Evolution Pathway to Binary Black Holes

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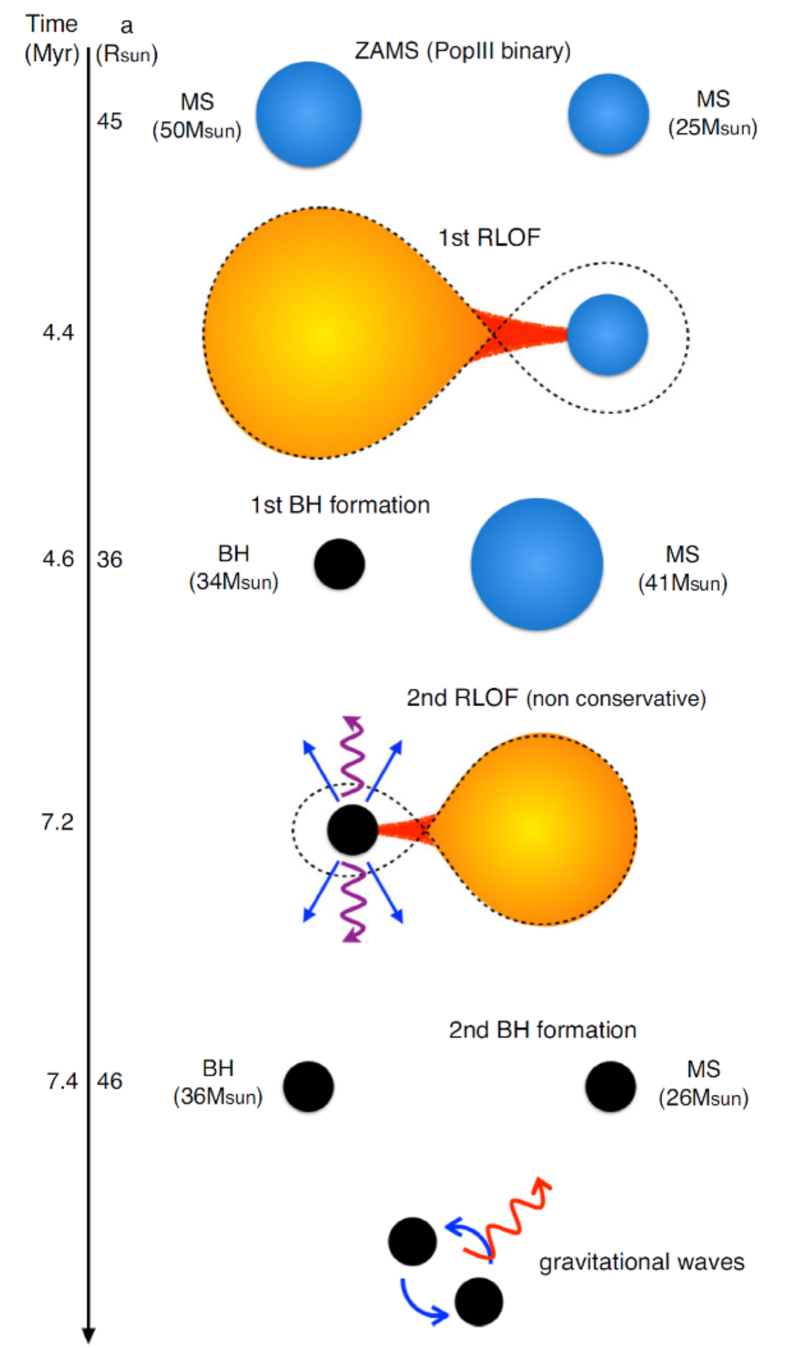
KICKOFF workshop on “Gravitational wave physics and astronomy: Genesis”

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 (Fujii, Tanikawa)
    - Isolated binary stars
    - Binary stars in globular clusters (GCs)

Isolated binary stars

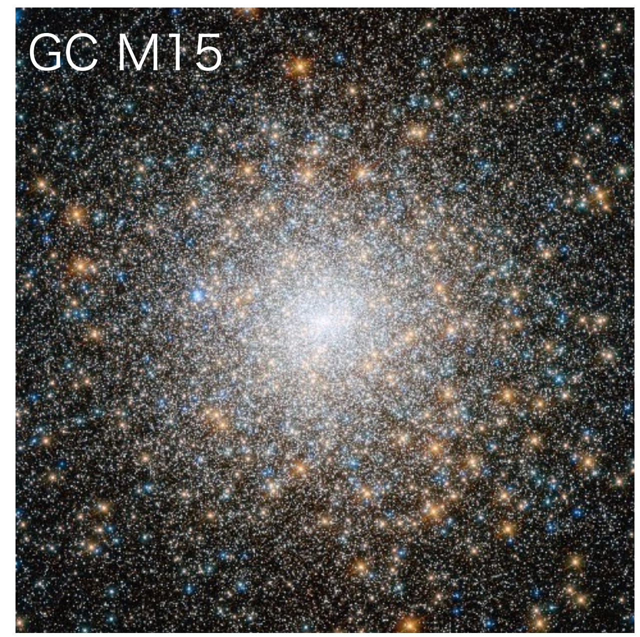
- Massive binary stars
- Binary interaction (Roche-lobe overflow)
  - Mass transfer (stable)
  - Common envelope (unstable)
- The interaction inevitable
  - A radius of a supergiant star exceeds separation of binary stars.

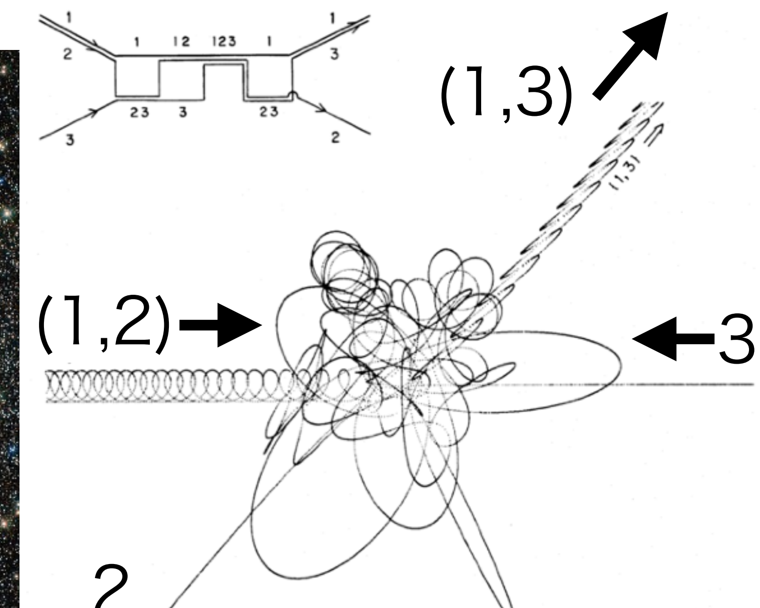


Inayoshi et al. (2017)

