連星ブラックホール形成：孤立連星と球状星団

Binary black hole formation: binary evolution and dynamical capture

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初代星・初代銀河研究会，First star and first galaxy

２０２０年１１月，東北大学, Nov. 2020, Tohoku U.

Contents

- From O1/O2 to O3a
- Globular clusters
- Pop. III binaries

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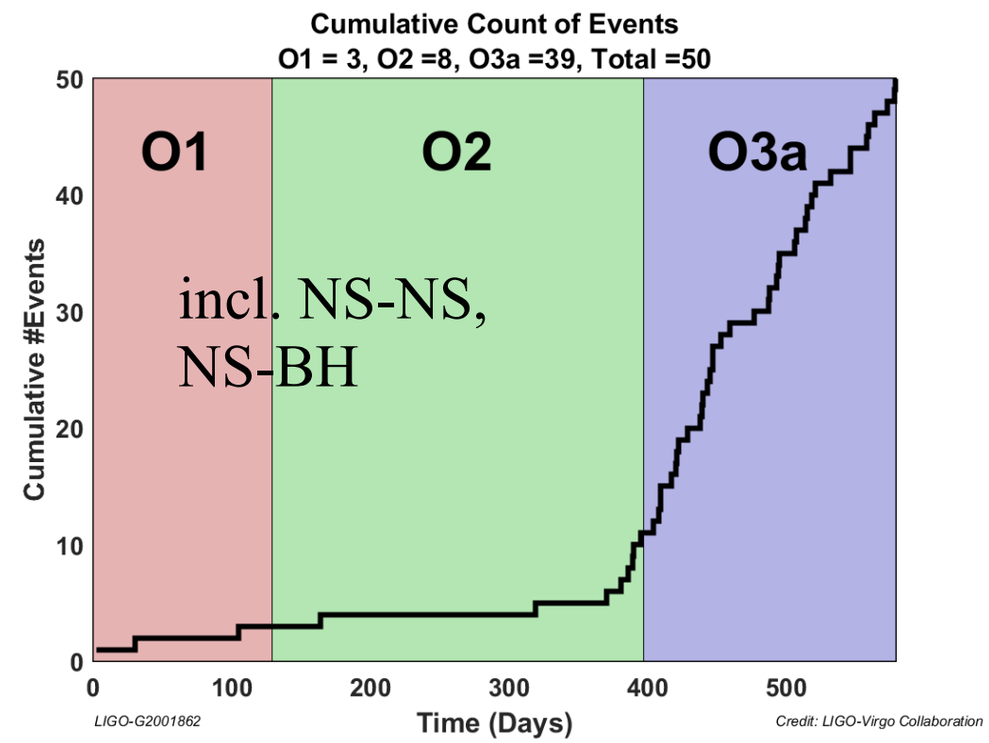
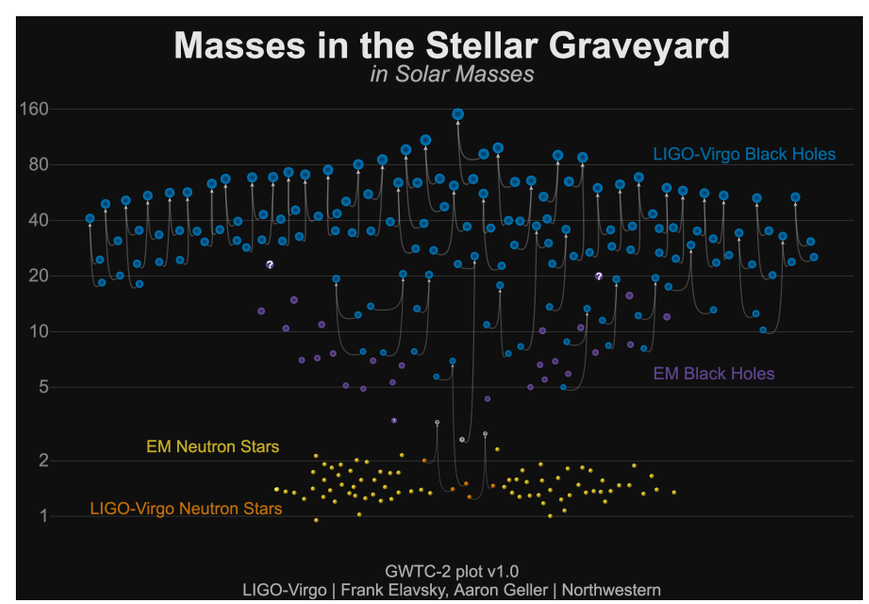
GW events

- The first detection GW150914 in 2015 (only LIGO)
- 10 BH-BHs discovered in O1/O2 by 2017 (entry of Virgo)
- 44 confident BH-BHs in O1/O2/O3a by the last month
- GW sensitivity to NS-NSs
  - H: 66Mpc to 108Mpc
  - L: 88Mpc to 135Mpc
  - V: 26Mpc to 45Mpc



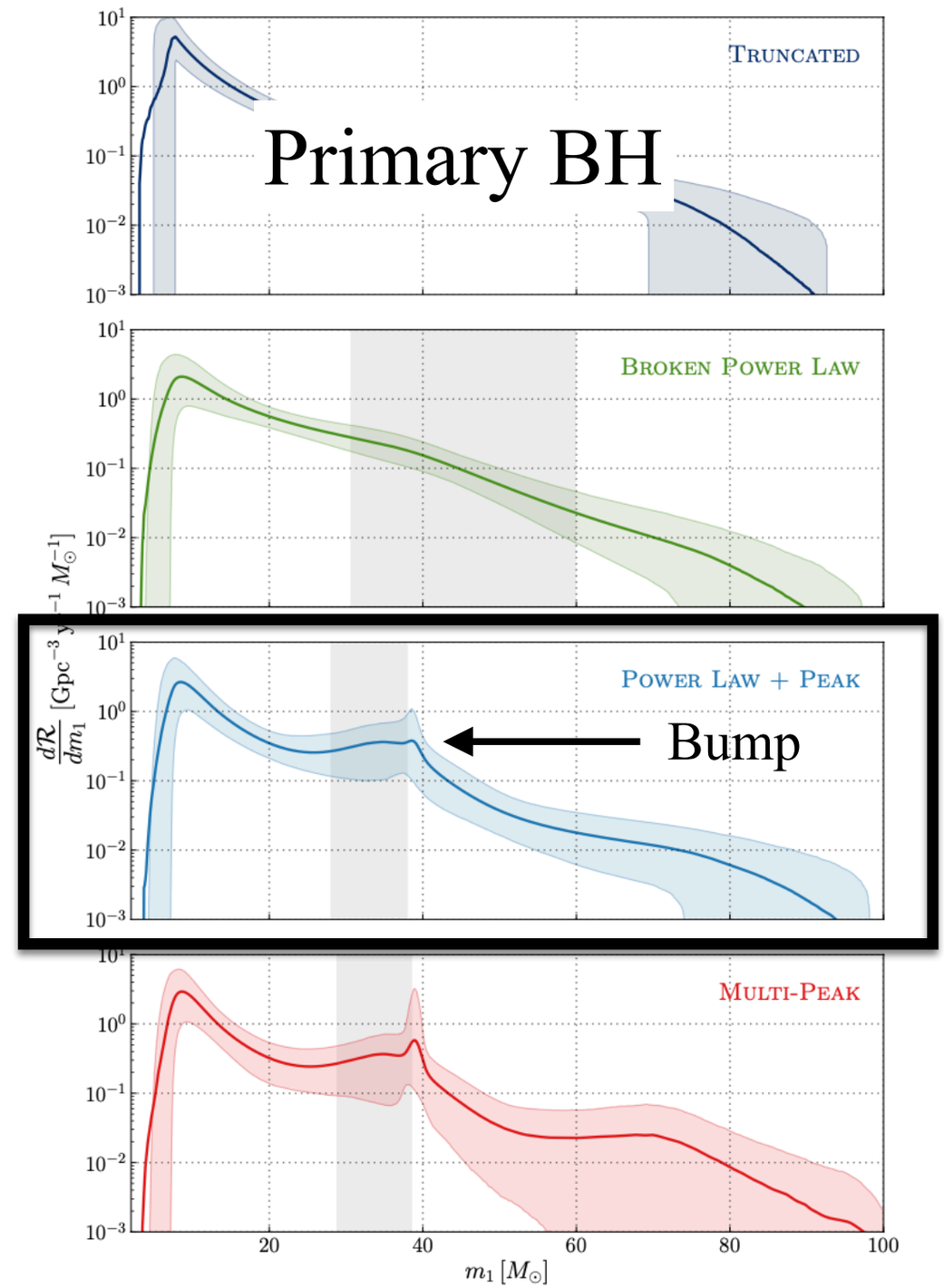


BH-BH rate density

- O1/O2: $53.2^{+55.8}_{-28.2}$ Gpc^{-3} yr^{-1}
- O1/O2/O3a
  - No cosmic evolution: $23.9^{+14.9}_{-8.6}$ Gpc^{-3} yr^{-1}
  - Cosmic evolution: $19.7^{+57.3}_{-15.9}$ Gpc^{-3} yr^{-1} at $z = 0$
- $\sim 10 - 100$ Gpc^{-3} yr^{-1} $\rightarrow$ ~ 10 Gpc^{-3} yr^{-1}
- Good news for scenarios other than binary evolution?

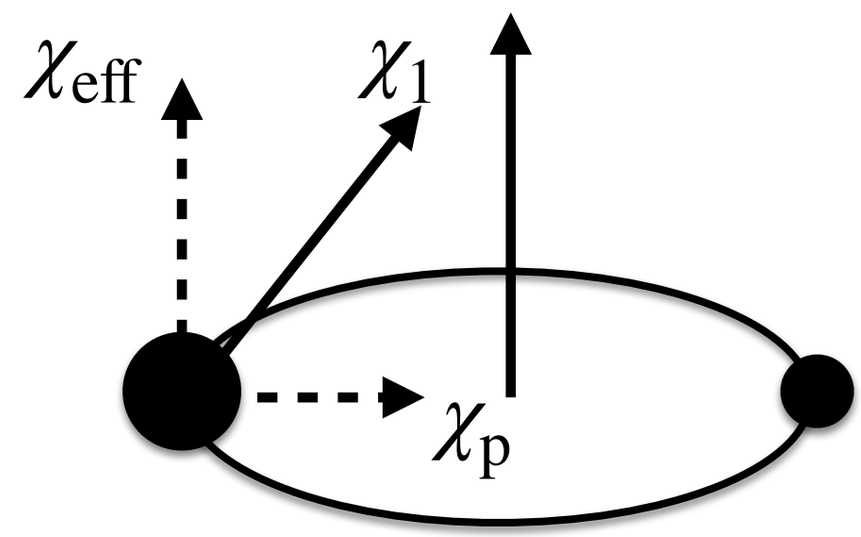
BH mass distribution

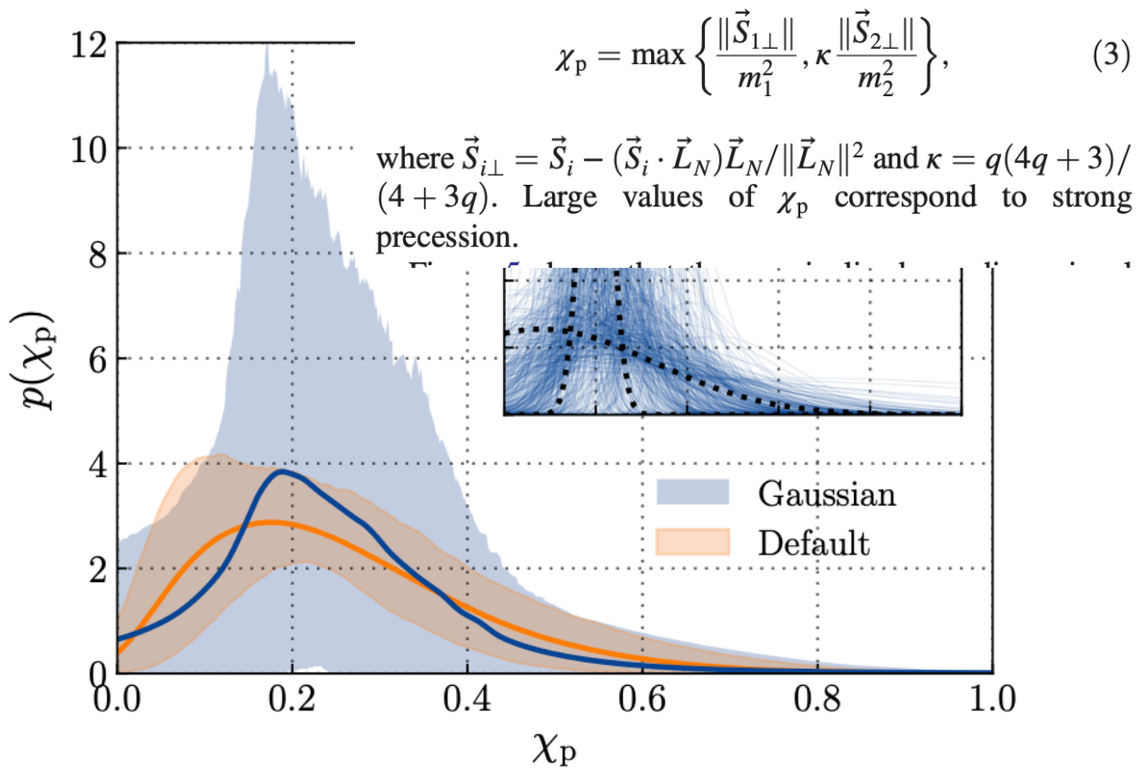
- Primary BH
  - Global maximum at $7.8^{+2.2}_{-2.1} M_\odot$
    - Lower mass gap inferred by BH X-ray binaries
  - Break or bump at $\sim 40 M_\odot$
    - Pair instability (or Pop. III?)
- Mass ratio
  - Consistent with $q = m_2/m_1 \sim 1$
  - But, see GW190412, GW190426_152155 (NS-BH?) and GW190814 (NS-BH?)

