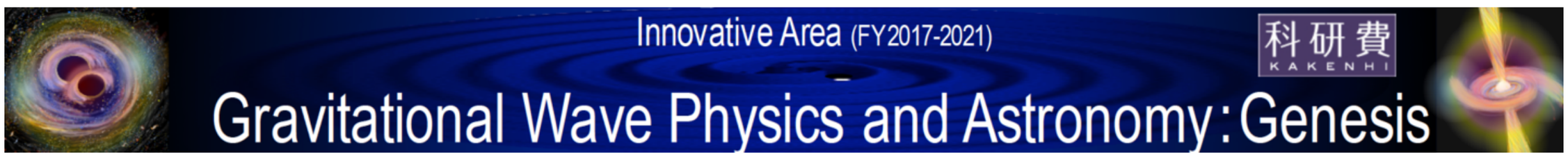
Formation of merging binary black holes from isolated binary stars with all metallicities

Genesis Group A Area Workshop 2022

Speaker: Ataru Tanikawa (University of Tokyo)
Collaborators: M. S. Fujii, K. Hijikawa, T. Hosokawa, T. Kinugawa, J. Kumamoto, K. Omukai, H. Susa, K. Takahashi, A. A. Trani, H. Umeda, L. Wang, T. Yoshida

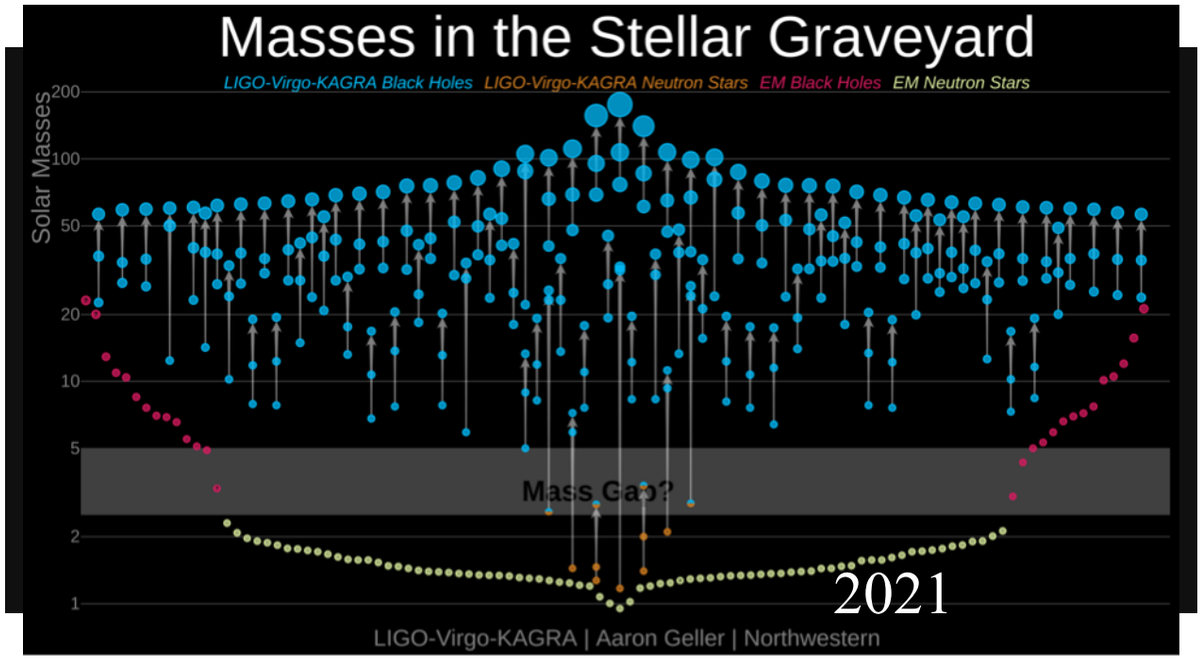
AT, Yoshida, Kinugawa, Trani, Hosokawa, Susa, Omukai (2021, arXiv:2110.10846, ApJ accepted)
Trani, AT, Fujii, Leigh, Kumamoto (2021, MNRAS, 910, 919
Kumamoto, Fujii, AT (2020, MNRAS, 495, 4268)

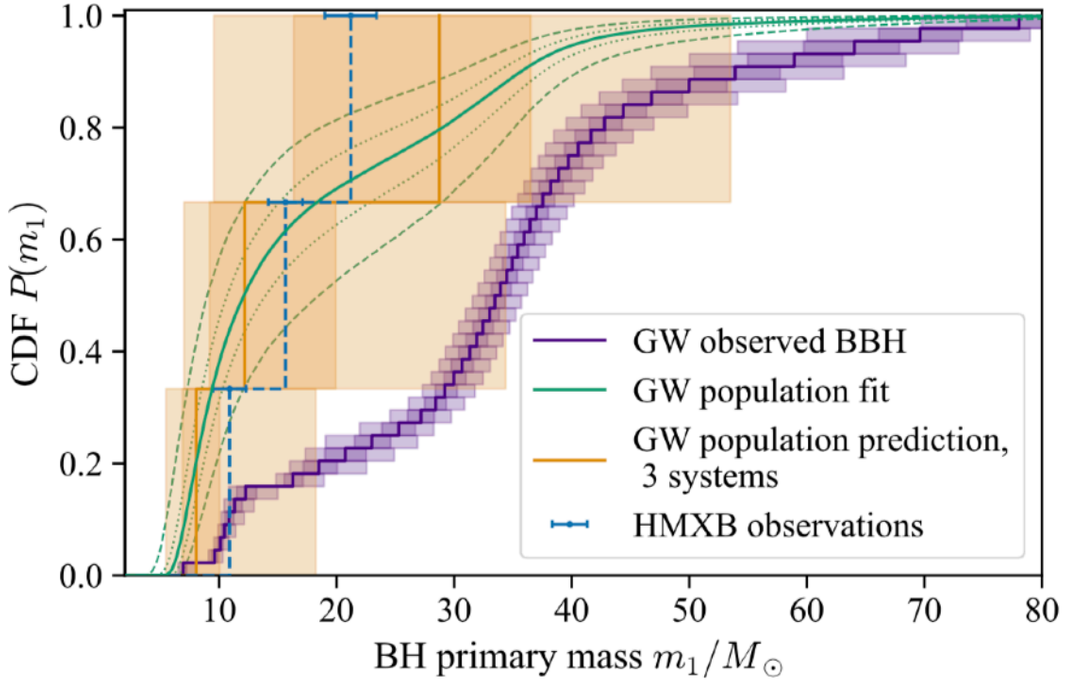


文部科学省 科学研究費助成事業（研究領域提案型）平成29～33年度 Gravitational wave physics and astronomy: Genesis（重力波物理学・天文学：創世記）領域番号：2905

Discovery of BH mergers

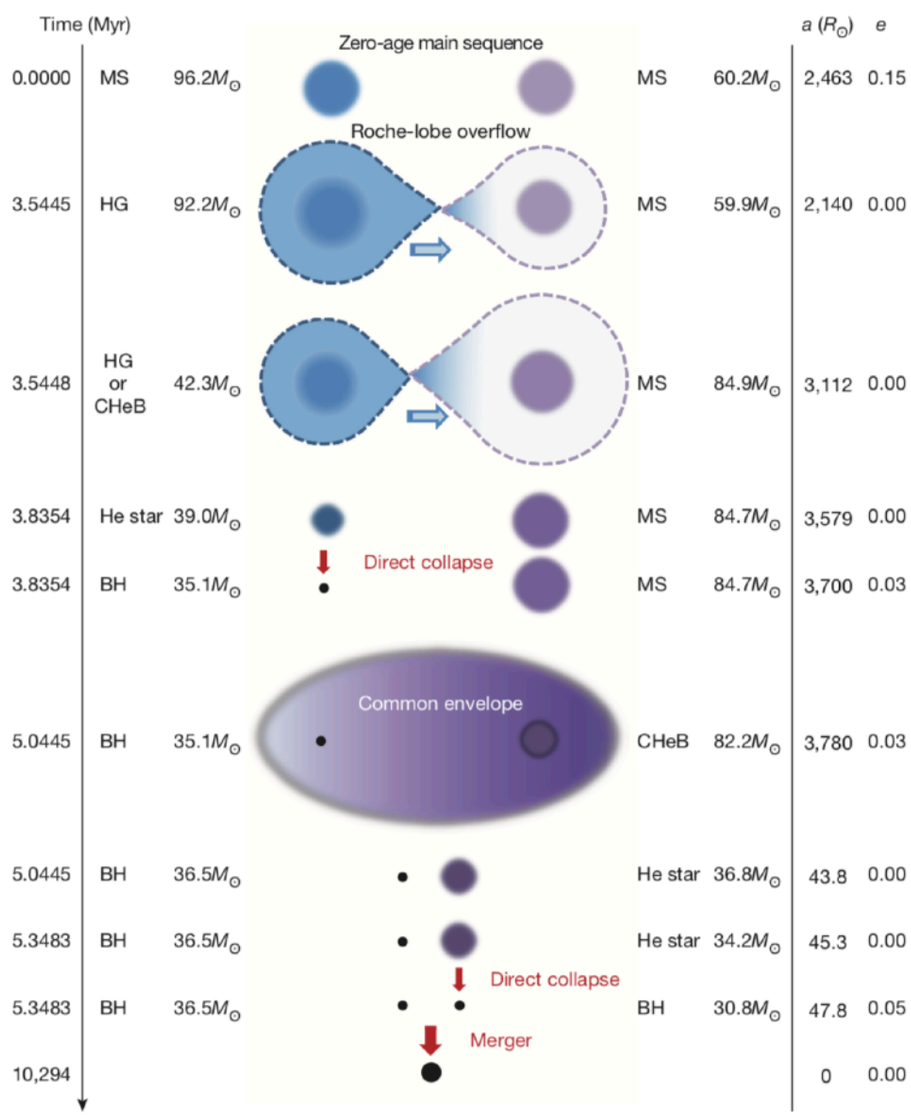
- Rapid growth of the number of BH mergers discovered by GW observations
  - 2015: The first BH merger (Abbott et al. 2016)
  - 2021: The number of BH mergers ~ 80 (Abbott et al. 2021)
- BH mass
  - X-ray observed BHs: $\sim 10 M_\odot$
  - GW observed BHs: $\sim 30 M_\odot$
- Difference of origins ?
  - Metal-poor binary stars, dense star clusters, galactic centers, PBHs, …



