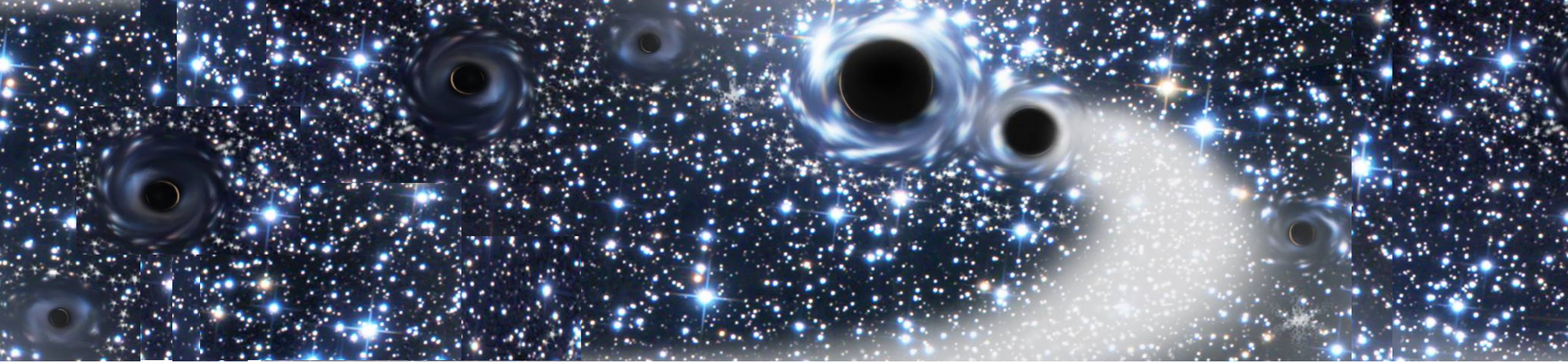

Breaching the limit: merging stellar and intermediate-mass black holes in dense star clusters

Manuel Arca Sedda

Colls: Pau Amaro-Seoane, Xian Chen, Francesco Rizzuto,
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ArXiv: 2007.13746
ArXiv: 2105.07003

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Accretion Processes in Galactic Nuclei

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UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

SFB 881

Summary

A. Formation of IMBHs in (young) clusters

B. IMBH-BH mergers in dense clusters

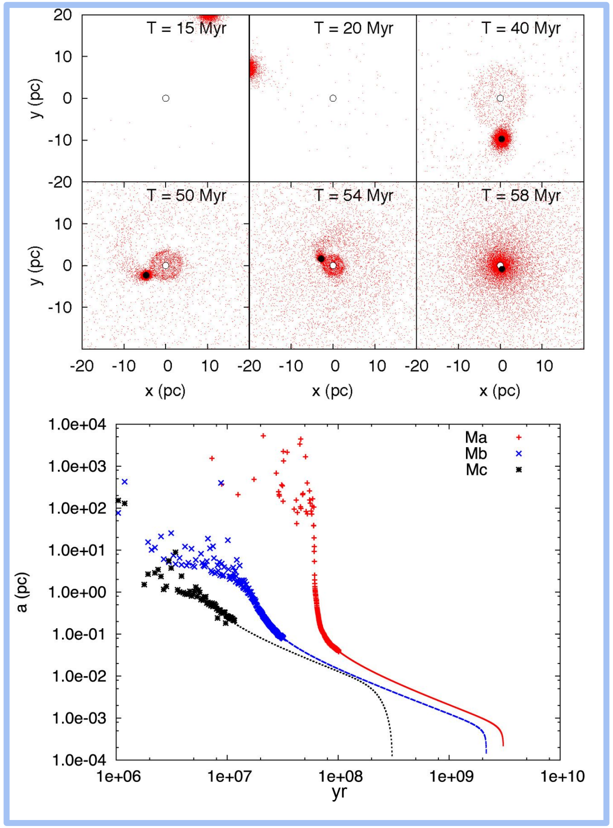
C. Perspectives for current and future GW detectors

Formation of IMBHs in star clusters: why are they relevant for the physics of galactic nuclei?

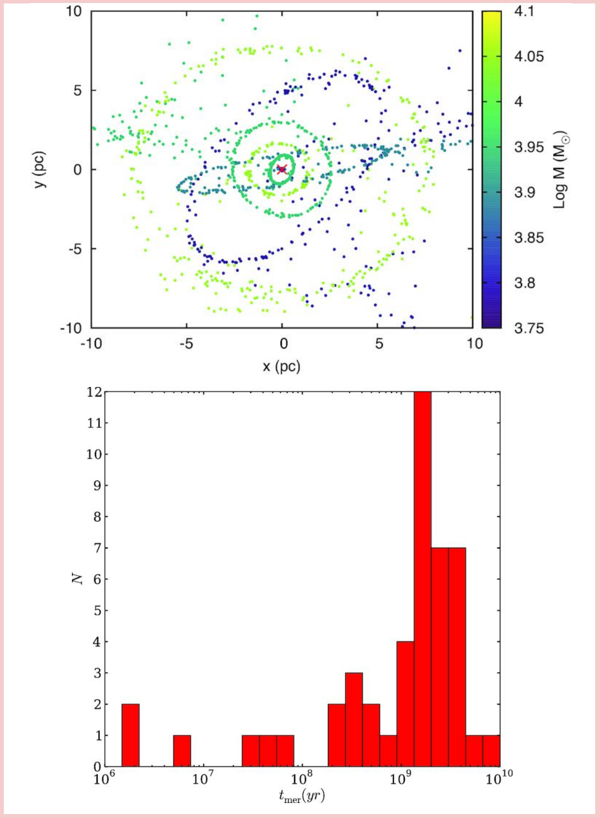
1. NCs in Galactic Nuclei might form (at least partly) via infall of massive clusters (e.g. *Tremaine et al 1975, Capuzzo-Dolcetta 1993, Antonini et al 2012,* ***Arca Sedda*** *and Capuzzo-Dolcetta 2014, 2016, 2017a, 2017b,* ***Arca Sedda*** *et al 2015, 2016, 2018, 2021*)

2. If infalling clusters host an IMBH, NCs might host IMBH-SMBH binaries and multiplets (e.g. *Ebisuzaki 2001, Portegies-Zwart et al 2006,* ***Arca Sedda*** *and Gualandris 2018,* ***Arca Sedda*** *and Capuzzo-Dolcetta 2019, Askar et al 2020, 2021*)

3. IMBH-SMBH mergers might be promising sources of GWs for future detectors (e.g. *Amaro Seoane et al 2017, Sesana et al (incl.* ***Arca Sedda)*** *2020, Amaro Seoane,* ***Arca Sedda*** *et al 2021*)

