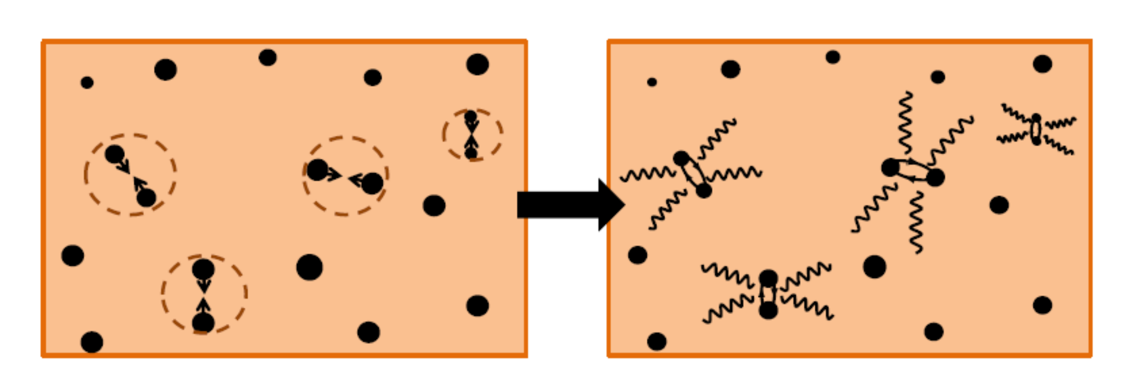
Binary PBH formation

- At some z more than one PBH is inside the Hubble horizon:

$$H(z)\ell_{\rm PBH}(z) = H(z)n_{\rm PBH}^{-1/3}(1+z)^{-1} \simeq 6\times 10^{-6}\ f_{\rm PBH}^{-1/3}\left(\frac{1+z}{1+z_{\rm eq}}\right)\left(\frac{M_{\rm PBH}}{30\ M_\odot}\right)^{1/3}$$

z_{eq}~10^4

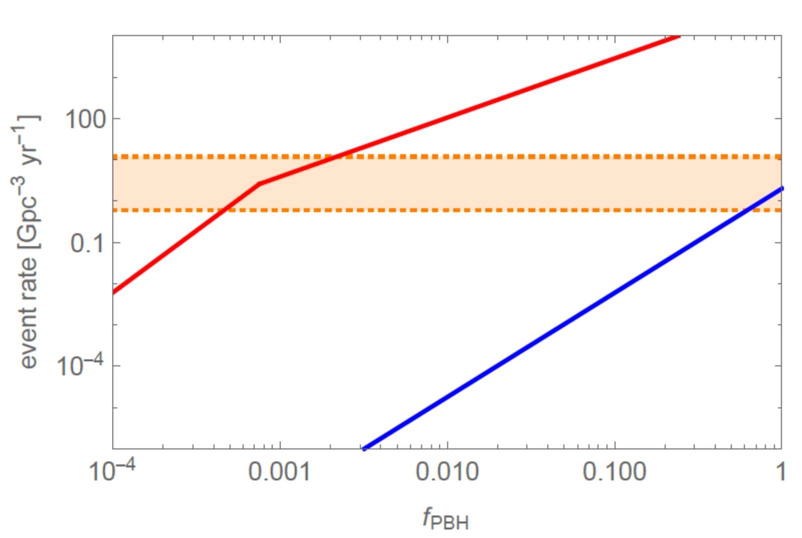
- Decoupling from the Hubble flow $x < x_{\rm max} \equiv f_{\rm PBH}^{1/3}\ell_{\rm PBH}(z=0)$ at $1+z_{\rm dec} = (1+z_{\rm eq})\left(\frac{x_{\rm max}}{x}\right)^3$



Merging rate (model-dependent)

$$\mathcal{R} = n_{\rm PBH}\frac{dP}{dt} = \frac{3n_{\rm PBH}}{58}\left(\frac{t}{T}\right)^{\frac{3}{8}}\left[\frac{1}{(1-e_{\rm upper}^2)^{\frac{25}{16}}}-1\right]\frac{1}{t}$$

Sazaki+'16



f_{pbh} can be ~O(1)
for PBH in clusters
(Eroshenko, Stasenko 2302.06157)

