連星ブラックホールGW190521は初代星起源か？恒星進化，特に対流のオーバーシュートへの依存性について

Is GW190512 formed from a Pop. III binary? Dependence on convective overshooting

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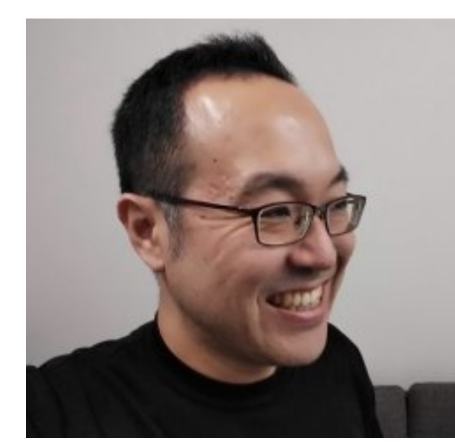
- Tanikawa et al. (2020a, MNRAS, 495, 4170)
- Tanikawa et al. (2020b, arXiv:2008.01890)
- Tanikawa et al. (2020c, arXiv:2010.07616)



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- Pair instability (PI) mass gap and GW190521
- Difficulty to form PI mass gap BH
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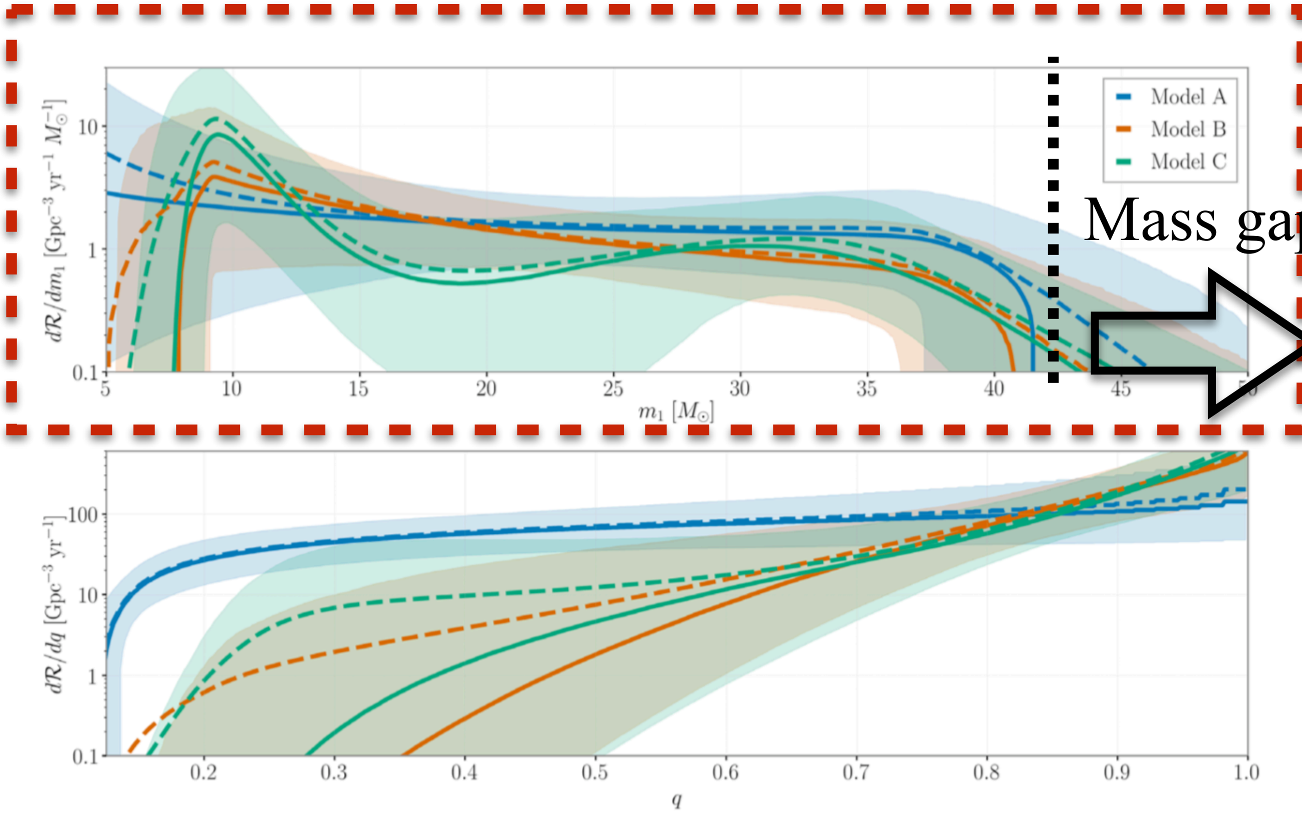
Merger of binary black hole

- The first and second observing runs of LIGO/Virgo (O1/O2) found 10 BH-BH mergers.
- The BH mass distribution appears not to have BHs with $\gtrsim 50M_{\odot}$.
    - Second mass gap
    - Higher mass gap
    - <u>Pair instability (PI) mass gap</u>
- No BH with $50 - 130M_{\odot}$ due to pulsational PI (PPI) and PI supernova (PISN)?

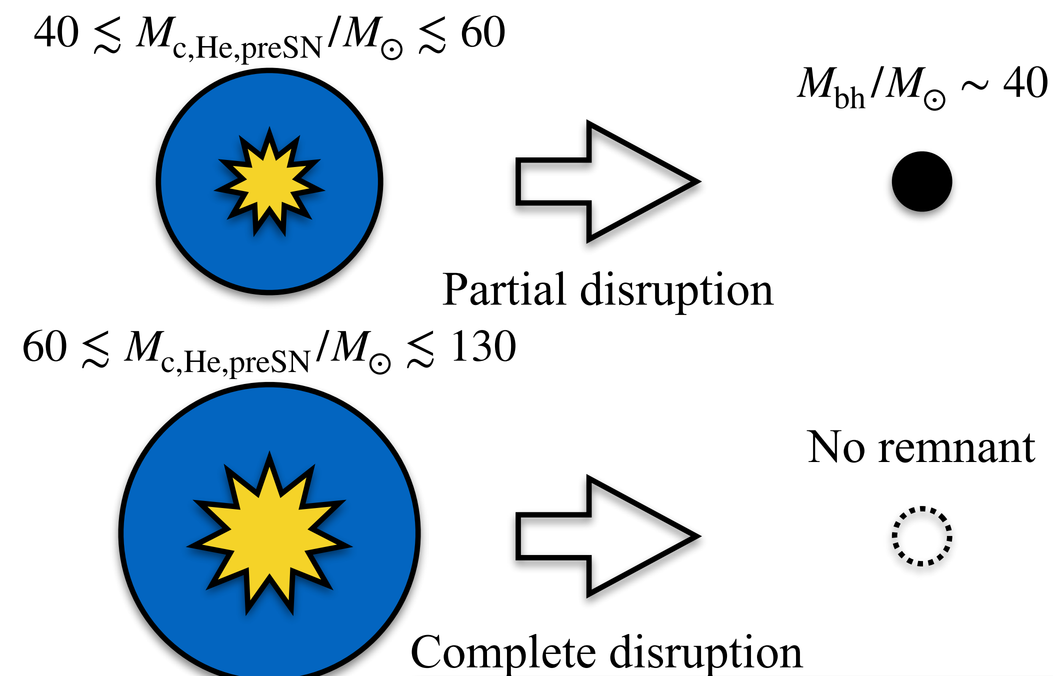
Event	$m_1/M_{\odot}$	$m_2/M_{\odot}$	$\mathcal{M}/M_{\odot}$	$\chi_{\rm eff}$	$M_f/M_{\odot}$	a_f	$E_{\rm rad}/(M_{\odot}c^2)$	$\ell_{\rm peak}/({\rm erg\ s^{-1}})$	$d_L/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0} \times 10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	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	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1} \times 10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

