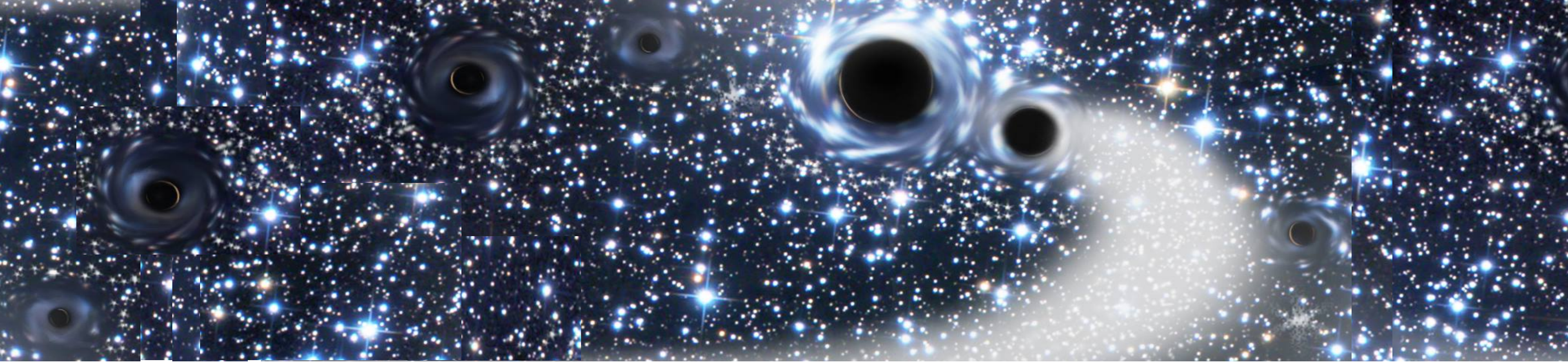


Merging stellar- and intermediate-mass black holes in dense clusters: implications for LIGO, LISA and the next generation of GW detectors

Manuel Arca Sedda

Colls: Pau Amaro-Seoane, Xian Chen, Francesco Rizzuto, Thorsten Naab, Rainer Spurzem, Mirek Giersz, Jeremiah Ostriker

ArXiv: 2007.13746

ArXiv: 2105.07003

Unterstützt von / Supported by

Alexander von Humboldt Stiftung/Foundation

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

SFB 881

11th IGWM | 09/11 - 06 - 2021

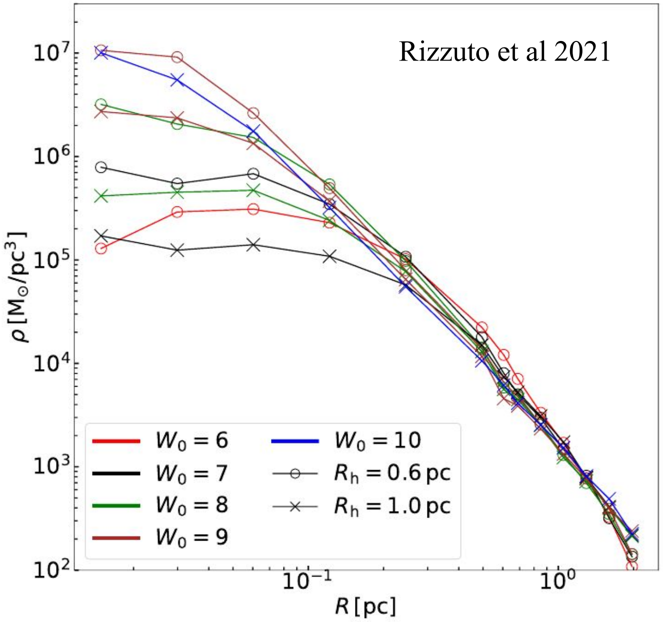
Summary

A. Formation of IMBH seeds

B. IMBH-BH mergers

C. Perspectives for current and future GW detectors

Formation of IMBH seeds in young clusters



From Rizzuto et al (2021)

1. Direct *N*-body simulations with GR effects for binary COs

1.1 No GW recoil!

1.2 No Spins!!

2. An IMBH forms in 17 cases out of 80 (~20%)

From Arca Sedda et al (ArXiv: 2105.07003)

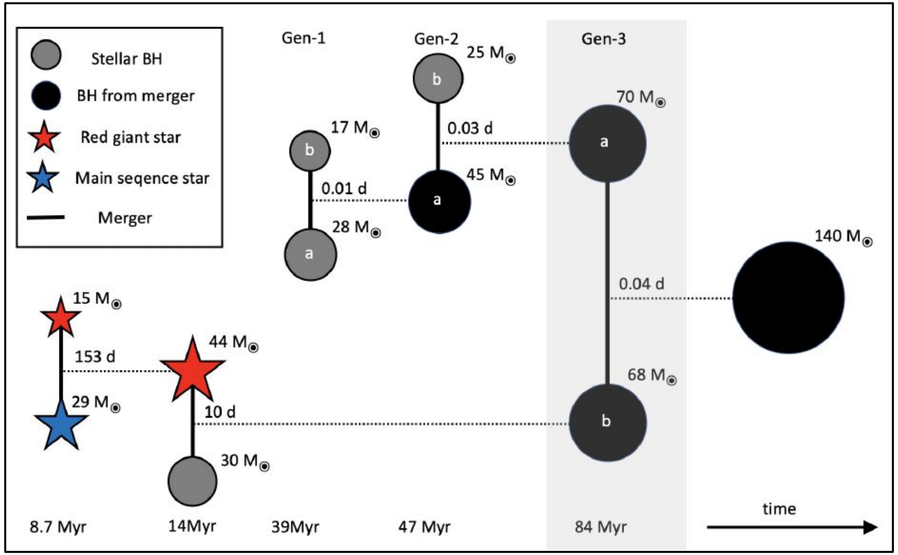
Use NR fitting formulae to measure spin and GW kicks for;

a. **2 IMBH-BH mergers**
b. **1 IMBH-BH-BH merger**
c. **1 triple BH merger chain**

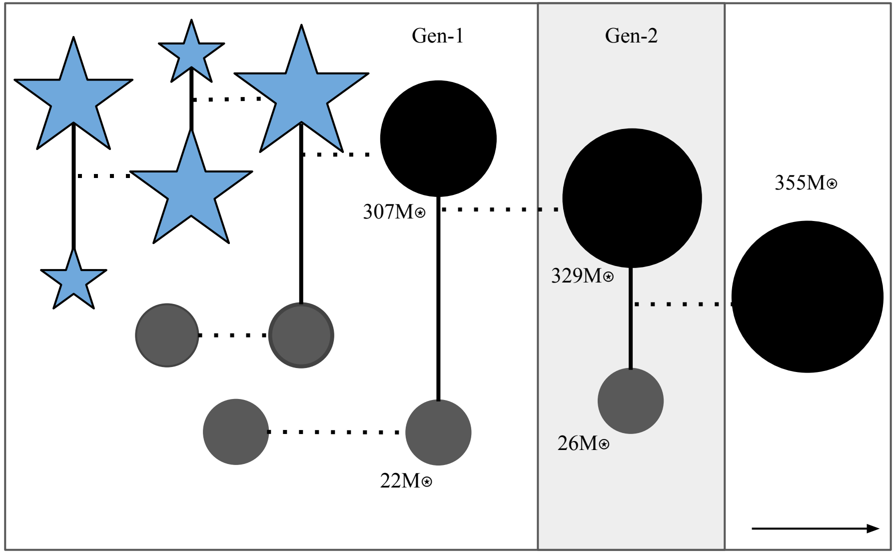
Rizzuto et al (2021), MNRAS, 501, pp 5257-5273
Arca Sedda, M. et al, ArXiv: 2105.07003

