Binary Black Holes

（連星ブラックホール）

and

Black Holes in Binaries

（ブラックホール連星）

Ataru Tanikawa

Komaba colloquium 27th May 2020

Binary black holes

(連星ブラックホール)

- A binary star system has two black holes (BHs).
- >10 systems are discovered by gravitational wave observatories since 2015.
- The BHs have $\sim 10-40M_{\odot}$, so-called stellar-mass BHs.
- I call them **BH-BHs**.

天文学辞典 > 高エネルギー現象 > 連星ブラックホール

連星ブラックホール

高エネルギー現象

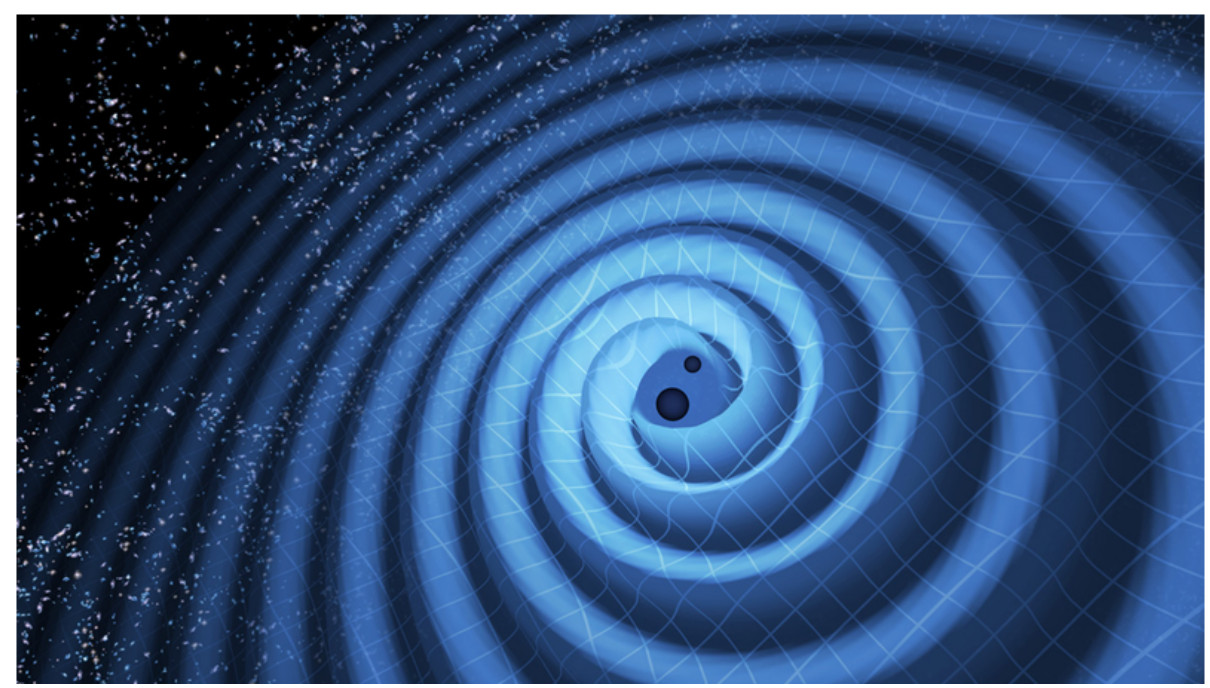
よみ方 れんせいぶらっくほーる

英語 binary black hole

A binary star system with two BHs

説明

ブラックホールとブラックホールの連星系。巨大銀河の合体の産物である超大質量ブラックホールの連星系も考えられる。
ブラックホール連星系と同じ意味で通常の恒星とブラックホールとの連星系をいう場合もある。このような近接連星系では相手の星からの質量降着で強いX線が放射される。
2015年9月にLIGOにより初めて観測された重力波信号は、それぞれ太陽質量の数十倍のブラックホール-ブラックホール連星の合体に伴うものであったと解釈されており、その後も次々と観測例が見つかっている。

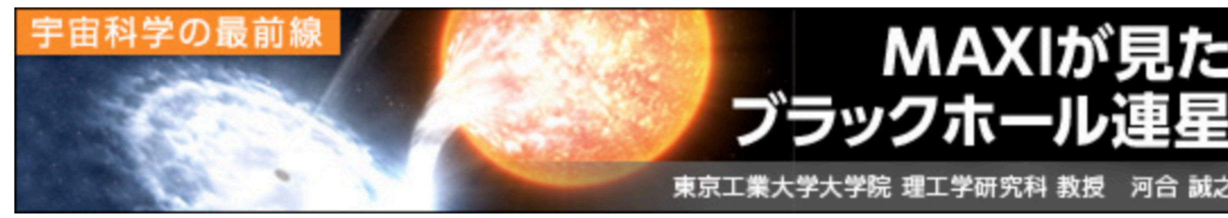


T. Pyle/LIGO

Black holes in binaries

（ブラックホール連星）

- A binary star system has BH and ordinary star, such as main-sequence, and red-giant stars.
- ~ 100 systems are discovered by X-ray observations.
- ~ 1 systems are reported by radial velocity observations (under dispute).
- The BHs are also stellar-mass BHs, but slightly lighter than those in BH-BHs, $\lesssim 20 M_{\odot}$.
- I call them BH-LCs (luminous companions).



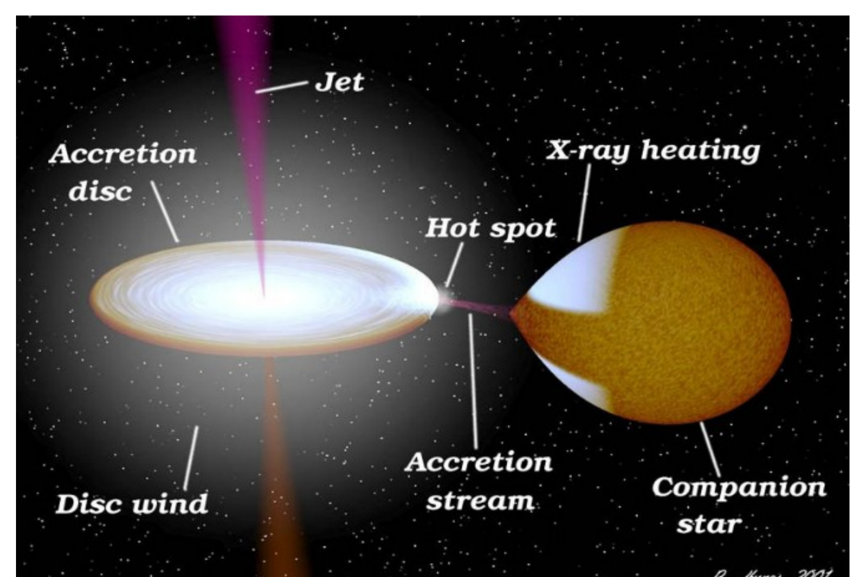
| 1 | 2 | 3 |

A binary star system with BH and ordinary star

ブラックホール連星

銀河面に沿って並ぶ明るいX線源のいくつかは、ブラックホールと普通の恒星の連星です（図2）。最も有名なブラックホール連星であるはくちょう座X-1は、常に明るくX線で輝いていますが、放射スペクトルが極端な二つの状態の間で変化します。多くの場合は「ハード状態」と呼ばれる、高エネルギーまでX線光子が分布しているべき乗型スペクトルを示します。ところが時折、「ソフト状態」と呼ばれる、低エネルギー光子が支配的な熱的なスペクトルに移ります。それぞれ、ブラックホールのまわりのガスが高温で希薄に広がった「コロナ」になっている状態と、ガス密度が高く厚みがない（レ

JAXA website



NASA/R. Hynes

Our motivation

- Formation processes of BH-BHs and BH-LCs
- Massive star evolution, such as formation, stellar wind, supernovae, natal kick, final states, and etc.
- Binary star evolution, such as mass transfer, common envelope, tidal interaction, and etc.

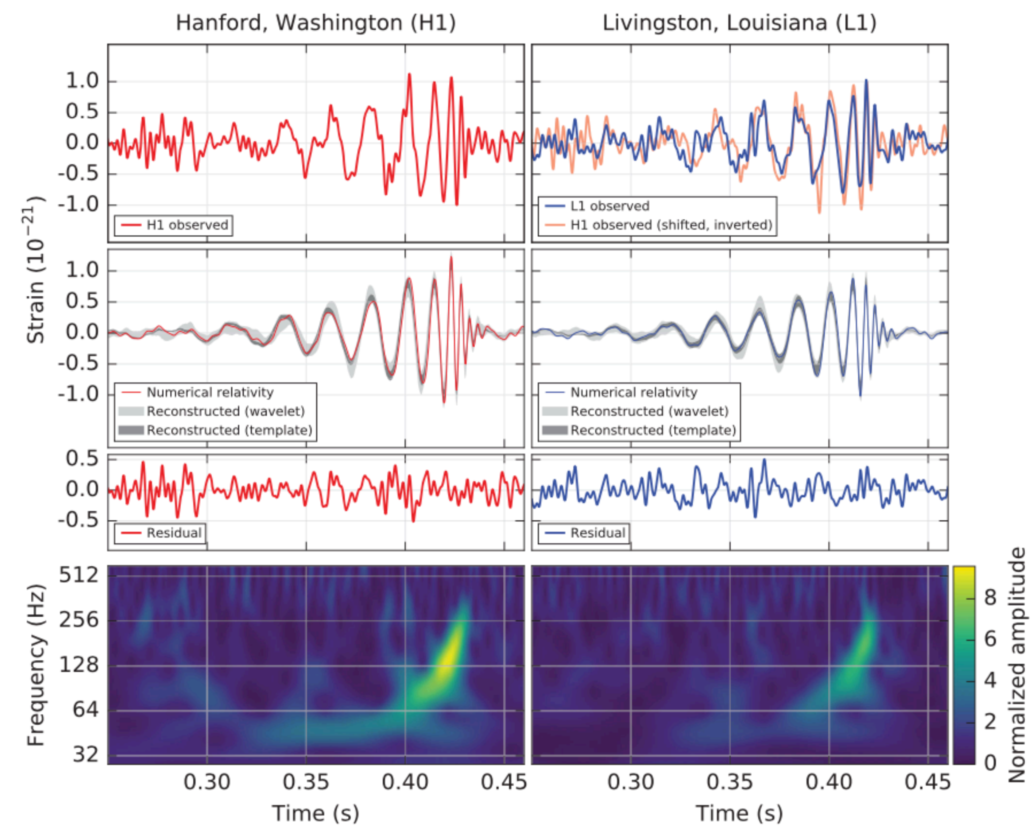
Our studies

- The formation of BH-BHs in open clusters (OCs) (Kumamoto et al. 2019; 2020)
- OC-origin BH-LCs observable by Gaia (Shikauchi et al. 2020)
- On dynamical formation of LB-1: a system with $70M_{\odot}$ BH (Tanikawa et al. 2020)

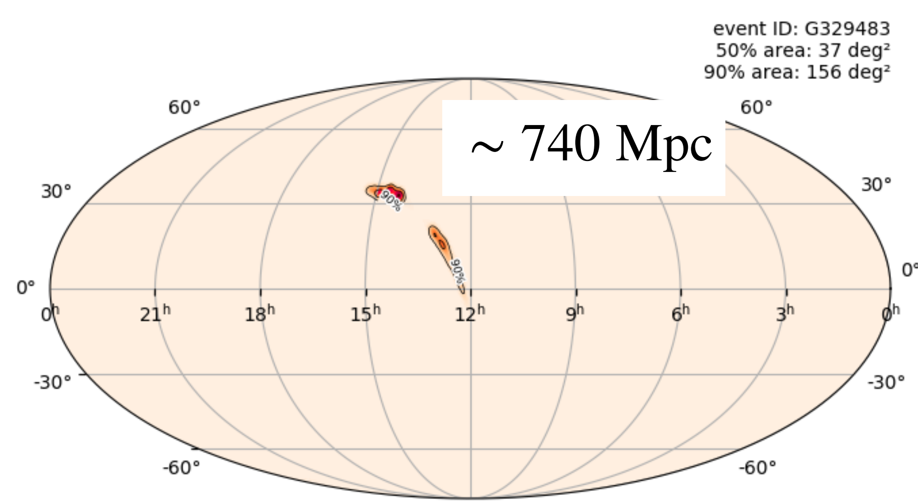
BH-BHs

Motivation

- >10 systems have been found, and the number is rapidly growing.
- The origin is yet unclear.
  - Binaries, Multiple systems, star clusters, galactic centers, primordial BHs, etc.
- GW observations tell us only BH mass, spin, and distance ($z \lesssim 0.1$, but rarely $z \sim 0.8$).
  - Quite low space resolution
  - A huge number of galaxies



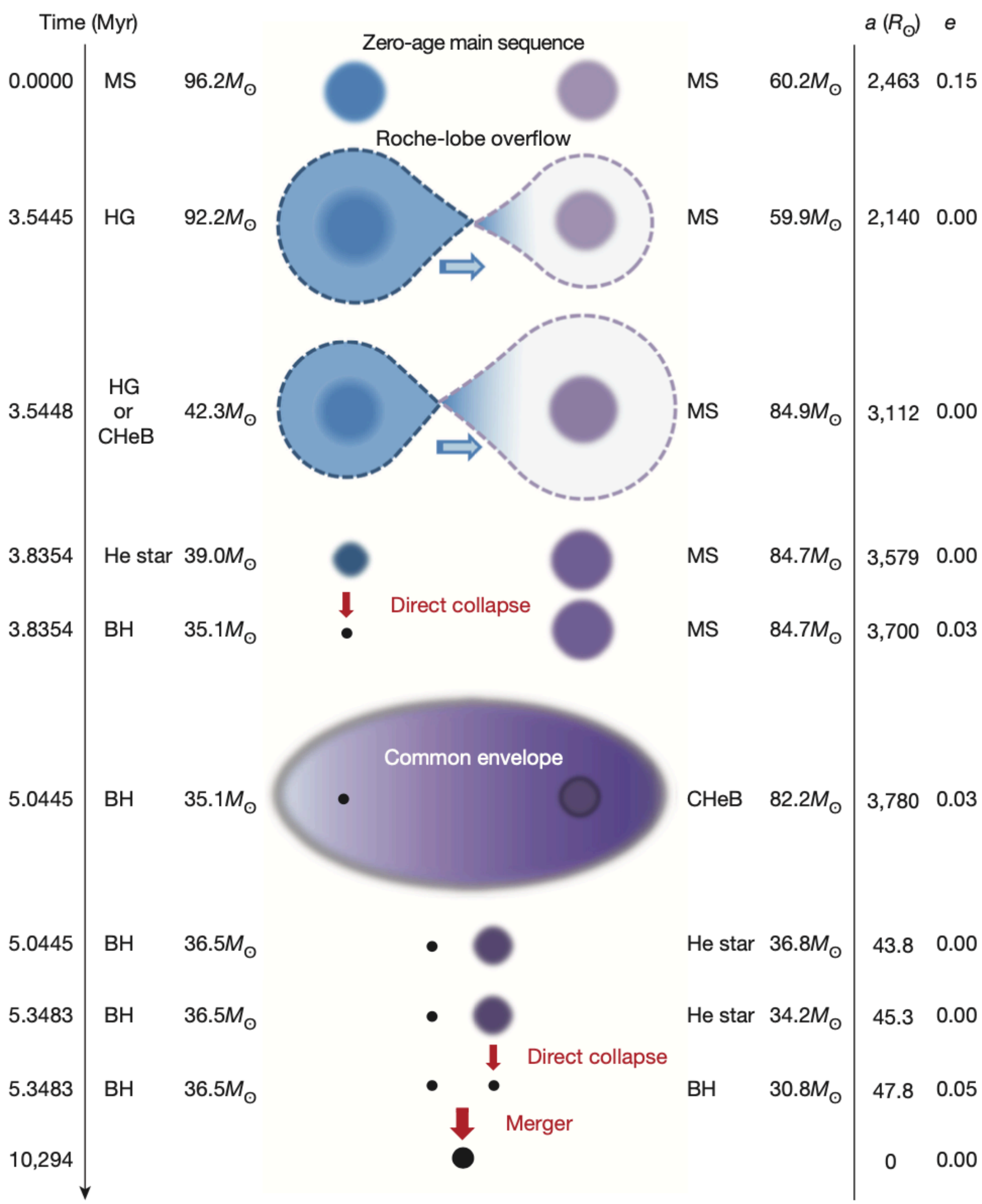
Abbott et al. (2016)



GW190412 (from Grace DB)

