70太陽質量ブラックホールを含むとされるLB-1の力学的相互作用による形成率について

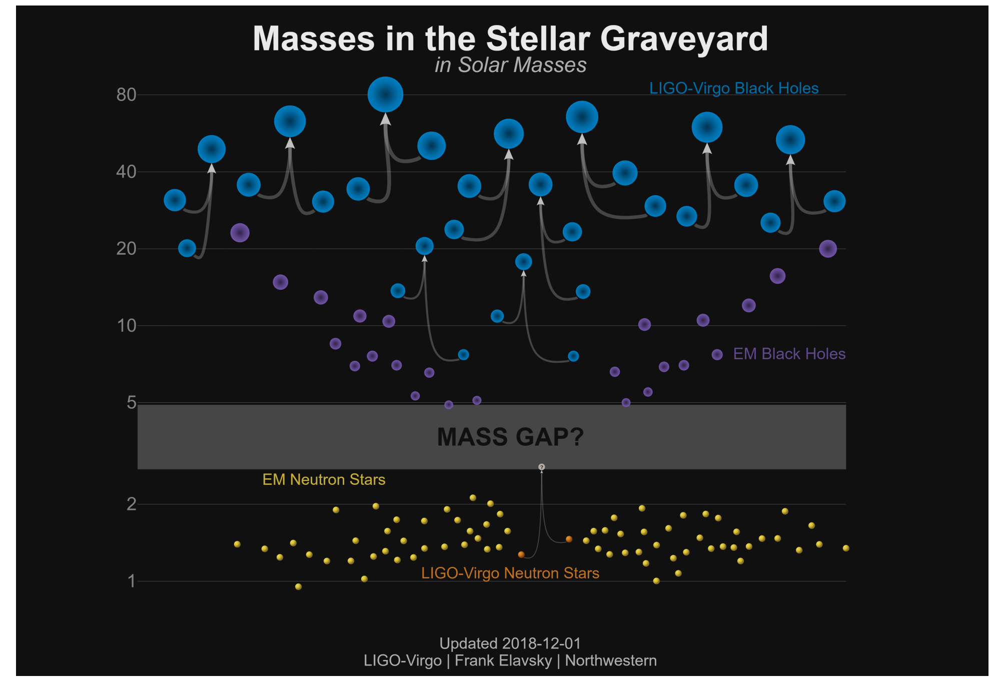
Ataru Tanikawa (University of Tokyo, Komaba)
Collaborators:
T. Kinugawa (UoT, ICRR),
J. Kumamoto, M. S. Fujii (UoT, Dept. Astronomy)

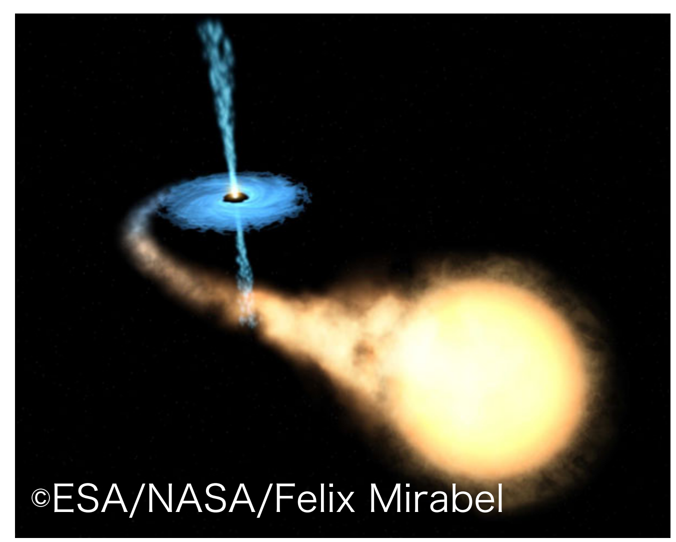
Tanikawa et al. (2020, arXiv:2019.04509, PASJ accepted)

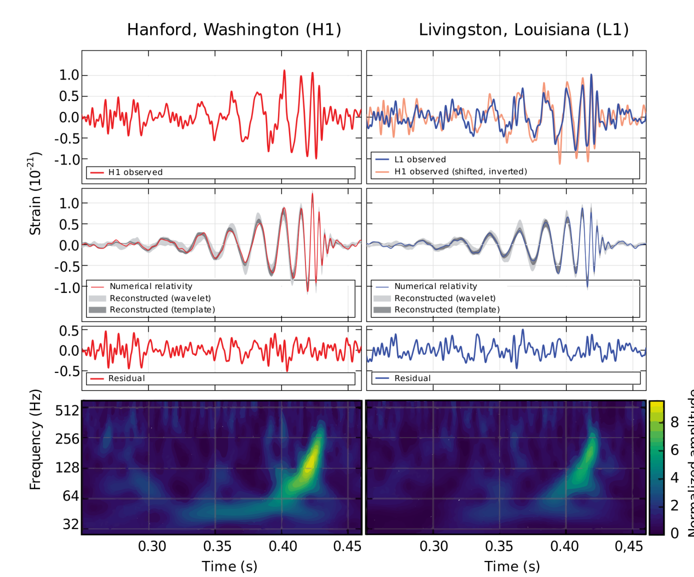
Colloquium, Dept. Astronomy, Koto University

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.



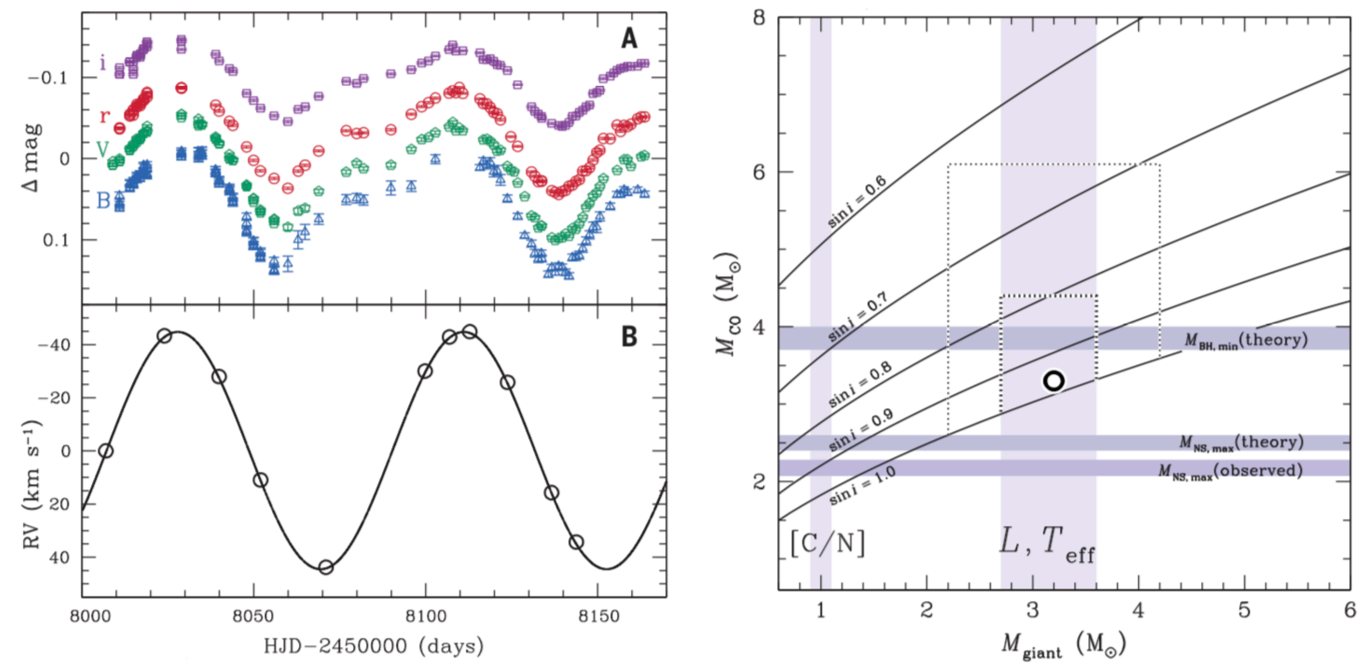




GW150914 (Abbott et al. 2016)

BHs in long-period binaries

- Astrometry (Shikauchi san's talk)
- Spectroscopy
  - AS 386: 131days, $7M_{\odot}$ 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: 83days, $3.3M_{\odot}$ compact object (Thompson et al. 2019, Science 366, 637)



Thompson et al. (2019)

