ブラックホール連星形成の理論的研究
特に全質量150$M_{\odot}$であるGW190521を
初代星連星で作れるかどうかについて

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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)

Contents

- Pair instability (PI) mass gap and GW190521
- Difficulty to form PI mass gap BH
- Pop. III binary scenarios
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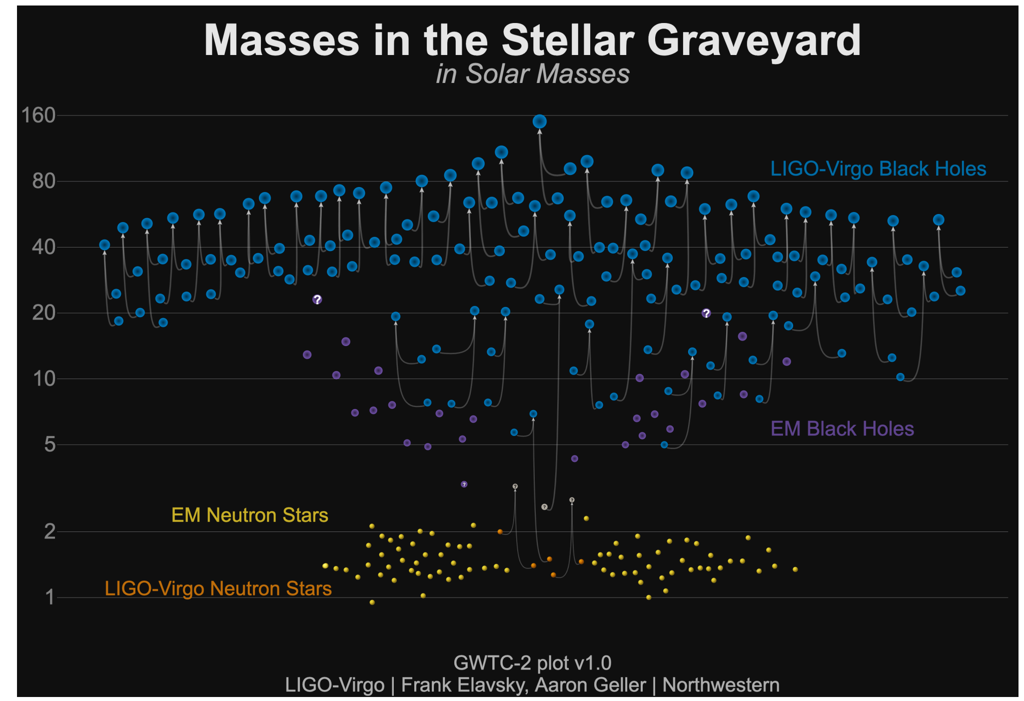
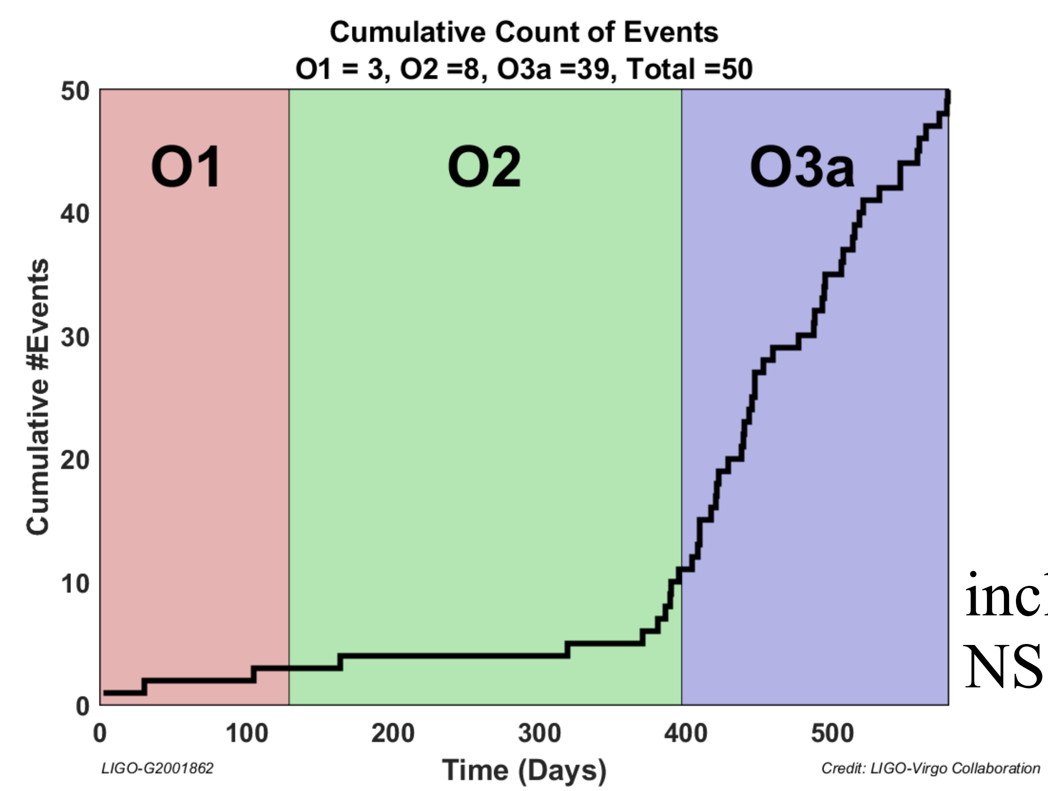
Merger of binary black holes

- Gravitational wave (GW) observations have rapidly increased the number of discovered BH-BHs.
- The first detection is 2015 (GW150914).
- 10 BH-BHs were found until 2017 (O1/O2)
- 44 BH-BHs have been found until now (O1/O2/O3a).
- The number of BHs is larger than that discovered by X-ray observations.