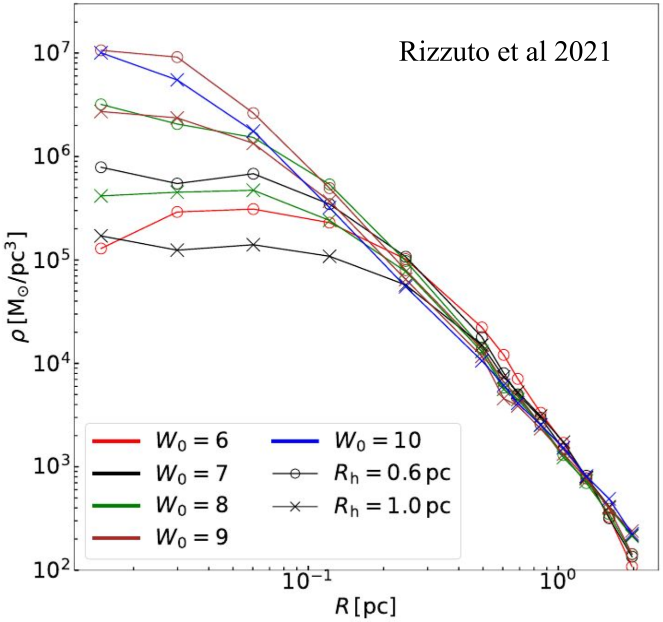


Arca Sedda, M. & Gualandris, A. (2018)



Arca Sedda, M. & Capuzzo-Dolcetta, R. (2019)

Formation of IMBHs 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 <u>IMBH forms in 17 cases out of 80</u> (~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, ApJ accepted

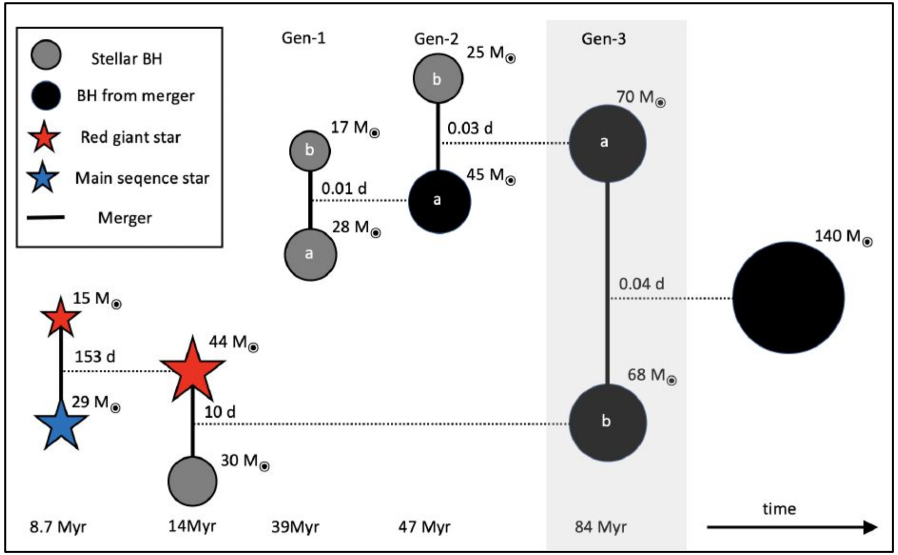
Formation of IMBHs in young clusters

Simulation ID	Merger generation	σ_{YC} km s^{-1}	M_a M$_\odot$	M_b M$_\odot$	q	a R$_\odot$	e	$t_{\rm form}$ Myr	$t_{\rm gw}$ yr
				IMBH-BH mergers					
R06W9sim3	Gen-1	7	328	21	0.064	1.21	0.41	113	44
R06W9sim7	Gen-1	6	307	22	0.072	0.7	0.085	348	16
R06W9sim7	Gen-2	6	329	26	0.079	697	0.997	369	30, 000
R06W6sim6	Gen-1	10	285	22	0.077	36.7	0.955	11.2	8500
				Mass-gap mergers					
R06W6sim1	Gen-1	9	28	17	0.607	337	0.999	38.6	36.7
R06W6sim1	Gen-2	9	45	25	0.556	83.4	0.99978	46.9	10
R06W6sim1	Gen-3	8	70	68	0.971	1.08	0.8927	83.9	10

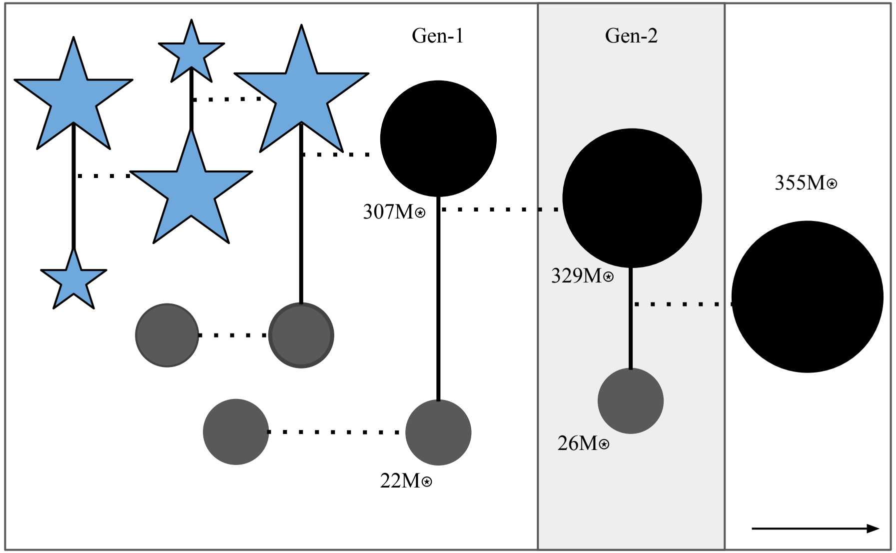
Arca Sedda, M. et al, ArXiv: 2105.07003, ApJ accepted