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

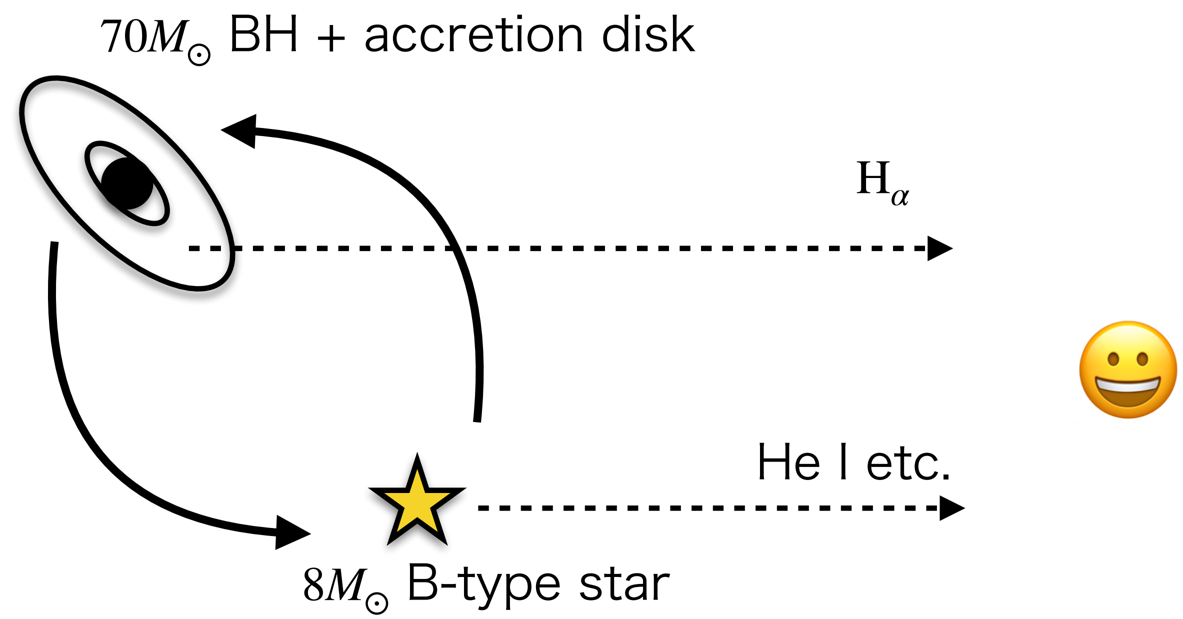
$$R_{giant} = v_{spin} P_{spin}/2\pi \sim \frac{23 \pm 1 R_{\odot}}{\sin i_{spin}} \left(\frac{v_{spin}}{14.1 \mathrm{kms}^{-1}}\right)\left(\frac{P_{spin}}{82.2 \mathrm{day}}\right)$$

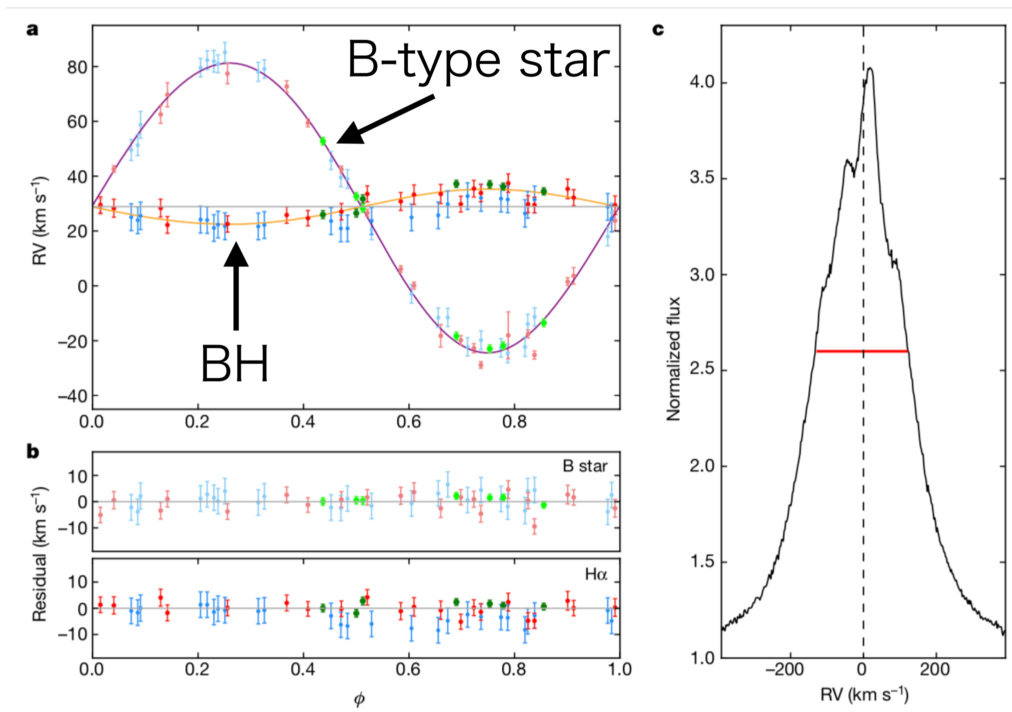
$$M_{giant} = g_{giant} R_{giant}^2 / G \sim \frac{4.4^{+2.2}_{-1.5} M_{\odot}}{\sin^2 i_{spin}} \left(\frac{R_{giant}}{23 R_{\odot}}\right)^2 \left(\frac{g}{10^{2.35} \mathrm{cms}^{-2}}\right)$$

$P_{spin} \sim P_{orb}$, $e \sim 0 \rightarrow i_{spin} \sim i_{orb} \sim i$ (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 contrain B-type star mass.
- The ratio of radial velocity determines BH mass.

