初代星による
重い連星ブラックホール形成

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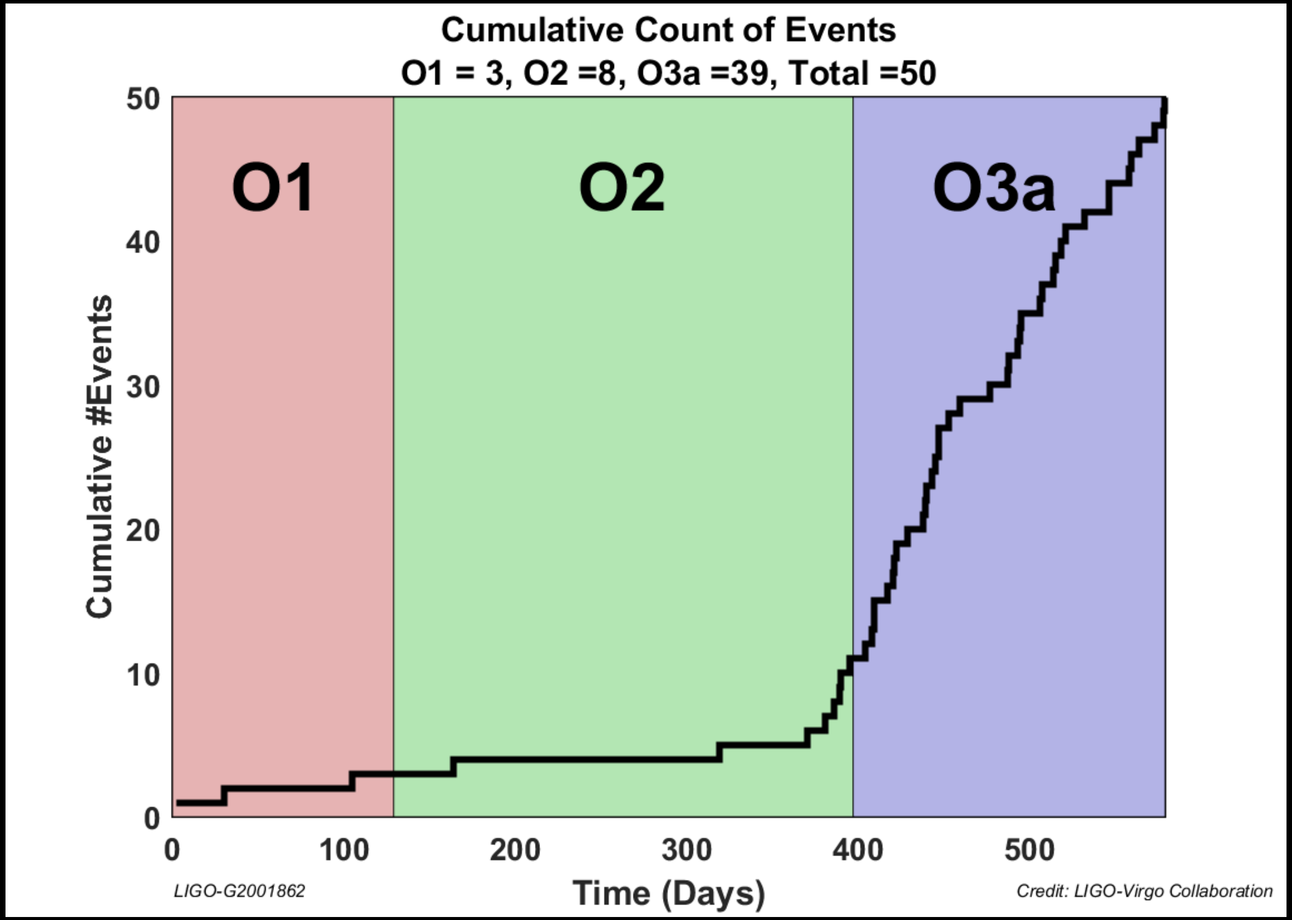
Takashi Yoshida, Kotaro Hijikawa, Hideyuki Umeda

LIGO O3a



Cumulative Count of Events
O1 = 3, O2 =8, O3a =39, Total =50
O1
O2
O3a
Cumulative #Events
Time (Days)
0
10
20
30
40
50
0
100
200
300
400
500
LIGO-G2001862
Credit: LIGO-Virgo Collaboration

- GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run

  arXiv:2010.14527

- Population properties of compact objects from the second LIGO–Virgo Gravitational-Wave Transient Catalog

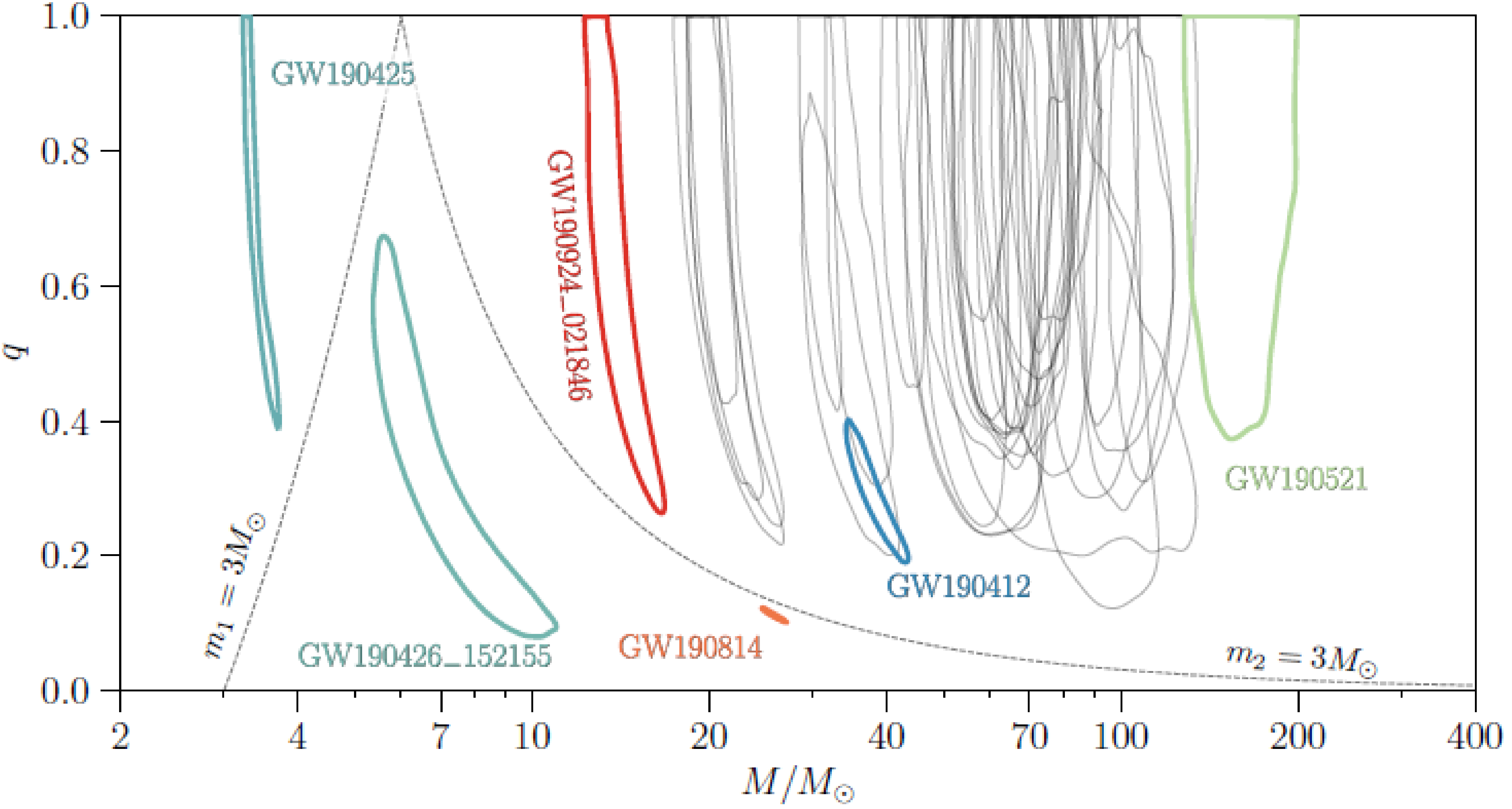
  arXiv:2010.14533

Name	Inst.	cWB		GstLAL			PyCBC			PyCBC BBH		
		FAR (yr^{-1})	SNR*	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR*	p_{astro}	FAR (yr^{-1})	SNR*	p_{astro}
GW190408_181802	HLV	$< 9.5 \times 10^{-4}$	14.8	$< 1.0 \times 10^{-5}$	14.7	1.00	$< 2.5 \times 10^{-5}$	13.5	1.00	$< 7.9 \times 10^{-5}$	13.6	1.00
GW190412	HLV	$< 9.5 \times 10^{-4}$	19.7	$< 1.0 \times 10^{-5}$	18.9	1.00	$< 3.1 \times 10^{-5}$	17.9	1.00	$< 7.9 \times 10^{-5}$	17.8	1.00
GW190413_052954	HLV	–	–	–	–	–	–	–	–	7.2×10^{-2}	8.6	0.98
GW190413_134308	HLV	–	–	3.8×10^{-1}	10.0	0.95	–	–	–	4.4×10^{-2}	9.0	0.98
GW190421_213856	HL	3.0×10^{-1}	9.3	7.7×10^{-4}	10.6	1.00	1.9×10^{0}	10.2	0.89	6.6×10^{-3}	10.2	1.00
GW190424_180648	L			$7.8 \times 10^{-1\dagger}$	10.0	0.91						
GW190425	LV			$7.5 \times 10^{-4\dagger}$	13.0	–						
GW190426_152155	HLV	–	–	1.4×10^{0}	10.1	–	–	–	–	–	–	–
GW190503_185404	HLV	1.8×10^{-3}	11.5	$< 1.0 \times 10^{-5}$	12.1	1.00	3.7×10^{-2}	12.2	1.00	$< 7.9 \times 10^{-5}$	12.2	1.00
GW190512_180714	HLV	8.8×10^{-1}	10.7	$< 1.0 \times 10^{-5}$	12.3	1.00	3.8×10^{-5}	12.2	1.00	$< 5.7 \times 10^{-5}$	12.2	1.00
GW190513_205428	HLV	–	–	$< 1.0 \times 10^{-5}$	12.3	1.00	3.7×10^{-4}	11.8	1.00	$< 5.7 \times 10^{-5}$	11.9	1.00
GW190514_065416	HL	–	–	–	–	–	–	–	–	5.3×10^{-1}	8.3	0.96
GW190517_055101	HLV	6.5×10^{-3}	10.7	9.6×10^{-4}	10.6	1.00	1.8×10^{-2}	10.4	1.00	$< 5.7 \times 10^{-5}$	10.2	1.00
GW190519_153544	HLV	3.1×10^{-4}	14.0	$< 1.0 \times 10^{-5}$	12.0	1.00	$< 1.8 \times 10^{-5}$	13.0	1.00	$< 5.7 \times 10^{-5}$	13.0	1.00
GW190521	HLV	2.0×10^{-4}	14.4	1.2×10^{-3}	14.7	1.00	1.1×10^{0}	12.6	0.93	–	–	–
GW190521_074359	HL	$< 1.0 \times 10^{-4}$	24.7	$< 1.0 \times 10^{-5}$	24.4	1.00	$< 1.8 \times 10^{-5}$	24.0	1.00	$< 5.7 \times 10^{-5}$	24.0	1.00
GW190527_092055	HL	–	–	6.2×10^{-2}	8.9	0.99	–	–	–	–	–	–
GW190602_175927	HLV	1.5×10^{-2}	11.1	1.1×10^{-5}	12.1	1.00	–	–	–	1.5×10^{-2}	11.4	1.00
GW190620_030421	LV			$2.9 \times 10^{-3\dagger}$	10.9	1.00						
GW190630_185205	LV			$< 1.0 \times 10^{-5}$	15.6	1.00						
GW190701_203306	HLV	5.5×10^{-1}	10.2	1.1×10^{-2}	11.6	1.00	–	–	–	–	–	–
GW190706_222641	HLV	$< 1.0 \times 10^{-3}$	12.7	$< 1.0 \times 10^{-5}$	12.3	1.00	6.7×10^{-5}	11.7	1.00	$< 4.6 \times 10^{-5}$	12.3	1.00
GW190707_093326	HL	–	–	$< 1.0 \times 10^{-5}$	13.0	1.00	$< 1.0 \times 10^{-5}$	12.8	1.00	$< 4.6 \times 10^{-5}$	12.8	1.00
GW190708_232457	LV			$2.8 \times 10^{-5\dagger}$	13.1	1.00						
GW190719_215514	HL	–	–	–	–	–	–	–	–	1.6×10^{0}	8.0	0.82
GW190720_000836	HLV	–	–	$< 1.0 \times 10^{-5}$	11.7	1.00	$< 2.0 \times 10^{-5}$	10.6	1.00	$< 3.7 \times 10^{-5}$	10.5	1.00
GW190727_060333	HLV	8.8×10^{-2}	11.4	$< 1.0 \times 10^{-5}$	12.3	1.00	3.5×10^{-3}	11.5	1.00	$< 3.7 \times 10^{-5}$	11.8	1.00
GW190728_064510	HLV	–	–	$< 1.0 \times 10^{-5}$	13.6	1.00	$< 1.6 \times 10^{-5}$	13.4	1.00	$< 3.7 \times 10^{-5}$	13.4	1.00
GW190731_140936	HL	–	–	2.1×10^{-1}	8.5	0.97	–	–	–	2.8×10^{-1}	8.2	0.96
GW190803_022701	HLV	–	–	3.2×10^{-2}	9.0	0.99	–	–	–	2.7×10^{-2}	8.6	0.99
GW190814	LV			$< 1.0 \times 10^{-5}$	22.2	1.00						
GW190828_063405	HLV	$< 9.6 \times 10^{-4}$	16.6	$< 1.0 \times 10^{-5}$	16.0	1.00	$< 1.5 \times 10^{-5}$	15.3	1.00	$< 3.3 \times 10^{-5}$	15.3	1.00
GW190828_065509	HLV	–	–	$< 1.0 \times 10^{-5}$	11.1	1.00	5.8×10^{-5}	10.8	1.00	$< 3.3 \times 10^{-5}$	10.8	1.00
GW190909_114149	HL	–	–	1.1×10^{0}	8.5	0.89	–	–	–	–	–	–
GW190910_112807	LV			$1.9 \times 10^{-5\dagger}$	13.4	1.00						
GW190915_235702	HLV	$< 1.0 \times 10^{-3}$	12.3	$< 1.0 \times 10^{-5}$	13.1	1.00	8.6×10^{-4}	13.0	1.00	$< 3.3 \times 10^{-5}$	12.7	1.00
GW190924_021846	HLV	–	–	$< 1.0 \times 10^{-5}$	13.2	1.00	$< 6.3 \times 10^{-5}$	12.5	1.00	$< 3.3 \times 10^{-5}$	12.4	1.00
GW190929_012149	HLV	–	–	2.0×10^{-2}	9.9	1.00	–	–	–	–	–	–
GW190930_133541	HL	–	–	5.8×10^{-1}	10.0	0.92	3.4×10^{-2}	9.7	1.00	3.3×10^{-2}	9.8	0.99