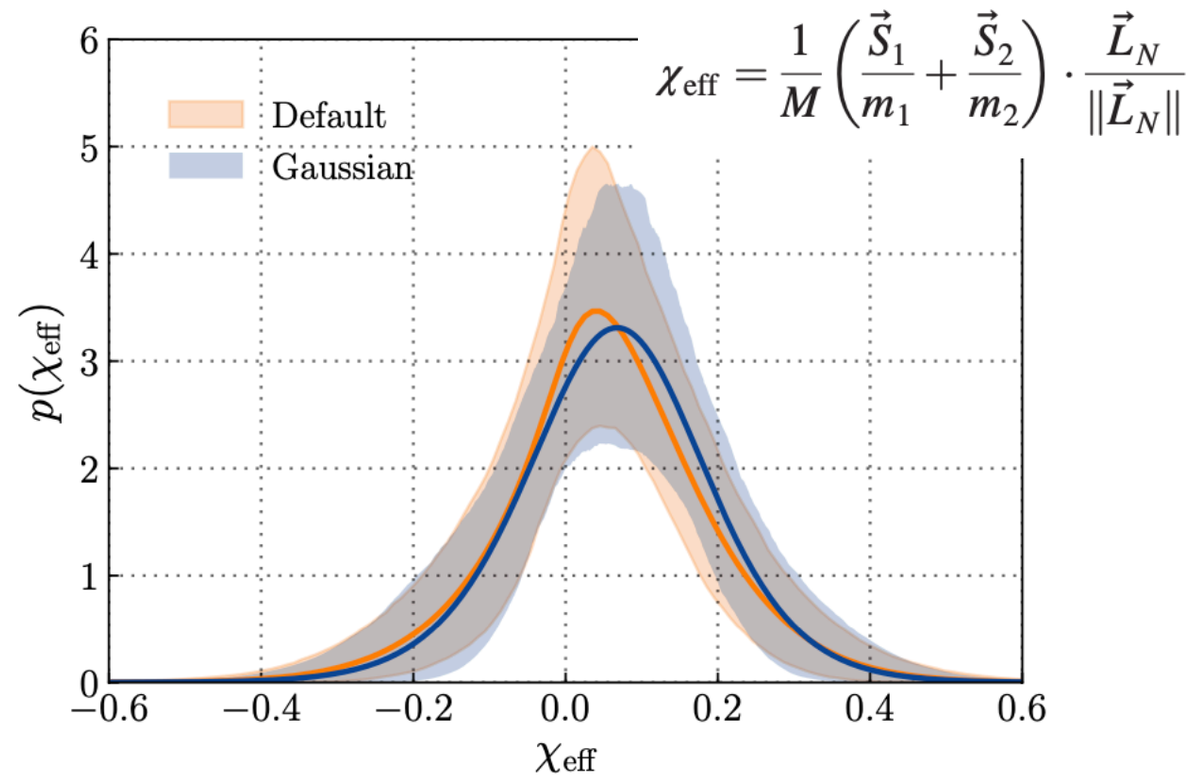


BH spin distribution

- 12-44% of BH-BH spins tilted by $> 90^\circ$
  - ~ 500 km/s BH kick?
  - Intrinsic spin?
  - Dynamical capture?
- No single event with $\chi_p > 0$ nor $\chi_{eff} < 0$

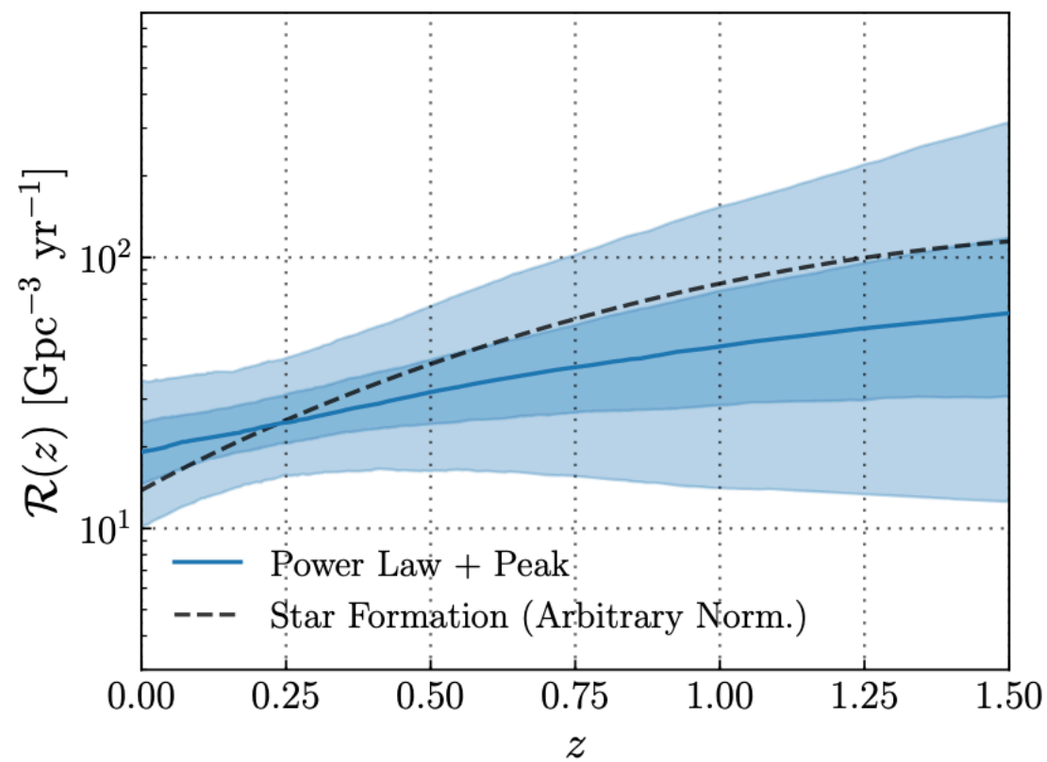






Cosmic evolution

- $\mathscr{R}_{\mathrm{BH-BH}} \propto (1+z)^{\kappa}$
- Consistent with a non-evolving distribution ($\kappa = 0$)
- But, more consistent with $\kappa = 1.3^{+2.1}_{-2.1}$ and $\kappa = 1.8^{+2.1}_{-2.2}$
- Slower than the star formation rate ($\kappa = 2.7$)
- BH-BHs with long delay time



BH-BH formation scenarios

- Binary evolution (Kinugawa's talk)
  - Pop. I/II common envelope evolution
  - Pop. I/II chemically homogeneous evolution
  - Pop. III stable mass transfer
- Dynamical capture in dense stellar clusters
  - Globular cluster (Alessandro's and Long's talks)
  - Open cluster (Kumamoto's and Alessandro's talks)
  - Galactic center (Tagawa's talk)
- Hierarchical multiple star evolution
- Primordial BH

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Black hole budget (GC)

- BH-BH density: $n_{\mathrm{BH-BH}} \sim 10^{11}\mathrm{Gpc}^{-3} \left(\frac{\Gamma_{\mathrm{BH-BH}}}{10\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}}\right) \left(\frac{T_{\mathrm{Hubble}}}{10\mathrm{Gyr}}\right)$
- Binary evolution:
  - $n_{\mathrm{BH,star}} \sim 10^{15}\mathrm{Gpc}^{-3} \left(\frac{\rho_{\mathrm{star}}}{10^{18}M_{\odot}\mathrm{Gpc}^{-3}}\right) \left(\frac{\eta_{\mathrm{BH}}}{10^{-3}M_{\odot}}\right)$
  - $\frac{n_{\mathrm{BH-BH}}}{n_{\mathrm{BH,star}}} \sim 10^{-4} \left(\frac{\Gamma_{\mathrm{BH-BH}}}{10\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}}\right)$
- Dynamical capture in globular clusters:
  - $n_{\mathrm{BH,GC}} \sim 10^{12}\mathrm{Gpc}^{-3} \left(\frac{\rho_{\mathrm{star}}}{10^{18}M_{\odot}\mathrm{Gpc}^{-3}}\right) \left(\frac{\eta_{\mathrm{BH}}}{10^{-3}M_{\odot}}\right) \left(\frac{\rho_{\mathrm{GC}}/\rho_{\mathrm{star}}}{10^{-3}}\right)$
  - $\frac{n_{\mathrm{BH-BH}}}{n_{\mathrm{BH,GC}}} \sim 0.1 \left(\frac{\Gamma_{\mathrm{BH-BH}}}{10\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}}\right) \left(\frac{\rho_{\mathrm{GC}}/\rho_{\mathrm{star}}}{10^{-3}}\right)$

Abbott et al. (2020)

Kroupa (2001), $M_{\mathrm{zams}} \gtrsim 20M_{\odot} \rightarrow$ BH

Madau, Dickinson (2014)

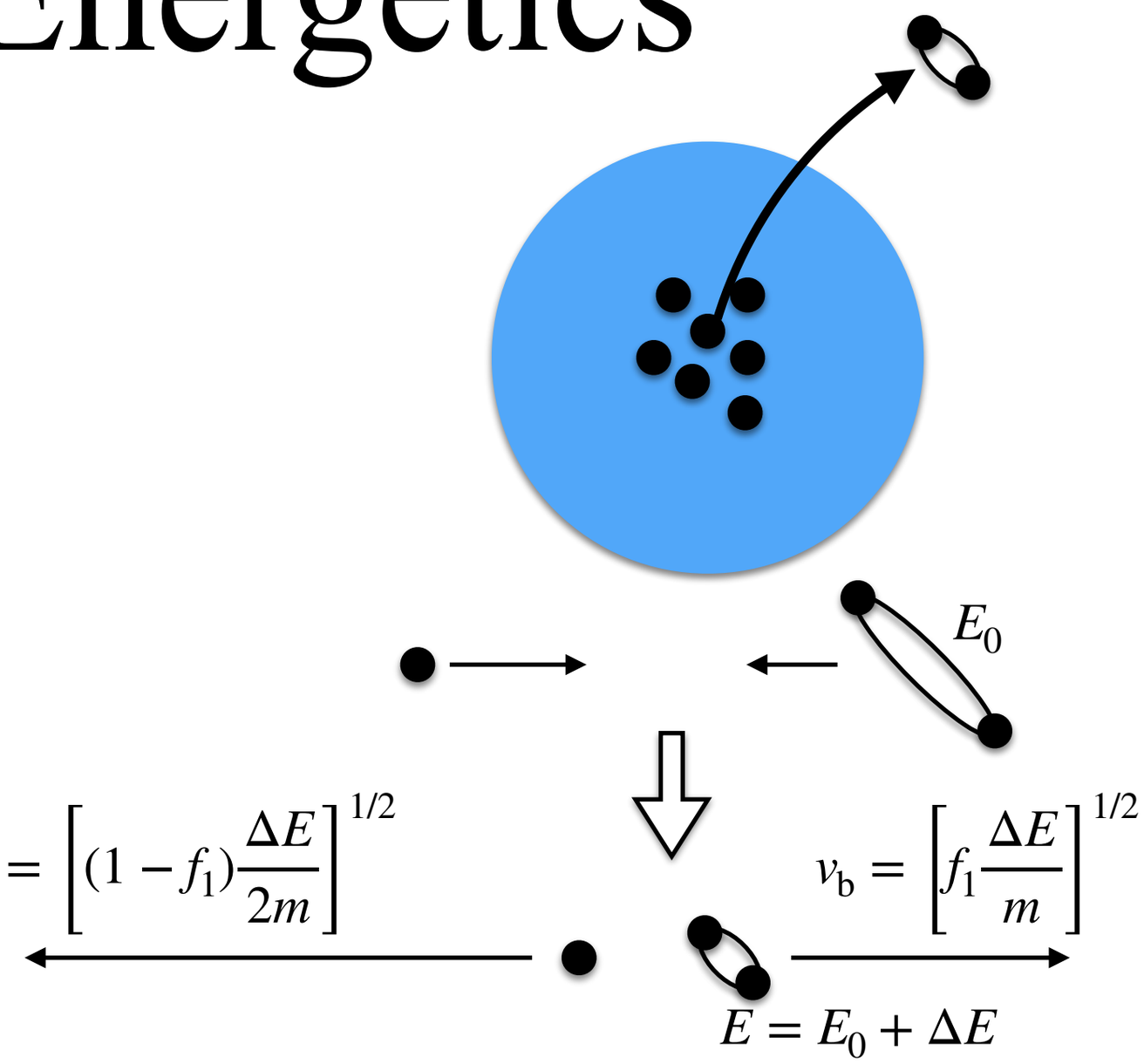
MW GC

Supplementary budget

- More many GCs at the formation time ($\rho_{\rm GC}/\rho_{\rm star} > 10^{-3}$)
  - Gas expulsion
  - Stellar evolution mass loss (stellar wind, supernova)
  - Thermodynamical evaporation
- Repeated mergers (e.g. Rodriguez et al. 2019)
- Dark clusters (e.g. Wang 2020)

