Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation Ⅰ-Ⅳ

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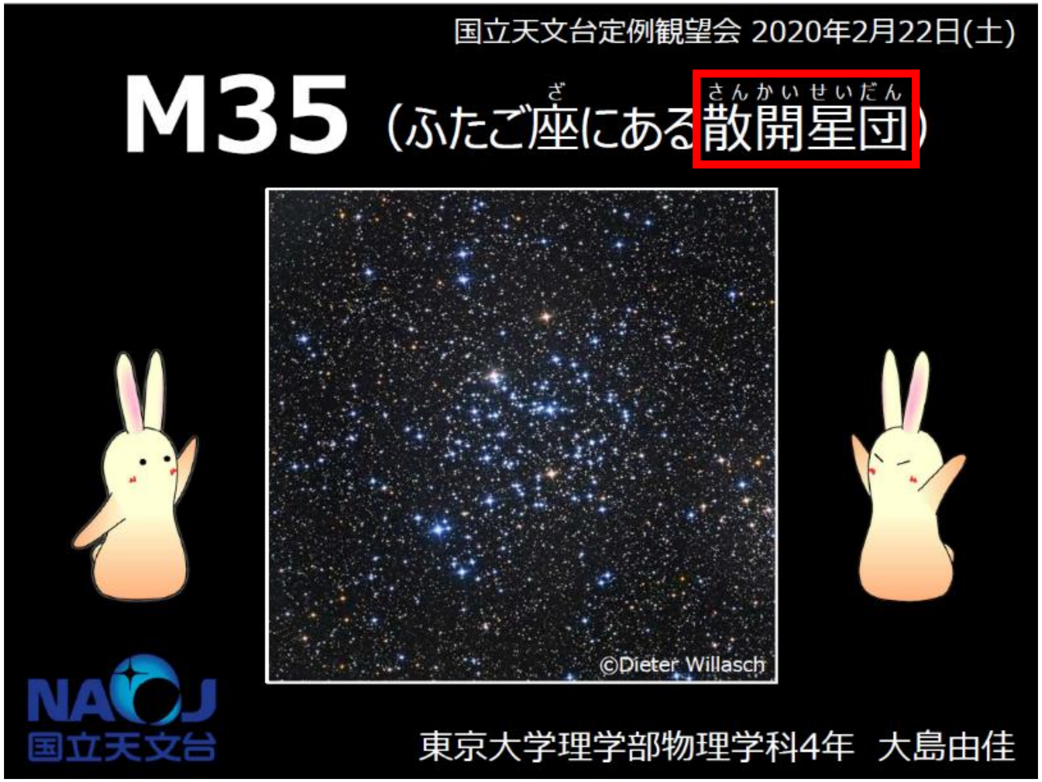
Why star clusters?



Cancelled due to COVID-19

I saw beautiful すばる with the naked eye in Kiso
Star clusters are my favorites

→ I looked for papers about “star clusters × GWs”

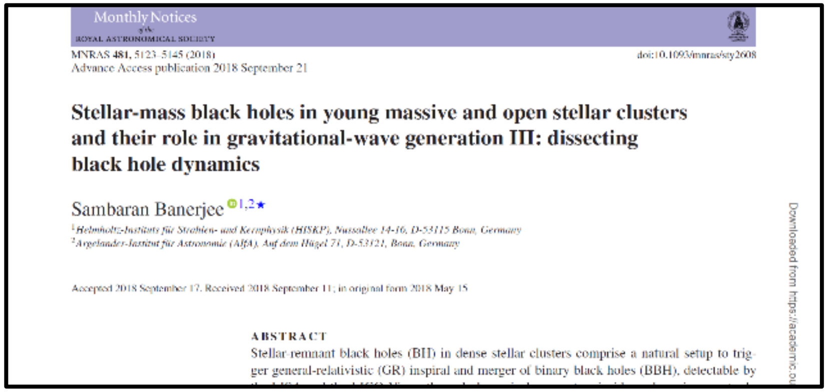
⚠ not galaxy clusters

Today's papers

Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation

by Sambaran Banerjee

Ⅰ: MNRAS **467**, 524–539 (2017)



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 481, 5123–5145 (2018) doi:10.1093/mnras/sty2608
Advance Access publication 2018 September 21

Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation III: dissecting black hole dynamics

Sambaran Banerjee[1,2]★
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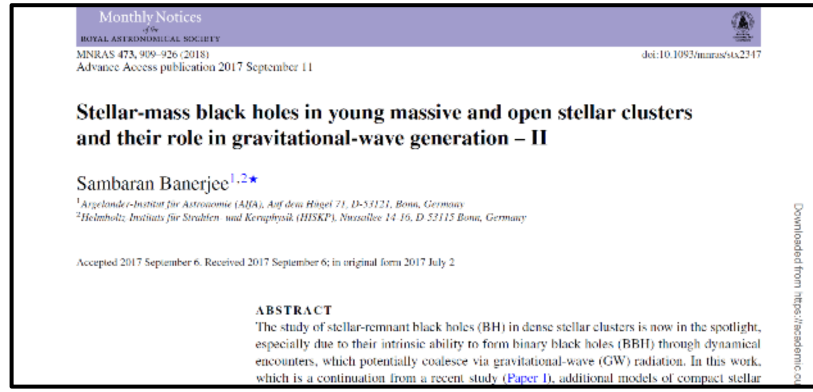
ABSTRACT
Stellar-remnant black holes (BH) in dense stellar clusters comprise a natural setup to trigger general-relativistic (GR) inspiral and merger of binary black holes (BBH), detectable by

Ⅱ: MNRAS **473**, 909–926 (2018)



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Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation – II

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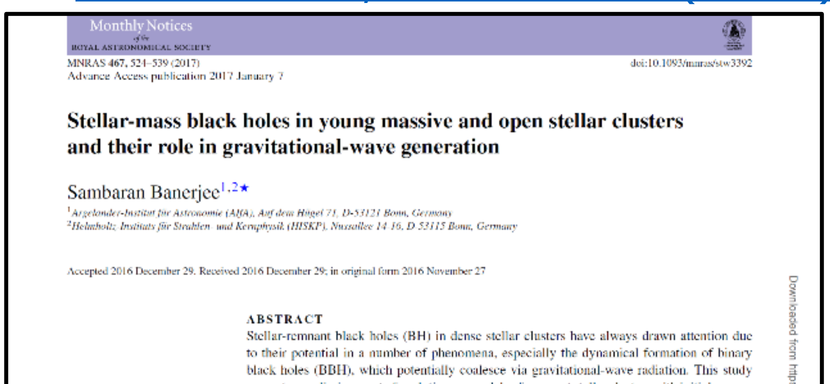
ABSTRACT
The study of stellar-remnant black holes (BH) in dense stellar clusters is now in the spotlight, especially due to their intrinsic ability to form binary black holes (BBH) through dynamical encounters, which potentially coalesce via gravitational-wave (GW) radiation. In this work, which is a continuation from a recent study (Paper I), additional models of compact stellar

Ⅲ: MNRAS **481**, 5123–5145 (2018)



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Stellar-mass black holes in young massive and open stellar clusters and their role in gravitational-wave generation

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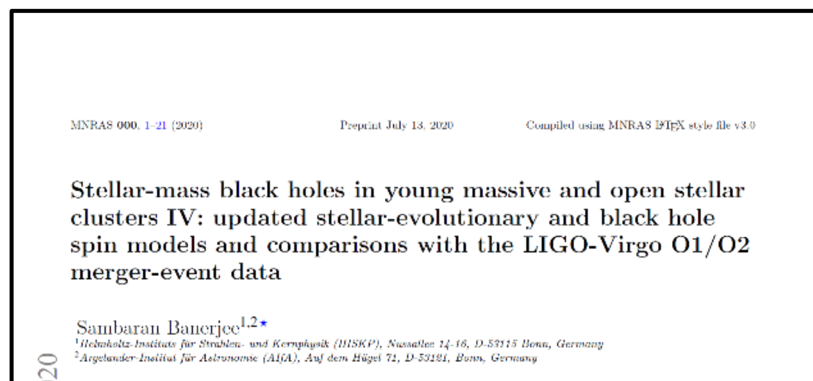
ABSTRACT
Stellar-remnant black holes (BH) in dense stellar clusters have always drawn attention due to their potential in a number of phenomena, especially the dynamical formation of binary black holes (BBH), which potentially coalesce via gravitational-wave radiation. This study presents a preliminary set of evolutionary models of compact stellar clusters with initial masses

Ⅳ: arXiv:2004.07382v3



MNRAS 000, 1–21 (2020) Preprint July 13, 2020 Compiled using MNRAS LaTeX style file v3.0

Stellar-mass black holes in young massive and open stellar clusters IV: updated stellar-evolutionary and black hole spin models and comparisons with the LIGO-Virgo O1/O2 merger-event data

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Summary

- In general, star clusters are classified into open clusters and globular clusters by their age
- Many models of young massive and open clusters are prepared
- The dynamical formation of BBHs in clusters are simulated by N-body evolution program
- The results are similar to LIGO-Virgo data

