

# GW231123 formation from Population III binary stars

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Multi-Messenger Astrophysics in the Dynamic Universe,  
4th week at Yukawa Institute for Theoretical Physics,  
Kyoto University

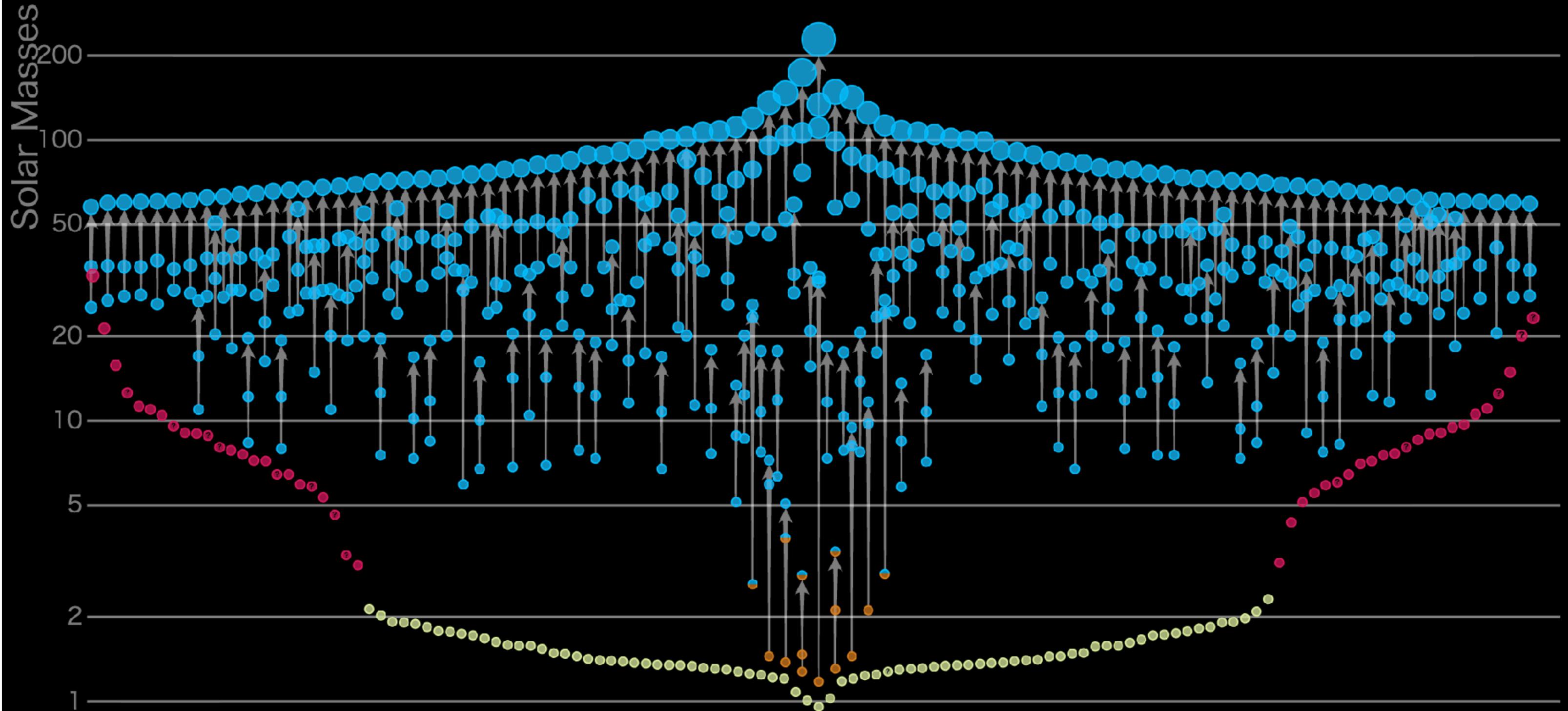
# Outline

- Pair instability mass gap (PIMG) events
- Formation scenario of PIMG events
- Implications for pair instability supernovae (PISNe)

# Masses in the Stellar Graveyard

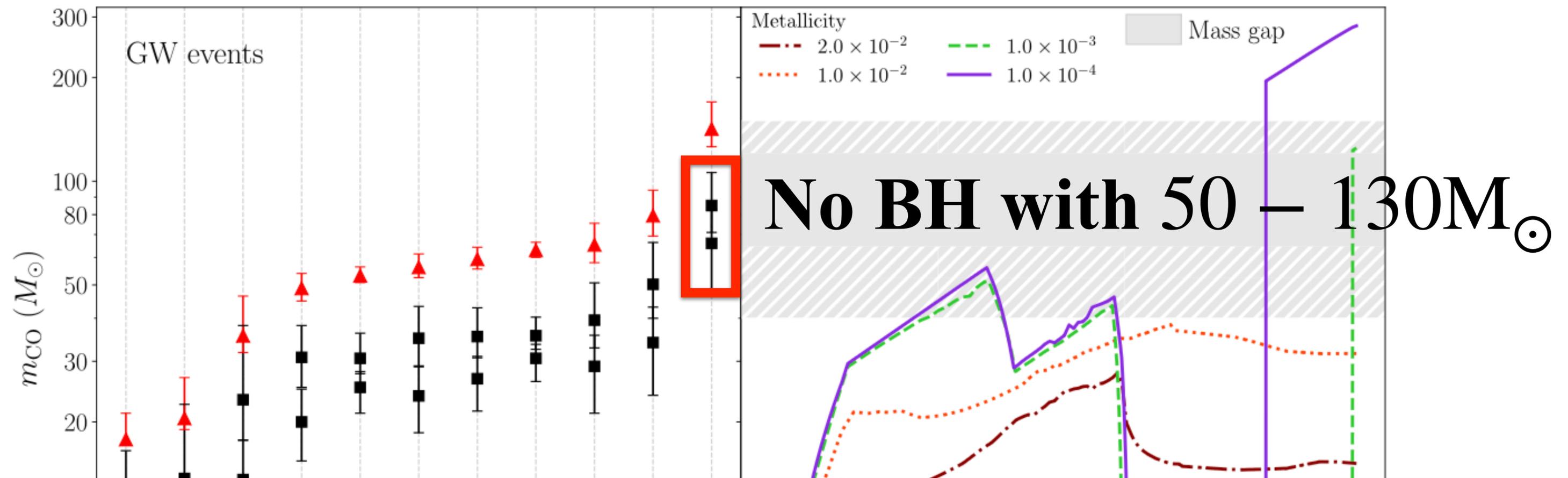


*LIGO-Virgo-KAGRA Black Holes* *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



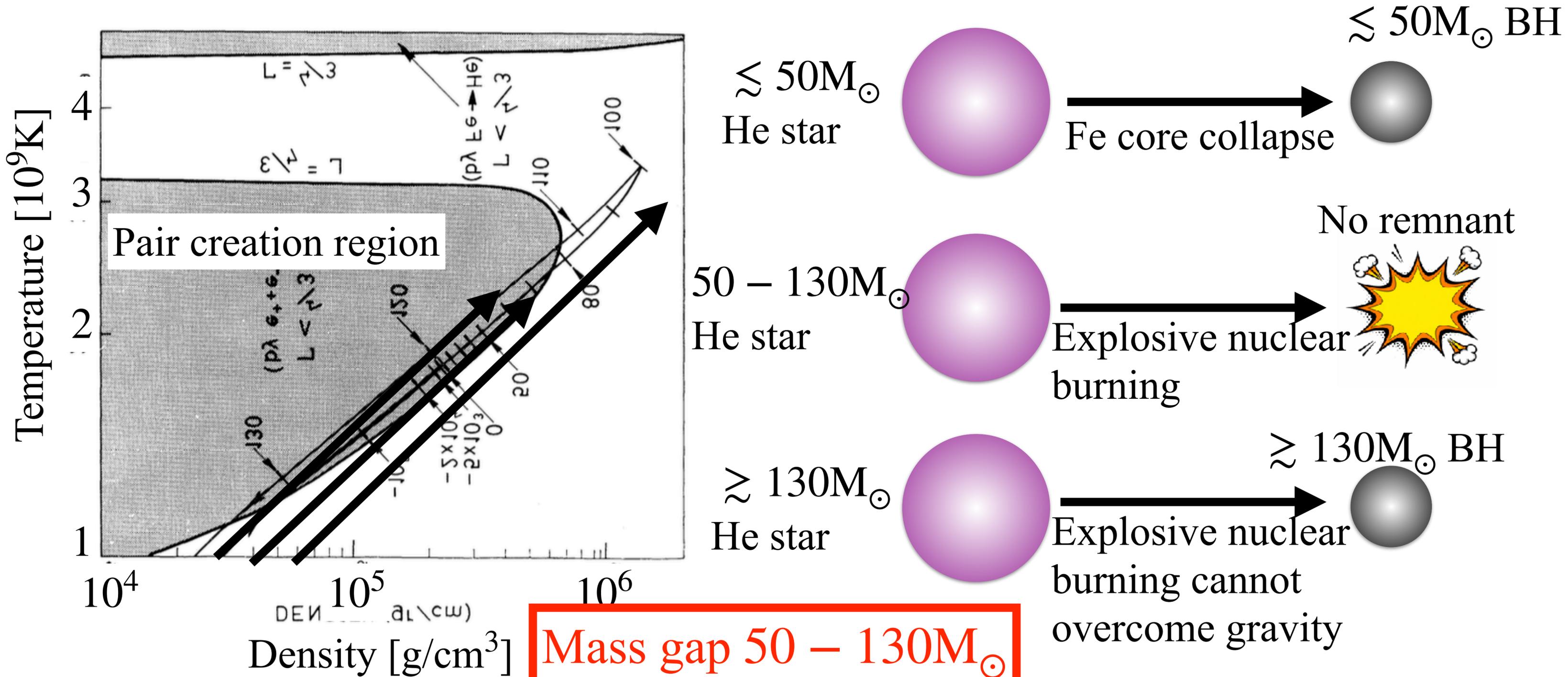
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