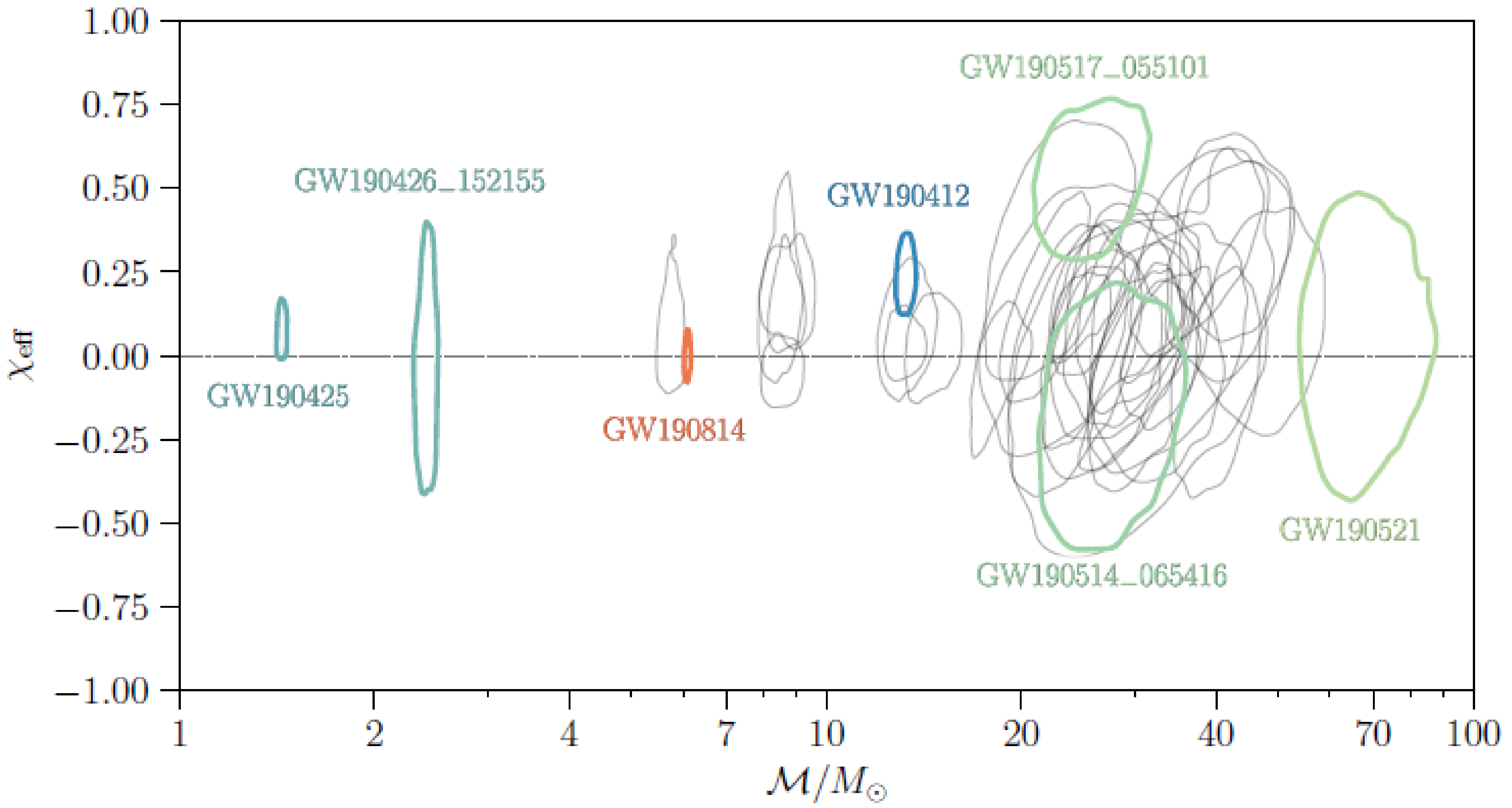
LIGO GWTC-2 paper

"we present *39 candidate* gravitational wave events. At this threshold, we expect a contamination fraction of *less than 10%.*"

Some FARs are near 1/yr...



1.0
0.8
0.6
0.4
0.2
0.0
q
2
4
7
10
20
40
70
100
200
400
$M/M_\odot$
GW190425
GW190426_152155
GW190924_021846
GW190814
GW190412
GW190521
$m_1 = 3M_\odot$
$m_2 = 3M_\odot$



1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
$\chi_{\rm eff}$
1
2
4
7
10
20
40
70
100
$\mathcal{M}/M_\odot$
GW190425
GW190426_152155
GW190814
GW190412
GW190517_055101
GW190514_065416
GW190521

Event rates of compact binary mergers

- Population properties paper

“We report on the population properties of the 47 compact binary mergers detected with a false-alarm rate (FAR) < 1 yr^{-1} in GWTC-2, including all Advanced LIGO–Virgo observing runs through the most recent observing run O3a”

- BBH

$$\mathcal{R}_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

- BNS

$$\mathcal{R}_{\mathrm{BNS}} = 320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Primary BH mass distribution

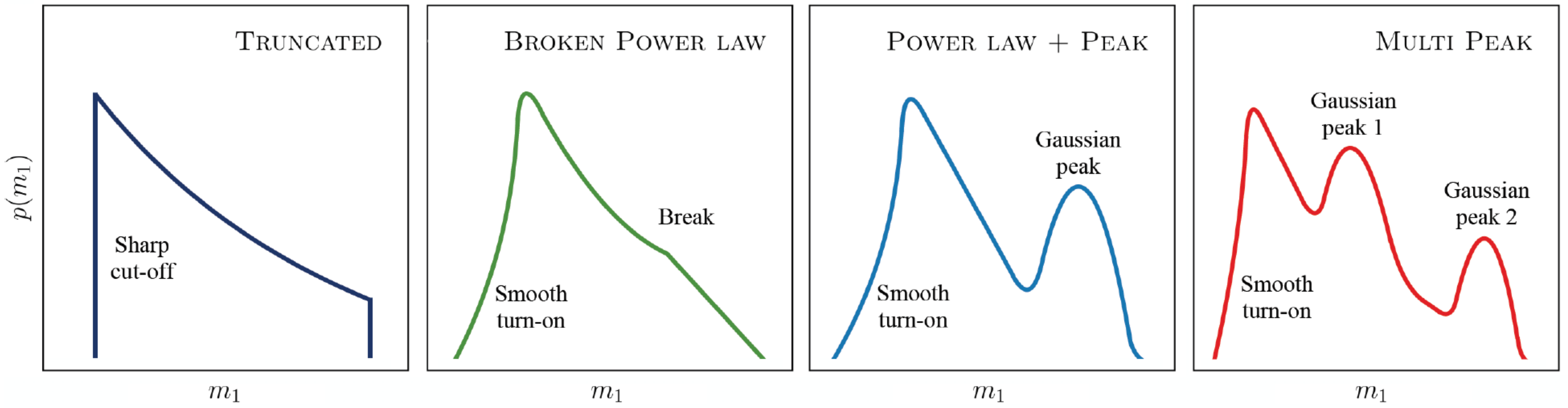
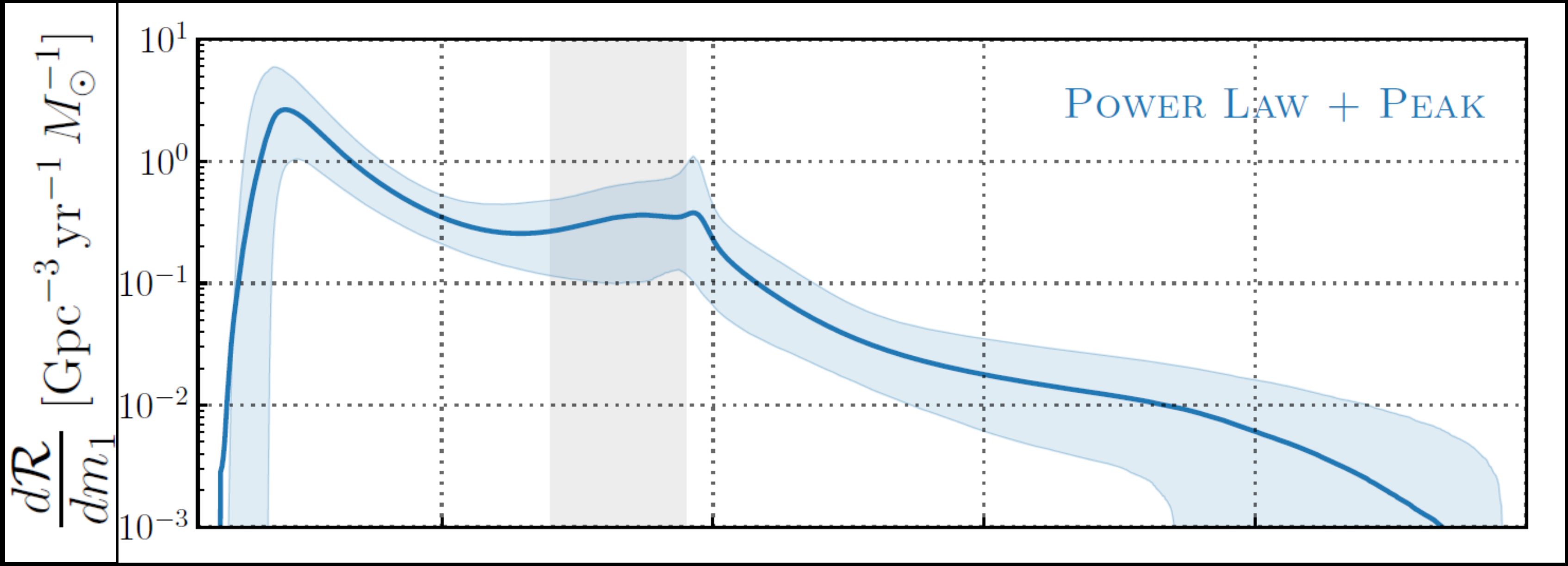


Figure 1. Graphical representations of the various mass distributions described in Section 3.1. MULTI SPIN, a model of both mass and spin, is similar to the mass distribution of POWER LAW + PEAK, with a sharp lower mass cutoff rather than the smooth low mass turn-on.

