On the Pop. III binary BH mergers beyond the pair-instability mass gap

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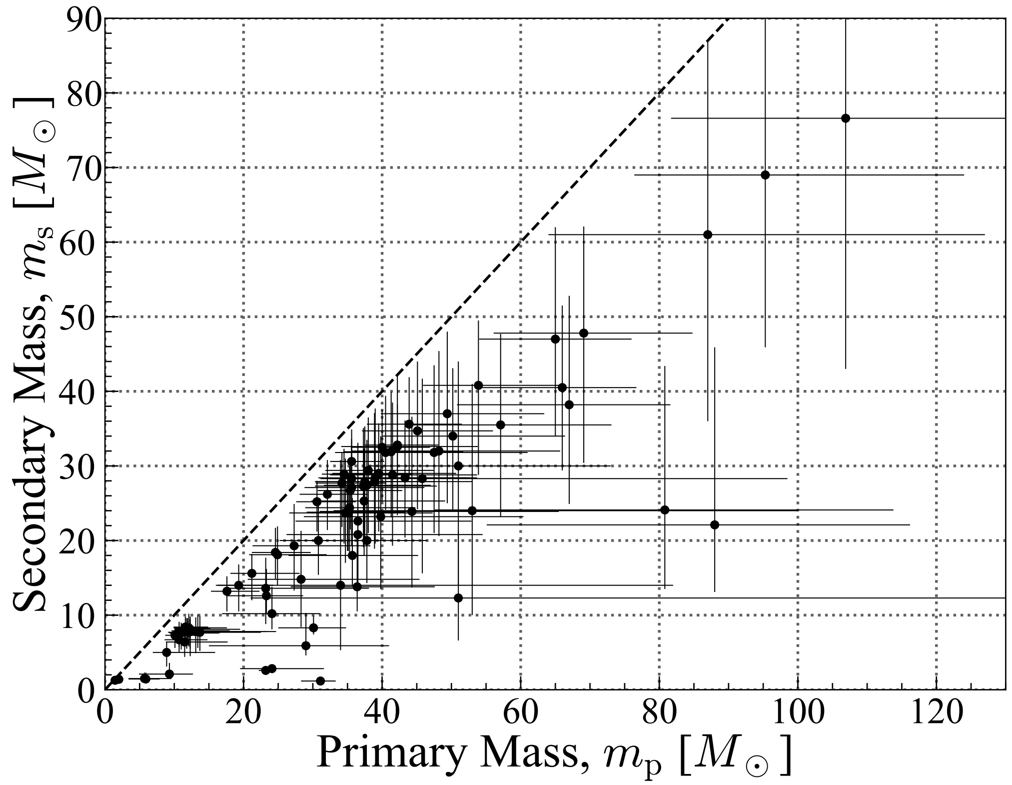
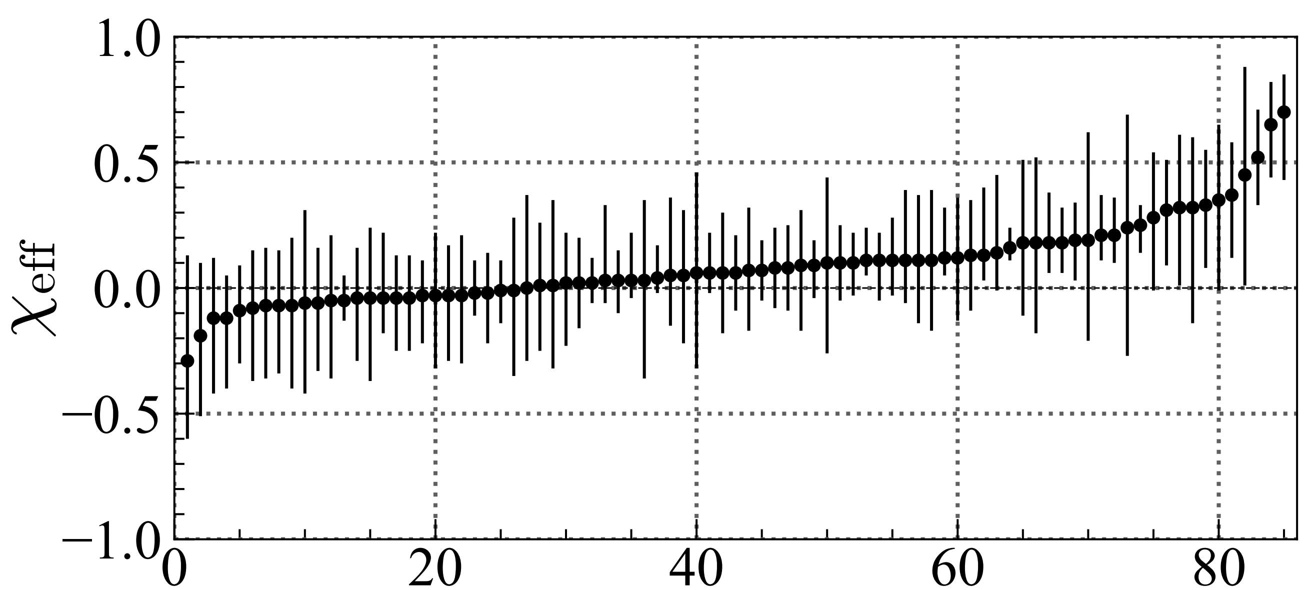
Introduction

BBHs detected by aLIGO and Virgo

- **The third observing run (O3): 2019/4—2020/3**
- **Catalogue, GWTC-3 (O1—O3): 2021/11**





93 events
85: binary BH (BBH)
2: binary NS (BNS)
4: BH-NS
2: BH-gap

typical mass ~ 30—40$M_\odot$
typical spin ~ 0

⇔ BHs in X-ray binaries:
low mass (~ 10$M_\odot$)
high spin (~ 1)

Pop. III BBH mergers

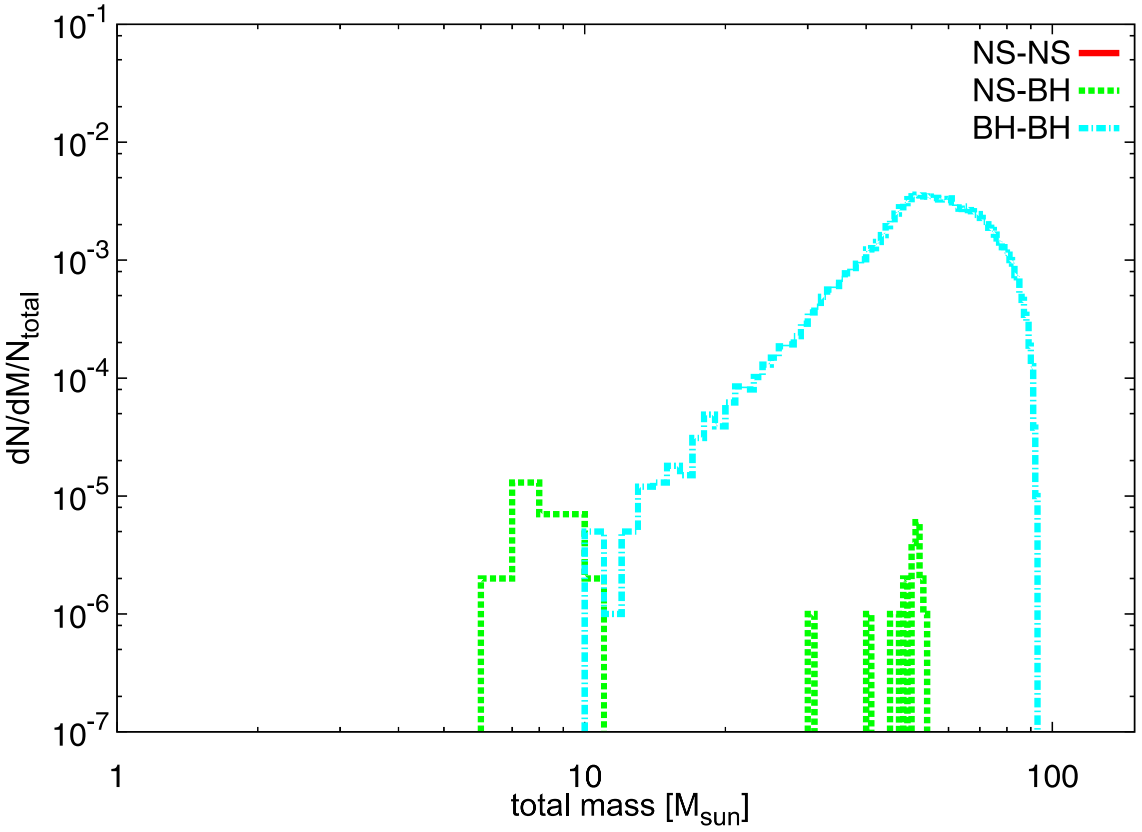
- **Formation channel candidates of BBHs:**
  Pop. I/II binaries, clusters, AGN disks, primordial BHs,…