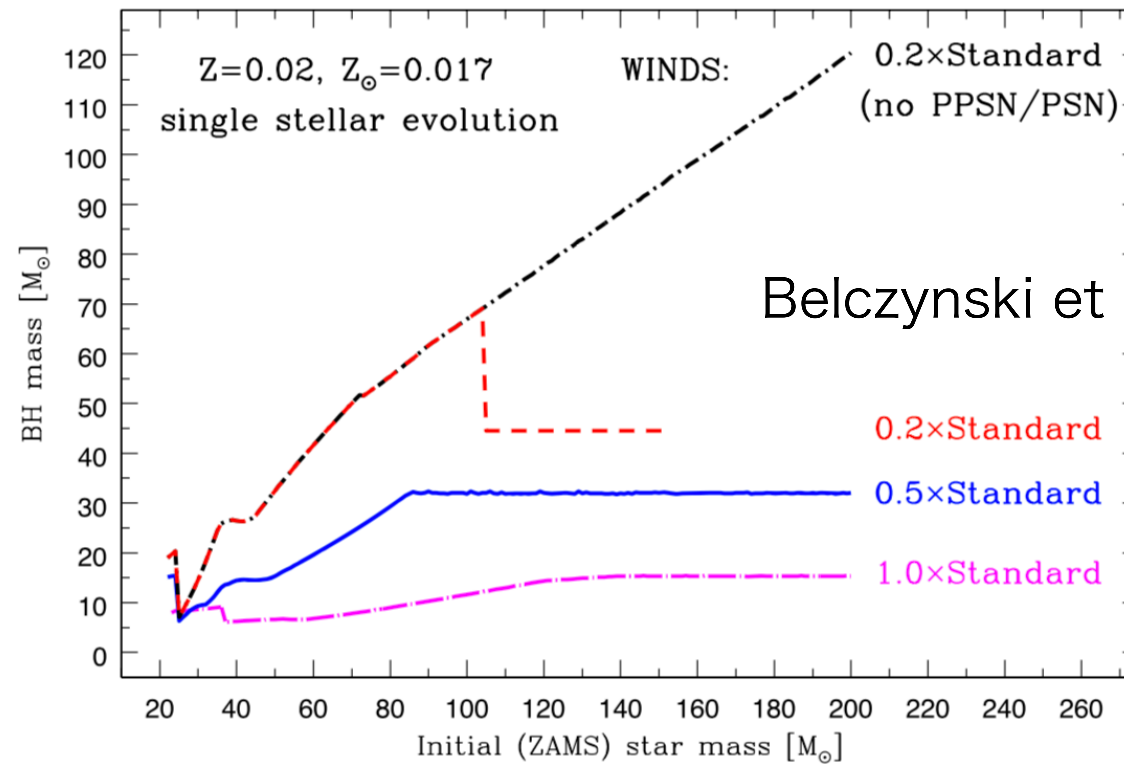




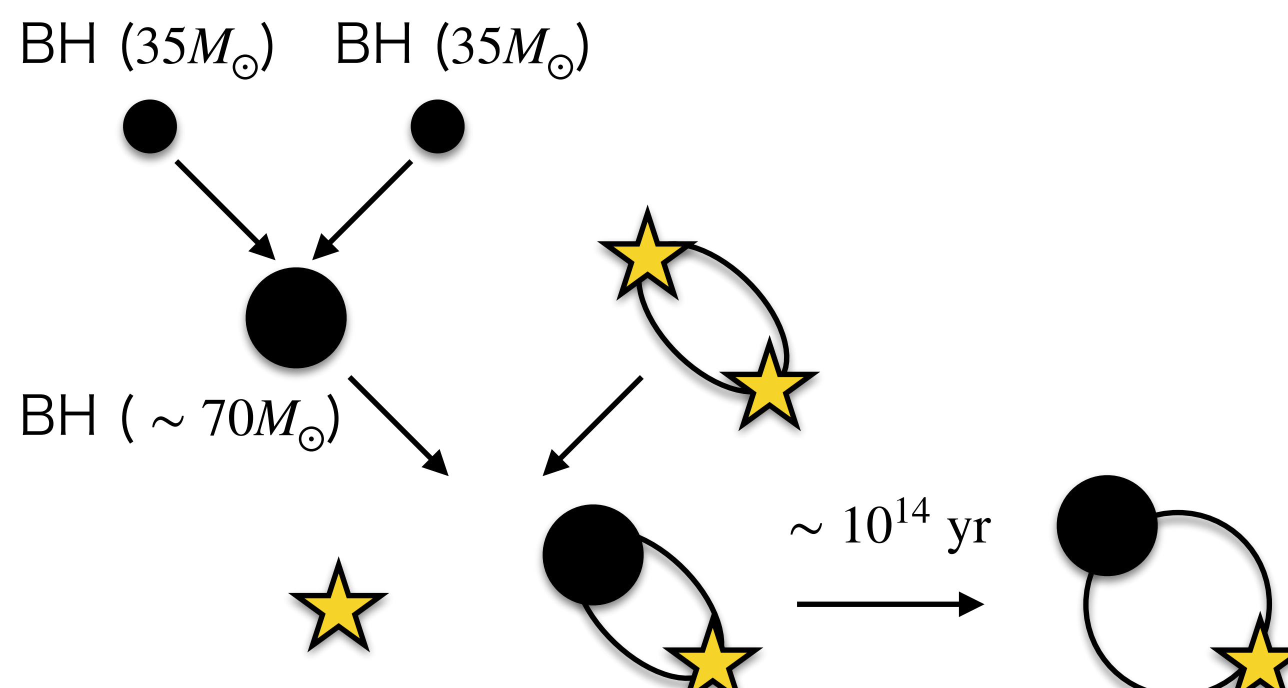
Liu et al. (2019, Nature, 575, 618)

What's surprising?

- High metallicity ($Z \sim Z_\odot$)
  - Stellar wind mass loss reduces BH mass to $\lesssim 20M_\odot$.
  - 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 (Liu et al. 2019)



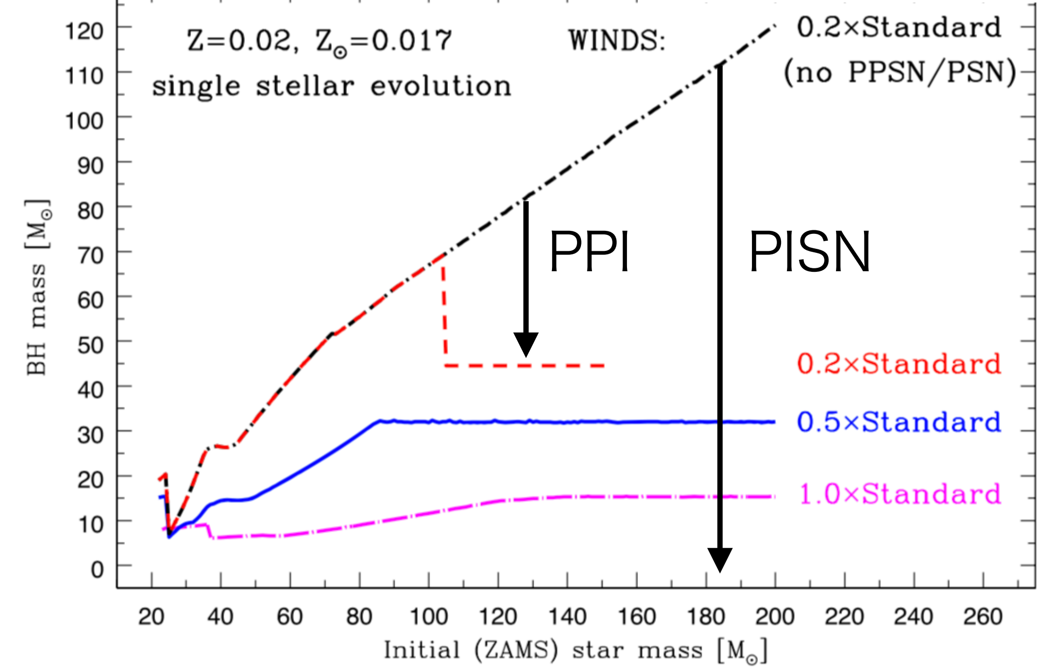
Belczynski et al. (2020)

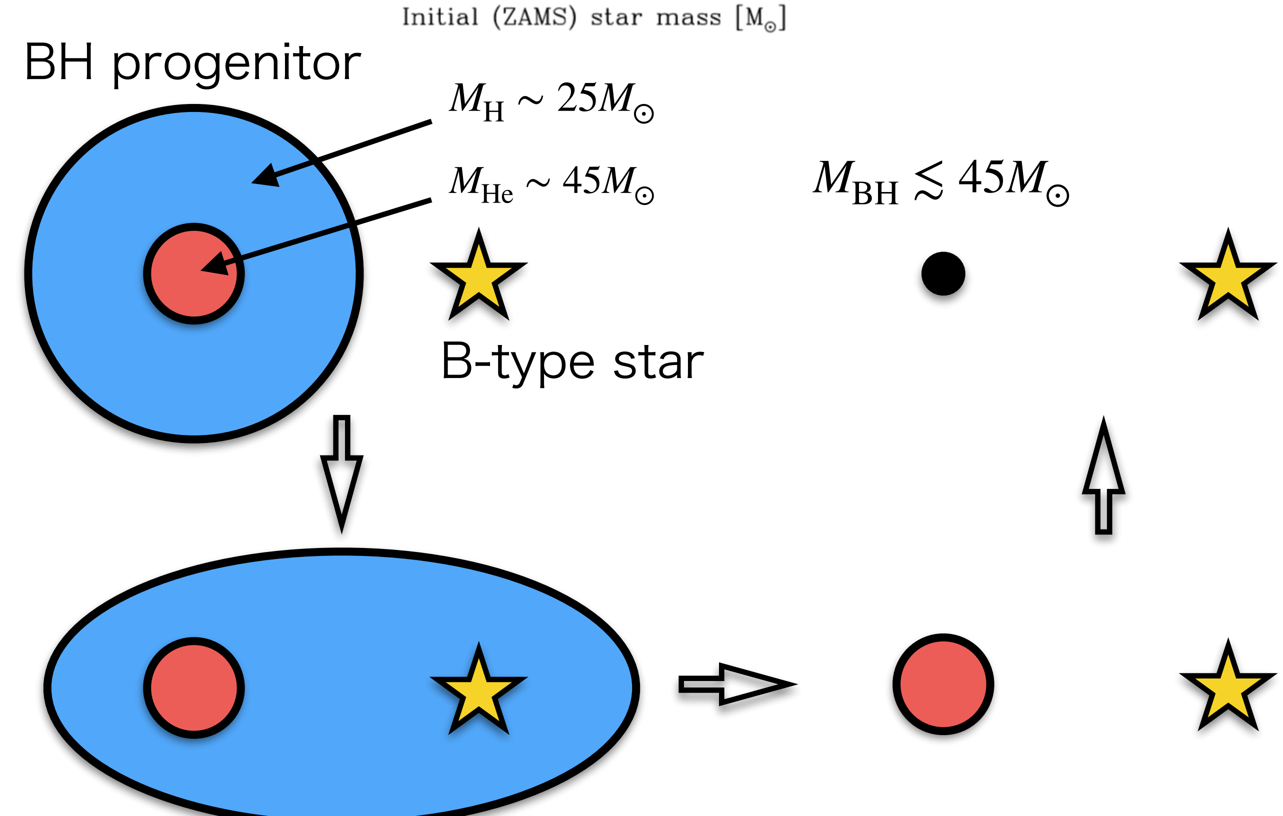


Reduced stellar wind

- BH progenitors should have $M_{\rm tot} \gtrsim 70M_\odot$ and $M_{\rm c,He} \lesssim 45M_\odot$.
  - BH progenitors with $M_{\rm c,He} \gtrsim 45M_\odot$ reduce BH masses to $M_{\rm BH} \sim 45M_\odot$ throught mass loss of pulsational pair instability (PPI).
  - BH progenitors with $M_{\rm c,He} \gtrsim 65M_\odot$ leave no remnants due to pair instability (PI) supernovae (SNe).
  - GW observation supports PPI/PISN (Abbott et al. 2019).
- The binary size ($a \sim 1{\rm au} \sim 200R_\odot$)
  - $a_i \lesssim 1{\rm au}$ ⋯ Merge
  - $a_i \gtrsim 1{\rm au}$ ⋯ Common envelope
    - Even if the binary survives, $M_{\rm BH} \lesssim 45M_\odot$.
  - $a_i \gg 1{\rm au}$ ⋯ No interaction ($a \gg 1{\rm au}$)