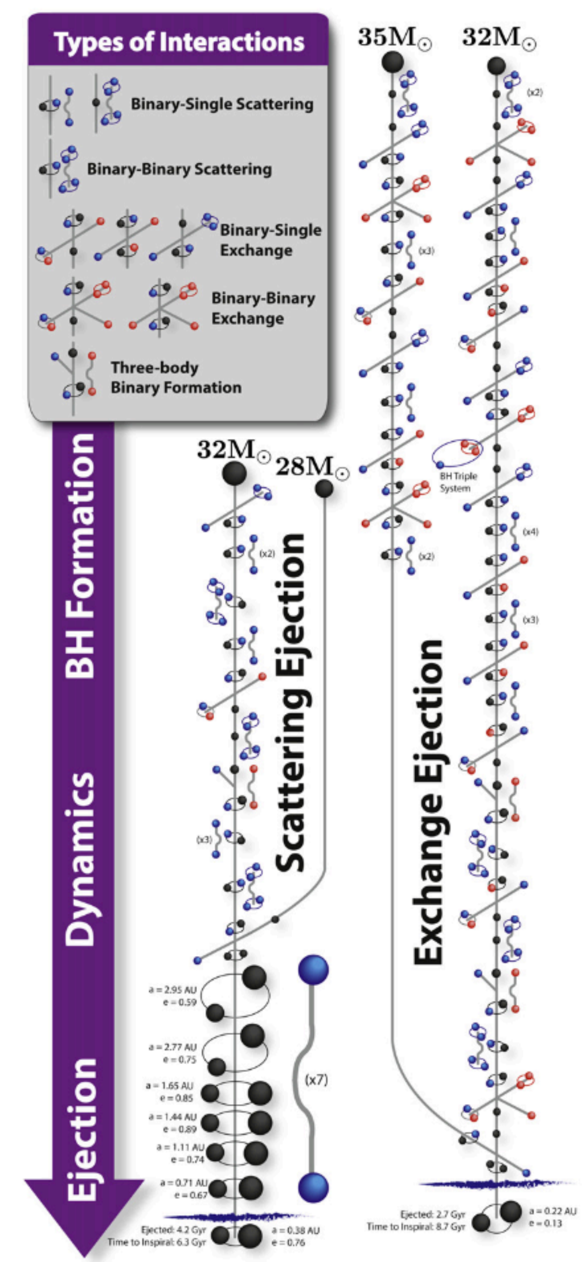
Popular scenarios

Binary evolution



Belczynski et al. (2016)

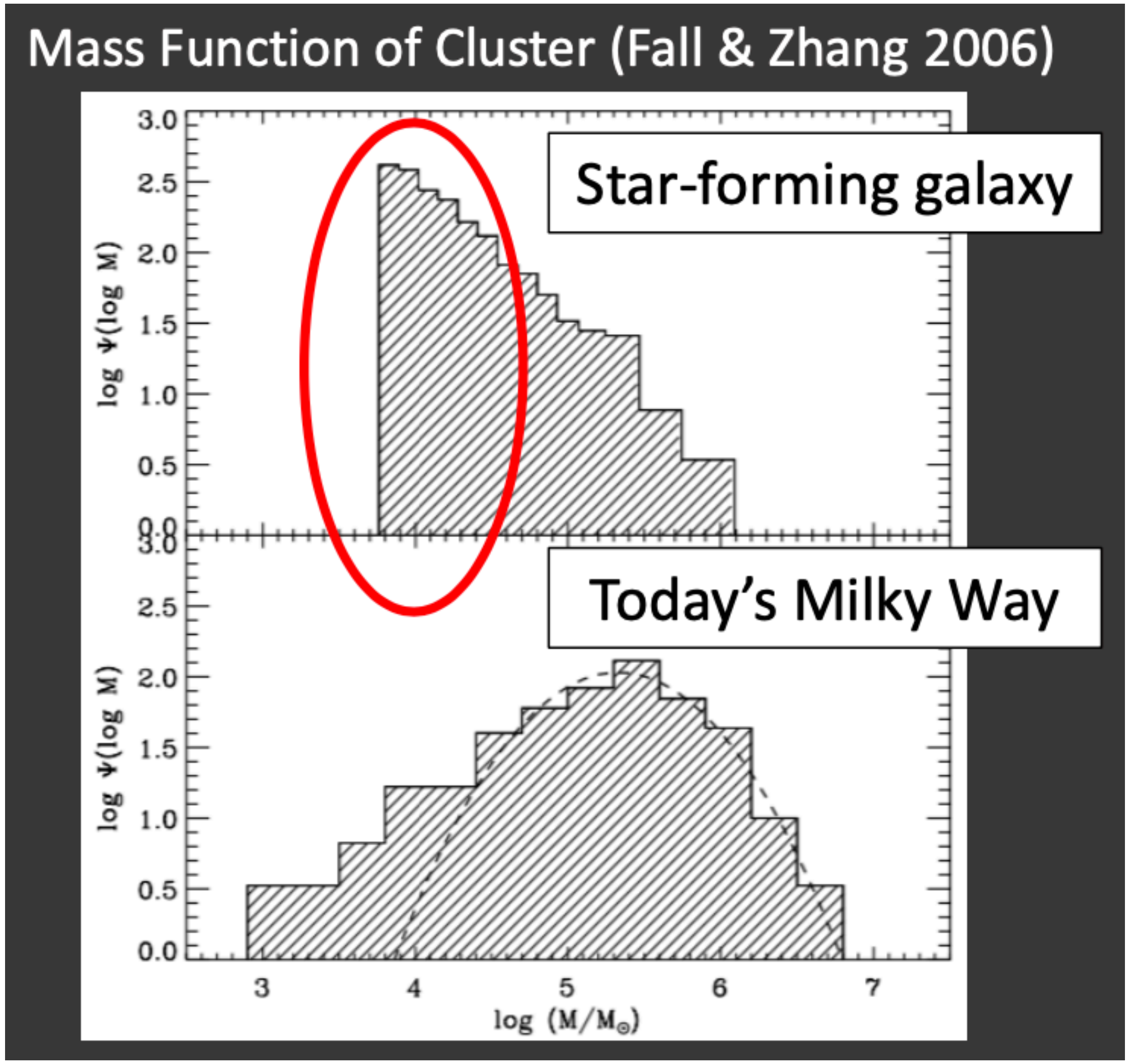
Dynamical interactions in globular clusters



Rodrigues et al. (2016)

Open clusters

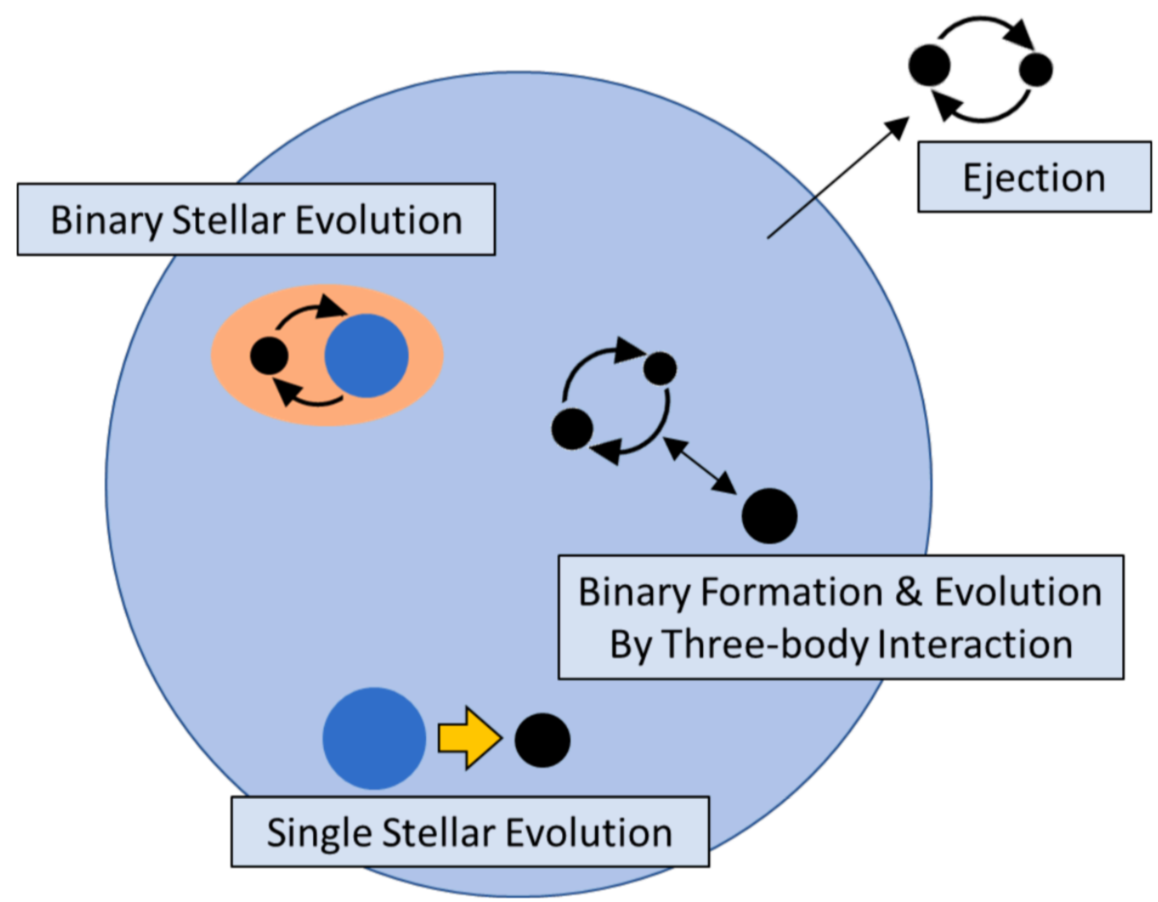
- Scientific motivations
  - Most of stars are formed in open clusters.
  - Most of open clusters were disrupted previously.
  - Open clusters can be cradles of BH-BHs.
- Technical motivations
  - N-body simulations can follow evolution of open clusters ($N \sim 10^3 - 10^4$).
  - N-body simulations cannot follow evolution of realistically dense globular clusters ($N \sim 10^6, \rho \sim 10^5 M_\odot \mathrm{pc}^{-3}$).
    - The largest simulation has $N \sim 10^6, \rho \sim 10^2 M_\odot \mathrm{pc}^{-3}$ (Wang et al. 2016)



From Kumamoto's slides

Method

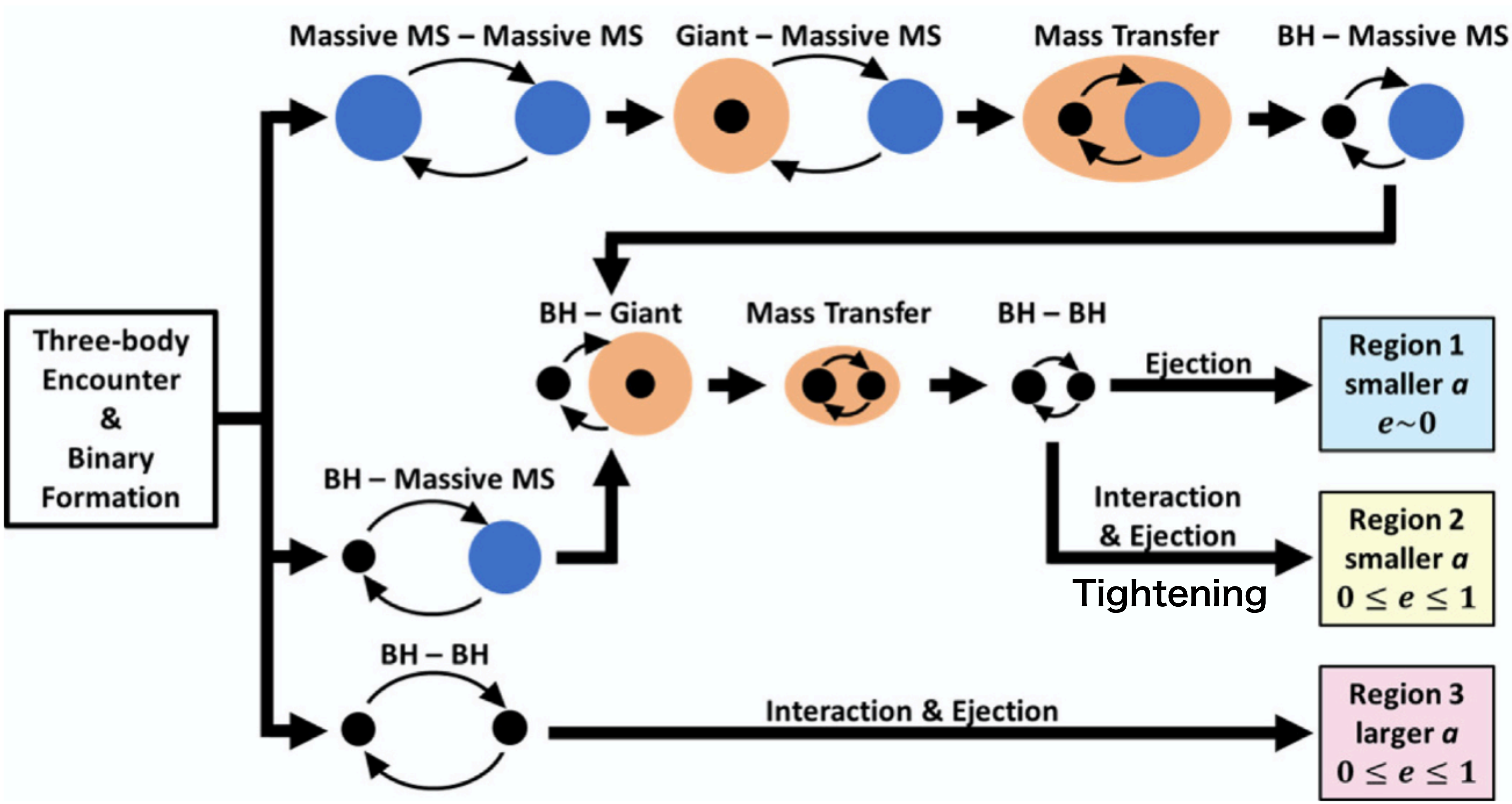
- NBODY6++GPU
  - N-body interactions
  - Stellar evolution
  - Common envelope etc.
- Initial conditions
  - Cluster mass: $\sim 2500 M_\odot$
  - Density: $\sim 10^4 M_\odot \mathrm{pc}^{-3}$
  - Kroupa IMF with $0.08 < M/M_\odot < 150$
  - No initial binary
  - $Z = 0.1Z_\odot, 0.25Z_\odot, 0.5Z_\odot, Z_\odot$
  - ~ 1000 clusters for each Z



Only ejected BH-BHs taken into account for the merger rate

- Compact
- Evolved no more

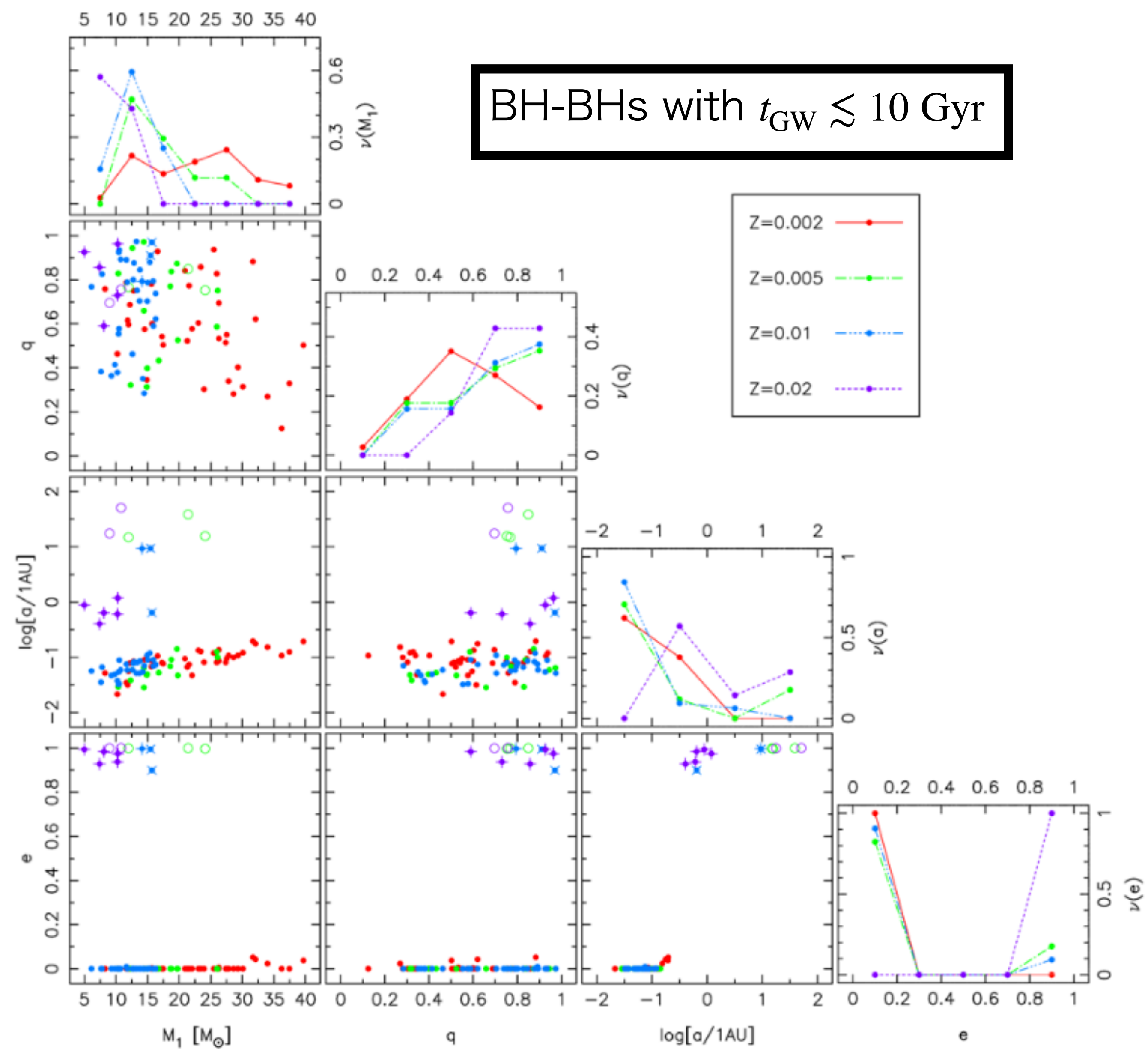
Formation process



A significant fraction of BH-BH progenitors are formed dynamically, and they become compact through common envelope evolution (Kumamoto et al. 2019; see also Di Carlo et al. 2019)

