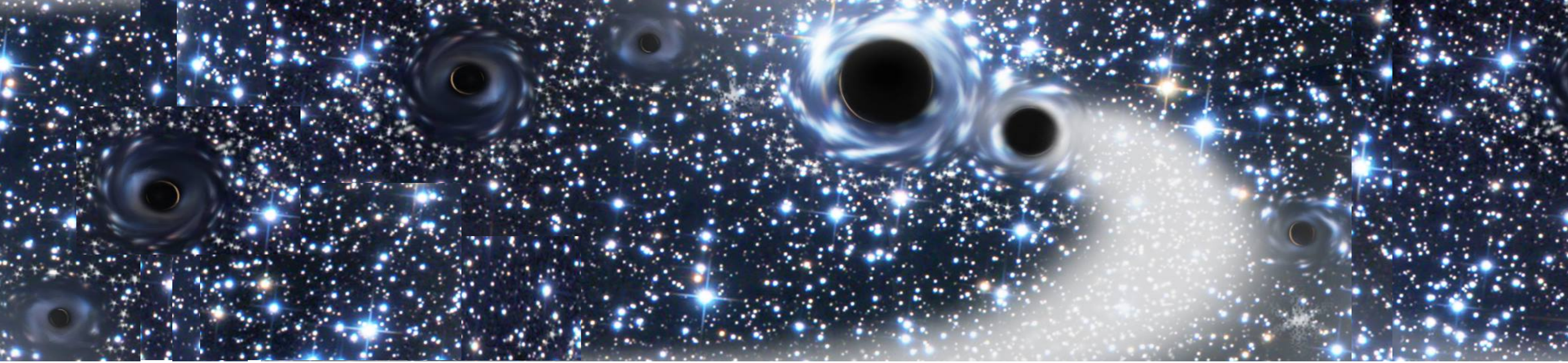

Intermediate-mass ratio inspirals in massive star clusters: detection perspectives for current and future GW detectors

Manuel Arca Sedda

grace

MARIE CURIE ACTIONS

ET Symposium
OSB-Div 3 session

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G S S I GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