Formation of IMBHs in young clusters

Mergers in the upper mass-gap

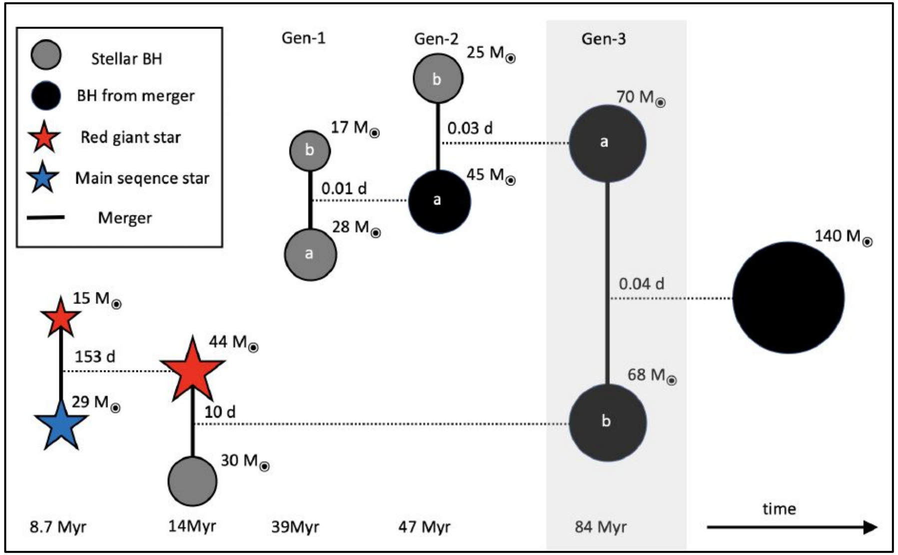


IMBH-BH mergers



Formation of IMBHs in young clusters

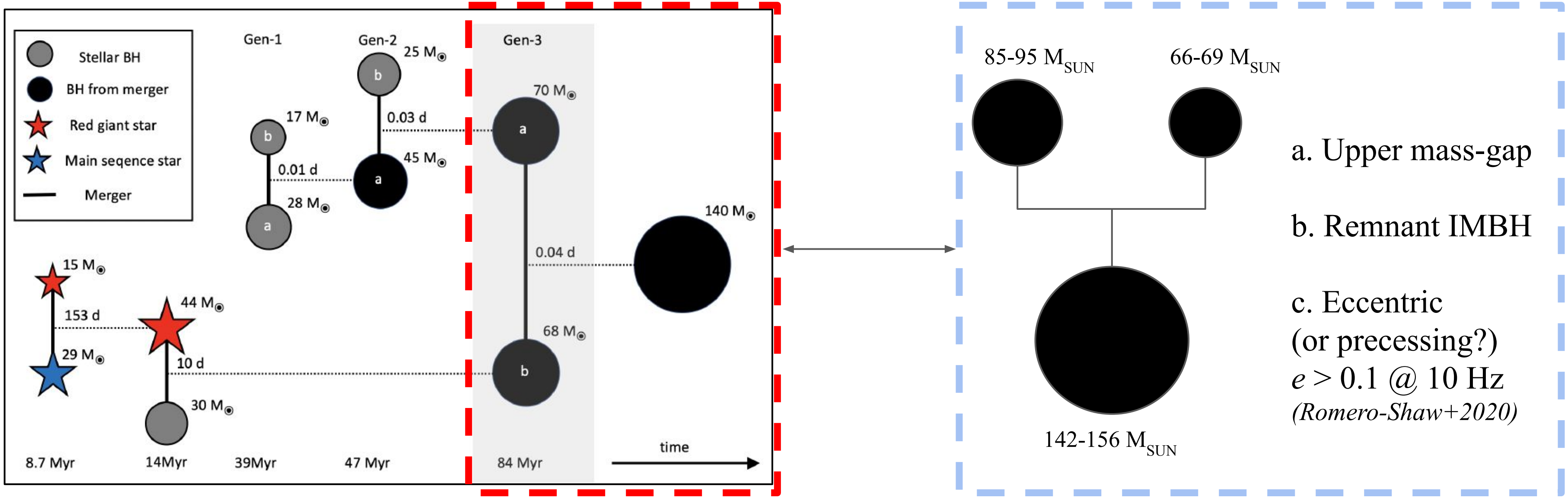
Mergers in the upper mass-gap



Formation of IMBHs in young clusters

Mergers in the upper mass-gap

GW190521



Mergers in the upper mass-gap: eccentricity at merger

					Mass-gap mergers						$f > 10$ Hz	
										e_{10s}	e_{1s}	$e_{0.1s}$
R06W6sim1	Gen-1	9	28	17	0.607	337	0.999	38.6	36.7	1.1×10^{-4}	4.7×10^{-5}	2.2×10^{-5}
R06W6sim1	Gen-2	9	45	25	0.556	83.4	0.99978	46.9	10	0.02	0.008	0.004
R06W6sim1	Gen-3	8	70	68	0.971	1.08	0.8927	83.9	10	6.4×10^{-4}	3.6×10^{-4}	3.0×10^{-4}

Despite a dynamical origin, our GW190521-like mergers has
e ~ 0.00036 @ 10 Hz

Why?
At decoupling, the BBH is still relatively wide:
Semimajor axis ~ 1.08 R_{SUN}
Eccentricity ~ 0.8927

So?
Not all dynamical sources are eccentric LIGO sources!

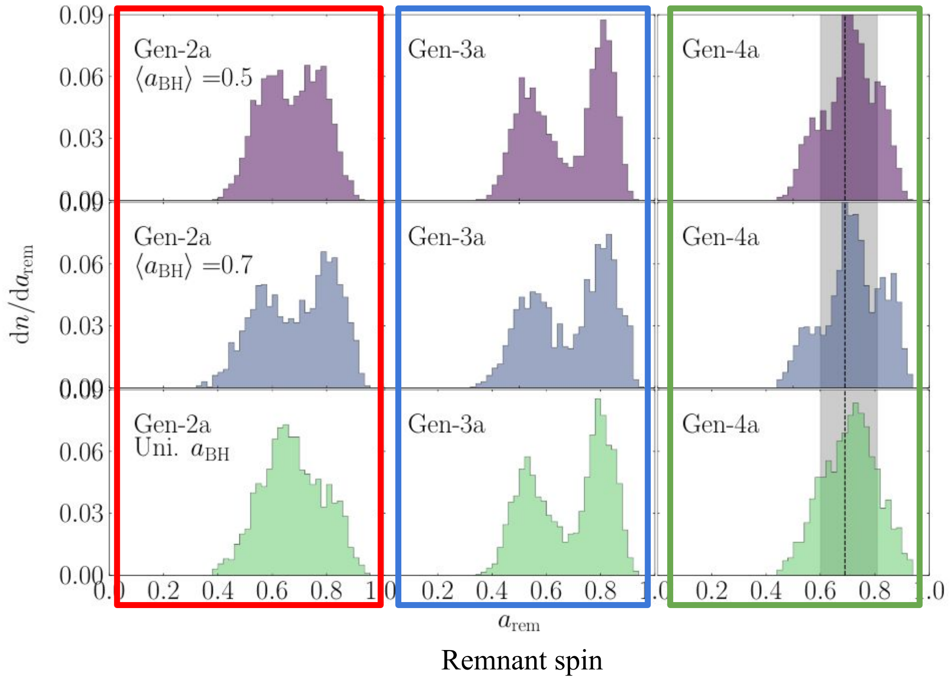
Mergers in the upper mass-gap: spin and kicks of hierarchical merger products

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,* ***Arca Sedda****, Amaro-Seoane, Chen 2021*)
   (Gen-1a + Gen-1b) → Gen-2a

