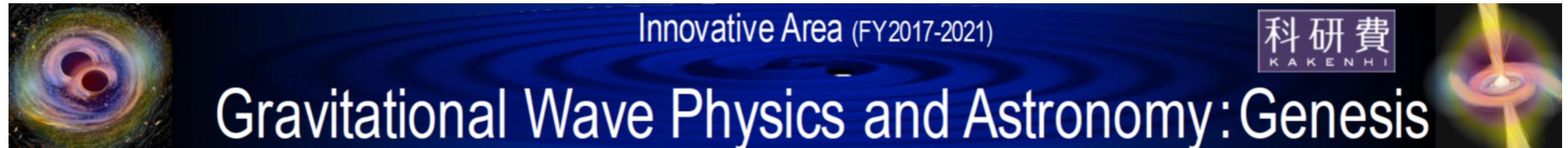


# 孤立連星から形成される 連星ブラックホールと初代星の重要性

初代星・初代銀河研究会 2021  
谷川衝（東大駒場）

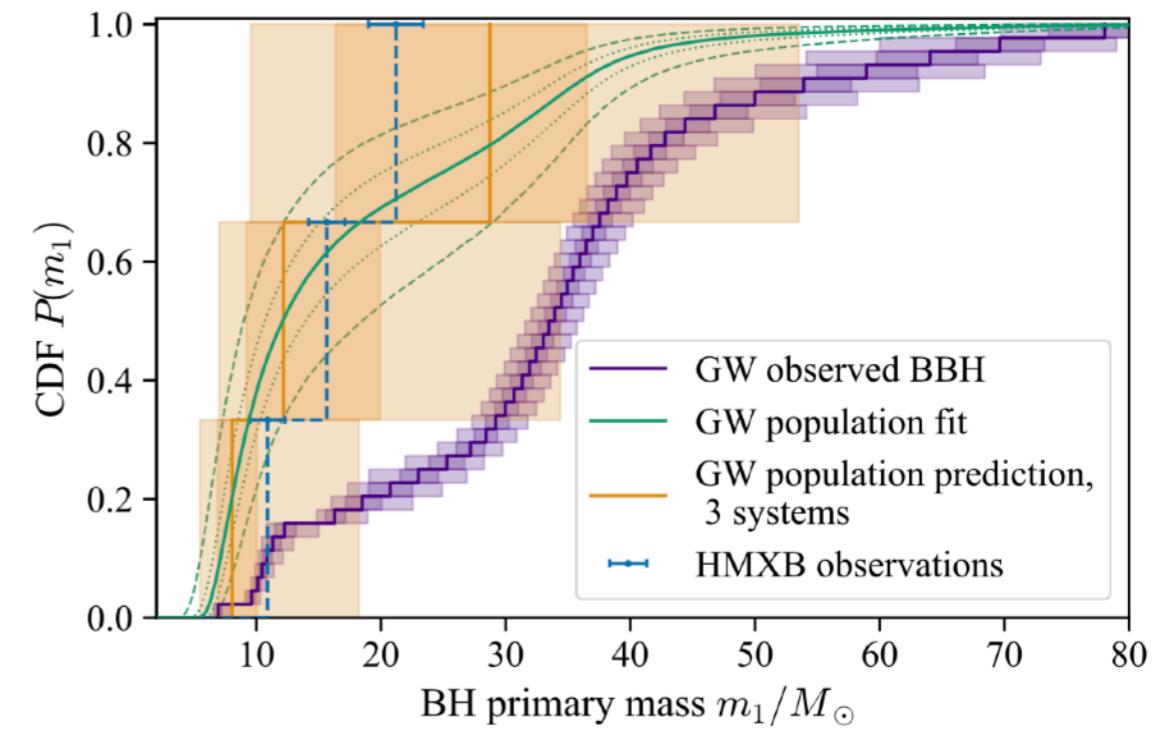
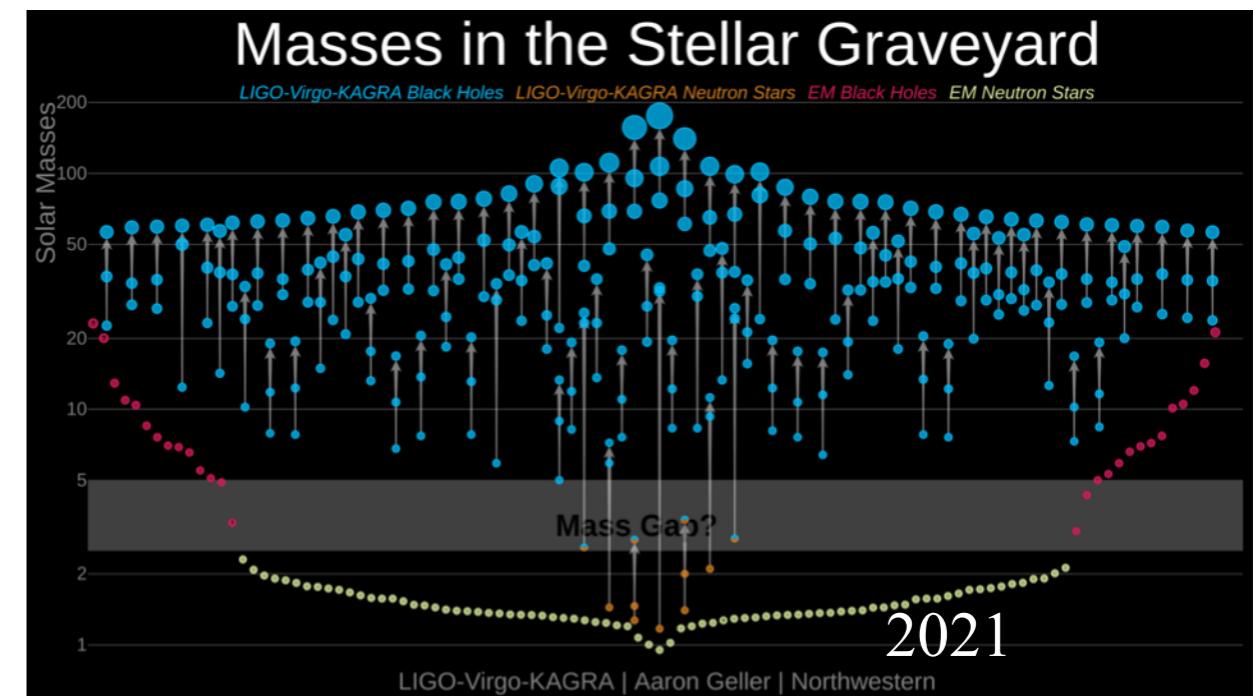
AT, Yoshida, Kinugawa, Trani, Hosokawa, Susa, Omukai (2022, ApJ, 926, 83)  
AT, Kinugawa, Yoshida, Hijikawa, Umeda (2021, MNRAS, 505, 2170)  
AT, Susa, Yoshida, Trani, Kinugawa (2021, ApJ, 910, 30)



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  $\sim 80$  (Abbott et al. 2021)
- BH mass
  - X-ray observed BHs:  $\sim 10M_{\odot}$
  - GW observed BHs:  $\sim 30M_{\odot}$
- Difference of origins ?
  - Metal-poor binary stars, dense star clusters, galactic centers, PBHs, ...