UNIVERSITÀ DEGLI STUDI DI PADOVA

SUMMARY

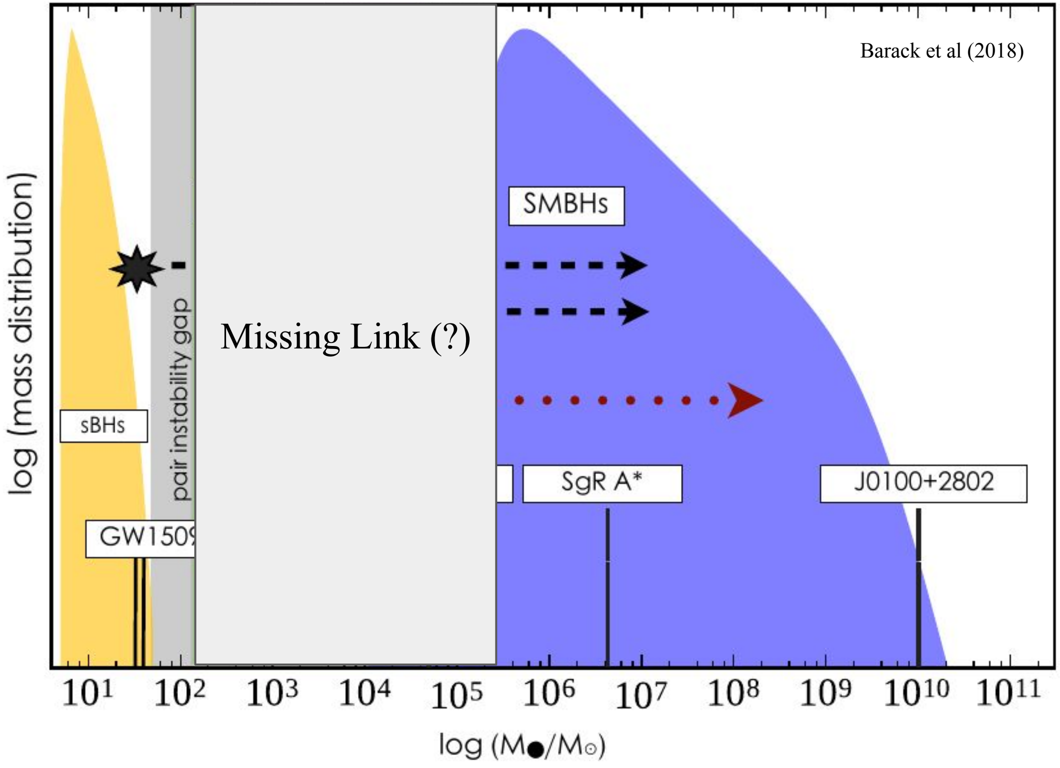
1. IMBHs: what we do and don’t know

2. The build-up of IMBHs in massive clusters

3. Growing IMBHs via repeated IMRI phases in Globular Clusters

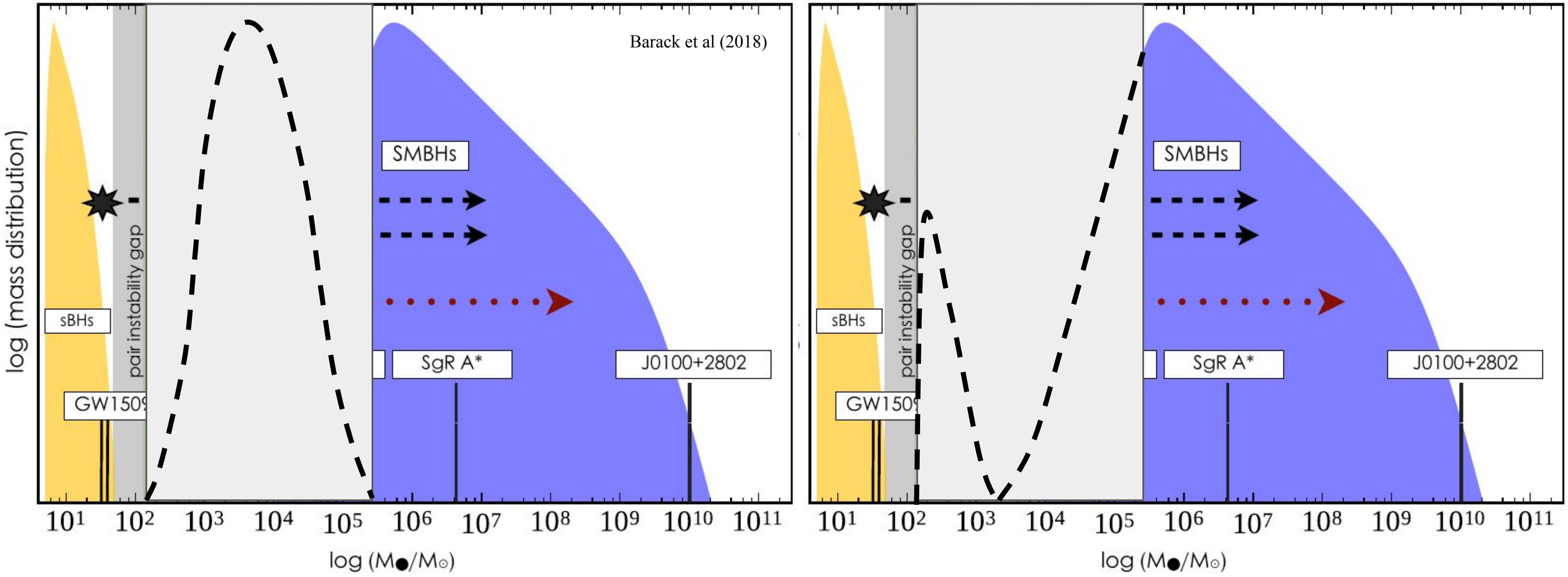
4. Implications for current and future GW detectors: IMRIs cosmic merger rate

IMBHs: what we do and don't know



IMBHs: what we do and don't know

Do IMBHs constitute a special class of IMBHs? What is the IMBH mass spectrum?



IMBHs: what we do and don't know

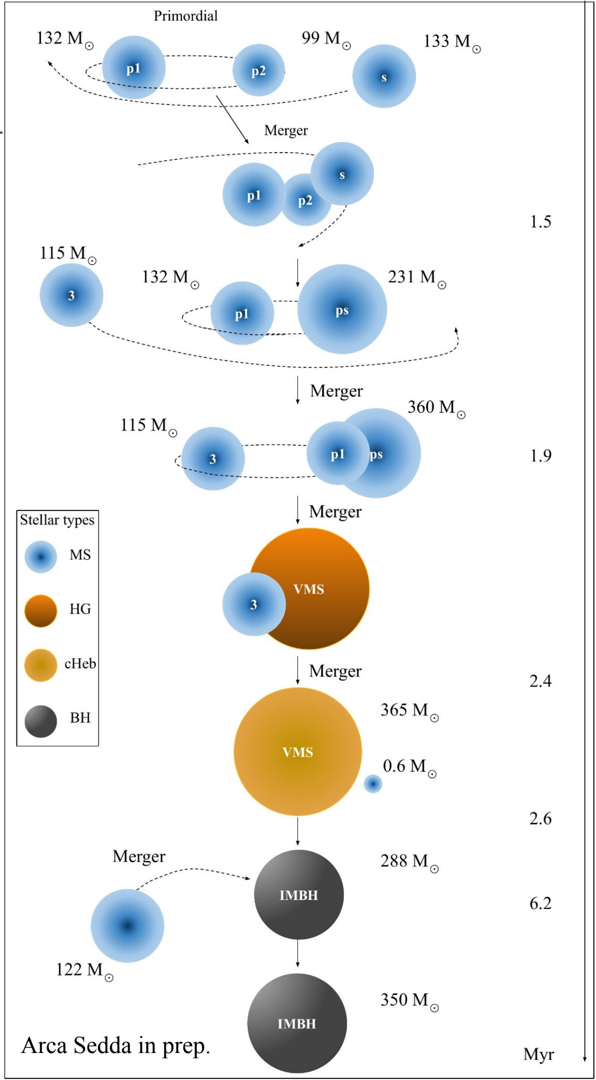
Do IMBHs constitute a special class of IMBHs?