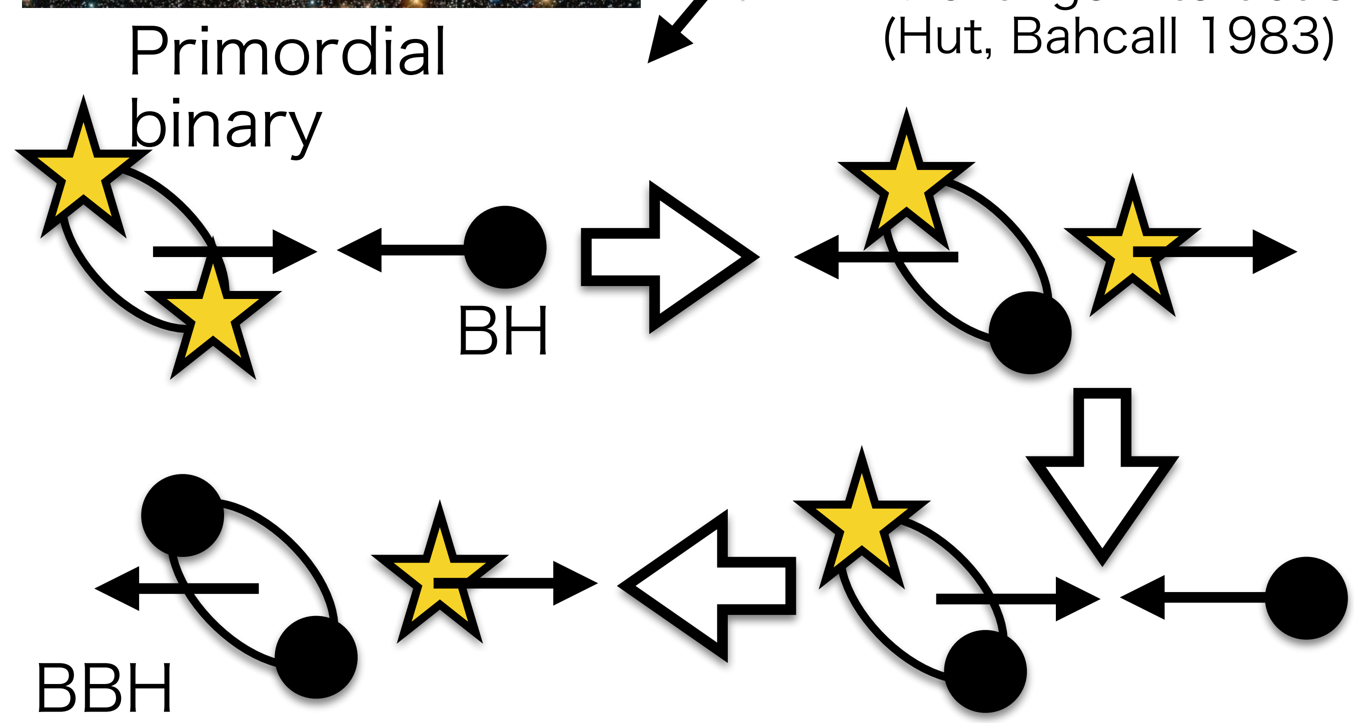
GC Binary stars

- Formation of two single BHs at different places in a GC
- Dynamical formation of BBHs
    - No Roche-lobe overflow
- BHs are the most massive objects
    - Preferential falling into the GC center
    - Preferential retention in binary stars





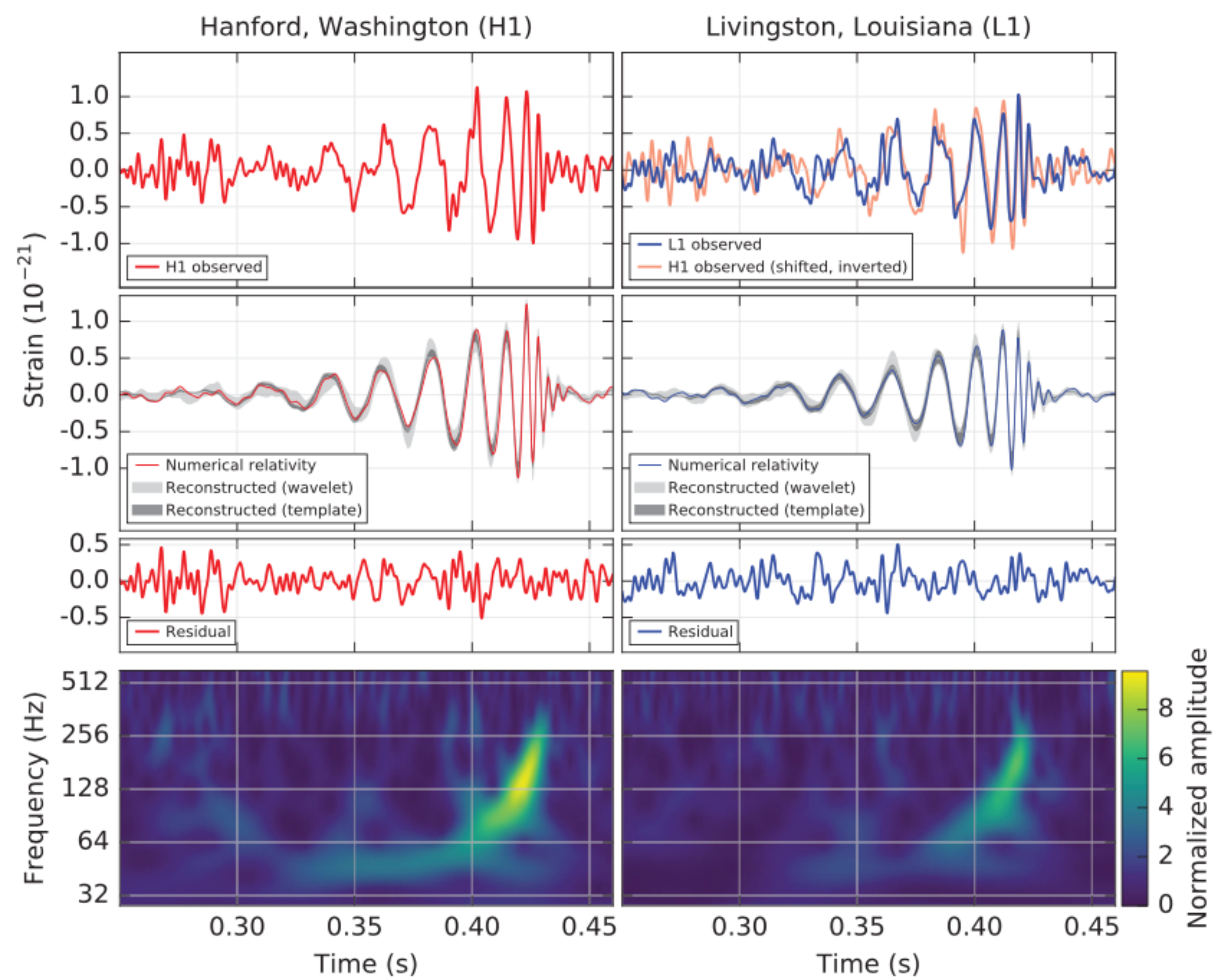
Exchange interaction
(Hut, Bahcall 1983)



How do they look?