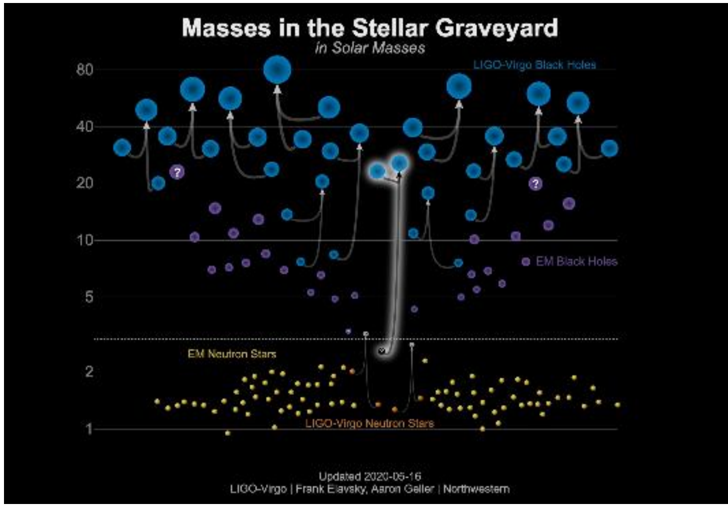
Contents

Introduction

- The study of dynamical interactions of BHs in star clusters has been started since 1993 (Nature **364**, 421–423)

- BH mass detected by LIGO is typically $10 - 100\ M_{\odot}$

- The scenario of formation of stellar-mass BBHs in star clusters is simple and easy



LIGO Gallery

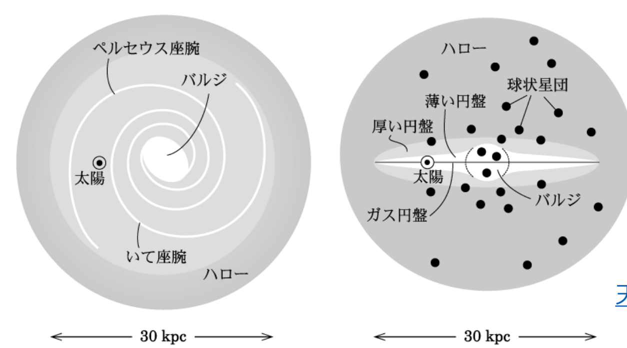
Classification of star clusters

	Age	Total mass	Number of stars	Metallicity	Shape & Location	Example
Young massive cluster	$\lesssim 100\ \mathrm{Myr}$	$10^4\ M_\odot - 10^5\ M_\odot$	–	$\gtrsim 1\ Z_\odot$	–	–
Open cluster	$\lesssim 300\ \mathrm{Myr}$	$\lesssim 10^4\ M_\odot$	$10^2 - 10^3$	$\sim 1\ Z_\odot$	Irregular, Disk	
Globular cluster	$\gtrsim 10\ \mathrm{Gyr}$	$10^5\ M_\odot - 10^6\ M_\odot$	$10^5 - 10^6$	$\lesssim 1\ Z_\odot$	Globe, Halo	

Definition of the papers (Age, Total mass)

Metallicity : $Z = \sum_{i>\mathrm{He}} \frac{m_i}{M_{\mathrm{total}}}$

$(Z_\odot = 0.02)$



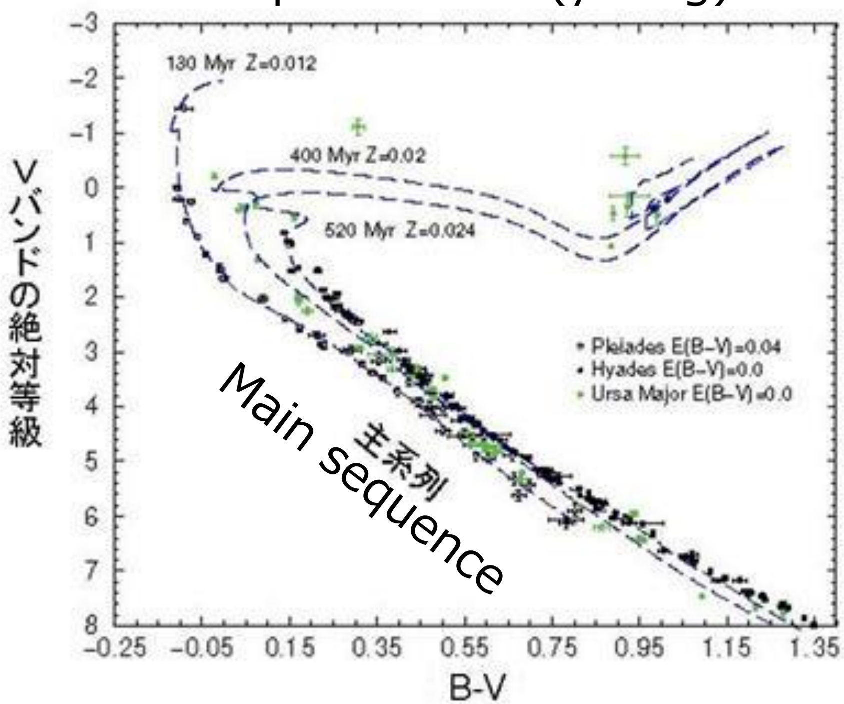
天文学辞典

Star cluster's age

- Make Hertzsprung-Russell Diagram
- Estimate cluster's age by location of turnoff point

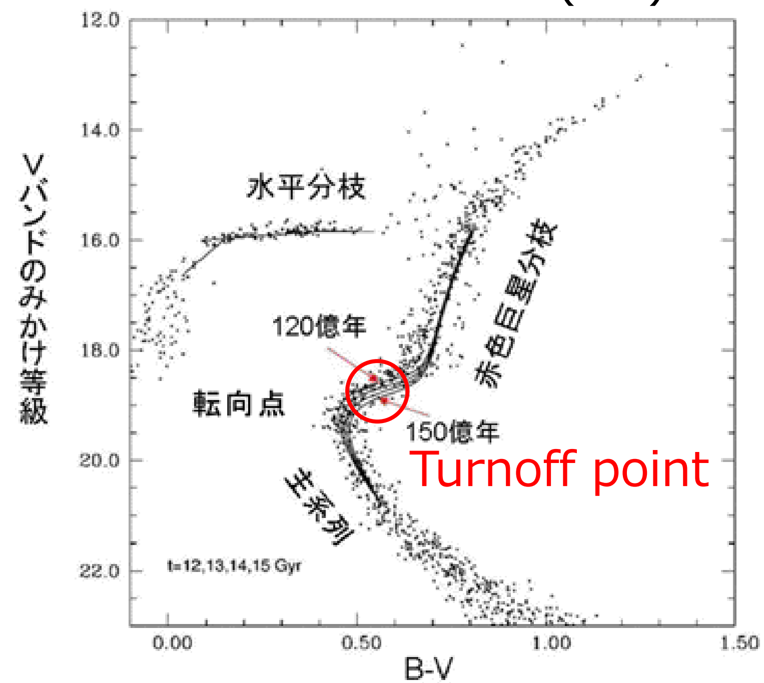
Open cluster (young)

dark ← magnitude → light
(or luminosity)



blue ← color → red
(or temperature, spectrum type)

Globular cluster (old)



理科年表オフィシャルサイト

- Born in the same place and time
  → Separate in long time
- The way to be born and evolve is not understood well

NBODY7

- NBODY7:
  N-body evolution program,
  descendant of NBODY6

TABLE 1

MAIN N-BODY CODES

Keyword	Period	Name
Primitive beginnings	1961–1969	NBODY1
Two-body regularization	1969–1974	NBODY3
Cosmological experiments......	1974–1983	NBODY2
Star cluster simulations	1979–1992	NBODY5
Hermite integration	1993–1999	NBODY6
The HARP challenge	1994–1999	NBODY4

S. J. Aarseth (1999)

- 4th-order Hermite integrator
- Neighbor-based scheme
- Post-Newtonian approximation

4th-order Hermite integrator

① Predict positions and velocities of all particles at time $t_{n+1} = t_n + \Delta t$

$$\boldsymbol{x}_{p,j} = \boldsymbol{x}_{n,j} + \boldsymbol{v}_{n,j}\Delta t + \boldsymbol{a}_{n,j}\frac{\Delta t^2}{2} + \dot{\boldsymbol{a}}_{n,j}\frac{\Delta t^3}{6} \quad + O(\Delta t^4)$$

predictor　particle j　time t_n

$$\boldsymbol{v}_{p,j} = \boldsymbol{v}_{n,j} + \boldsymbol{a}_{n,j}\Delta t + \dot{\boldsymbol{a}}_{n,j}\frac{\Delta t^2}{2}$$

② Calculate the acceleration and its time derivative for particle i at time t_{n+1} using predictors

$$\boldsymbol{a}_{n+1,i} = \sum_j G m_j \frac{\boldsymbol{r}_{ij}}{(r_{ij}^2 + \varepsilon^2)^{3/2}}$$

$$\dot{\boldsymbol{a}}_{n+1,i} = \sum_j G m_j \left[\frac{\boldsymbol{v}_{ij}}{(r_{ij}^2 + \varepsilon^2)^{3/2}} + \frac{3(\boldsymbol{v}_{ij}\cdot\boldsymbol{r}_{ij})\boldsymbol{r}_{ij}}{(r_{ij}^2 + \varepsilon^2)^{5/2}}\right]$$

where $\boldsymbol{r}_{ij} = \boldsymbol{x}_{p,j} - \boldsymbol{x}_{p,i}$, $\boldsymbol{v}_{ij} = \boldsymbol{v}_{p,j} - \boldsymbol{v}_{p,i}$