Answer the question requires to find a (few) process(es) capable of growing IMBHs in the whole $10^{2\text{-}5} M_{SUN}$ *mass range*

The build-up of IMBHs in massive clusters

Four (uncertain) formation channels:

1. Stellar collisions build-up a very massive star (VMS) M= 200–500 M_{SUN} and directly collapse to an IMBH;
   (Portegies-Zwart and McMillan02, Glebbek+09, Di Carlo+19, Arca Sedda+23)



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2. A VMS that accretes part of its matter onto a sBH;
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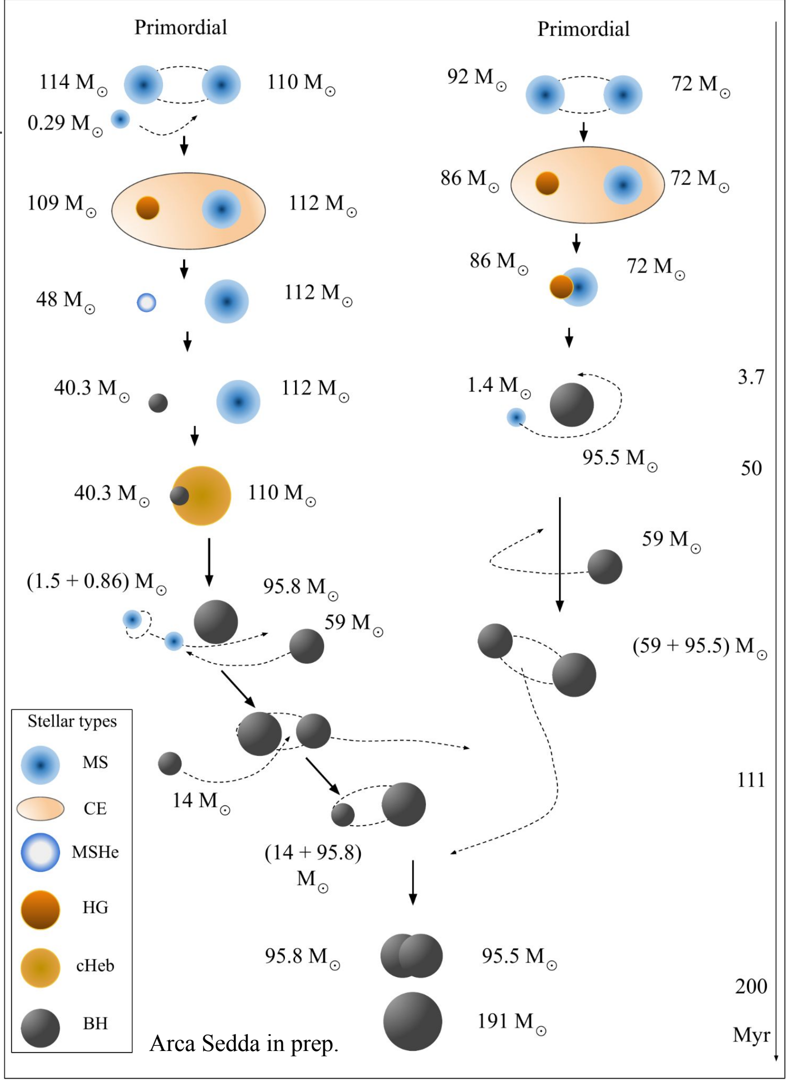

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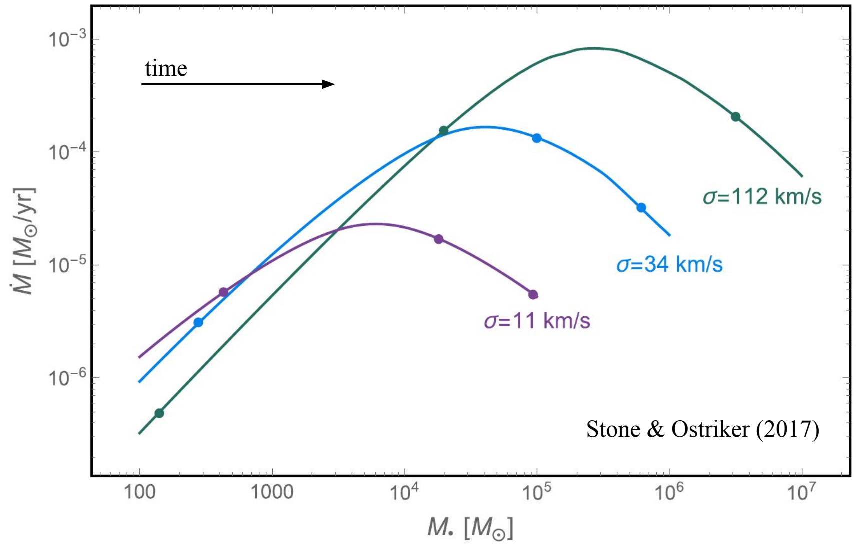