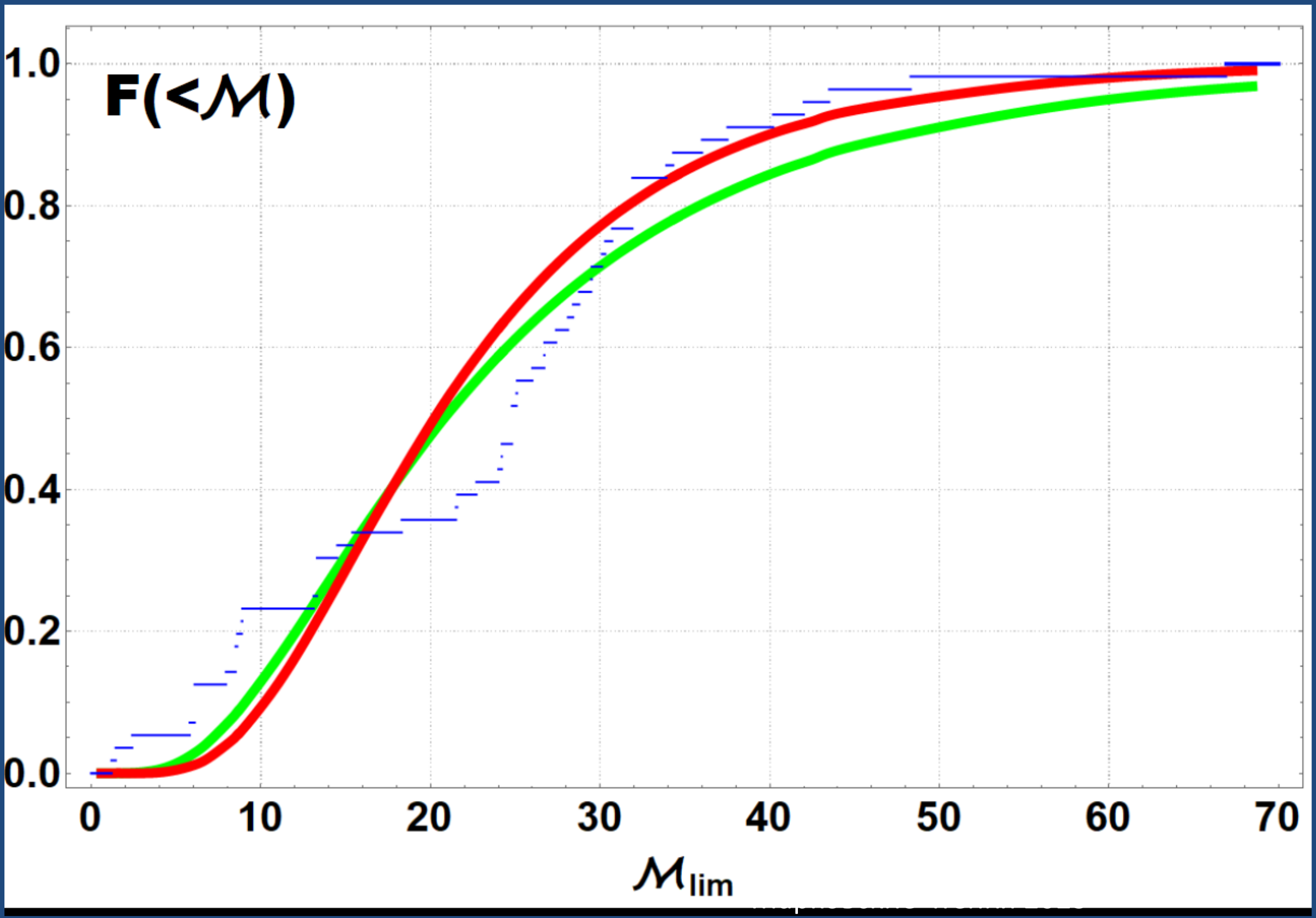
$$\mathrm{d}R_0 = \frac{1.6\times10^6}{\mathrm{Gpc}^3\ \mathrm{yr}} f_{\rm PBH}^{\frac{53}{37}}\eta^{-\frac{34}{37}}\left(\frac{M}{\mathrm{M}_\odot}\right)^{-\frac{32}{37}}\left(\frac{t}{t_0}\right)^{-\frac{34}{37}}\psi(m_1)\,\psi(m_2)\ \mathrm{d}m_1\,\mathrm{d}m_2$$

$$\psi(m) = \frac{1}{\sqrt{2\pi}\sigma m}\exp\left(-\frac{\ln^2(m/m_c)}{2\sigma^2}\right)$$