ε : softening parameter

4th-order Hermite integrator

③ Construct 3rd-order Hermite interpolation polynomial

$$\boldsymbol{a}_i(t) = \boldsymbol{a}_{n,i} + \dot{\boldsymbol{a}}_{n,i}(t - t_n) + \boldsymbol{a}_{n,i}^{(2)} \frac{(t - t_n)^2}{2} + \boldsymbol{a}_{n,i}^{(3)} \frac{(t - t_n)^3}{6}$$

where
$$\boldsymbol{a}_{n,i}^{(2)} = \frac{-6(\boldsymbol{a}_{n,i} - \boldsymbol{a}_{n+1,i}) - \Delta t(4\dot{\boldsymbol{a}}_{n,i} + 2\dot{\boldsymbol{a}}_{n+1,i})}{\Delta t^2}$$

$$\boldsymbol{a}_{n,i}^{(3)} = \frac{12(\boldsymbol{a}_{n,i} - \boldsymbol{a}_{n+1,i}) + 6\Delta t(\dot{\boldsymbol{a}}_{n,i} + \dot{\boldsymbol{a}}_{n+1,i})}{\Delta t^3}$$

④ Integrate $\boldsymbol{a}_i(t)$ from t_n to t_{n+1} to obtain correctors and set $\boldsymbol{x}_{n+1,i} = \boldsymbol{x}_{c,i}$ and $\boldsymbol{v}_{n+1,i} = \boldsymbol{v}_{c,i}$

$$\boldsymbol{x}_{c,i} = \boldsymbol{x}_{p,i} + \boldsymbol{a}_{n,i}^{(2)} \frac{\Delta t^4}{24} + \boldsymbol{a}_{n,i}^{(3)} \frac{\Delta t^5}{120}$$

corrector

$$\boldsymbol{v}_{c,i} = \boldsymbol{v}_{p,i} + \boldsymbol{a}_{n,i}^{(2)} \frac{\Delta t^3}{6} + \boldsymbol{a}_{n,i}^{(3)} \frac{\Delta t^4}{24}$$

⑤ Update t_n and go back to step ①

Neighbor-based scheme

- Neighbor-based scheme is used in order to ease computing time

- Each CPU stores a copy of its local checkpoint in the memory of its neighbor CPU
- Whenever a CPU fails, the lost local checkpoint data can be recovered from its neighbor CPU

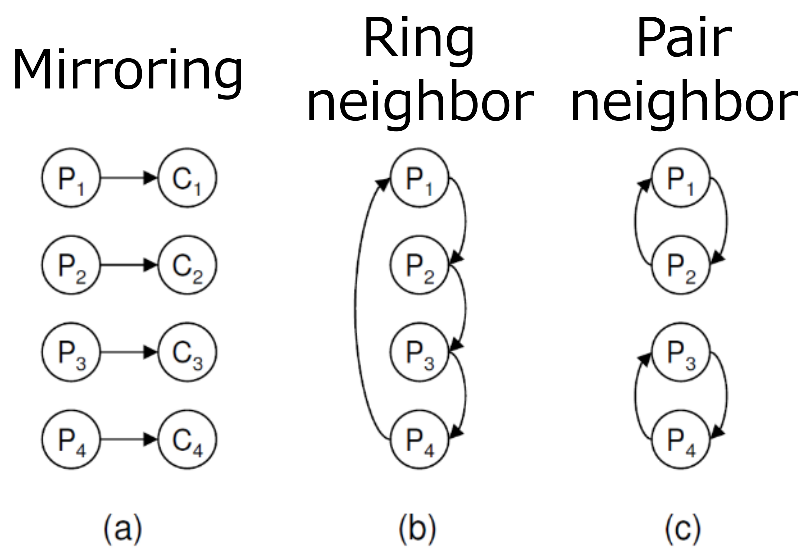


Figure 1: Neighbor-Based Schemes Z. Chen+ (2005)

Post-Newtonian approximation

- Post-Newtonian approximation:
  an approximate solution of Einstein’s equation
  in the case of weak field

- Starting at Newton's law of gravity, higher order terms can be added to increase accuracy

  Expansion parameter: $\varepsilon = \left(\frac{v}{c}\right)^2 \ll 1$

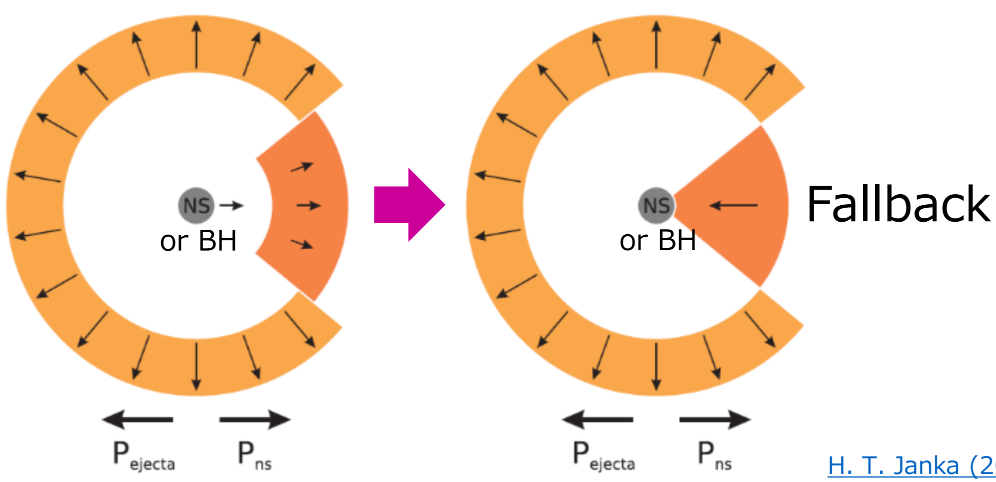
  - PN-1, PN-2: GR periastron precession
  - PN-2.5: orbital shrinking due to GW radiation
  - PN-3, PN-3.5: spin-orbit coupling

- PN terms up to the order 2.5 are applied
- BH spins are taken to be zero for the economy in computing time

Remnant masses

- The remnant (NS or BH) masses are determined by
  - Wind mass-loss until core collapse
  - CO and FeNi core mass
  - The amount of material fallback

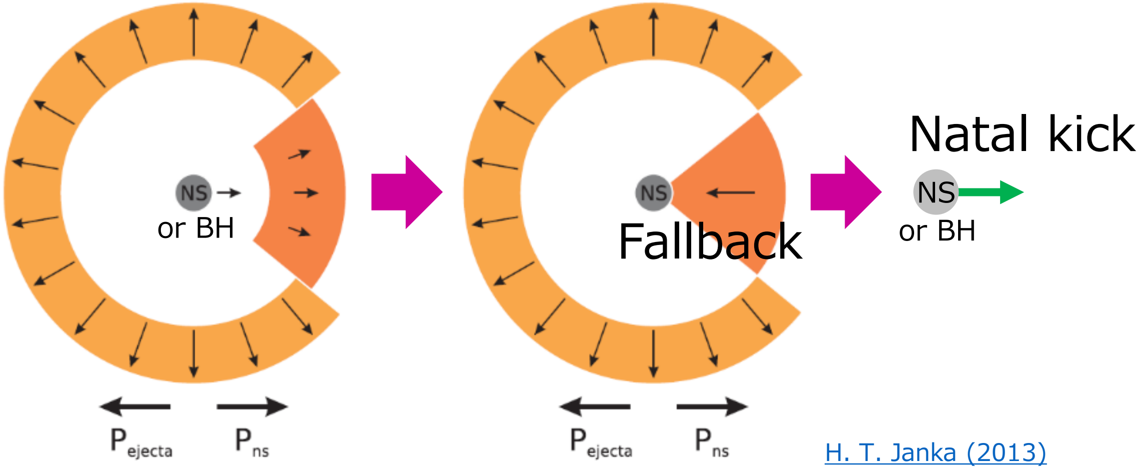
- "Fallback":
  during supernovae, some of the stellar material does not receive enough energy to escape the potential of NS and it falls back on to the core



H. T. Janka (2013)

Natal kicks

- Asymmetric mass ejection will lead to material fallback and natal kicks
- If NSs and BHs receive a high natal kick velocity, they will escape from the host clusters



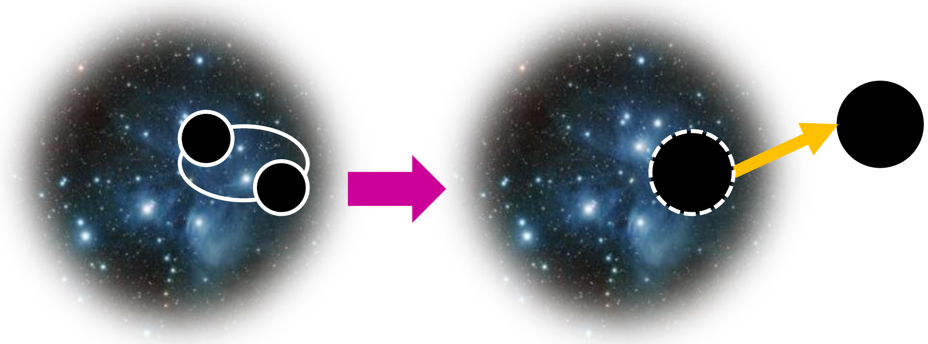
H. T. Janka (2013)

Merger kicks (Ⅰ-Ⅲ)

- PN-2.5 $\rightarrow$ BH spins are not taken

- In reality, when BHs have spins, BBHs will receive a large GW merger kick $(100 - 1000\,\mathrm{km/s})$ during inspiral phase
- Merged BH will escape from the cluster

- A kick velocity is applied on to the merged BH immediately after a coalescence in order to eject the merged BH out of the cluster