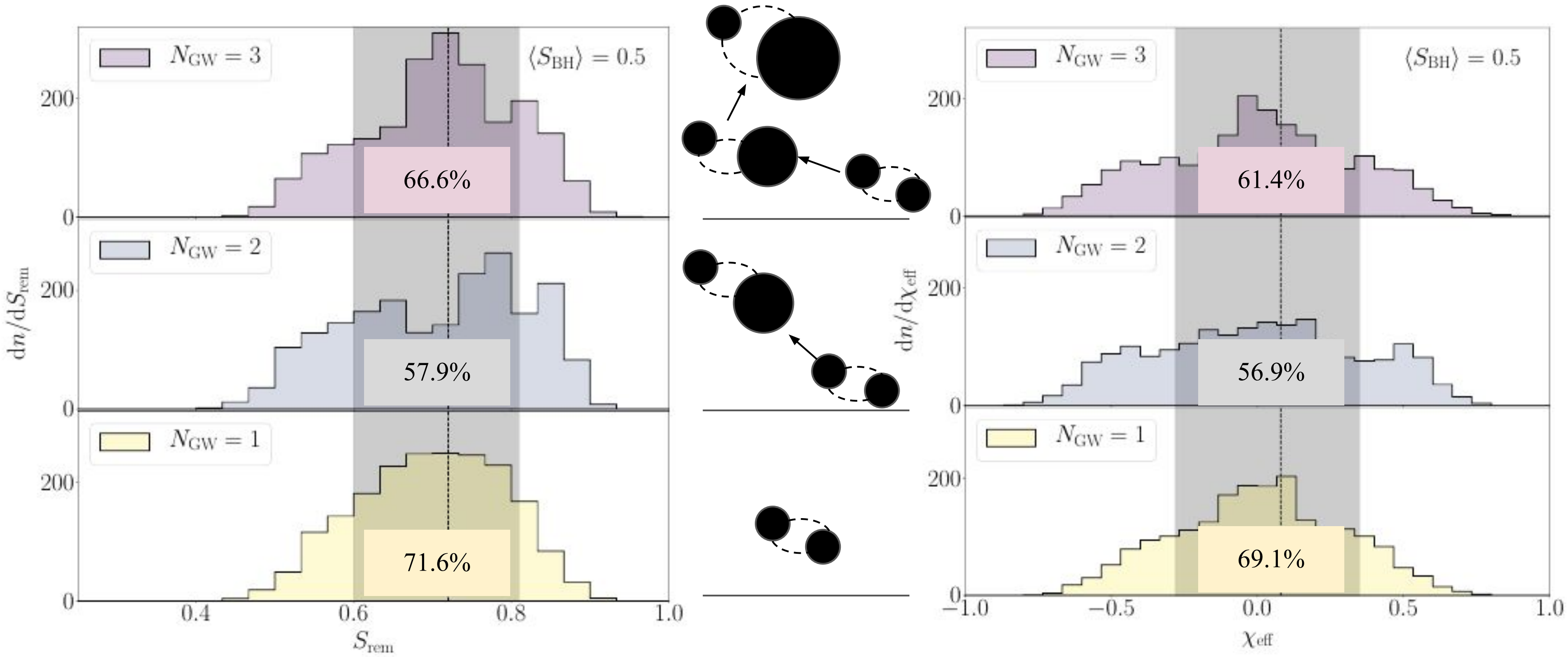
4. Merge the remnant with the next stellar BH
   (Gen-2a + Gen-2b) → Gen-3a



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

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?

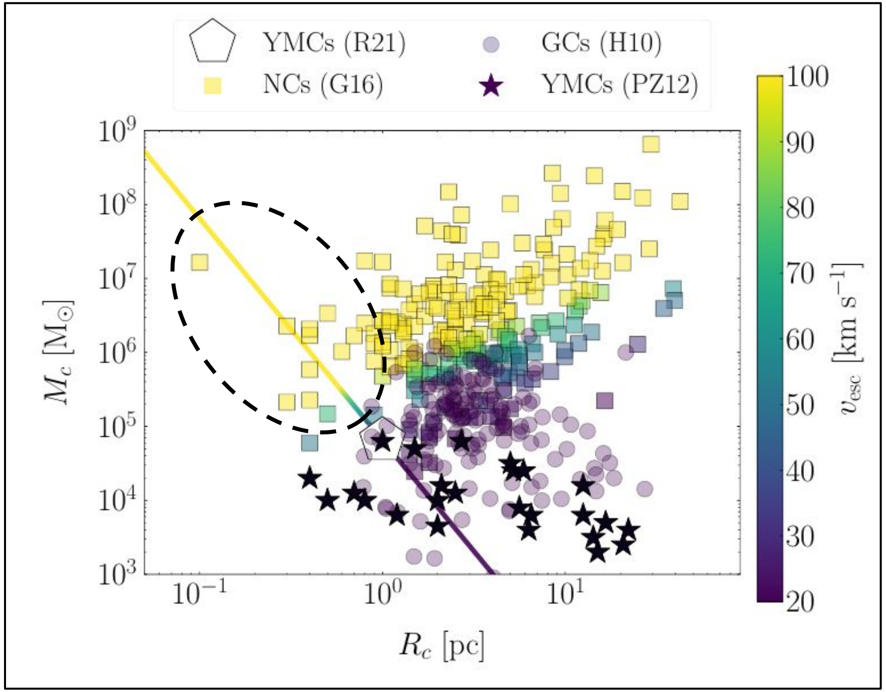
1. The timescale for the merger formation is connected with the relaxation time

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

2. The central escape velocity must increase

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

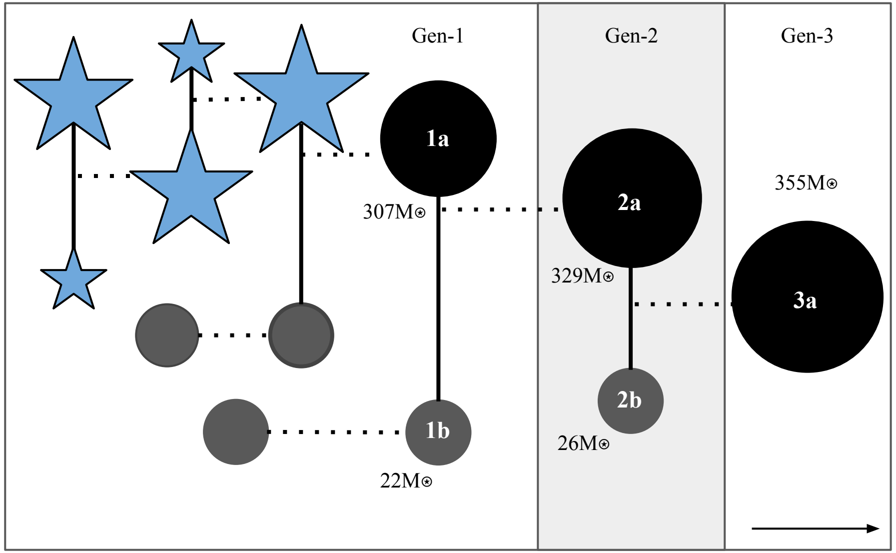
3. Possible host have same $t_{\rm rlx}$ and $v_{\rm esc} > v_{\rm kick}$



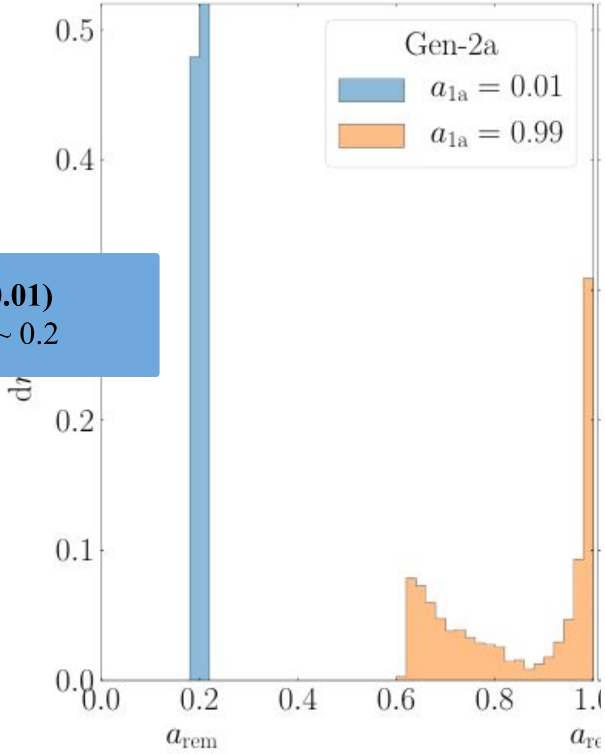
Only cluster with $M_c > 3 \times 10^5$ M$_\odot$ and $R_c < 0.6$ pc can retain long merger chains