Raidal+'17

Example: log-normal PBH mass function GWTC1+GWTC2

$$F(M) = A\exp[-\gamma \ln^2(M/M_0)]$$

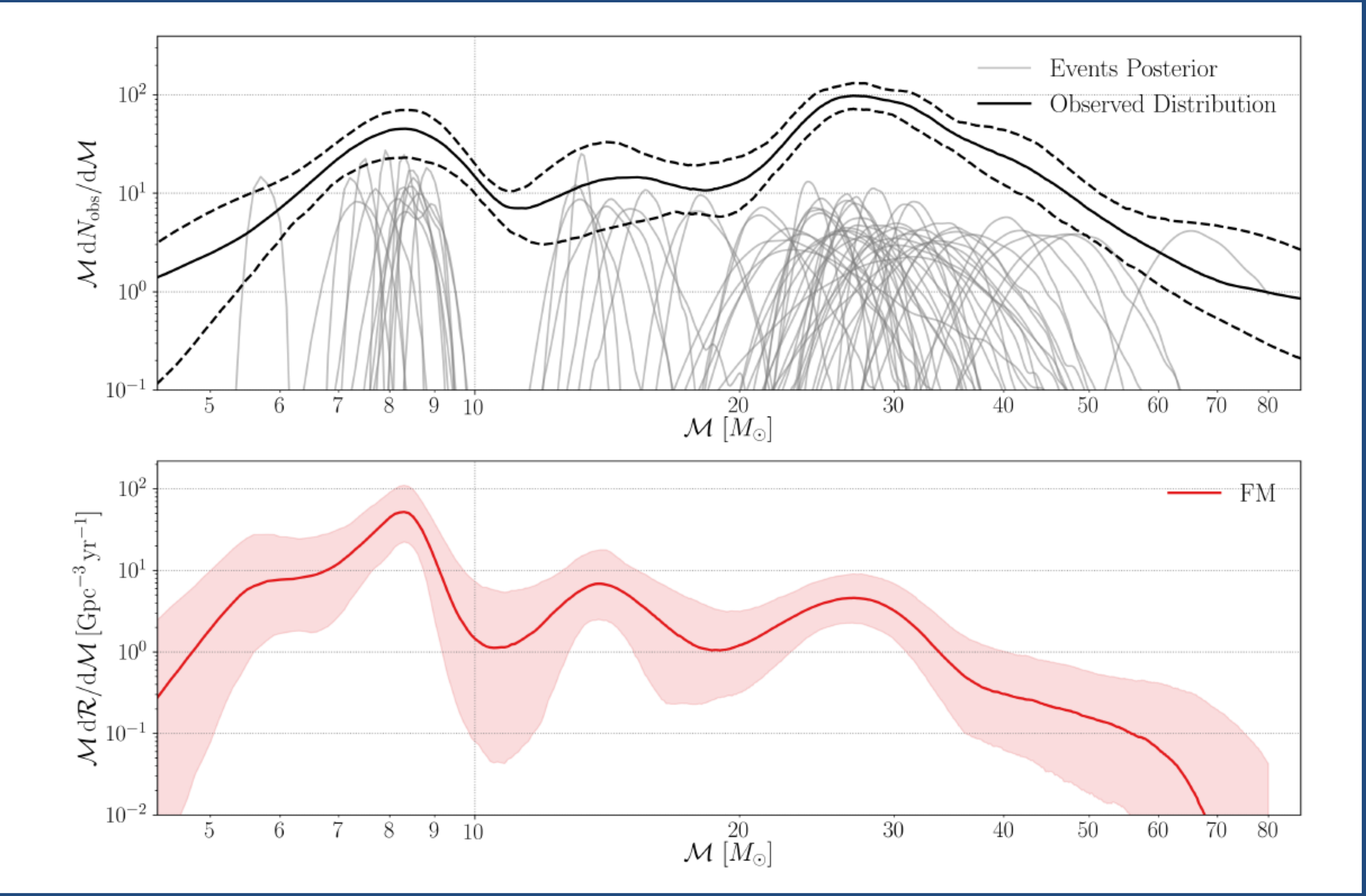


$$\gamma = 0.7,\ M_0 = 19$$

$$\mathrm{DR}(M_{ch})dM_{ch} \sim Ae^{-B\ln^2\left(\frac{M_{ch}}{M_0}\right)}dM_{ch}$$