# Pair instability mass gap (PIMG)



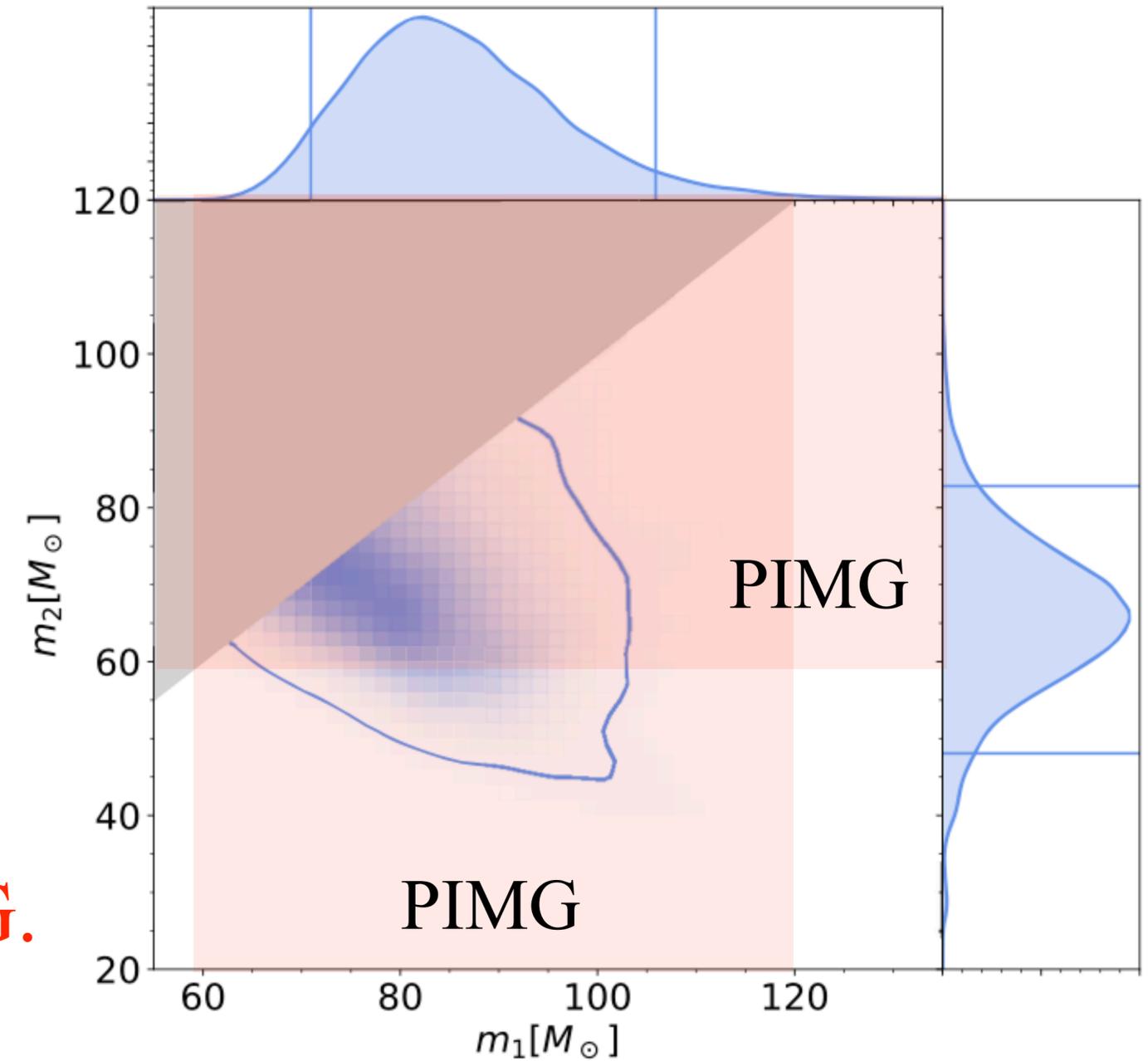
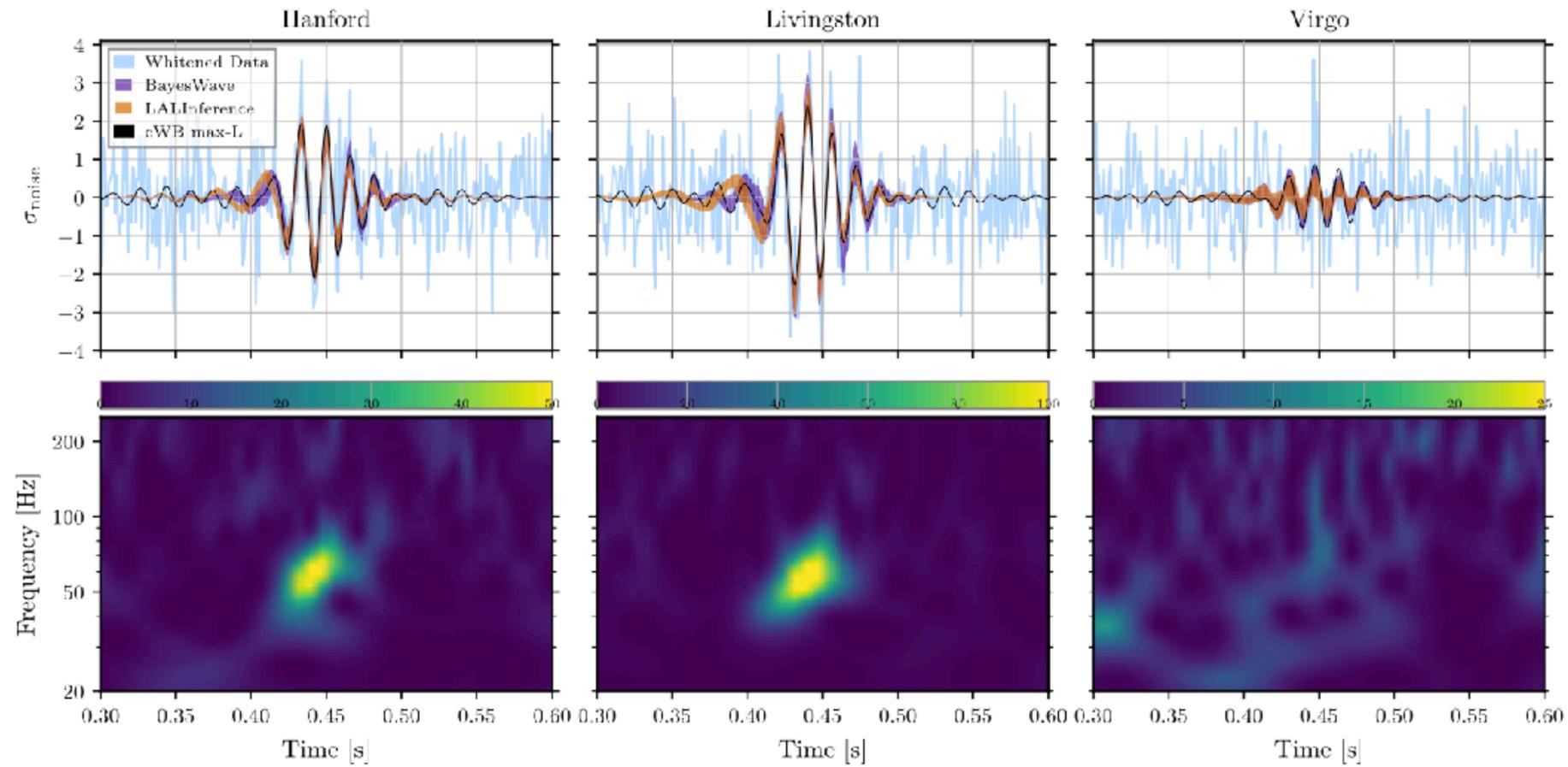
Isolated binary scenario needs to explain the presence of PIMG events.

# Pair instability supernova



# GW190521

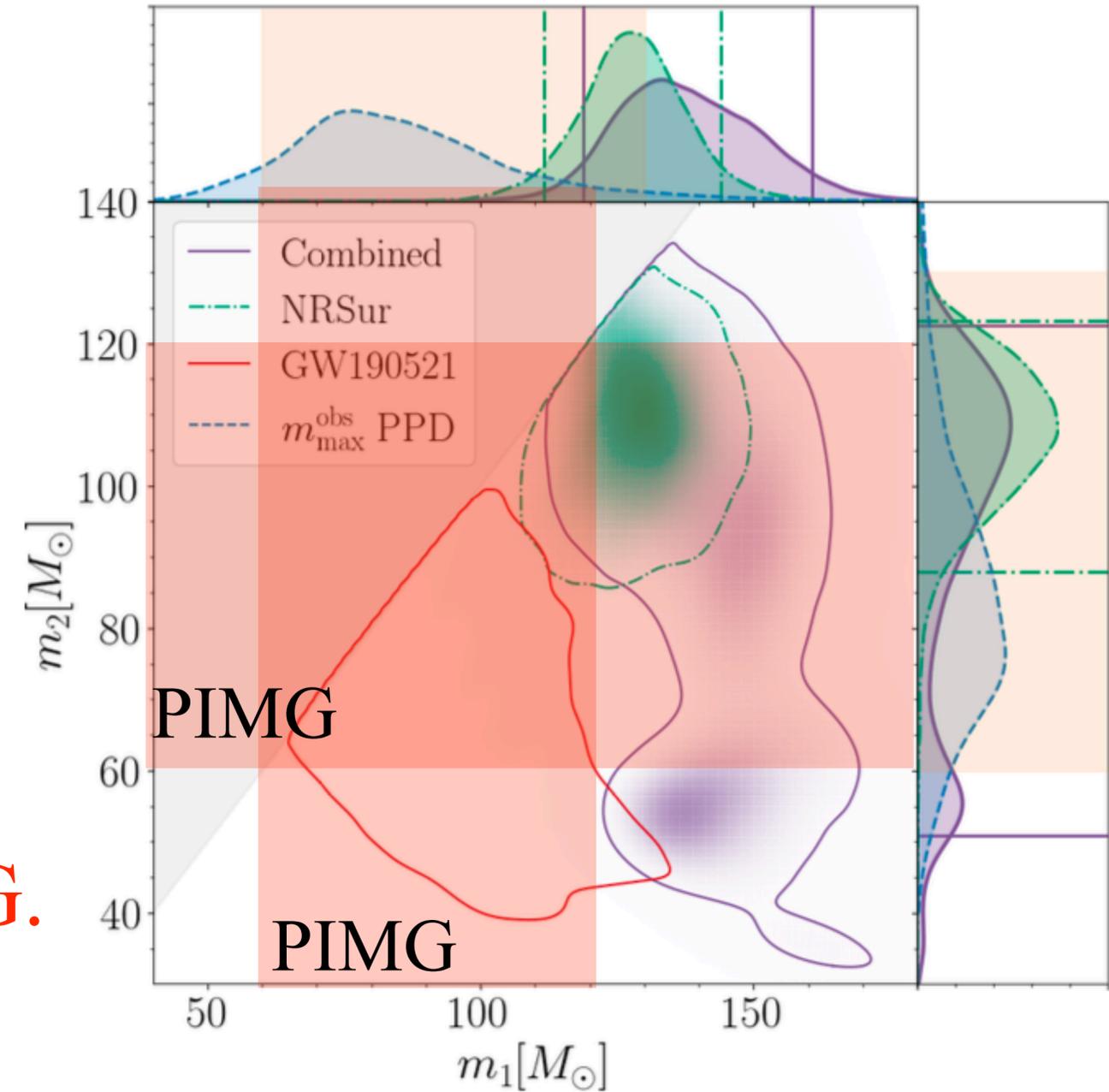
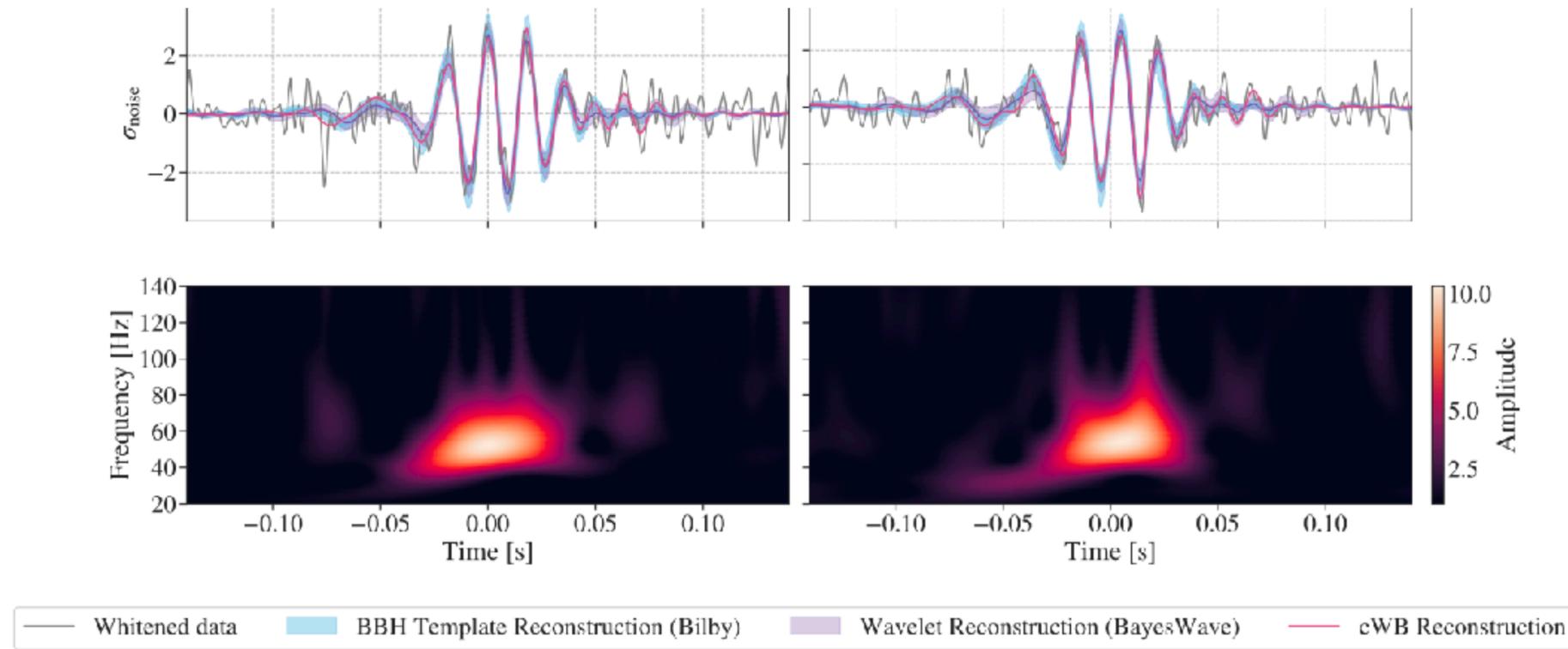
Abbott et al. (2020, PRL, 125, 101102)



At least the primary BH is within the PIMG.

# GW231123

Abac et al. (2025, ApJL, 993, 25)



The primary BH is within, or beyond the PIMG.