BH-BH Energetics

- $t_{\rm gw} = \frac{5}{256}\frac{c^5}{G^3}\frac{a^4}{m_1 m_2 (m_1+m_2)} g(e)$
  - $g(e) = \frac{(1-e^2)^{3.5}}{1+(73/24)e^2+(37/96)e^4}$
- $a_{\rm esc} = \frac{f_1 f_2}{2}\frac{Gm}{v_{\rm esc}^2}$
  - $v^2 = f_1 \frac{\Delta E}{m}$
  - $\Delta E = f_2 E = f_2 \frac{Gm^2}{2a}$
- $t_{\rm gw} = 12{\rm Gyr}\left(\frac{f_1}{1/3}\right)^4\left(\frac{f_2}{1/1.4}\right)^4\left(\frac{m}{30M_\odot}\right)\left(\frac{v_{\rm esc}}{50{\rm km/s}}\right)^{-8}\left(\frac{g(e)}{g(0.9)}\right)$

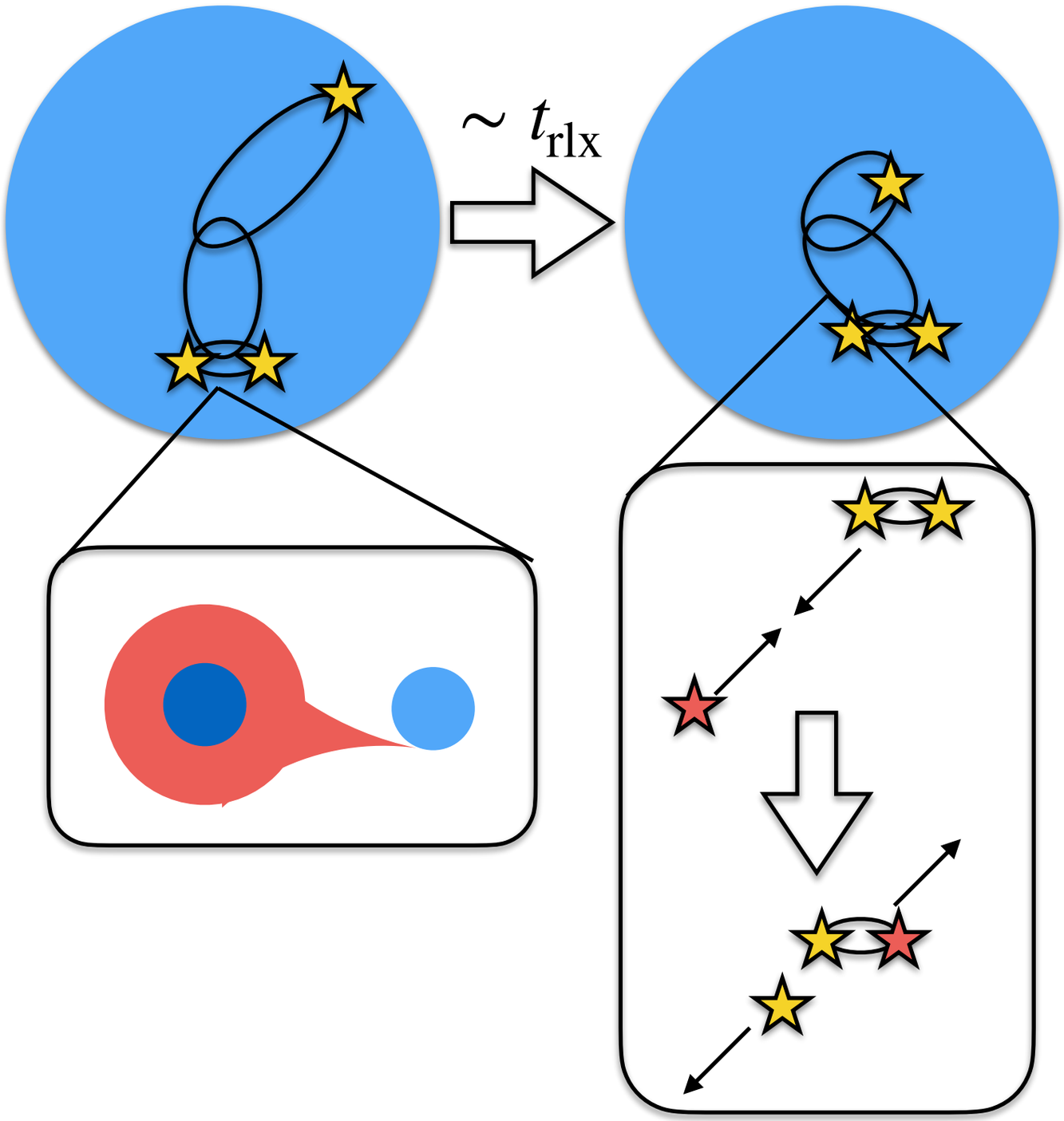


Numerical simulation

- N-body simulation (Portegies Zwart, McMillan 2000; Banerjee et al. 2010; Tanikawa 2013; Fujii et al. 2017; etc)
  - Small N ($\lesssim 10^5$) , but $N \sim 10^6$ in reality
- Toy model (O'Leary et al. 2006; Sadowski et al. 2008; etc)
  - No cluster evolution
- Monte Carlo method (Downing et al. 2010; Rodriguez et al. 2016; Askar et al. 2017; etc)
  - $N \sim 10^6$, but approximate evolution

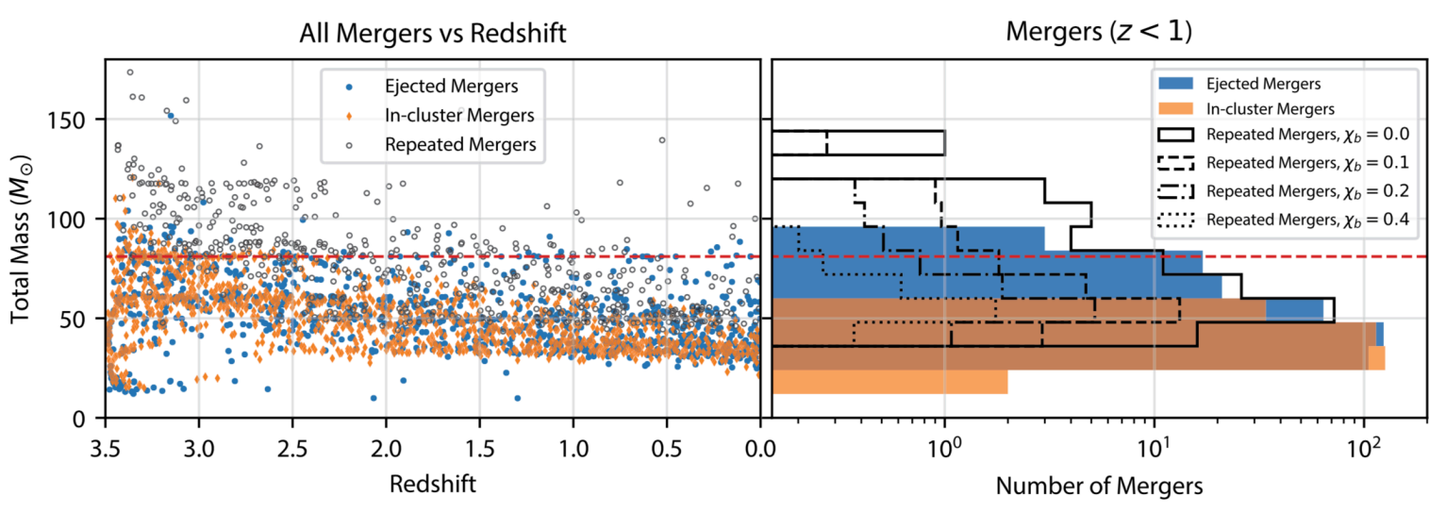
Monte Carlo method

- Single and binary stars orbit in a GC with constant E and J during two-body relaxation time.
- Their E and J diffuse every two-body relaxation time.
- They probabilistically experience close encounters with other single or binary stars, which calculated as gravitational few-body problems.
- They evolve due to stellar evolution and binary evolution, such as tidal interaction, mass transfer, common envelope evolution, and so on.
- Two codes: CMC (Rodriguez), MOCCA (Giersz)
- Several problems are becoming clear (Long 's talk).

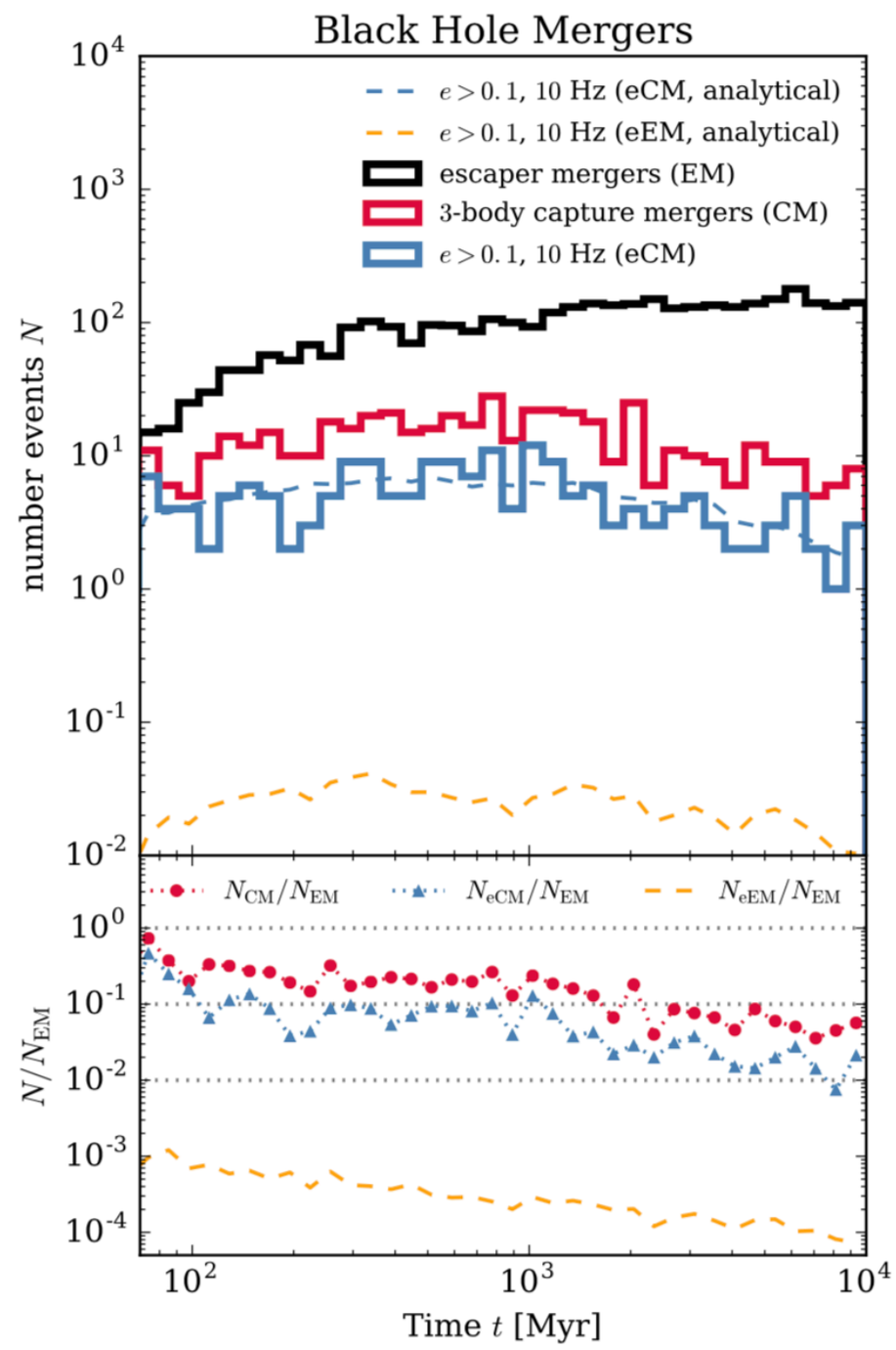


In-cluster mergers

- 10% of BH-BHs merge inside of GCs owing to high eccentricity.
  - The MOCCA code (right)
  - The CMC code (below)
- This allows repeated mergers.
  - BHs with large masses and spins
  - Filling of pair-instability mass gap