Primary BH mass distribution

Mass model	$\mathcal{B}$	$\log_{10}\mathcal{B}$
Power Law + Peak	1.0	0.0
Multi Peak	0.25	−0.61
Broken Power Law	0.12	−0.91
Truncated	0.01	−1.9
Broken Power Law + Peak	0.76	−0.12
Power Law + Peak ($\delta_m = 0$)	0.57	−0.24
Broken Power Law ($\delta_m = 0$)	0.36	−0.45
Power Law + Peak ($\lambda_{\rm peak} = 0$)	0.04	−1.35

Table 2. Bayes factors for each mass model relative to the favored Power Law + Peak model, which gives the highest Bayesian evidence for GWTC-2. For models that have a smooth turn on at low masses parameterized by δ_m, we also compare the corresponding sub-model with a sharp minimum mass cutoff ($\delta_m = 0$). For the Power Law + Peak model which includes a fraction $\lambda_{\rm peak}$ of systems in the Gaussian component, we compare the sub-model with $\lambda_{\rm peak} = 0$.



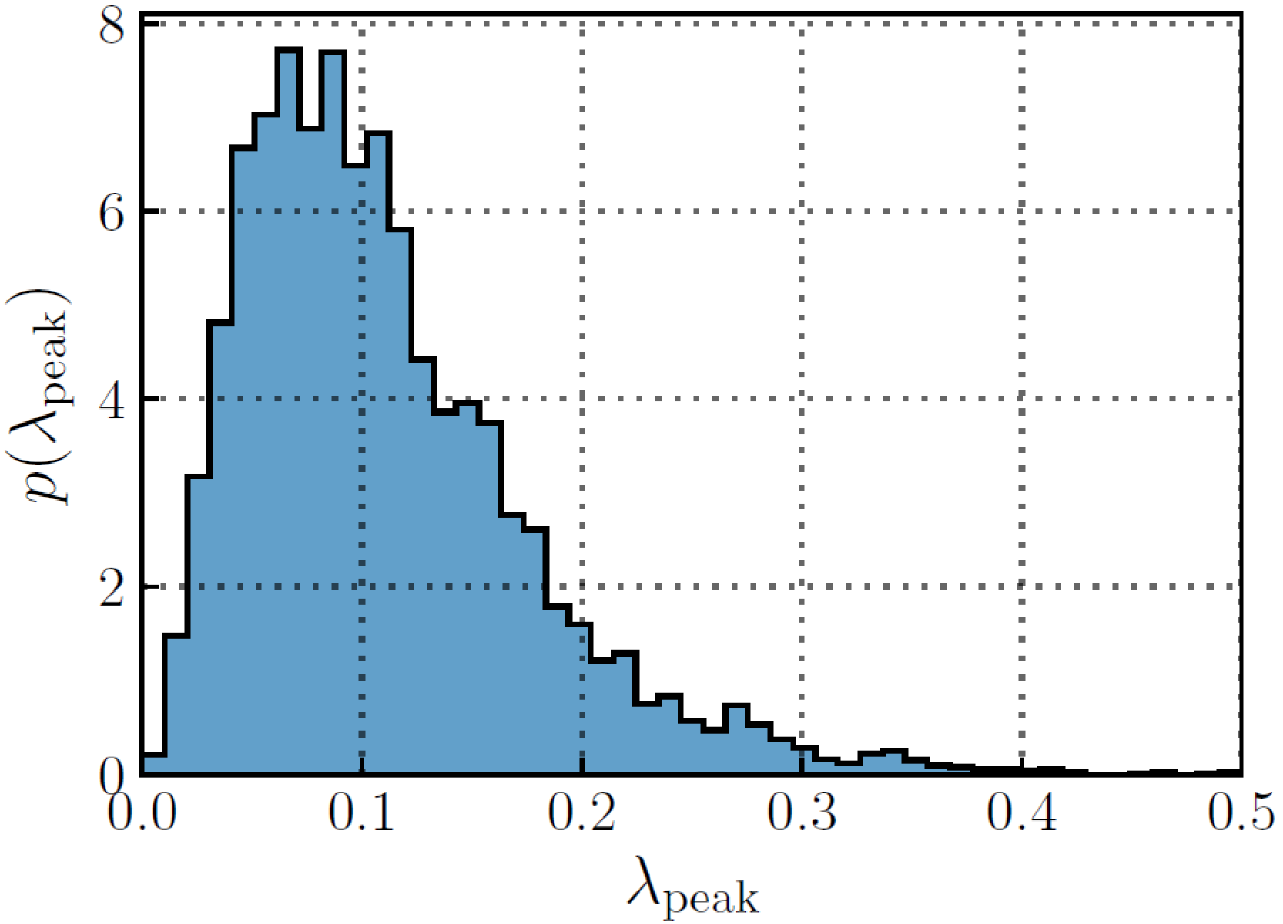
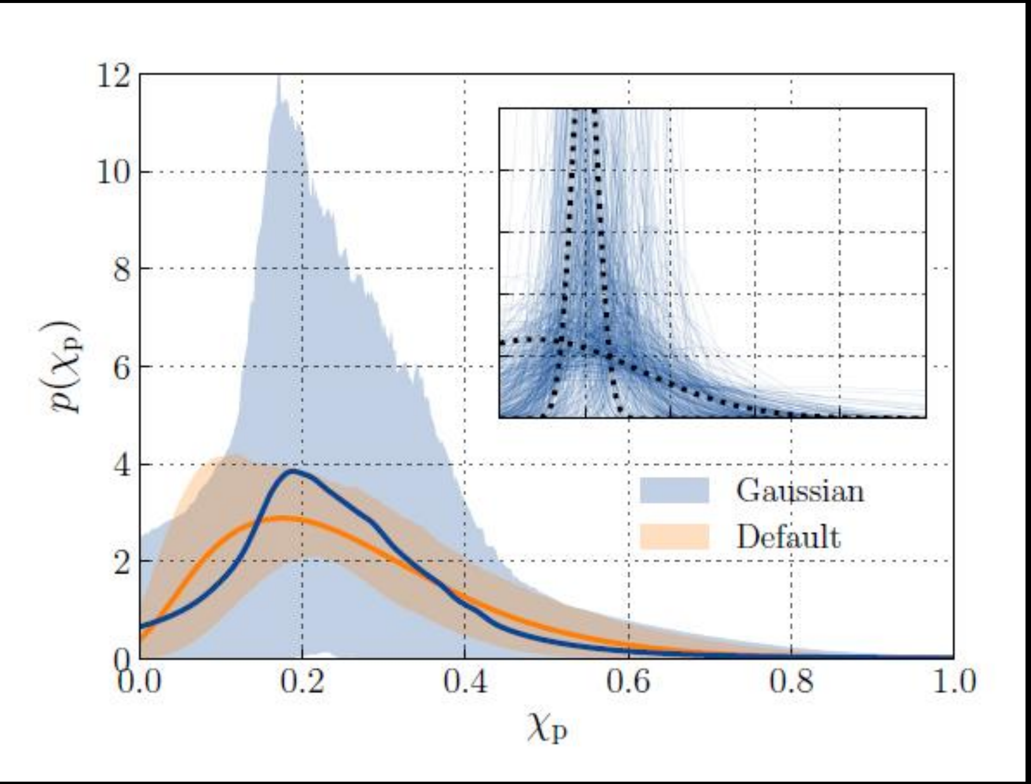
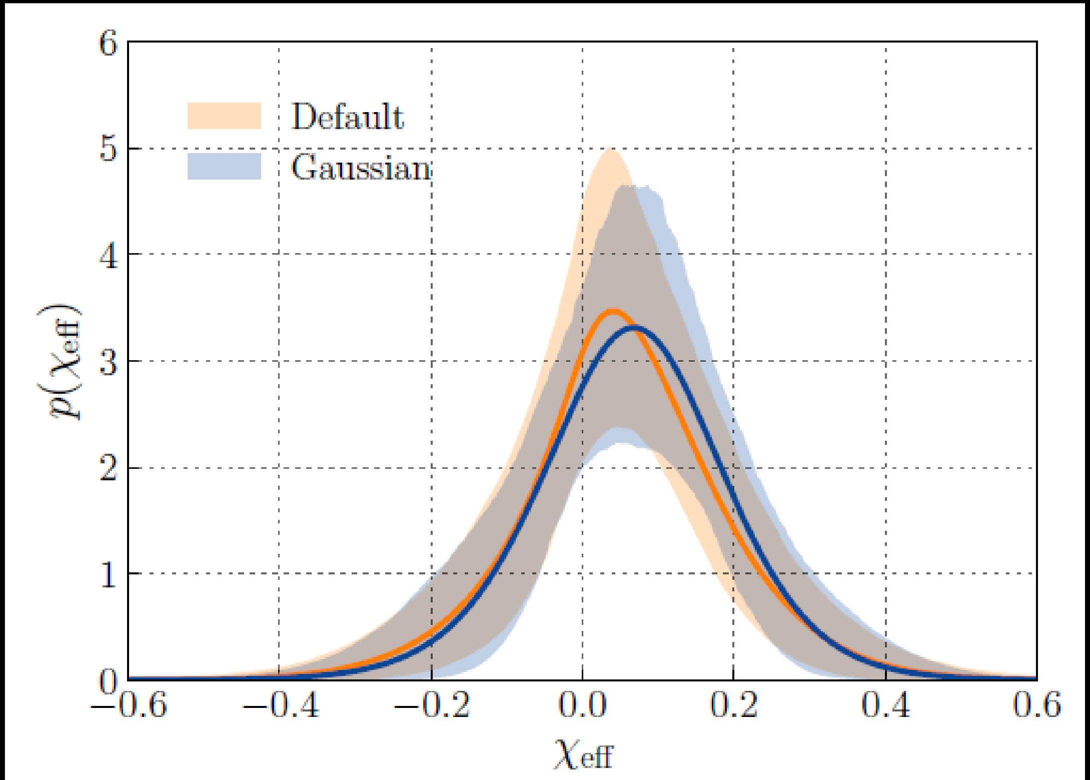


Figure 6. Posterior distribution on the fraction of binaries ($\lambda_{\rm peak}$) in the Gaussian component of Power Law + Peak model, under a flat prior on $\lambda_{\rm peak}$; see Appendix B.2. We find that $\lambda_{\rm peak} = 0$ (which corresponds to no Gaussian peak) is disfavored, supporting the hypothesis that there is a feature in the black hole primary mass spectrum.

