Population III binary population synthesis

International Teeminar

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About me

Hongo campus
(main campus)

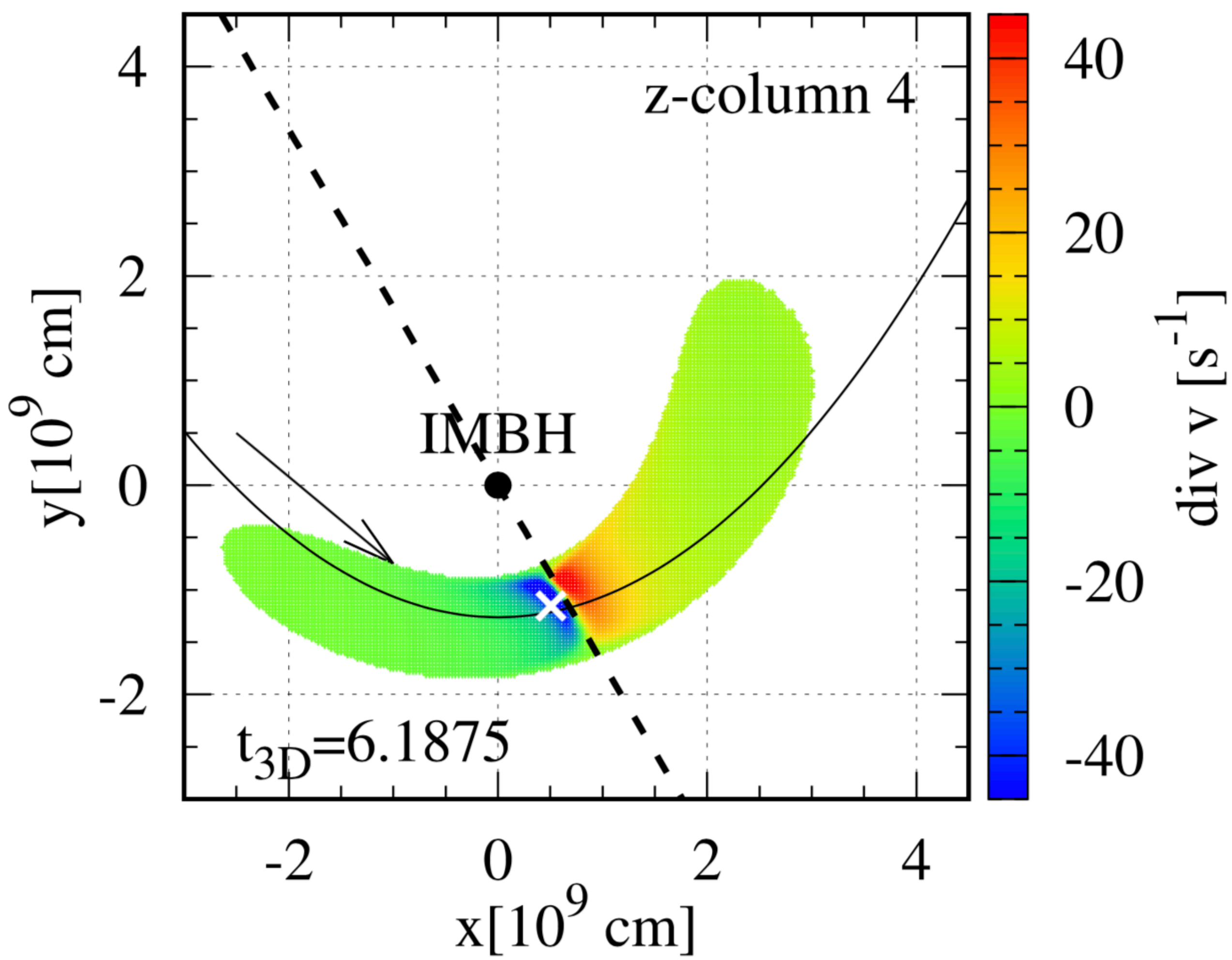
Komaba campus (here!)

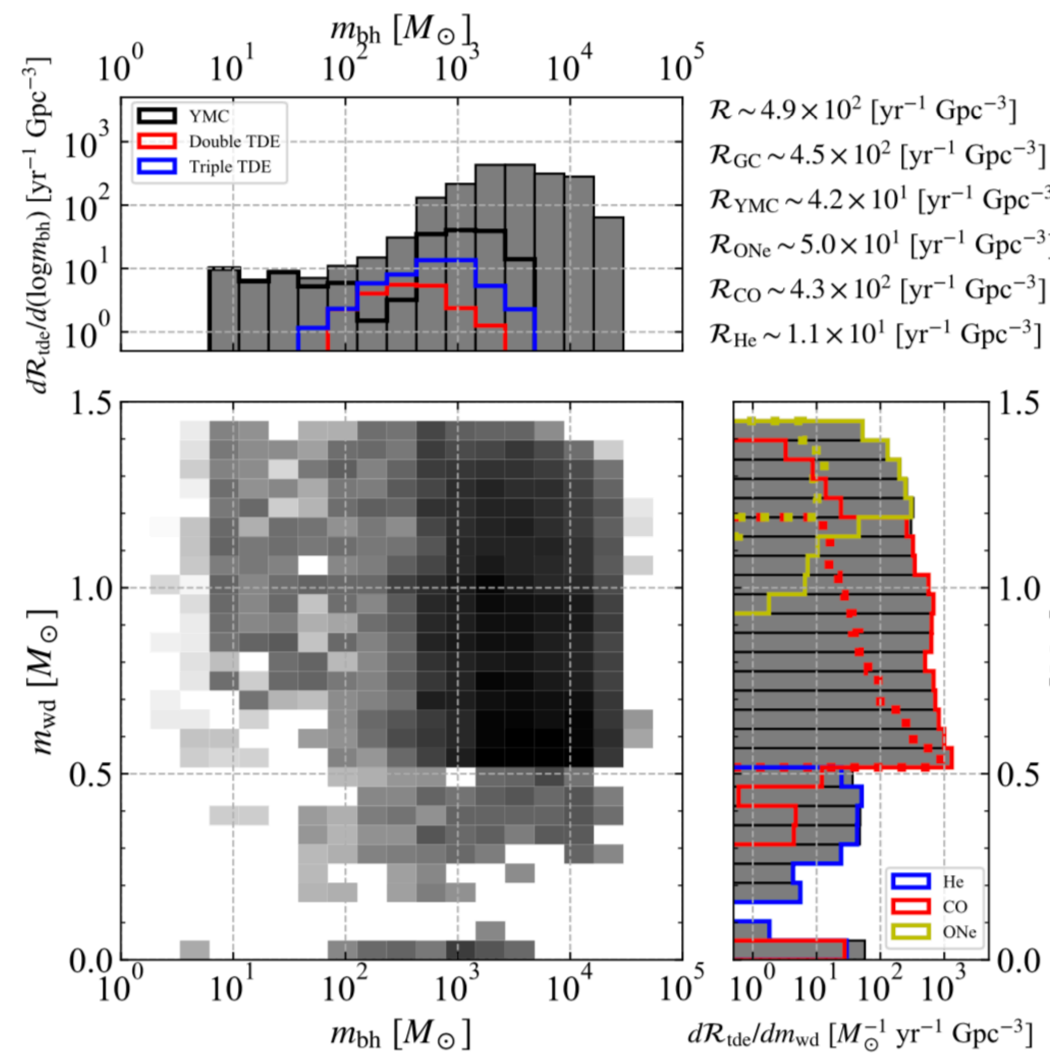
Shibuya crossing

Statue of Hachiko

About me

- Ataru Tanikawa





Tanikawa (2018, ApJ, 858, 26)

Tanikawa, Giersz, Arca Sedda (2021, arXiv:2103.14185)

- ...ts of white ... intermediate mass BH

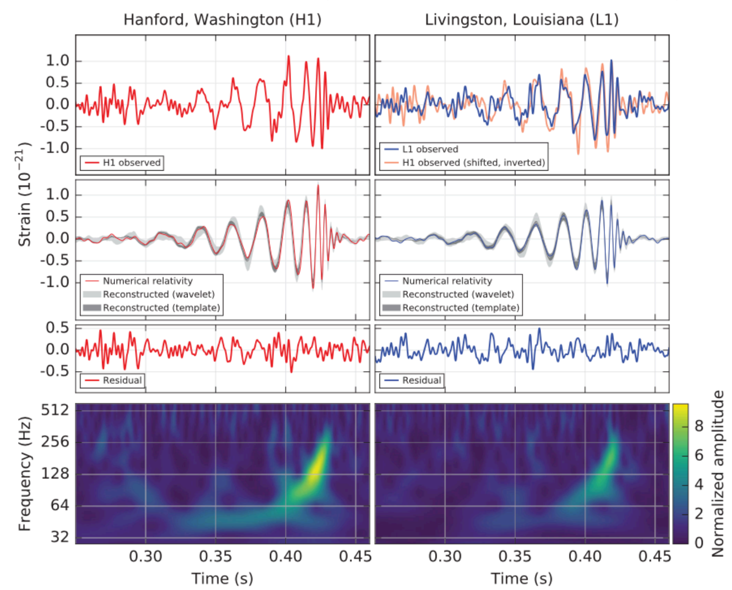
Contents

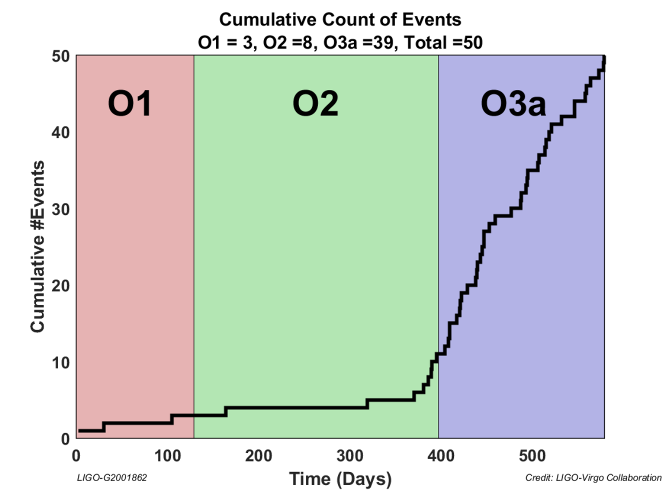
- Gravitational wave (GW) observations and black hole (BH) mergers
- Fitting formulae of extremely metal poor (EMP) stars and very massive stars
- BH mergers from Population (Pop) III stars
- The pair instability (PI) mass-gap event GW190521

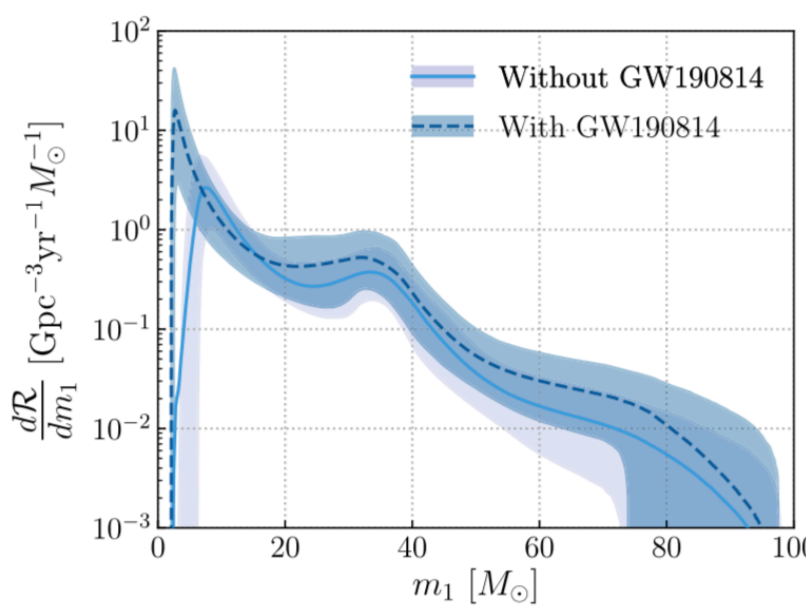
Gravitational wave (GW)

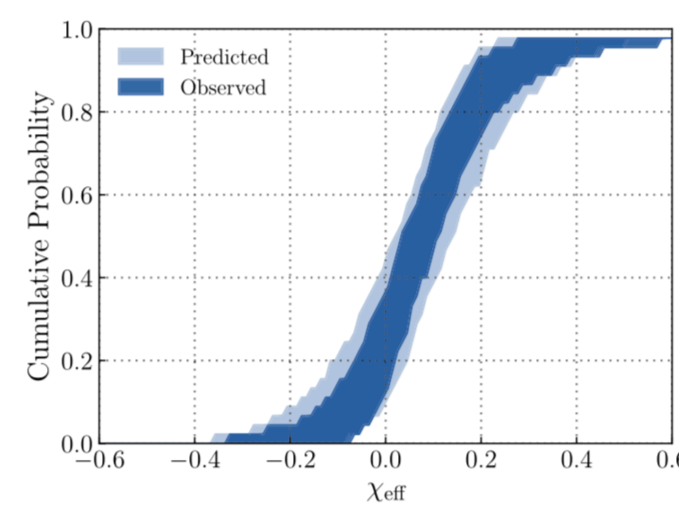
- The first detection of GWs is the first discovery of a BH merger 2015.
- The number of BH-BHs grows to ~ 50 only during 5 years.
- The origin of BH mergers
  - Isolated binary stars?
  - Multiple star systems?
  - Dense star clusters?
  - More than one channel?