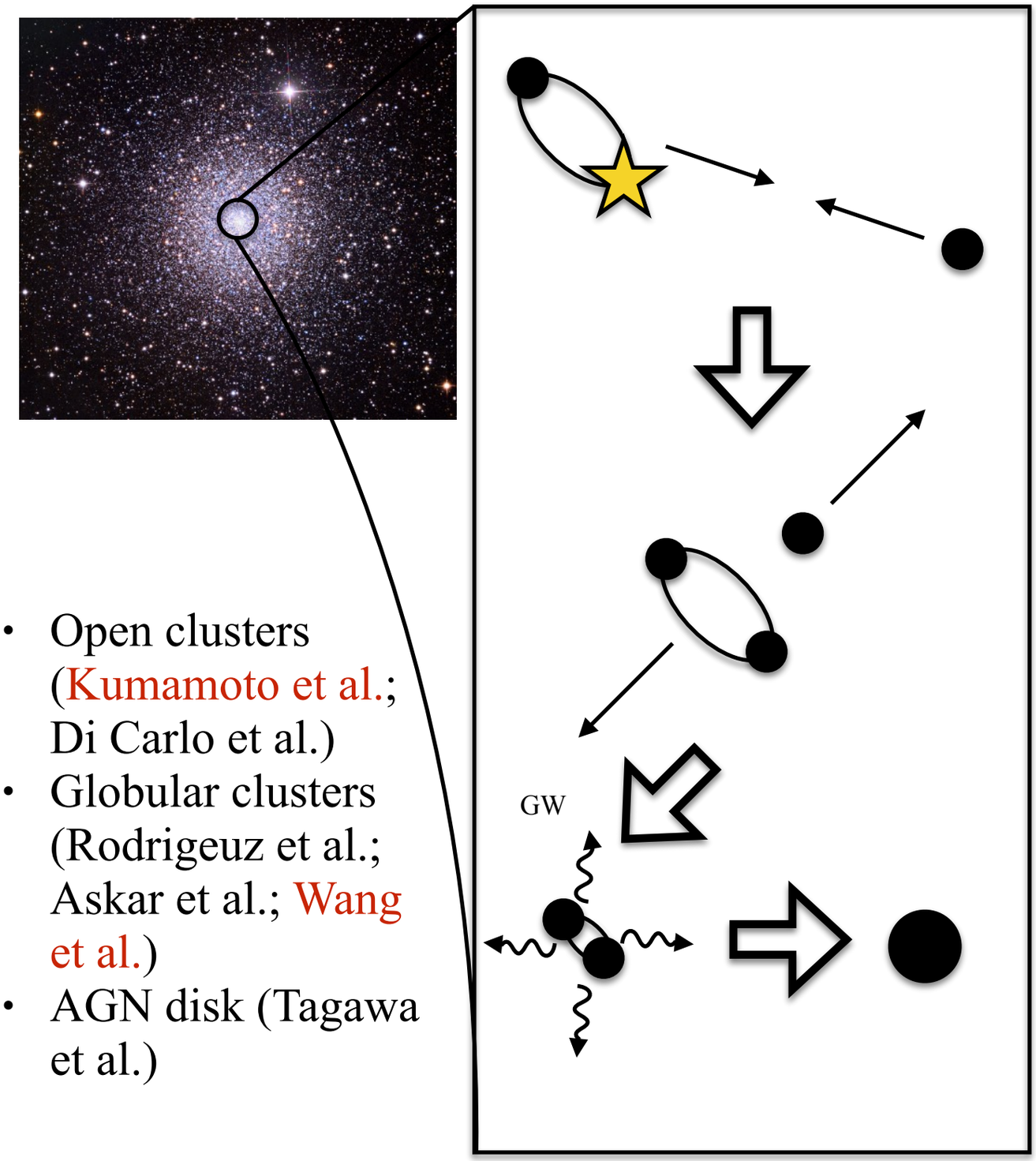


Fishbach & Kalogera (2021)

Isolate binary scenario



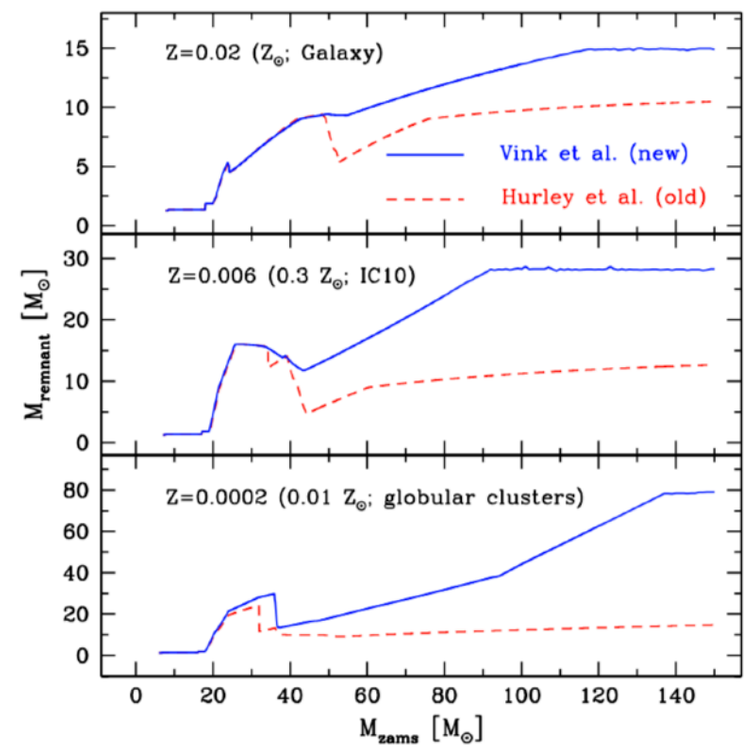
Belczynski et al.; Eldridge et al.; Giacobbo et al.; Kinugawa et al.; Kruckow et al.; Stevenson et al.; Tanikawa et al.;



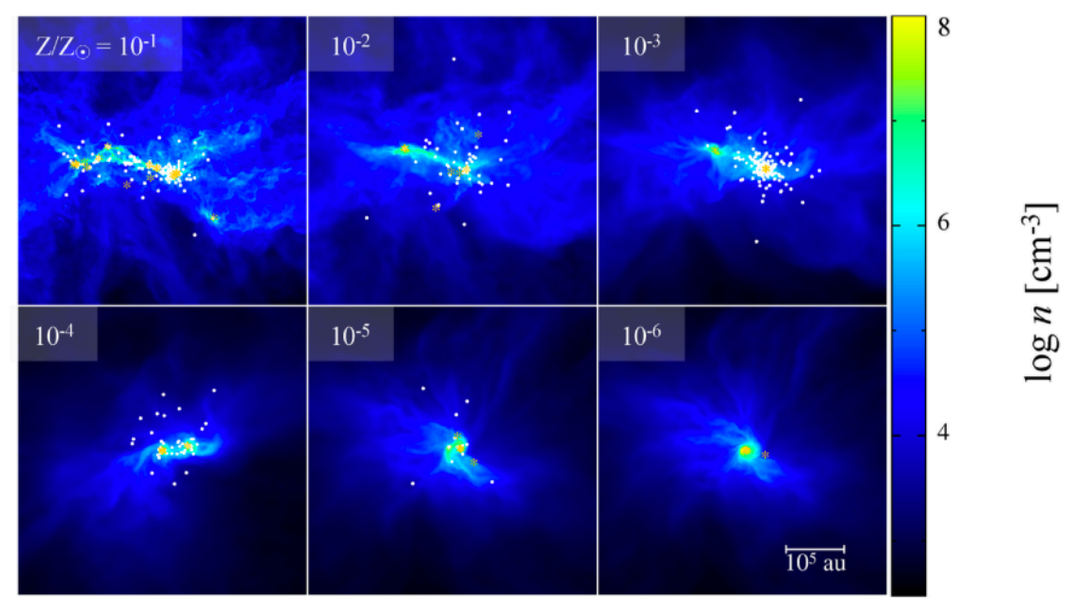
- Open clusters (Kumamoto et al.; Di Carlo et al.)
- Globular clusters (Rodrigeuz et al.; Askar et al.; Wang et al.)
- AGN disk (Tagawa et al.)