Formation of IMBH seeds in young clusters

Mergers in the upper mass-gap



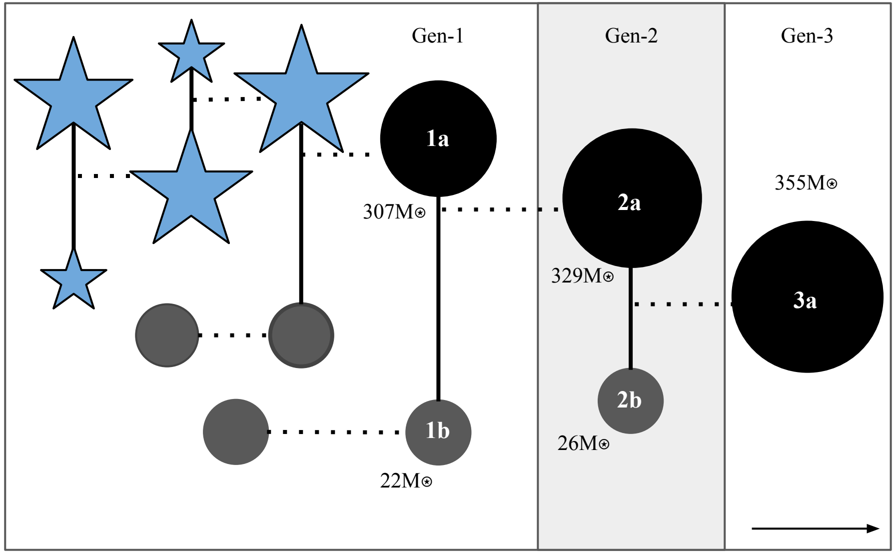
IMBH-BH mergers



Arca Sedda, M. et al, ArXiv: 2105.07003

Formation of IMBH seeds in young clusters

IMBH-BH mergers



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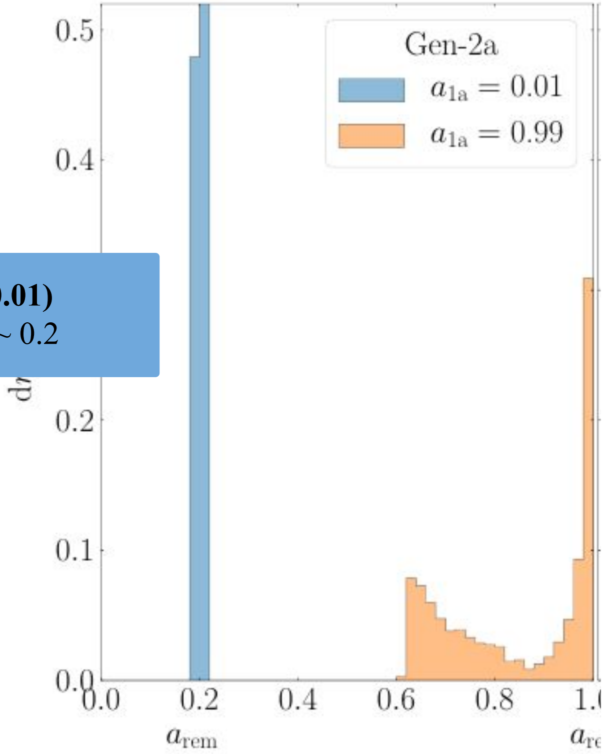
Merging IMBHs and BHs: spin and kicks of hierarchical merger products

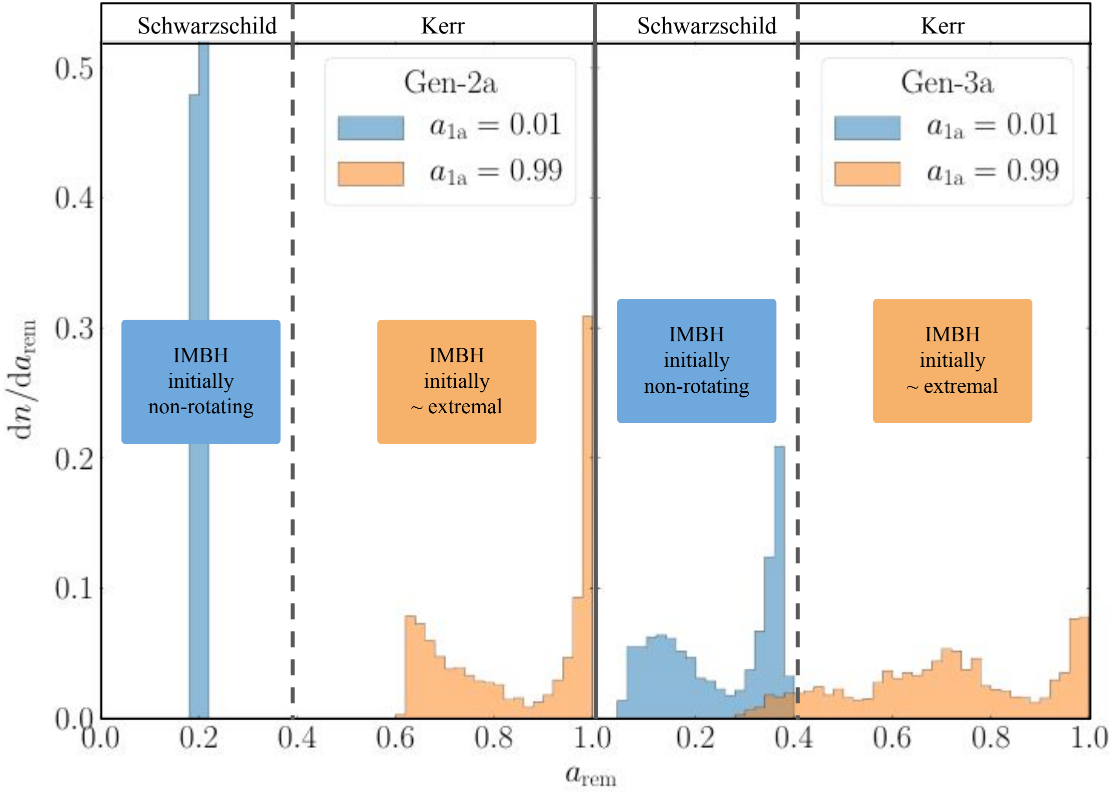


non-rotating IMBH (a_{1a} = 0.01)
remnant spin narrowly peaked $a_{rem} \sim 0.2$

nearly extremal IMBH (a_{1a} = 0.99)
wide spin distribution, peaks at $a_{rem} \sim 1$ and $a_{rem} \sim 0.6$

Arca Sedda, M. et al, ArXiv: 2105.07003

Merging IMBHs and BHs: spin and kicks of hierarchical merger products



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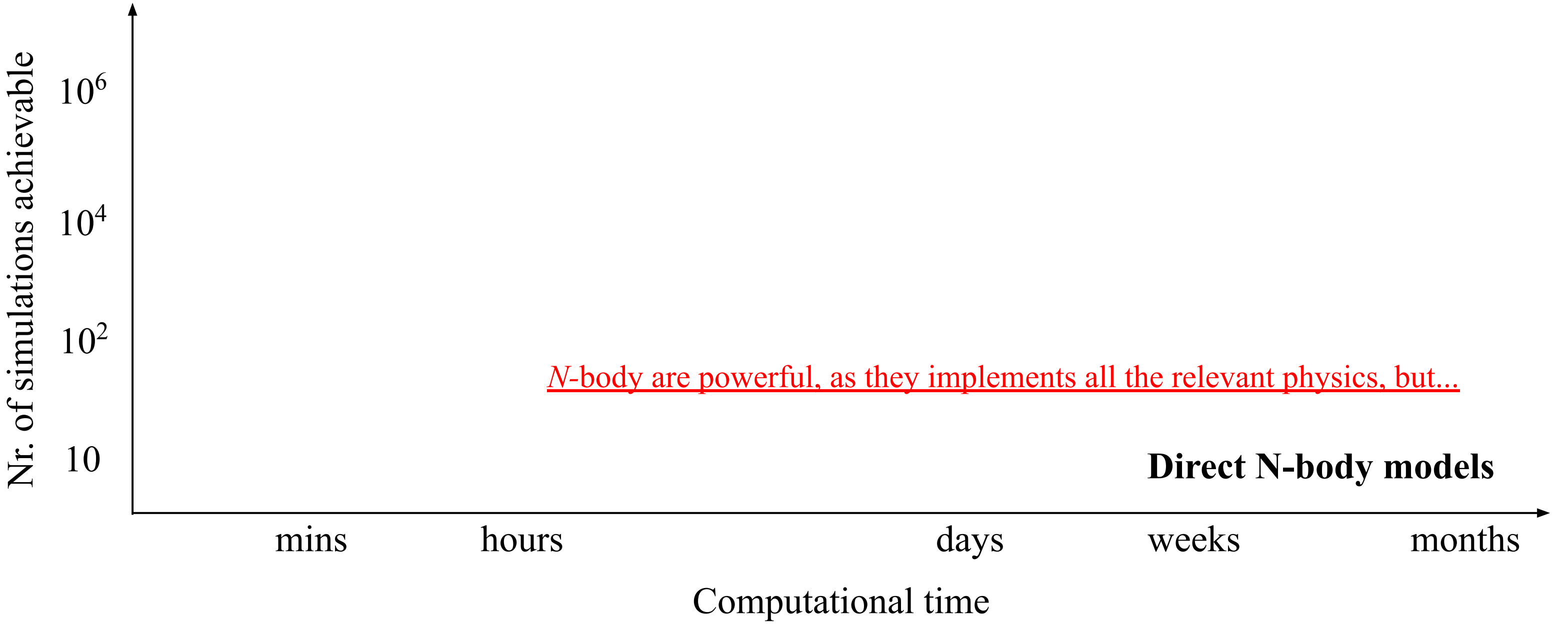
Beyond *N*-body: statistics with few-body simulations