- **Pop. III binaries can also form BBHs.**
  Binary population synthesis for Pop. III binaries
  ⇒ Belczynski et al. (2004), Kinguawa et al. (2014,2020) and Tanikawa et al. (2021)

- **typical mass ~ 30$M_\odot$ + 30$M_\odot$;**
  spin ~ 0 at z~0
  ⇔consistent with observation

- **promising candidate**

Fig.6 in Kinugawa et al. (2014)



Pop. III BBH mergers

- **Previous works: ZAMS mass range 10—O(10^2)$M_\odot$**
- **There is a chance that O(10^3)$M_\odot$ Pop.III stars can be born.**
- **THIS WORK: 10—1500$M_\odot$**
- **Aims:**
  - **mass distribution**
  - **spin distribution**
  - **merger rate density**
  - **the maximum primary BH mass of BBHs with massive BHs (>100$M_\odot$)**
- **Furthermore, we impose restrictions on the Pop.III IMF**

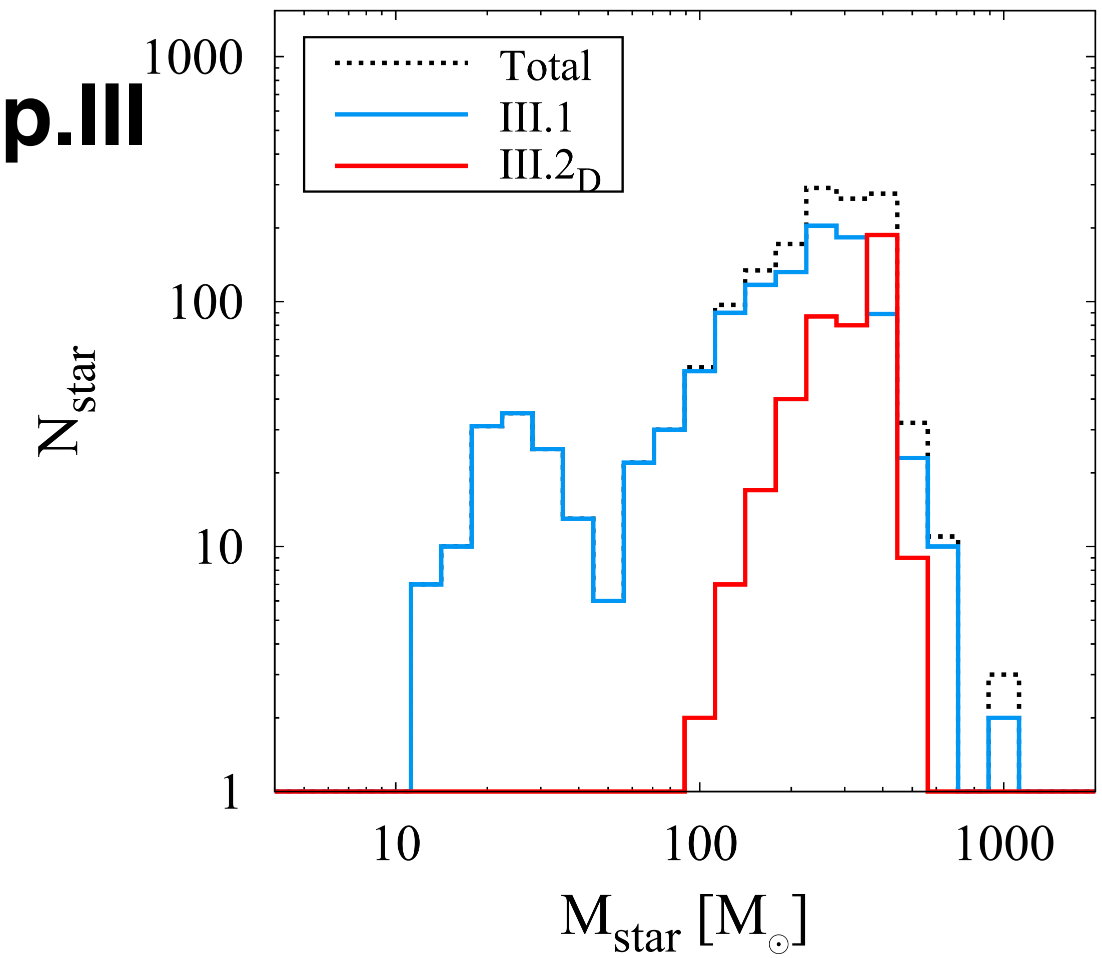


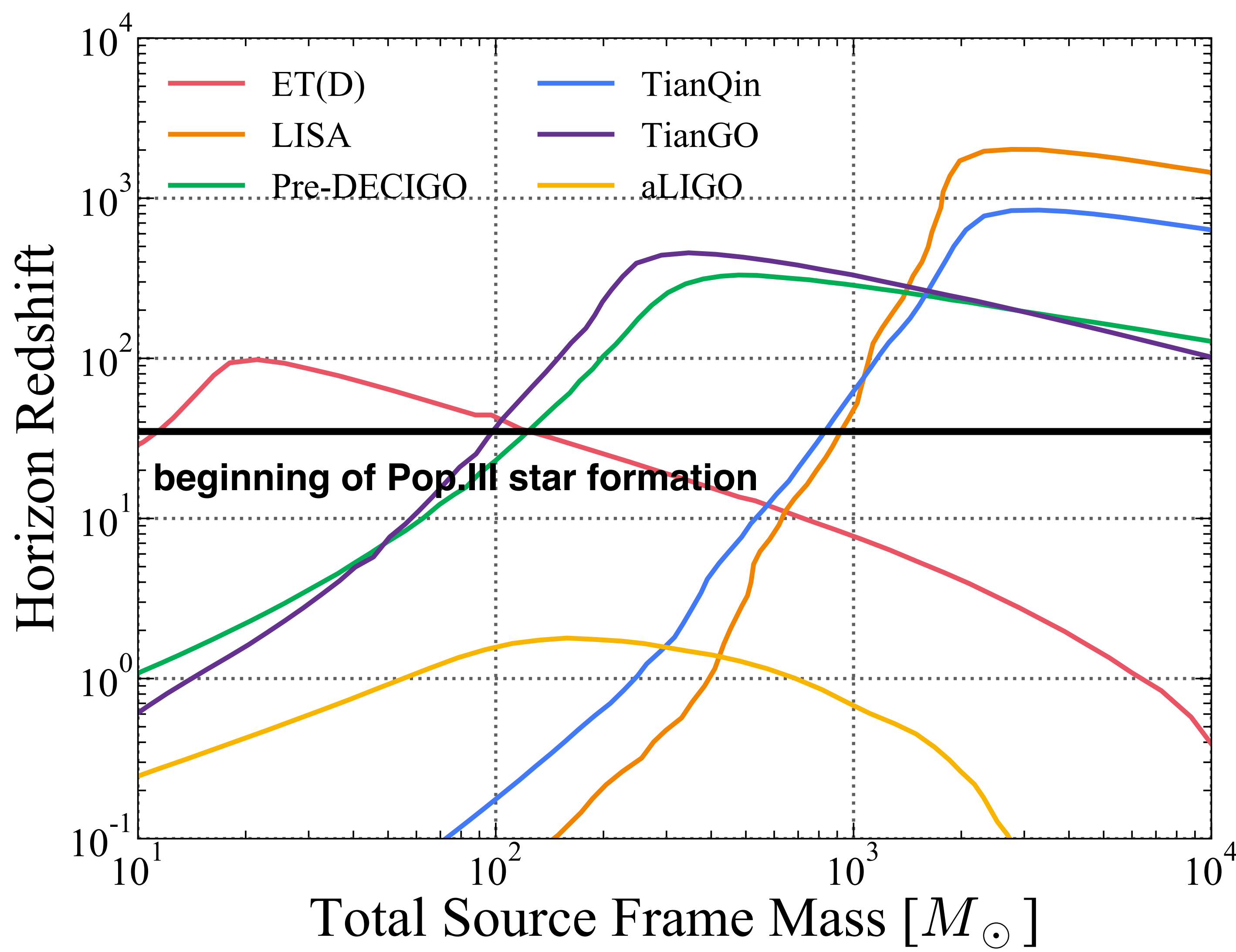
Fig.6 in Hirano et al. (2015)