Metallicity

- Metallicity dependence is a reasonable solution of BH mass difference between X-ray and GW observed BHs.
- Stellar winds
  - Metal-poor → weak stellar winds → massive BHs
  - (Heger et al. 2003; Mapelli et al. 2009; Belczynski et al. 2010; Spera et al. 2015)
- IMF
  - Top-light for $Z/Z_\odot \gtrsim 10^{-5}$
  - Top-heavy for $Z/Z_\odot \lesssim 10^{-5}$
  - (Bromm, Larson 2004; Omukai et al. 2005; Schneider et al. 2006; Maio et al. 2010)



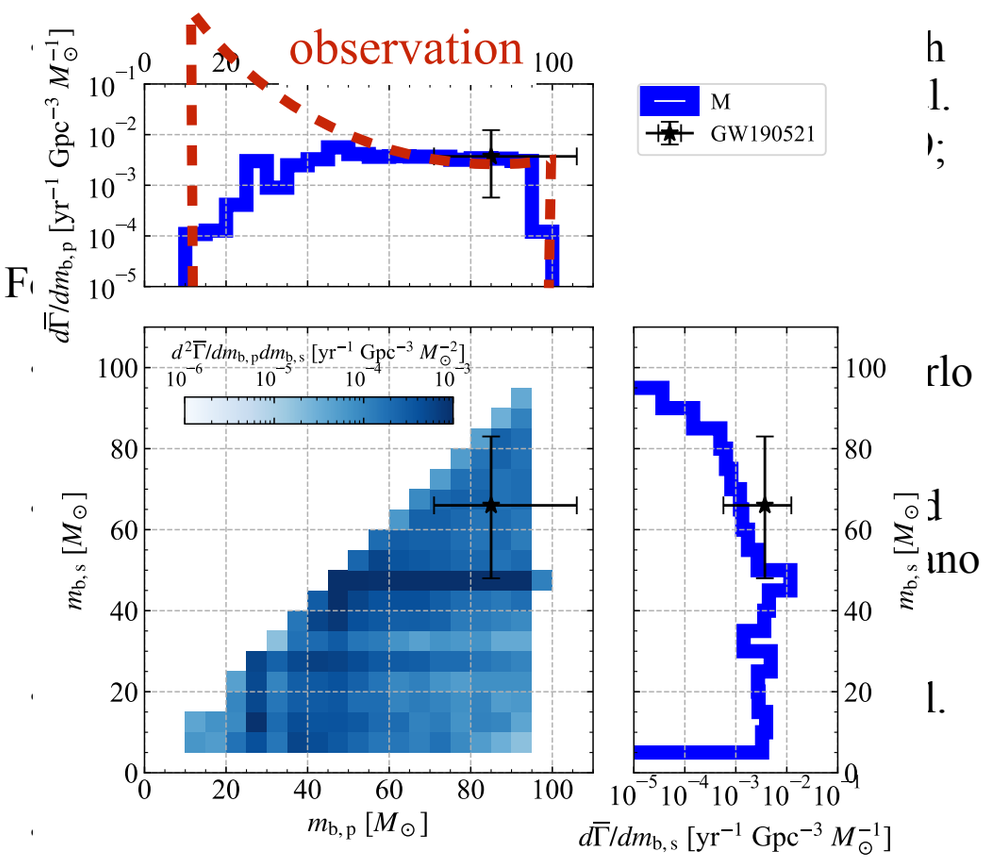
Belczynski et al. (2010)



Chon et al. (2021)

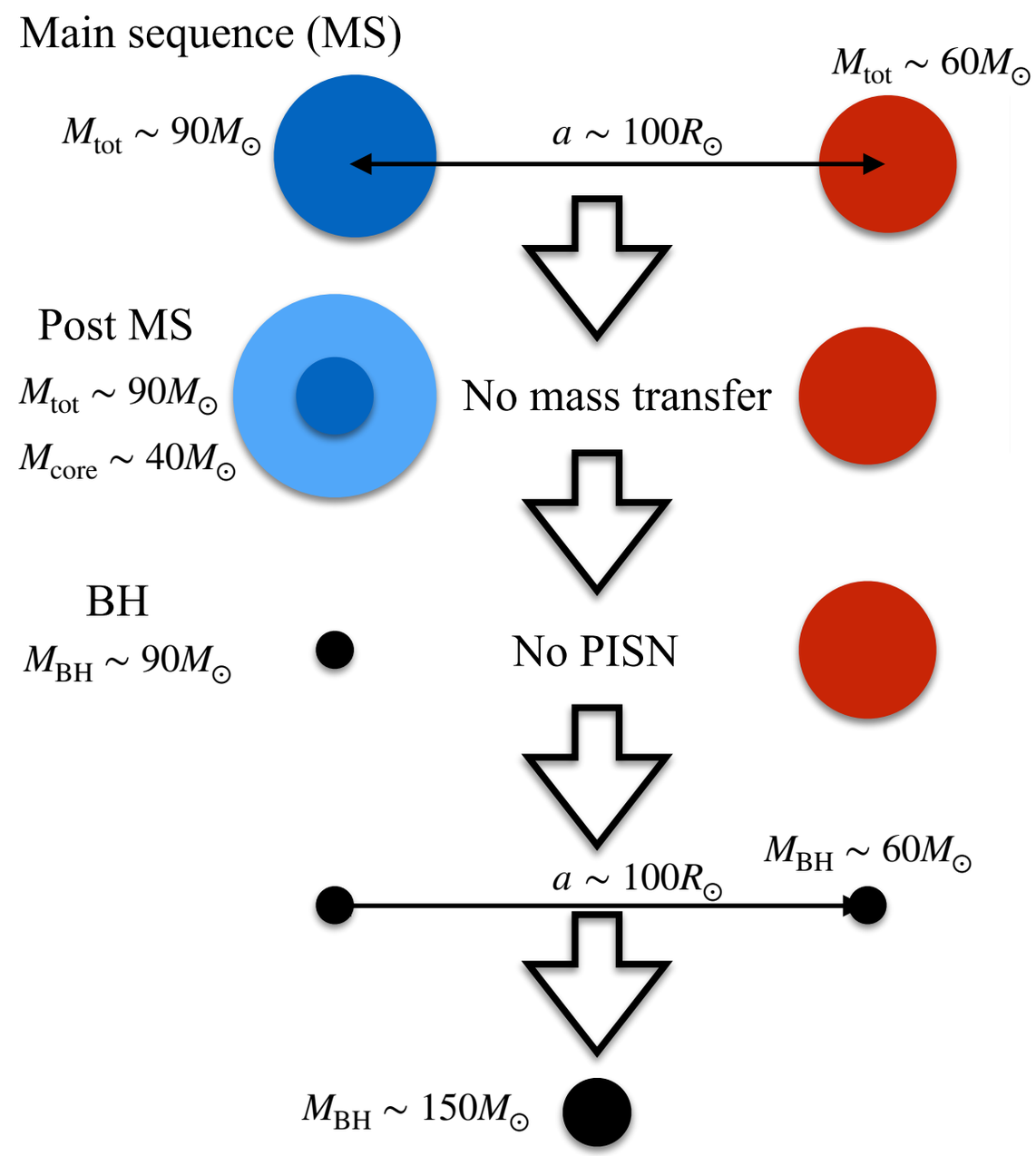
Pair instability (PI) Mass gap

- GW190521: a merger of $85M_\odot$ and $66M_\odot$ BHs



mass gap (Farmer et al. 2020; Costa et al. 2021)