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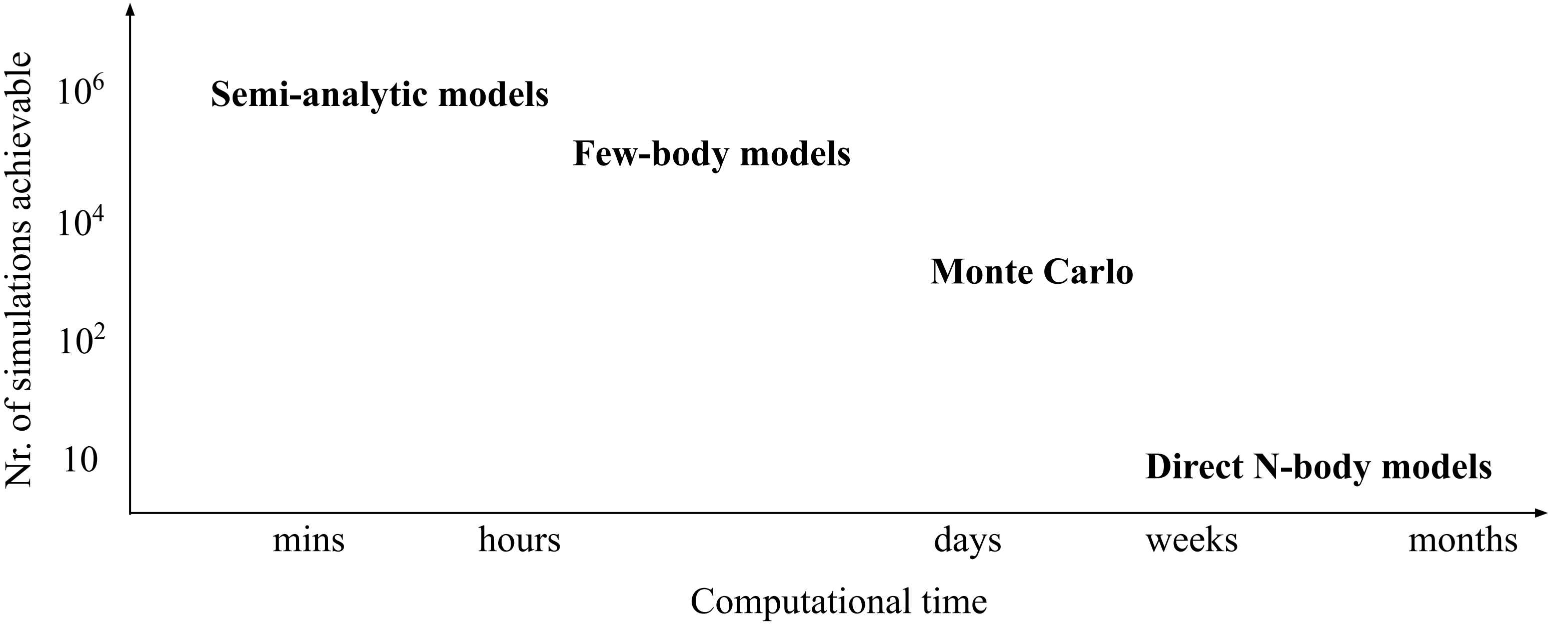

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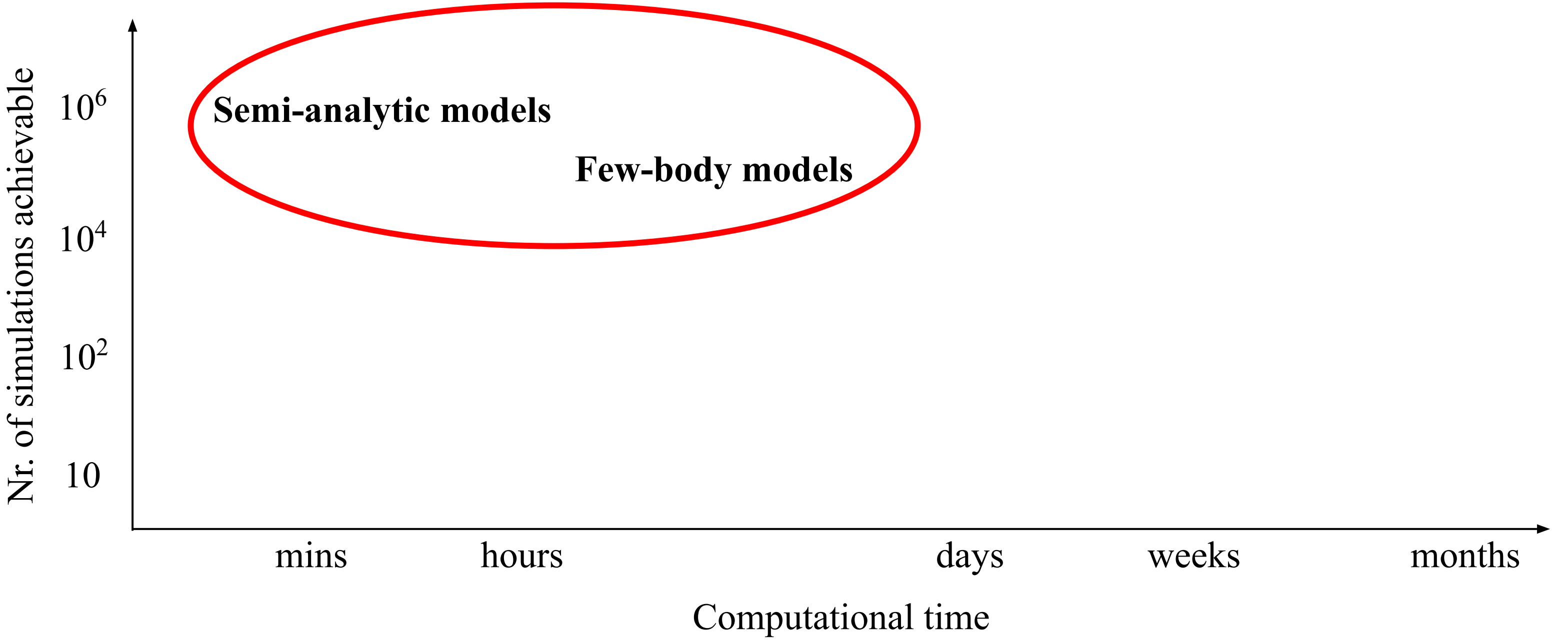


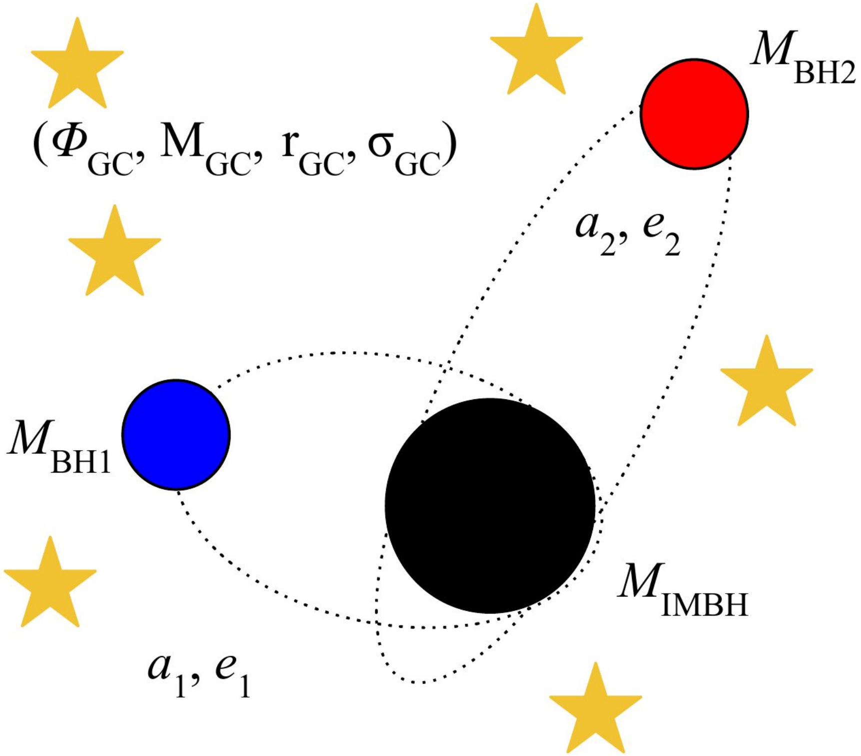
Perspectives for IMBH growth in dense clusters via repeated IMRI phases

Our phase space:

1. 2 stellar BHs orbiting around 1 IMBH
2. no initial hierarchy
3. PN1, 2, and 2.5 included
4. cluster overall field included

Main properties

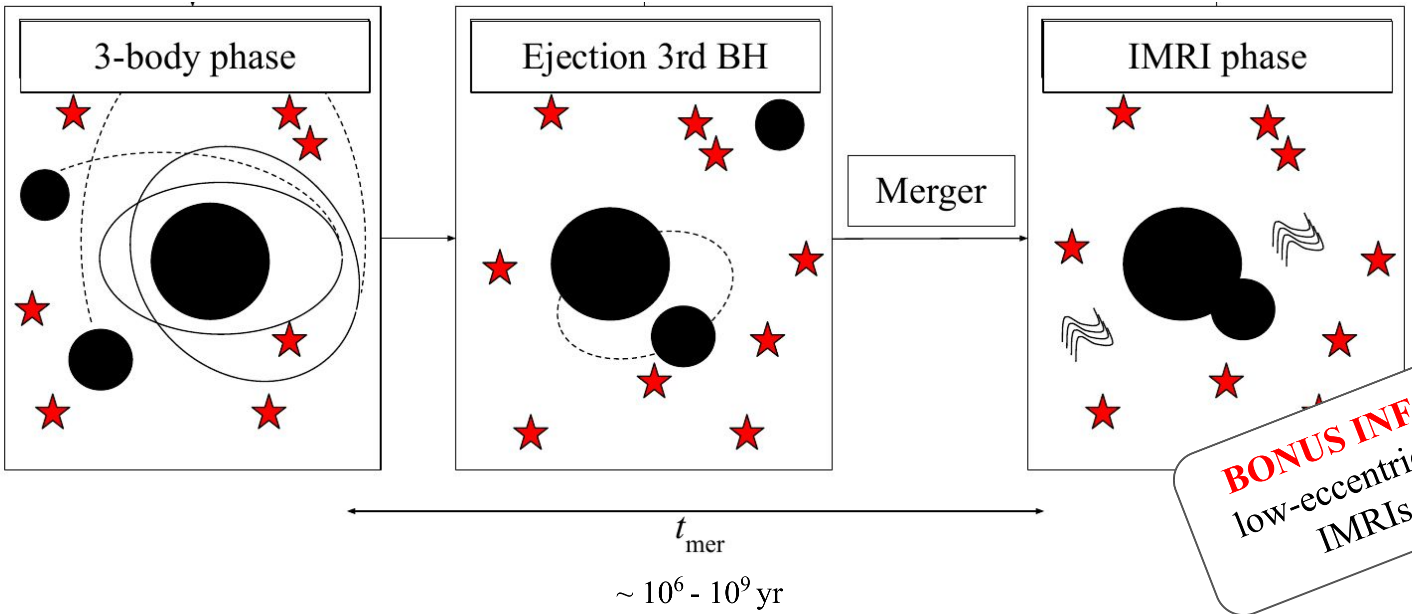
a. IMBH mass: 4 values
b. Cluster density: 3 cases
c. BH masses: 3 spectra
d. Metallicity: 2 values
e. Orbital distribution: 2 cases



Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

Perspectives for IMBH growth in dense clusters via repeated IMRI phases: a semi-analytic approach to quantify the impact of multiple IMBH-BH mergers

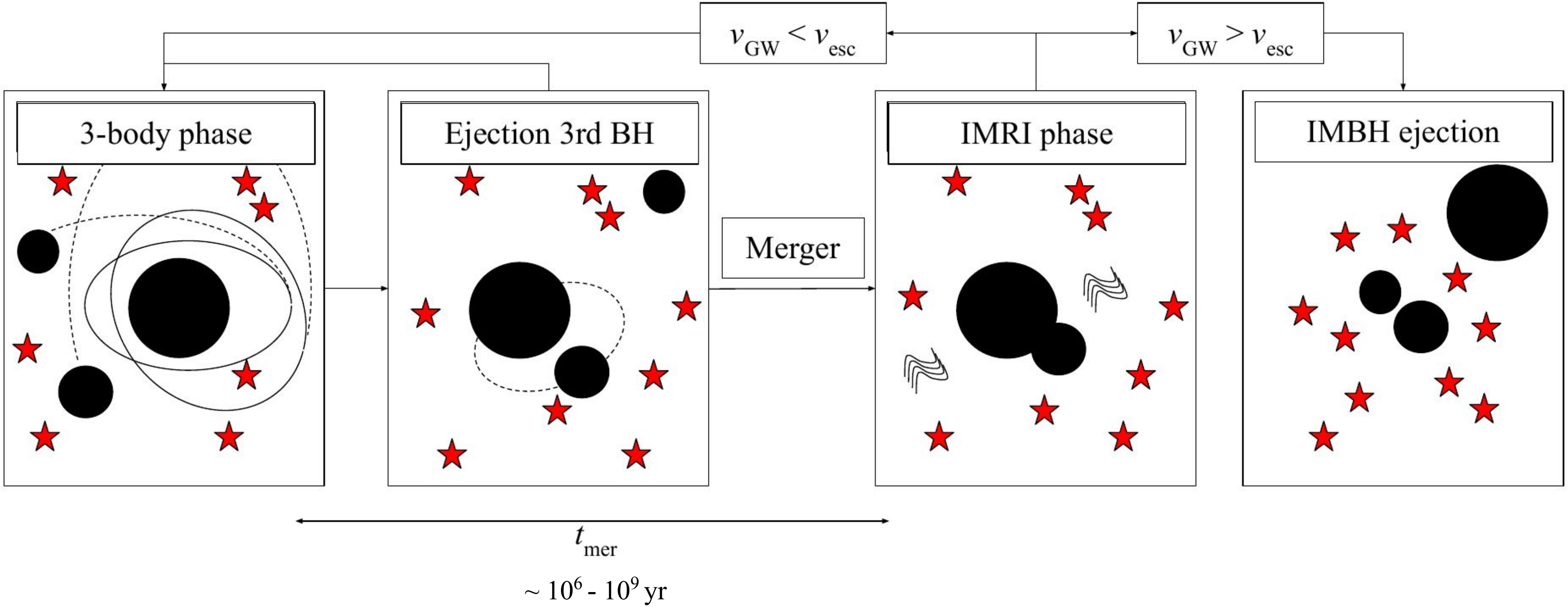
Probed with three-body simulations: merger probability ~5-50%



BONUS INFO low-eccentricity IMRIs

Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

Perspectives for IMBH growth in dense clusters via repeated IMRI phases: a semi-analytic approach to quantify the impact of multiple IMBH-BH mergers



Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

Perspectives for IMBH growth in dense clusters via repeated IMRI phases: IMBH mass and spin across cosmic times

How?

Use previous scheme, with:

z = 2-6

M_{seed} = 100-500 M⊙

M_c = 10^5 - 5×10^6 M⊙

$f(M)$ = kM^{-2}

Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

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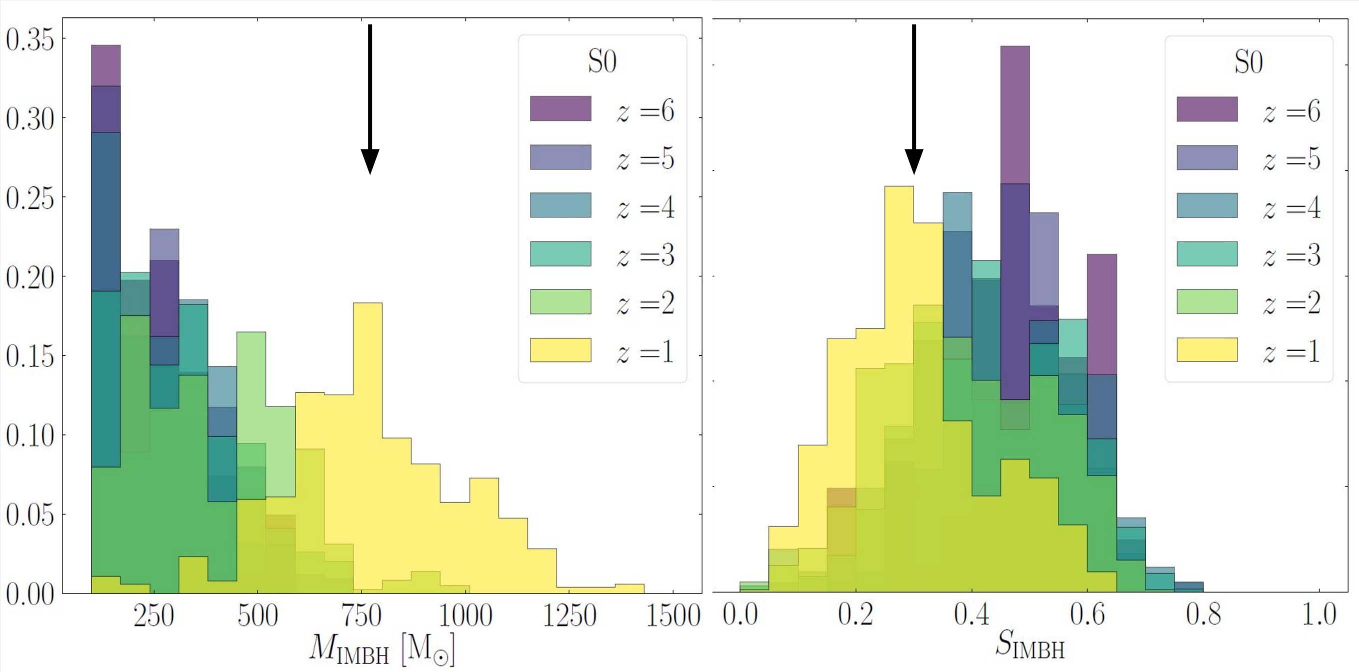
What IMBHs @ $z < 1$?

i. Mass spectrum

M_{IMBH} = 750M⊙

ii. spins distribution

S_{IMBH} = 0.3



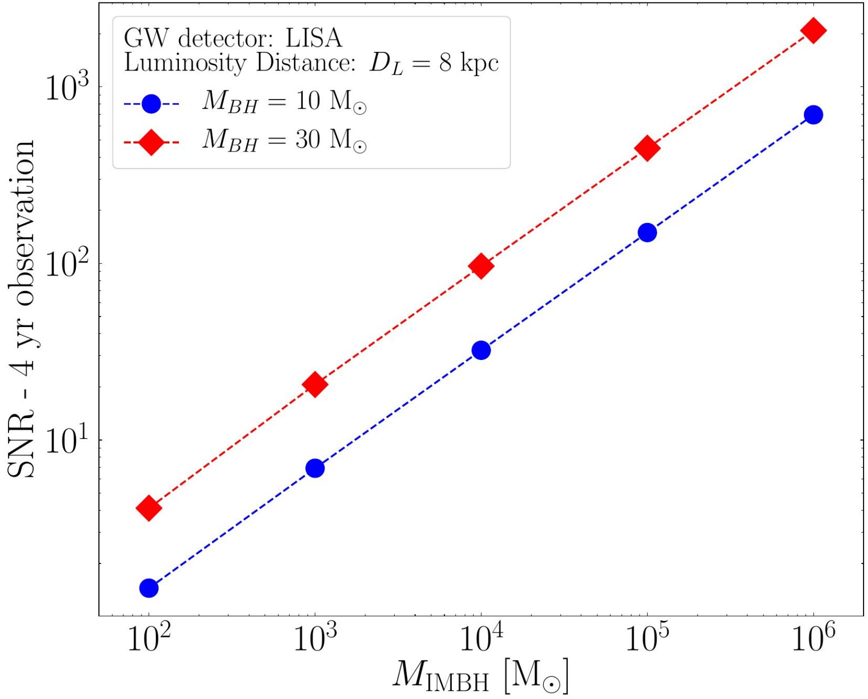
Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

Implications for current and future GW detectors: IMBHs in Milky Way globulars with LISA

- Our models suggests ~ circular IMRIs in the LISA band (on average)

  GW signal: $$h_{\rm GB} = \frac{8T_{\rm obs}^{1/2}(G\mathcal{M}/c^3)^{5/3}(\pi f)^{2/3}}{\sqrt{5}D_L/c}$$

- Do we have any chance to observe the closest one (e.g. within 8 kpc)?