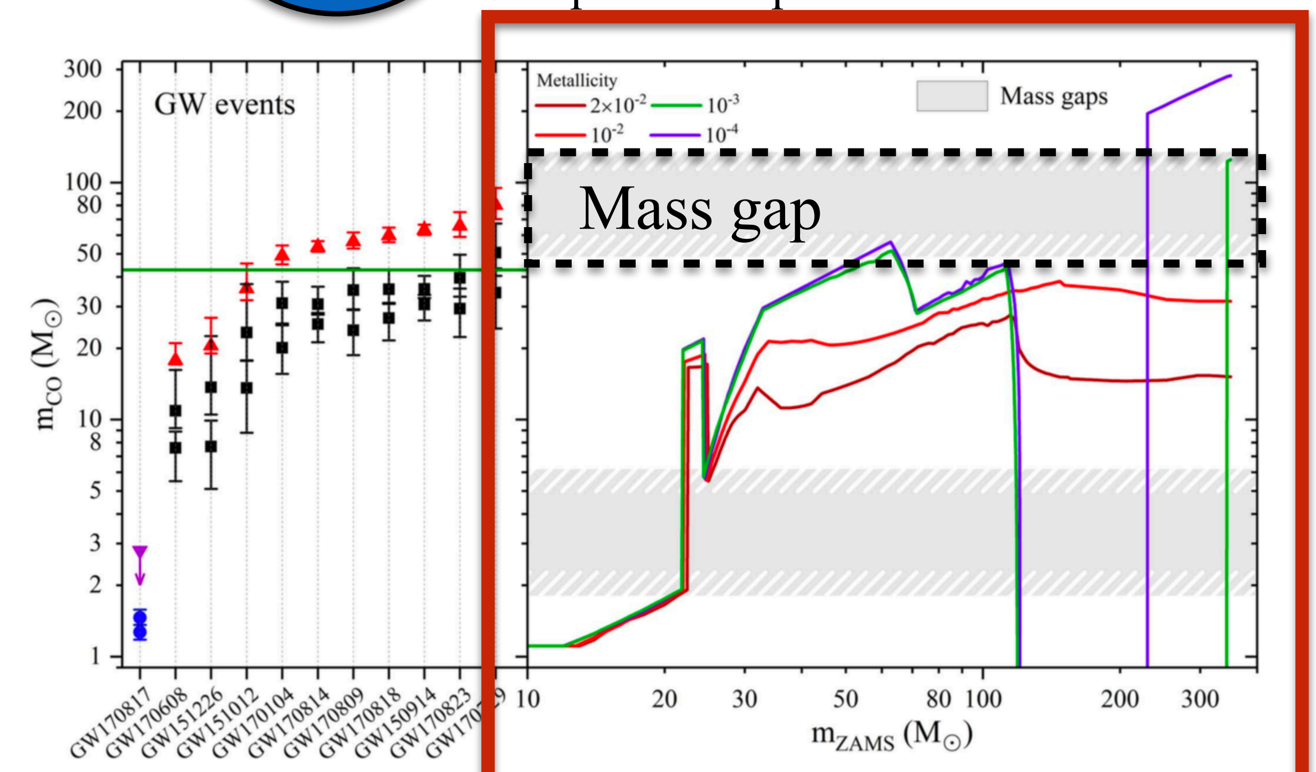


Abbott et al. (2019)

PPI and PISN

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

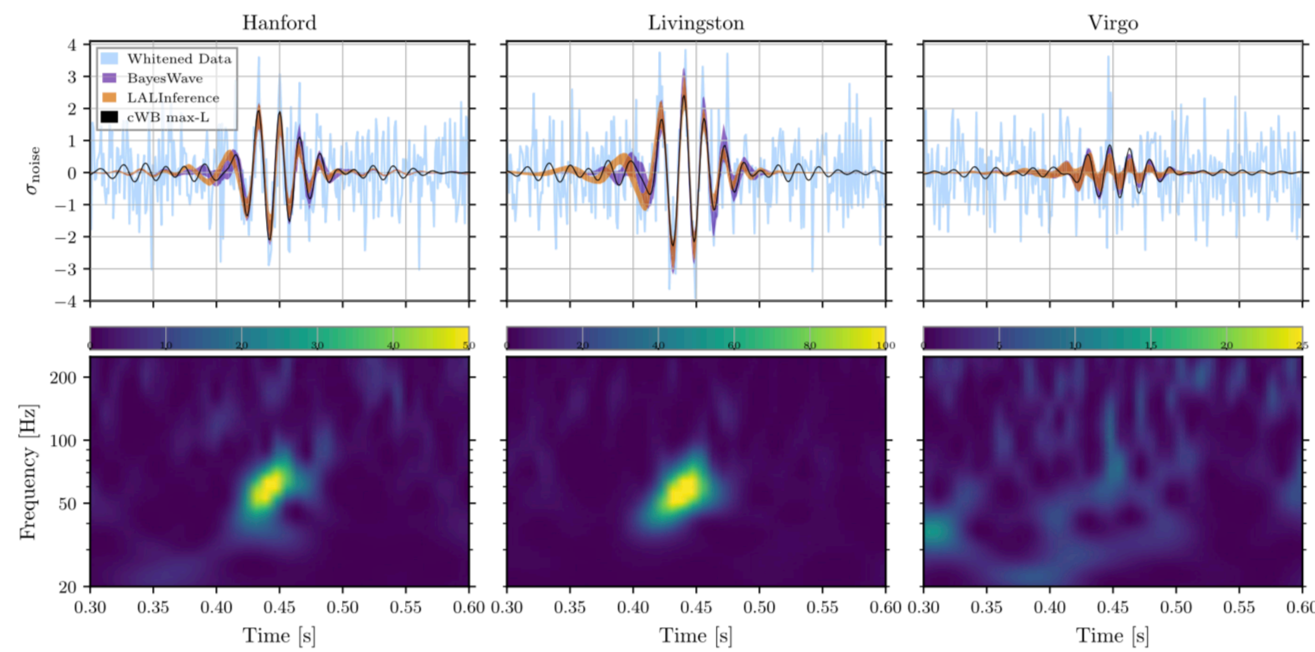




Abbott et al. (2019)

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.



