$70M_{\odot}$のブラックホールを持つとされる連星系LB-1の形成過程について

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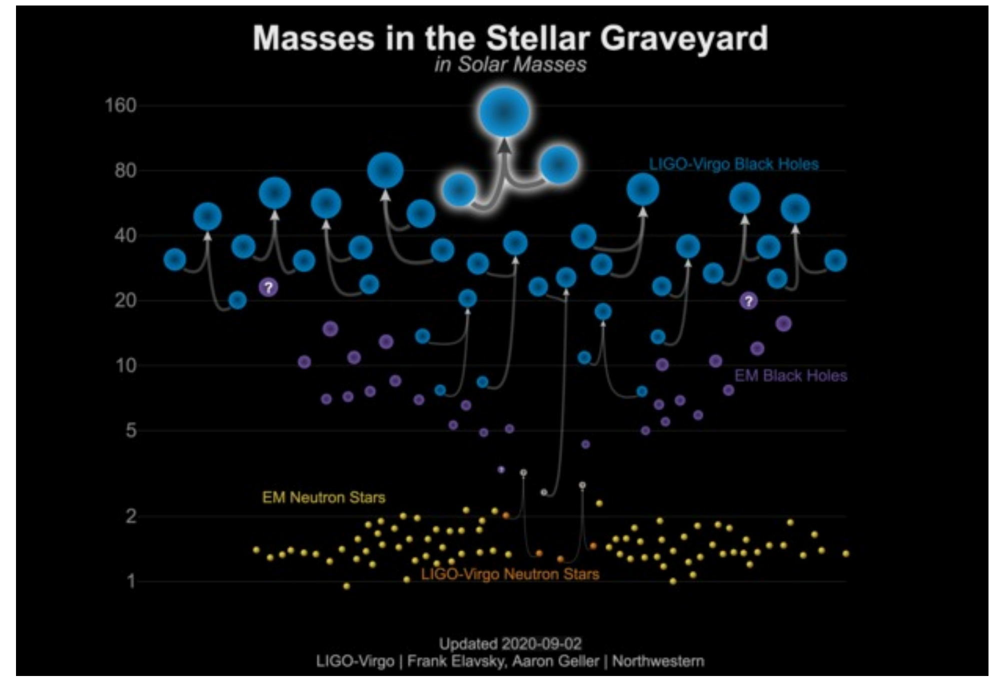
Tanikawa, Kinugawa, Kumamoto, Fujii (2020, PASJ, 72, 39)
arXiv:1912.04509

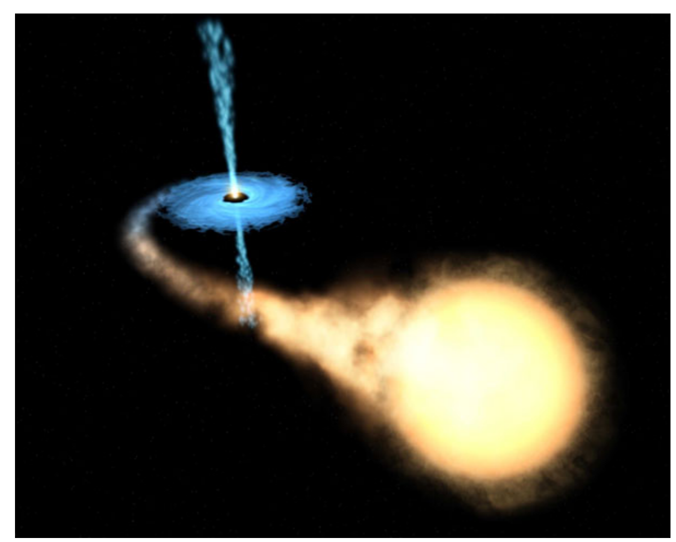
概要

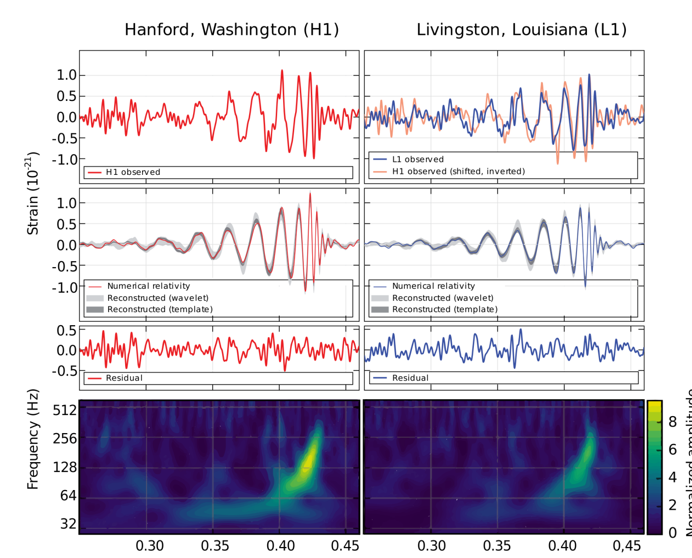
- 天の川銀河の全散開星団内でできるLB-1のような天体の形成率を見積もった.
- この形成率からはLB-1の存在を説明できない.
- 観測，恒星・連星進化理論のどこかに間違いがあると考えられる.

Stellar-mass black hole (BH)

- A final state of massive stars
- X-ray binaries and merging BHs
- Not enough information
  - X-ray binaries are short-period binaries, $P \lesssim 1$ day (Corral-Santana et al. 2016).
  - The origin of merging BHs are unknown.

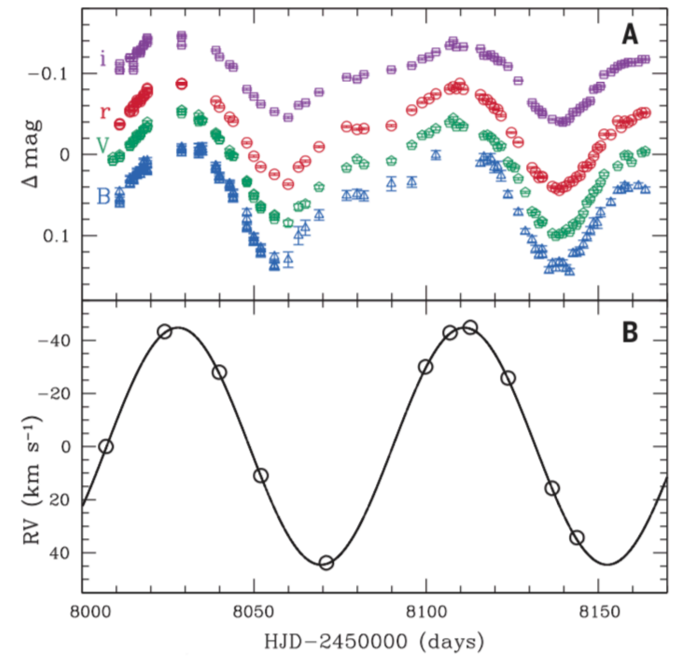


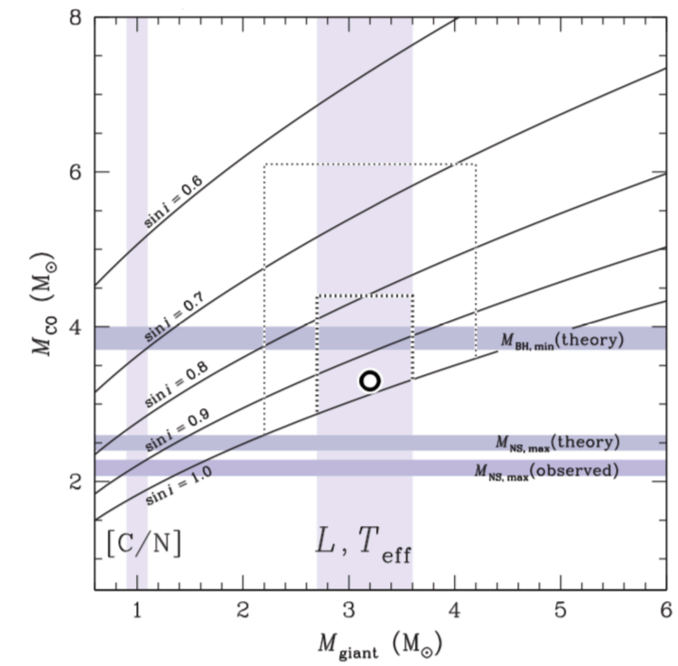




BHs in long-period binaries

- AS 386: 131 days, $7M_\odot$ compact object (Khokhlov et al. 2018)
- A detached binary in NGC 3201: 167 days, $4.36M_\odot$ compact object (Giesers et al. 2018)
- 2MASS J05215658+4359220: 83 days, $3.3M_\odot$ compact object (Thompson et al. 2019, Science, 366, 637)





$$\frac{M_{\rm CO}^3 \sin^3 i_{\rm orb}}{(M_{\rm giant}+M_{\rm CO})^2} = \frac{K^3 P_{\rm orb}}{2\pi G}(1-e^2)^{3/2} \sim 0.766 M_\odot \rightarrow \boxed{M_{\rm CO} \gtrsim 2.9 M_\odot}$$

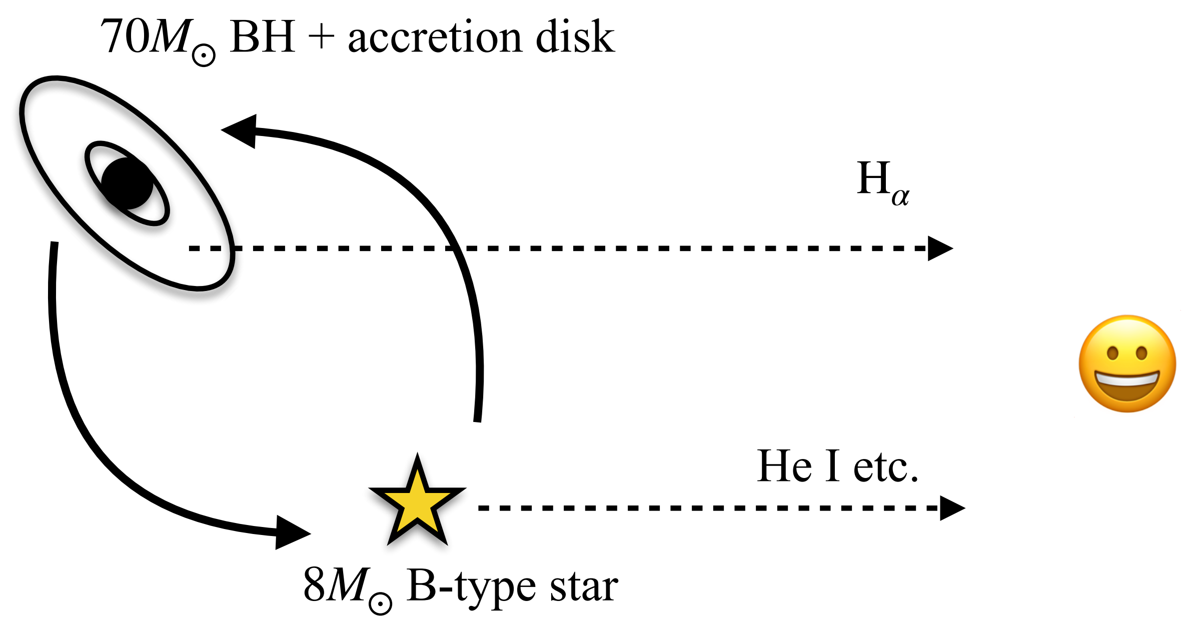
$$R_{\rm giant} = v_{\rm spin} P_{\rm spin}/2\pi \sim \frac{23 \pm 1 R_\odot}{\sin i_{\rm spin}} \left(\frac{v_{\rm spin}}{14.1 {\rm kms}^{-1}}\right)\left(\frac{P_{\rm spin}}{82.2 {\rm day}}\right)$$

