Massive star clusters
as a host of compact binaries

Michiko Fujii (藤井　通子)
The University of Tokyo

Outline

Massive star clusters and compact binaries

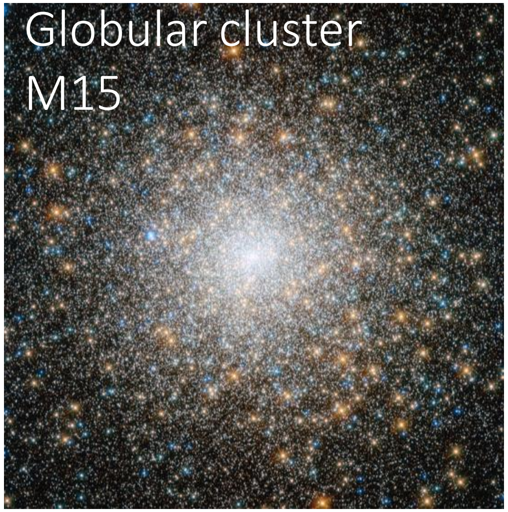
Dynamical evolution of star clusters

Distribution of binary black holes (BBHs) formed in star clusters

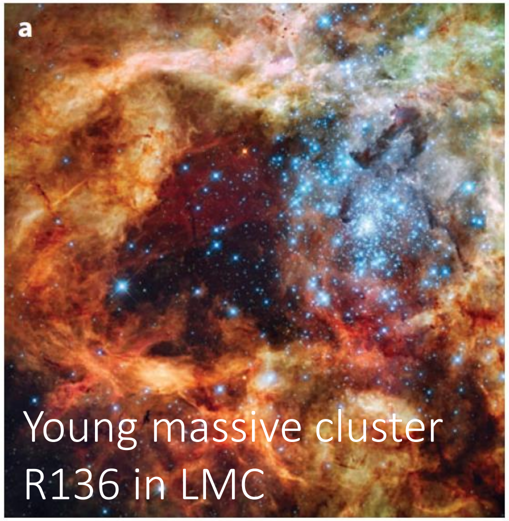
Expected detection rate and mass function of BBHs by gravitational wave

Future plans

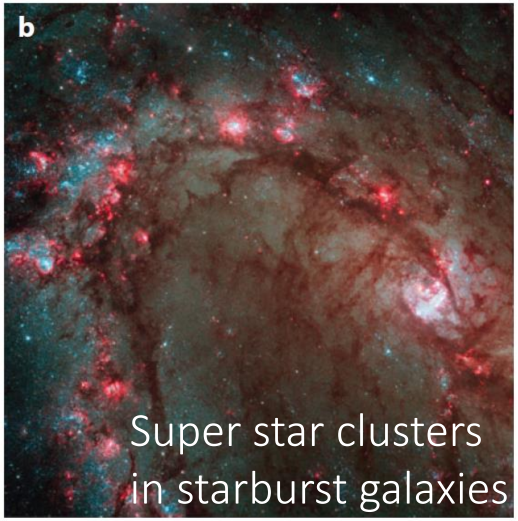
Massive star clusters



R136



M83



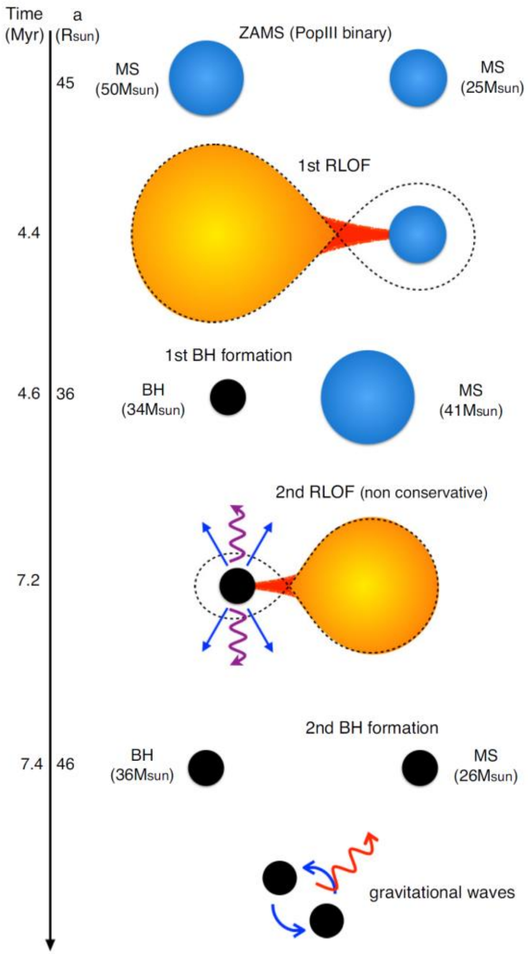
Cluster	Age [Gyr]	$m_{\rm to}$ [$M_\odot$]	M [$M_\odot$]	$r_{\rm vir}$ [pc]	ρ_c [$M_\odot$ pc^{-3}]	Z [$Z_\odot$]	Location	$t_{\rm dyn}$ [Myr]	$t_{\rm rh}$ [Myr]
OC	$\lesssim 0.3$	$\lesssim 4$	$\lesssim 10^3$	1	$\lesssim 10^3$	~ 1	Disk	~ 1	$\lesssim 100$
GC	$\gtrsim 10$	~ 0.8	$\gtrsim 10^5$	10	$\gtrsim 10^3$	<1	Halo	$\gtrsim 1$	$\gtrsim 1000$
YMC	$\lesssim 0.1$	$\gtrsim 5$	$\gtrsim 10^4$	1	$\gtrsim 10^3$	$\gtrsim 1$	Galaxy	$\lesssim 1$	$\lesssim 100$

Portegies Zwart et al. (2010)

Young massive clusters (super star clusters)
- As dense and massive as globular clusters
- As young as open clusters