Formation of IMBHs in young clusters

IMBH-BH mergers



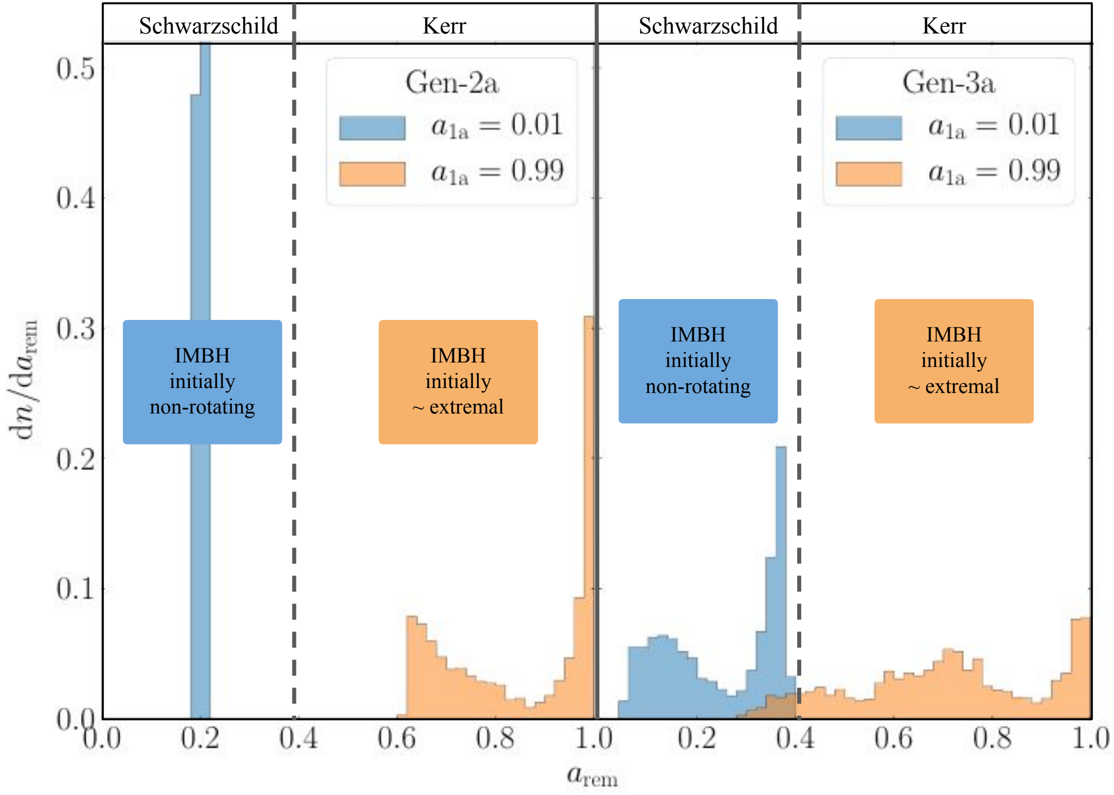
Merging IMBHs and BHs: spin and kicks of hierarchical merger products



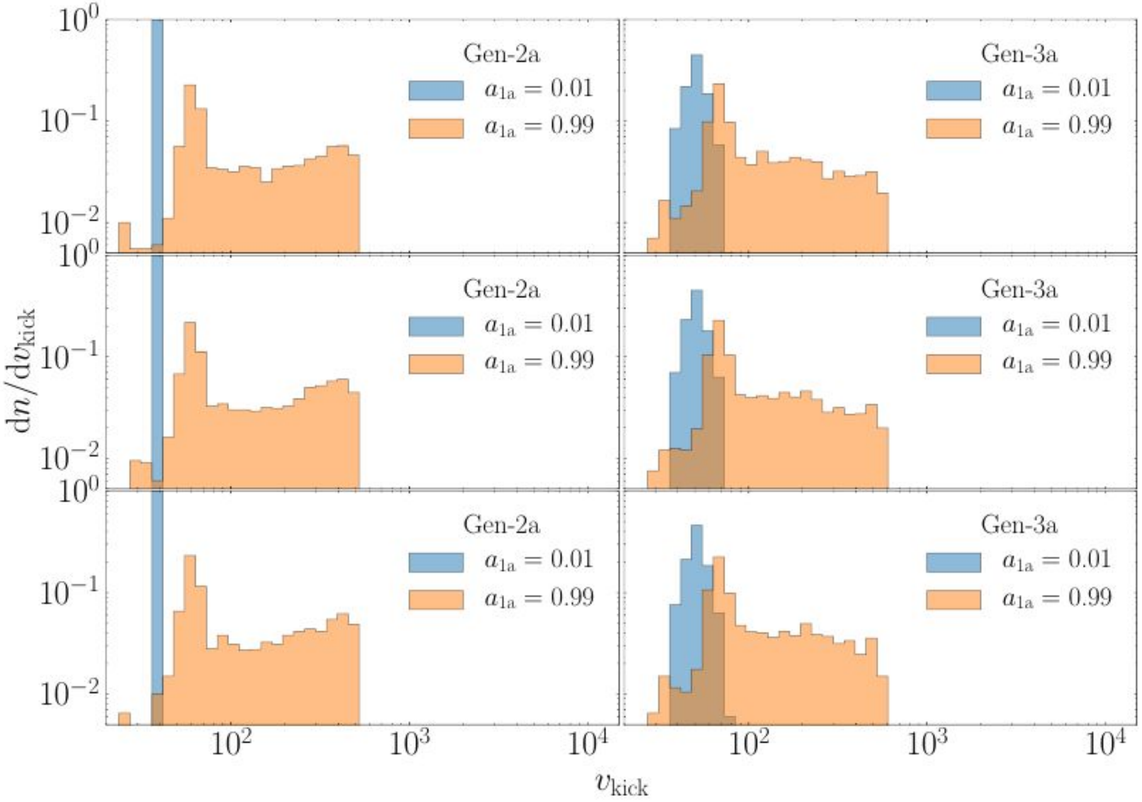
non-rotating IMBH (a_{1a} = 0.01)
remnant spin narrowly peaked $a_{rem} \sim 0.2$