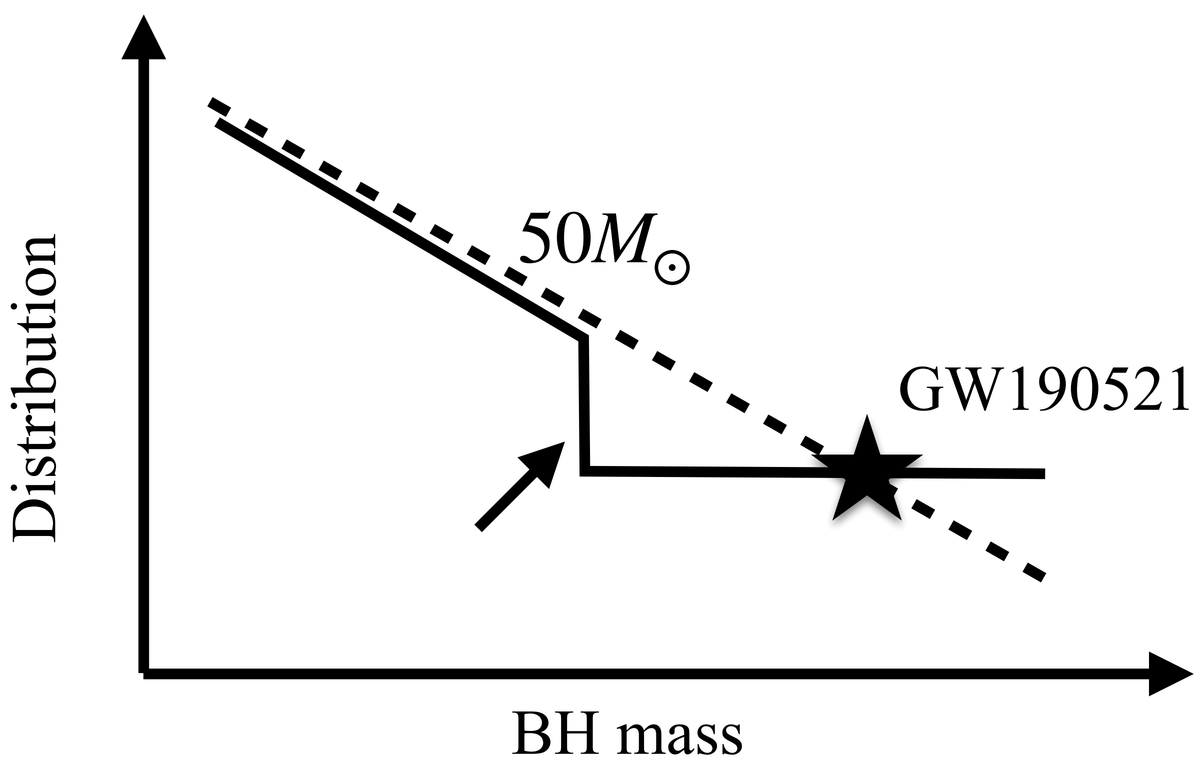


TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

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)

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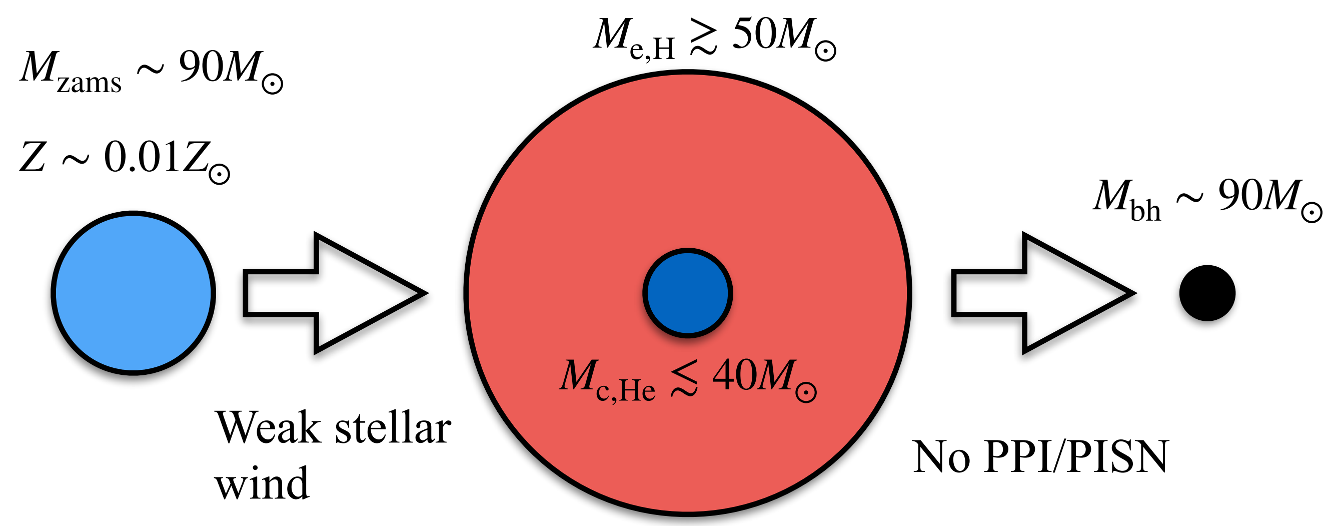
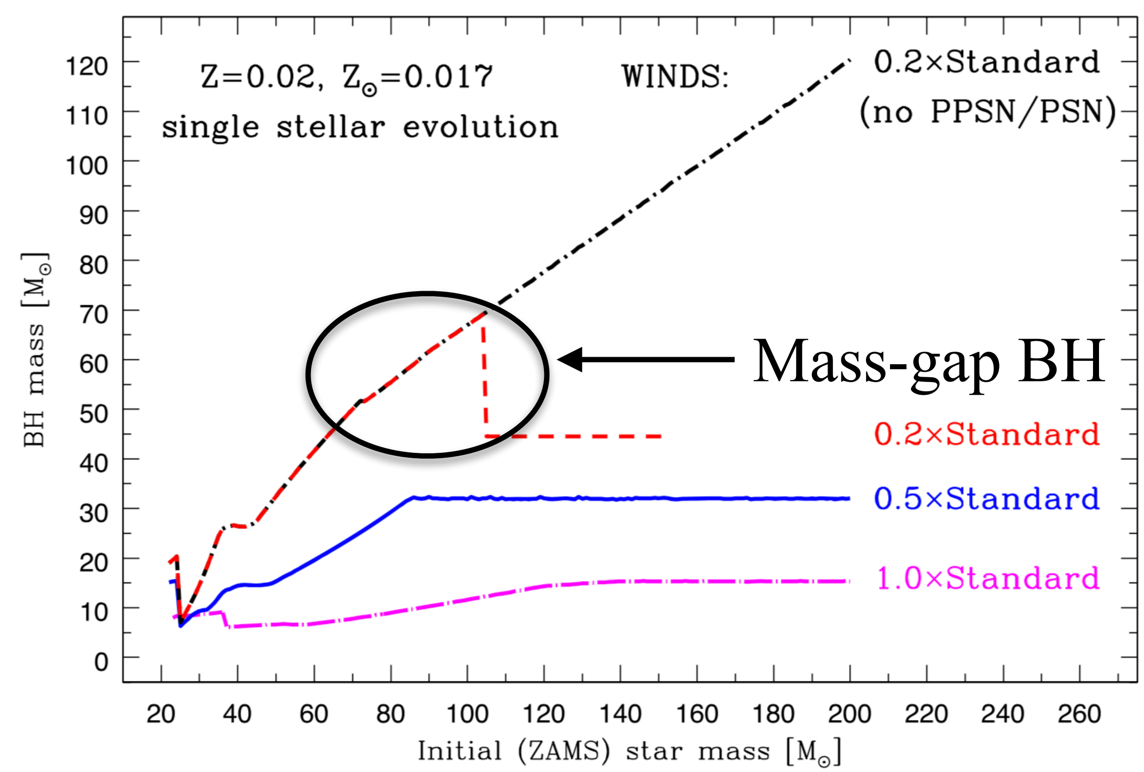
Single star evolution