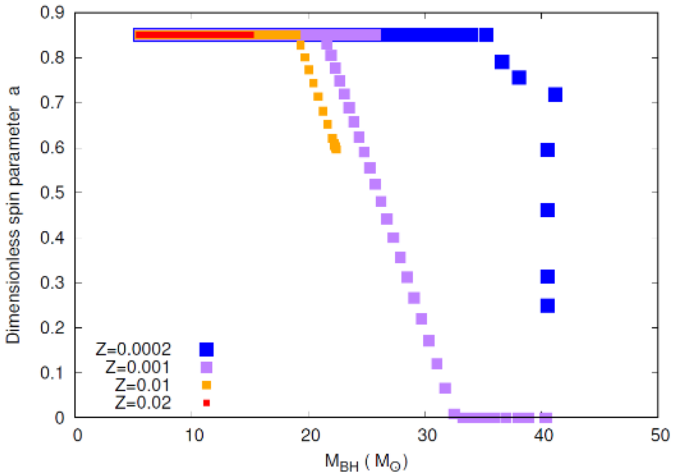


Natal spins (Ⅳ)

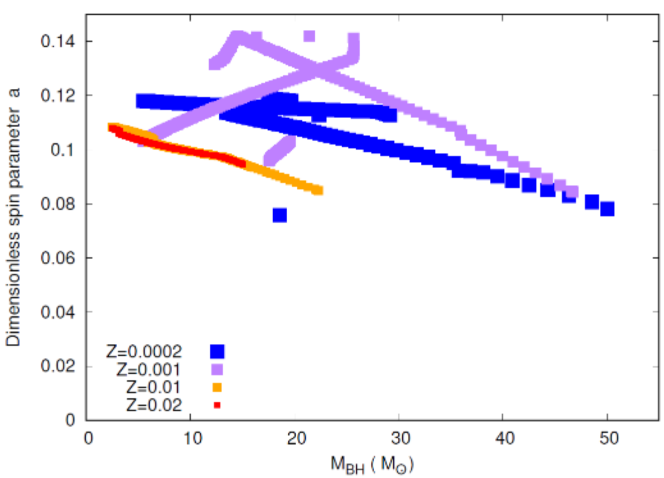
- BH spins are applied in Ⅳ

Dimensionless spin parameter $\boldsymbol{a} = \dfrac{c\boldsymbol{S}_{\mathrm{BH}}}{GM_{\mathrm{BH}}^2}$

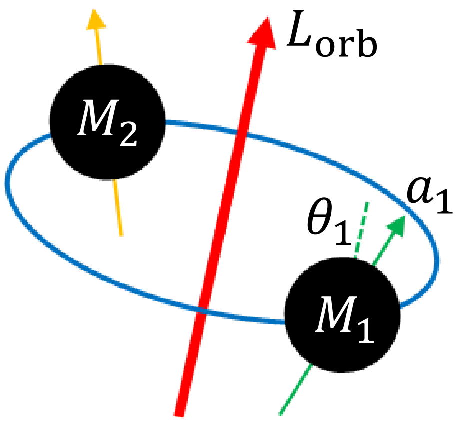
- Geneva BH-spin model
  - Not include magnetic field
  - Angular momentum transport from core to envelope is purely convective
  - BHs have a high spin ($a = 0.85$)



- MESA BH-spin model
  - Include magnetic field
  - Angular momentum transport from core to envelope is much more efficient
  - BHs have a small spin ($a = 0.1$)

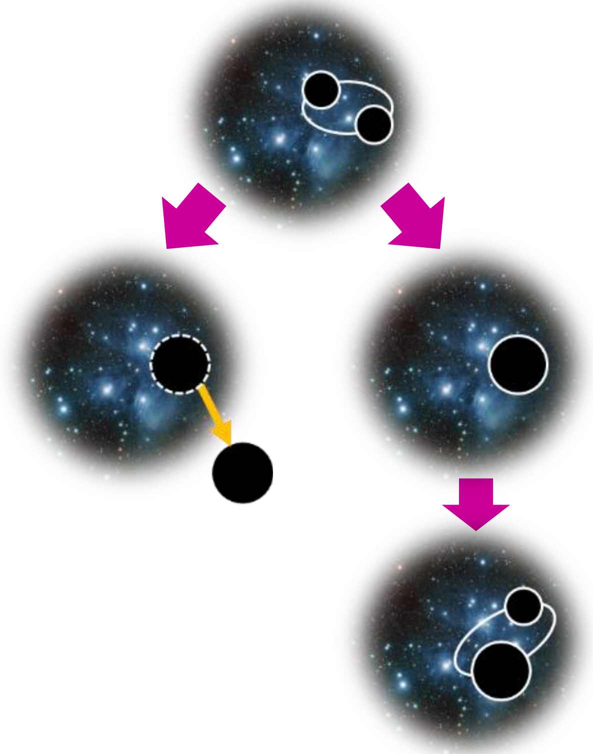


Final spins & merger kicks (Ⅳ)



- For all mergers, effective spin parameter is evaluated

$$\chi_{\mathrm{eff}} = \frac{M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2}{M_1 + M_2}$$



- Orbital angular momentum L_{orb} and natal spins a_1, a_2 determine merger kick velocity v_{k}
- Merger kick velocity v_{k} determines whether the merged BH should stay in the clusters or escape
- If the BH stays, it is allowed for second-generation BBH mergers

Primordial-binary fraction (Ⅱ-Ⅳ)

- Binary stars are initially included
- This makes the models more realistic
- However, the system will become more complicated
  → A reduction in computation is needed

- All stars are ZAMS (Zero-Age Main Sequence) stars
- Initial masses of stars are distributed over $0.08 - 150\ M_{\odot}$

- For $M_{\rm ZAMS} \geq 16\ M_{\odot}$ (O-type stars)
  primordial-binary fraction $f_{\rm bin,O} \approx 100\ \%$
- For $M_{\rm ZAMS} < 16\ M_{\odot}$
  primordial-binary fraction $f_{\rm bin} \approx 2 - 50\ \%$

- The population of O-type stars is much smaller than the total stellar population ($N_{\rm O} \ll N_{\rm total}$)
- Note that $f_{\rm bin}$ represents the overall primordial-binary fraction ($f_{\rm bin} \approx f_{\rm bin,total}$)

Initial conditions of model clusters

Paper	Number of models	Total mass $[M_\odot]$	Half-mass radius [pc]	Metallicity $[Z_\odot]$	Primordial -binary fraction
I	12	7×10^3 – 5×10^4	$1, 2$	0.05 – 1.0	0
II	23 (include I)	7×10^3 – 1×10^5	$1, 2$	0.05 – 1.0	$0, 0.02, 0.05, 0.1$
III	22	7.5×10^3 – 5×10^4	$1, 1.5, 2$	0.05 – 1.0	$0.05, 0.1, 0.3, 0.5$
IV	65 (spins)	1×10^4 – 1×10^5	$1, 1.5, 2, 3$	$0.0001 - 0.02$	$0, 0.05, 0.1$

- Initial conditions are typical for young massive and open clusters
- All stars in the clusters are initially unsegregated
- All models are evolved for $10 - 13.7$ Gyr or until they dissolve completely
- Half-mass radius: the radius that contains half the total mass (c.f. Half-light radius)

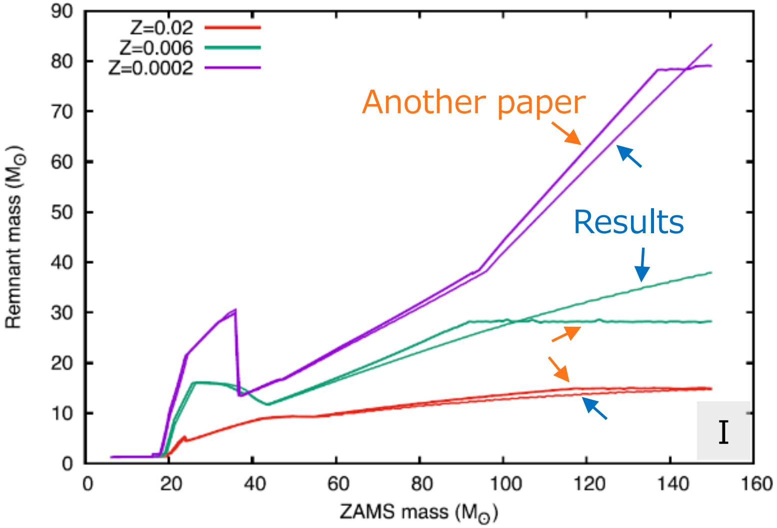
Initial conditions of model clusters

Paper	Number of models	Total mass [$M_\odot$]	Half-mass radius [pc]	Metallicity [$Z_\odot$]	Primordial -binary fraction
Ⅰ	12	7×10^3 – 5×10^4	$1, 2$	0.05 – 1.0	0
Ⅱ	23 (include Ⅰ)	7×10^3– 1×10^5	$1, 2$	0.05 – 1.0	$0, 0.02, 0.05, 0.1$
Ⅲ	22	7.5×10^3– 5×10^4	$1, 1.5, 2$	0.05 – 1.0	$0.05, 0.1, 0.3, 0.5$
Ⅳ	65 (spins)	1×10^4– 1×10^5	$1, 1.5, 2, 3$	$0.0001 - 0.02$	$0, 0.05, 0.1$

