Modeling of formation for objects related to black holes: Gaia BHs, pair instability mass gap events, and very massive stars

Ataru Tanikawa (Fukui Prefectural University)

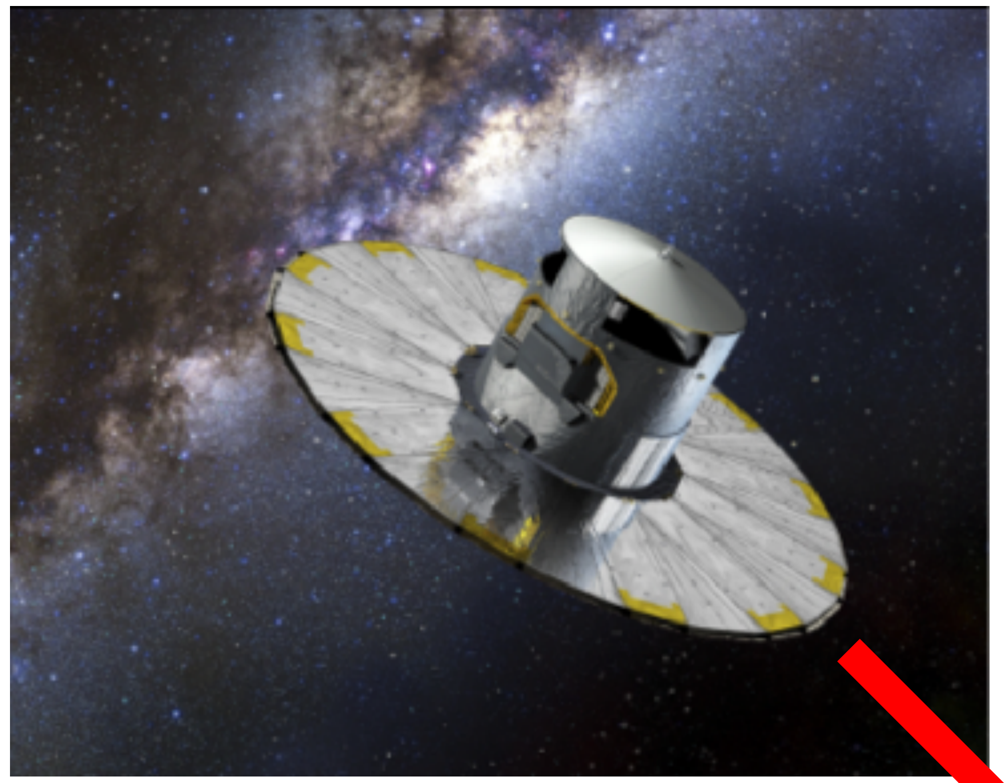
Multi-Messenger Astrophysics in the Dynamic Universe, 2nd week at Yukawa Institute for Theoretical Physics, Kyoto University

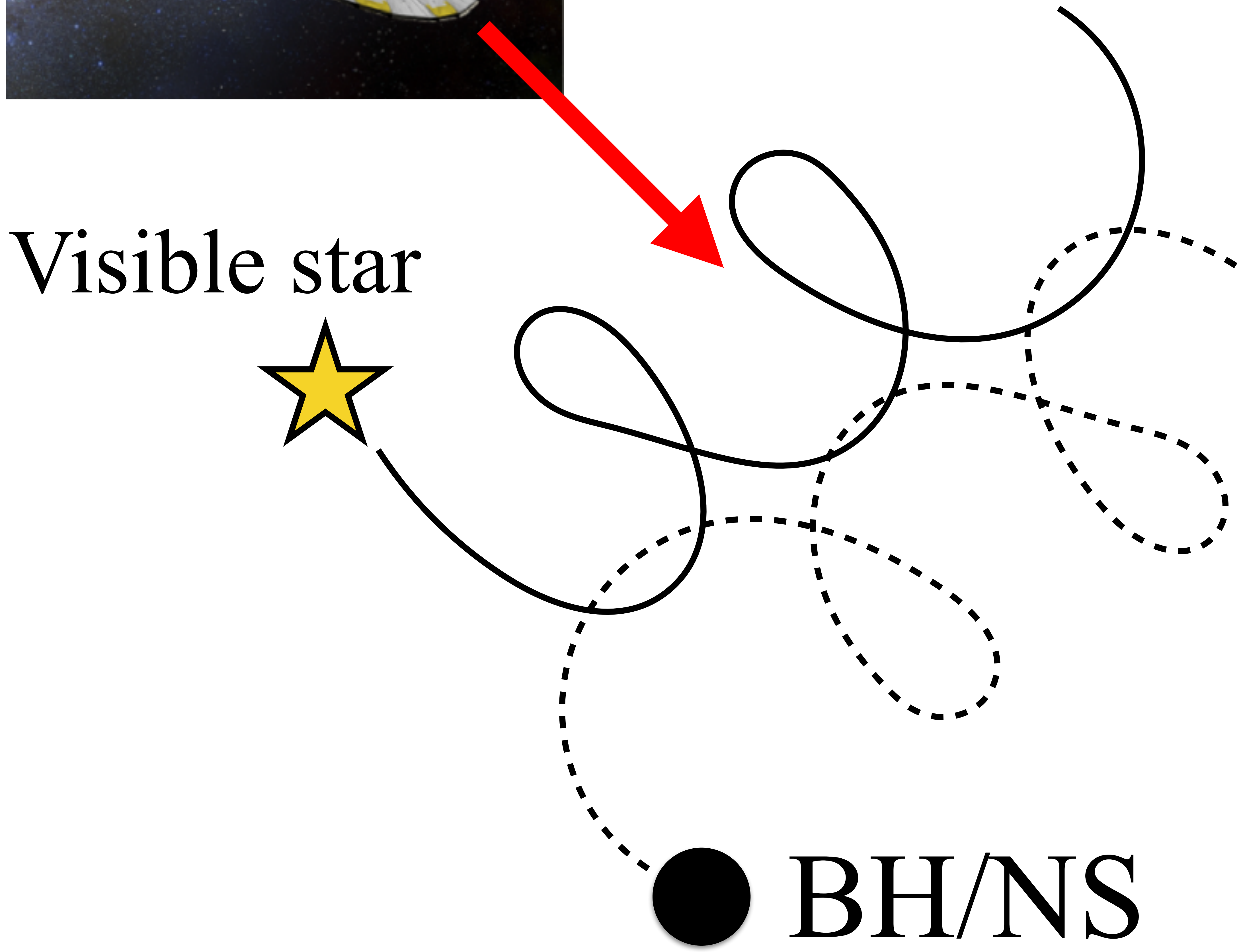
Outline

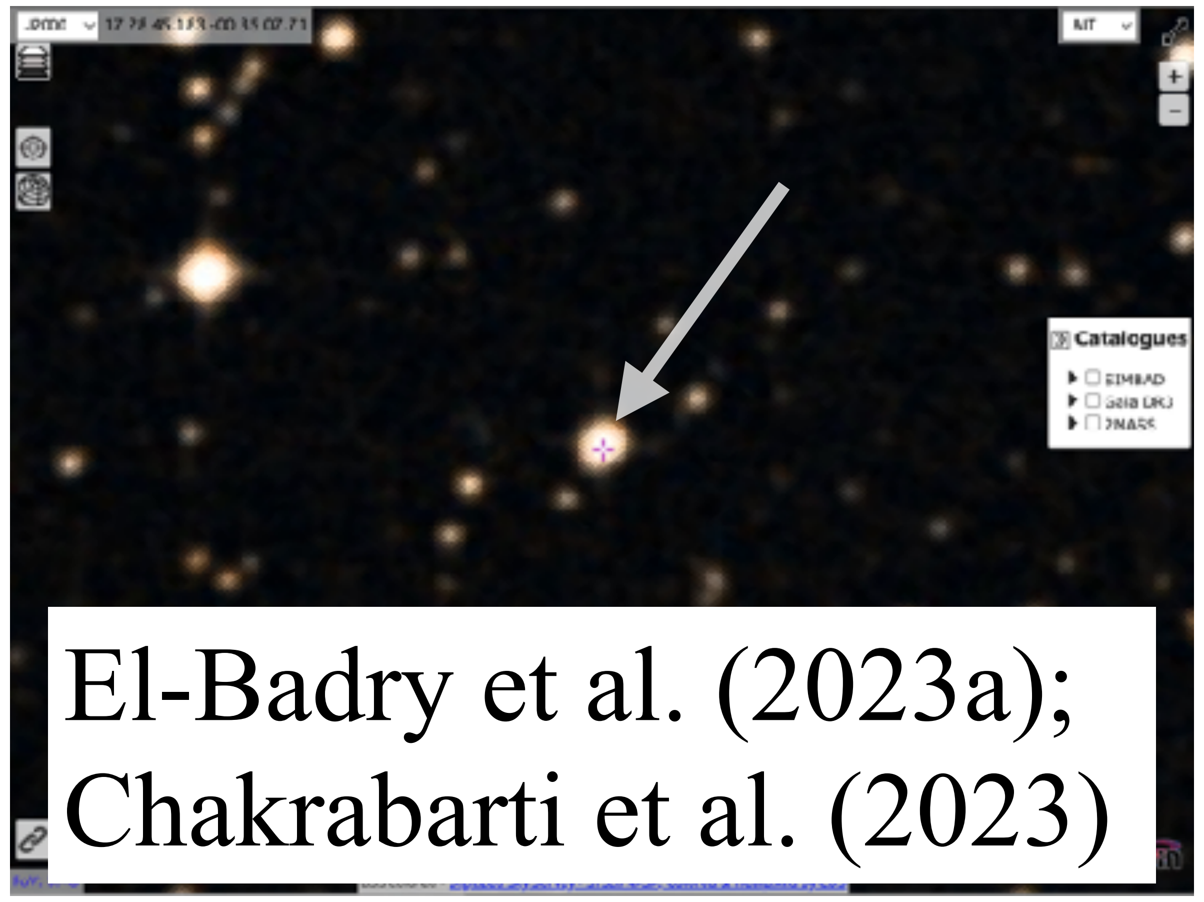
- Formation of Gaia black hole (BH)
- Formation of pair instability mass gap (PIMG) events
- Formation and property of very massive star (VMS)

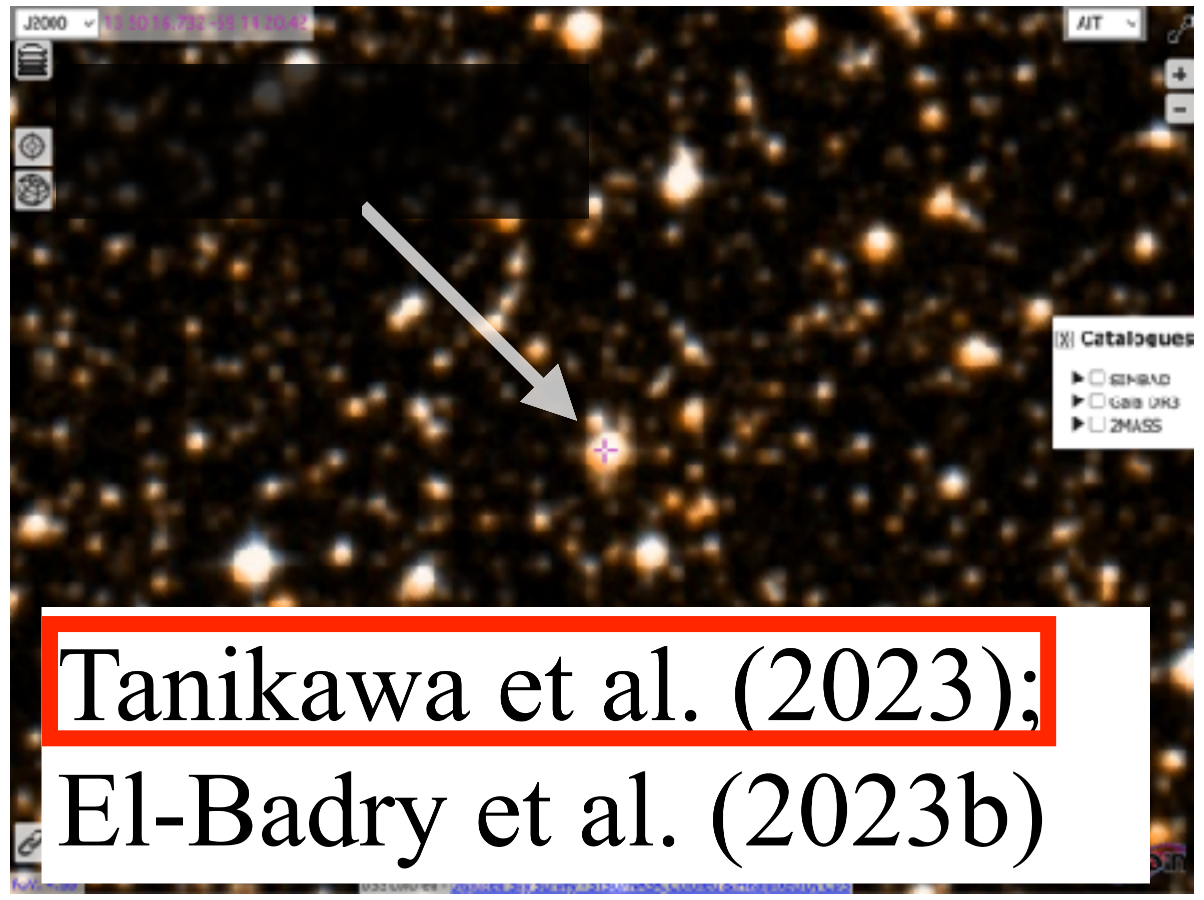
Gaia has discovered compact binaries

Gaia

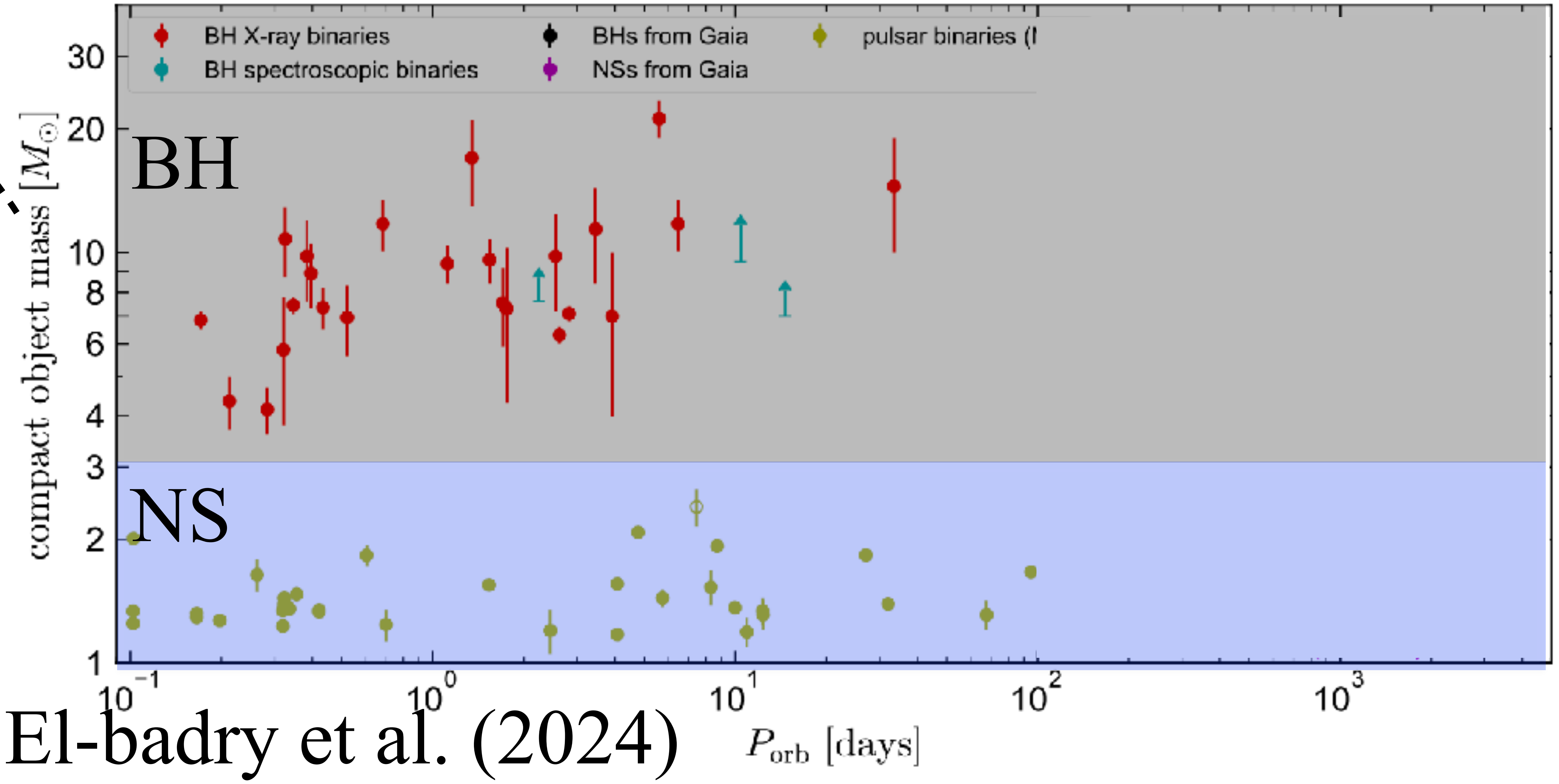








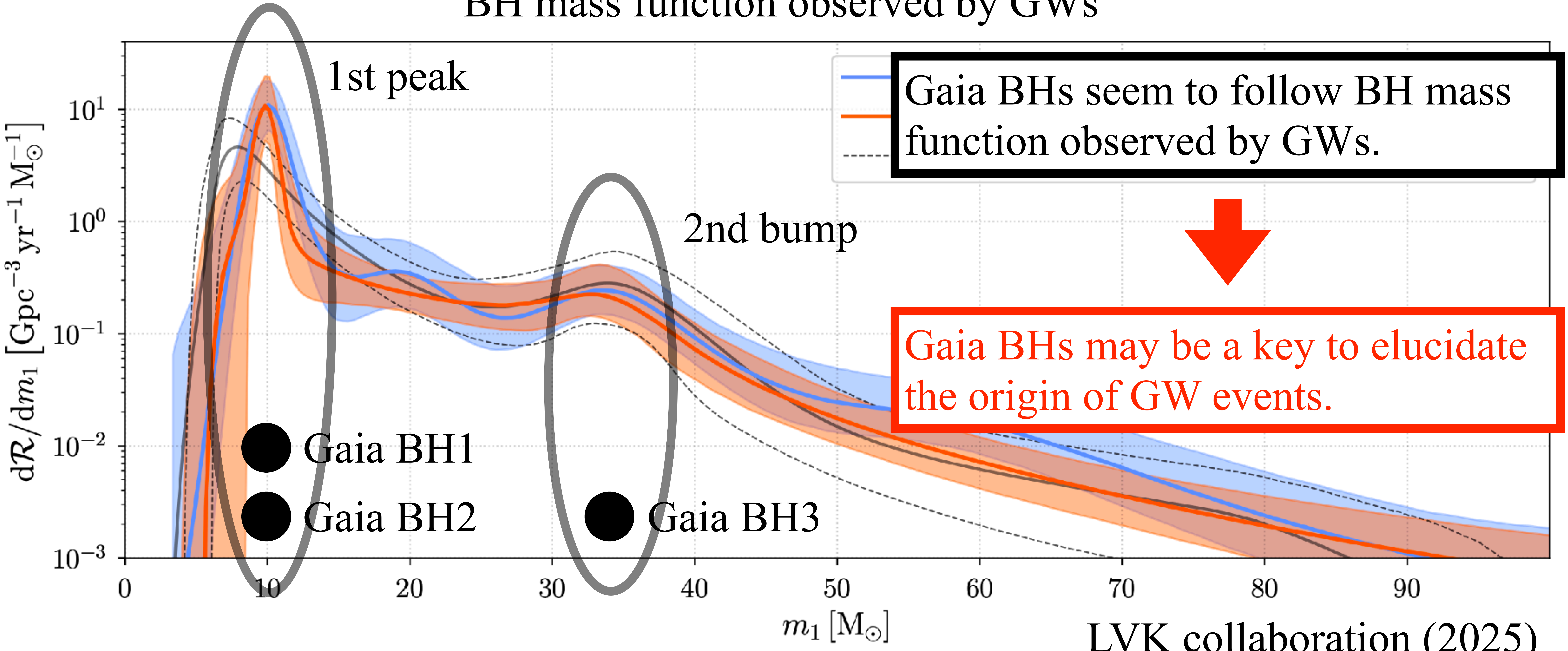
Gaia BH3 (Gaia collaboration 2024); Gaia NS1 (El-Badry et al. (2024a) …



El-badry et al. (2024)

Possible link between GW events and Gaia BHs

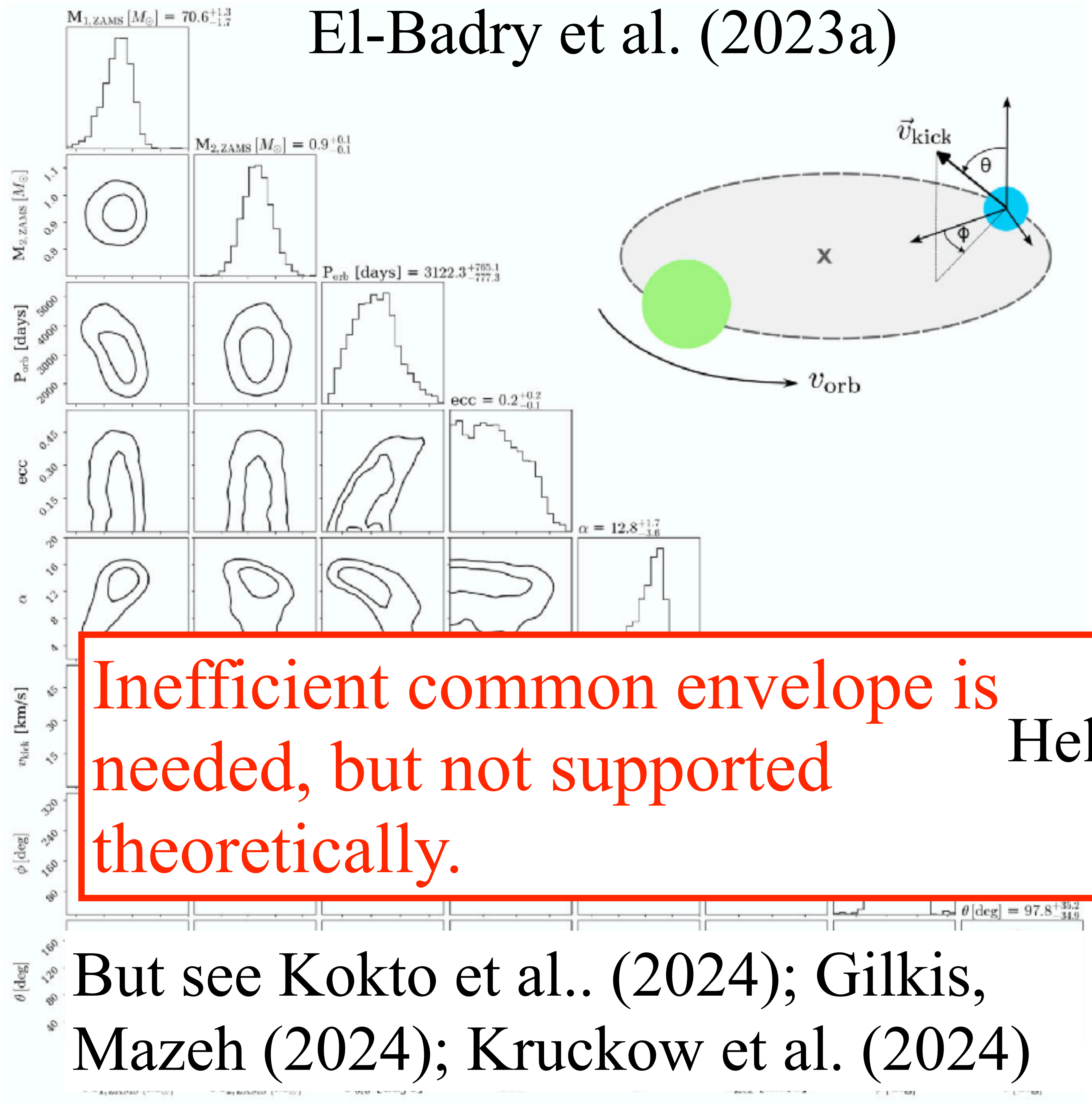
BH mass function observed by GWs



LVK collaboration (2025)