- 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

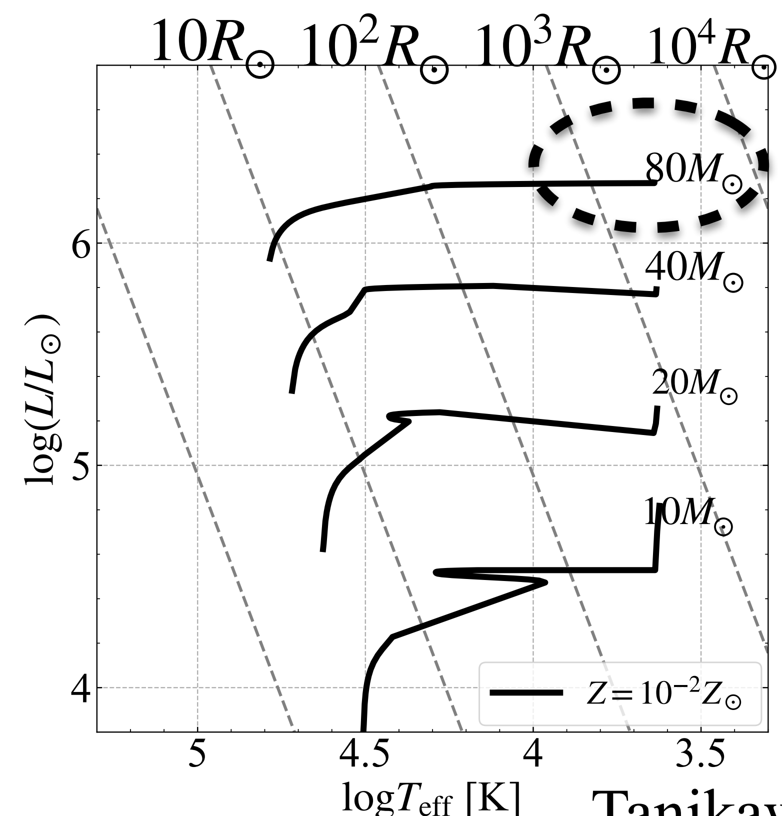




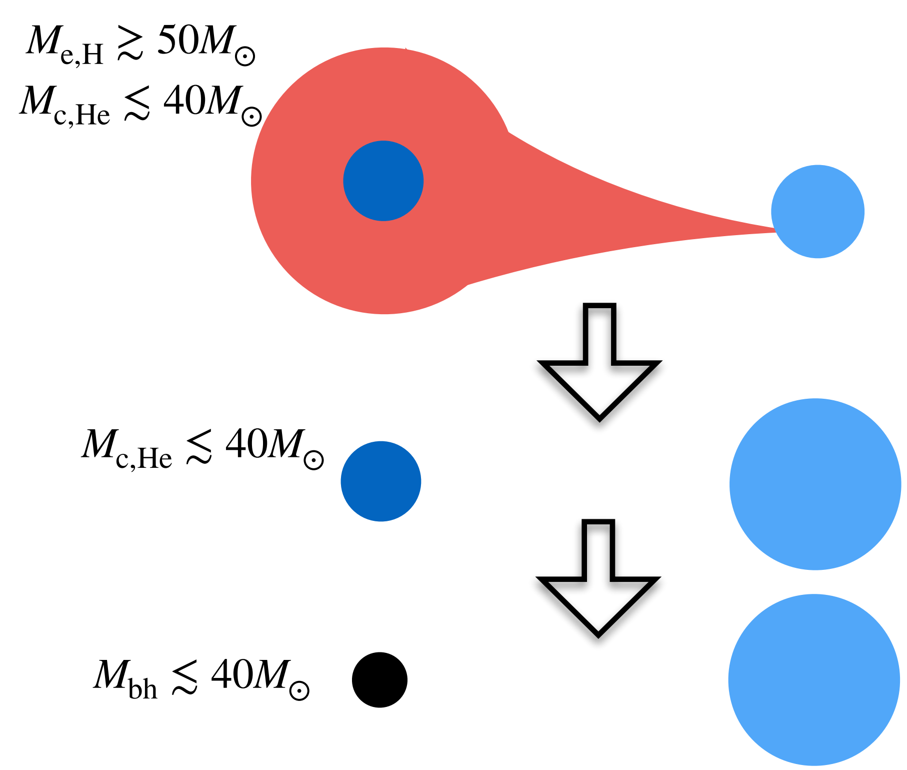
Belczynski et al. (2020)

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)



Many scenarios other than binary evolution

- Globular clusters, open clusters, AGN disks (e.g. Rodriguez et al. 2019; Di Carlo et al. 2020; Yang et al. 2019)

- PPI/PISN occurs in $M_{\rm c,He} \gtrsim 90 M_\odot$ if the $^{12}{\rm C}(\alpha,\gamma)^{16}{\rm O}$ rate is 3 times smaller than the standard one (Takahashi 2018; Farmer et al. 2020; Costa et al. 2020).