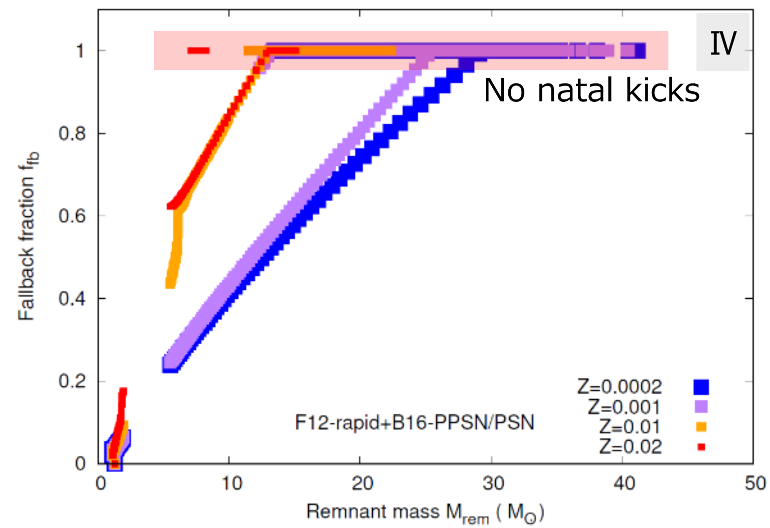
- Ⅰ : not important
- Ⅱ : large total mass, small primordial-binary fraction
- Ⅲ : large primordial-binary fraction
- Ⅳ : many models, spins, low metallicity