- EMP and Pop III stars (Kinugawa et al. 2020; Tanikawa et al. 2021, MNRAS, 505, 2170)

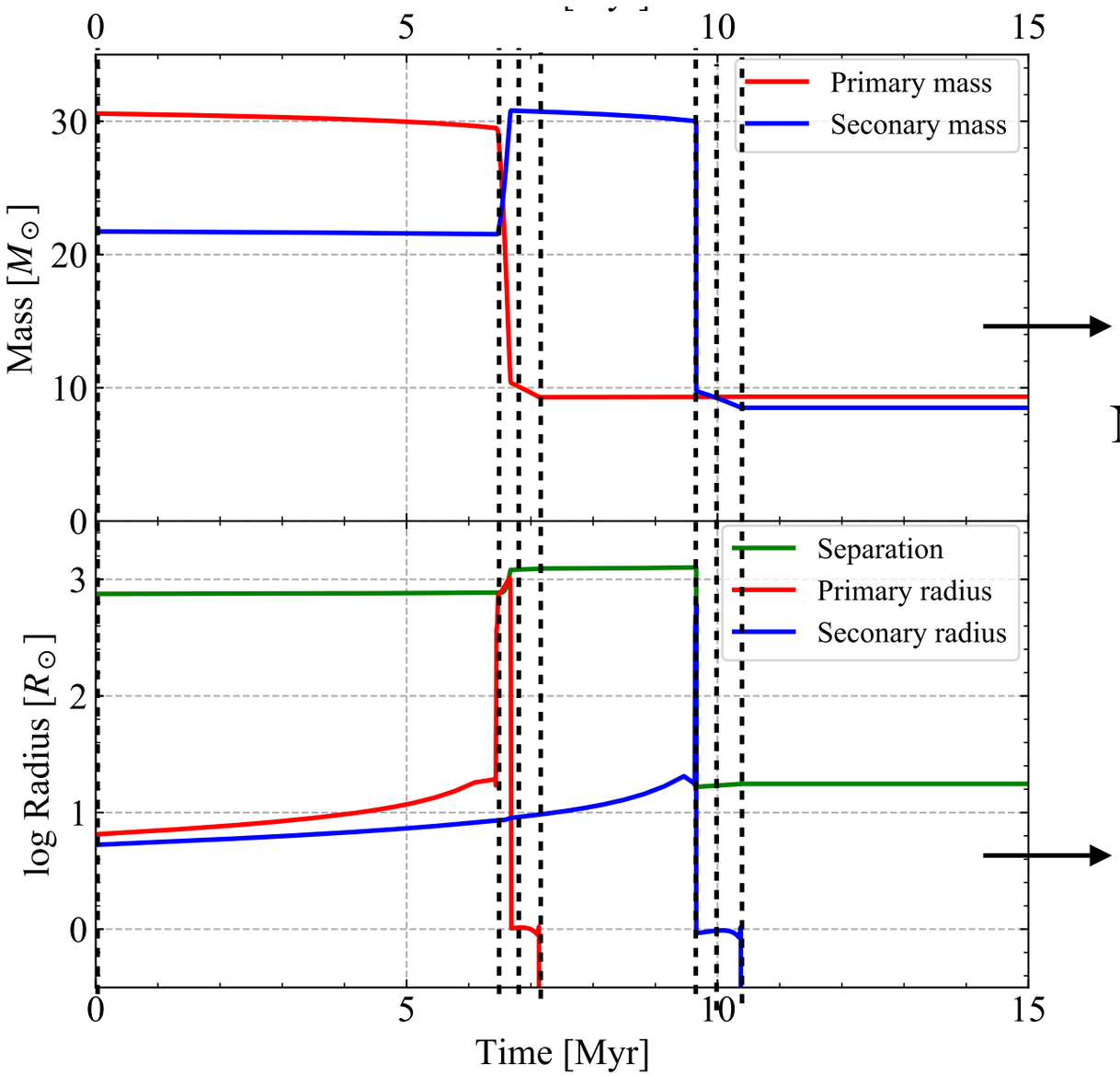


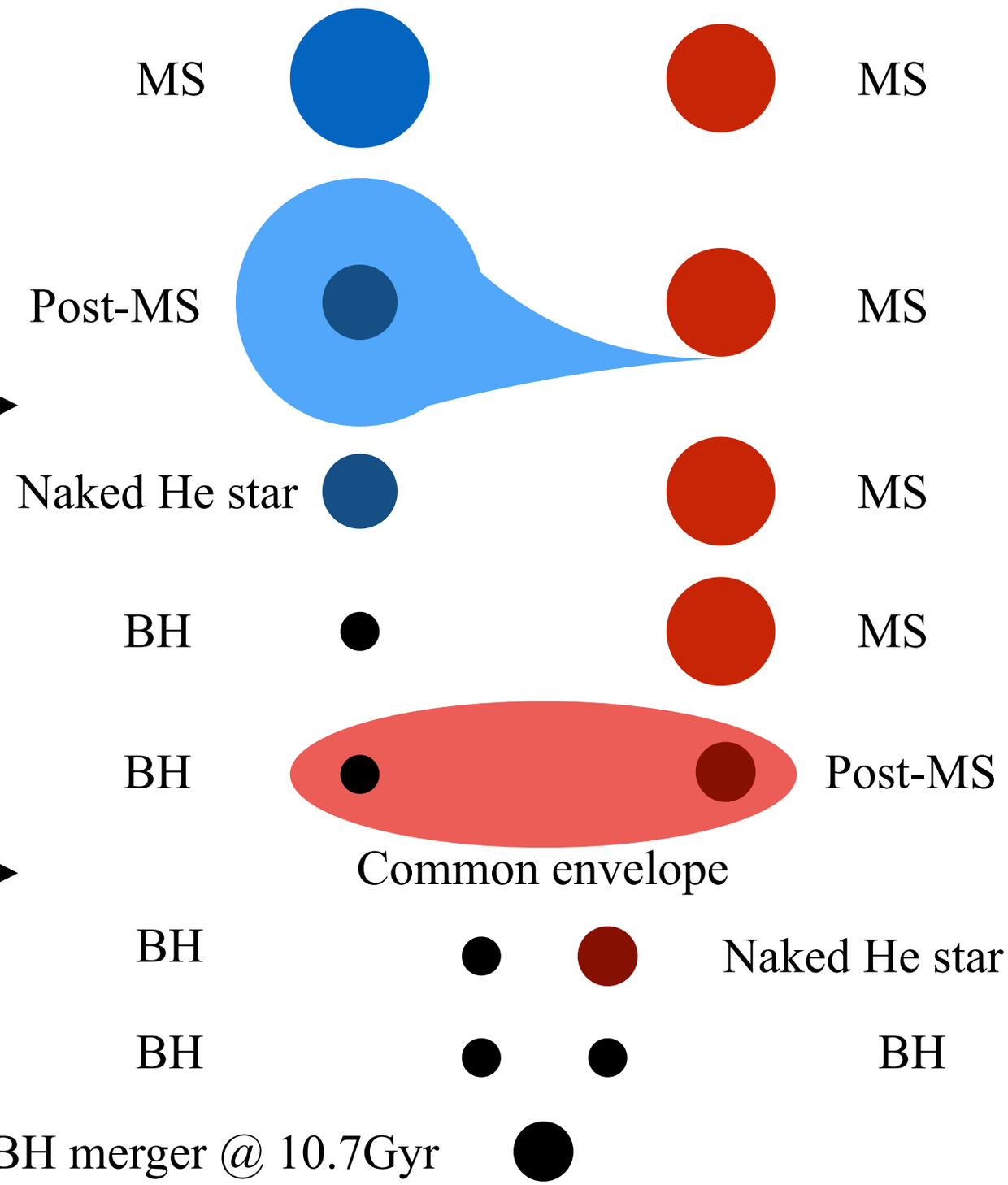
Our study

- Merging binary BHs from all the metallicities (Pop I, II, III, EMP stars) by the world's first binary population synthesis calculations
  - Only Pop I/II: BSE (Hurley et al. 2002); binary_c (Izzard et al. 2009); SeBa (Toonen et al. 2012); BPASS (Eldridge, Stanway 2016); MOBSE (Giacobbo et al. 2018); COSMIC (Breivik et al. 2020); COMPAS (Team COMAS et al. 2021)
  - Pop I/II/III: BSE+Pop III (Kinugawa et al. 2020); StarTrack (Belczynski 2002; 2017, but see Inayoshi et al. 2017)
- Pop I: $Z/Z_\odot > 0.16$, Pop II: $10^{-3} < Z/Z_\odot \leq 0.16$, EMP: $0 < Z/Z_\odot \leq 10^{-3}$, Pop III: $Z/Z_\odot = 0$