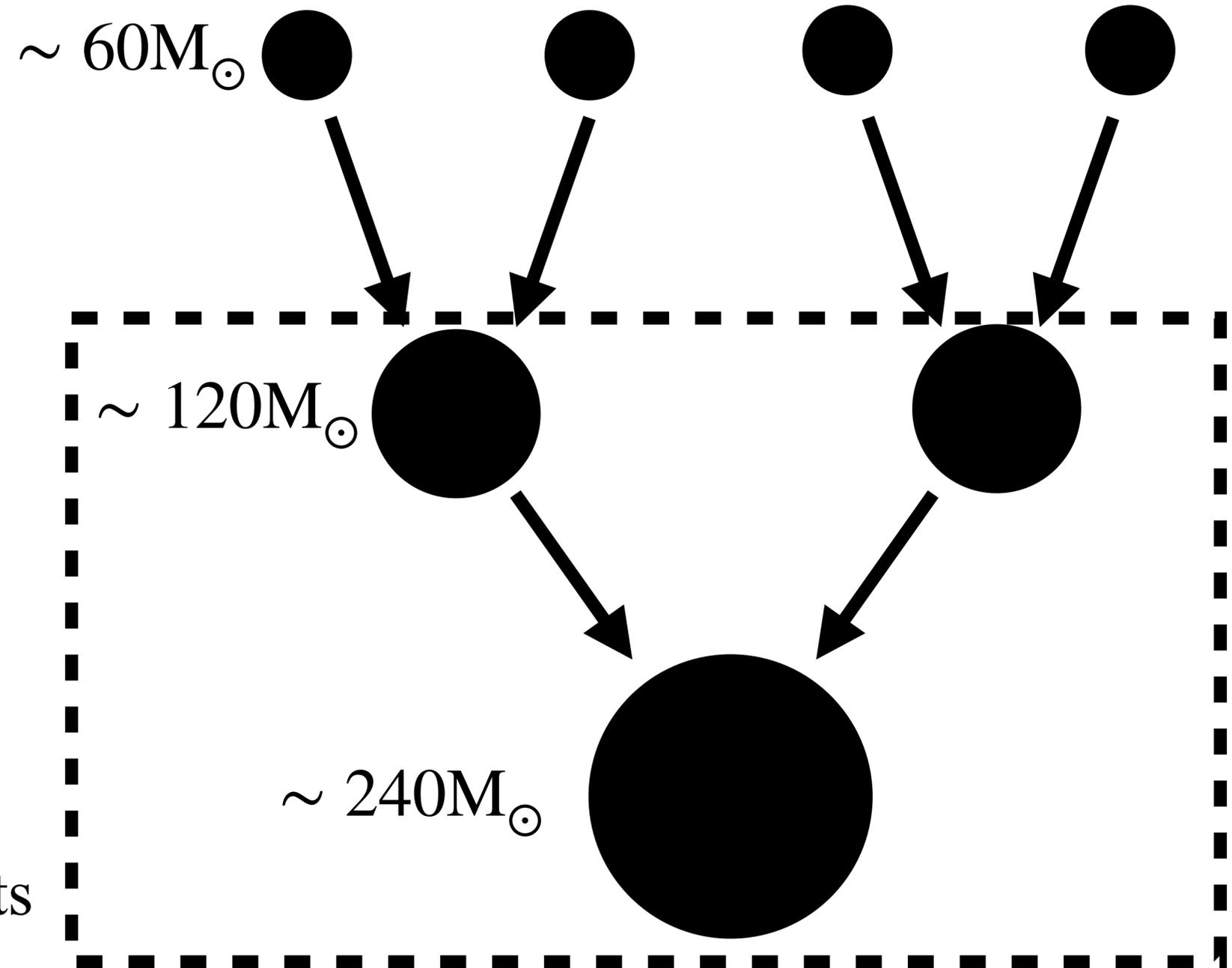
# Formation scenarios for PIMG events

- Hierarchical mergers in star clusters (Rodriguez et al. 2019; Rizzuto et al. 2021; Di Carlo et al. 2021; Wang et al. 2022; Liu et al. 2024) and AGN disks (Tagawa et al. 2020)

- Isolated binary stars (Belczynski et al. 2020; Kinugawa et al. 2021; Tanikawa et al. 2021; Tanikawa et al. 2025)

- Collapse of rotating very massive stars (Shibata et al. 2021; Shibata, Fujibayashi 2026)

PIMG events

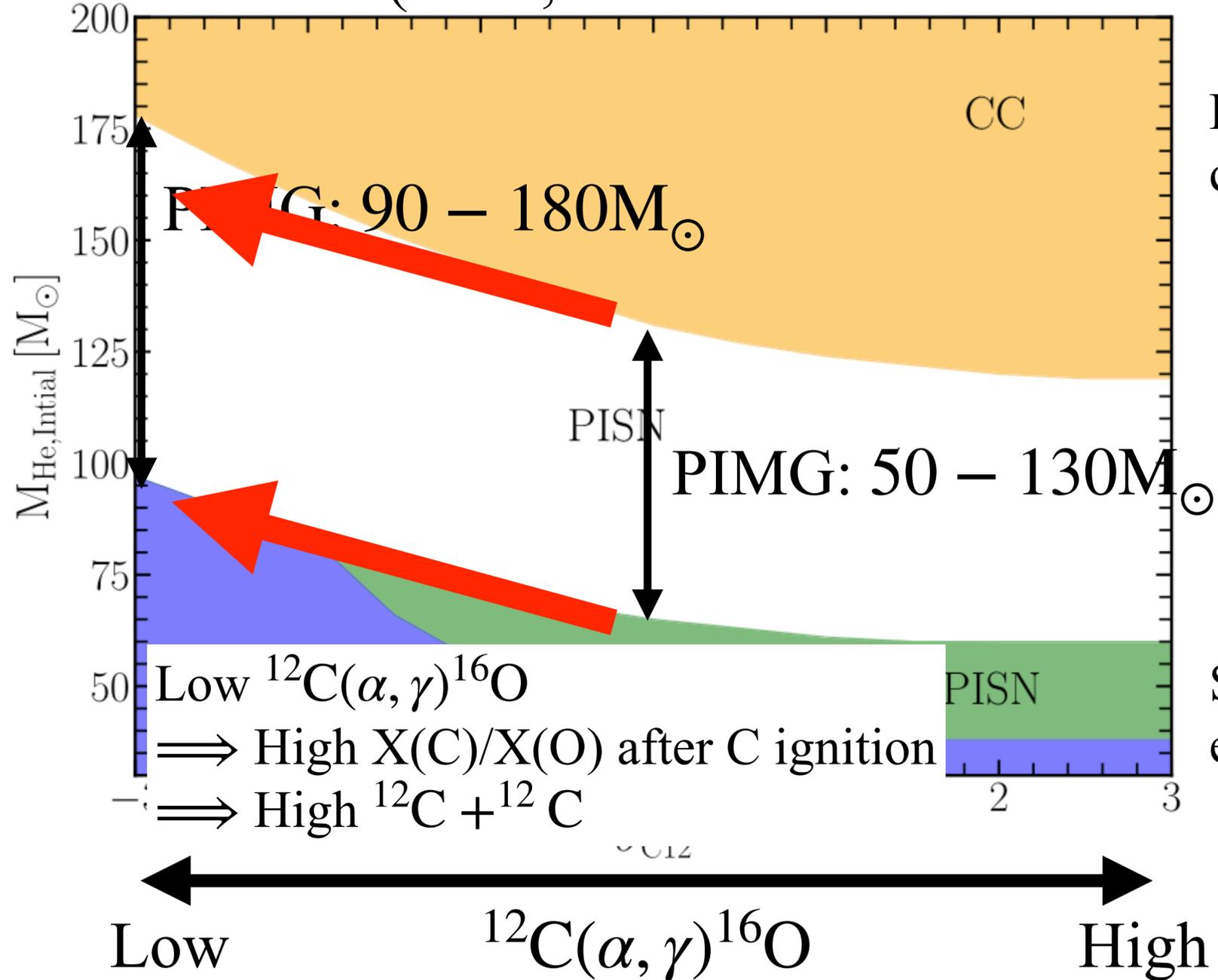


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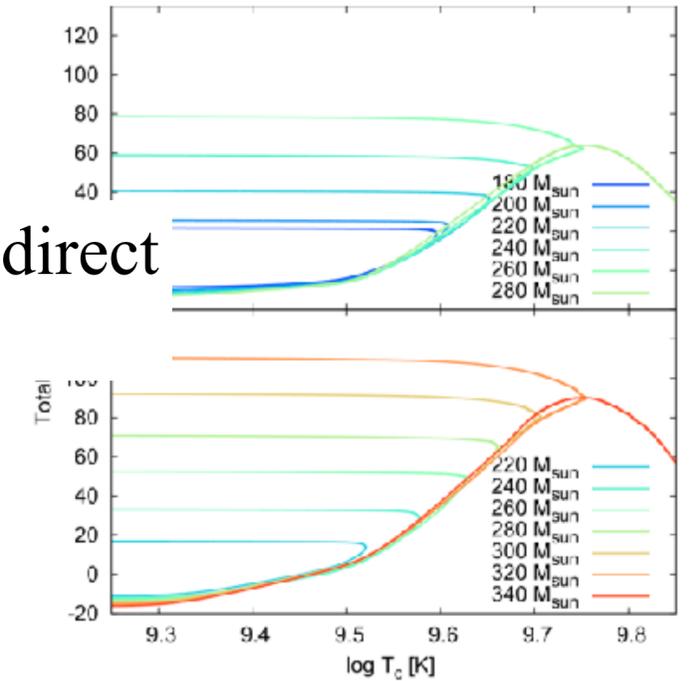
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# Uncertainty of the PIMG range

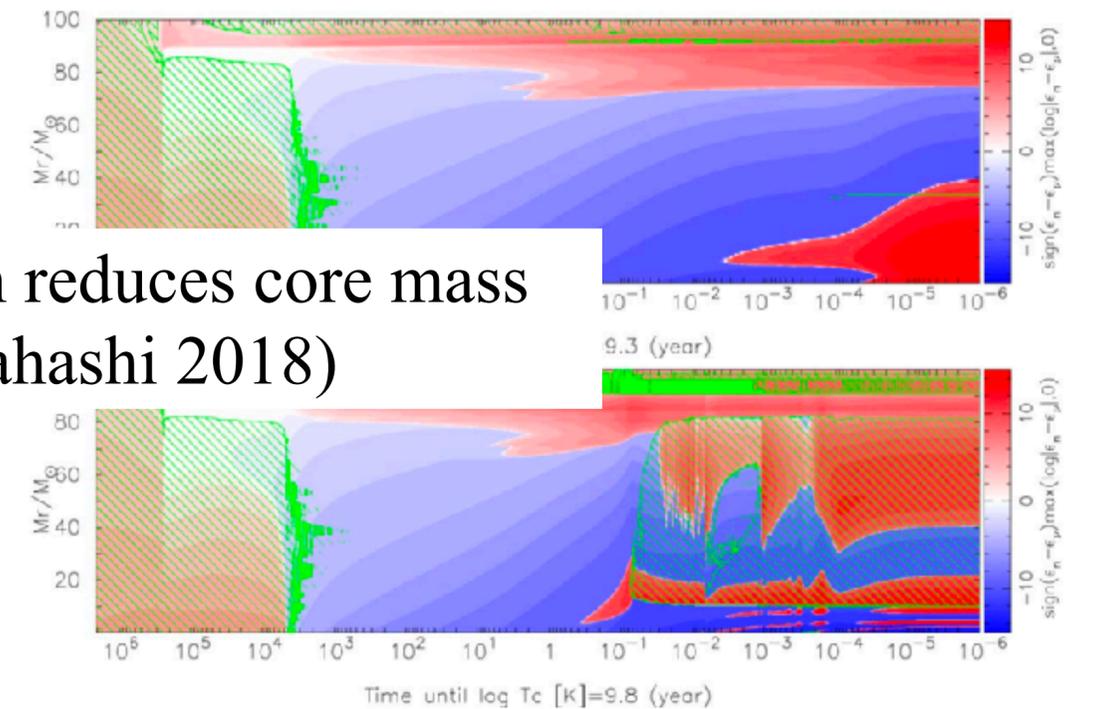
Farmer et al. (2020; see also Costa et al. 2021)