Basic quantities

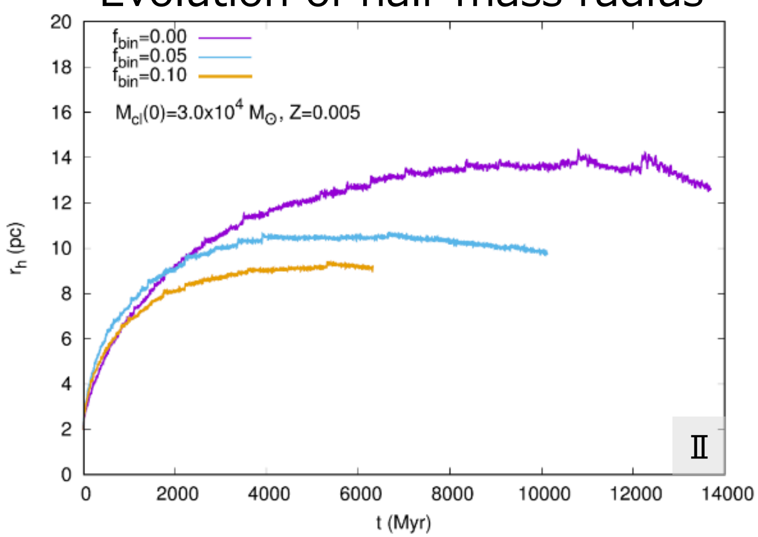
Remnant mass – ZAMS mass



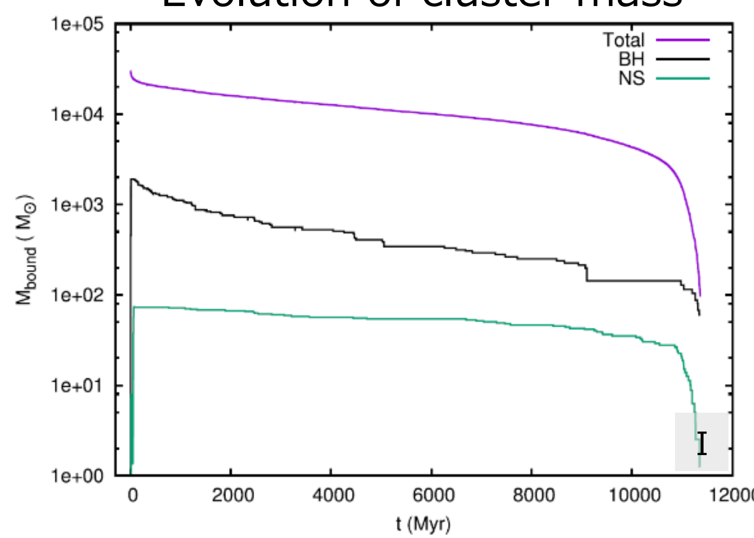
Fallback fraction - remnant mass



Evolution of half-mass radius

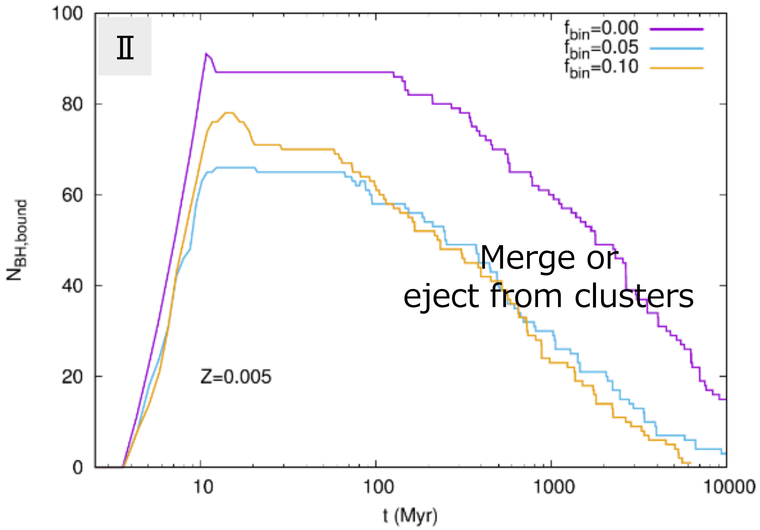


Evolution of cluster mass

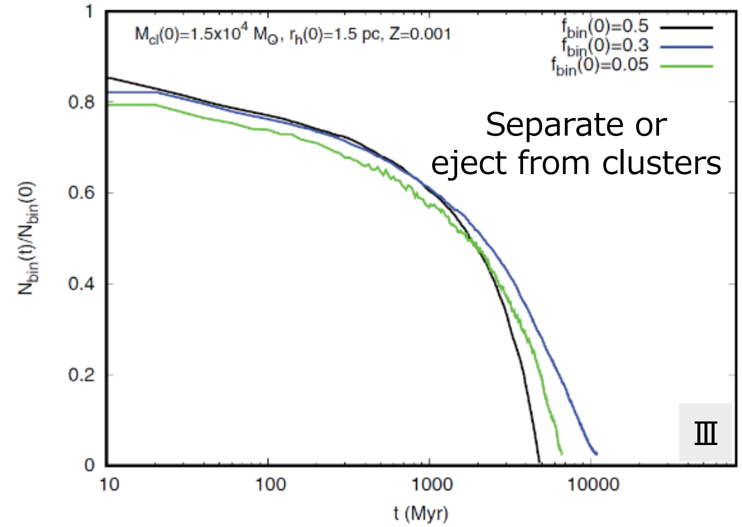


Basic quantities

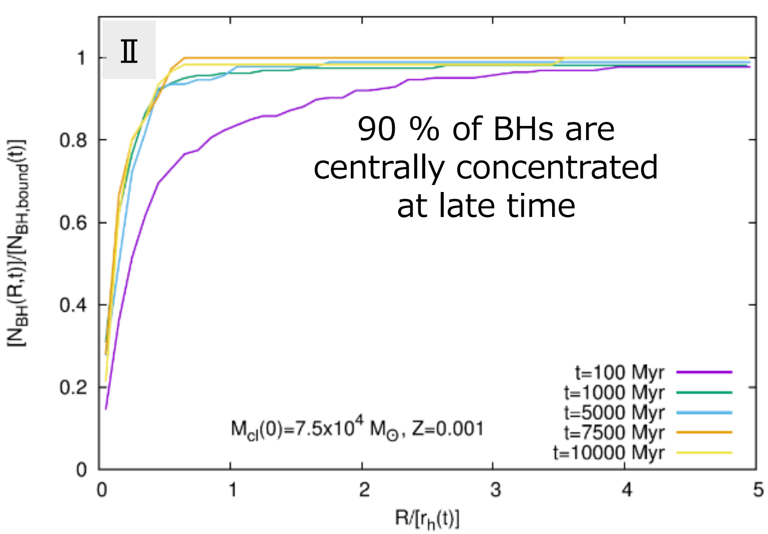
Evolution of BH number in cluster



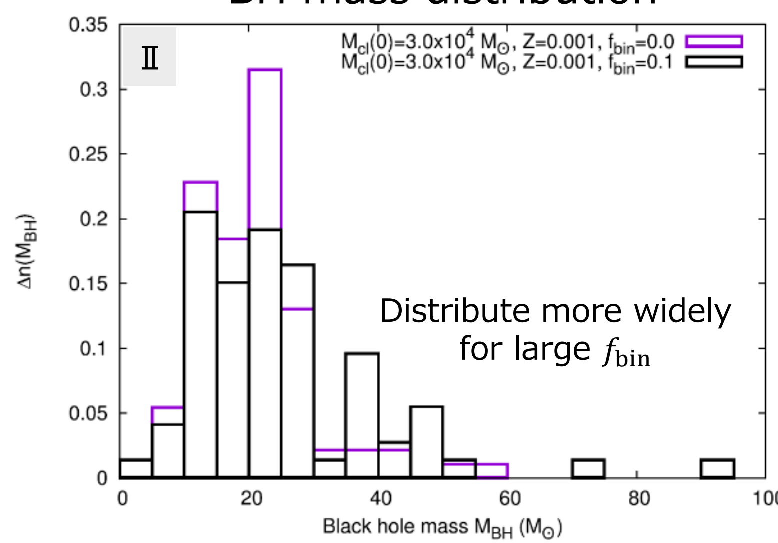
Evolution of binary number in cluster



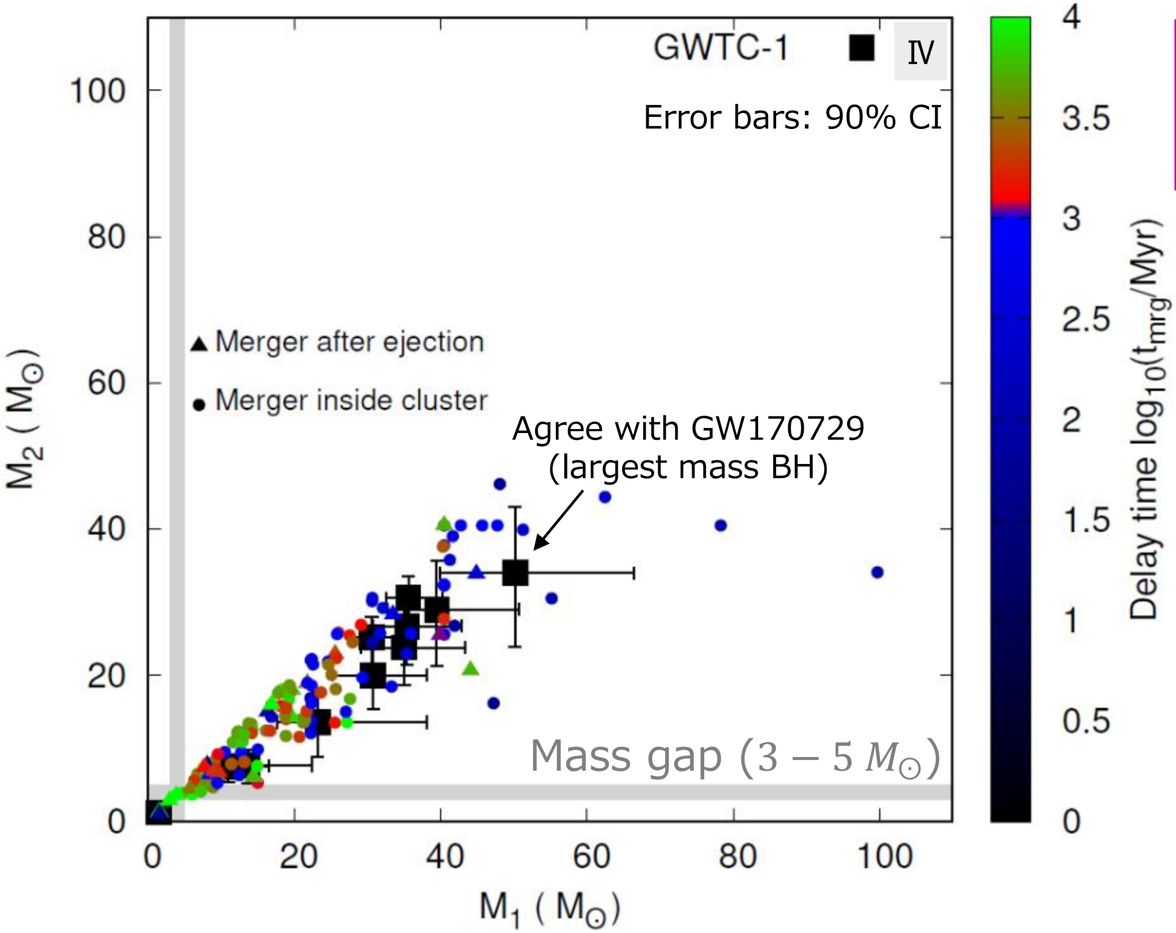
Cumulative radial distribution of BH in cluster



BH mass distribution



Primary mass - secondary mass



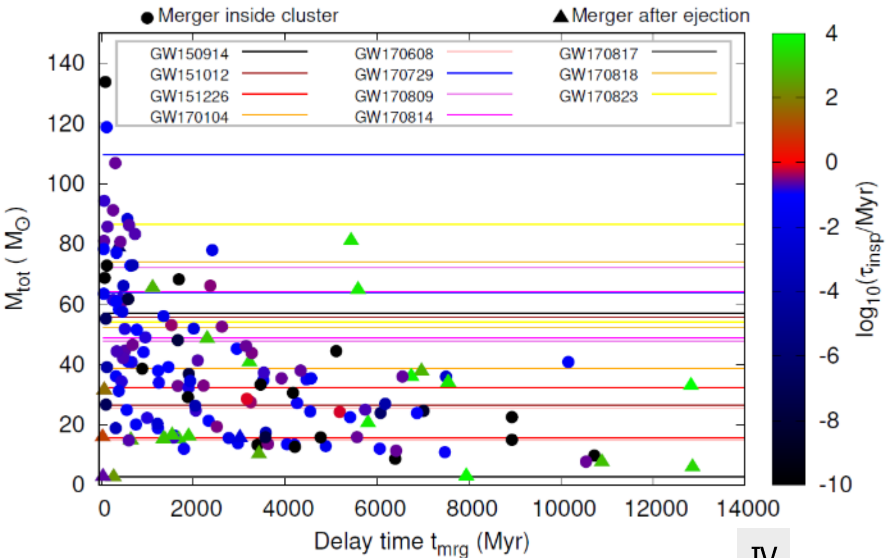
t_{mrg}: time interval between the beginning of cluster evolutions and the occurrence of mergers

Event
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170817
GW170818
GW170823

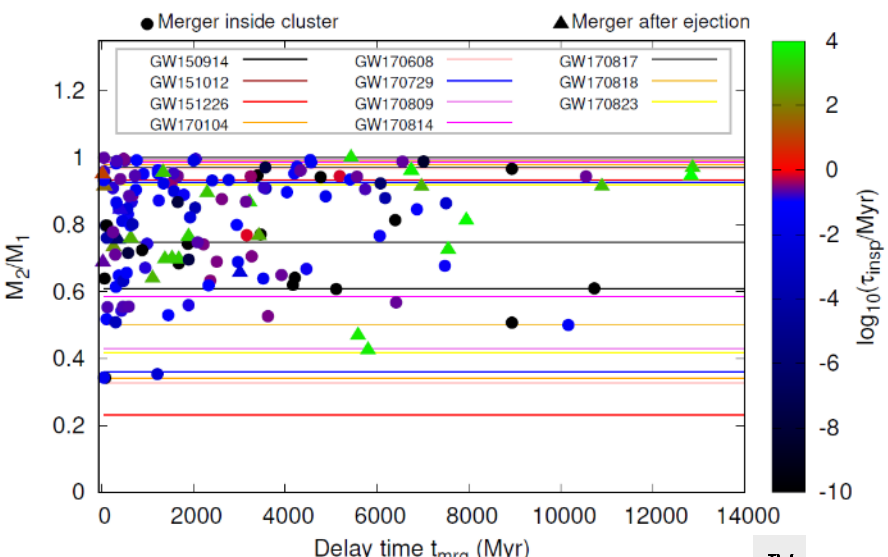
B. P. Abbott+ (2019)

GWTC (GW Transient Catalog) -1:
11 events with LIGO and Virgo during O1/O2

Total mass & mass ratio



IV



IV

Color horizontal lines: 90% CI
Coalescence time:

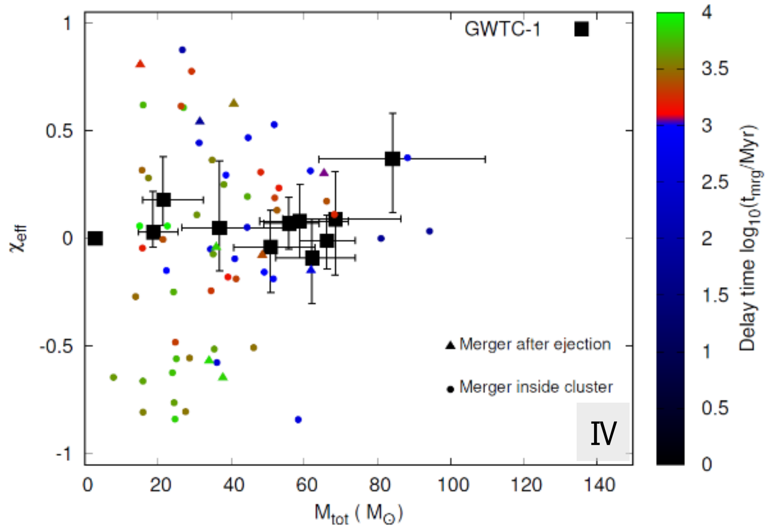
$$\tau_{\rm insp} \approx \frac{5}{64}\frac{c^5 a_{\rm ej}^4 (1-e_{\rm ej}^2)^{7/2}}{G^3 M_1 M_2 (M_1+M_2)}\left(1+\frac{73}{24}e_{\rm ej}^2+\frac{37}{96}e_{\rm ej}^4\right)^{-1}$$