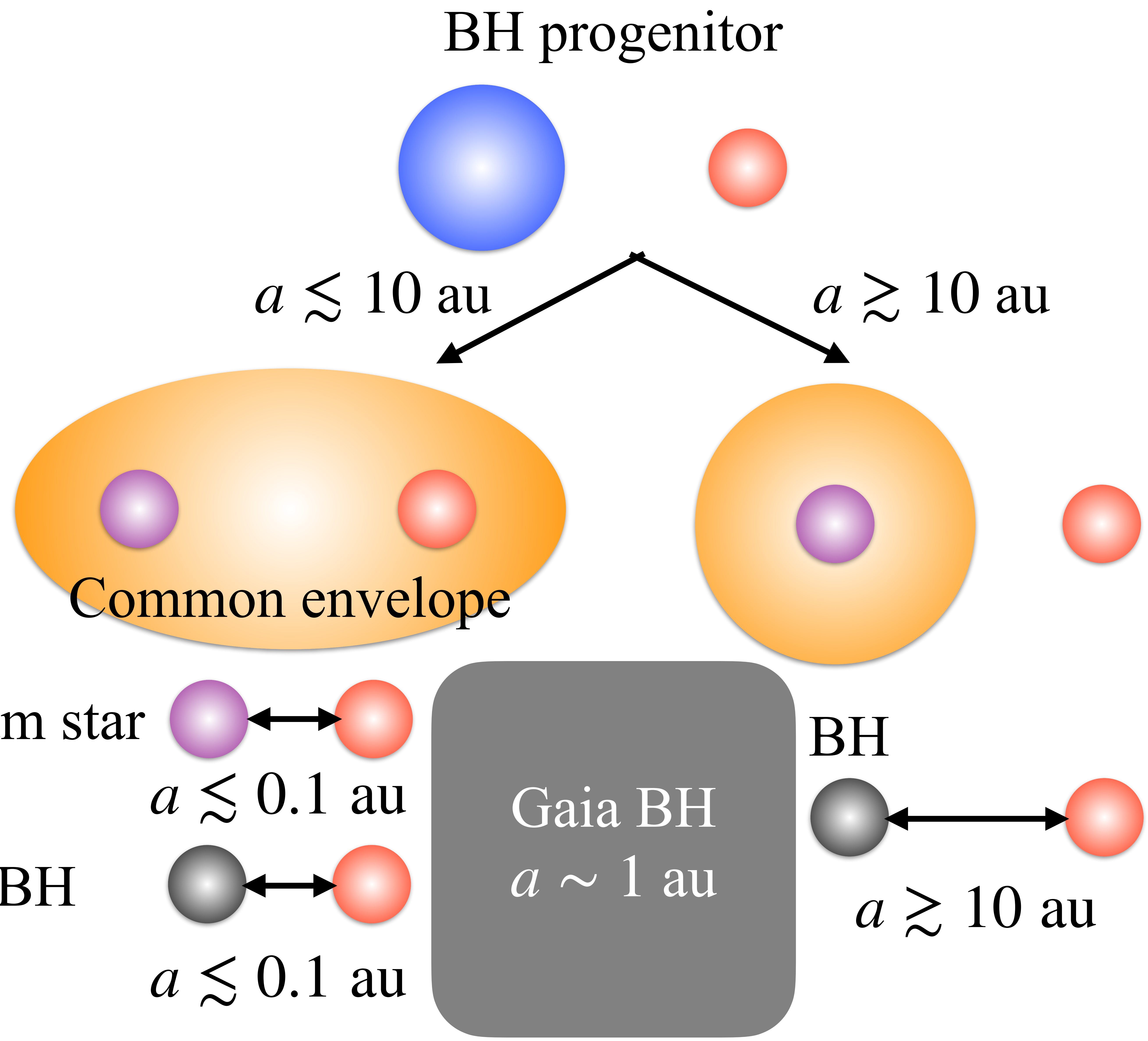
Mystery of the Gaia BH formation

El-Badry et al. (2023a)

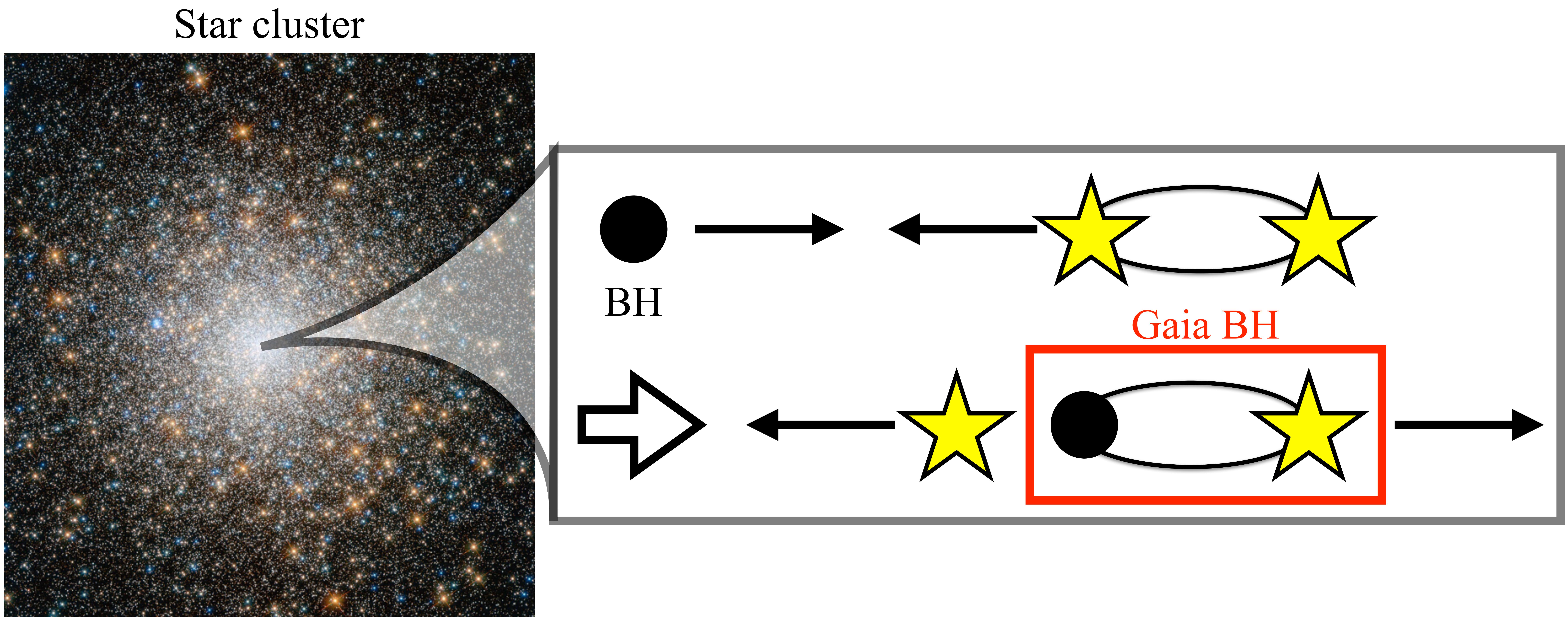


Inefficient common envelope is needed, but not supported theoretically.

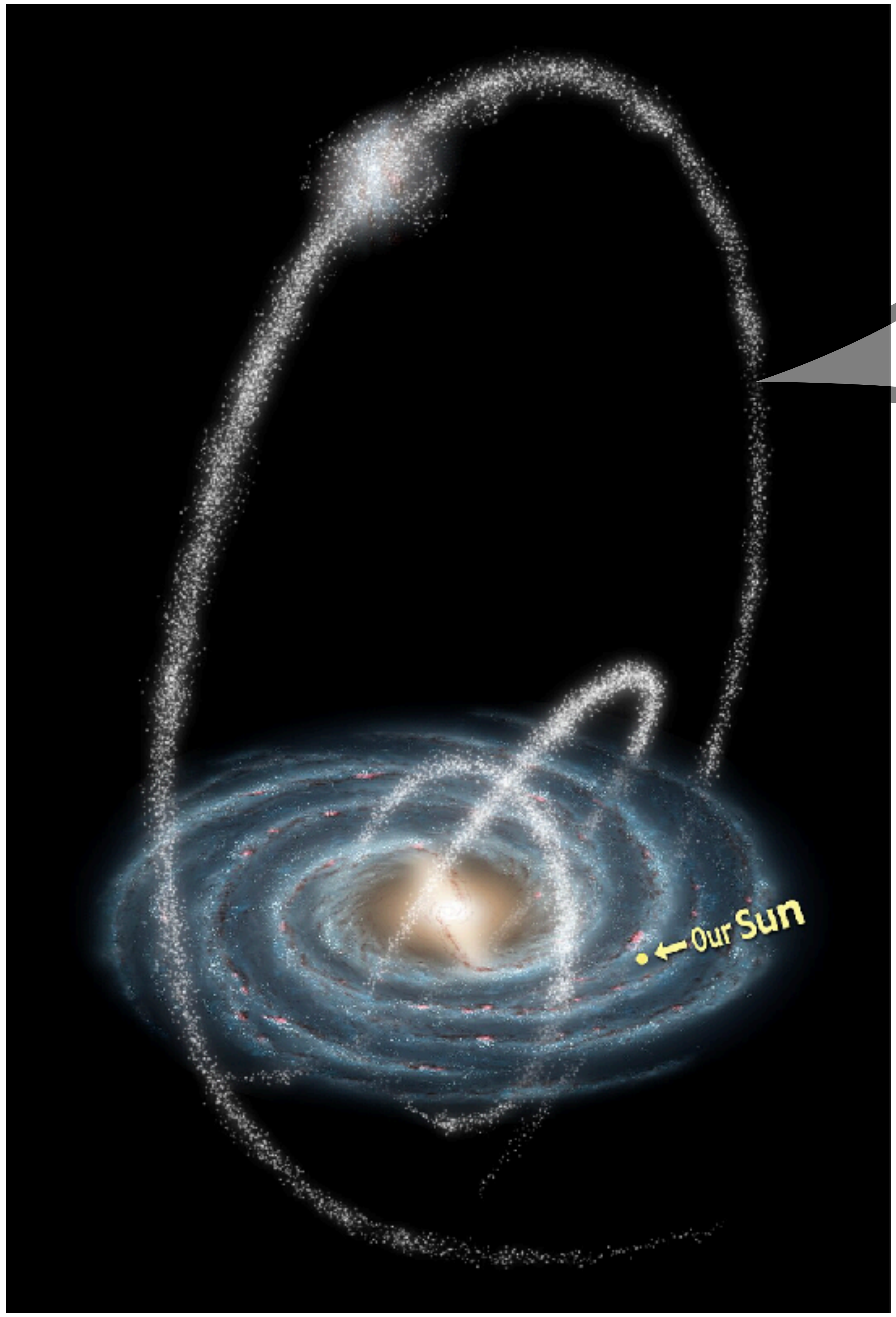
But see Kokto et al.. (2024); Gilkis, Mazeh (2024); Kruckow et al. (2024)



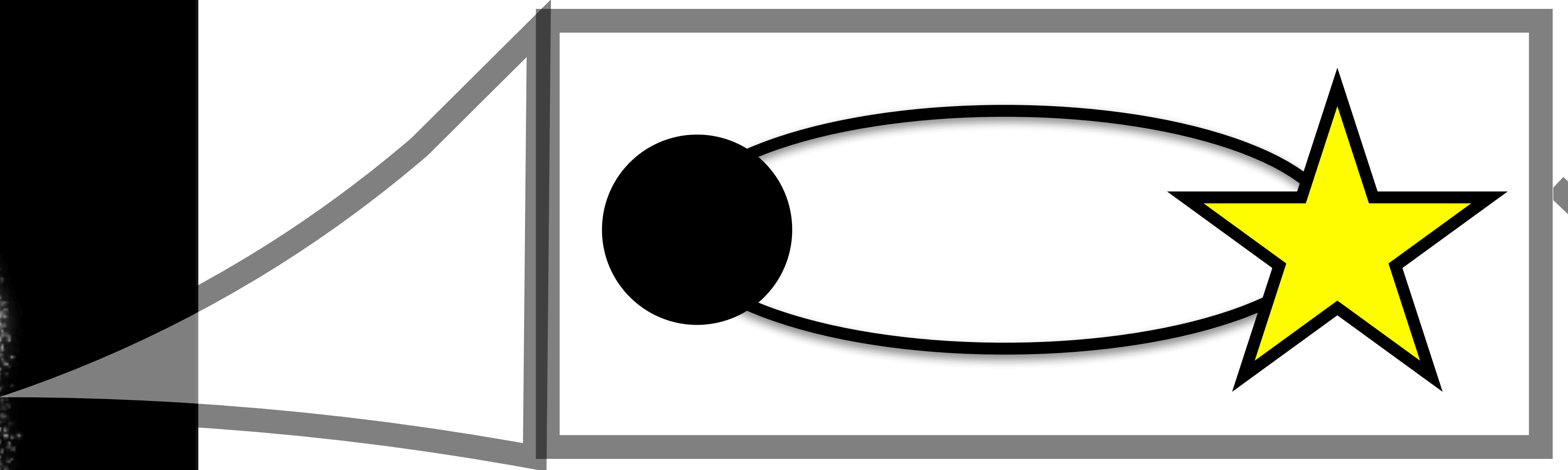
Gaia BH formation in star clusters

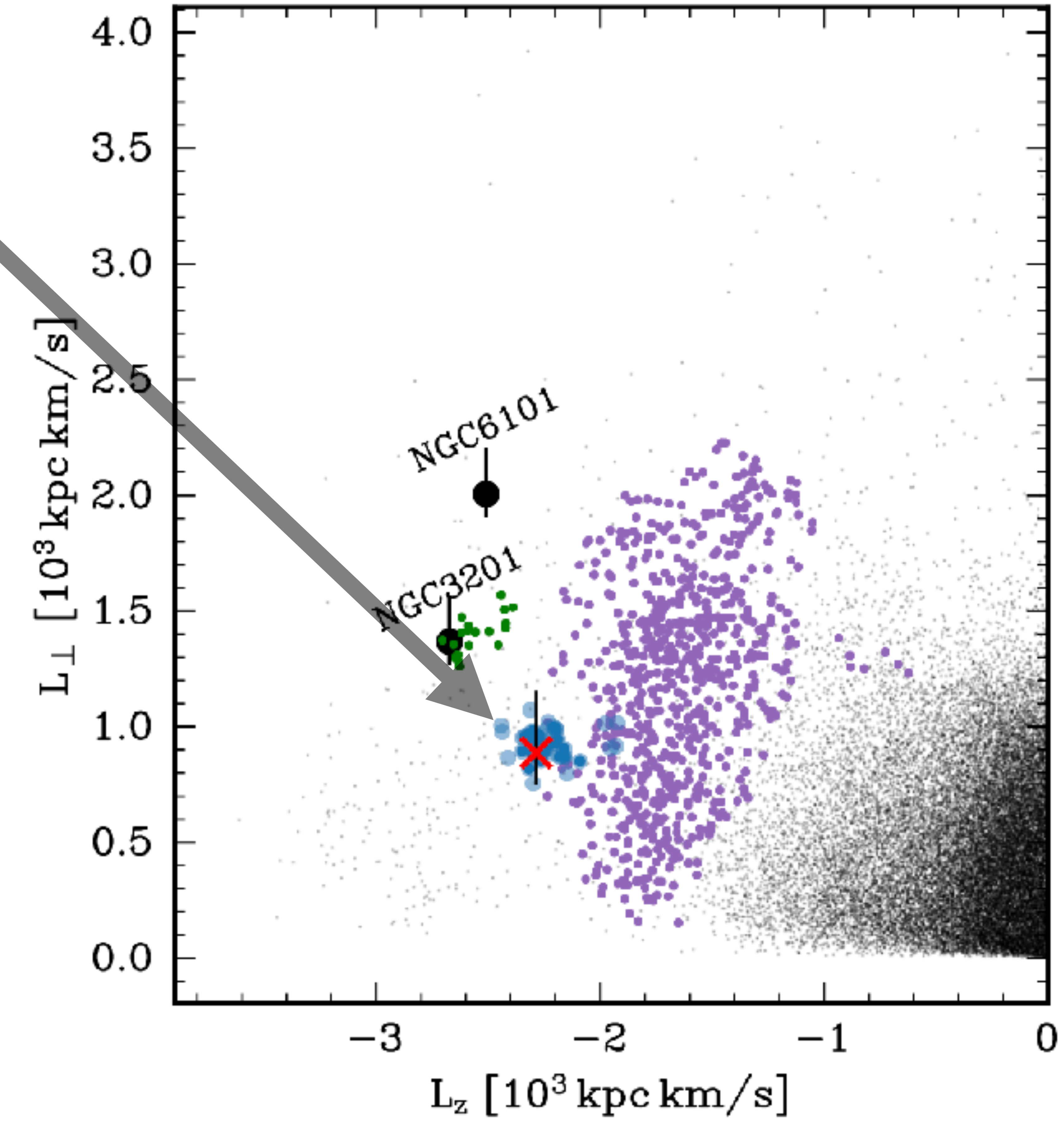


Gaia BH3 found in a disrupted star cluster



Gaia BH3

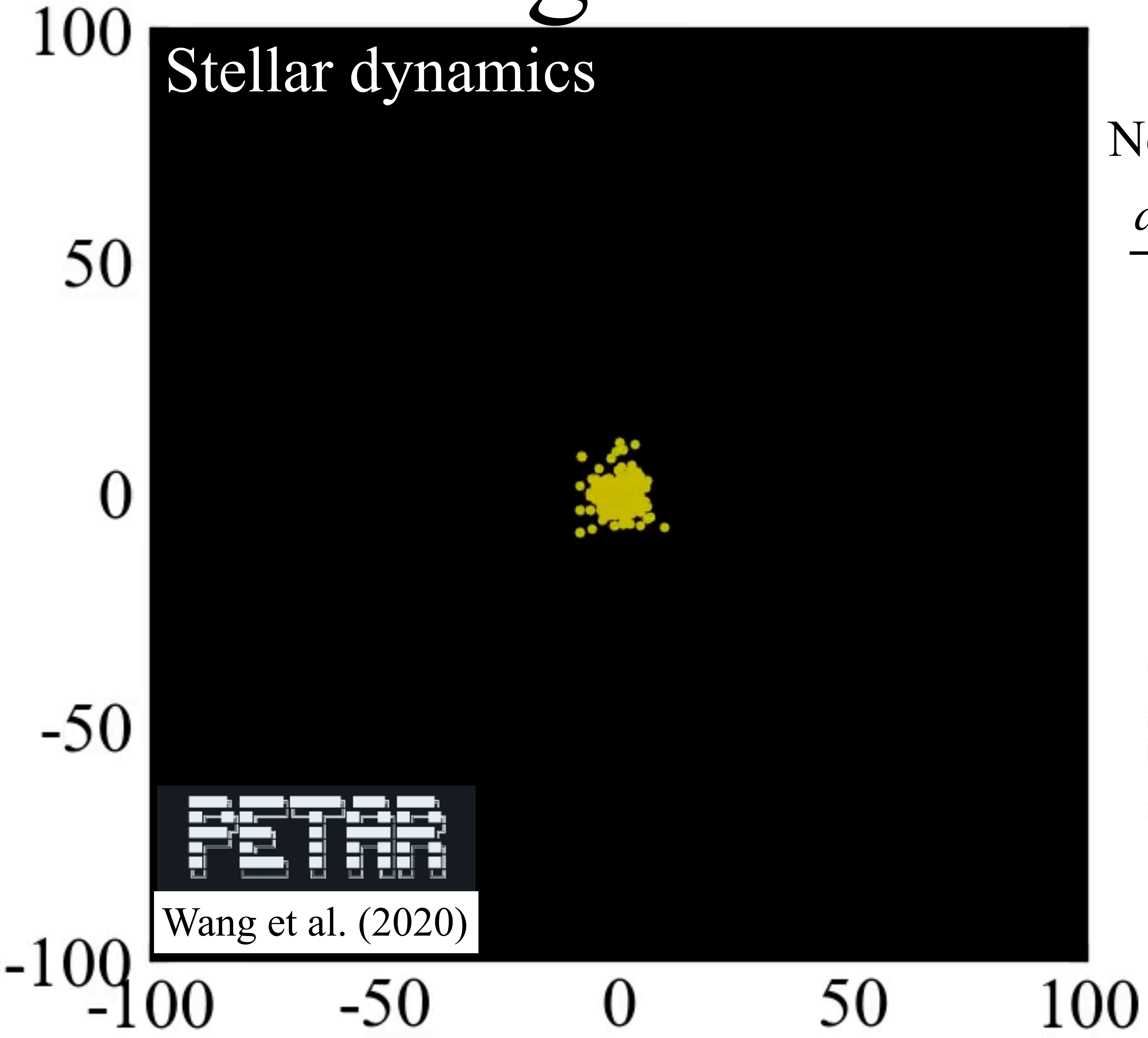




This is just an image!
ED-2 stream is much more faint!