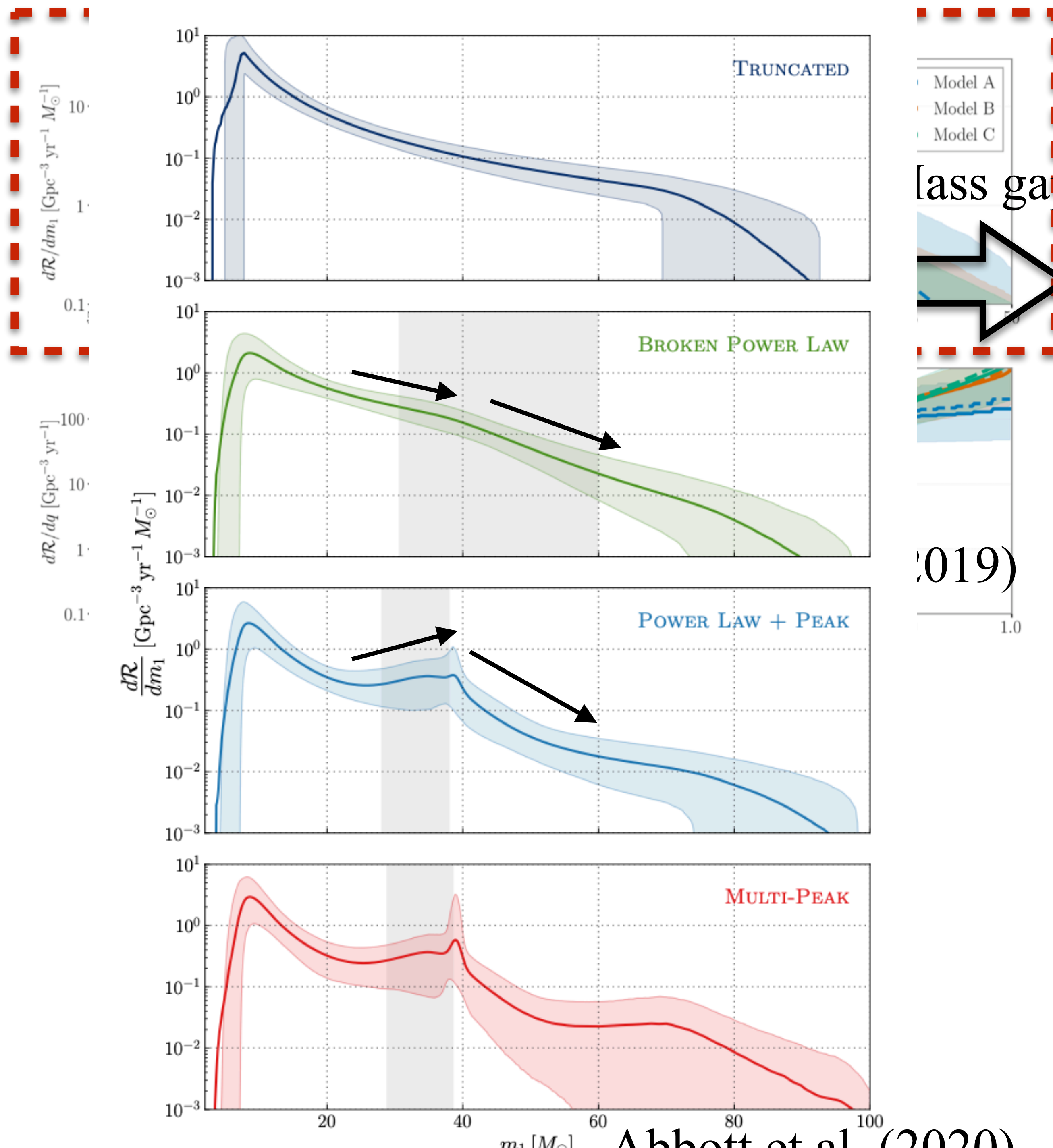




incl. NS-NS, NS-BH

BH mass distribution

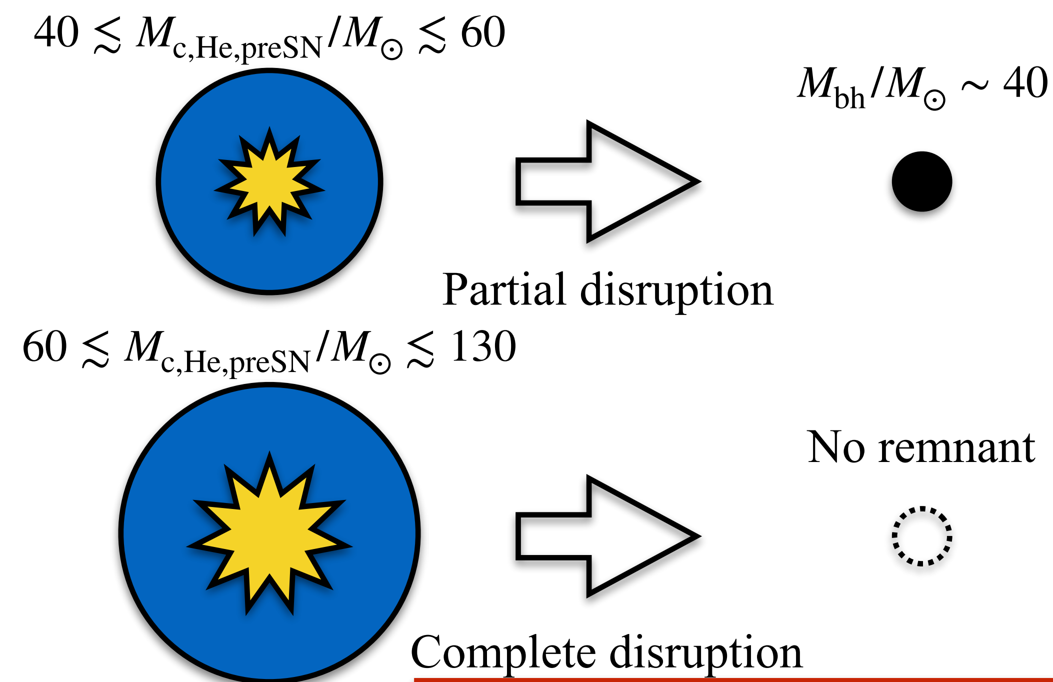
- The BH mass distribution appears not to have BHs with $\gtrsim 50 M_{\odot}$.
  - Second mass gap
  - Higher mass gap
  - <u>Pair instability (PI) mass gap</u>
- No BH with $50 - 130 M_{\odot}$ due to pulsational PI (PPI) and PI supernova (PISN)?

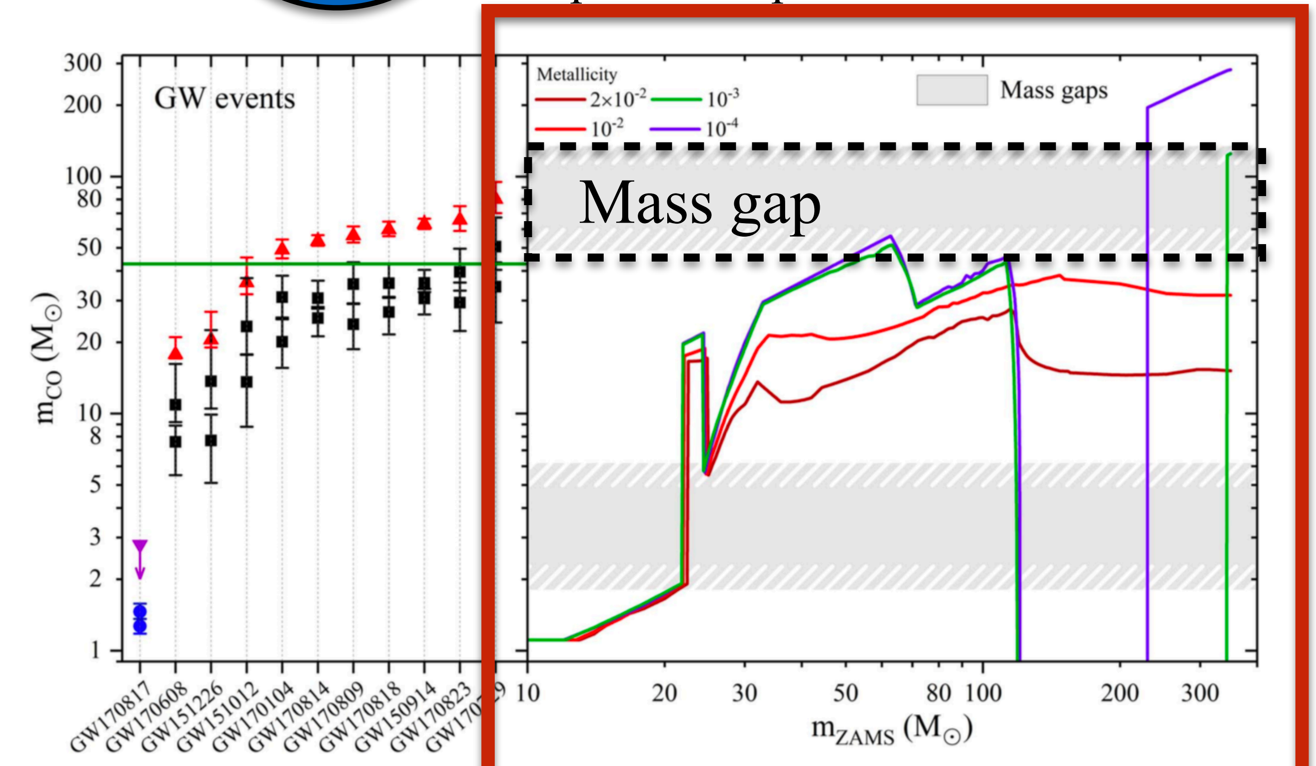


Abbott et al. (2020)