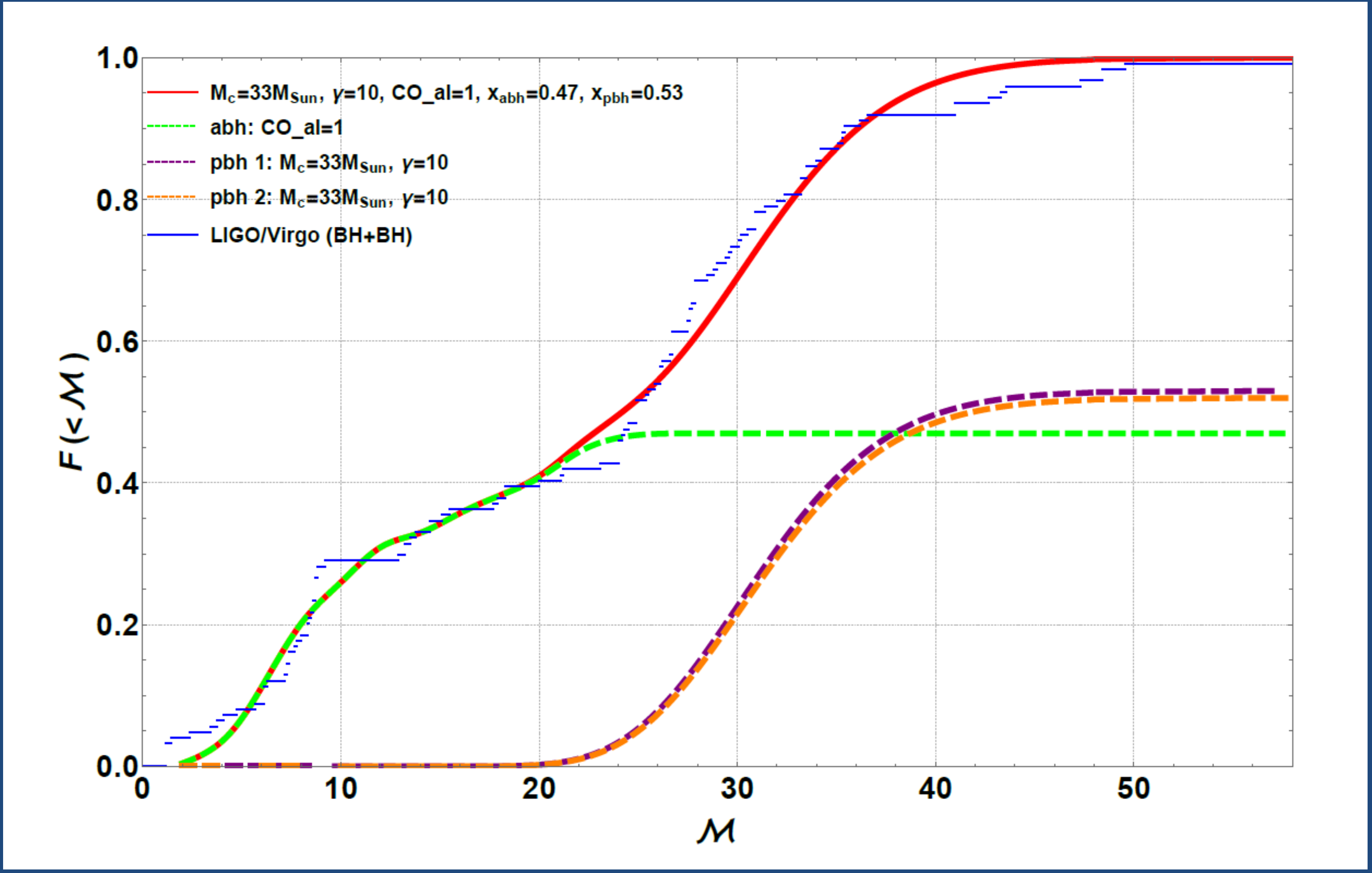
Dolgov+'19

GWTC-3 features



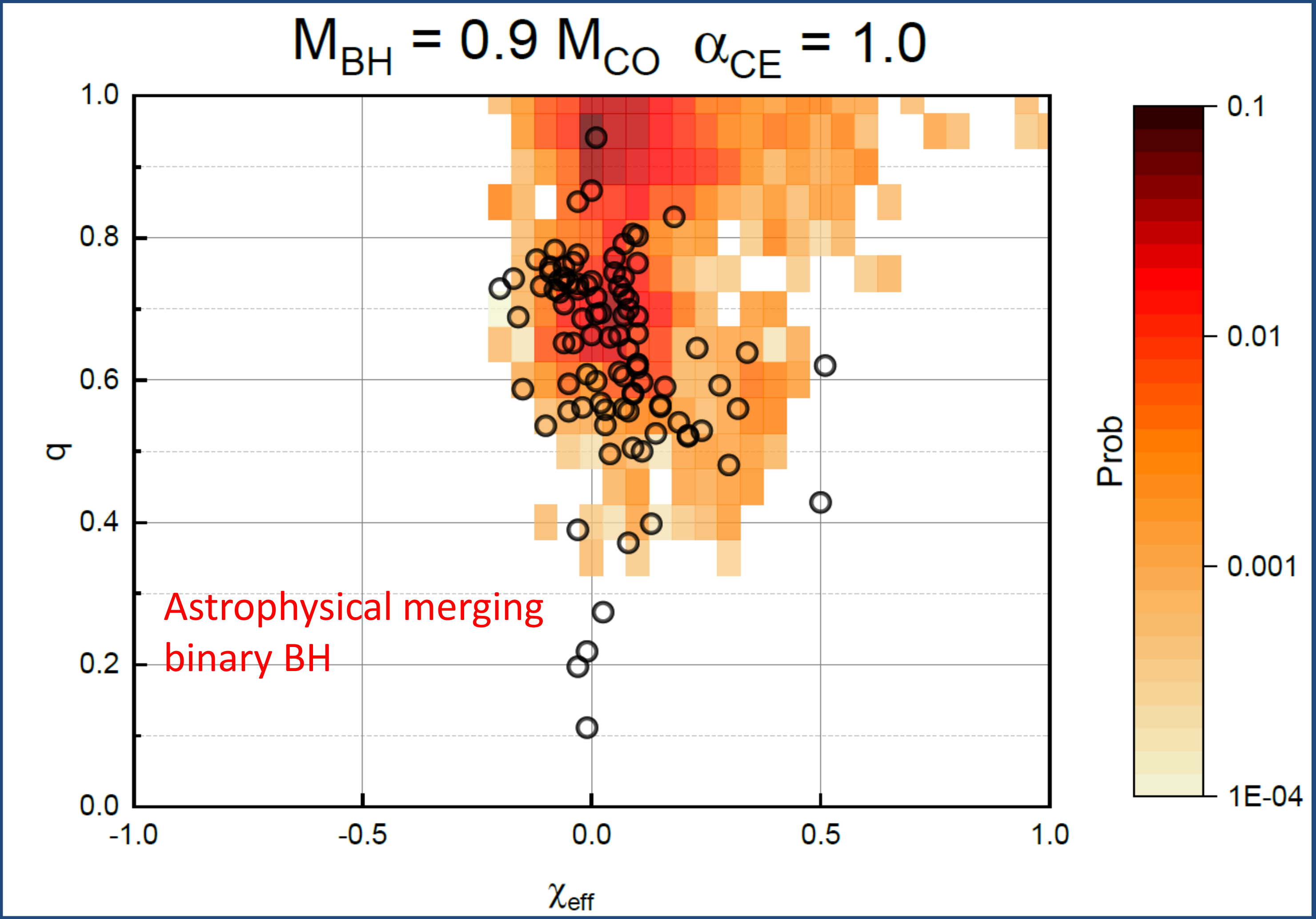
2111.03634

Astrophysical BHs +PBHs in GWTC-3



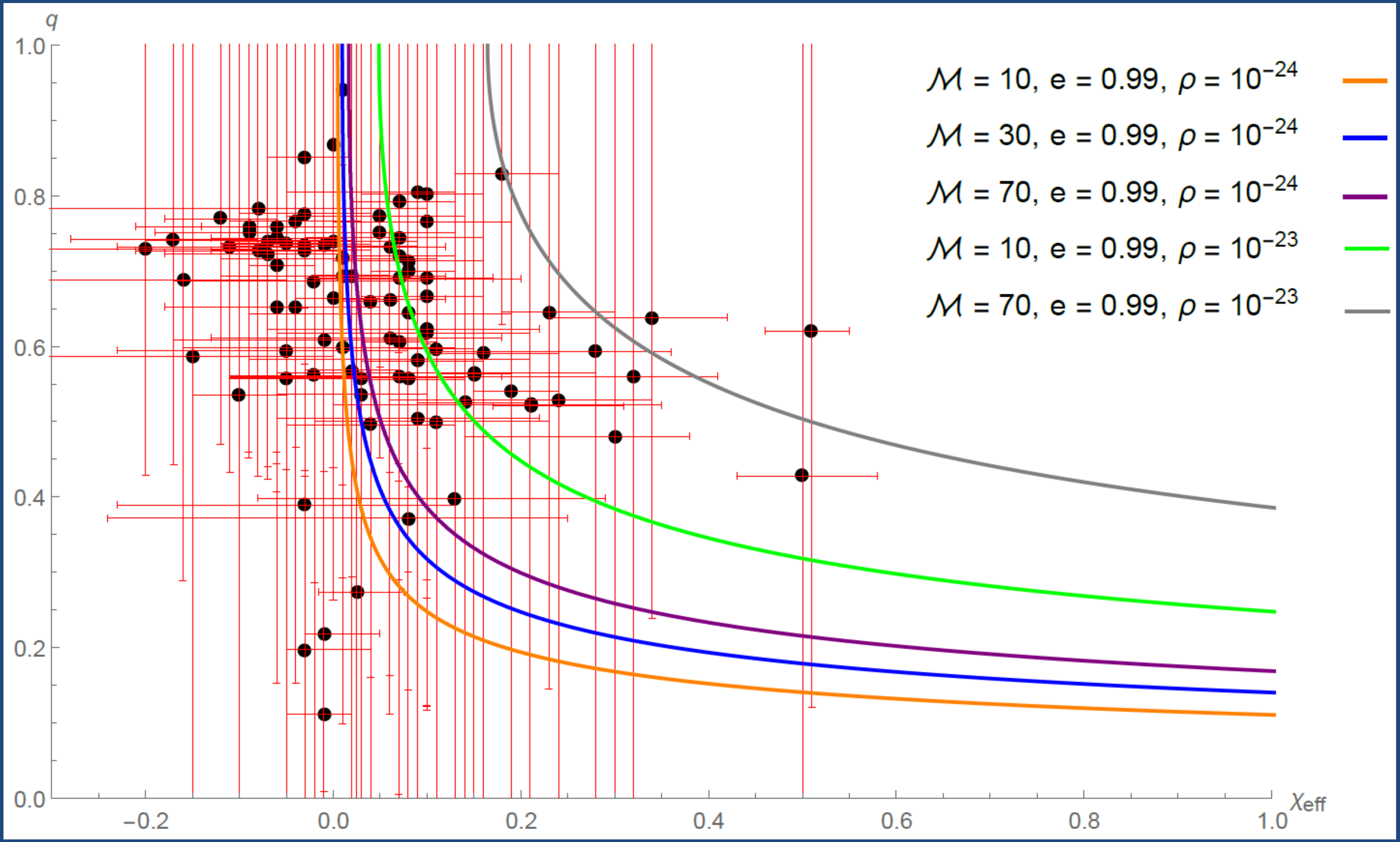
PK, Mitichkin 2302.06981

Effective spin – mass ratio correlation?

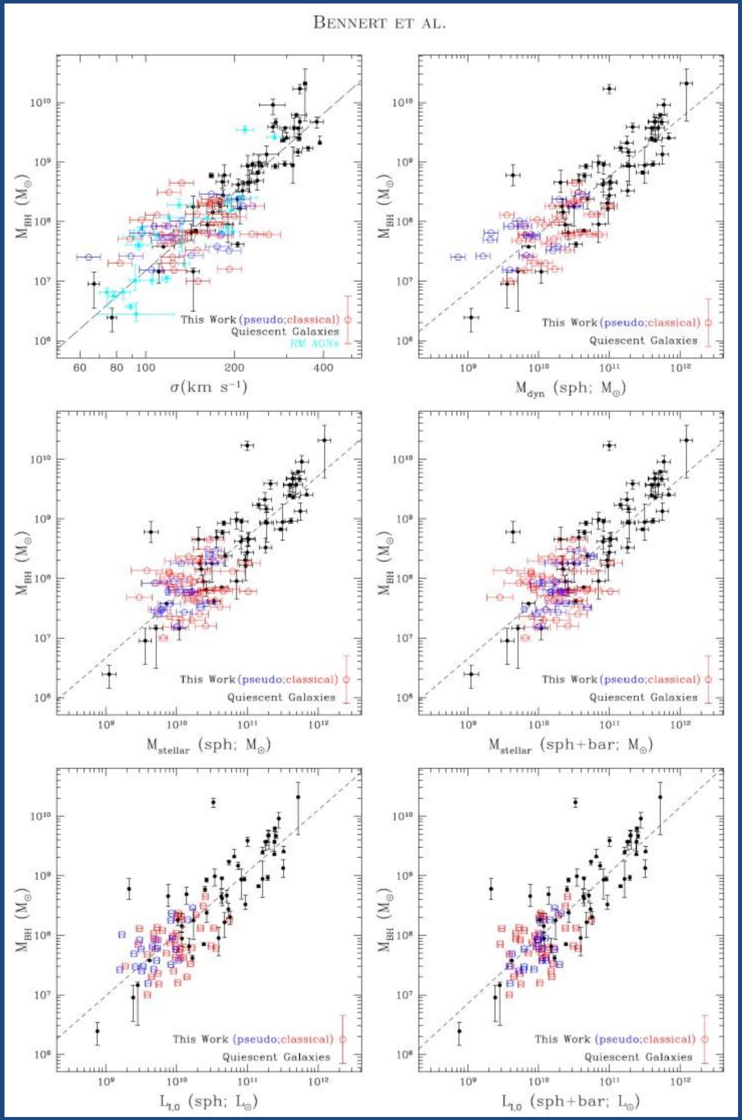


PK+, in prep.

Accretion induced spin in eccentric PBH binaries