Balbinot et al. (2024)

Gravitational N-body simulation coupled with single and binary star evolution

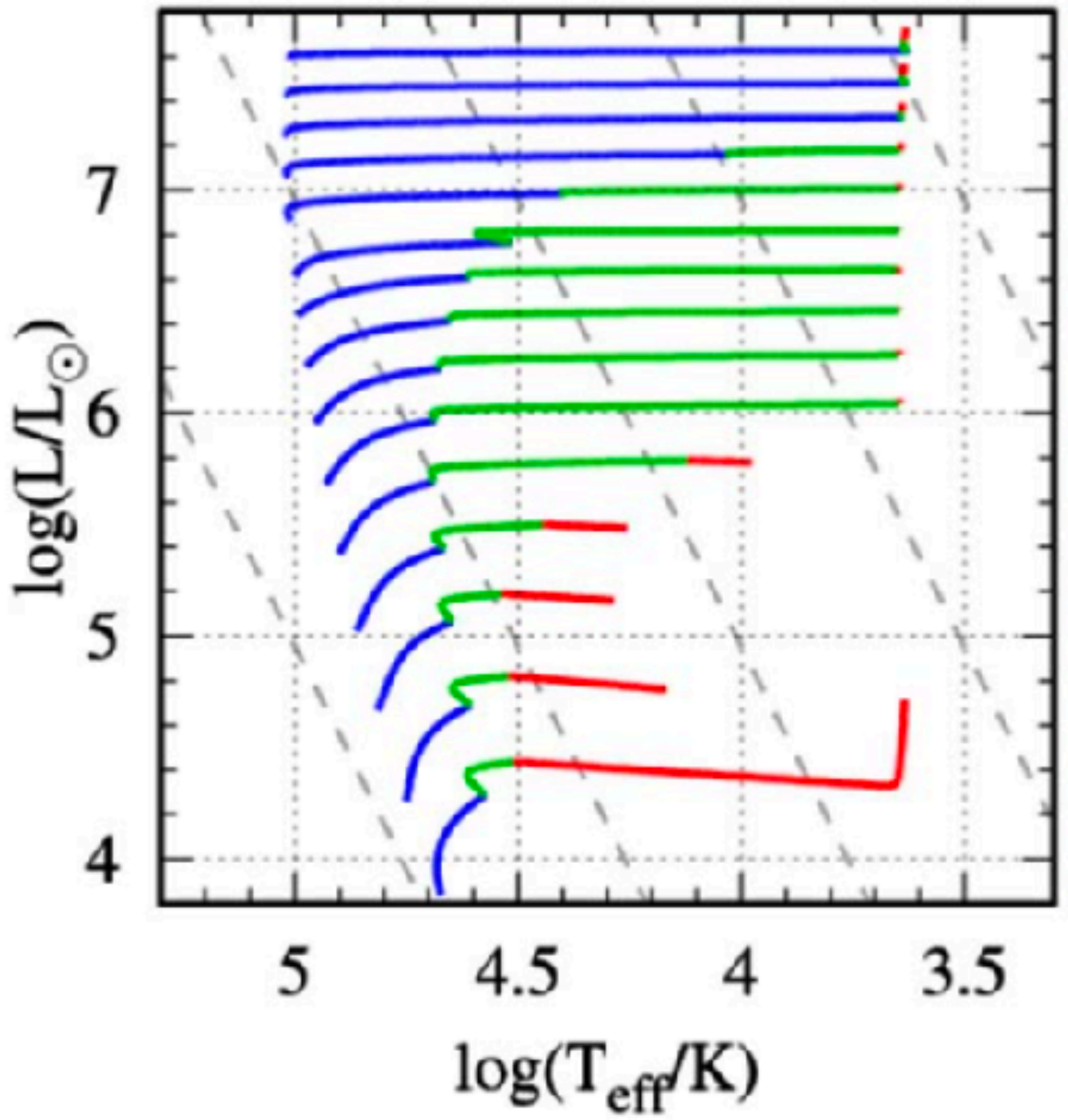


Newton's law of gravitation

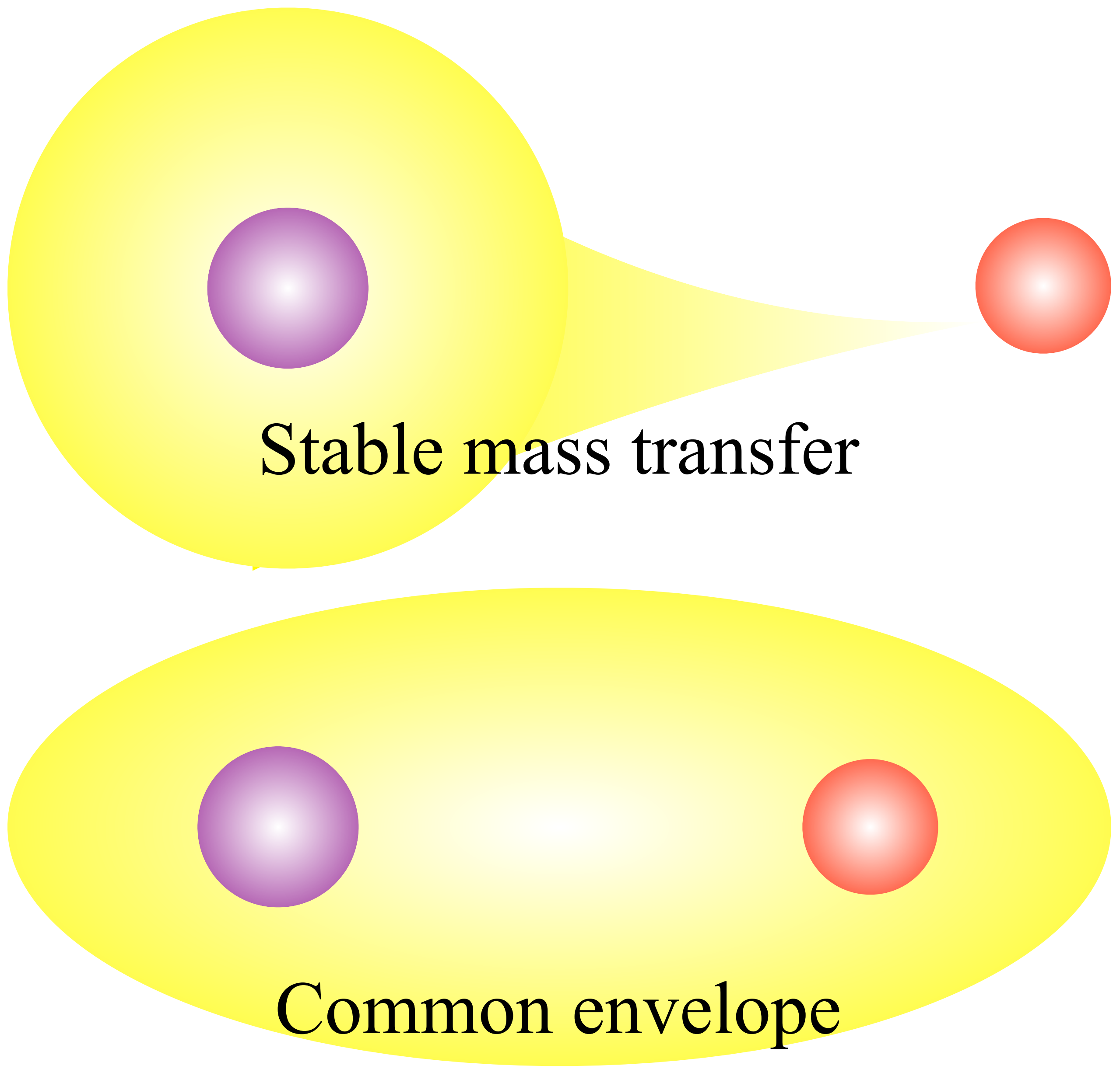
$$\frac{d^2\vec{r}_i}{dt^2} = \sum \frac{m_j}{|\vec{r}_j - \vec{r}_i|^2} \frac{\vec{r}_j - \vec{r}_i}{|\vec{r}_j - \vec{r}_i|}$$

No assumption regarding dynamical binary formation

Single star evolution



Binary star evolution




From open clusters
From binaries
× 100
η [M⊙^−1]
Initial cluster mass M [M⊙]
Initial half-mass density ρ [M⊙ pc^−3]
Inert BHB (10^2-10^3 days)
Inert NSB (10^2-10^3 days)
Initial binary fraction f_b, <5M⊙
Metallicity Z

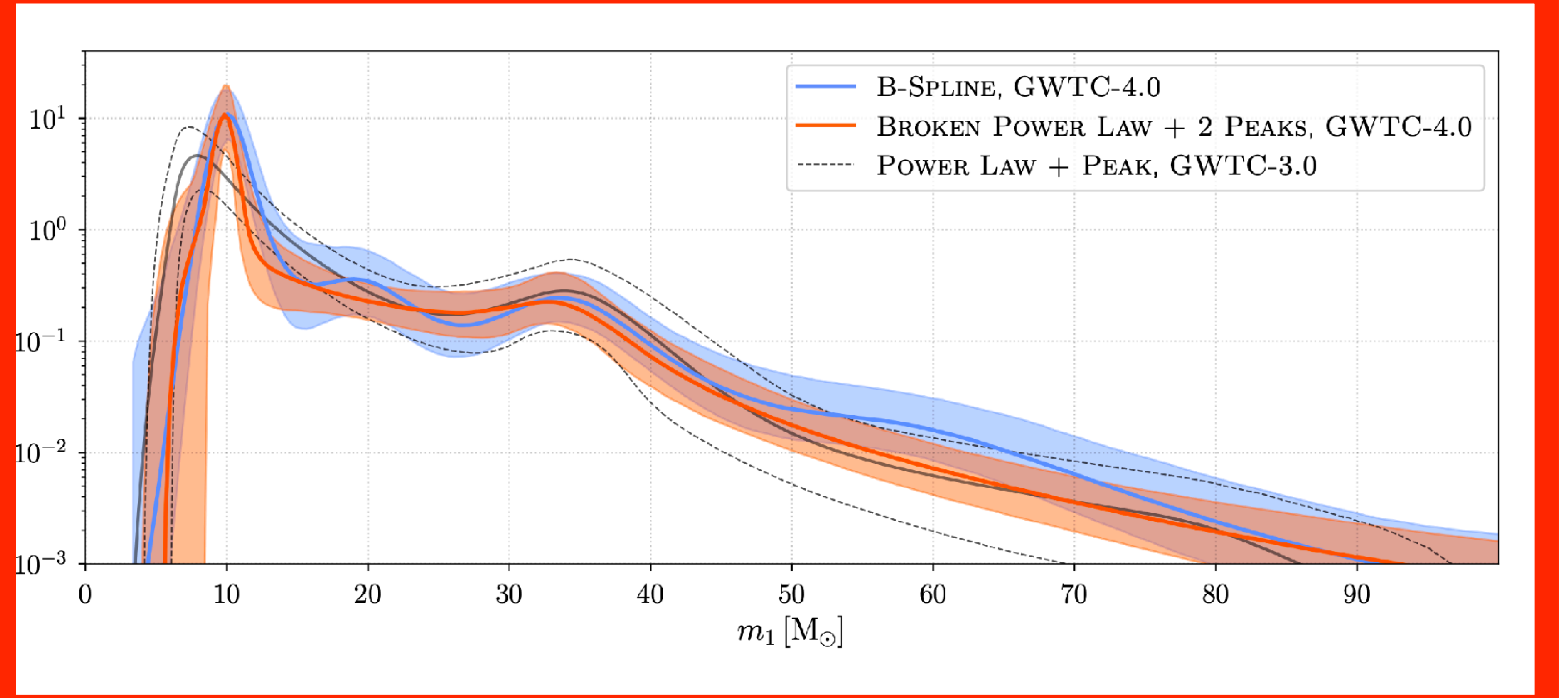
Outline

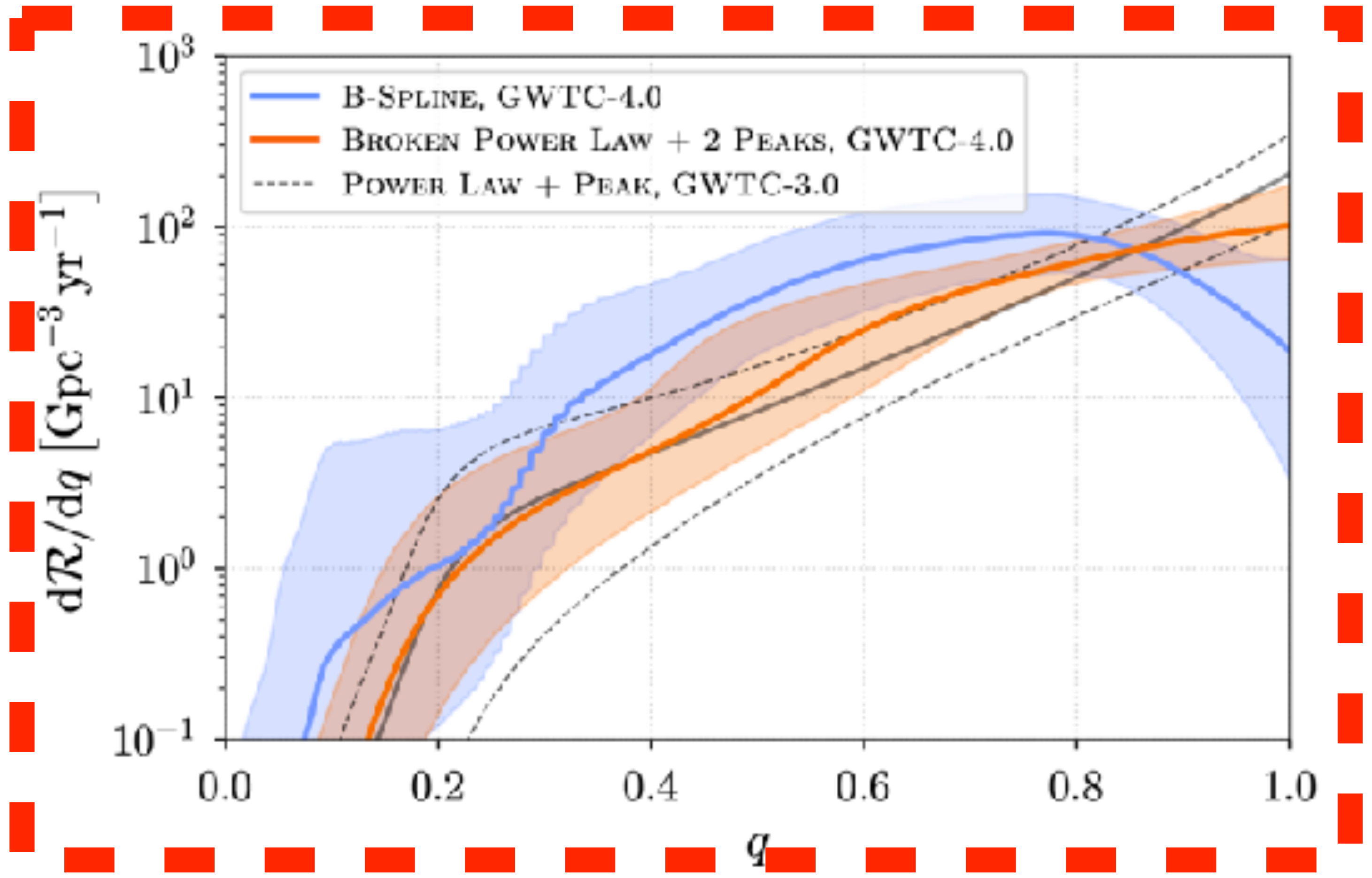
- Formation of Gaia black hole (BH)
- Formation of pair instability mass gap (PIMG) events
- Formation and property of very massive star (VMS)

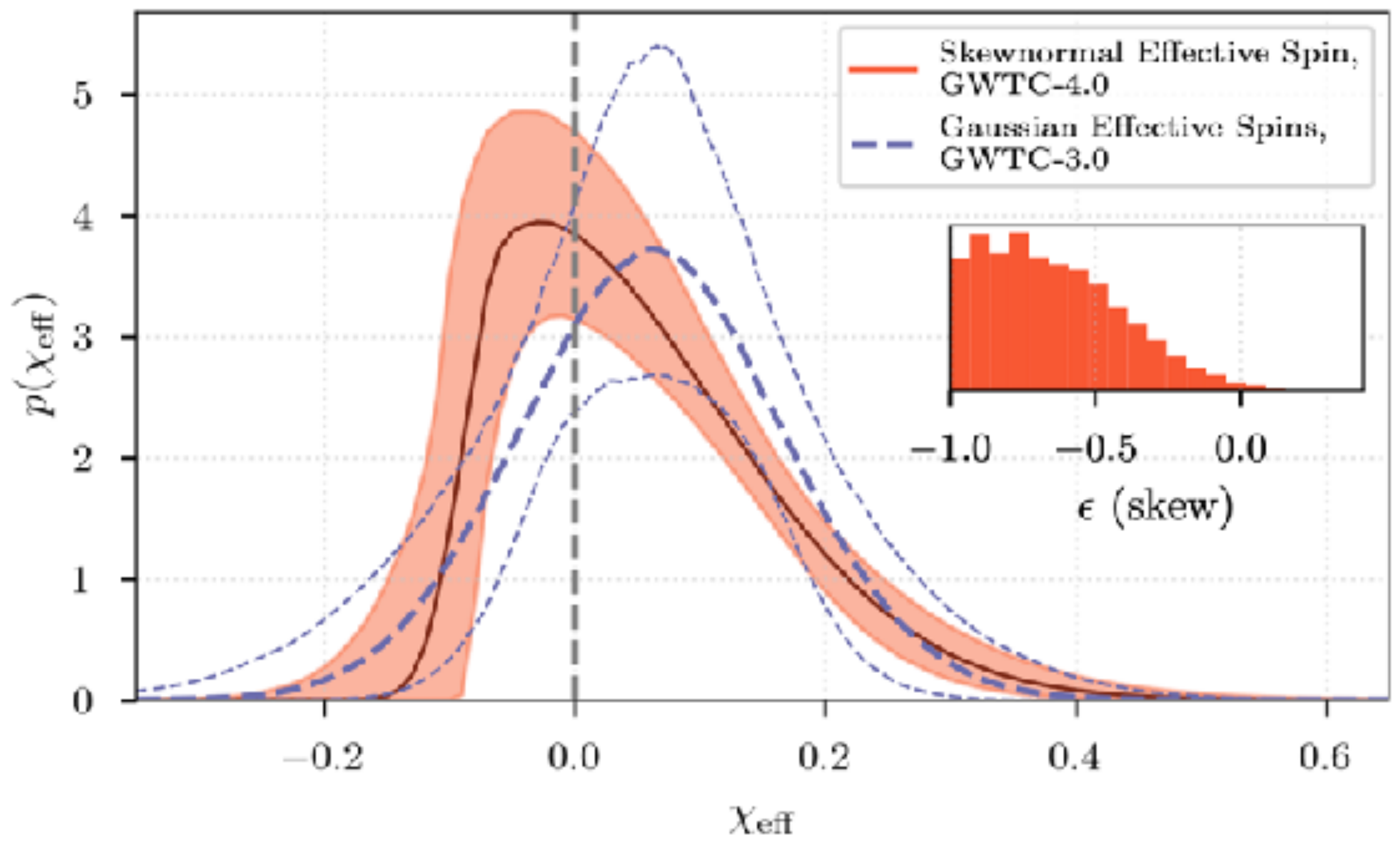

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

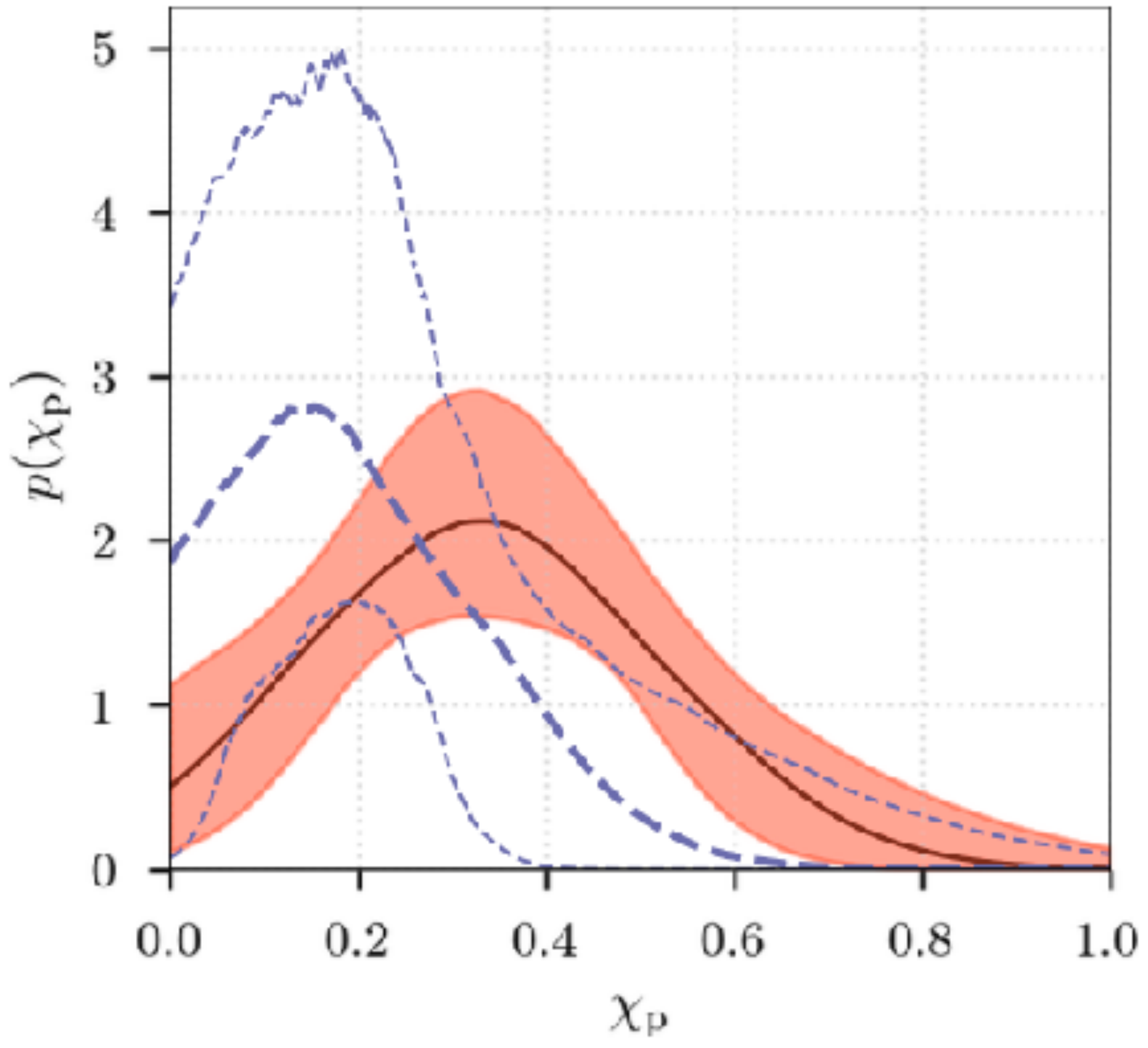
Clues for the origins of binary BHs

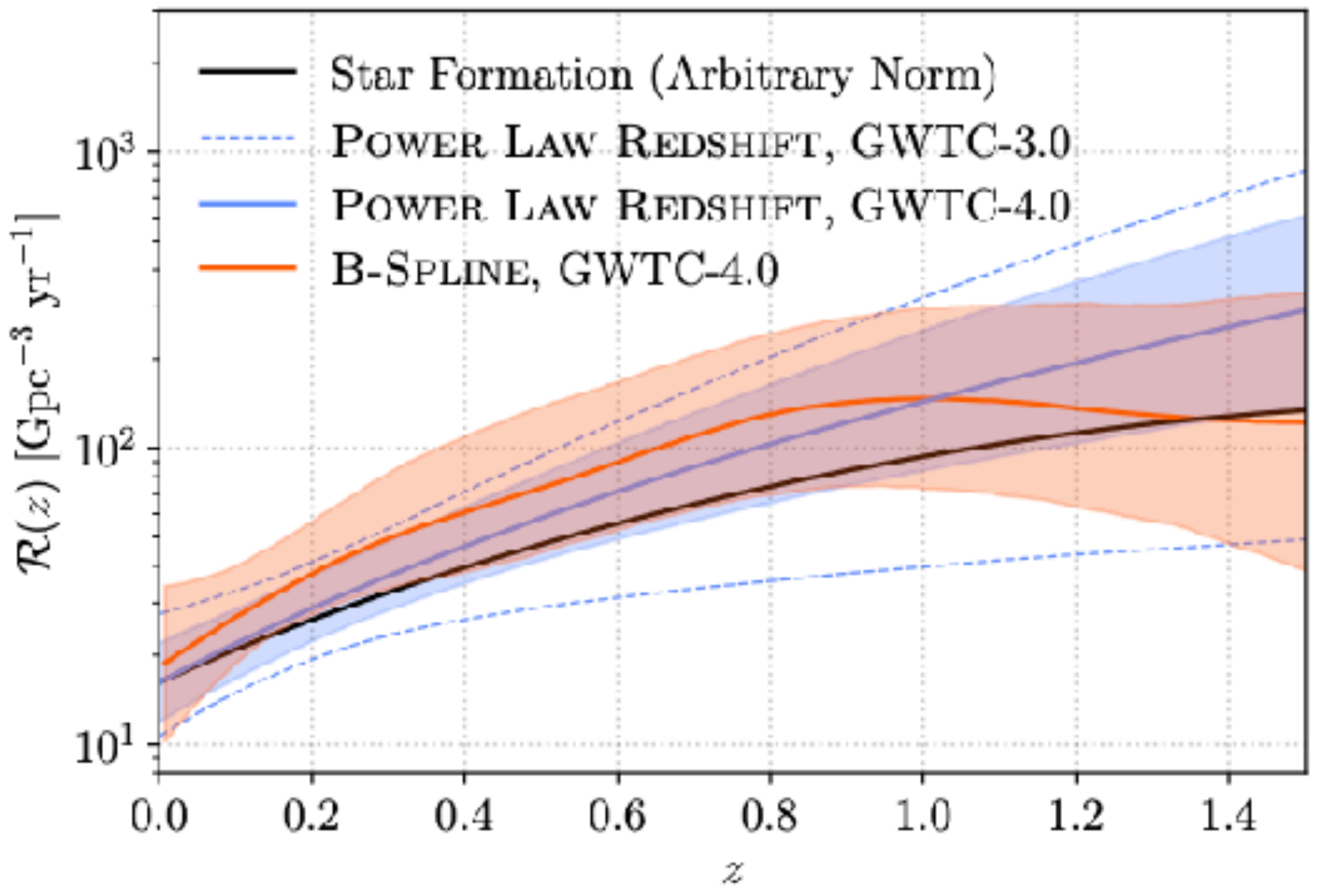
- The primary BH mass distribution
- The Mass ratio distribution
- The effective spin distribution
- The precession spin distribution
- The redshift evolution
- Etc.





