Pop. III binary evolution to form GW190521: effects of single star evolution

Group A winter Camp 2021
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- Tanikawa et al. (2020a, MNRAS, 495, 4170)
- Tanikawa et al. (2020b, arXiv:2008.01890, accepted for ApJ)
- Tanikawa et al. (2020c, arXiv:2010.07616)

Pop. III BH budget

- 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)

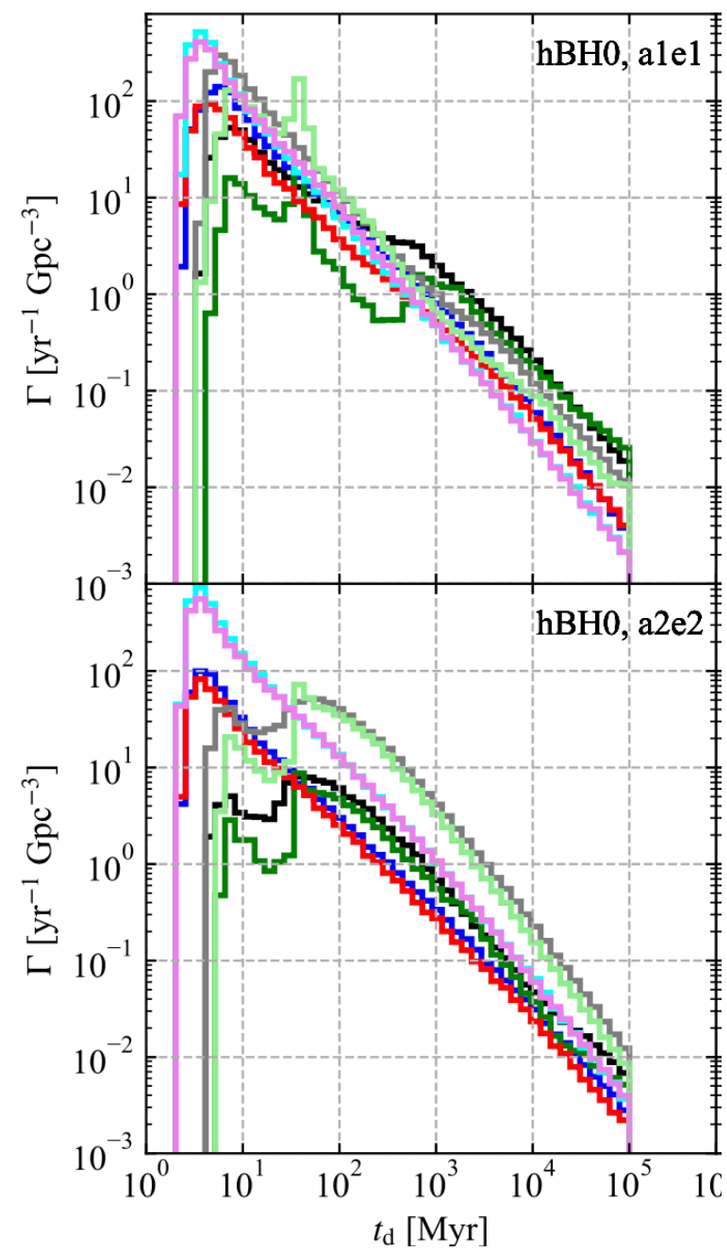
- Pop. III binary evolution
  - $n_{\rm BH,III} \sim 10^{11}{\rm Gpc}^{-3} \left(\frac{\rho_{\rm star}}{10^{13}M_\odot{\rm Gpc}^{-3}}\right)\left(\frac{\eta_{\rm BH}}{10^{-2}M_\odot}\right)$
  - $\frac{n_{\rm BH-BH}}{n_{\rm BH,III}} \sim 1\left(\frac{\Gamma_{\rm BH-BH}}{10{\rm Gpc}^{-3}{\rm yr}^{-1}}\right)$

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

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

Pop. III BH-BH rate

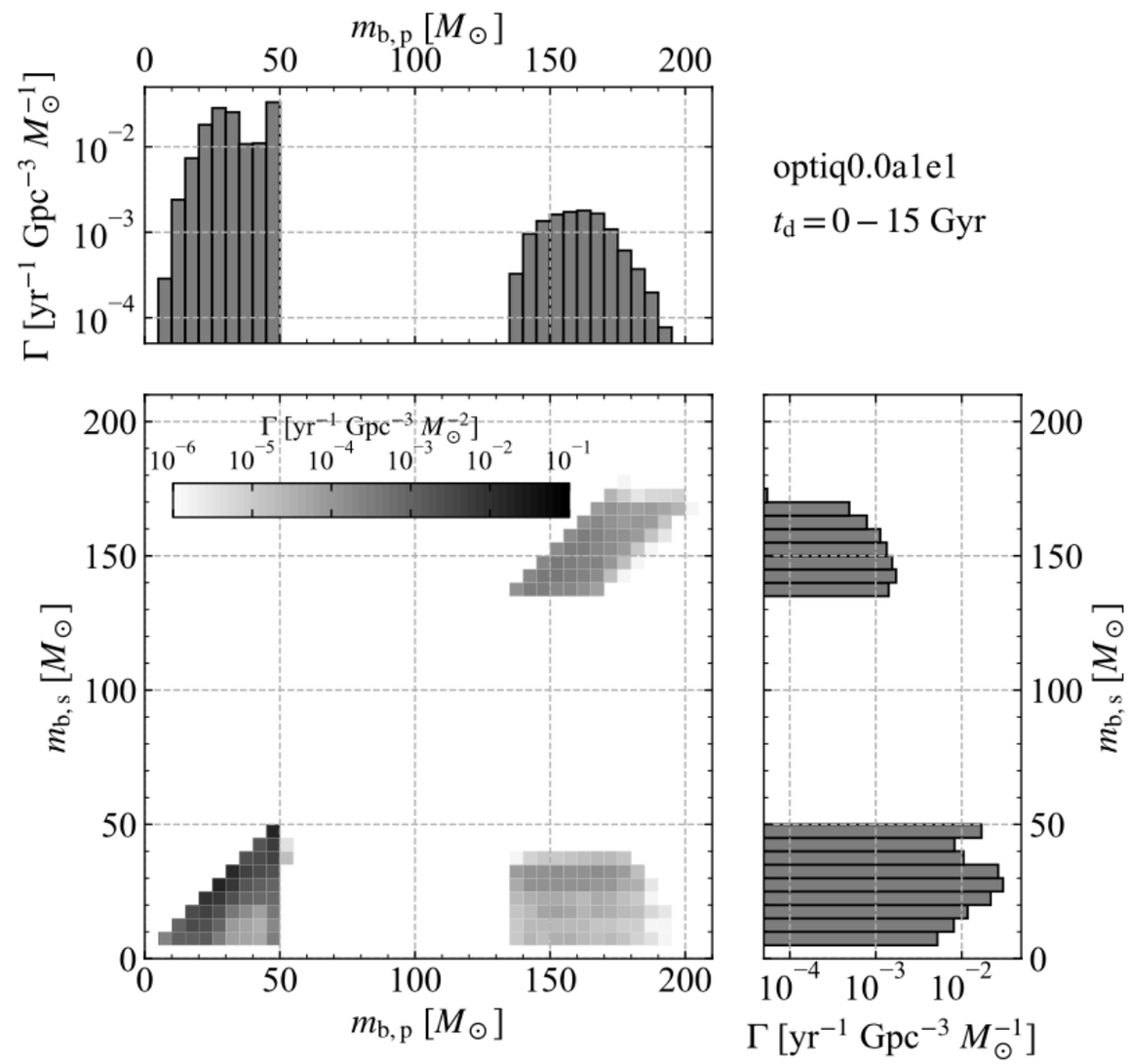
- The local Pop. III BH-BH merger rate: $\sim 10^{-1}\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$
- The merger rate weakly depends on
  - Minimum pericenter distance: 10 or $200 R_{\odot}$
  - Minimum mass ratio: 0.0 or 0.9
  - BH natal kick: 0 or 265 km s^{-1}
  - w/o and w/ stellar winds
- Mass and spin distributions are sensitive.