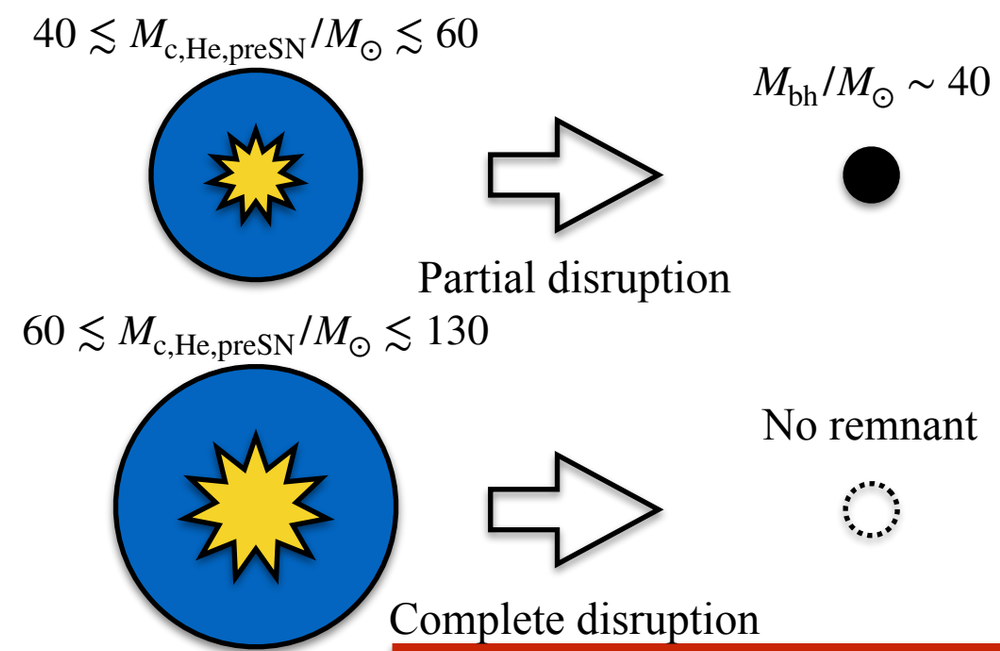
Rodriguez et al. (2018)

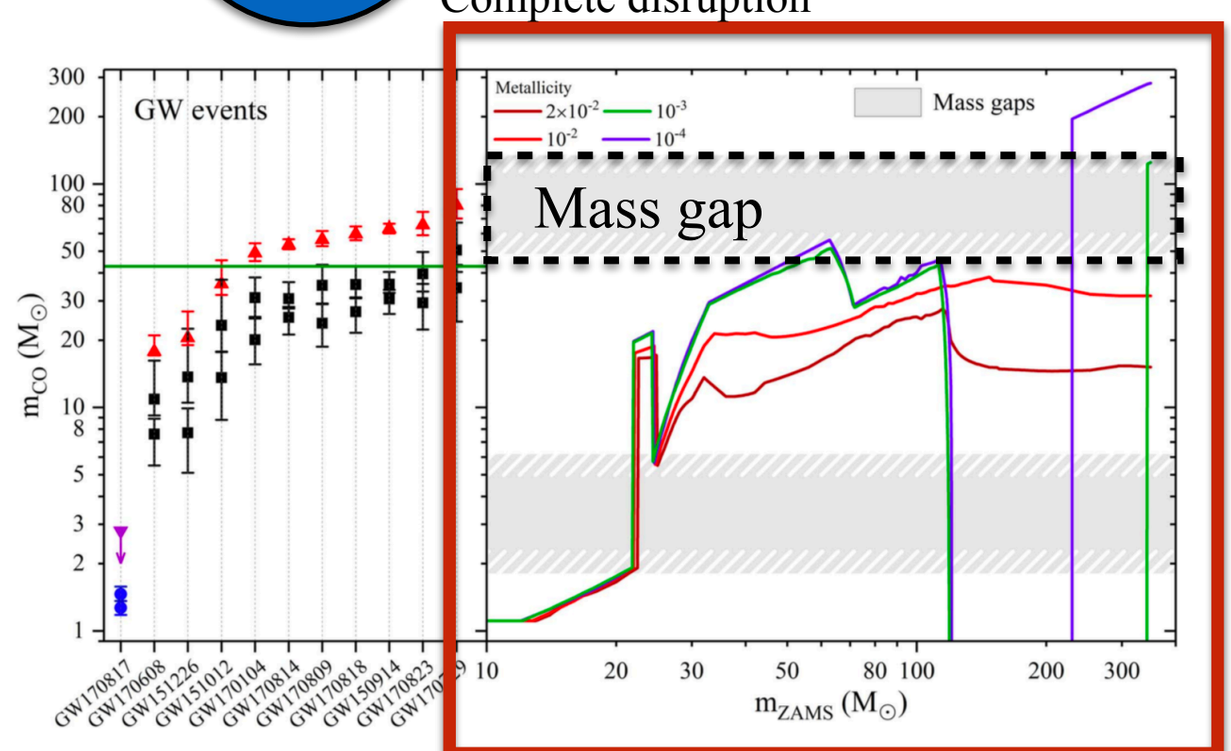


Samsing et al. (2018)

PPI and PISN

- Pulsational Pair Instability (PPI)
  - $40 \lesssim M_{\mathrm{c,He,preSN}}/M_\odot \lesssim 60$
  - He core partially disrupted
  - $M_{\mathrm{bh}} \sim 40 M_\odot$
- Pair instability supernova (PISN)
  - $60 \lesssim M_{\mathrm{c,He,preSN}}/M_\odot \lesssim 130$
  - He core completely disrupted
  - No remnant

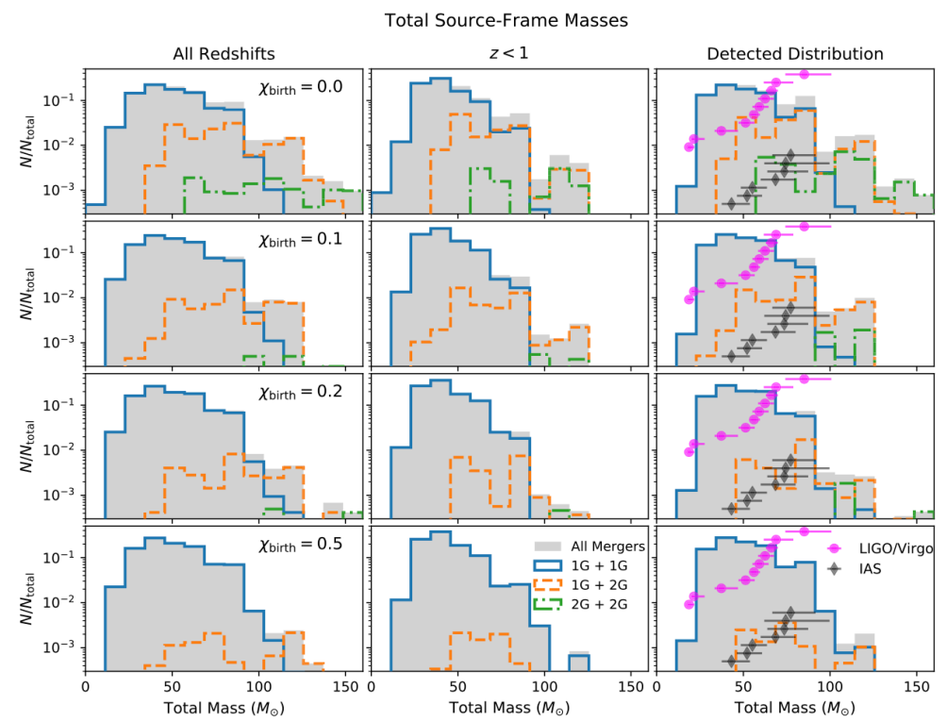


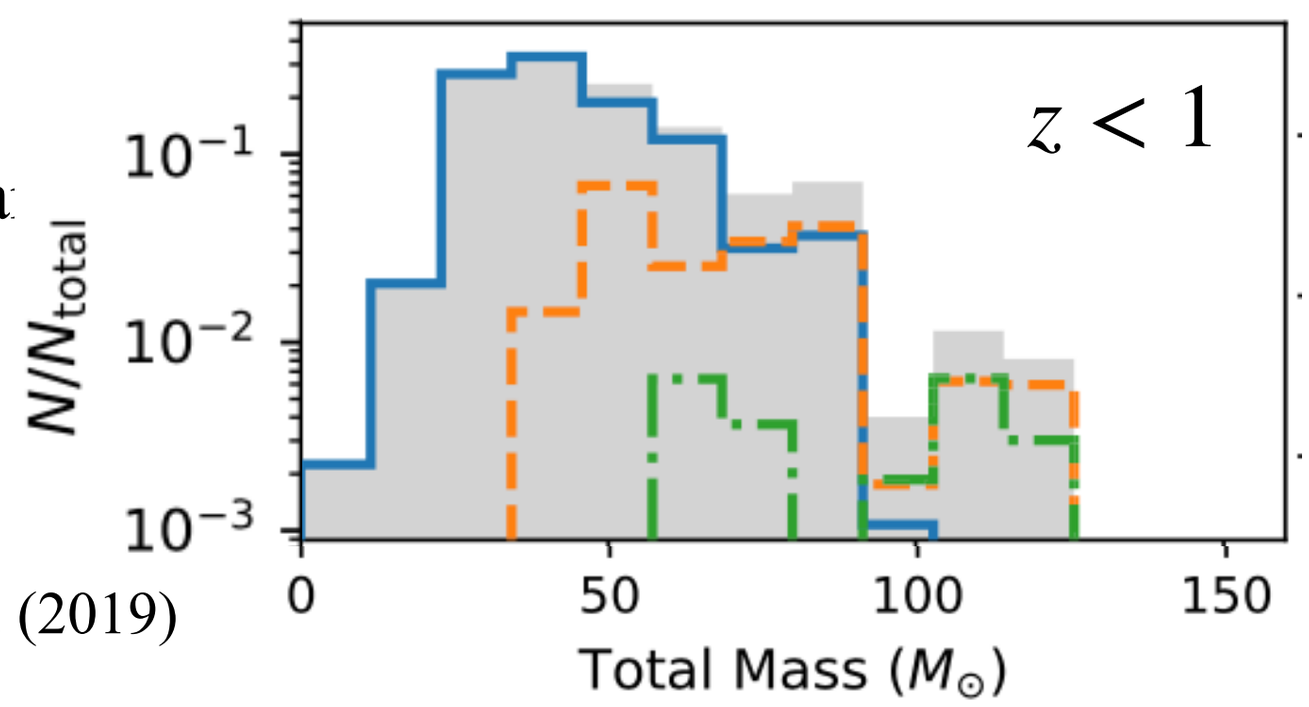


Abbott et al. (2019)

BH Mass distribution

- $\dfrac{\mathscr{R}_{\mathrm{BH-BH}}(M_{\mathrm{tot}} = 150M_{\odot})}{\mathscr{R}_{\mathrm{BH-BH}}(M_{\mathrm{tot}} = 70M_{\odot})} \sim 10^{-1} - 10^{-1.5}$ at $z < 1$ inferred by GW observations
- $\dfrac{\mathscr{R}_{\mathrm{BH-BH}}(M_{\mathrm{tot}} = 150M_{\odot})}{\mathscr{R}_{\mathrm{BH-BH}}(M_{\mathrm{tot}} = 70M_{\odot})} < 10^{-2}$ at $z < 1$ for GCs
- Strong PPI/PISN model (No $> 40M_{\odot}$ BH without stellar a BH mergers)

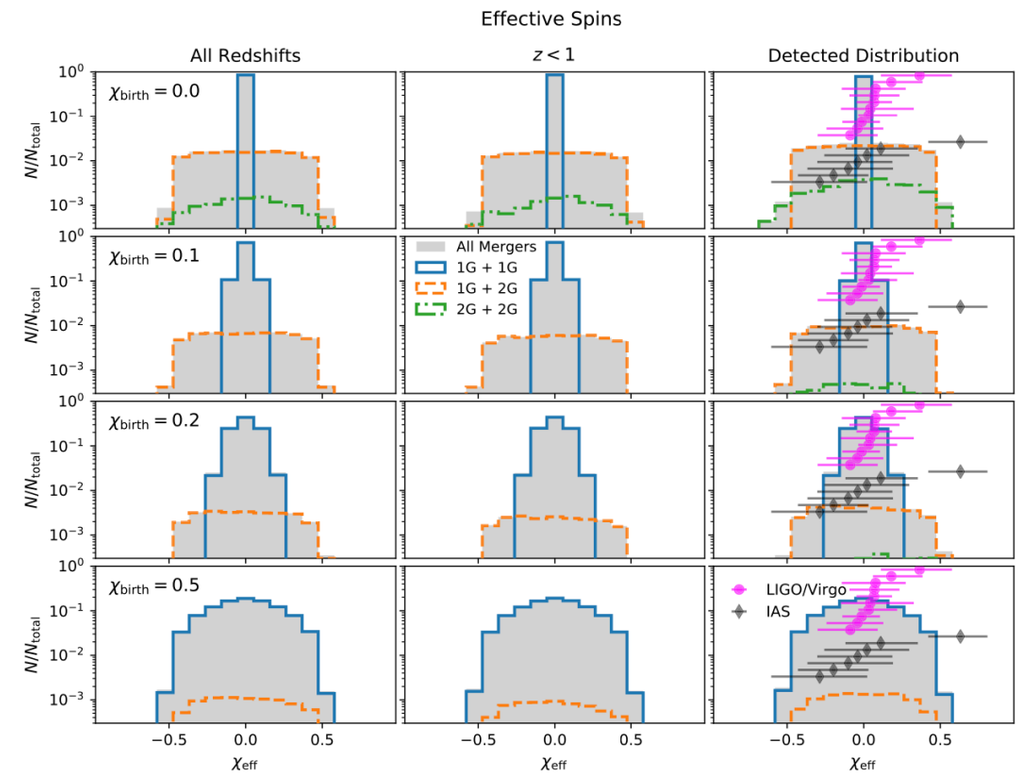




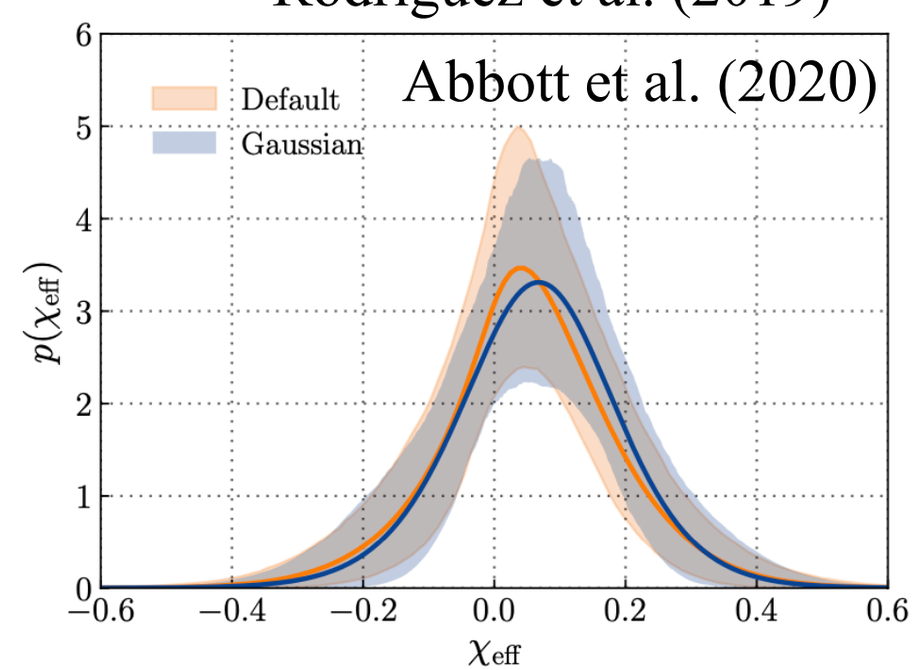
Rodriguez et al. (2019)

BH spin distribution

- Isotropic spin distribution for GCs
- GC BH-BHs may need other populations if they are the major component.