Properties of BH-BHs

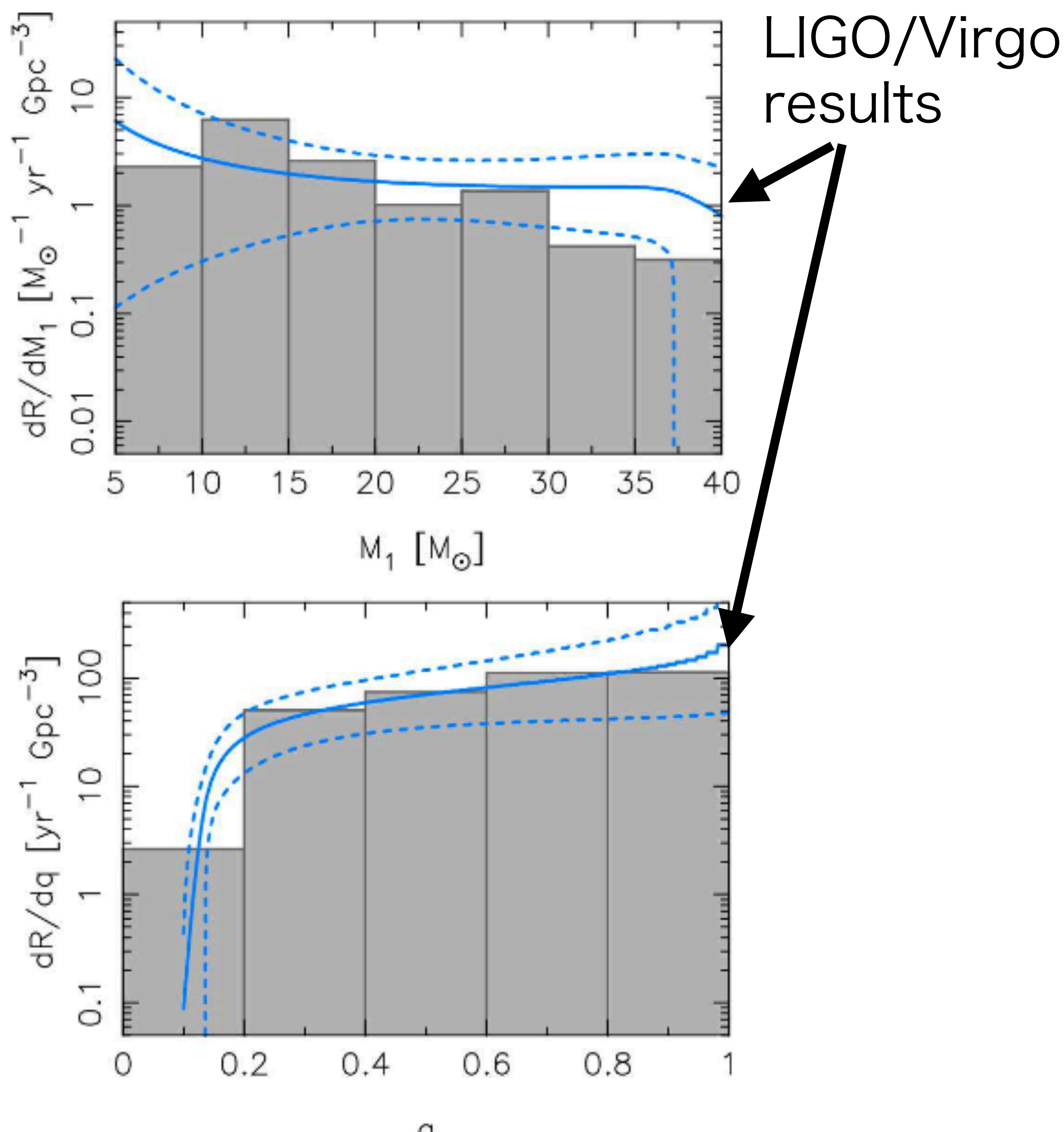
- Tightening process
  - Common envelope under low-metallicity environment (BH-BHs with zero eccentricities)
  - Dynamical interactions under high-metallicity environment (BH-BHs with high eccentricities)
- Order estimate
  - Purely dynamical BH-BHs
    - $t_{\rm GW} \sim a^4 m^{-3} \sim m v^{-8} \sim m v_{\rm esc}^{-8}$
      - $a = G m v^{-2}$
  - Merging timescale is smaller with smaller mass (higher metallicity) when escape velocity is the same.



Kumamoto et al. (2020)

Merger rate density

- The predicted merger rate density is quite similar to the LIGO/Virgo results.
- 20% of stars are formed in open clusters.
- 5% of stars are formed under $Z = 0.1Z_{\odot}$ environment in the present day.
  - GW events with $M_1 \gtrsim 20M_{\odot}$ come from low-metal populations in the present day.

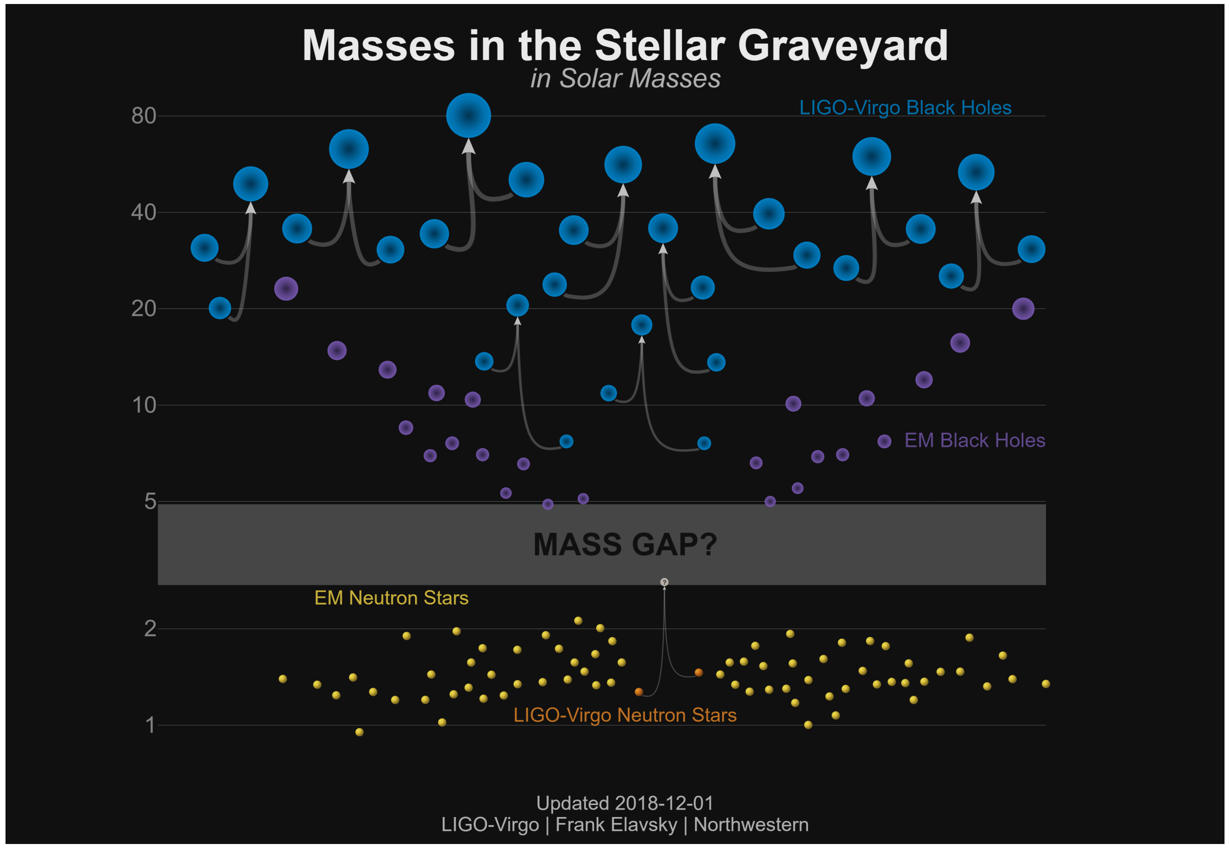


Kumamoto et al. (2020)

BH-LCs: Gaia

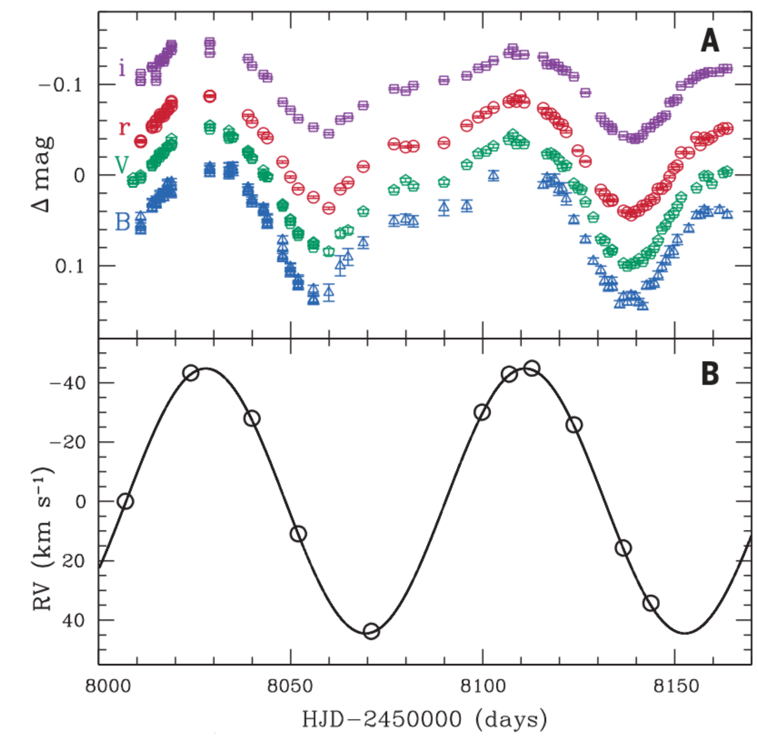
Motivation

- ~ 100 BHs have been discovered in the milky way and neighbor galaxies by X-ray observations.
  - BH-BHs discovered by GW observations are located in the distant universe.
- $\sim 10^8 - 10^9$ BHs should be in the milky way.
- Discovered BHs are preferentially in close binaries with $P \sim \mathrm{hrs} - \mathrm{days}$.
- We aim to relax this limitation.

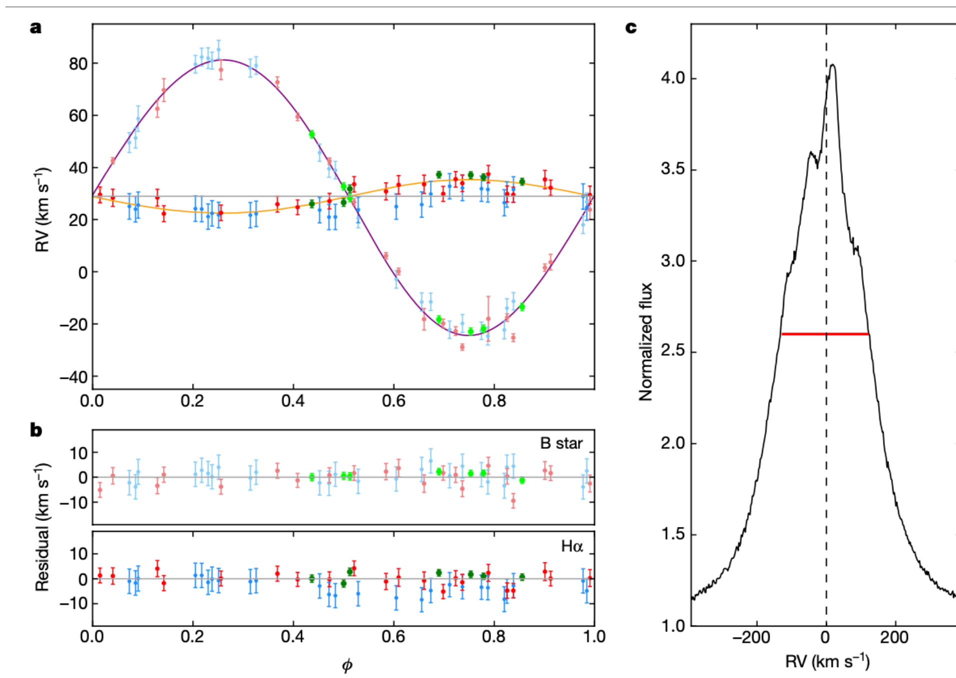


Radial velocity observation

- 2MASS J05215658+4359220 with $\sim 3.3 M_{\odot}$ unseen object (Thompson et al. 2019, Science)
    - Under dispute (van den Heuvel, Tauris 2020, Science; Thompson et al. 2020, Science)
- LB-1 with $\sim 70 M_{\odot}$ unseen object (Liu et al. 2020, Nature)
    - Many objections (El_Badry, Quataert 2020; Irrgang et al. 2020; Tanikawa et al. 2020; Safarzadeh et al. 2020; etc.)
- RV observations are hard due to uncertainties of distances, and inclinations (my personal opinion).



Thompson et al. (2019)



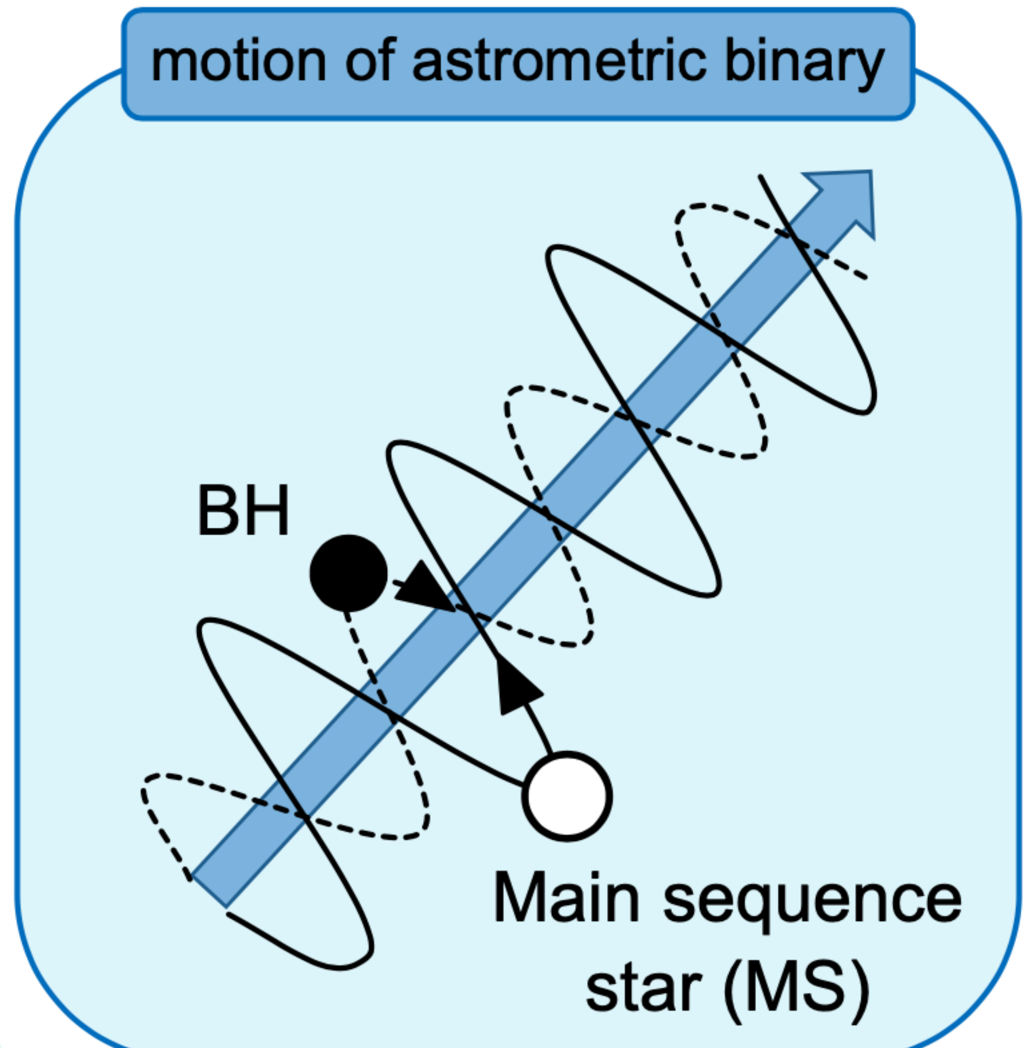
Liu et al. (2019)

Expectations for Gaia (astrometry)

- Gaia is expected to discover many BH-LCs with $P \sim 10 - 1000$ days.