Future observations and detectability

- Pop.III star formation: $z \sim 35$—

- Pop.III massive BBHs: 10^2—10^3 $M_\odot$

- third generation detector: Einstein telescope(2035—)
  space-borne detectors:
    LISA(2034–)
    B-DECIGO(late 2020s)
    TianGO(20XX—)
    TianQin(天琴)(2030s)
  can detect BBHs
  up to $z \sim$ O(10)



Method

Binary Population Synthesis (BPS)

What is population synthesis?

Using fitting formulae (e.g. Hurley et al. 2000) that describe stellar parameters (such as luminosity, radius, core mass, …) as a function of time and metallicity, we can follow up a large number of stellar evolution.

We can obtain a statistical quantity, such as the event rate of SNe, chirp mass distribution of BBH merger events …

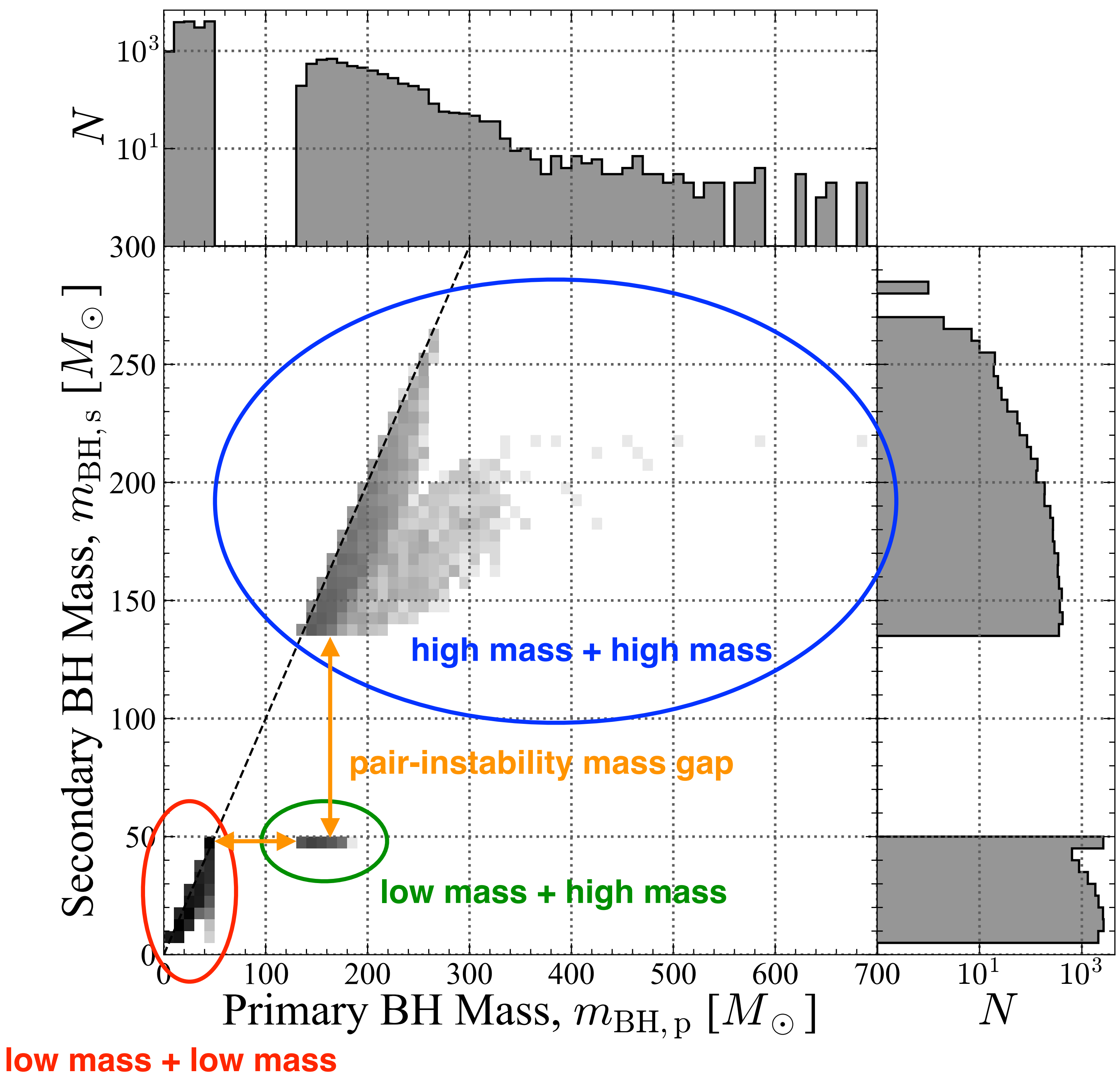
- The fitting formulae for massive pop. III ($\sim 10^3\ M_\odot$)

- number of simulated binaries: 10^6
  IMF: m^{-1} ($10 M_\odot < m < 1500 M_\odot$)

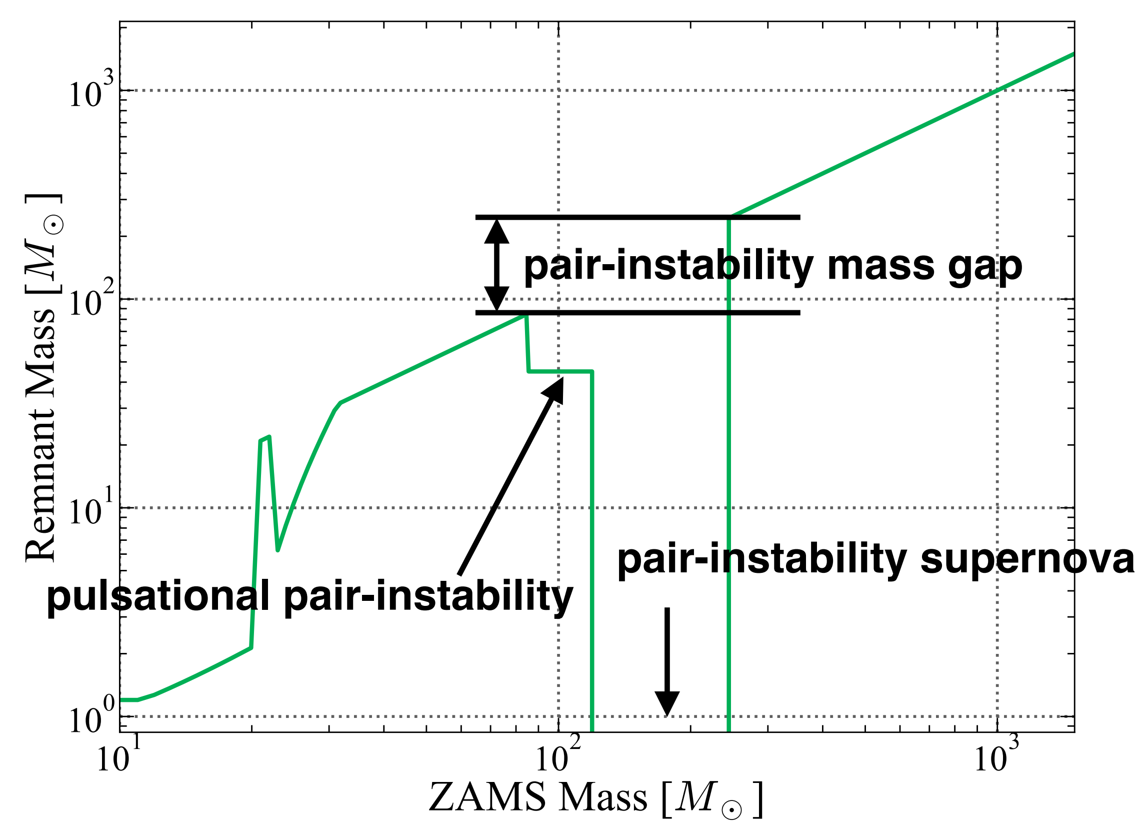
- Common envelope: $\alpha_{\rm CE} \lambda_{\rm CE} = 1$