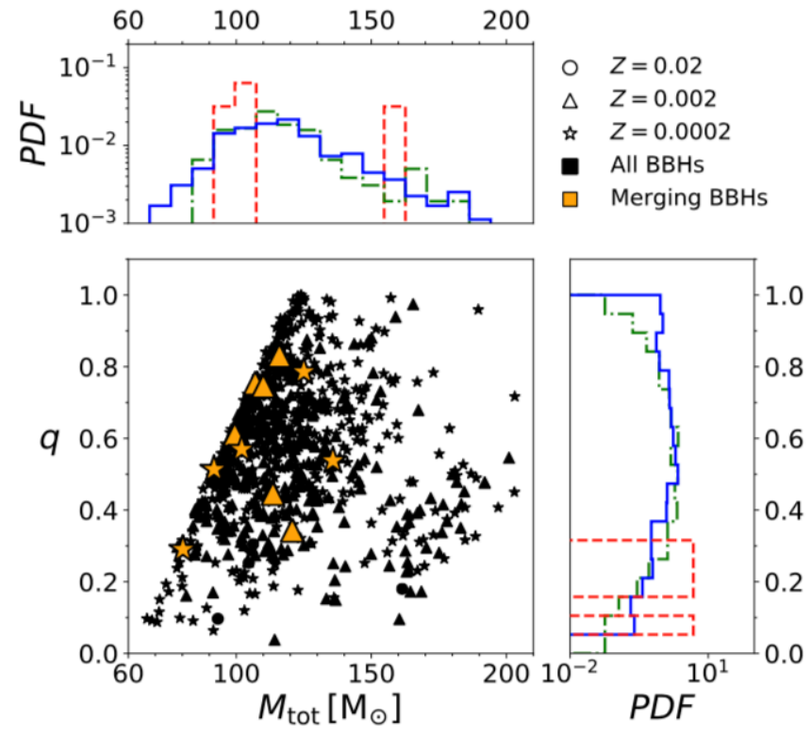


Rodriguez et al. (2019)

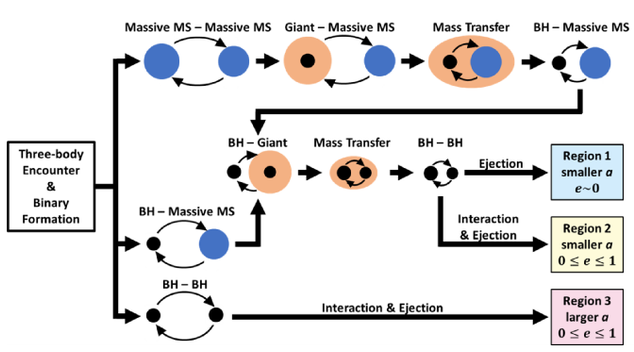


Open clusters

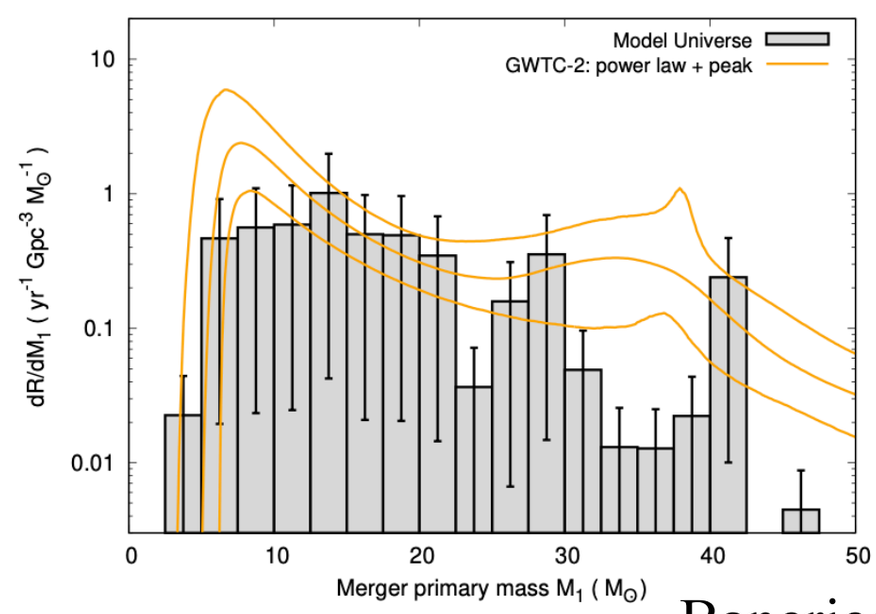
- Enough BH budget
- Common envelope and dynamical capture (Kumamoto et al. 2019; 2020)
- Mass gap BHs (Di Carlo et al. 2019; 2020) via post-MS and MS mergers (Kirihara's study can apply to)
- Strong PPI/PISN model (No $> 40 M_{\odot}$ BH without stellar and BH mergers)



Di Carlo et al (2020)



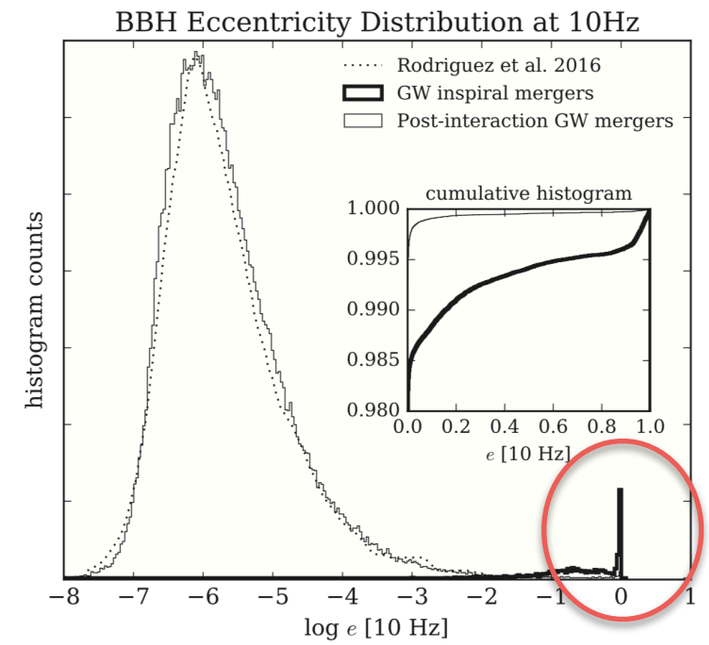
Kumamoto et al. (2019;2020)



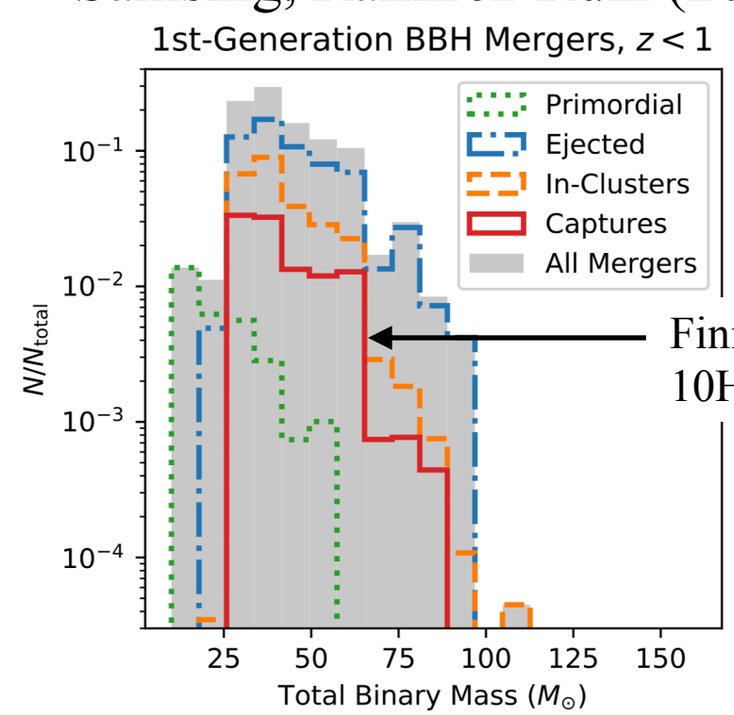
Banerjee (2020)

BH-BH eccentricity

- ~1% of BH-BH mergers leave finite eccentricities at LIGO/Virgo/KAGRA bands.
- Their masses are similar to those of in-cluster mergers, but smaller than those of ejected BH-BHs.
- The present-day BHs in GCs are lighter than previously ejected BHs.
- GW190521 might be an eccentric merger (Gayathri et al. 2020; Romero-Shaw et al. 2020).
  - But, people who believe it are supporters of the AGN scenario (Samsing et al. 2020; Tagawa et al. 2020).



Samsing, Ramirez-Ruiz (2017)



Finite eccentricity at 10Hz

Rodriguez et al. (2018)

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  - Tanikawa, Yoshida, Kinugawa, Takahashi, Umeda (2020a, MNRAS, 495, 4170)
  - Tanikawa, Susa, Yoshida, Trani, Kinugawa (2020b, arXiv:2008.01890)
  - Tanikawa, Kinugawa, Yoshida, Hijikawa, Umeda (2020c, arXiv:2010.07616)

Black hole budget (Pop. III)

- BH-BH density: $n_{\rm BH-BH} \sim 10^{11}{\rm Gpc}^{-3} \left(\frac{\Gamma_{\rm BH-BH}}{10{\rm Gpc}^{-3}{\rm yr}^{-1}}\right) \left(\frac{T_{\rm Hubble}}{10{\rm Gyr}}\right)$

Abbott et al. (2020)

- Binary evolution:
  - $n_{\rm BH,star} \sim 10^{15}{\rm Gpc}^{-3} \left(\frac{\rho_{\rm star}}{10^{18}M_\odot{\rm Gpc}^{-3}}\right) \left(\frac{\eta_{\rm BH}}{10^{-3}M_\odot}\right)$
  - $\frac{n_{\rm BH-BH}}{n_{\rm BH,star}} \sim 10^{-4} \left(\frac{\Gamma_{\rm BH-BH}}{10{\rm Gpc}^{-3}{\rm yr}^{-1}}\right)$

Kroupa (2001), $M_{\rm zams} \gtrsim 20M_\odot \rightarrow$ BH

Madau, Dickinson (2014)