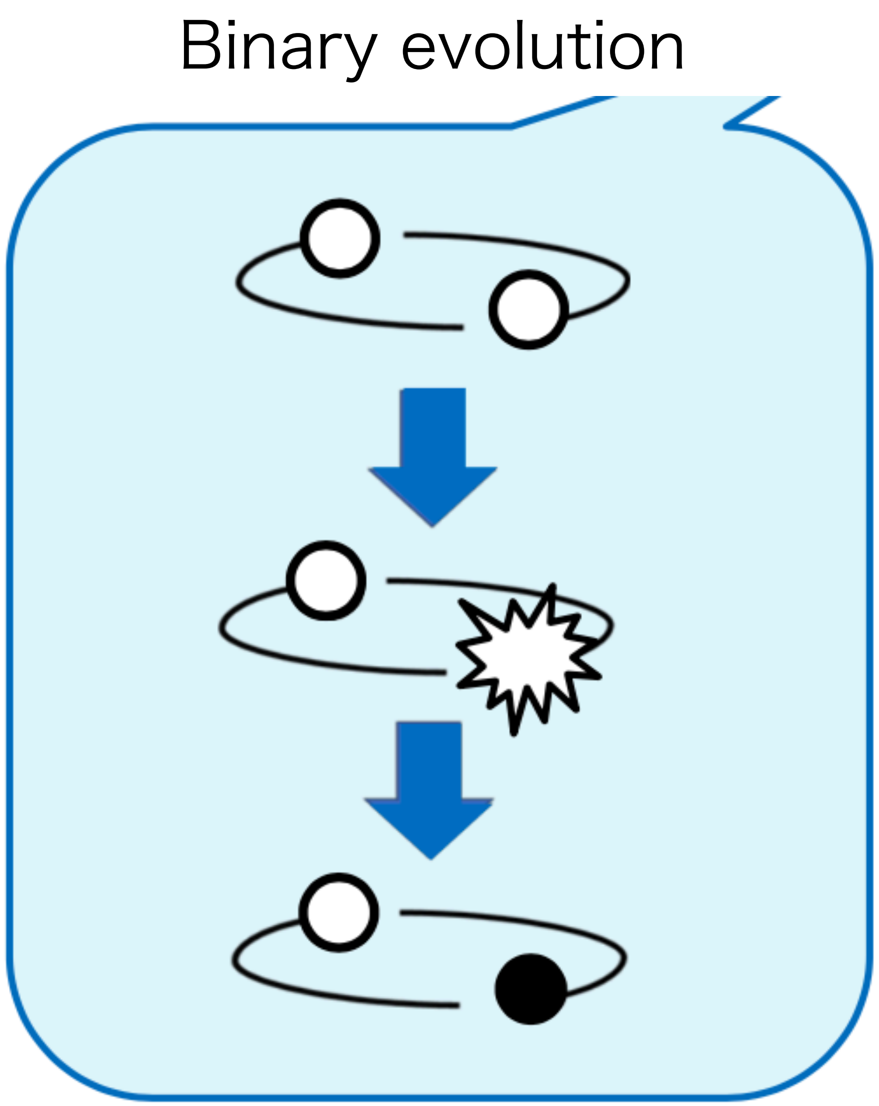
- Gaia DR3 (H2 2021) will contain internal and external motions of BH-LCs.

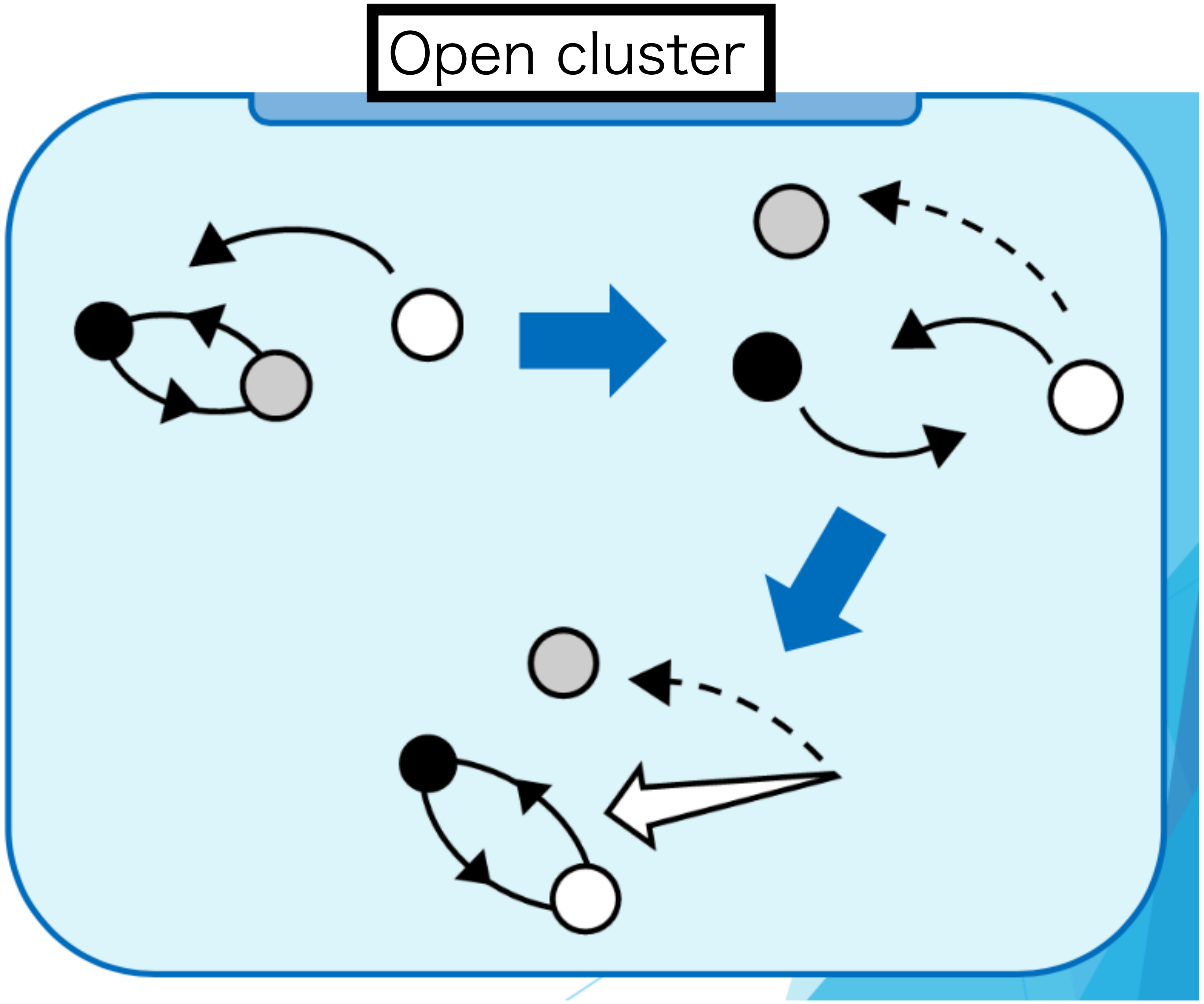
- There is no degeneracy (e.g. distances, inclinations, etc.) if there are many data points with sufficient accuracy.



From Shikauchi's slides

Previous and our studies



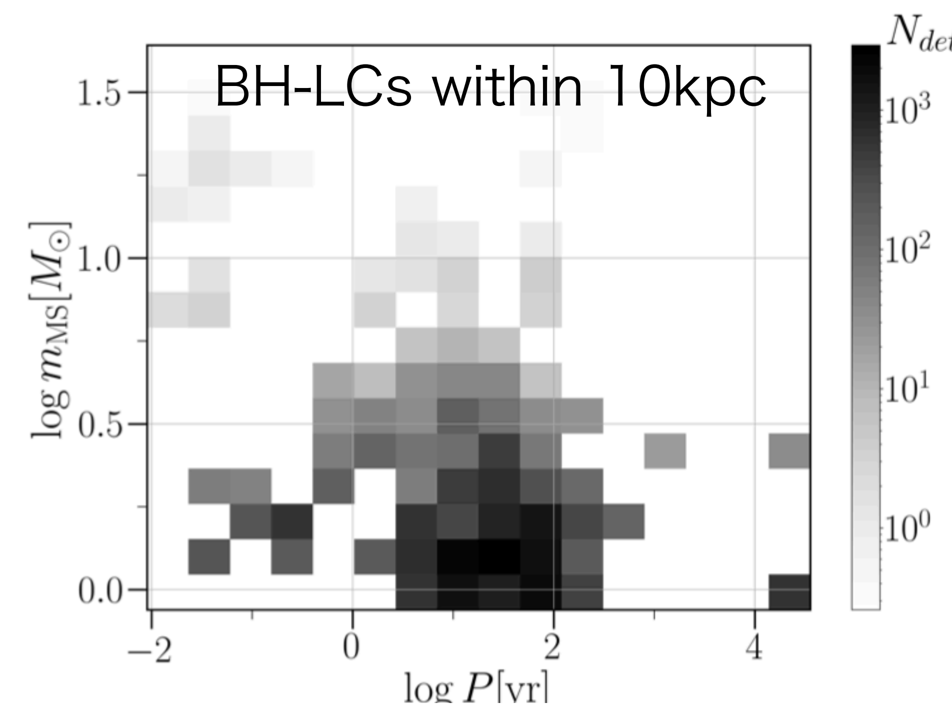


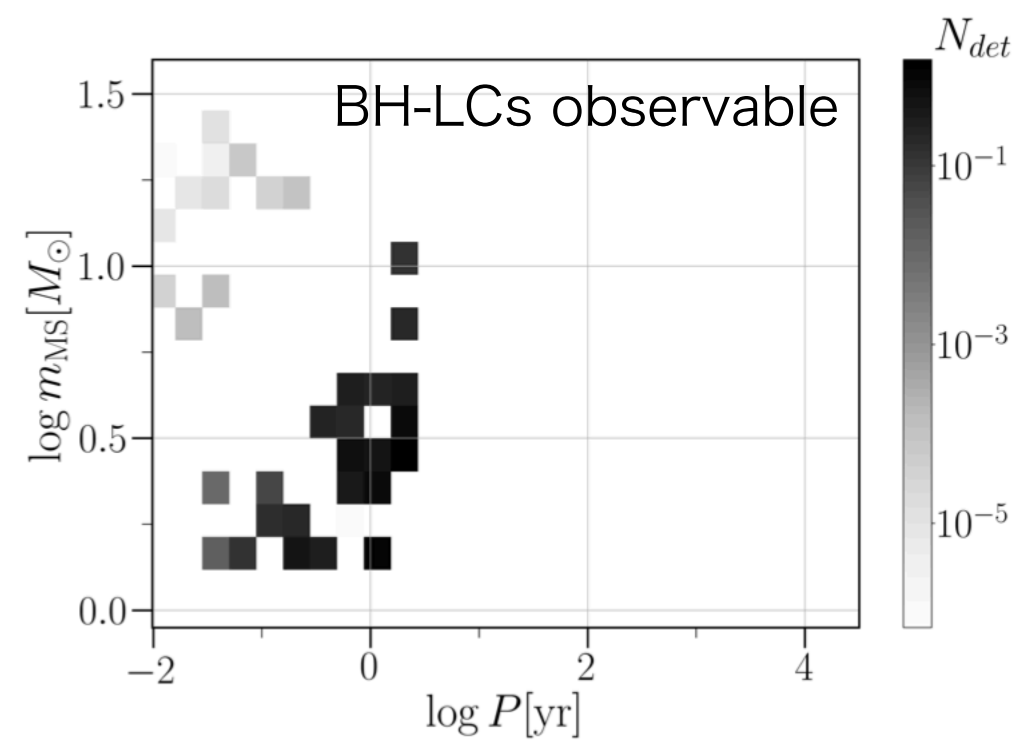
From Shikauchi's slides

- $\sim 100 - 1000$ BH-LCs formed through binary evolution (Mashian, Loeb 2017; Breivik et al. 2017; Yamaguchi et al. 2018; etc.)
- How many BH-LCs formed in open clusters? Their properties?

Results

- Search for Kumamoto's results
- The number of observable BH-LCs is $10 - 100$, depending on Gaia lifetime ($3 - 20$ yrs).
- Observational constraints
  - Apparent magnitude
  - Parallax
  - Period

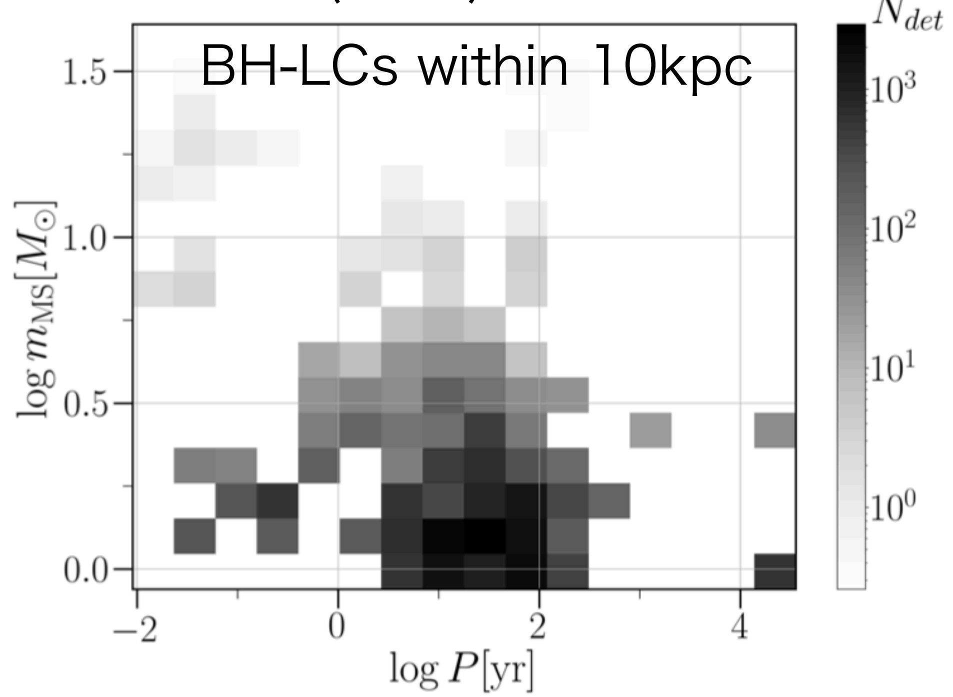


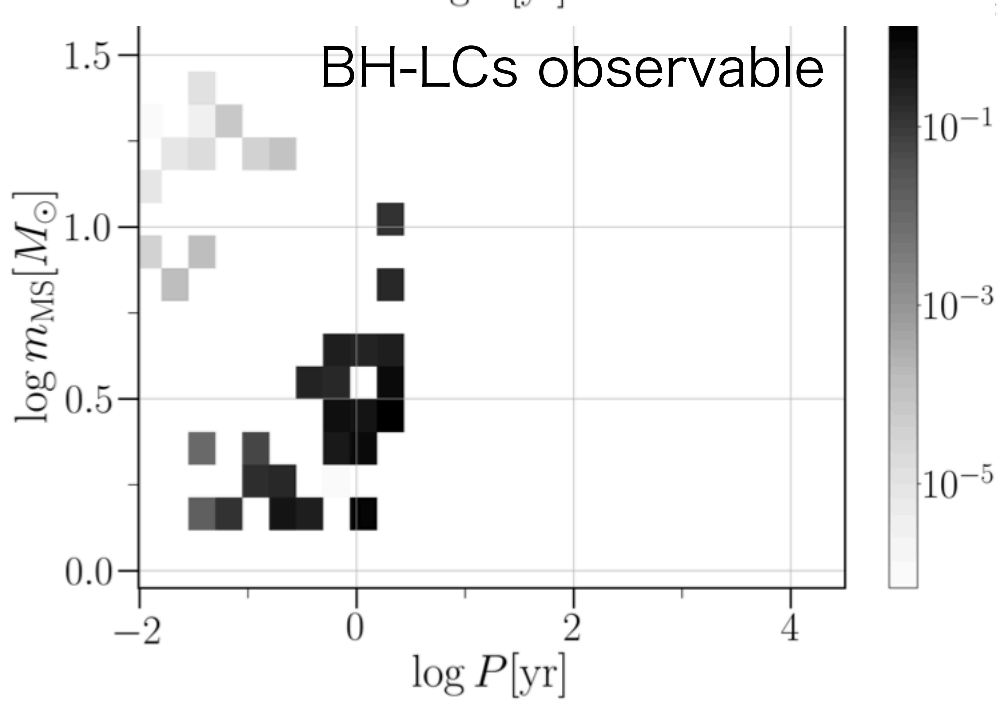


Shikauchi et al. (2020)