GW150914 (Abbott et al. 2016)





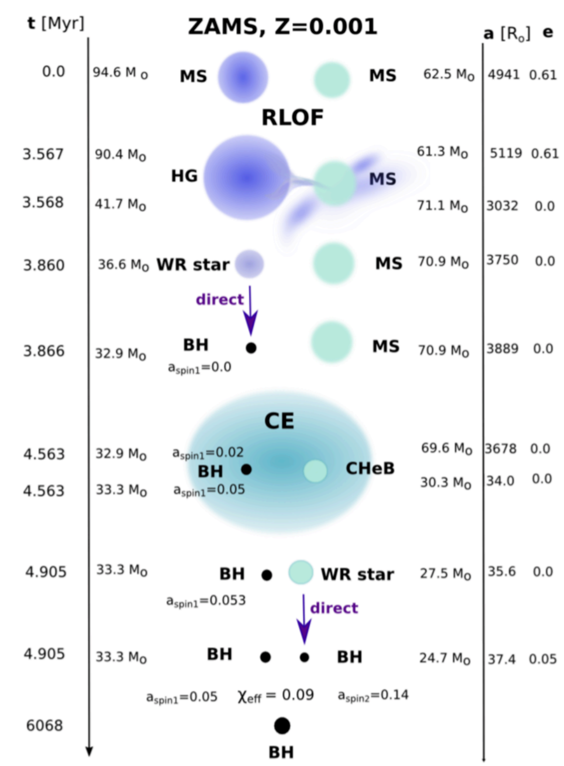




Abbott et al. (2021)

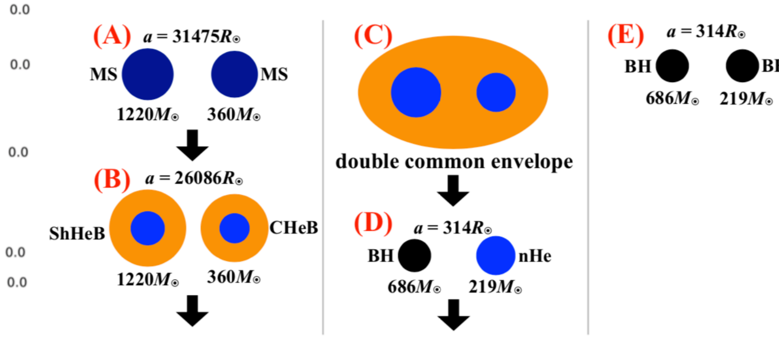
Binary population synthesis and star cluster simulation

- Binary population synthesis and star cluster simulation are very powerful to predict properties of BH mergers.
- Single star evolution has to be followed in parallel with binary interaction and cluster evolution.
- Usually, the single star evolution is followed with
  - ***Fitting formulae***
  - Lookup table
- Not hydrodynamic simulation due to the high calculation cost

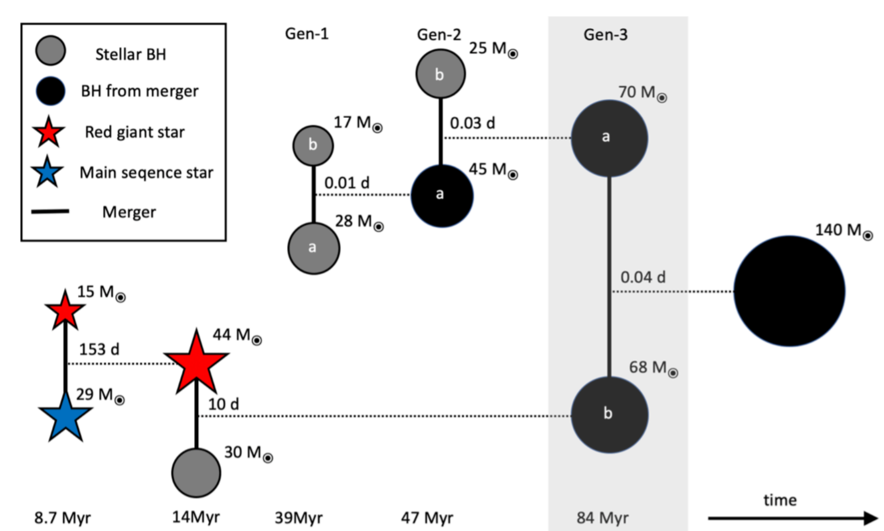


Belczynski et al. (2020)

Pop III very massive binary stars



Hijikawa, AT et al. (2021, MNRAS in press)

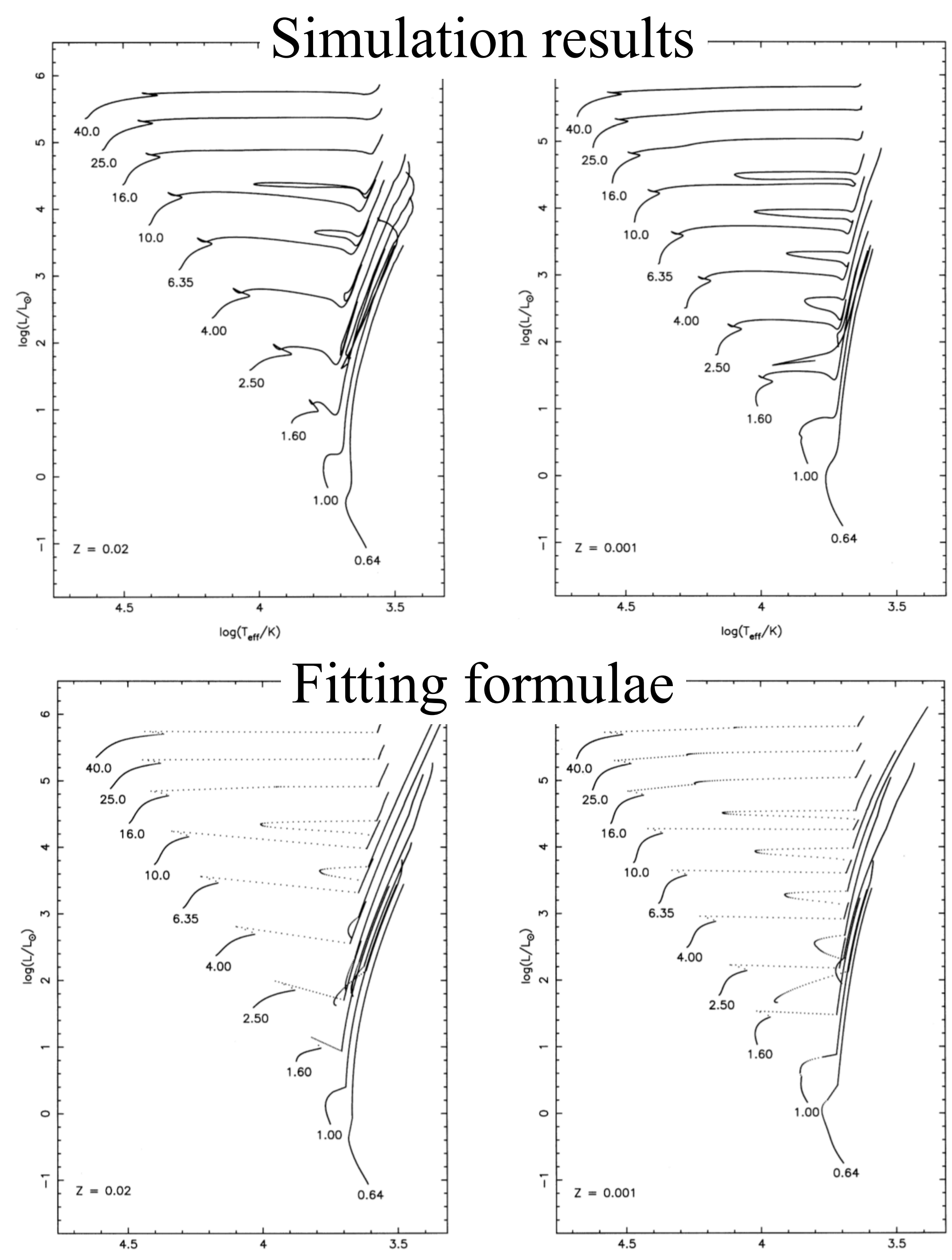


Arca Sedda et al. (2021)

Fitting formulas (FFs) of EMP stars and very massive stars

FFs for single star evolution

- Single-Star Evolution (SSE) (Hurley et al. 2000)
- Fitting formulae for stars with $M = 0.5 - 50 M_\odot$ and $Z = 0.0001 - 0.03$
- Extended to $M \sim 1000 M_\odot$
- Coupled with
  - Binary population synthesis codes: BSE, MOBSE, StarTrack, COSMIC, …
  - Star cluster simulation codes: NBODY6++GPU, MOCCA, PeTar, CMC…



Hurley et al. (2000)

Our FFs

- Extensions
  - To EMP stars with $Z = 10^{-8} Z_{\odot}$, identical to $Z = 0 Z_{\odot}$ stars
  - To very massive stars with $M = 1280 M_{\odot}$ for $Z = 10^{-8} Z_{\odot}$ and $Z = 10^{-2} - 10^{-1} Z_{\odot}$
- Support for
  - BSE (e.g. Tanikawa et al. 2021, ApJ, 910, 30; Tanikawa et al. 2021, MNRAS in press, Hijikawa, AT et al. 2021, MNRAS in press)
  - MOCCA … incorporated.
  - NBODY6++GPU and PeTar … I'm happy to incorporate.