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

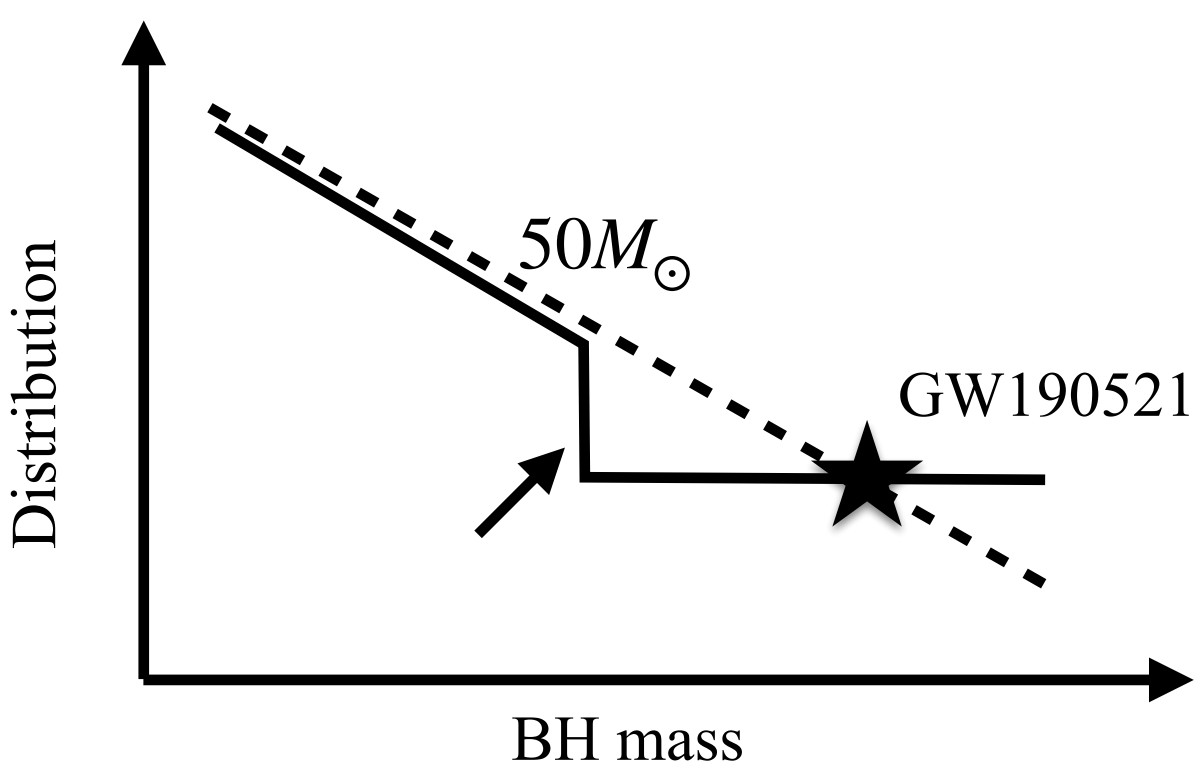




Abbott et al. (2019)

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 $65M_\odot$.
- At least one BH lies within the PI mass gap.



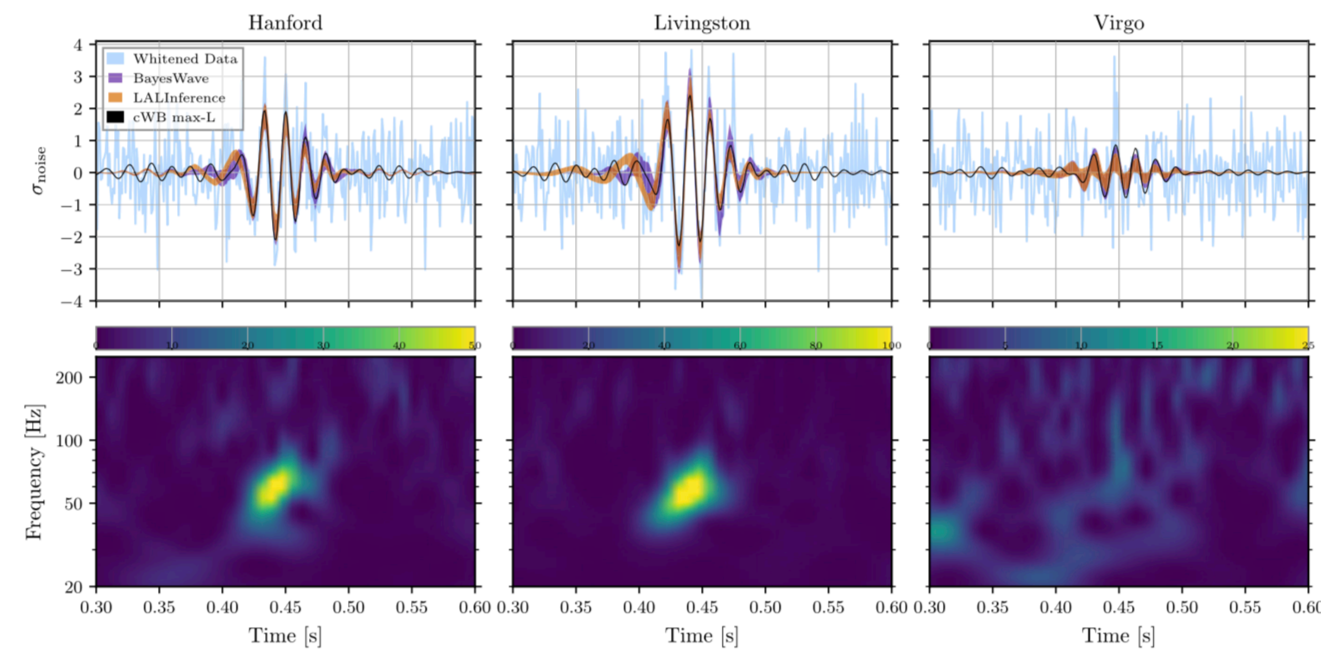


TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

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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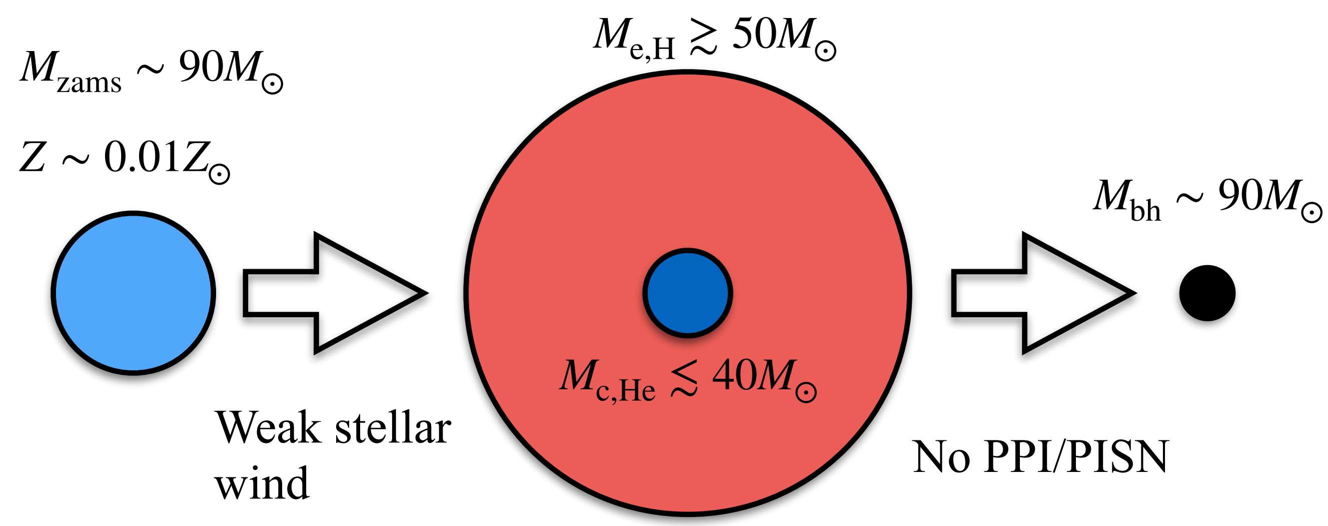
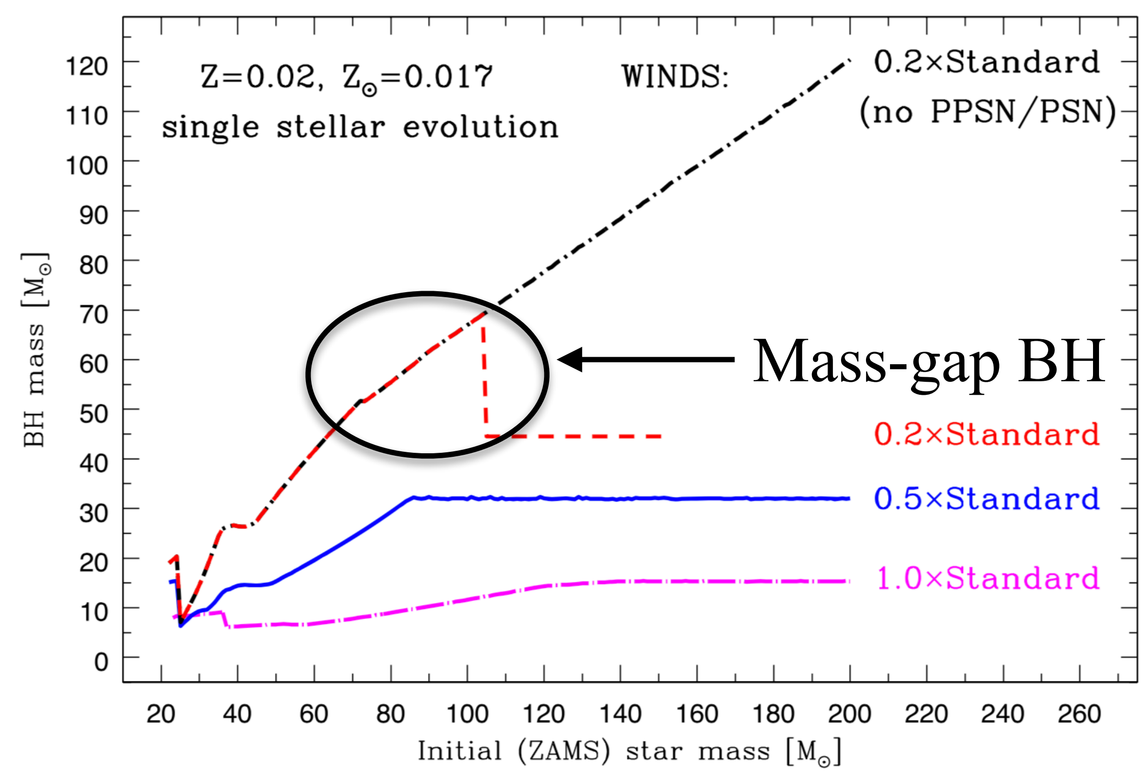
Single star evolution