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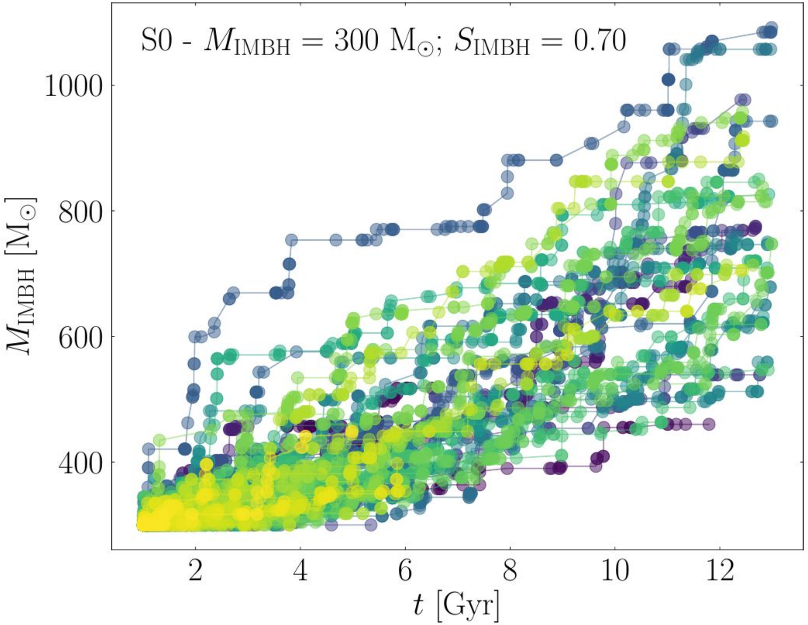
4. A series of repeated (hierarchical) mergers between stellar BHs
   (Miller&Hamilton02, Holley-Bockelmann+08, Fragione&Kocsis18, Arca Sedda+21,23, Mapelli+21, Antonini+19, Maliszewski+22)

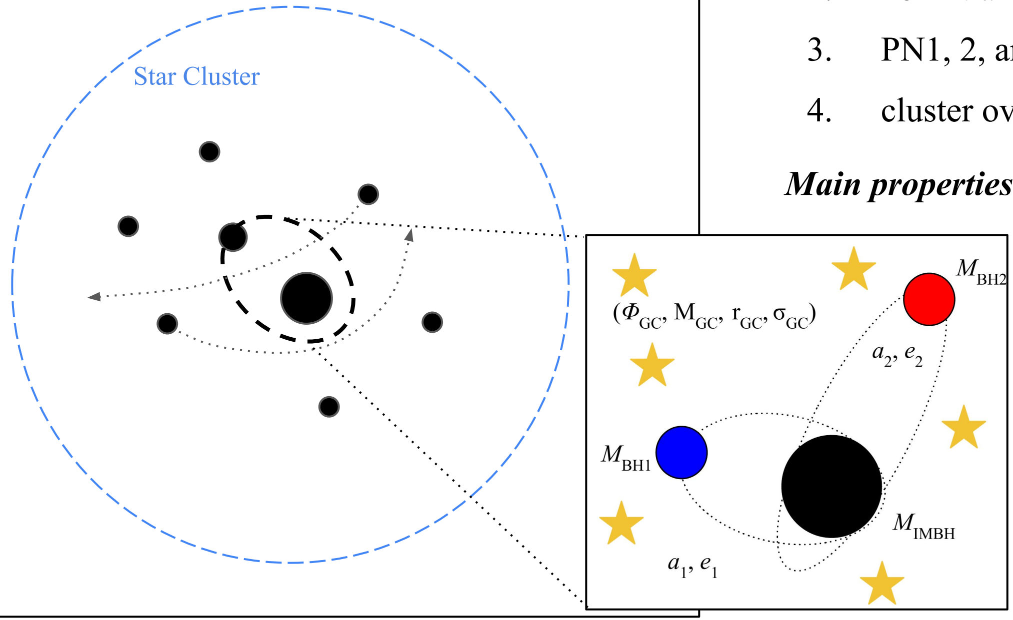
Arca Sedda, Amaro-Seoane, Chen (2021)



The build-up of IMBHs in massive clusters: hierarchical BH mergers

Light IMRIs: IMBH + compact object (Amaro-Seoane+07)
- IMBH mass ?
- compact object: BHs (2.7%), WDs (16%), NSs (0.2%)

(Arca Sedda+19, see also Konstantinidis+13, MacLeod+16)



Our phase space

(Arca Sedda, Amaro-Seoane, and Chen (2021) A&A)

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 (28,000 N-body simulations)

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

The build-up of IMBHs in massive clusters: hierarchical BH mergers

Main properties (28,000 N-body simulations)