Reasons for EMP FFs

- Difficult to reproduce EMP star evolution by the FF of the most metal-poor stars in SSE ($Z = 10^{-4}$)

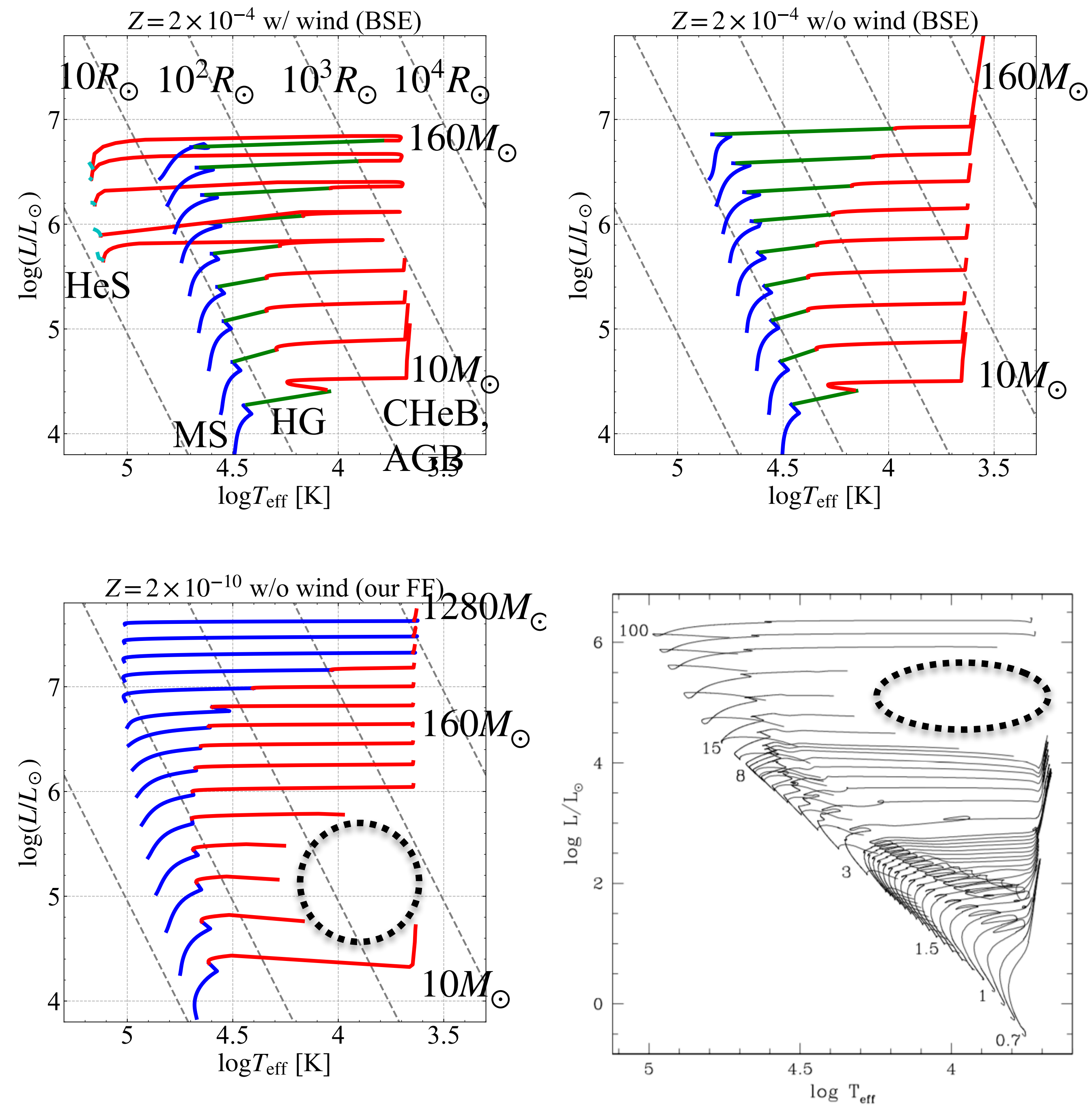
- $Z = 2 \times 10^{-10}$ stars

  - No Hertzsprung-gap (HG)

  → Common envelope (CE) becomes easier to succeed.

  - No red supergiants for $10M_\odot \lesssim M \lesssim 50M_\odot$

  → Mass transfer (MT) becomes more stable (or avoids CE).

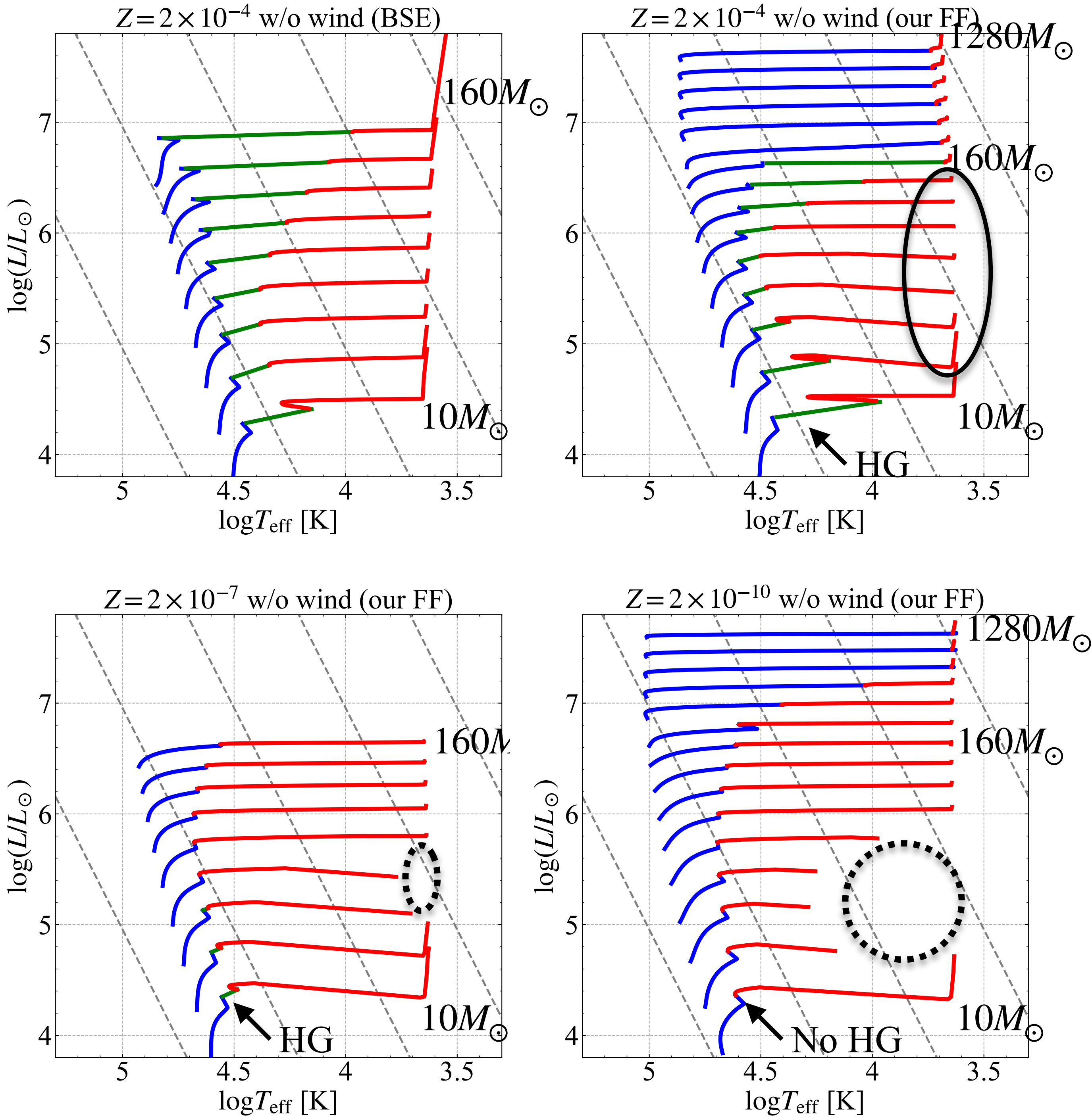


Marigo et al. (2001)

Overview of our FFs

- HG gradually appears with metallicity increasing.
- Red supergiant range becomes wider with metallicity increasing.
- $Z = 2 \times 10^{-4}$ star models look similar between original SSE and our FFs.
  - Not the same, because of different simulation data
- $Z = 2 \times 10^{-3}$ star models are also supported.

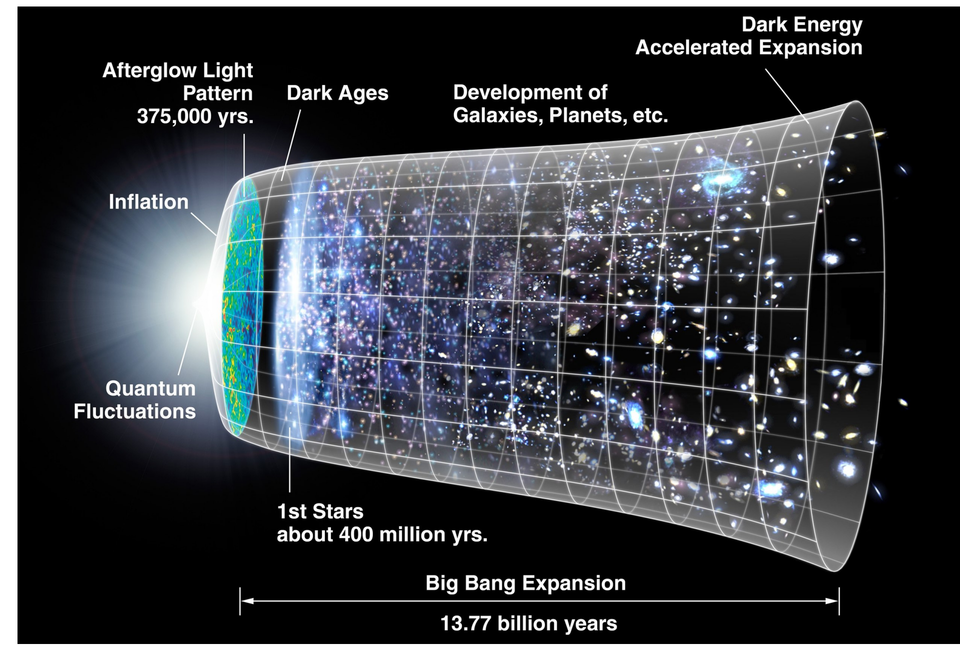
Tanikawa et al. (2020, MNRAS, 495, 4170)

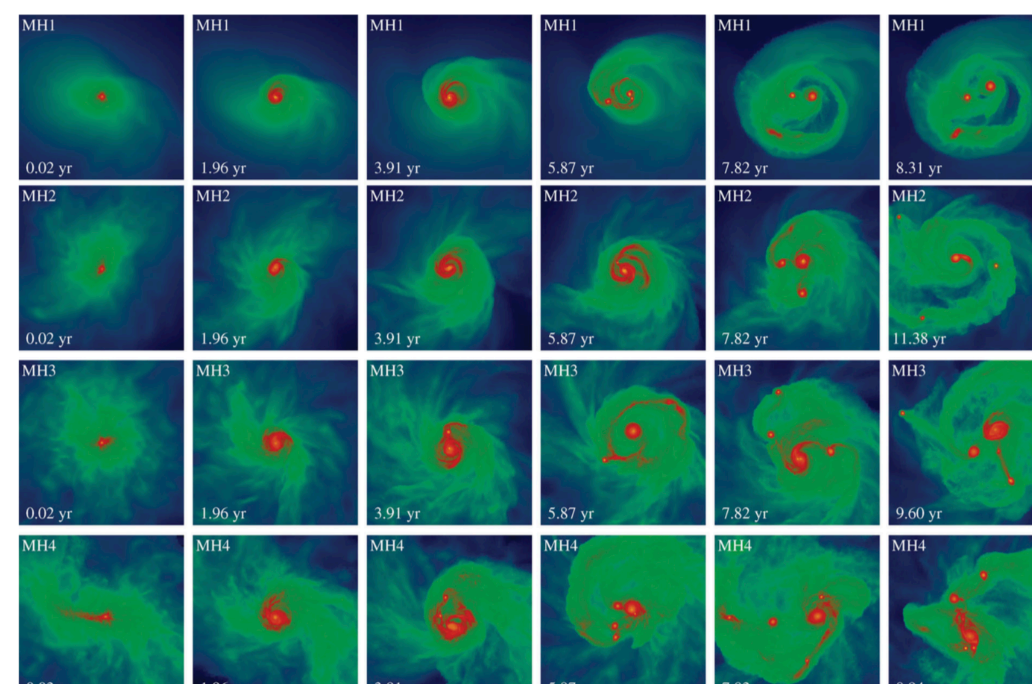


BH mergers from Pop III stars

Pop III stars
(First and metal-free stars)