- Theoretical generation of BBH population
  - Merger event rate
  - Redshift
  - Primary mass
  - Mass ratio
  - (Spin)
  - (Eccentricity@10Hz)

Observation (e.g. Abbott et al. 2016)

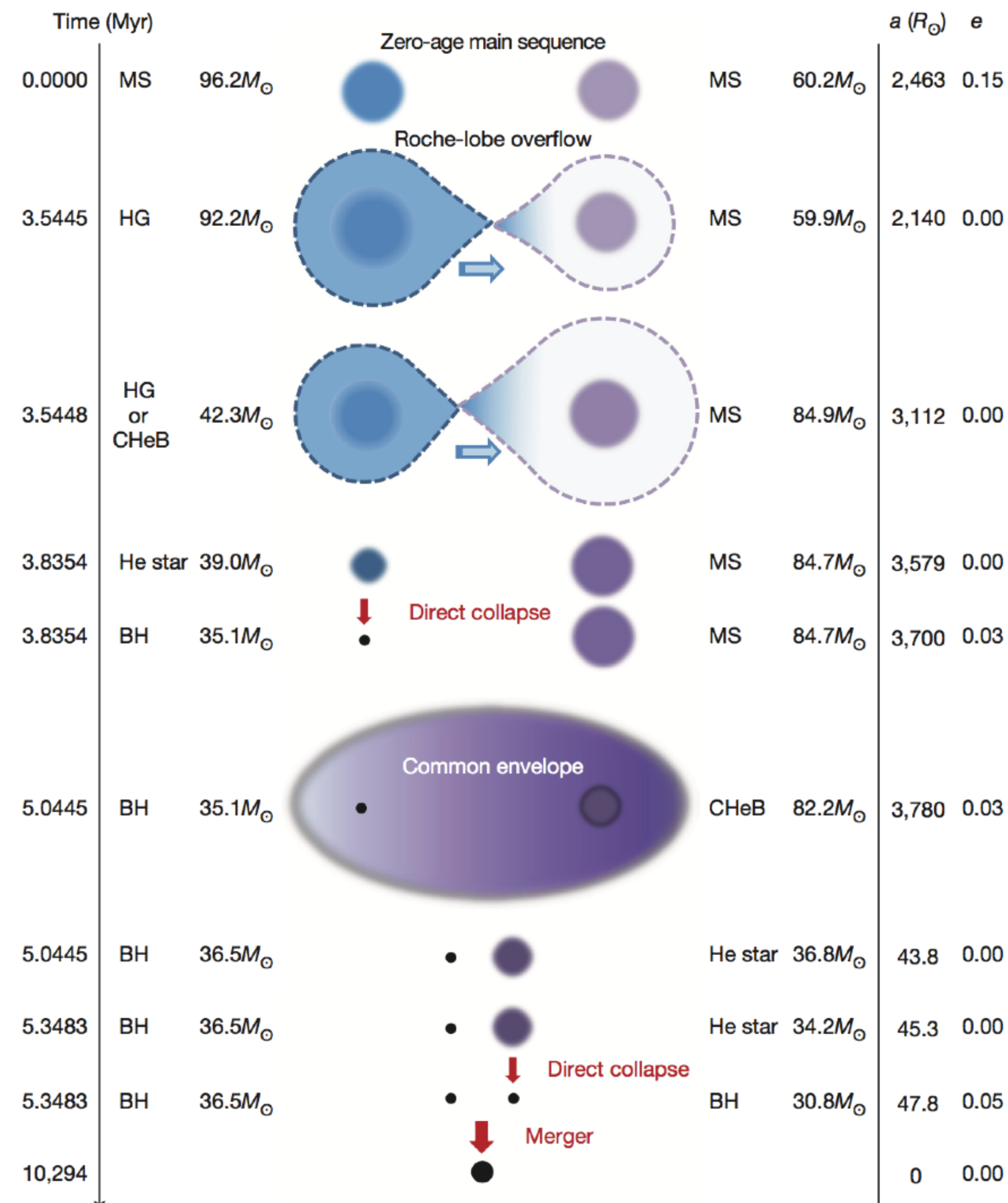


Identification of BBH origin(s)

Plan for isolated binary stars

- Binary population synthesis (BPS) technique for all metallicity ($Z/Z_{\odot}$=0 - 1.5)
- Previous studies
  - Pop I/II ($Z/Z_{\odot}=5\times10^{-3}$ - 1.5) (e.g. Belczynski et al. 2016)
  - Pop III ($Z/Z_{\odot}$=0) (Kinugawa et al. 2014)
- New points
  - Accurate initial conditions (Susa san's talk)
  - Massive stars (>100$M_{\odot}$)
  - Extreme metal poor (EMP) stars ($0<Z/Z_{\odot}<5\times10^{-3}$)