Spin

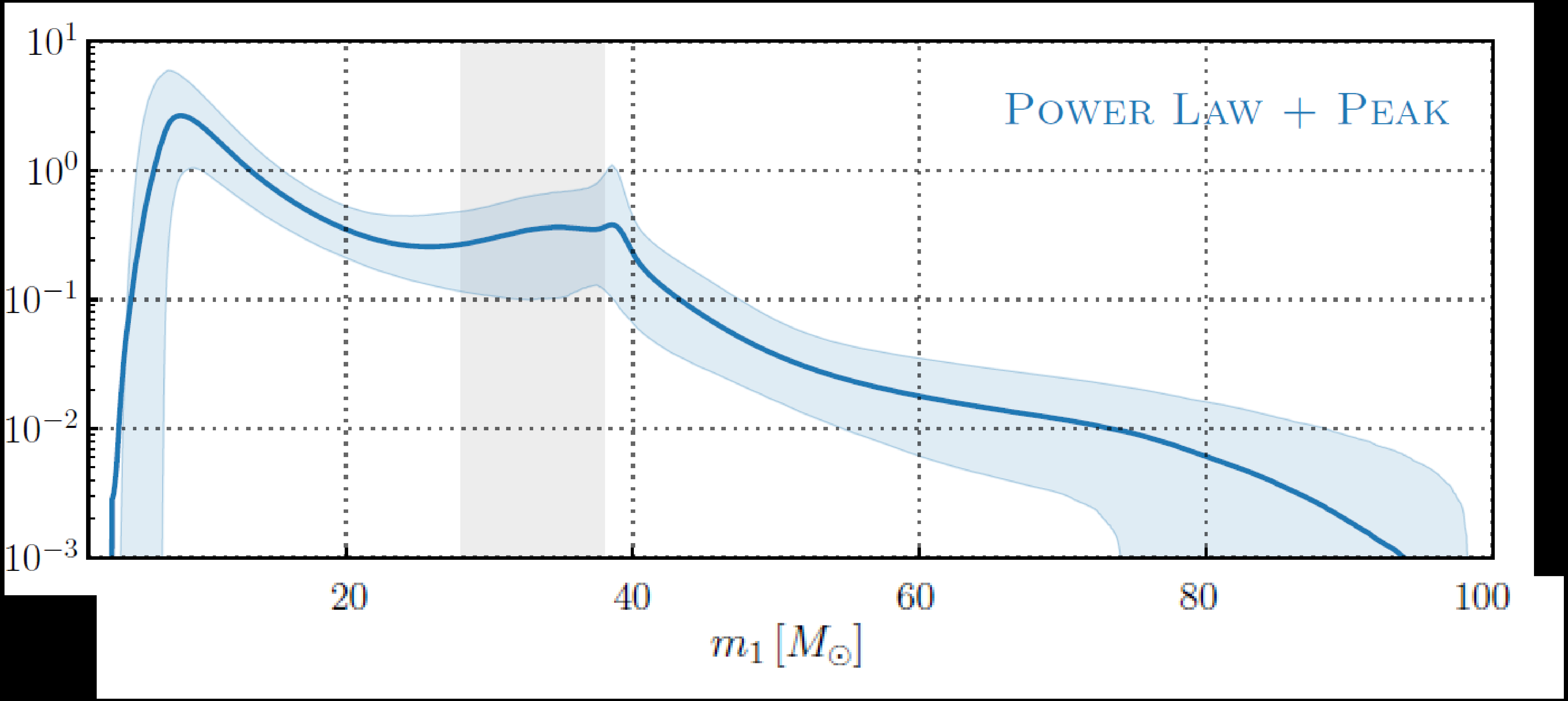


$$\chi_p = \max\left[\chi_1 \sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q\,\chi_2 \sin\theta_2\right]$$