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

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



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



1. Slowly spinning IMBHs:

Gen-2a: $v_{kick} \sim 30$ km/s

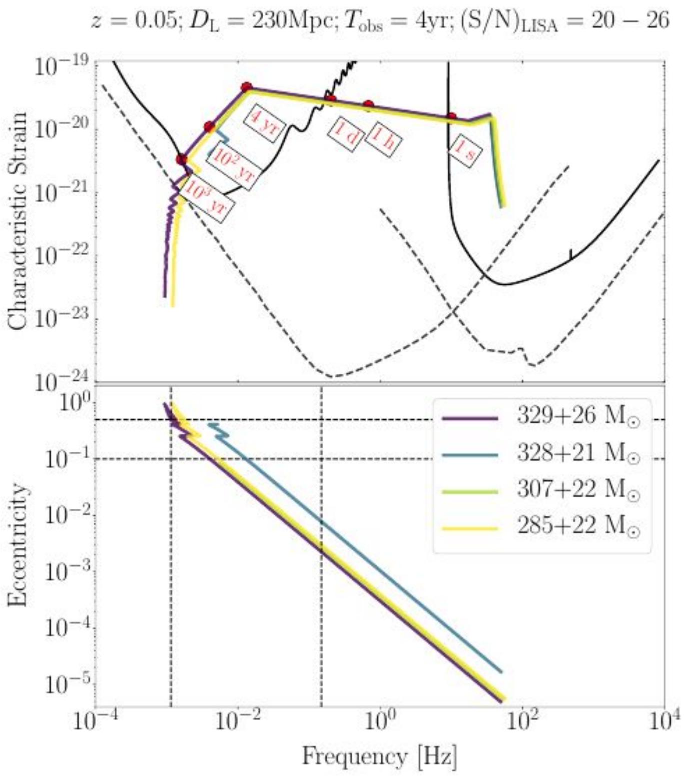
Gen-3a: $v_{kick} < 50$ km/s

2. Highly spinning IMBHs:

Gen-2a: $v_{kick} \sim 30 - 500$ km/s

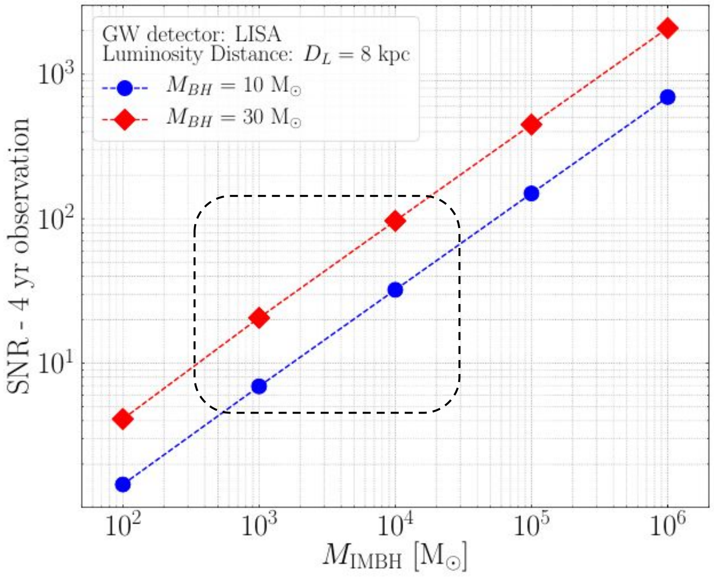
Gen-3a: $v_{kick} < 20 - 500$ km/s

Perspectives for current and future GW detectors

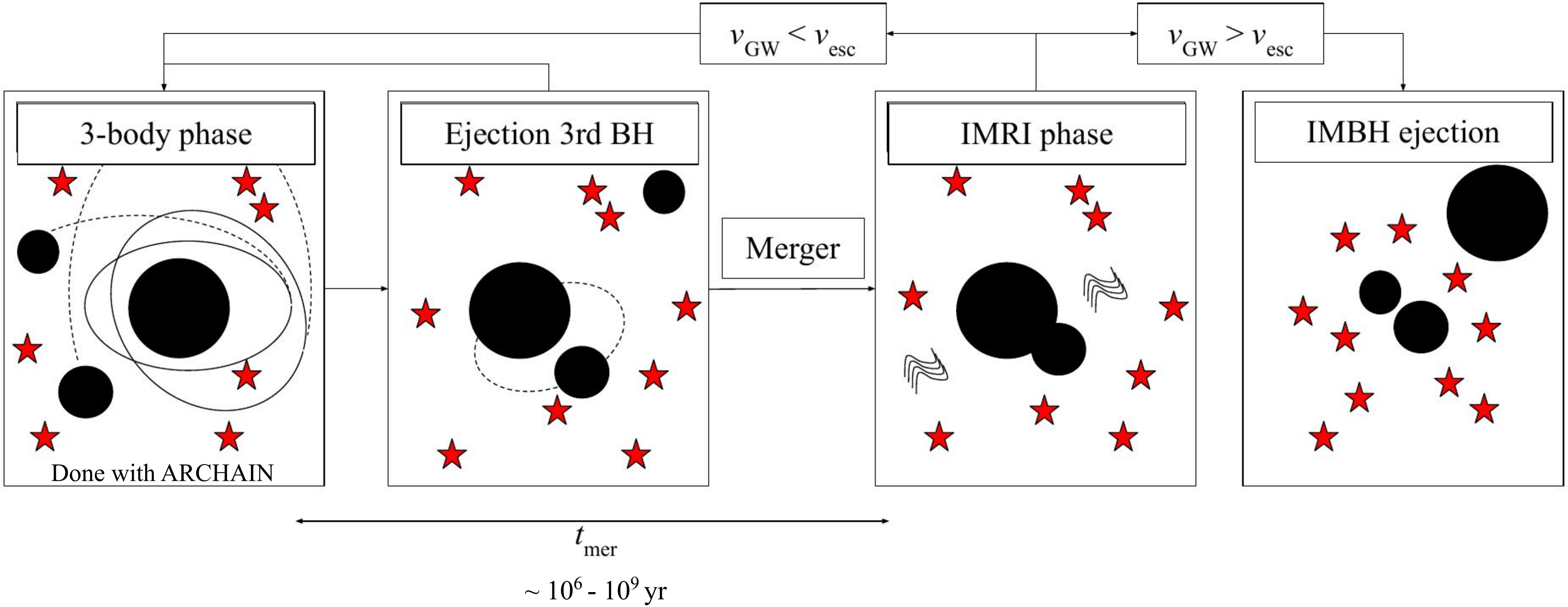


Arca Sedda M. et al., ArXiv:2105.07003, ApJ accepted

Arca Sedda M., Amaro Seoane P., Chen X. (2021) A&A

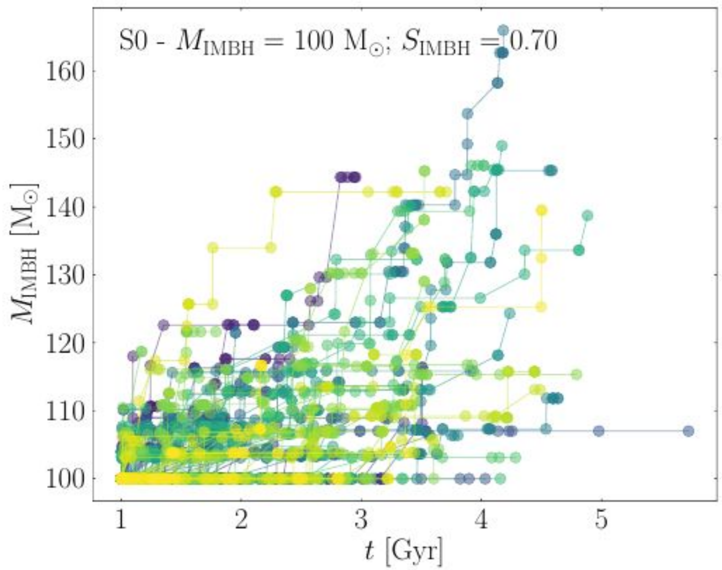


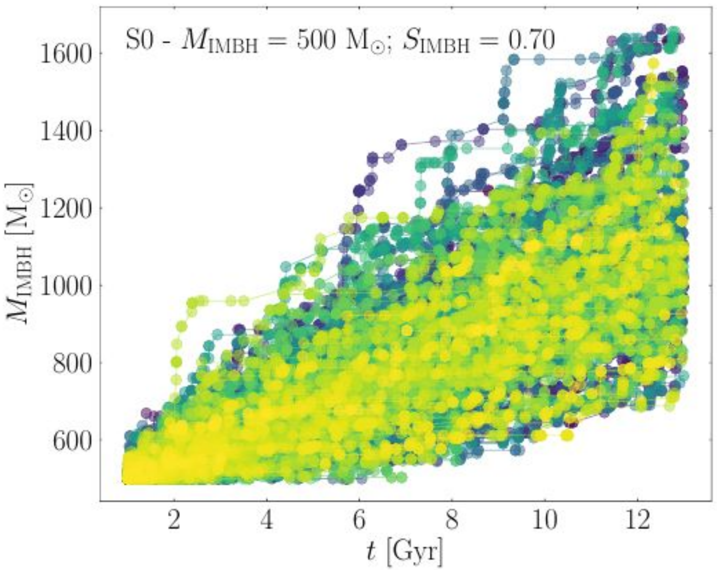
Perspectives for IMBH growth in dense clusters via repeated IMRI phases: a semi-analytic approach to quantify the impact of multiple IMBH-BH mergers