Model	IMBH mass	Star cluster mass	Density profile and slope		Semimajor axis and eccentricity		BH mass spectrum		Metallicity	Models number
ID	$M_{\rm IMBH}$ $M_\odot$	$M_{\rm GC}$ $M_\odot$	$\rho_{\rm GC}$	$\gamma_{\rm GC}$	a	e	BH	$m_{{\rm BH},min/ma}$ $M_\odot$	Z	$N_{\rm sim}$
S0	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Dehnen	0.5	density	thermal	SM17	$4 - 53.4$	0.0002	$1{,}000\times4$
S1	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Dehnen	1.0	density	thermal	SM17	$4 - 53.4$	0.0002	$1{,}000\times4$
S2	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Plummer	0.0	density	thermal	SM17	$4 - 53.4$	0.0002	$1{,}000\times4$
S3	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Dehnen	0.5	density	thermal	O+16	$3 - 30$	0.0002	$1{,}000\times4$
S4	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Dehnen	0.5	density	thermal	FLAT	$3 - 30$	0.0002	$1{,}000\times4$
S5	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Dehnen	0.5	logflat	thermal	SM17	$4 - 53.4$	0.0002	$1{,}000\times4$
S6	$10^2 - 10^5$	$1.7\times10^4 - 1.7\times10^7$	Dehnen	0.5	density	thermal	SM17	$4 - 53.4$	0.02	$1{,}000\times4$

Arca Sedda, Amaro-Seoane, and Chen (2021), A&A, 652, id.A54, 17 pp.

The build-up of IMBHs in massive clusters: hierarchical BH mergers

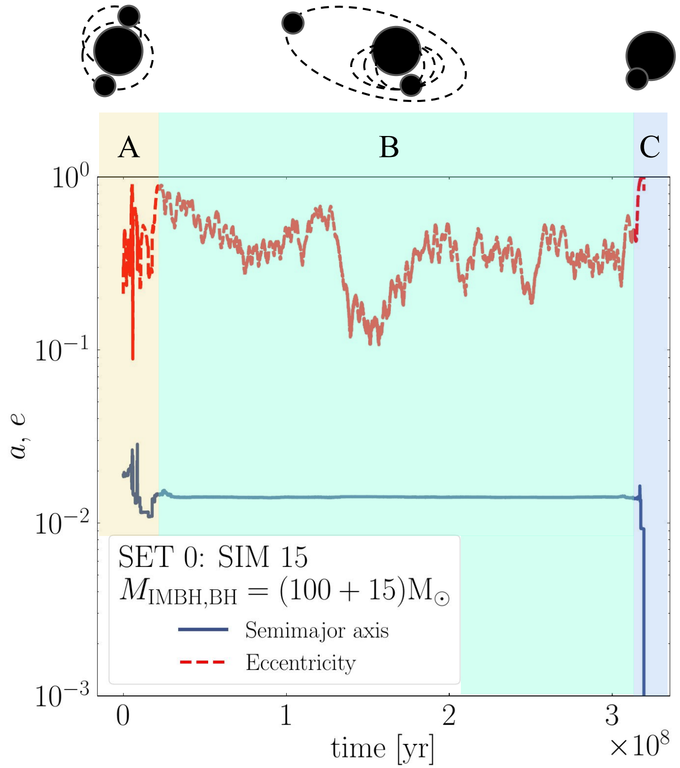
There are three main phases (in most cases):

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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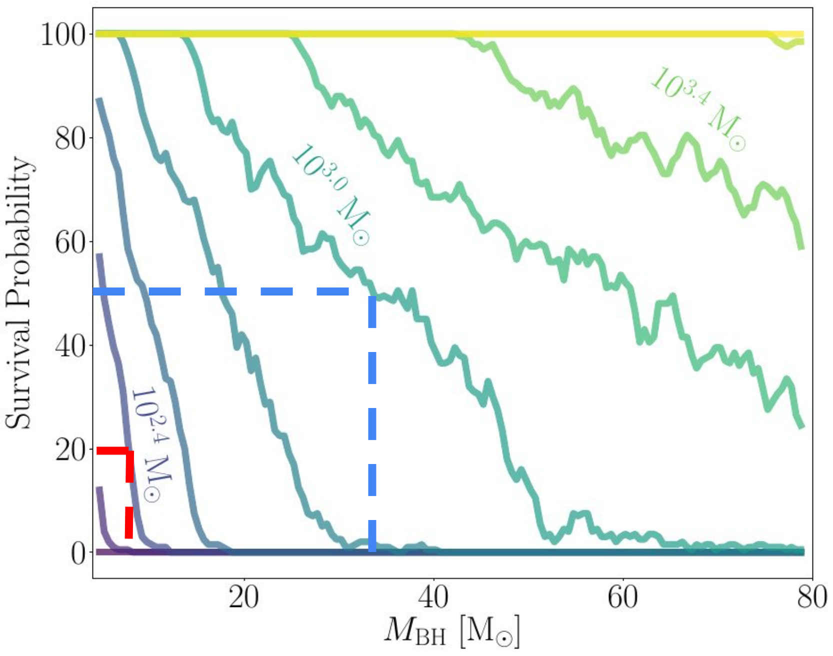
The build-up of IMBHs in massive clusters: hierarchical BH mergers