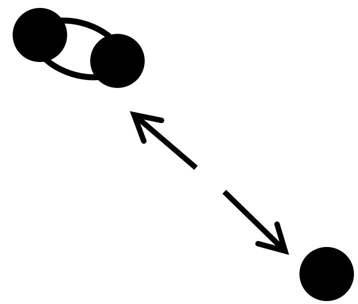
As a host of compact binaries

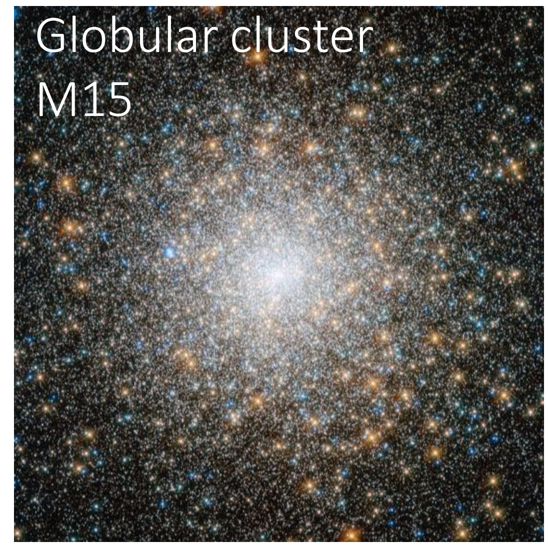
Evolution of isolated massive binaries



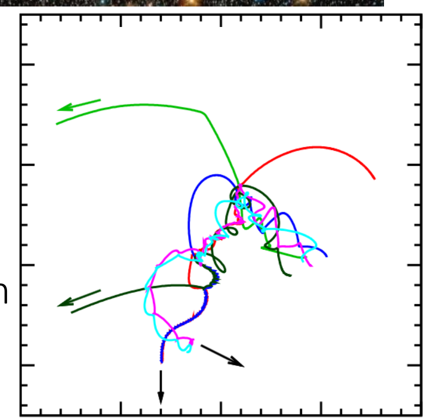
Inayoshi+(2017)

Dynamical interactions form compact binaries in star clusters





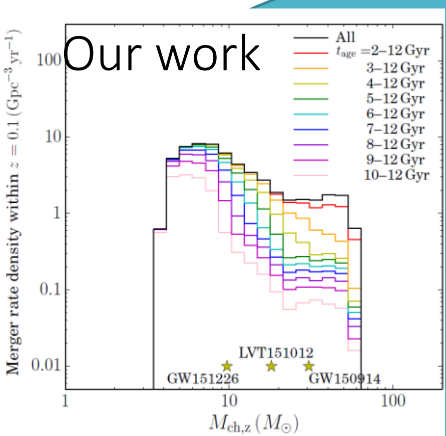
An example of the dynamical binary formation at a globular cluster center (Tanikawa et al. 2012)



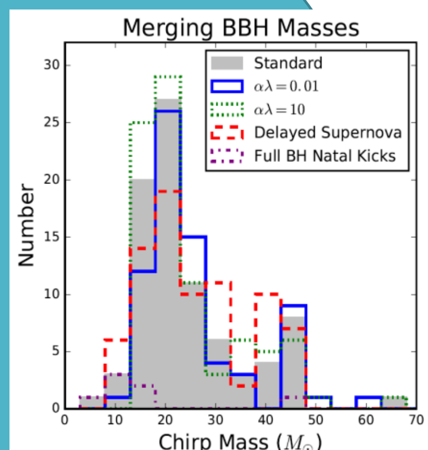
Expected BBH mass distribution

Different mass distributions of merging BBHs are expected

Our work

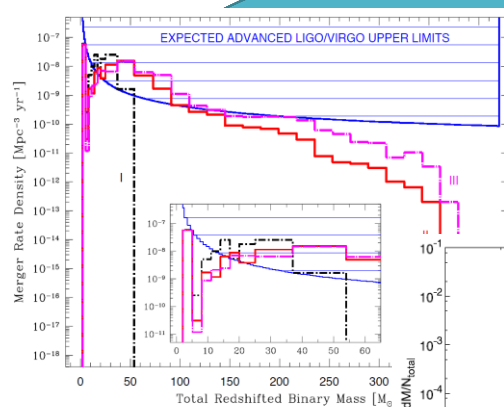


Rodriguez et al. (2016)

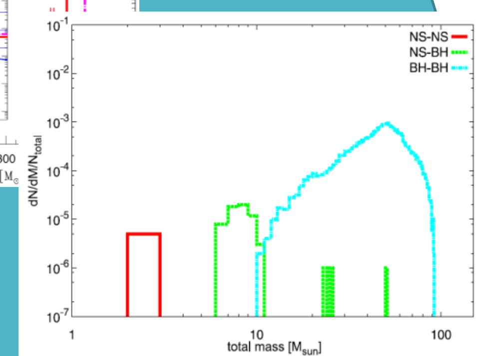


Star clusters

Belczynski et al. (2016)



Kinugawa et al. (2014)



Isolated binaries

Of course, these results depend on stellar evolution models and initial binary distribution

Dynamical Evolution of Globular Clusters

Globular clusters in the Milky Way

Age ~ 10 Gyr

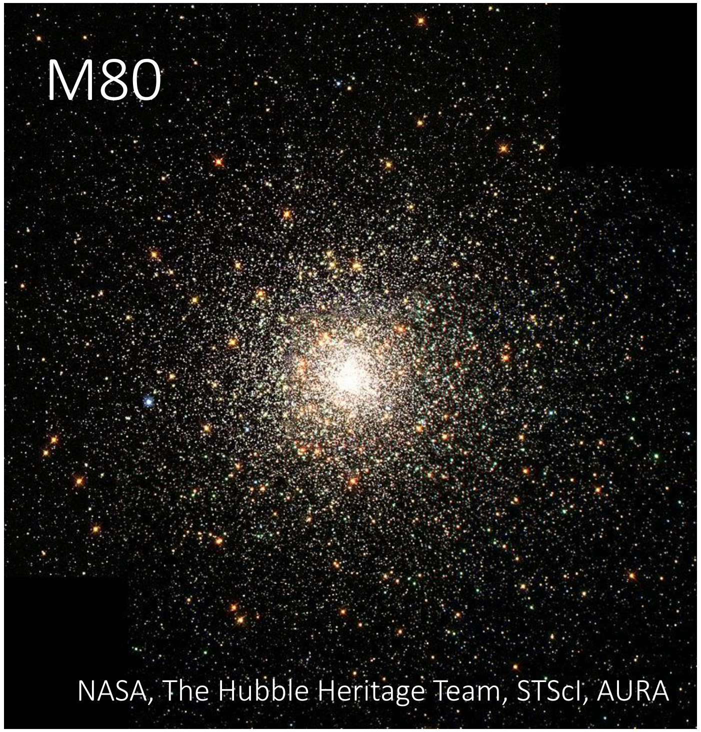
Mass ~ $10^{5\text{-}6}$Msun

Size ~ 10 pc

Located in the Galactic halo

Old, massive, and dense star clusters

The densest environment in the MW except for the Galactic center



The formation process is still unclear

Core of dwarf galaxy? (Omega Cen)

Accreted with dwarf galaxies?