- Consisting of primordial gas (mostly H and He)
- Born in the high-redshift universe
- Astrophysical importance: stellar nucleosynthesis, reionization, …
- Top-heavy initial mass function (IMF) predicted theoretically (Omukai, Nishi 1998; Abel et al. 2002; Bromm, & Larson 2004)
- Not yet discovered (Frebel, Norris 2015 for review)
- ***Detectability of GWs from Pop III BH mergers***

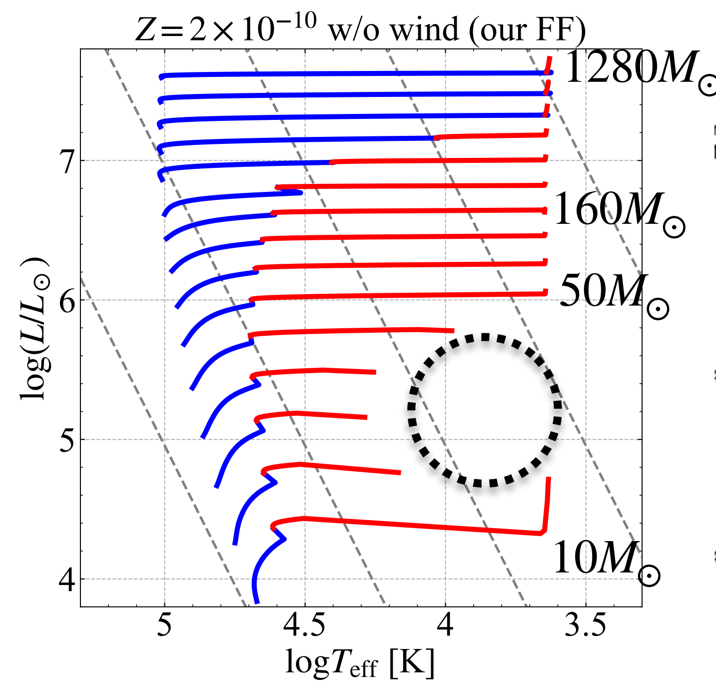


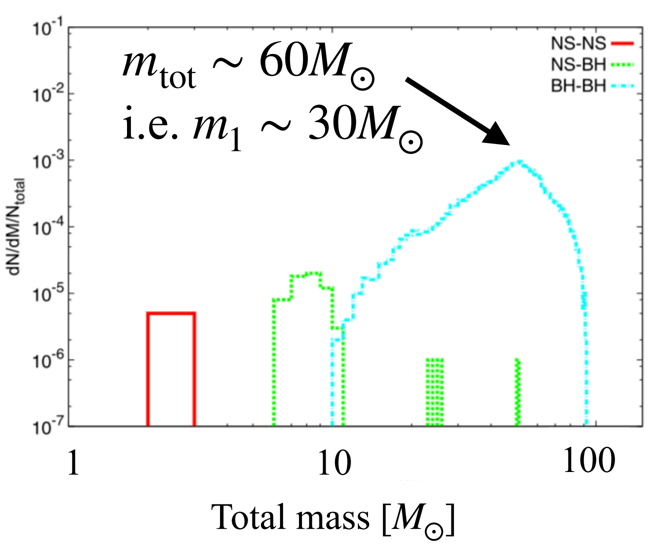


Greif et al. (2012)

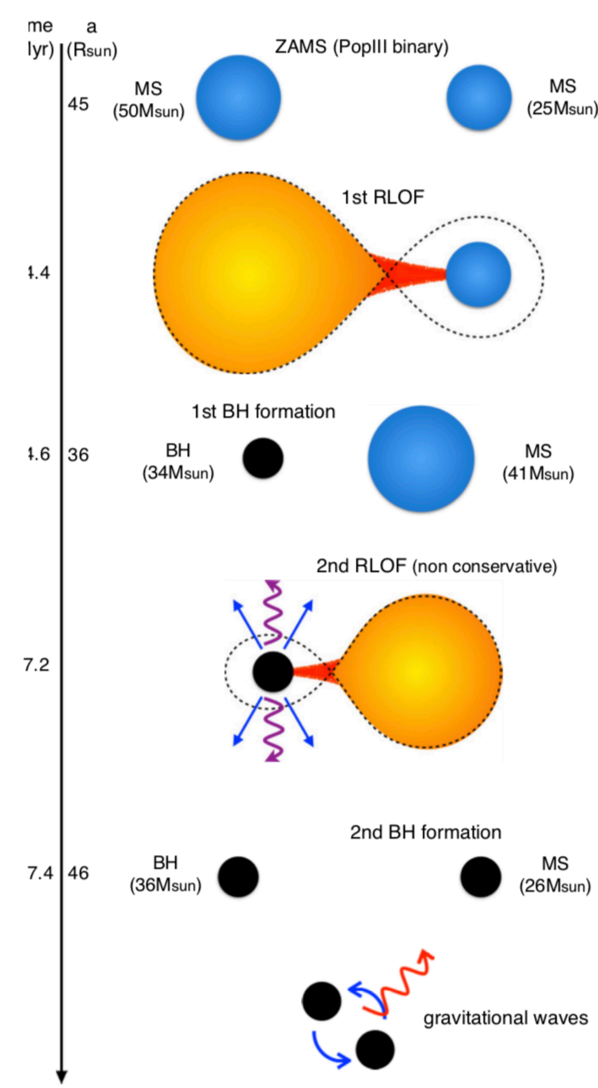
Pop III BH mergers

- $\sim 30 M_\odot$ peak in BH mergers
  - A few $10 M_\odot$ Pop III stars end with blue supergiants.
  - Blue supergiants tend to experience stable MT, not CE.
- Top-heavy IMF
  - Possibly many $> 100 M_\odot$ Pop III stars
  - IMBH mergers?
- But, …
  - Pop III formation rate may be too small (Hartwig et al. 2016; Belczynski et al. 2017)
  - Pop III binary stars might be only wide.





Kinugawa et al. (2014)



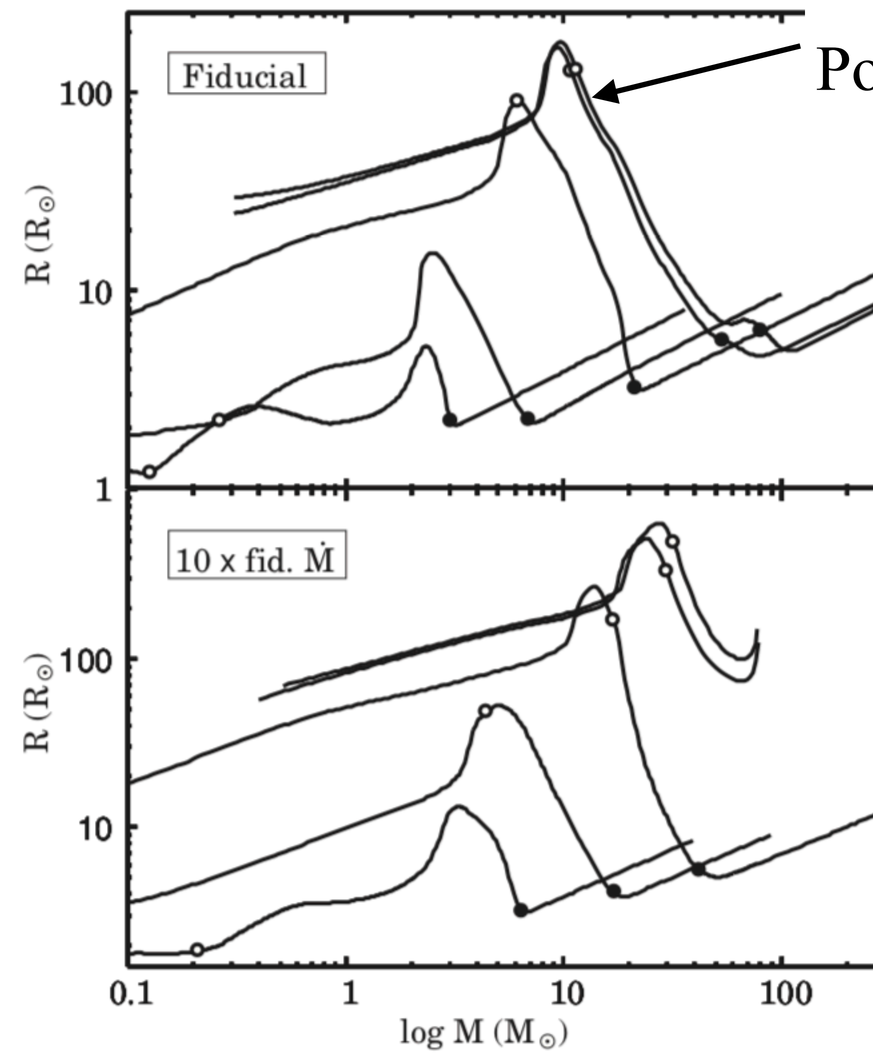
Inayoshi et al. (2017)

Pop III binary stars

- Pop III single stars expand up to $\sim 100R_{\odot}$ in protostar phases due to high mass accretion.
- Pop III stars may not form short-period binary stars with $a \lesssim 100R_{\odot}$.
- But, …
    - Pop III binary stars may be formed after protostar phases.
    - Mass accretion is different between Pop III single and binary stars
- Two cases
    - With short-period binaries
    - Without short-period binaries

Evolution of proto single star

$\sim 100M_{\odot}$
Pop III star

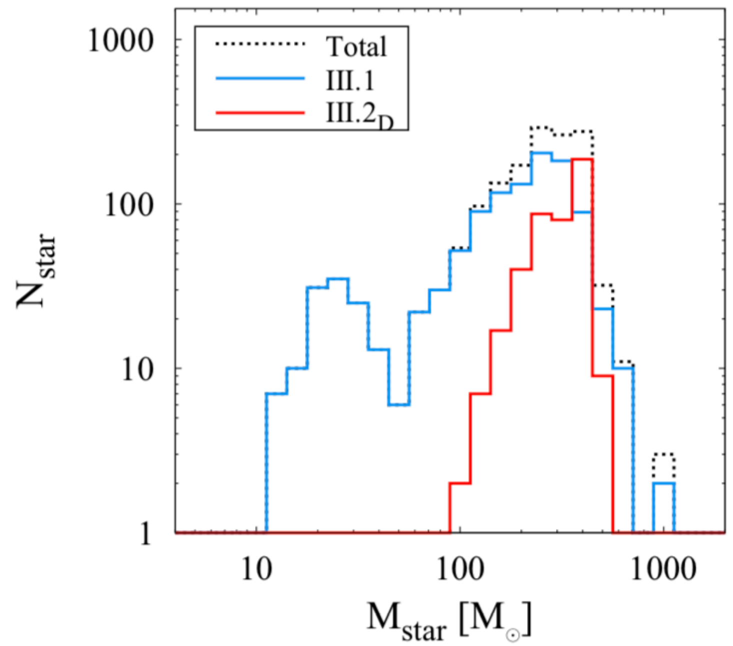


Hosokawa & Omukai (2009)

Initial conditions

- Instantaneous formation of Pop III stars: $\sim 10^{13} M_\odot \mathrm{Gpc}^{-3}$ at $z \sim 10$
  - Consistent with numerically predicted results (Magg et al. 2016; Skinner, Wise 2020; but see Inayoshi et al. 2021)
- Binary fraction: 1 (e.g. Sugimura et al. 2020)
- Primary IMF: $f(m_1) \propto m_1^{-1}$ $(10 M_\odot \leq m_1 \leq 300 M_\odot)$
- Mass ratio: $f(q) \propto \mathrm{const}$ $(10 M_\odot / m_1 \leq q \leq 1)$
- Semi-major axis: $f(a) \propto a^{-1}$ $(a_{\min} \leq a \leq 2000 R_\odot)$
  - $a_{\min} = 10 R_\odot$ or $200 R_\odot$
- Eccentricity: $f(e) \propto e$