IMBH retention (survival) probability



Key result #1

- One line → IMBH and host cluster masses
- Survival = prob. to be retained upon GW kick

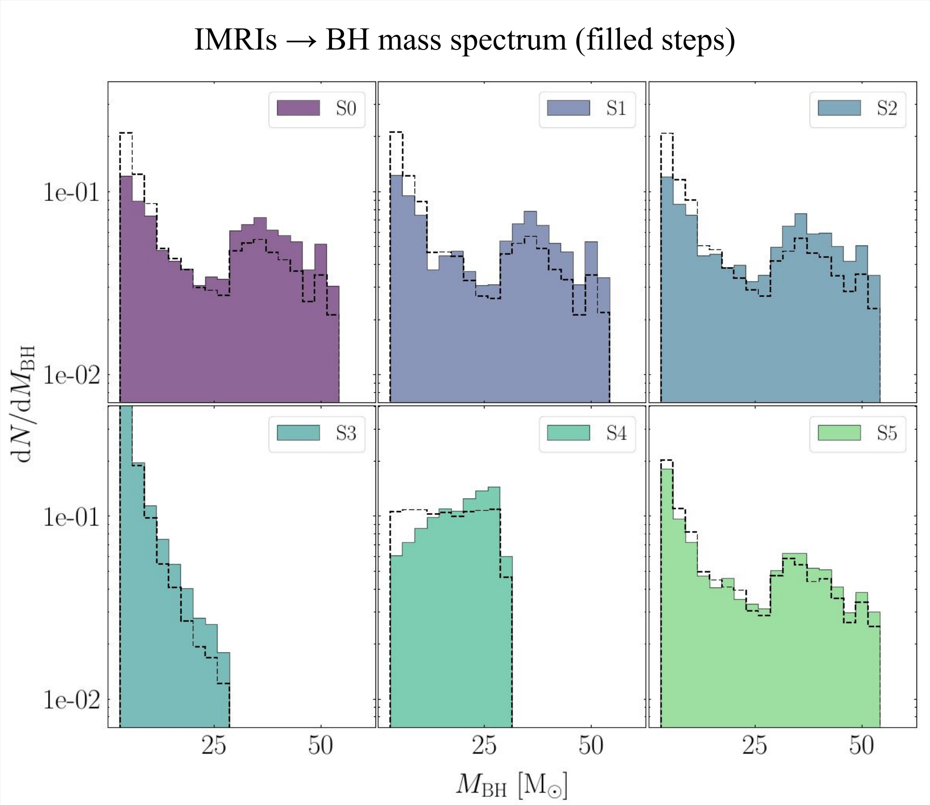
Result:

- $M_{IMBH} \sim 10^3$ M_{SUN} : $P_{SUR} > 50\%$ only if $M_{BH} < 35$ M_{SUN}
- $M_{IMBH} \sim 250$ M_{SUN} : $P_{SUR} > 20\%$ only if $M_{BH} < 10$ M_{SUN}

Takehome

it's difficult to retain the merger product and grow the IMBH mass too

The build-up of IMBHs in massive clusters: hierarchical BH mergers



Key result #2

- Empty step: initial BH mass spectrum
- Filled step: merging BH mass spectrum

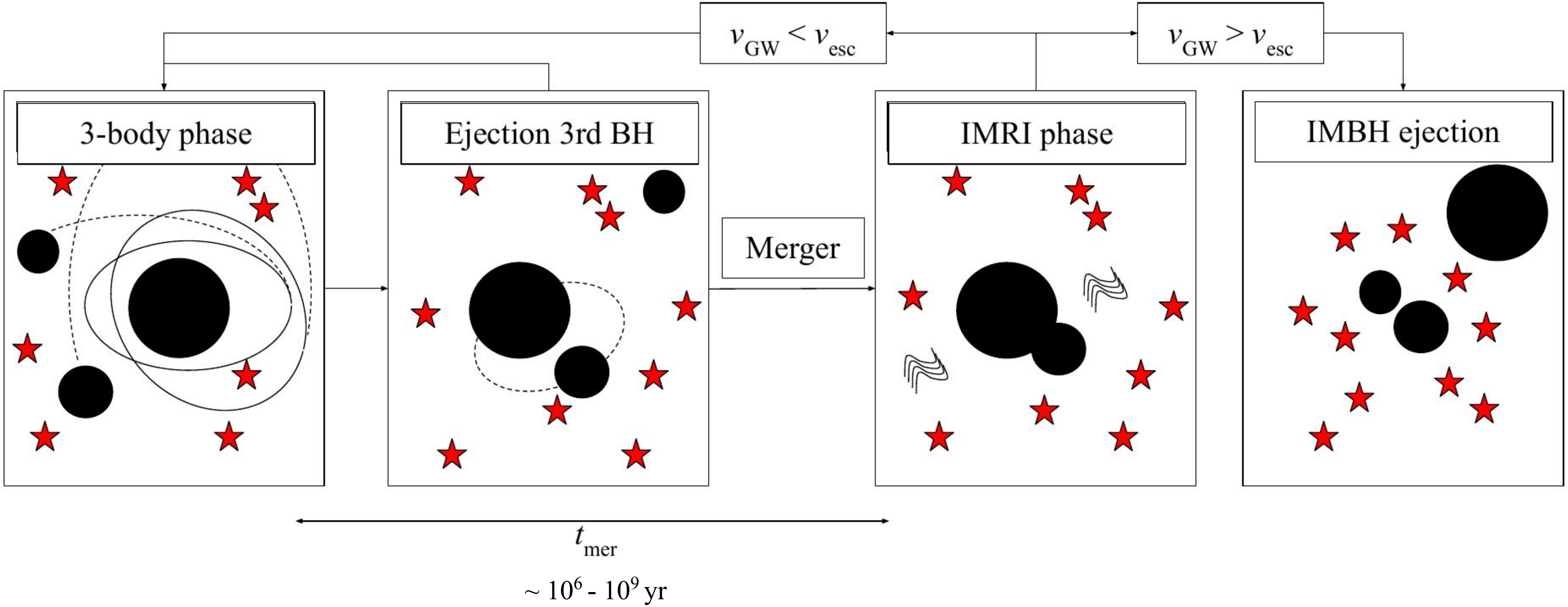
Results:

