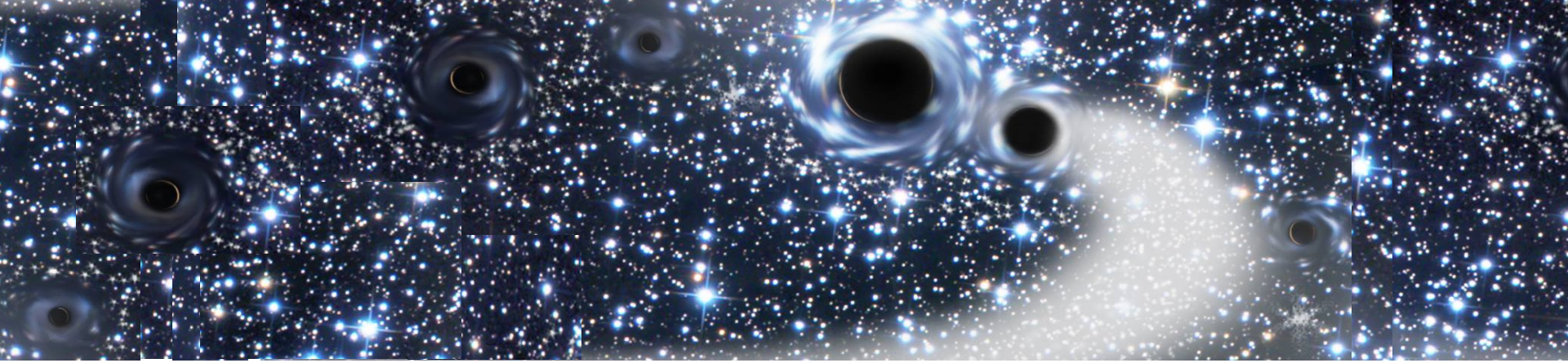


Can deci-Hz detectors shed light on the true nature of intermediate-mass black holes?

Manuel Arca Sedda

LGWA - WP
kick-off meeting

09 - 02 - 2023

SUMMARY

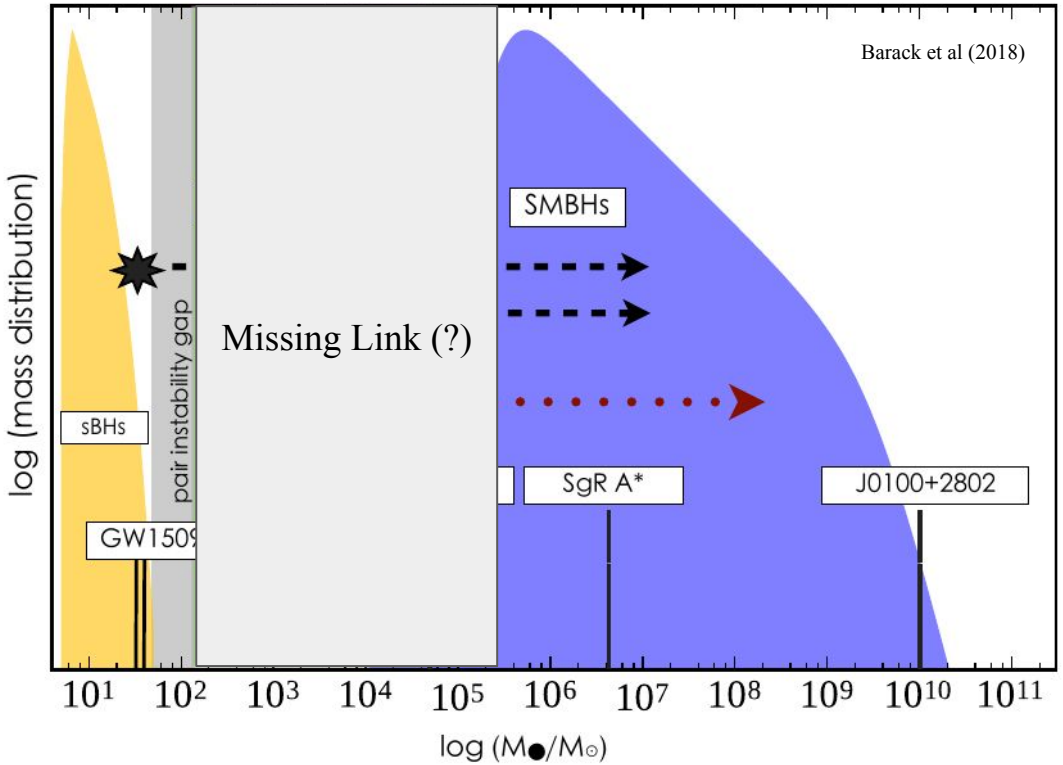
1. IMBHs: what we do and don't know

2. The build-up of IMBHs in massive clusters

3. IMBHs as gravitational-wave sources

4. Discoveries waiting in the decihertz range: IMBHs (?)

IMBHs: what we do and don't know



IMBHs: what we do and don't know

Do IMBHs live in galaxies?

- Centre of low-mass galaxies, $\mathbf{M_{IMBH}>50{,}000M_{SUN}}$ (Mezcua18, Greene+20)
- Offset source ULX (Kaaret+17)
- Dynamics (Nguyen+17,18,19)
- TDEs (Angus+22)
- X-rays in AGNs (Reines+13, Baldassarre+17, Chilingarian+18)
- Jet Radio emission (Mezcua+17)
- Optical variability (Baldassarre+18, Burke+23)
- Multi-wavelength Spectroscopy (Greene+20)

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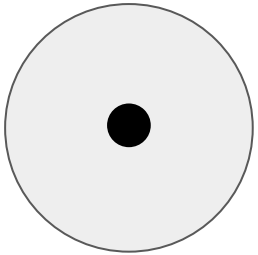
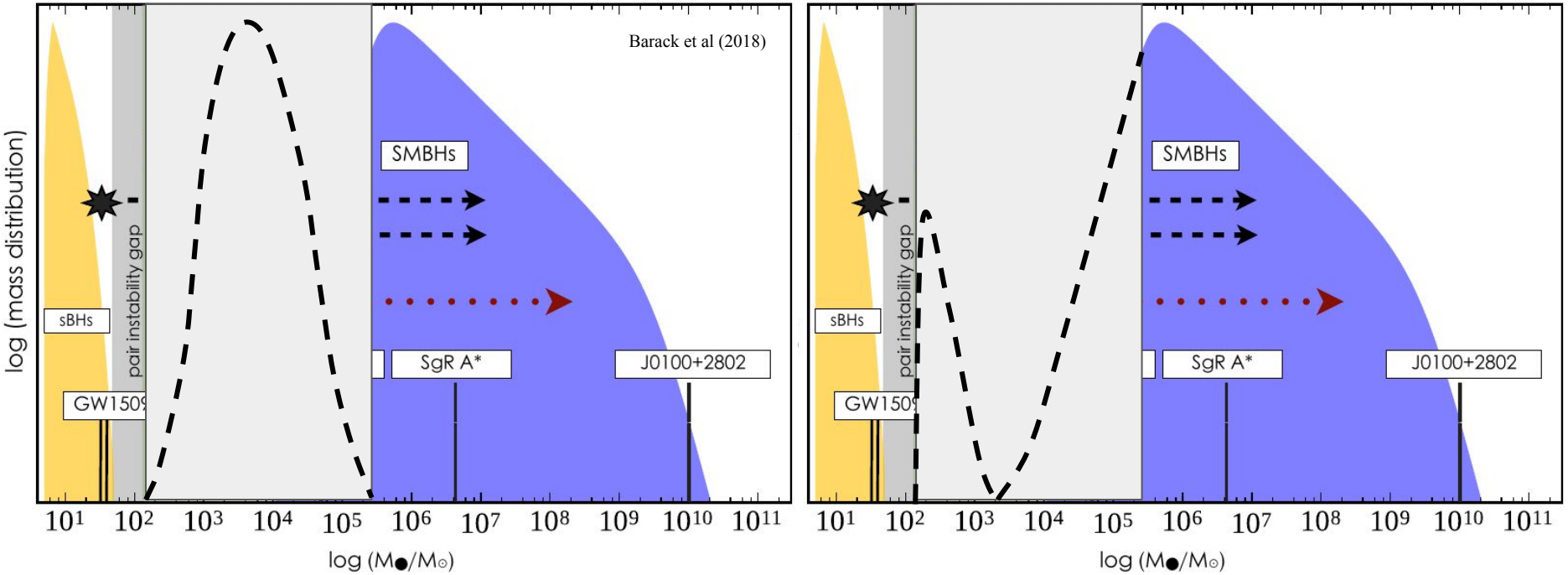
Do IMBHs live in star clusters?