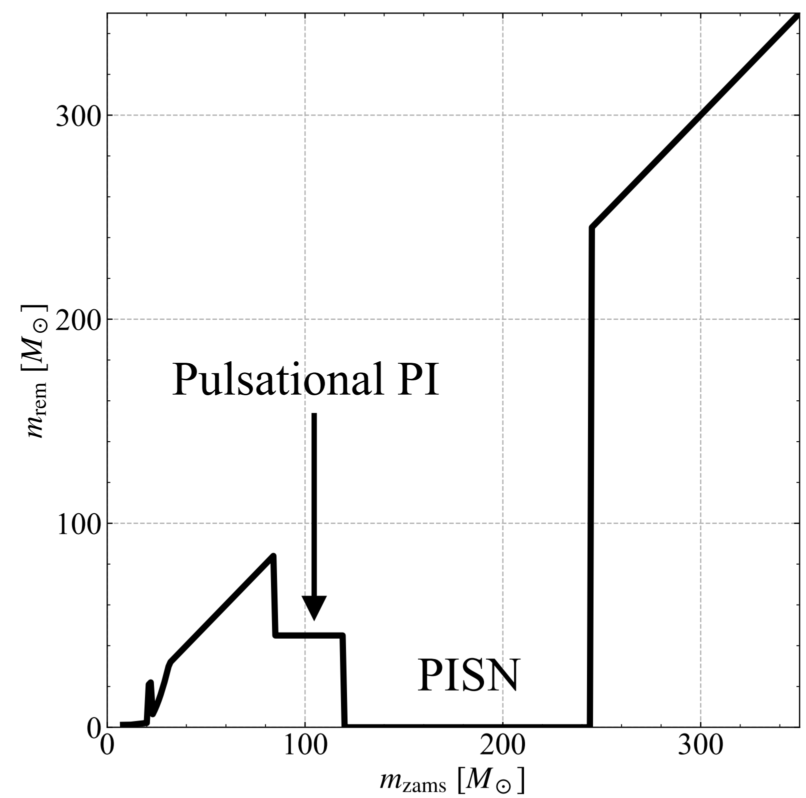
Pop III IMF

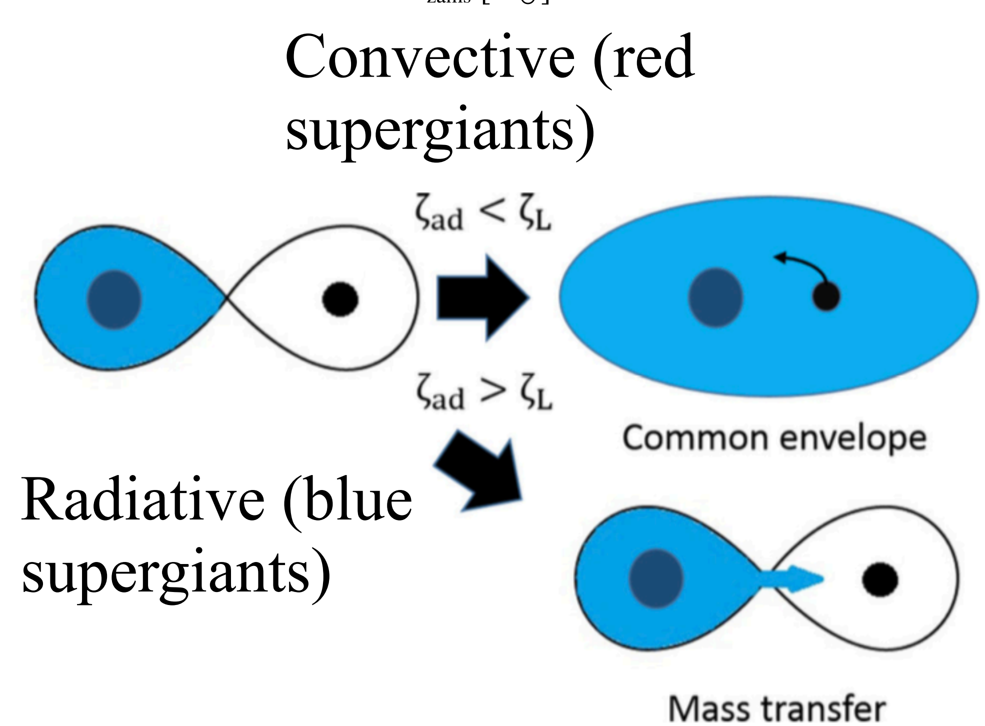


Hirano et al. (2015)

Numerical setup

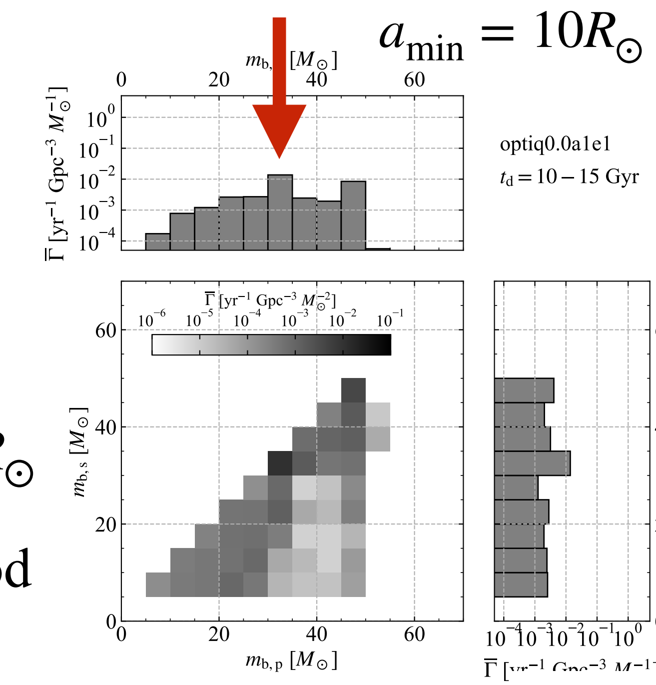
- Tanikawa's FF with $Z = 10^{-8} Z_{\odot}$
- No stellar wind
- Fryer's rapid model for supernova with pair instability (PI) model like the strong PI of Belczynski et al. (2020).
- No natal kick
- Stellar envelope property in Post-MS phases
    - Radiative: $\log(T_{\mathrm{eff}}) > 3.65$
        - CHeB phase in the original BSE
    - Convective: $\log(T_{\mathrm{eff}}) < 3.65$
        - AGB phase in the original BSE

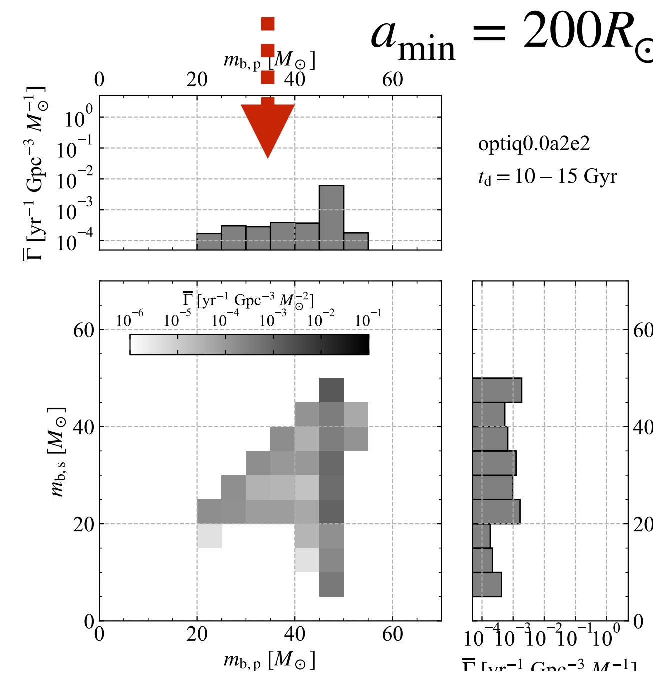


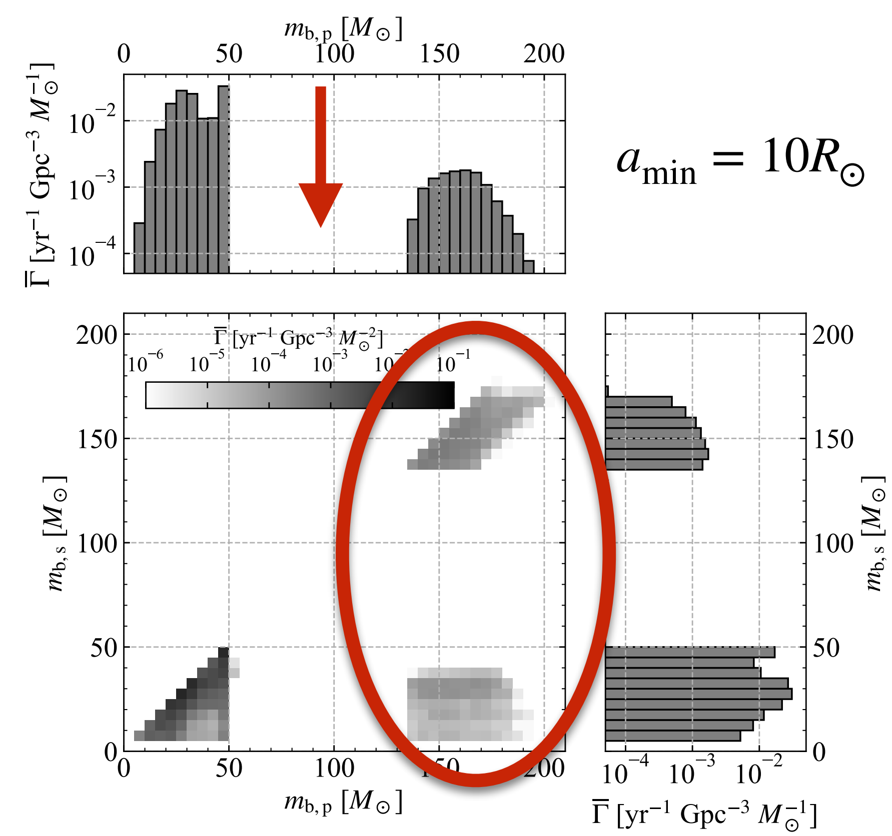


Mass distribution

- The merger rate density is $\sim 0.1 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ regardless of a_{min}.
  - Much smaller than the observed rate ($\sim 10 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$).
- The $30 M_{\odot}$ peak disappears for $a_{\mathrm{min}} = 200 R_{\odot}$
  - The stable MT channel needs short-period binaries.
- The PI mass gap $50 - 130 M_{\odot}$
- The merger rate density of IMBH mergers (IMBH-IMBH or IMBH-BH) is $\sim 0.01 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ regardless of a_{min}.
  - Not violate the upper limit of $\sim 0.056 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ (LVK, arXiv: 2105.15120)
  - ***Detectable soon if our model is correct***







Tanikawa et al. (2021, ApJ, 910, 30)

The PI mass-gap event GW190521

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.
- Possible scenarios
  - Cluster origins (Rodriguez et al. 2019; Di Carlo et al. 2020; Tagawa et al. 2020; Fragione et al. 2020; Rizzuto et al. 2021)
  - Uncertainty of PI mass gap boundary (Farmer et al. 2020; Belczynski et al. 2020; Costa et al. 2021)
  - ***Uncertainty of convective overshoot***