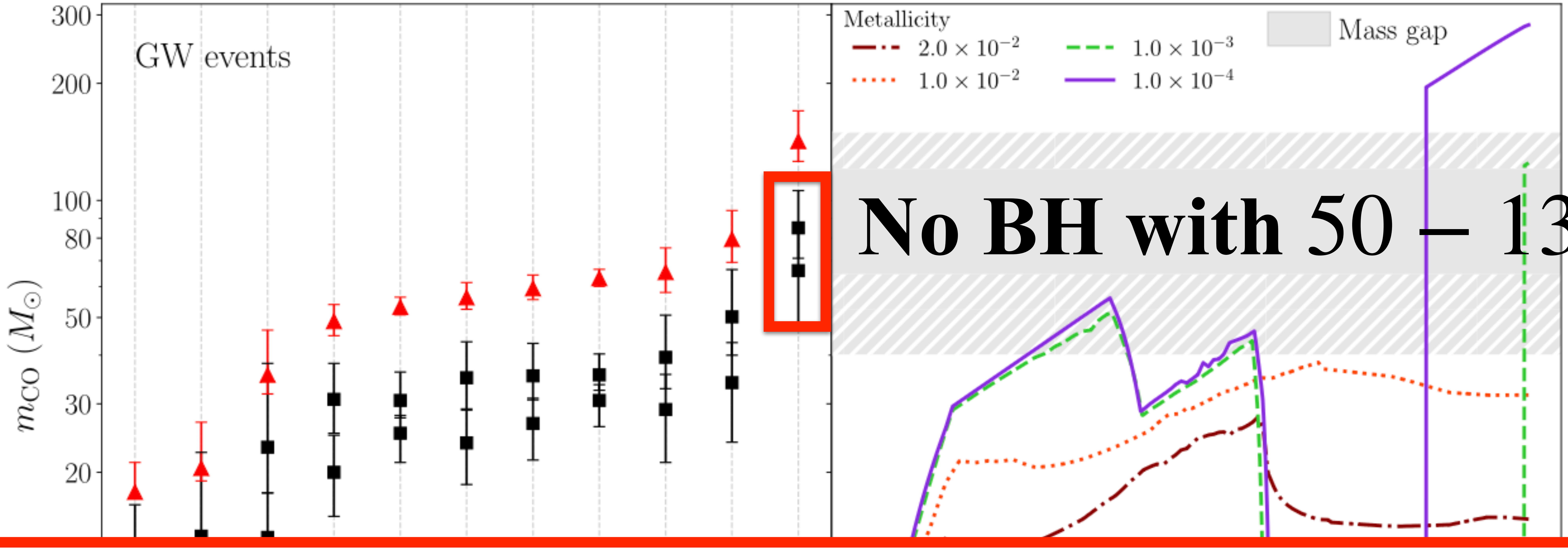






LVK collaboration (2025, arXiv:2508.18083)

Pair instability mass gap (PIMG)

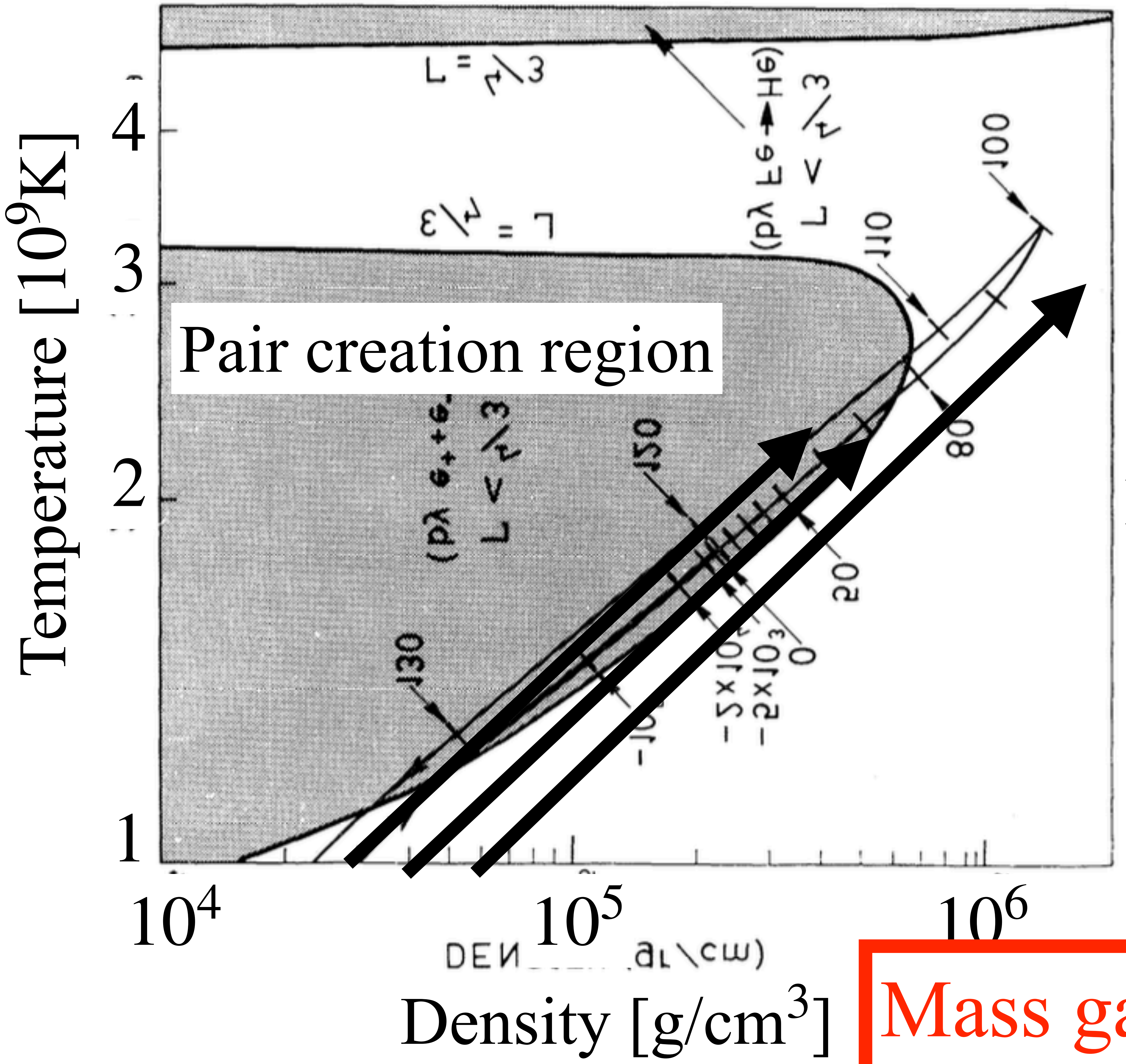


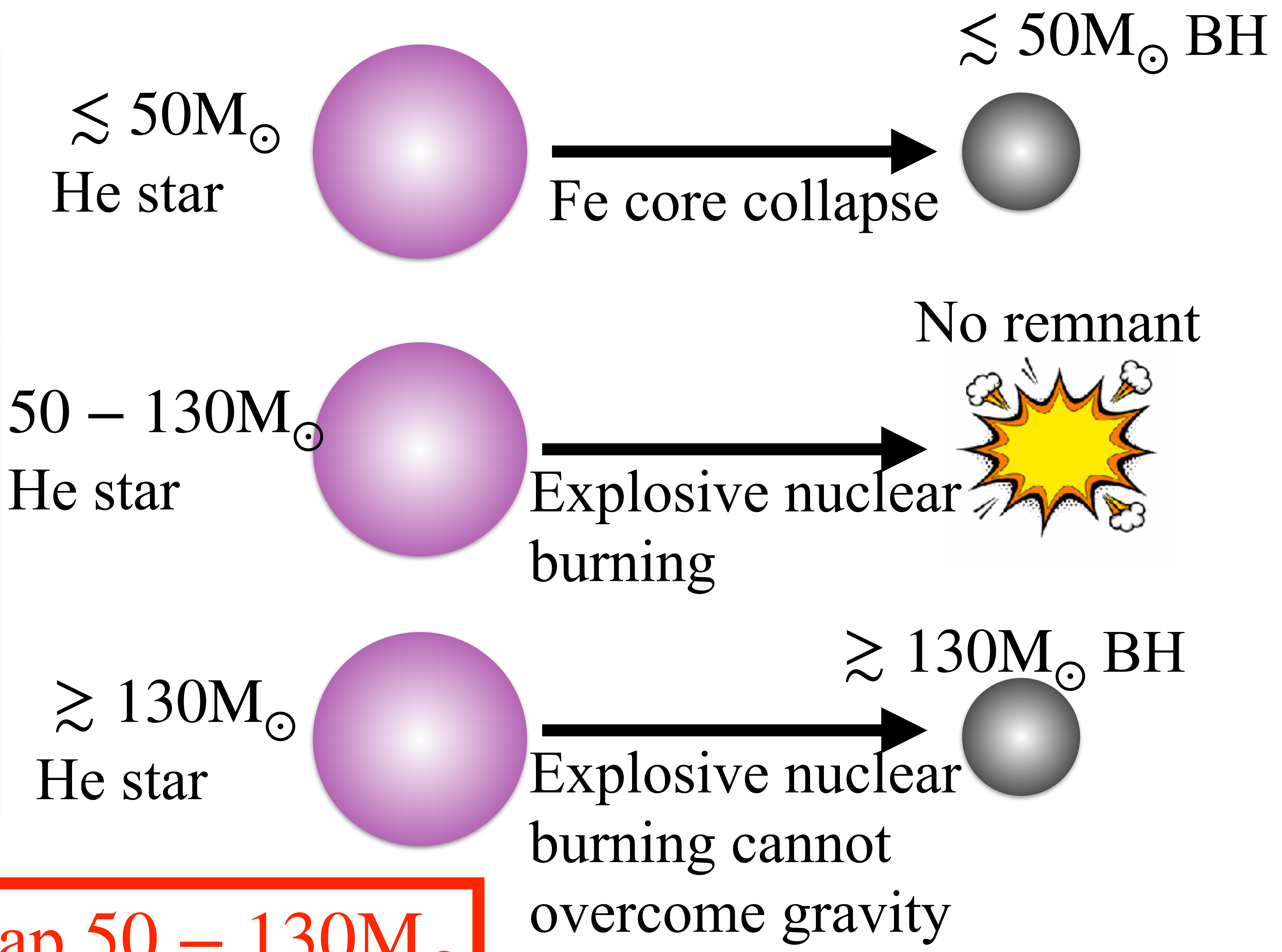
No BH with $50-130M_\odot$

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

Abbott et al. (2020, ApJL, 900, 13)

Pair instability supernova

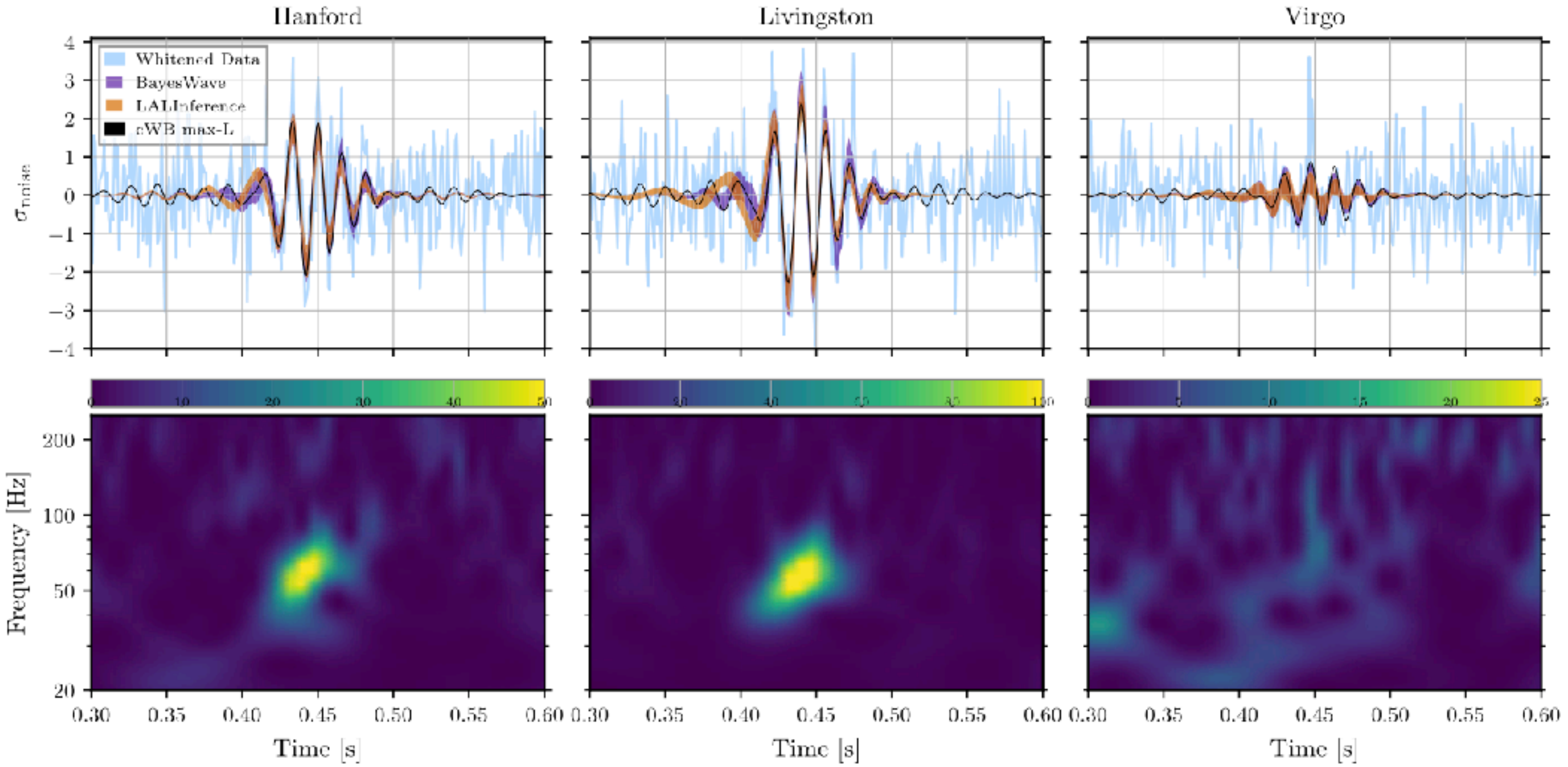


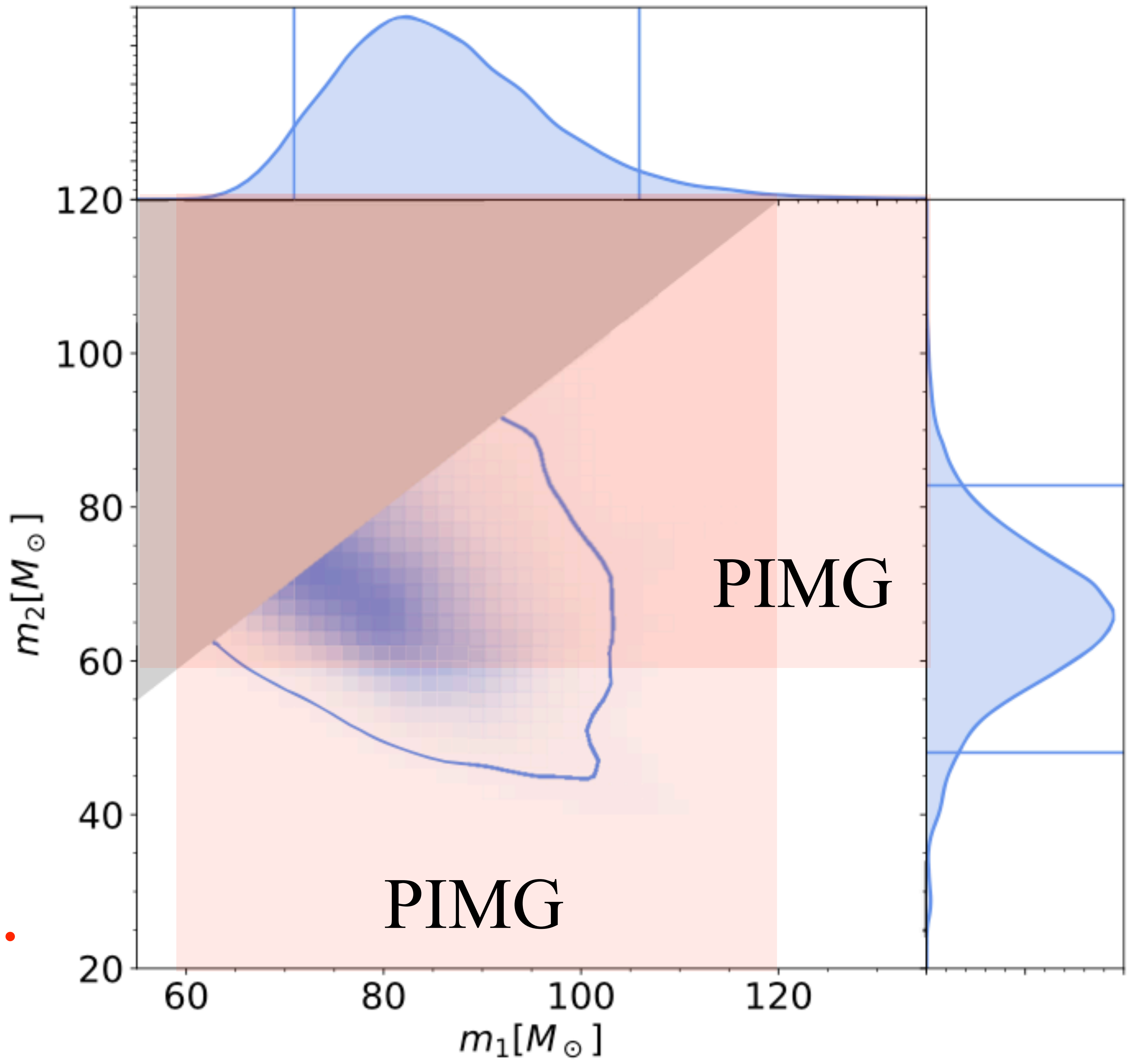


Mass gap $50 - 130M_\odot$

GW190521

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

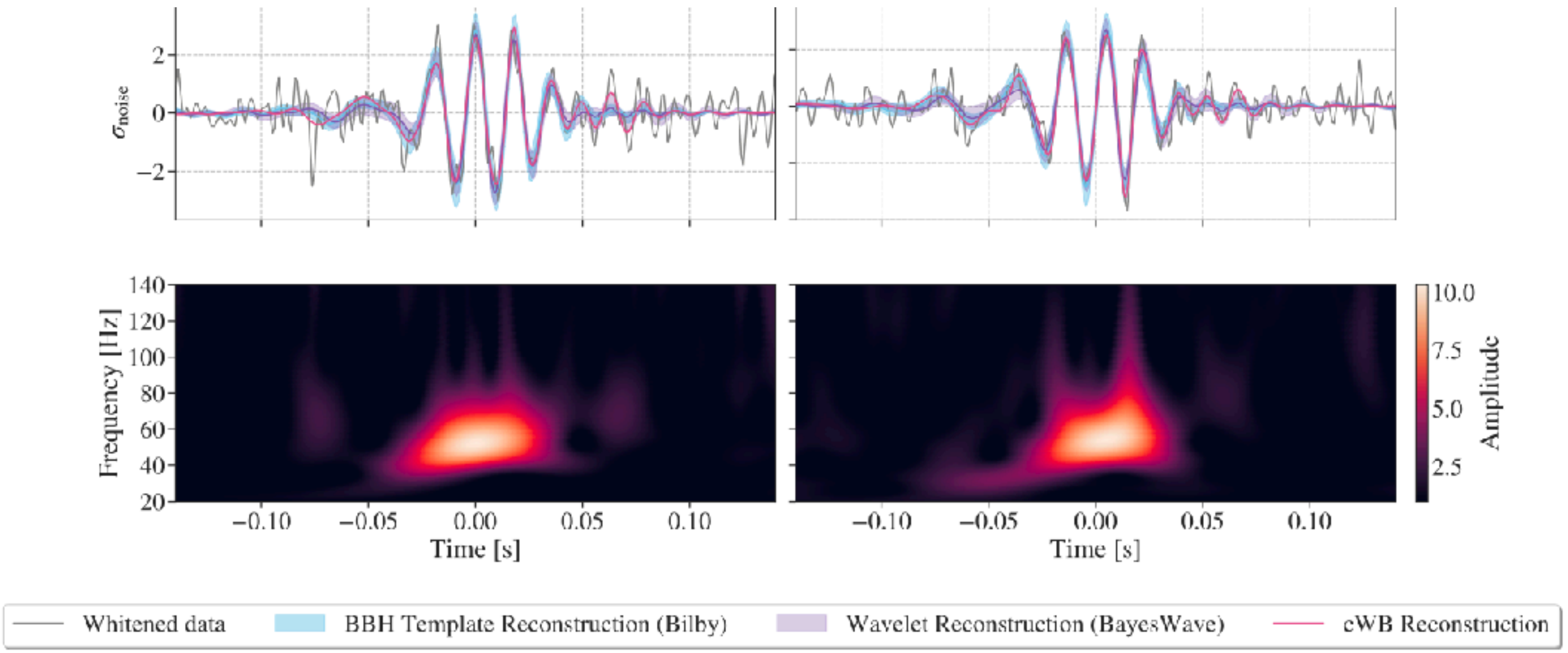


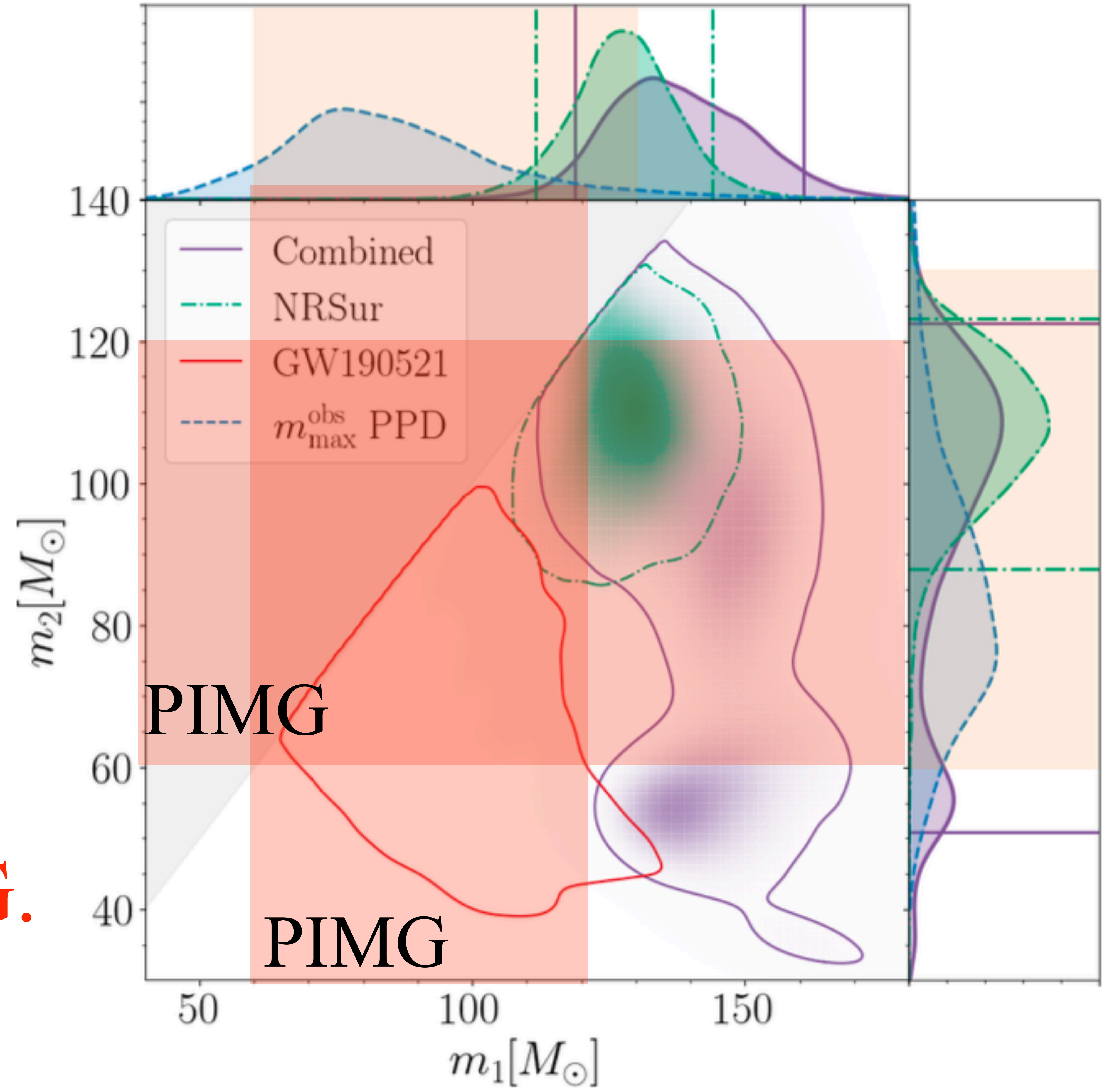


At least the primary BH is within the PIMG.