Results

Mass Distribution

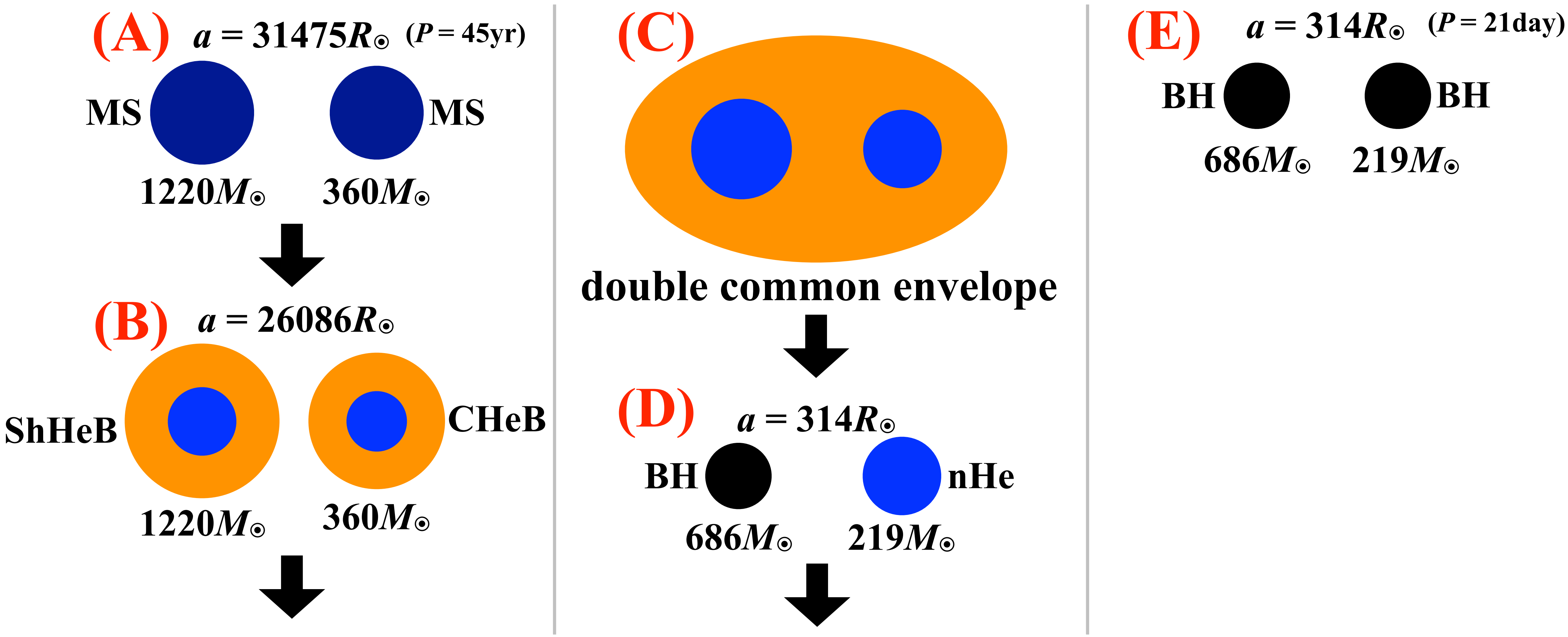


↓ Pop.III single stellar evolution ↓



The maximum primary BH mass

- MS(1220$M_\odot$)+MS(360$M_\odot$) → BH(686$M_\odot$)+BH(219$M_\odot$)

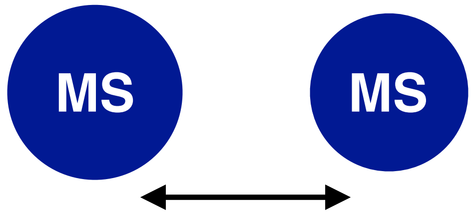


- MS(>1220$M_\odot$)+MS → BH+BH ??

The maximum primary BH mass

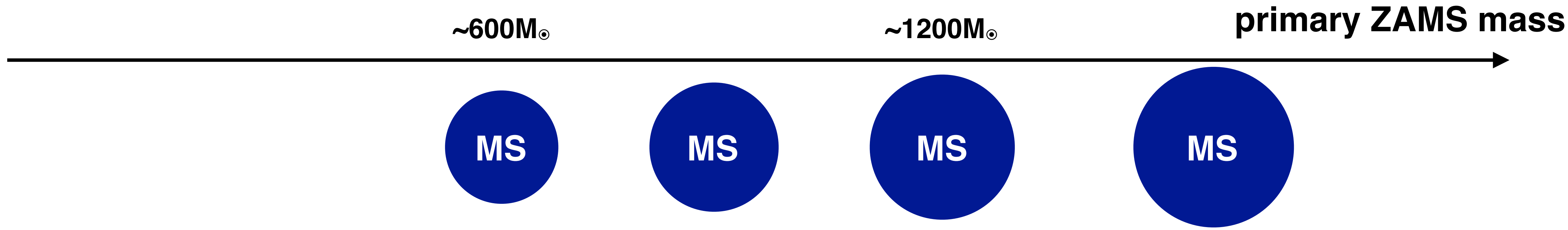
1. If ZAMS > 600$M_{\odot}$, it reaches the Hayashi track (convective) during MS.
2. If a convective star fills its Roche lobe, a common envelope may occur.
3. If a MS star causes a common envelope, the binary disrupts.

$m > 600M_{\odot}$



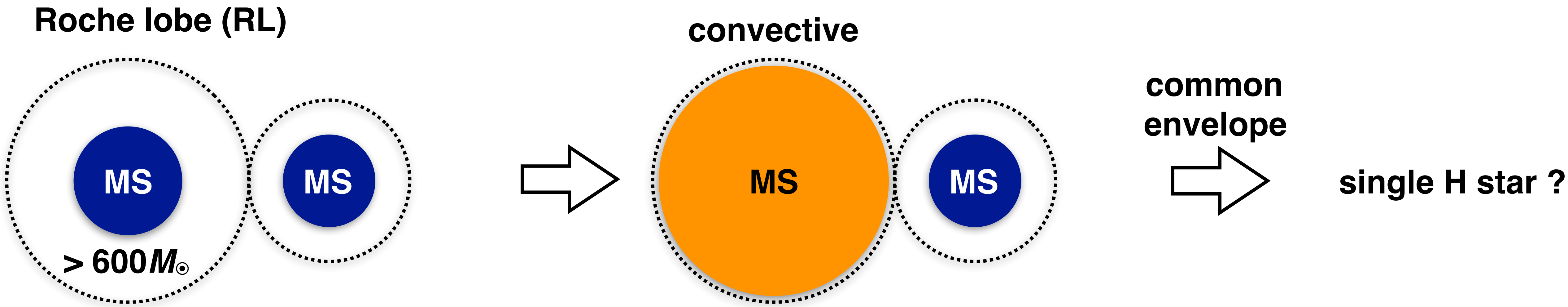
Roche lobe radius ∝ orbital separation

wide enough not to fill the Roche lobe during the MS phase
If fills, the binary system always coalesces



The heavier, the larger the radius ⇒ The heavier, the wider the orbital separation needs to be.