- 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

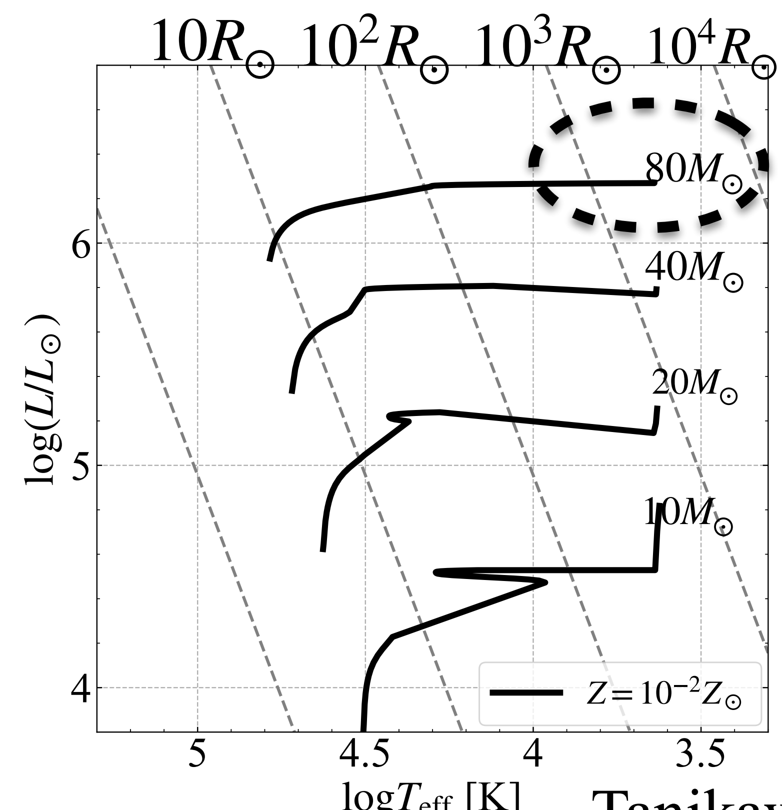




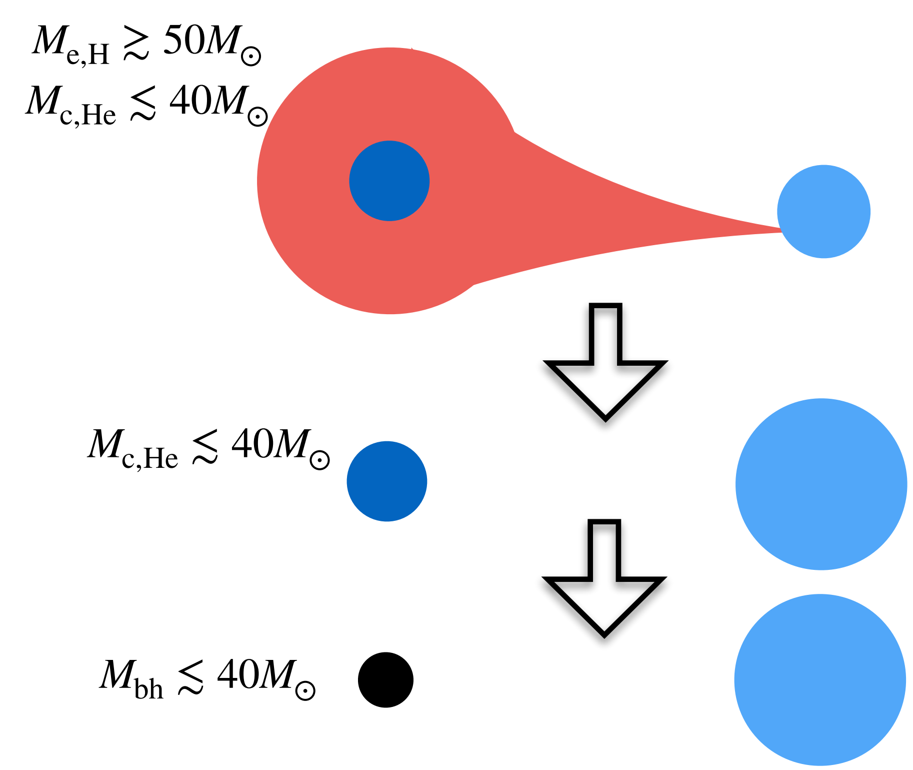
Belczynski et al. (2020)

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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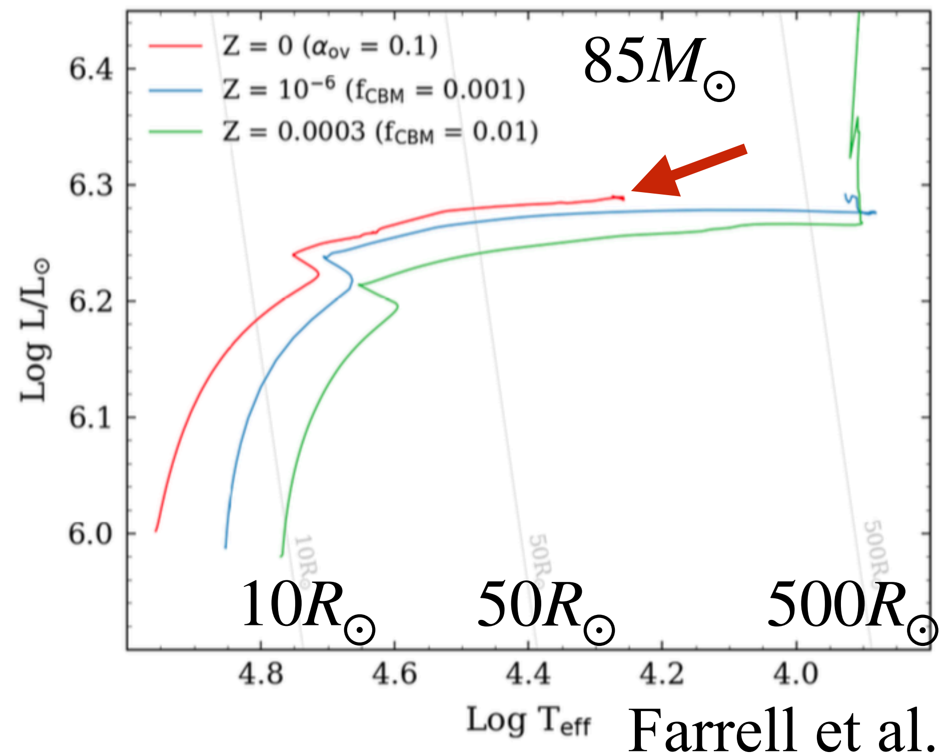
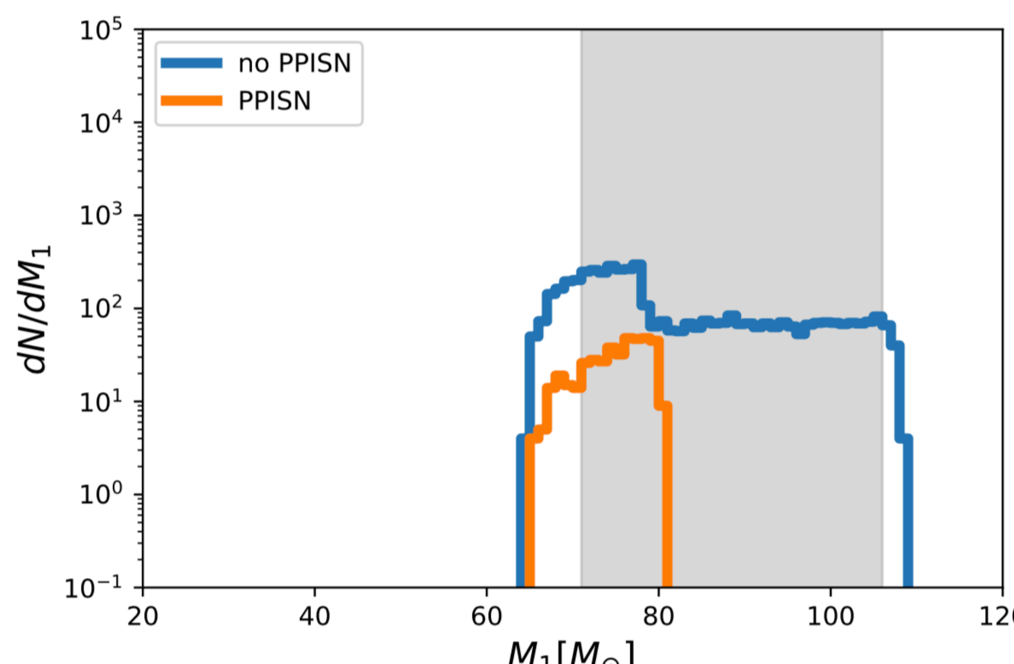
Pop. III binary star evolution