Internal dynamical evolution of clusters

Core collapse: The core shrinks on the relaxation timescale

Mass segregation: Massive stars concentrates on the cluster core due to the energy equipartition

Binary formation: Three-body encounters form hard binaries

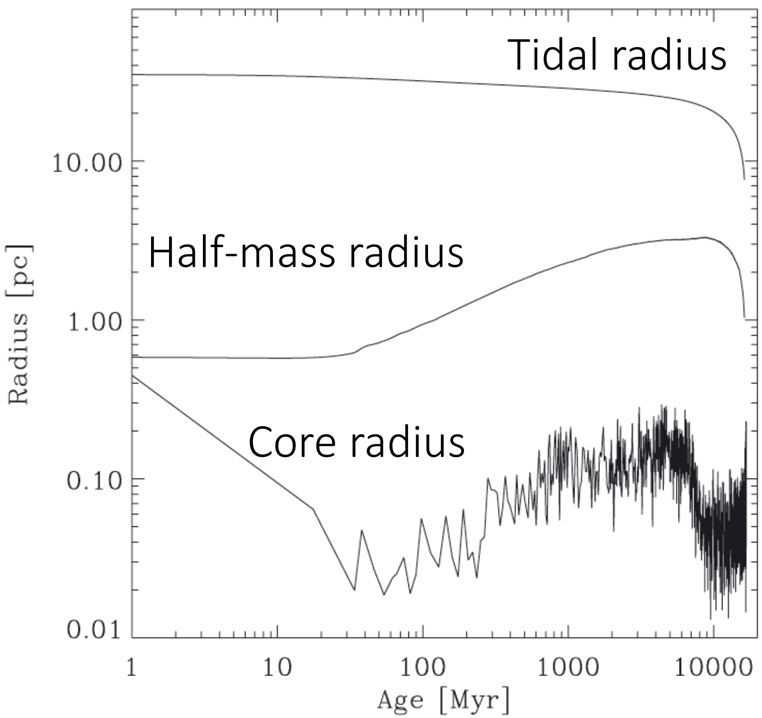
Post-collapse evolution (expansion):
Cluster expands after the core-collapse due to the energy flux from hard binaries

Globular clusters host hard binaries of massive objects such as black holes and neutron stars

These proceed on the relaxation timescale

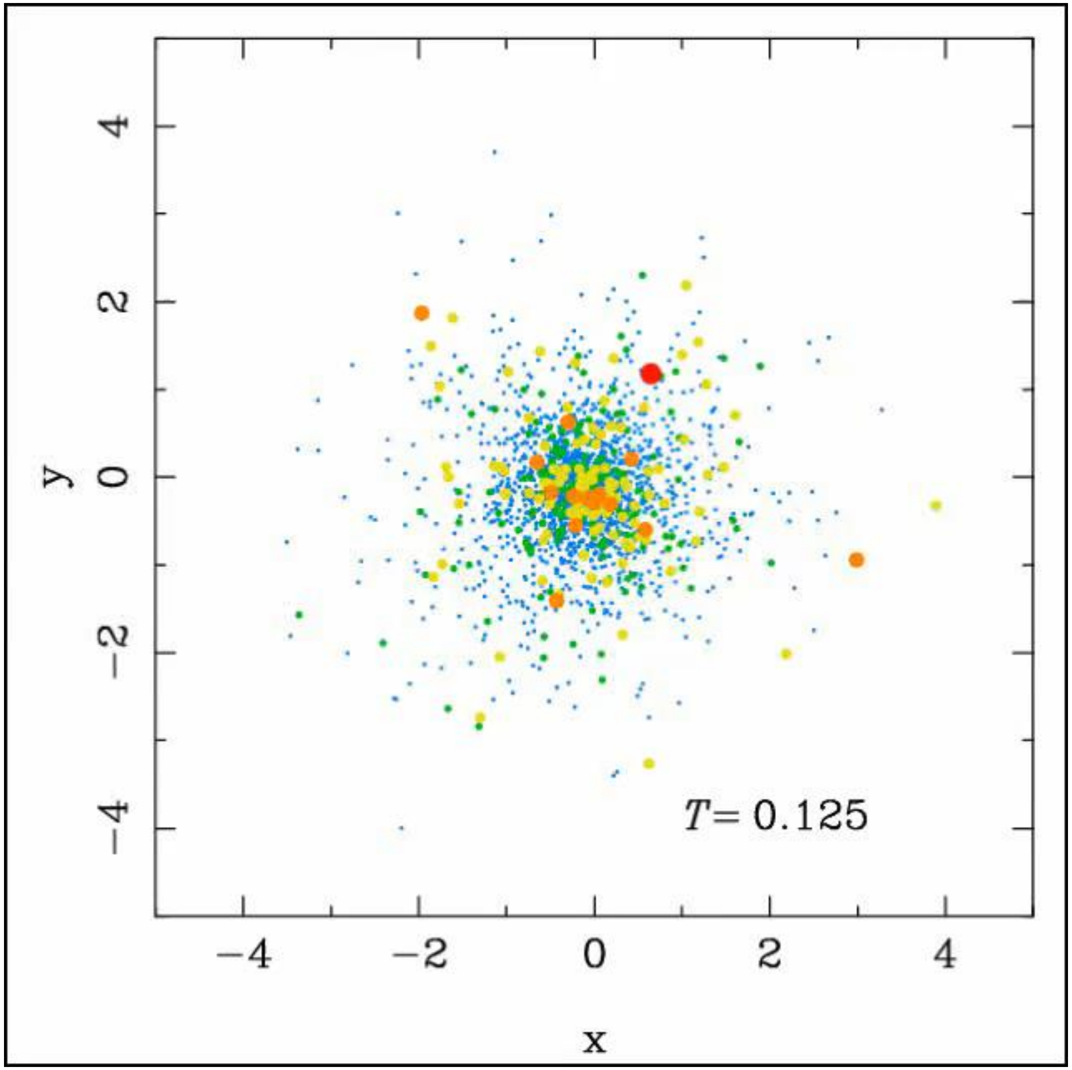
$$t_{\rm rh} \sim 2 \times 10^8 \,{\rm year} \left(\frac{M}{10^6\,{\rm M}_\odot}\right)^{1/2} \left(\frac{r_{\rm vir}}{1{\rm pc}}\right)^{3/2} \left(\frac{\langle m \rangle}{{\rm M}_\odot}\right)^{-1}$$

Stellar evolution (incl. evolution of binaries)



Simulation of M4-like globular cluster
Including tidal effect (Giersz & Heggie 2008)
Figure from Gieles et al. (2011)

N-body simulation of star clusters



Direct N-body simulations ($N \sim 10^6$) for 10 Gyr including binaries are still not easy.