Tanikawa et al. (2020b)

Mass distribution

- Pop. III stars can have $\sim 300 M_\odot$.
  - Two types of BHs: stellar-mass BHs (sBH, $\lesssim 50 M_\odot$) and intermediate mass BHs (IMBHs, $\gtrsim 130 M_\odot$)
- Three subpopulations of BH-BHs
  - sBH-sBH
  - sBH-IMBH
  - IMBH-IMBH
- The merger rates:
  - $\sim 10^{-1}$ yr^{-1} Gpc^{-3} for two sBHs
  - $\sim 10^{-2}$ yr^{-1} Gpc^{-3} for BH-BHs with at least one IMBH

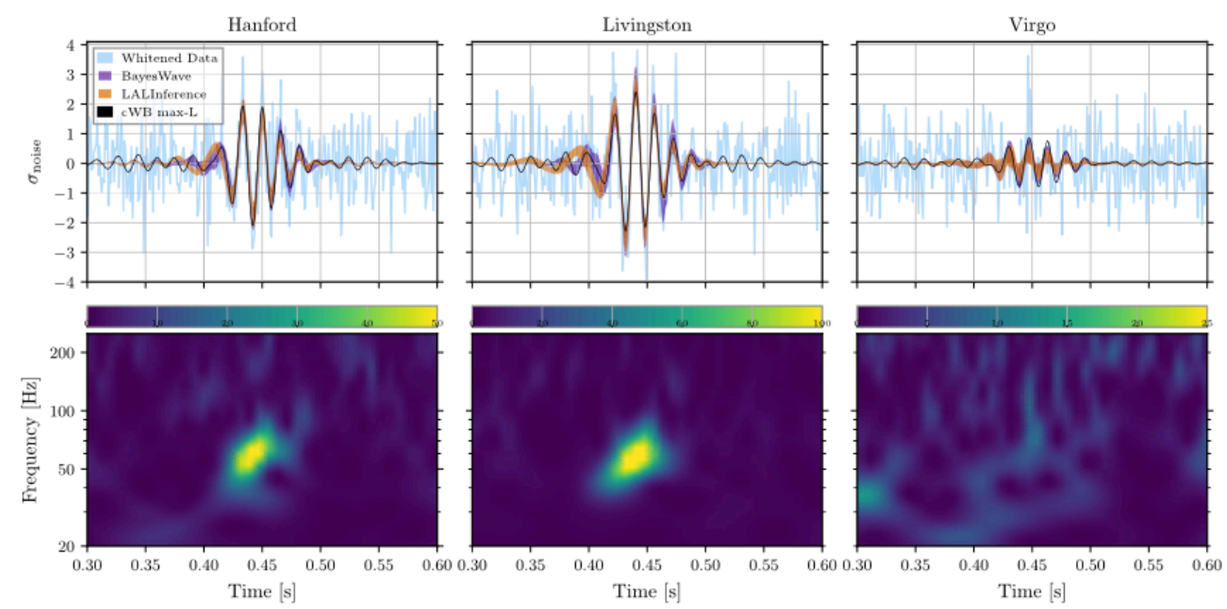


Tanikawa et al. (2020b)

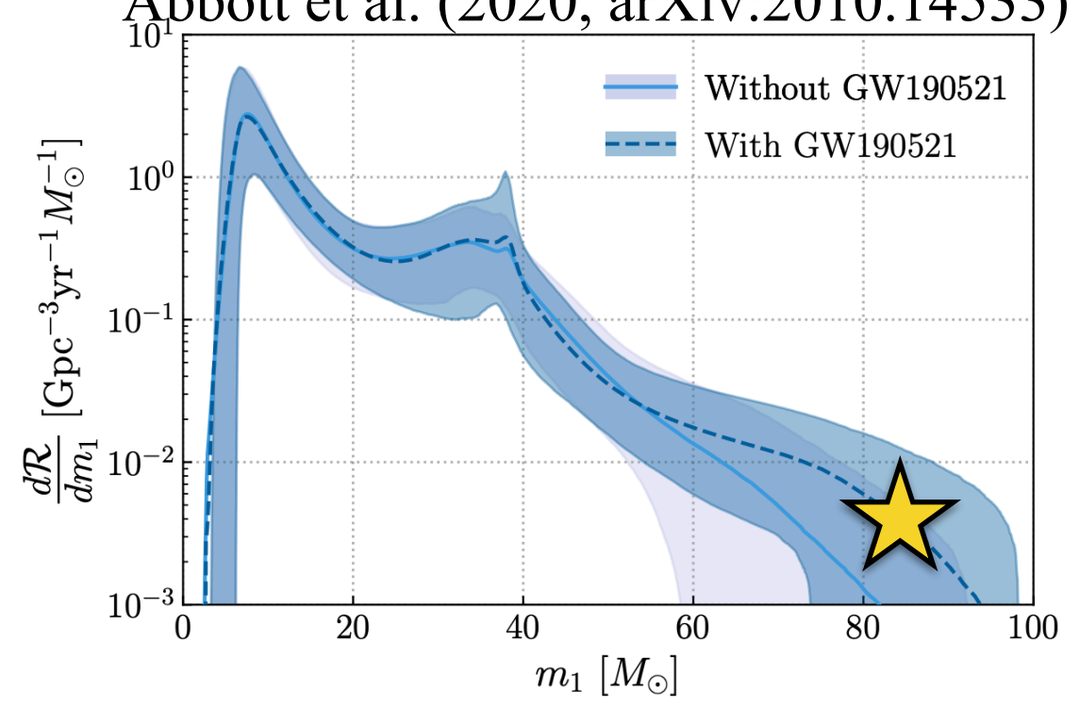
GW190521

- The most massive BH-BH so far
  - $85^{+21}_{-14} M_\odot$ and $66^{+17}_{-18} M_\odot$ BH
- The heavier BH in the higher mass gap
- Difficult to form through binary evolution

Abbott et al. (2020, PRL, 125, 101102)



Abbott et al. (2020, arXiv:2010.14533)



Problem in binary evolution

- Mass gap by Pair instability supernova (PISN)
- Reducing of the mass gap by single star evolution
- Revival of the mass gap by binary star evolution