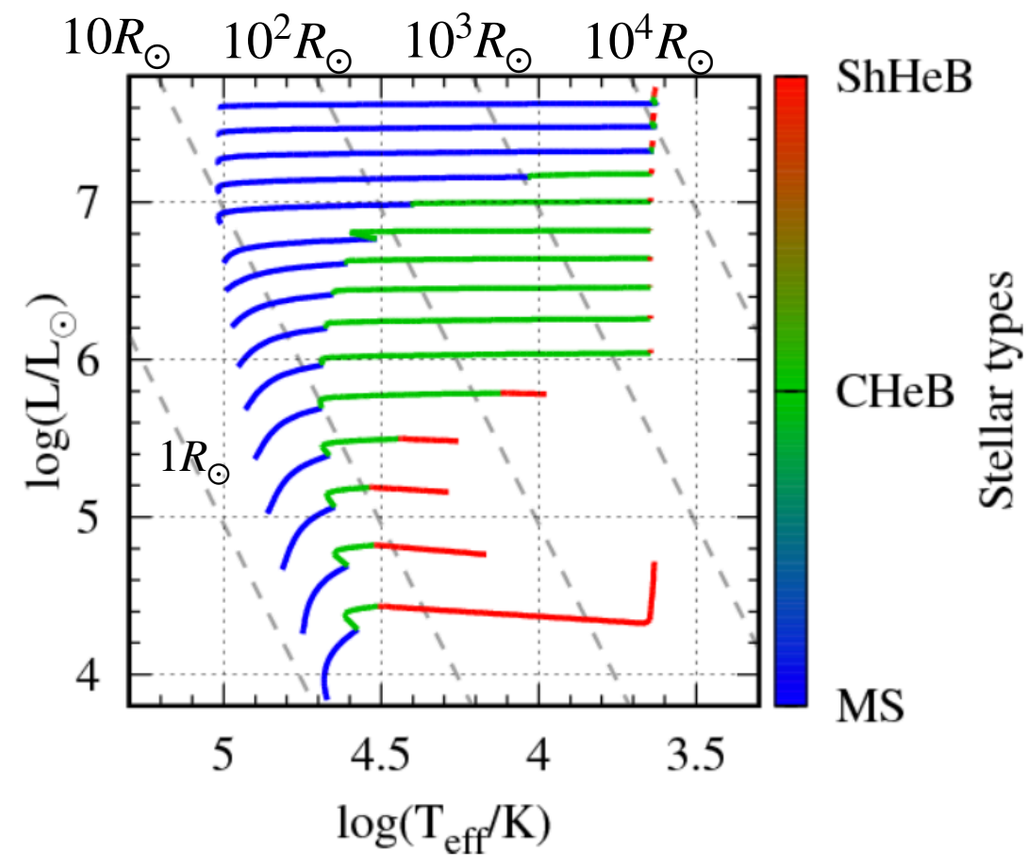
- Pop. III binary evolution
  - $n_{\rm BH,III} \sim 10^{11}{\rm Gpc}^{-3} \left(\frac{\rho_{\rm star}}{10^{13}M_\odot{\rm Gpc}^{-3}}\right) \left(\frac{\eta_{\rm BH}}{10^{-2}M_\odot}\right)$
  - $\frac{n_{\rm BH-BH}}{n_{\rm BH,III}} \sim 1 \left(\frac{\Gamma_{\rm BH-BH}}{10{\rm Gpc}^{-3}{\rm yr}^{-1}}\right)$

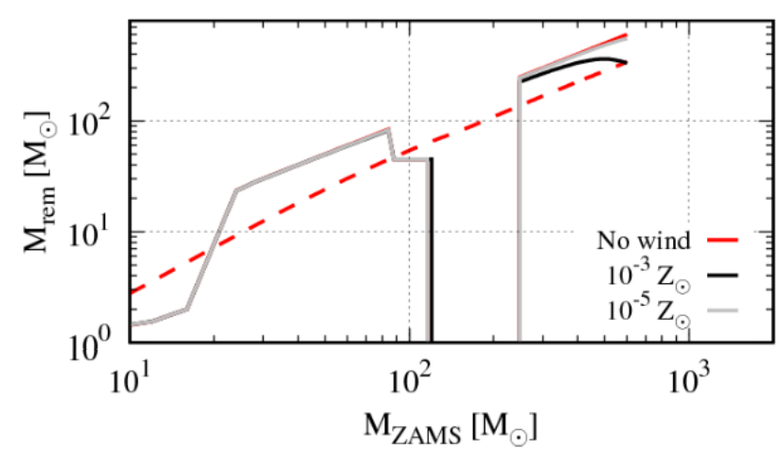
$f(M) \propto M^{-1}$ $(10 \leq M/M_\odot \leq 100)$
$M_{\rm zams} \gtrsim 20M_\odot \rightarrow$ BH

Magg et al. (2016); Skinner, Wise (2020);
but de Souza et al. (2011); Inayoshi et al. (2016)

Binary population synthesis

- $10 \leq m_{1,\mathrm{zams}}/M_\odot \leq 300$
- $10/m_{1,\mathrm{zams}} \leq m_{2,\mathrm{zams}}/m_{1,\mathrm{zams}} \leq 1$
- $r_{\mathrm{p,i}} \geq 10$ or $200R_\odot$
- Pop. III model with large convective overshooting (L model)
- Mass transfer, common envelope etc.
- Fryer's SN model with PPI/PISN
- One Pop. III binary per minihalo



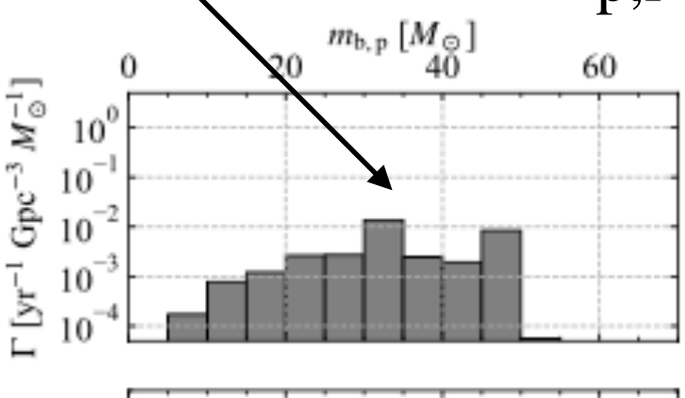


Tanikawa et al. (2020a)

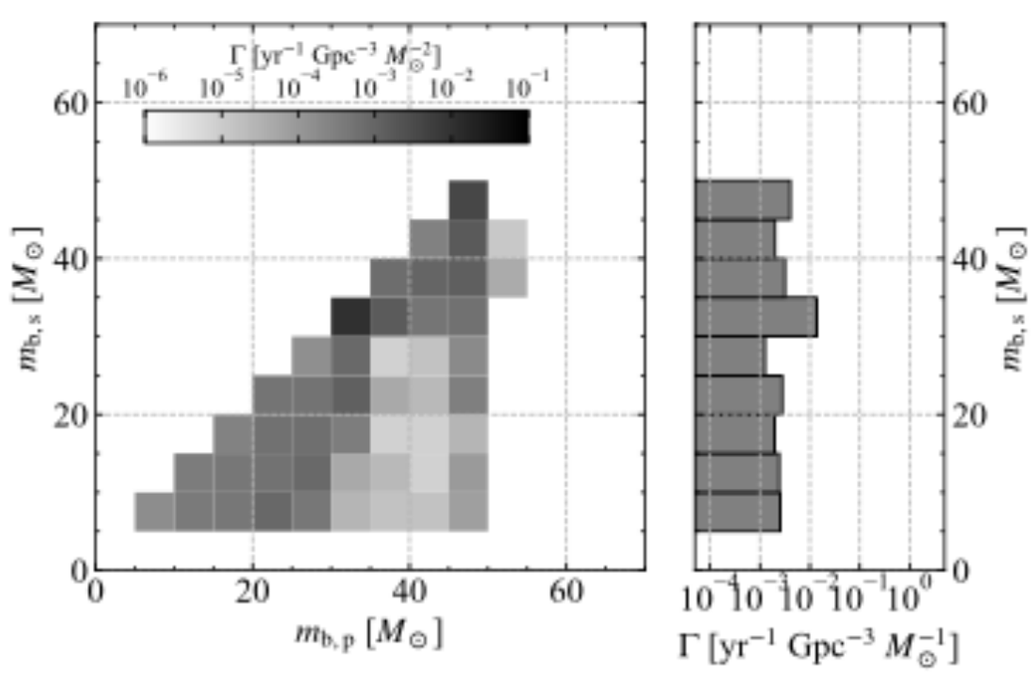
Pop. III BH-BHs

Kinugawa's peak

$r_{\mathrm{p,i}} \geq 10R_\odot$

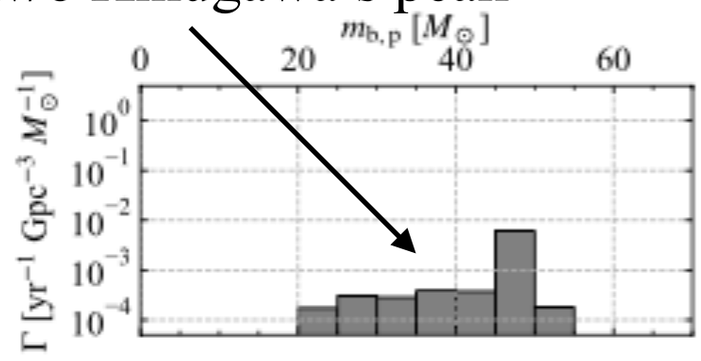


MT path
CE path



w/o Kinugawa's peak

$r_{\mathrm{p,i}} \geq 200R_\odot$



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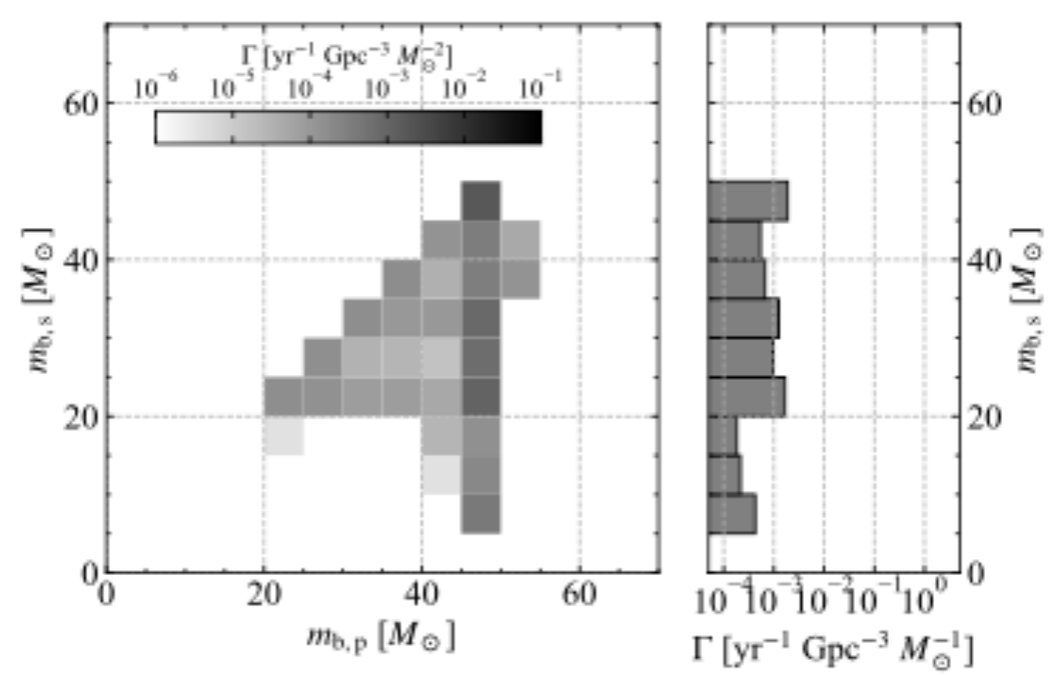
CE path