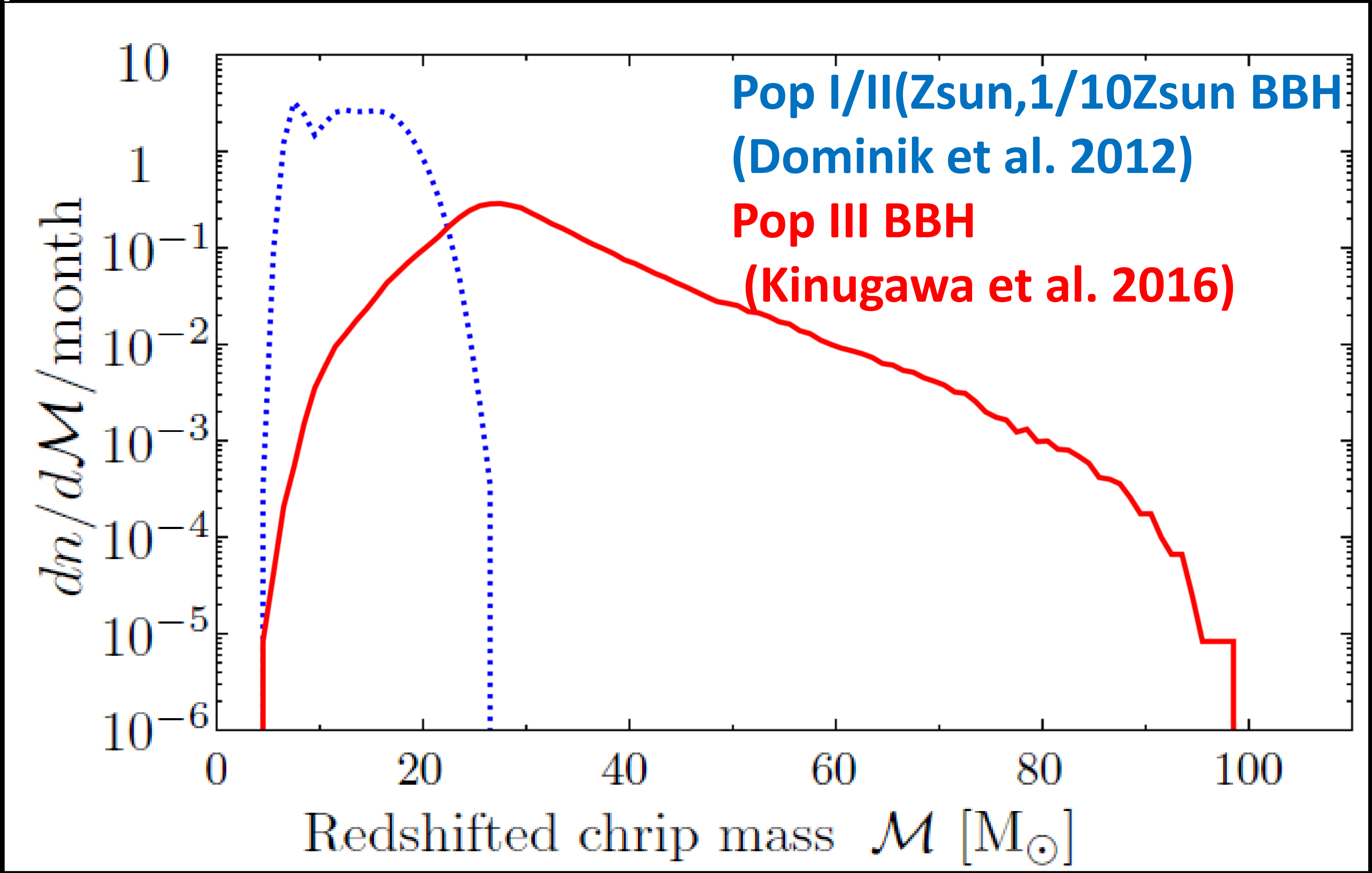


$$\chi_{eff} = \frac{\chi_1 \cos\theta_1 + q\,\chi_2 \cos\theta_2}{1+q}$$

LIGO result



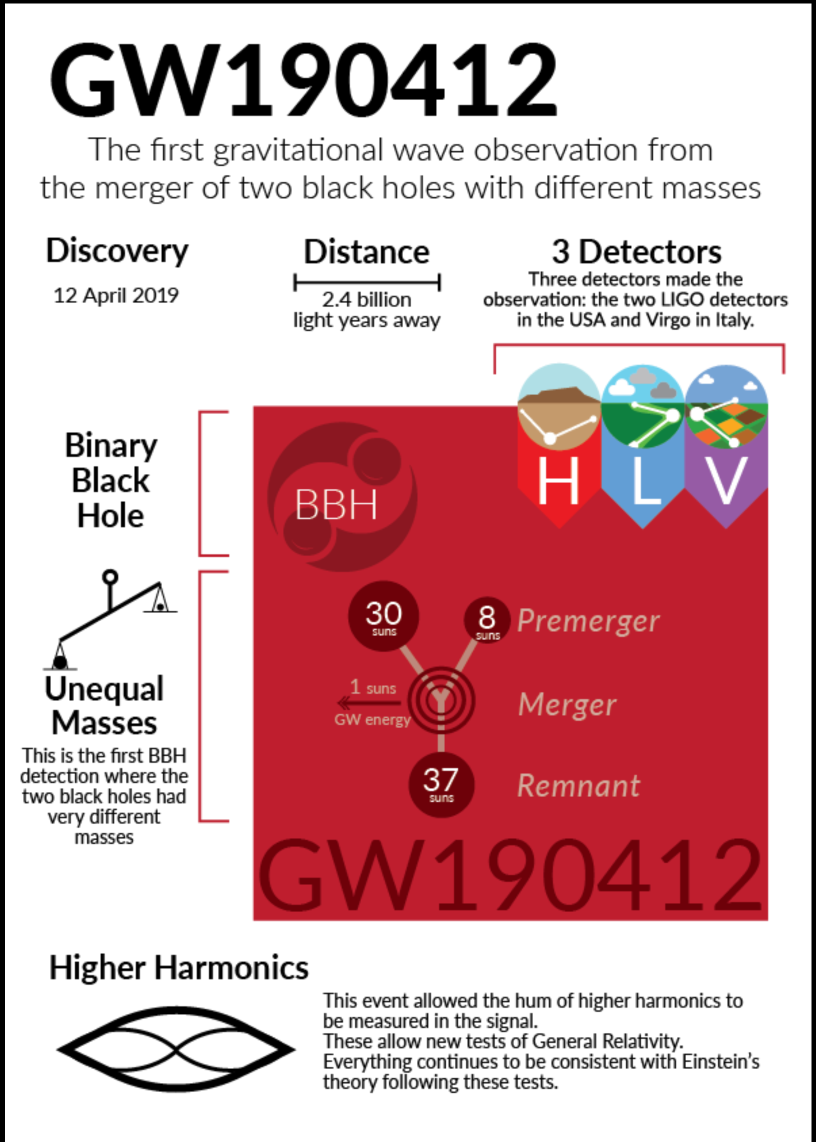
Our prediction

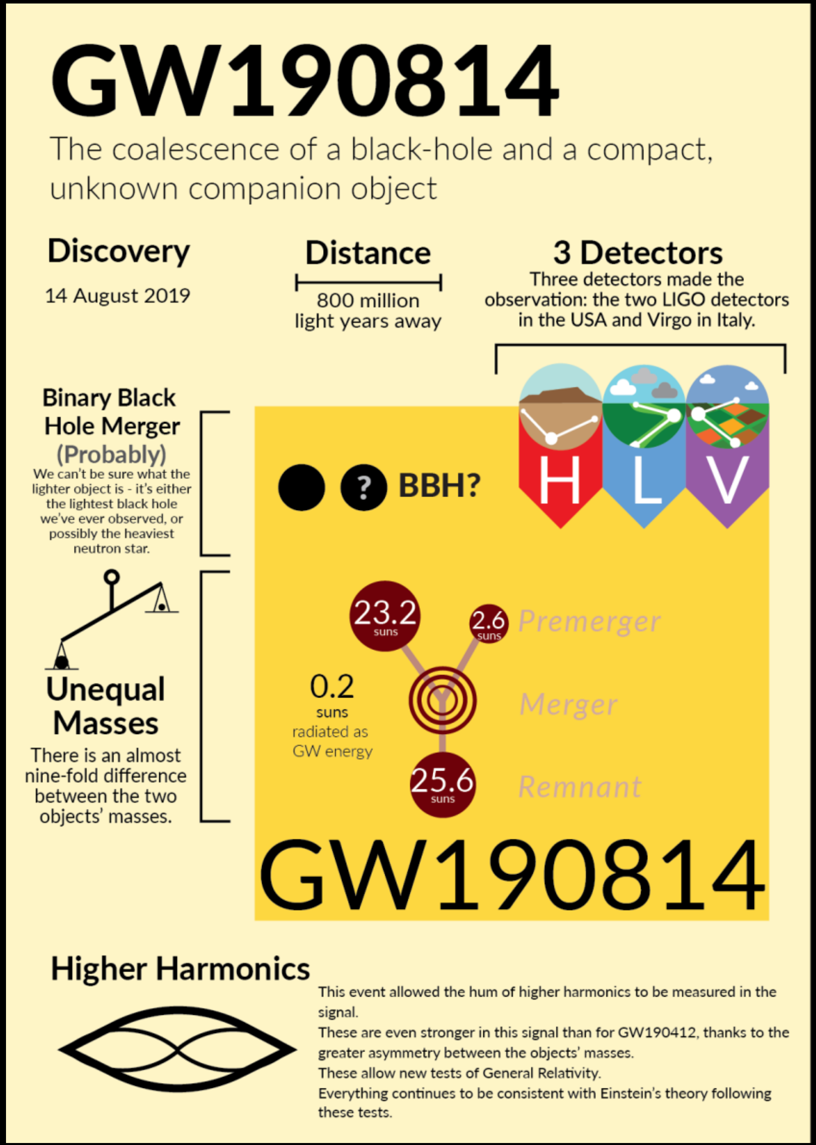


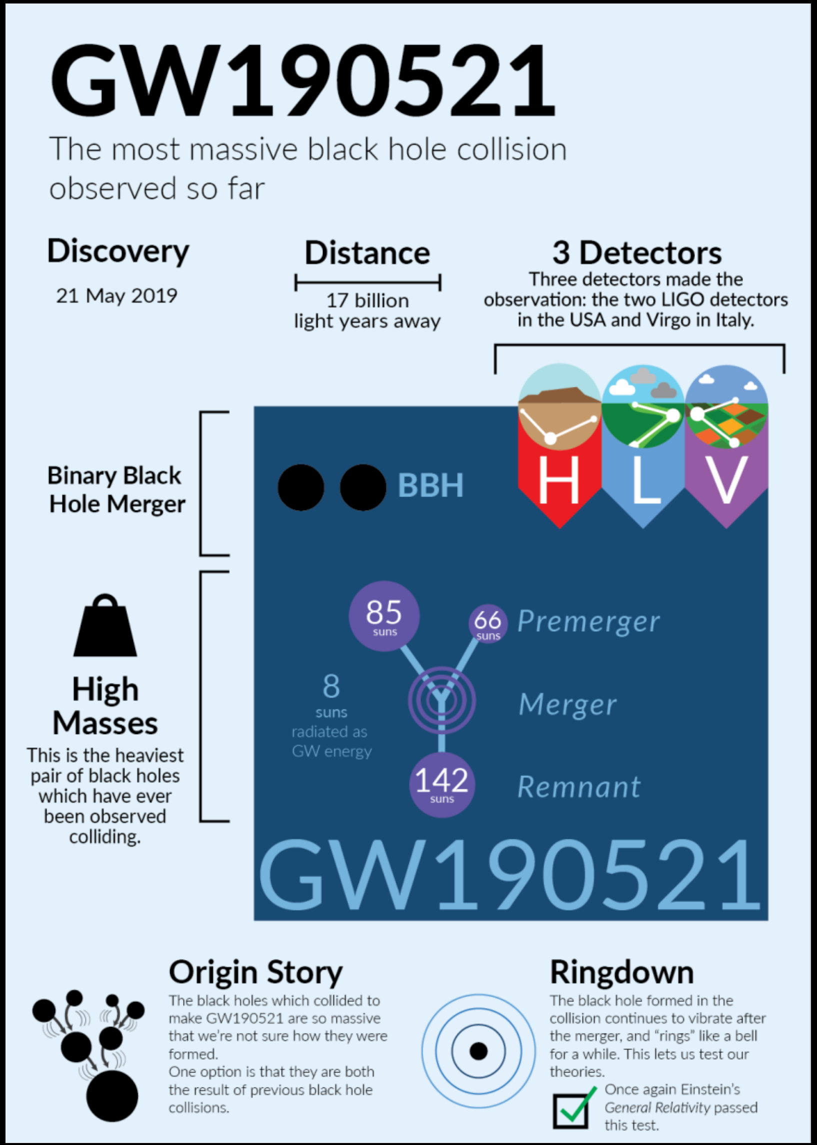
(Miyamoto et al. 2017)

