A03 Progress report: binary star evolution

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The first annual symposium of the innovative area
“Gravitational Wave Physics and Astronomy: Genesis”

Purpose of A03 group

- Formation process of merging binary black holes (BBHs)
  - Formation of massive binary stars (Omukai, Hosokawa, Machida, Susa)
  - Evolution of massive binary stars
    - Isolated binary stars (Tanikawa)
    - Binary stars in globular clusters (Fujii)

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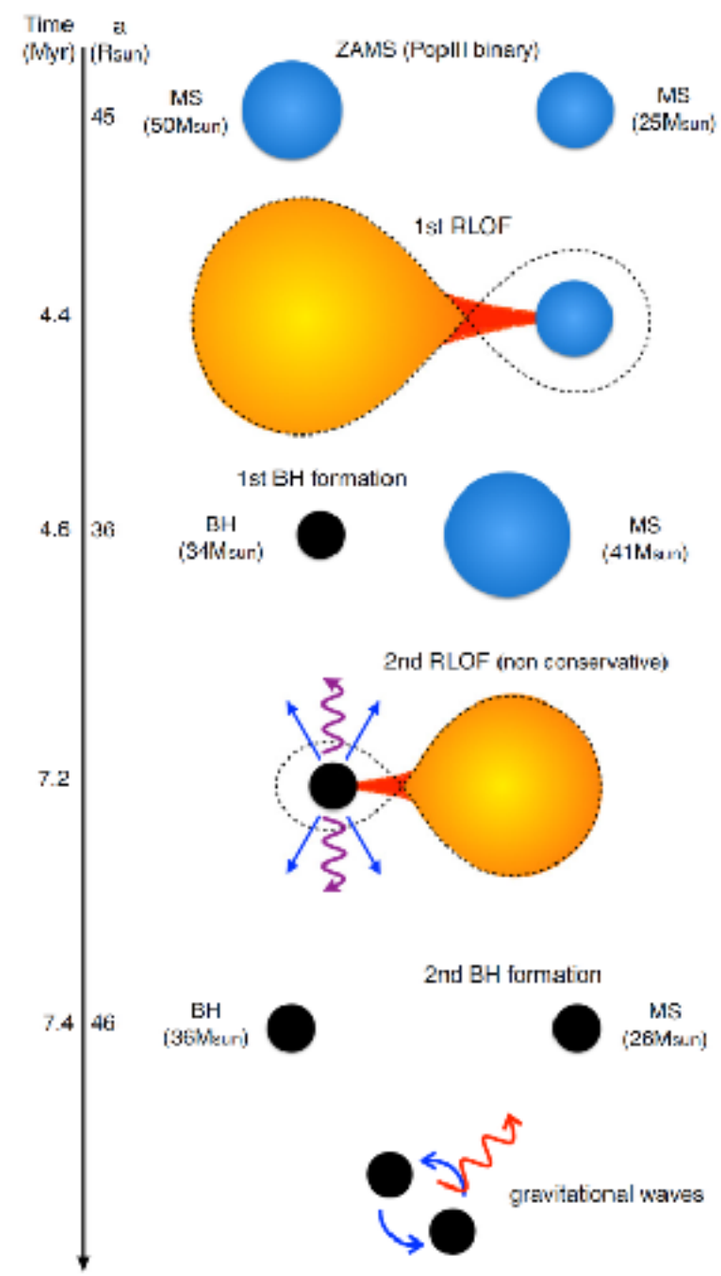
Pathway to merging BBHs

- **Pathway from massive binary stars to merging BBHs is not simple!**

- Massive binary stars cannot evolve to merging BBHs when they evolve independently.

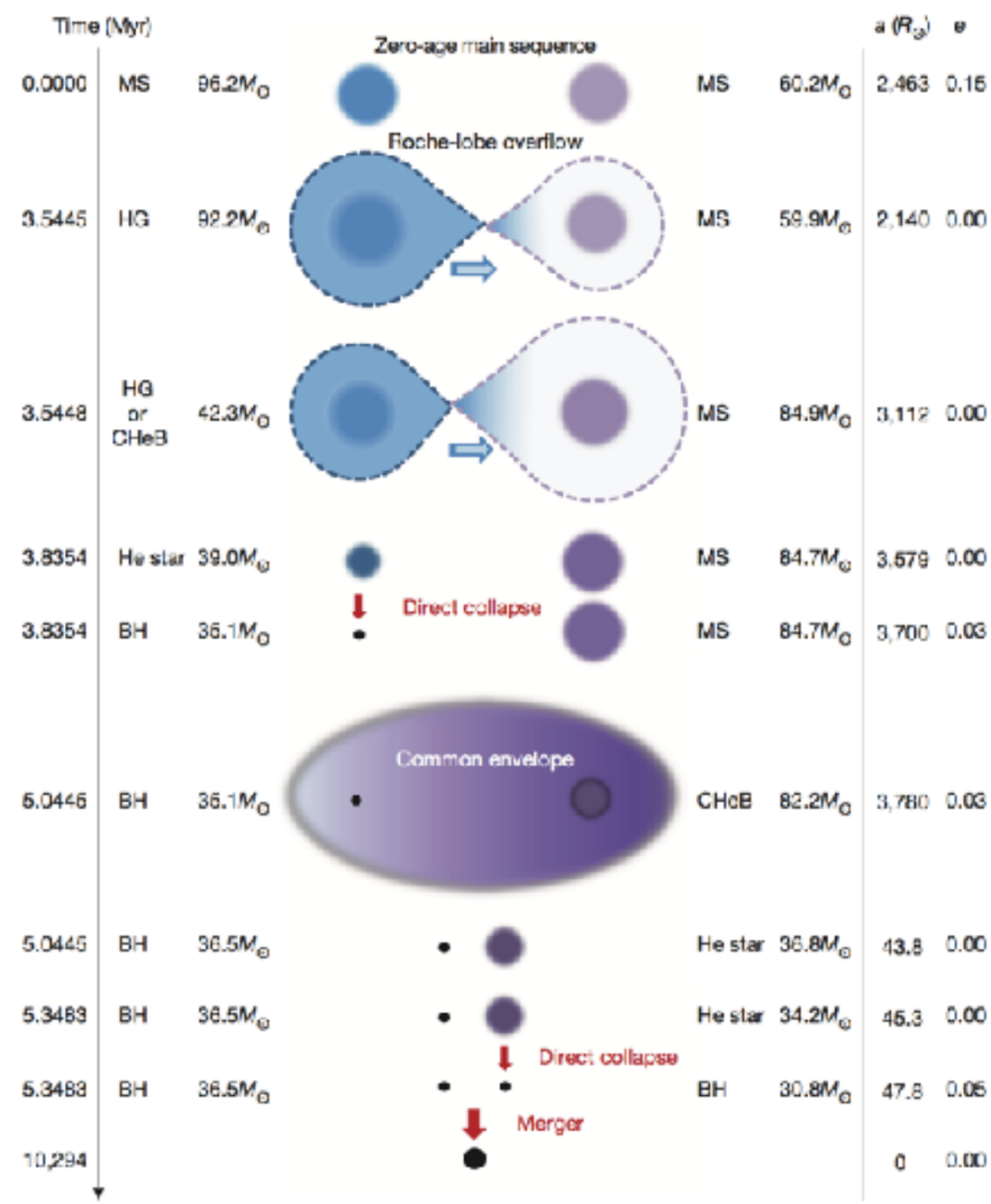
- They cannot avoid undergoing Roche-lobe overflow.



Inayoshi et al. (2017)