II. SMBH Astronomy



- $M \sim \sigma^4$
- $M \sim M_{sph}$
- $M \sim L_{sph}$

2101.10355

SMBH records

- >200 QSOs @ z>6, ~a few @z>7 (700 mln yrs)

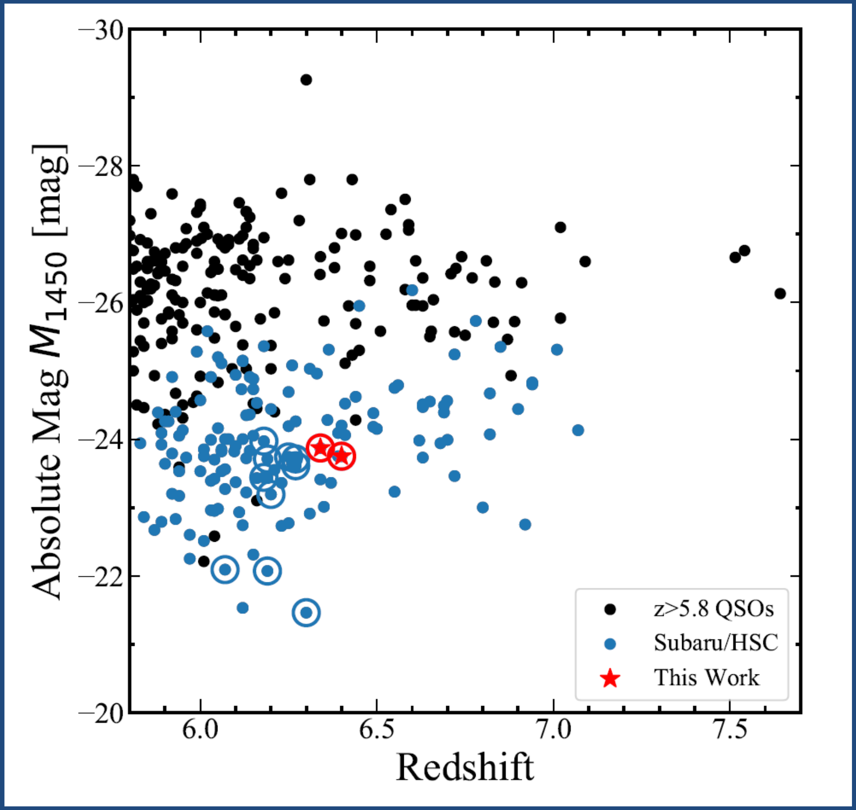
Source	Z	$M/M_{\odot}$
SDSS J0100+2802	6.3	1.2×10^{10}
J1007+2115	7.52	1.5×10^{9}
ULAS J1342+0928	7.54	7.8×10^{8}
J0313-1806	7.62	1.6×10^{9}