- **No smoking gun yet!**
- Centre of star clusters, $\mathbf{M_{IMBH}< 10{,}000M_{SUN}}$
- Dynamics? (Van der Marel10, Lanzoni+13, Lutzgendorf+13)
- X-ray? (e.g. Gebhardt02,05)
- Radio? (Tremou+18)
- Pulsar acceleration (Kiziltan+18, Abbate+19)
- TDEs (Lin+18,19)
- GWs (GW190521)

IMBHs: what we do and don't know

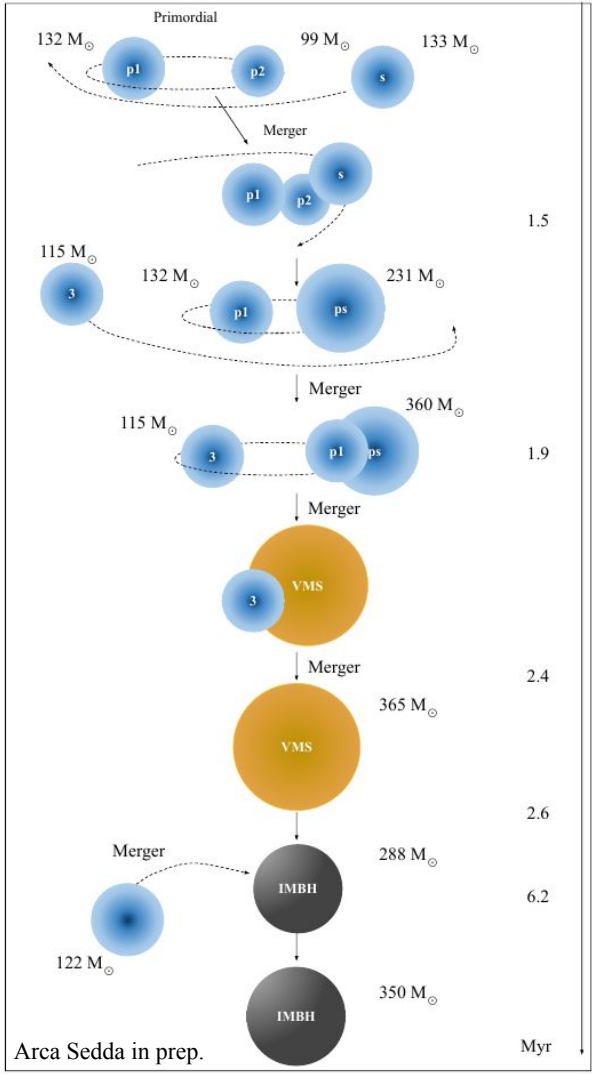
Do IMBHs constitute a special class of IMBHs? What is the IMBH mass spectrum?



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)



Arca Sedda in prep.

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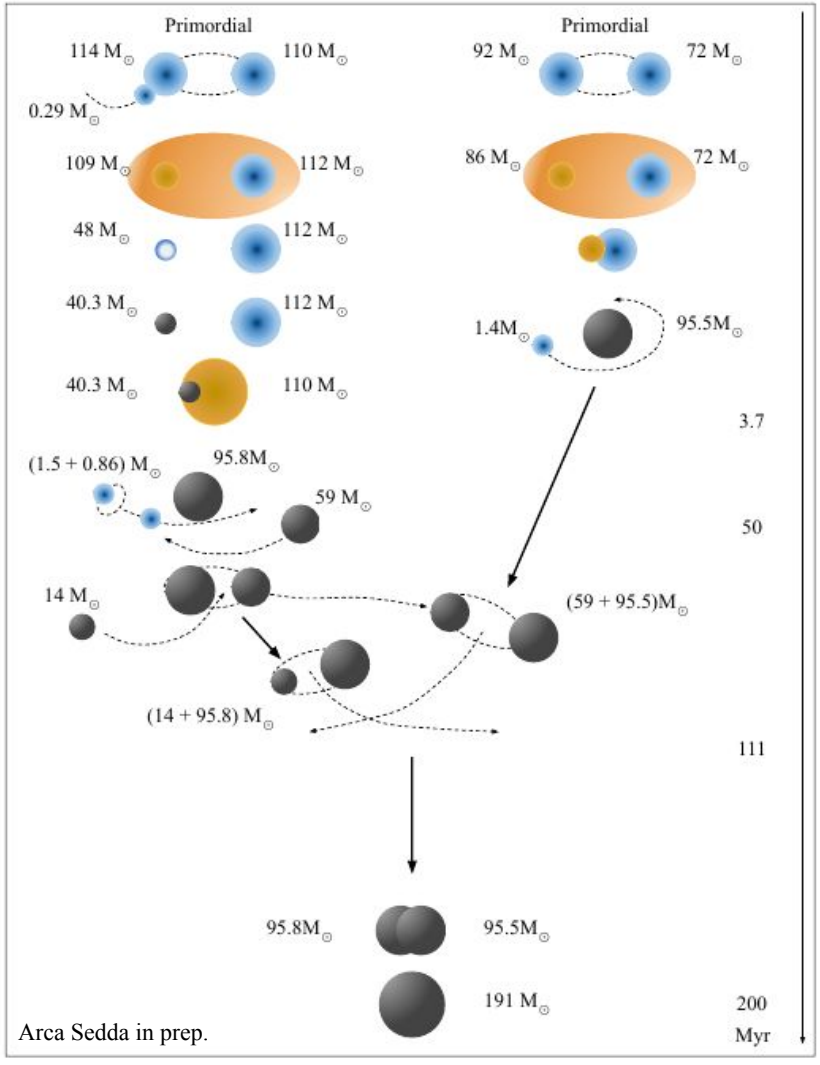