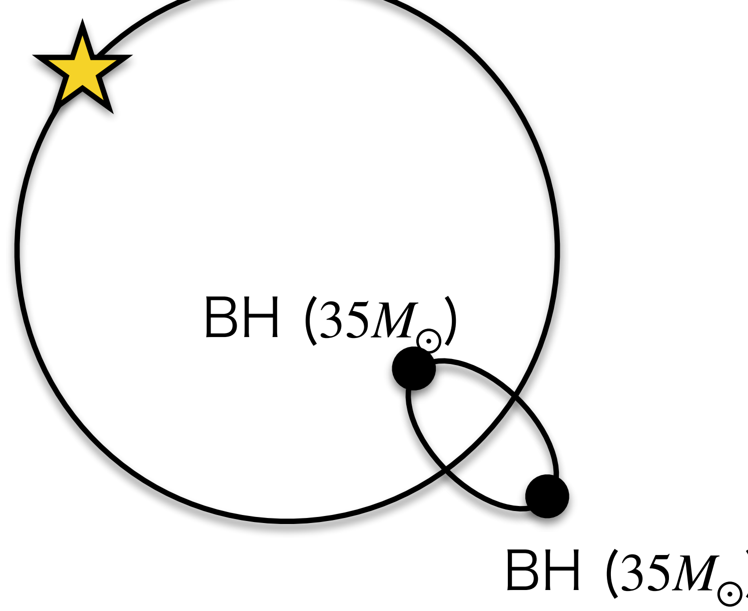
Belczynski et al. (2020)





Is $70M_\odot$ BH single BH?

- 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 small.
- (Shen et al. 2019)

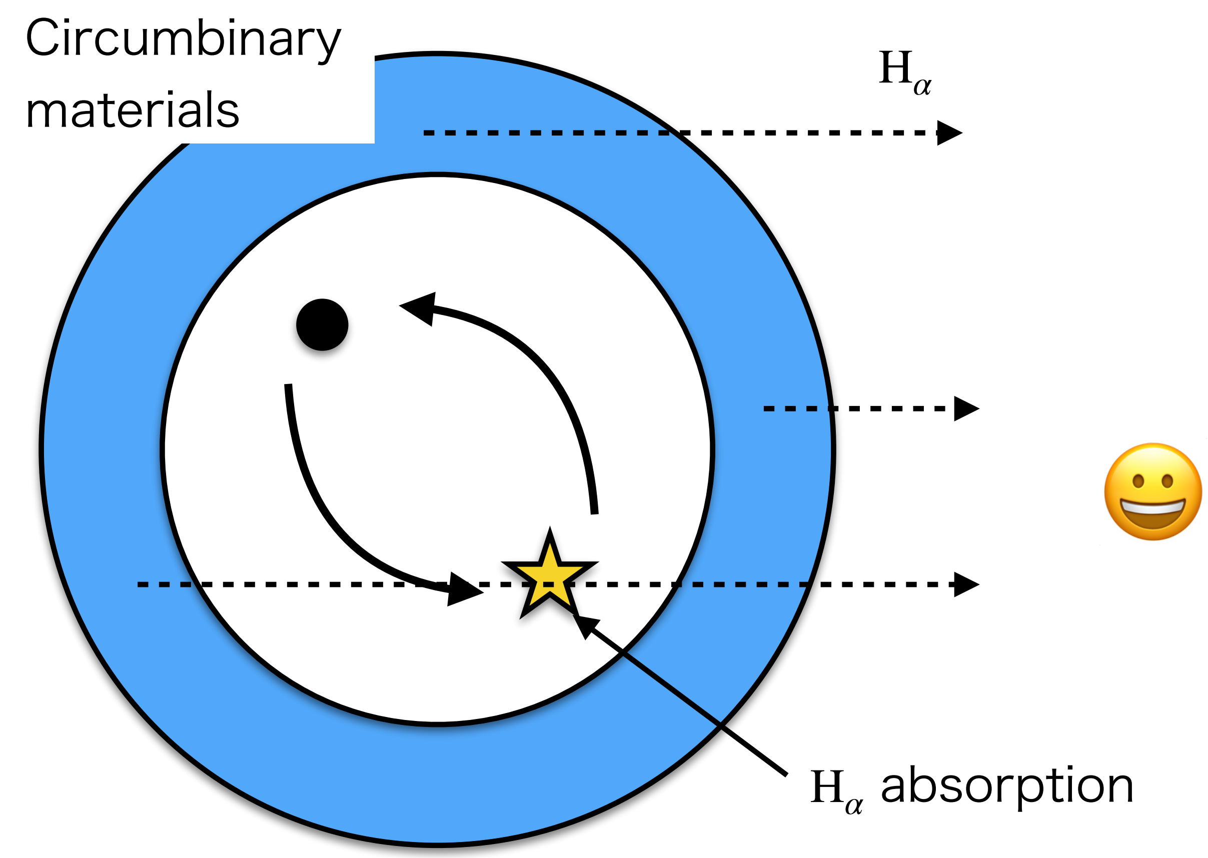


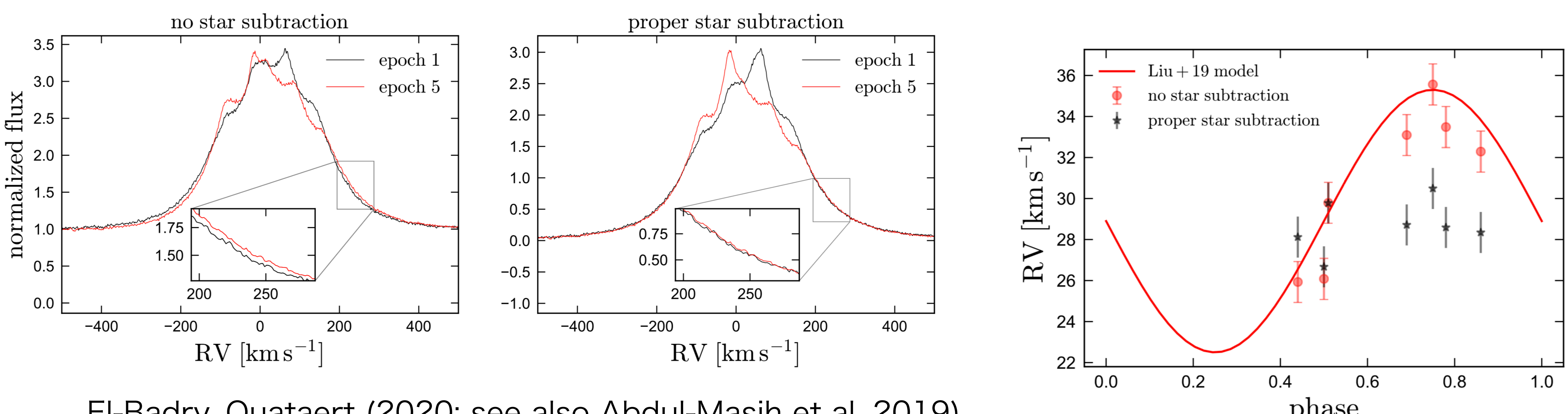
Possible scenarios

- Isolated environment
  - ~~Binary system~~
  - Hierarchical triple system
    - ~~Inner BH-BH~~
    - More complicating channels
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - More complicating interactions

Counter opinions on "$70M_\odot$" BH

- 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.