Difficulties

Hard (tight) binaries

- Massive stars form hard binaries
- BH-BH, NS-BH, NS-NS… these cause problems…

Long simulation time up to 10Gyr

- Compared to the time scale of binaries (days or less), globular cluster life time is too long

Relatively large N for direct summation of the gravity

- Direct method $O(N^2)$
- Close encounters require high accuracy

Algorithm

(KS) Regularization

A method to treat hard binaries

Transform the coordinates in addition to time

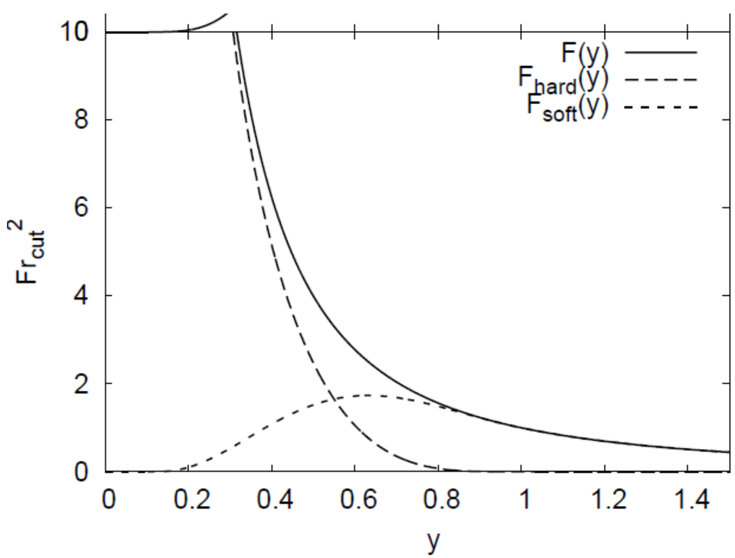
NBODY6 (Aarseth)

Tree and Direct Hybrid method

Use tree method (approximate force for distant particles)

$O(N \log N)$

P^3T: Iwasawa+ (2015)



Hardware

- GRAPE
  - Special purpose hardware for N-body problem
- CPU clusters
- GPU clusters
  - NBODY6++GPU

- Parallelization is not so efficient, especially after core collapse
  - Binaries decide the minimum step size

The largest N-body simulation

Wang+(2016): DRAGON simulation

N=10^6

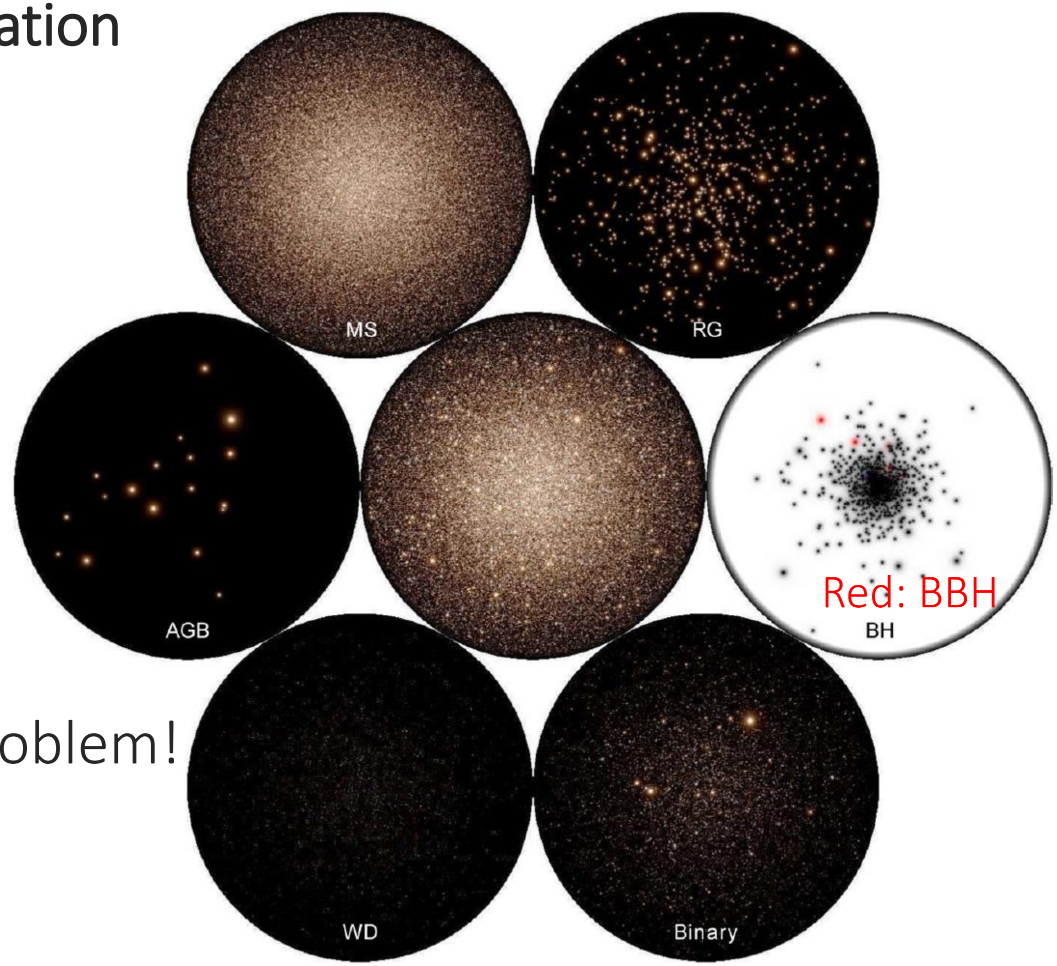
Star-by-star

NBODY6++GPU

BUT, the cluster density is relatively low
-> Not many BBHs formed

Dense run is up to 1Gyr

Hard binaries always cause problem!



Monte-Carlo simulations

The evolution of E, J (ΔE, ΔJ) of particles is analytically computed using two-body relaxation theory

- 3-body encounters are directly solved
- Some parameters are tuned compared with direct N-body simulations
  - *These treatments depend on codes*