Binary population synthesis

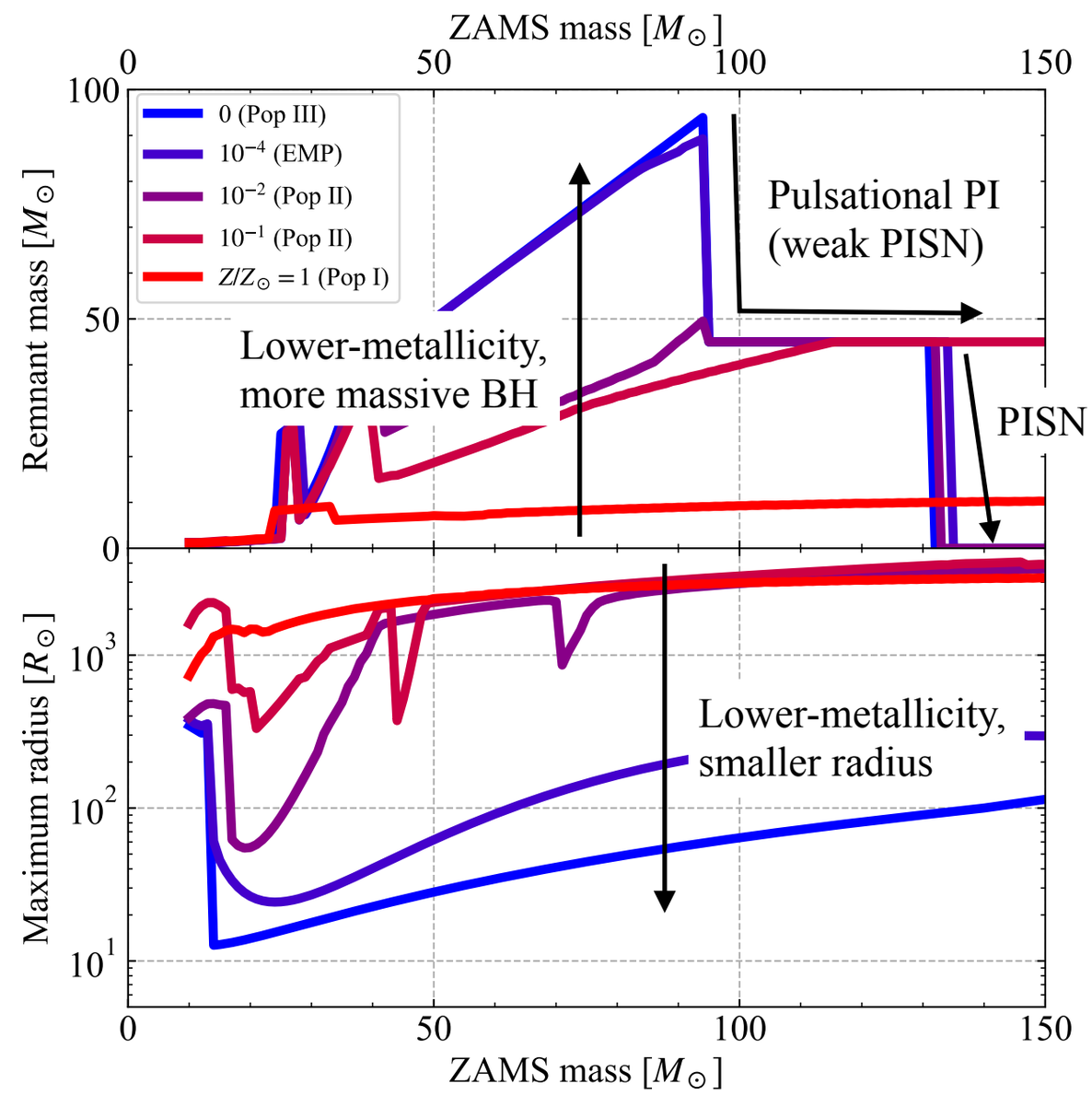
$0.25Z_\odot$, $31M_\odot$, $22M_\odot$, $7500R_\odot$





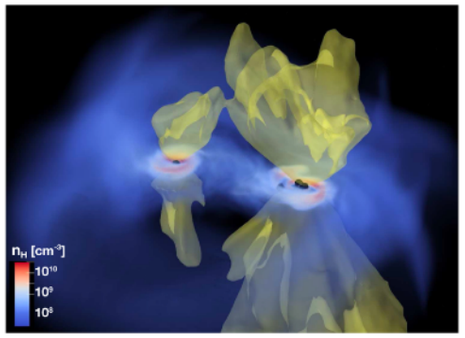
Binary evolution model

- Metallicity
  - $0, 10^{-6}, 10^{-4}, 10^{-2}, 0.025, 0.05, 0.1 Z_{\odot}$ (Tanikawa et al. 2021)
  - $0.25, 0.5, 1 Z_{\odot}$ (Hurley et al. 2000)
- Stellar winds (Belczynski et al. 2010), Supernova model (Fryer et al. 2012; Belczynski et al. 20160), Fallback BH kick (Hobbs et al. 2005; Fryer et al. 2012)
- Wind accretion, tidal interaction, mass transfer, common envelope, gravitational wave radiation… (Hurley et al. 2002)

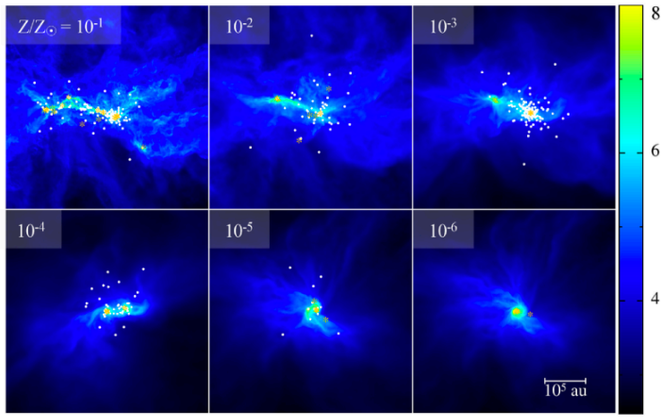


Initial conditions

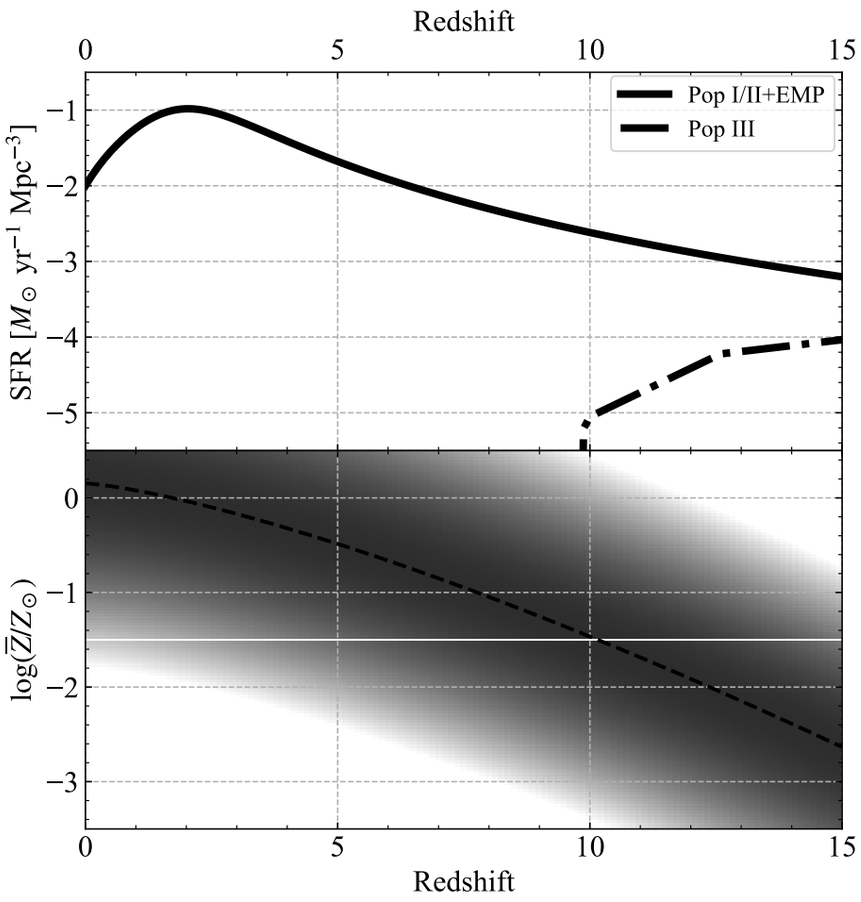
- Binary stars
  - Binary number fraction: 50% for all Z
  - Chon's IMF
    - $f(m)dm \propto m^{-2.3}dm$ ($Z/Z_\odot > 10^{-2}$)
    - $f(m)dm \propto m^{-1}dm$ ($Z/Z_\odot \leq 10^{-6}$)
    - Mixture ($10^{-6} < Z/Z_\odot \leq 10^{-2}$)
  - Distributions of mass ratios, periods, and eccentricities (Sana et al. 2012)
- Overall star formation
  - Star formation rate (Madau, Fragos 2017; Skinner, Wise 2020)
  - Average metallicity (Madau, Fragos 2017)
  - Metallicity distribution for non-Pop III: log-norma distribution with $\sigma = 0.35$