Arca Sedda M., Amaro Seoane P., Chen X. (2021) A&A

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





Arca Sedda M., Amaro Seoane P., Chen X. (2021) A&A

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⊙

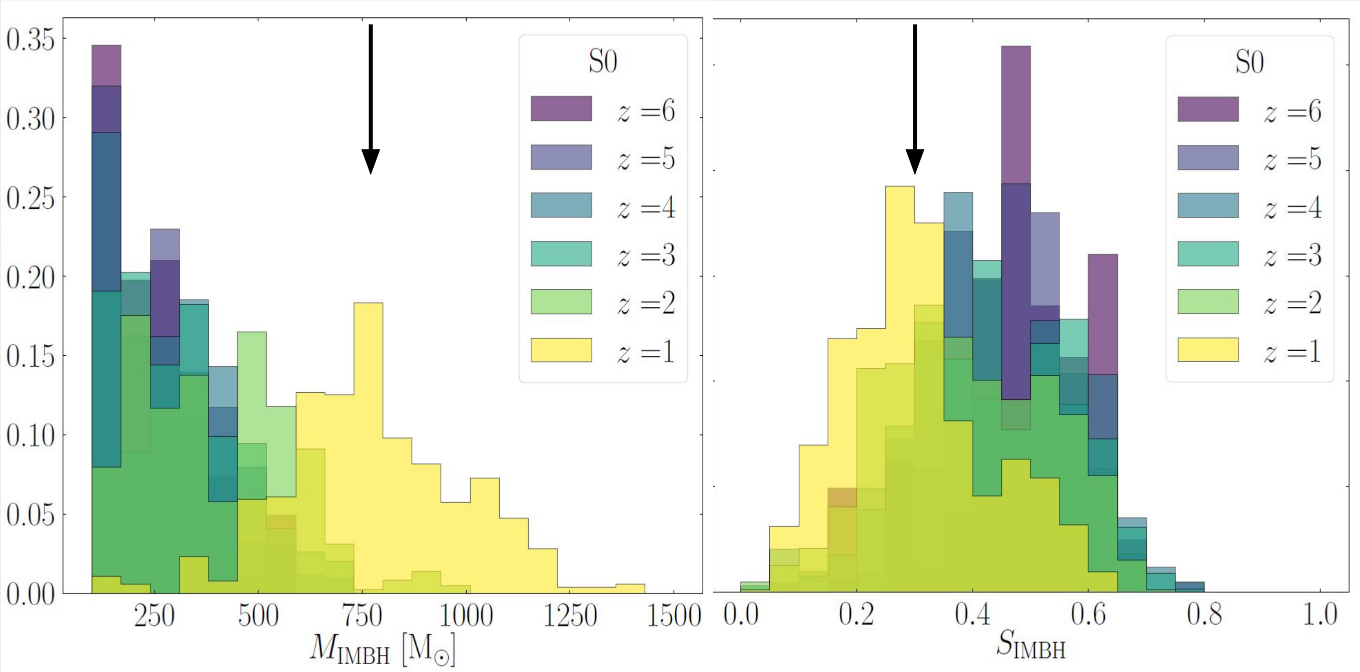
M_c = 10^5 - 5×10^6 M⊙

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

What IMBHs @ $z < 1$?

i. Mass spectrum
$M_{IMBH} = 750M_\odot$

ii. spins distribution
$S_{IMBH} = 0.3$



Arca Sedda M., Amaro Seoane P., Chen X. (2021) A&A

Perspectives for IMBH growth in dense clusters via *N*-body models (PRELIMINARY!)

DRAGON-IMBH-2
on Booster cluster

- N = 120-300-600-1,000k
- Binary = 5-20%
- M_{MAX} = 150 M_{SUN}
- Mass segregation

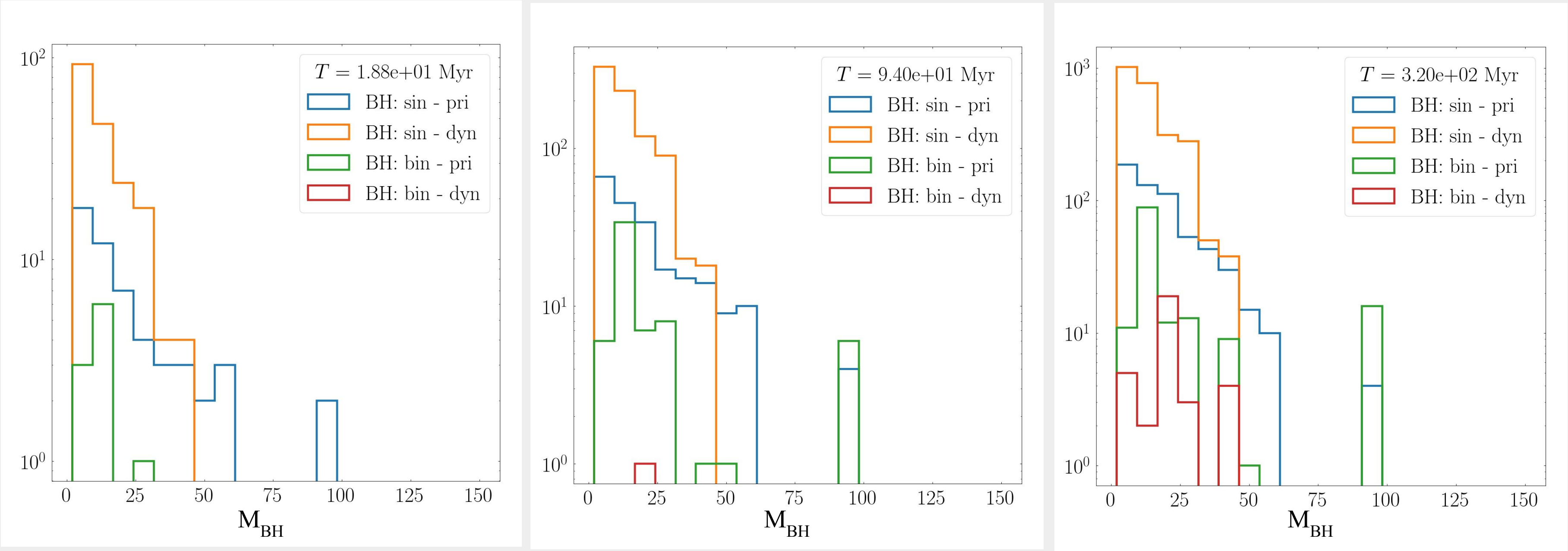
Preliminary:
- Sim time ~ 0.1-2 Gyr
- N_{GW} ~ O(100)
- f_{IMBH} ~ 20-30%