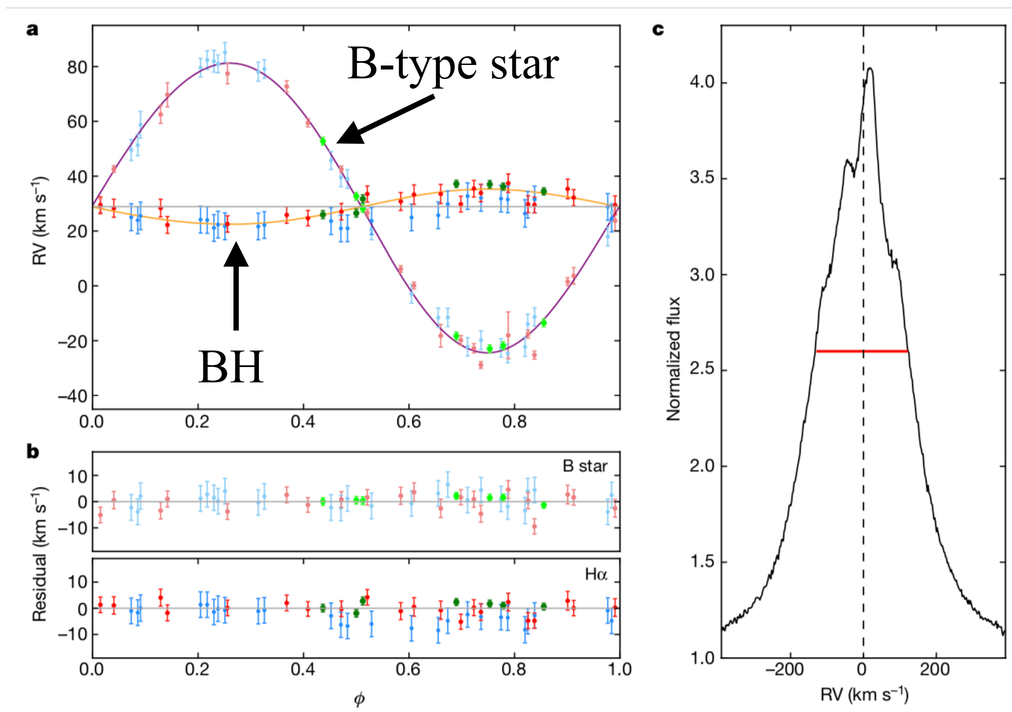
$$M_{\rm giant} = g_{\rm giant} R_{\rm giant}^2/G \sim \frac{4.4^{+2.2}_{-1.5} M_\odot}{\sin^2 i_{\rm spin}} \left(\frac{R_{\rm giant}}{23 R_\odot}\right)^2 \left(\frac{g}{10^{2.35} {\rm cms}^{-2}}\right)$$

$P_{\rm spin} \sim P_{\rm orb}$, $e \sim 0 \rightarrow i_{\rm spin} \sim i_{\rm orb} \sim i$ (synchronized)

LB-1

- $8M_\odot$ B-type star - $70M_\odot$ BH
- $a \sim 1$ au, $e \sim 0.03$, $Z \sim Z_\odot$
- L, T, and g constrain B-type star mass.
- The ratio of radial velocity determines BH mass.

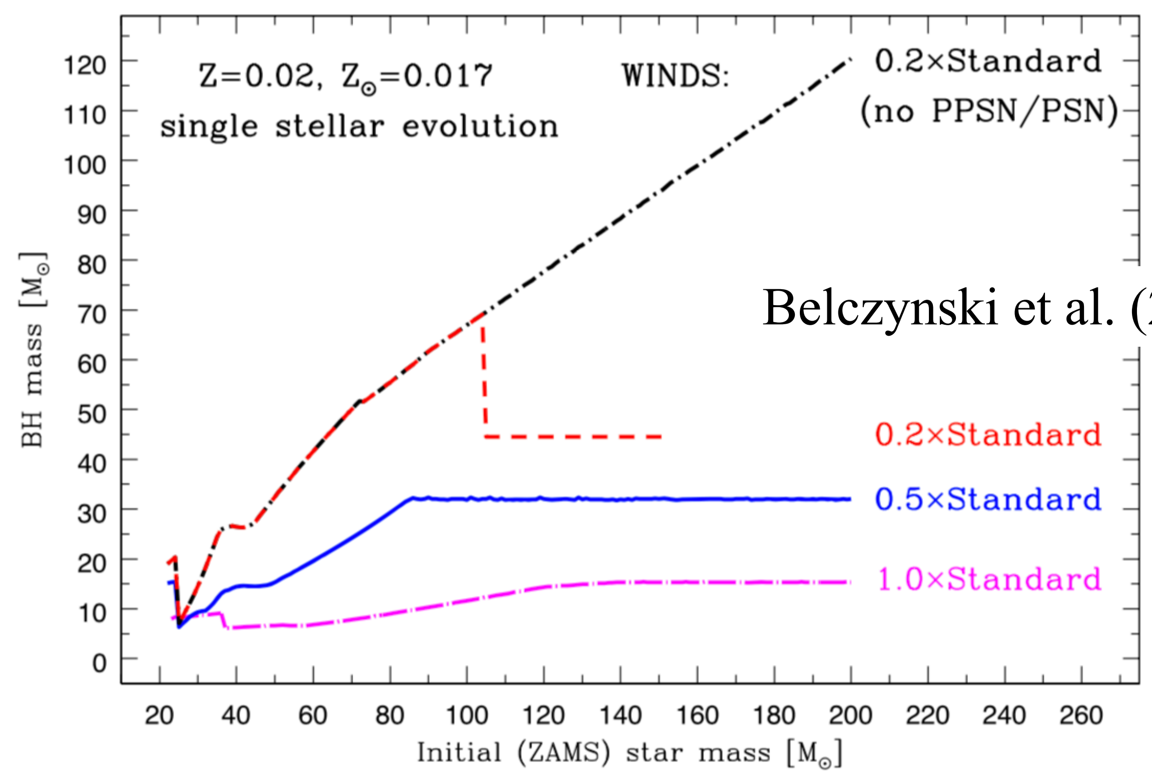




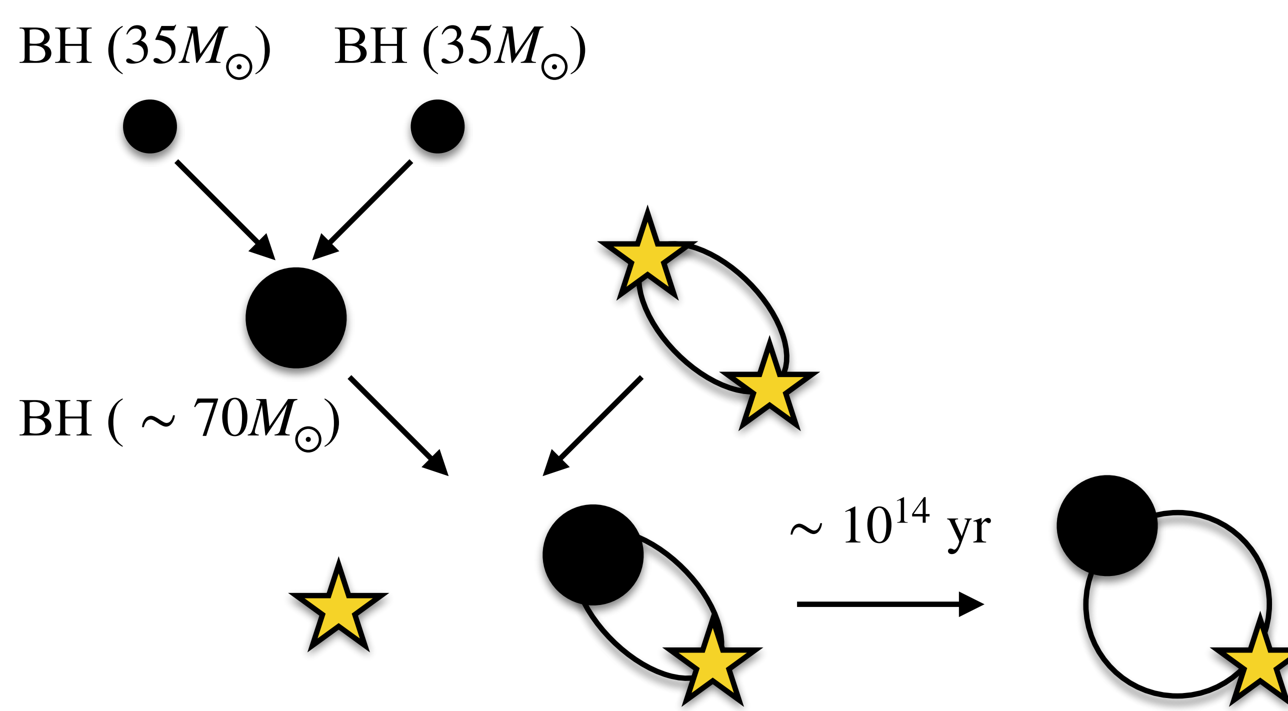
Liu et al. (2019, Nature, 575, 618)

What's surprising?

- High metallicity ($Z \sim Z_\odot$)
  - Stellar wind mass loss reduces BH mass to $\lesssim 20 M_\odot$.
  - The mass loss rate should be 5 times smaller than previously thought.
- Circular orbit ($e \sim 0.03$)
  - Circularization timescale ($\sim 10^{14}$ yr) is much more than the Hubble time.