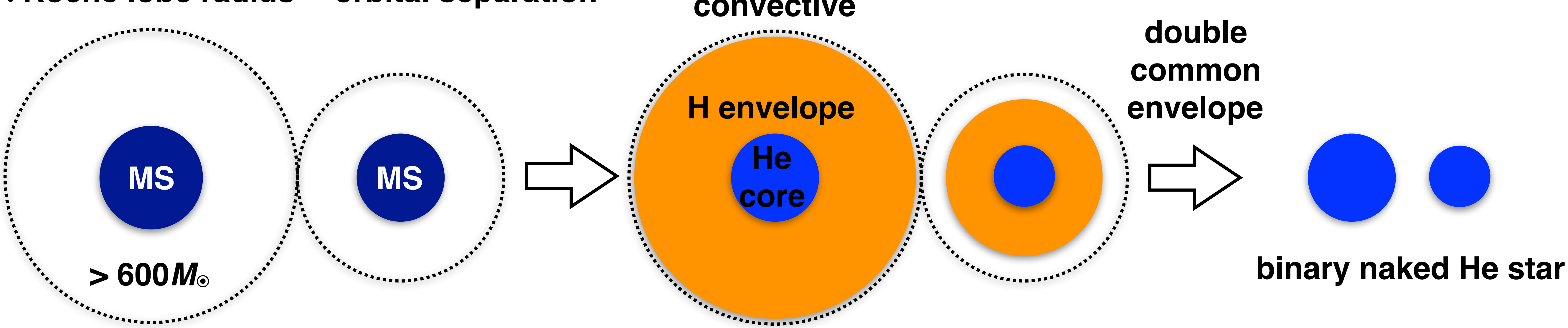
The maximum primary BH mass



shorter orbital separation
⇒shorter Roche lobe radius

fills the RL when the primary is
still in the MS phase

∵Roche lobe radius ∝ orbital separation

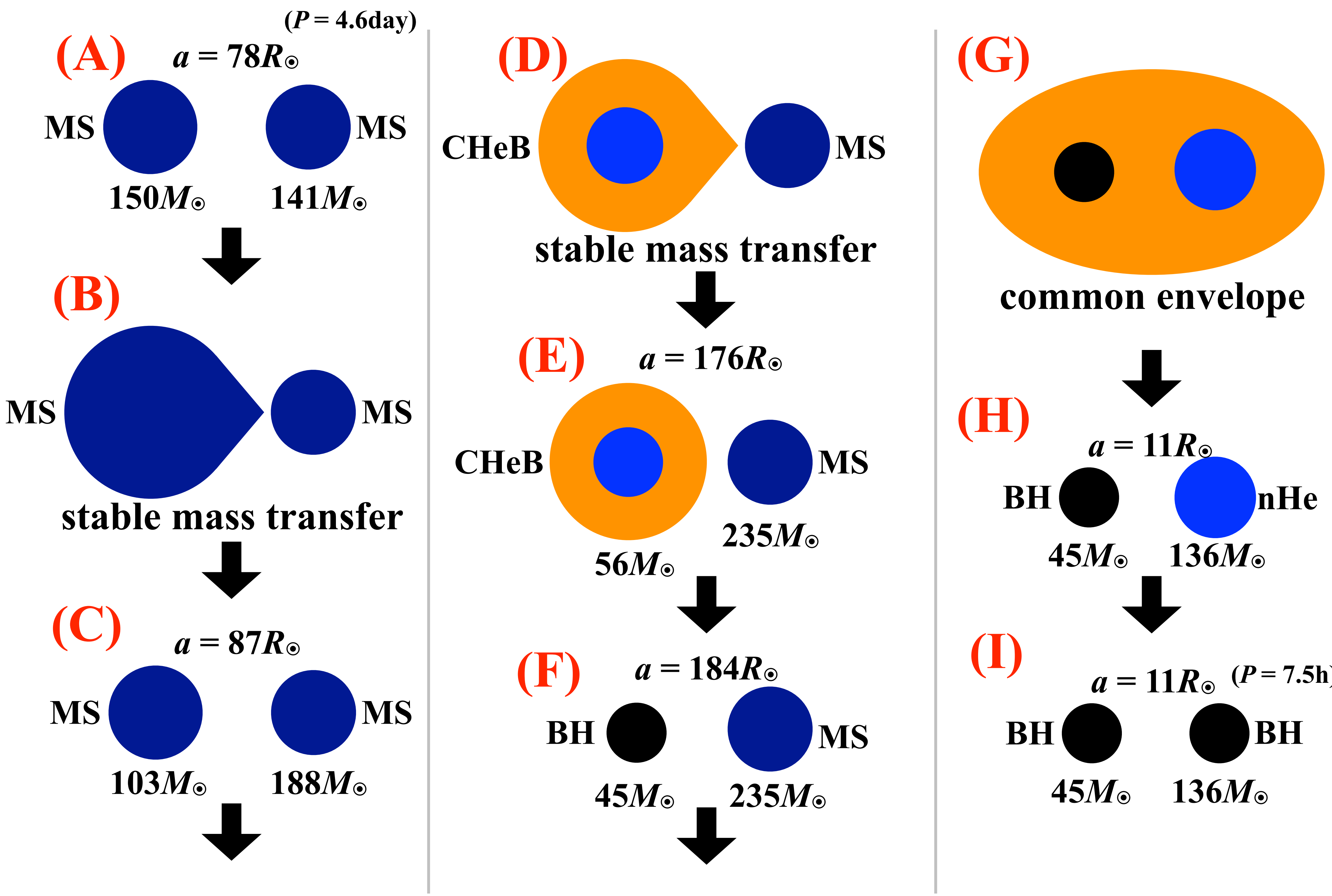


wider orbital separation
⇒wider Roche lobe radius

fills the RL when the primary is
in the giant phase

low mass + high mass

- $m_{BH,s} = 45 M_\odot$ ← formed through pulsational pair-instability



Spin Distribution

- **high mass + high mass: ~ 0**
- **low mass + high mass: ~ 0.75—0.8**

$$\chi_{\rm eff} = \frac{m_{\rm BH,p}\chi_{\rm BH,p} + m_{\rm BH,s}\chi_{\rm BH,s}}{m_{\rm BH,p} + m_{\rm BH,s}}$$

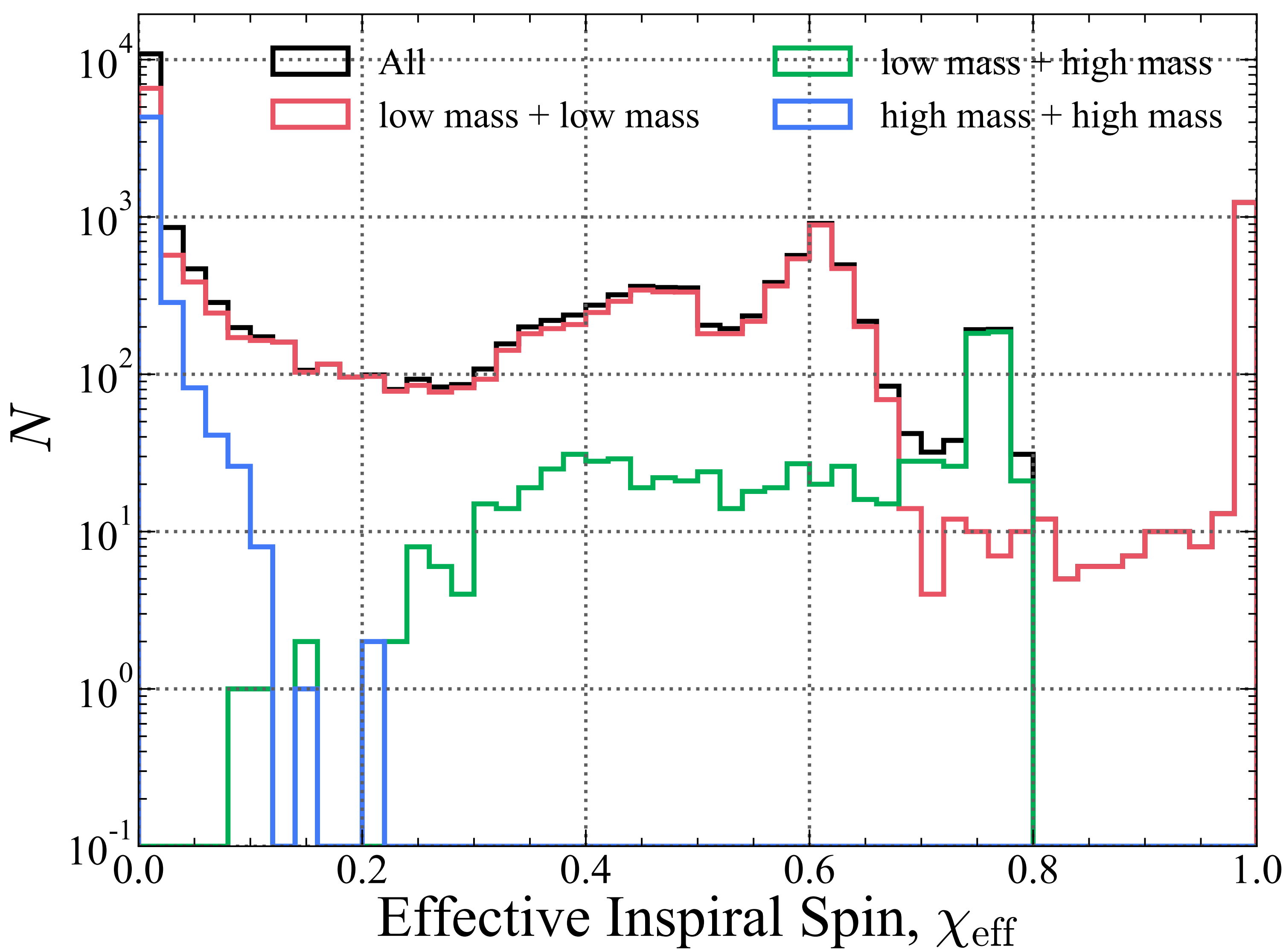
$$\vec{\chi}_{\rm BH,i} = \frac{c\vec{J}_{\rm BH,i}}{Gm^2_{\rm BH,i}}$$