- $L \sim 0.6\, L_{edd}$, SFR ~ 200 $M_{\odot}$ per year (~100 x MW)

- Require BH seeds >100-$10^5 M_{\odot}$

2006.13452
2101.03179

High-redshift QSOs and SMBH growth



- >200 QSO z>6
- Central SMBH M~10^9 M⊙
- Inefficient merging
- Eddington-limited accretion
- Need for ‘massive ‘seeds’ M~10^3 -10^4 M⊙
- Population III star? Primordial massive BHs?

2211.14329

JWST

2303.15431

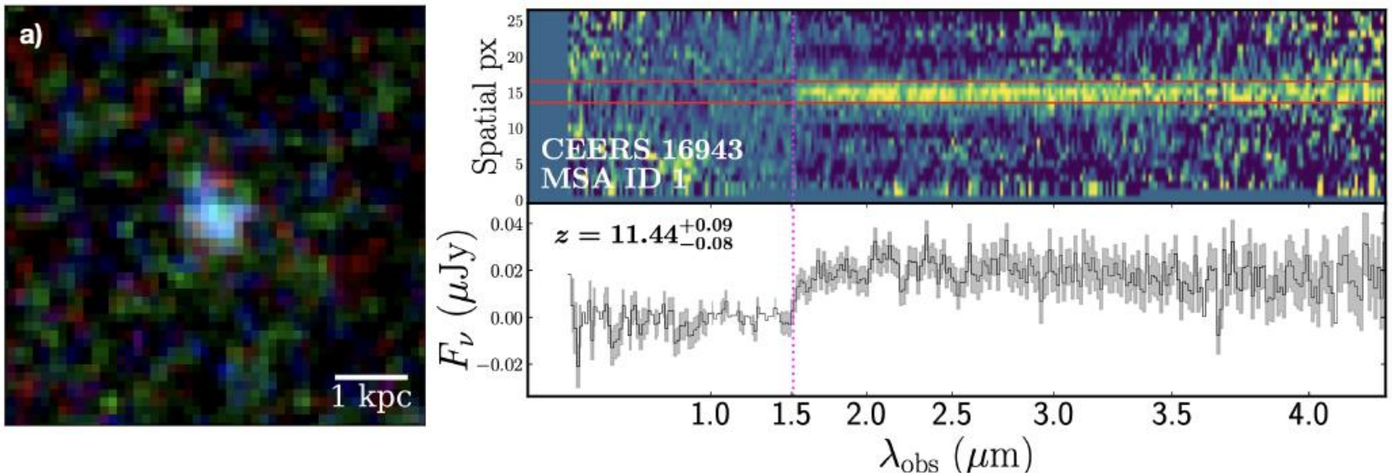
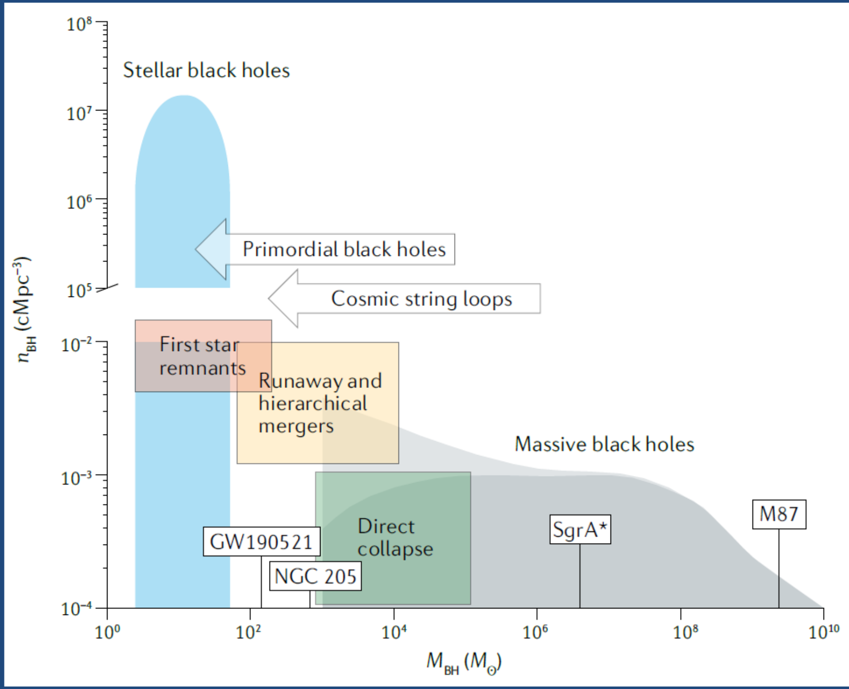
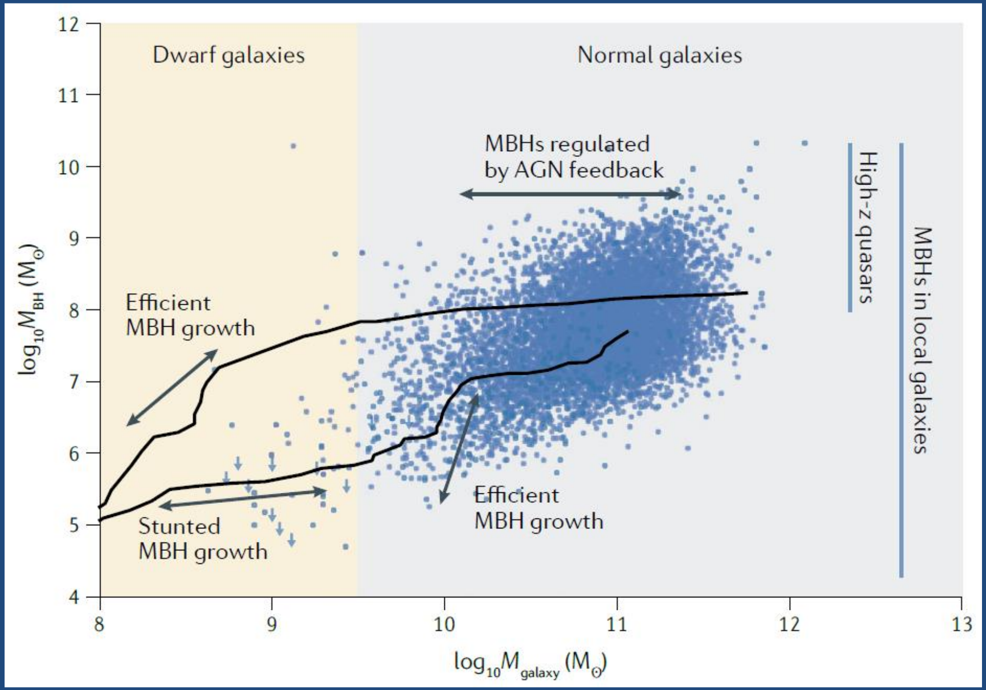