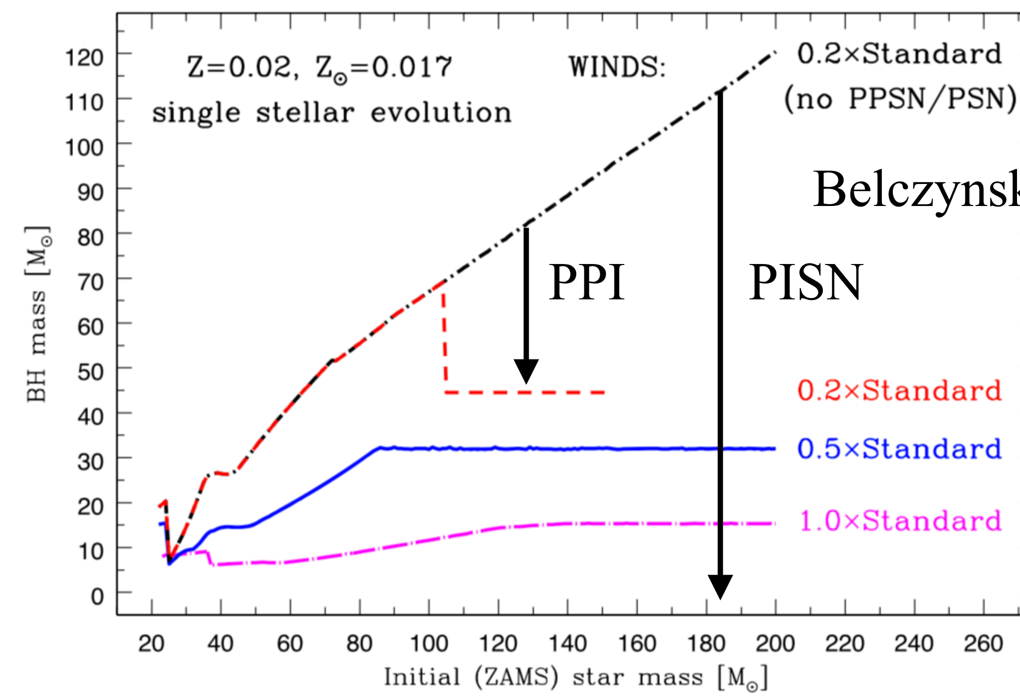


Belczynski et al. (2020)

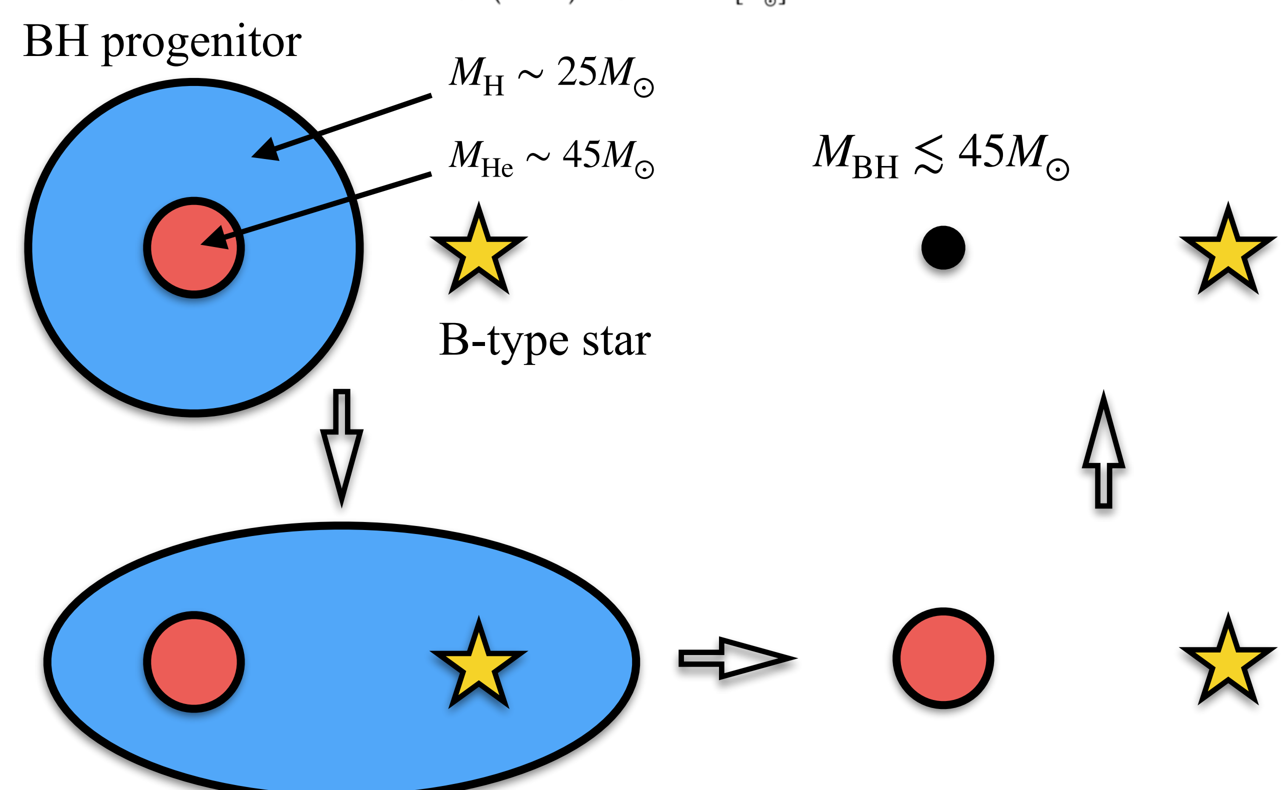


Reduced stellar wind

- BH progenitors should have $M_{\rm tot} \gtrsim 70 M_\odot$ and $M_{\rm c,He} \lesssim 45 M_\odot$.
  - BH progenitors with $M_{\rm c,He} \gtrsim 45 M_\odot$ reduce BH masses to $M_{\rm BH} \sim 45 M_\odot$ through mass loss of pulsatoinal pair instability (PPI).
  - BH progenitors with $M_{\rm c,He} \gtrsim 65 M_\odot$ leave no remnants due to pair instability supernovae (PISNe)
  - GW observation supports PPI/PISN.
- The binary size ($a \sim 1\text{au} \sim 200 R_\odot$)
  - $a_i \lesssim 1\text{au}$ … MS merger
  - $a_i \gtrsim 1\text{au}$ … Common envelope
  - $a_i \gg 1\text{au}$ … No interaction ($a \gg 1\text{au}$)

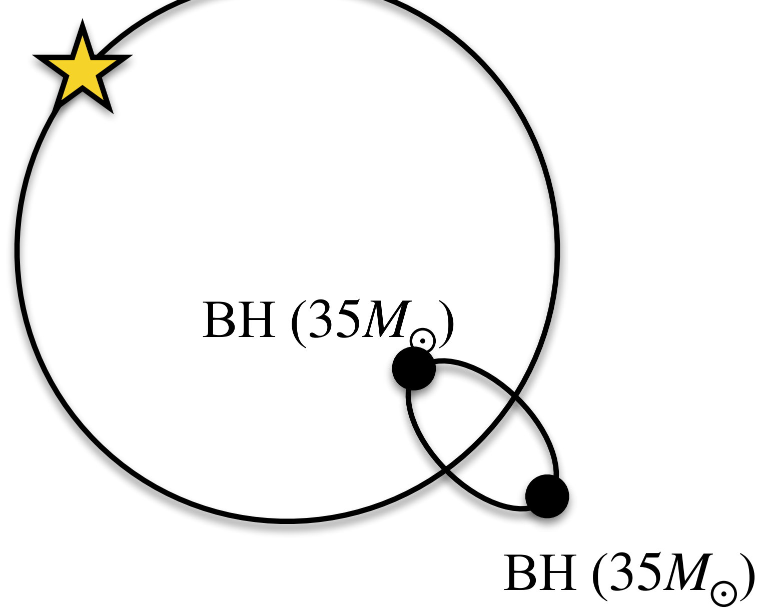


Belczynski et al. (2020)



Possibility of double BHs

- The merger time through gravitational wave is $\sim 10^4$ yr.
- The merger time is smaller than the lifetime of the B-type star by three order of magnitude.
- This probability is quite low.
- (Shen et al. 2019)