- Many more …

- Our study of GW190521 formation

  - Binary evolution isolated from star clusters

  - PPI/PISN for $M_{\rm c,He} \gtrsim 40 M_\odot$ as usual

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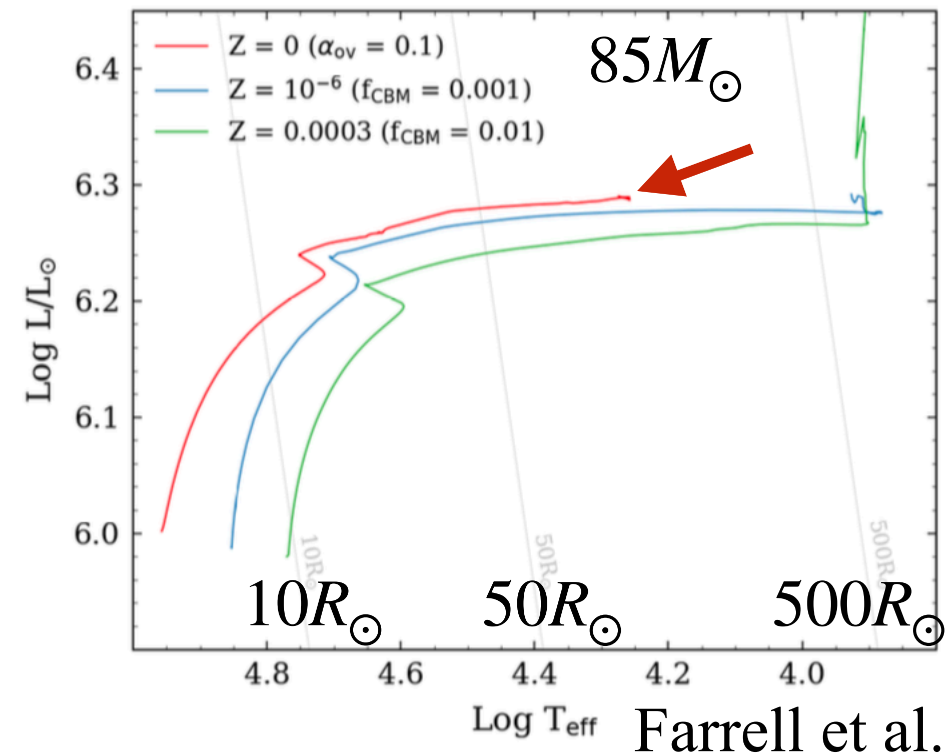
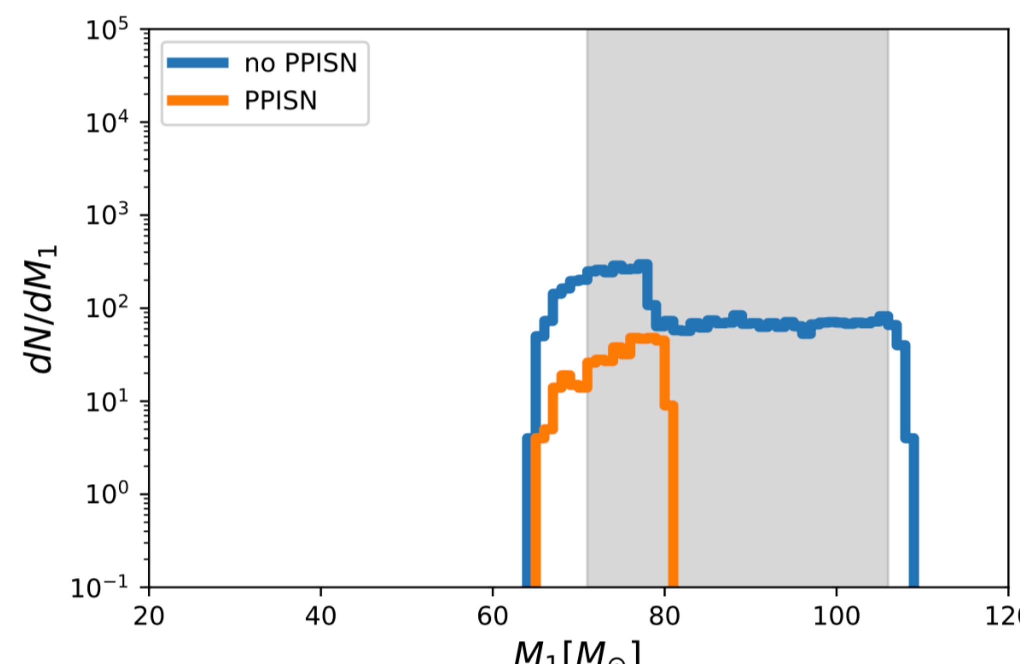
Pop. III binary star evolution

- Pop. III star with $M_{\rm zams} = 85 M_\odot$
  - Weak stellar wind mass loss
  - Expansion up to $\sim 160 R_\odot$
  - He core with $\lesssim 40 M_\odot$
- GW190521 can be formed from a Pop. III binary !!!



Farrell et al. (2020)



Kinugawa et al. (2020)

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)