Fishbach & Kalogera (2021)

# Isolated binary scenario

- BH-BH density:

$$n_{\text{BH-BH}} \sim 10^{11} \text{Gpc}^{-3} \left( \frac{\Gamma_{\text{BH-BH}}}{10 \text{Gpc}^{-3} \text{yr}^{-1}} \right) \left( \frac{T_{\text{Hubble}}}{10 \text{Gyr}} \right)$$

- Isolated binary (IB):

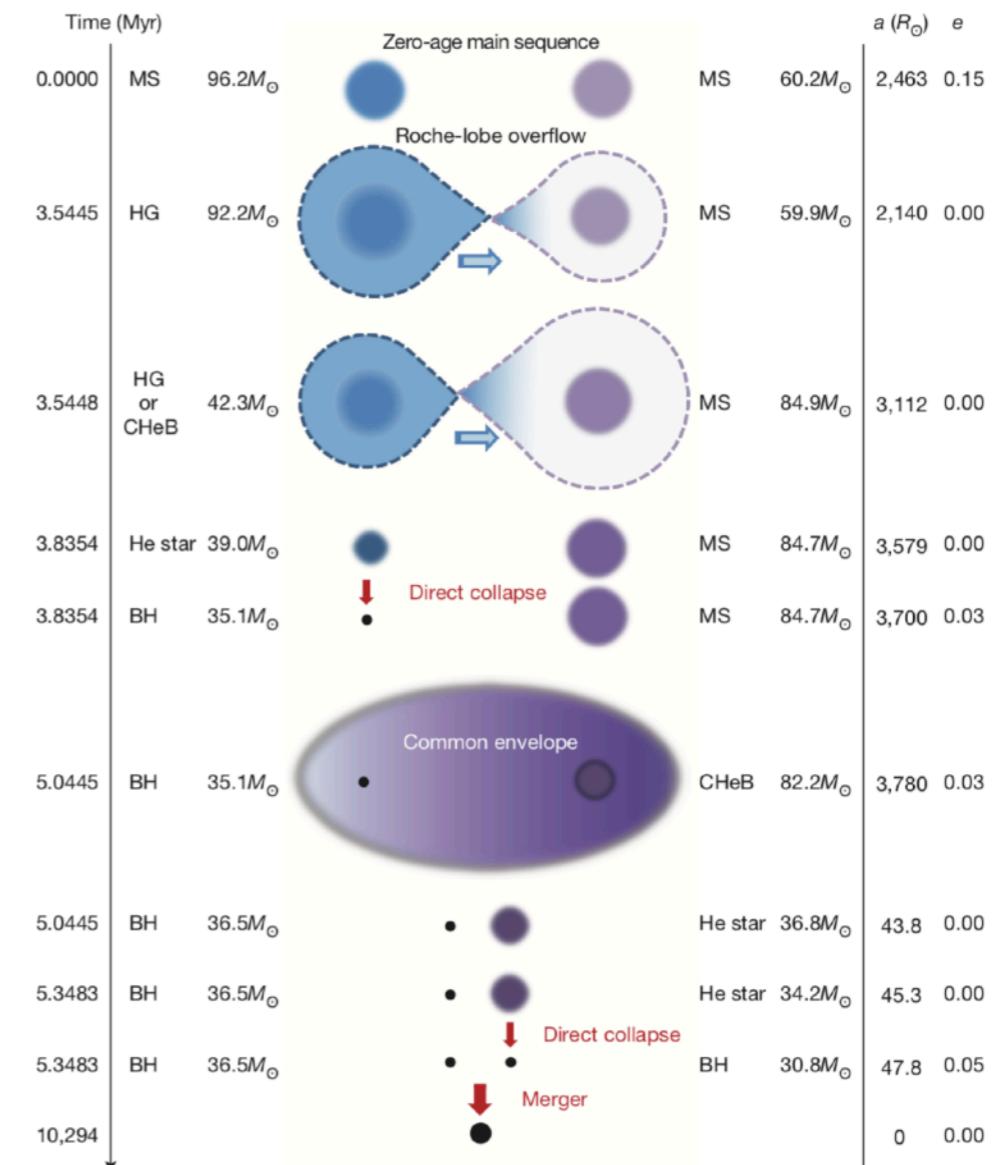
- $n_{\text{BH,IB}} \sim 10^{15} \text{Gpc}^{-3} \left( \frac{\rho_{\text{star}}}{10^{18} M_{\odot} \text{Gpc}^{-3}} \right) \left( \frac{\eta_{\text{BH}}}{10^{-3} M_{\odot}^{-1}} \right)$
- $\frac{n_{\text{BH-BH}}}{n_{\text{BH,IB}}} \sim 10^{-4} \left( \frac{\Gamma_{\text{BH-BH}}}{10 \text{Gpc}^{-3} \text{yr}^{-1}} \right)$

- All BH mergers can be explained if only 0.01% of BHs merge.

- Pop III isolated binary (IB3):

- $n_{\text{BH,IB3}} \sim 10^{11} \text{Gpc}^{-3} \left( \frac{\rho_{\text{star}}}{10^{13} M_{\odot} \text{Gpc}^{-3}} \right) \left( \frac{\eta_{\text{BH}}}{10^{-2} M_{\odot}^{-1}} \right)$
- $\frac{n_{\text{BH-BH}}}{n_{\text{BH,IB3}}} \sim 1 \left( \frac{\Gamma_{\text{BH-BH}}}{10 \text{Gpc}^{-3} \text{yr}^{-1}} \right)$

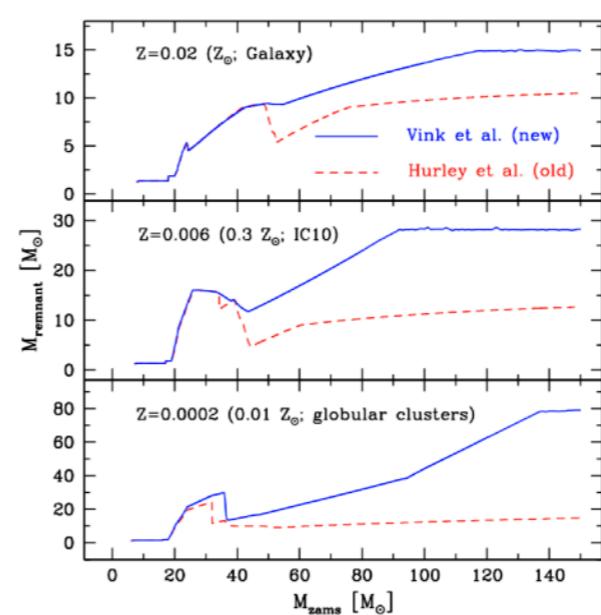
- Pop III stars possibly contribute to a part of BH mergers.