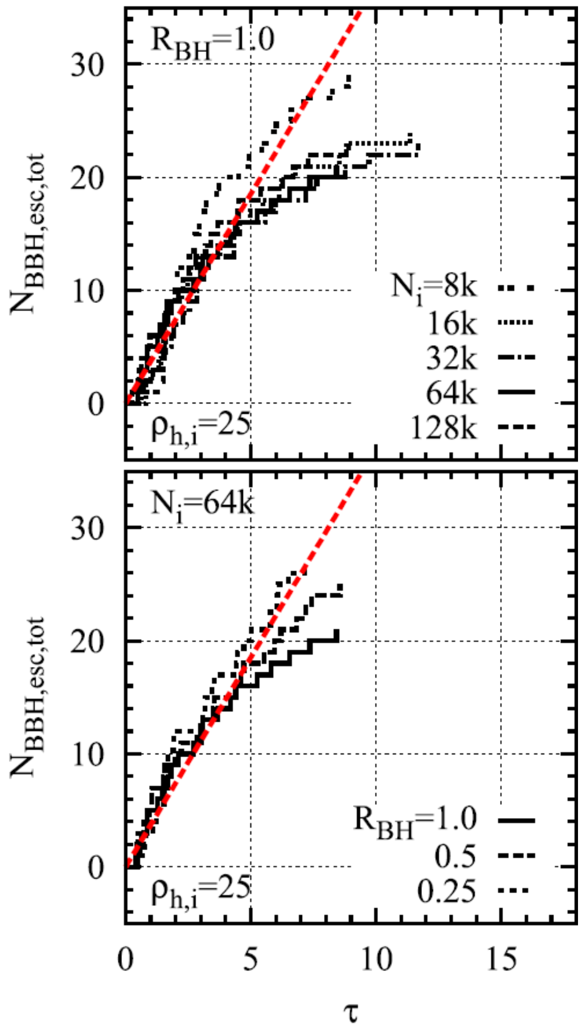
Less computational resources than direct N-body

Two- or a few-body encounters (strong interactions) may not be correct

Rodriguez's group use this method

What we can do using direct N-body simulations?

N-scaling relation



Tanikawa (2013)

Performed N-body simulations with different N

The results are scaled by thermodynamical time (which depends on *N*)

$$\tau = \int_0^t \frac{dt'}{t_{rh}}$$

$$t_{rh} = 0.0477 \frac{N}{(G\rho_h)^{1/2} \log(0.4N)}$$

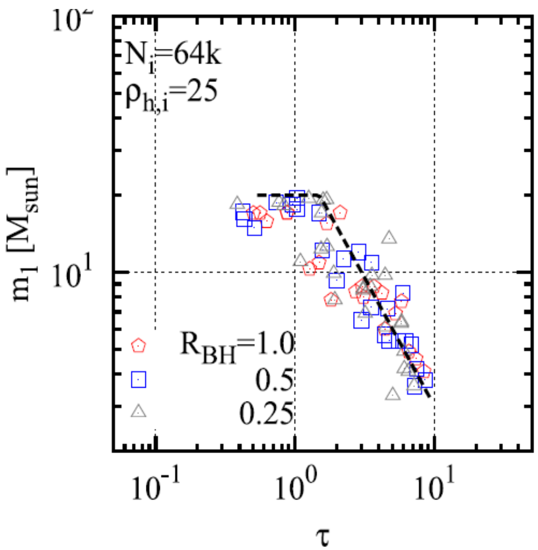
Distribution of BBHs formed in star clusters is modeled as a function of thermodynamical time

Distribution of Merging BBHs formed in Star Clusters

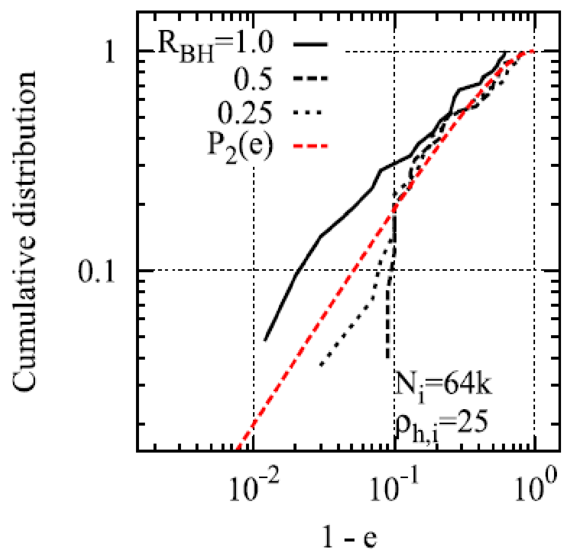
Model for BBH merger history per cluster

Tanikawa (2013)

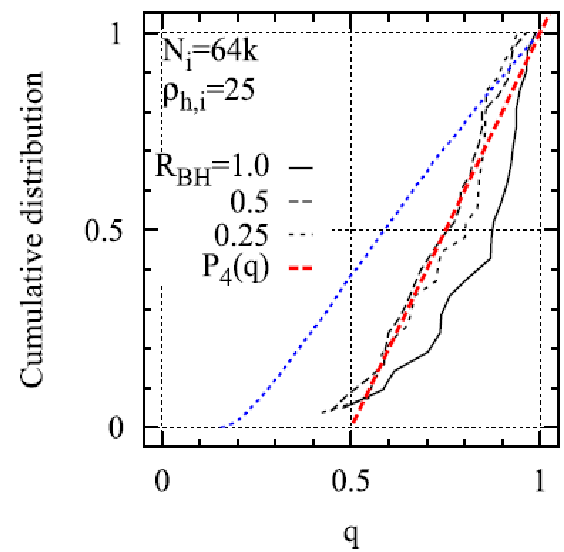
Timescale for merger



Eccentricity distribution



Mass-ratio distribution



Using the results of N-body simulations, Tanikawa (2013) constructed a model for BBH merger history per cluster

But, maximum mass of BH is 20Msun

We can generate a merger history of BBHs for a cluster

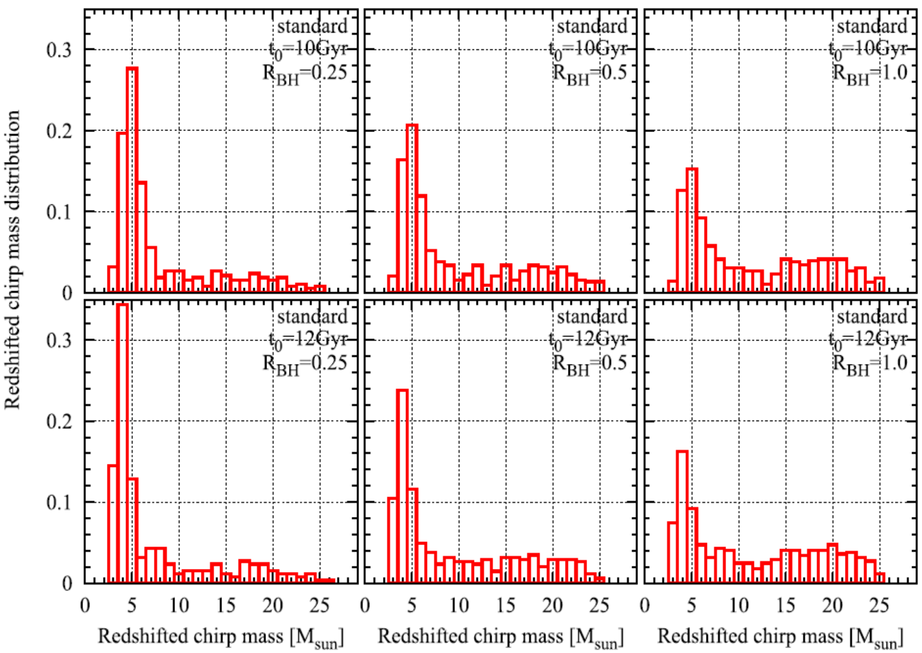
Estimate merging BBHs formed in globular clusters