Fig. 2 a) A color image of Maisie's Galaxy, showing a
color (made from the F277W, F356W, and F444W i
of low dust attenuation and a fairly young stellar p
Galaxy's spectrum around the detected Lyα break. Th
the bright trace, with the negative "shadows" represent
nods. The red horizontal lines show the spatial extent
in the bottom panel, was extracted. A clear spectral b
significant flux. We interpret this as the Lyα break at
a time 390 Myr after the Big Bang.

Property	Maisie's Galaxy
RA (J2000)	214.943152
Dec (J2000)	52.942442
Photometric Redshift	$11.08^{+0.36}_{-0.39}$
Spectroscopic Redshift	$11.44^{+0.09}_{-0.08}$
$\mathcal{T}_{\rm BigBang}$ (Myr)	391
$\log(M_\star/M_\odot)$	$8.4^{+0.3}_{-0.4}$
A_V (mag)	$0.07^{+0.09}_{-0.05}$
$\log({\rm sSFR/yr^{-1}})$	$-8.0^{+0.4}_{-0.5}$

Massive BH formation

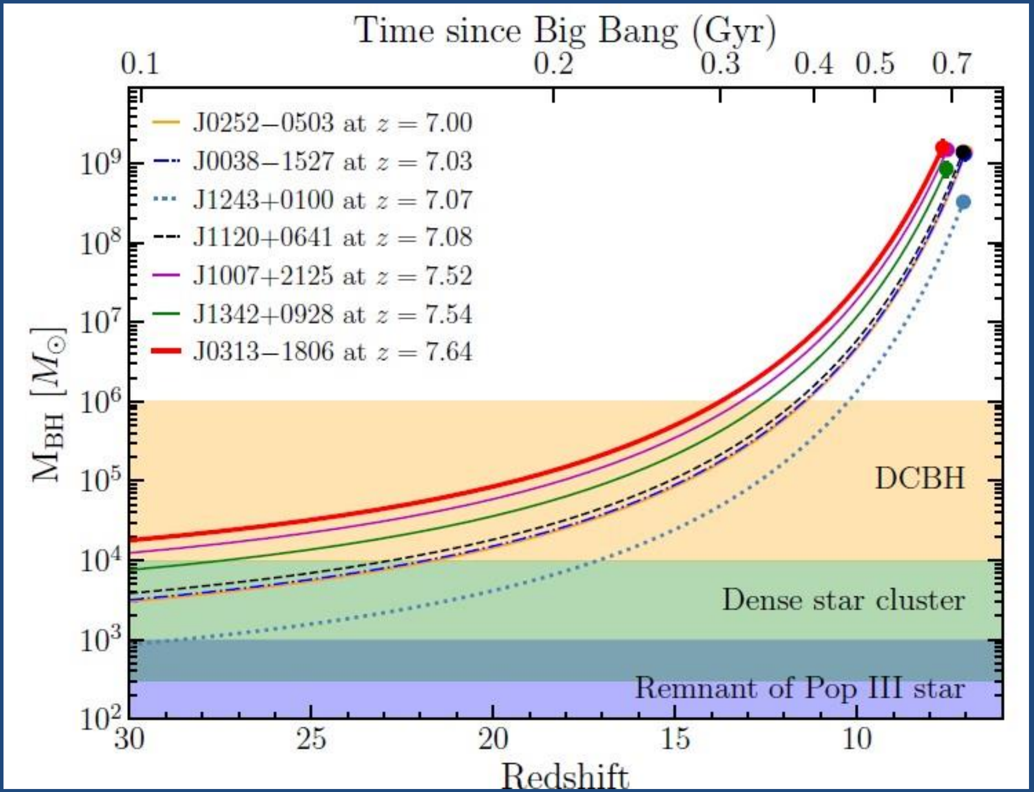




Massive BH seeds can outshine their host galaxies in far IR and mm!

Volonteri +'21

SMBH mass growth



Massive PBH seeds?