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



Farrell et al. (2020)

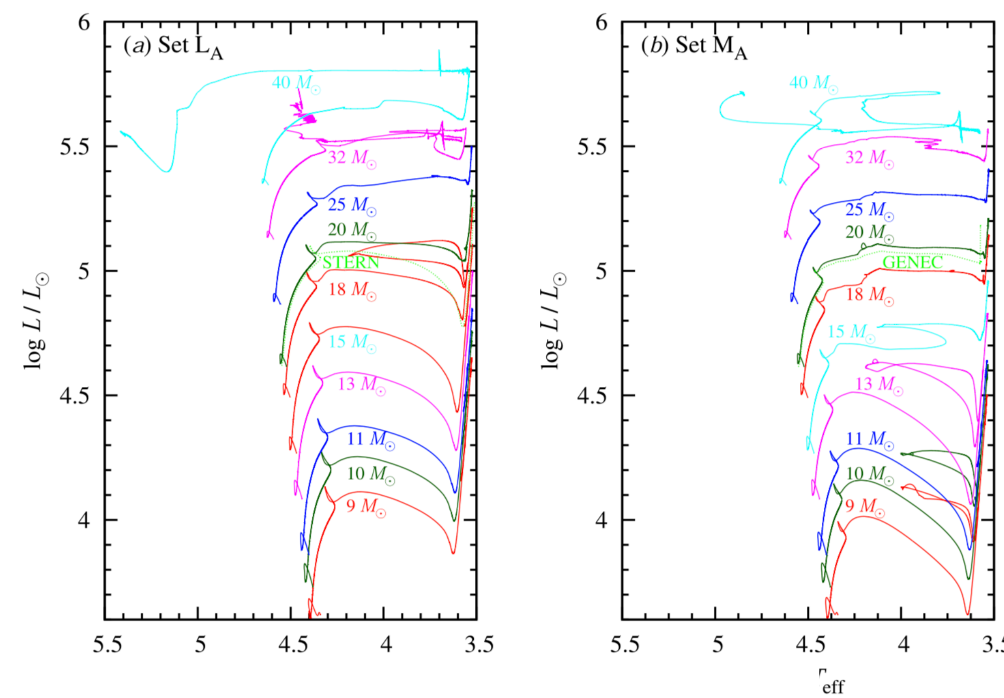


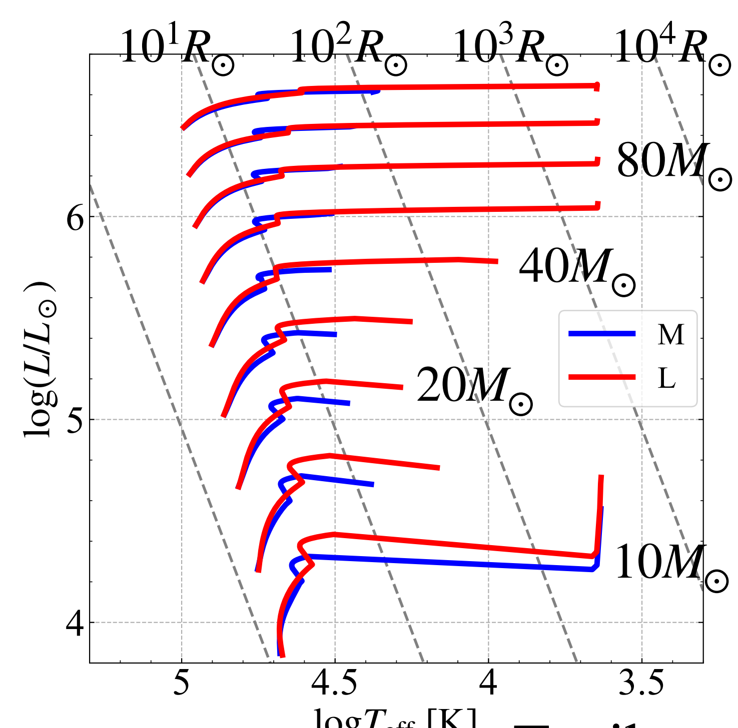
Kinugawa et al. (2020)

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 $80M_\odot$ star
  - M model: $\sim 40R_\odot$, similar to Farrell et al. (2020)
  - L model: $\sim 3\times10^3R_\odot$, 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)