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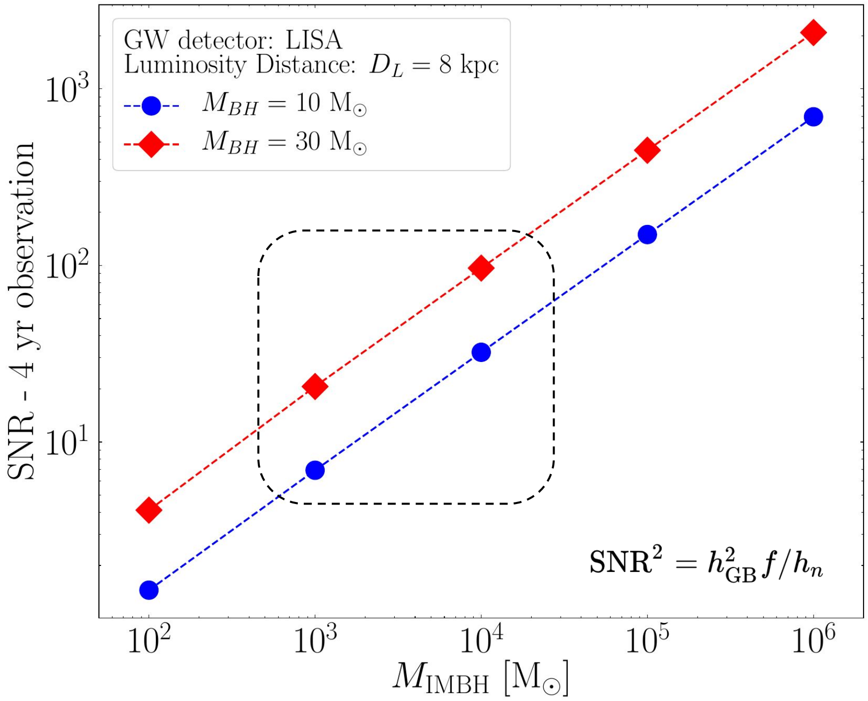
➢ Is there any cluster within 8 kpc from us? Any IMBH host candidate?

  - 47Tuc (Kızıltan et al. 2017), NGC6266 (Abbate et al. 2019a), NGC6128 and NGC288 (Sollima et al. 2016), NGC6388 and NGC2808, the Galactic Centre (Oka et al 2017, Takekawa et al 2019)
  - **SNR = 6 – 100 [M_{IBH} = 10^3 - 10^4 M_{SUN} + M_{BH} = 10 - 30 M_{SUN}]**



Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

Implications for current and future GW detectors: IMRIs cosmic merger rate

- Signal to noise ratio (we set SNR = 15, observation time T_{obs} = 4 yr):

$$\mathrm{SNR}^2 = \int_{f_1}^{f_2} \frac{h_c^2(f, z_{\rm hor})}{S_n^2(f)} \mathrm{d}f$$

- IMRIs merger rate:

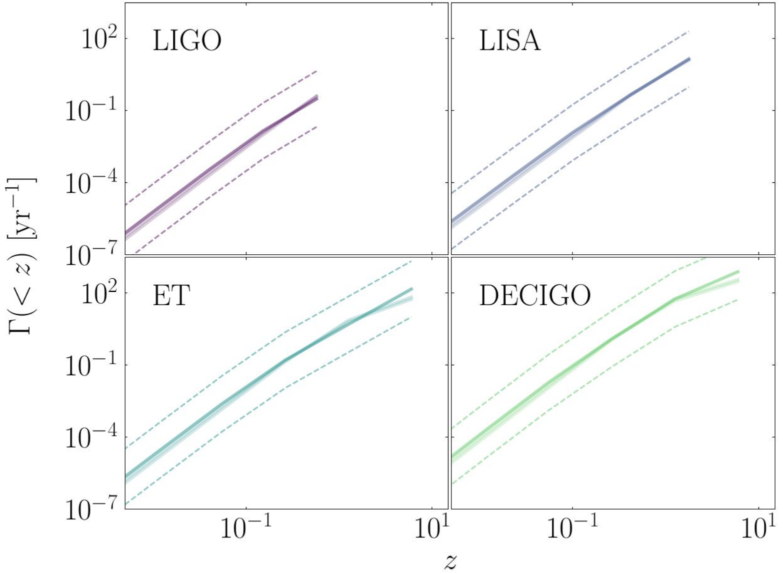
$$\Gamma_{\rm IMRI} = \Omega_s \int_{M_1}^{M_2} \int_0^{z_{\rm hor}} \frac{\mathrm{d}n_{\rm IMRI}}{\mathrm{d}M_{\rm IMBH}\mathrm{d}z} \frac{\mathrm{d}V_c}{\mathrm{d}z} \frac{\mathrm{d}z}{1+z} \mathrm{d}M_{\rm IMBH}$$

- Number of IMRIs per unit IMBH mass (3 approaches):

$$\frac{\mathrm{d}n_{\rm IMRI}}{\mathrm{d}M_{\rm IMBH}} = \xi_{\rm BH} f_{\rm GW} p_{\rm IMBH} n_{\rm rep} \frac{\mathrm{d}n}{\mathrm{d}M_g \mathrm{d}z} \frac{\mathrm{d}n_{\rm GC}}{\mathrm{d}M_{\rm GC}} \frac{\mathrm{d}M_{\rm GC}}{\mathrm{d}M_{\rm IMBH}}$$

BH abundance
IMRI merger probability
IMBH abundance
IMRI number per single IMBH
Galaxy cosmic mass function
Star cluster mass function
IMBH - cluster mass relation

Cumulative IMRIs merger rate vs. redshift



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Implications for current and future GW detectors: IMRIs cosmic merger rate

Instrument	$M_{\rm SBH}$ $M_\odot$	$z_{\rm max}$	$M_{{\rm IMBH},max}$ $M_\odot$	$\Delta\Gamma_1$ yr^{-1}
LIGO	10	0.38	200	0.003 – 0.54
LIGO	30	0.57	200	0.006 – 1.3
LISA	10	0.70	46240	0.024 – 5.1
LISA	30	1.78	46240	0.27 – 56.2
ET	10	6.00	2000	1.9 – 399.7
ET	30	6.00	2000	2.8 – 596.5
DECIGO	10	6.00	46240	15.0 – 3139
DECIGO	30	6.00	46240	15.0 – 3139

LIGO-Virgo-Kagra: ~1-2 IMRIs with $M < 200\ M_\odot$ in 1 yr of observation

LISA: ~5-60 IMRIs with $M < 46{,}000\ M_\odot$ in 1 yr of observation

ET/DECIGO: >10^3 IMRIs with $M < 46{,}000\ M_\odot$ in 1 yr of observation

Nr. of detection per yr

Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746

Takehome

1. From direct *N*-body + postprocessing (*Arca Sedda, M. et al, ArXiv: 2105.07003*):

   a. Formation probability of IMBHs in young clusters ~ 20% (stellar accretion efficiency?)

   b. IMBH-BH mergers attain masses ~ 300 $M_{\odot}$ in dense clusters (long-term retention?)

   c. if long IMBH-BH merger chain are rare, IMRIs can tell us more about IMBHs natal spins (natal spins?)

2. From the three-body + semi-analytic approach (*Arca Sedda, Amaro-Seoane, and Chen, ArXiv: 2007.13746*):

   a. IMRI mergers ~ 5-50% of models (how many BHs if an IMBH is there?)

   b. For $M_{\rm IMBH} \sim 500\ M_{\odot} \rightarrow$ retention <50% if $M_{\rm BH} > 15\ M_{\odot}$ (mass spectra of BHs?)

   c. IMBH mass and spin distributions at $z < 1$ peak at $M_{\rm IMBH} \sim 750\ M_{\odot}$ and $a_{\rm IMBH} \sim 0.3$ (parameter space?)