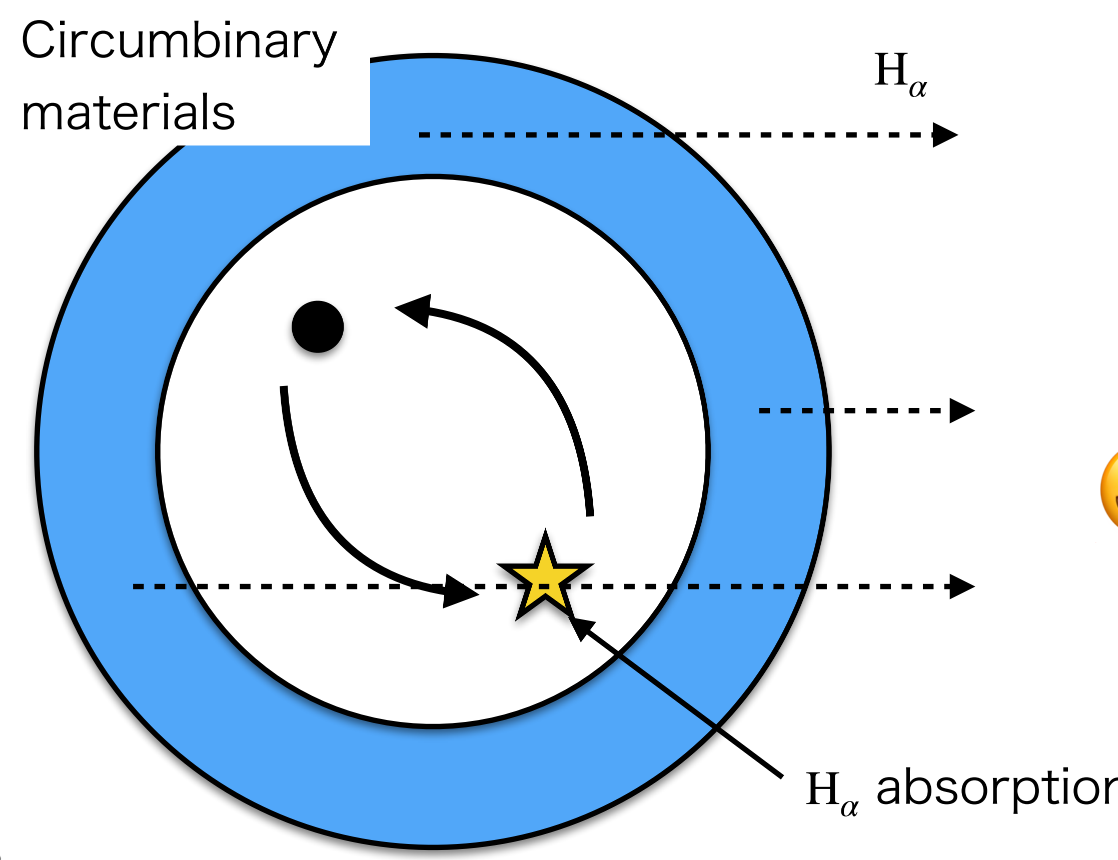


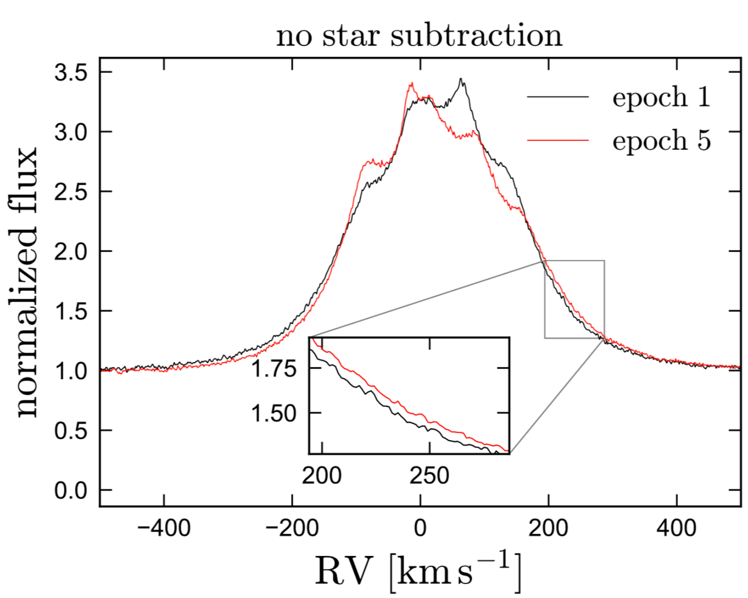
Possible scenario

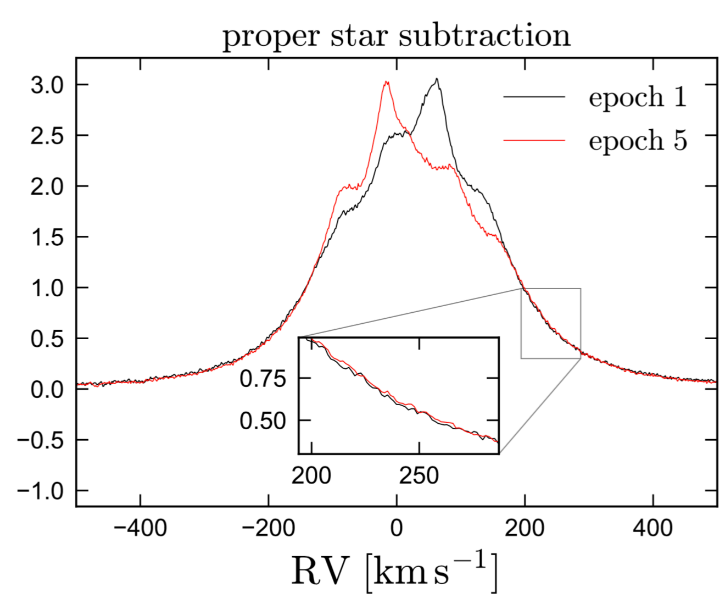
- ~~Binary evolution~~
- Hierarchical multiplicity
  - ~~Inner BH-BHs~~
  - (More complicating channels)
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - More complicating channels

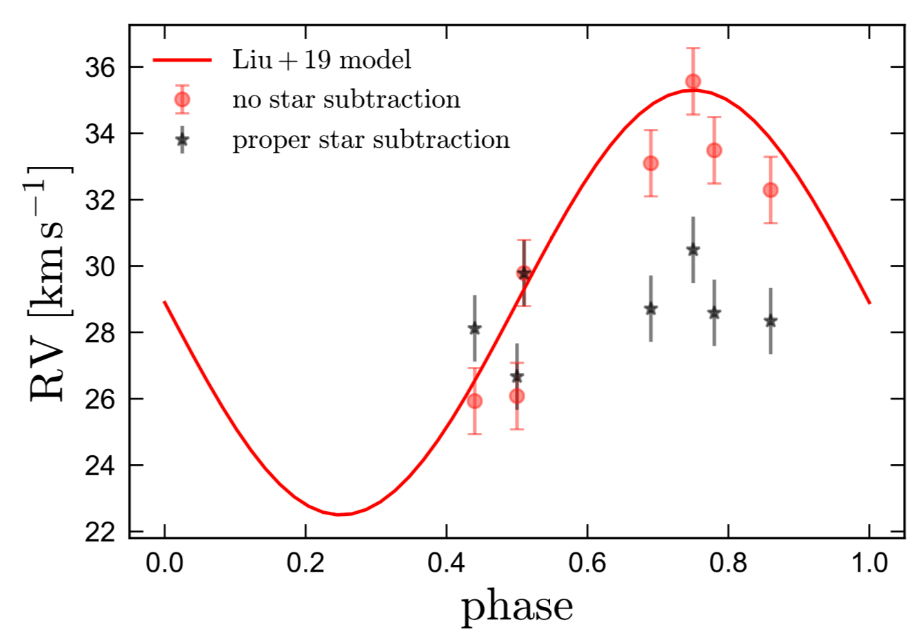
Counter opinions on “$70 M_\odot$”

- No evidence that H_α is associated with the BH
- Radial velocity variability disappears when H_α absorption by the B-type star is considered.
- H_α may be associated with circumbinary materials.





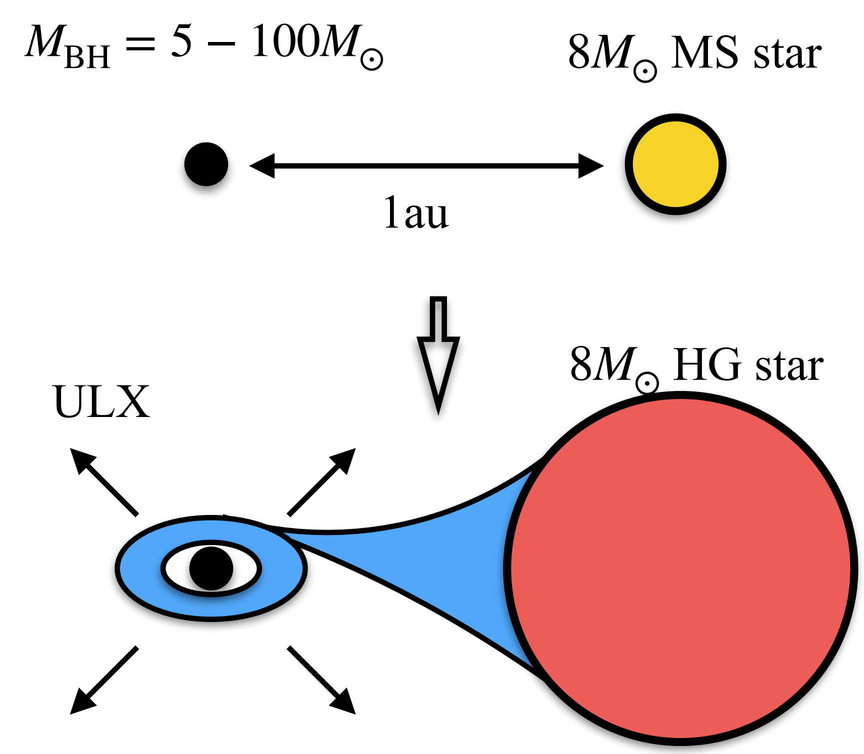


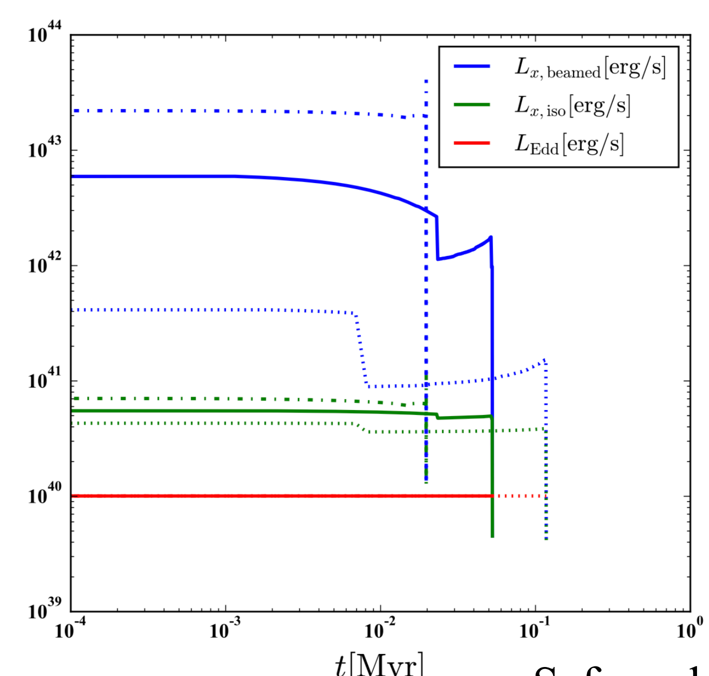


El-Badry, Quataert (2020; see also Abdul-Masih et al. 2019)

"Postgenitor" problem

- LB-1 system will evolve to an ULX source in future.
  - Roche-lobe overflow will starts when the B-type star enters into a Hertzsprung gap (HG) phase.
  - The HG star rapidly expands, and achieves a high accretion rate onto the BH.
- The number of ULXs inferred by LB-1 is larger than observed in the MW by an order of magnitude.