N_* 10^3	M_c 10^5 $M_\odot$	R_h pc	f_b	f_{segreg}	N_{seed}	T_{sim} Gyr	N_{GW}	M_{IMBH} $M_\odot$
120	0.7	2.2	0.2	0.5	2	1.2 1.7	3 4	102 191, 260
300	1.7	2.2	0.2	0.5	2			
600	3.5	2.2	0.2	0.5	2			
120	0.7	1.0	0.2	0.5	2			
300	1.7	1.0	0.2	0.5	2			
120	0.7	0.6	0.2	0.5	2			
300	1.7	0.6	0.2	0.5	1			
120	0.7	2.2	0.05	0.5	2			
300	1.8	2.2	0.05	0.5	2			
1000	5.9	2.2	0.05	0.5	2			

Arca Sedda M. et al, in prep

Perspectives for IMBH growth in dense clusters via *N*-body models (PRELIMINARY!)

Overall BH mass distribution in 120k sim.



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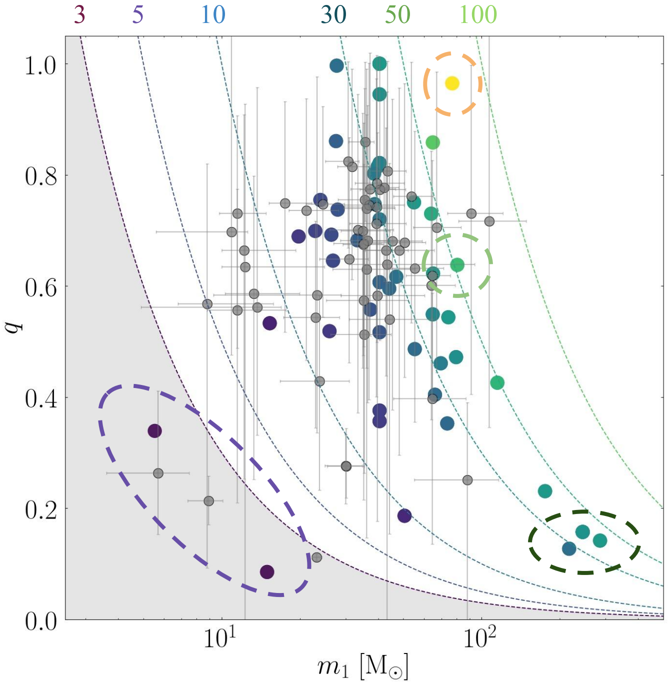
Perspectives for IMBH growth in dense clusters via *N*-body models (PRELIMINARY!)



DRAGON-IMBH-2 on Booster cluster: mergers!

- ~ IMBH-IMBH mergers
- GW190521-like mergers
- Hierarchical mergers
- NS-BH mergers

Arca Sedda M. et al, in prep

Takehome

✓ Analysis of 80 *N*-body simulations of YMCs: 4 IMBH-BH mergers and 1 triple merger leading to a GW190521-like source

✓ Post-processing of the data to include GR for remnant mass, spin, and recoil (not included in *N*-body models)

✓ About IMBHs:
- The spin of the remnant depends strongly on IMBH “natal” spin
- GW kick can eject rotating IMBHs from YCs, thus preventing further growth
- GW detectors (especially the next generation) will help us in unravelling IMBH “seeds”

✓ About mass-gap mergers:
- The triple merger channel leads to a spin that match observations better than a simpler double merger. (Note: a single merger is disfavored by stellar evolution)
- The GW kick in such mergers is large (>100 km/s in 90% of the cases explored): no retention in YCs
- Only compact and massive GCs and NCs could harbour such merger chains
- Improved observations of cluster central regions could help in constraining escape velocities

✓ What to expect from the future
- A new simulation database with N = 120-1,000k, 20% binaries, new stellar evolution, etc.. is on the way
- So far, we found several IMBHs with M > 100-300 M_{SUN} , O(100) BBH mergers, 2 NS-BH mergers

BONUS: IMBH merger rates

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:

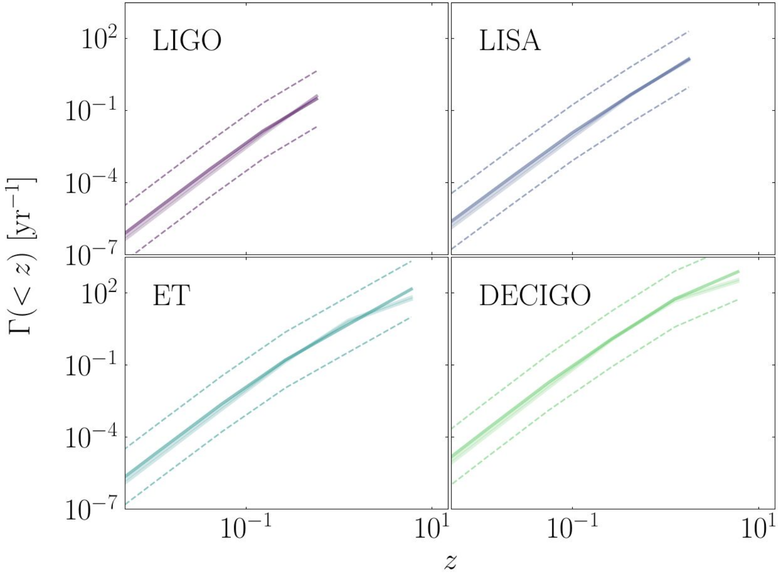
$$\Gamma_{\rm IMRI} = \Omega_s \int_{M_1}^{M_2} \int_0^{z_{\rm hor}} \frac{\mathrm{d}n_{\rm IMRI}}{\mathrm{d}M_{\rm IMBH}\mathrm{d}z} \frac{\mathrm{d}V_c}{\mathrm{d}z} \frac{\mathrm{d}z}{1+z} \mathrm{d}M_{\rm IMBH}$$

- 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



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⊙ in 1 yr of observation

LISA: ~5-60 IMRIs with *M* < 46,000 M⊙ in 1 yr of observation

ET/DECIGO: >10^3 IMRIs with *M* < 46,000 M⊙ in 1 yr of observation

Nr. of detection per yr