Tanikawa (2013)

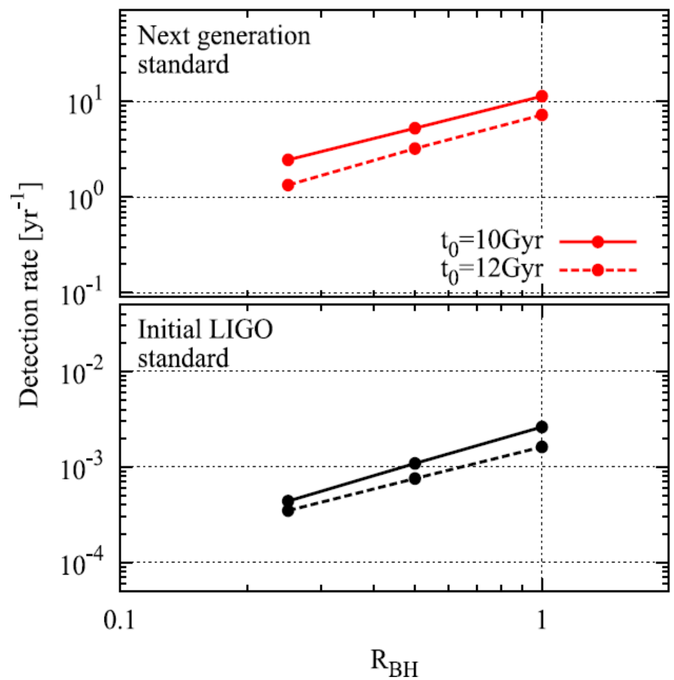
Modelling BBH merger history based on the results of N-body simulation

Assuming number density of star clusters, they estimate the mass function of observed BBHs

Red-shifted Chirp Mass Function for Detected BBHs



Estimated Detection Rate



All globular clusters ware assumed to be born 10 or 12 Gyr ago

Younger massive clusters?

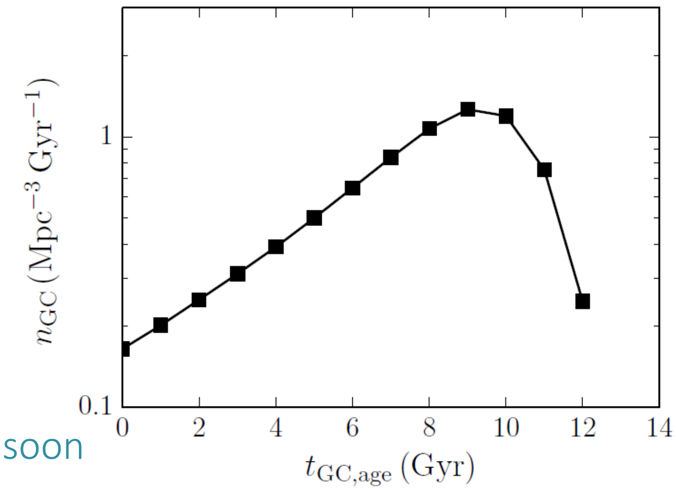
Fujii, Tanikawa, and Makino (2017)

- Use BBH model of Tanikawa (2013)
- But add
  - *Cosmic Star-Cluster formation history*
  - *Cluster mass function*
  - *Model up to 54Msun BH*