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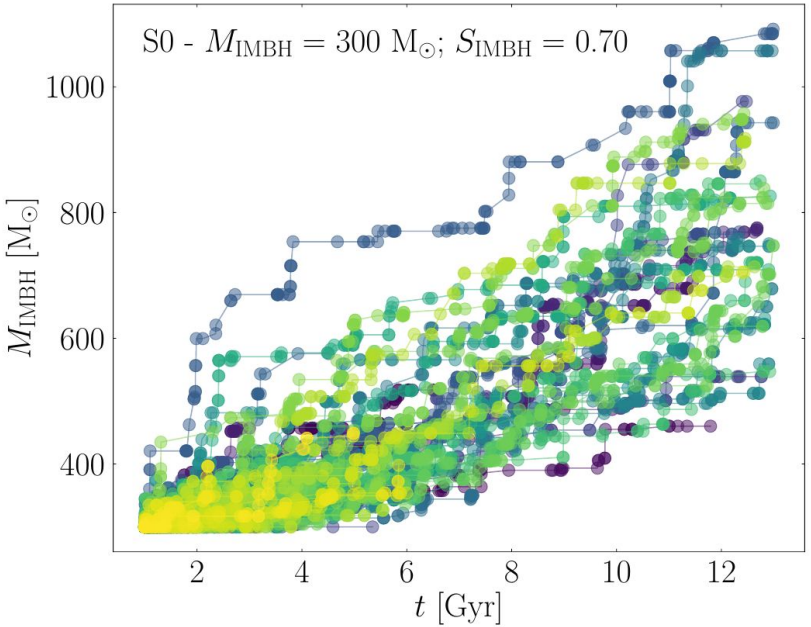
Arca Sedda, Amaro-Seoane, Chen (2021)



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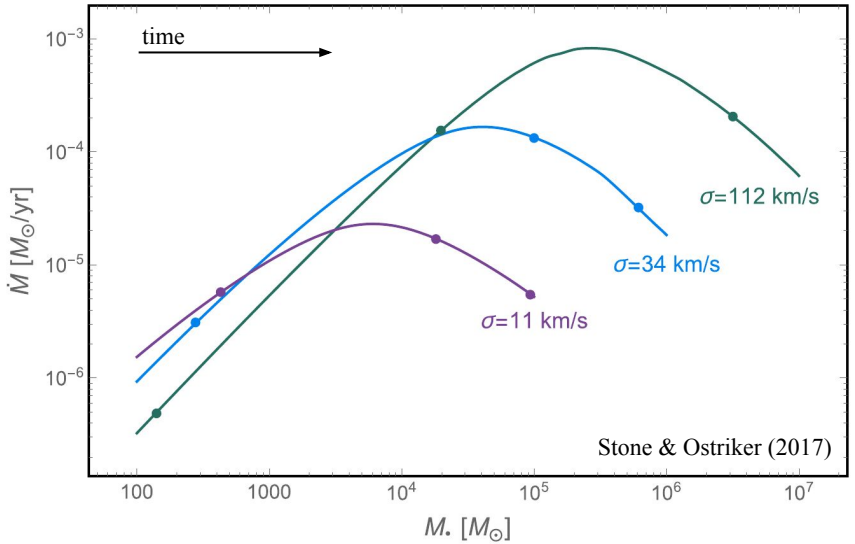
4. Accretion of stellar material via tidal disruption events (TDEs)
(Giersz+15, Stone&Ostriker17, Rizzuto+22)



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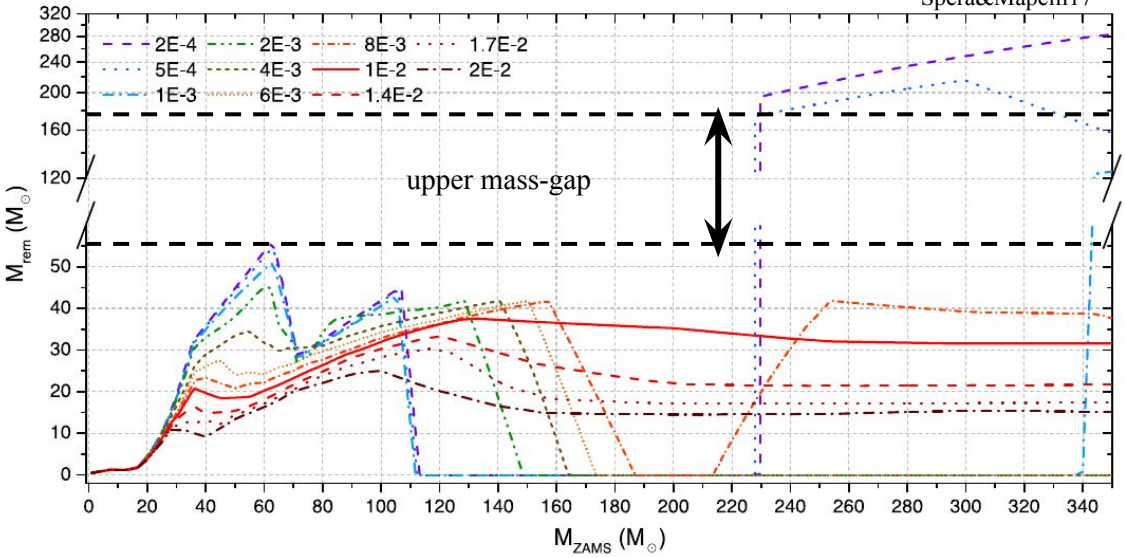
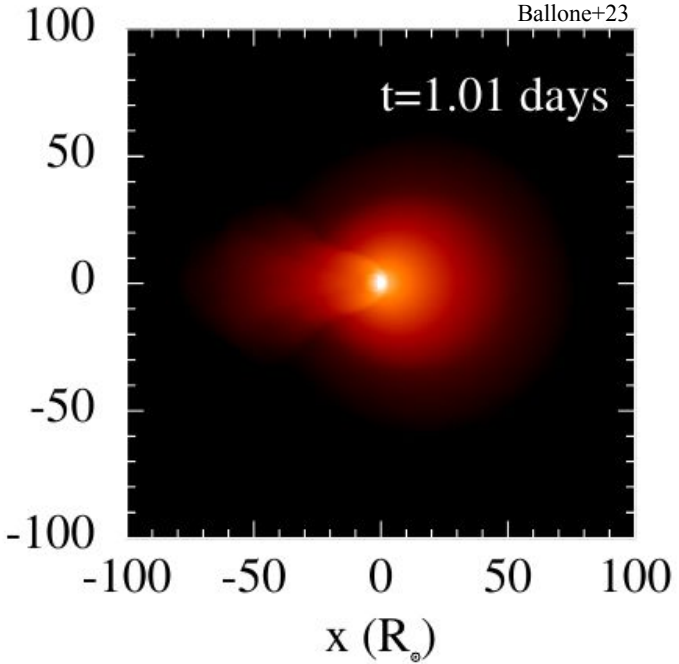
Spera&Mapelli17