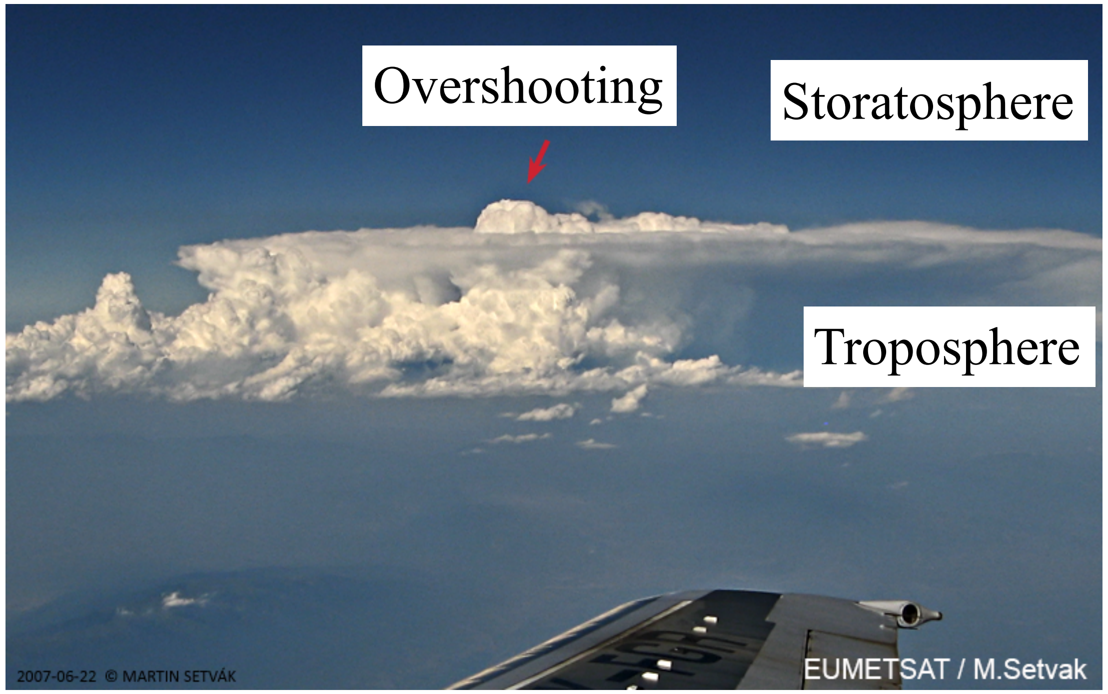


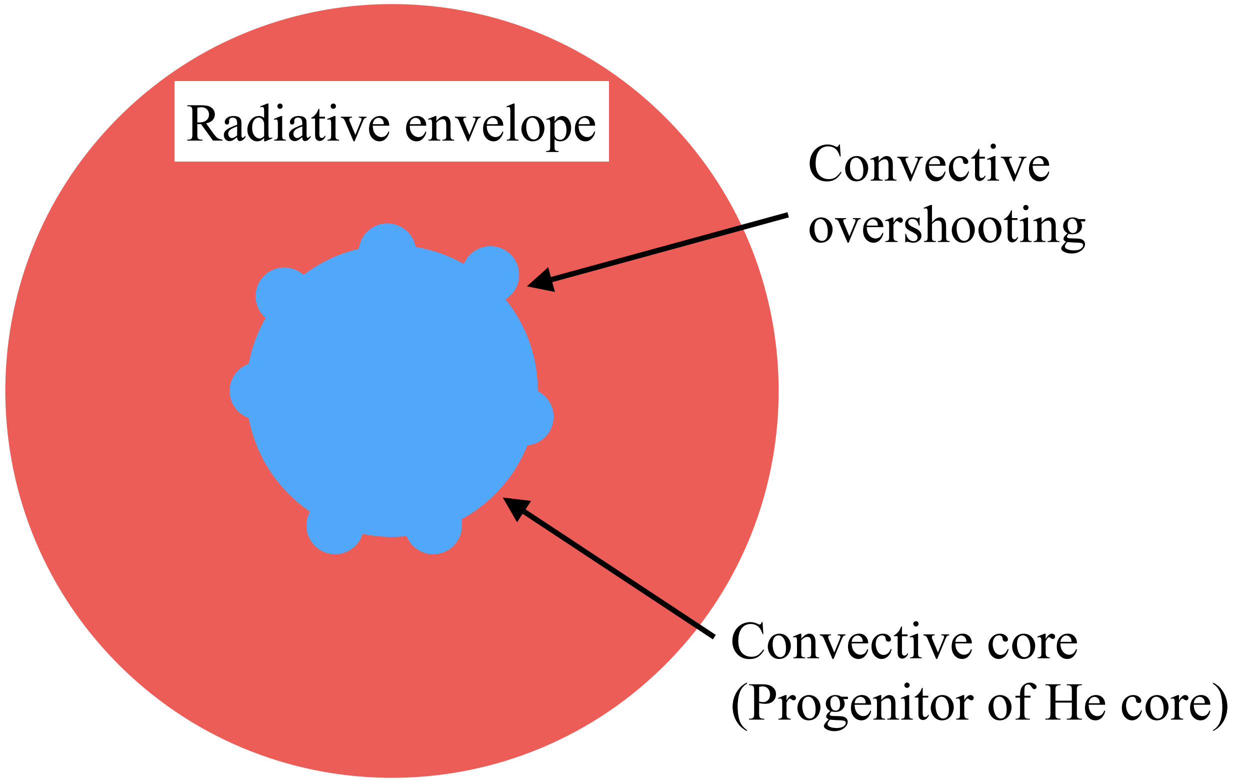
Two Pop. III models

Tanikawa et al. (2020c)

Convective overshooting

- Overshoot parameter: $f_{\mathrm{ov}} \sim 0.02$ (Kippenhahn et al. 1990; 2012)
  - $D(z) = D_0 \exp \dfrac{-2z}{f_{\mathrm{ov}} H_{\mathrm{P}}}$
  - M model: $f_{\mathrm{ov}} = 0.01$
  - L model: $f_{\mathrm{ov}} = 0.03$
- 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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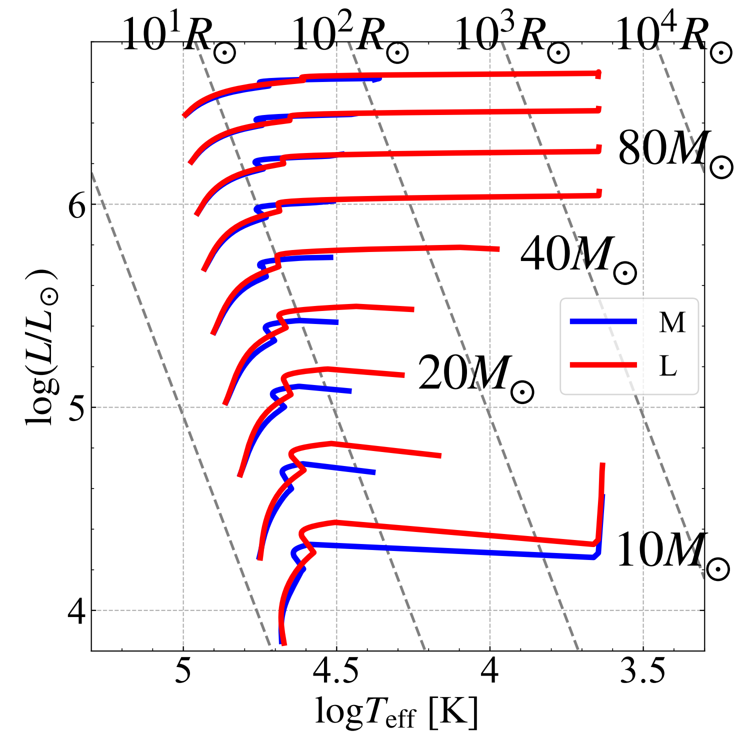
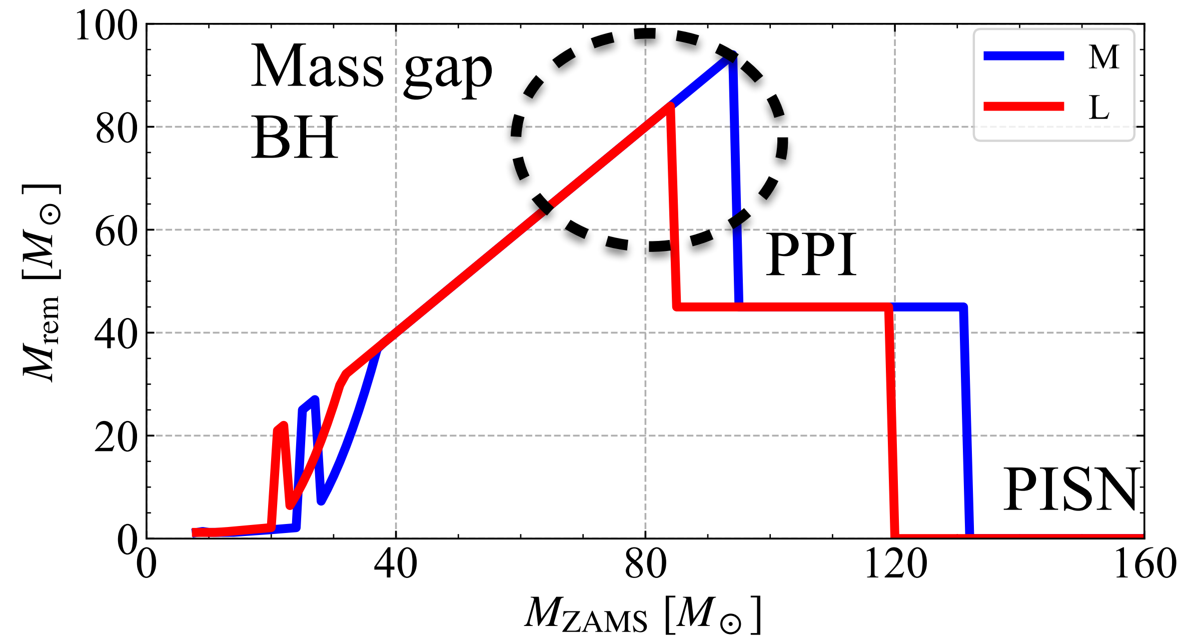
Binary population synthesis