GW231123

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

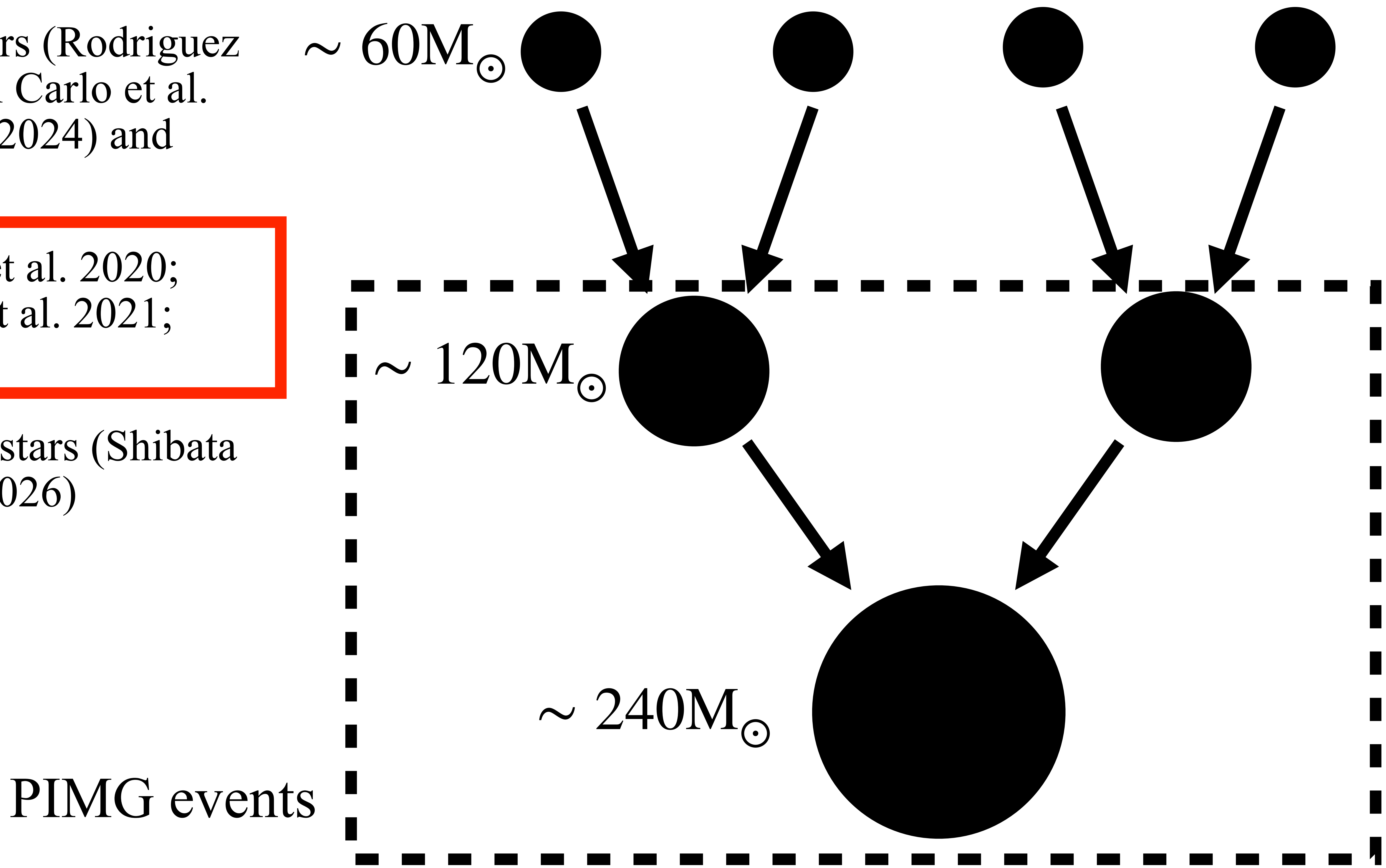




The primary BH is within, or beyond the PIMG.

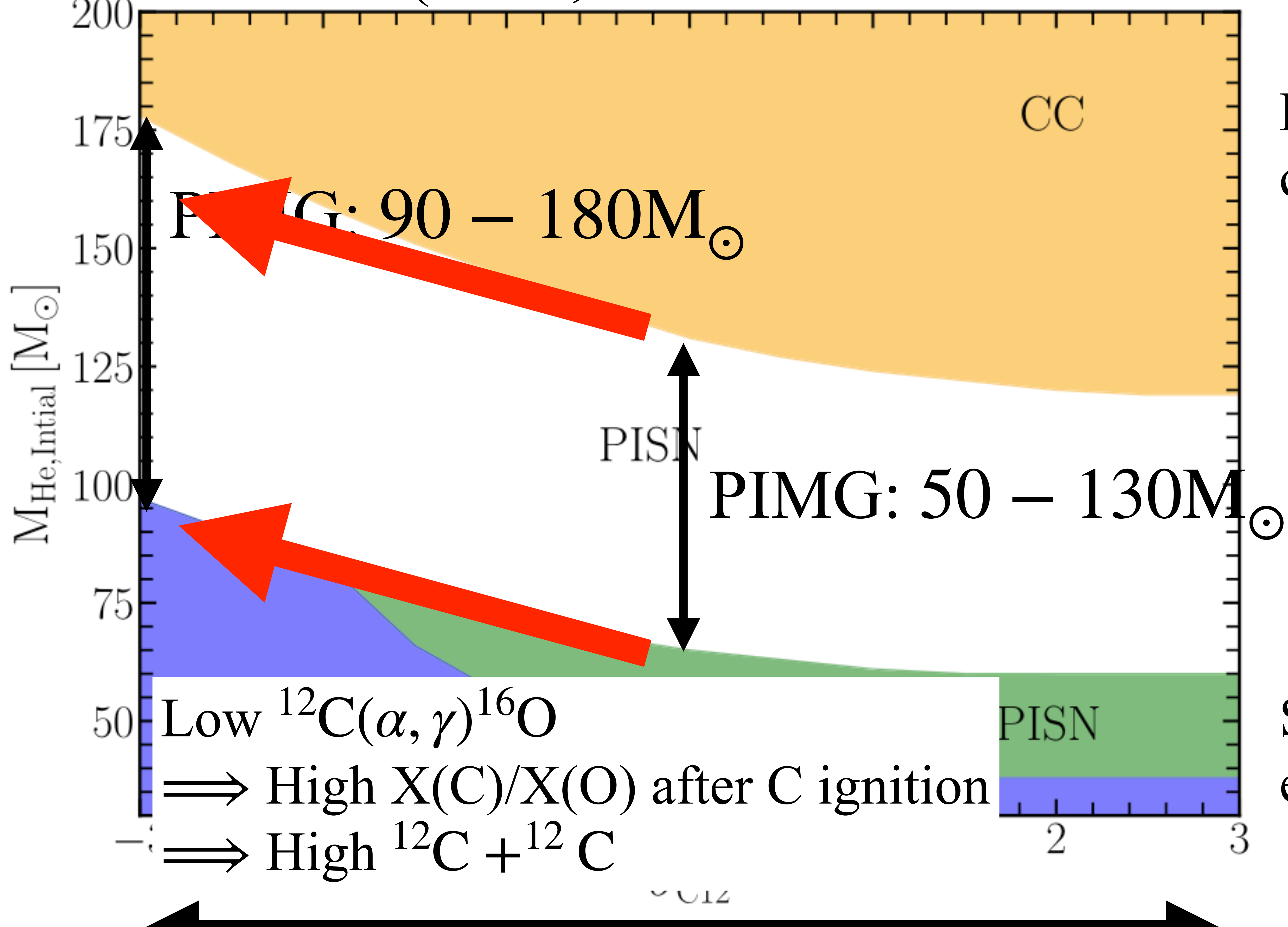
Formation scenarios for PIMG events

- 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)



Uncertainty of the PIMG range

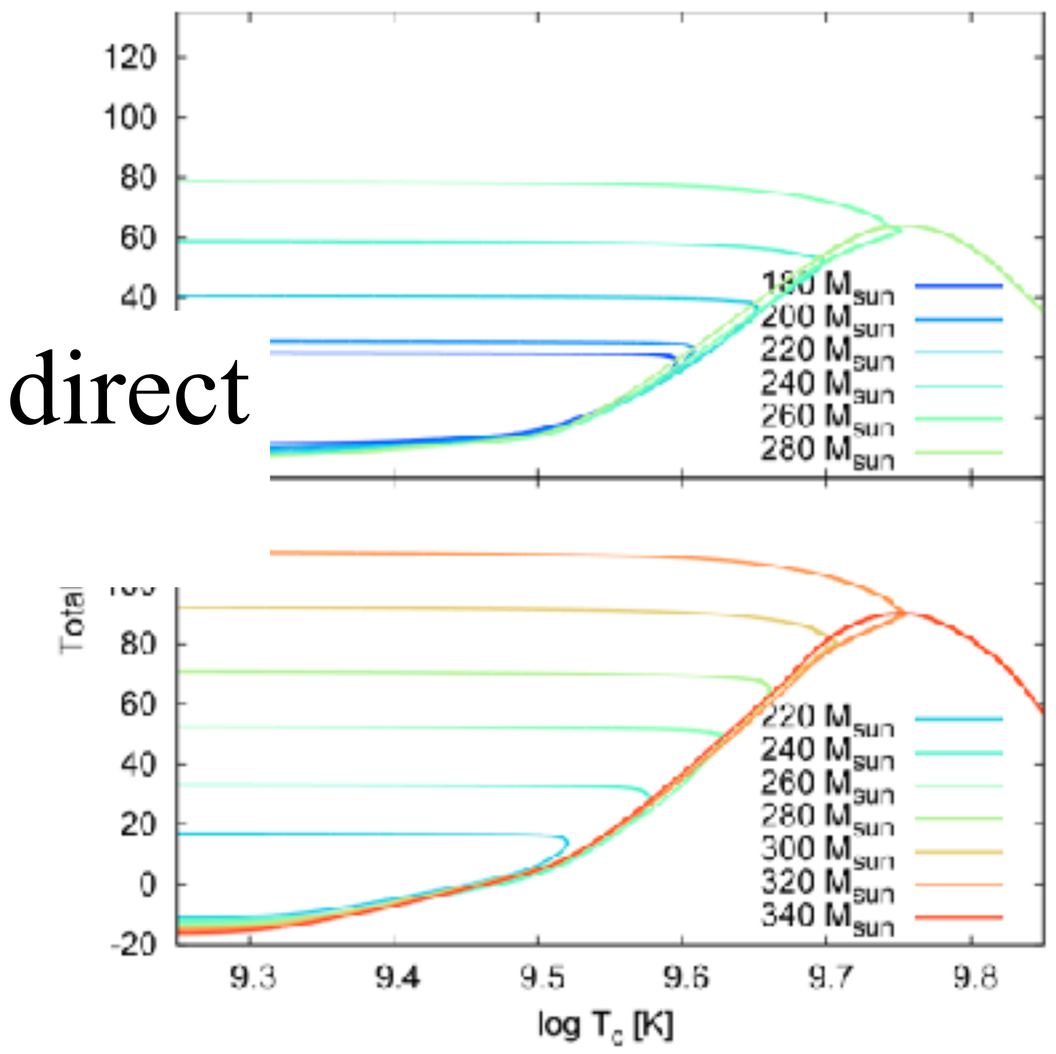
Farmer et al. (2020; see also Costa et al. 2021)



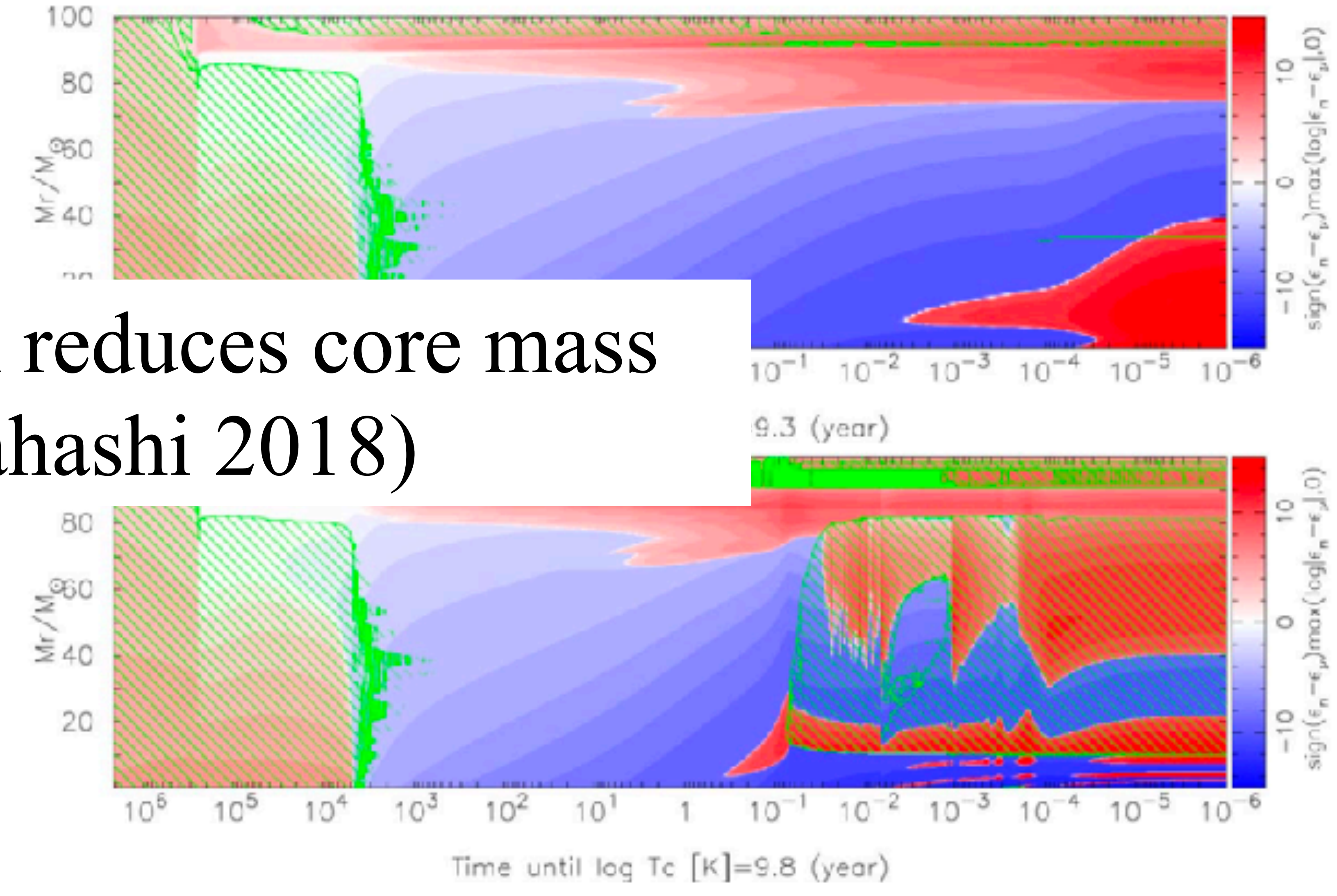
Low $^{12}C(\alpha,\gamma)^{16}O$
$\Longrightarrow$ High X(C)/X(O) after C ignition
$\Longrightarrow$ High $^{12}C + ^{12}C$

Low — $^{12}C(\alpha,\gamma)^{16}O$ — High

High C burning rate suppresses direct collapse (Takahashi 2018)

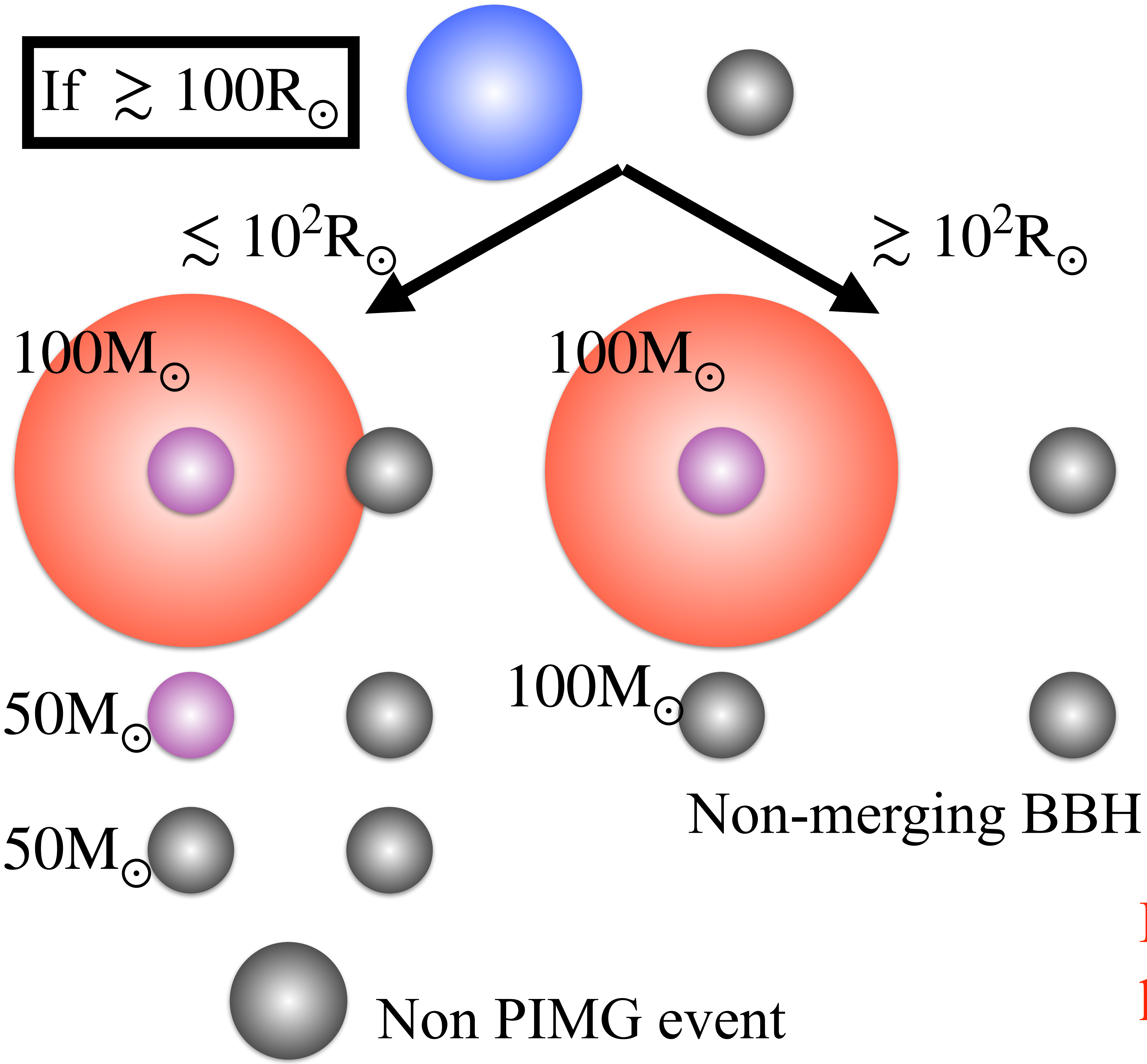


Shell convection reduces core mass effectively (Takahashi 2018)

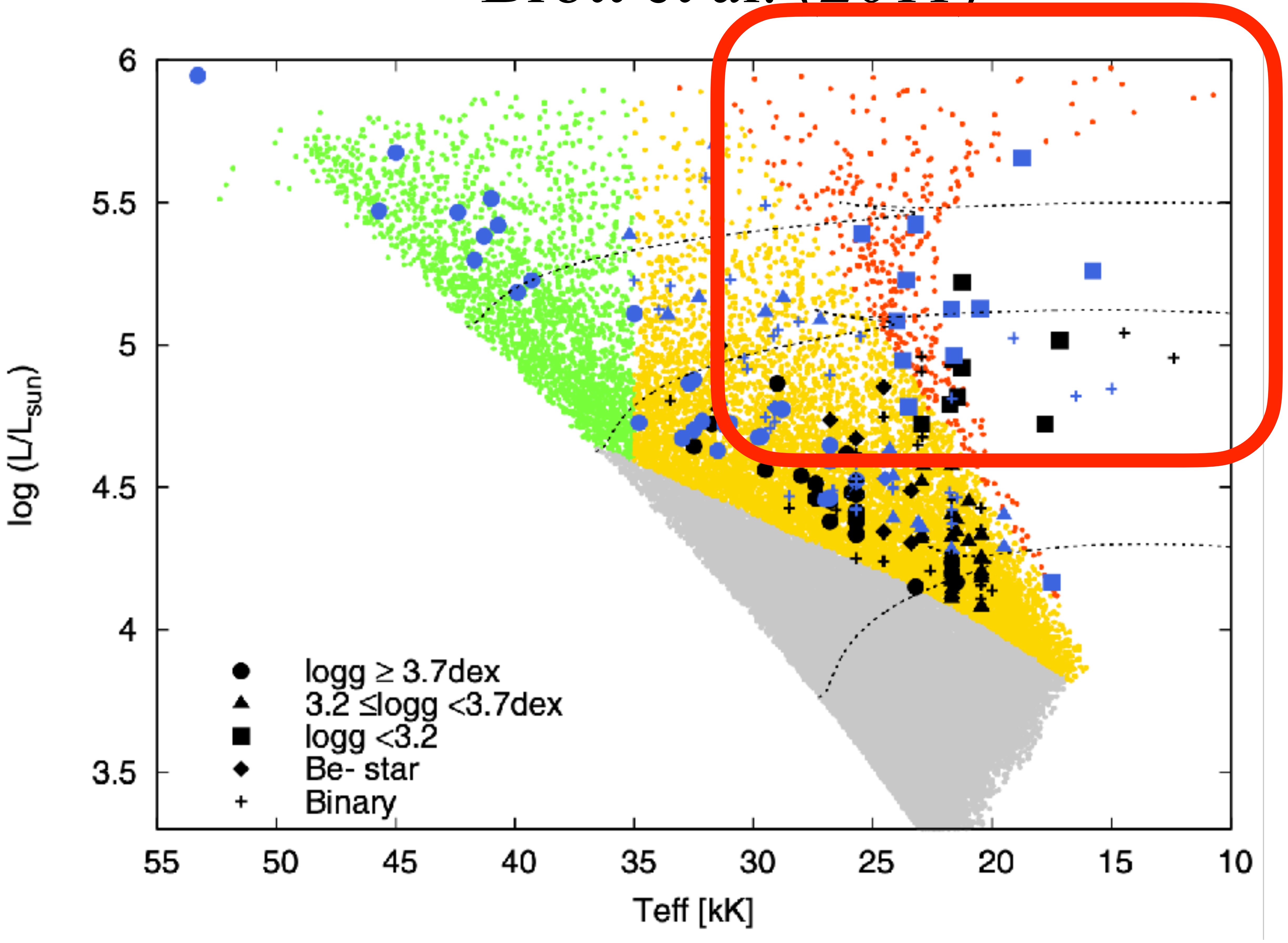


Dependence of the PIMG on metallicity

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



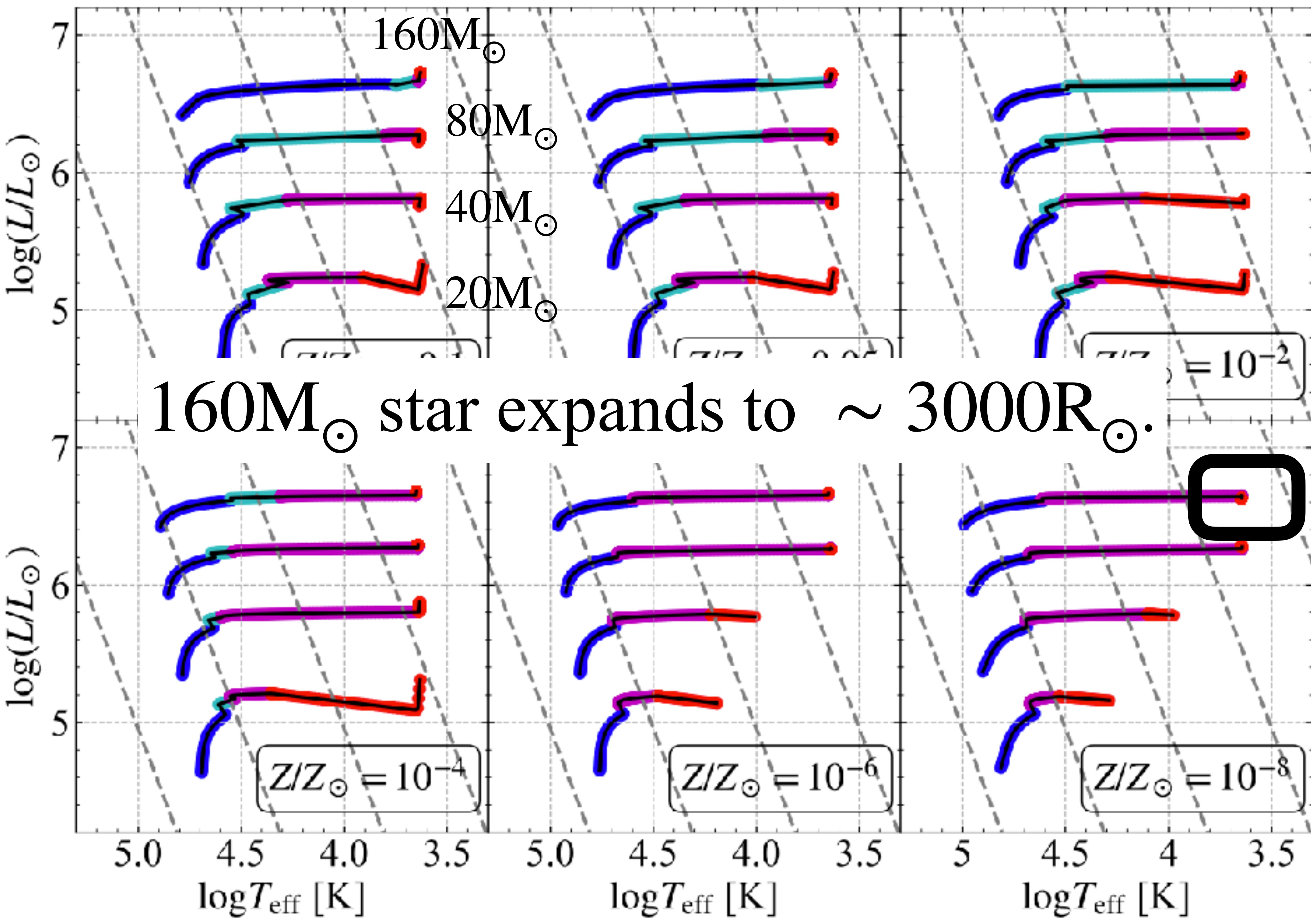
Brott et al. (2011)