- **high+high**
  - **primary ~ 0**
  - **secondary ~ 0**

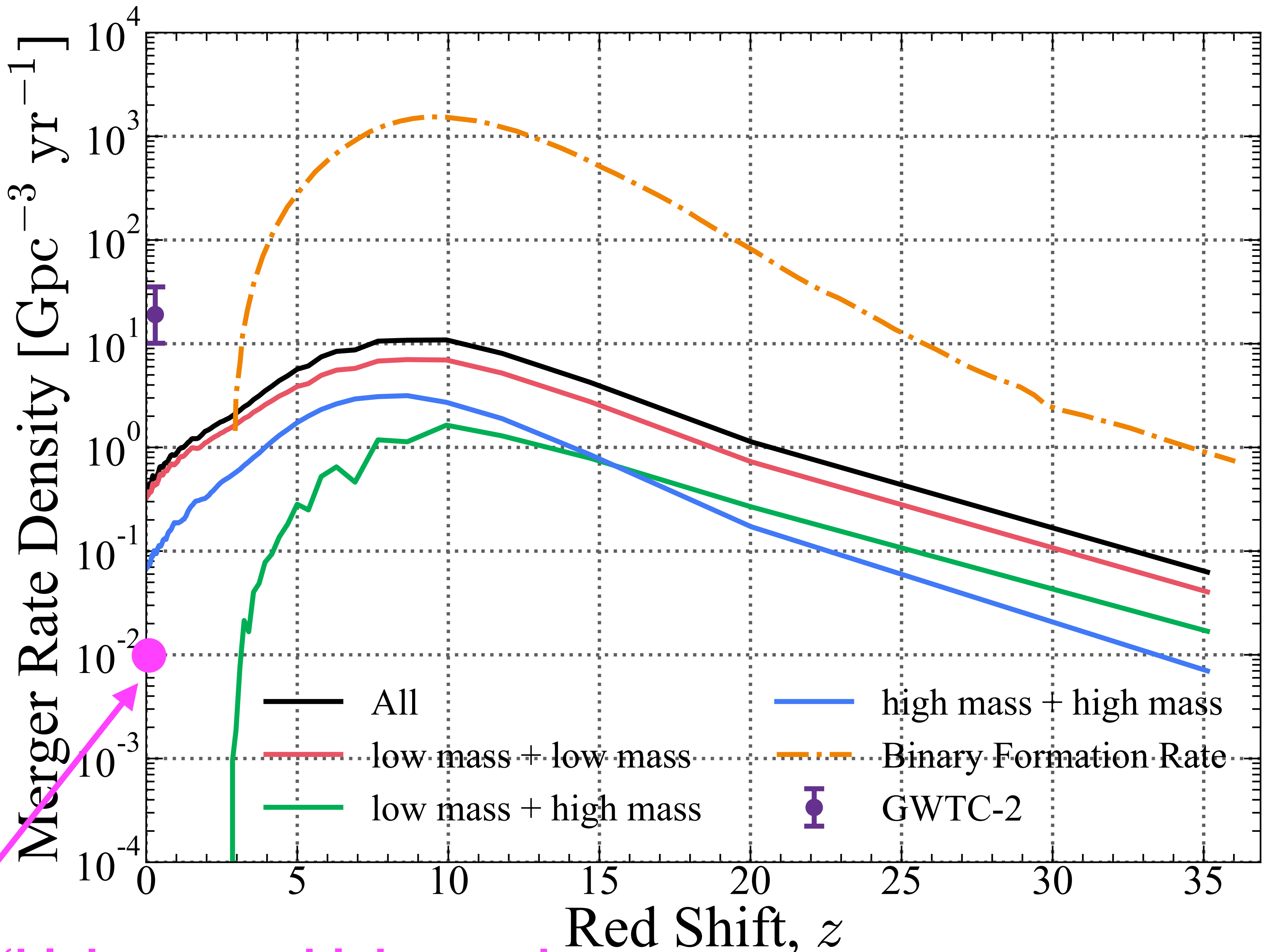
- **low+high**
  - **primary ~ 1**
  - **secondary ~ 0**