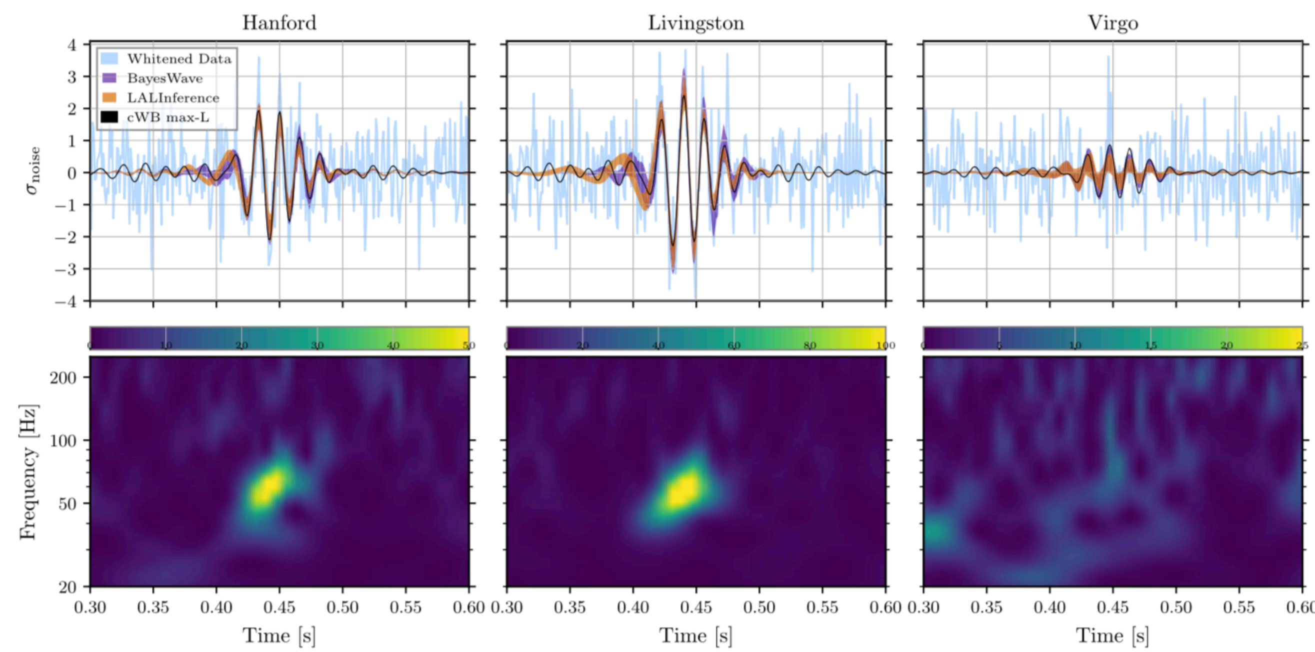
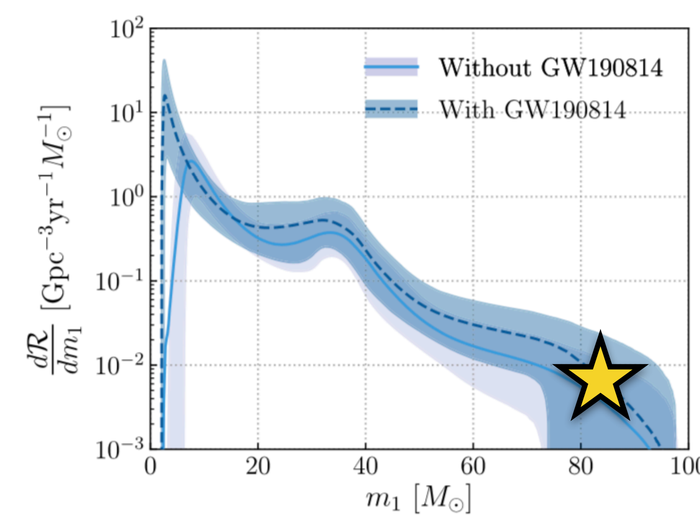


TABLE I. Parameters of GW190521 according to the NRSur7dq4 waveform model. We quote median values with 90% credible intervals that include statistical errors.

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 ($m_2/m_1 \le 1$)	$0.79^{+0.19}_{-0.29}$
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	$-0.38^{+0.06}_{-0.06}$

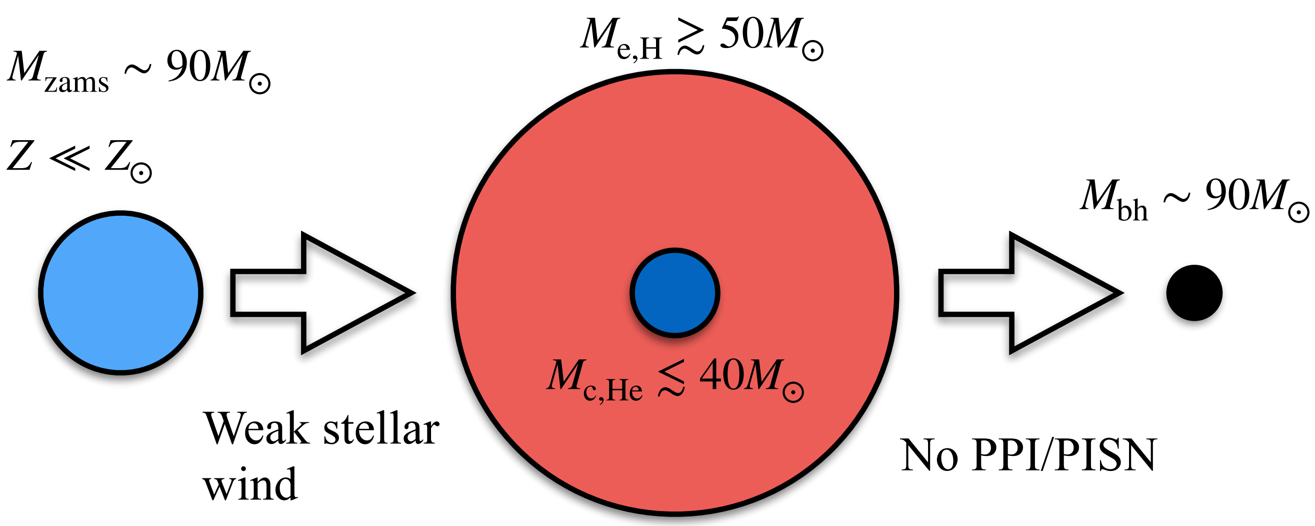
Abbott et al. (2020)

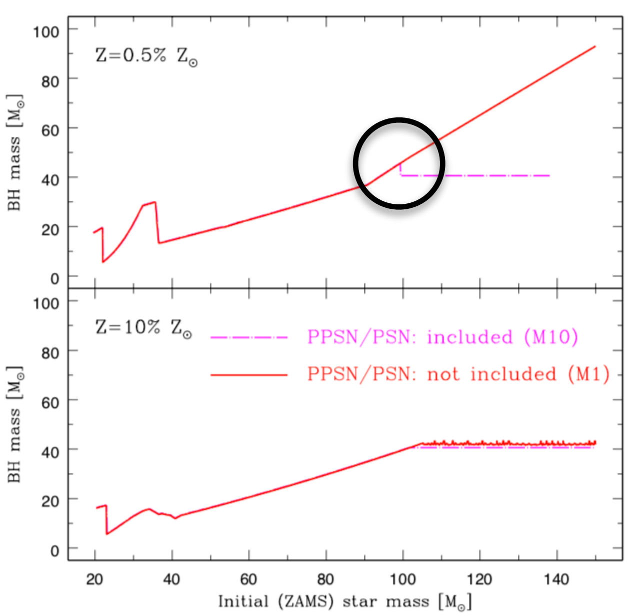


Abbott et al. (2021)

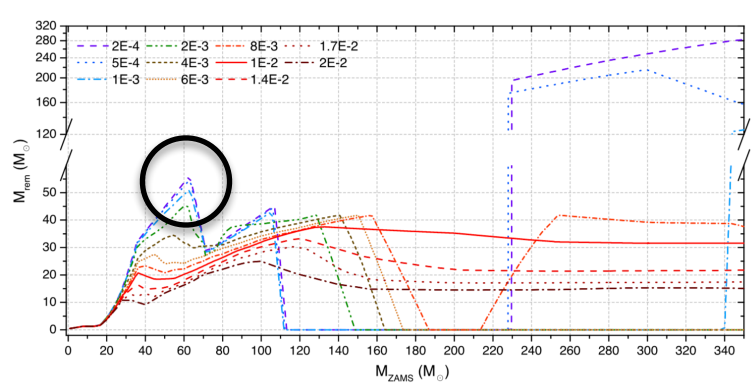
Revisit of the PI mass gap

Single star evolution



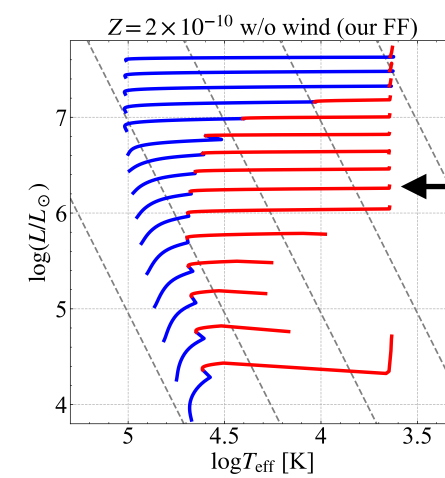


Belczynski et al. (2016)

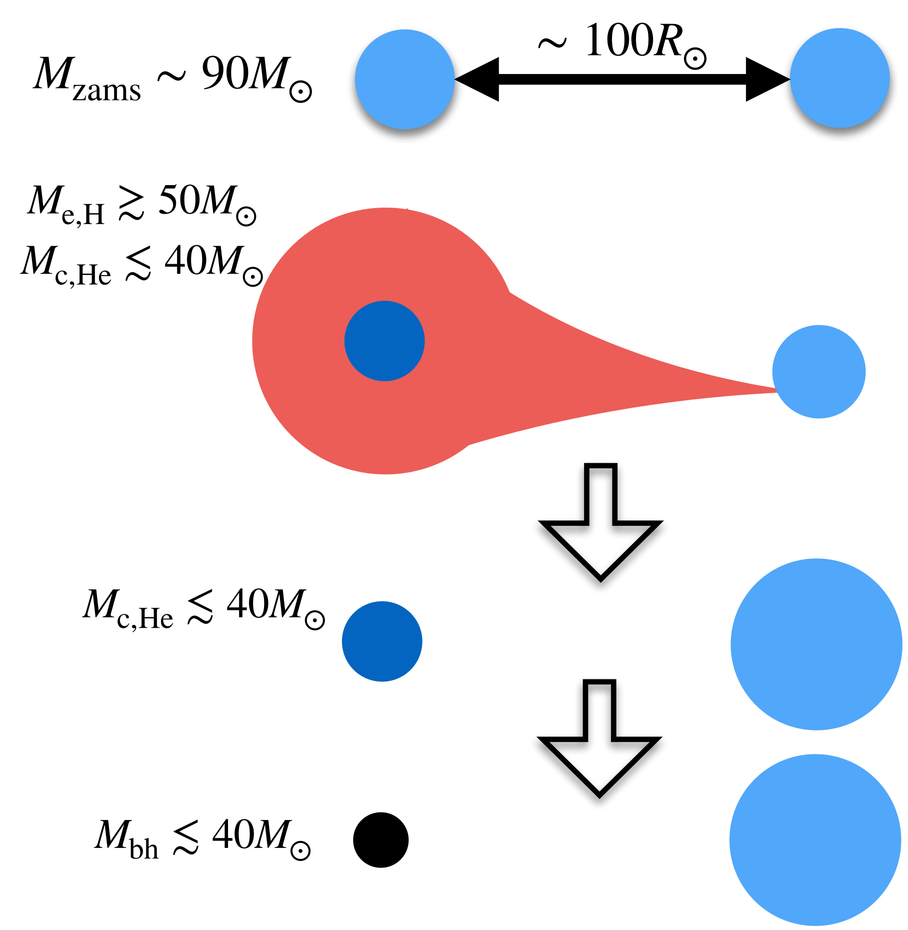


Spera, Mapelli (2017)