Population synthesis

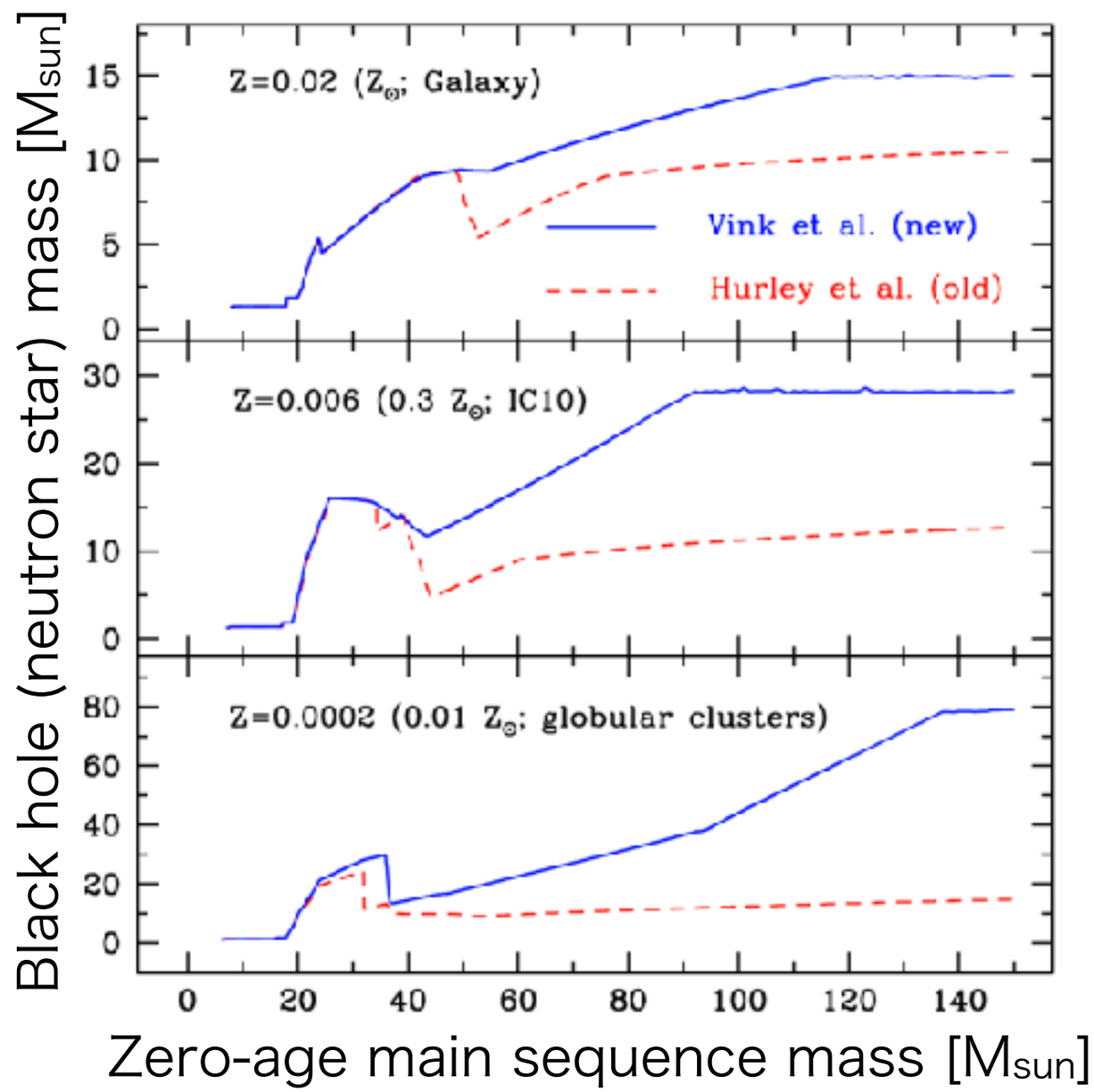
- Follow the evolution of a large number of binary stars.
- Investigate the BBH merger rate, and the BBH distribution of chirp mass, mass ratio, and so on.
- Constrain the pathway from massive binary stars to merging BBHs.



Belczynski et al. (2016)

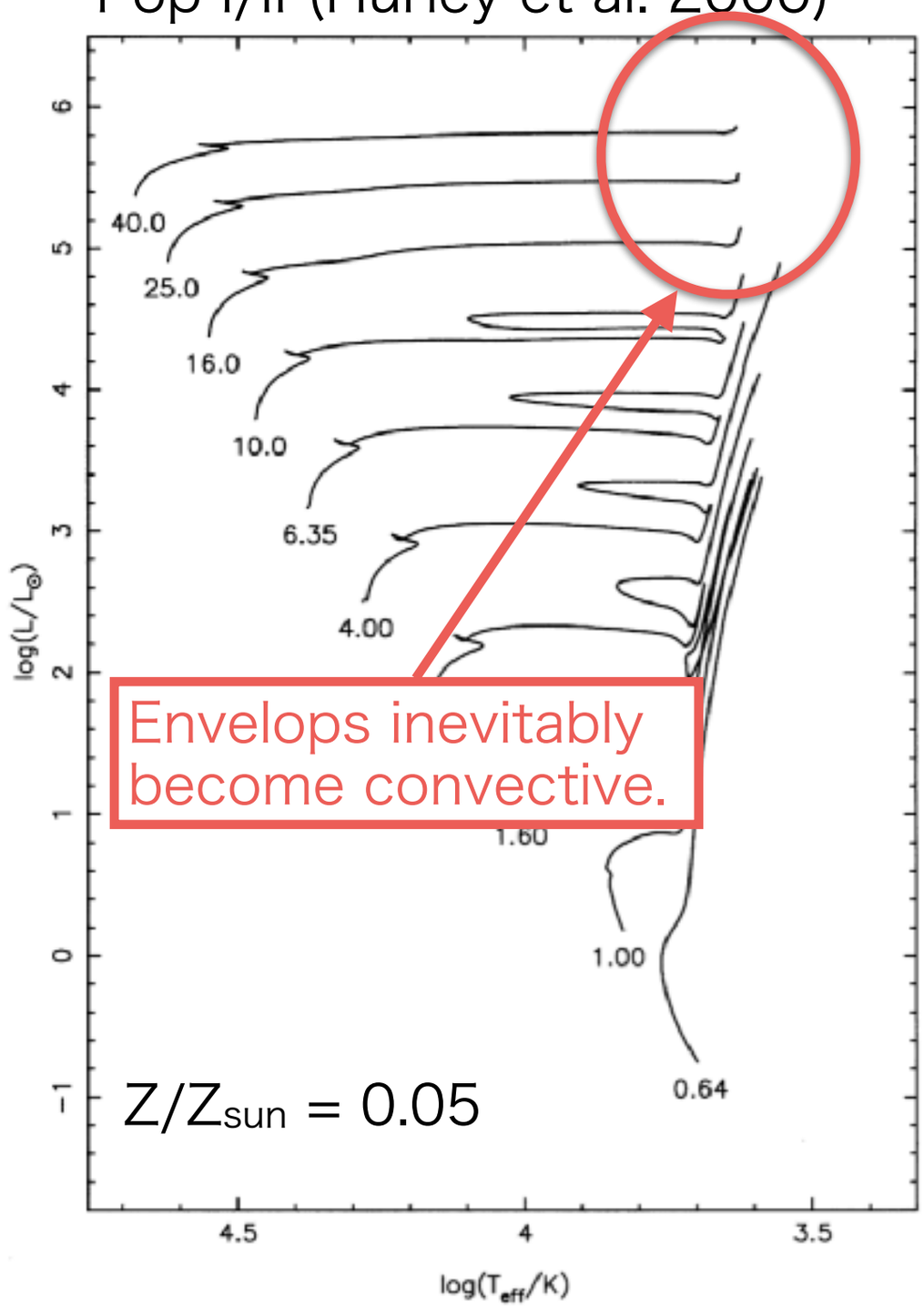
Metallicity (1)

- Metallicity is an important factor for the formation of merging BBHs.
- Stellar-wind mass-loss is weaker with metallicity smaller.
- Low-metal stars tend to leave massive black holes.