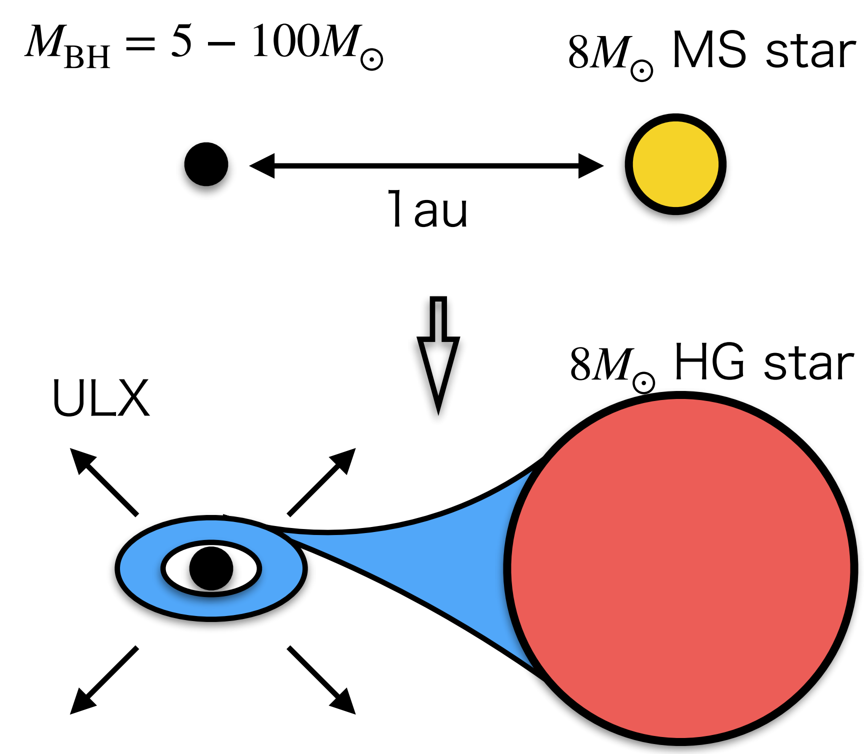


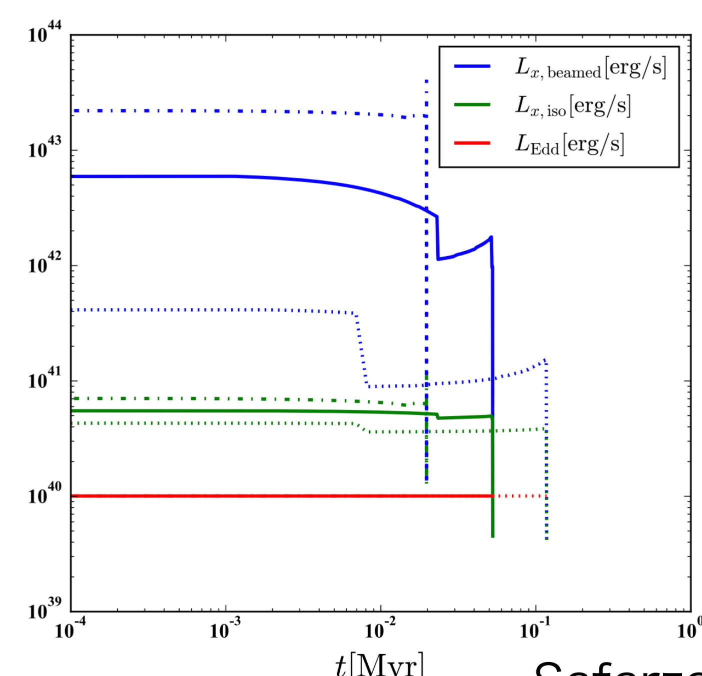


El-Badry, Quataert (2020; see also Abdul-Masih et al. 2019)

“Postgenitor” problem

- LB-1 system will evolve to a ultra-luminous X-ray (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.

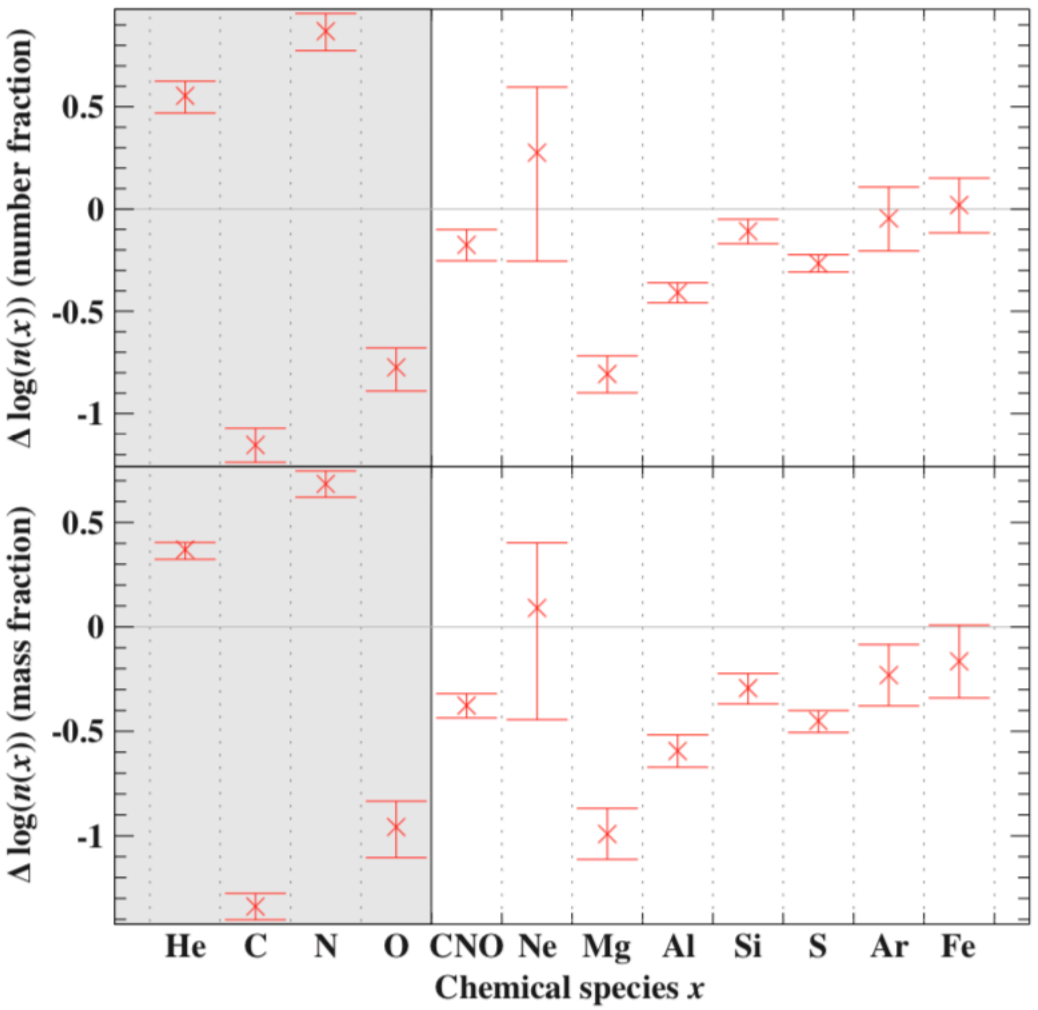




Safarzadeh et al. (2019)

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.