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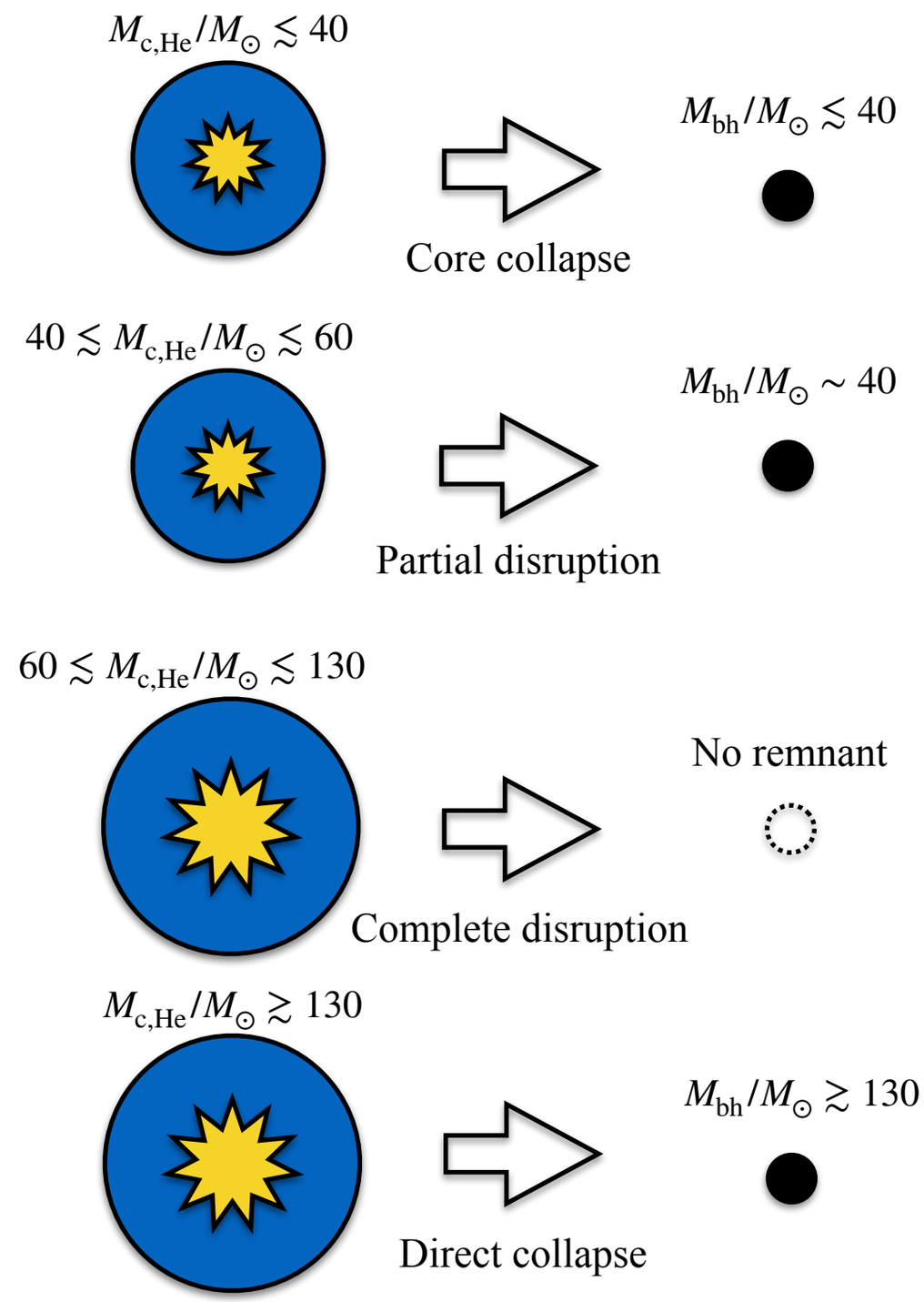
Mass gap: no BHs in the mass range of $40 - 130 M_\odot$



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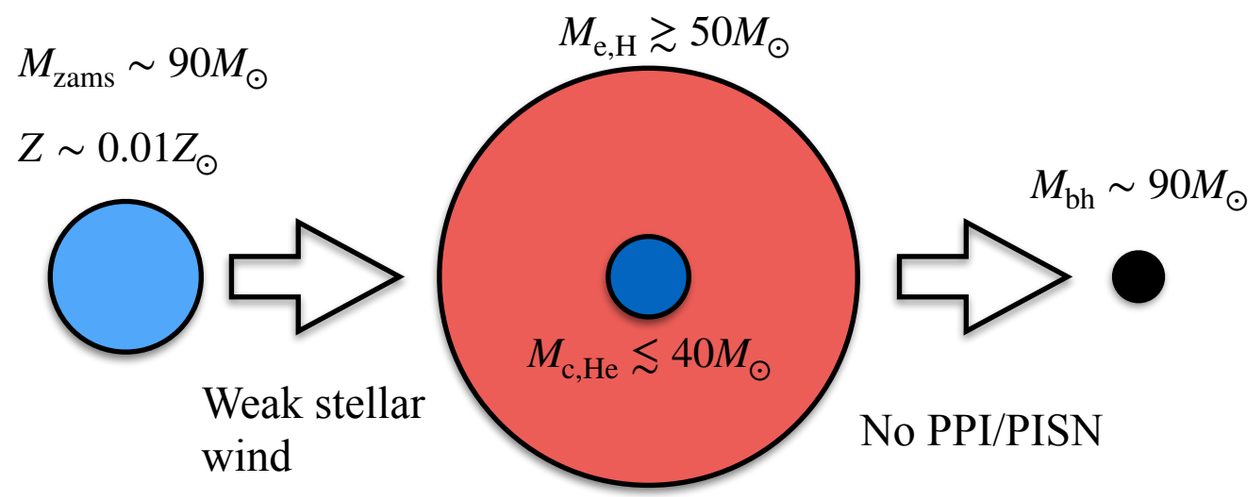
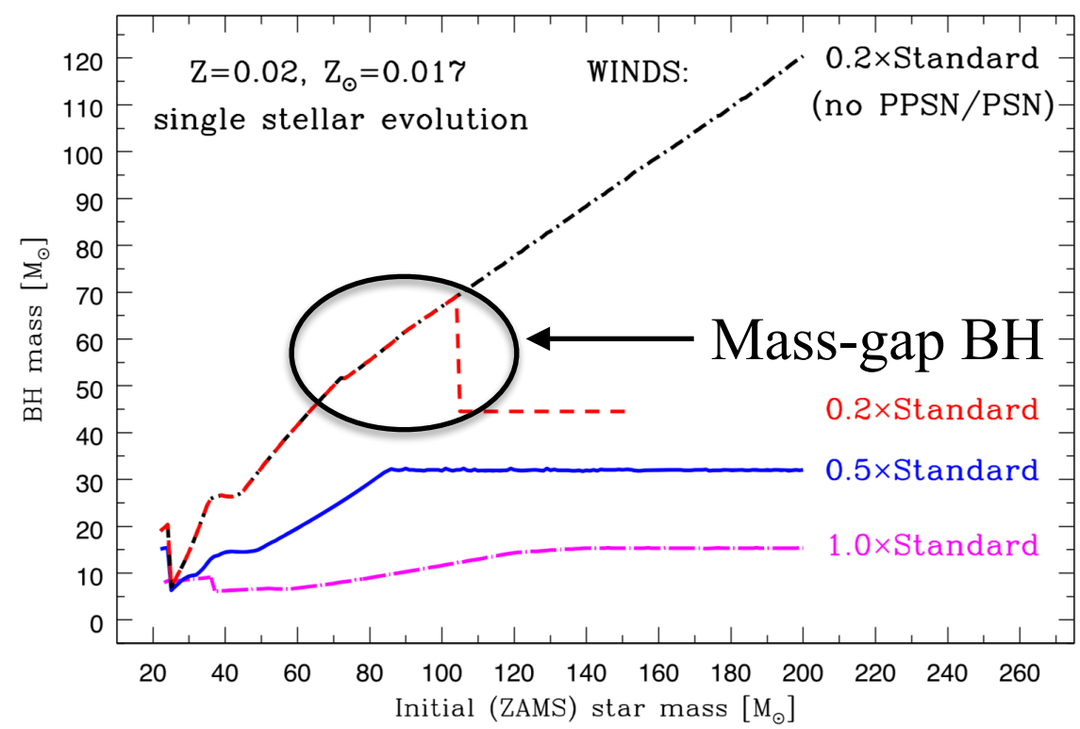


The mass gap is partly filled by stars with <u>small He cores</u> and <u>massive H envelopes</u>



Belczynski et al. (2020)