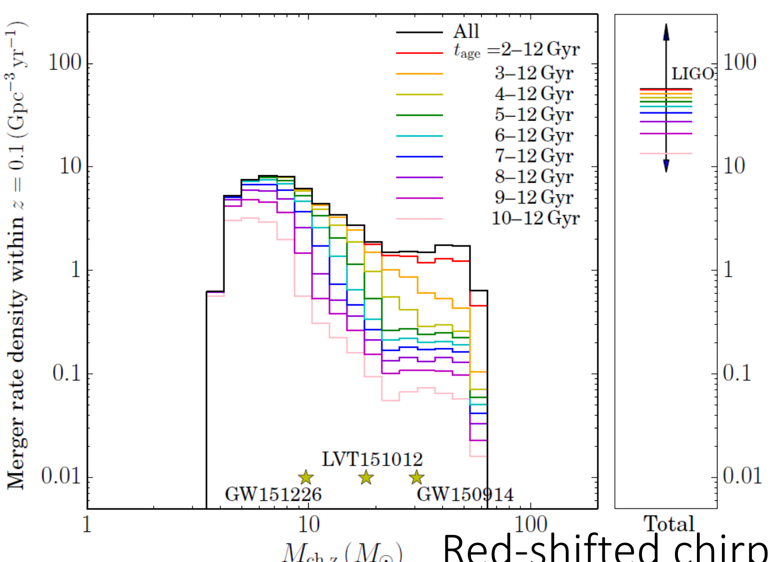
PASJ, accepted

Will appear in Astro-ph, soon

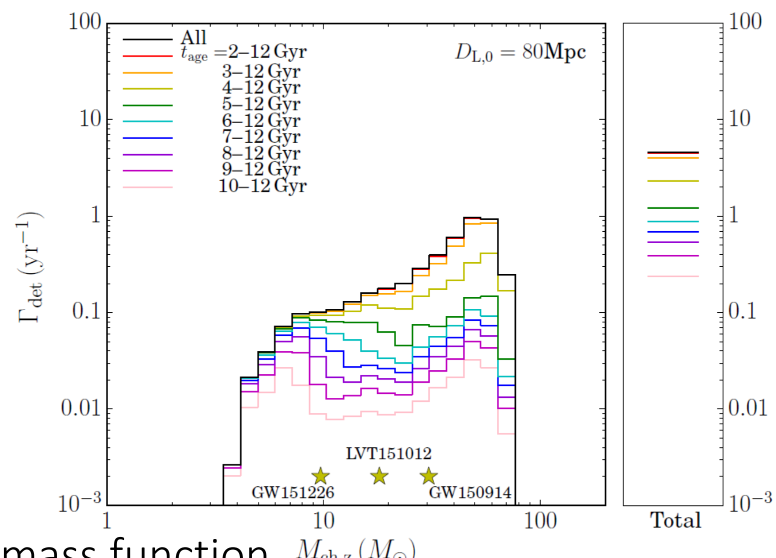
Cosmic Star-Cluster formation history



Estimated Merger Rate Density



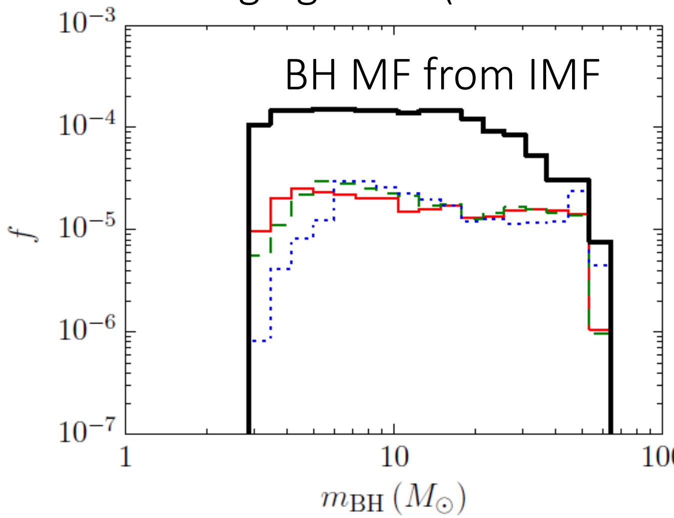
Estimated Detection Rate



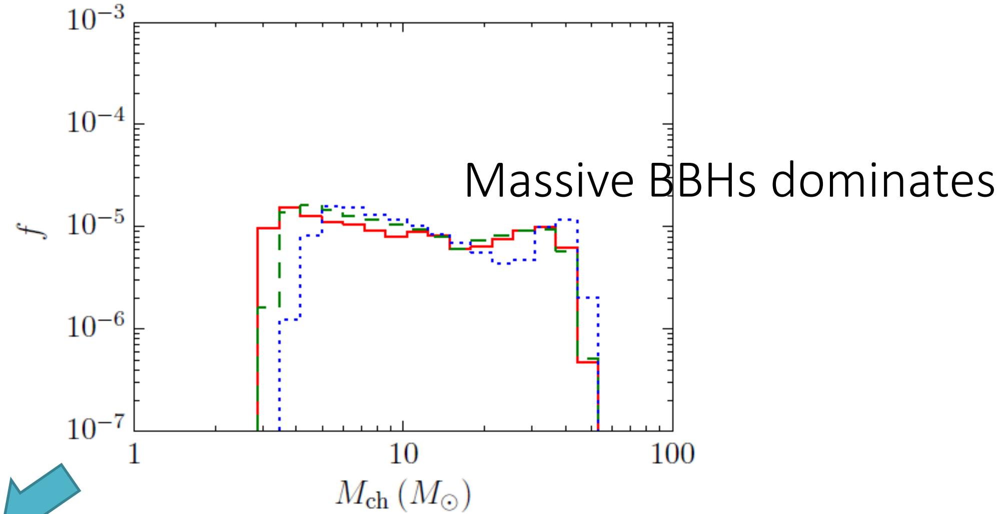
Red-shifted chirp mass function

Dynamical evolution of BBH distribution

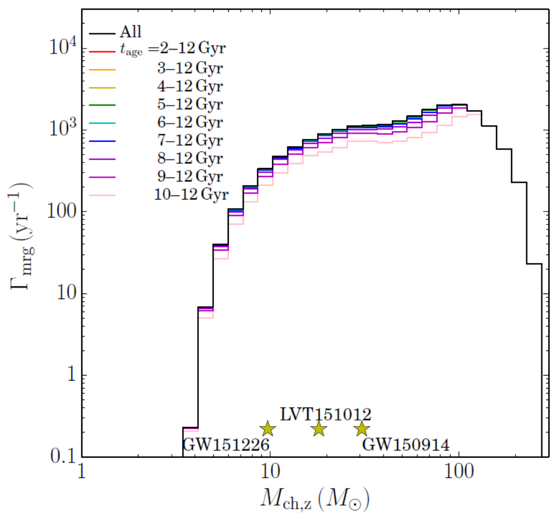
MF of merging BBHs (from model)



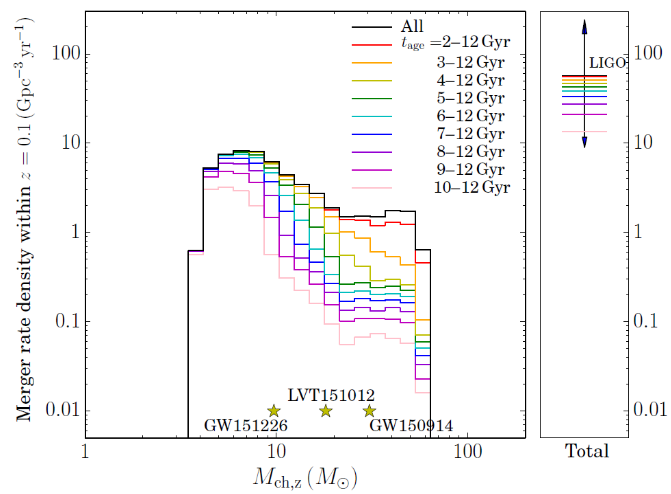
Chirp MF of merging BBHs (model)