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

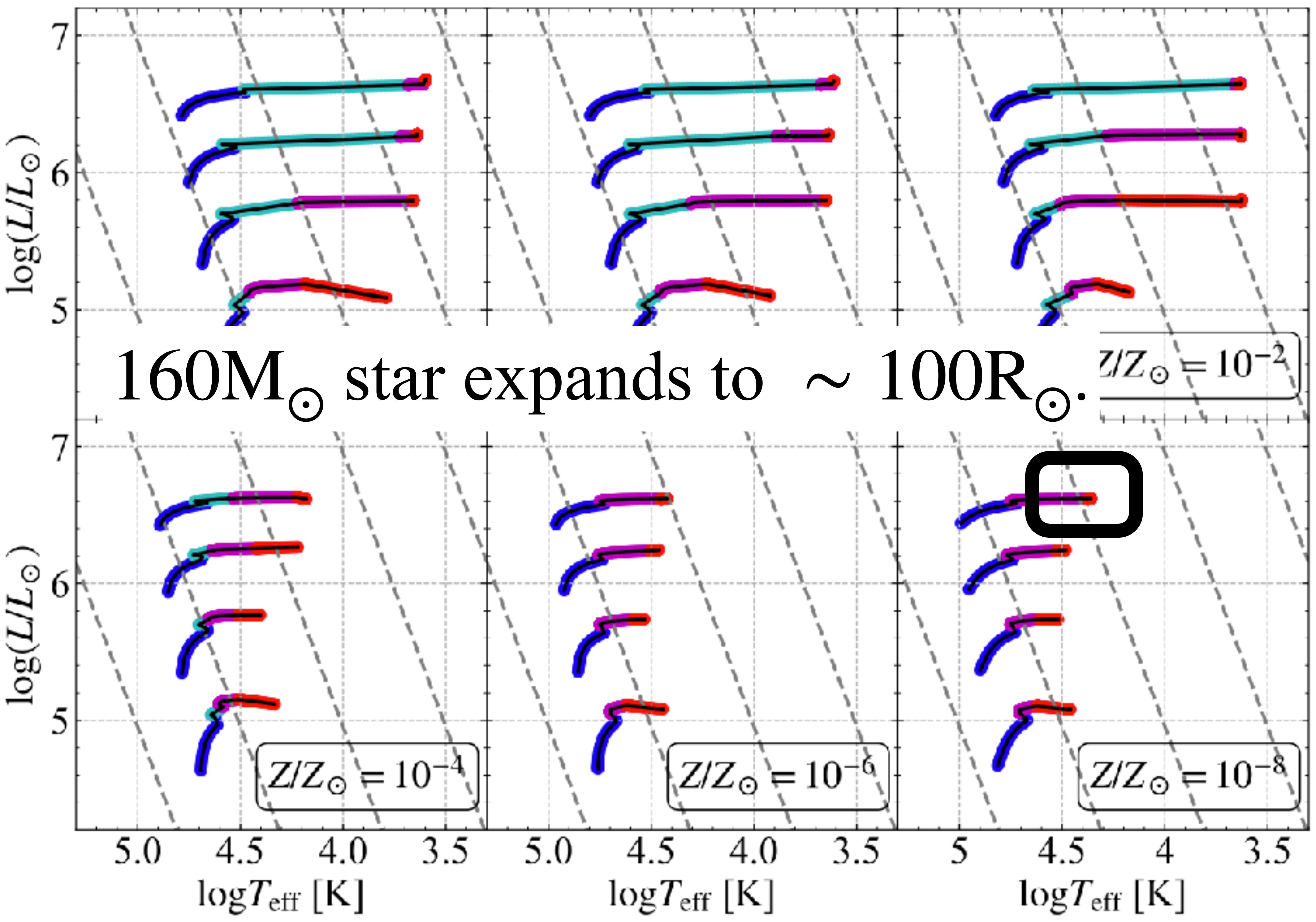
Metal-free stars with inefficient convective overshoot

Efficient case



160M$_\odot$ star expands to ~ 3000R$_\odot$.

Inefficient case

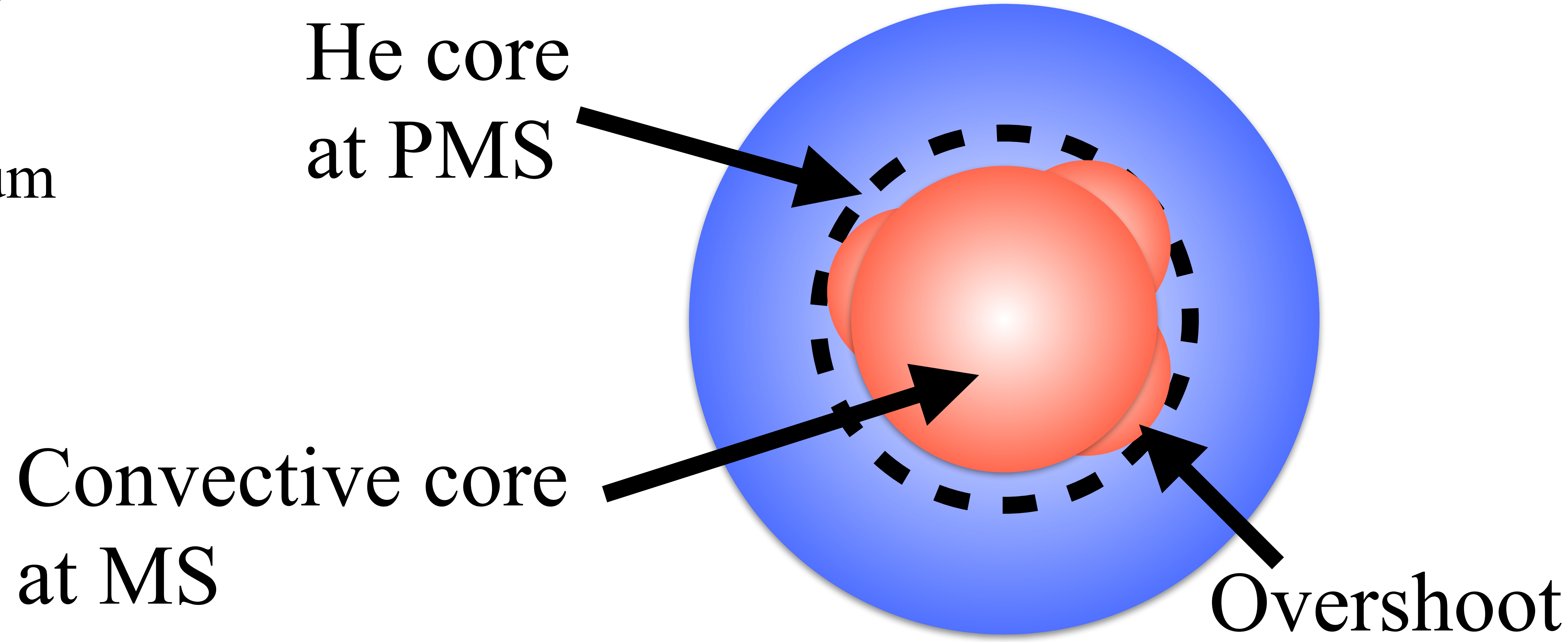


160M$_\odot$ star expands to ~ 100R$_\odot$.

Tanikawa et al. (2022, ApJ, 926, 83)

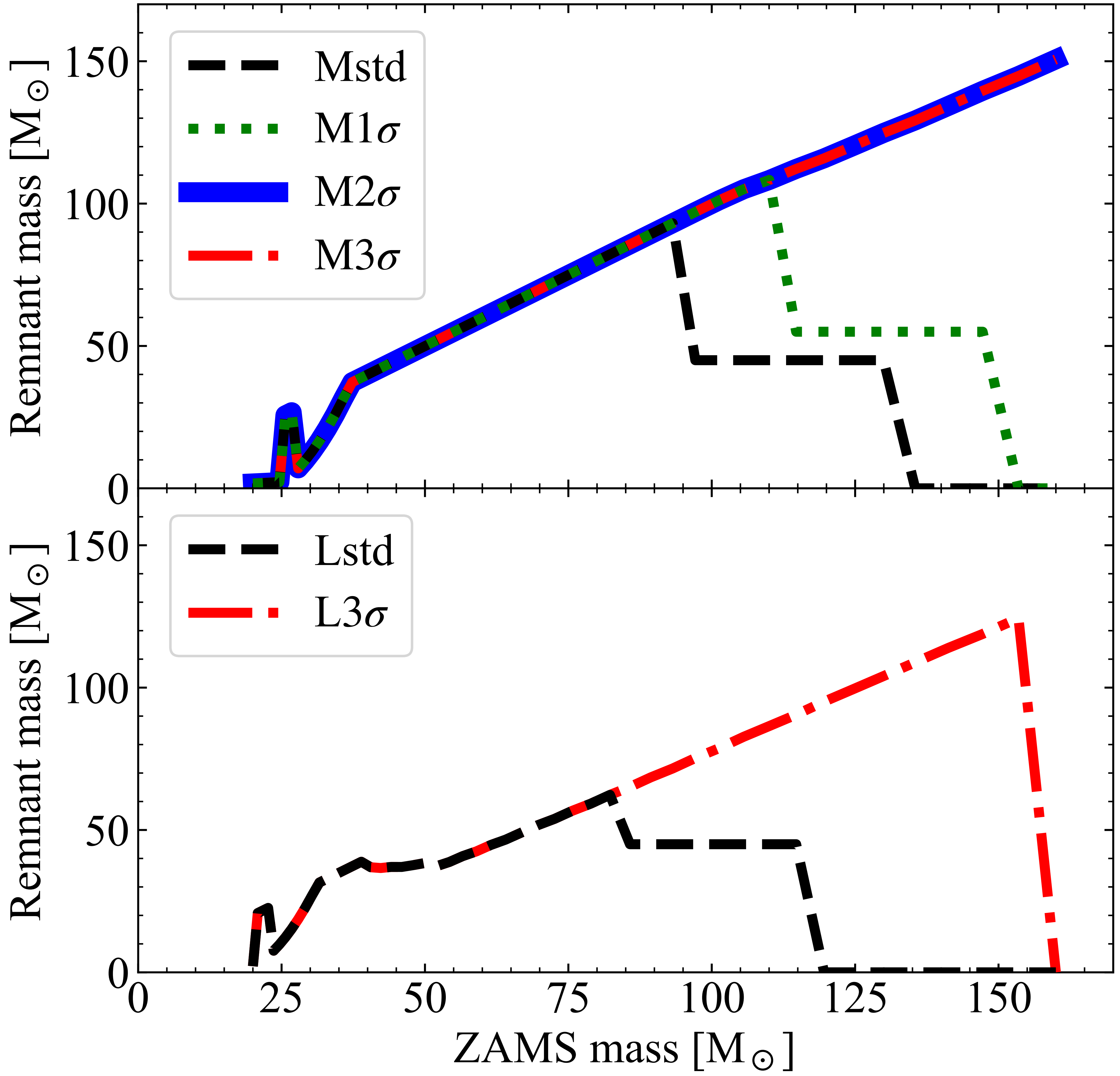
Why are metallicity and overshoot important?

- Metallicity
  - Lower metallicity, lower opacity.
- Convective overshoot
  - Less efficient overshoot, smaller He core at the end of the MS phase.
  - Smaller He core has smaller luminosity at the PMS phase.
  - Smaller luminosity results in smaller maximum radius at the PMS phase.



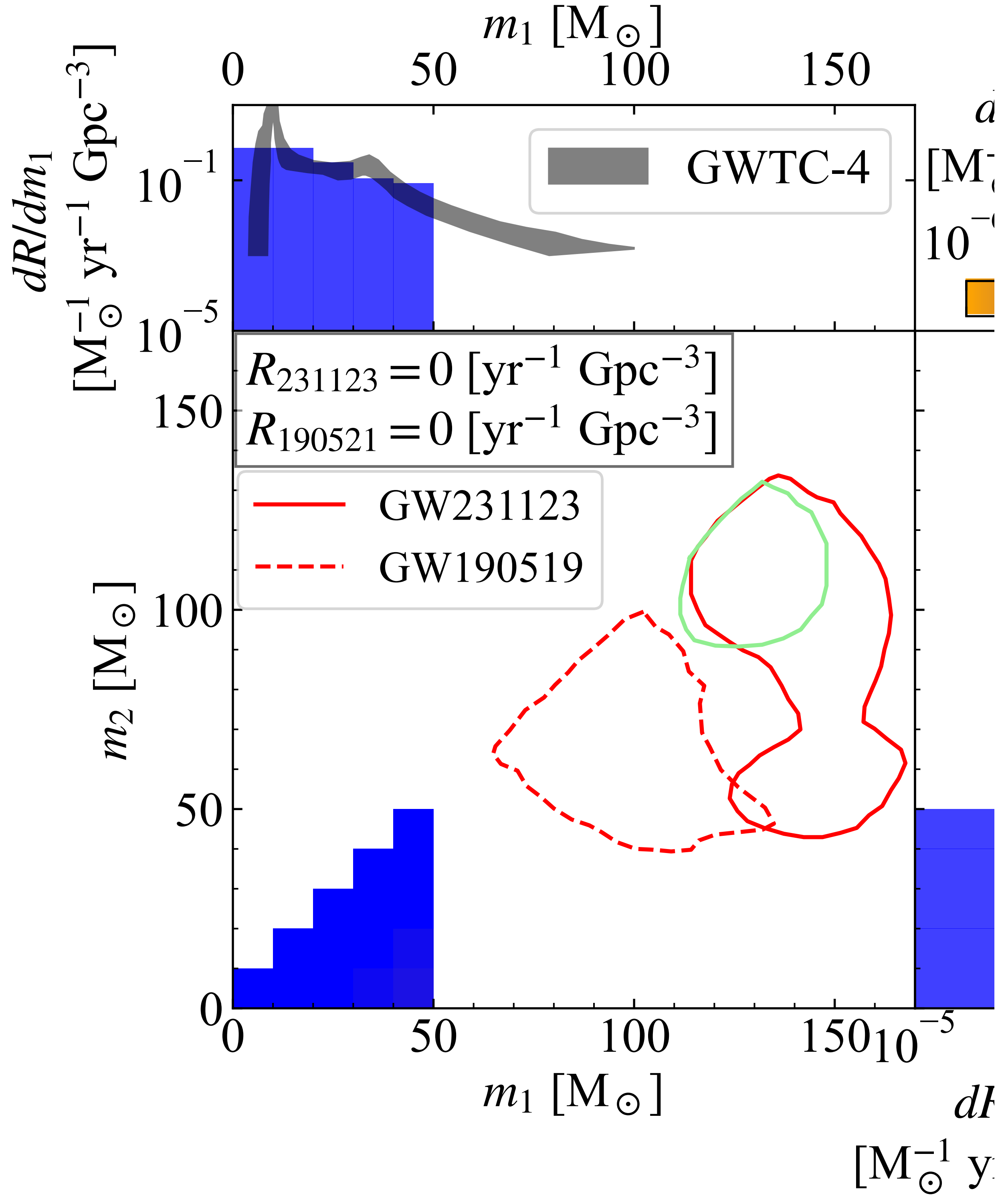
Binary population synthesis calculation

- 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 3σ-lower $^{12}C(\alpha,\gamma)^{16}O$
- Binary evolution: stable mass transfer, common envelope evolution, tidal evolution, etc.