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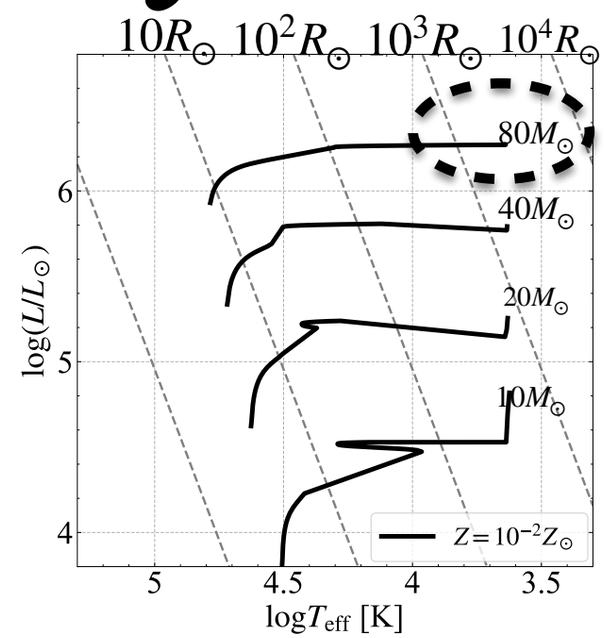
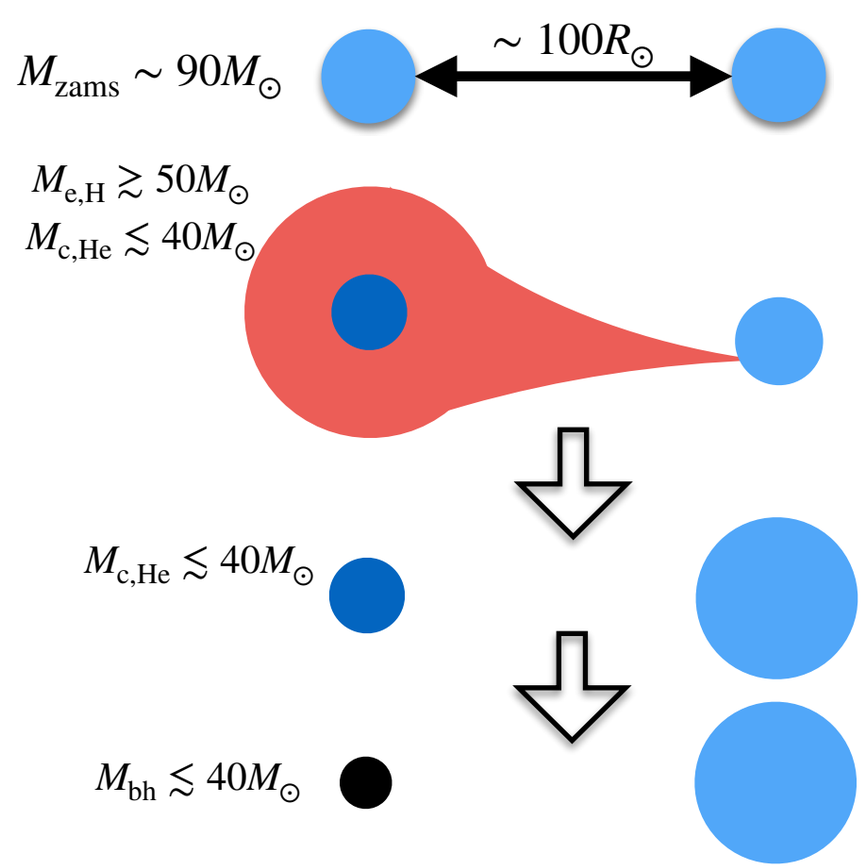


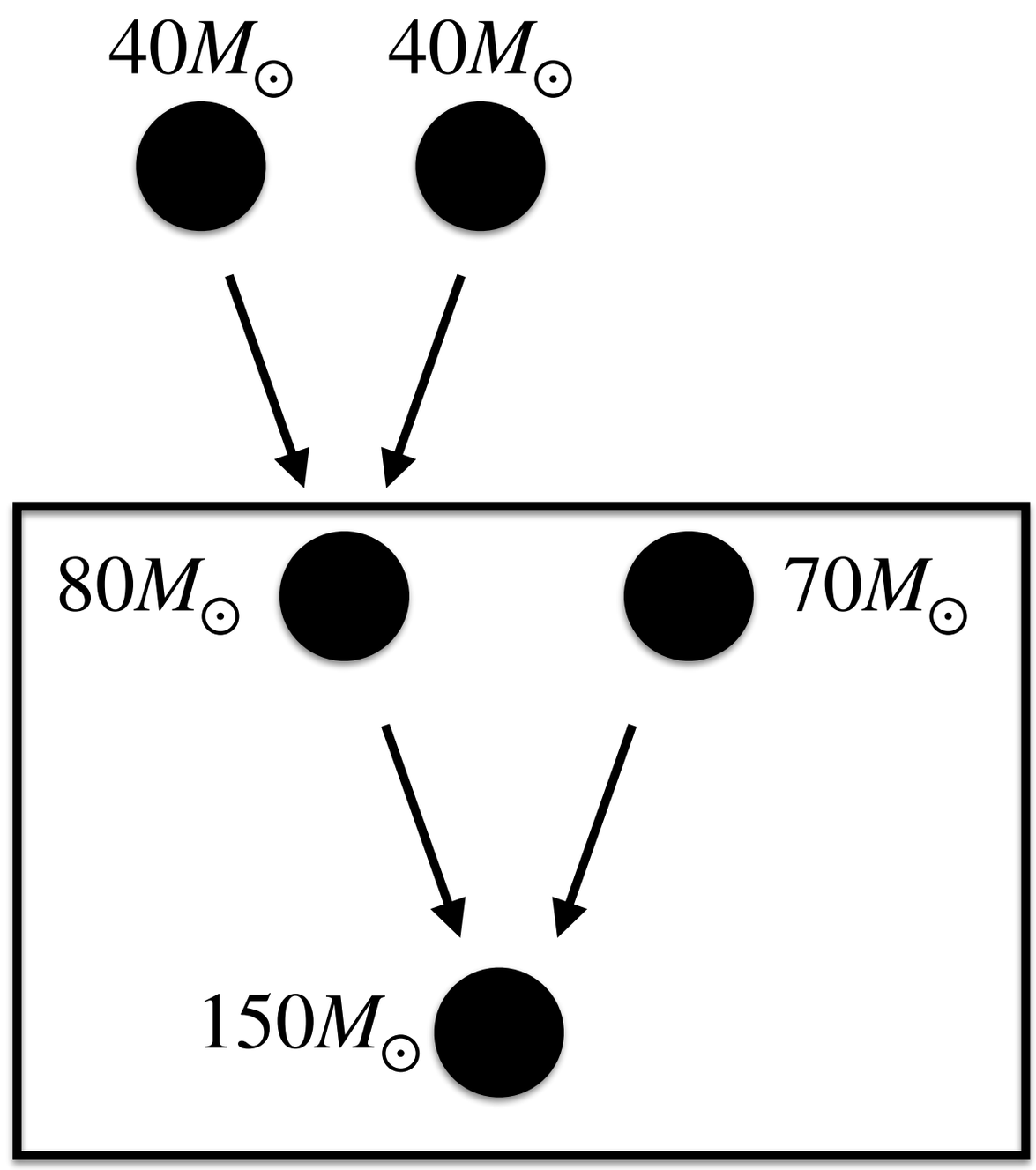
Tanikawa et al. (2020a)

The mass gap cannot be filled, because all the stars lose their H envelopes through binary evolution.



Cluster scenarios

- Globular clusters
- Open clusters
- Galactic centers
- Etc.