Safarzadeh et al. (2019)

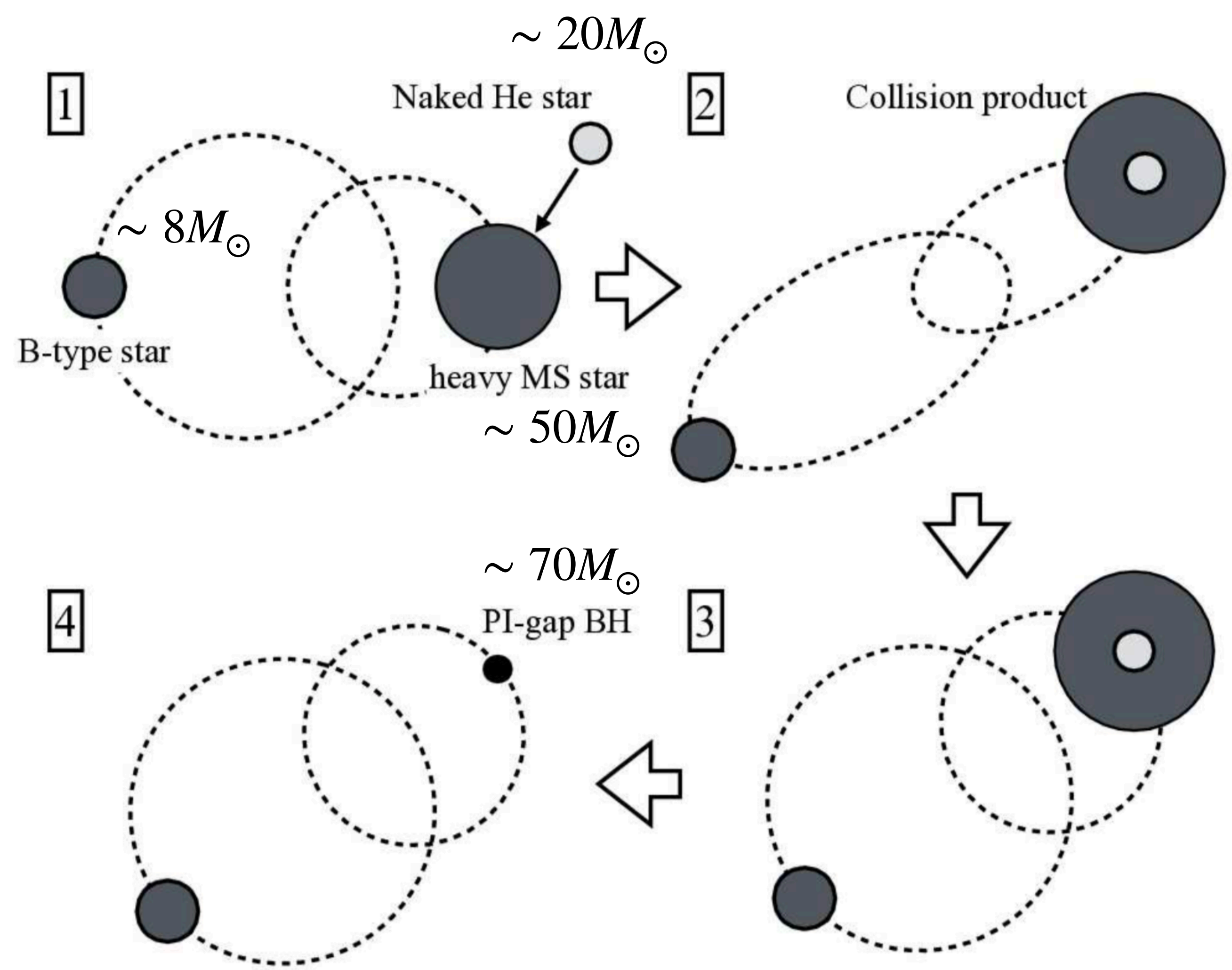
Our stance

- The presence of the $70M_{\odot}$ BH may be doubtful.
- However, another theoretically-challenging binary may be reported in future.
- The usual meaning of the “theoretically-challenging” is “challenging in the framework in binary evolution”.
- We use this opportunity to notice dynamical formation of a binary in dense stellar clusters, using LB-1 as a good example.

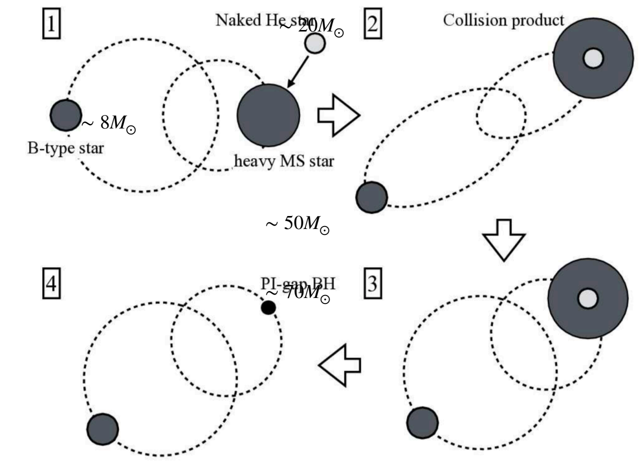
The most efficient process

1. Collision of a naked He star with a MS star which has a B-type companion.
   - The He star must not have Hydrogen envelope.
2. The collision product and B-type companion form a binary system.
3. The binary system is circularized through dynamical tide of the collision product's envelope.
4. The collision product collapses to a $70M_{\odot}$ BH.
   - It can avoid PPI/PISN because of small He core.

In an open cluster of the MW galaxy

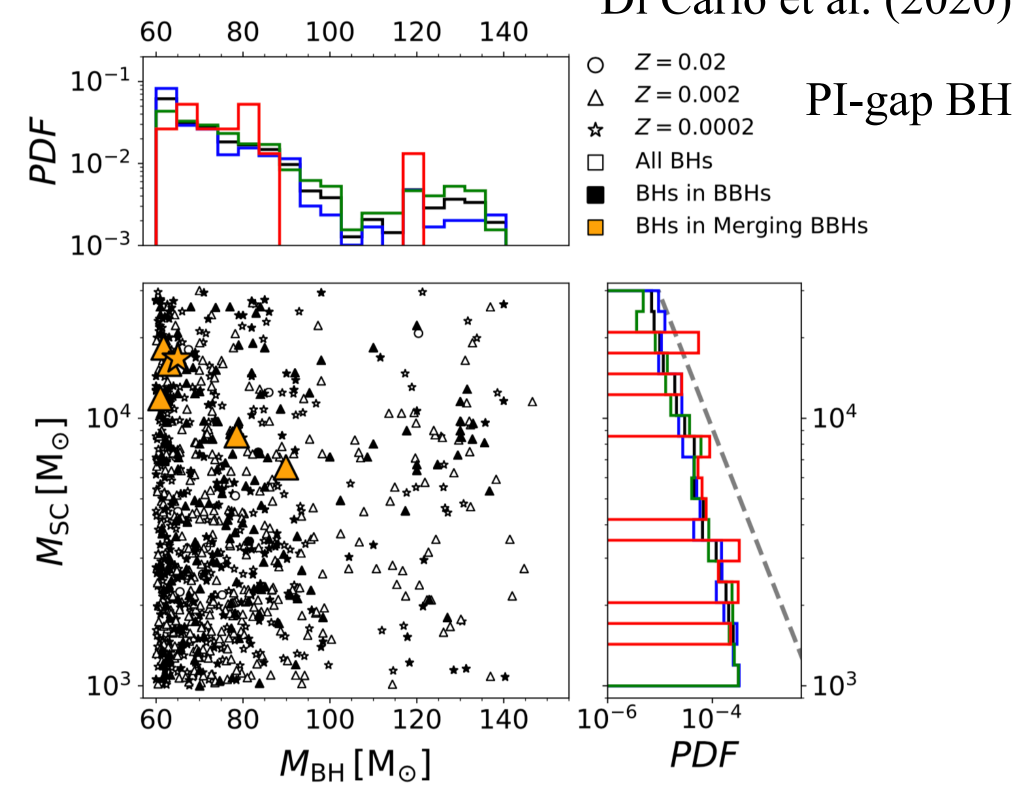


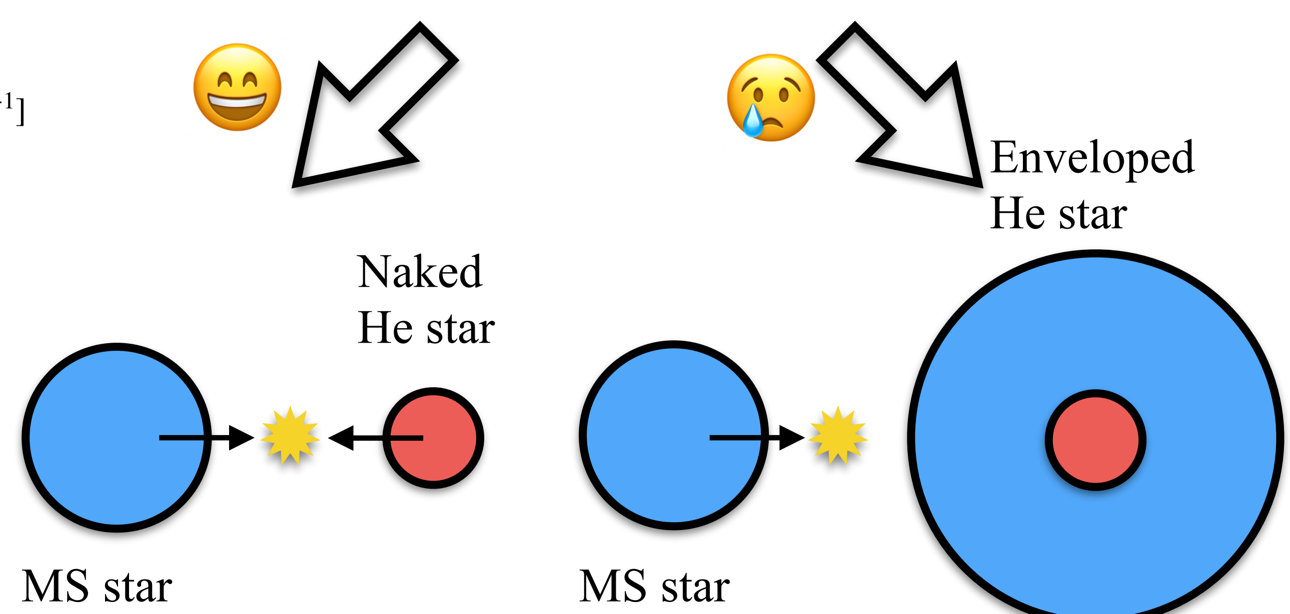
Collision rate



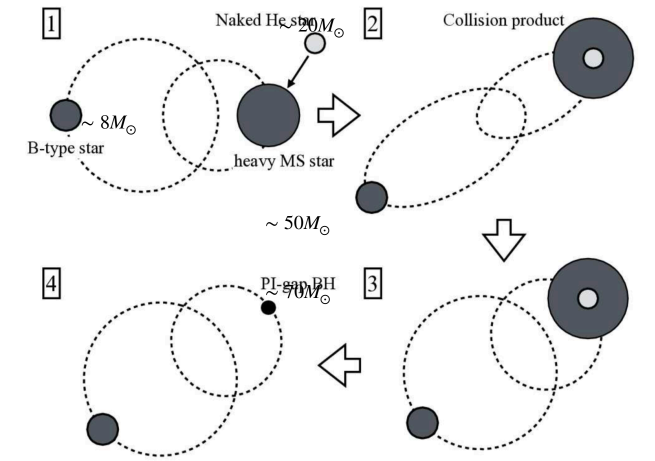
Di Carlo et al. (2020)