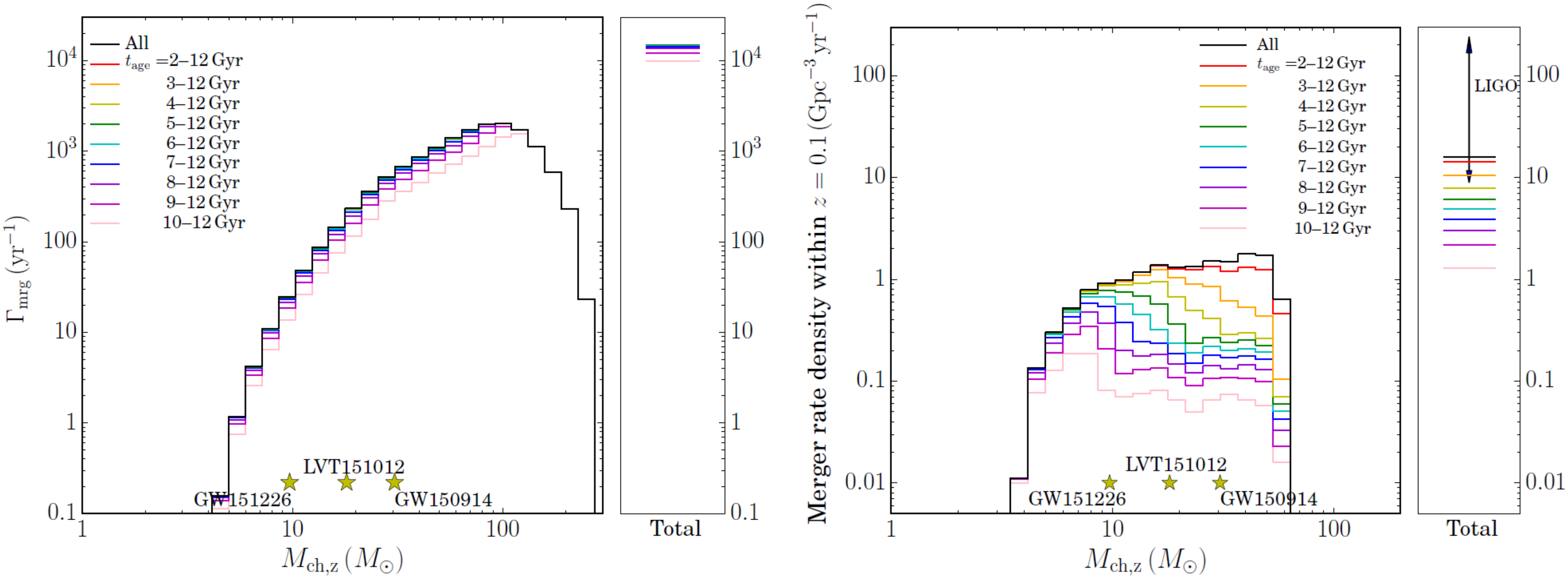
Entire merger rate from all clusters



Estimated Merger Rate Density



With natal kicks



Retention fraction proportional to the BH mass

0.1—1.0 for 3—20Msun (1.0 for >20Msun)

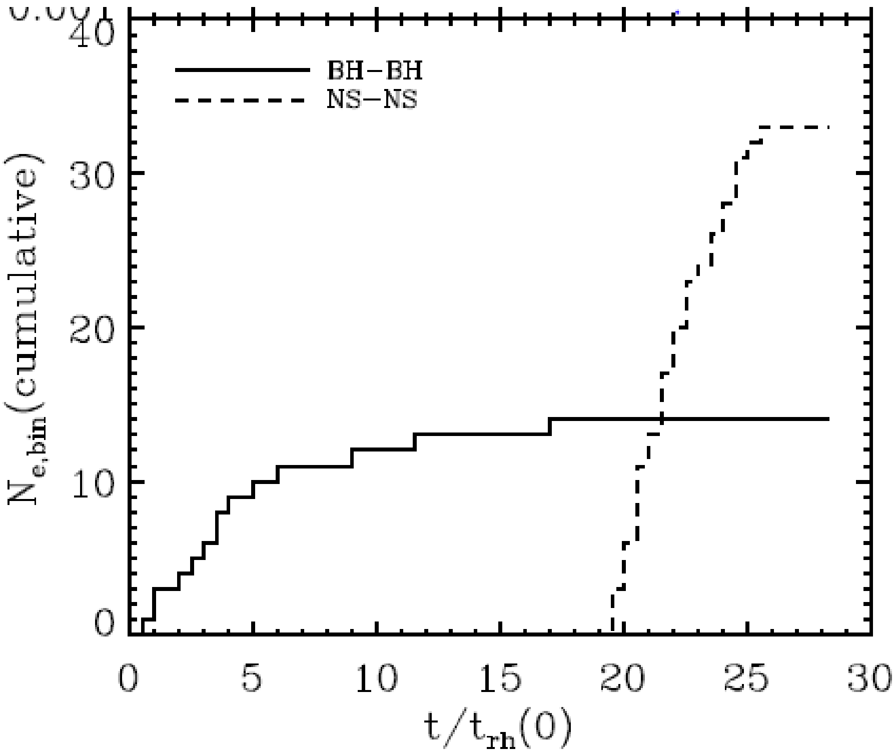
The total retention fraction was ~0.7

NS-NS mergers

After most of BHs are ejected, NS-NS merger starts

The expected NS-NS merger rate is an order of magnitude lower than that of BH-BH

- Later dynamical evolution than BH-BH
- Natal kick



Bae et al. (2014)

t_{rh}: relaxation time
Typically a few hundred Myr

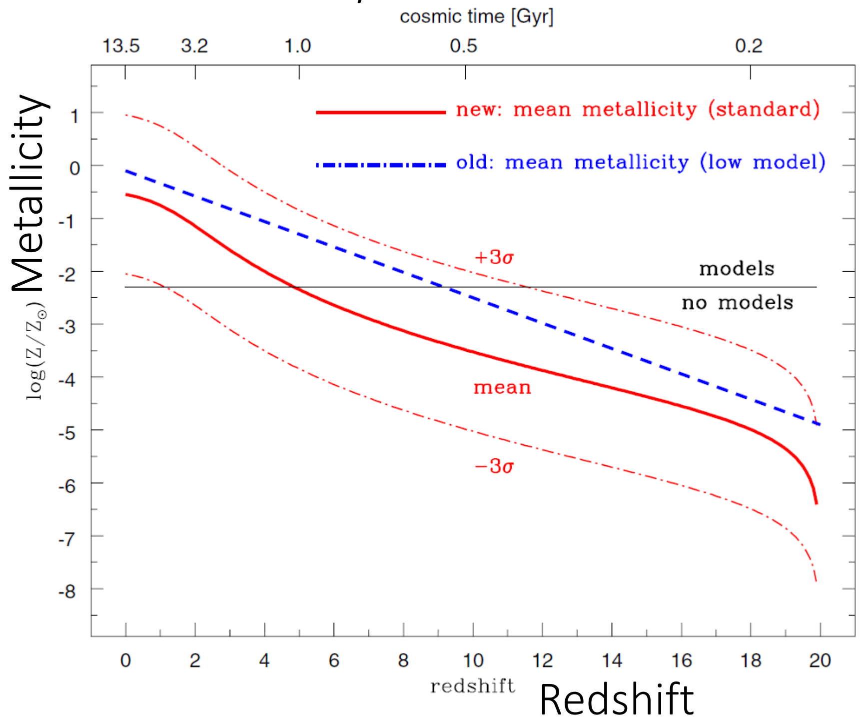
Future plans

Update stellar evolution model
- Massive stars
- Metallicity (0 to Solar)
  - *Especially* $Z<10^{-4}$
- Binary evolution due to common envelope evolution
  - *How dynamical evolution works?*

Perform direct N-body simulations with the new models

Investigate the formation rate of BBHs and their mass function
- For each metallicity and cluster mass etc.

Mean metallicity evolution of the Universe



From Belczynski et al. (2016)

Summary

Massive clusters (globular clusters) are a host of merging BBHs

The distribution of merging BBHs (mass ratio, eccentricity) is different from that of isolated binaries (common envelope evolution, only)

Future N-body simulations will answer the merger rate of BBHs in star clusters and the mass distribution for different metallicity, mass, density of star clusters