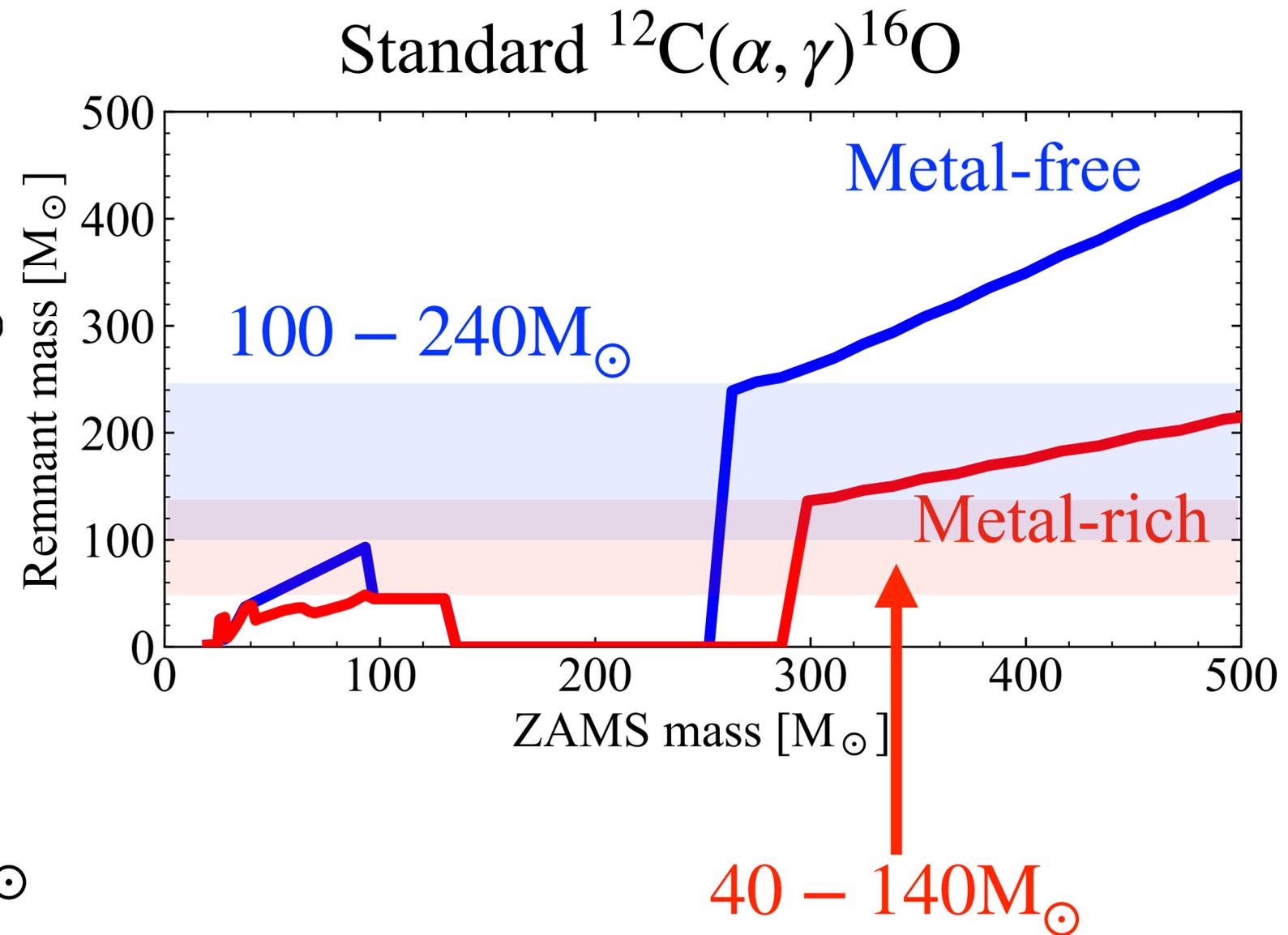
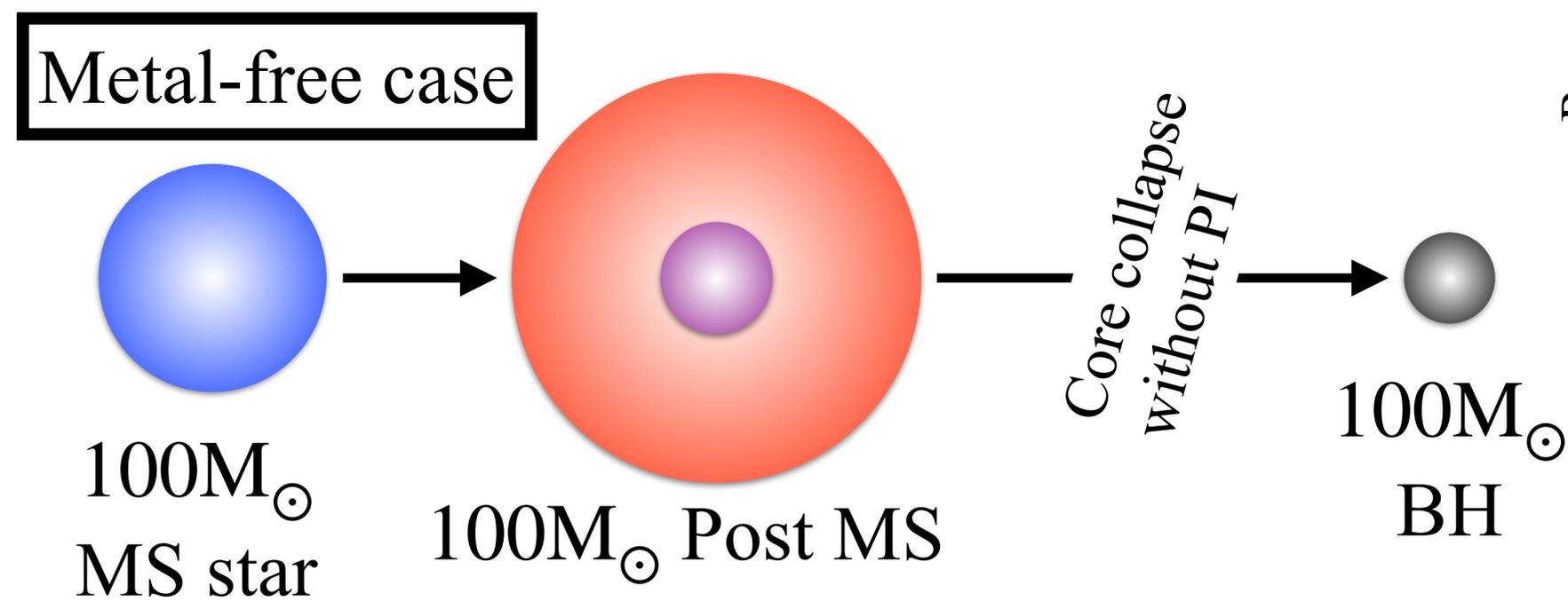
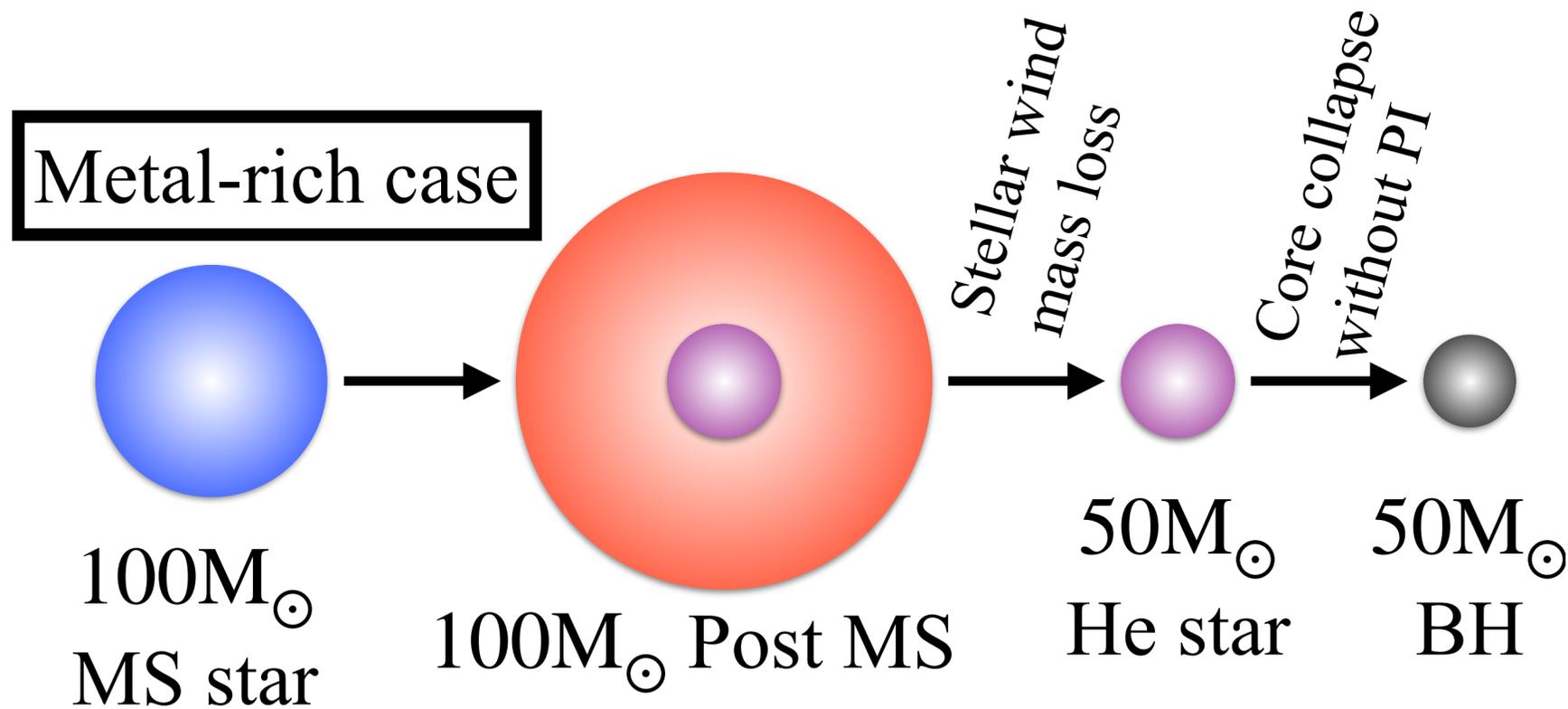
High C burning rate suppresses direct collapse (Takahashi 2018)



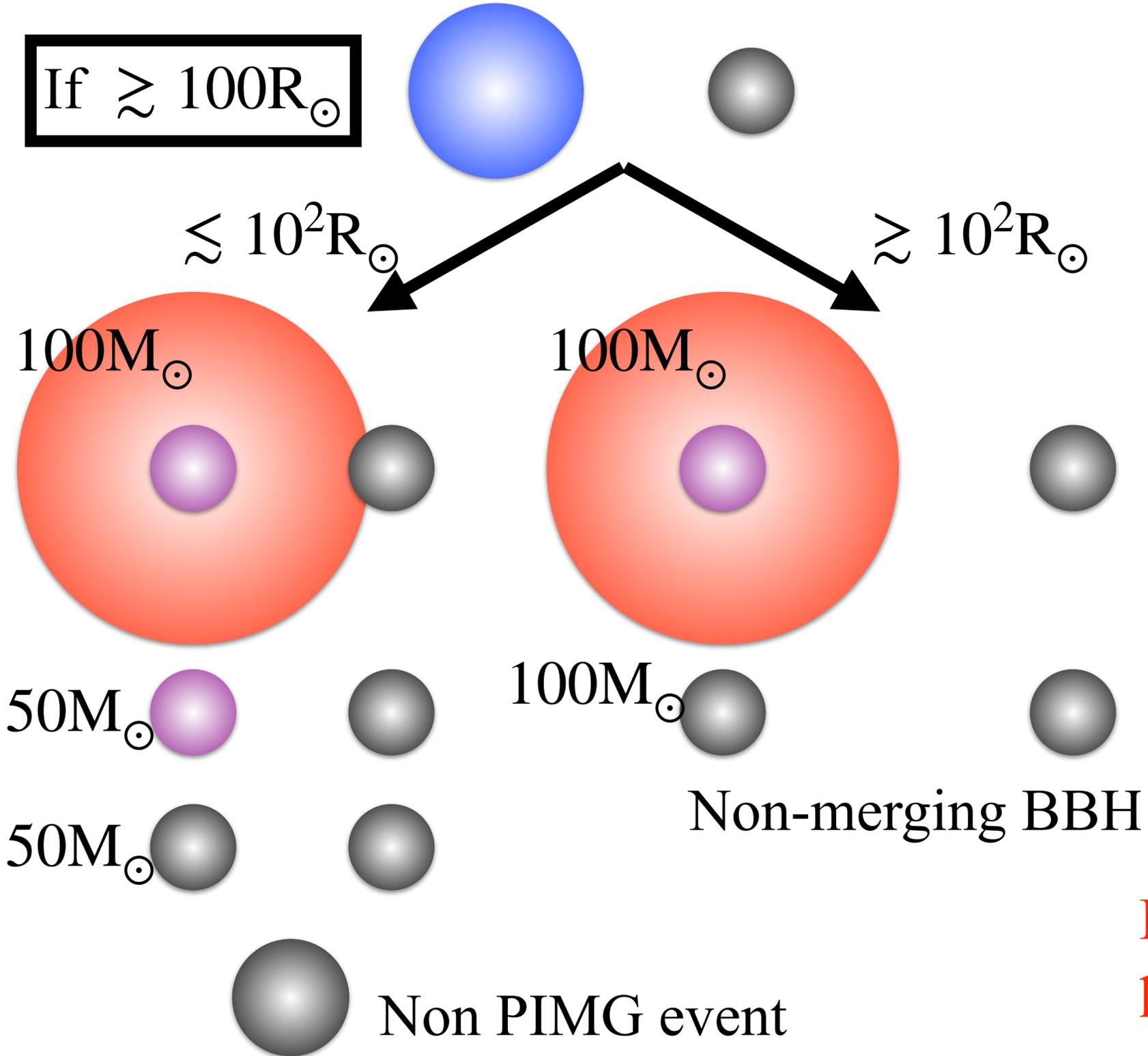
Shell convection reduces core mass effectively (Takahashi 2018)