Sugimura et al. (2020)



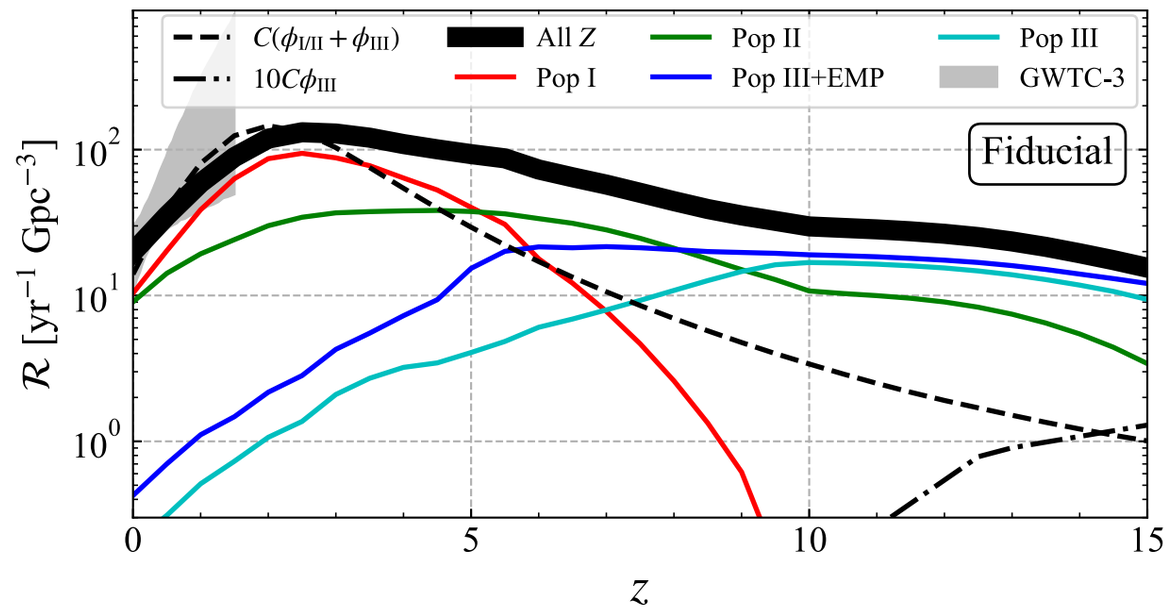
Chon et al. (2021)



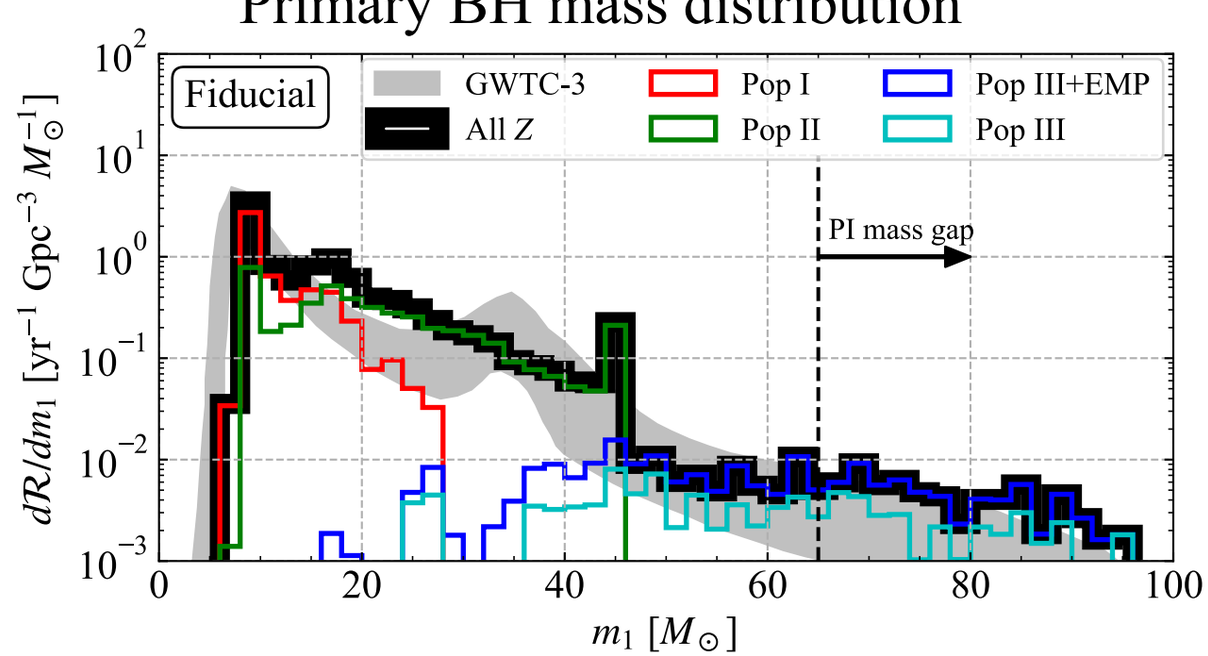
Merger rate and mass distribution

- Consistent with the local merger rate
  - Dominance of Pop I/II stars in low-redshift universe
  - Dominance of EMP+Pop III stars in high-redshift universe
- Consistent with the mass distribution in the local universe
  - $5 - 20 M_\odot$: Pop I
  - $20 - 50 M_\odot$: Pop II
  - $50 - 100 M_\odot$: EMP+Pop III
- All metallicities are required for all BH mergers!