Example of BPS

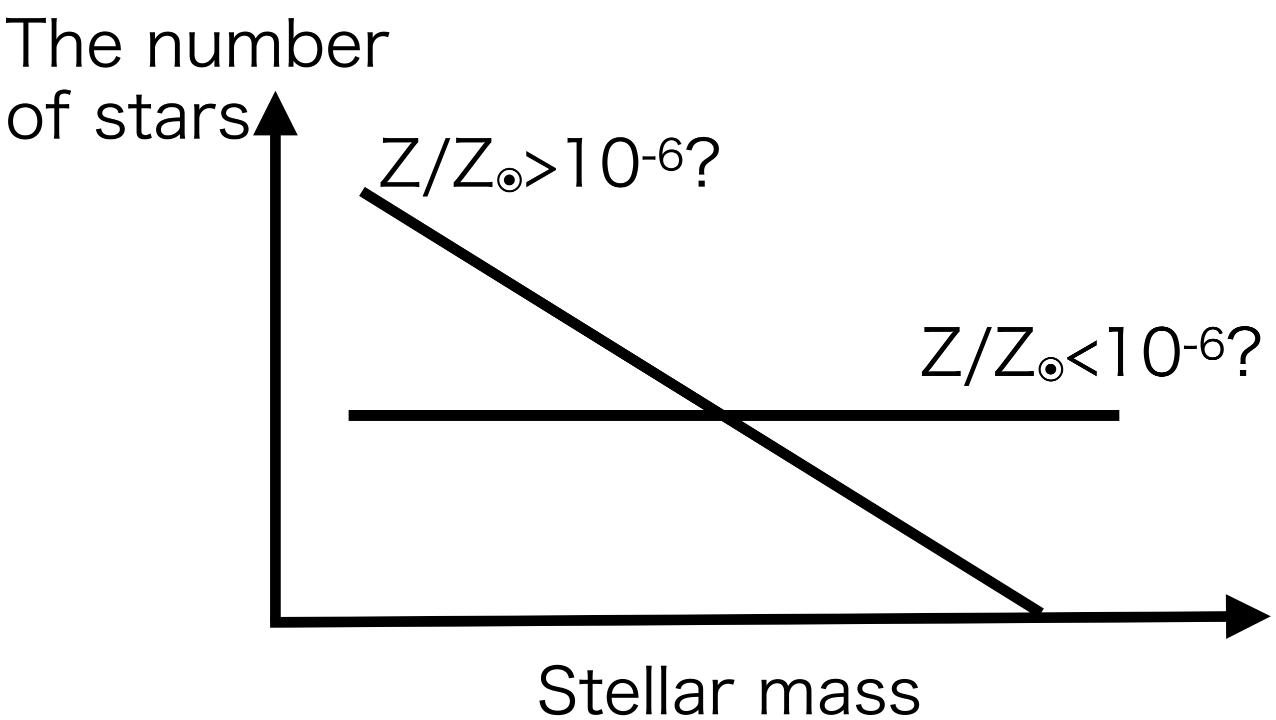


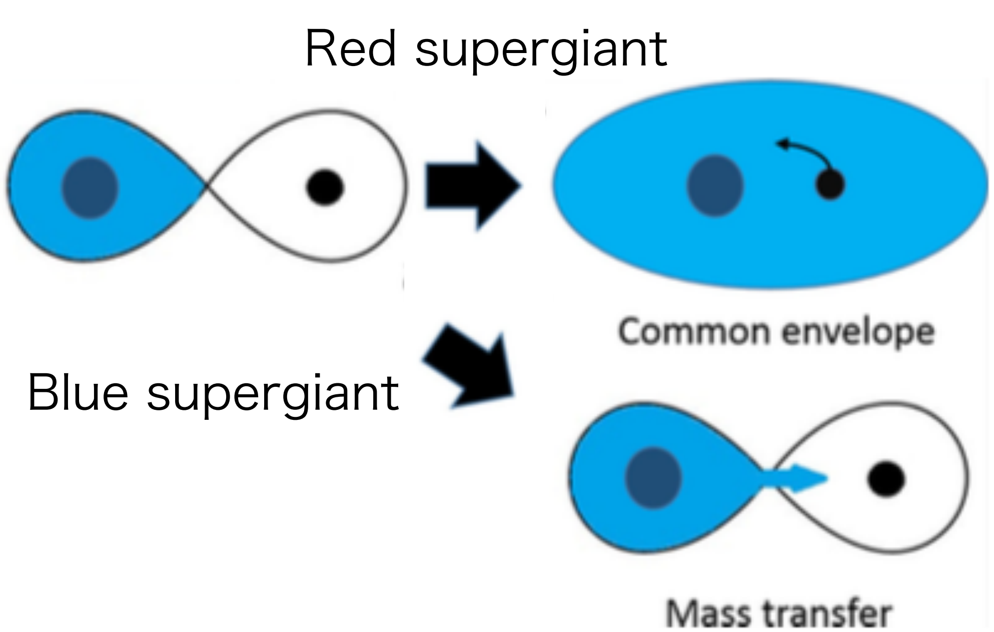
Belczynski et al. (2016)

Importance of EMP stars

- Formation of massive BHs
  - Weak stellar-wind mass loss
- Two transitions from $Z/Z_\odot = 0$ to $Z/Z_\odot = 5\times10^{-3}$
  - Top heavy initial mass function (IMF) to top light IMF
  - Blue supergiant star to red supergiant star

BBH population changes drastically.





Kinugawa et al. (2014)

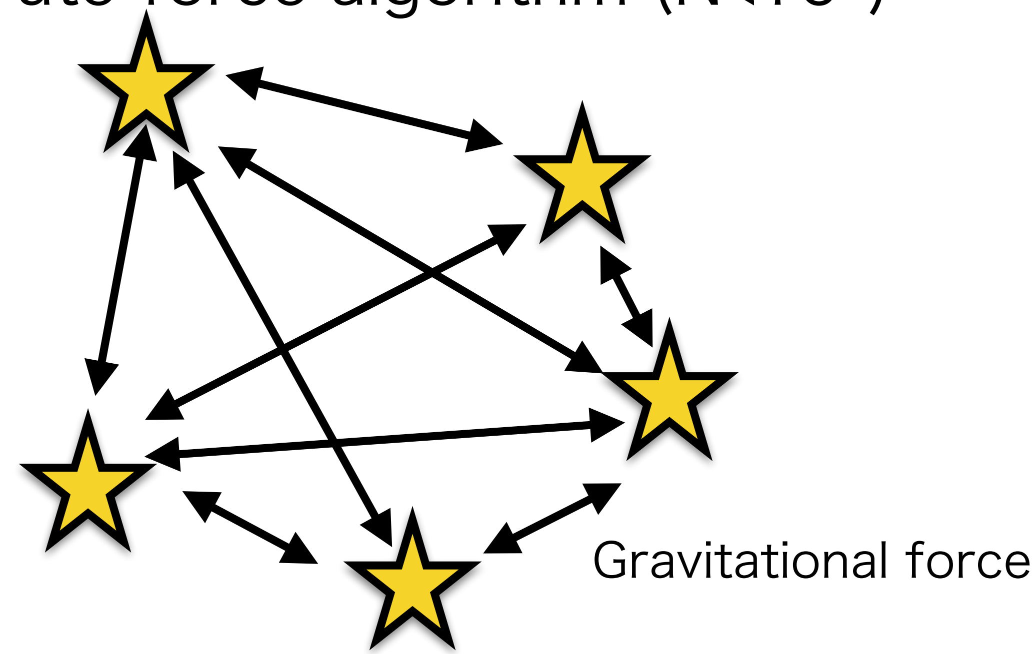
Timeline

- First stage (present - 2019.03?)
  - Making evolution track of EMP stars (with Takashi Yoshida-san)
  - BPS for EMP binary stars (with Kinugawa-san)
    - Existing initial conditions of massive binary stars
- Second stage (2019.04? - 2022.03)
  - BPS for all metallicity binary stars
    - Accurate initial conditions of massive binary stars (Susa san's talk)

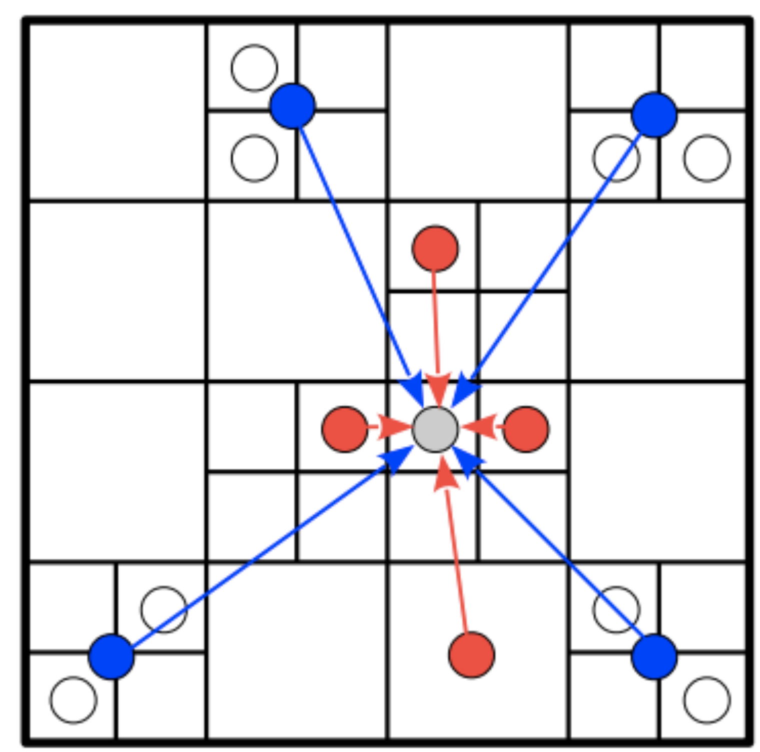
Plan for GC binary stars

- N-body simulation for large GCs ($N=10^6$)
  - Previous studies
    - N-body simulation with $N=10^5$ (AT 2014; MF, AT+ 2017)
    - Monte Carlo simulation (Rodriguez et al. 2016)
    - Pop III small cluster (Sakurai+MF+2017)
- N-body simulation for small GCs ($N=10^5$)
  - Disrupted GCs
  - Young (~ several Gyrs) GCs