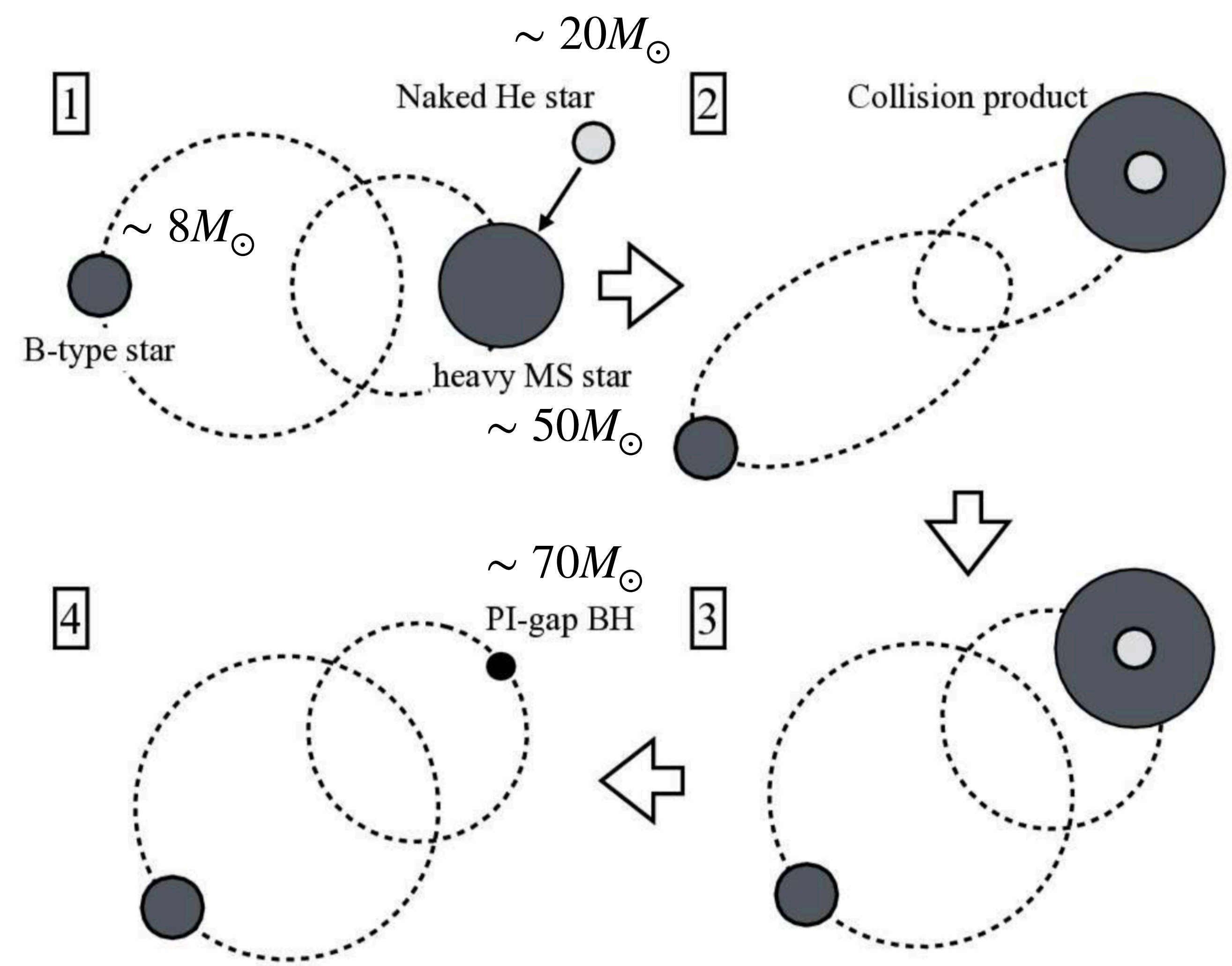
Our stance

- The presence of the $70 M_{\odot}$ 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 of isolated binary evolution”.
- We use this opportunity to notice dynamical formation of a binary in DSCs, 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.

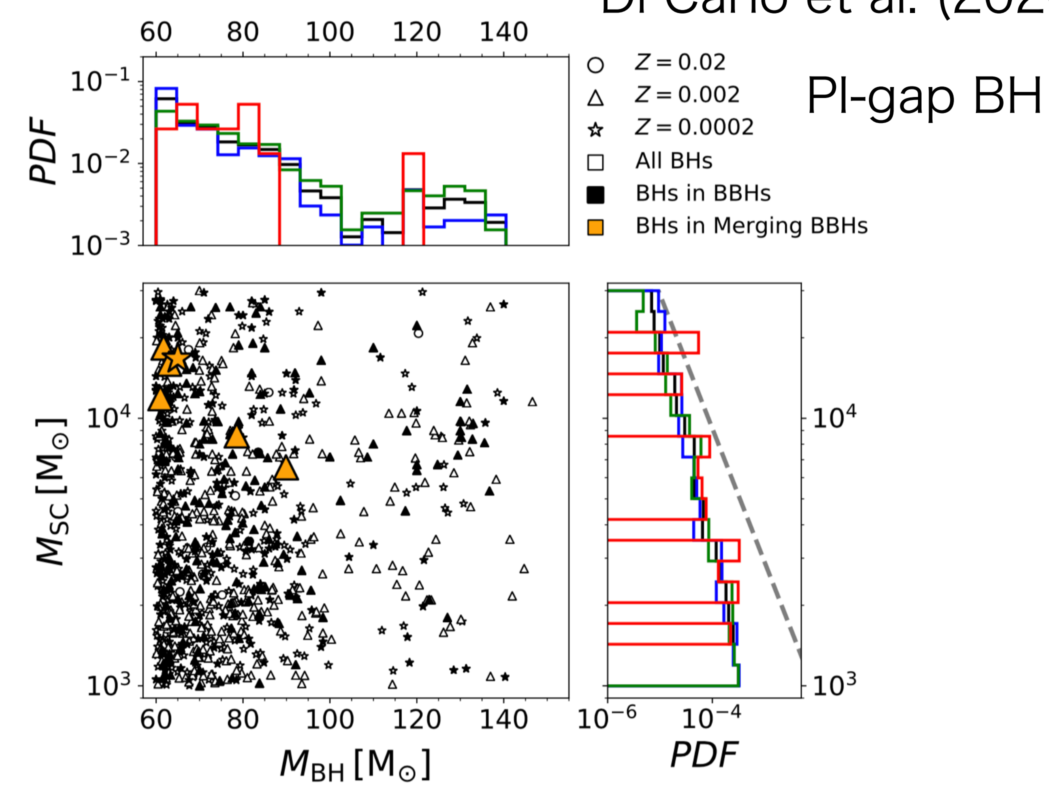
In an open cluster of the MW galaxy

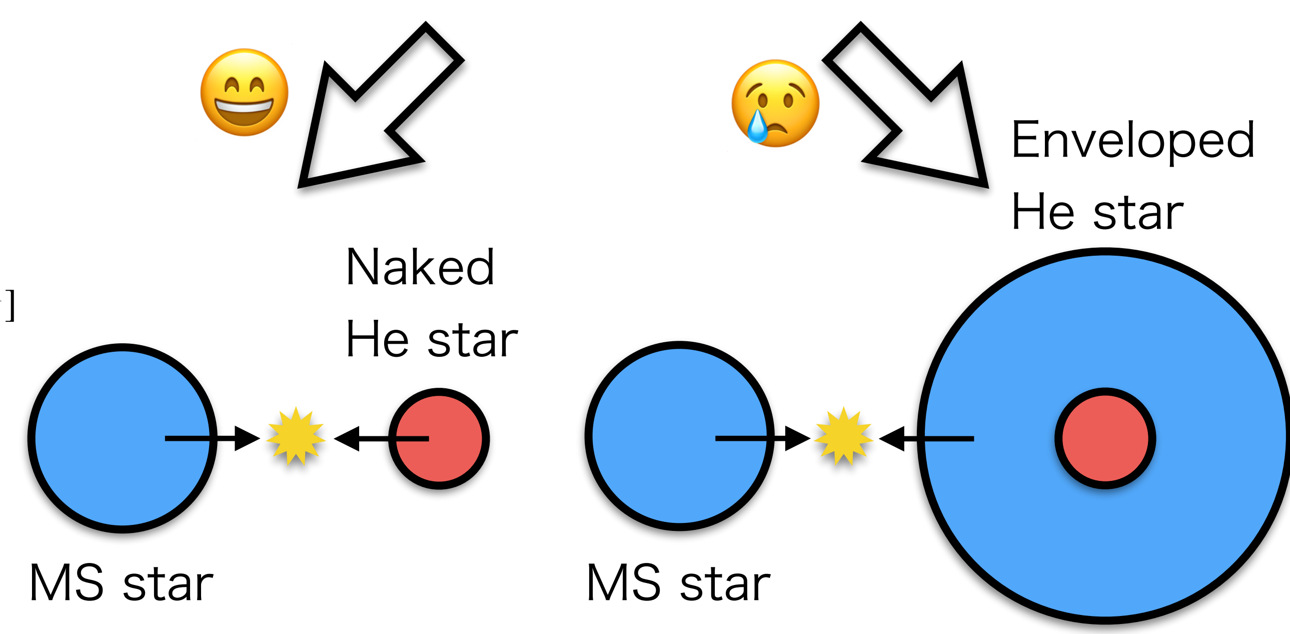


Collision rate

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

Di Carlo et al. (2020)