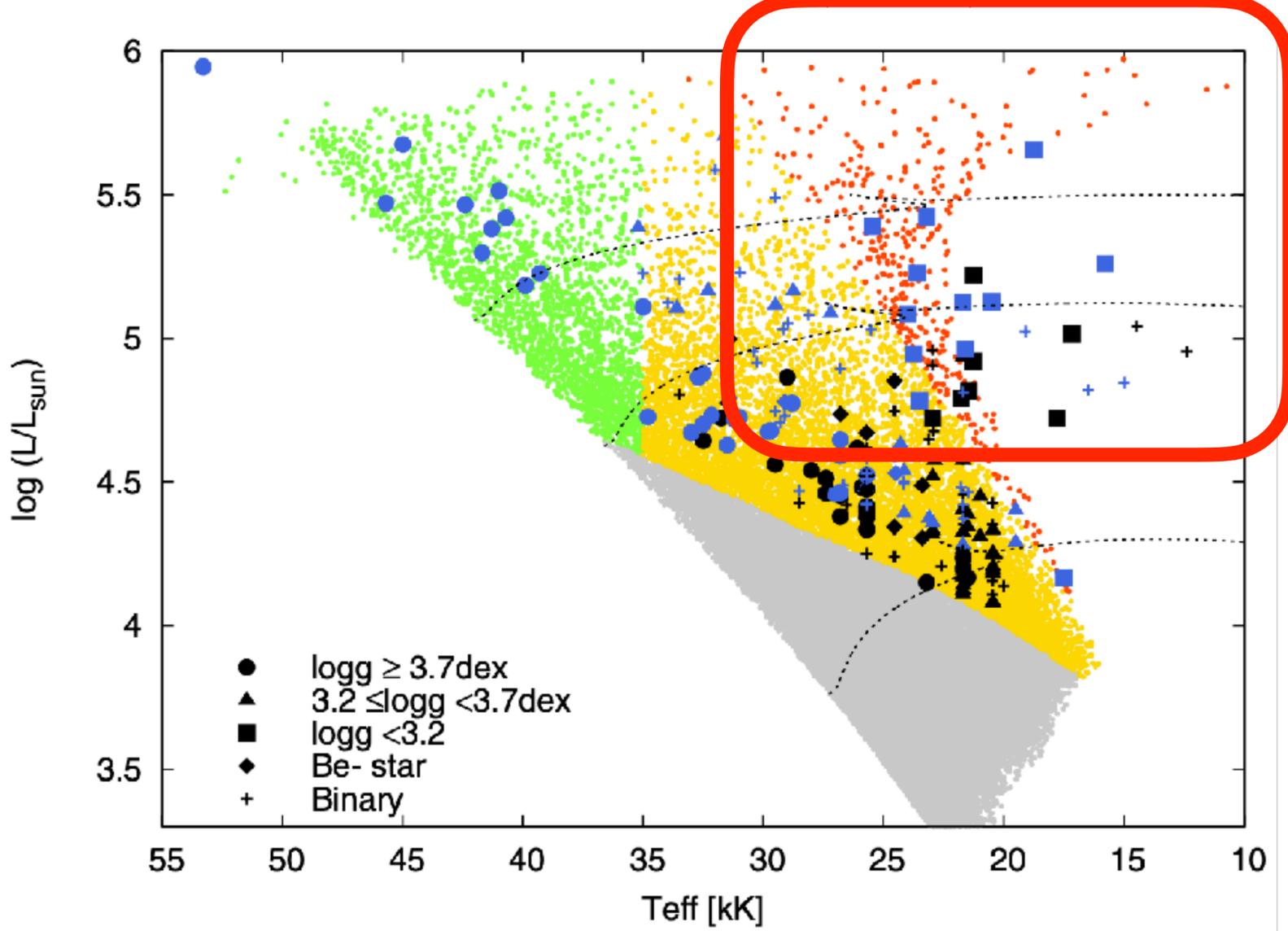
# Dependence of the PIMG on metallicity



# BH progenitors should have the maximum radii of $\lesssim 100R_{\odot}$



Brott et al. (2011)



BH progenitors with metal-rich ( $Z/Z_{\odot} \gtrsim 0.1$ ) have the maximum radii of  $> 10^3 R_{\odot}$ .

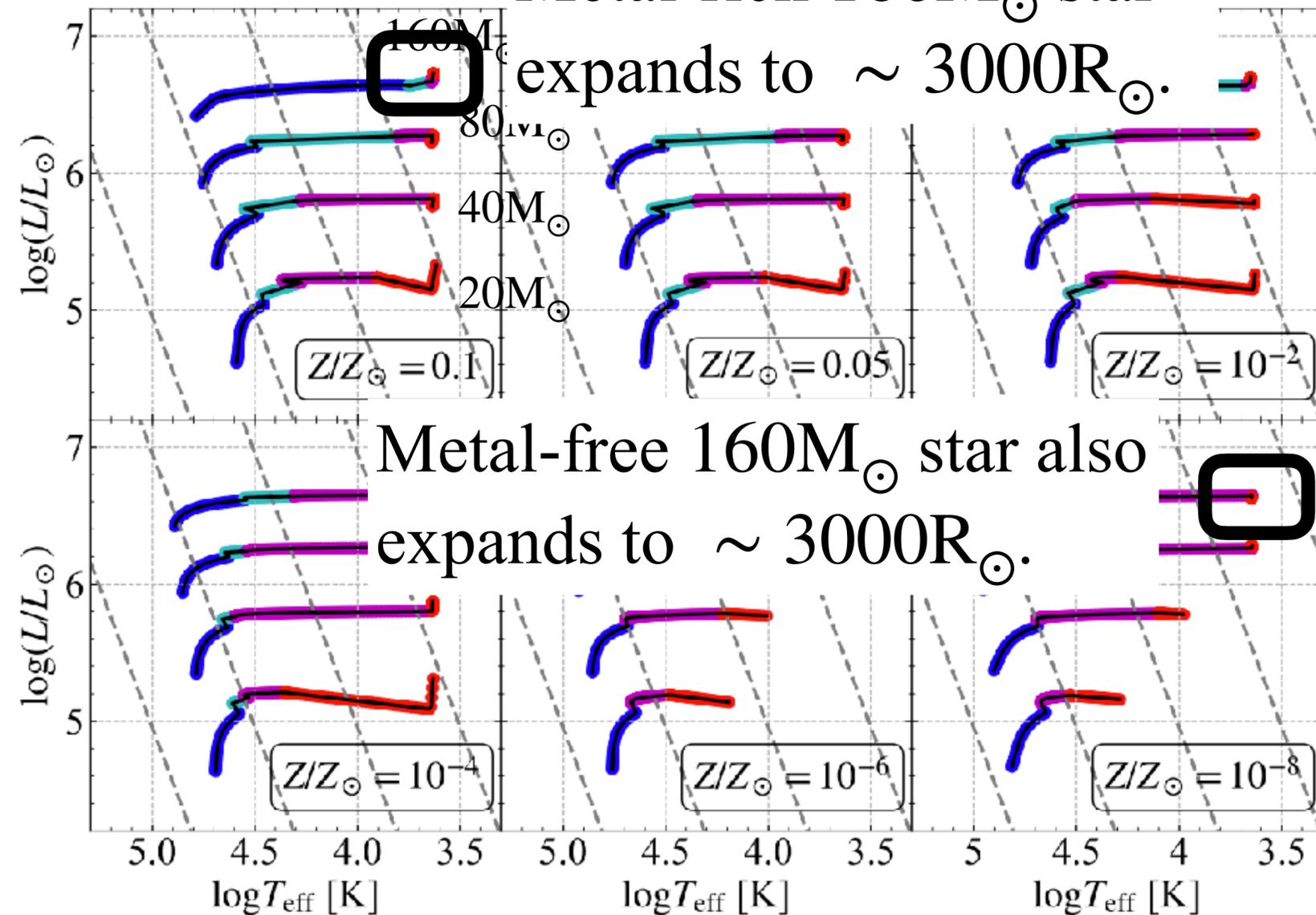
# Metal-free stars with inefficient convective overshoot



Efficient case

Metal-rich  $160M_{\odot}$  star

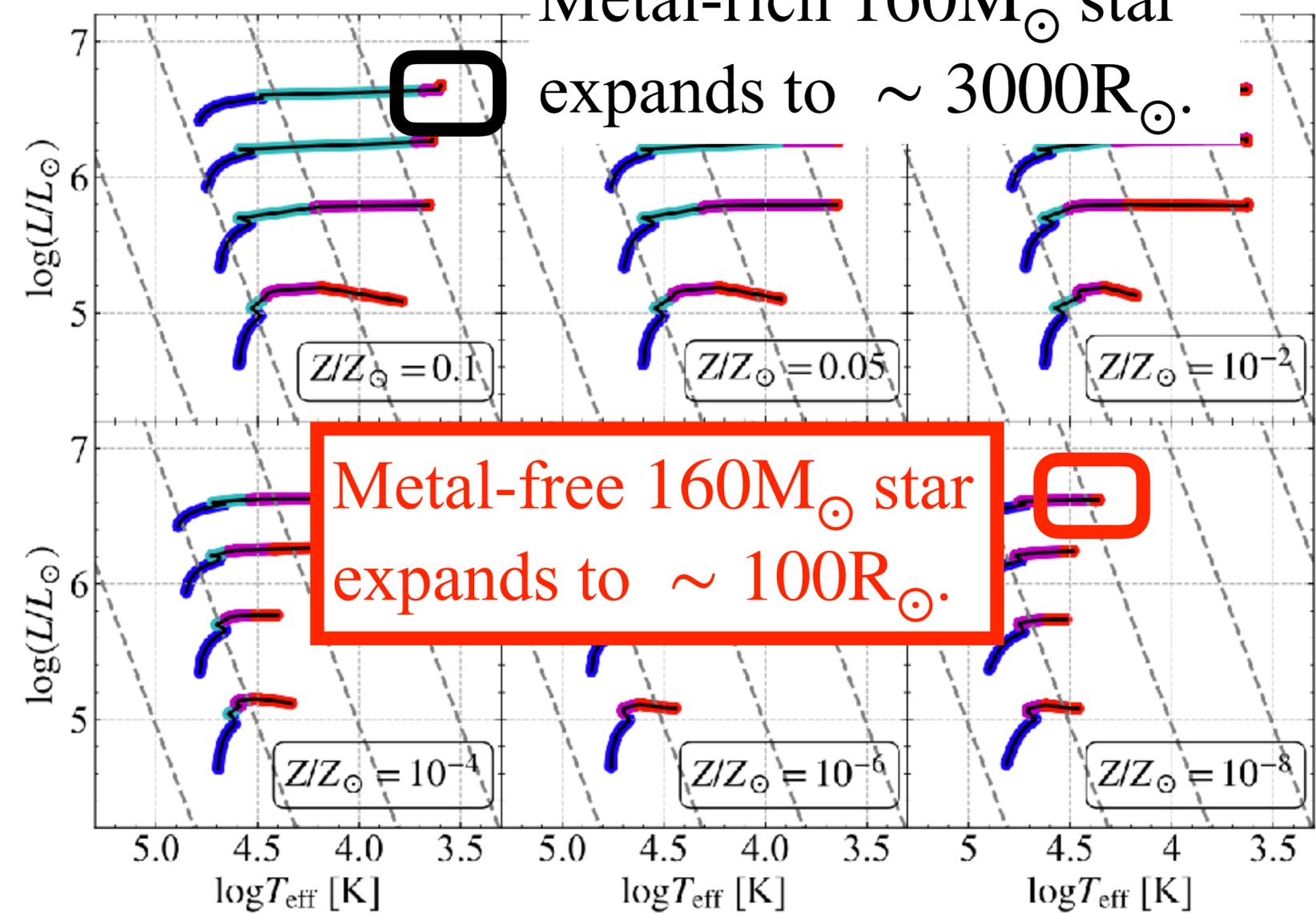
expands to  $\sim 3000R_{\odot}$ .