- IMRIs map the BH mass spectrum

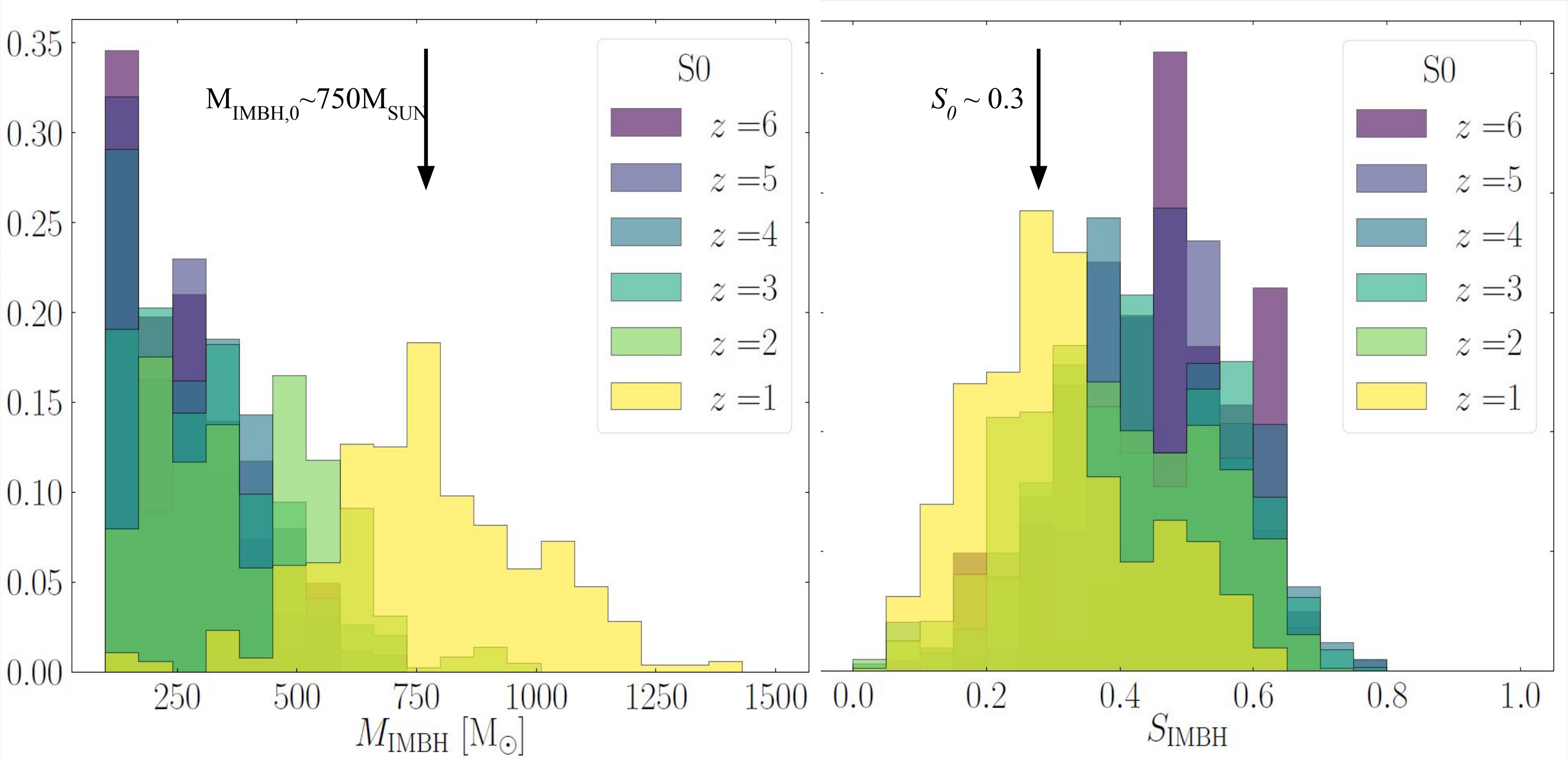
Takehome

can shed light on the impact of dynamics on stellar BHs and the BH mass spectrum in clusters