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

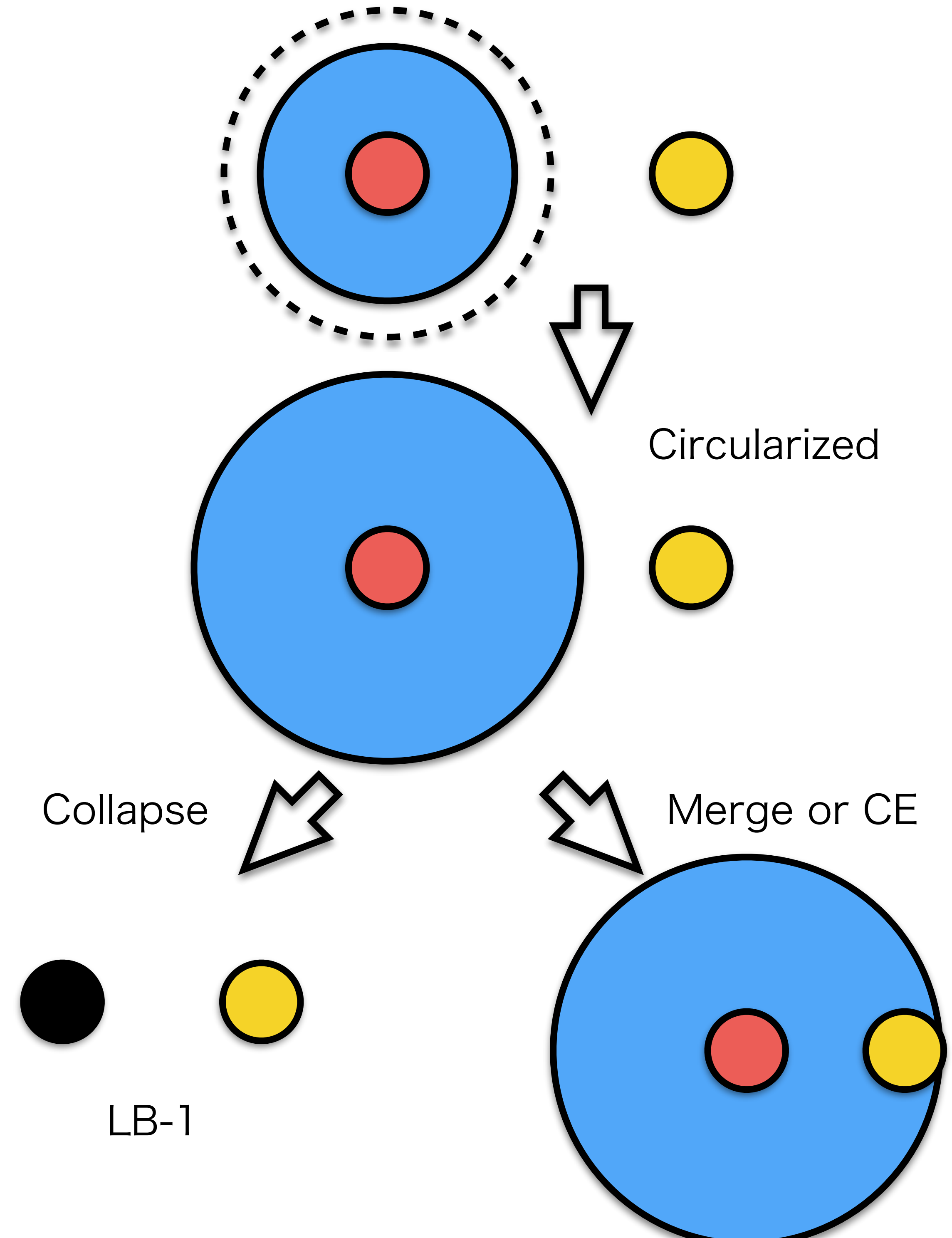
$$t_{\rm cric} \sim 2 \times 10^4 \left(\frac{R_{\rm coll}}{100 R_\odot} \right)^{-9} \ [{\rm yr}]$$

- 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

- $$N_{\rm LB1} \sim 0.01 \left(\frac{\dot{N}_{\rm coll}}{3 \times 10^{-9} {\rm yr}^{-1}} \right) \left(\frac{P_{\rm surv}}{0.1} \right) \left(\frac{T_{\rm B}}{40 {\rm Myr}} \right)$$

- No chance to form LB-1-like systems in OCs

Possible scenarios

- Isolated environment
  - ~~Binary system~~
  - Hierarchical triple system
    - ~~Inner BH-BH~~
    - More complicating channels
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - More complicating interactions