Redshift evolution of the merger rate

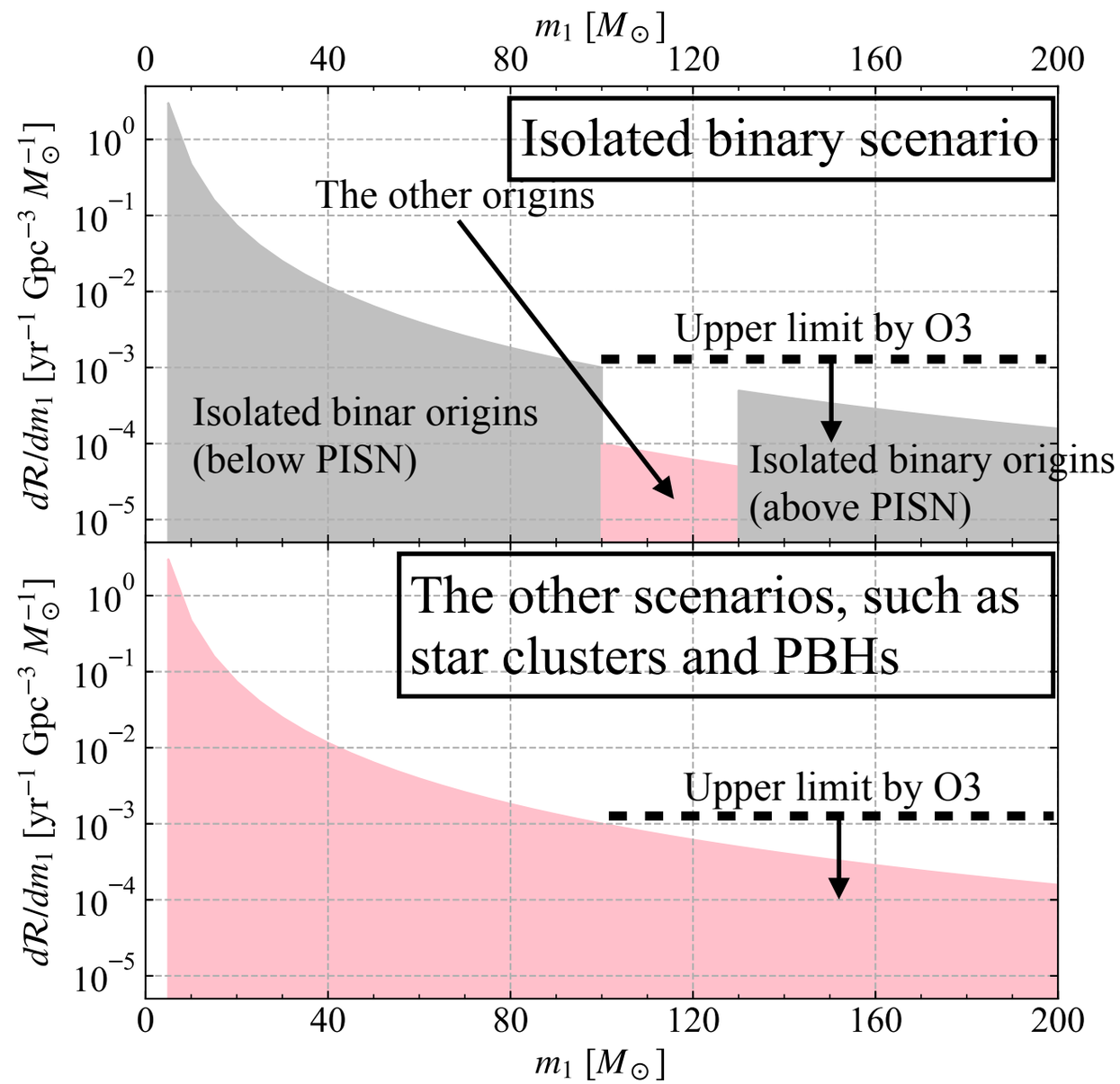


Primary BH mass distribution



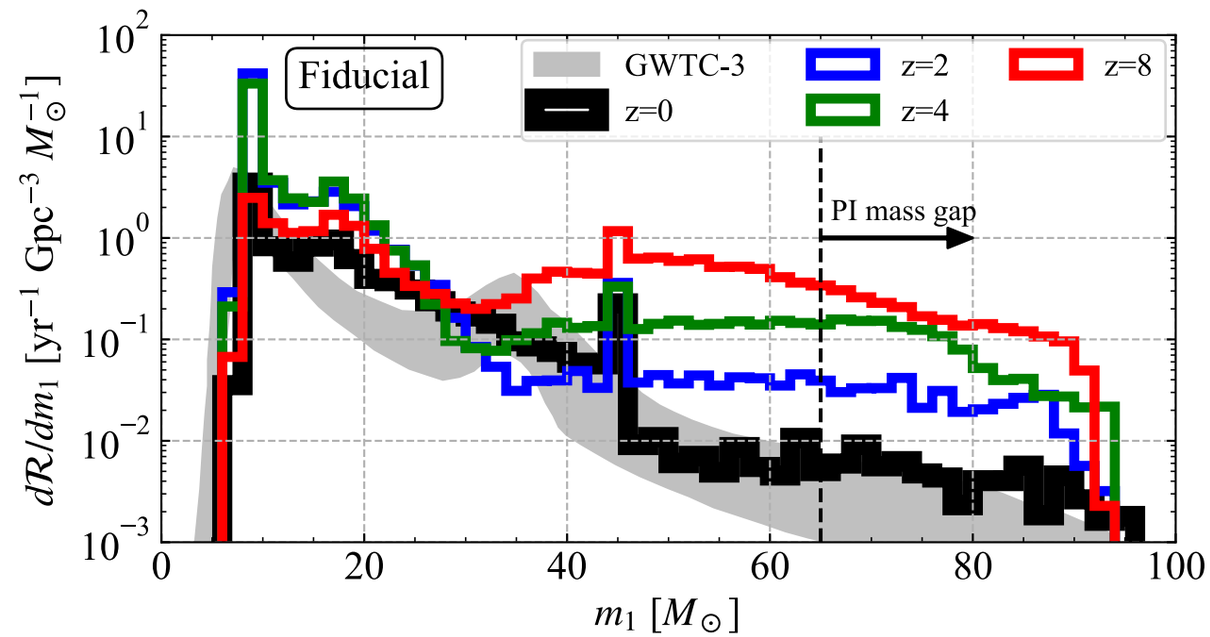
Difference from other scenarios

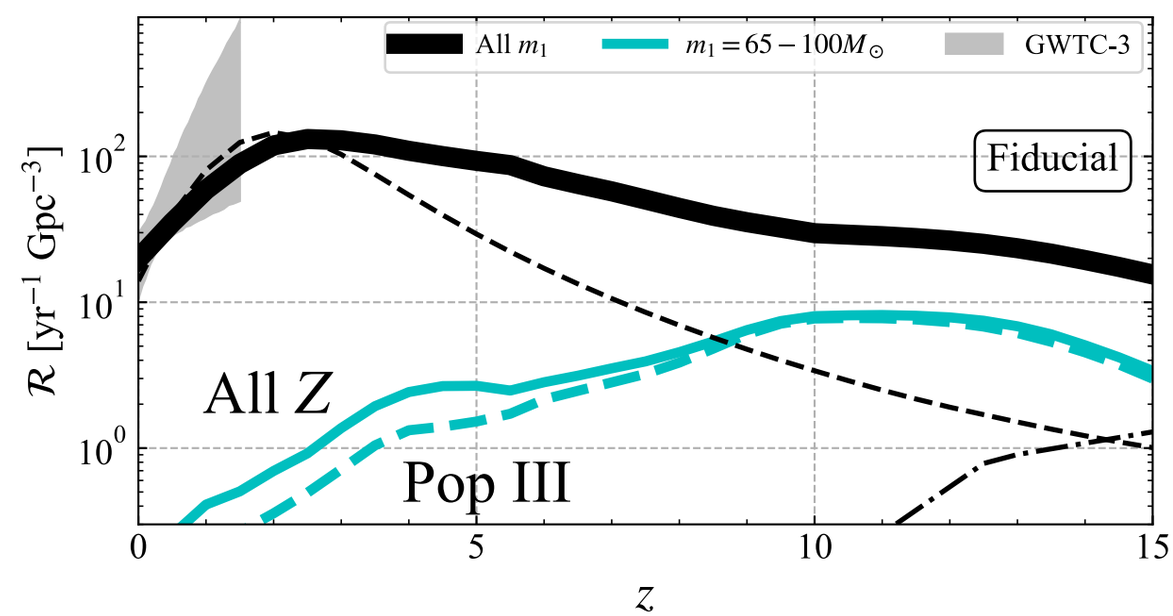
- No BH with $m_1 = 100 - 130 M_\odot$ in the isolated binary scenario
  - $m_1 \lesssim 100 M_\odot$: below PISN
  - $m_1 \gtrsim 130 M_\odot$: above PISN
- Not true in the other scenarios
- If isolated binary origins are dominant, there should be a sort of "hole" in the range of $m_1 = 100 - 130 M_\odot$
- Merger rate of BHs with $m_1 > 100 M_\odot$ can be constrained in the near future
  - The upper limit becomes more stringent from O2 to O3 (Abbott et al. 2021, arXiv: 2105.15120).



Redshift evolution of mass distribution

- $< 20 M_\odot$: Similar to star formation history
- $20 - 40 M_\odot$: no redshift evolution
- $> 40 M_\odot$: Larger with redshift
- PI mass gap ($65 - 100 M_\odot$)
  - Peat at $z \sim 11$
  - Pop III is dominant in the high-redshift universe
- A possible probe for Pop III stars