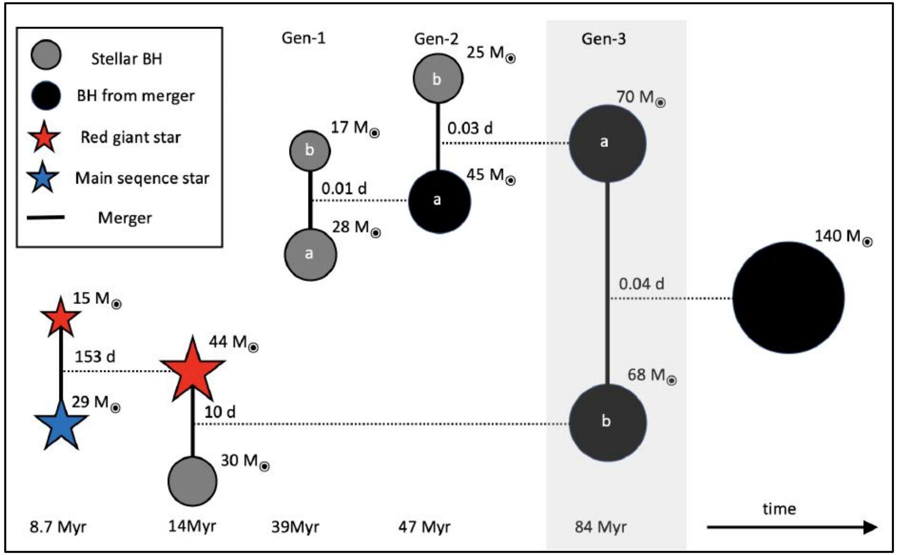
   d. LISA in the Milky Way: detection of $M_{\rm IMBH} \sim 10^{3\text{-}4}\ M_{\odot}$ (SNR ~ 6 – 100) (how many IMBHs in MW?)

   e. LIGO < 2 detections yr^{-1}, LISA < 60 yr^{-1}, ET/DECIGO ~ (500 - 3000) yr^{-1} (sensitivity curves?)

Supplementary slides

Formation of IMBH seeds in young clusters

Mergers in the upper mass-gap



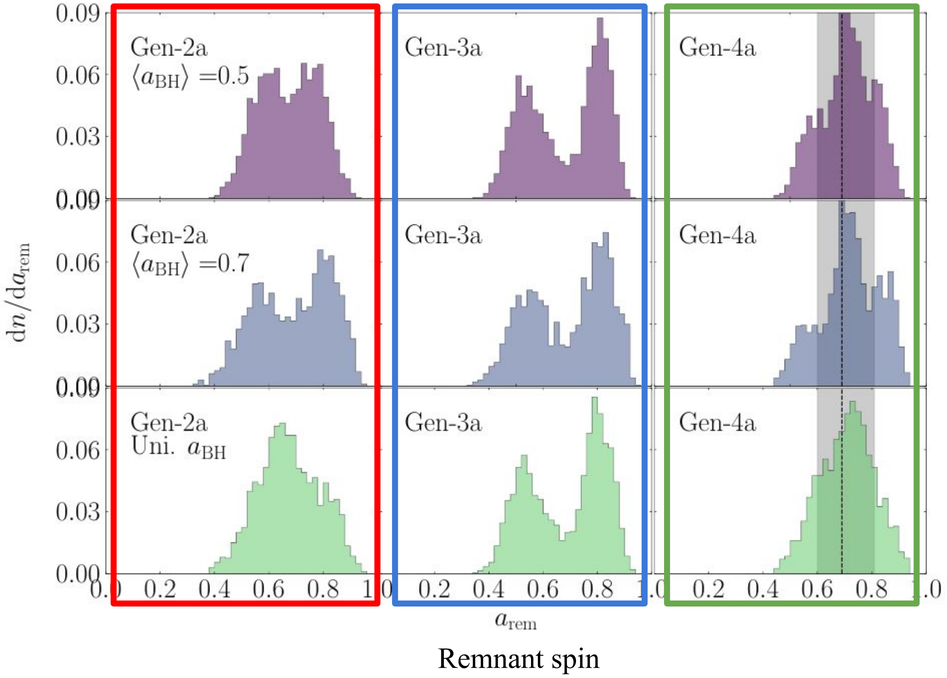
Mergers in the upper mass-gap: spin and kicks of hierarchical merger products

1. Extract BH masses from direct *N*-body (Gen-1a + Gen-1b)

2. Sample BH spins from a distribution (Gaussian centered on 0.5 or 0.7, Uniform)

3. Calculate remnant mass and spin through NR fitting formulae and recoil kicks (e.g. Arca Sedda & Benacquista 19, Arca Sedda+20) (Gen-1a + Gen-1b) → Gen-2a

4. Merge the remnant with the next stellar BH (Gen-2a + Gen-2b) → Gen-3a



A triple merger leads to a final BH spin compatible with GW190521 in 60-78% of cases

Mergers in the upper mass-gap: spin and kicks of hierarchical merger products

What environment could retain the merger remnant?

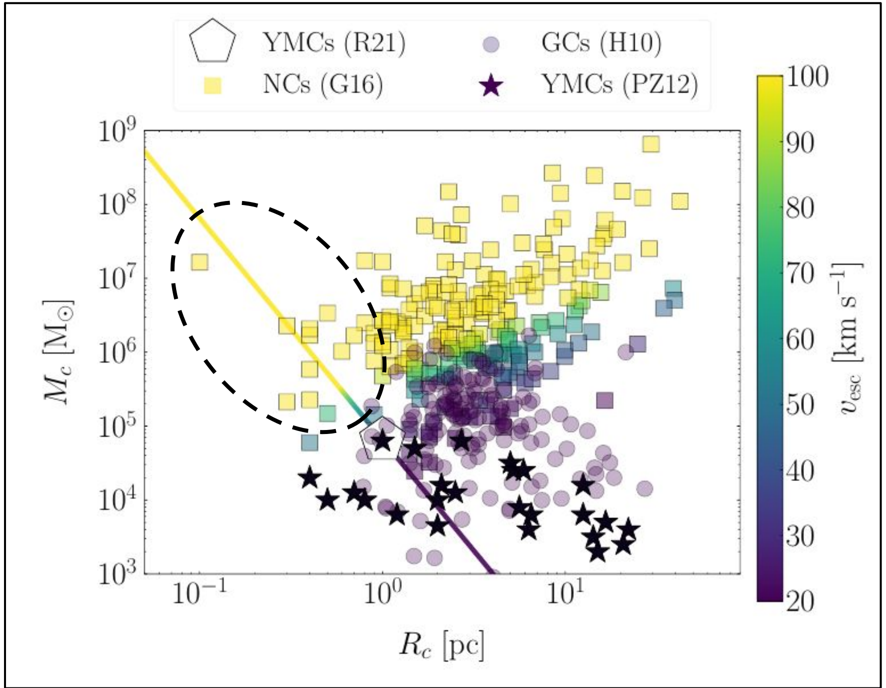
1. The timescale for the merger formation is connected with the relaxation time

$$t_{\rm rlx} \propto M^{1/2} r_h^{3/2}$$

2. The central escape velocity must increase

$$v_{\rm esc}^2 \propto M/r_h$$

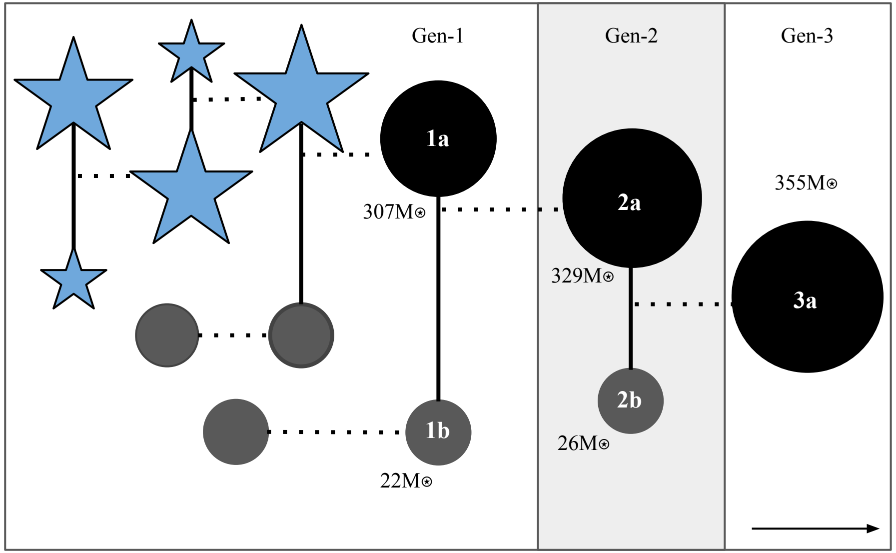
3. Possible host have same $t_{\rm rlx}$ and $v_{\rm esc} > v_{\rm kick}$