$$\chi_{\rm eff} = \frac{m_{\rm BH,p}}{m_{\rm BH,p} + 45}$$

  - **$m_{\rm BH,p}$ = 135—180$M_\odot$**



Merger Rate Density

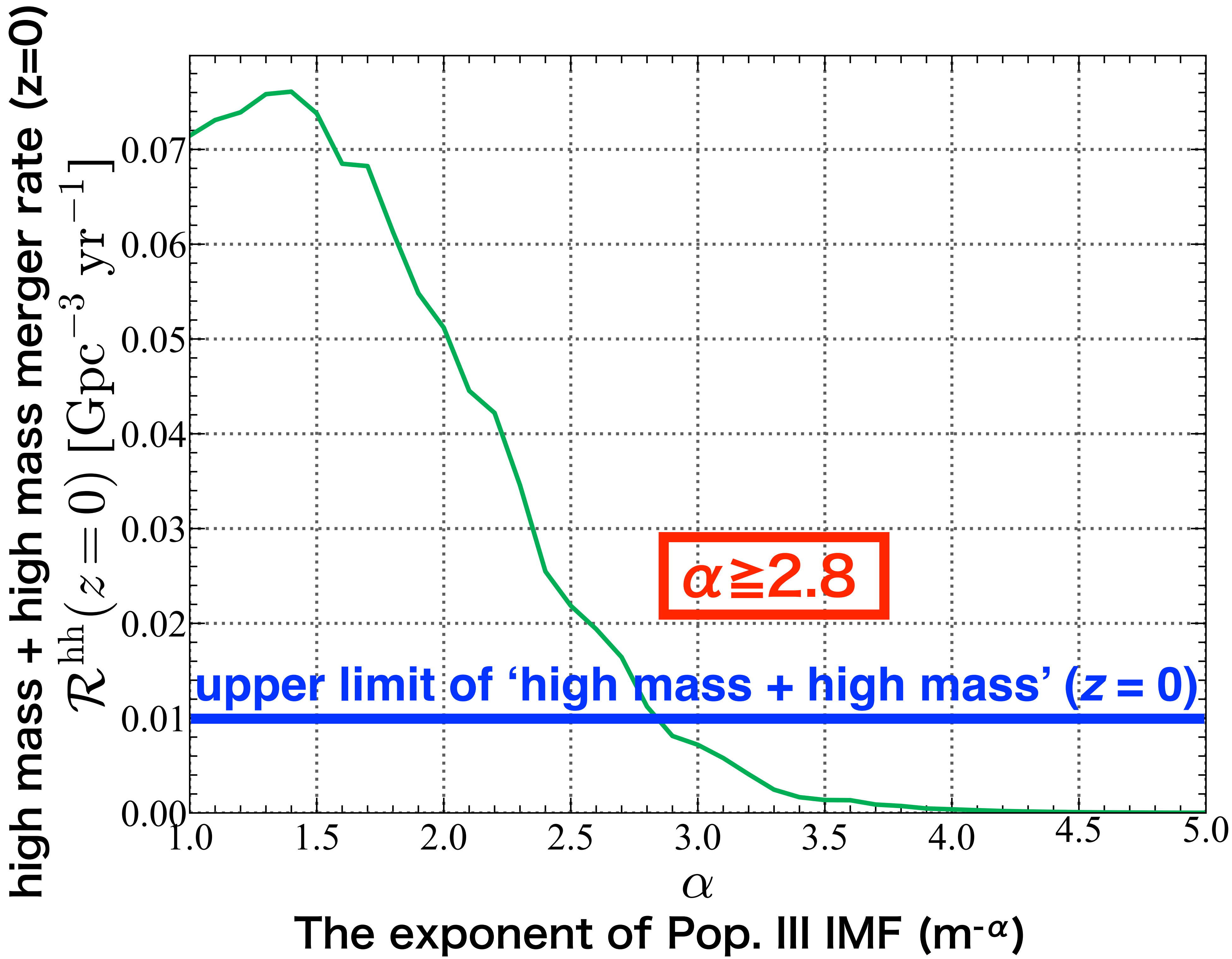


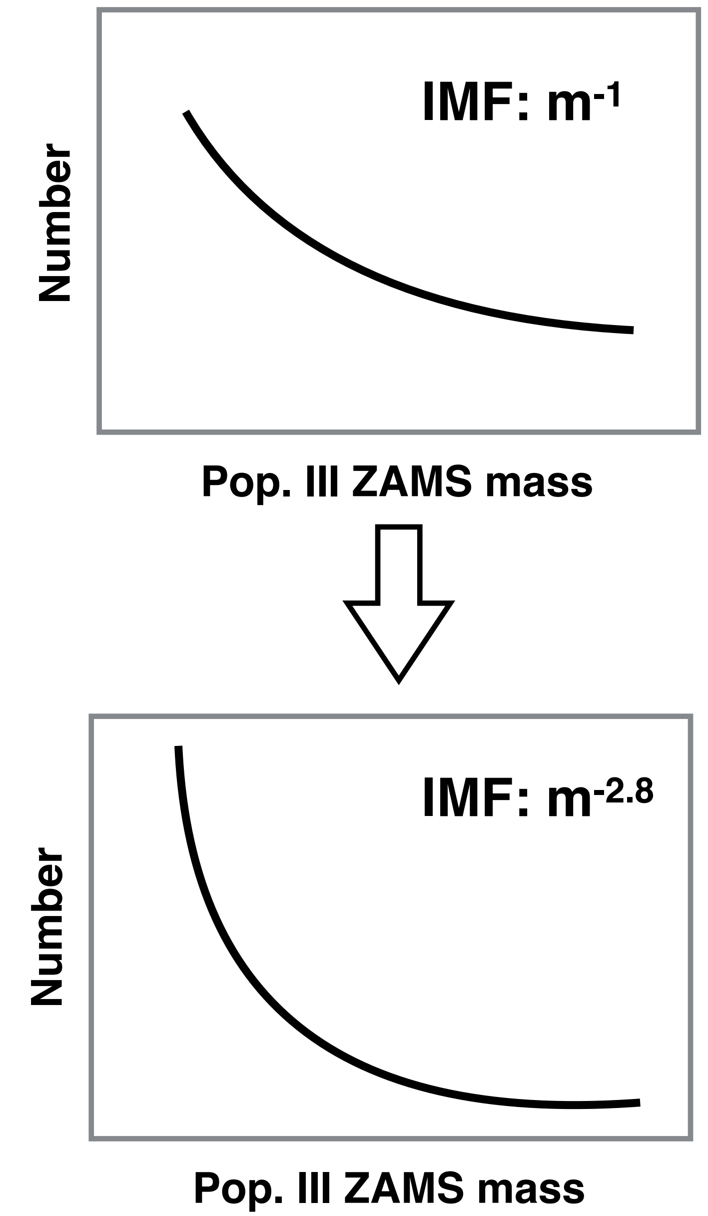
upper limit of 'high mass + high mass'

! our 'high mass + high mass' rate ($z = 0$) > upper limit !

Discussion

Dependence of IMF (single power law)



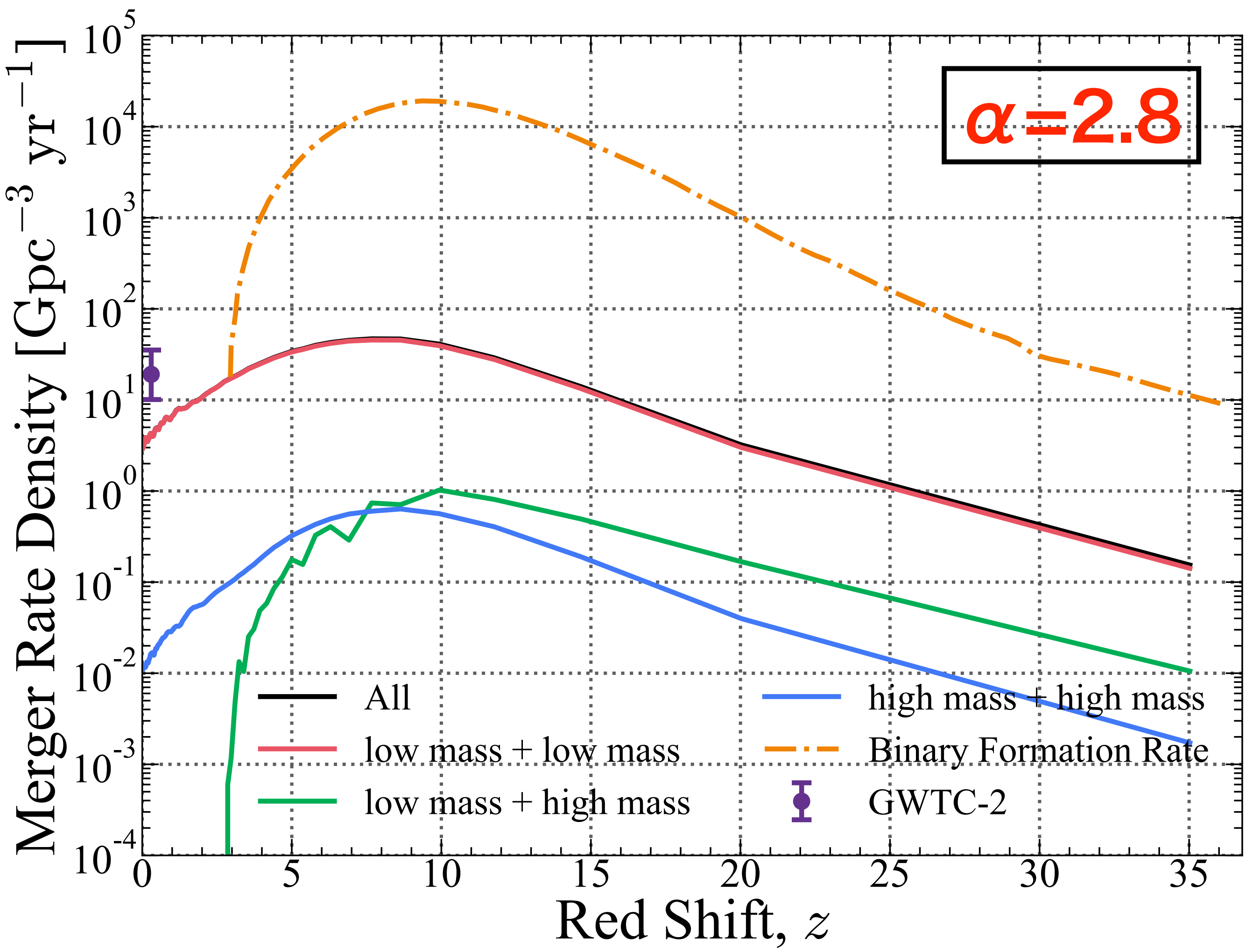


(Updated) Merger Rate Density

- α = 2.8

- $R^{all}(z=0)$ = 2.89 Gpc^{-3} yr^{-1}
  - obs.: $19.1^{+16.2}_{-9.0}$ Gpc^{-3} yr^{-1}
  - ~ 15% (8–28%)