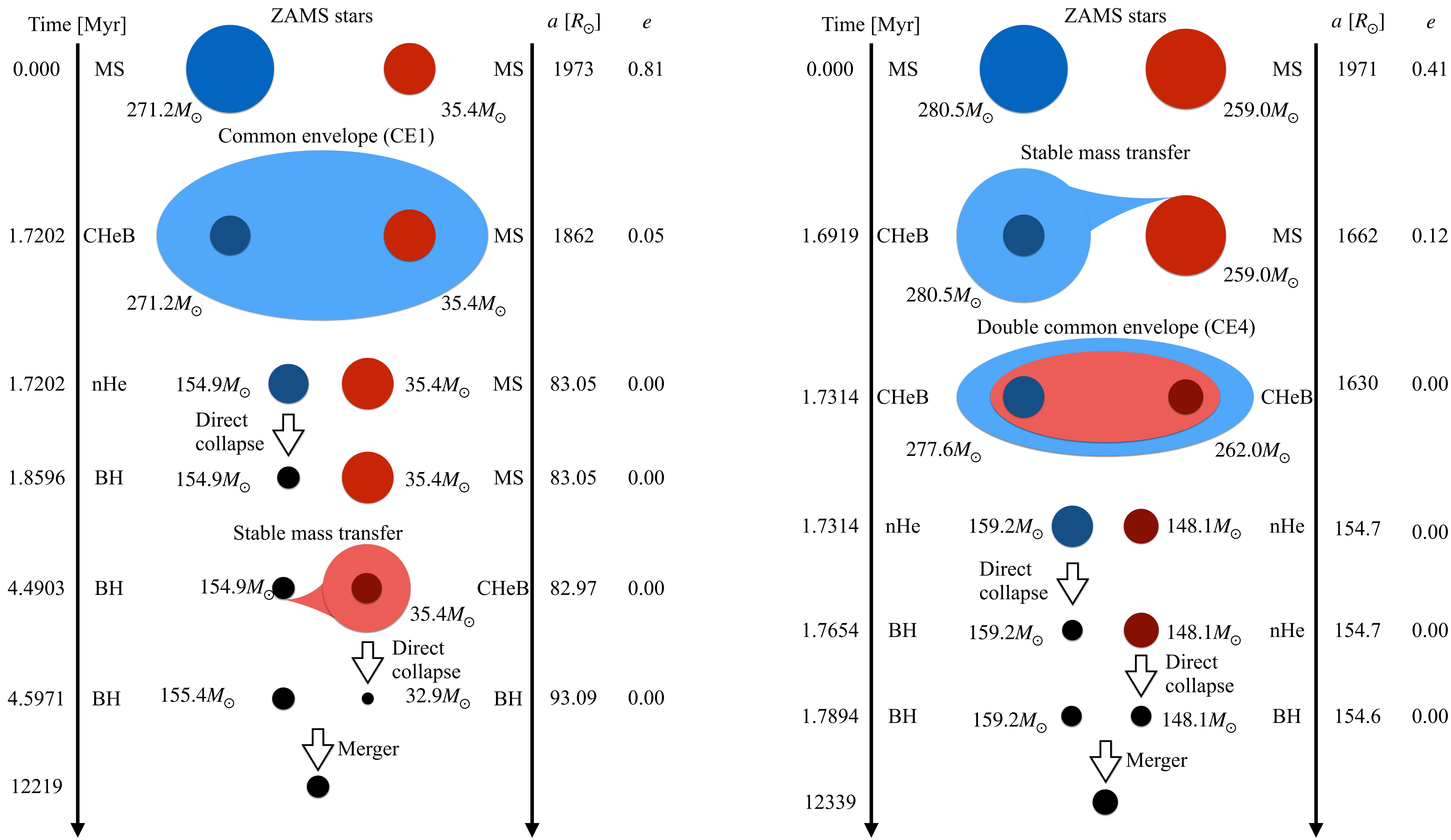
- BSE (Hurley et al. 2000; 2002) modified by Tanikawa et al. (2020a)
- Single star evolution
  - Fryer's rapid model with PPI/PISN
  - No stellar wind nor BH natal kick
- Binary star evolution
  - Tidal interaction
  - Stable mass transfer, common envelope
  - GW orbital decay
  - Etc.
- Initial conditions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





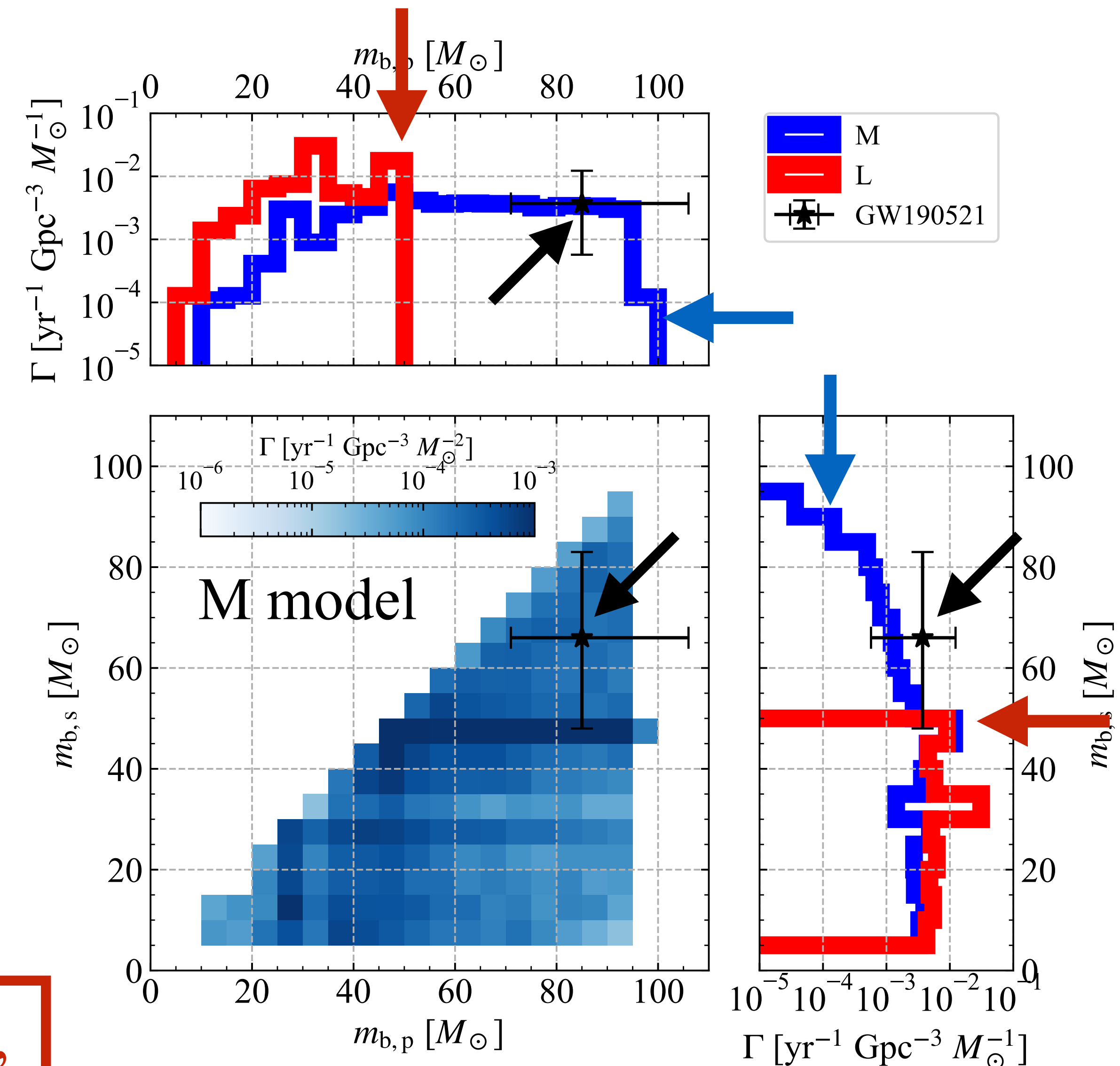
Tanikawa et al. (2020c)