Inefficient case

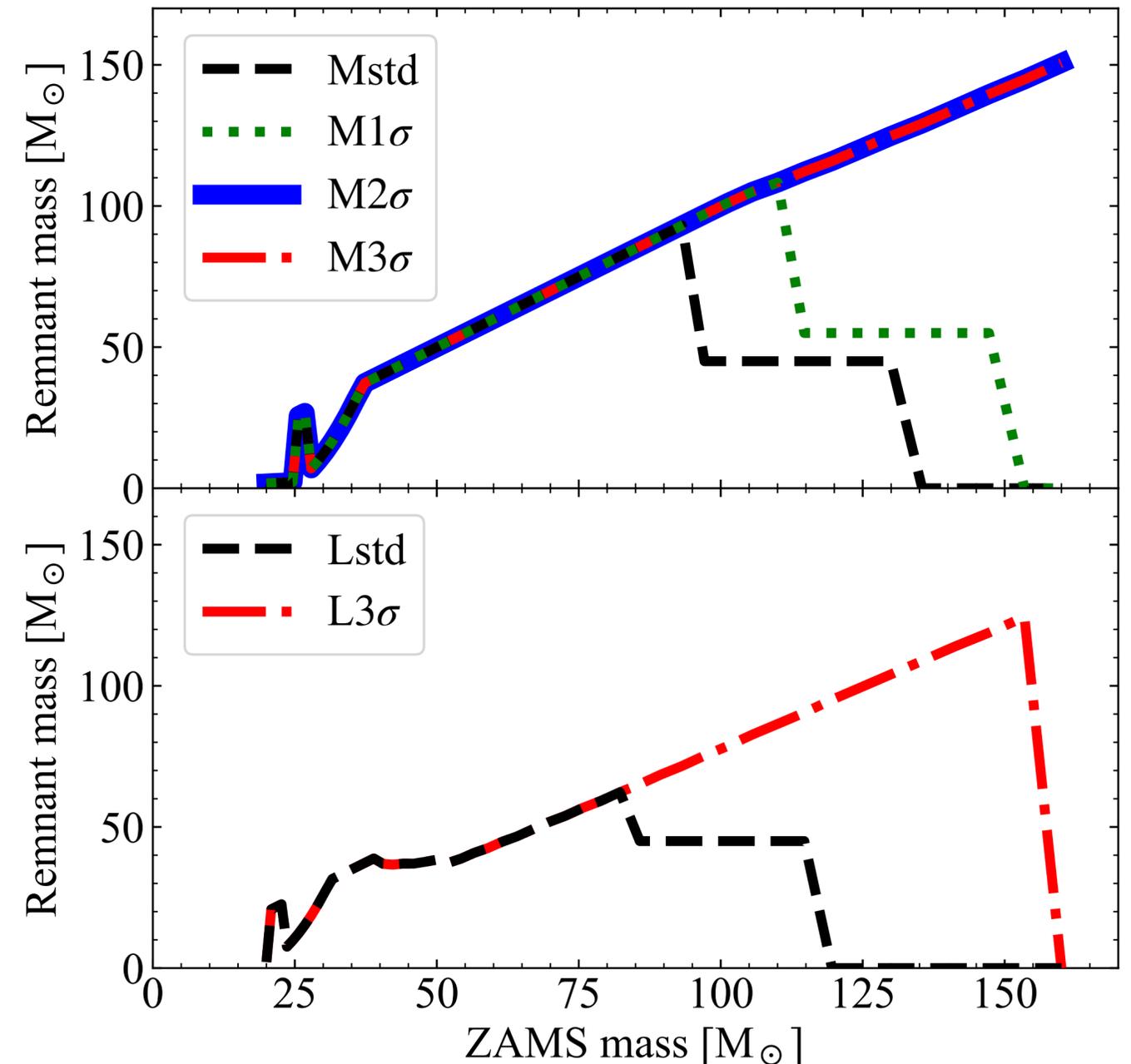
Metal-rich  $160M_{\odot}$  star

expands to  $\sim 3000R_{\odot}$ .



# Binary population synthesis calculation

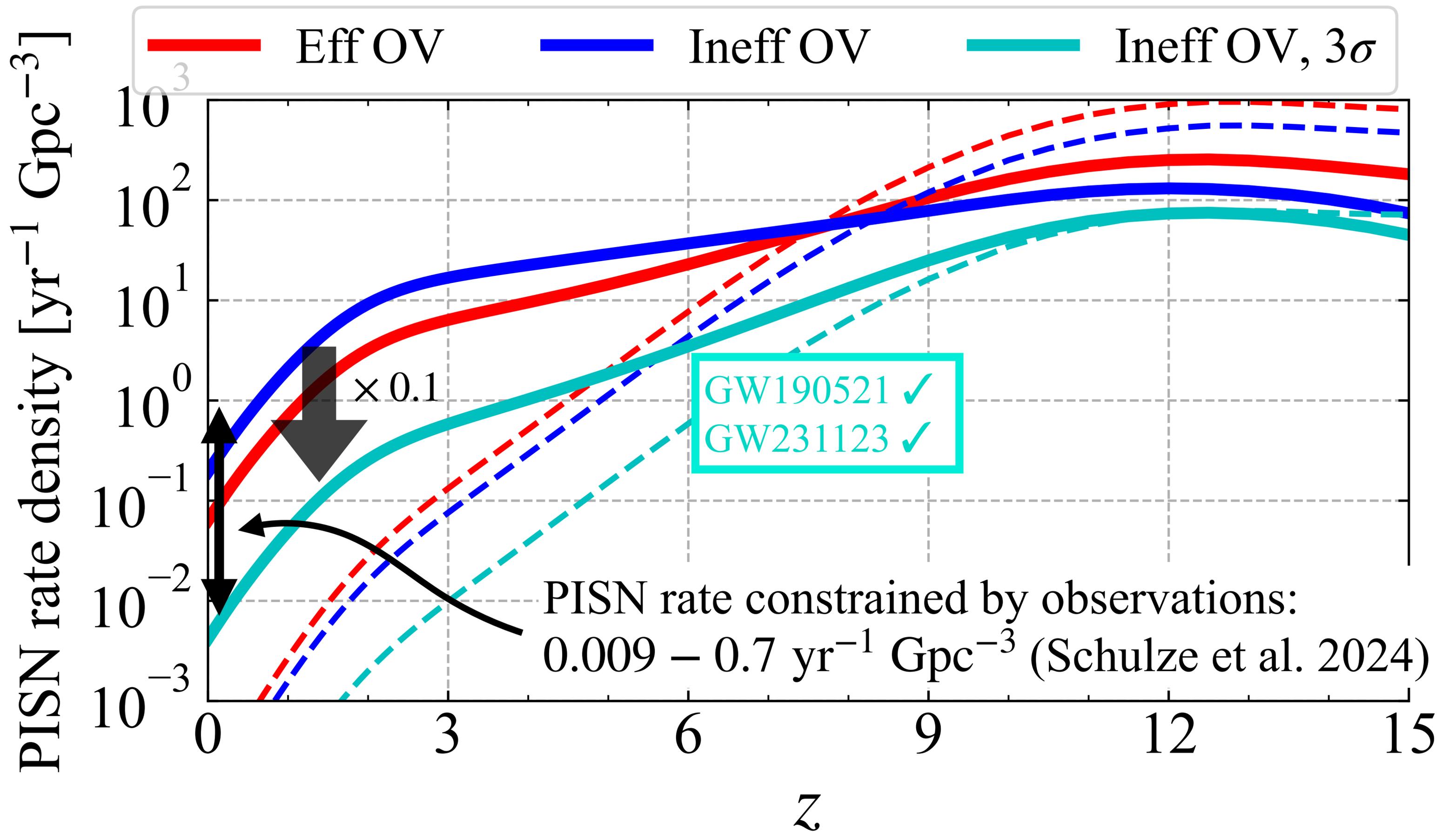
- BSEEMP (Tanikawa et al. 2020, MNRAS, 495, 4170; Tanikawa et al. 2022, ApJ, 926, 83)
- Extension of BSE (Hurley et al. 2002) down to extremely metal-poor stars
- <https://github.com/atrtnkw/bseemp>
- Pop I, II, and III binary stars with efficient and inefficient convective overshoot
- Stellar winds, supernovae (CCSNe, PPISNe, PISNe), etc.
- Standard and  $3\sigma$ -lower  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- Binary evolution: stable mass transfer, common envelope evolution, tidal evolution, etc.