Ballone+23



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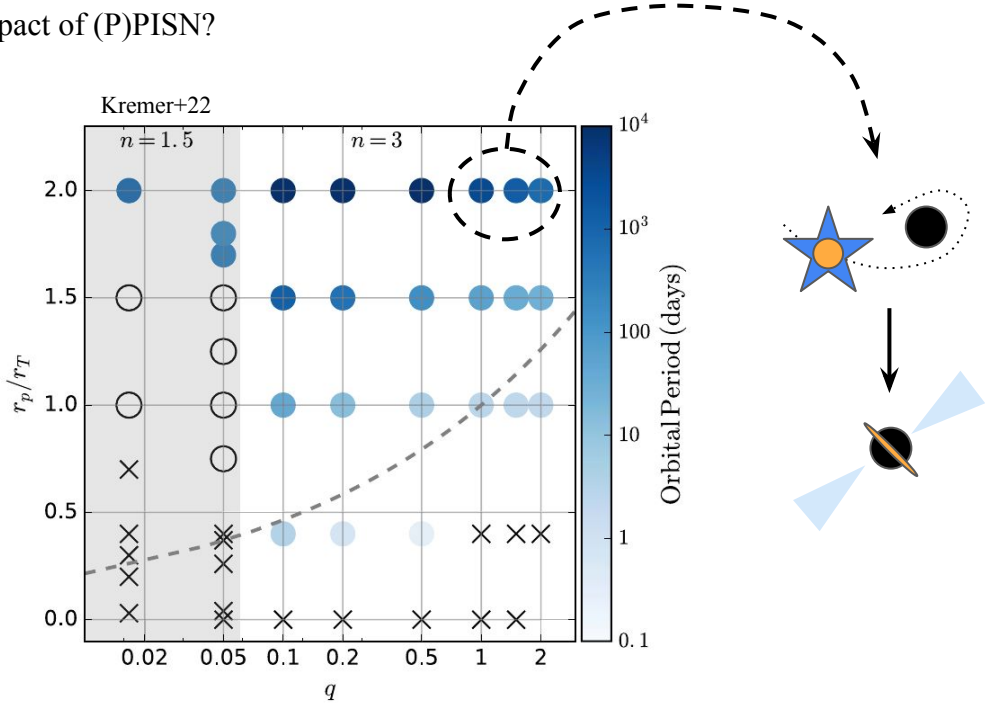

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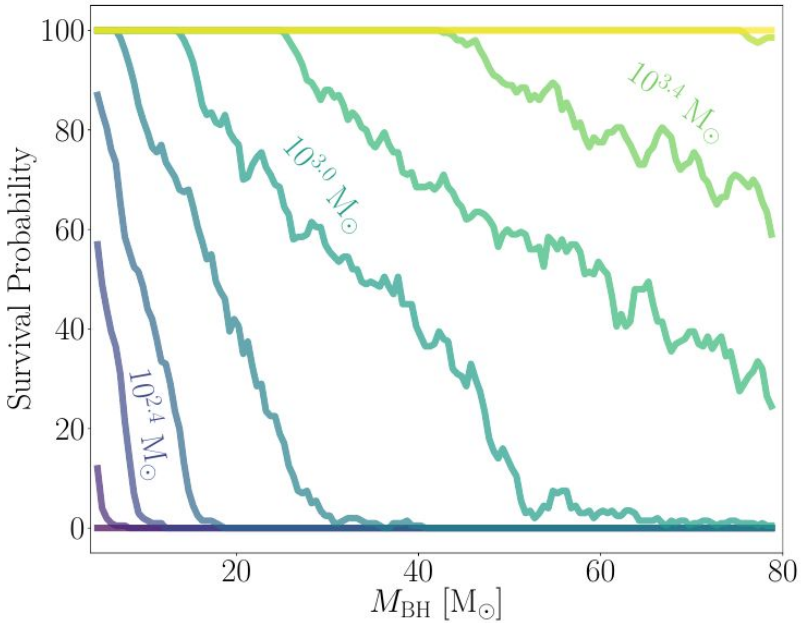

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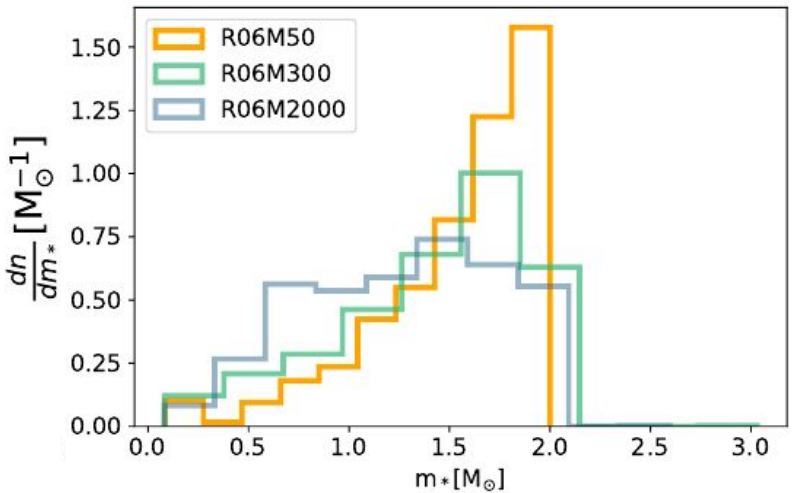
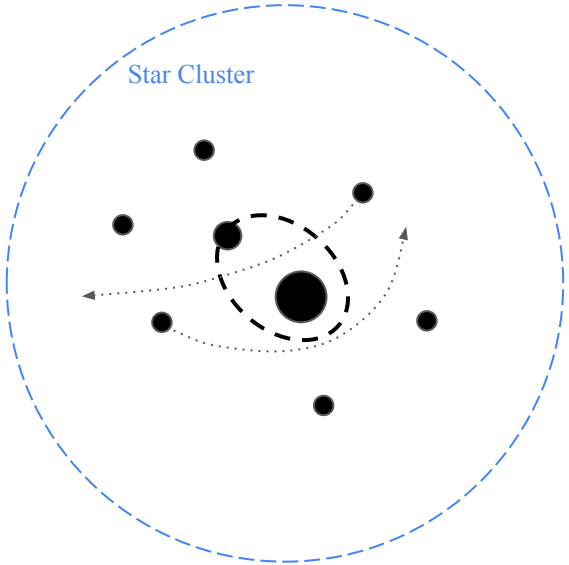
4. TDEs: what is the mass function around a growing IMBH? (Giersz+15, Stone&Ostriker17, Rizzuto+22)

Rizzuto+22



IMBHs as gravitational-wave sources: IMRIs

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)