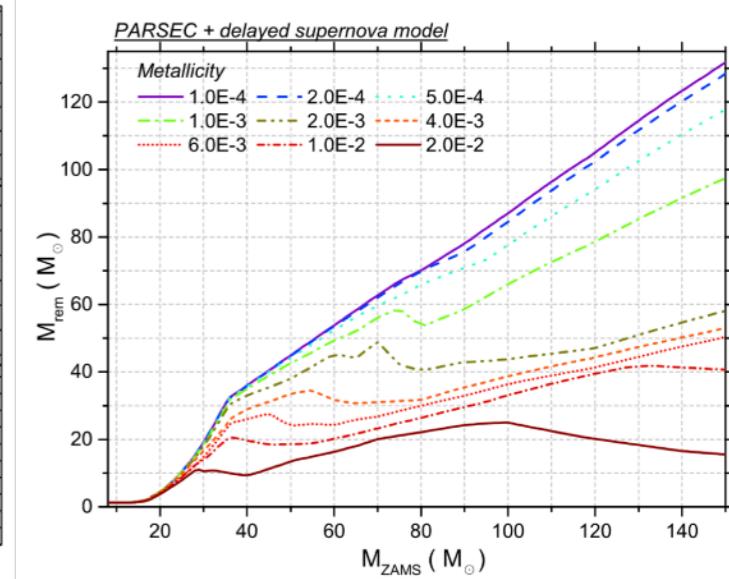
Belczynski et al.; Eldridge et al.; Giacobbo et al.; Kinugawa et al.; Kruckow et al.; Stevenson et al.; Tanikawa et al.;

# Metallicity BH mass and formation efficiency

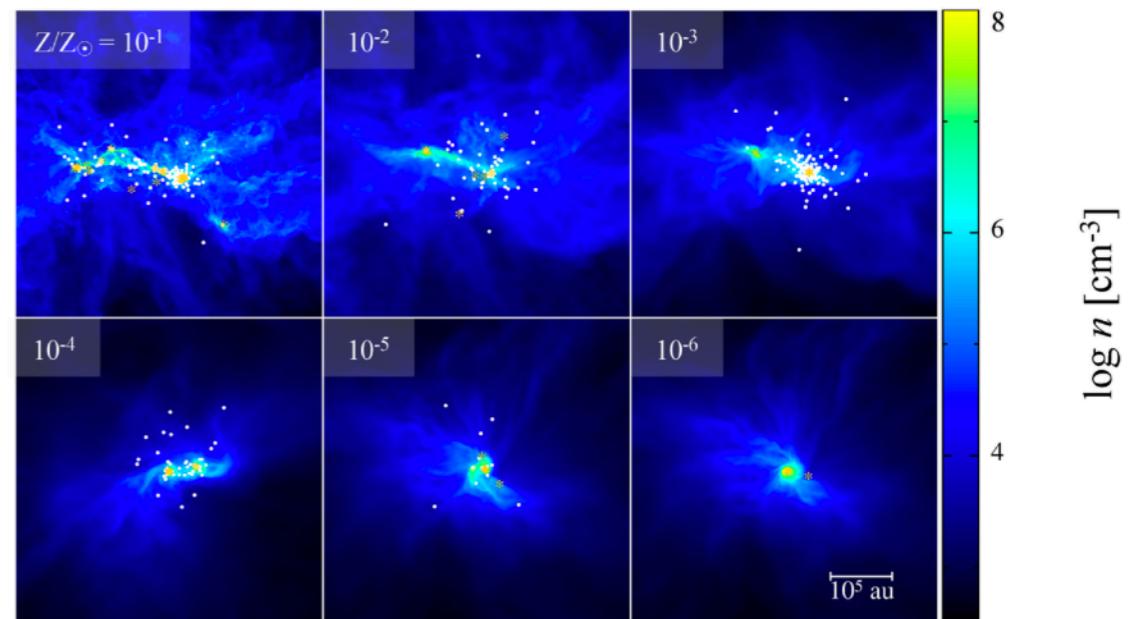
- BH mass sensitive to stellar wind mass loss via metallicity (Heger et al. 2003; Mapelli et al. 2009; Belczynski et al. 2010; Spera et al. 2015)
- BH formation efficiency sensitive to IMF via metallicity
  - Top-light IMF for  $Z/Z_{\odot} \gtrsim 10^{-5}$  and Top-heavy IMF for  $Z/Z_{\odot} \lesssim 10^{-5}$  (Bromm, Larson 2004; Omukai et al. 2005; Schneider et al. 2006; Maio et al. 2010)
  - Mixed IMF for an intermediate metallicity range (Chon et al. 2021)



Belczynski et al. (2010)



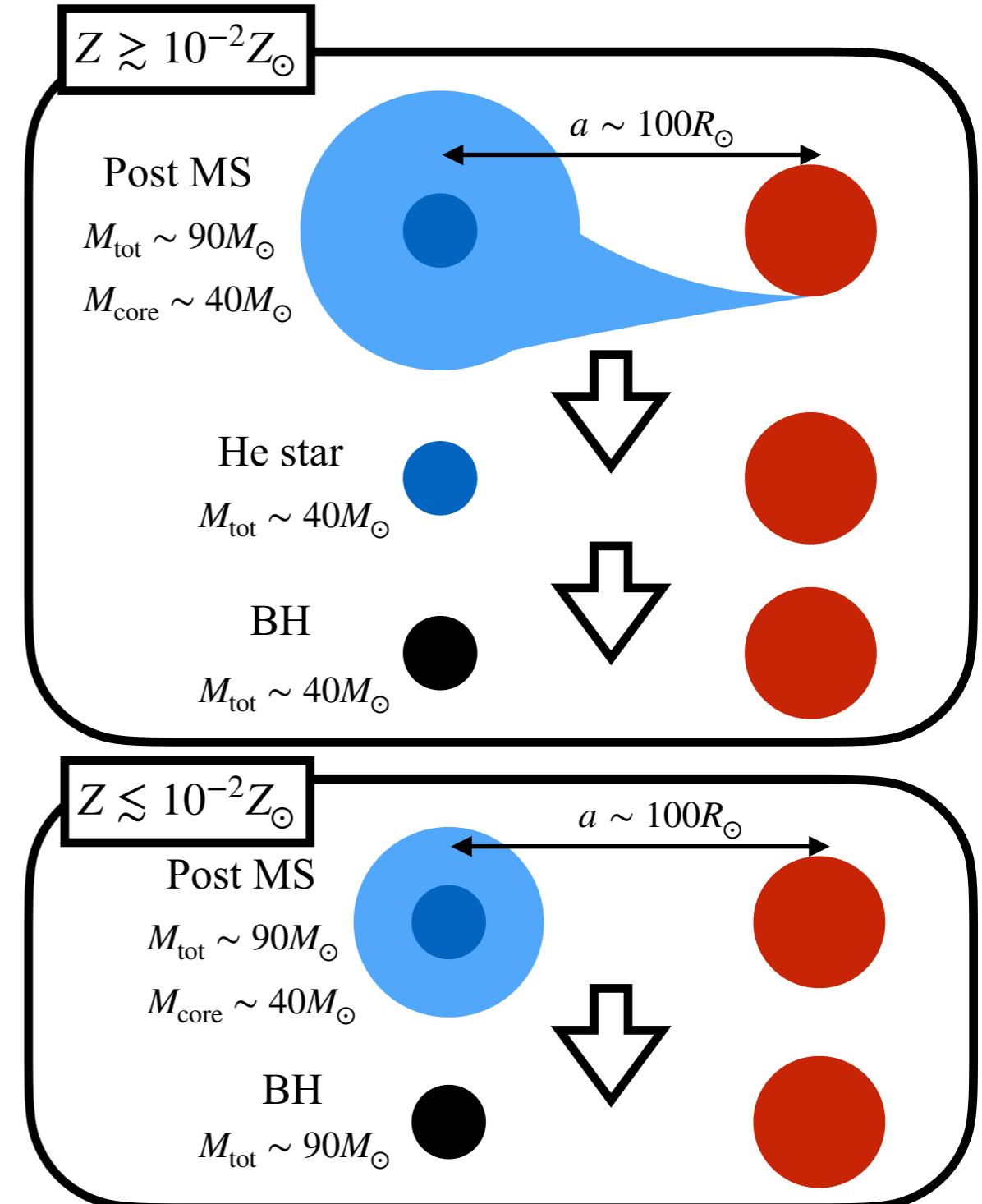
Spera et al. (2015)