Brute-force algorithm ($N<10^6$)

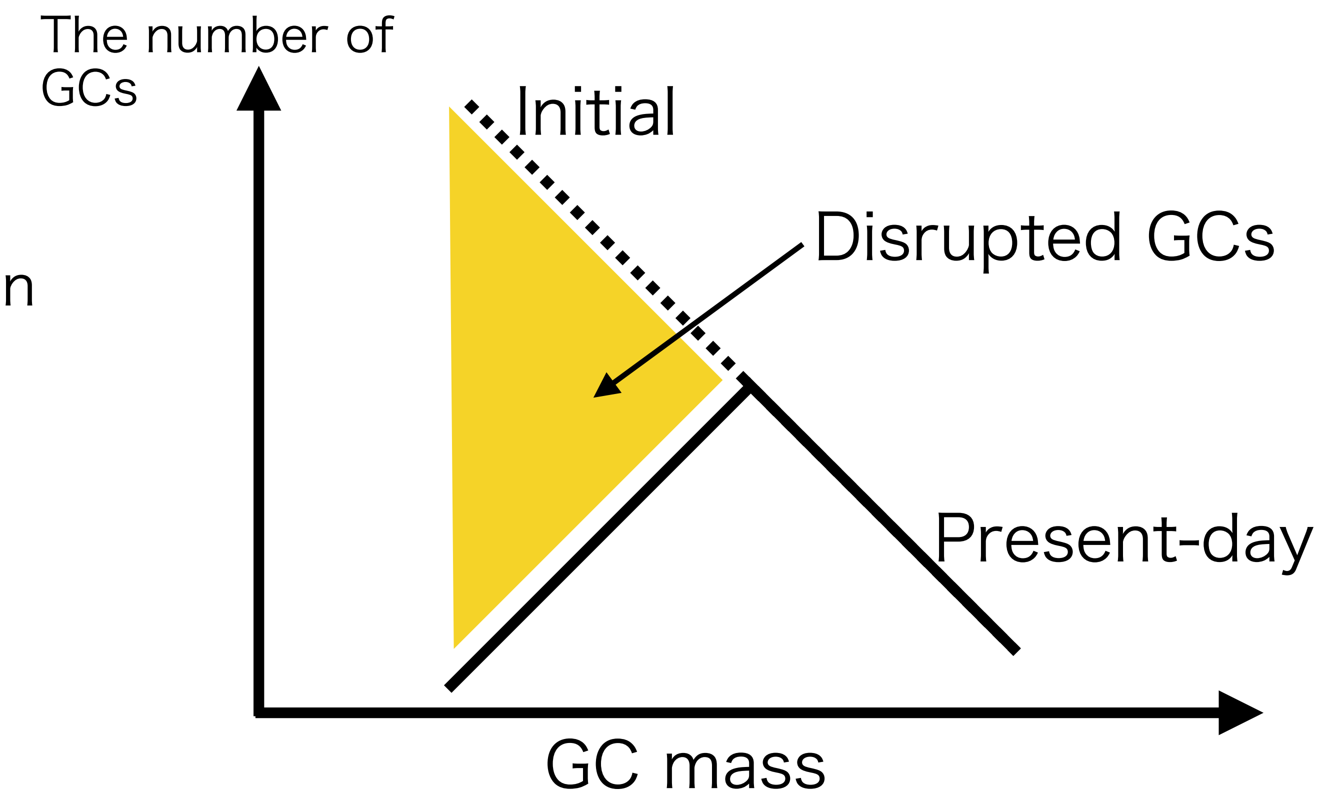


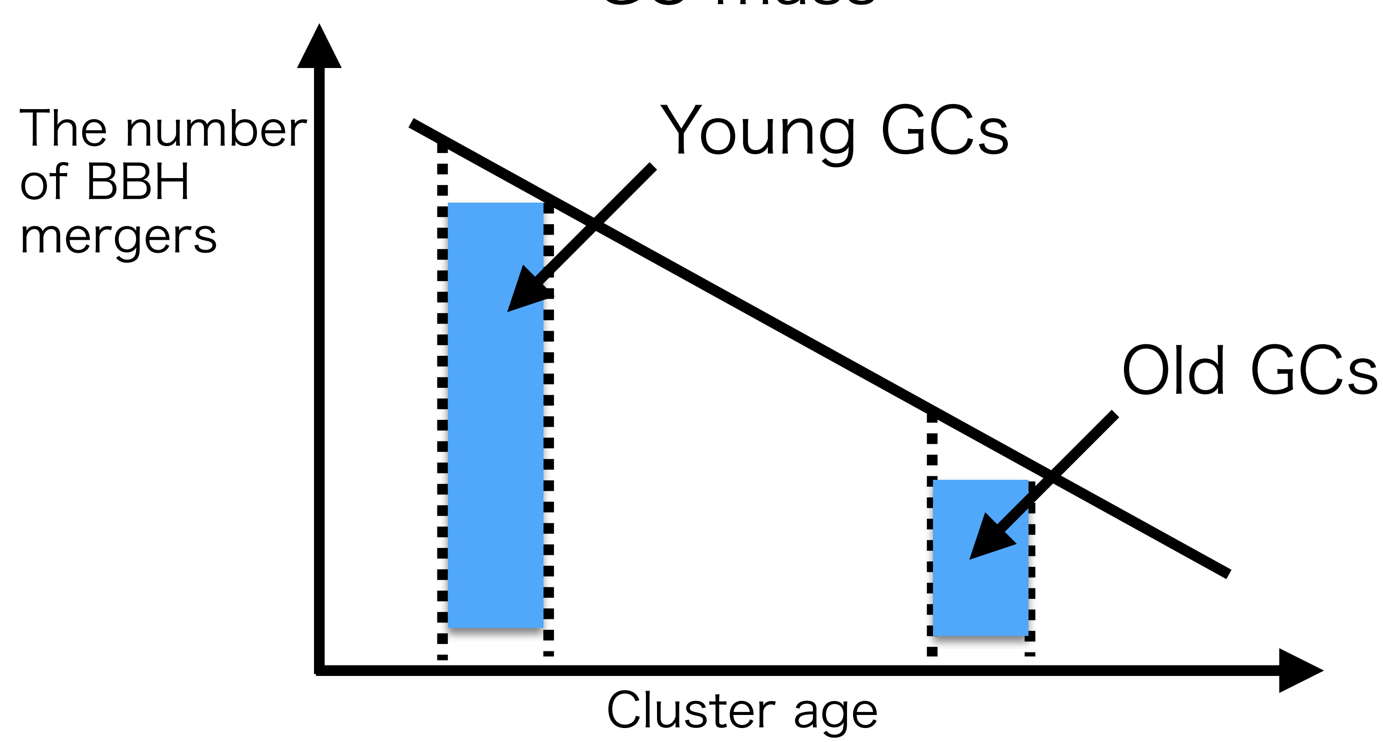
Tree algorithm for GCs ($N>10^6$), not for cosmological simulation