GW190521

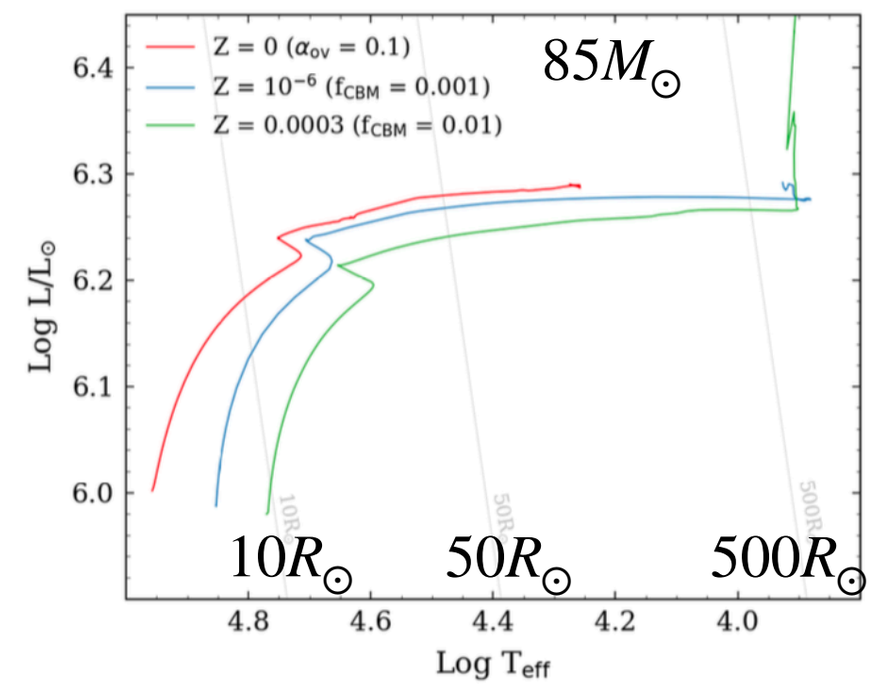
Our study

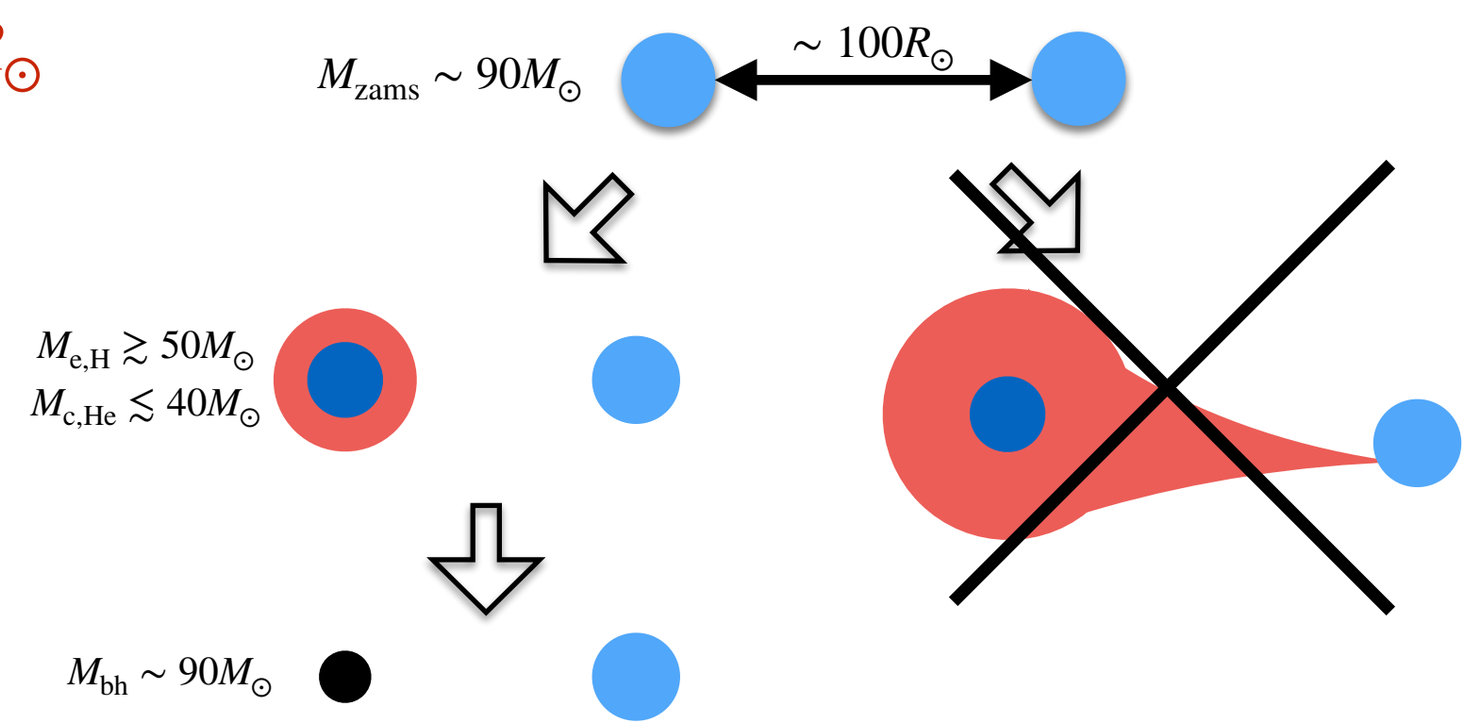
- Re-examination of binary evolution
- How about Pop. III binaries?
- How robust Pop. III scenario?

Pop. III scenario

Farrell et al. (2020)

- Evolution of Pop. III star with $85M_\odot$
  - Small He core: $\lesssim 40M_\odot$
    - No PISN
  - Weak stellar wind mass loss
  - Maximum radius: $\sim 160R_\odot$
    - No mass stripped by its companion star





Uncertainty in Pop. III model

- No massive Pop. III stars discovered so far
- Extrapolation from nearby stars to Pop. III stars
- Nearby star models

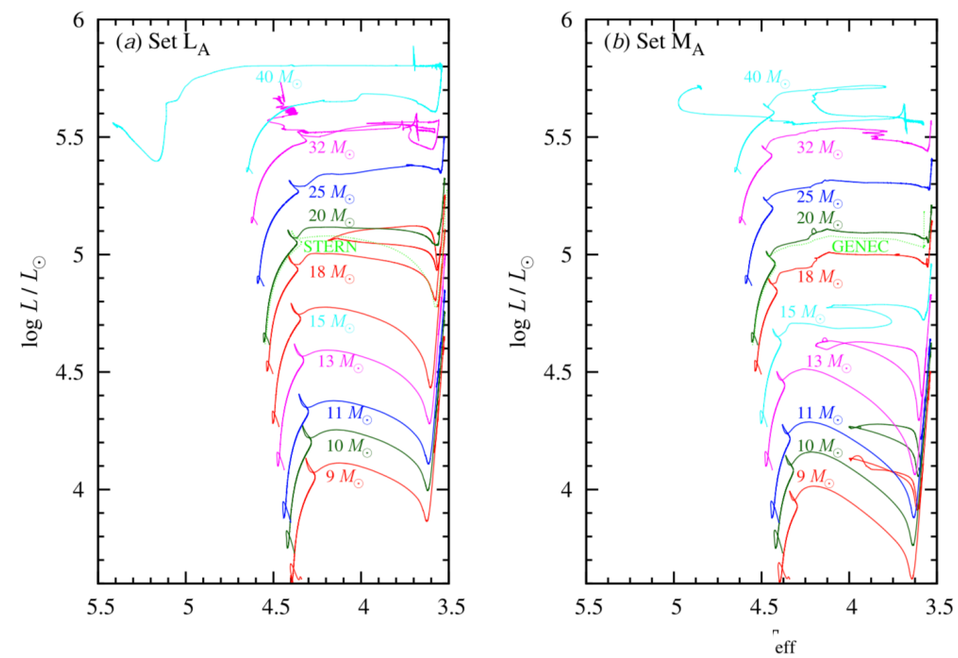
M model

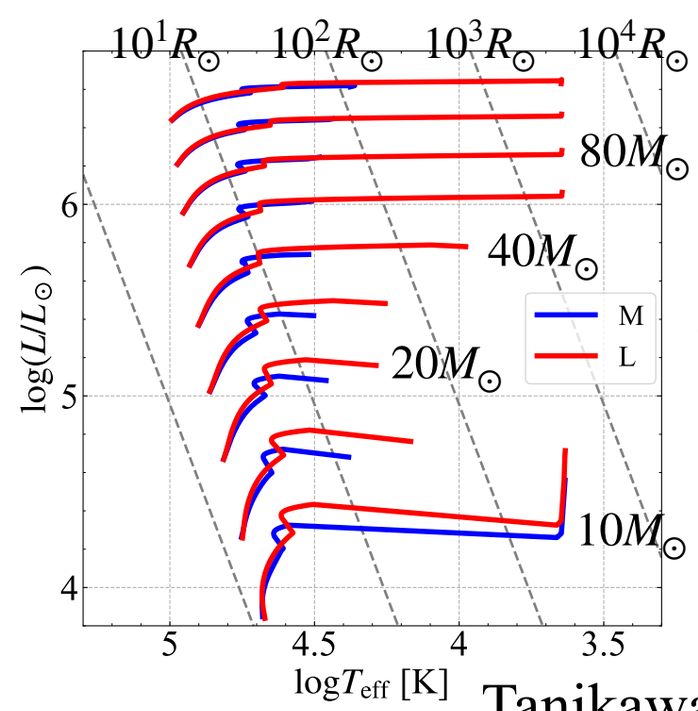
  - AB-type stars in MW open clusters, GENEC(Ekstrom et al. 2012), adopted by Farrell et al. (2020)
  - Early B-type stars in LMC, Stern (Brott et al. 2011)