Chon et al. (2021)

# Metallicity Pair instability mass gap

- GW190521 (Abbott et al. 2020)
  - $85\text{--}66M_{\odot}$  BH merger
  - The pair instability mass gap event
  - Pair instability supernova prohibits the formation of BHs with  $65 - 130M_{\odot}$  (Heger et al. 2003; Belczynski et al. 2016; Spera, Mapelli 2017; Woosley 2017; 2019; Giacobbo et al. 2018).
  - Pop III binary stars can form GW190521 (Tanikawa et al. 2021; see also Kinugawa et al. 2020).

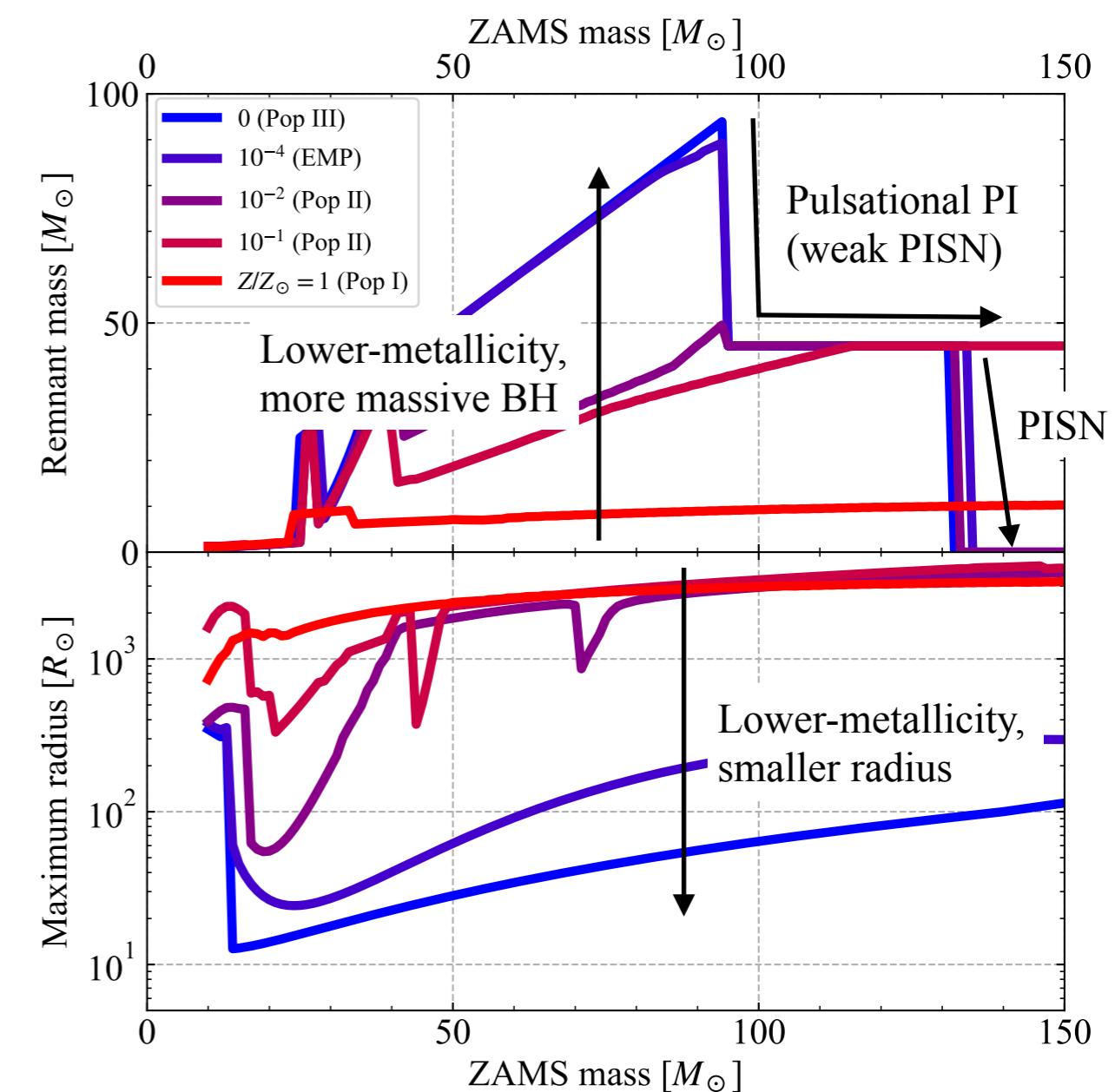


# Our study

- Merging binary BHs from all the metallicities by the world's first binary population synthesis calculations
  - Pop III:  $Z/Z_{\odot} = 0$ , EMP:  $0 < Z/Z_{\odot} \leq 10^{-3}$ , Pop II:  $10^{-3} < Z/Z_{\odot} \leq 0.16$ , Pop I:  $Z/Z_{\odot} > 0.16$
- Impacts of uncertainties related to Pop III binary stars
- Features of our scenario