Small or young GCs

- Disrupted GCs
  - Small GCs dominate GC population
    - Initial cluster mass function: ∝ M^{-2}
    - Present-day cluster mass funciton: log normal at peak ~ $2 \times 10^5 M_\odot$
- Young GCs (~ a few Gyr)
  - BBHs are formed at present.
  - Delay time distribution: ∝ t^{-1}





Timeline

- First stage (present - 2019.03?)
  - N-body simulation for small GCs
    - Existing initial conditions
    - PopI/II/III evolution model ($Z/Z_{\odot}$=0, 5x10^{-3} - 1.5)
  - Developing N-body simulation code for large GCs (with Iwasawa-san at RIKEN AICS)
- Second stage (2019.04? - 2022.03)
  - N-body simulation for small and large GCs
    - Accurate initial conditions (Susa san's talk)
    - PopI/II/III and EMP stellar evolution model

Expected results

- Identification of BBH origin(s)
    - PopI/II, or Pop III/EMP stars ?
        - Constraints on Pop III formation rate
        - Constraints on cosmic metal evolution
    - Isolated or GC binary stars ?
        - Constraints on GC formation model

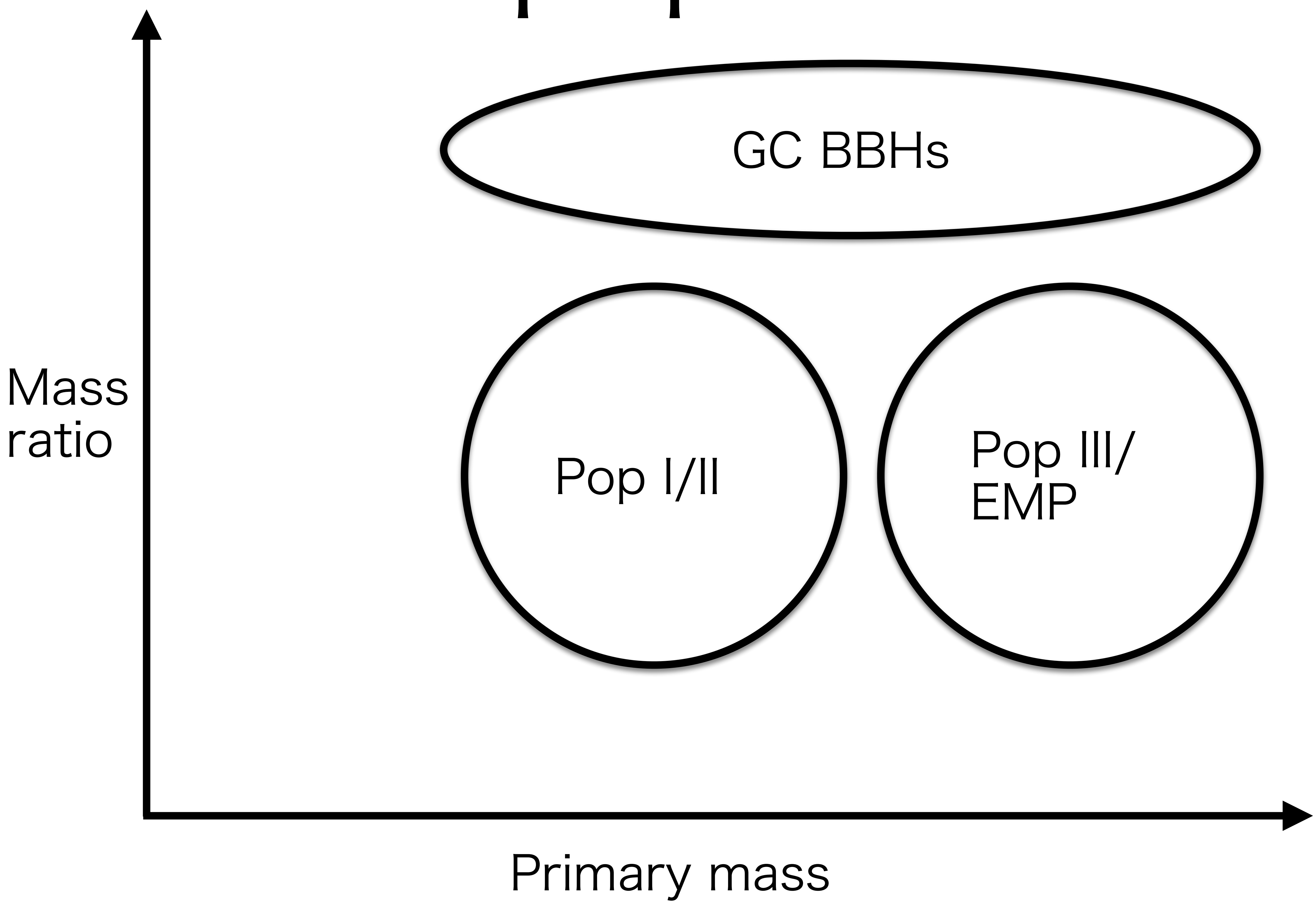
Collaboration

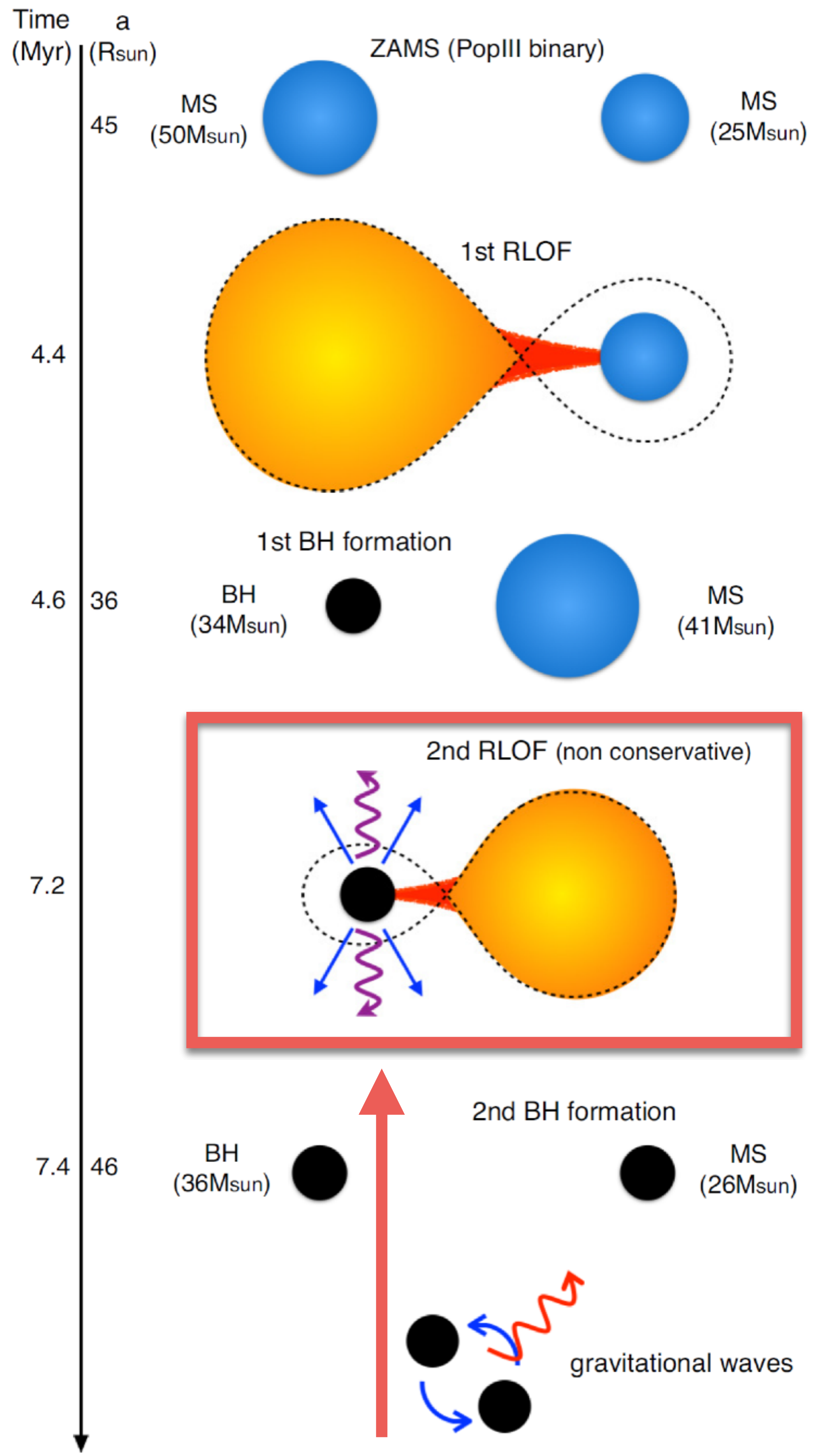
- Other A groups
  - Finding BBH population(s) other than from isolated and GC binary stars
- B groups
  - Identification of NS-NS/BH origin(s)
  - Formation and evolution of X-ray sources
- C groups
  - Feedback to supernova explosion model

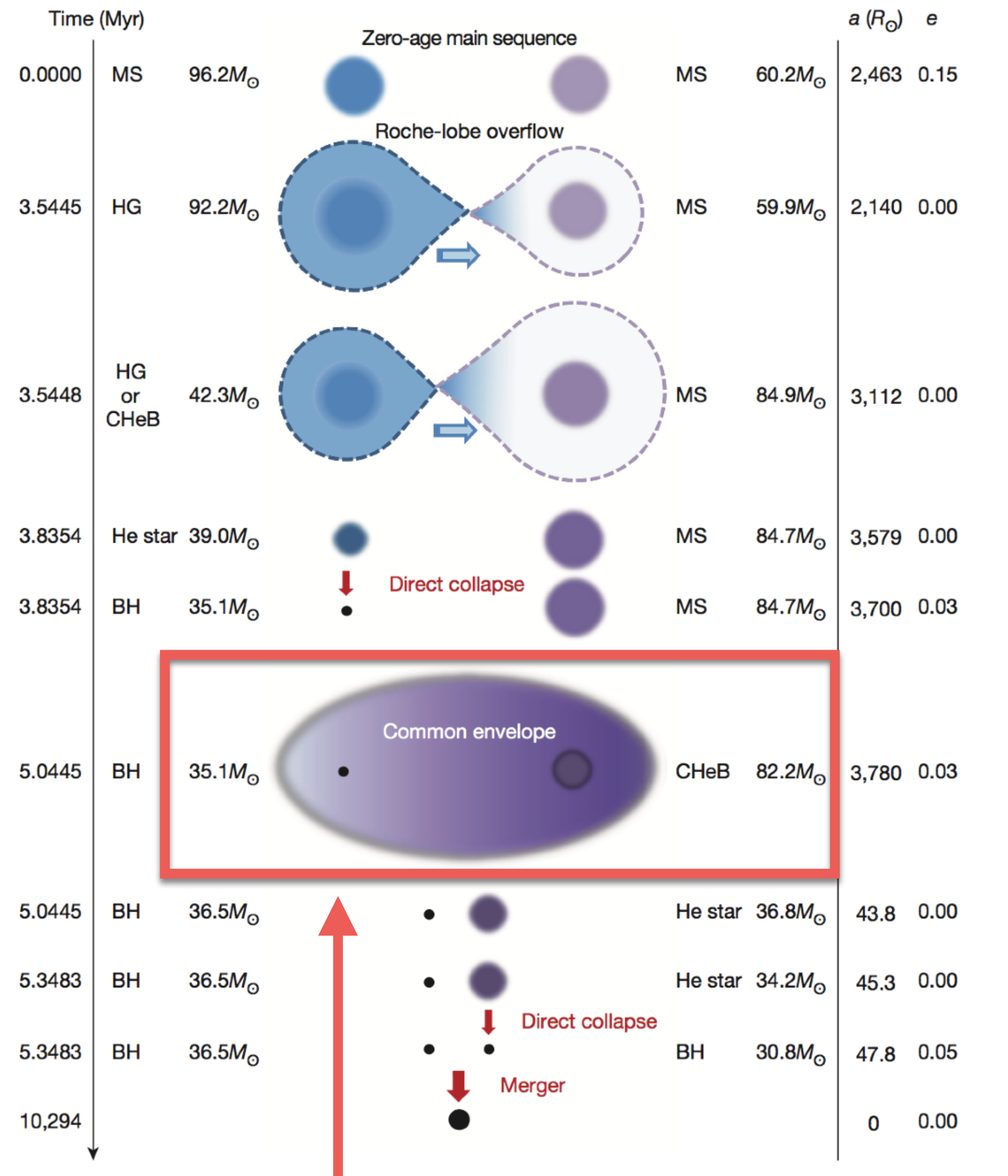
Summary

- Evolution pathway to BBH populations
- Isolated binary stars
    - All metallicity range
    - EMP binary stars have been not yet investigated in the world.
- GC binary stars
    - N-body simulation of large (10^6) and small (10^5) GCs

BBH populations







How much is mass lost ?