Introduction of BPS



BH mass distribution

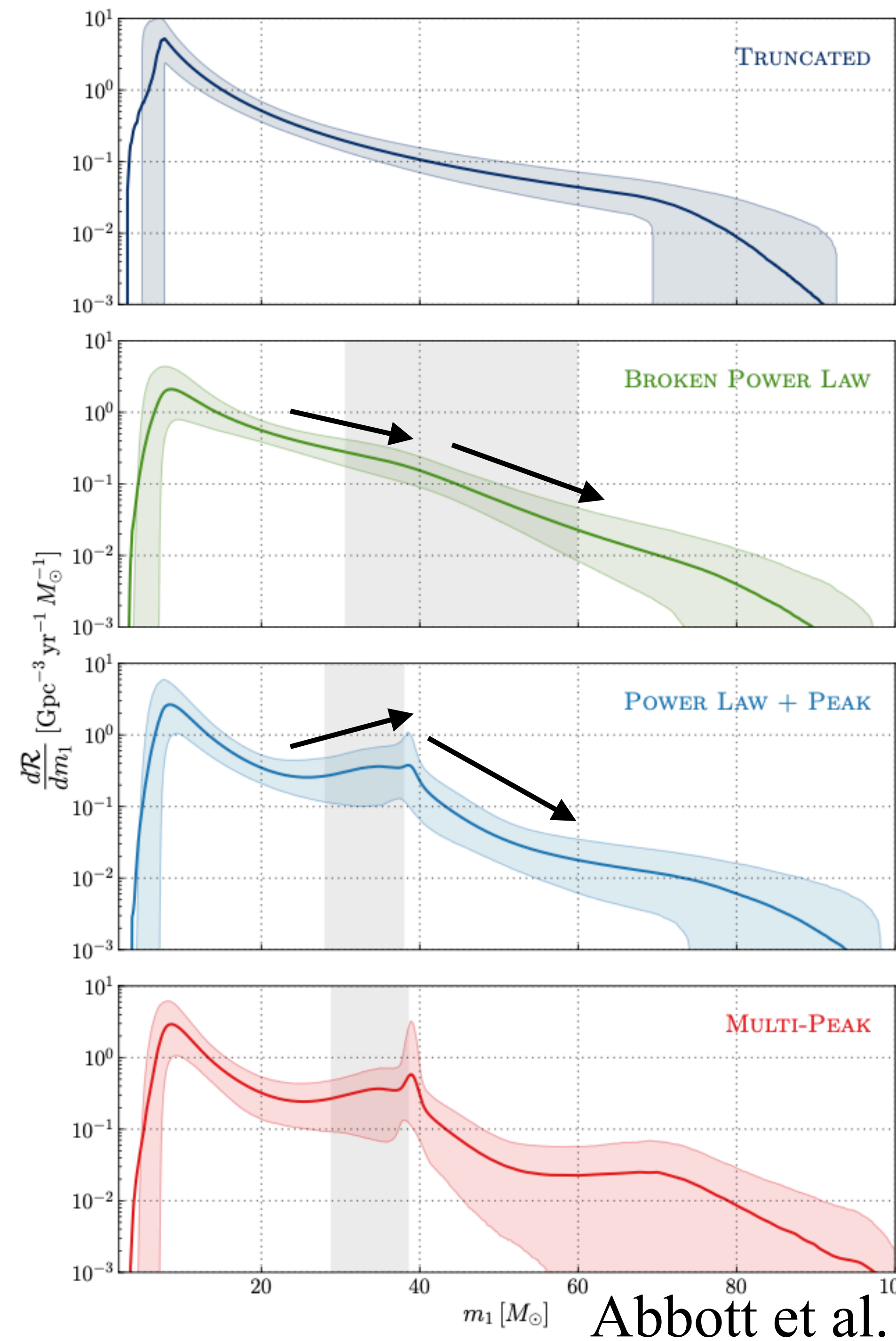
- M model
  - The maximum mass: $\sim 100 M_\odot$
  - Stars lose little mass through binary interactions.
  - Pop. III stars can form GW190521-like BH-BHs.
  - Support for the claims of Farrell et al. (2020) and Kinugawa et al. (2020)
- L model
  - The maximum mass: $\sim 50 M_\odot$
  - Stars lose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



ove PISN
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2020b)

ove PISN

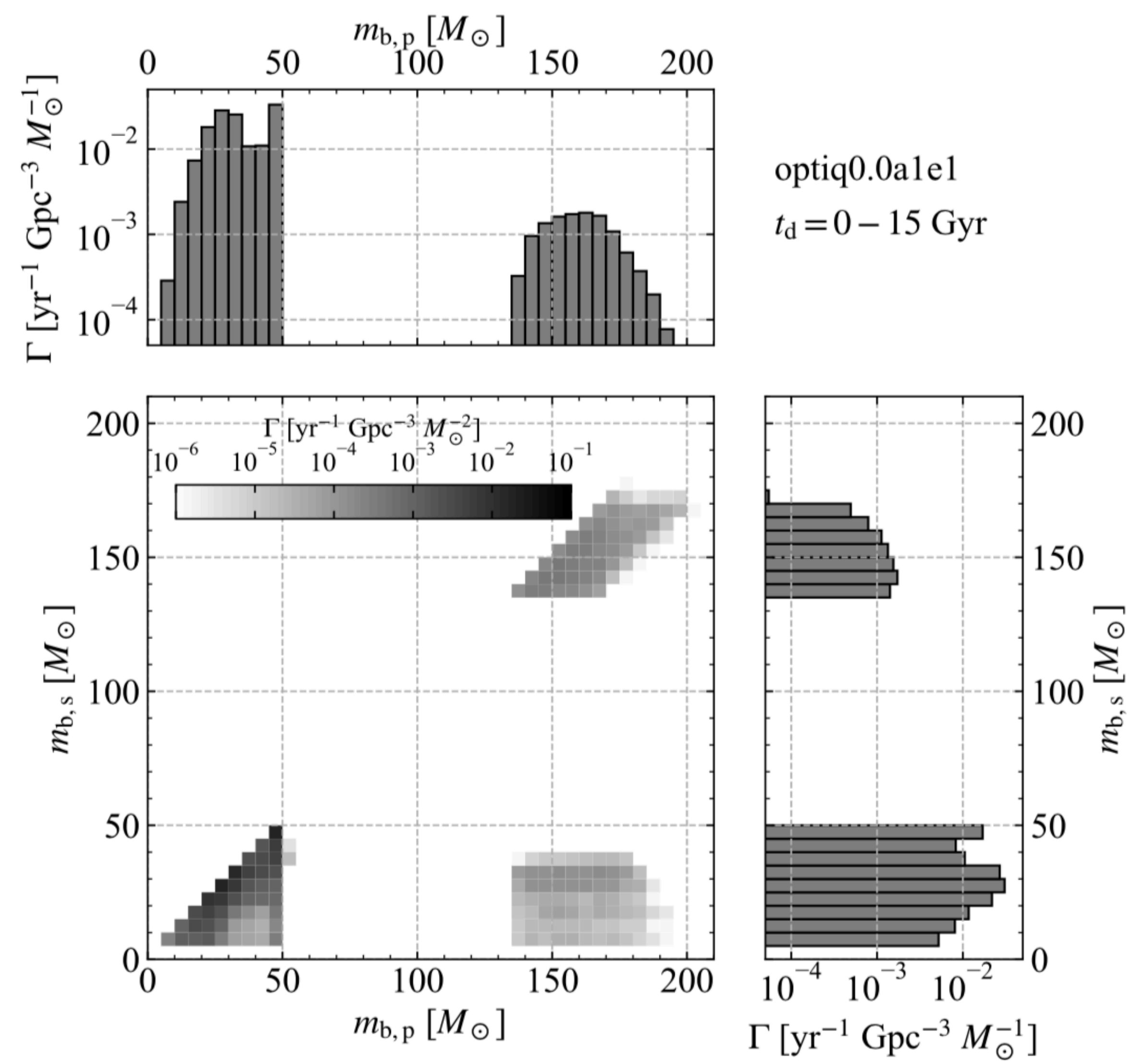
Abbott et al. (2020)

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 $100 - 130M_{\odot}$ BHs is much smaller than that of $50 - 100M_{\odot}$.
    - But, the converse is not true.

Lモデル詳細

- Initial conditions
  - $m_{1,\max} = 150M_\odot \rightarrow 300M_\odot$
- $130M_\odot$以上のBH形成
- BH Mergers of $> 130M_\odot$ and $< 50M_\odot$ are $\sim 10^{-2}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$.
- GW190521 could be below and above the mass gap (Fishbach, Holtz 2020; Nitz, Capano 2020).



Tanikawa et al. (2020b)