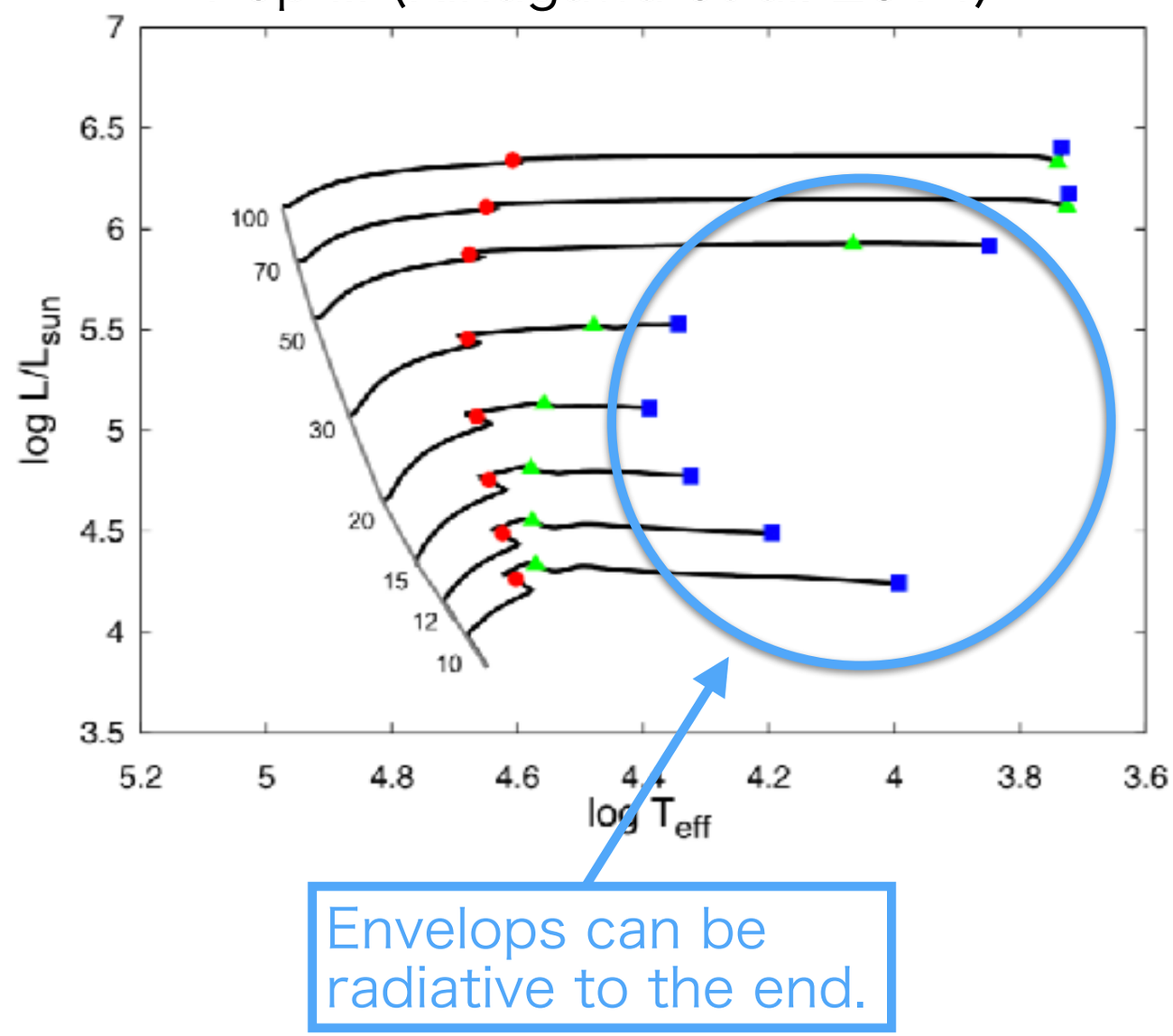


Metallicity (2)

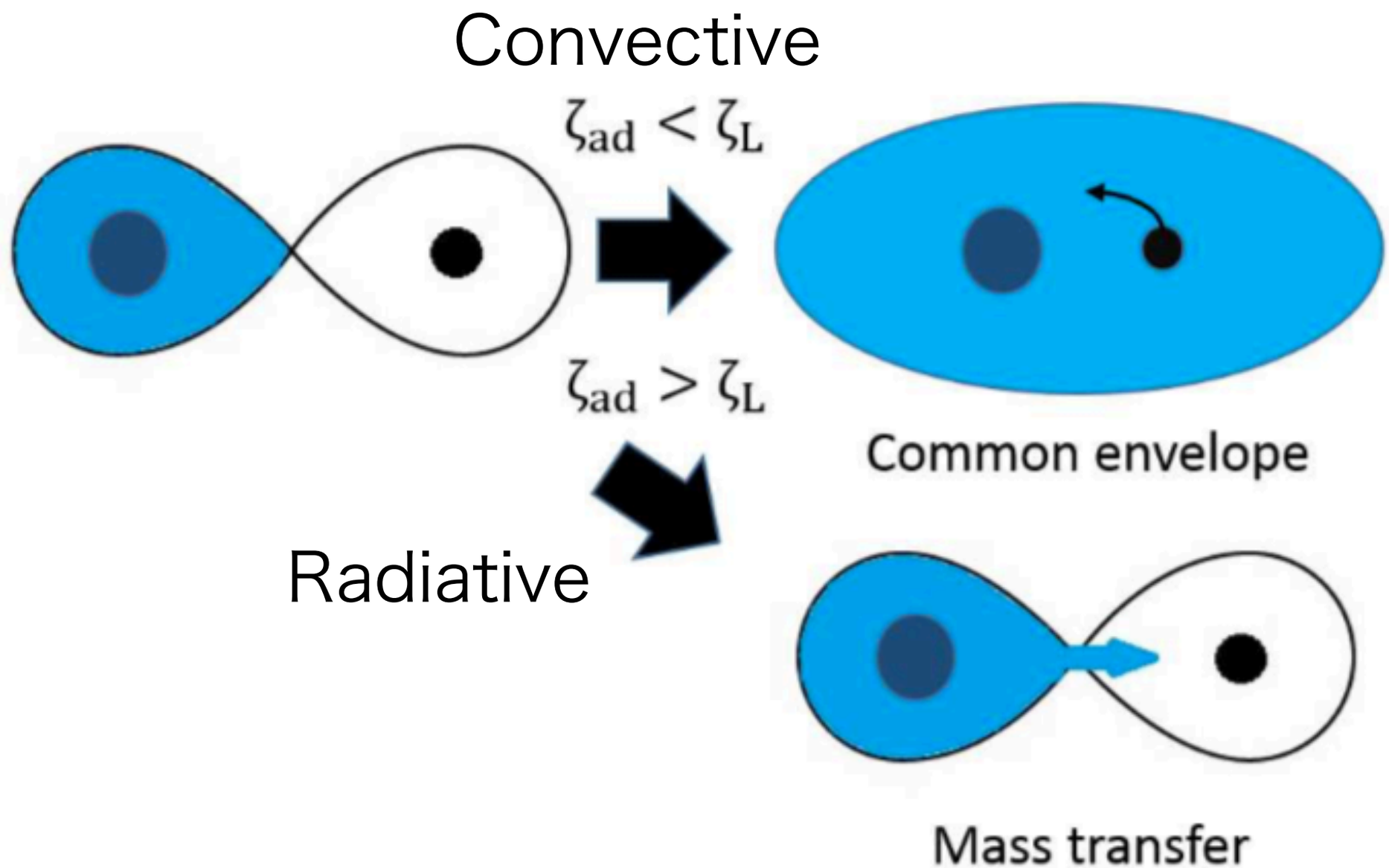
Pop I/II (Hurley et al. 2000)



Pop III (Kinugawa et al. 2014)



Envelop



Kinugawa et al. (2014)

Previous studies

- Population synthesis for Pop I/II stars (Z/Z_{sun} = 5×10^{-3} - 1.5) (e.g. Belczynski et al. 2016)

- Population synthesis for Pop III stars (Z/Z_{sun} = 0) (e.g. Kinugawa et al. 2014)

Our study

- Bridge the gap between Pop I/II and Pop III
  - Population synthesis for extremely metal-poor (EMP) stars ($0 < Z/Z_{sun} < 5x10^{-3}$)
- Construct Fitting formula for EMP star evolution
- Investigate population synthesis of EMP stars
- Focus on transition between Pop I/II and Pop III

Simplified model of single stellar evolution

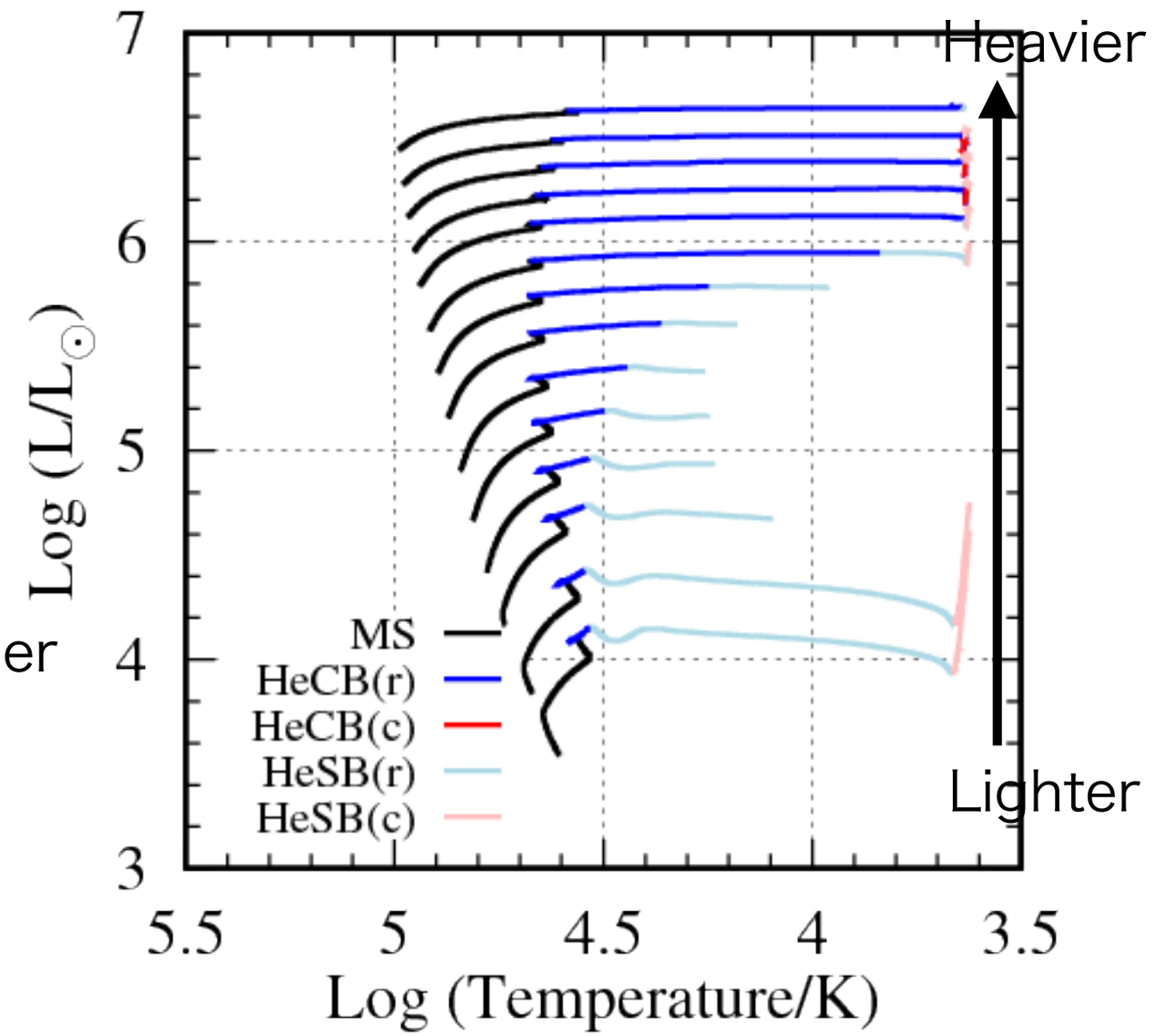
- Population synthesis deals with **a large number of binary stars (~10^6 per model)**.
- We need **simplified single stellar evolution model**.
- Fitting formula for single stellar evolution
  - Radius: R(t; Mass, Metallicity, Phase)
  - Luminosity: L(t; Mass, Metallicity, Phase)
  - He core mass: M_{He}(t; Mass, Metallicity, Phase)