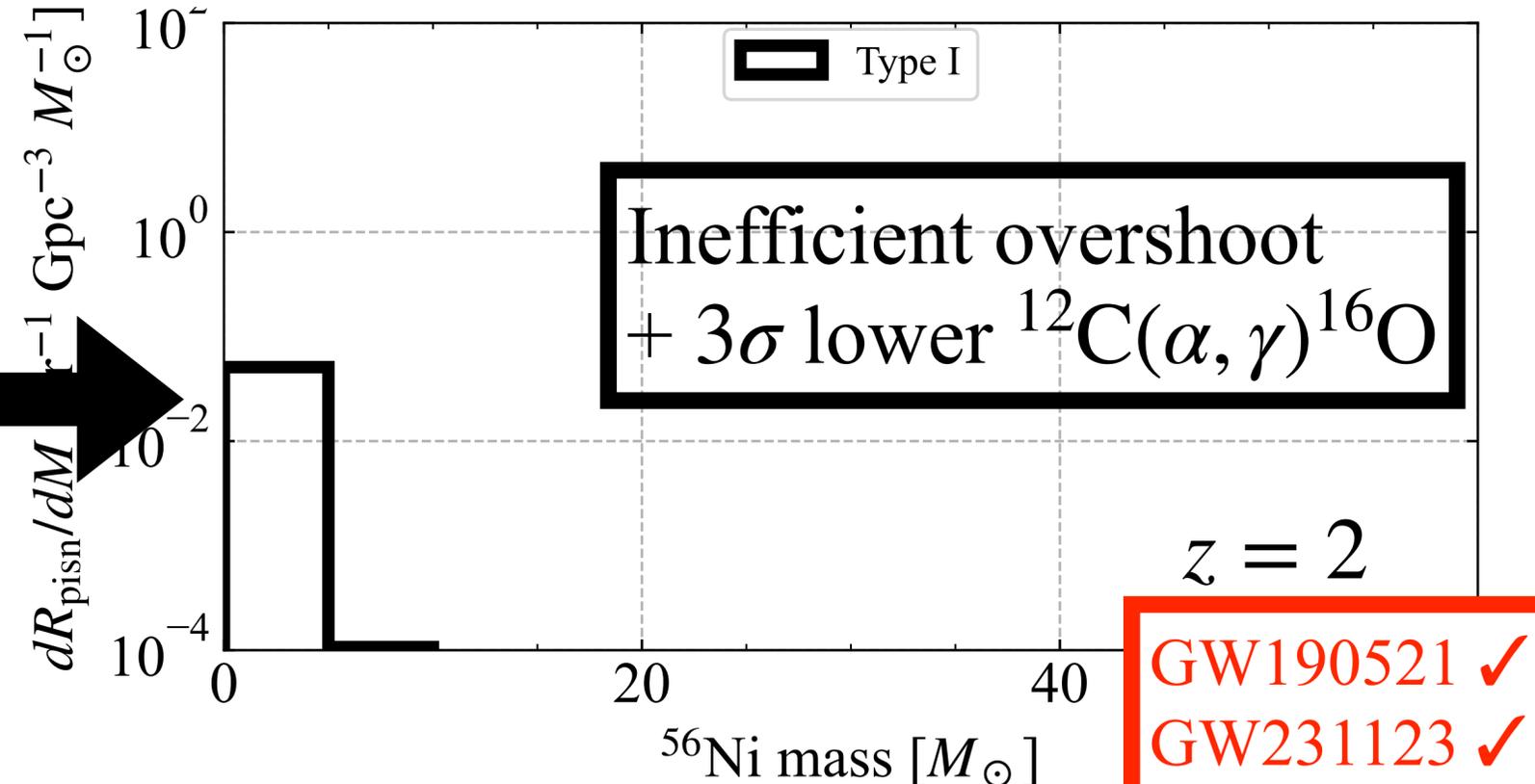
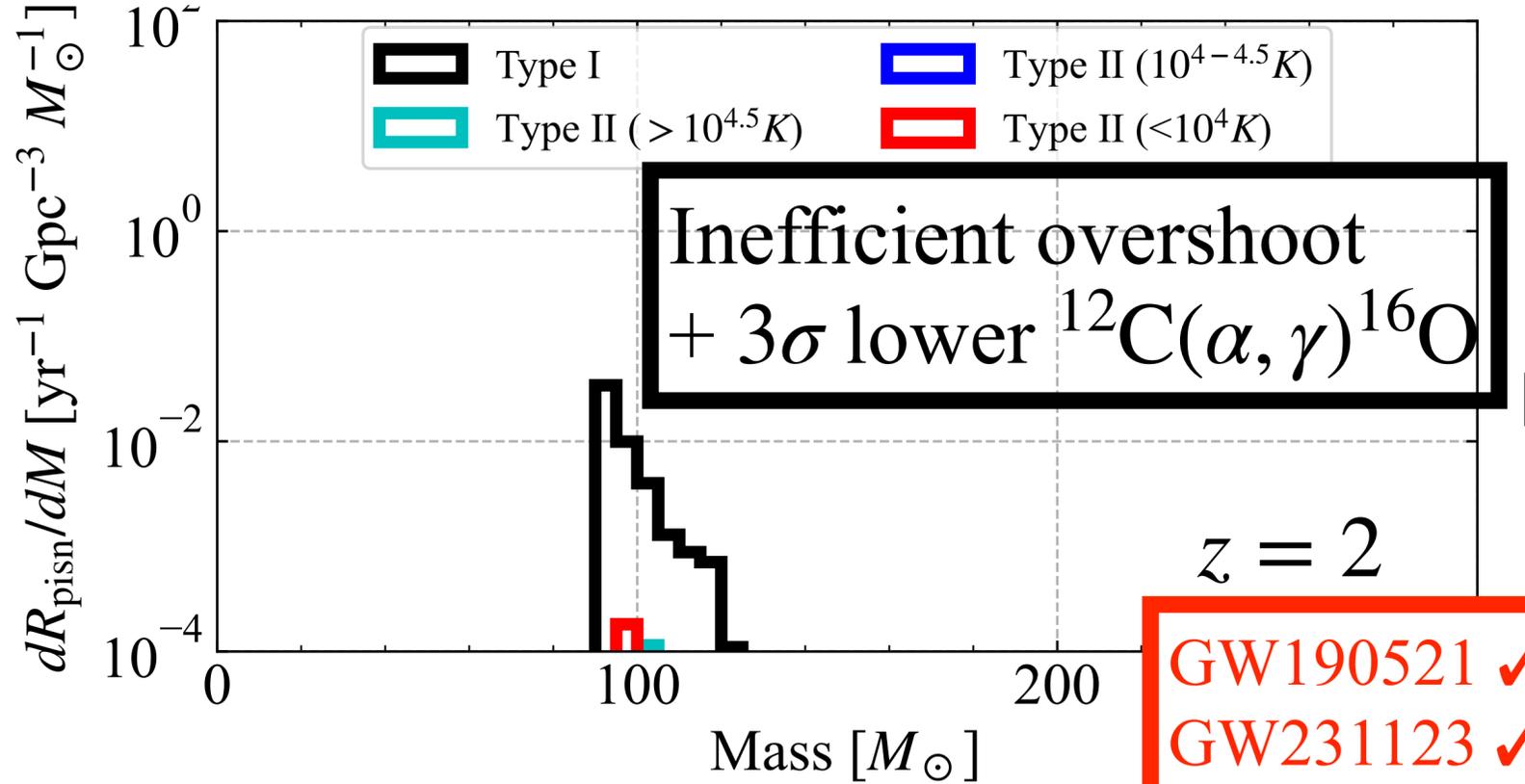
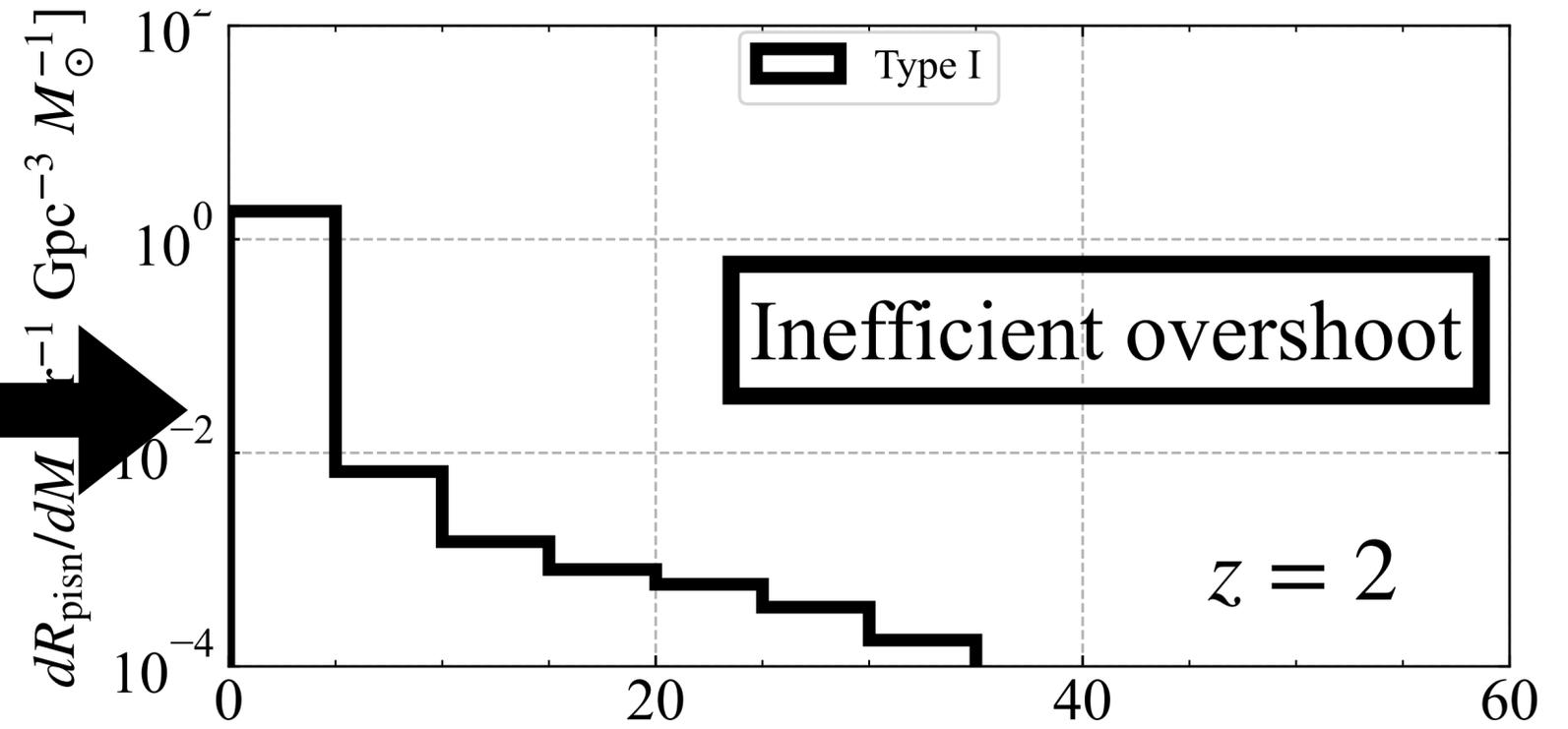
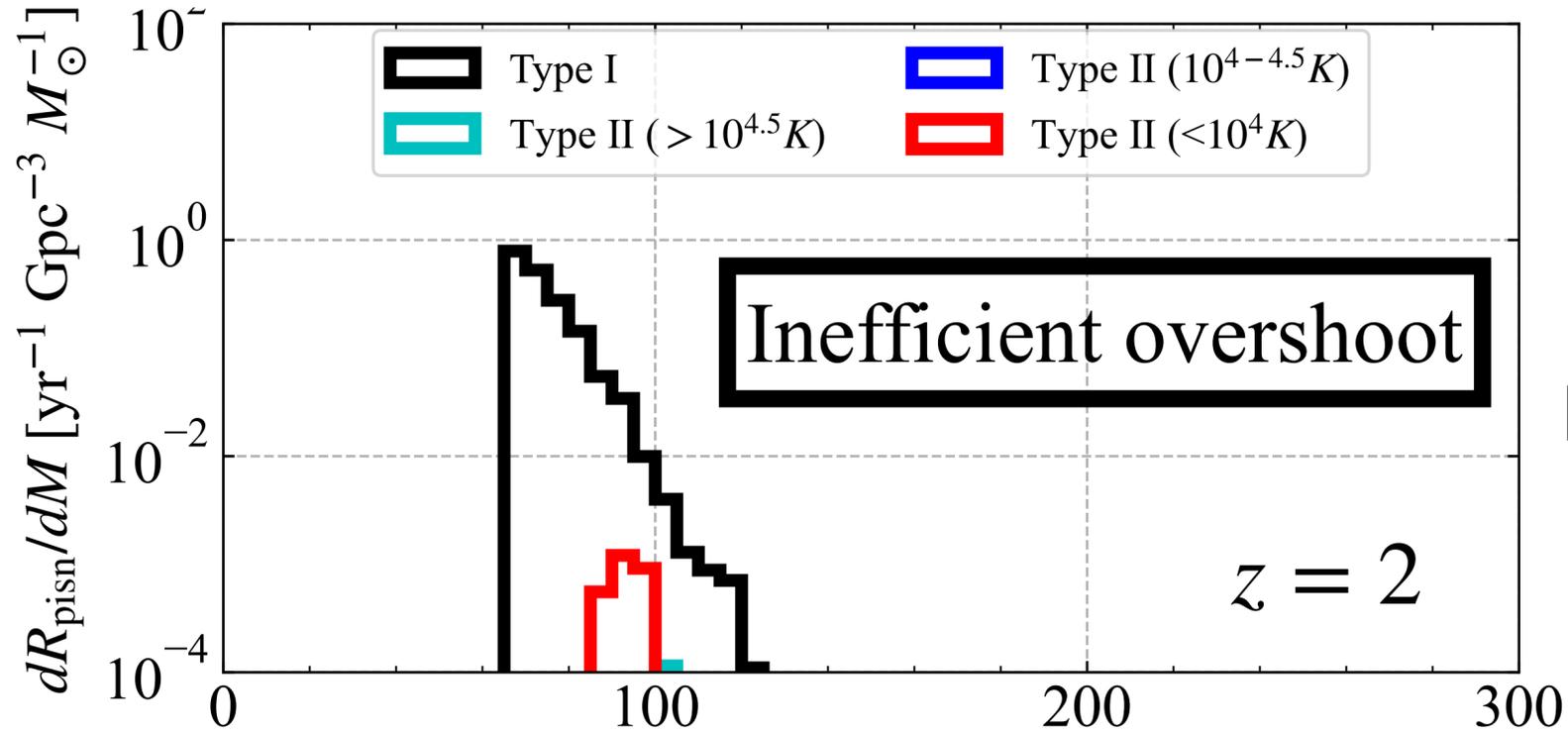
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# PISN progenitor (He star) mass