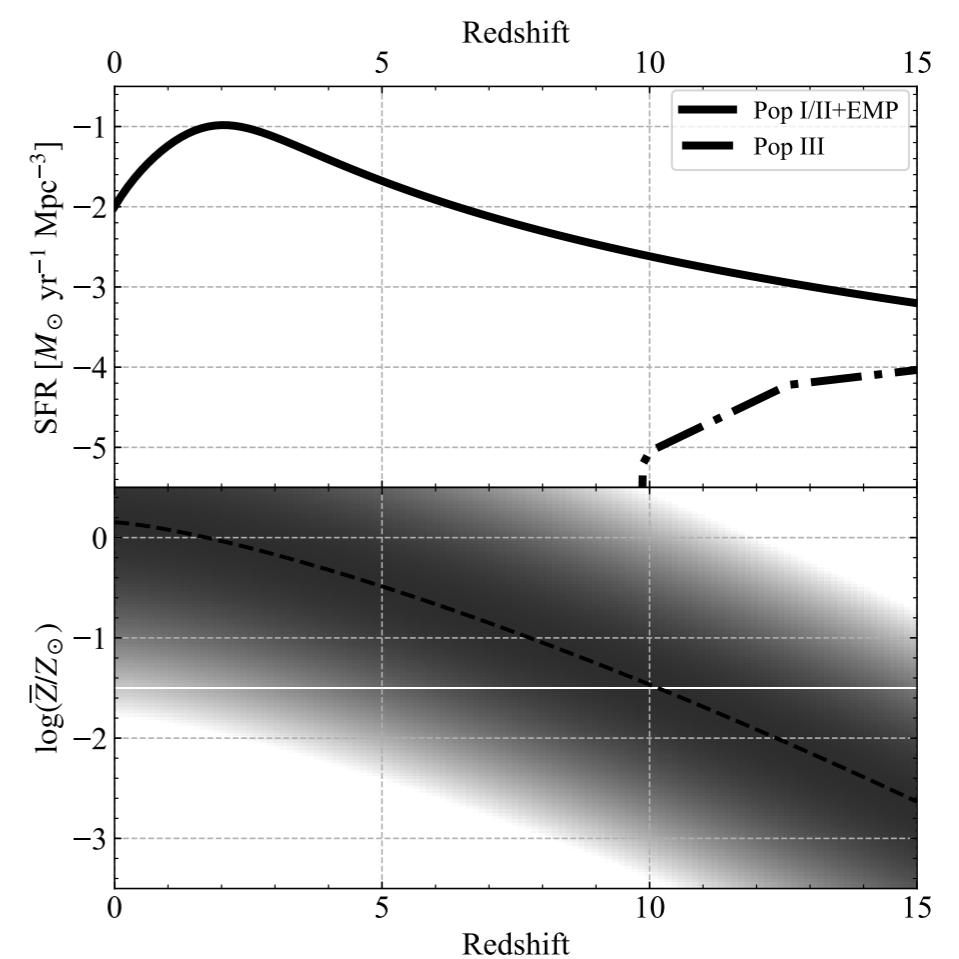
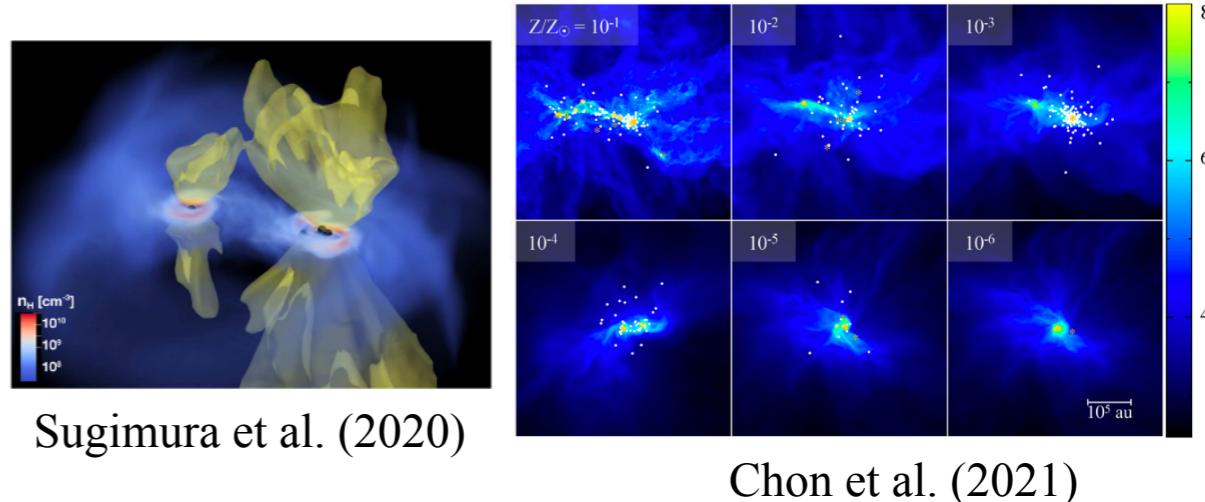
# Binary population synthesis

- 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

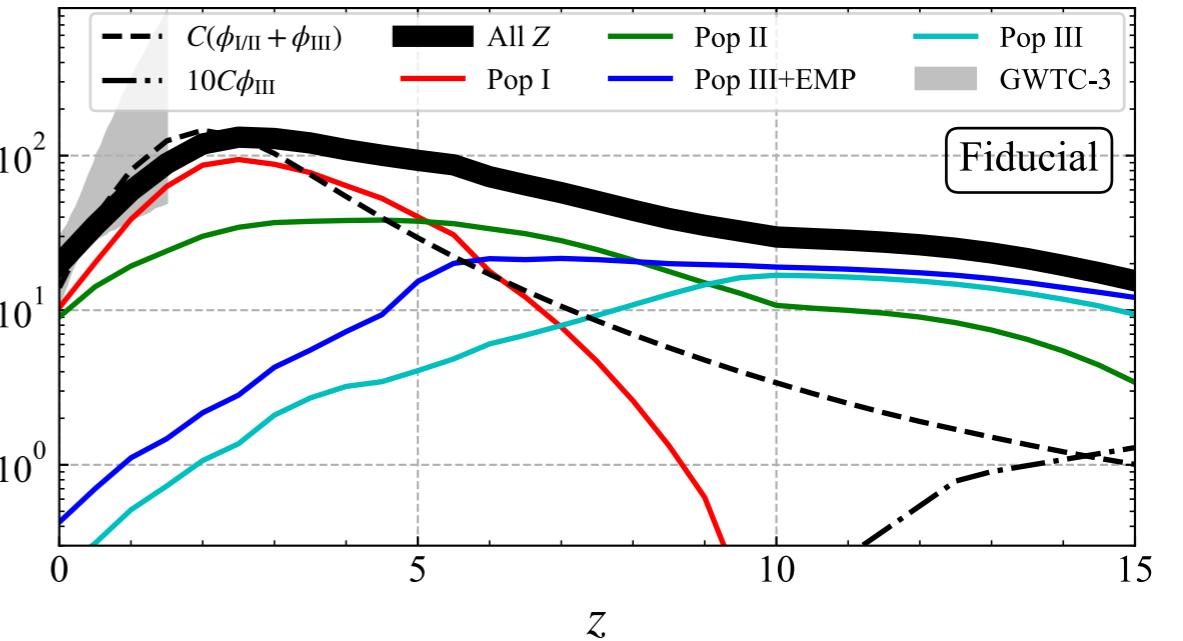
- Binary stars
  - Binary number fraction: 50% for all Z
  - Chon's IMF
    - $f(m)dm \propto m^{-2.3}dm$  ( $Z/Z_{\odot} > 10^{-2}$ )
    - $f(m)dm \propto m^{-1}dm$  ( $Z/Z_{\odot} \leq 10^{-6}$ )
    - Mixture ( $10^{-6} < Z/Z_{\odot} \leq 10^{-2}$ )
  - Distributions of mass ratios, periods, and 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-normal distribution with  $\sigma = 0.35$