$$\mathcal{M} = (1+z)\frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

Extraordinary BH events in O3a run

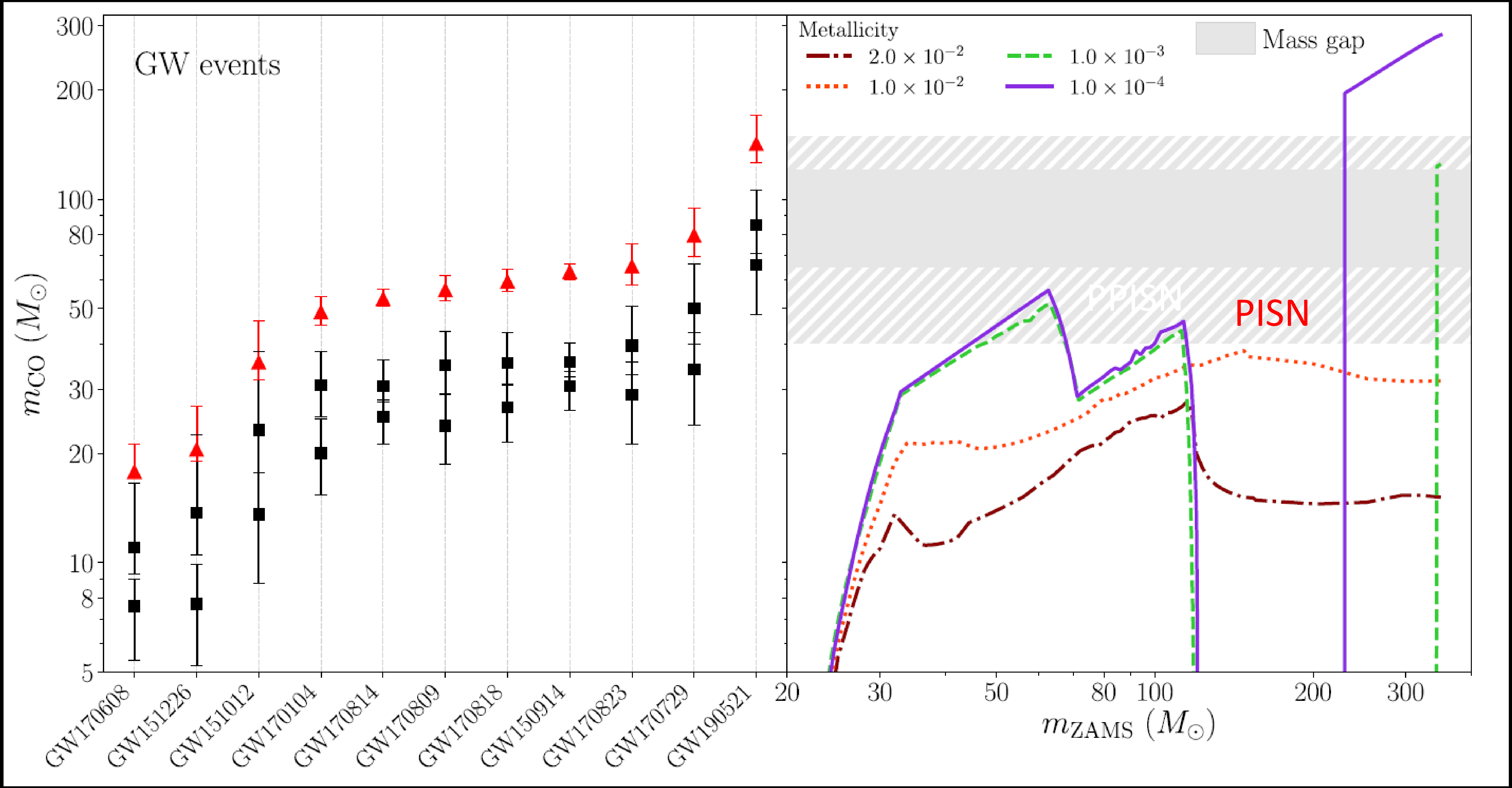






Why GW190521 is extraordinary BH

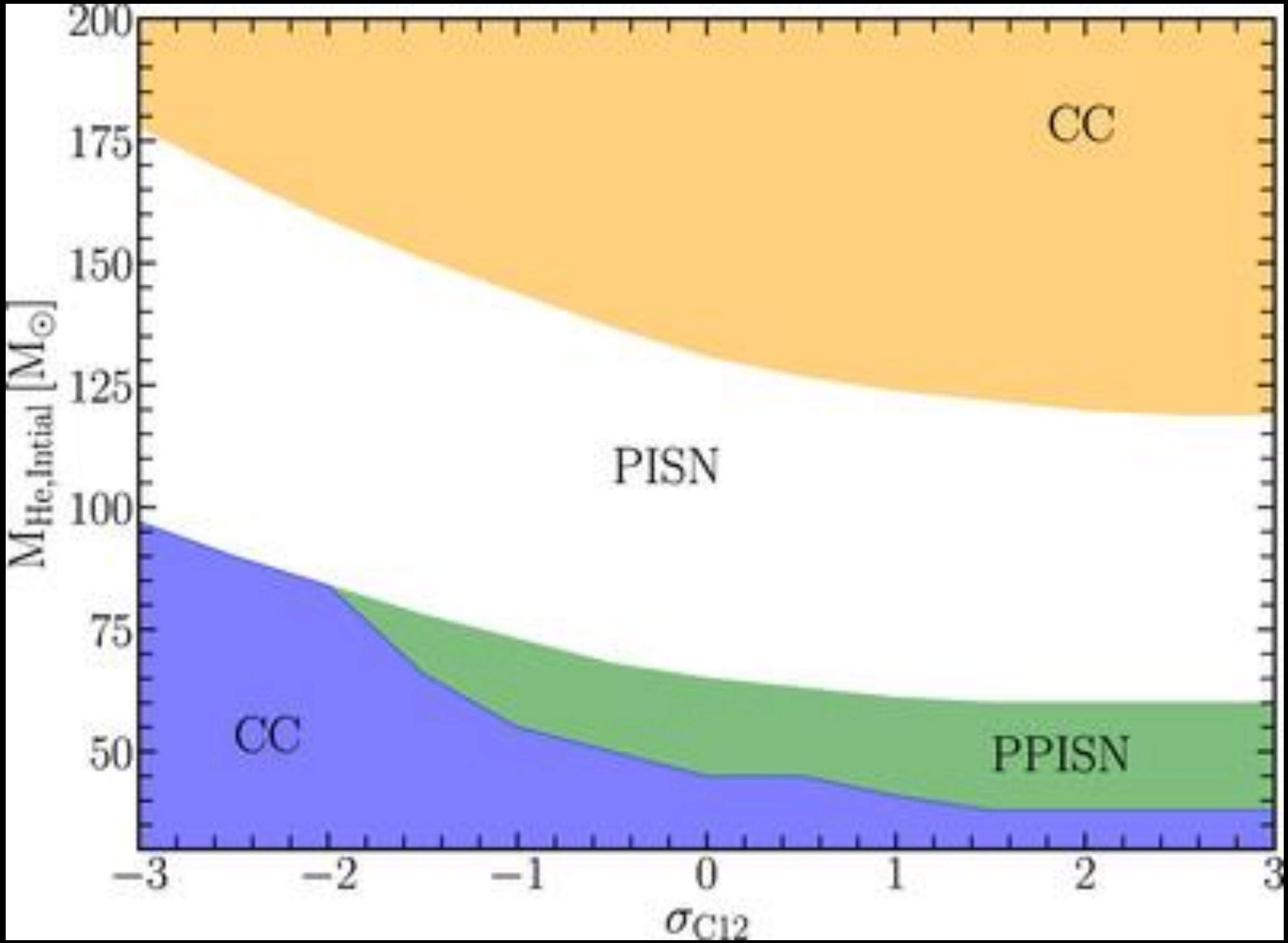
Mass 85Msun+66Msun



GW190521 Formation models

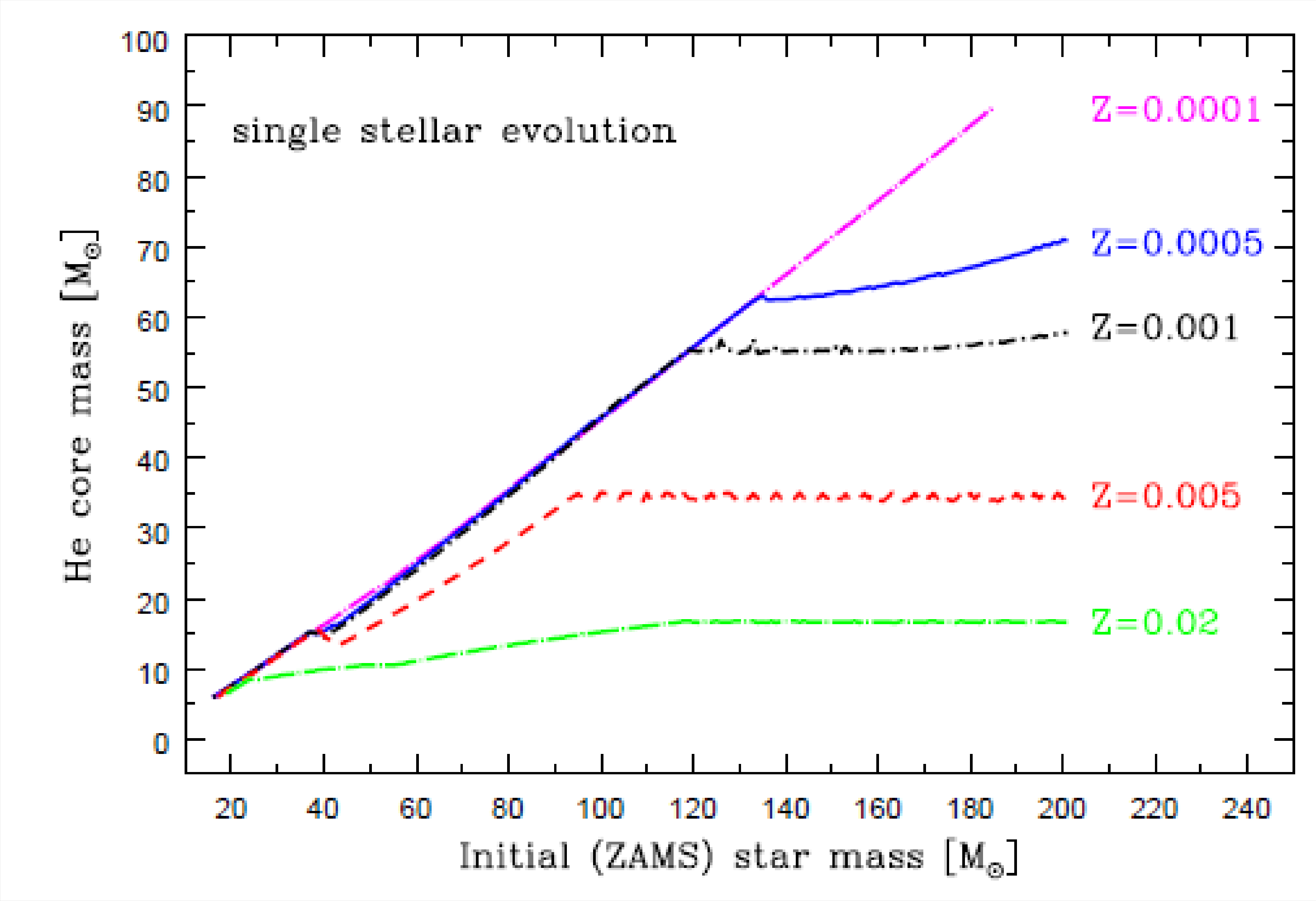
- Hierarchical Black-Hole Mergers (e.g. Liu &Lai 2020)
- Pop II without PPISN (Belczynski 2020)
- Pop III (Farrell et al. 2020, *Kinugawa et al.2020*, *Tanikawa et al. 2020*)
- Accretion onto BHs in dense molecular cloud (Rice et al.2020)
- Primordial BH, Modified Gravitation Theory, Beyond standard theory.....

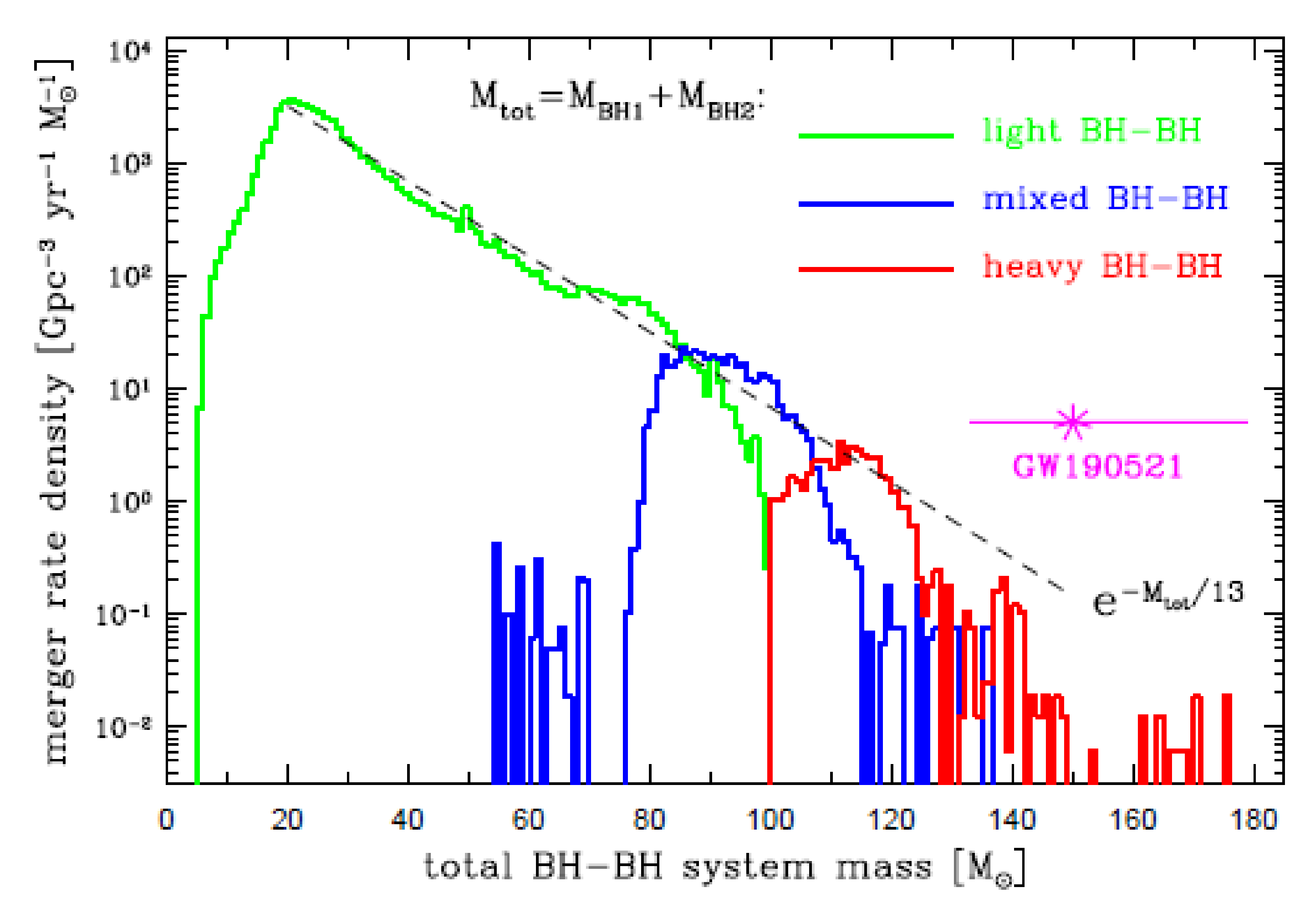
Pop II without PPISN



- Change 12C(α,γ)O rate

(Farmer et al. 2020)


single stellar evolution
Z=0.0001
Z=0.0005
Z=0.001
Z=0.005
Z=0.02
He core mass [M⊙]
Initial (ZAMS) star mass [M⊙]
0
10
20
30
40
50
60
70
80
90
100
20
40
60
80
100
120
140
160
180
200
220
240



$M_{tot} = M_{BH1} + M_{BH2}$:
light BH-BH
mixed BH-BH
heavy BH-BH
GW190521
$e^{-M_{tot}/13}$
merger rate density [Gpc^{-3} yr^{-1} $M_\odot^{-1}$]
total BH-BH system mass [$M_\odot$]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
20
40
60
80
100
120
140
160
180

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Calculation models

In the case of Pop III, it is still unknown how much envelope is elected by PPISN

- No PPISN model
- PPISN model

We calculate 10^6 Pop III binaries for each model.

SFR:ρ_{SFR}= 6×10^5 Msun/Mpc^3 (Inayoshi et al. 2015)