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)

Yoshida et al. (2019)



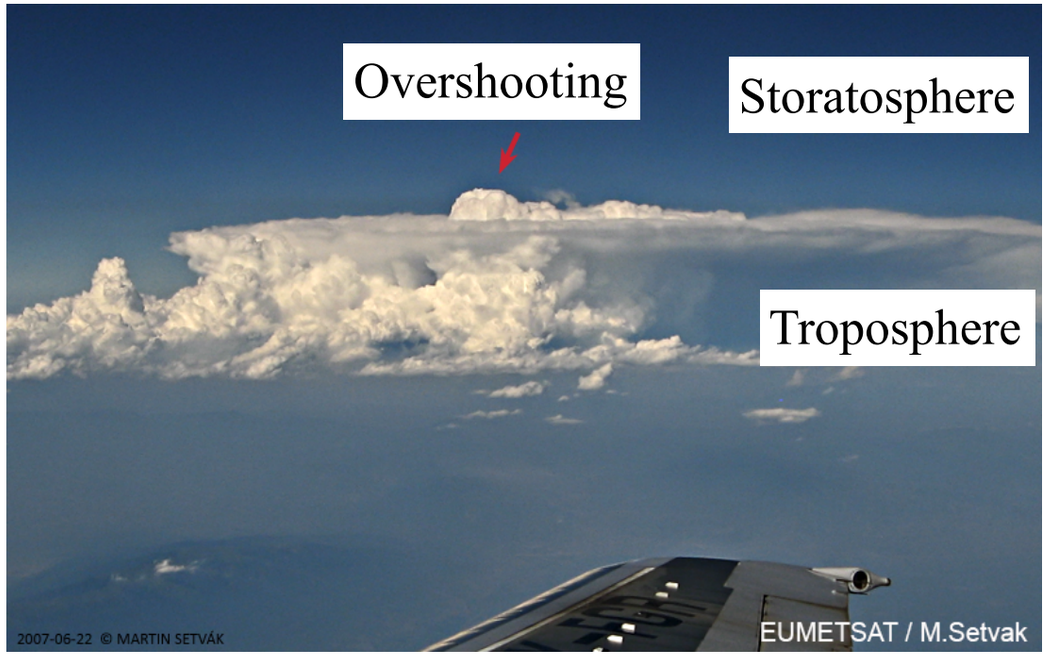


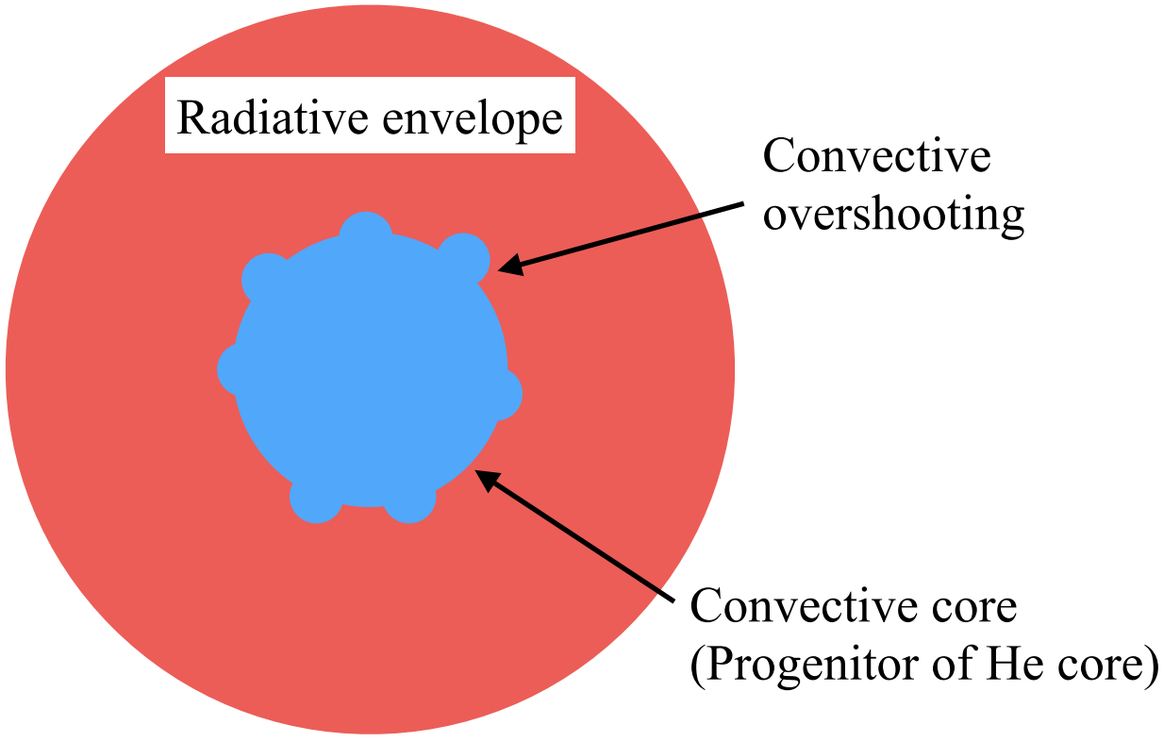
Two Pop. III models

Tanikawa et al. (2020c)

Convective overshooting

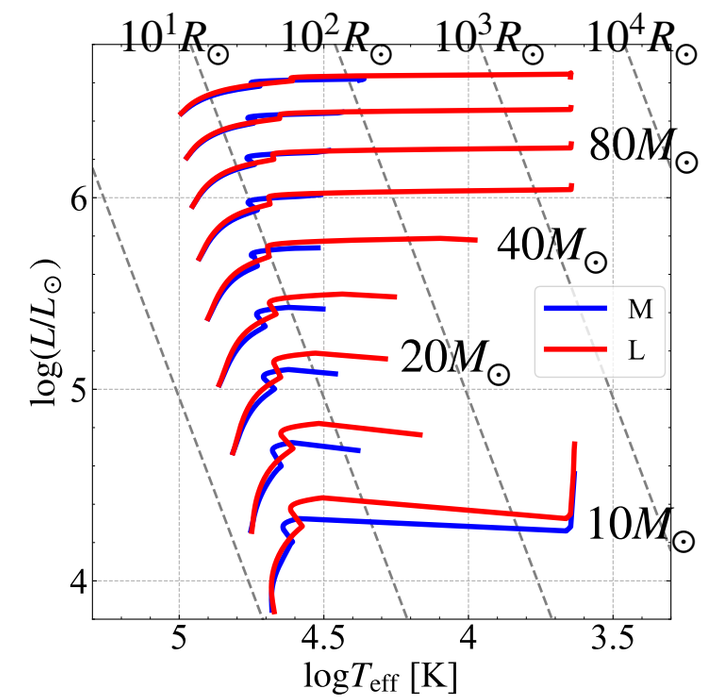
- Overshoot parameter: $f_{\rm ov} \sim 0.02$ (Kippenhahn et al. 1990; 2012)
  - $D(z) = D_0 \exp \dfrac{-2z}{f_{\rm ov} H_{\rm P}}$
  - M model: $f_{\rm ov} = 0.01$
  - L model: $f_{\rm ov} = 0.03$
- Larger overshoot parameter (more effective overshooting)
  - Larger He core at the end of MS
  - Larger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