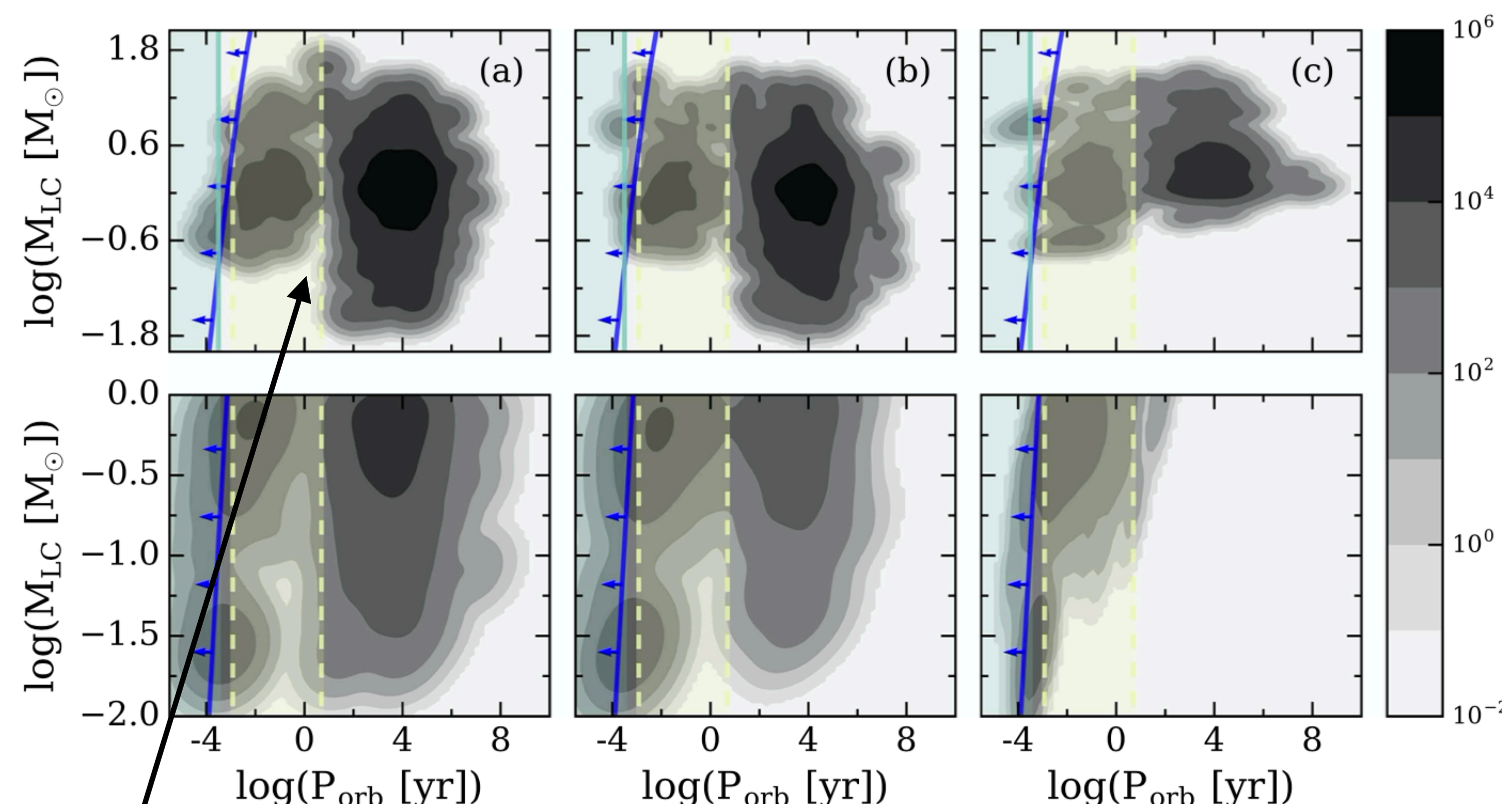
Comparison with binary evolution

Shikauchi et al. (2020)





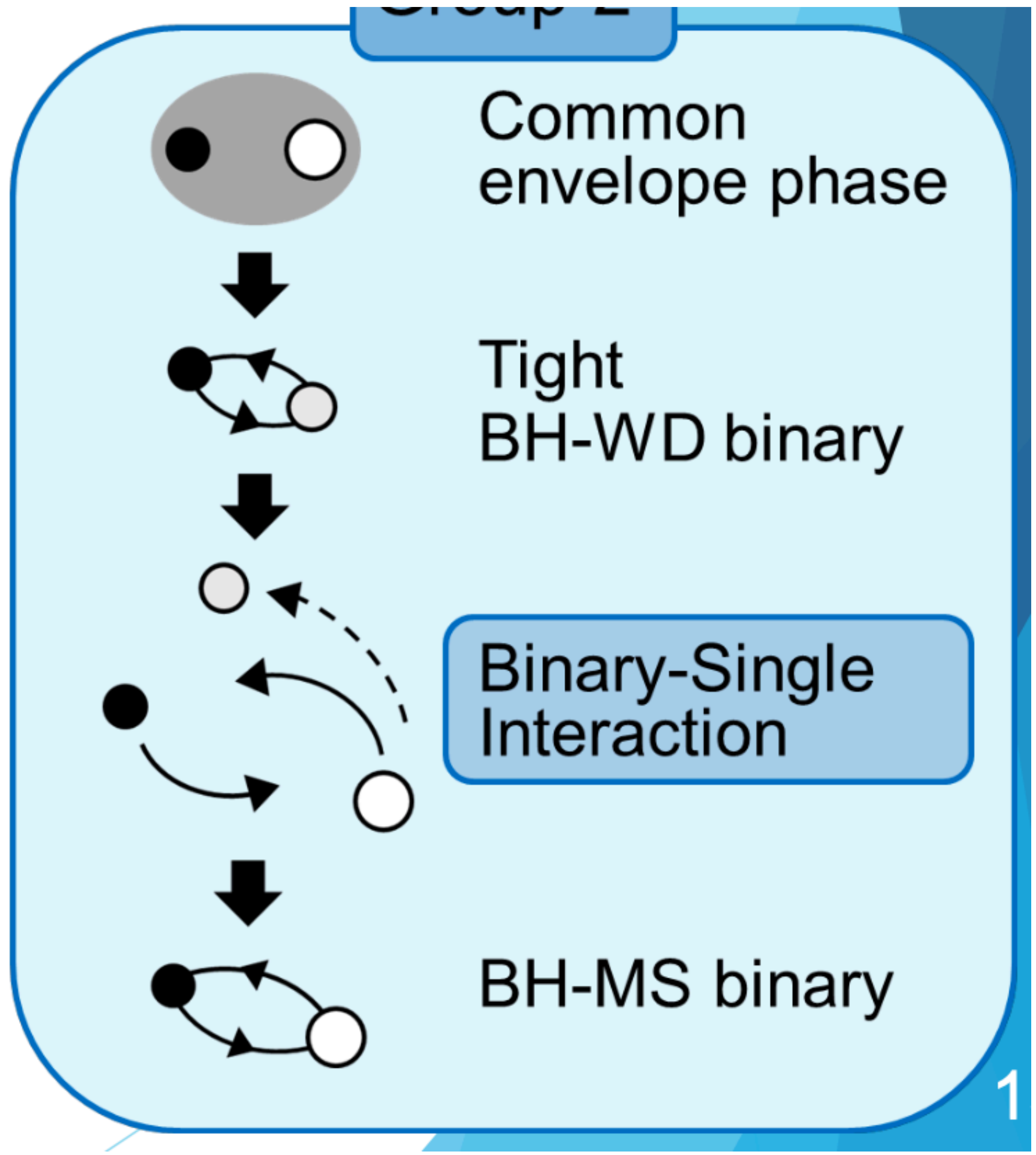
Breivik et al. (2017)



OC-origin BH-LCs can fill the gap due to common envelope evolution.

Chemical abundance

- LCs in BH-LCs formed through binary evolution can be polluted by outflows of BH progenitors, such as stellar wind, supernova ejecta, etc.
    - X-ray binaries indicate such features.
- LCs in BH-LCs formed in OCs are NOT polluted, since they become the members after the BHs are formed.

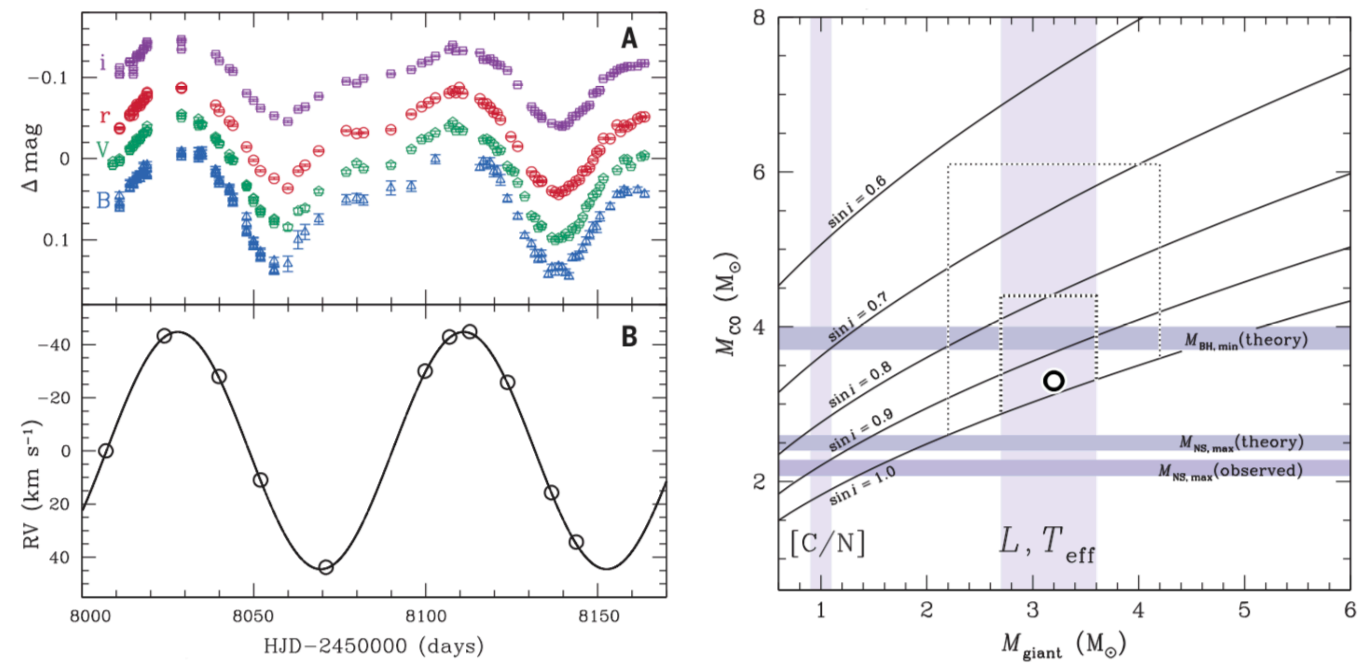


From Shikauchi's slides

BH-LCs: LB-1

BHs by RV observations

- 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)
    - Under dispute



Thompson et al. (2019)

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

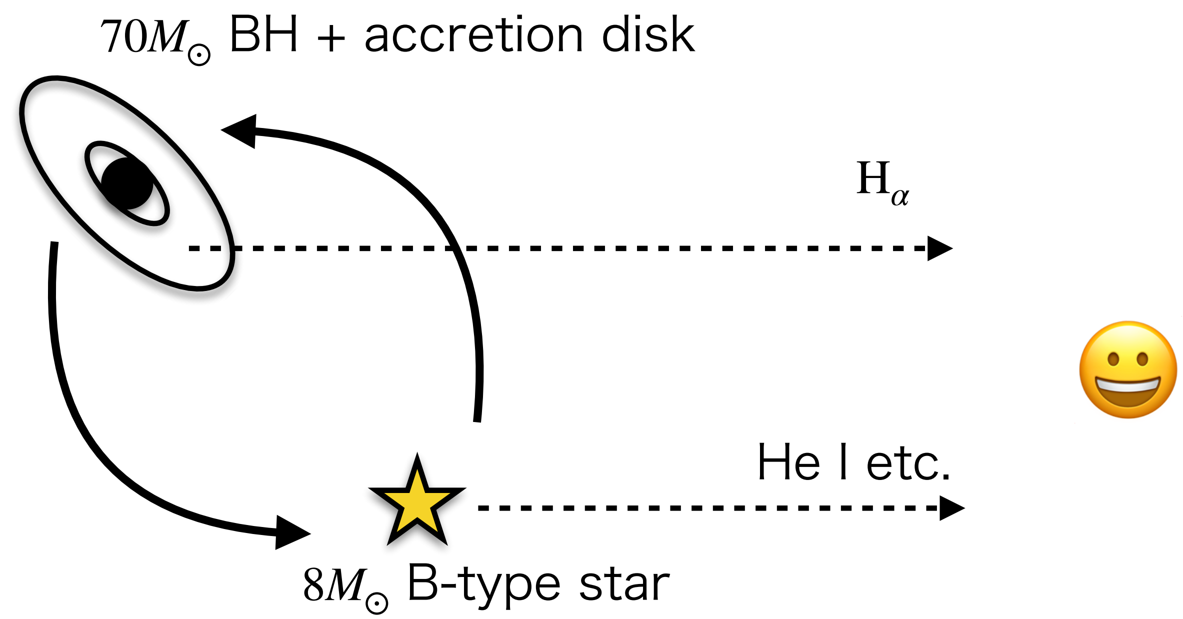
$$R_{\rm giant} = v_{\rm spin} P_{\rm spin}/2\pi \sim \frac{23 \pm 1 R_\odot}{\sin i_{\rm spin}} \left(\frac{v_{\rm spin}}{14.1 {\rm kms}^{-1}}\right)\left(\frac{P_{\rm spin}}{82.2 {\rm day}}\right)$$

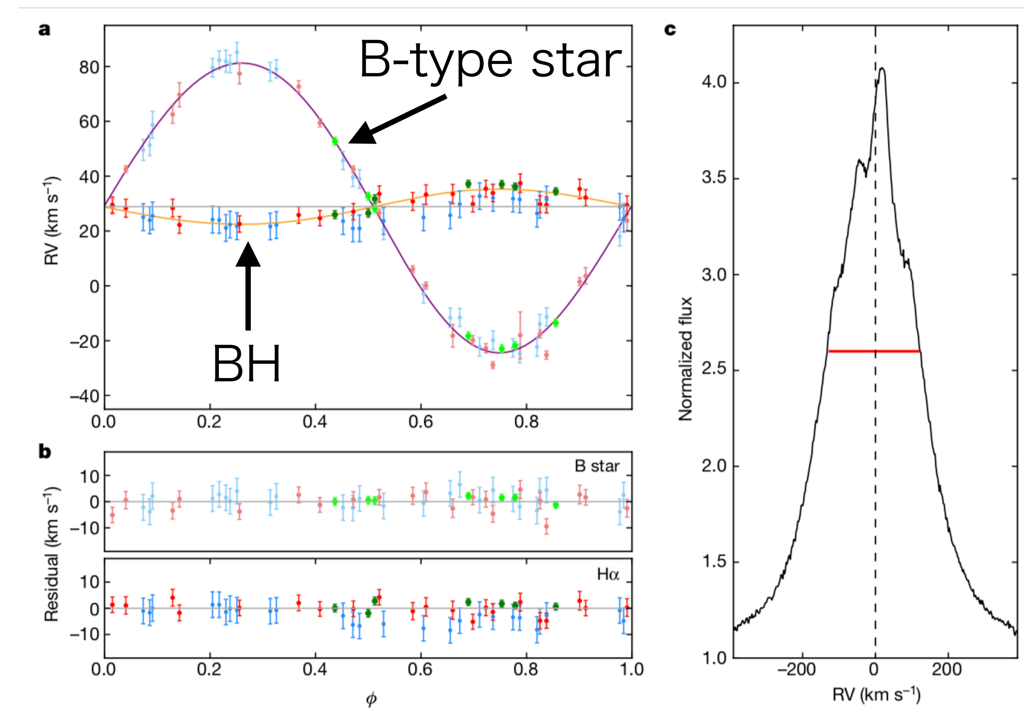
$$M_{\rm giant} = g_{\rm giant} R_{\rm giant}^2/G \sim \frac{4.4^{+2.2}_{-1.5} M_\odot}{\sin^2 i_{\rm spin}} \left(\frac{R_{\rm giant}}{23 R_\odot}\right)^2 \left(\frac{g}{10^{2.35} {\rm cms}^{-2}}\right)$$