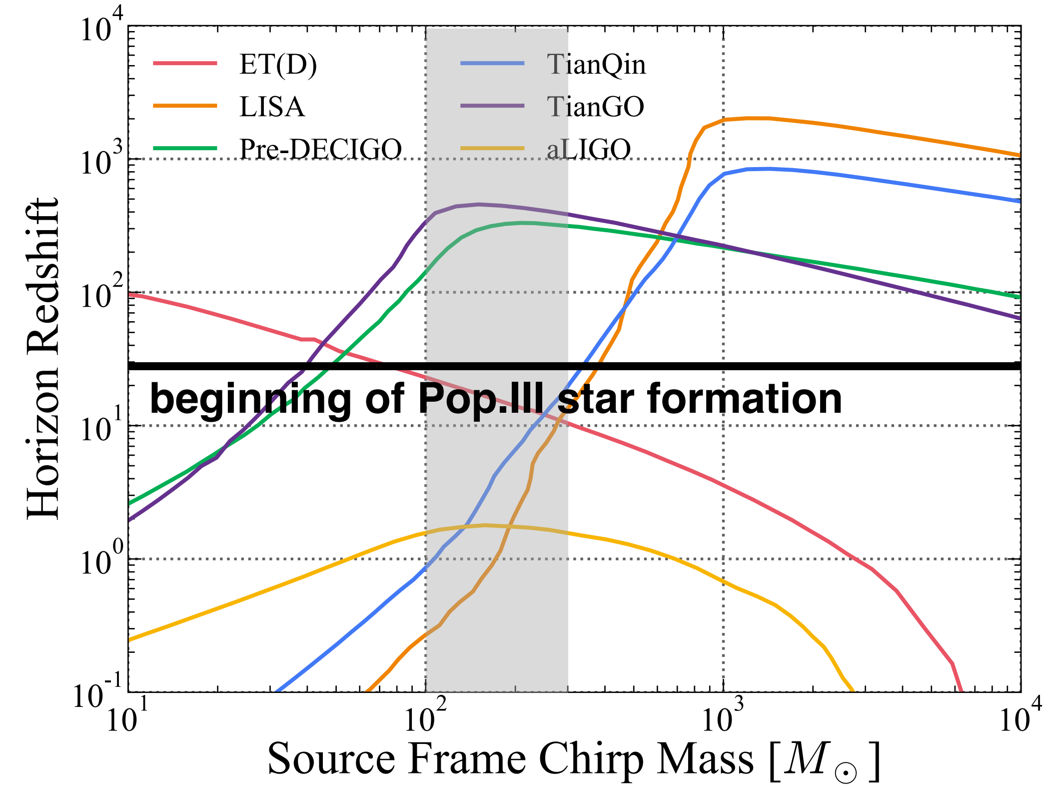
- $R^{lh}(z=0)$ = 0
  too short merger time



Detection Rate of ‘high mass + high mass’

- α = 2.8
- Chirp mass of high+high BBH →100—300$M_\odot$

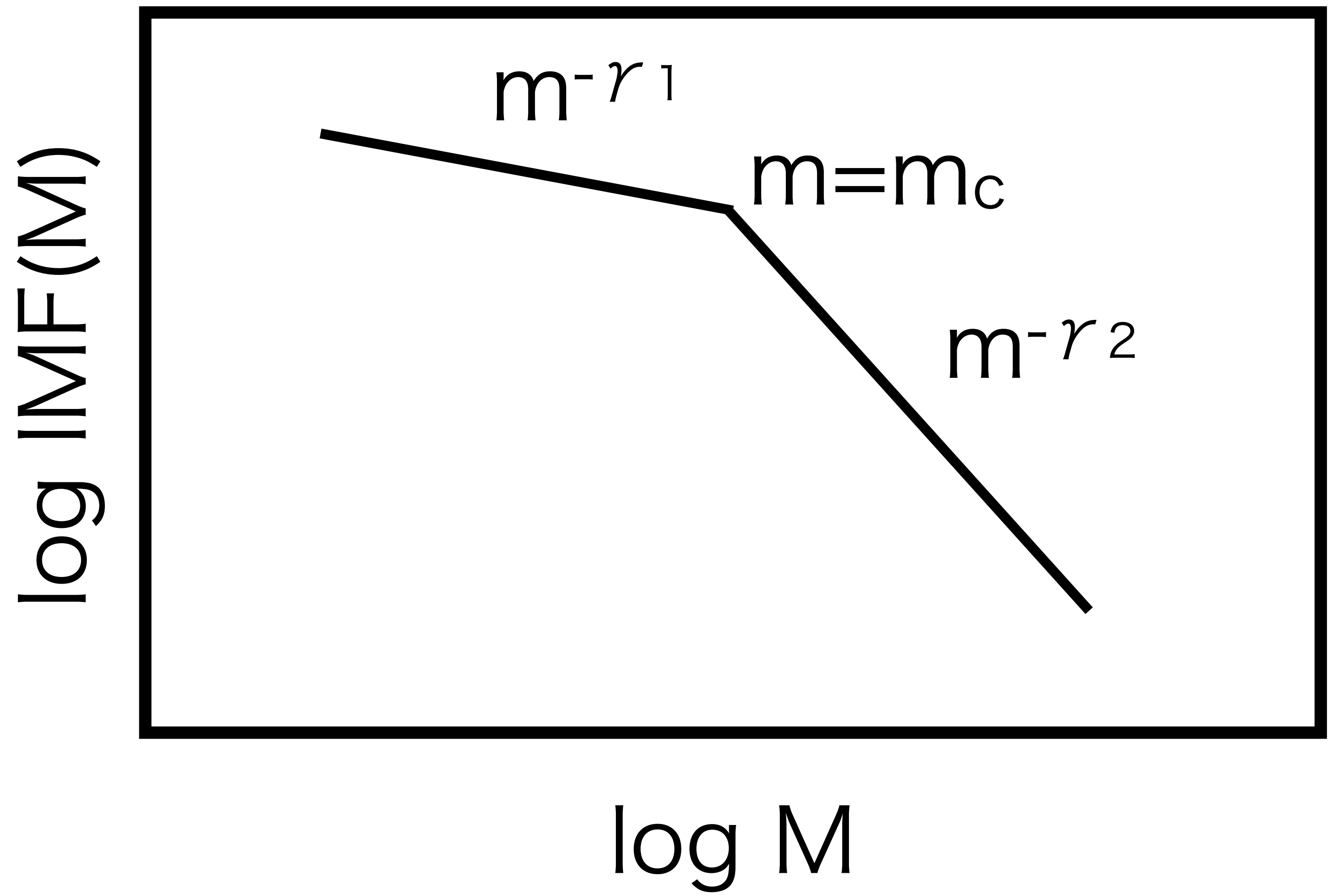
$$\mathcal{M}_\mathrm{c} = \frac{(m_\mathrm{BH,p} m_\mathrm{BH,s})^{3/5}}{(m_\mathrm{BH,p} + m_\mathrm{BH,p})^{1/5}}$$



Survey	Detection Rate [yr^{-1}]
B-DECIGO	200.9
TianGO	200.9
Einstein telescope	126.1
TianQin(天琴)	7.9
LISA	1.1
aLIGO(O5)	0.9

Future works

- **Future work:**
  - **double power law IMF**
  - **initial orbital separation distribution**
  - $\alpha_{CE}\lambda_{CE}$



Appendix

The maximum primary BH mass (more strictly)

$$t_{\rm GW} \propto a^4 m_{\rm BH,p}^{-2}$$

$$a \propto r_{\rm giant,p} \propto m_{\rm ZAMS,p}^{0.6} \quad m_{\rm BH,p} \propto m_{\rm ZAMS,p}$$

$$(m_{\rm ZAMS,p} > 600 M_\odot)$$

$$t_{\rm GW} \propto m_{\rm ZAMS,p}^{0.4}$$