Binary star evolution



- $M_{\rm tot} \sim 80 M_\odot$
- $M_{\rm c} \sim 40 M_\odot$
- $R \gtrsim 10^3 R_\odot$

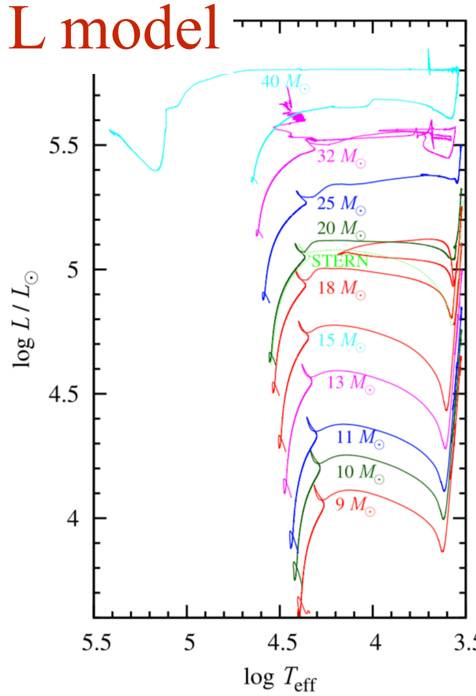


Reconsider Pop III model

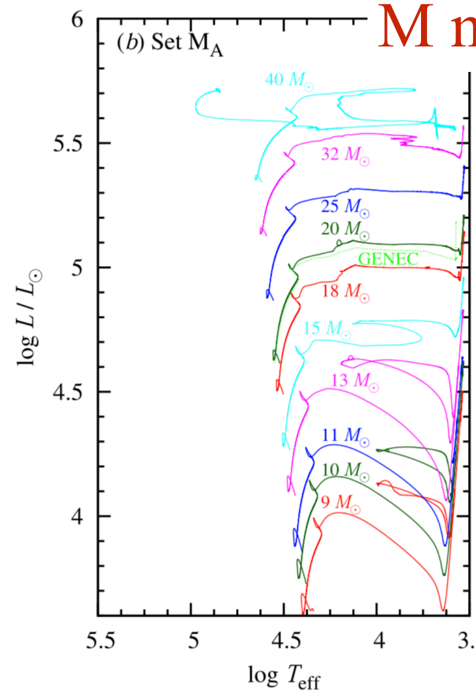
- No massive Pop. III stars discovered so far
- Extrapolation from nearby stars to Pop. III stars
  - L model: the same as before, similar to Stern (Brott et al. 2011)
  - M model: similar to GENEC (Ekstrom et al. 2012; Farrell et al. 2020)
- The maximums radius of a $80M_\odot$ star
  - M model: $\sim 40R_\odot$, similar to Farrell et al. (2020)
  - L model: $\sim 3 \times 10^3 R_\odot$, similar to Yoon et al. (2012)
- Similar issue is also discussed by Vink et al. (2021)

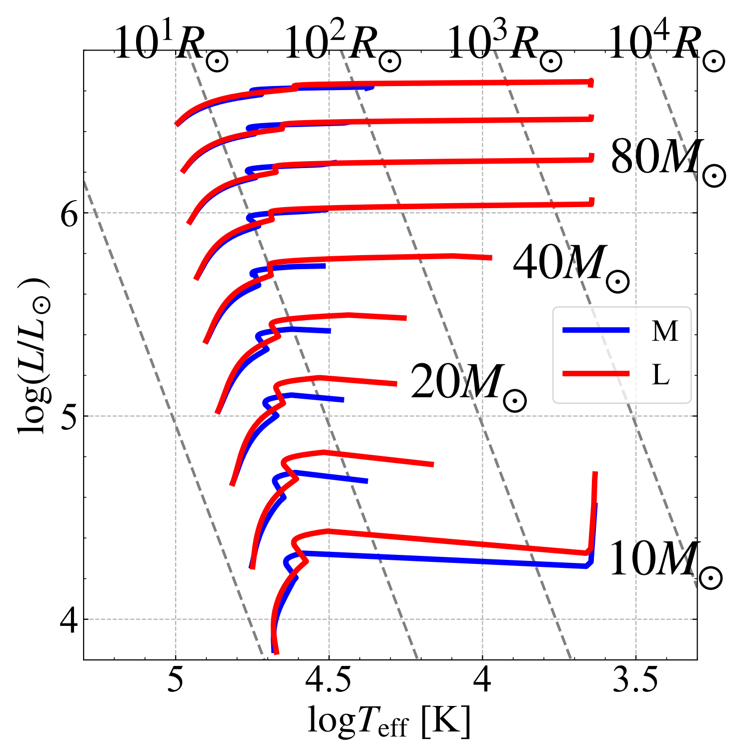
Yoshida et al. (2019)

L model



M model





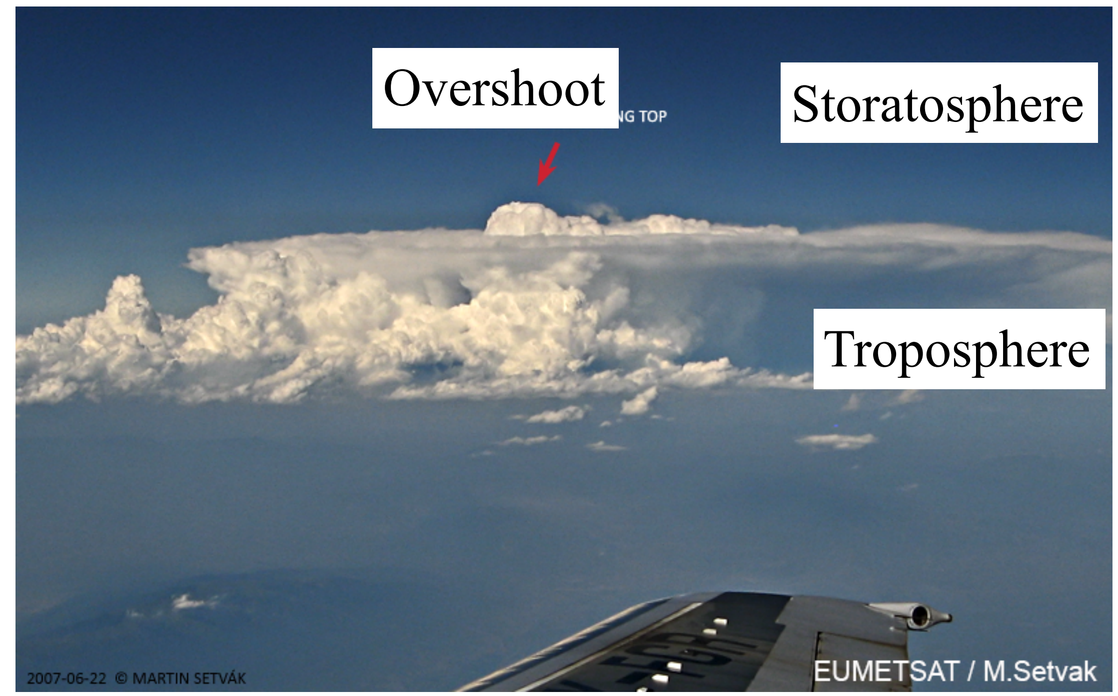
Two Pop. III models

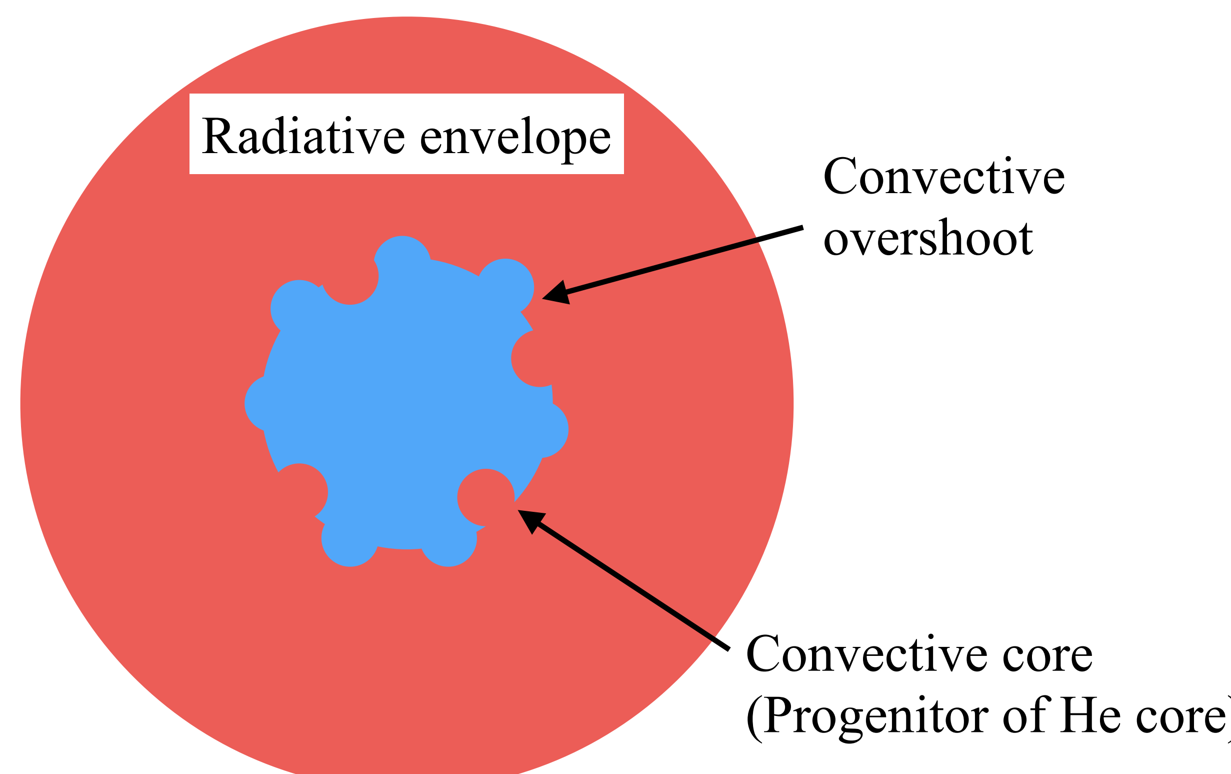
Convective overshoot

- More effective overshoot
  - Larger He core at the end of MS
  - Larger luminosity in post-MS
  - Larger radius in post-MS
- Effectiveness of overshoot
  - M model: less effective overshoot
  - L model: more effective overshoot