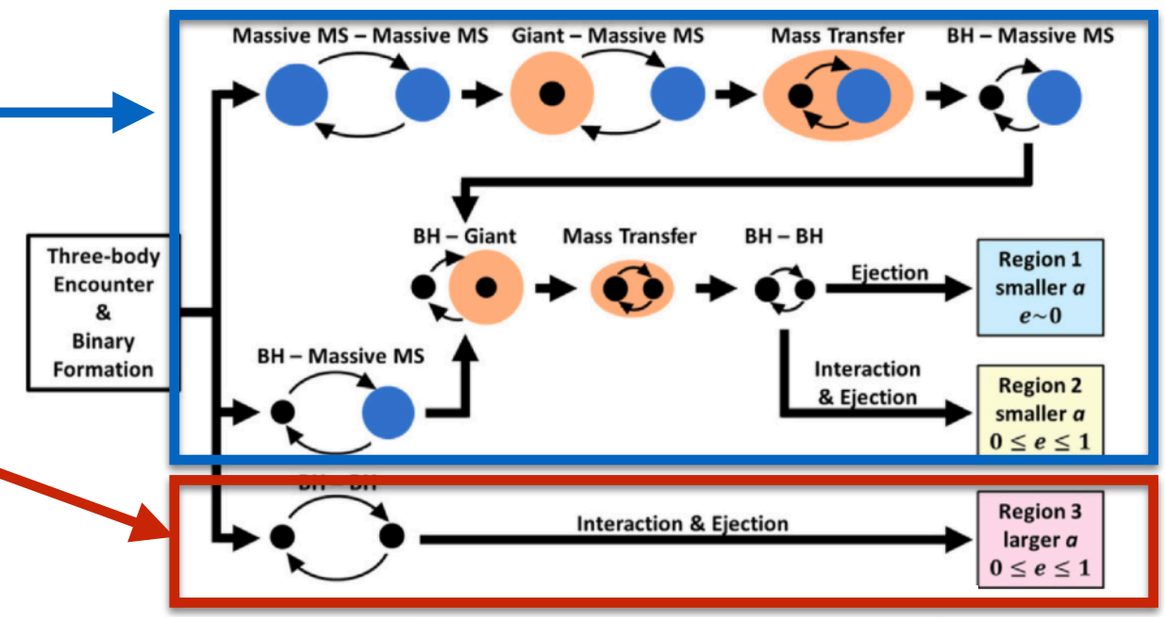


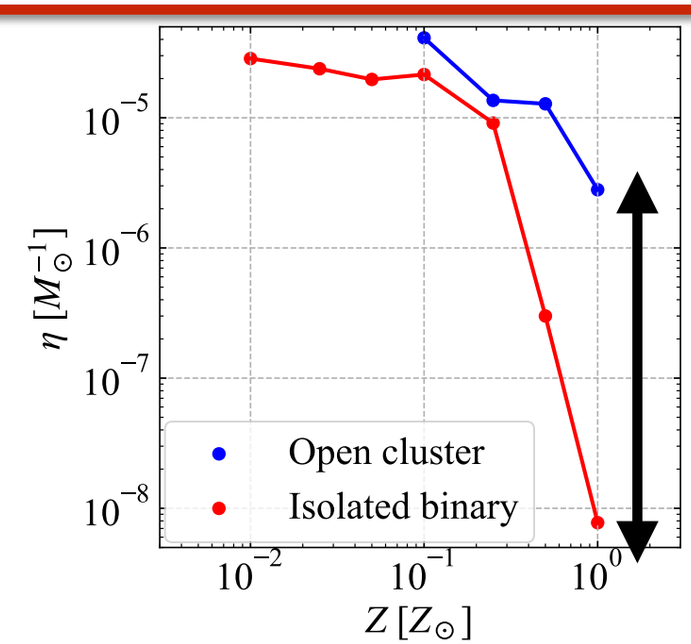


Difference between isolated binaries and open clusters

- Main processes
  - Metal-poor stars: common envelope evolution
  - Metal-rich stars: dynamical capture
- Merger efficiency: $\eta = N_{\mathrm{BH-BH}}/M_{\mathrm{star}}\ [M_\odot^{-1}]$
- N-body processes are more effective for lower-mass BHs (see also Wang et al. 2021)

BH-BH formation in open clusters



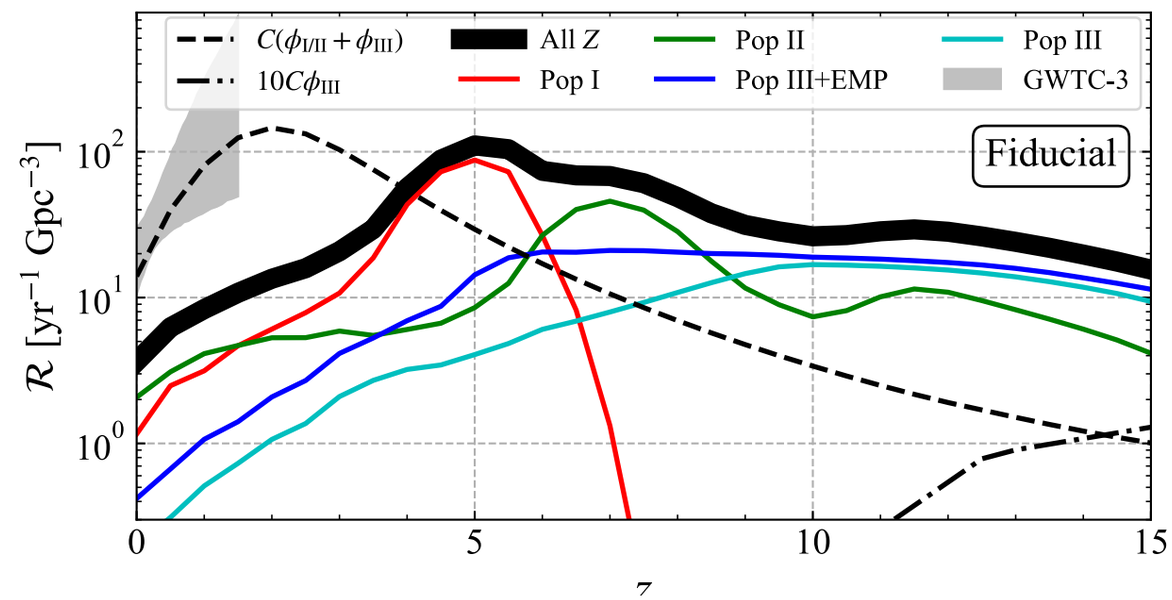


Kumamoto et al. (2020; see also Boufanais et al. 2021)

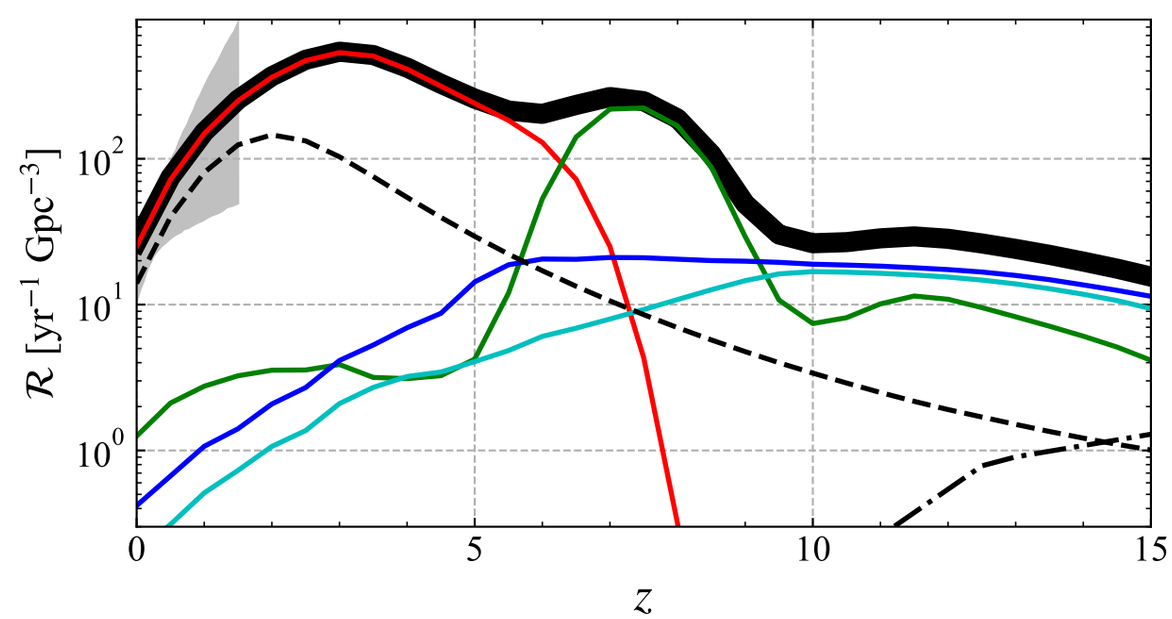
Metallicity dispersion

- Cosmic evolution of metallicity distribution
  - $p(z, Z) = (2\pi\sigma_Z)^{-1/2}\exp\left\{-\frac{\left[\log(Z/\overline{Z})\right]^2}{2\sigma_Z^2}\right\}$
  - Average metallicity
    - $\log \overline{Z}/Z_\odot = 0.153 - 0.074z^{1.34}$
  - Metallicity dispersion: σ_Z
    - $\sigma_Z = 0.35 \rightarrow 0.10$
- A numerical simulation prefers to 0.35 (Chruslinska et al. 2019)
- BH formation in open clusters can be mandatory if the actual metallicity dispersion is smaller than expected by the numerical simulation.

Isolated binary with $\sigma_Z = 0.10$



Open cluster with $\sigma_Z = 0.10$



Summary

- Binary population synthesis for binary stars with all the metallicities
- Need all the metallicities Pop I, II, III and EMP stars to reproduce the BH merger rate and mass distribution consistent with the GW observations
- Predict little merging BHs with $m_1 = 100 - 130 M_\odot$, verifiable by LIGO, Virgo, and KAGRA in 2020s.
- Predict that the merger rate of BHs with $m_1 \geq 65 M_\odot$ achieves a peak at $z \sim 11$, verifiable by Einstein Telescope, Cosmic Explorer, and DECIGO in 2030s.
- Suggest that $m_1 \geq 65 M_\odot$ BH mergers are a probe for Pop III stars.
- Require open-cluster origin BHs if this universe has small metallicity dispersion.