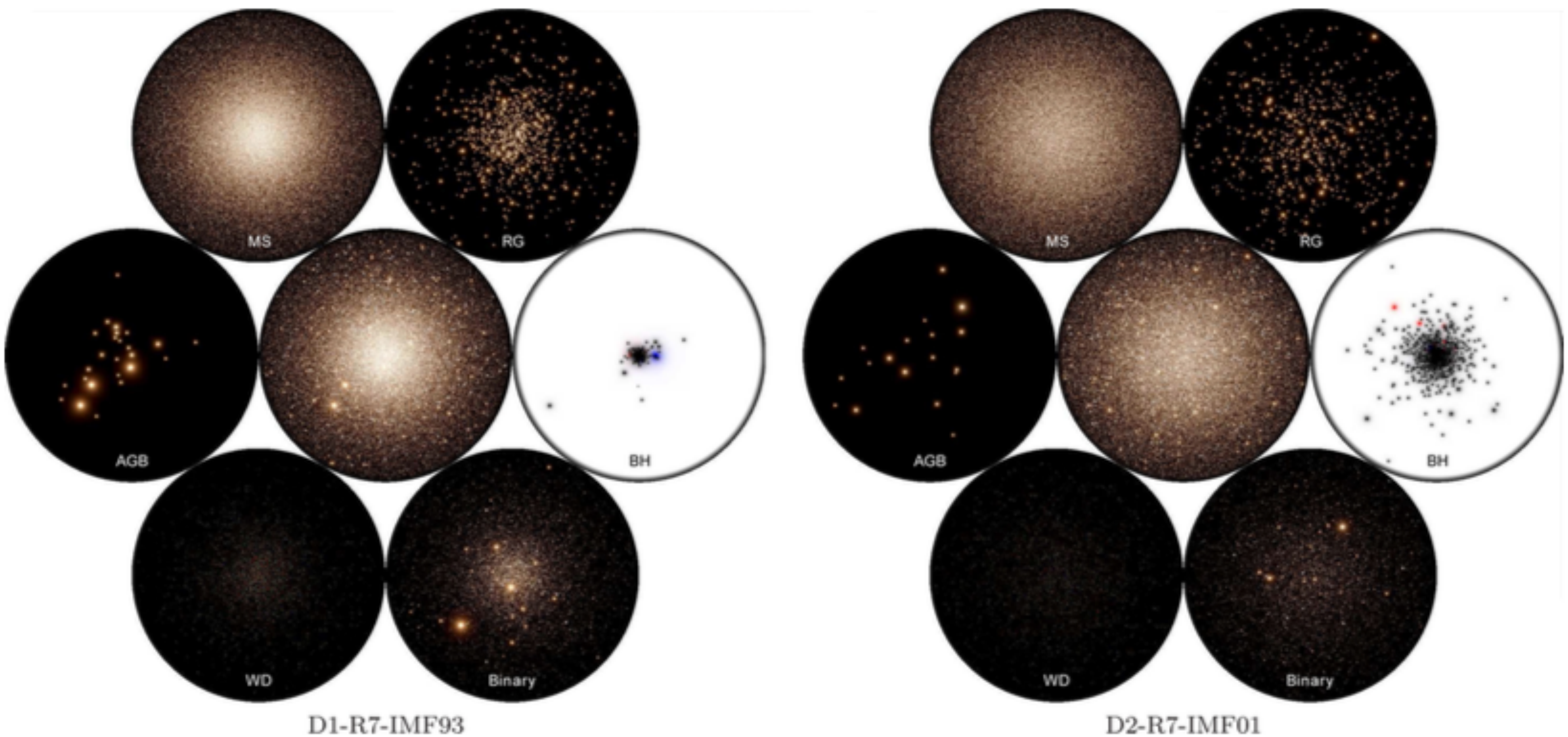
How efficient does orbital energy convert to gas ejection?

Tree algorithm for a GC

- Close encounter
  - 4th order integration scheme
    - usually 2nd order integration scheme used for tree algorithm
- Binary treatment
  - KS regularization
  - Algorithmic regularization

Dragon simulation

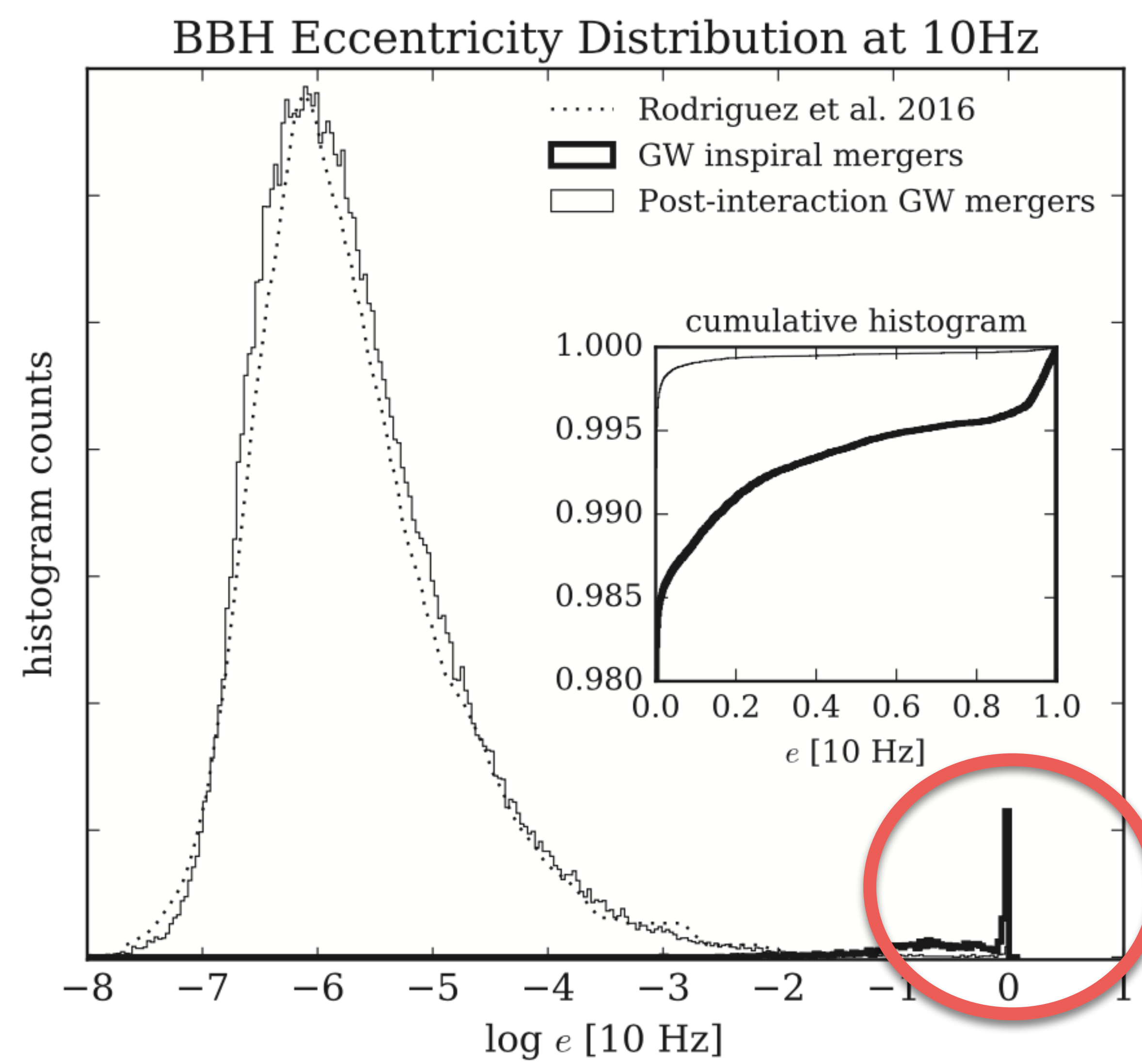
- N-body simulation of a large GC (~10^6)
- But, the initial density is unrealistically small.



Wang et al. (2016)

Eccentricity@10Hz

- 2.5×10^5 binary-single scattering experiments
- About 1% of BBHs from GCs may leave eccentricity at 10Hz of GW frequency.
- These BBHs are formed through captures during very close encounters.



Samsing, Ramirez-Ruiz (2017)