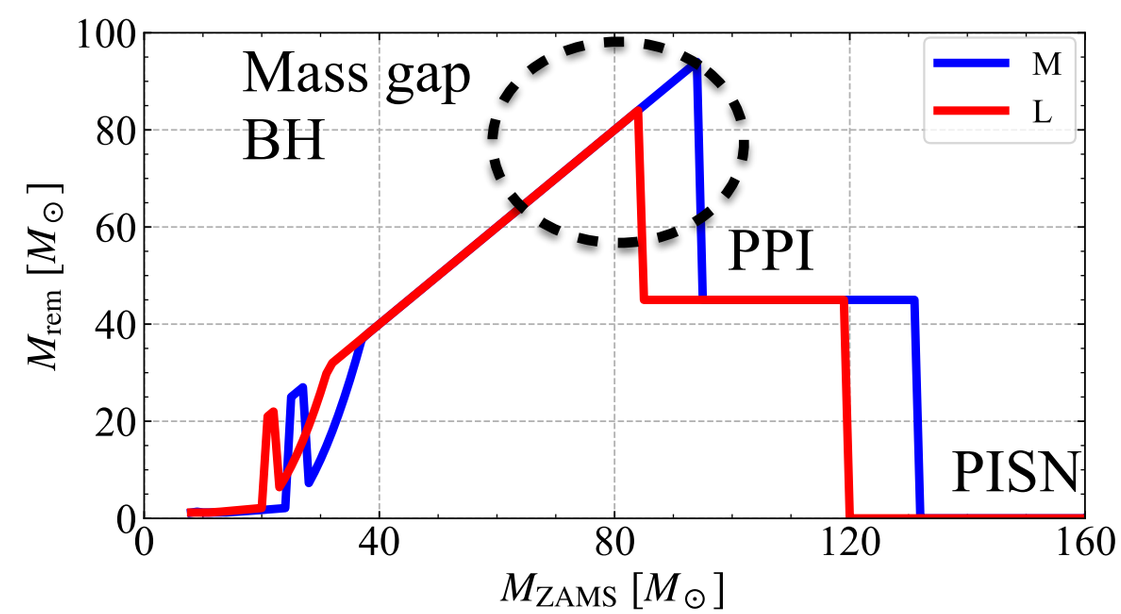




Binary population synthesis

- 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)

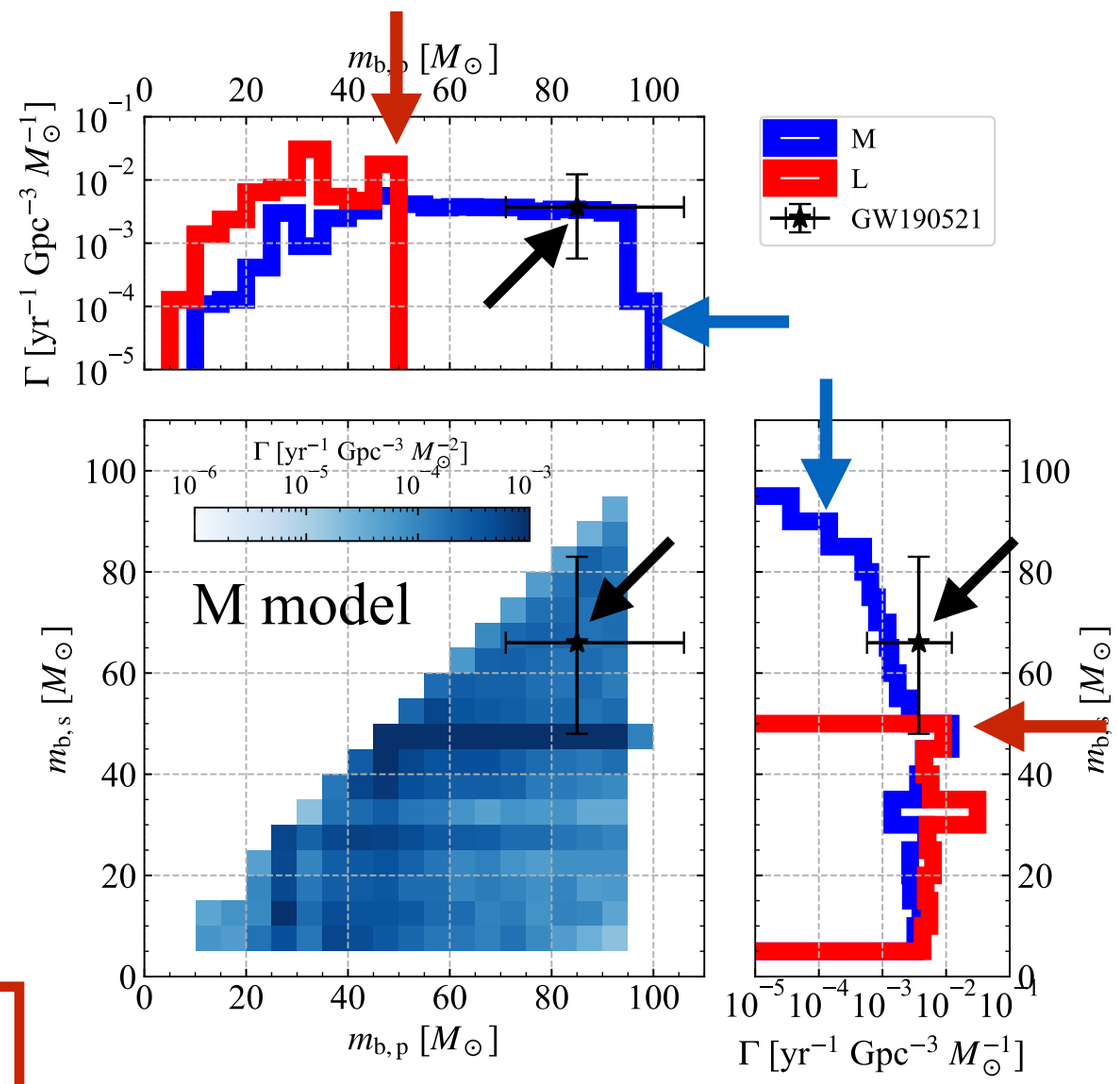




Tanikawa et al. (2020c)