Results

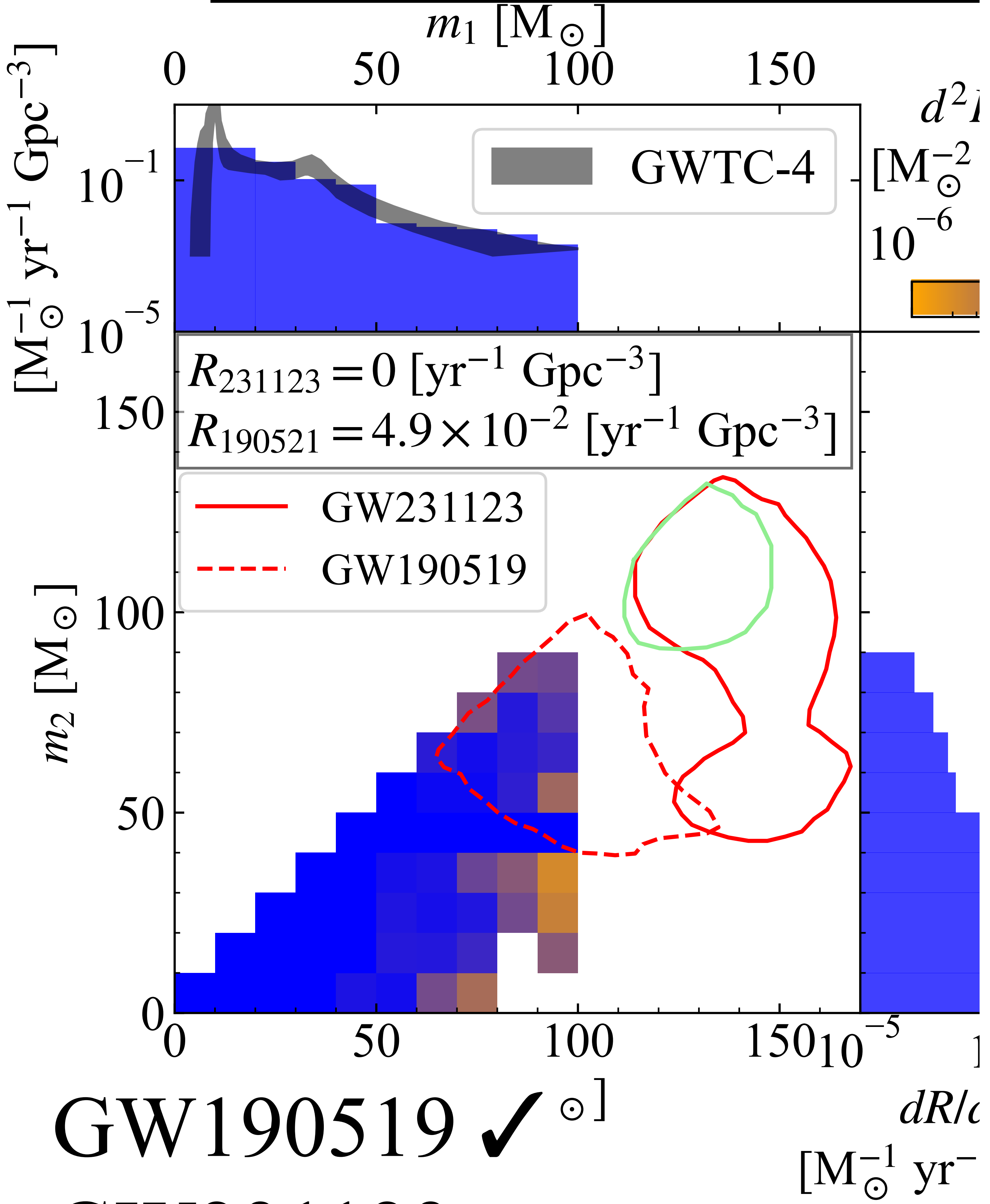
Efficient overshoot



GW190519 ×

GW231123 ×

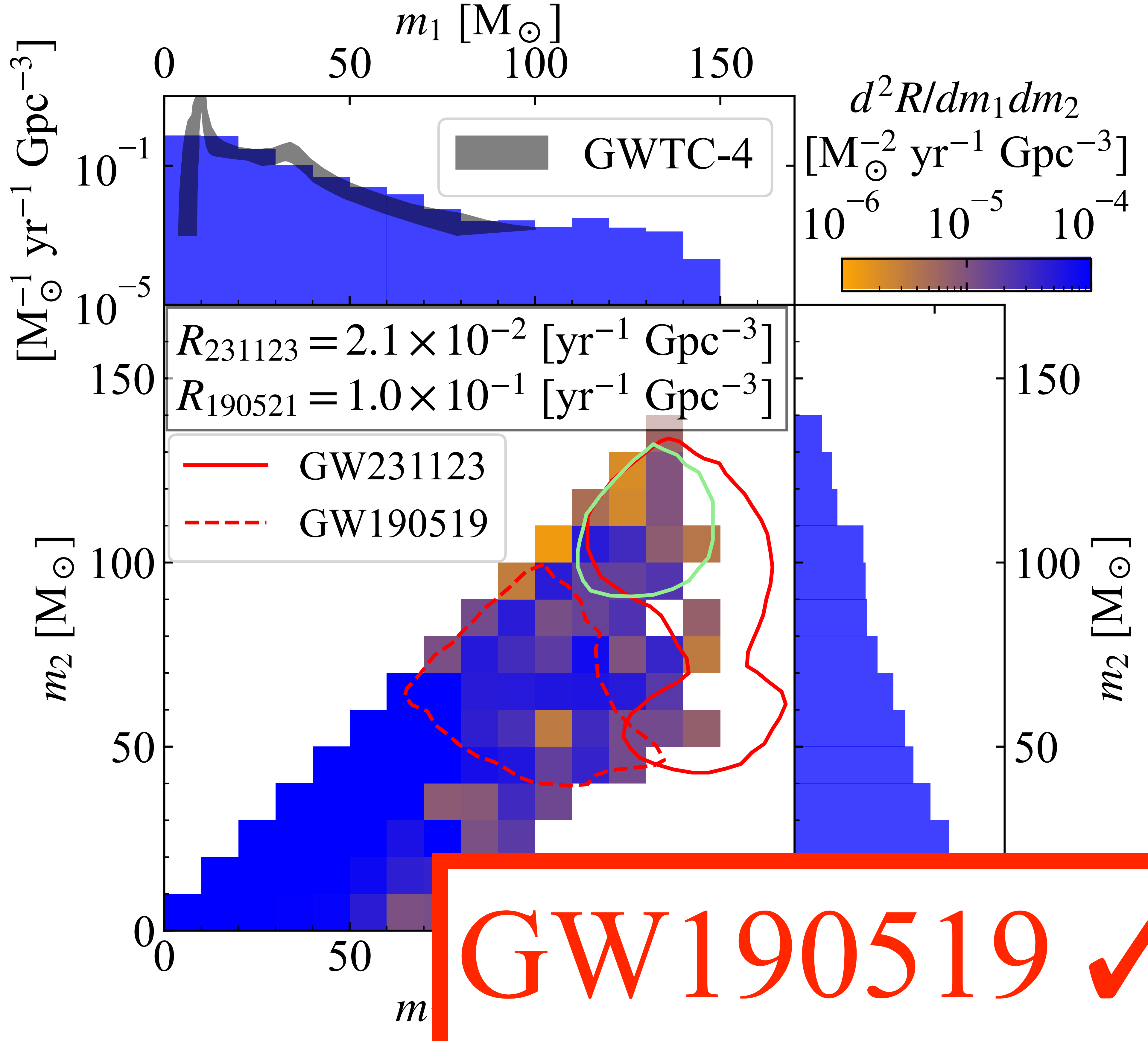
Inefficient overshoot



GW190519 ✓

GW231123 ×

Inefficient overshoot + 3σ lower ^{12}C(α,γ)^{16}O



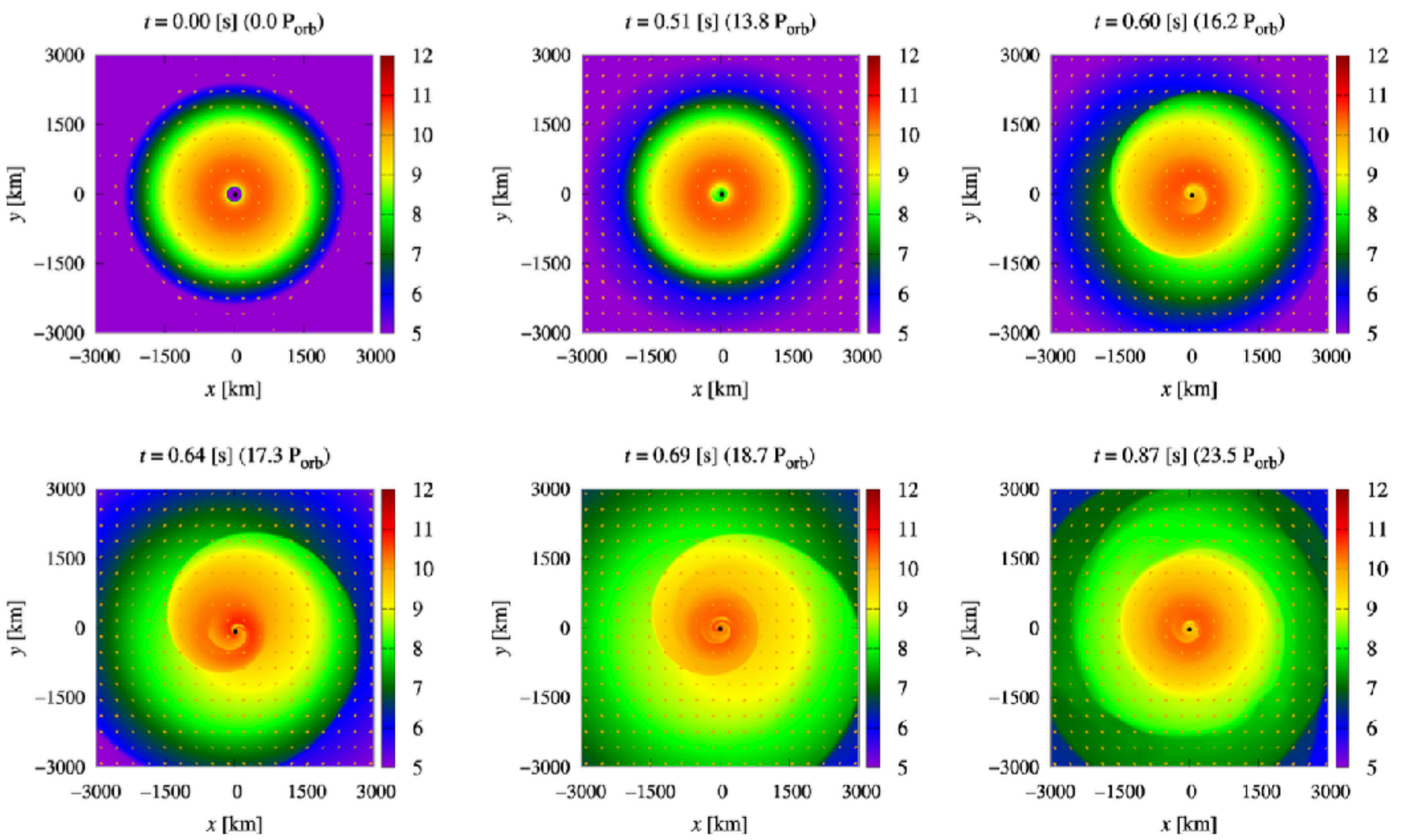
GW190519 ✓

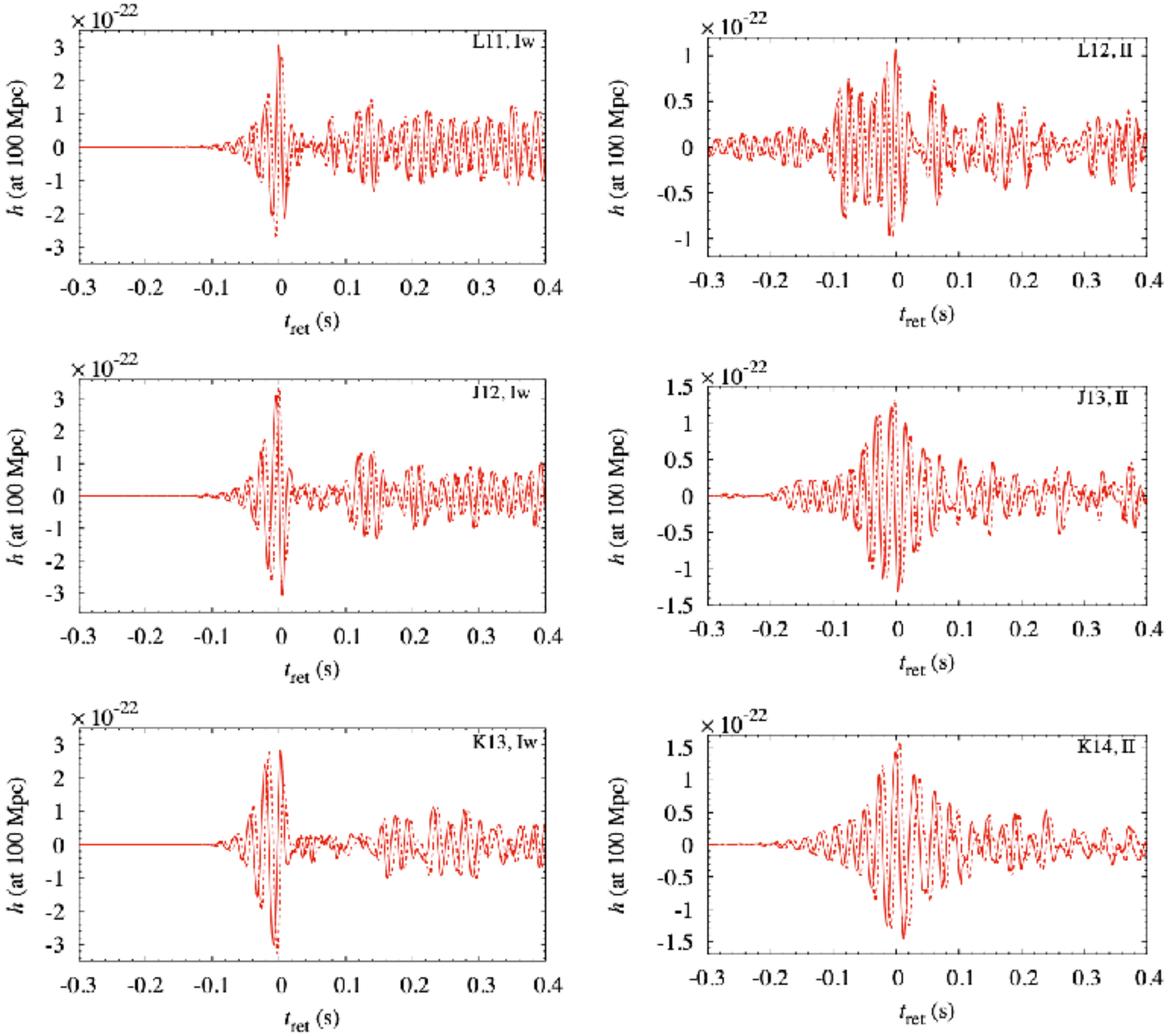
GW231123 ✓

Outline

- Formation of Gaia black hole (BH)
- Formation of pair instability mass gap (PIMG) events
- Formation and property of very massive star (VMS)

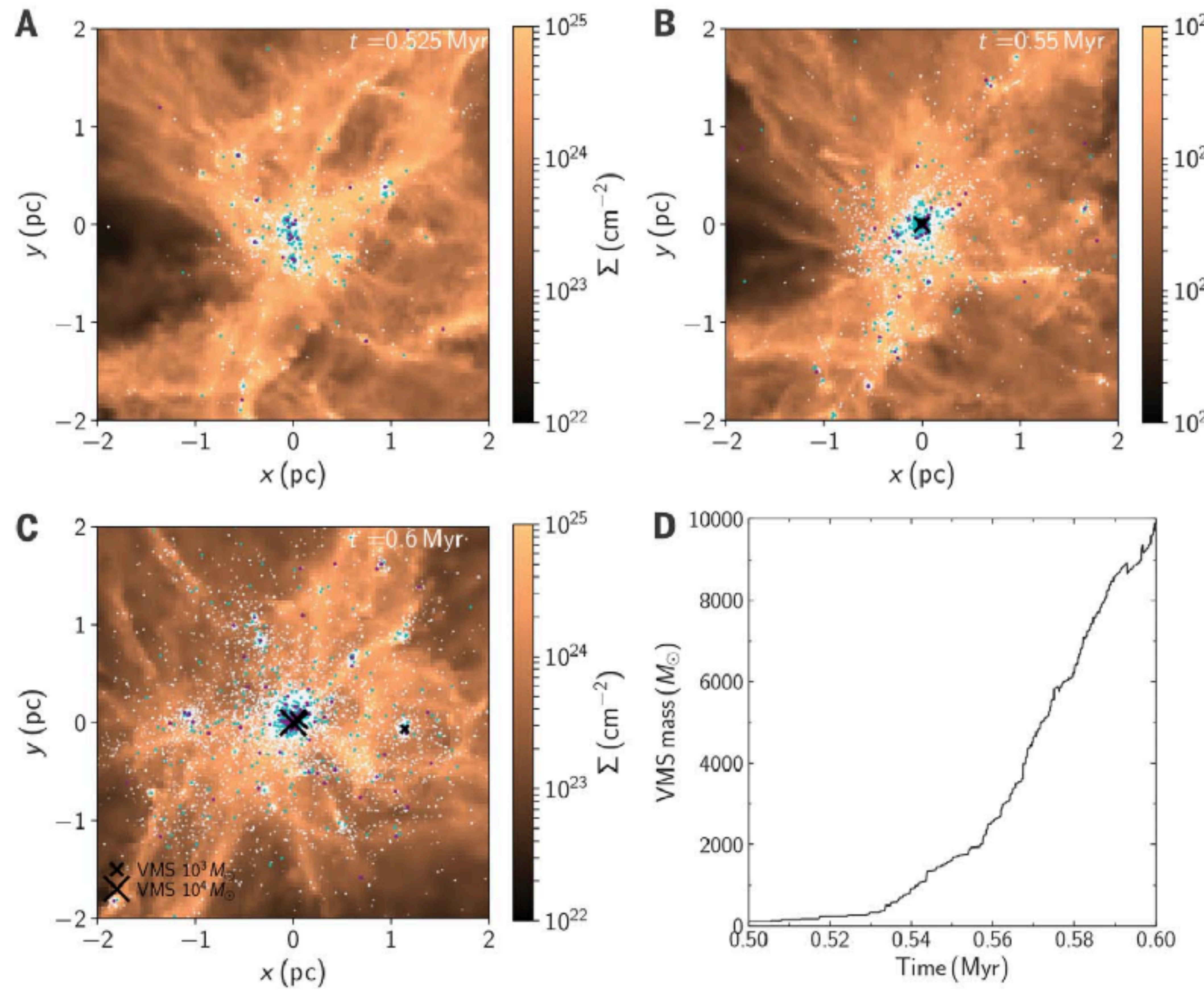
Collapse of rotating VMSs
⟹ PIMG-like GW signals



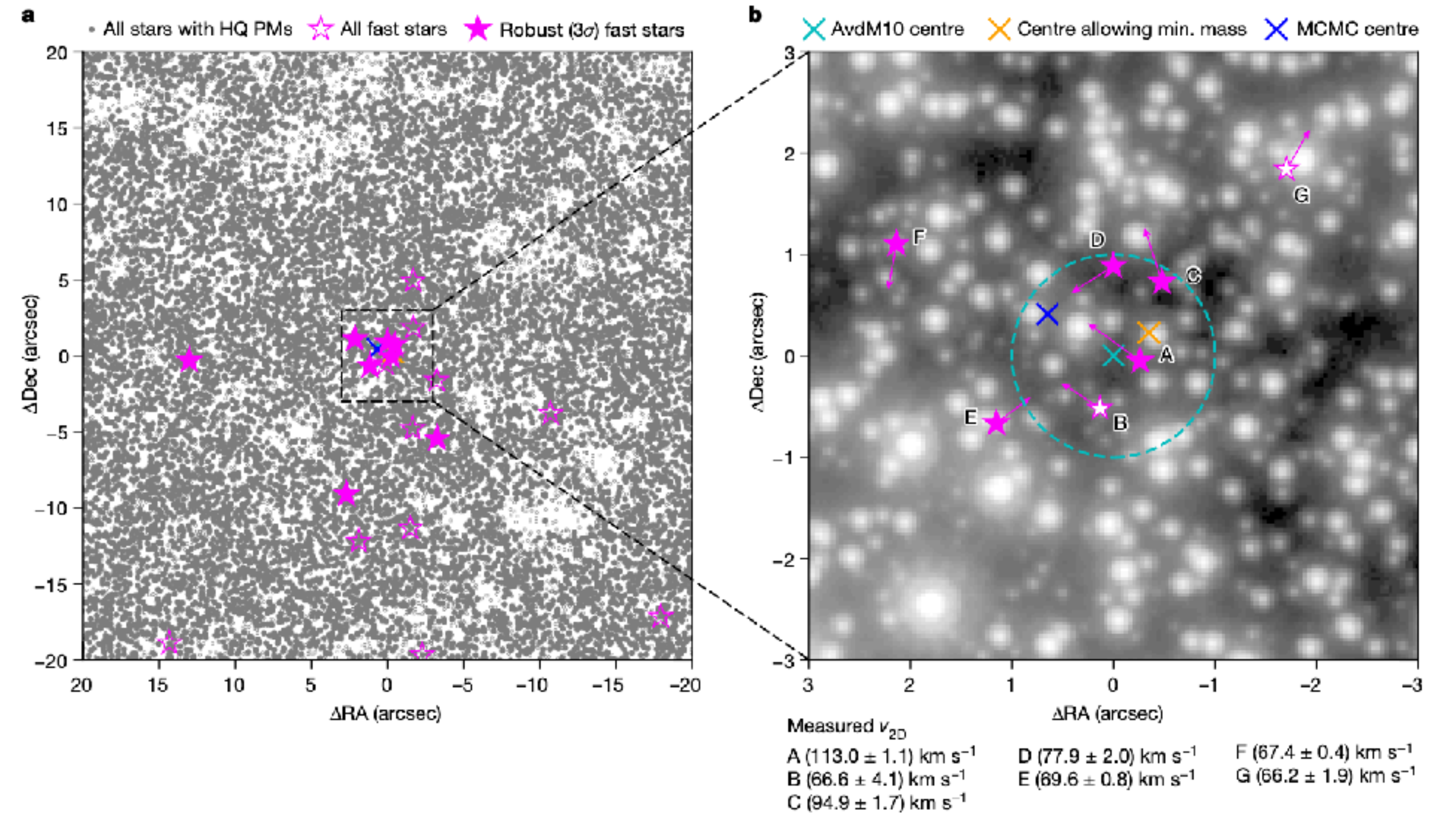


Shibata et al. (2021); Shibata, Fujibayashi (2025)

Possible formation process of VMS
— Runaway collisions in star clusters —



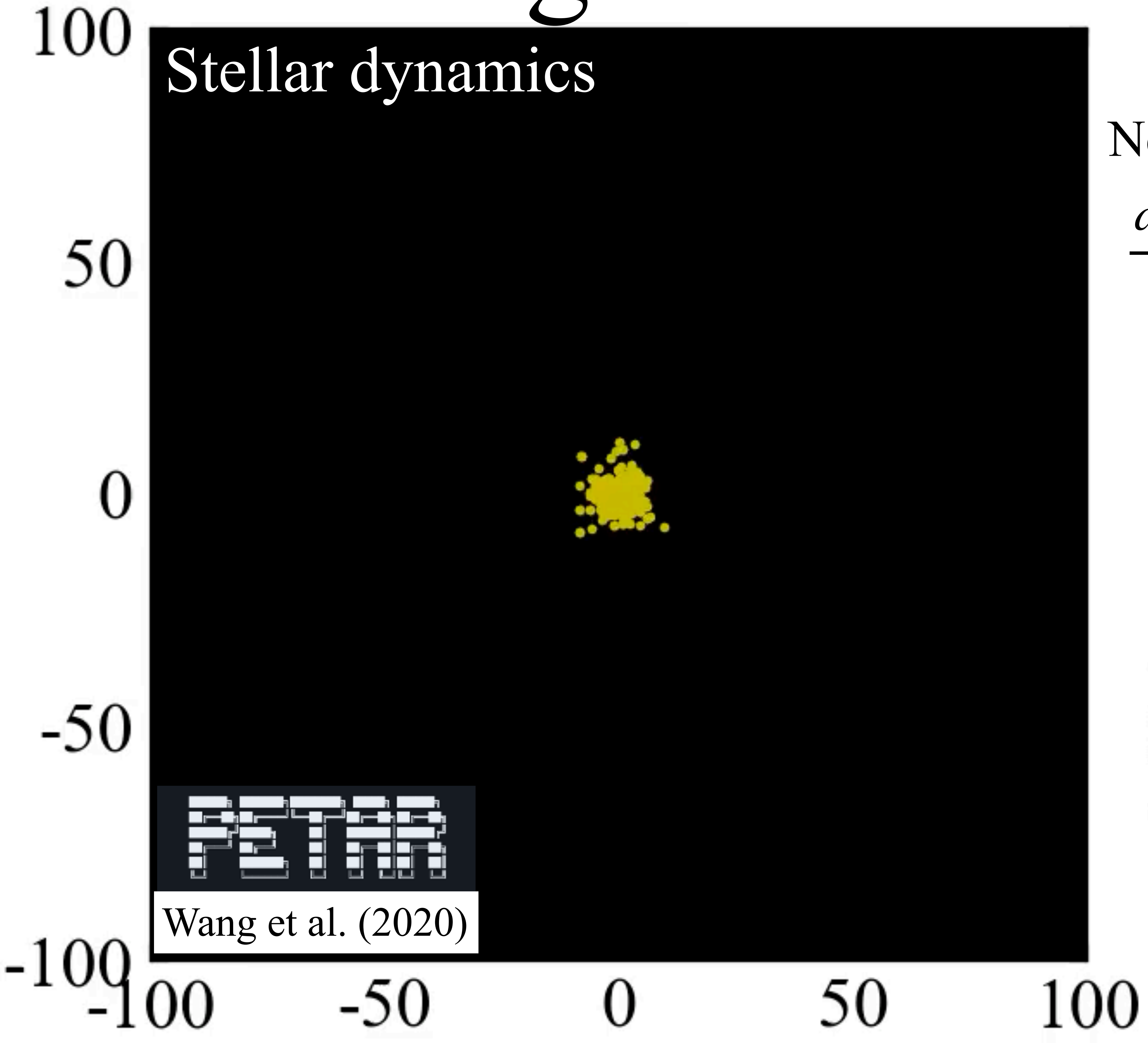
Fujii et al., AT et al. (2024, Science, 384, 1488)



Haberle et al. (2024, Nature, 631, 285)

Is a VMS rapidly rotating?