- Formation rate of PI-gap BHs in OCs
  - $\dot{N}_{\rm PIgap} \sim 2\times10^{-6}\left(\frac{f_{\rm PIgap}}{0.002}\right)\left(\frac{\rho_{\rm oc}}{10^4 M_\odot {\rm pc}^{-3}}\right)\left(\frac{\eta_{20}}{0.003 M_\odot^{-1}}\right)\left(\frac{f_{\rm oc}}{0.2}\right)\left(\frac{\dot{M}_{\rm mw}}{2 M_\odot {\rm yr}^{-1}}\right)$ [yr^{-1}]
- Formation path fraction
  - $\frac{\Gamma_{\rm nHe}}{\Gamma_{\rm eHe}} \sim 10^{-2}\left(\frac{N_{\rm 1,nHe}/N_{\rm 1,eHe}}{2}\right)\left(\frac{M_{\rm 12,nHe}/M_{\rm 12,eHe}}{0.7}\right)\left(\frac{R_{\rm 12,nHe}/R_{\rm 12,eHe}}{0.01}\right)$
- Collision rate
  - $\dot{N}_{\rm coll} = \dot{N}_{\rm PIgap}\frac{\Gamma_{\rm nHe}}{\Gamma_{\rm eHe}}P_{\rm b} \sim 3\times10^{-9}\left(\frac{\dot{N}_{\rm PIgap}}{2\times10^{-6}\ {\rm yr}^{-1}}\right)\left(\frac{\Gamma_{\rm nHe}/\Gamma_{\rm eHe}}{10^{-2}}\right)\left(\frac{P_{\rm b}}{0.1}\right)$ [yr^{-1}]

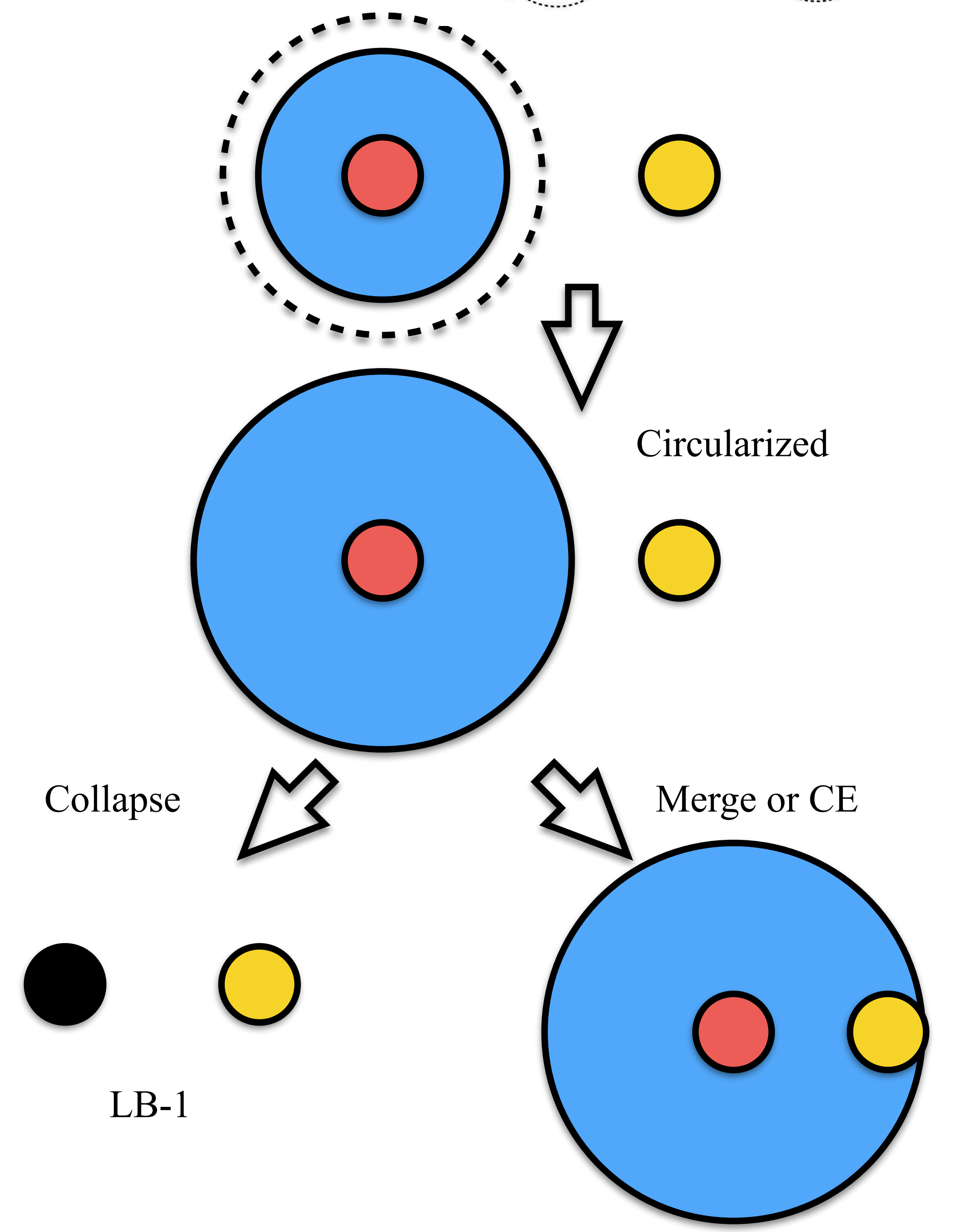


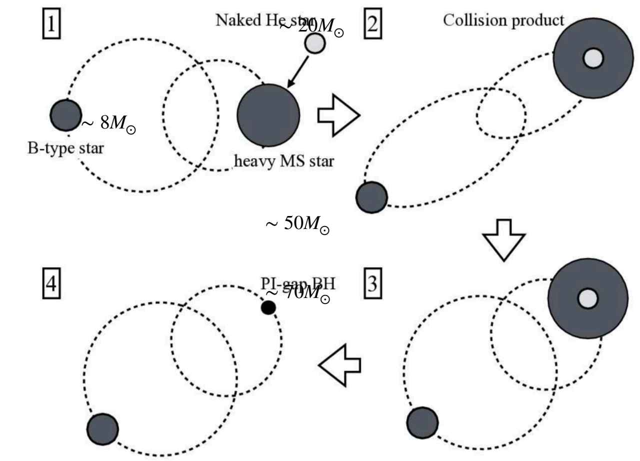


Circularization



- The binary is rapidly circularized through tidal interaction.
- If the collision product collapses to a BH before swallowing the B-type star, the binary becomes LB-1.
  - The collapse time is at random, since the naked He star wandered in an OC for a long time.
- Circularization time
  - $$t_{\rm cric} \sim 2 \times 10^4 \left(\frac{R_{\rm coll}}{100 R_\odot} \right)^{-9} \ [{\rm yr}]$$
- Kelvin-Helmholtz time (expansion time)
  - $$t_{\rm KH} \sim 2 \times 10^4 \left(\frac{M_{\rm coll}}{70 M_\odot} \right)^{2} \left(\frac{R_{\rm coll}}{100 R_\odot} \right)^{-1} \left(\frac{L_{\rm coll}}{10^5 L_\odot} \right)^{-1} \ [{\rm yr}]$$
- Surviving probability
  - $$P_{\rm surv} = t_{\rm KH} / t_{\rm coll,life,max} \sim 0.1 \left(\frac{t_{\rm coll,life,max}}{0.2 {\rm Myr}} \right)^{-1}$$





The formation rate

- The number of LB-1-like systems in the MW
- $$N_{\rm LB1} \sim 0.01 \left(\frac{\dot{N}_{\rm coll}}{3 \times 10^{-9} \mathrm{yr}^{-1}} \right) \left(\frac{P_{\rm surv}}{0.1} \right) \left(\frac{T_{\rm B}}{40 \mathrm{Myr}} \right)$$
- No chance to form LB-1-like systems in OCs

Other stellar collisions

- Collision of He stars with H envelope does not work.
  - He star have $R \gg a$.
- Collision products of two MSs or two naked He stars cannot avoid PPI/PISN
- Collision rate of BH and other stars is lower than or similar to the above process.

	MS	He star	Naked He star	BH
MS	PPI/ PISN			
He star	R>>a	R>>a		
Naked He star	Done	R>>a	PPI/ PISN	
BH	Similar rate	R>>a	Lower rate	Lower rate

Possible scenario

- ~~Binary evolution~~
- Hierarchical multiplicity
  - ~~Inner BH-BHs~~
  - (More complicating channels)
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - ~~More complicating channels~~