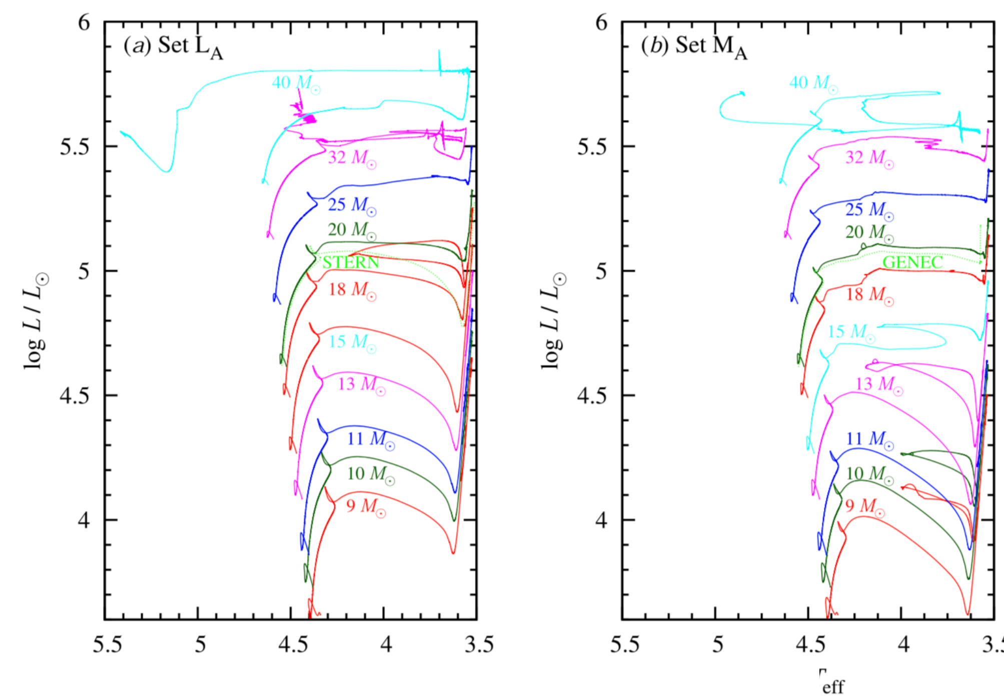
M model

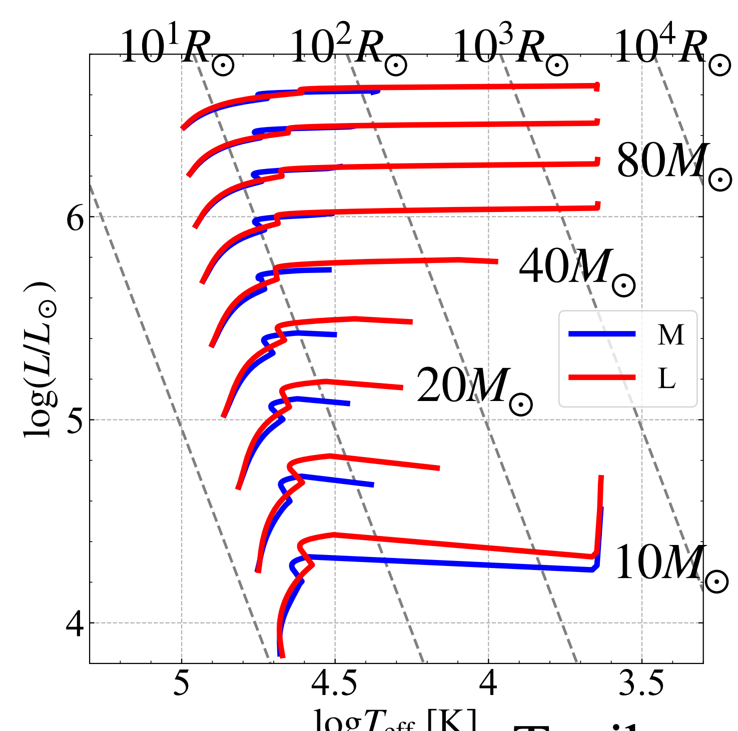
  - Early B-type stars in LMC, Stern (Brott et al. 2011)

L model

- The maximums radius of a $80 M_{\odot}$ star
  - M model: $\sim 40 R_{\odot}$, 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)



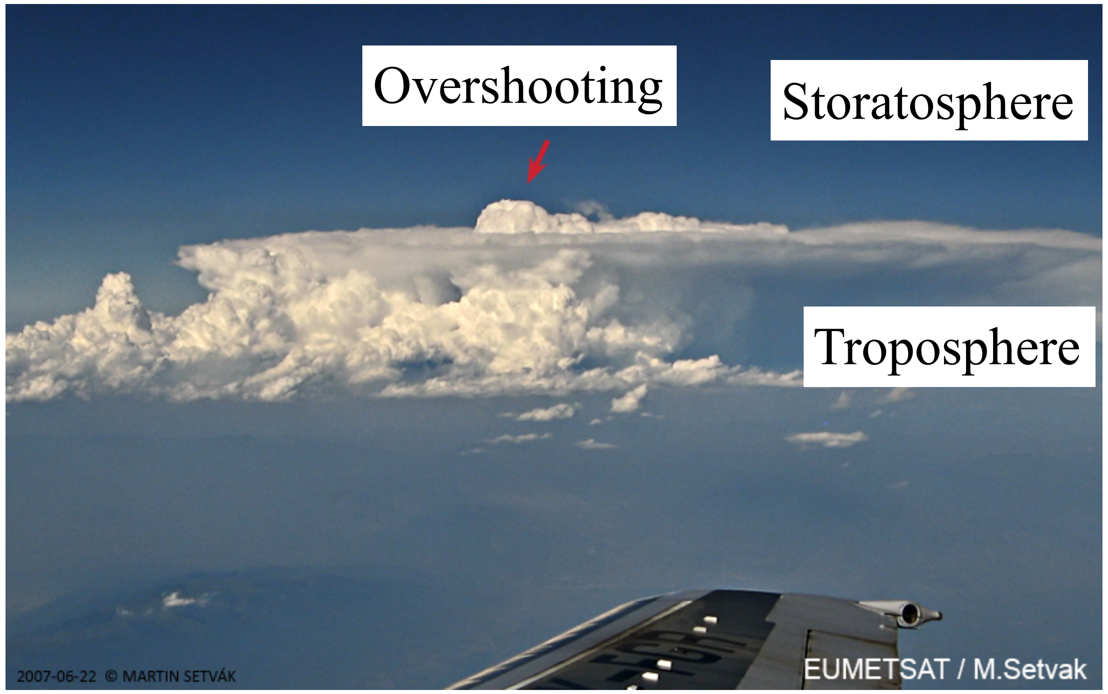


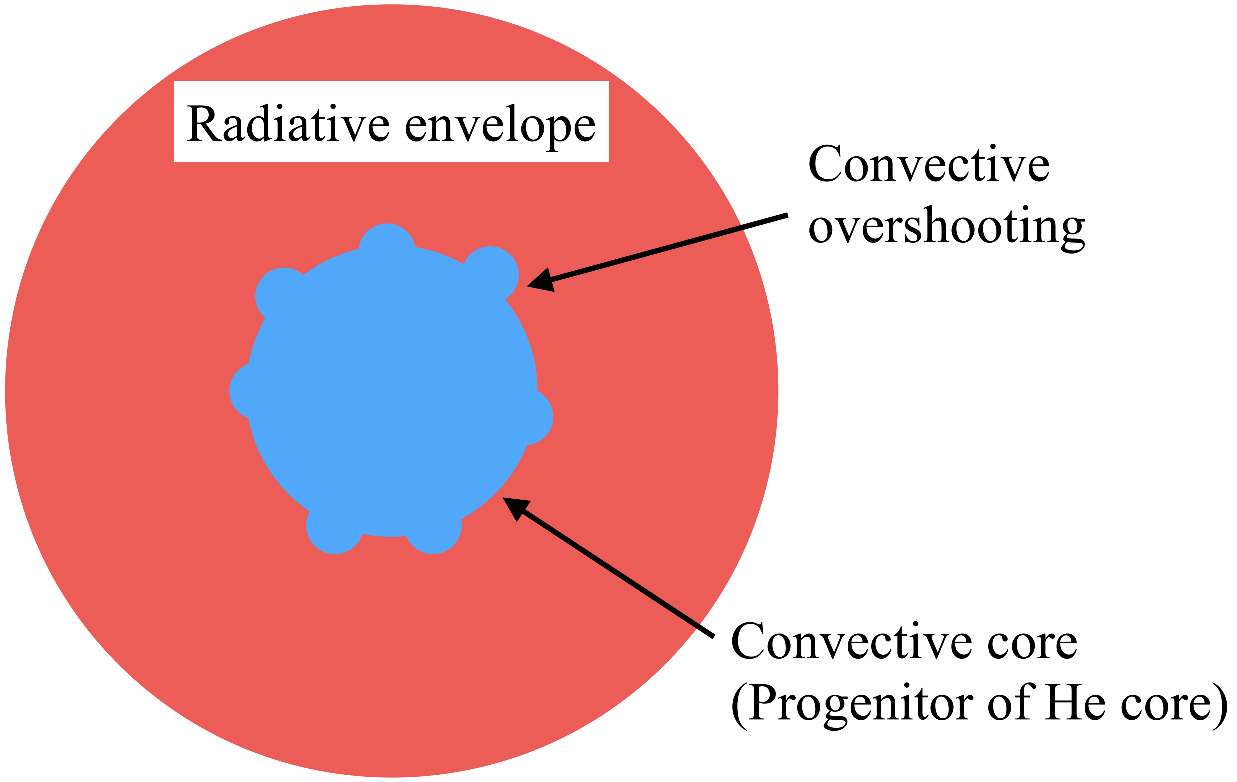
Two Pop. III models

Tanikawa et al. (2020c)