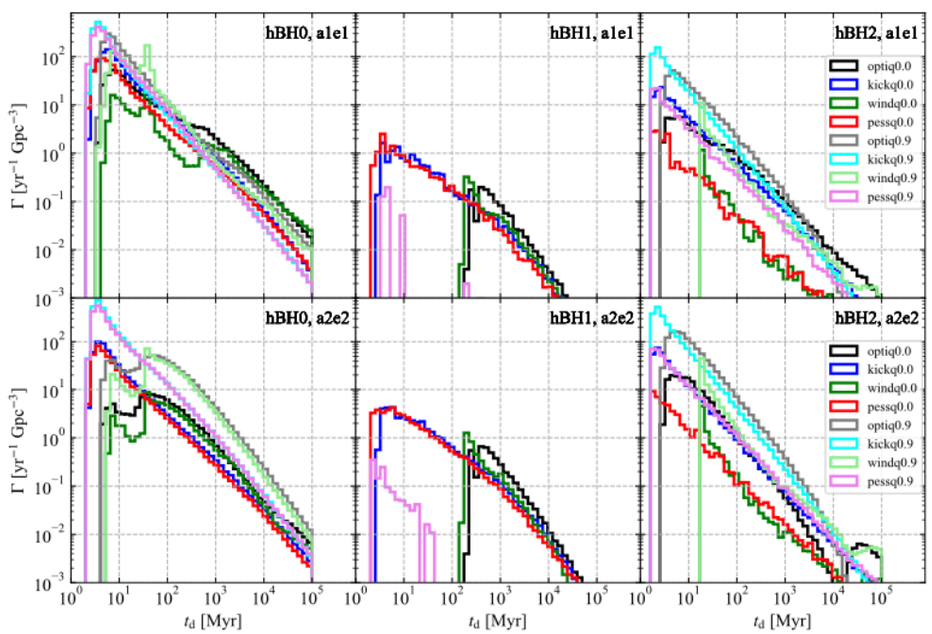


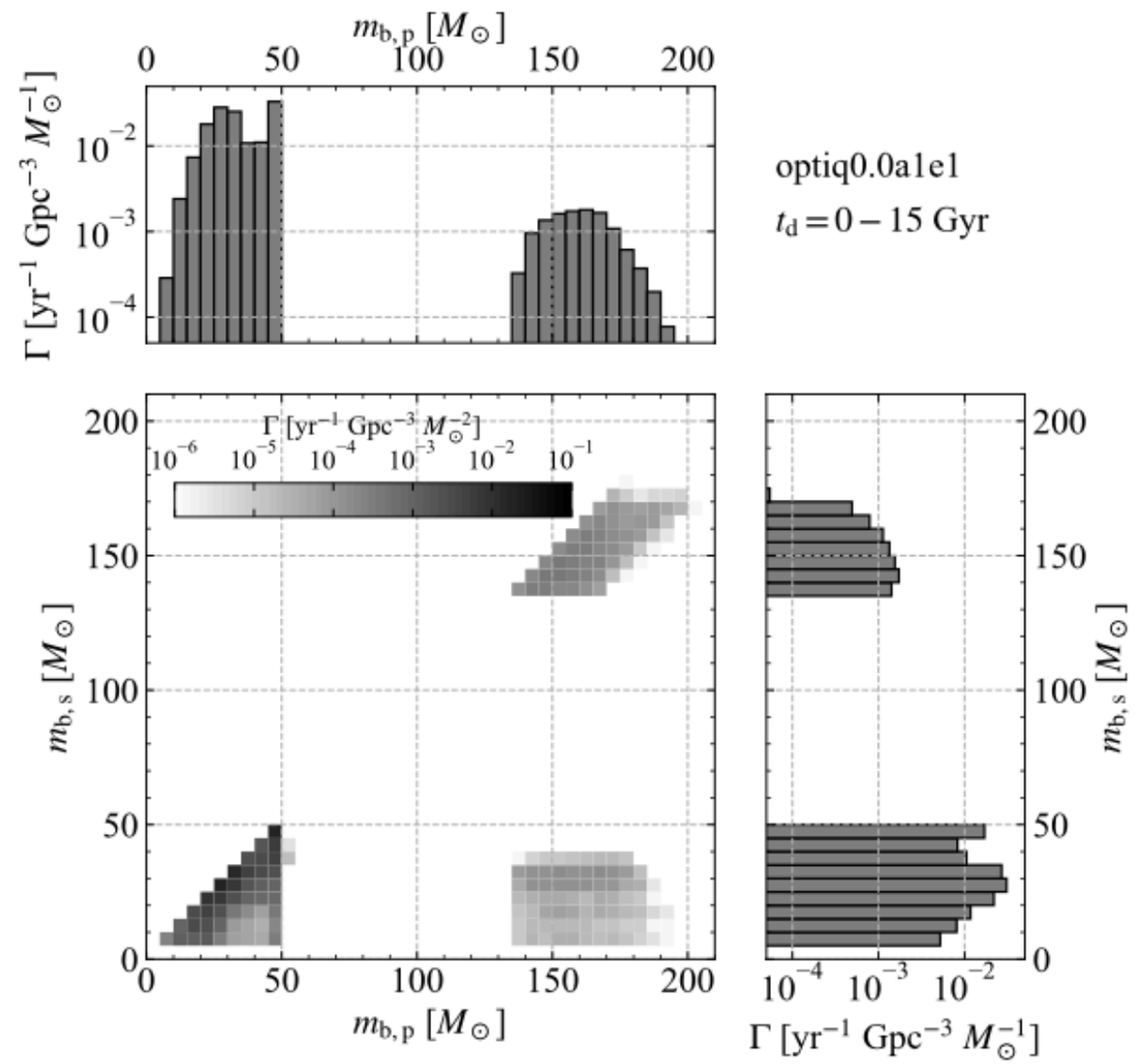
$$\Gamma_{m_1 \lesssim 50 M_\odot} \sim 0.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

Tanikawa et al. (2020b)

Pop. III BH-BHs

- $\Gamma_{m_1 \lesssim 50 M_\odot} \sim 0.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- $\Gamma_{50 M_\odot \lesssim m_1 \lesssim 130 M_\odot} \sim 0\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- $\Gamma_{m_1 \gtrsim 130 M_\odot} \sim 0.01\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
  - GW190521 can be $m_1 \gtrsim 130 M_\odot$ (e.g. Fishbach, Holz 2020).





Tanikawa et al. (2020b)

GW190521

- Merger of $85^{+21}_{-14} M_\odot$ and $66^{+17}_{-18} M_\odot$ BHs
- The primary BH has only a 0.32% probability of being below $65 M_\odot$.
- At least one BH lies within the PI mass gap.

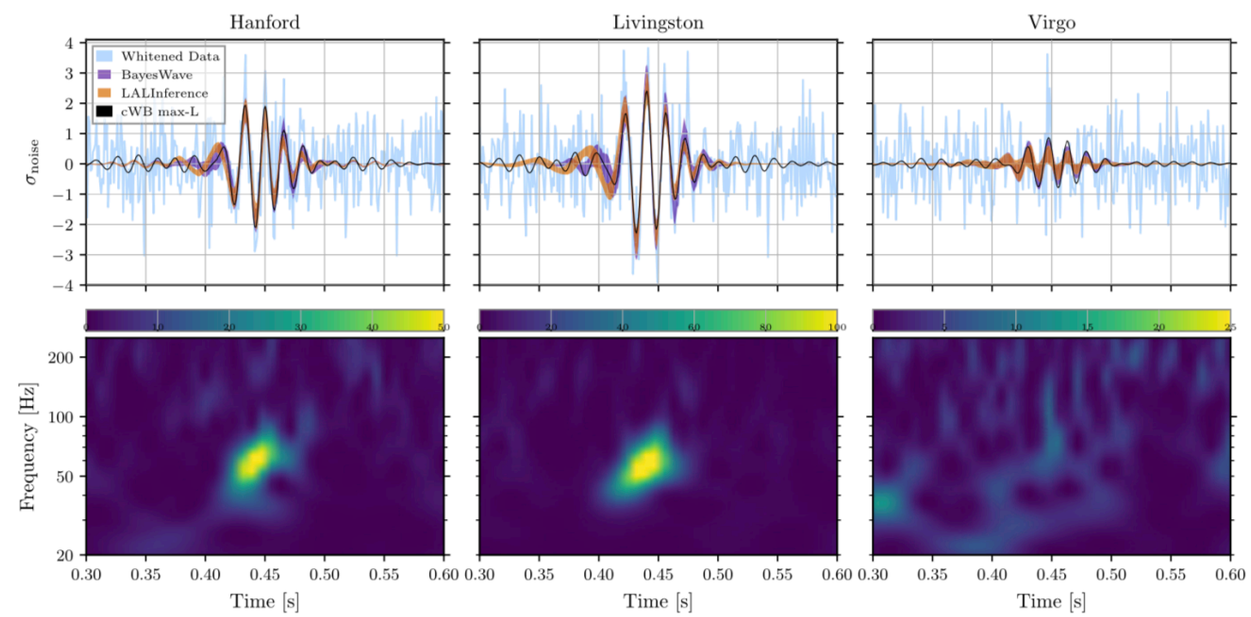
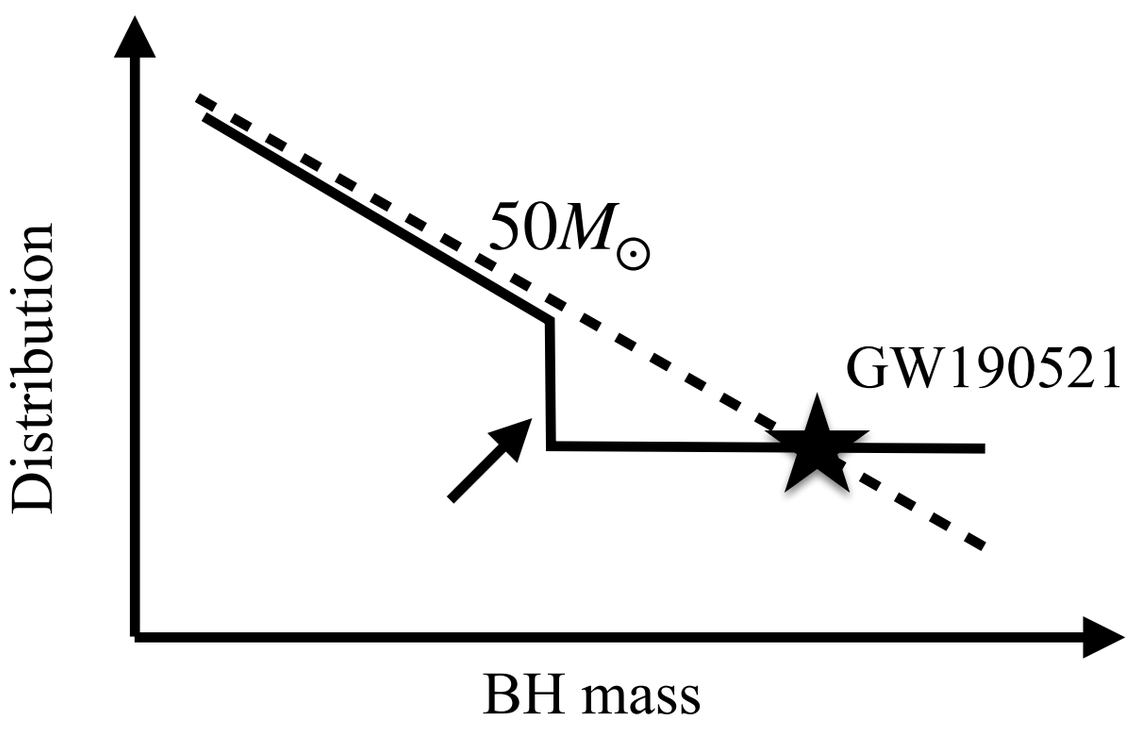


TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

Parameter	
Primary mass	$85^{+21}_{-14}\ M_\odot$
Secondary mass	$66^{+17}_{-18}\ M_\odot$
Primary spin magnitude	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude	$0.73^{+0.24}_{-0.64}$
Total mass	$150^{+29}_{-17}\ M_\odot$
Mass ratio ($m_2/m_1 \leq 1$)	$0.79^{+0.19}_{-0.29}$
Effective inspiral spin parameter ($\chi_{\rm eff}$)	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter ($\chi_{\rm p}$)	$0.68^{+0.25}_{-0.37}$
Luminosity Distance	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift	$0.82^{+0.28}_{-0.34}$
Final mass	$142^{+28}_{-16}\ M_\odot$
Final spin	$0.72^{+0.09}_{-0.12}$
$P\ (m_1 < 65\ M_\odot)$	0.32%
$\log_{10}$ Bayes factor for orbital precession	$1.06^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for nonzero spins	$0.92^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for higher harmonics	$-0.38^{+0.06}_{-0.06}$

Abbott et al. (2020)



Single star evolution

- It is not hard to form mass-gap BH through single star evolution.
- Formation Process
  - A star with $M_{\rm zams} \sim 90 M_\odot$ and $Z \sim 0.01 Z_\odot$.
  - Evolution to a BH progenitor with $M_{\rm tot} \sim 90 M_\odot$ and $M_{\rm c,He} \lesssim 40 M_\odot$.
  - Collapse to $\sim 90 M_\odot$ BH without PPI/PISN owing to small He core mass.
- Light He core, massive H envelope

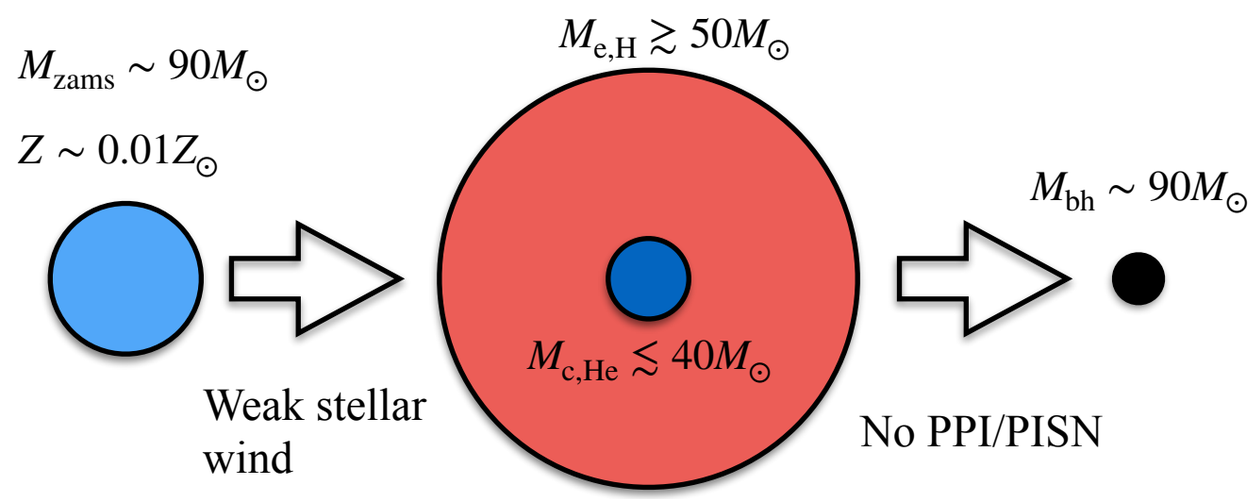


Table 1. Summary of the results

$M_{\rm ini}$ ($M_\odot$)	$M_{\rm CO}$ ($M_\odot$)	$M_{\rm He}$ ($M_\odot$)	# of PPI	Ejection #	Log $T_{\rm peak}$ (K)	$M_{\rm rem}$ ($M_\odot$)	Ejecta Energy (10^{50}erg)
			L Models ($f_{\rm OV}$=0.03)				
70	34.2	38.9-48.8	4	0	-	70	-
75	34.9	39.3	4	1	9.81	42.4	6.5
80	37.4	42.2-42.9	3	1	9.71	42.4	0.18
100	48.1	53.6	2	1	9.65	52.2	4.5
120	57.9	64.9	1	1	9.66	60.3	4.7
135	65.4	73.5	1	1	9.63	66.9	5.6
			M Models ($f_{\rm OV}$=0.01)				
70	27.0	30.3-34.4	0	0	-	70	-
80	31.8	35.3-39.4	5	0	-	80	-
90	37.2	41.9-44.8	3	1	9.76	83.0	1.4
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	(interval: 3.1 yr)			2	9.80	77.7	39
35	58.3	65.3-72.6	1	1	9.64	108.7	5.6