Phase of EMP stars

- Core: H core burning (MS)
  → He core burning (HeCB)
  → He shell burning (HeSB)
- Envelop: radiative (r) → convective (c)
- MS→HeCB(r)
  - →HeCB(c)→HeSB(c)
  - →HeSB(r)→HeSB(c)
  - →HeSB(r)
  - →HeSB(r)→HeSB(c)

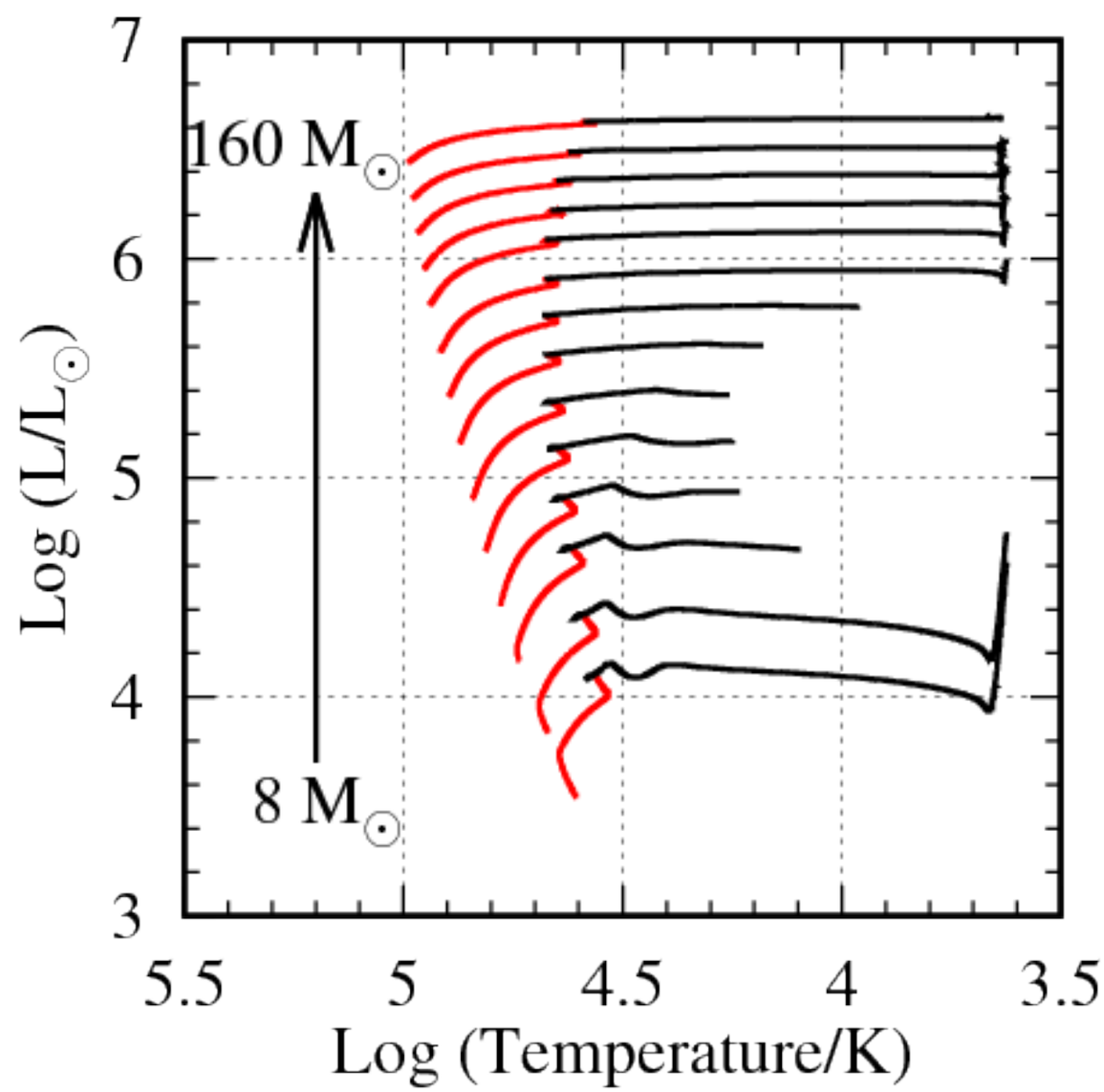
Heavier

Lighter



Current status

- Stellar evolution data made by Takashi Yoshida at University of Tokyo
- Z/Z_{sun} = **10^{-8}**, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}
- Fitting formula for **MS radius and luminosity**
- (He core mass is zero.)



Radius ($Z/Z_{sun}=10^{-8}$)

$$\log R_{\rm ms} = \log R_{\rm zams} + a_{\rm ms}^{(r)}(t/t_{\rm ms}) + b_{\rm ms}^{(r)}(t/t_{\rm ms})^{10} + c_{\rm ms}^{(r)}(t/t_{\rm ms})^{100} + (\log R_{\rm ms} - \log R_{\rm zams} - a_{\rm ms}^{(r)} - b_{\rm ms}^{(r)} - c_{\rm ms}^{(r)})(t/t_{\rm ms})^3$$