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

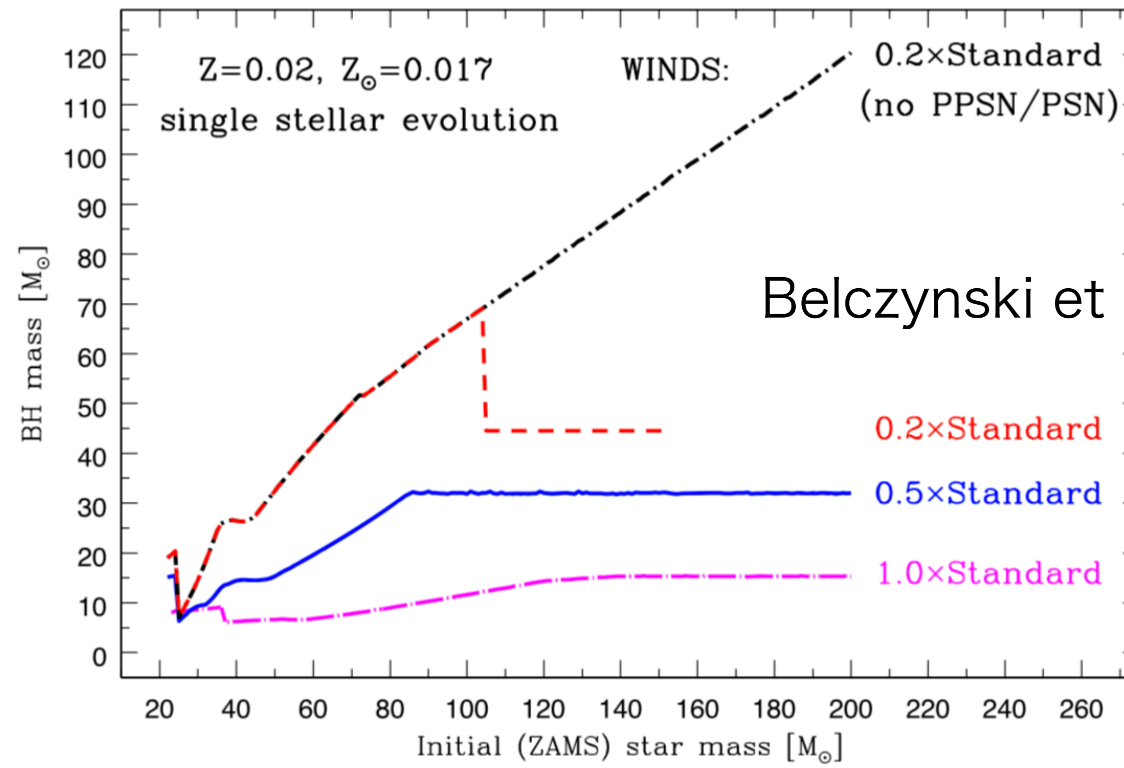




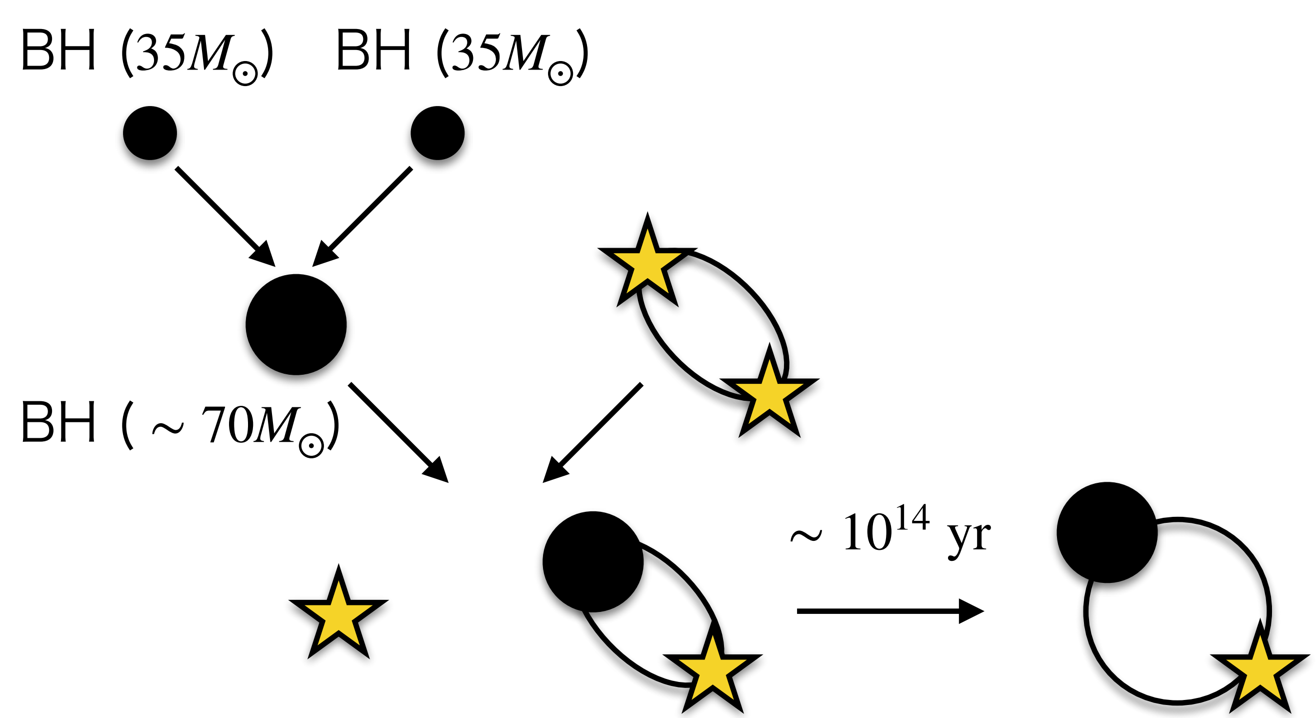
Liu et al. (2019, Nature, 575, 618)

What's surprising?

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



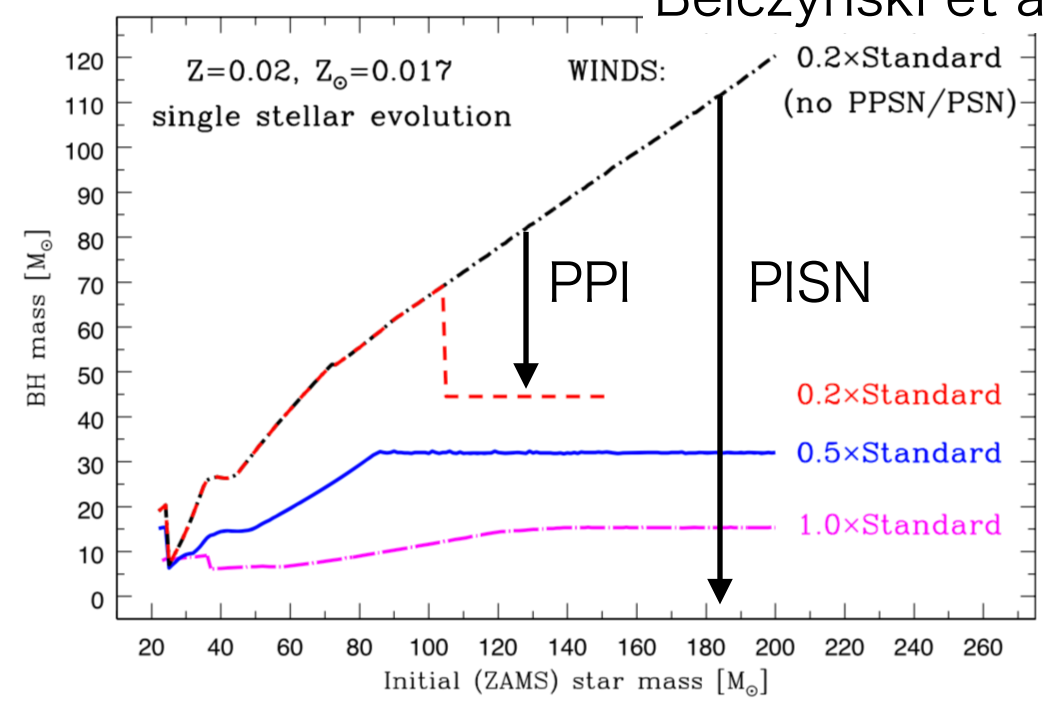
Belczynski et al. (2020)

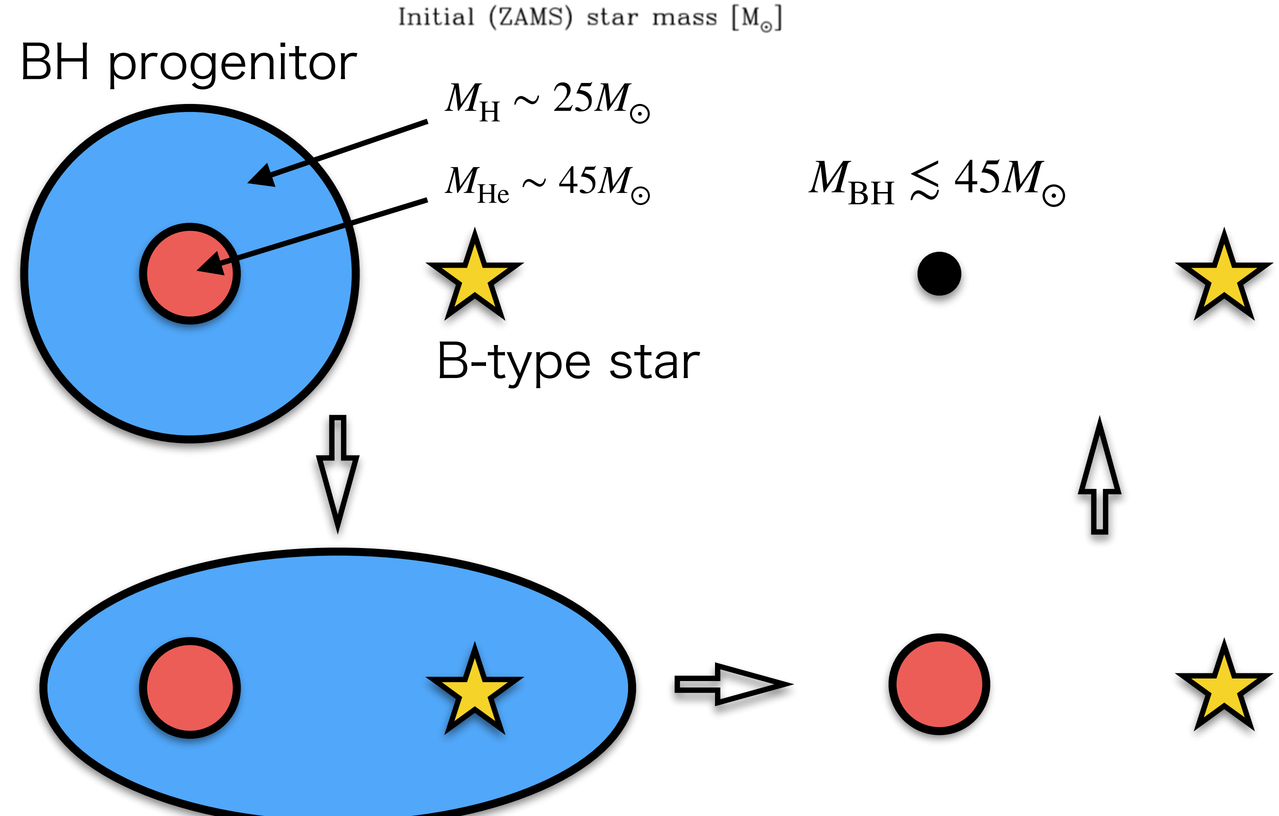


Reduced stellar wind

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

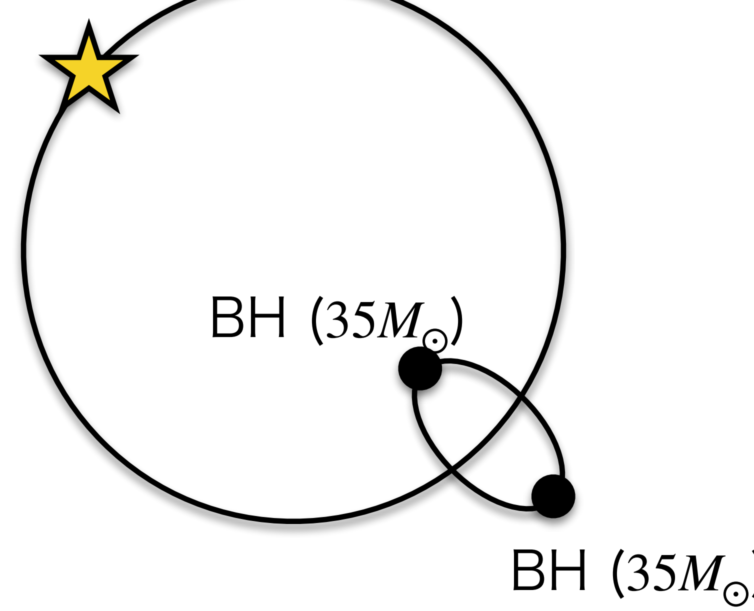
Belczynski et al. (2020)





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)