2101.03179, 2012.01458

$$M_{BH}(t) = M_{seed} \times \exp\left(\frac{t - t_{form}}{t_{Sal}} \delta l_E\right)$$

$$t_{Sal} = \frac{\kappa_{e.s.} c}{4\pi G} \frac{\epsilon}{1-\epsilon} \simeq 45 \frac{\epsilon}{0.1} \frac{0.9}{1-\epsilon} \text{Myr}$$

Conclusions

- LVK O1+O2+O3: ~ 91 detections of binary BH and NS mergings, mostly binary BH, rate ~10-200 Gpc^{-3} yr^{-1}
  - Astrophysical problems in formation of massive BH with $M \sim 100\ M_{\odot}$, extreme mass ratio BH+BH inspirals, BH+NS
  - Possibility of ~10+ $M_{\odot}$ PBH is still open!
- LIGO, Virgo, and KAGRA are closely coordinating to start the O4 Observing run together on **May 24 2023**.
  - LIGO sensitivity goal of 160-190 Mpc for binary neutron stars. Virgo target sensitivity of 80-115 Mpc. KAGRA should be running with greater than 1 Mpc sensitivity at the beginning of O4, and will work to improve the sensitivity toward the end of O4.
- $\sim 10^4$+ $M_{\odot}$ PBH as seeds of high-redshift galaxies

Backup slides

Mass-redshift degeneracy

$$f_0 = f/(1+z),\ \ dt_0 = dt(1+z)$$

$$\left.\frac{df}{dt}\right|_o = \frac{df}{dt}\frac{1}{(1+z)^2}$$

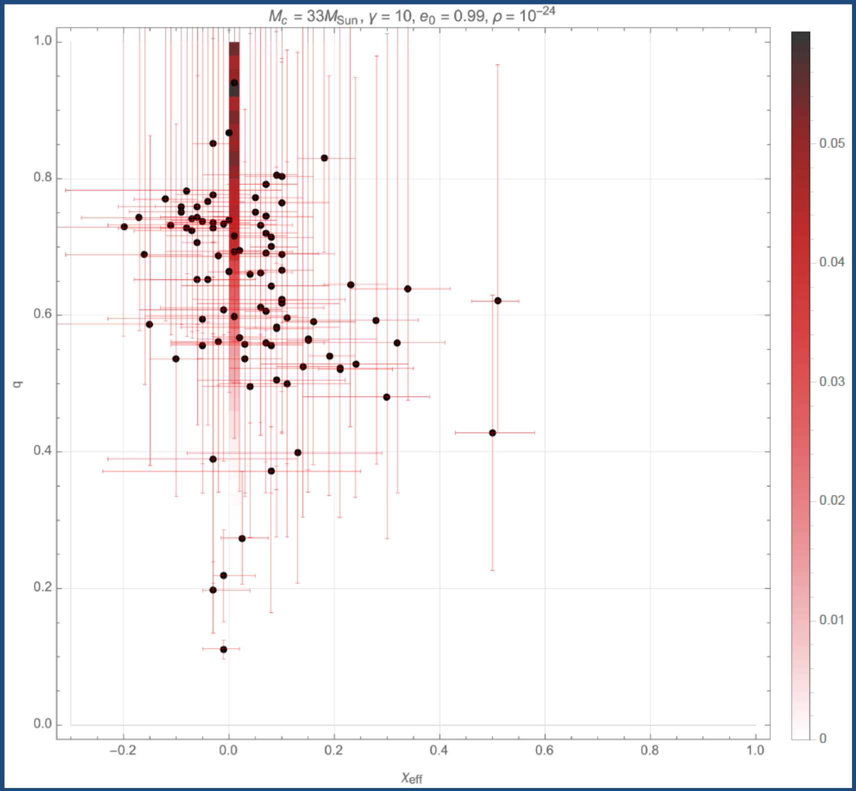
$$\left.M_{ch}\right|_o = \left(\frac{5 f_o^{-11/3}(df_o/dt)}{96\pi^{8/3}}\right)^{3/5} = M_{ch}(1+z) ==> \ fM_{ch} = inv$$

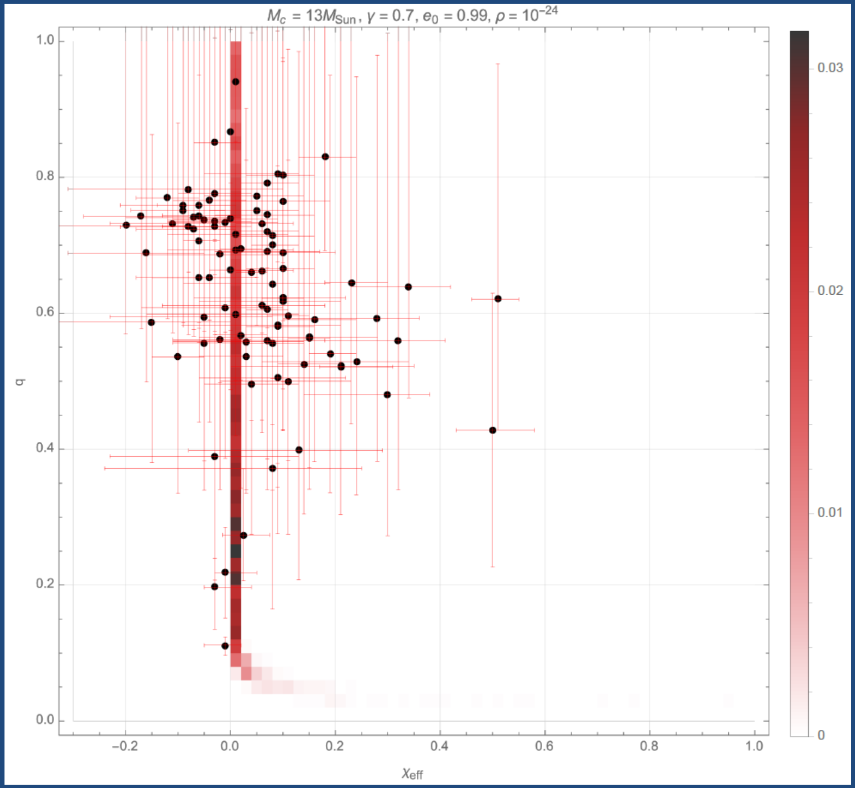
$$h_o \sim \frac{M_{ch}}{d_m}(\pi f M_{ch})^{2/3}$$

$$d_o \sim \frac{4(M_{ch})_o}{h_o}(\pi f_o (M_{ch})_o)^{2/3} = d_m(1+z)$$

Luminosity distance

Binary merging PBH





Chirp mass determines detection horizon. $h_{lim} \sim M^{(5/6)}$