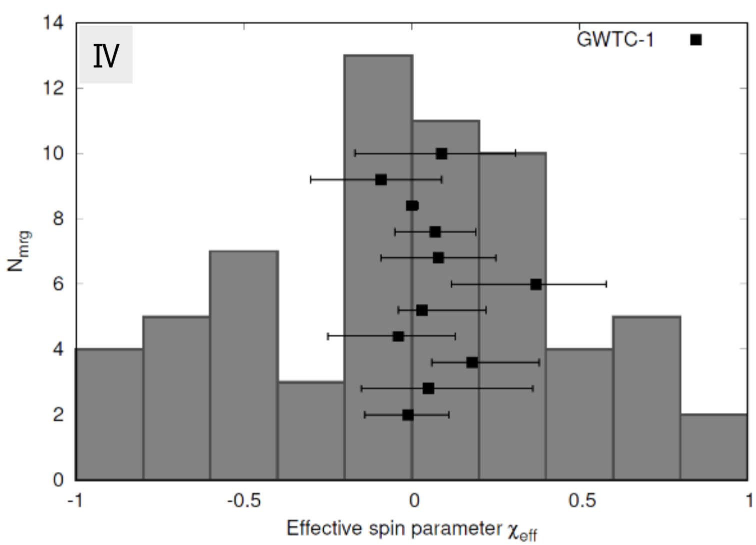
- $\tau_{\rm insp} \ll 1$ Myr for in-cluster mergers
- 1 Gyr $< \tau_{\rm insp} <$ 14 Gyr for ejected mergers

- Agree with O1/O2 data
- Not agree with GW190814 ($M_2/M_1 = 0.112^{+0.008}_{-0.009}$)

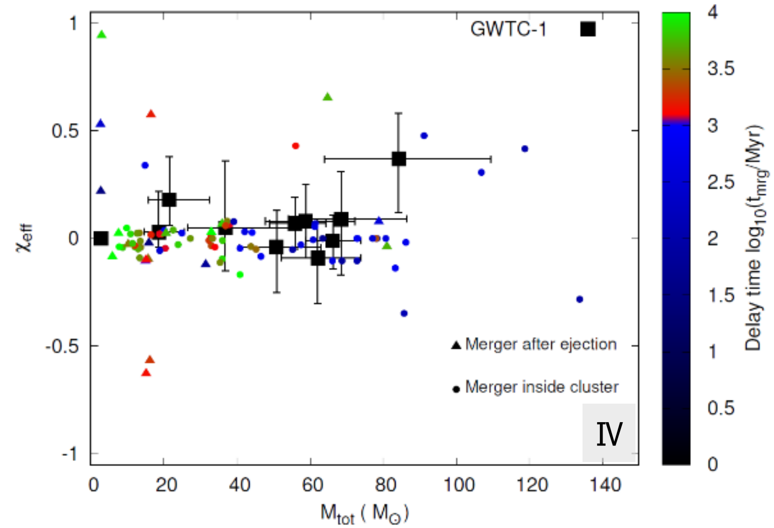
Effective spin parameter

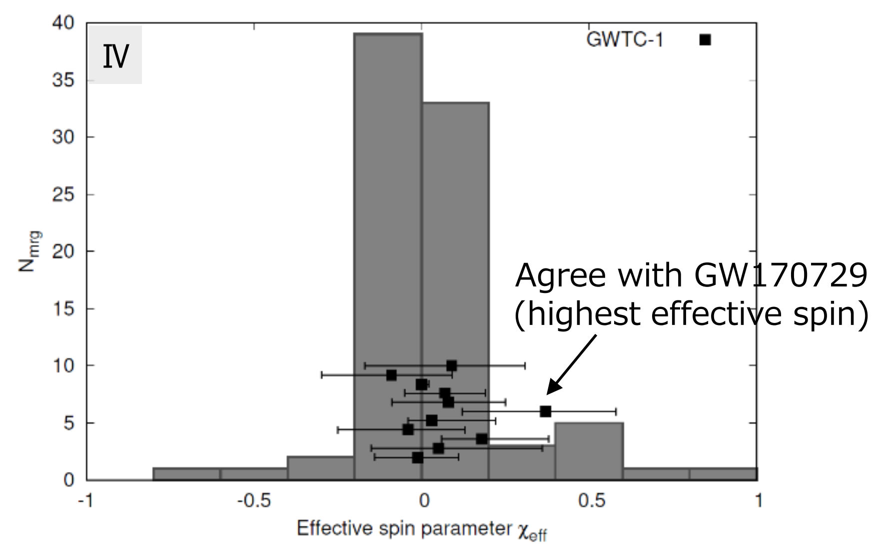
Geneva (high spin)





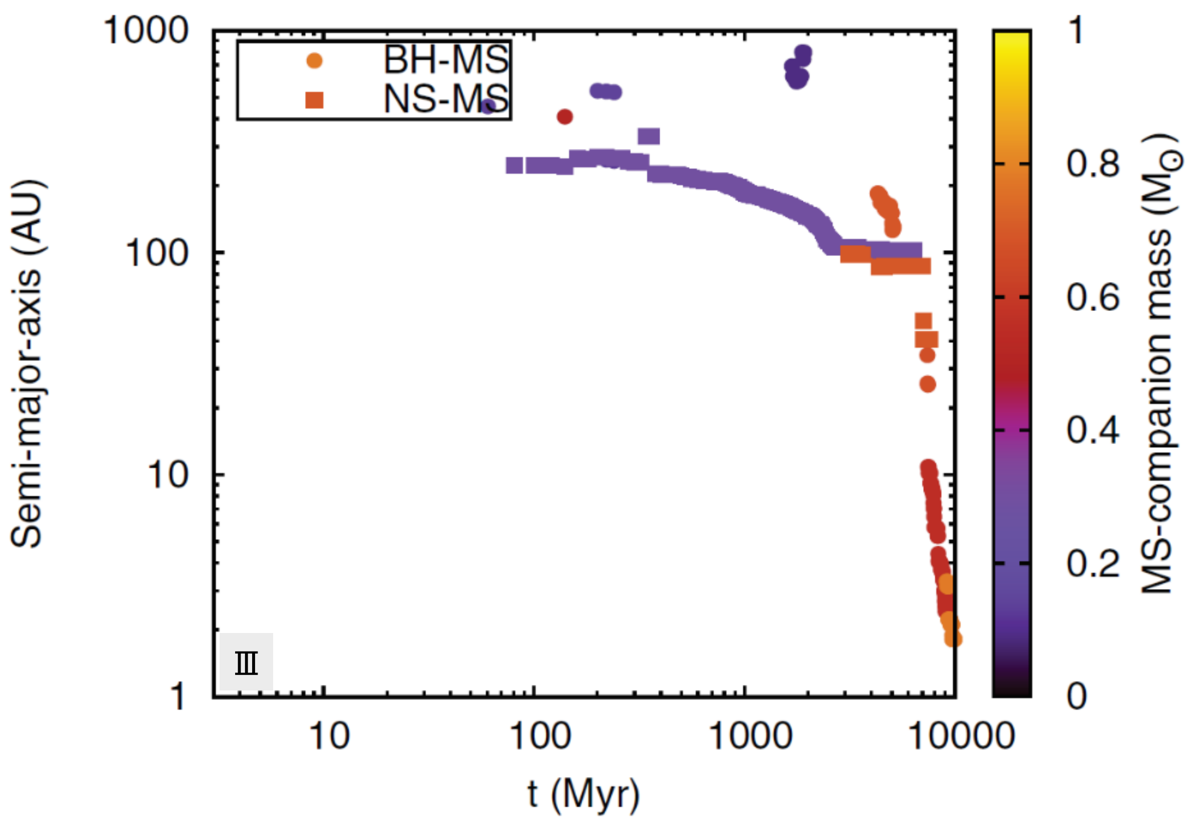
MESA (low spin)





non-BH binaries

- The majority of binaries are BBHs, but non-BH binaries are found
- For example, WD-WD, BH-WD and BH-MS (main sequence)
- Their mergers will leave electromagnetic signatures