Pop. III

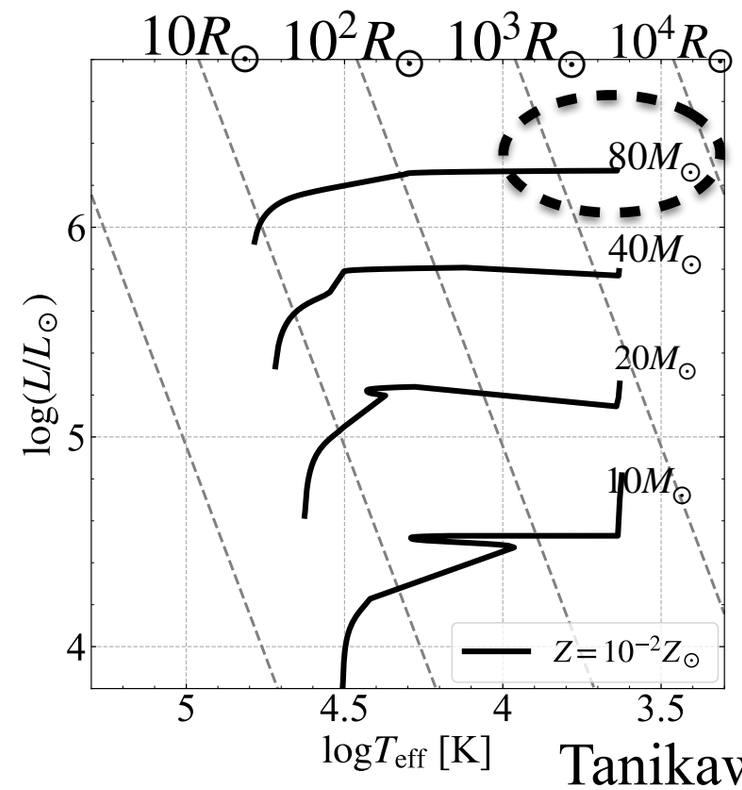
$$M_{\rm zams} = 70 M_\odot \rightarrow M_{\rm bh} = 70 M_\odot$$

$$M_{\rm zams} = 80 M_\odot \rightarrow M_{\rm bh} = 80 M_\odot$$

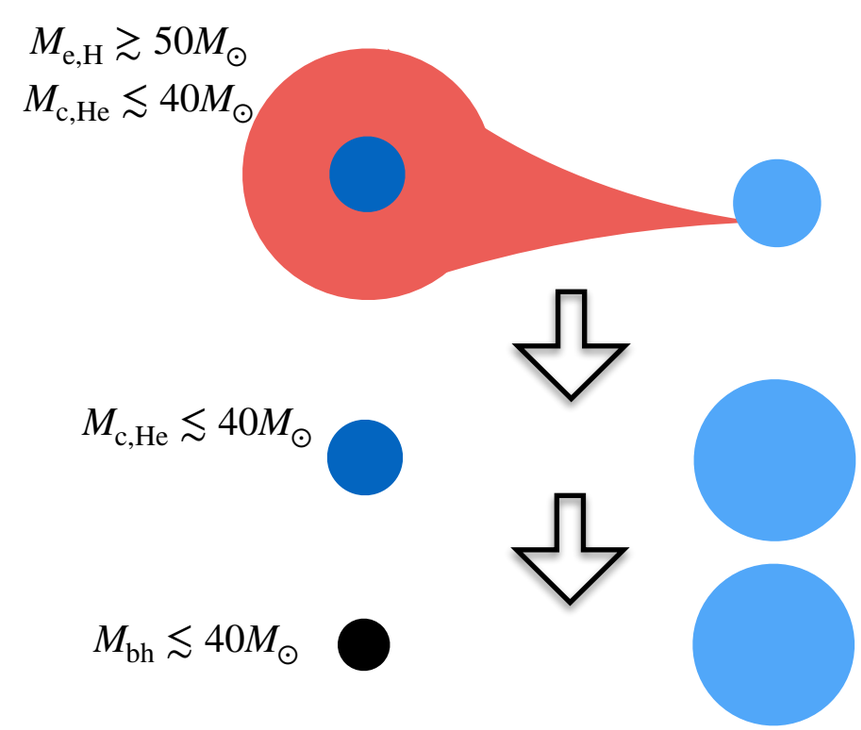
Umeda et al. (2020)

Binary star evolution

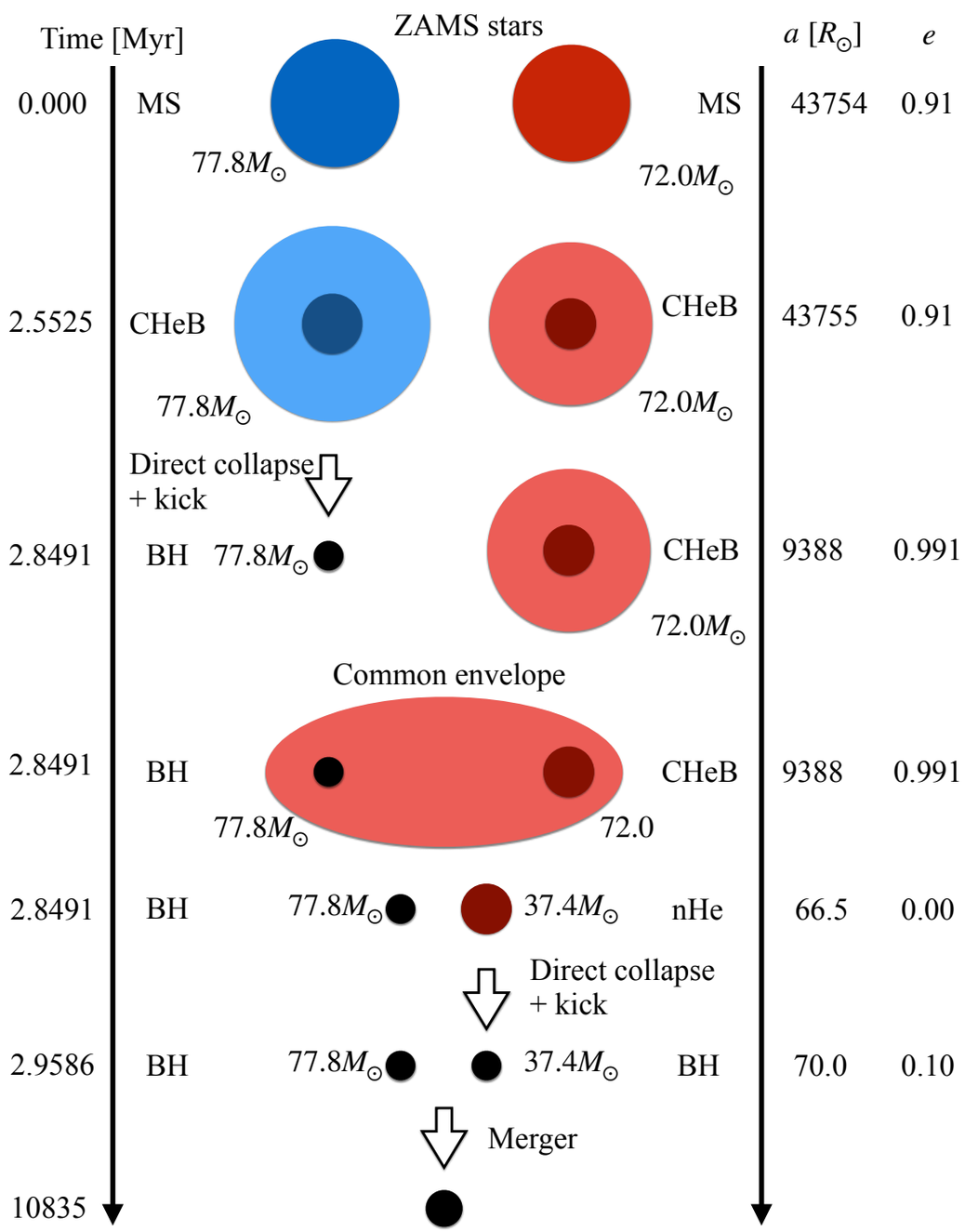
- Merger of $85M_\odot$ and $66M_\odot$ BHs
  - Merger time $\lesssim$ 10 Gyr
  - $a \lesssim 10^2 R_\odot$, $e \sim 0$
- A star with $M_{\rm zams} \gtrsim 80M_\odot$ expands to $R \gtrsim 10^3 R_\odot$.
- The star loses its H envelope, stripped by its companion star.
- No massive H envelope, no mass-gap BH.

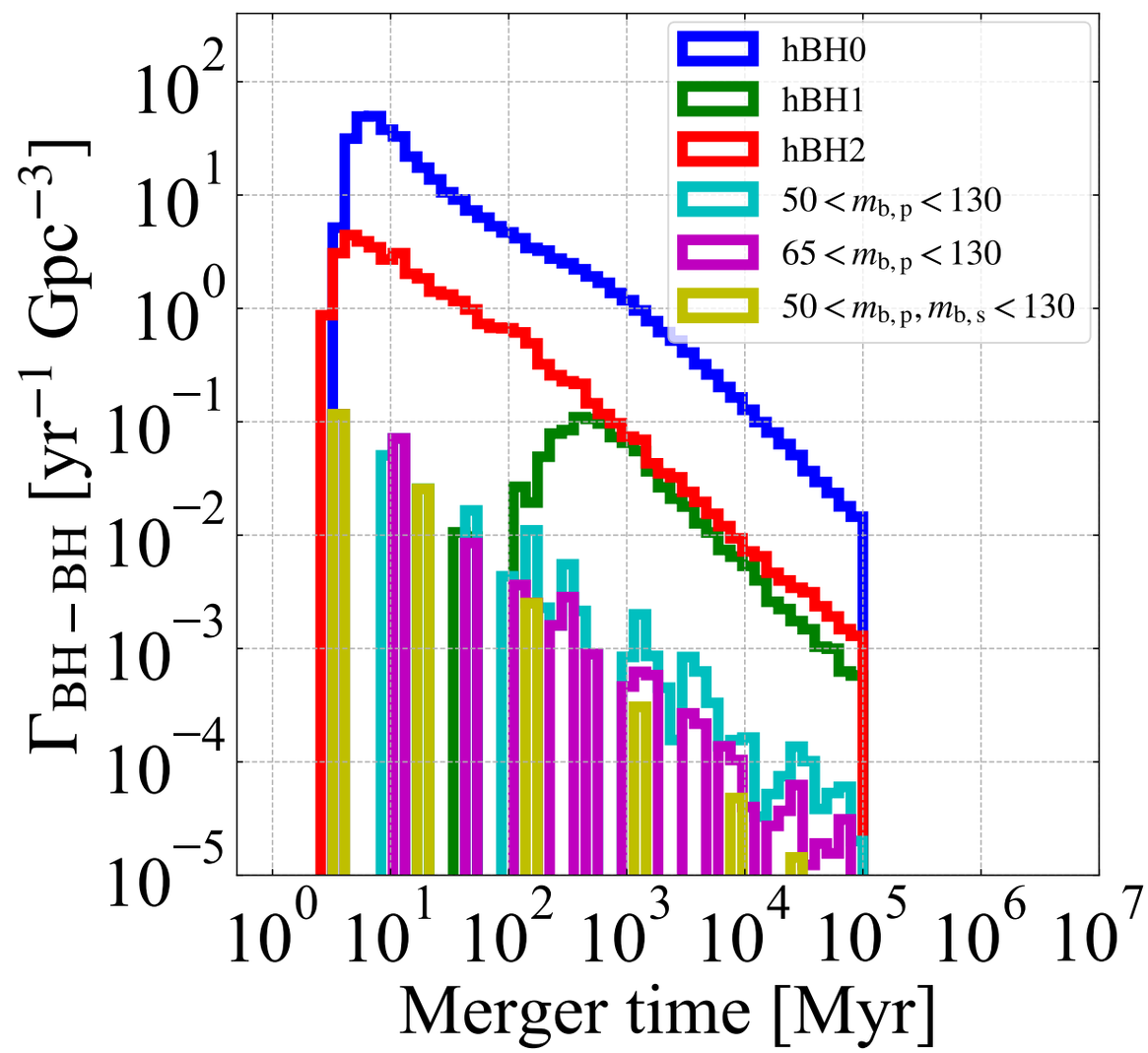


Tanikawa et al. (2020a)



BH natal kick





Tanikawa et al. (2020b)

Summary

- Globular clusters can fill the pair instability mass gap.
  - But, the event rate ratio does not seem consistent.
- Pop. III merger rate with $m_1 \gtrsim 130 M_\odot$ is $\sim 0.01\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.
  - It may be consistent with GW190521 if GW190521 contains $m_1 \gtrsim 130 M_\odot$ (e.g. Fishbach, Holtz 2020)
- Whether Pop. III binaries can form GW190521 strongly depends on convective overshooting.