Lifetime $t_{\rm ms} = \sum_{i=0}^{3} \alpha_i^{(r)} (m/10.)^{-i}$

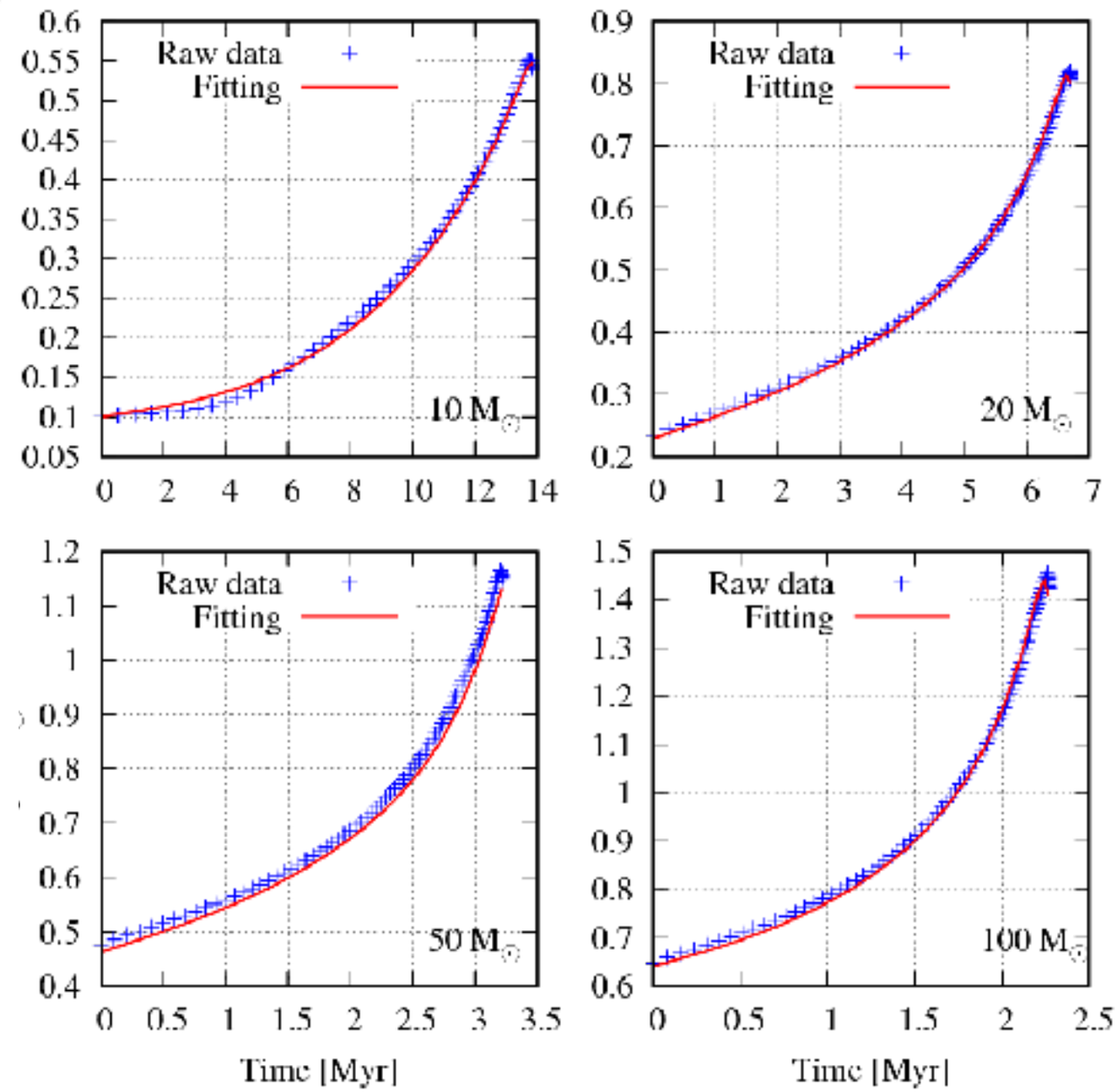
Radius at ZAMS $\log R_{\rm zams} = \sum_{i=0}^{3} \beta_i^{(r)} (\log(m))^i$

Radius at TMS $\log R_{\rm ms} = \sum_{i=0}^{3} \gamma_i^{(r)} (\log(m))^i$

$$a_{\rm ms}^{(r)} = \sum_{i=0}^{3} \delta_{i,a}^{(r)} (\log(m))^i$$

$$b_{\rm ms}^{(r)} = \sum_{i=0}^{3} \delta_{i,b}^{(r)} (\log(m))^i$$

$$c_{\rm ms}^{(r)} = \sum_{i=0}^{3} \delta_{i,c}^{(r)} (\log(m))^i$$



Luminosity ($Z/Z_{sun}=10^{-8}$)

$$\log L_{\rm ms} = \log L_{\rm zams} + a_{\rm ms}^{(l)}(t/t_{\rm ms}) + b_{\rm ms}^{(l)}(t/t_{\rm ms})^{10} + c_{\rm ms}^{(l)}(t/t_{\rm ms})^{100} + (\log L_{\rm ms} - \log L_{\rm zams} - a_{\rm ms}^{(l)} - b_{\rm ms}^{(l)} - c_{\rm ms}^{(l)})(t/t_{\rm ms})^3$$

Lifetime $t_{\rm ms} = \sum_{i=0}^{3} \alpha_i^{(l)} (m/10.)^{-i}$

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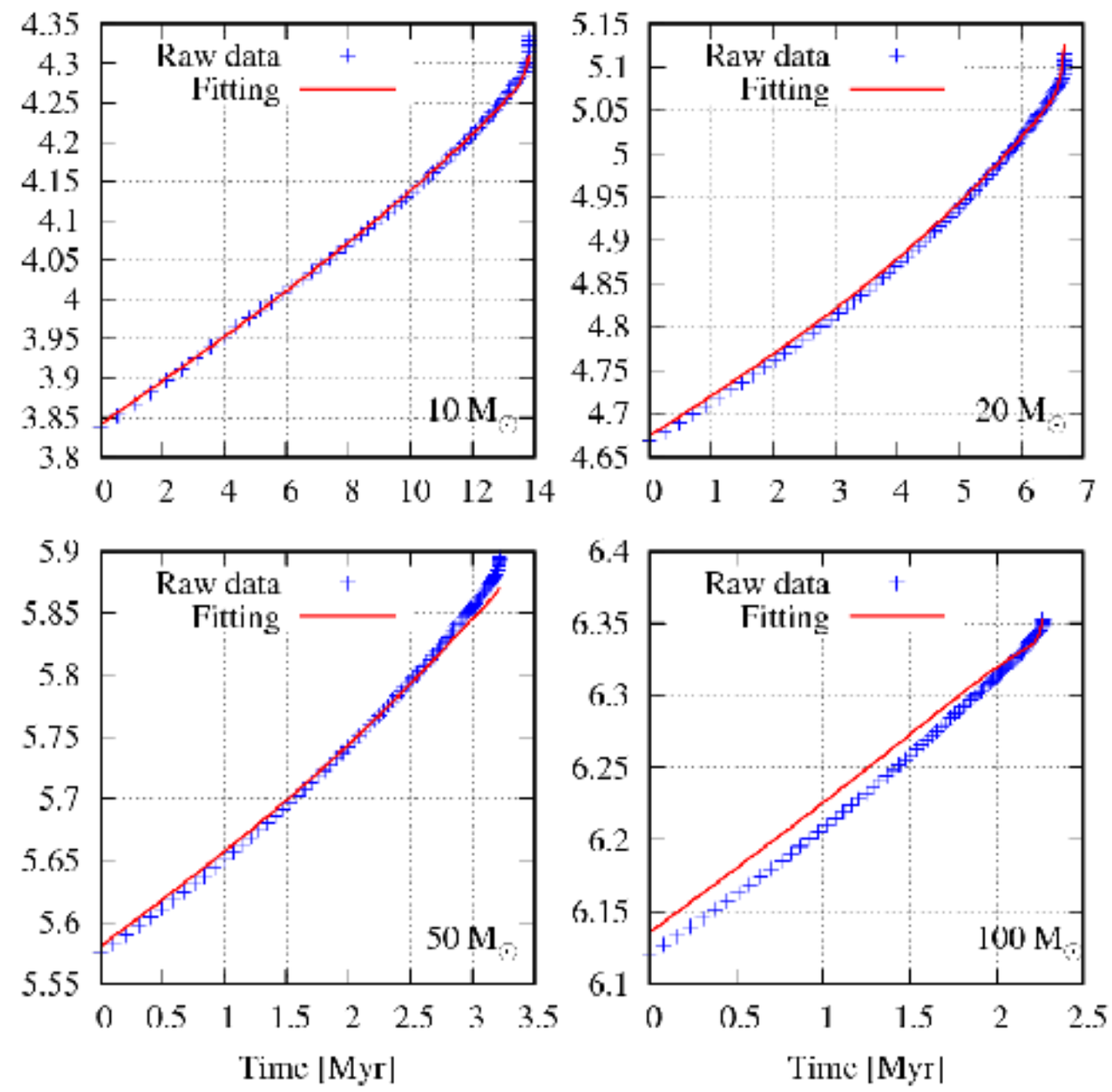

Summary of isolated binary stars

- We will investigate merging BBH formation from EMP stars by means of population synthesis method.

- We are now making fitting formula for EMP star evolution.

- We have made fitting formula for MS evolution of $Z/Z_{sun} = 10^{-8}$ stars.