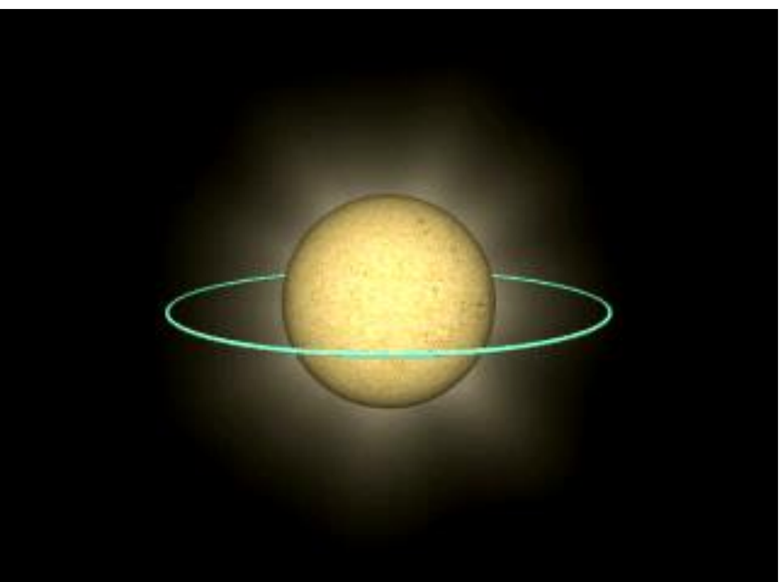


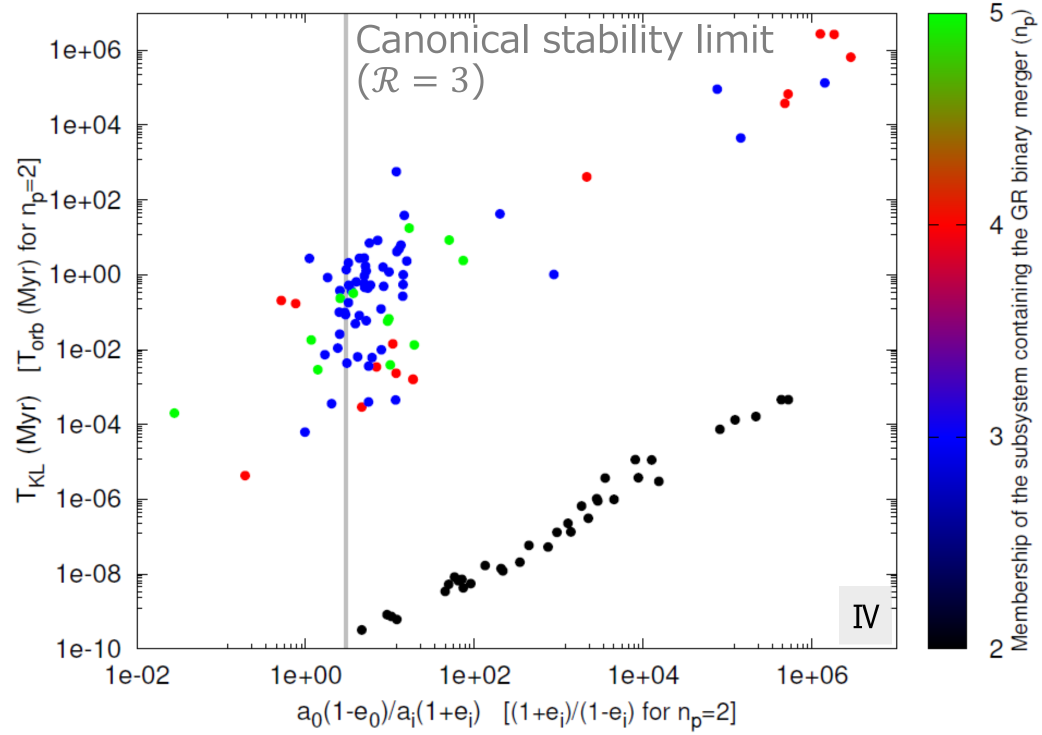
Triples or higher-order subsystems

- Some binary mergers occur in a triple or higher-order subsystems
- These subsystems are strongly perturbed and chaotic

Kozai-Lidov time period of the triple (innermost triple)

$$T_{\rm KL} = \frac{2P_{\rm o}^2}{3\pi P_{\rm i}}(1-e_{\rm o}^2)^{3/2}\frac{M_1+M_2+m_{\rm o}}{m_{\rm o}}$$





Ratio of the outer periastron to the inner apoastron of the triple (innermost triple)

$$\mathcal{R} = \frac{a_{\rm o}(1-e_{\rm o})}{a_{\rm i}(1+e_{\rm i})}$$

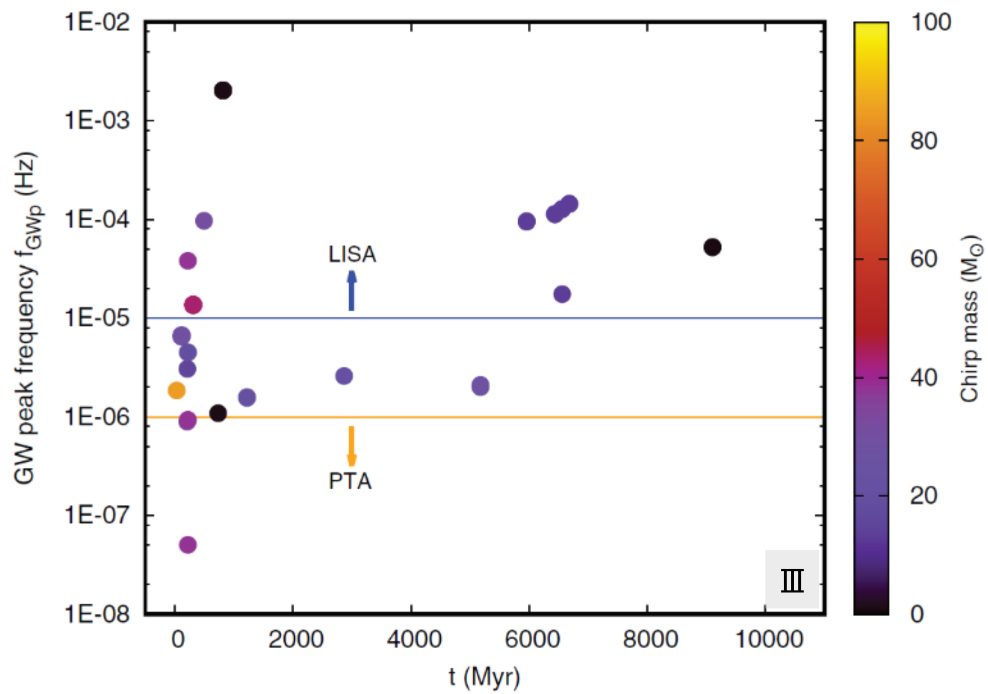
Wikipedia: HD 188753

Slingshot events

- "Slingshot" events:
  close fly-by interactions between a binary and
  a single object

- Slingshot events are highly eccentric ($e > 0.9$)
- The "proper" detection will be difficult
- They might contribute to GW background noise for LISA and PTA

[Wikipedia: Slingshot]

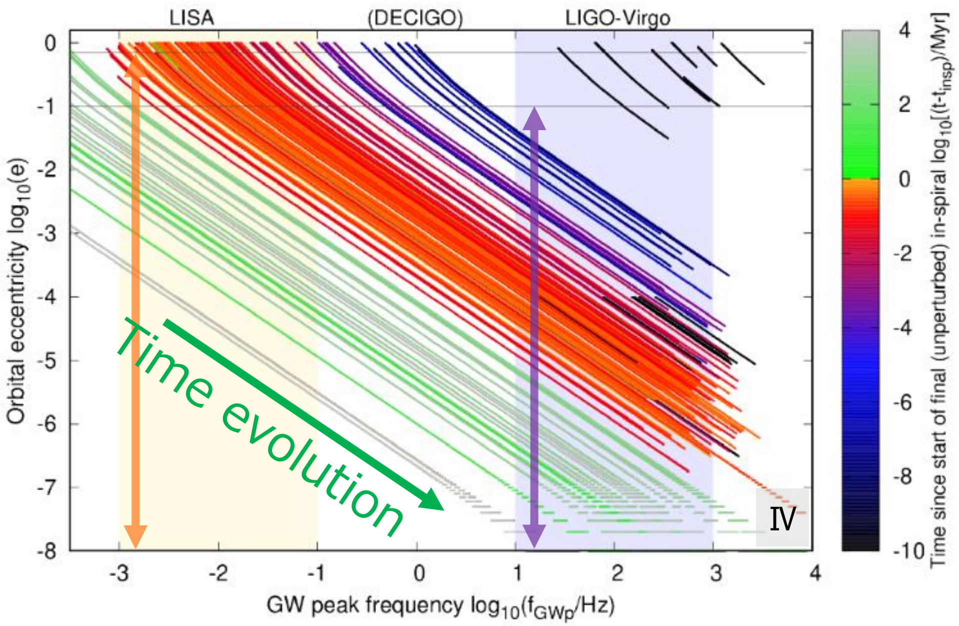


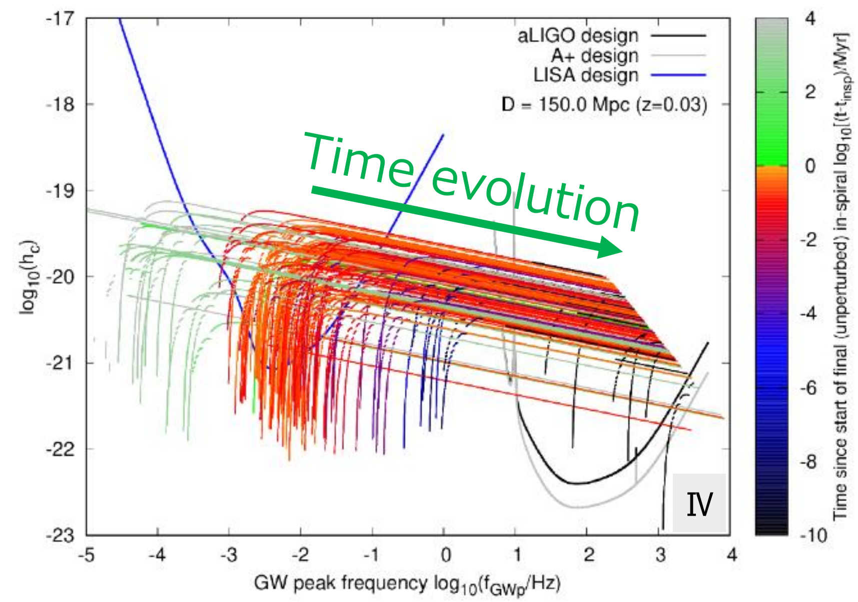
Evolution of orbital eccentricity

- Almost all BBHs have very high eccentricities
- The reason is slingshot events or in a triple

Detectable by LISA
$e \lesssim 0.7$

Detectable by LIGO-Virgo
$e \lesssim 0.1$





Peak-power GW frequency:

$$f_{\mathrm{GWp}} = \frac{\sqrt{G(M_1 + M_2)}}{\pi} \frac{(1 + e_t)^{1.1954}}{|a_t(1 - e_t^2)|^{1.5}}$$

Summary

- In general, star clusters are classified into open clusters and globular clusters by their age
- Many models of young massive and open clusters are prepared
- The dynamical formation of BBHs in clusters are simulated by N-body evolution program
- The results are similar to LIGO-Virgo data