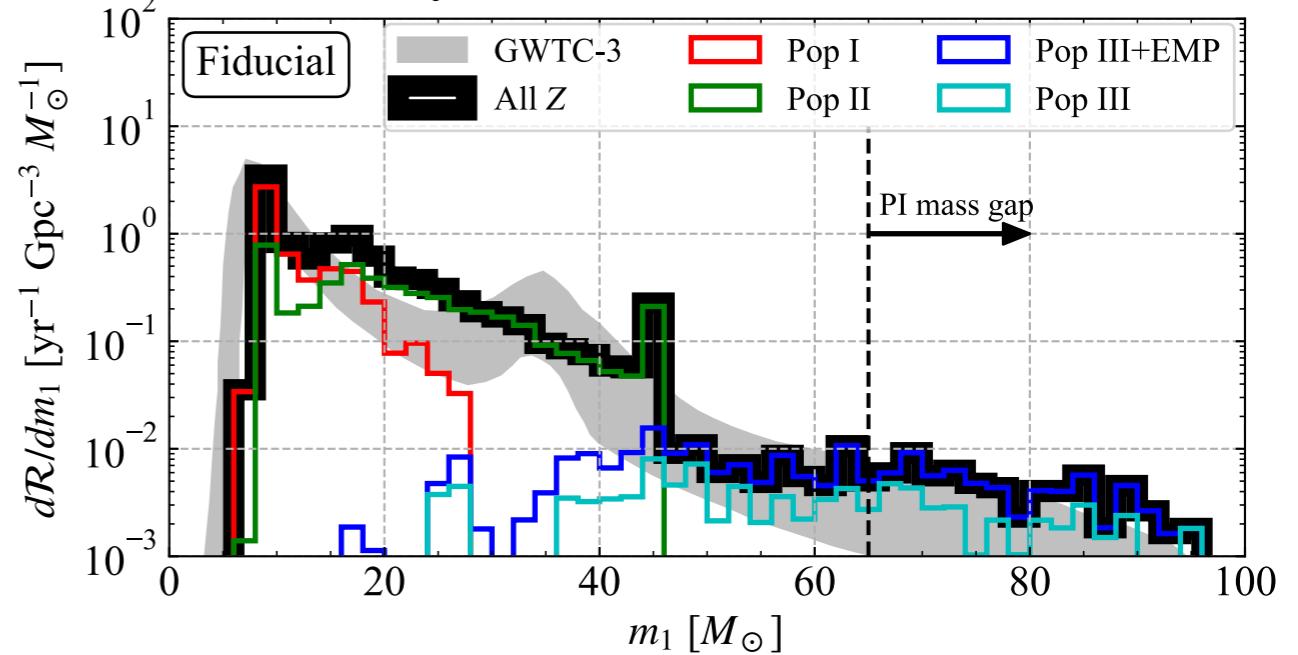
# Merger rate and mass distribution

- 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
  - $5 - 20M_{\odot}$ : Pop I
  - $20 - 50M_{\odot}$ : Pop II
  - $50 - 100M_{\odot}$ : EMP+Pop III
- All metallicities are required for all BH mergers!

Redshift evolution of the merger rate

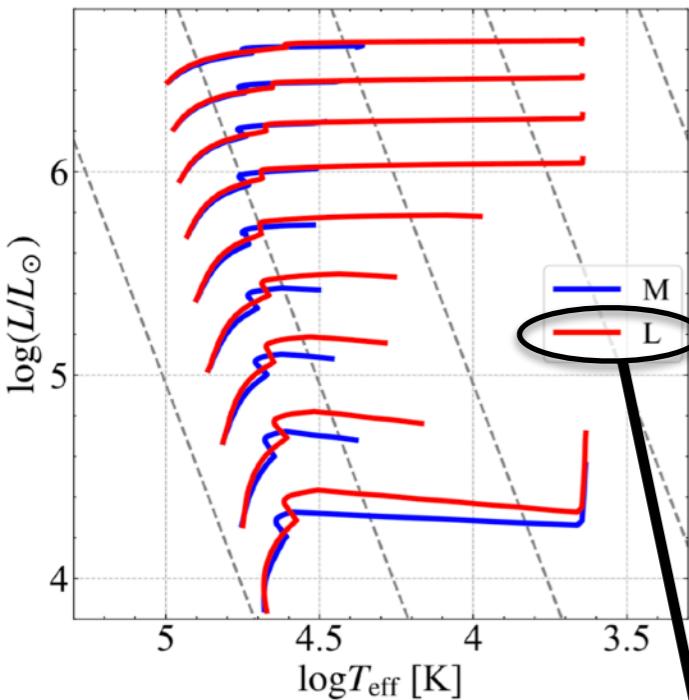
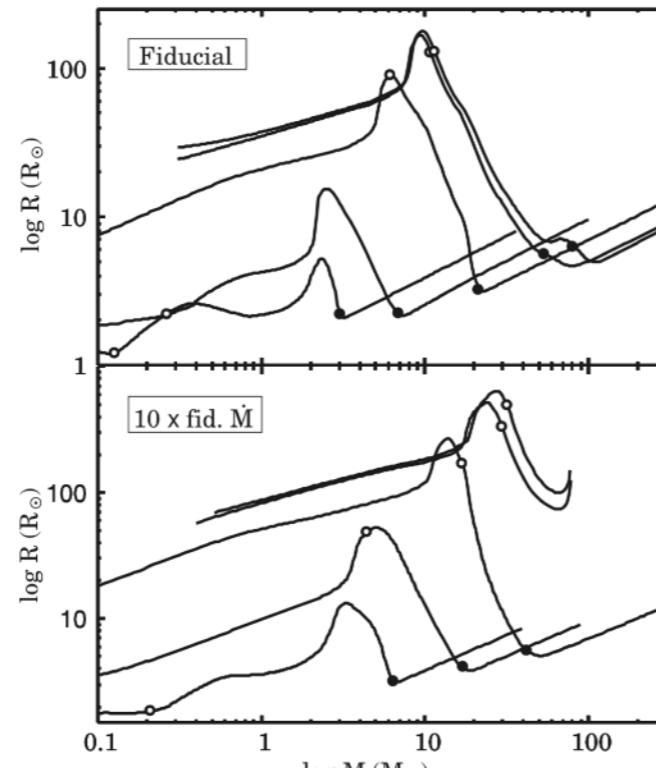