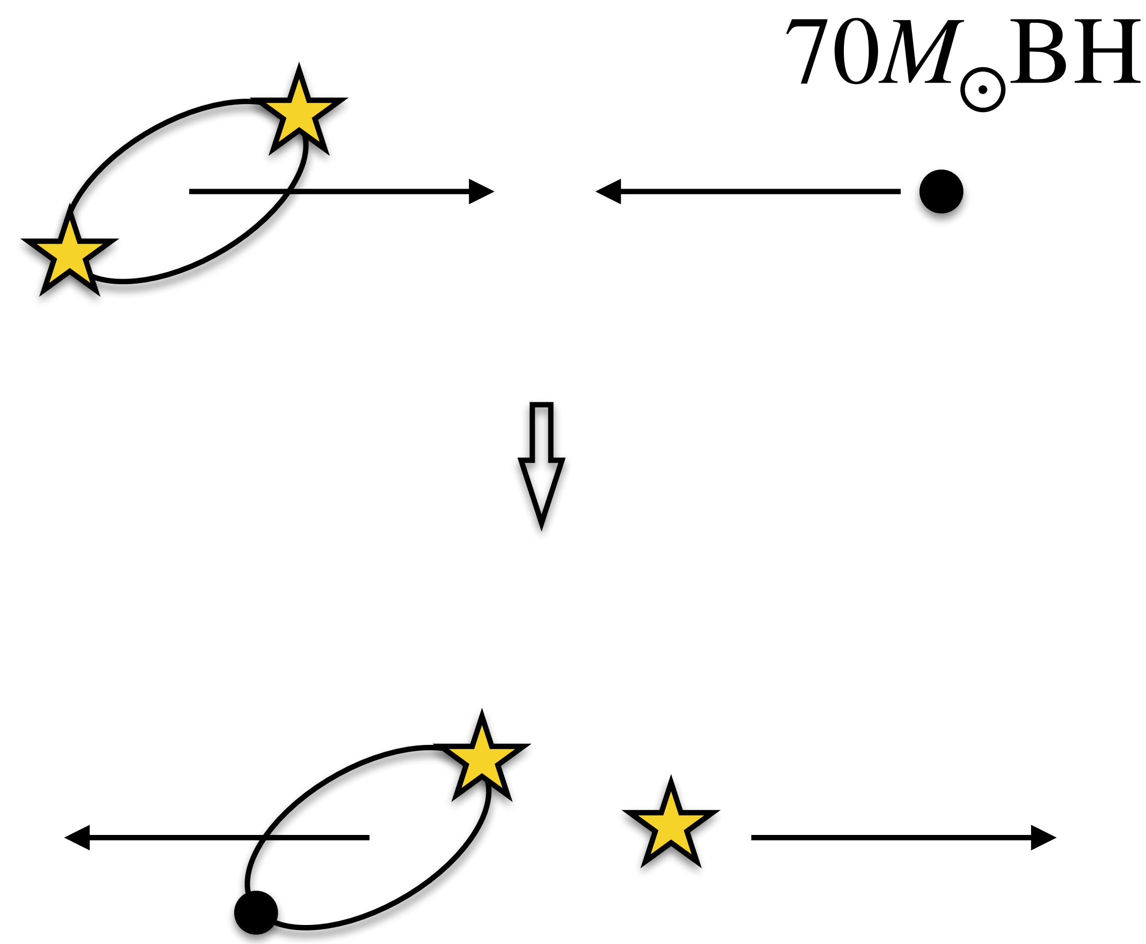
Other stellar collisions

- 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

Capture processes

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

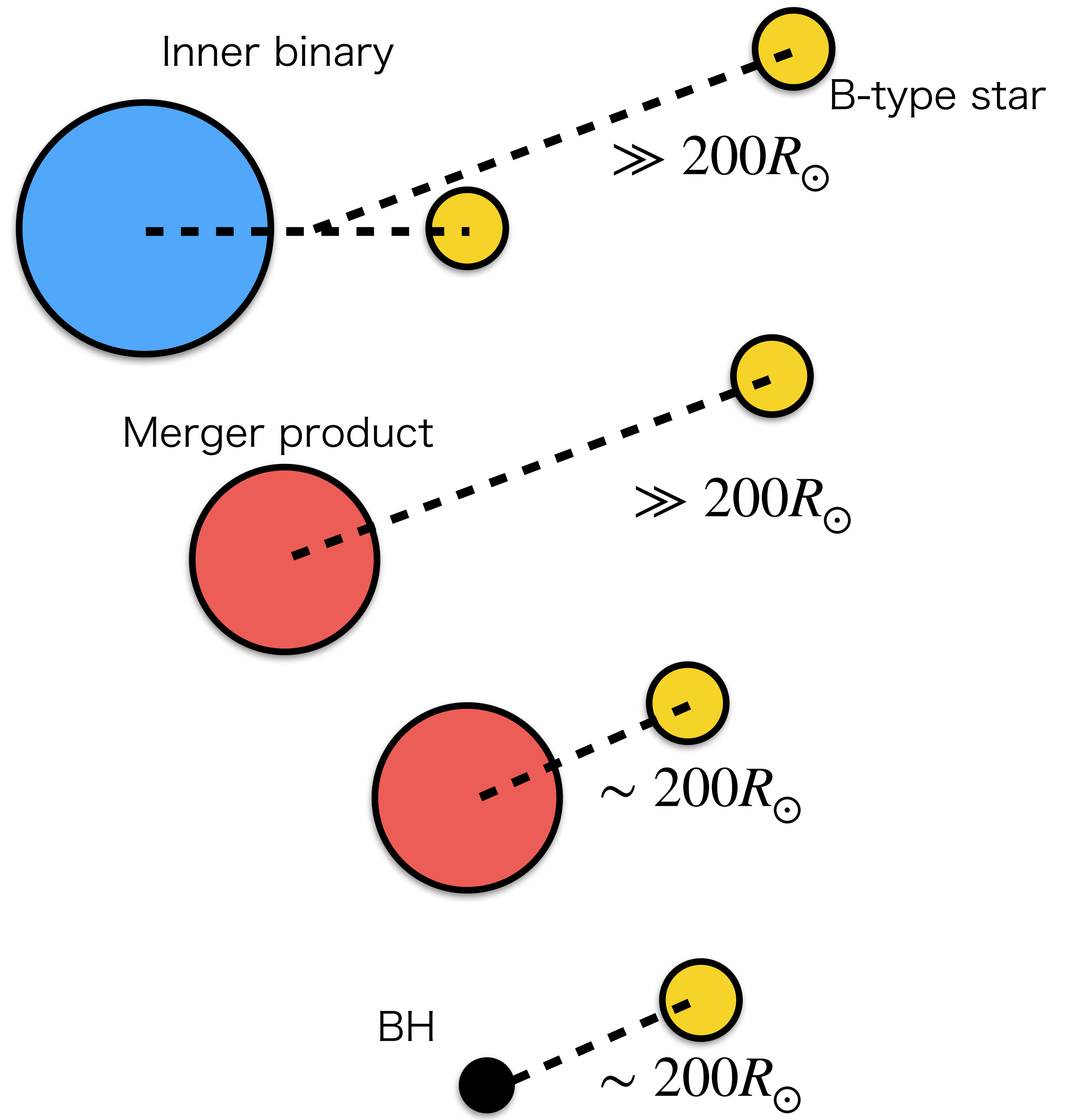


Possible scenarios

- Isolated environment
  - ~~Binary system~~
  - Hierarchical triple system
    - ~~Inner BH-BH~~
    - More complicating channels
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - ~~More complicating interactions~~

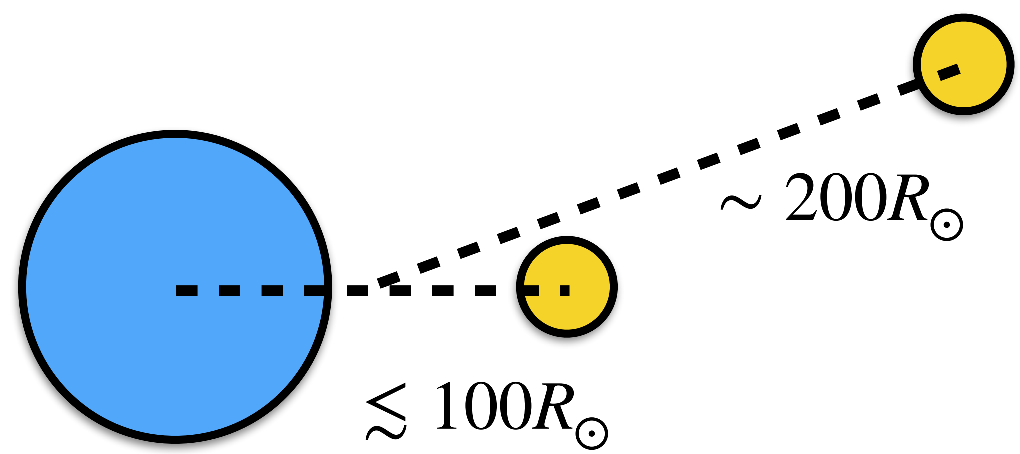
Hierarchical triple (1)

- 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.



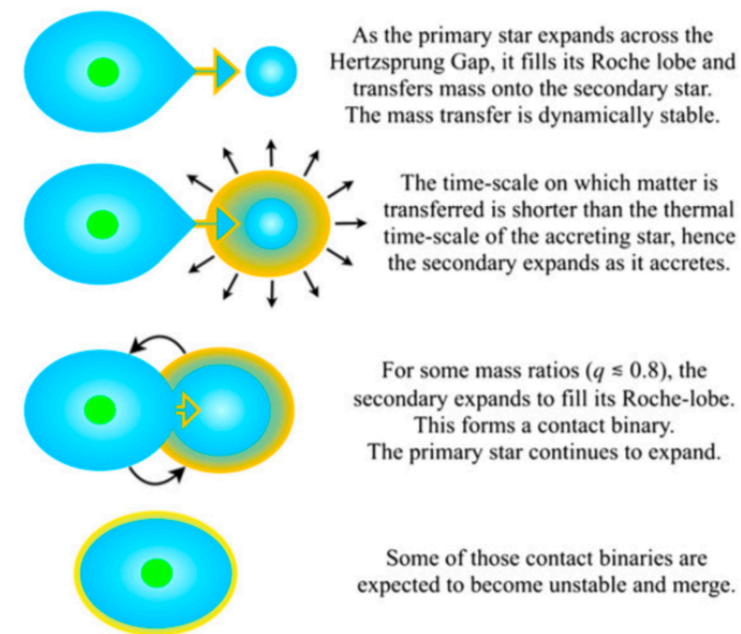
Hierarchical triple (2)

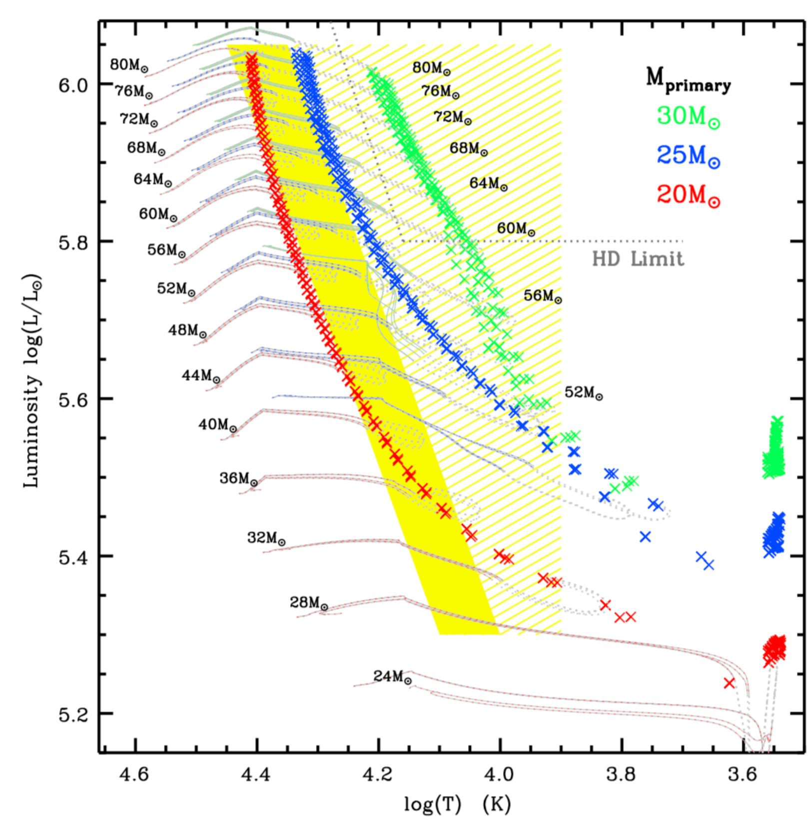
- The separation of the inner binary should be $\lesssim 100 R_\odot$. Otherwise, the system is unstable (Harrington 1972; Mardling, Aarseth 1999).
- The primary star of the inner binary should be $\gtrsim 35 M_\odot$.
  - $\lesssim 100 M_\odot$ stars exceed $\sim 100 R_\odot$ when they are in Hertzsprung gap phases. The inner binary experiences a Case B merger.
  - $\gtrsim 100 M_\odot$ stars exceed $\sim 100 R_\odot$ 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)

Possible scenarios

- Isolated environment
  - ~~Binary system~~
  - ~~Hierarchical triple system~~
    - ~~Inner BH-BH~~
    - ~~More complicating channels~~
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - ~~More complicating interactions~~

Summary

- A $70 M_\odot$ 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 $70 M_\odot$ BHs in wide binaries with $\gg 200 R_\odot$ under metal-poor environments.