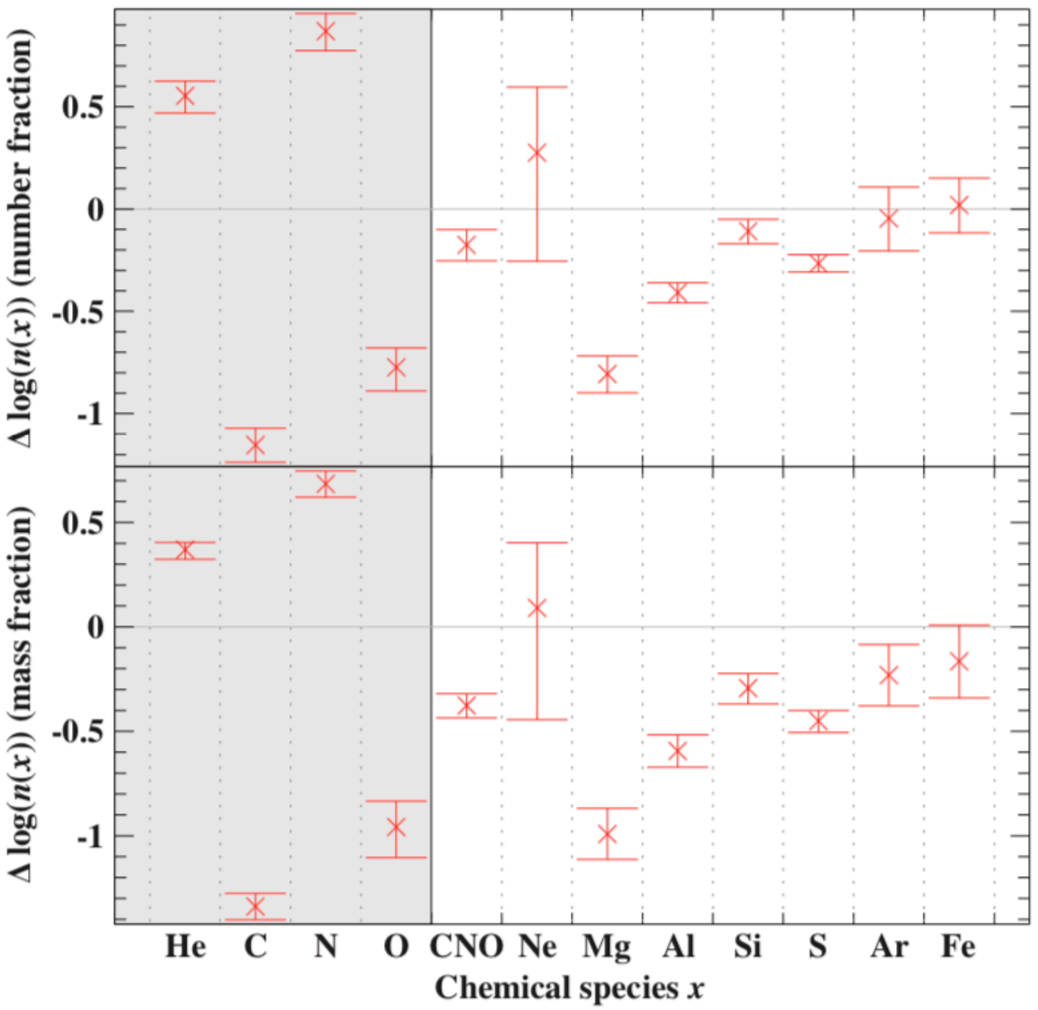
Summary

- A $70M_\odot$ BH in LB-1 has been reported.
- The presence may be doubtful, but is under dispute.
- We have examined the formation rate of LB-1, but LB-1 has no chance to be formed through dynamical interactions, and hierarchical triple systems, if the standard model of single and binary stars is correct.
- We don't deny the presence of $70M_\odot$ BHs in wide binaries with $\gg 200R_\odot$ under metal-poor environments.

Back-up slides

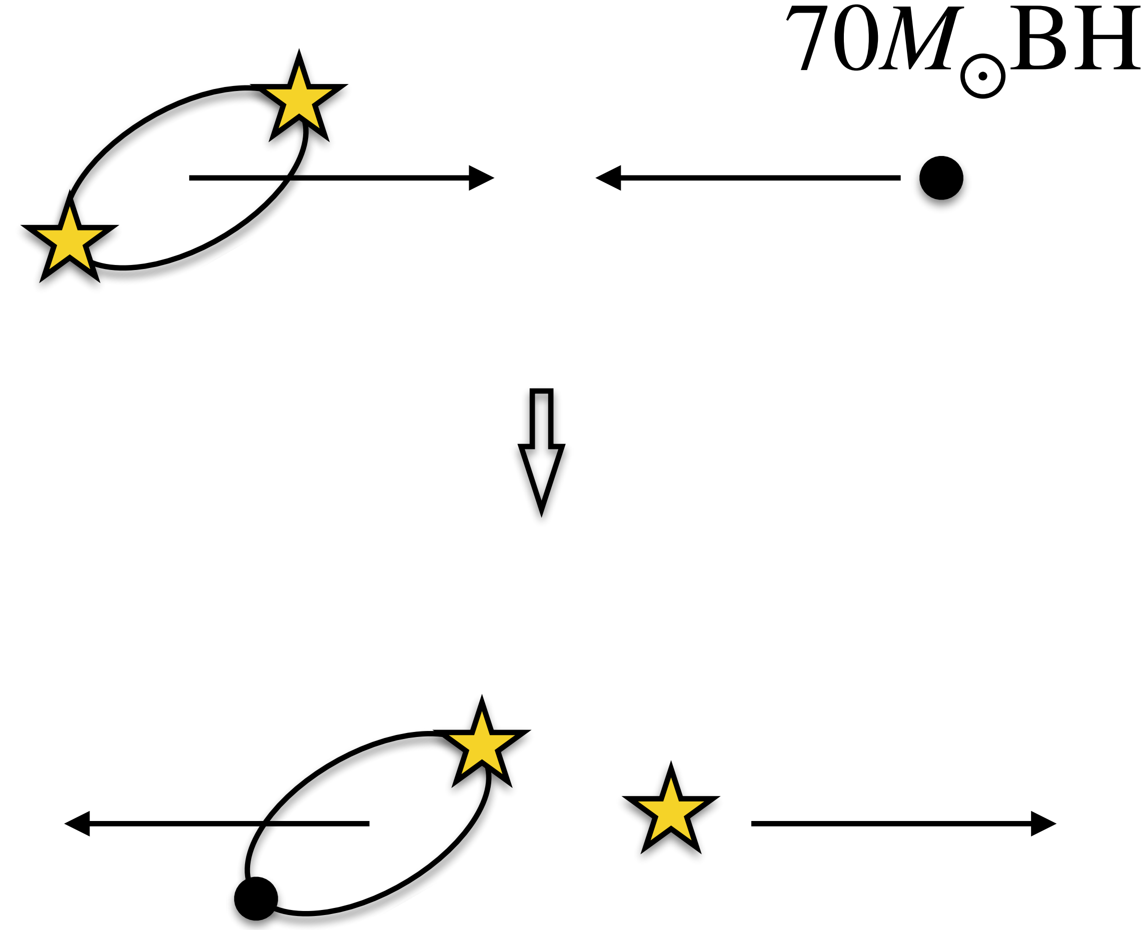
What is LB-1 in reality ?

- The B-type star can be a stripped helium star with $\sim 1.1 M_\odot$ (Irrgang et al. 2019).
- The luminosity is consistent if the Gaia distance is adopted (Eldridge et al. 2019; Irrgang et al. 2019).
- The unseen companion can be a neutron star.



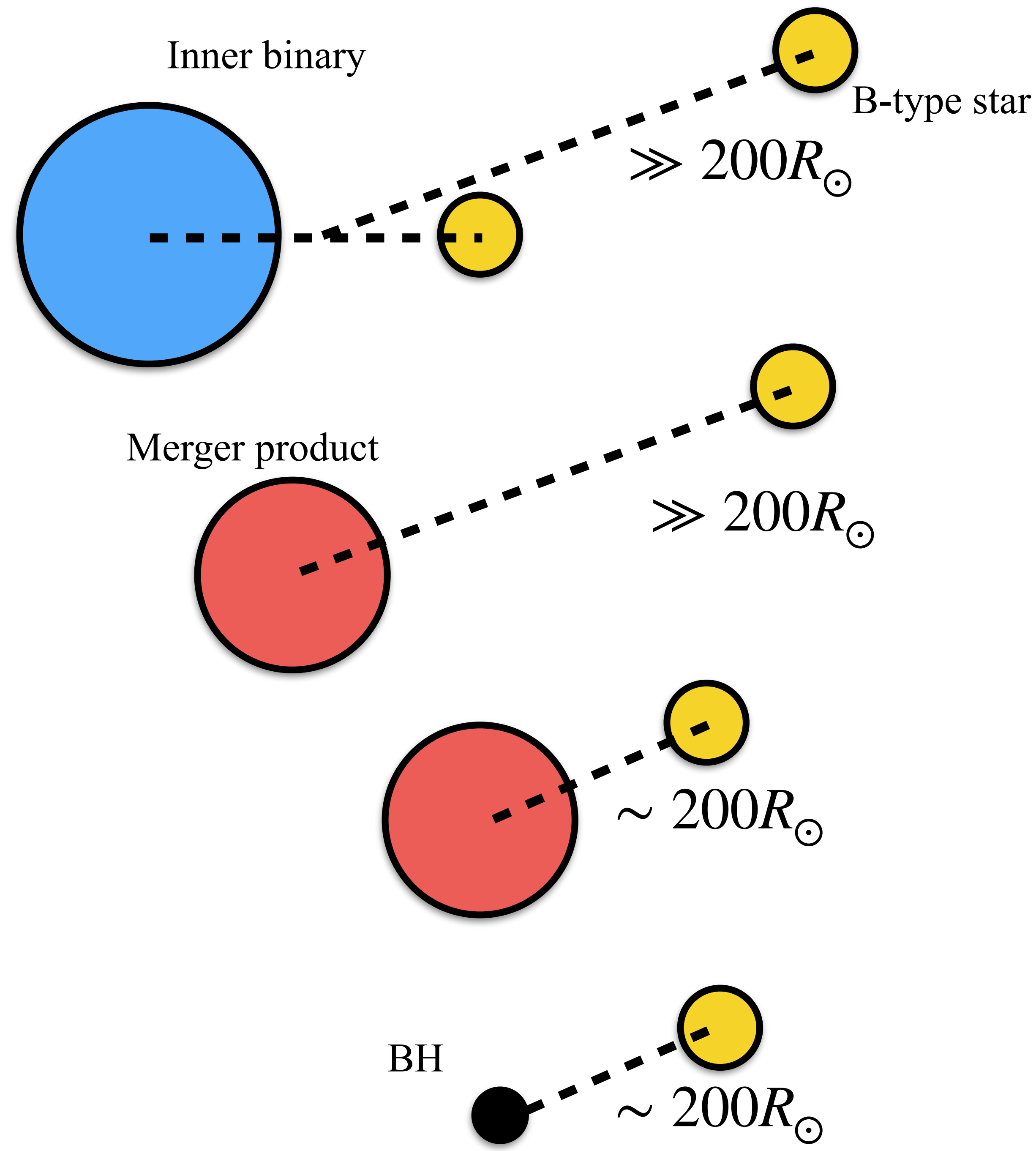
Capture processes

- At first, there is no circularization process
- OC-origin:
  $N_{\rm b} \sim 0.7 \to N_{\rm b,cir} \sim 7 \times 10^{-4}$
- GC-origin: No B-type star
- Interstellar space-origin:
  $N_{\rm b} \sim 7 \times 10^{-8}$



Hierarchical triple (1)

- The merger product should be $\gtrsim 70M_\odot$.
- If it has a radius of $\gg 200M_\odot$, it is a He star.
- It experiences common envelope evolution with the B-type star.
    - It loses its envelope, and collapses to a $\lesssim 45M_\odot$ BH.
    - It merges with the B-type star, and the system should not be a binary system.
- The inner binary should be separated from the B-type star by $\sim 200R_\odot$, and never has no interaction with the B-type star.