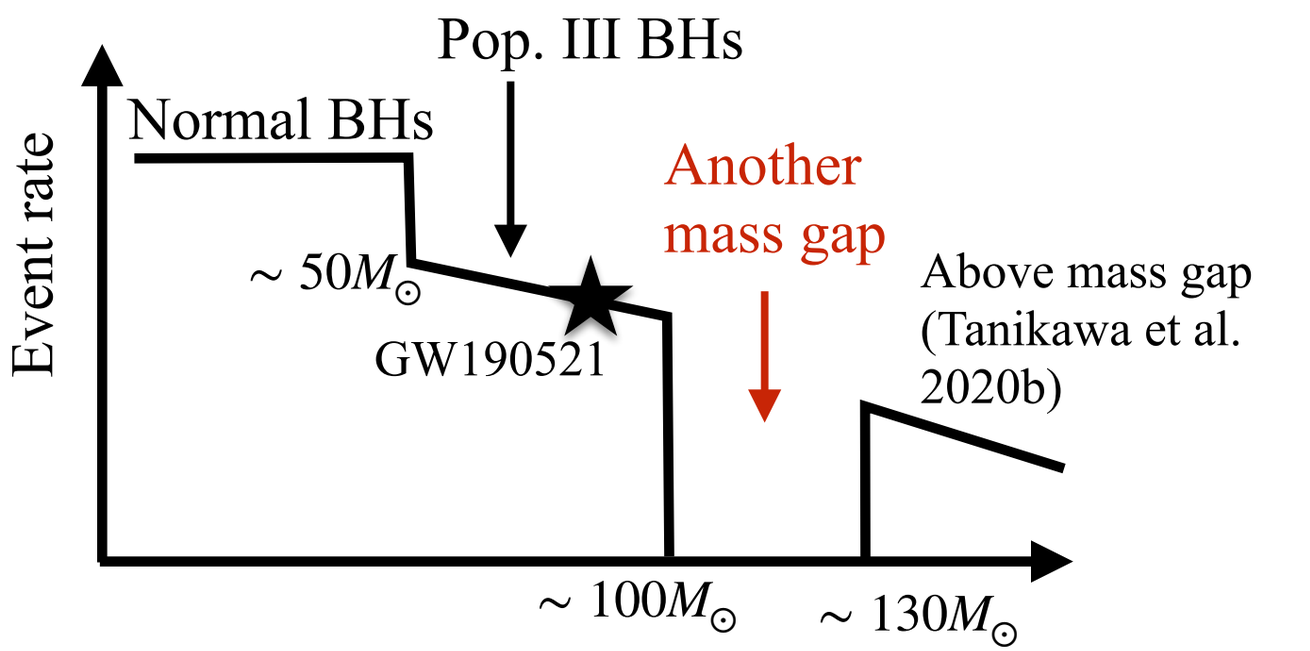
BH mass distribution

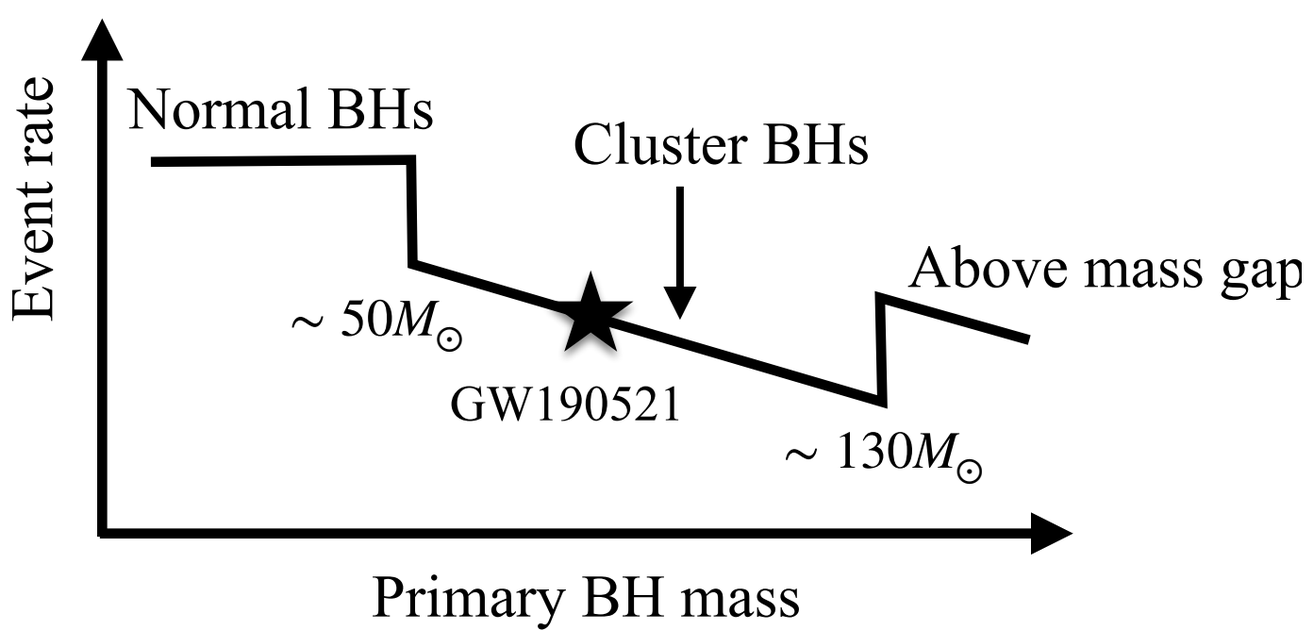
- M model
  - The maximum mass: $\sim 100 M_\odot$
  - Stars lose little mass through binary interactions.
  - Pop. III stars can form GW190521-like BH-BHs.
  - Support for the claims of Farrell et al. (2020) and Kinugawa et al. (2020)
- L model
  - The maximum mass: $\sim 50 M_\odot$
  - Stars lose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



Pop. III binaries can form GW190521, but it largely depends on overshoot parameters.

Discussion

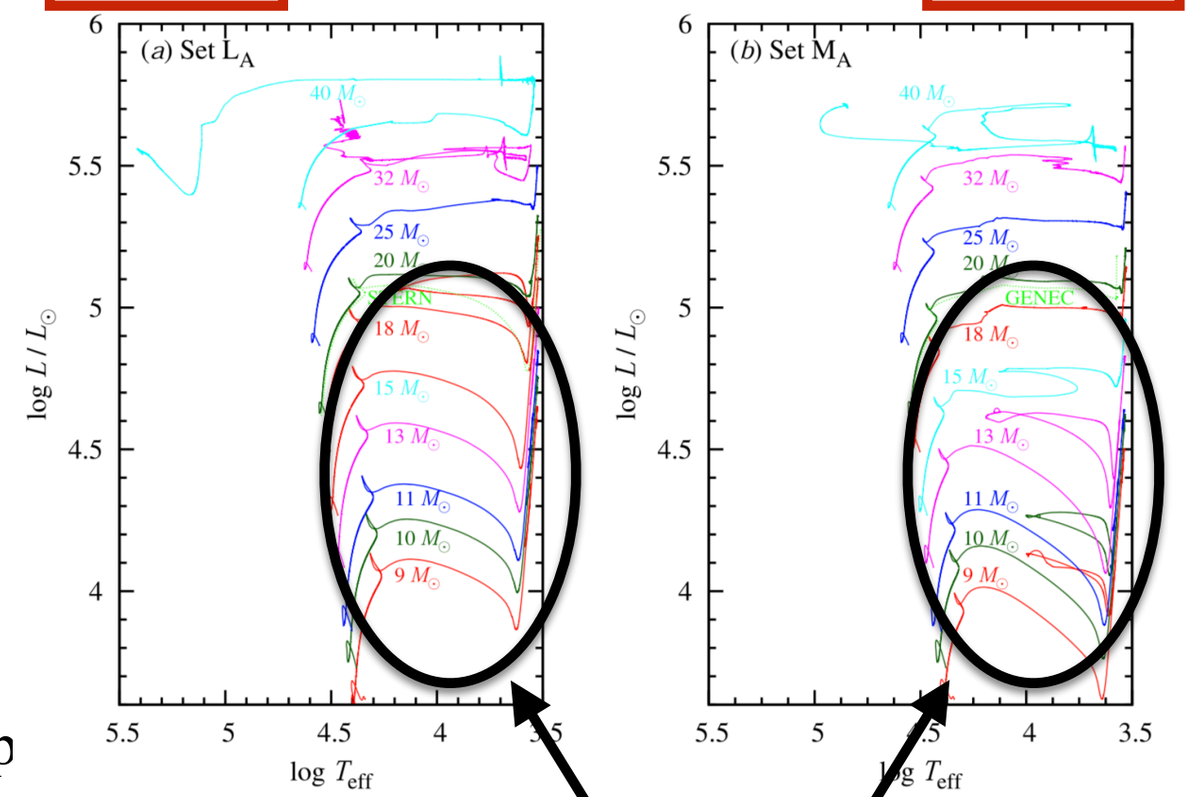




L model

Yoshida et al. (2019)

M model



The presence or absence of blue loop in nearby stars

Summary

- GW190521 contains the higher mass gap BH(s).
- It is thought to be difficult to form GW190521 through binary evolution.
- Pop. III binaries can form GW190521, but it largely depends on overshoot parameters.
- How to examine this scenario.
  - Another mass gap in $100 - 130 M_{\odot}$
  - Determination of overshoot parameters from nearby stars.