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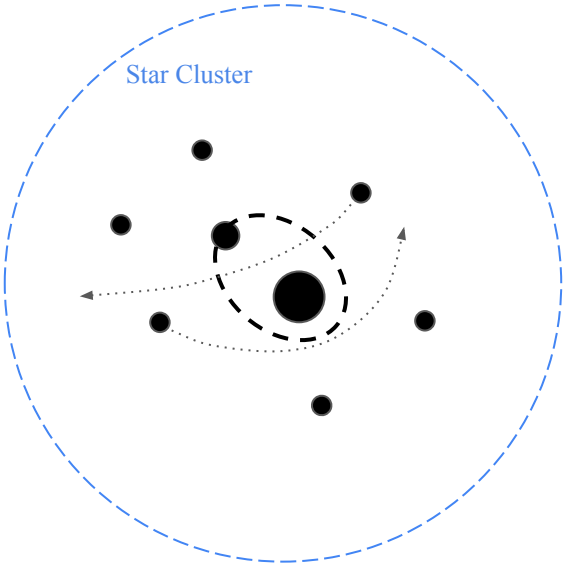
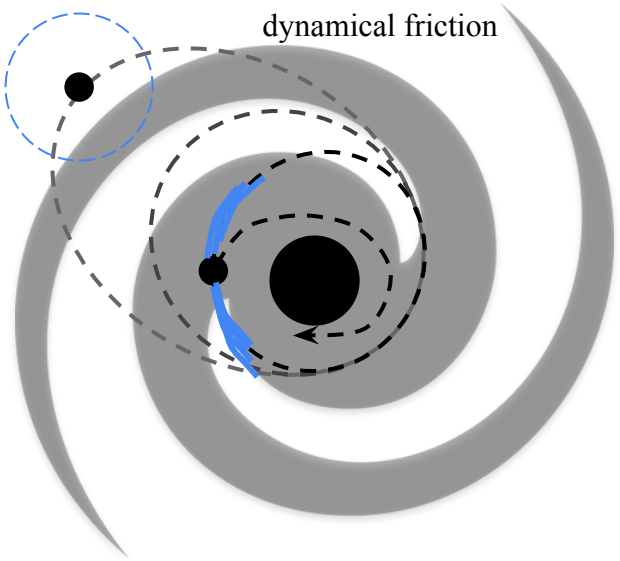
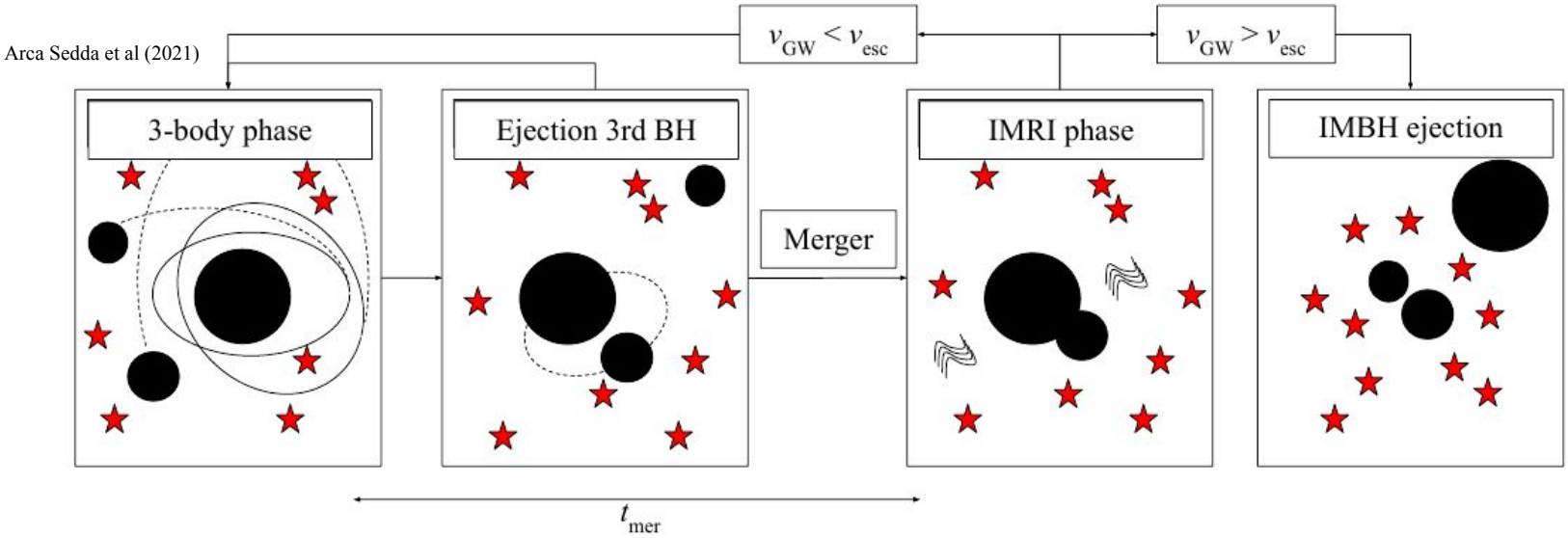


Heavy IMRIs: IMBH + SMBH (Amaro-Seoane+22)
- Minor galaxy mergers (?)
- Nuclear clusters (Ebisuzaki+01, Portegies-Zwart+06, Arca Sedda&Gualandris18, Arca Sedda&Capuzzo-Dolcetta19)



IMBHs as gravitational-wave sources: mass and spin spectrums

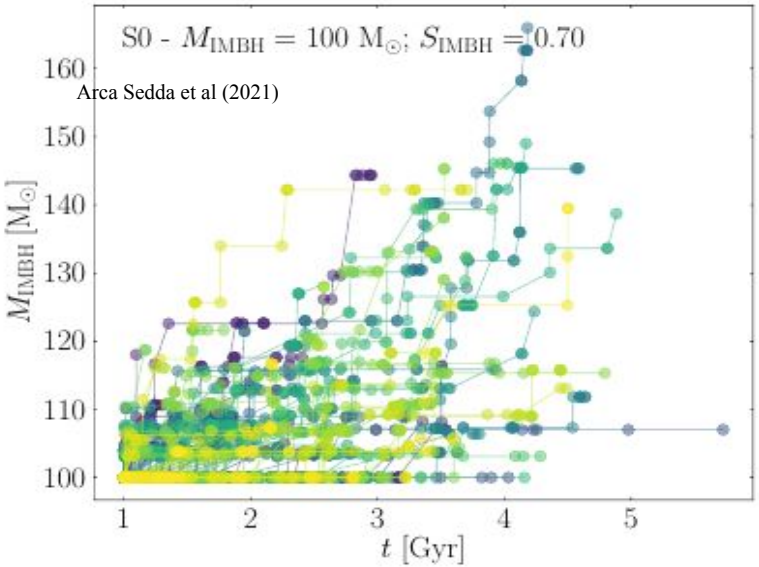


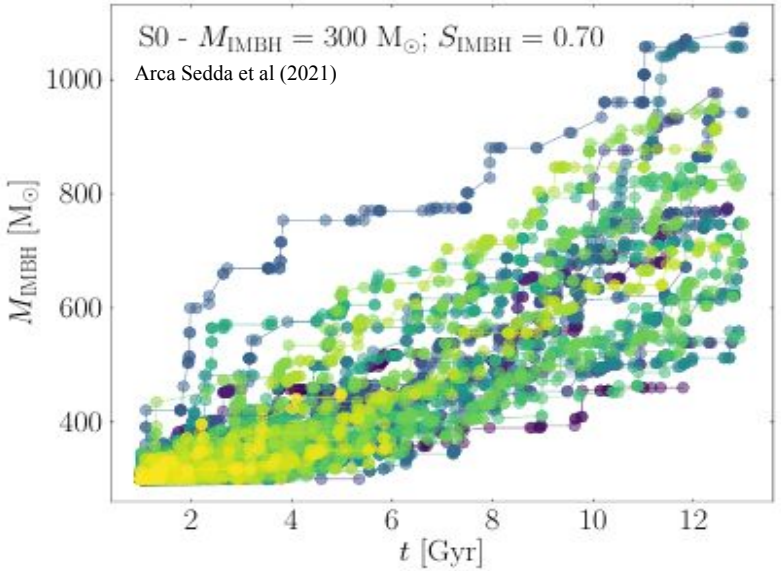
Huge parameter space:
IMBH seed mass distribution, star cluster initial mass function, IMBH-cluster scaling relations, cosmic star cluster formation history …

IMBHs as gravitational-wave sources: mass and spin spectrums

Mass

From stellar mergers	collapse of a VMS → ~ 100-300 M_{SUN}
From star-BH accretion	fraction of accreted material → ~ 30-50 M_{SUN}
From BH-BH mergers	retention probability