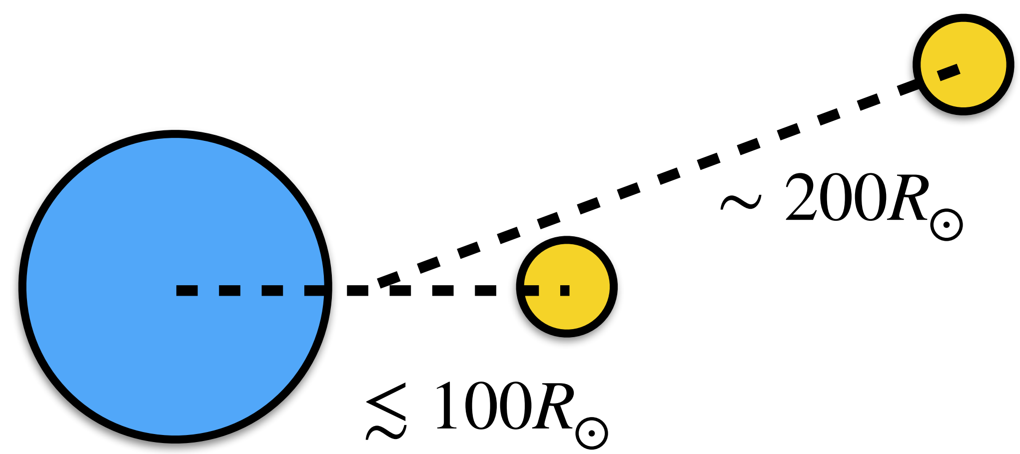
Hierarchical triple (2)

- The separation of the inner binary should be $\lesssim 100R_{\odot}$. Otherwise, the system is unstable (Harrington 1972; Mardling, Aarseth 1999).

- The primary star of the inner binary should be $\gtrsim 35M_{\odot}$.

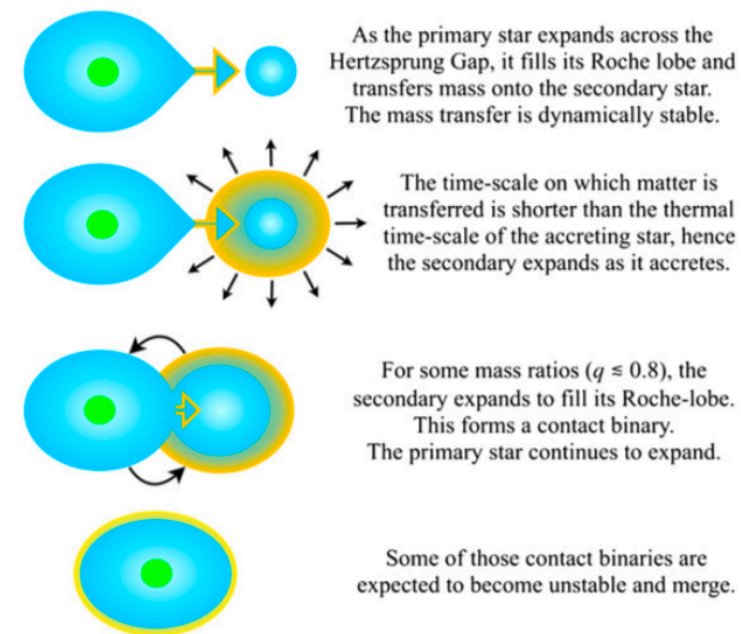
  - $\lesssim 100M_{\odot}$ stars exceed $\sim 100R_{\odot}$ when they are in Hertzsprung gap phases. The inner binary experiences a Case B merger.

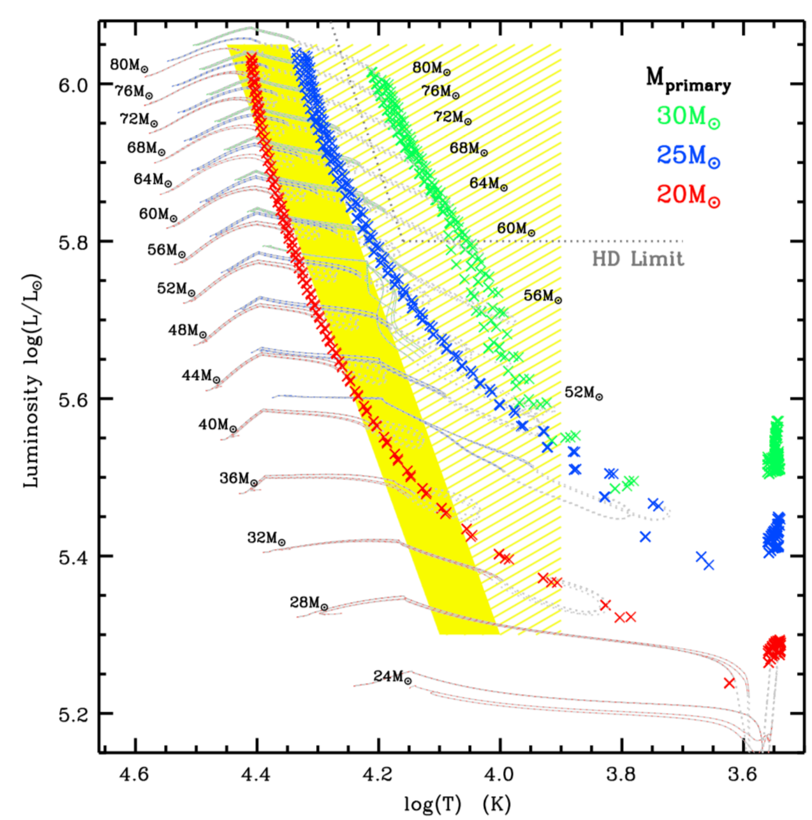
  - $\gtrsim 100M_{\odot}$ stars exceed $\sim 100R_{\odot}$ when they are in MS phases. The inner binary experiences a MS-MS merger. The merger product cannot avoid PPI/PISN.



Case B merger

- When the primary star is in a Hertzsprung gap phase, the binary can experience Case B merger.
- But, the merger product has $\sim 200 R_{\odot}$, and merges with the B-type companion.
  - A $35 M_{\odot} + 35 M_{\odot}$ merger product gets the smallest radius $\gtrsim 200 R_{\odot}$.
  - The mass ratio of the merger product to the B-type star is high $\gtrsim 10$.





Justham et al. (2014)

Pulsational Pair Instabiliity

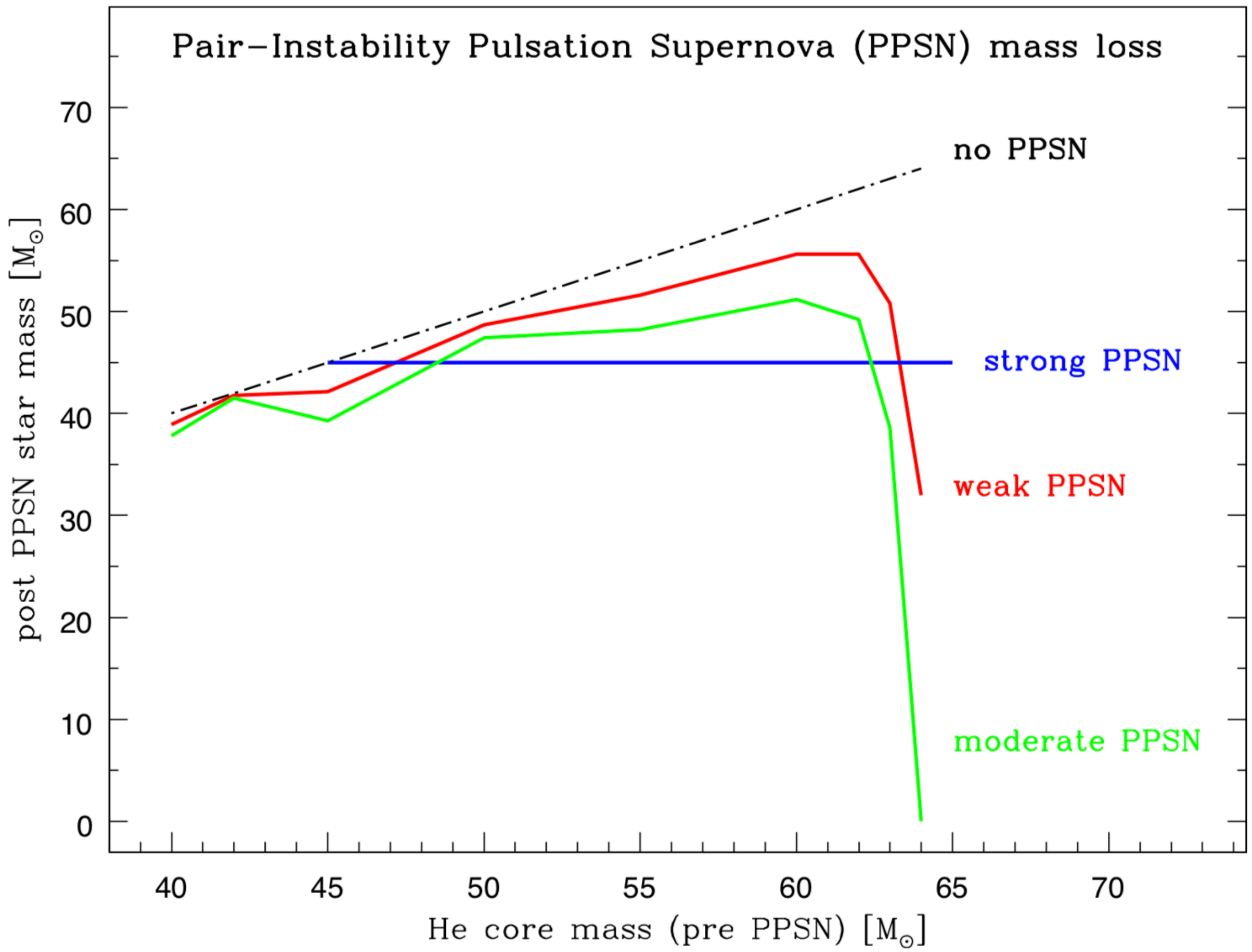


Fig. 3. Adopted models for pair-instability pulsation supernova mass loss. For a given He core mass we show the mass of a star after PPSN mass loss. Moderate PPSN mass loss is adopted directly from Leung et al. (2019), while its modified (50% reduced mass loss) version is presented as weak PPSN model. Strong PPSN are adopted from Belczynski et al. (2016c).