Convective overshooting

- Overshoot parameter: $f_{\rm ov} \sim 0.02$ (Kippenhahn et al. 1990; 2012)
  - $$D(z) = D_0 \exp \frac{-2z}{f_{\rm ov} H_{\rm P}}$$
  - 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





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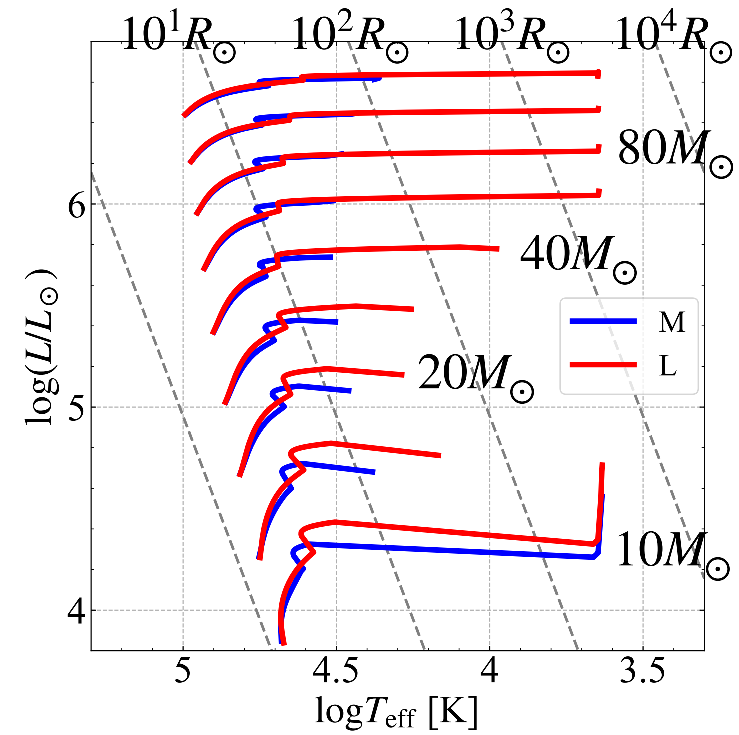
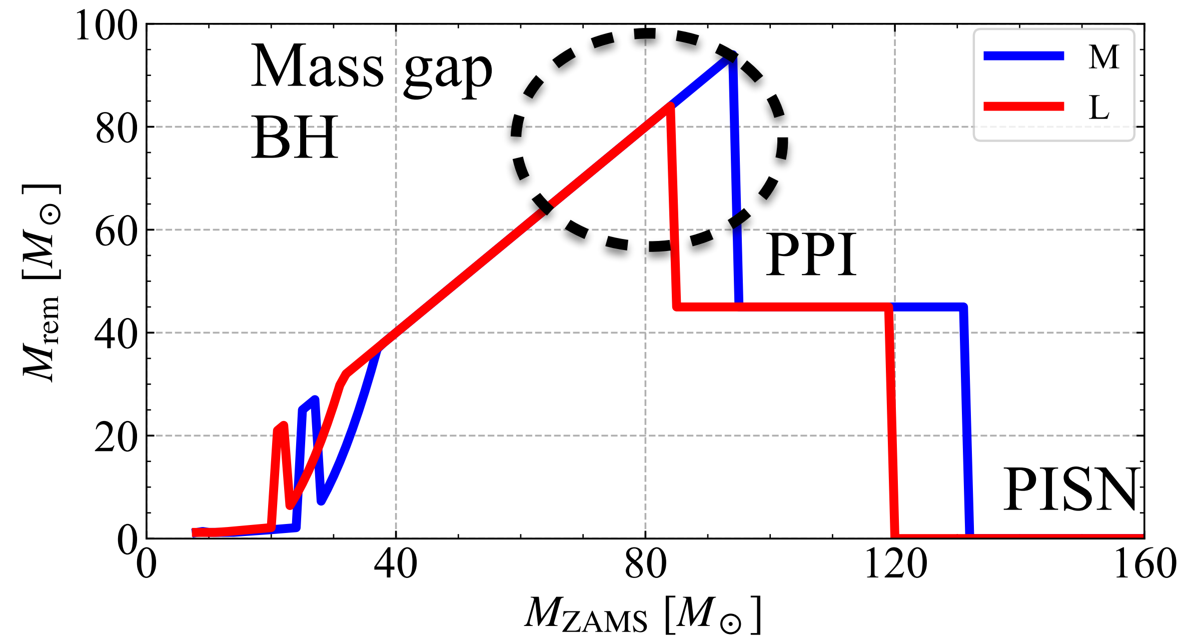
Binary population synthesis

- 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
  - $f(m_1) \propto m_1^{-1}, f(q) \propto \text{const}, f(a) \propto a^{-1}, f(e) \propto e$
- Cumulative Pop. III density
  - $\sim 10^{13} M_{\odot} \text{pc}^{-3}$ comparable to Magg et al. (2016) and Skinner, Wise (2020)