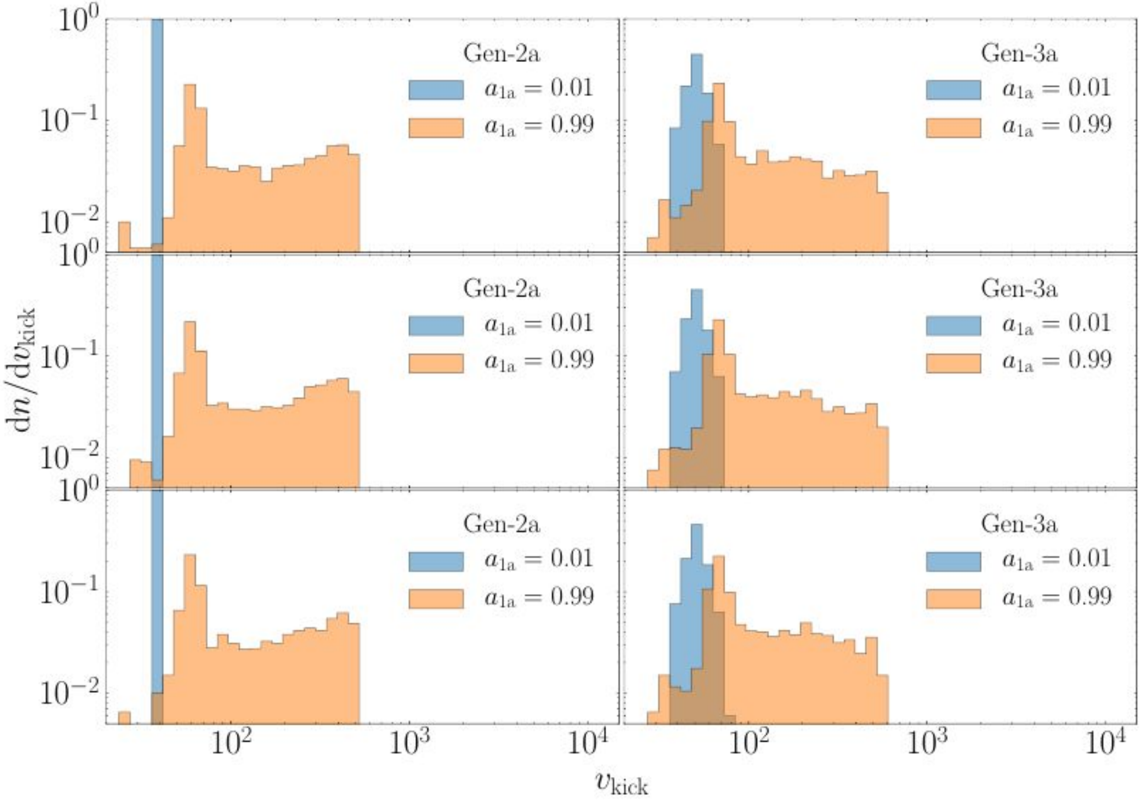
Only cluster with $M_c > 3 \times 10^5$ M$_\odot$ and $R_c < 0.6$ pc can retain long merger chains

Formation of IMBH seeds in young clusters

IMBH-BH mergers



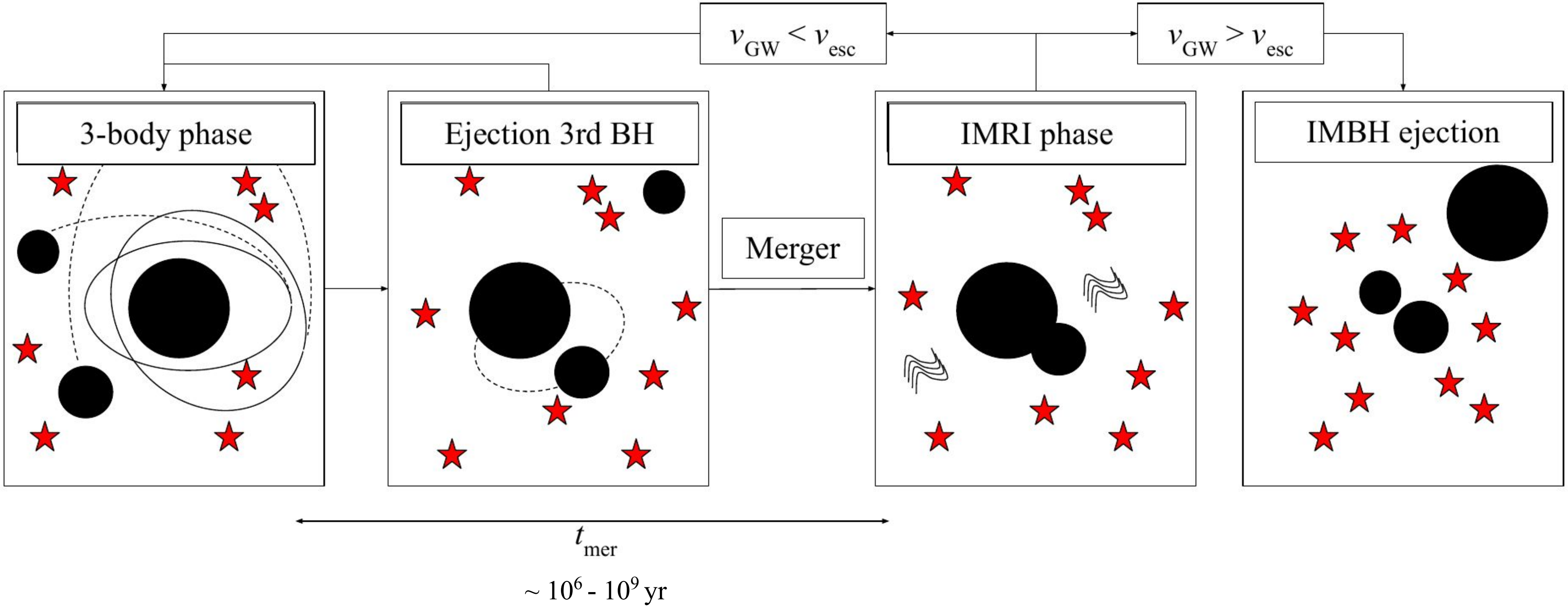
Merging IMBHs and BHs: spin and kicks of hierarchical merger products



1. Slowly spinning IMBHs:
   - Gen-2a: $v_{kick} \sim 30$ km/s
   - Gen-3a: $v_{kick} < 50$ km/s

2. Highly spinning IMBHs:
   - Gen-2a: $v_{kick} \sim 30 - 500$ km/s
   - Gen-3a: $v_{kick} < 20 - 500$ km/s

Perspectives for IMBH growth in dense clusters via repeated IMRI phases:
a semi-analytic approach to quantify the impact of multiple IMBH-BH mergers



Perspectives for IMBH growth in dense clusters via repeated IMRI phases

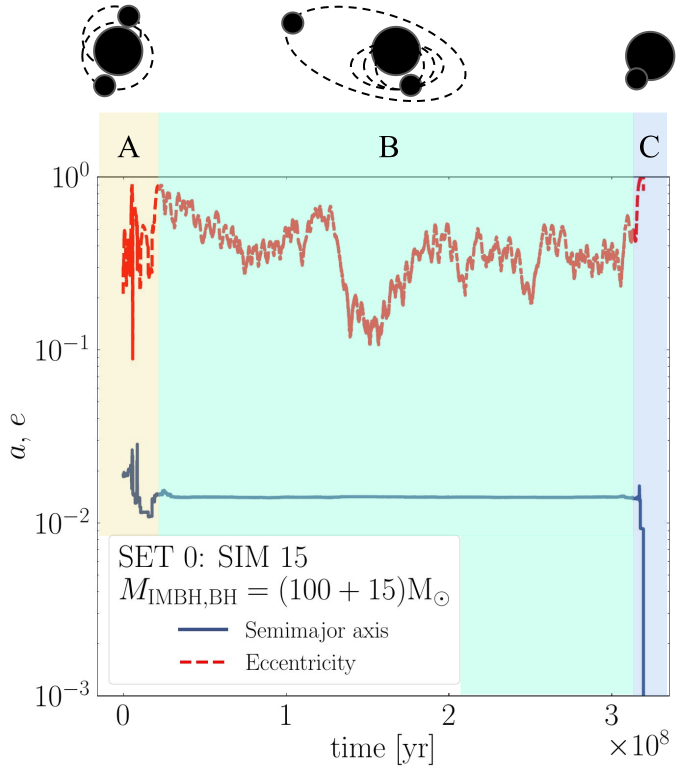
There are three main phases:

A. Chaotic: the three BHs interact continuously, exchanges may occur

B. Periodic/(mildly) hierarchical: the three objects from a triple, the outer BH exert perturbations on the inner BH-IMBH binary.