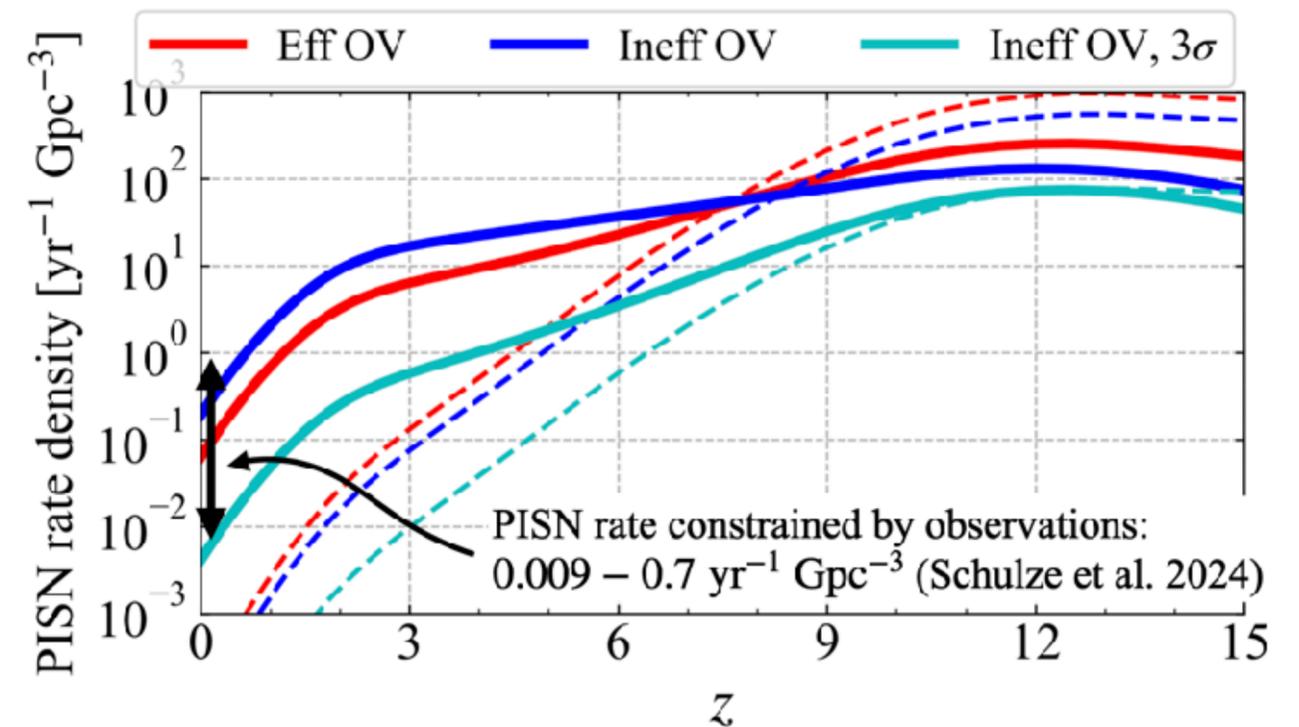
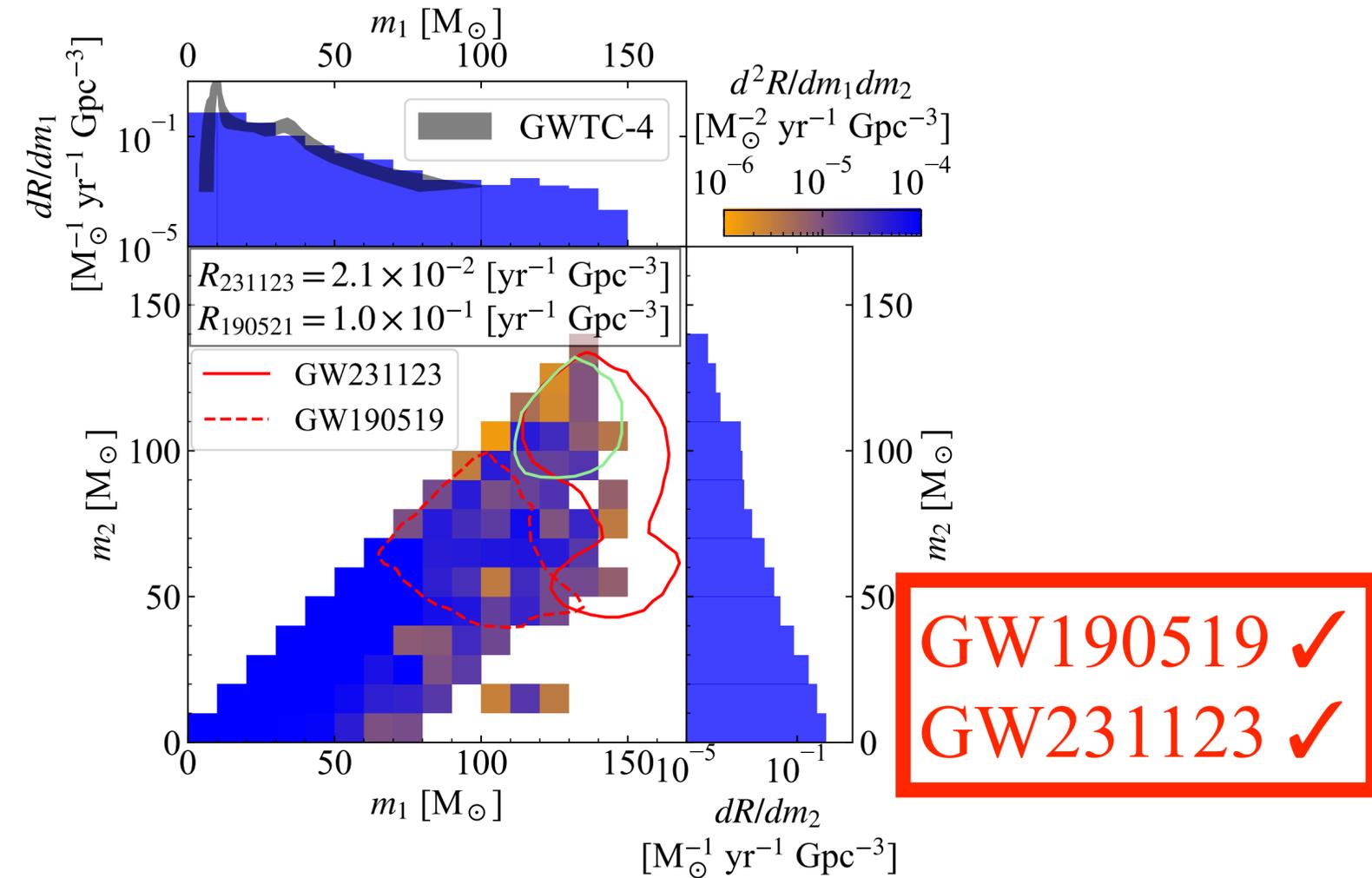
# Resulting $^{56}\text{Ni}$ mass



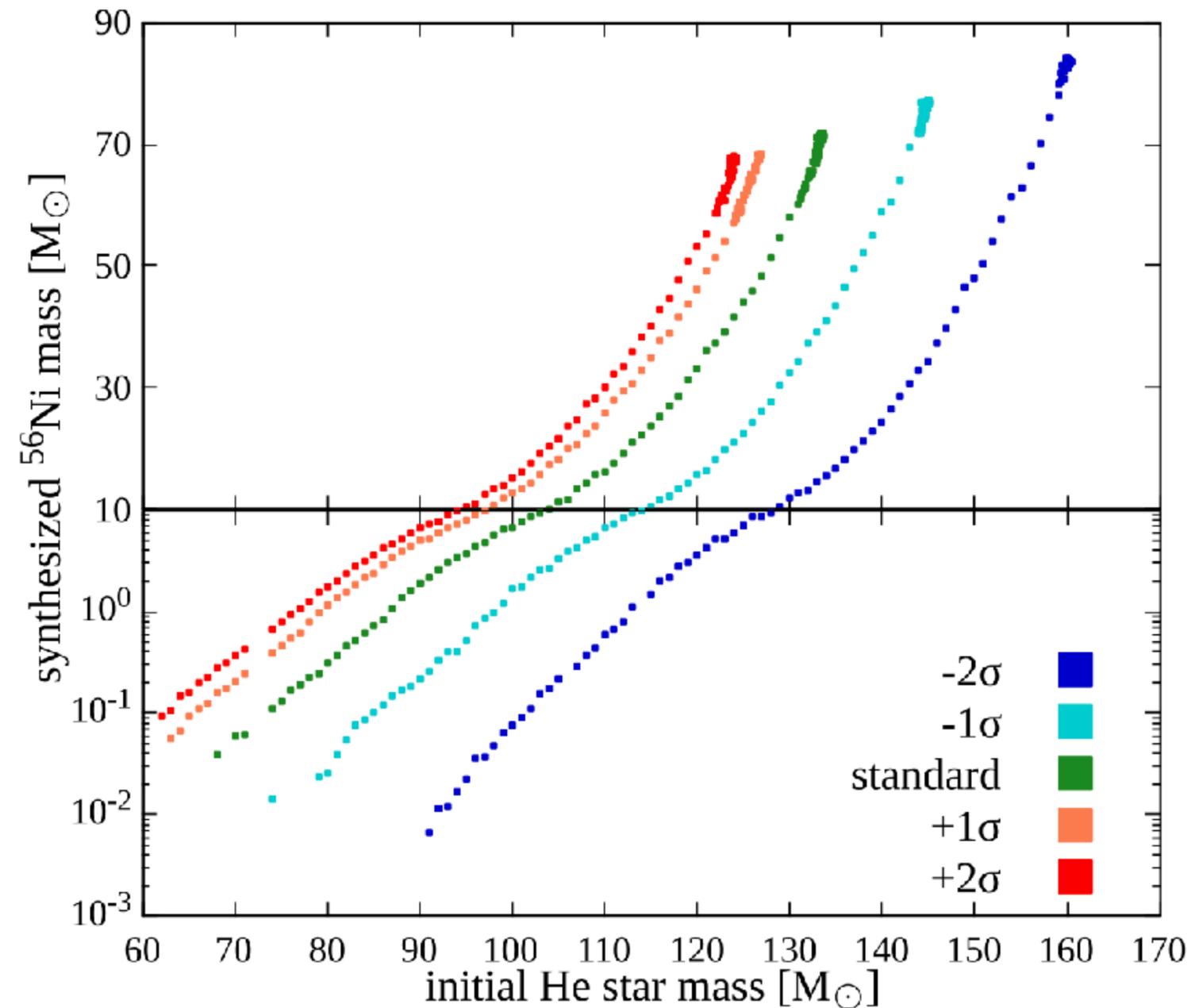
Updated results of Tanikawa et al. (2023) with considering of Kawashimo et al. (2024)

# Summary

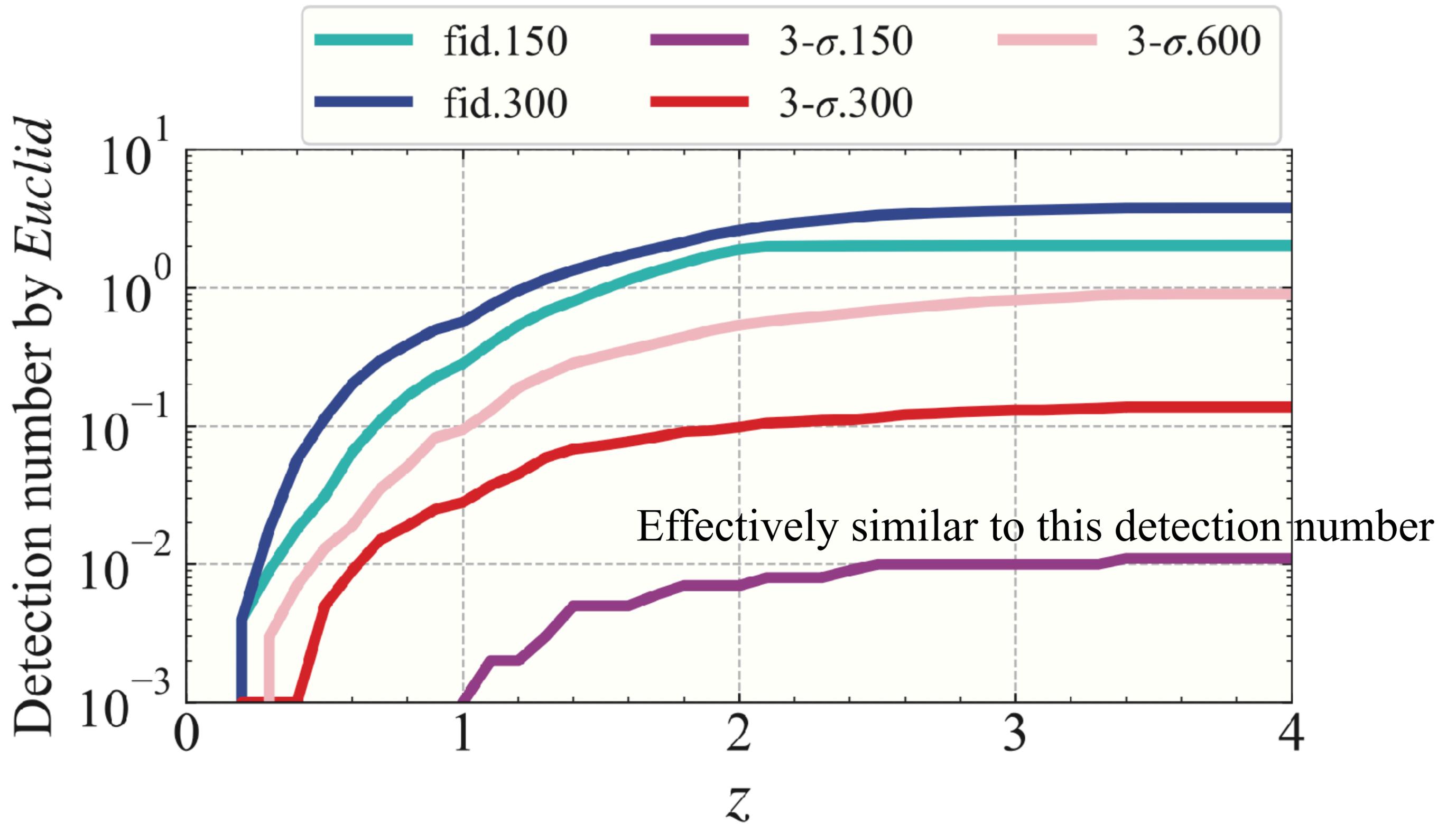
- Isolated binary stars can form PIMG events.
- For PIMS events, we need to consider metal-free stars and inefficient convective overshoot.
- If the future GW observations discover more massive BH events, we will need to reconsider the isolated binary scenario.
- If our scenario is correct,
  - The intrinsic PISN rate may be reduced by an order of magnitude.
  - The detection PISN rate may be reduced more.



# Prognitor-Ni mass relation



Kawashimo et al. (2024)



Tanikawa et al. (2023, MNRASL)