Gravitational N-body simulation coupled with single and binary star evolution

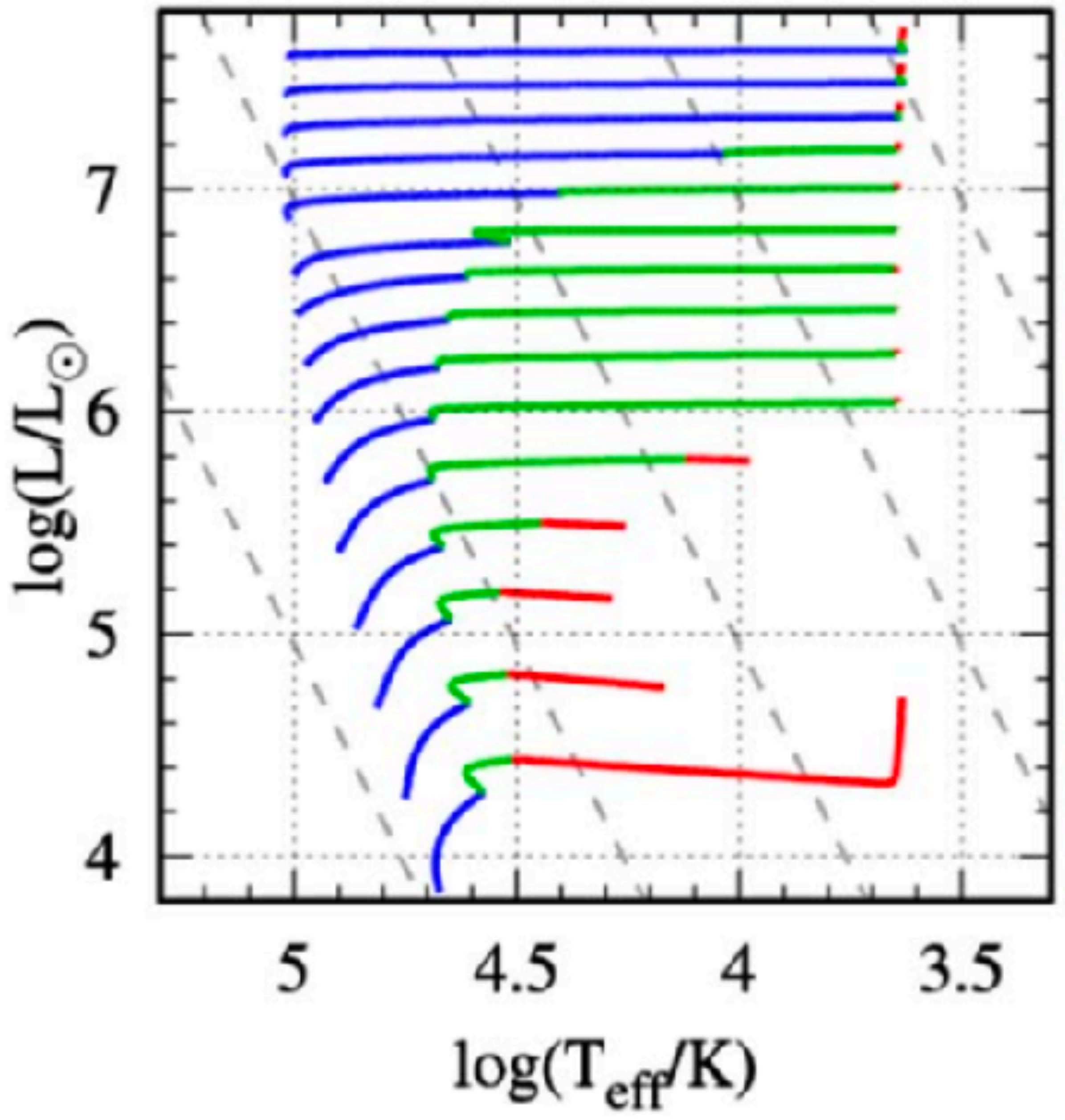


Newton's law of gravitation

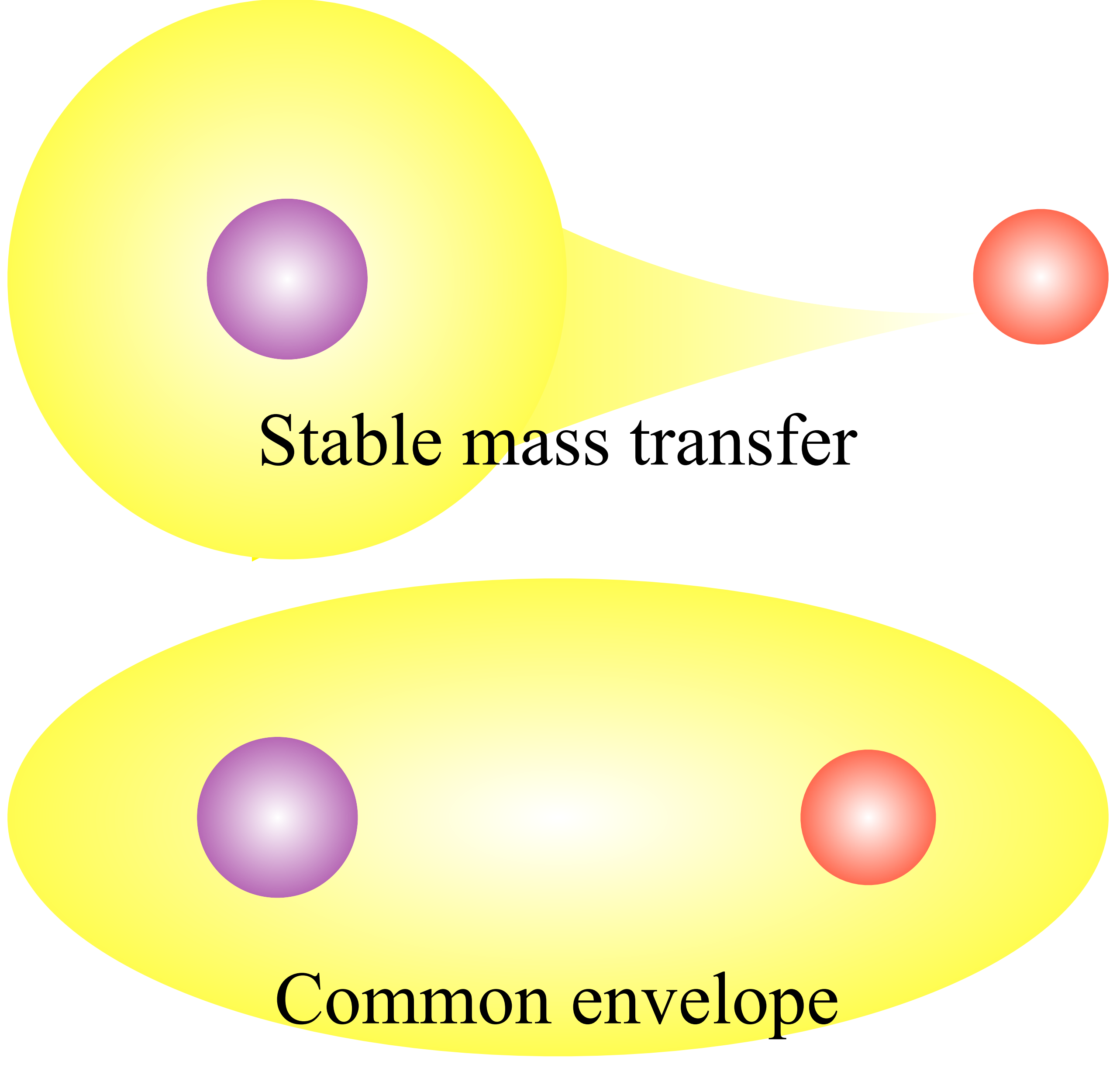
$$\frac{d^2\vec{r}_i}{dt^2} = \sum \frac{m_j}{|\vec{r}_j - \vec{r}_i|^2}\frac{\vec{r}_j - \vec{r}_i}{|\vec{r}_j - \vec{r}_i|}$$

No assumption regarding dynamical processes

Single star evolution



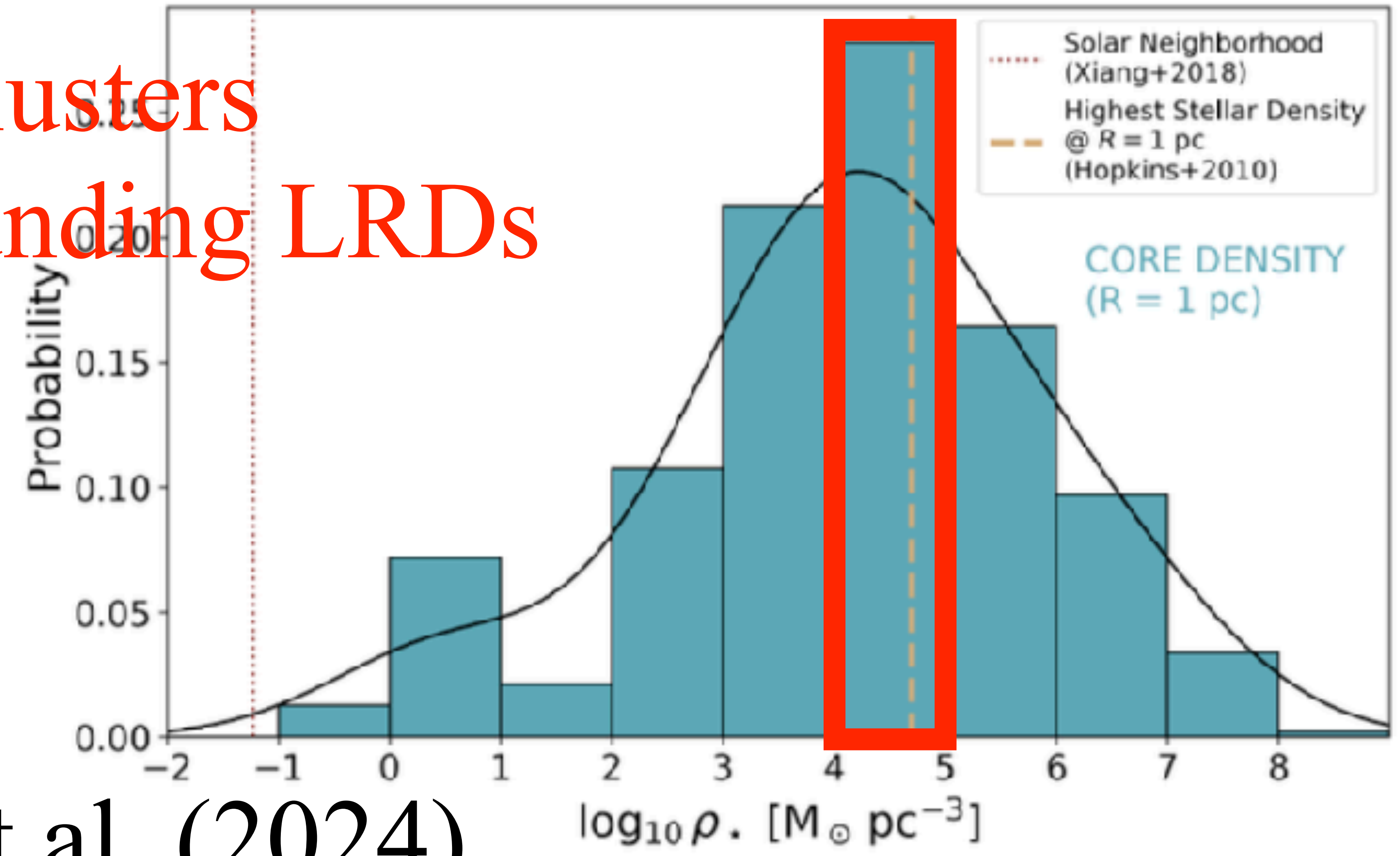
Binary star evolution



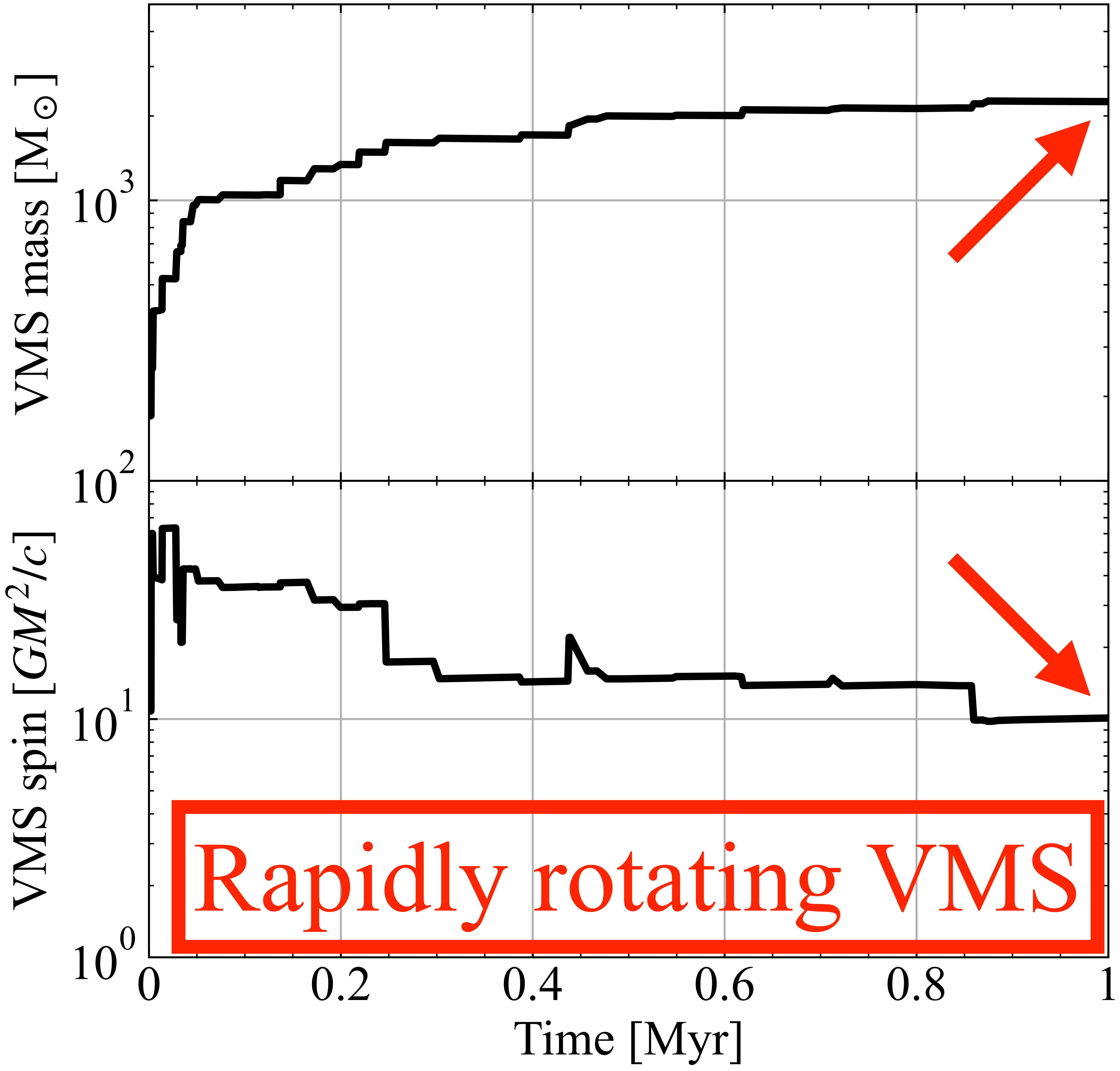
Runaway collision simulation

- Initial condition
  - Mass: $10^5\ M_\odot$ Density (<1pc): $2.4 \times 10^4\ M_\odot\ \mathrm{pc}^{-3}$
- Results:
  - VMS mass at 1Myr: $\sim 2000\ M_\odot$
  - VMS spin parameter at 1Myr: ~ 10

Star clusters surrounding LRDs



Guia et al. (2024)

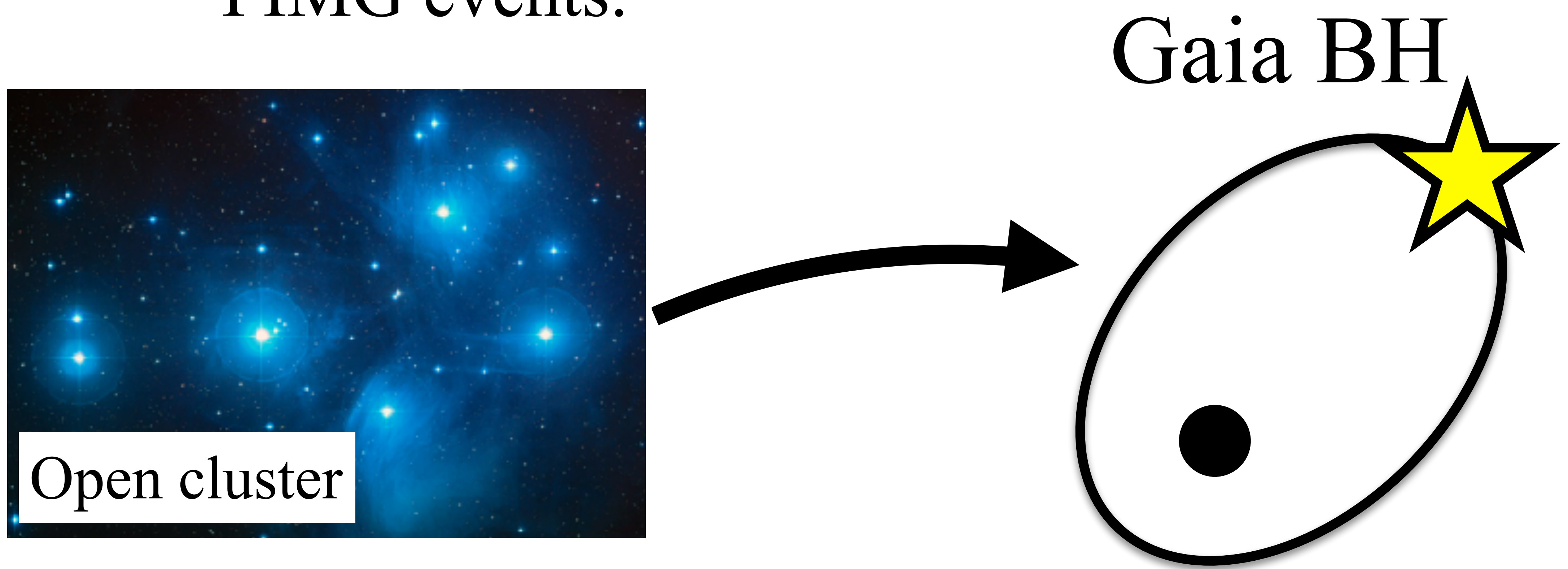


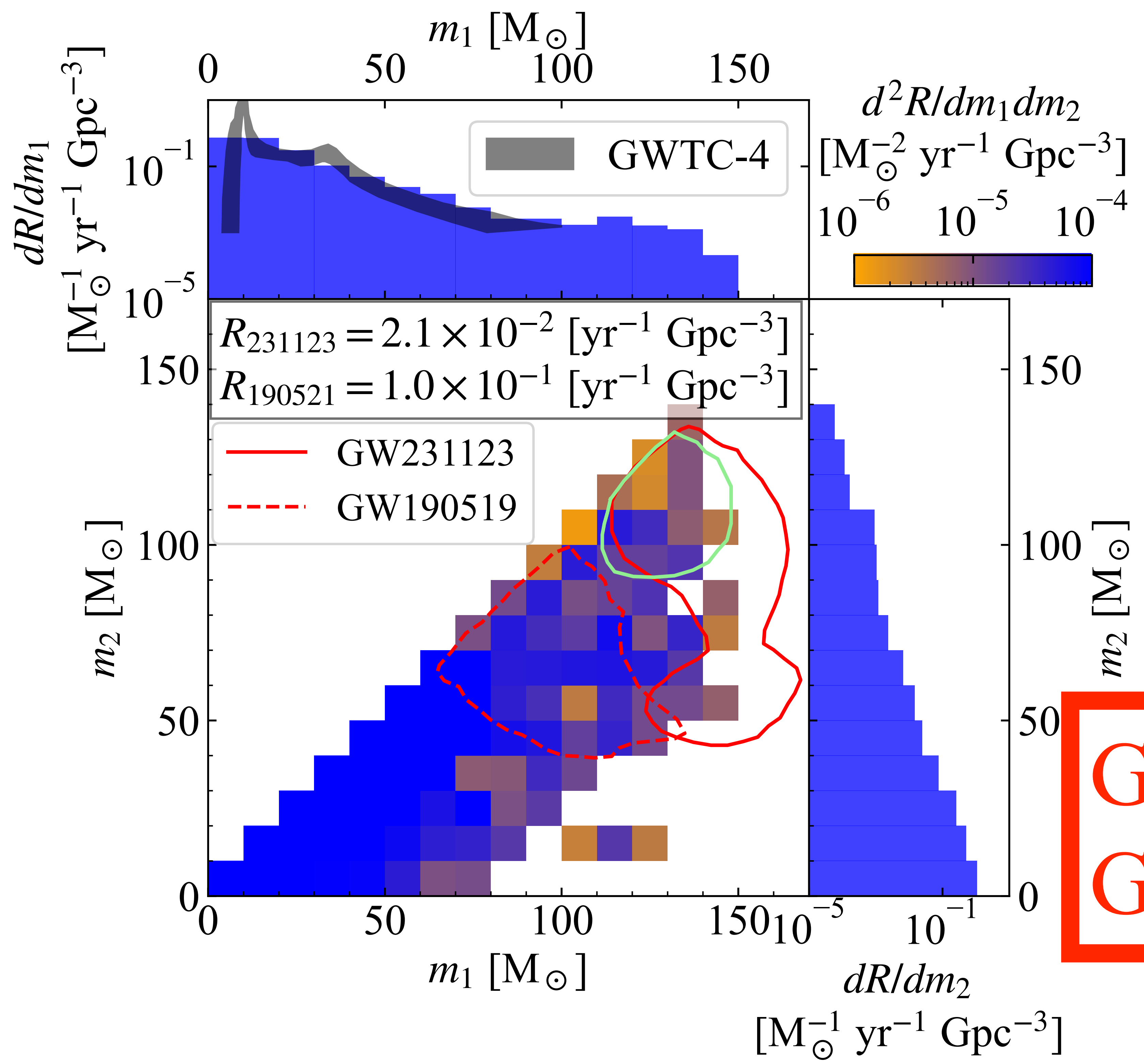
Caveats

- Orbital angular momenta of two pre-collision stars are completely converted into the spin angular momentum of the collision product.
- Spin angular momentum loss due to stellar winds is minimal.
  - We take into account only hot massive star wind (Vink et al. 2001) and LBV-like wind (Humphrey, Davidson 1994).
- We should regard the VMS spin as the theoretical upper limit of a VMS formed through runaway collisions.

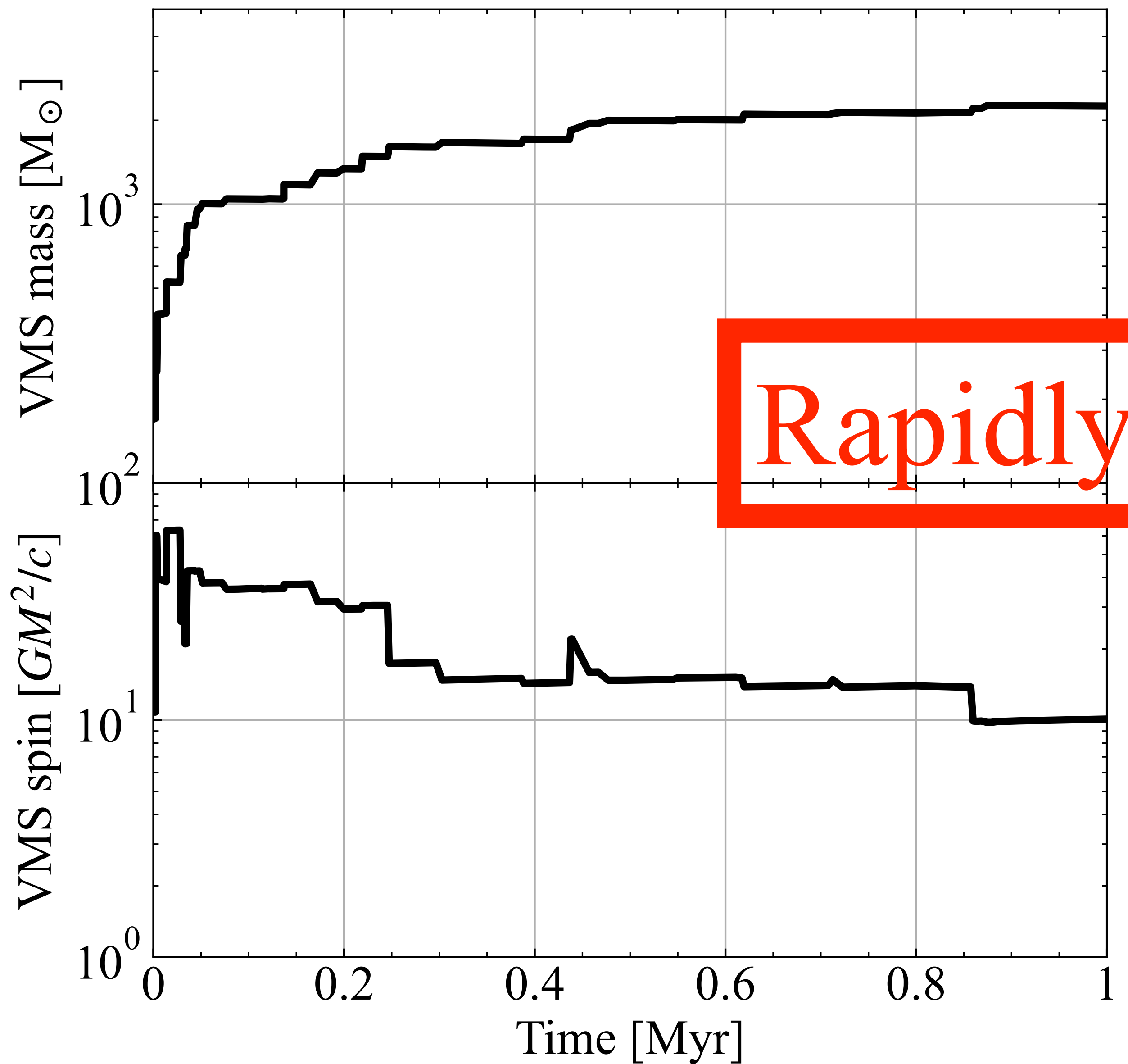
Summary

- Gaia BH can be formed in star clusters.
- 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.
- VMSs formed through runaway collisions can be rapidly rotating.
  - Collapse of a VMS can emit GW signals like PIMG events.





GW190519 ✓
GW231123 ✓



Rapidly rotating VMS