IMBHs as gravitational-wave sources: mass and spin spectrums

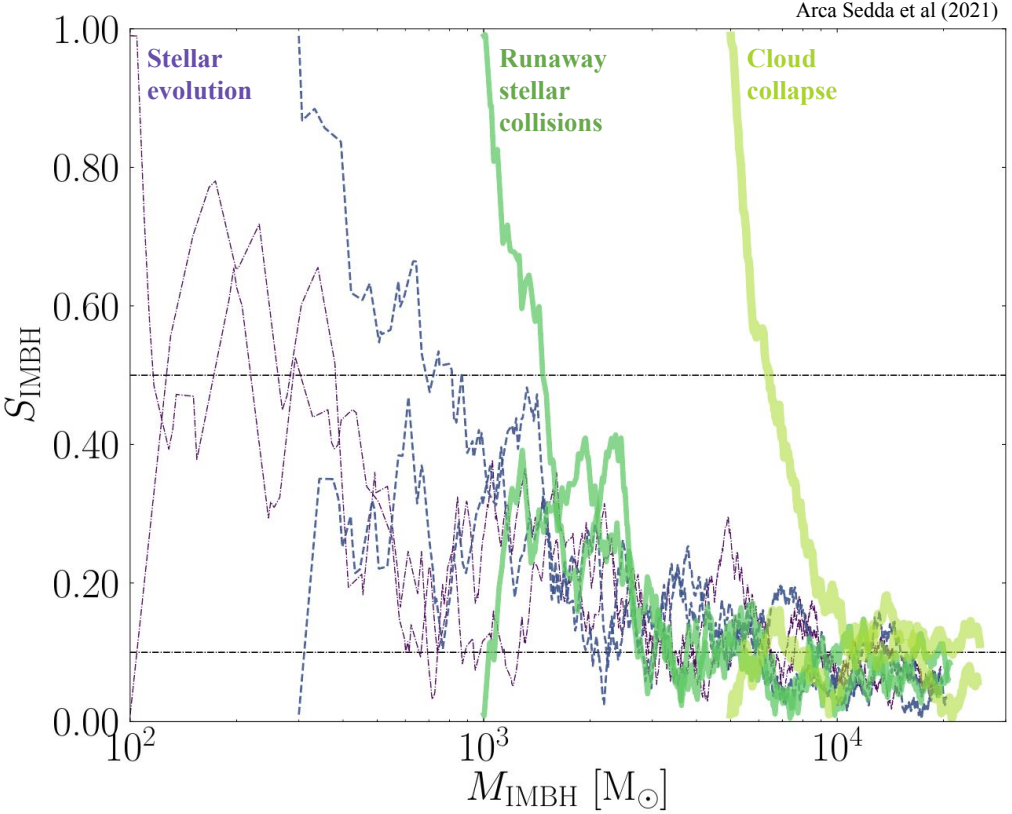
Spins

From stellar mergers:
collapse of a VMS → low spin (Fuller & Ma 19)

From star-BH accretion:
BH spin-up (Qin+19)

From BH-BH mergers:
Spin evolution →

Arca Sedda et al (2021)



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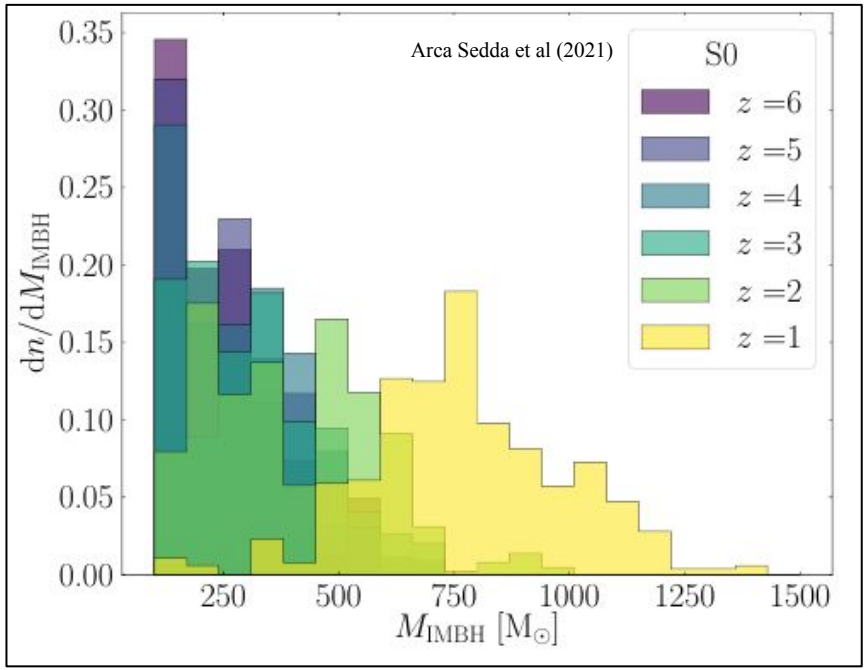