Growing IMBHs via repeated IMRI phases in Globular Clusters



Growing IMBHs via repeated IMRI phases in Globular Clusters



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:

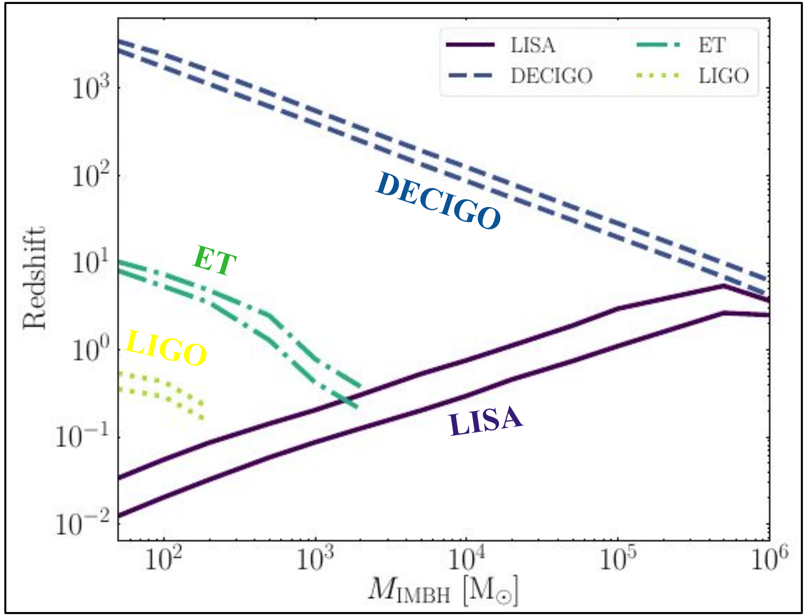
$$\Gamma_{\rm IMRI} = \Omega_s \int_{M_1}^{M_2} \int_0^{z_{\rm hor}} \frac{\mathrm{d}n_{\rm IMRI}}{\mathrm{d}M_{\rm IMBH}\mathrm{d}z} \frac{\mathrm{d}V_c}{\mathrm{d}z} \frac{\mathrm{d}z}{1+z} \mathrm{d}M_{\rm IMBH}$$

- 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

IMBH - cluster mass relation
Star cluster mass function
Galaxy cosmic mass function



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

Instrument	M_{SBH} $M_\odot$	z_{max}	$M_{IMBH,max}$ $M_\odot$	$\Delta\Gamma_1$ 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

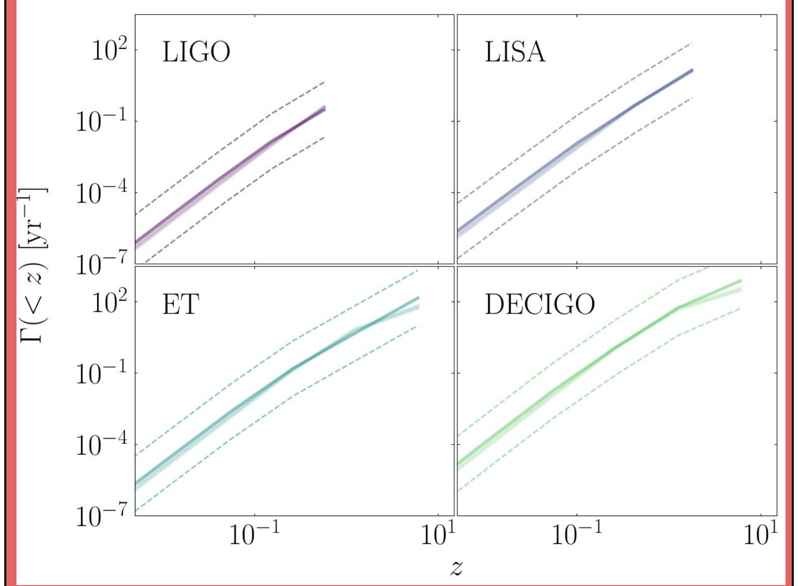
Nr. of detection per yr

LVK: ~1-2 IMRIs yr^{-1}

LISA: ~5-60 IMRIs yr^{-1}

ET: ~ 2 - 600 IMRIs yr^{-1}
DECIGO: >10^3 IMRIs yr^{-1}

Cumulative IMRIs merger rate vs. redshift



Conclusions

- ✓ Retention probability is rather low (< 20%) for IMBHs less massive than a few 10^2 M_{SUN} in globulars
- ✓ IMRIs map the stellar BH mass spectrum, carrying insights on the impact of dynamics on the BH population
- ✓ Repeated IMRIs lead to a characteristic IMBH mass and spin distribution at redshift $z<1$
- ✓ ET can detect ~2-600 IMRIs per year at $z > 1$, probing the physics of IMRIs and the IMBH mass spectrum