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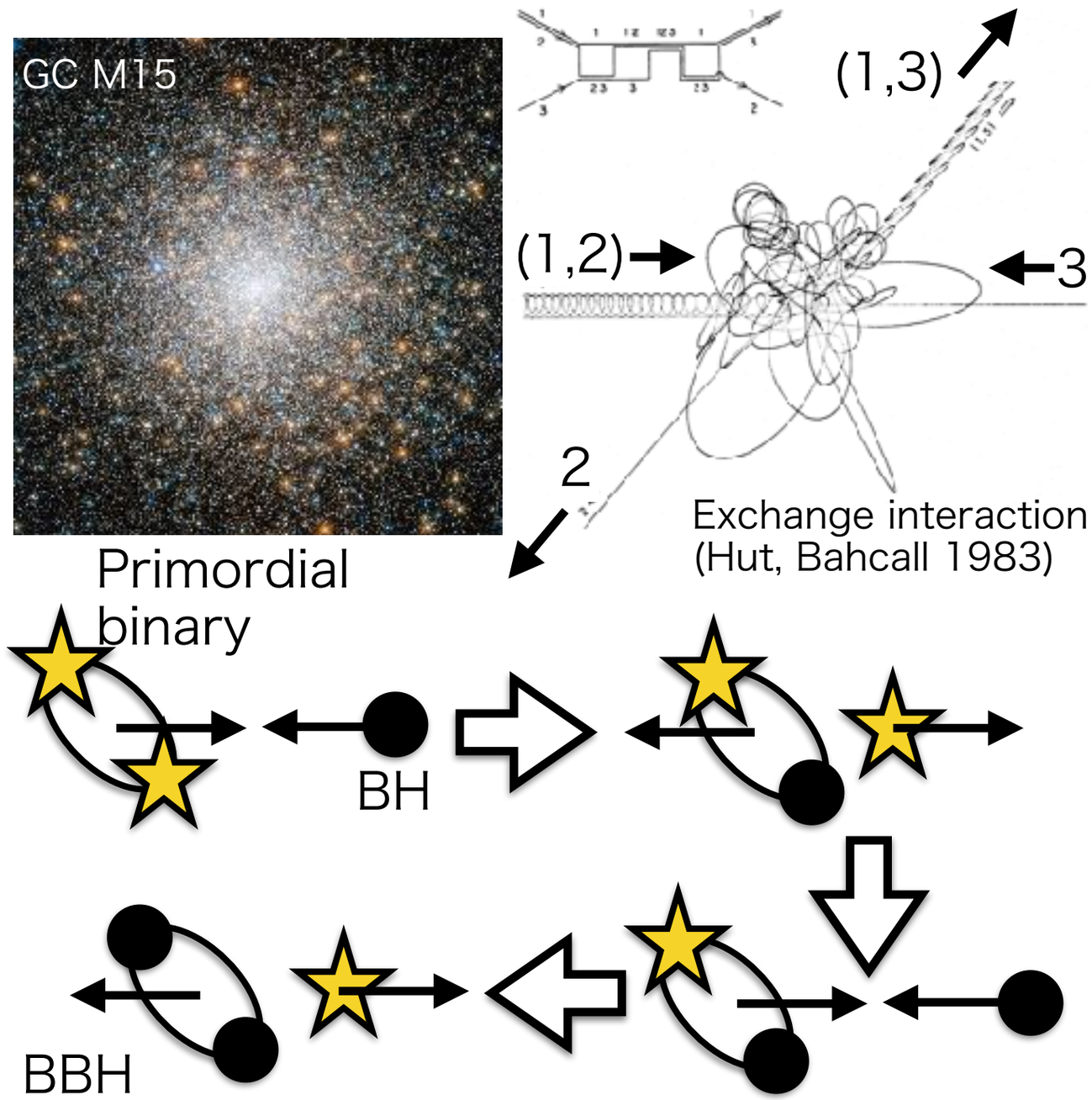
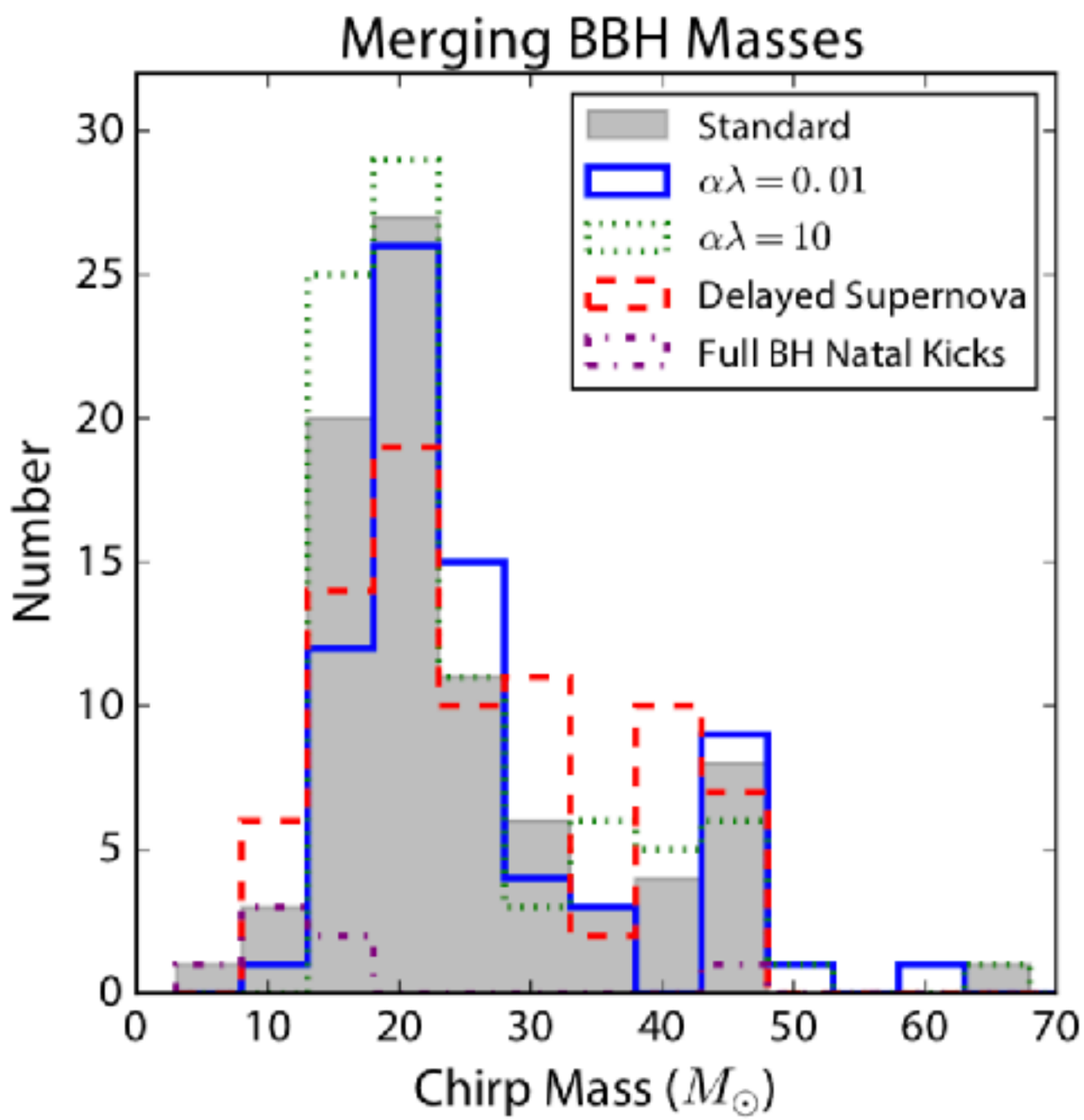
    - **Binary stars in globular clusters (Fujii)**

BBHs in globular clusters

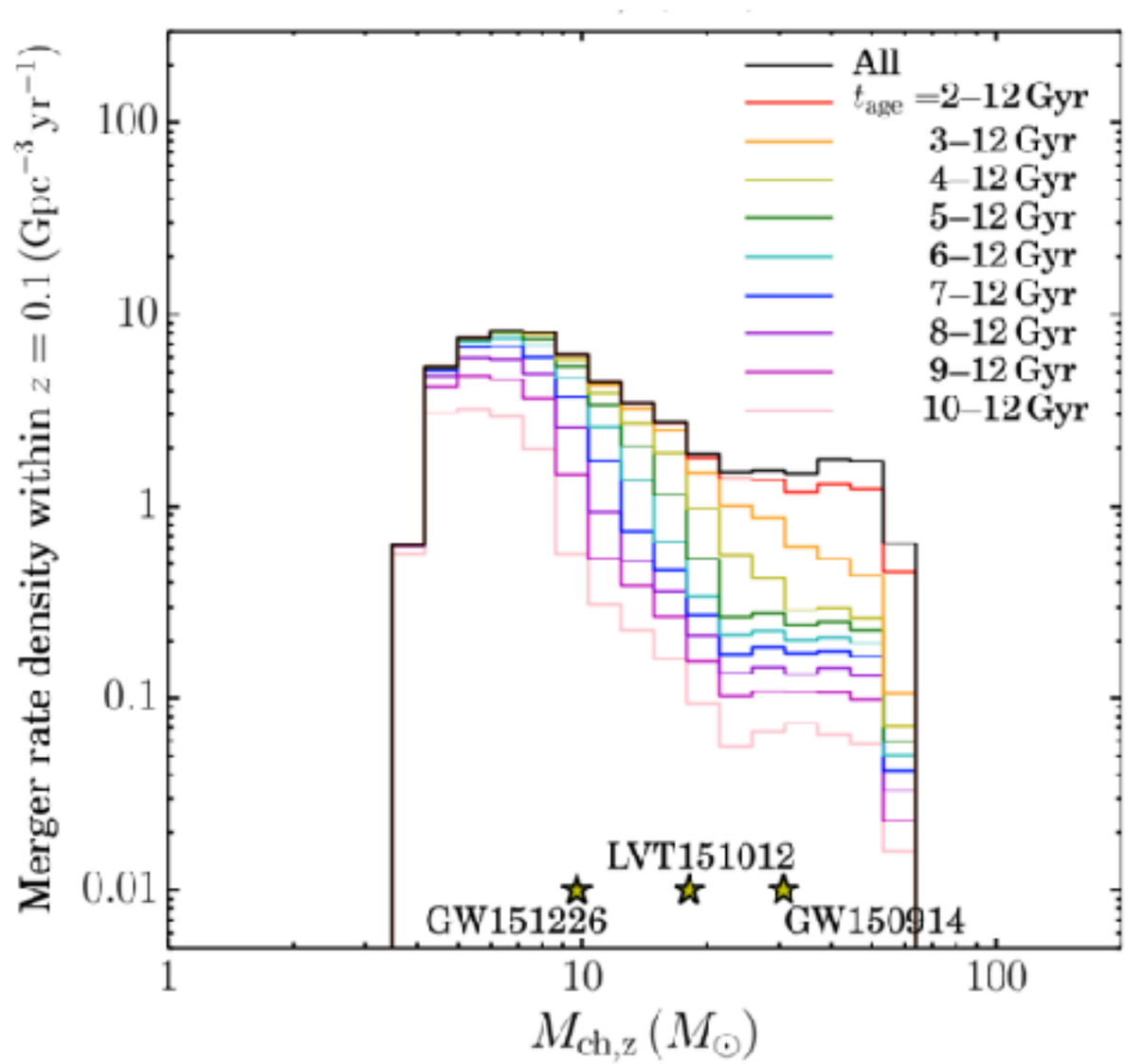
- Two massive stars evolve to two BHs at different places in a globular cluster.
- The BHs fall into the cluster center due to dynamical friction.
- The BHs replace other type stars in pre-existing binaries.
- **No Roche-lobe overflow**