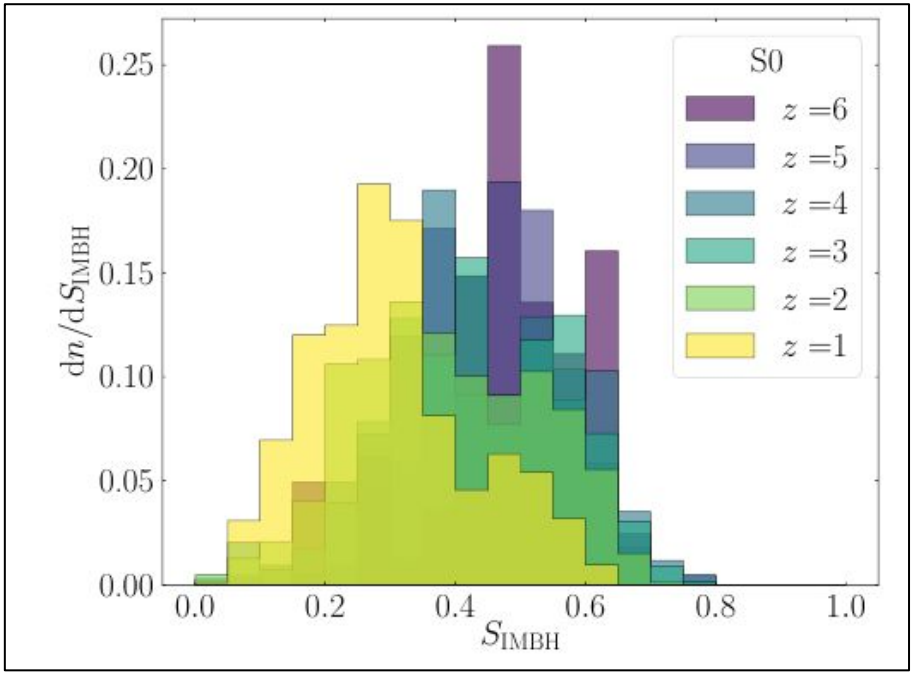

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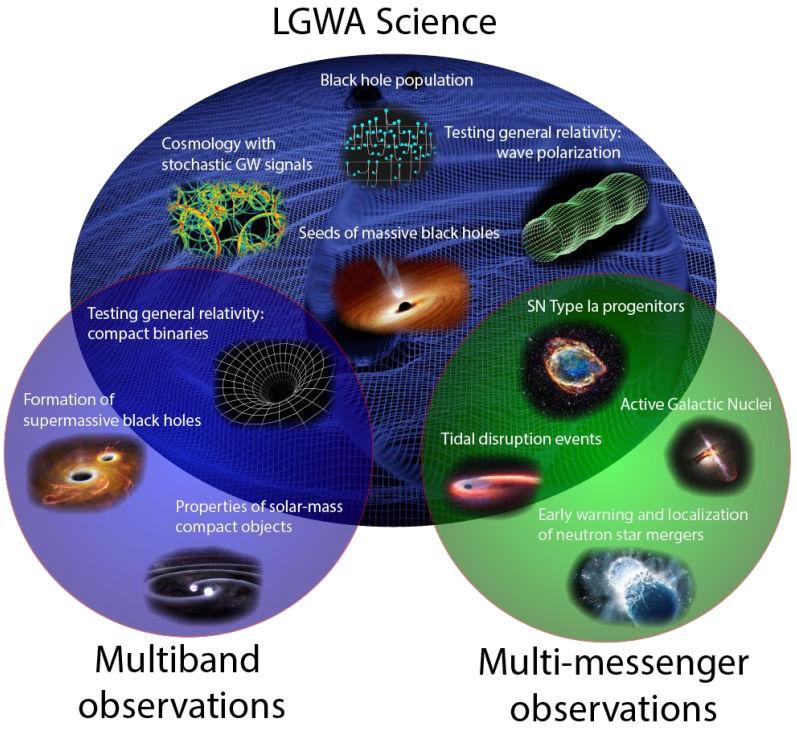
Discoveries waiting in the deci-Hz band

Prospects for future deci-Hz detectors

- Decihertz Observatory (LISA-like concept) (Arca Sedda et al 2020)
- LGWA (Seismographs on the Moon) (Harms et al 2013, 2021)
- ALIA (Heliocentric LISA-like) (Bender et al 2013, Baker et al 2019)
- DECIGO (short-arms LISA-like) (Kawamura et al 2001, 2020, Sato et al 2017)
- TianQin (Geocentric) Luo et al 2016)
- TianGo (Strawman) (Mandel et al 2016, Kuns et al 2020)
- MAGIS (Earth undergrounds) (Graham et al 2017)
- AEDGE (Earth orbit) (El-Neaj et al 2020)
- LION (> 0.5 Hz, Moon) (Amaro-Seoane et al 2021)
- GLOC (> 0.5 Hz, Moon) (Kani & Loeb 2020)



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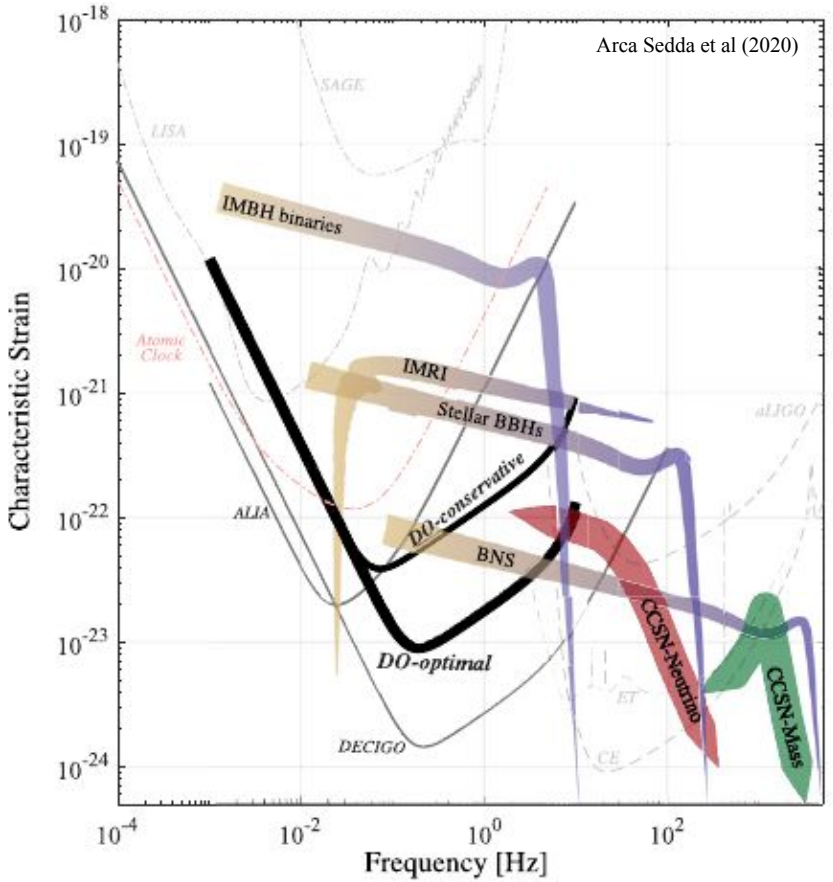


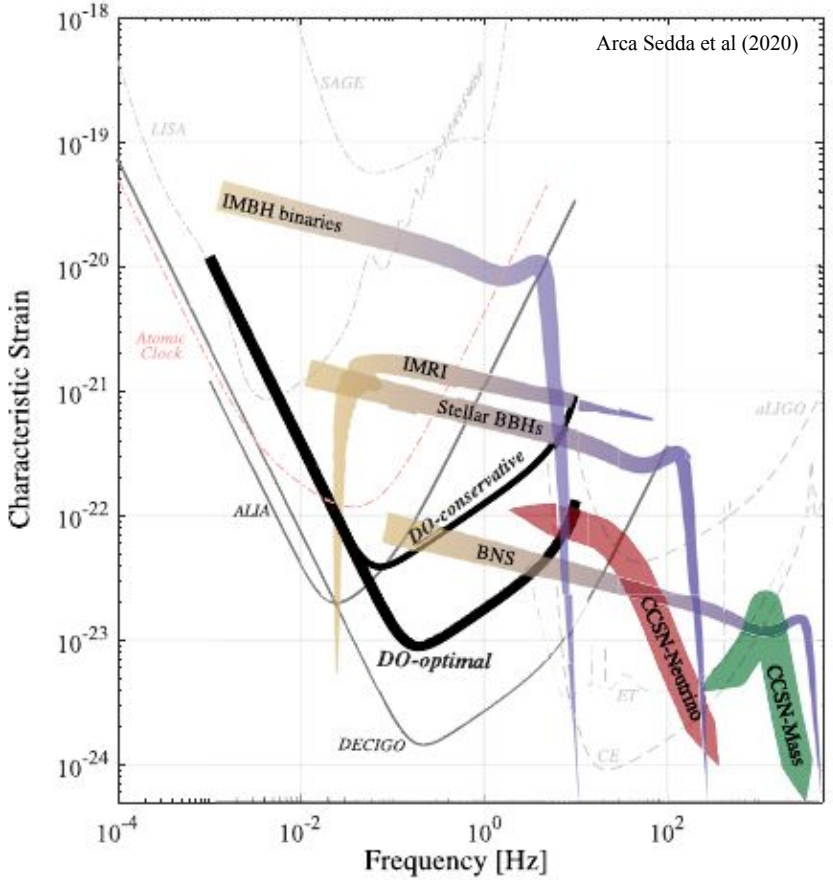
Discoveries waiting in the deci-Hz band

Why Decihertz?

a) Compact stellar remnants in binaries (WDs, NSs, BHs)
   i) multiband sources
   ii) guaranteed sources (thanks LVC!)

b) IMBHs (10^2 - 10^4 M_{SUN})
   i) IMBH binaries
   ii) IMRIs

c) Cosmological stochastic GW background (SGWB)
   i) New physics (?)
   ii) Test of GR and fundamental physics