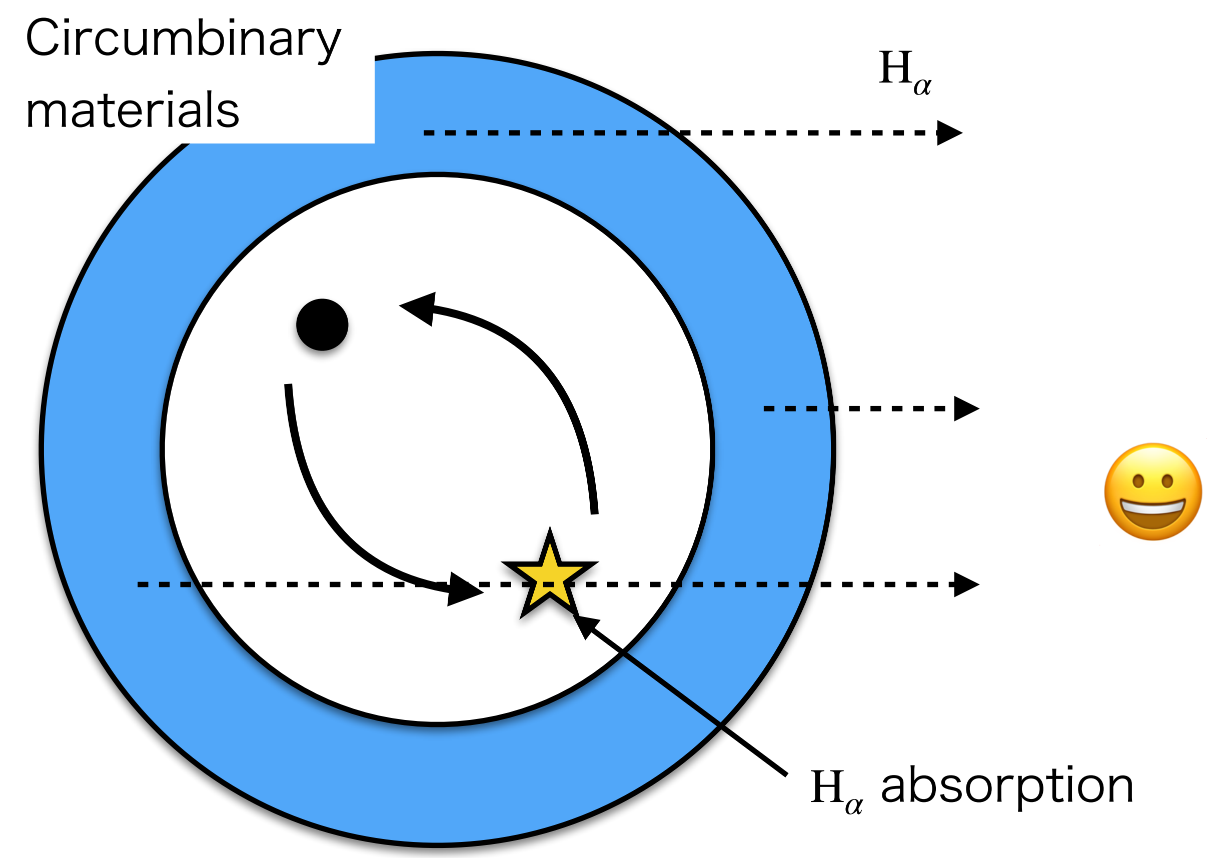


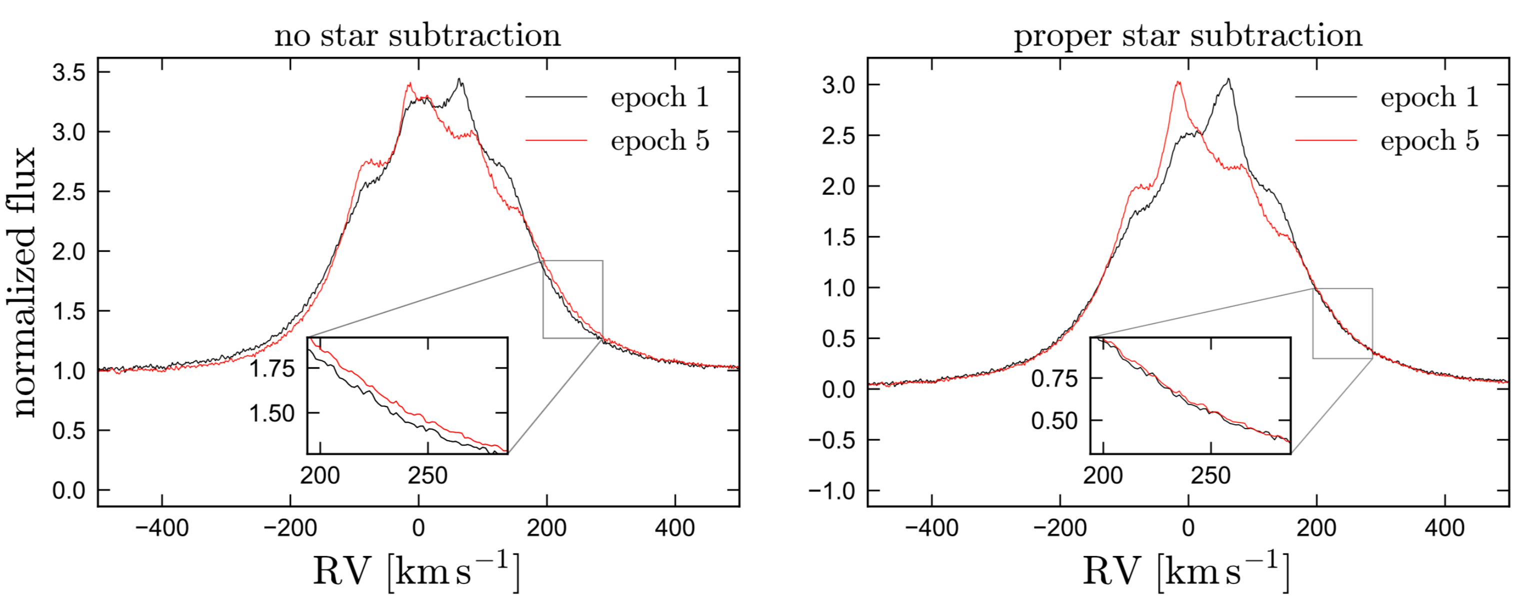
Possible scenarios

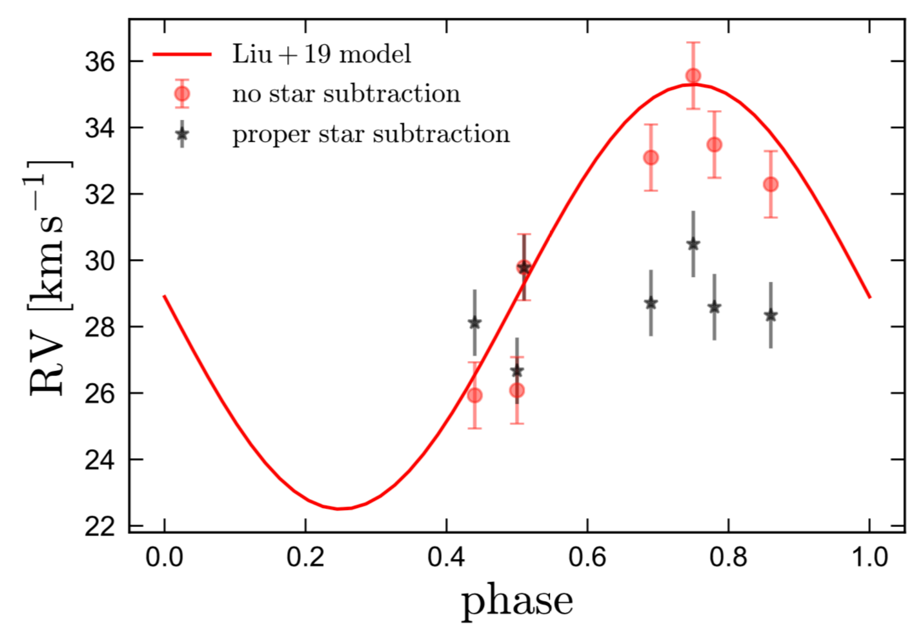
- Isolated environment
  - ~~Binary system~~
  - Hierarchical triple system
    - ~~Inner BH-BH~~
    - More complicating channels
- Dense stellar cluster
  - ~~Capture of a B-type star by a BH~~
  - More complicating interactions

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.



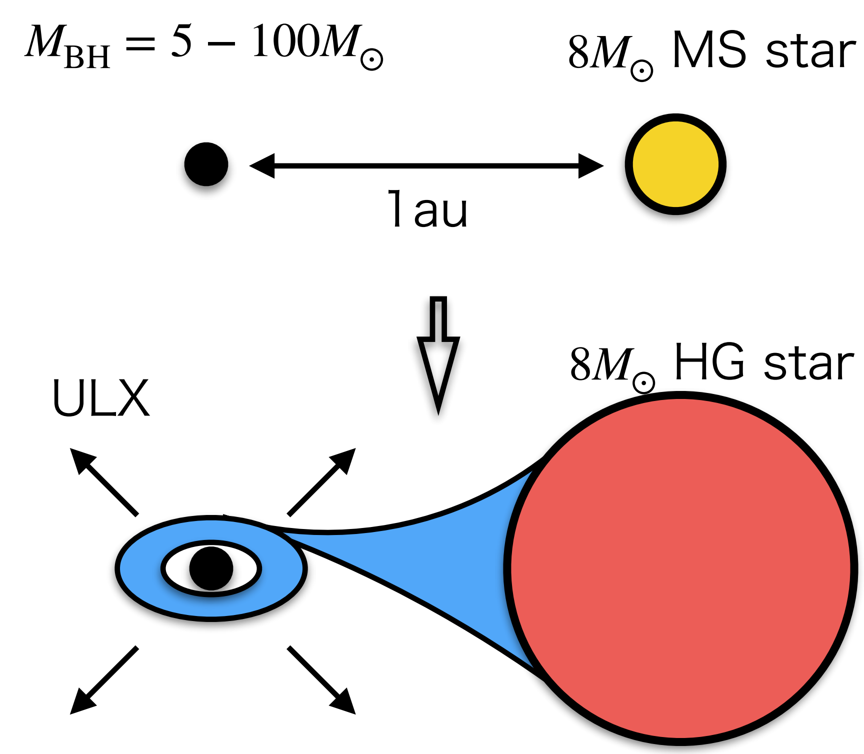


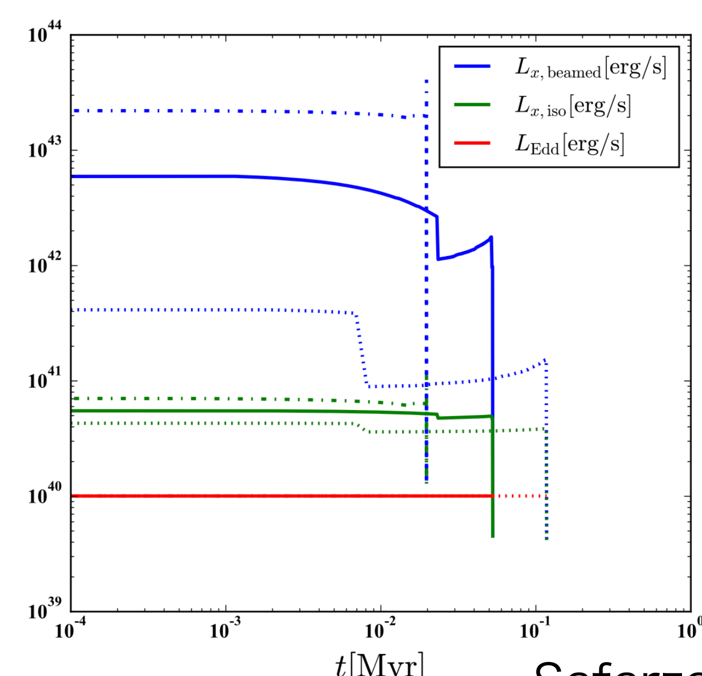


El-Badry, Quataert (2020; see also Abdul-Masih et al. 2019)

“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.

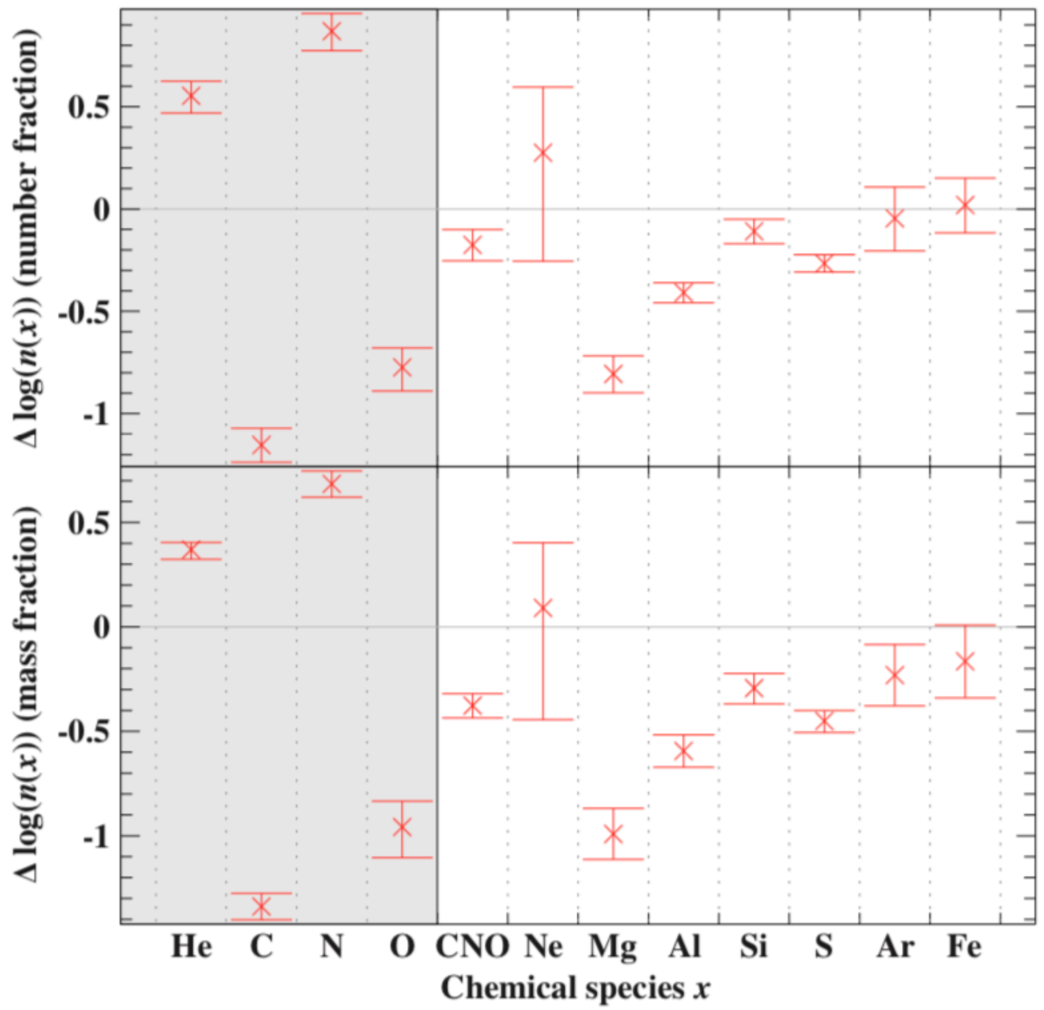




Safarzadeh et al. (2019)

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.



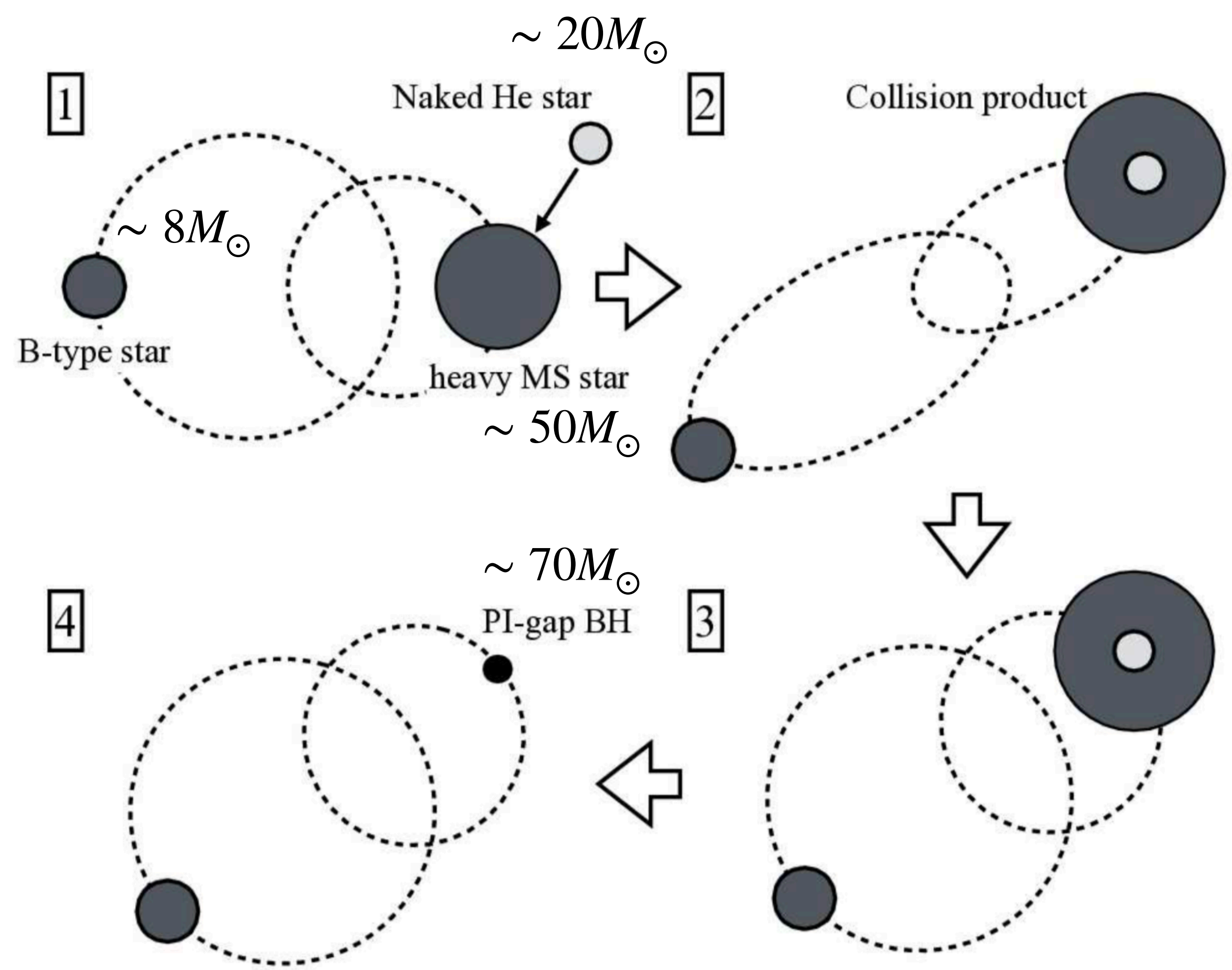
Our stance

- The presence of the $70M_\odot$ 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 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.