In this phase Kozai-Lidov (-like) oscillations may take place

C. GW emission kicks in and drives the IMBH-BH to merger



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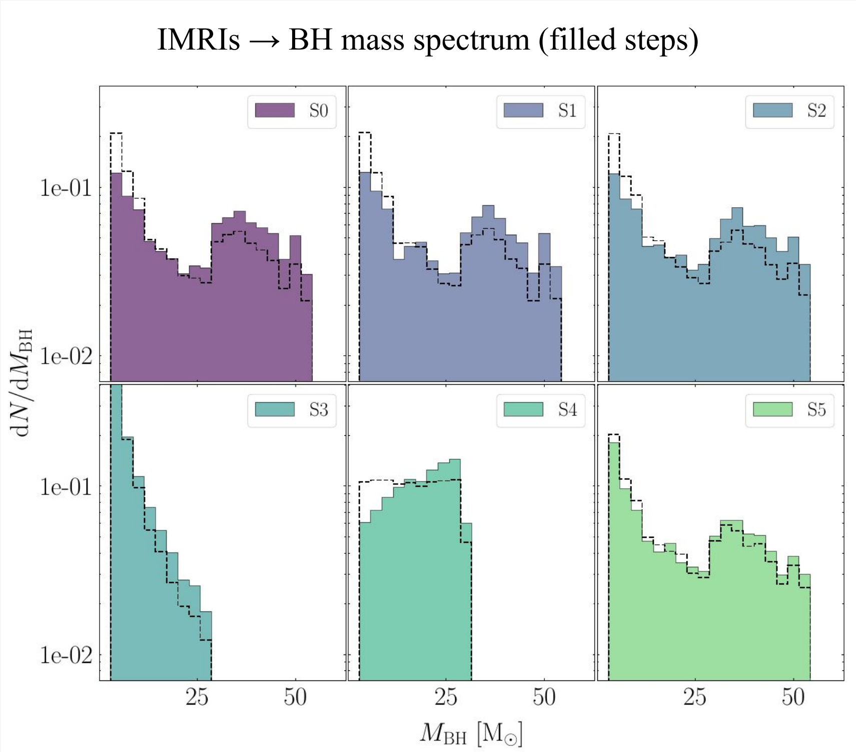

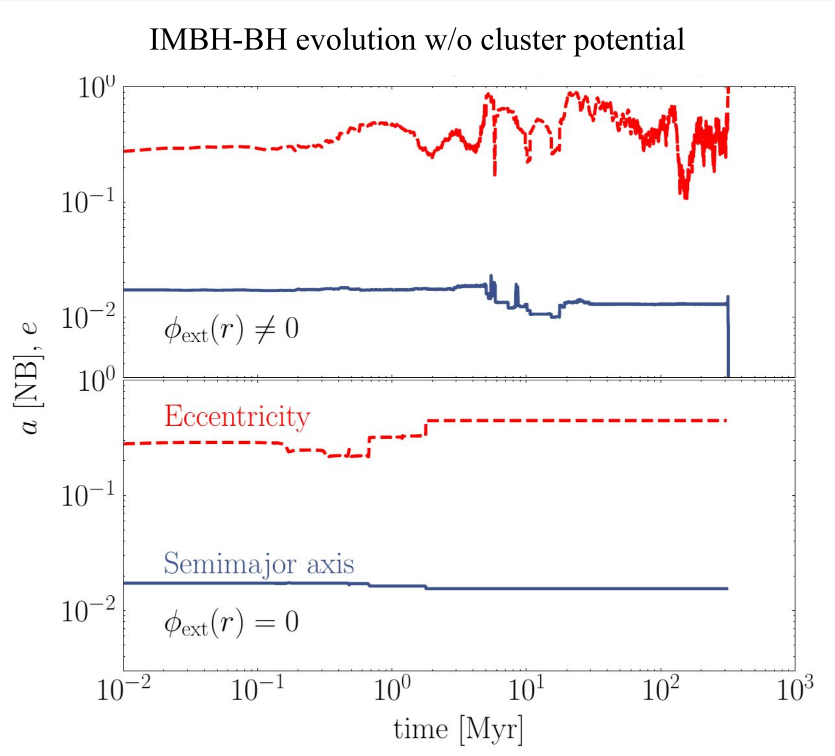

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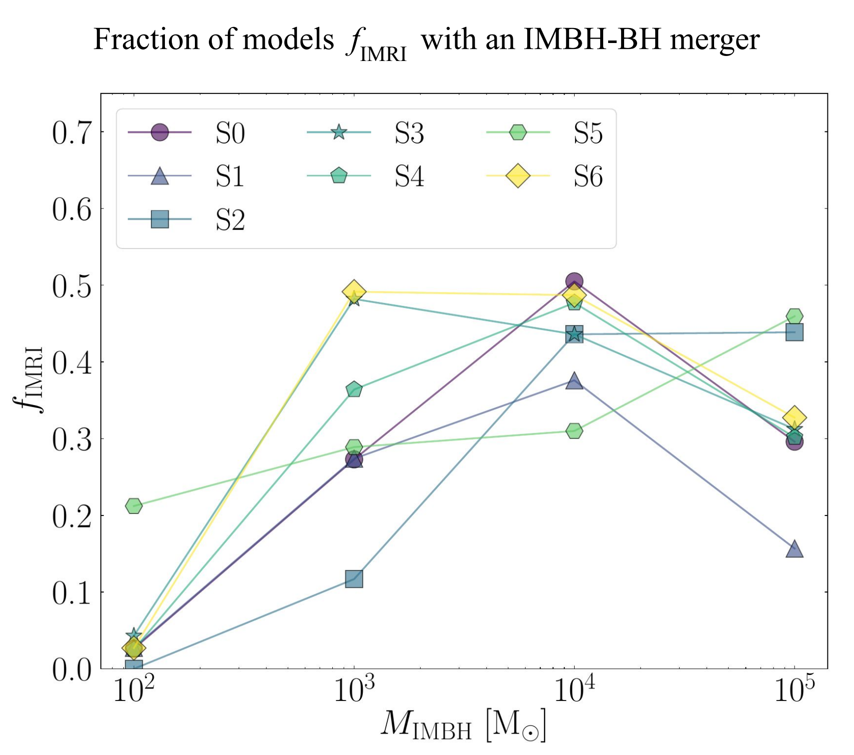
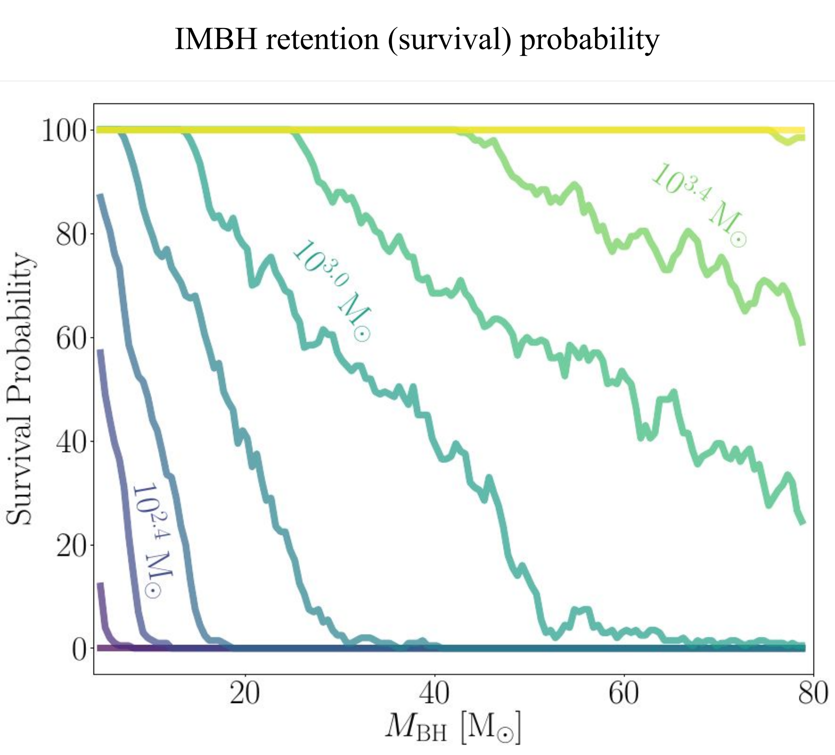
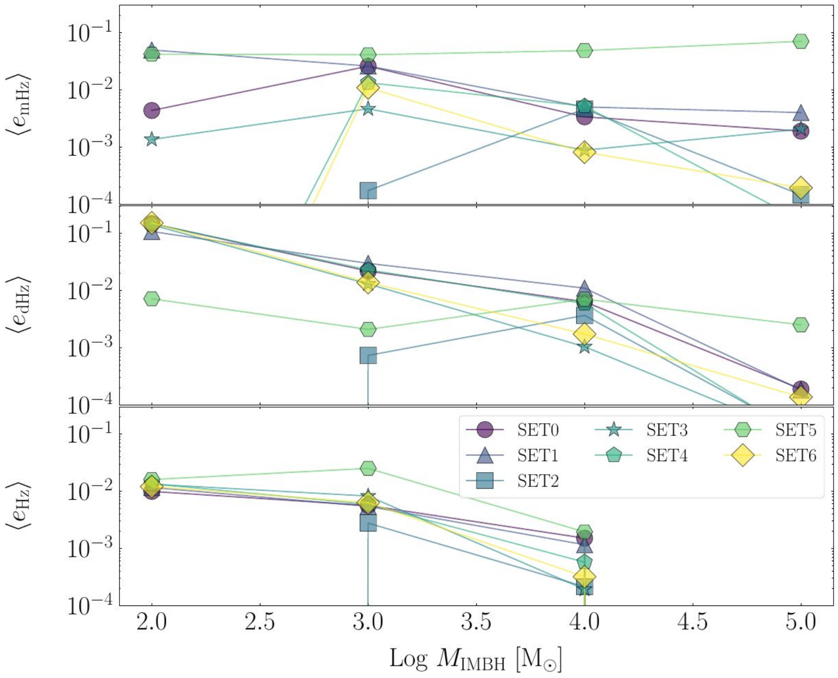




Perspectives for IMBH growth in dense clusters via repeated IMRI phases

IMRI average eccentricity in different frequency band



IMBH spin evolution upon multiple mergers
(time flows from left to right)