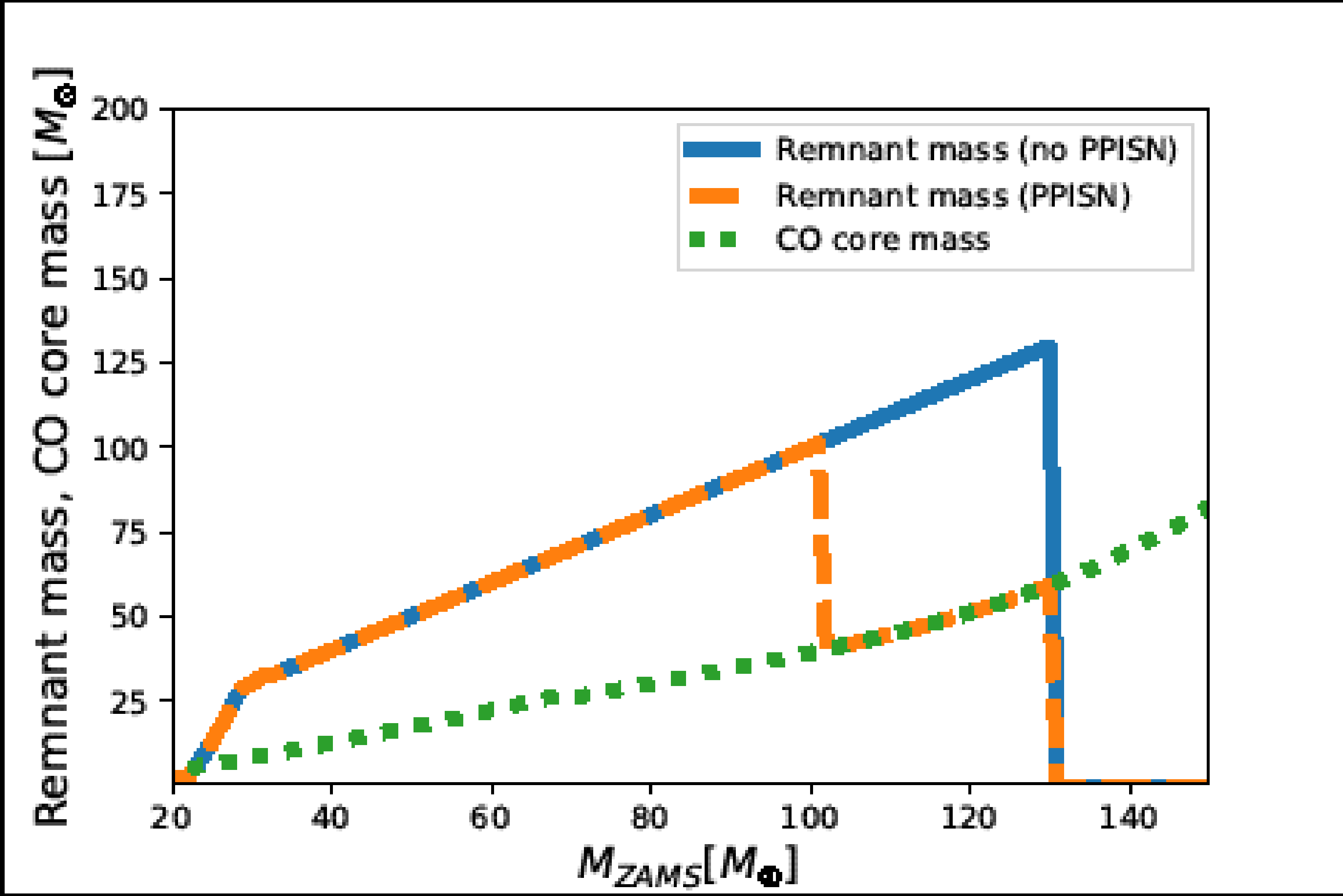
IMF: flat 10Msun<M<150Msun

Mass ration: flat 0<q<1

Separation: logflat a_{min}<a<10^6Rsun

Eccentricity: proportional to e, 0<e<1

Pop III remnant mass for single star case



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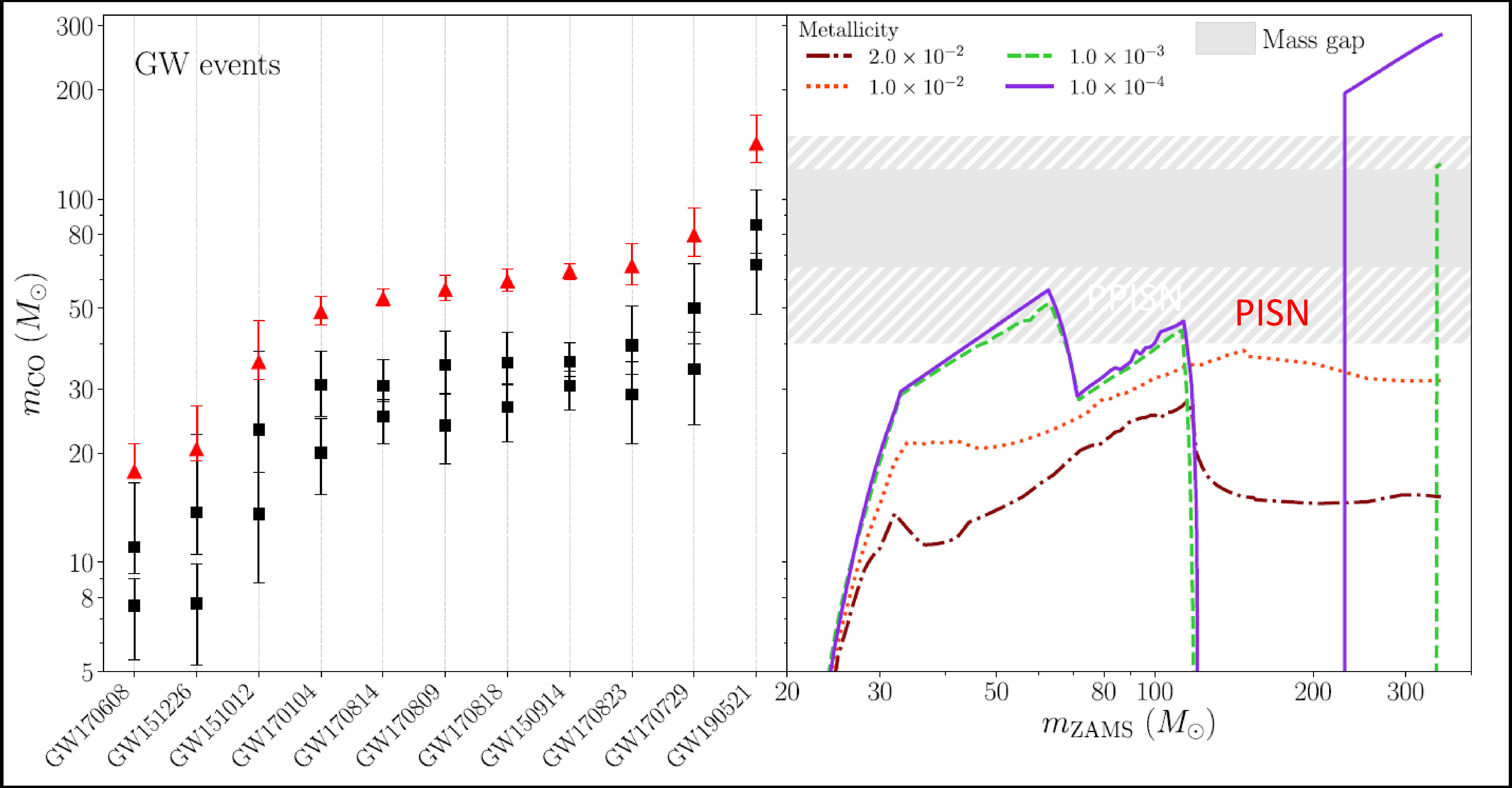
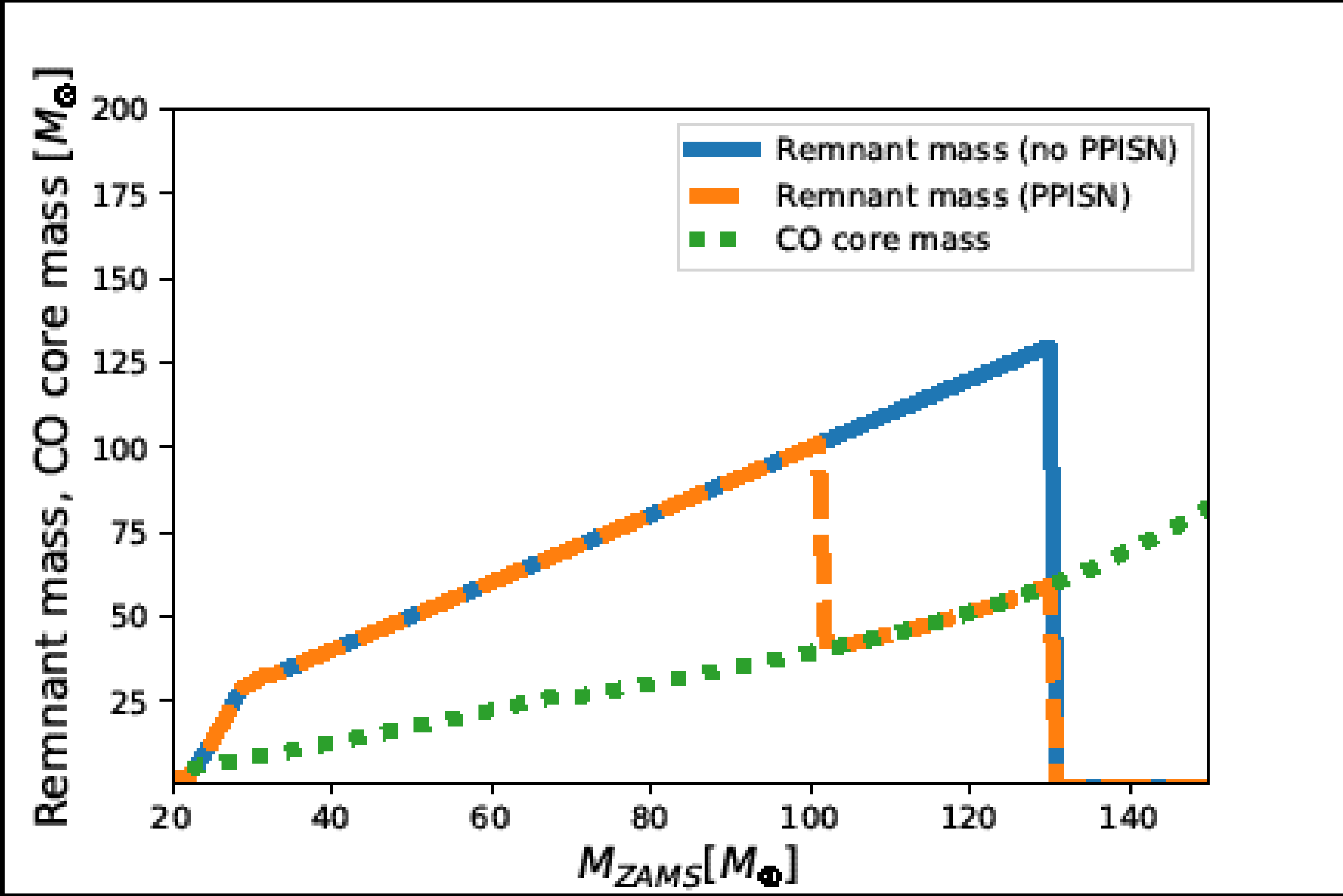
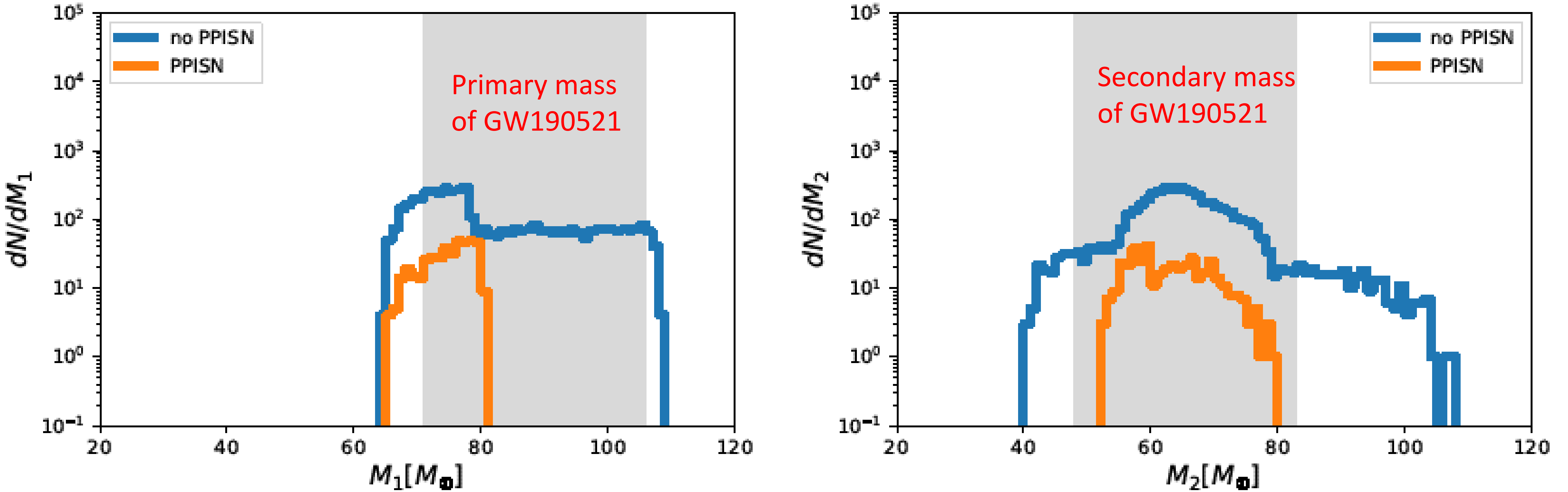


Pop III remnant mass for single star case



Masses of GW190521-like BBHs



Event rate

- 0.13 /yr/Gpc^3 for PPISN model
- 0.66 /yr/Gpc^3 for no PPISN model

- Detection rate of GW190521 is 0.02--0.43 /yr/Gpc^3

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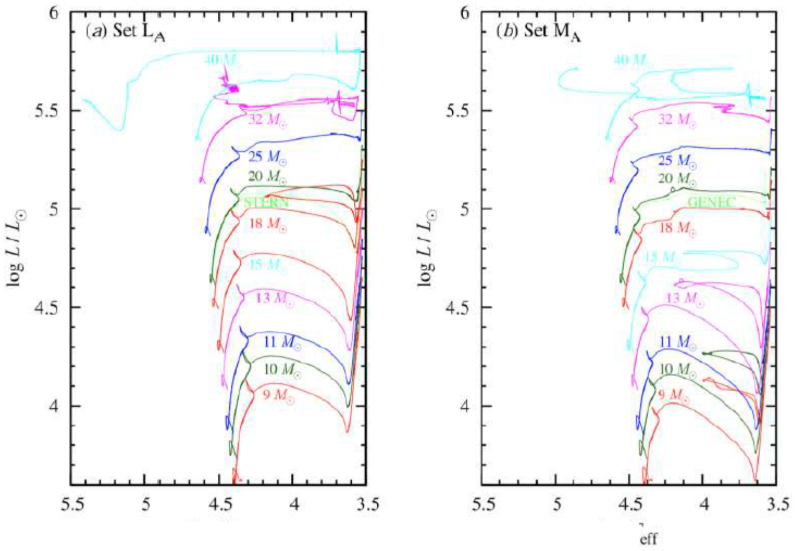
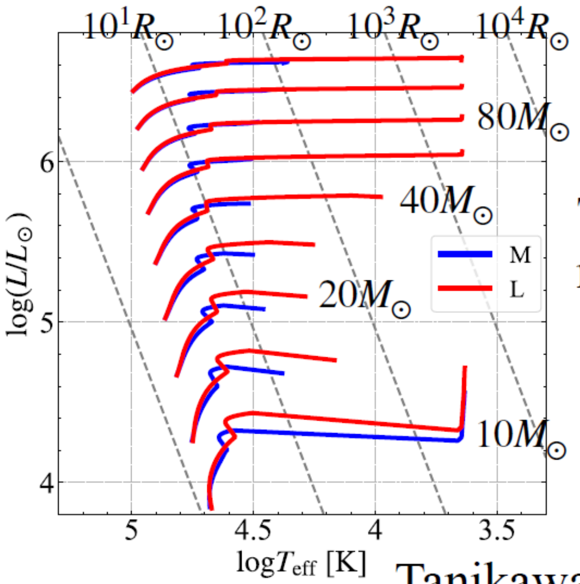
Uncertainty of Pop. III model

- No massive Pop. III star is discovered so far.
- Extrapolation from nearby stars to Pop. III stars
- Nearby star models
  - AB-type stars in MW open clusters, GENEC(Ekstrom et al. 2012), adopted by Farrell et al. (2020) **M model**
  - Early B-type stars in LMC, Stern (Brott et al. 2011) **L model**
- The maximums radius of a $80M_{\odot}$ star
  - M model: $\sim 40R_{\odot}$, similar to Farrell et al. (2020)
  - L model: $\sim 3 \times 10^3 R_{\odot}$, similar to Yoon et al. (2012)
- If the L model is correct, a Pop. III binary cannot form GW190521, the same as Pop. I/II binaries.