Both consistent with Pop I/II stars

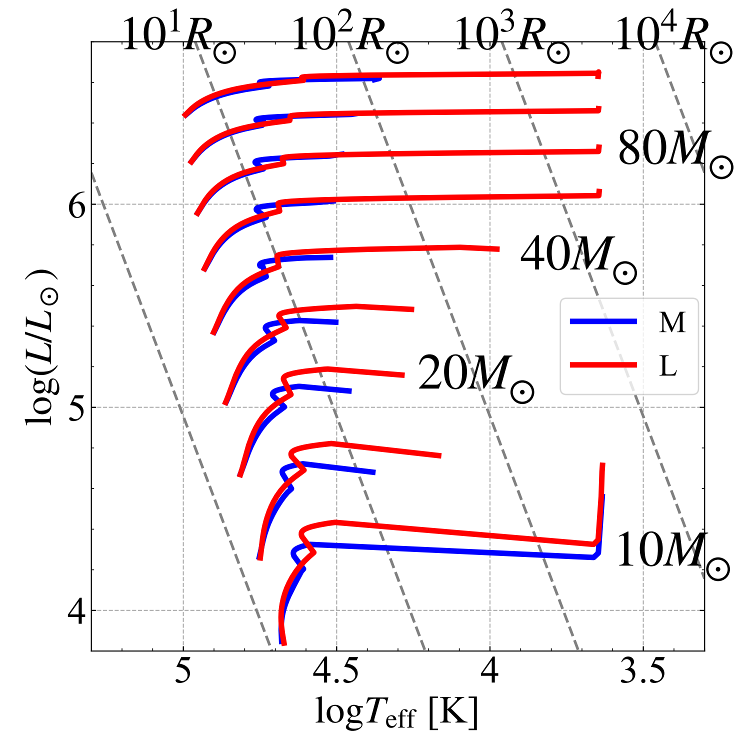
Different radii for Pop III stars

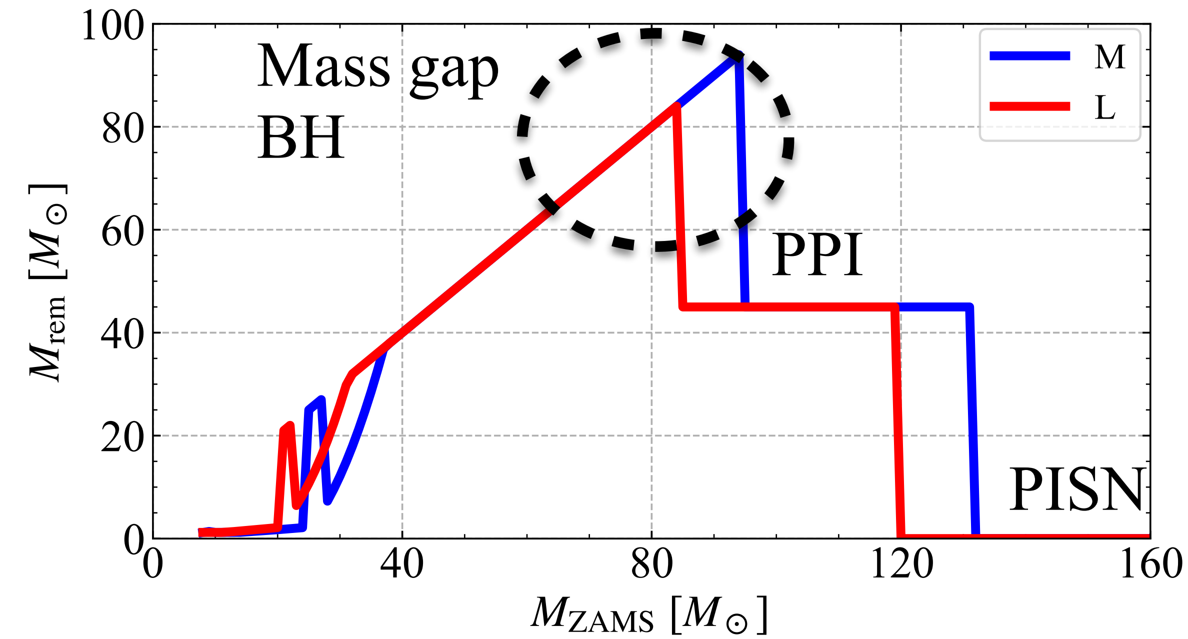




Binary population synthesis

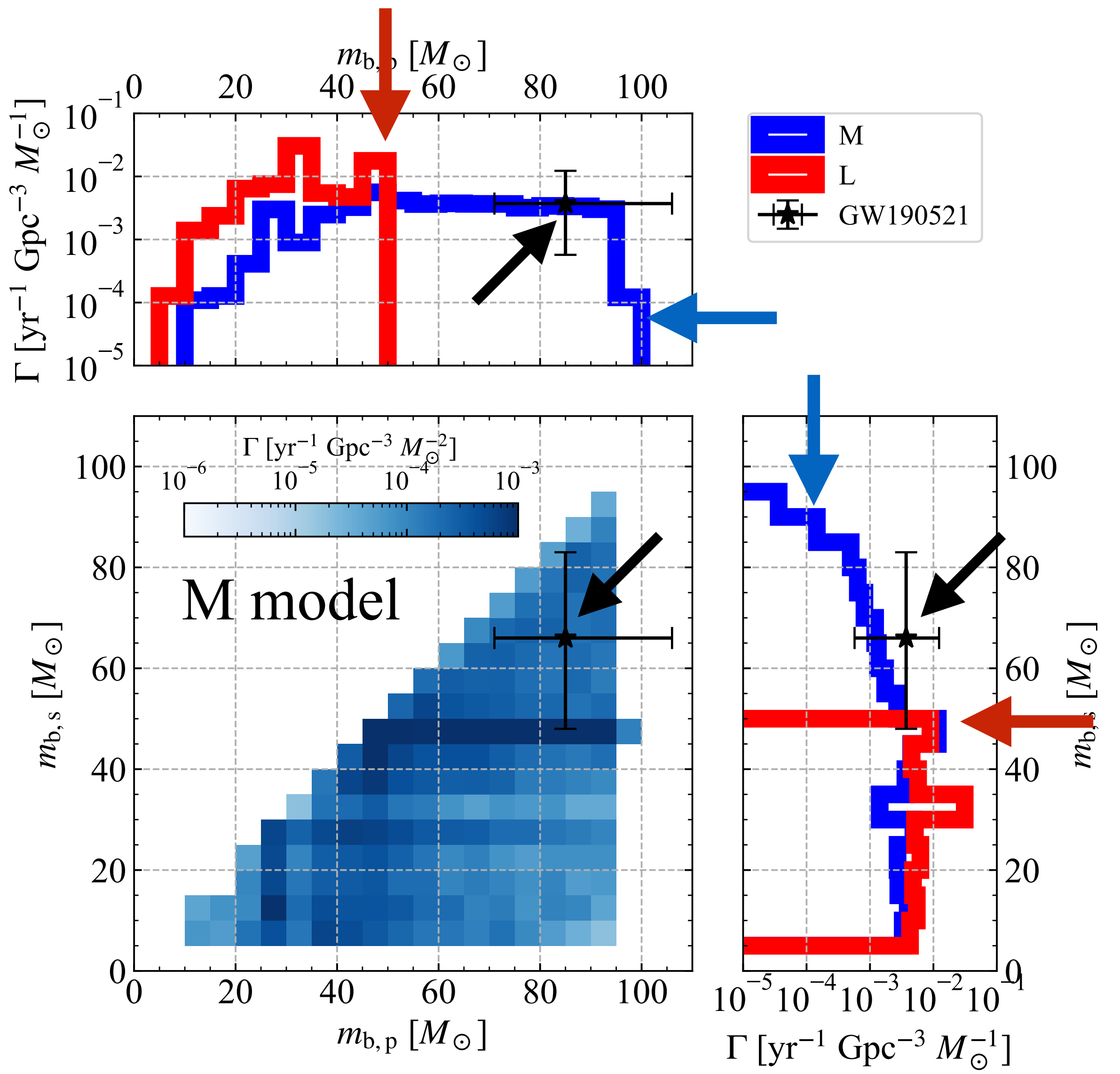
- FFs
  - L model, the same as previous Pop III ones
  - M model, the smaller overshoot
- Initial conditions
  - $f(m_1) \propto m_1^{-1}$
    $(10M_\odot \leq m_1 \leq 150M_\odot)$
  - $f(a) \propto a^{-1}$
    $(10R_\odot \leq m_1 \leq 2000R_\odot)$





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.
- 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.

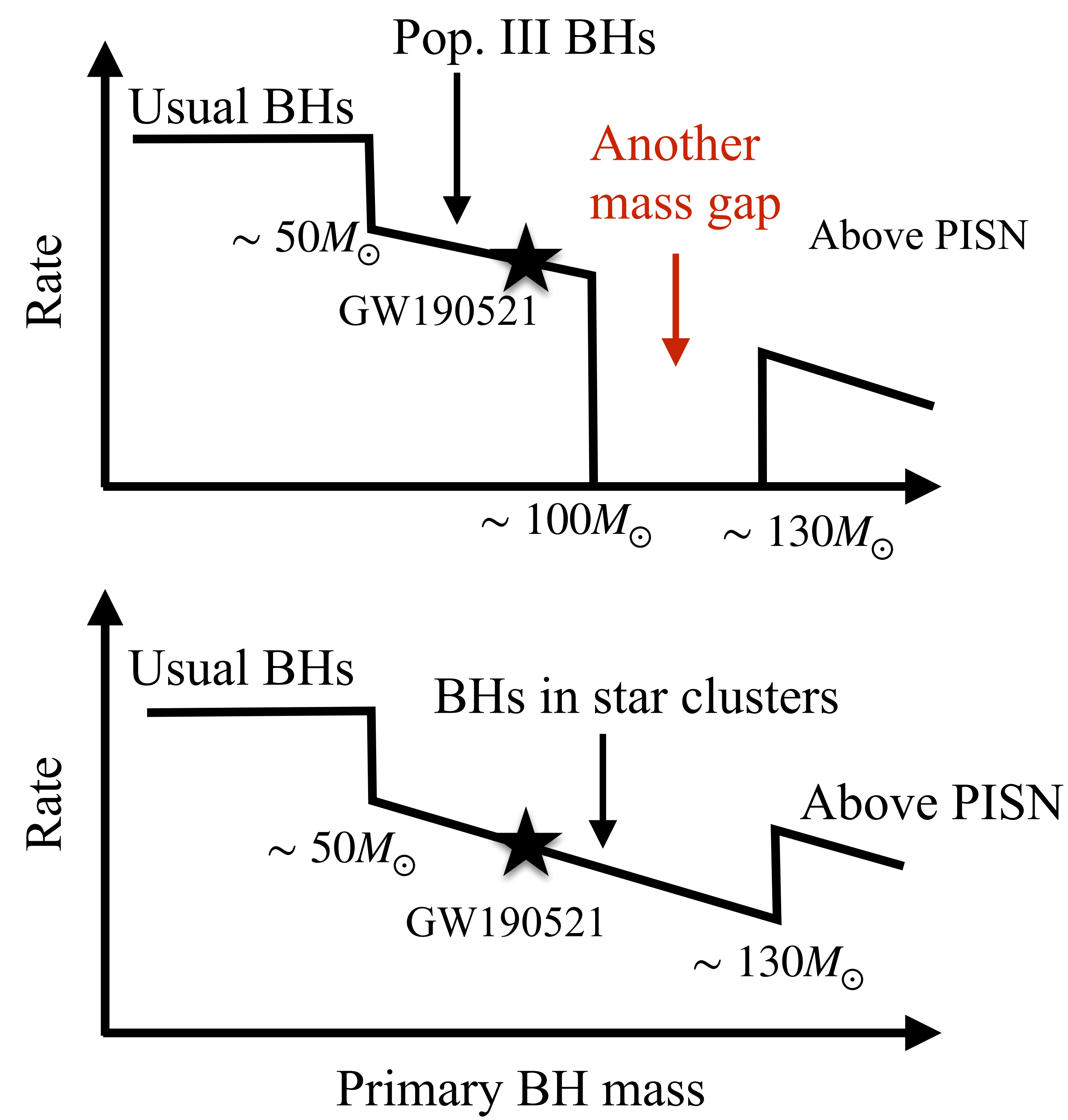


Pop III stars can form the PI mass-gap event if overshoot is ineffective.

Tanikawa et al. (2021, MNRAS in press)

Difference from cluster origin

- 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 $50 - 100 M_\odot$.



Summary

- The origins of BH mergers have been under debate.
- We have extended BSE to EMP stars and very massive stars.
- We have investigated Pop III BH mergers.
    - $\sim 30 M_\odot$ peak can disappear if Pop III binary stars are only long-period.
    - Pop III IMBH merger rate can be $\sim 0.01\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$, which may be detected in the near future.
    - Pop III stars can form the PI mass-gap event GW190521 if convective overshoot is not effective.