Primary BH mass distribution

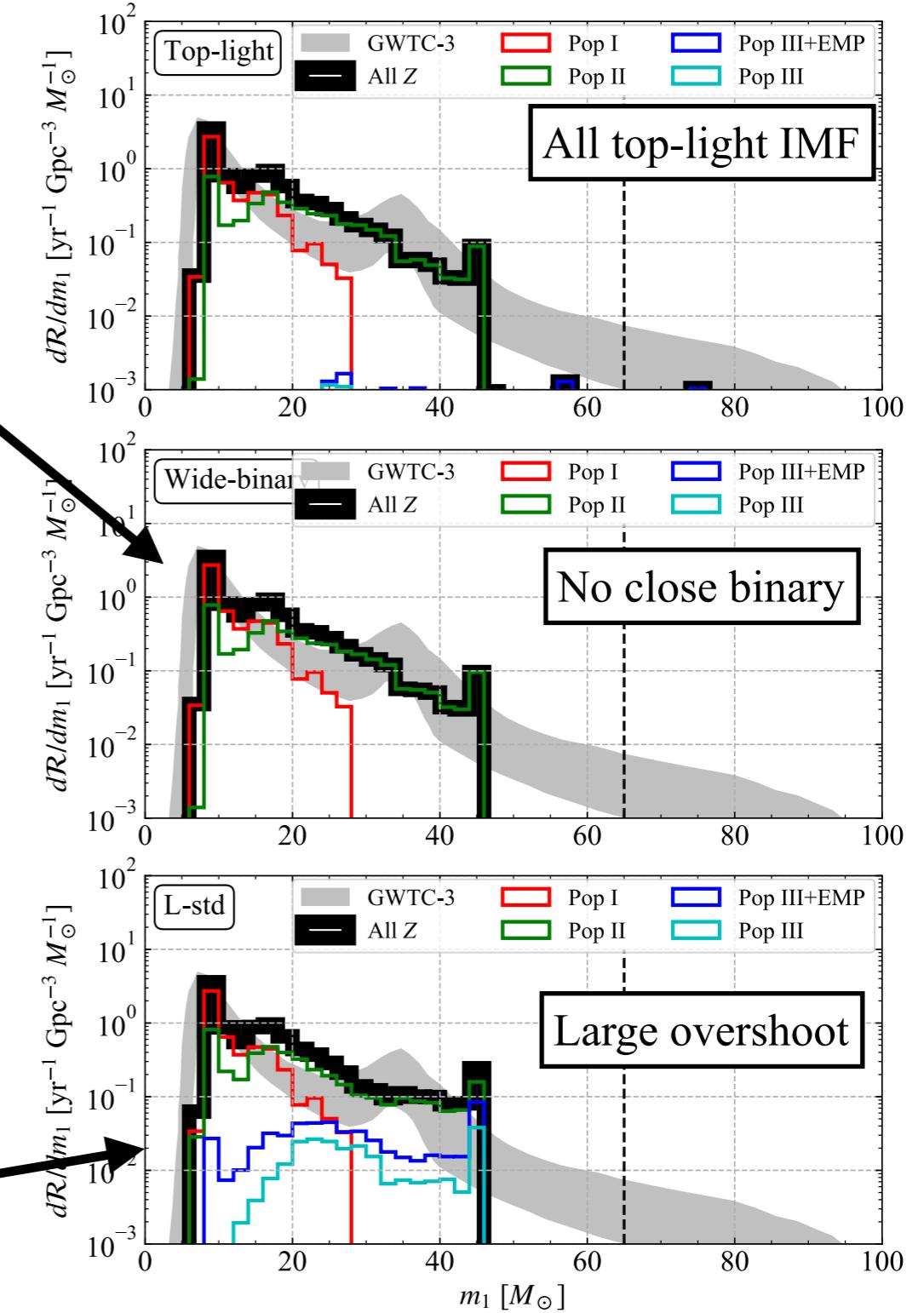


# Uncertainties in Pop III stars

- Pop III protostars can expand up to  $\sim 100R_{\odot}$  due to high accretion rates.
- The expansion may prevent close Pop III binary stars from forming.
- The expansion may be avoided through disk accretion.

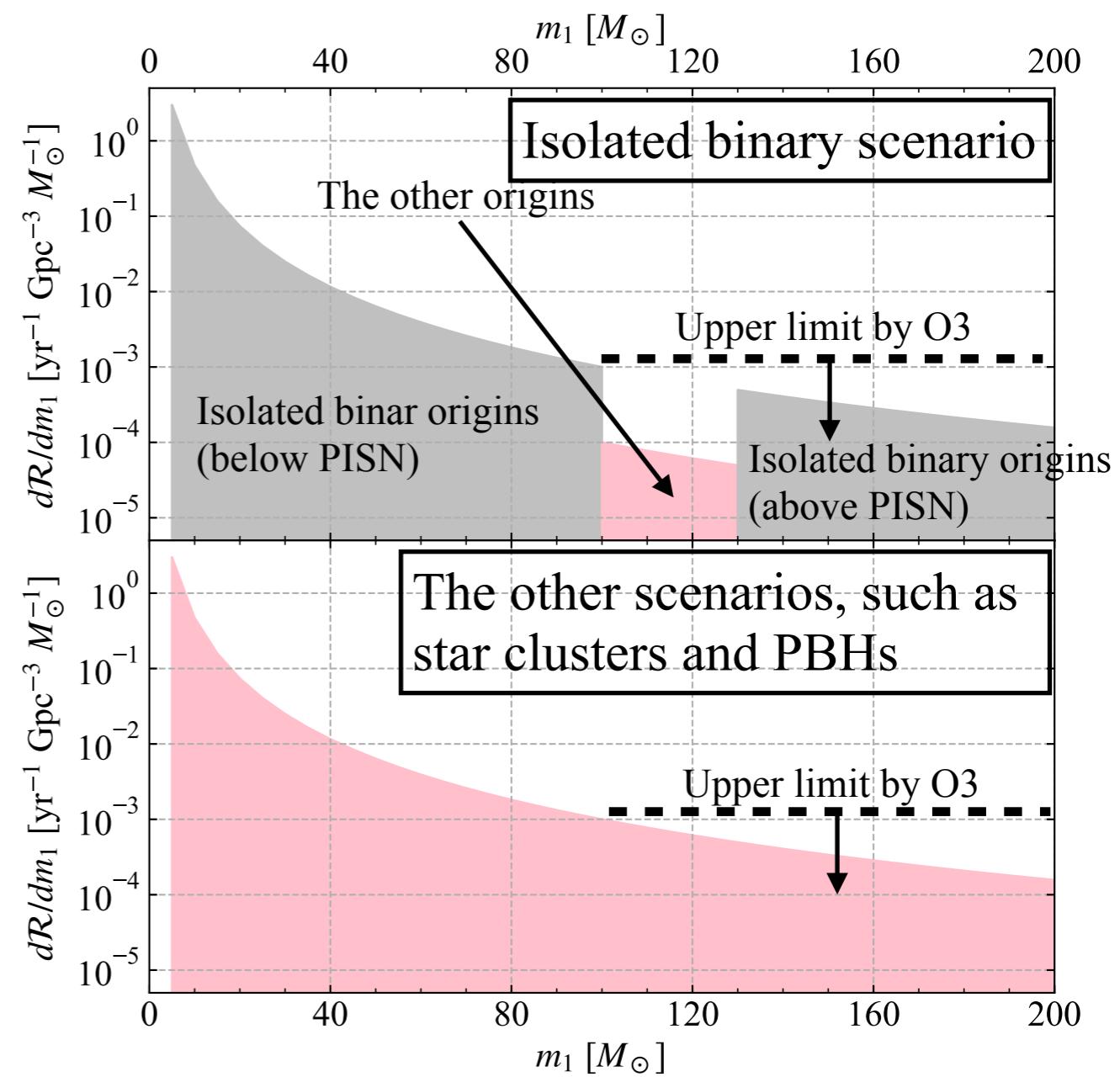


- Both star evolution models can be consistent with Pop I stars.