Previous and our studies



Rodriguez et al. (2016)



Fujii, AT, Makino (2017)
(see also AT 2013)

Caveats of Monte Carlo simulation

- Rodriguez's group treats dynamical evolution of a globular cluster by Monte Carlo method

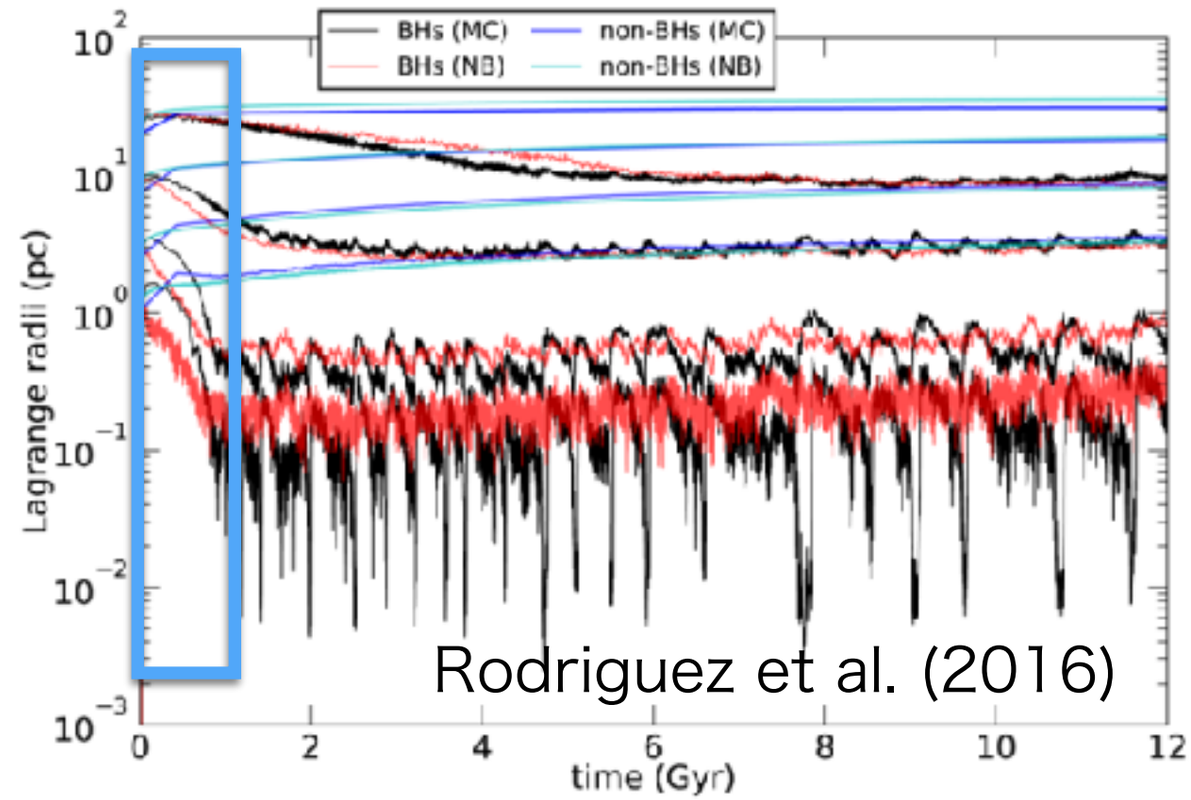
- Their Monte Carlo method solves

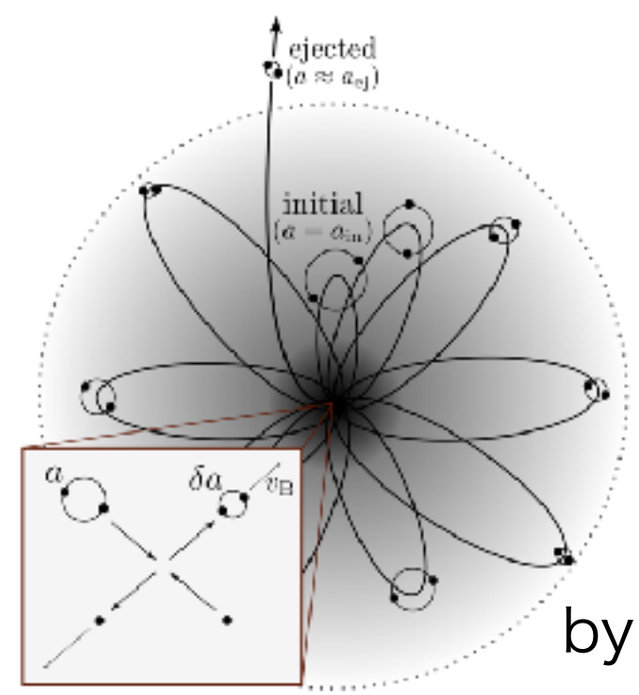
  - energy and angular momentum of stars with diffusion terms derived from two-body relaxation.

  - three-single, binary-single, and binary-binary interactions with cross section derived from theoretical consideration.

Slow dynamical friction

- Dynamical friction in their Monte Carlo simulation is slower than in N-body simulation.
- This may affect their estimate of BBH formation rate critically.
- This may NOT affect early evolution.
- BHs never stay at the cluster center.
- BHs are frequently ejected from the cluster center due to binary interaction, and come back to the cluster center due to dynamical friction.
- BHs may spend unrealistically longer time returning to the cluster center than in reality.