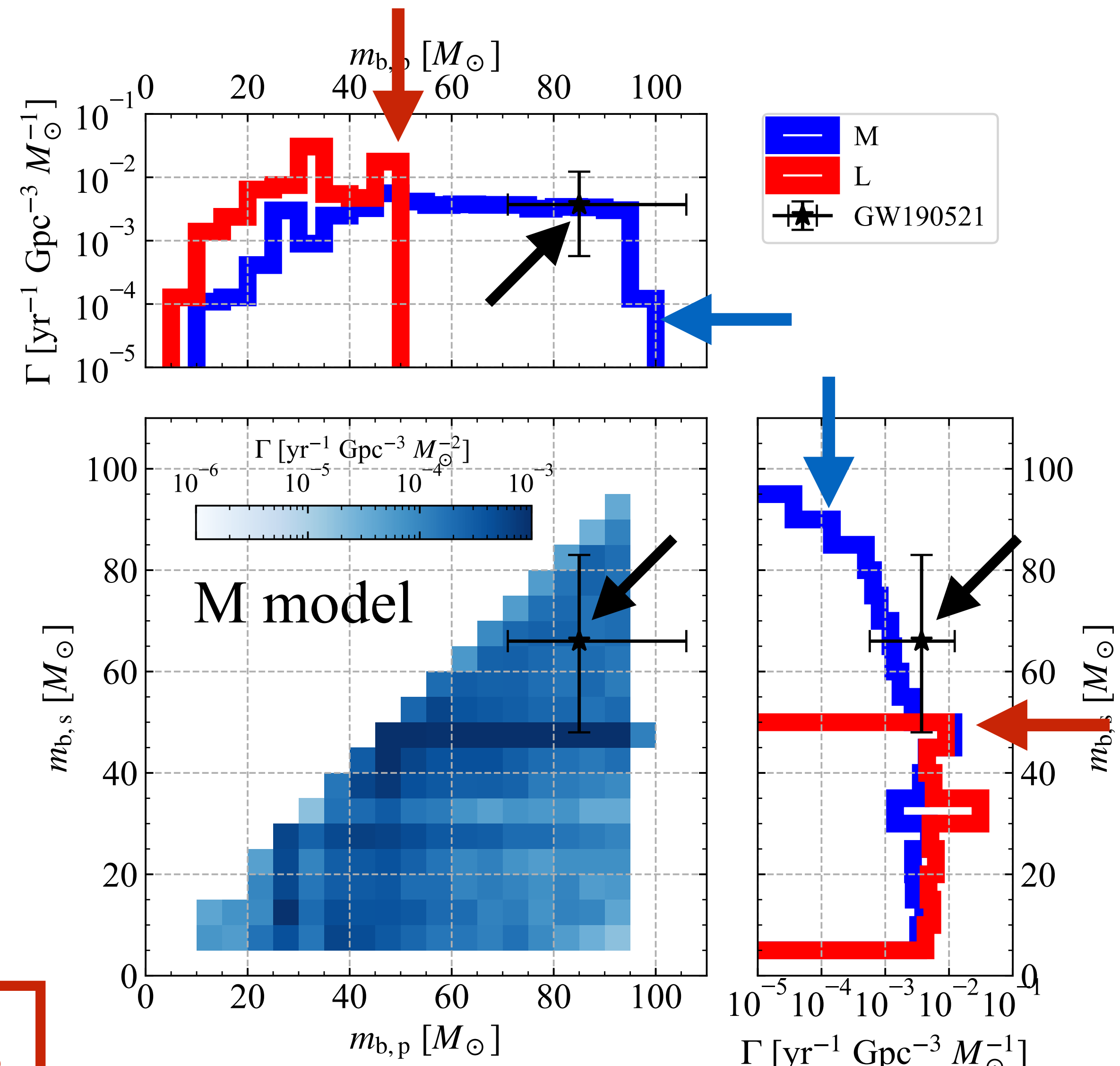




Tanikawa et al. (2020c)

BH mass distribution

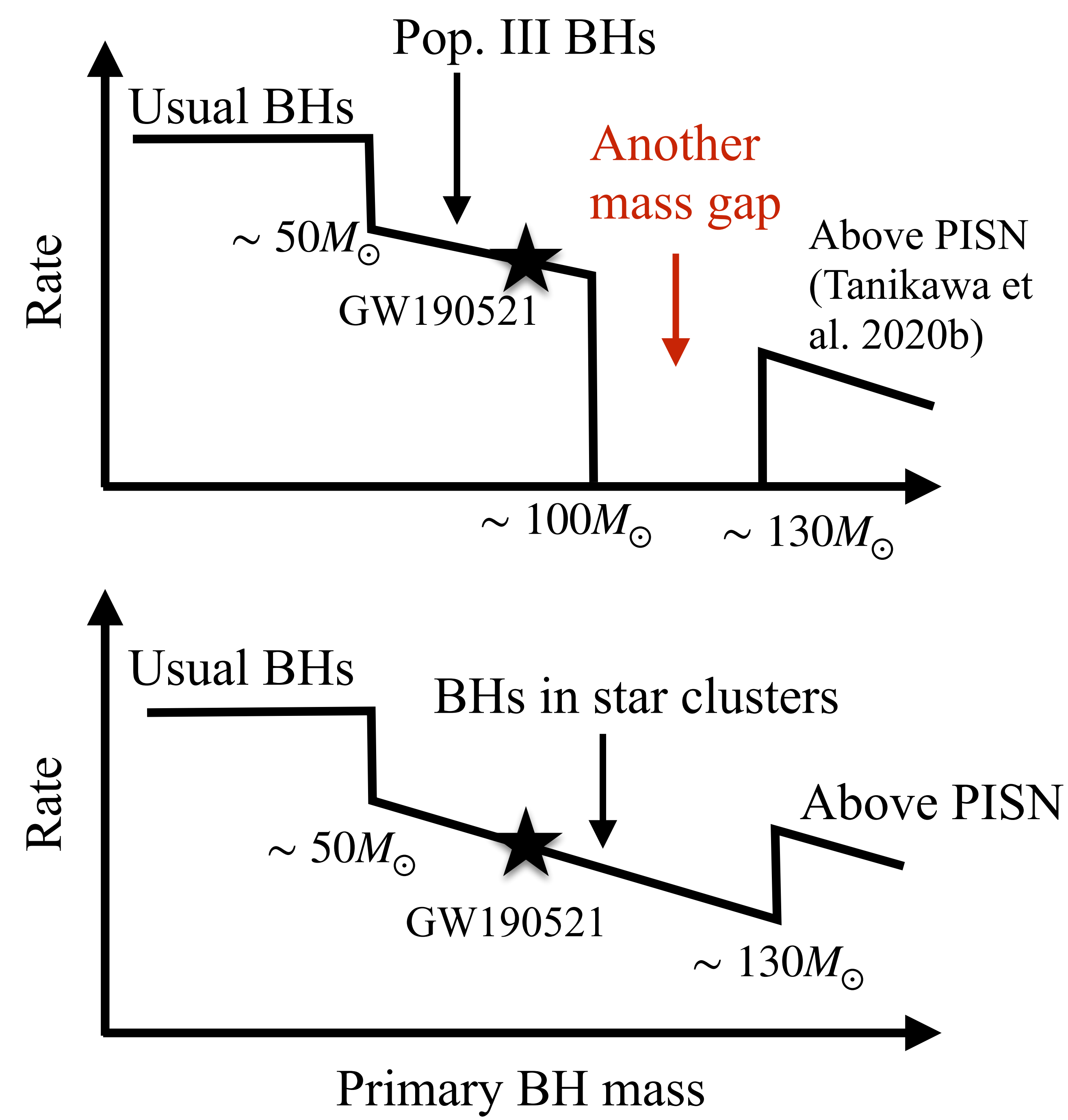
- M model
  - The maximum mass: $\sim 100 M_{\odot}$
  - Stars lose little mass through binary interactions.
  - Pop. III stars can form GW190521-like BH-BHs.
  - Support for the claims of Farrell et al. (2020) and Kinugawa et al. (2020)
- L model
  - The maximum mass: $\sim 50 M_{\odot}$
  - Stars lose 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

If GW190521 is Pop.III …

- Even if the M model is correct, no Pop. III binary can form BH-BHs with $100 - 130 M_{\odot}$.
- If GW190521 is Pop. III, the merger rate of BH-BHs with $100 - 130 M_{\odot}$ is much smaller than with $50 - 100 M_{\odot}$.
- But, the converse is not true.
  - A Pop. II binary can form GW190521 if the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate is 3 times smaller than the standard rate (Belczynski 2020).



Summary

- GW190521 is a merger of a BH-BH with at least a BH in the PI mass gap.
- GW190521 can be formed from a Pop. III binary (Farrell et al. 2020; Kinugawa et al. 2020)
- We have shown that the Pop. III scenario strongly depends on the effectiveness of convective overshooting.
- If GW190521 is a Pop. III origin, the merger rate of $100 - 130 M_{\odot}$ BHs is much smaller than that of $50 - 100 M_{\odot}$.
    - But, the converse is not true.