Yoshida et al. (2019)



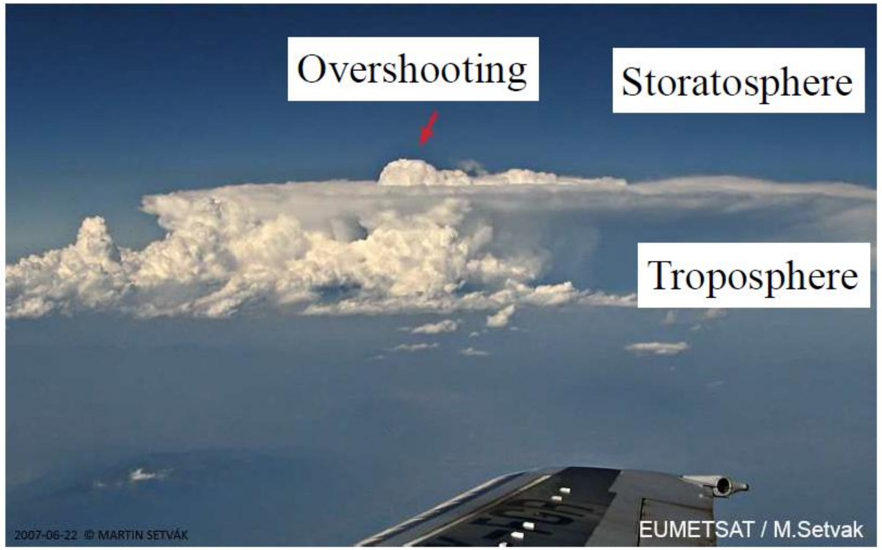


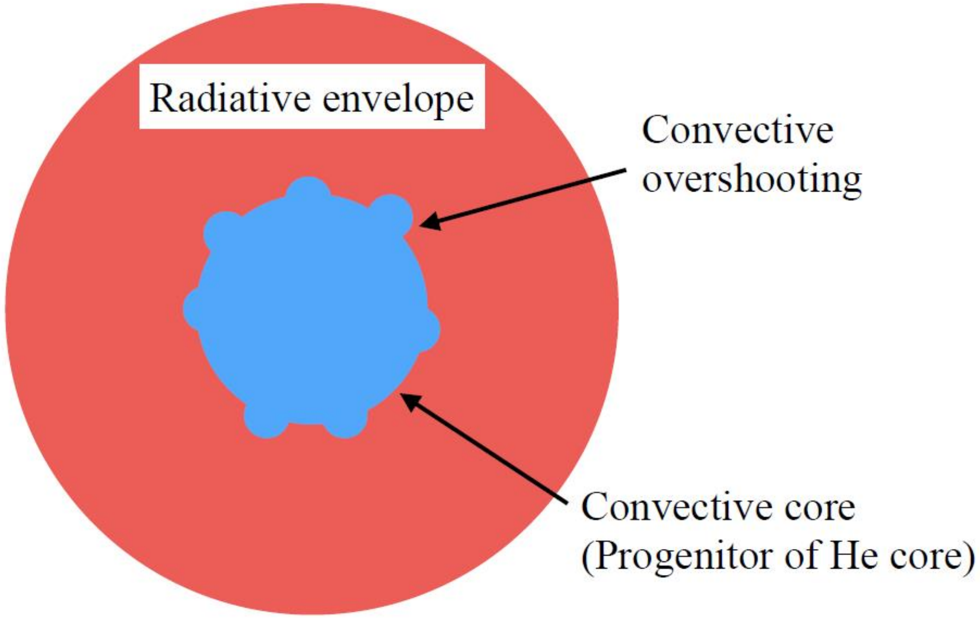
Two Pop. III models

Tanikawa et al. (2020c)

Convective overshooting

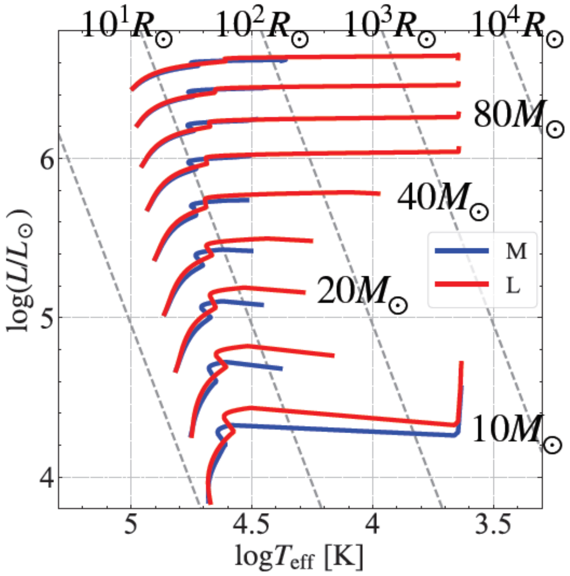
- Overshoot parameter: $f_{\rm ov} \sim 0.02$ (Kippenhahn et al. 1990; 2012)
  - $D(z) = D_0 \exp \dfrac{-2z}{f_{\rm ov} H_{\rm P}}$
  - M model: $f_{\rm ov} = 0.01$
  - L model: $f_{\rm ov} = 0.03$
- Larger overshoot parameter (more effective overshooting)
  - Larger He core at the end of MS
  - Larger luminosity in post-MS
  - Larger radius in post-MS

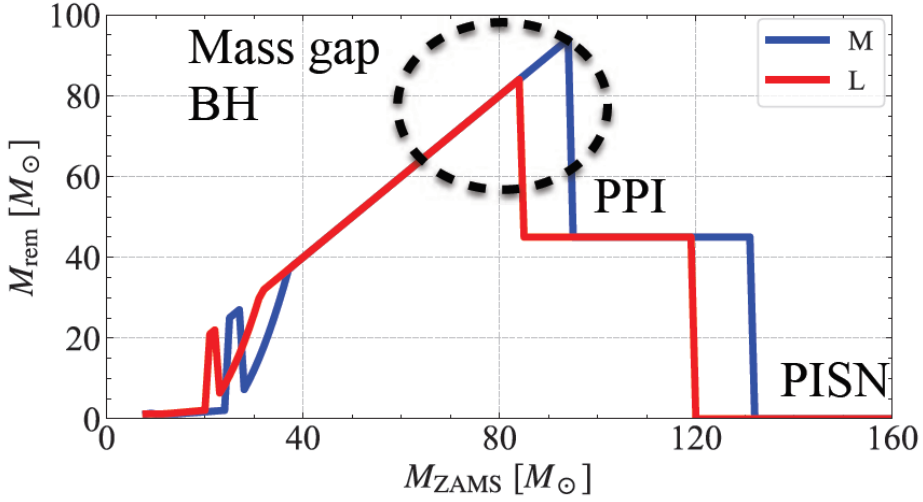




Binary population synthesis

- BSE (Hurley et al. 2000; 2002) modified by Tanikawa et al. (2020a)
- Single star evolution
  - Fryer's rapid model with PPI/PISN
  - No stellar wind nor BH natal kick
- Binary star evolution
  - Tidal interaction
  - Stable mass transfer, common envelope
  - GW orbital decay
  - Etc.
- Initial conditions
  - $f(m_1) \propto m_1^{-1}, f(q) \propto \mathrm{const}, f(a) \propto a^{-1}, f(e) \propto e$
- Cumulative Pop. III density
  - $\sim 10^{13} M_\odot \mathrm{pc}^{-3}$ comparable to Magg et al. (2016) and Skinner, Wise (2020)

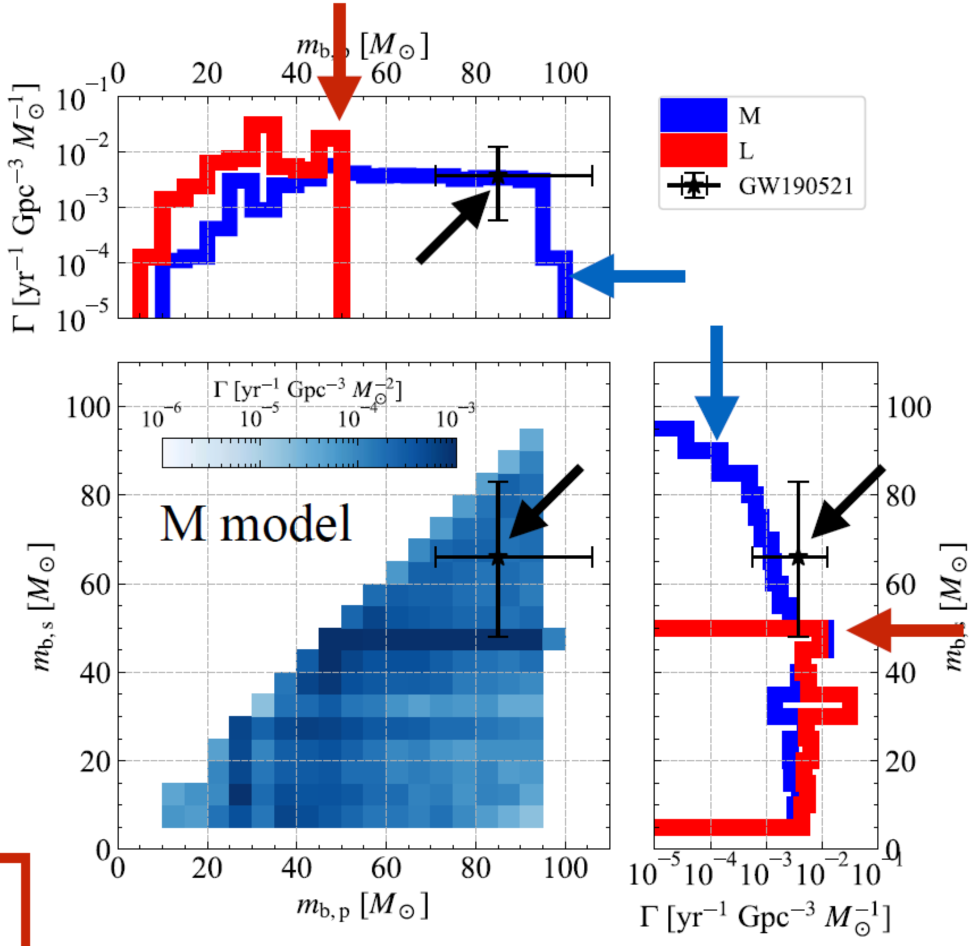




Tanikawa et al. (2020c)

BH mass distribution

- M model
  - The maximum mass: $\sim 100 M_\odot$
  - Stars lose little mass through binary interactions.
  - Pop. III stars can form GW190521-like BH-BHs.
  - Support for the claims of Farrell et al. (2020) and Kinugawa et al. (2020)
- L model
  - The maximum mass: $\sim 50 M_\odot$
  - Stars lose their H envelopes through binary interactions
  - No Pop. III stars can form GW190521-like BH-BHs.



It depends on the choice of Pop. III models, or overshoot parameters

Summary

- LIGO reported 50 GW events in O1-O3a.
- Primary Mass distribution : Power law +peak ?

  Pop III? Pop II+ PPISN? Hierarchical merger?...
- Maximum mass of primary BH~90Msun

  Pop III? Pop II+noPPISN? Hierarchical mergers?...