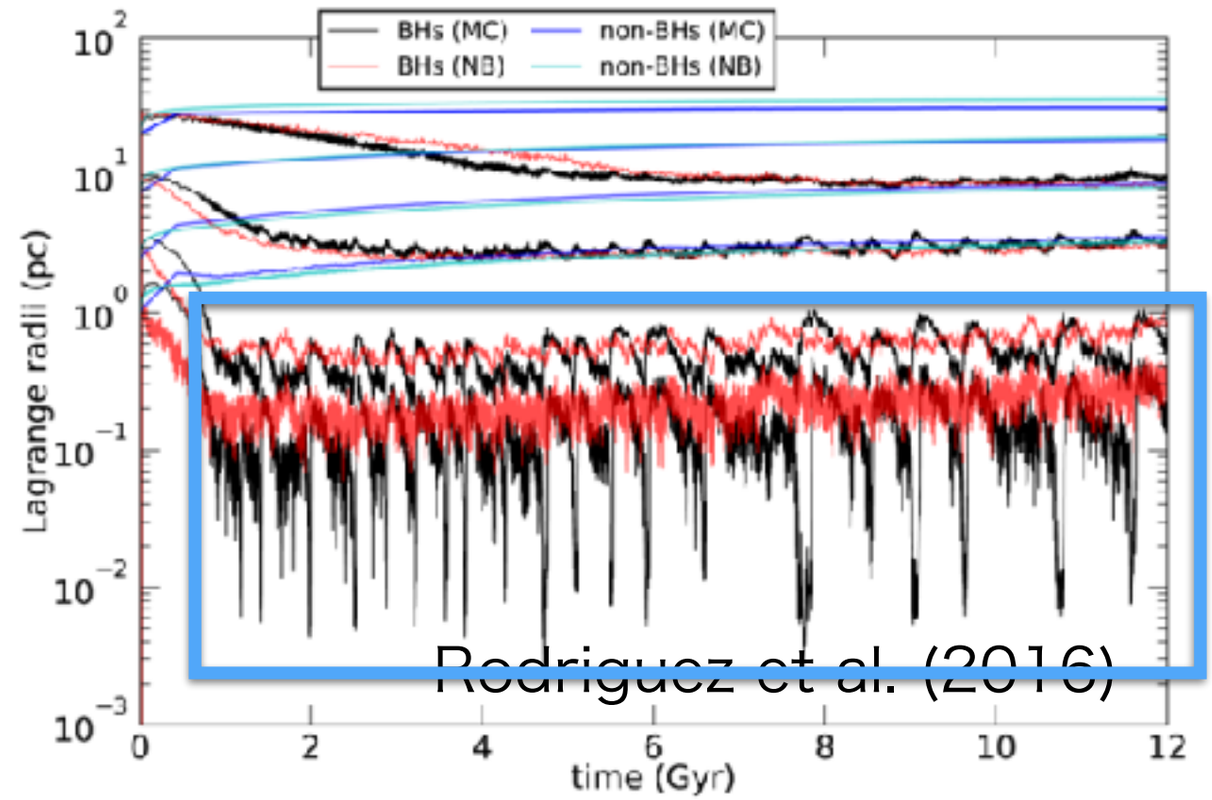


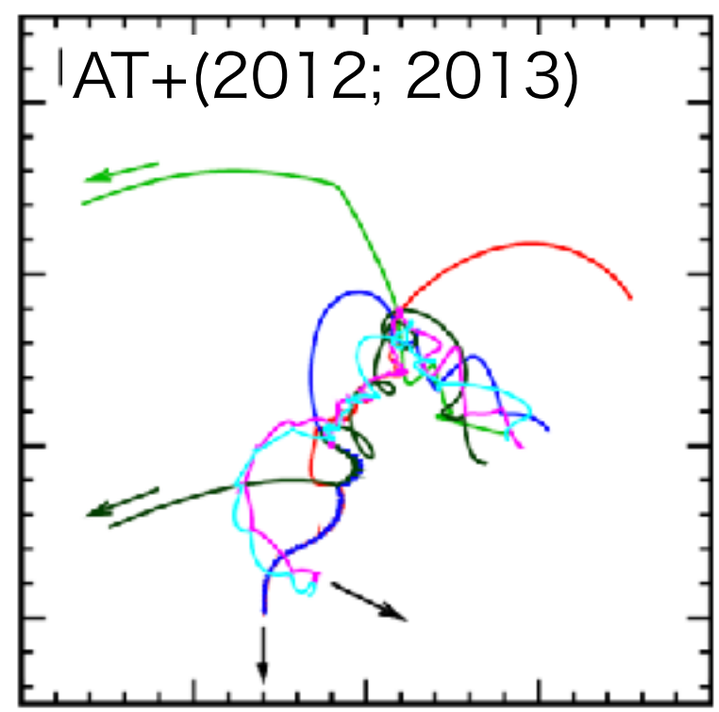


by Johan Samsing

Low binary interaction rate

- Core radii in their Monte Carlo simulation become much smaller than in N-body simulation.
- They may underestimate binary interaction rates.
- Bianry stars in a cluster act as energy source, and try to expand the cluster core and cluster itself.
- They include three-single, binary-single, and binary-binary interactions.
- But, we have shown binaries are frequently formed through few-body (>4) interactions (AT 2012; 2013).
- The cross section of few-body interaction will be larger than interactions Rodriguez include.





Caveats of N-body simulation

- We have estimated BBH event rates based on N-body simulation.

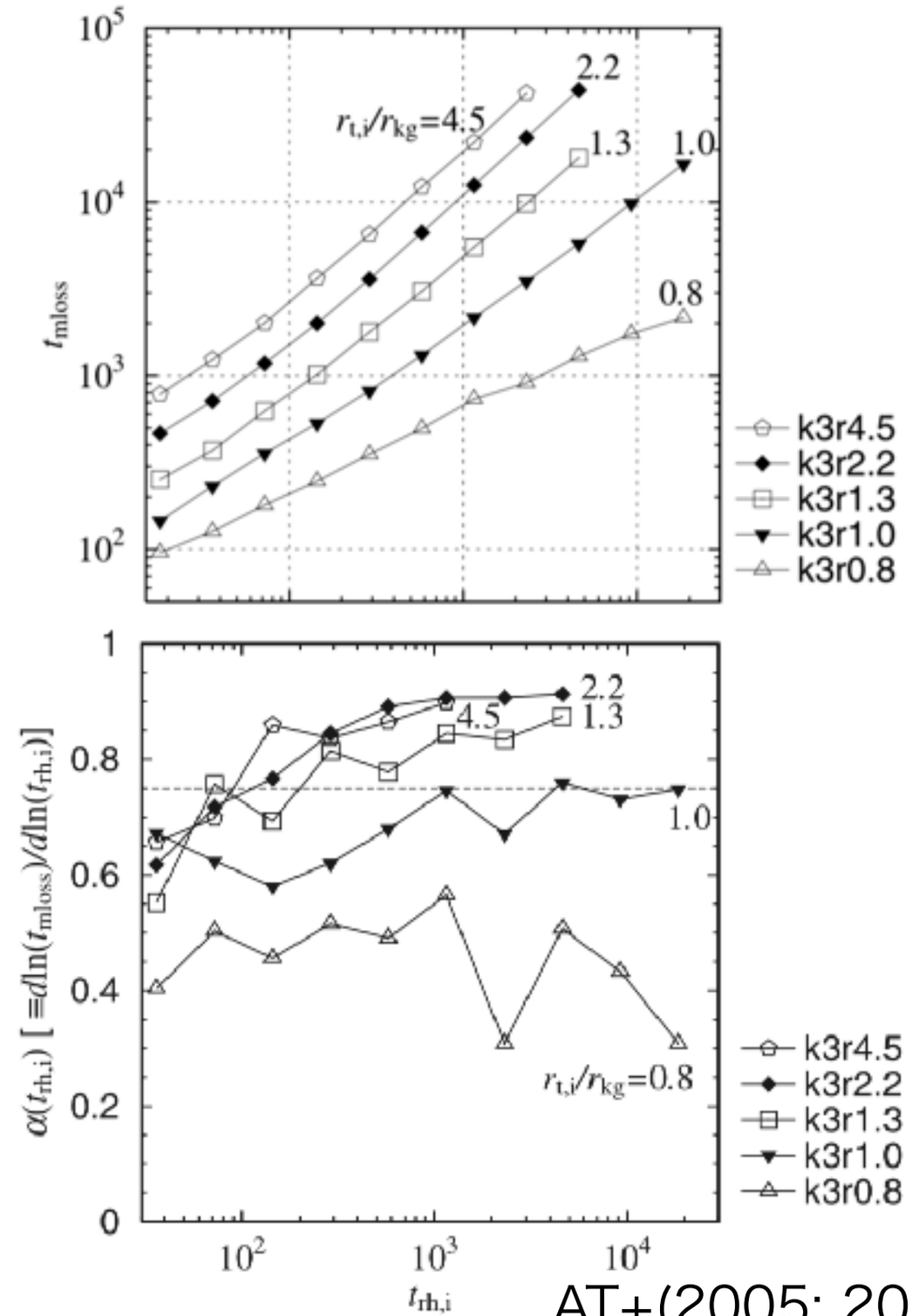
- N-body simulation naturally include dynamical friction and few-body interactions.

- But, N in N-body simulation ($< 10^5$) is much smaller than the number of stars in globular clusters ($N \sim 10^6$).

- We extrapolate $N=10^5$ results to clusters with 10^6 stars.

N-scaling

- N-scaling is not simple.
- Mass-loss timescale of globular clusters in a tidal field complexly depends on two-body relaxation timescale (~N/logN).
- Mass-loss time scale is proportional to $t_{relax}{}^{\alpha}$, and α depends on strength of tidal fields.
- **N-body simulation with N~10^6 is very important!**
  - Dragon simulation (Wang+ 2016) has 10^6, but treats unrealistically diffuse clusters.



AT+(2005; 2010)

Summary of binary stars in globular clusters

- Many groups (including us) estimate BBH merger rates by several types of methods.
- Their results seem to explain BBH properties observed by GW observatories.
- But, each method has each deficit.
- **We need N-body simulation with N~10^6** (or calibrated Monte Carlo simulation).
- We will do the best for N-body simulations with realistically large N and large density.