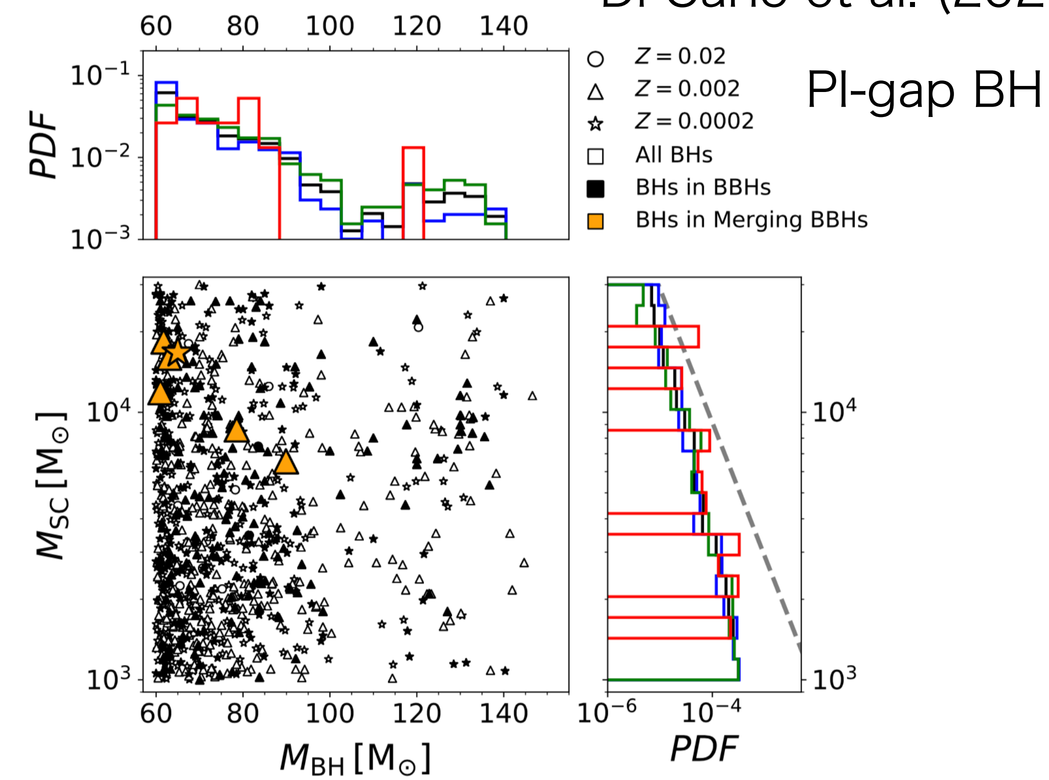
In an open cluster of the MW galaxy

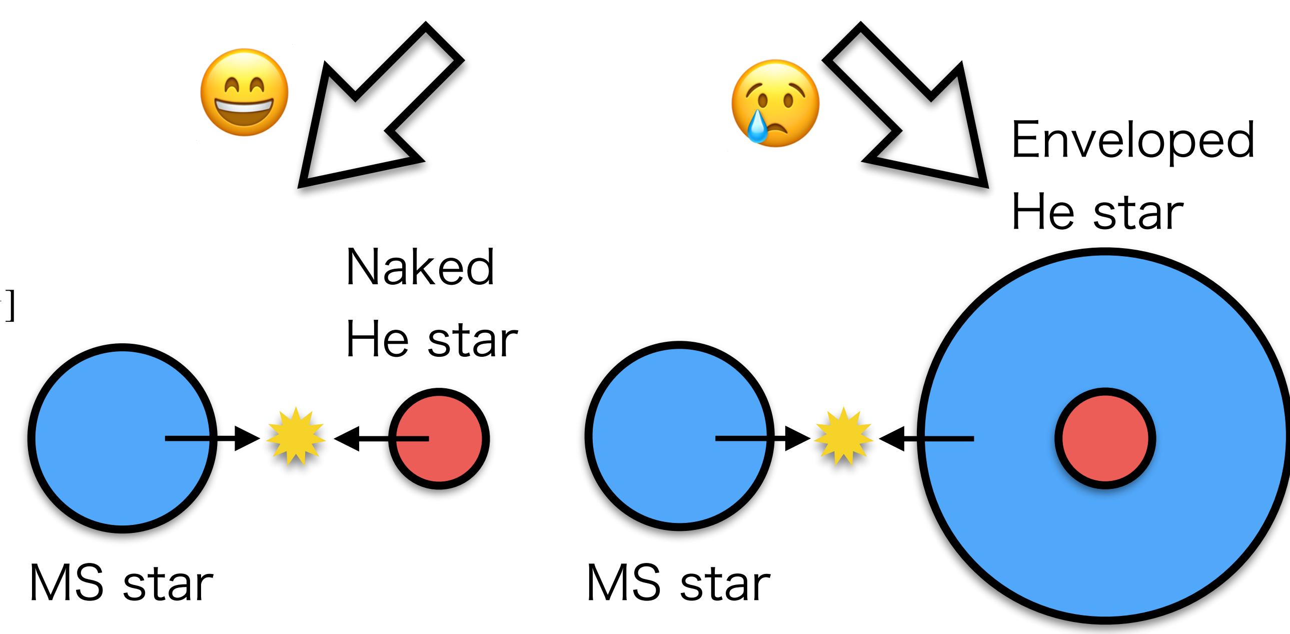


Collision rate

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

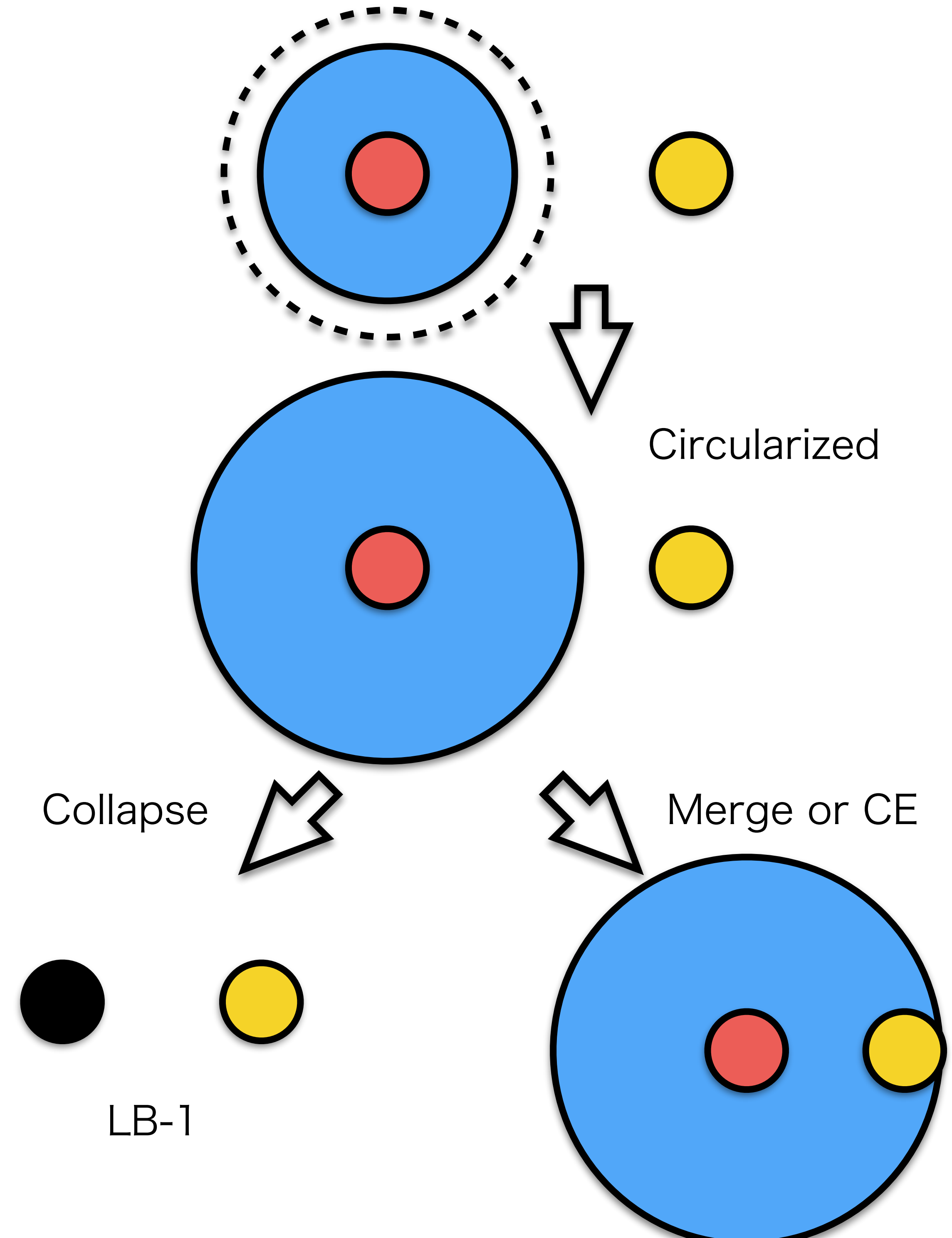
Di Carlo et al. (2020)





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
  - $$t_{\rm cric} \sim 2 \times 10^4 \left(\frac{R_{\rm coll}}{100 R_\odot} \right)^{-9} \quad [{\rm yr}]$$
- Kelvin-Helmholtz time (expansion time)
  - $$t_{\rm KH} \sim 2 \times 10^4 \left(\frac{M_{\rm coll}}{70 M_\odot} \right)^{2} \left(\frac{R_{\rm coll}}{100 R_\odot} \right)^{-1} \left(\frac{L_{\rm coll}}{10^5 L_\odot} \right)^{-1} \quad [{\rm yr}]$$
- 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 all OCs 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.

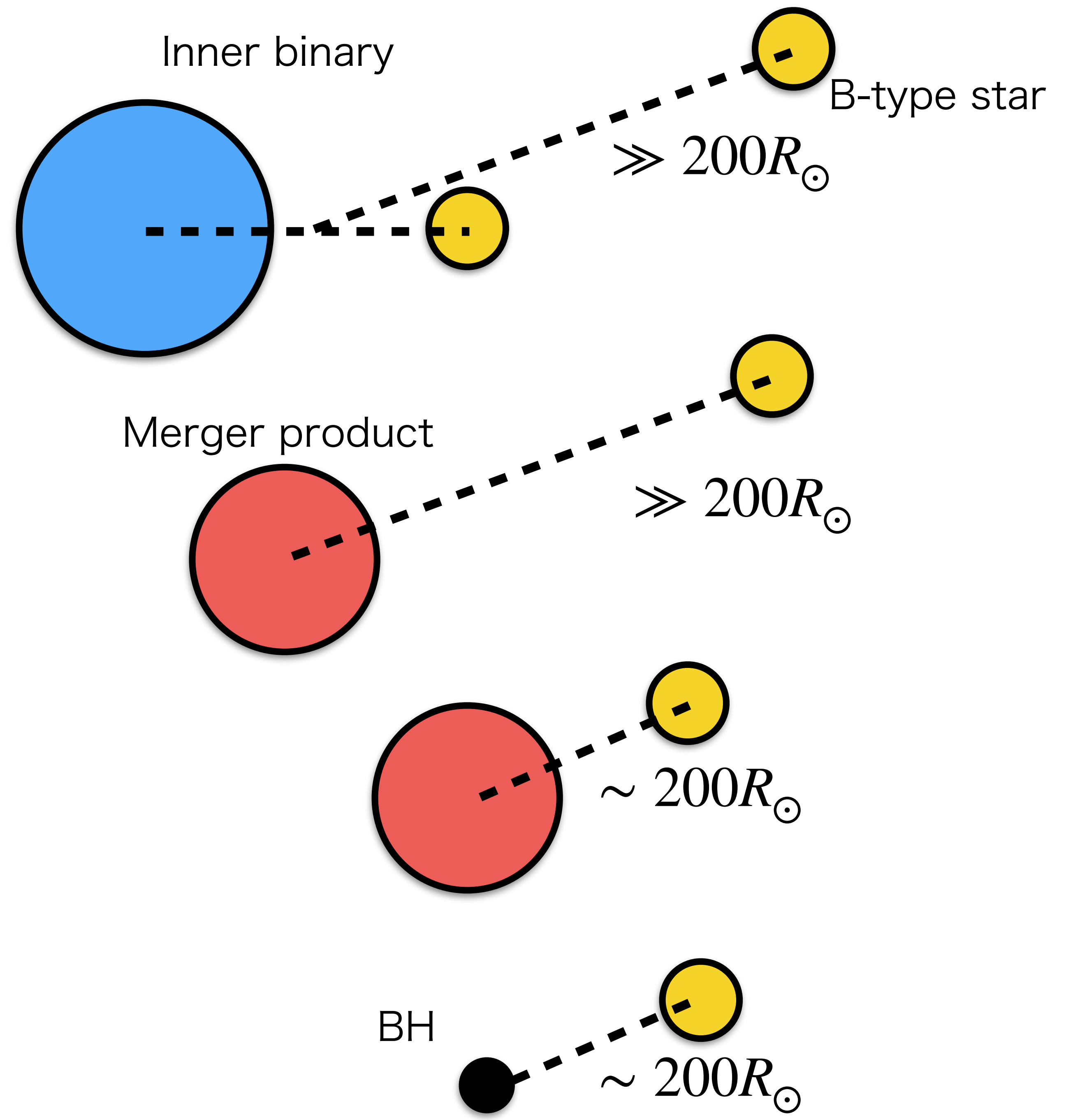
	MS	He star	Naked He star	BH
MS	PPI/ PISN			
He star	R>>a	R>>a		
Naked He star	Done	R>>a	PPI/ PISN	
BH	Similar rate	R>>a	Lower rate	Lower rate

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~~

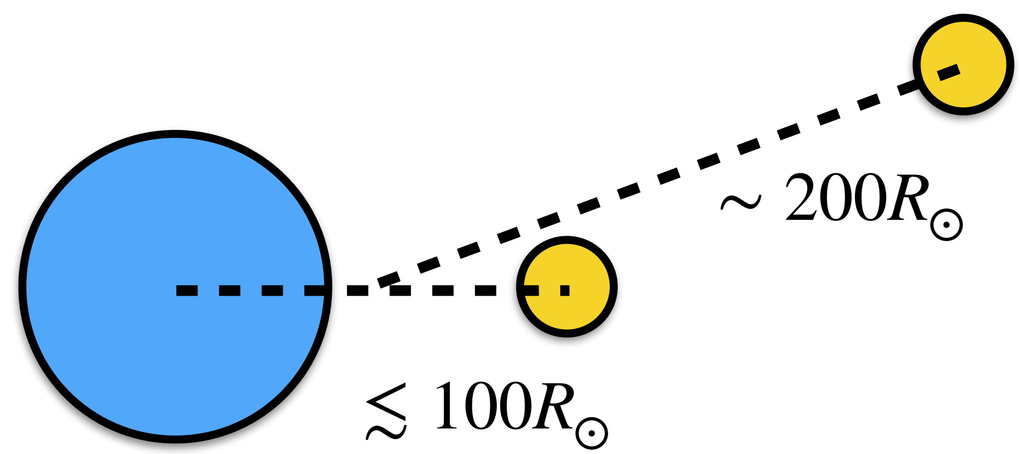
Hierarchical triple (1)

- The merger product should be $\gtrsim 70 M_\odot$.
- If it has a radius of $\gg 200 M_\odot$, it is a He star.
- It experiences common envelope evolution with the B-type star.
  - It loses its envelope, and collapses to a $\lesssim 45 M_\odot$ 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 $\sim 200 R_\odot$, and never has no interaction with the B-type star.



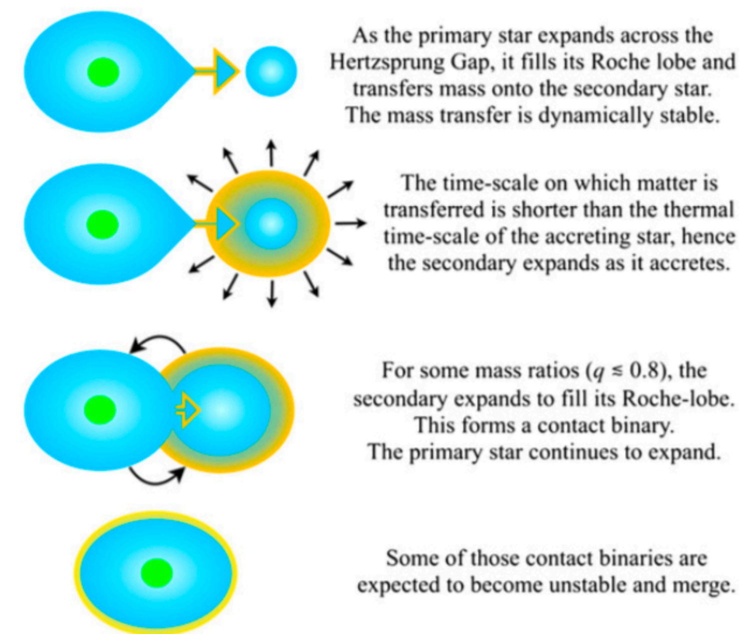
Hierarchical triple (2)

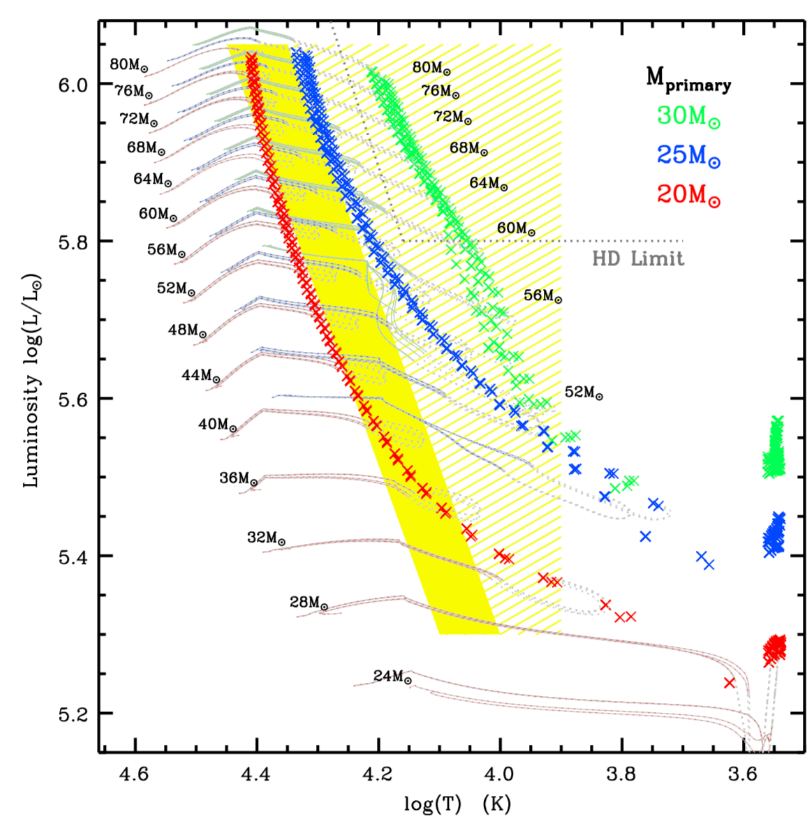
- The separation of the inner binary should be $\lesssim 100R_\odot$. Otherwise, the system is unstable (Harrington 1972; Mardling, Aarseth 1999).
- The primary star of the inner binary should be $\gtrsim 35M_\odot$.
    - $\lesssim 100M_\odot$ stars exceed $\sim 100R_\odot$ when they are in Hertzsprung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

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~~

Caution

- The formation of $\sim 70 M_\odot$ BH is not impossible.
- The formation of LB-1 is impossible.
    - $a \sim 1\ \mathrm{au}$, and $e \sim 0.03$
- $\sim 70 M_\odot$ BHs can be present in binaries systems with $a \gg 1\ \mathrm{au}$ or $e \gg 0$.

Summary

- OC-origin BH-BHs are promising (Kumamoto, AT, Fujii 2019; 2020).
- Many BH-LCs are expected to be discovered by Gaia, and some of them can be OC-origin (Shikauchi, Kumamoto, AT, Fujii 2020).
- LB-1 cannot be formed through dynamical interactions and hierarchical triple systems in the standard model of single and binary stars (AT et al. 2020).
  - If LB-1 really has a $70M_{\odot}$ BH, we should correct the standard model.

Future work

- Mechanism of spin-orbit misalignment of BH-BHs like GW190425, and many (Alessandro)
- Spin distribution of OC-origin BH-BHs (Kumamoto)
- Revisit of BH/NS-LC populations including X-ray binaries (Shikauchi)