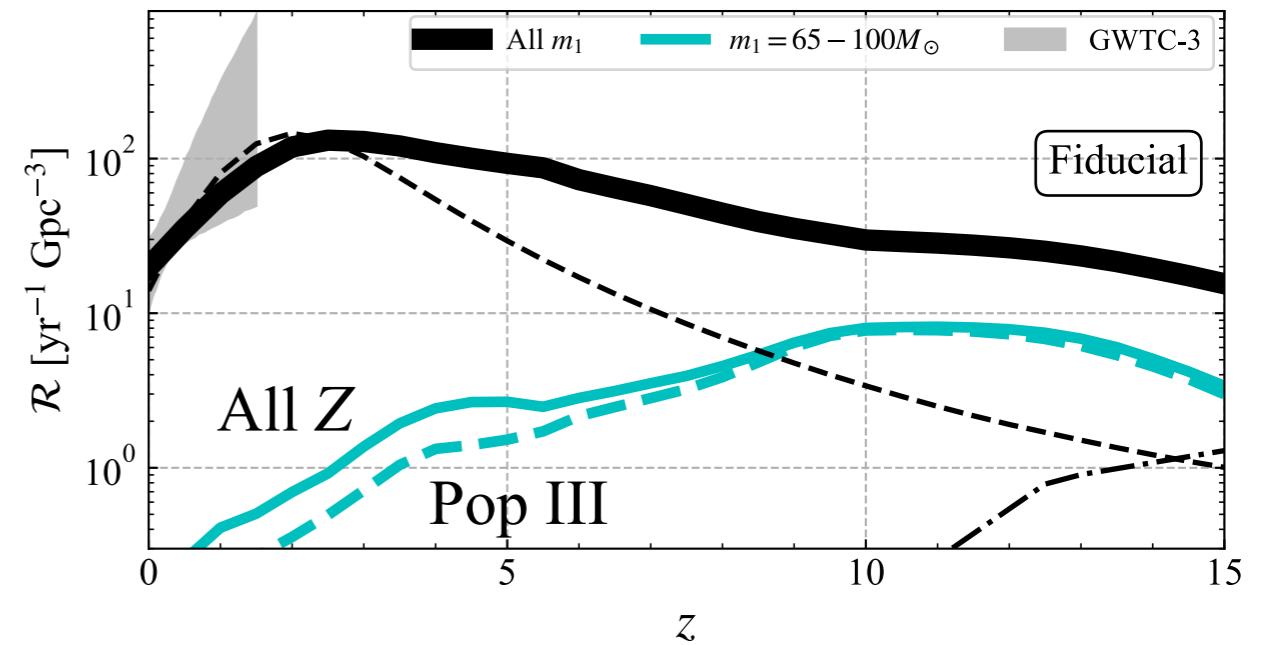
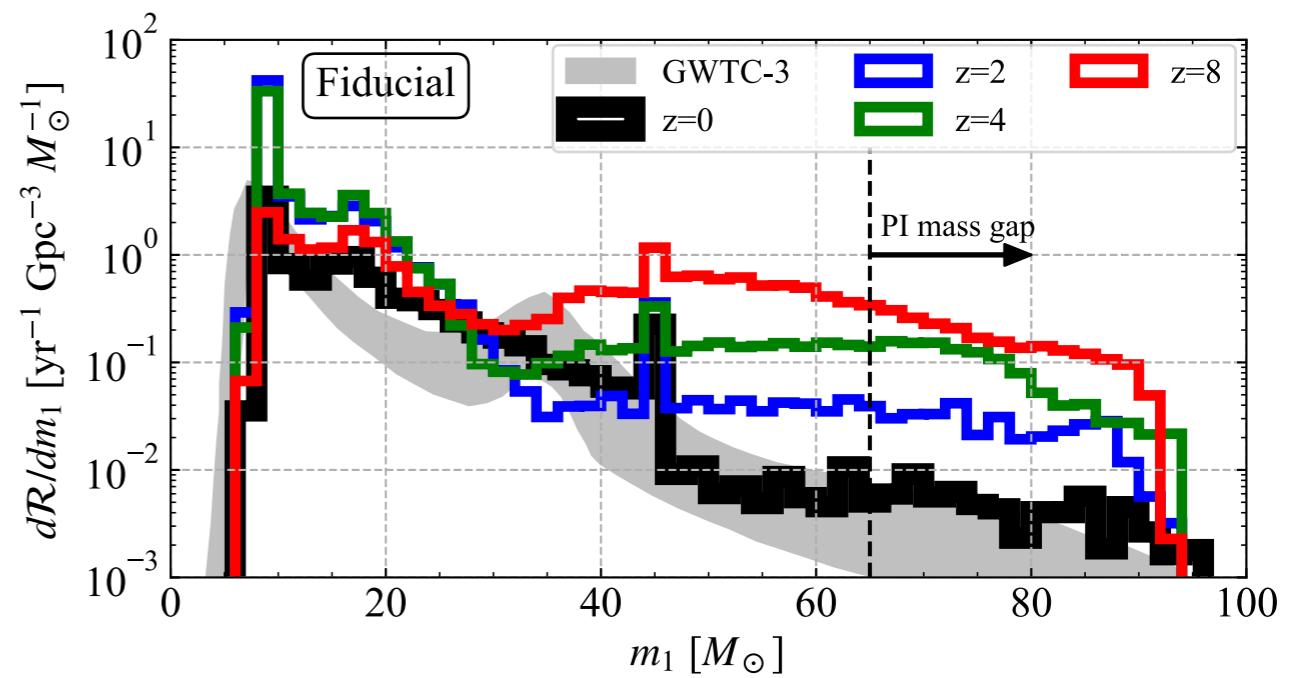
# Difference from other scenarios

- 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

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



# Summary

- Binary population synthesis for all metallicities
- PI mass gap events dominated by Pop III binary stars
- Our scenario sensitive to uncertainties of Pop III star formation and evolution
- Little BH merger with  $m_1 = 100 - 130M_{\odot}$  (LIGO, Virgo, and KAGRA in 2020s)
- A peak of PI mass gap events at  $z \sim 11$  (Einstein Telescope, Cosmic Explorer, and DECIGO in 2030s)