Discoveries waiting in the deci-Hz band

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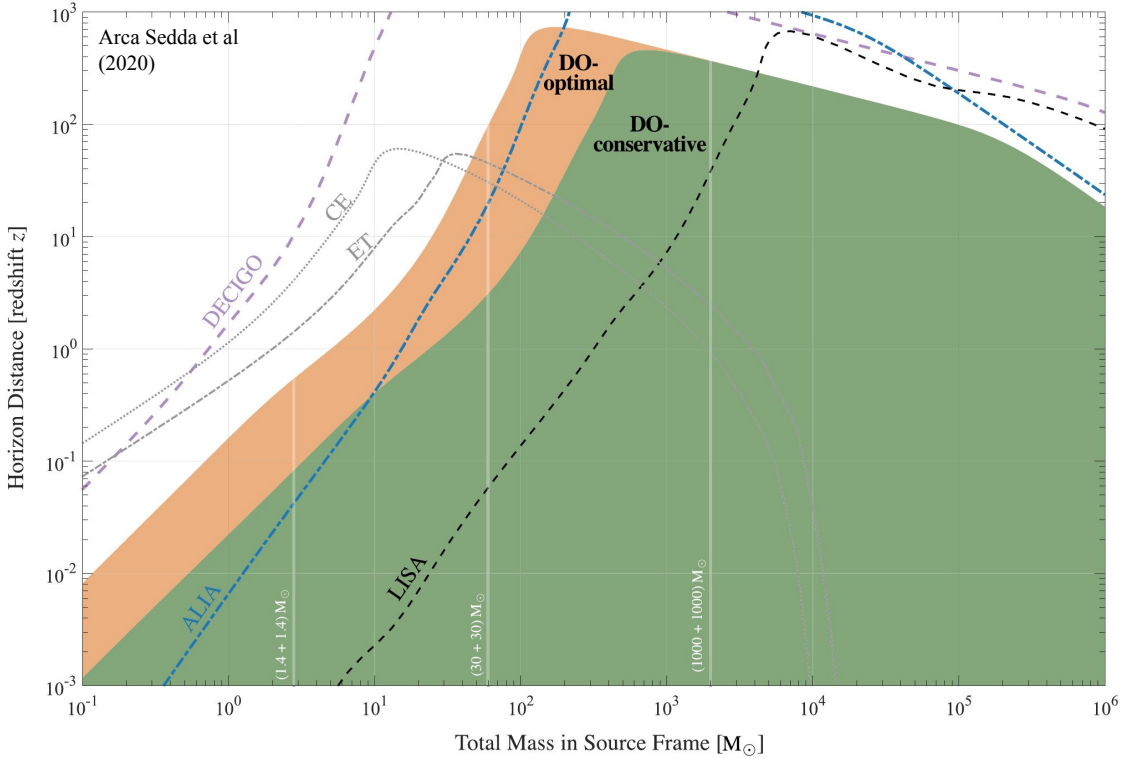


Discoveries waiting in the deci-Hz band

Why Decihertz?

Arca Sedda et al (2020)

Source type	Masses $(m_1 + m_2)/M_\odot$	DO-conservative	DO-optimal	ALIA	DECIGO	LISA
BNS	$1.4 + 1.4$	0.1	0.5	0.05	10	< 0.001
NSBH	$14 + 1.4$	0.3	2	0.5	170	< 0.01
NSBH	$70 + 1.4$	0.6	4	2	250	< 0.1
BBH	$30 + 30$	3	100	20	$>10^3$	~ 0.2
IMRI (IMBH–BH)	$100 + 10$	3	60	20	$>10^3$	~ 30
IMRI (IMBH–BH)	$2000 + 40$	30	50	180	160	~ 10
IMBH–IMBH	$1000 + 100$	90	160	600	470	~ 40
IMBH–IMBH	$1000 + 1000$	370	380	$>10^3$	$>10^3$	

Circular, non-spinning binaries

Discoveries waiting in the deci-Hz band

Why Decihertz? IMRIs

- 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:

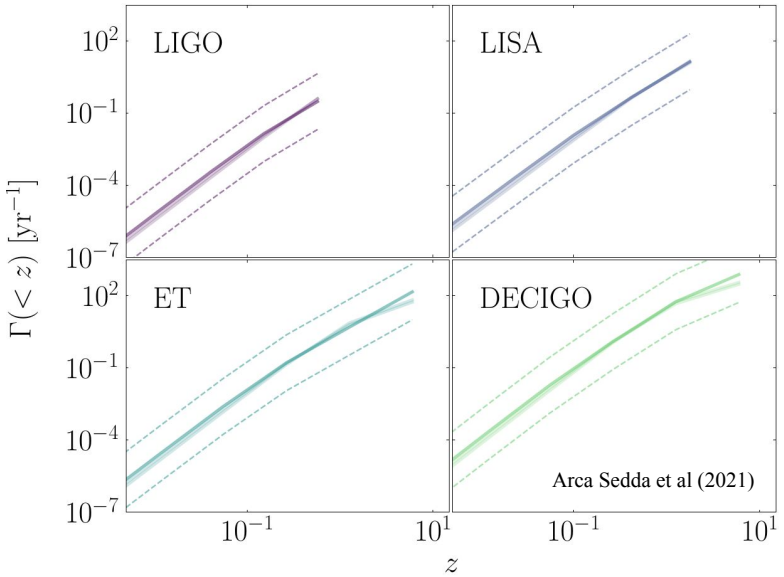
$$\Gamma_{\rm IMRI} = \Omega_s \int_{M_1}^{M_2} \int_0^{z_{\rm hor}} \frac{\mathrm{d}n_{\rm IMRI}}{\mathrm{d}M_{\rm IMBH}\mathrm{d}z} \frac{\mathrm{d}V_c}{\mathrm{d}z} \frac{\mathrm{d}z}{1+z} \mathrm{d}M_{\rm IMBH}$$

- 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

Cumulative IMRIs merger rate vs. redshift



Discoveries waiting in the deci-Hz band

Why Decihertz? IMRIs

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

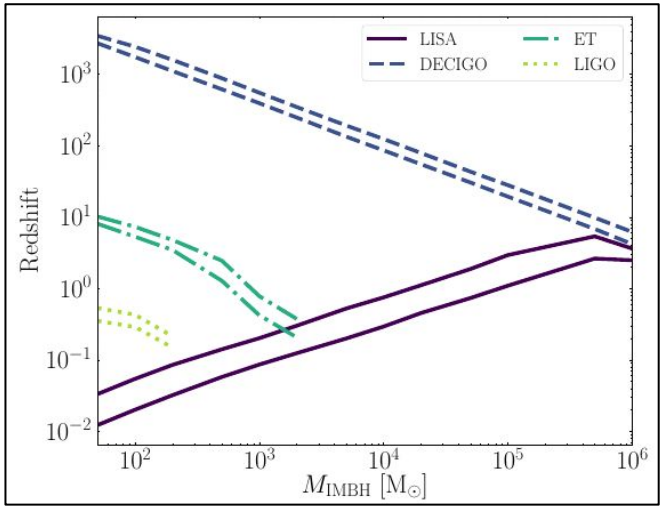
Arca Sedda et al (2021)

Nr. of detection per yr

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

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

ET/DECIGO: $>10^3$ IMRIs yr^{-1}



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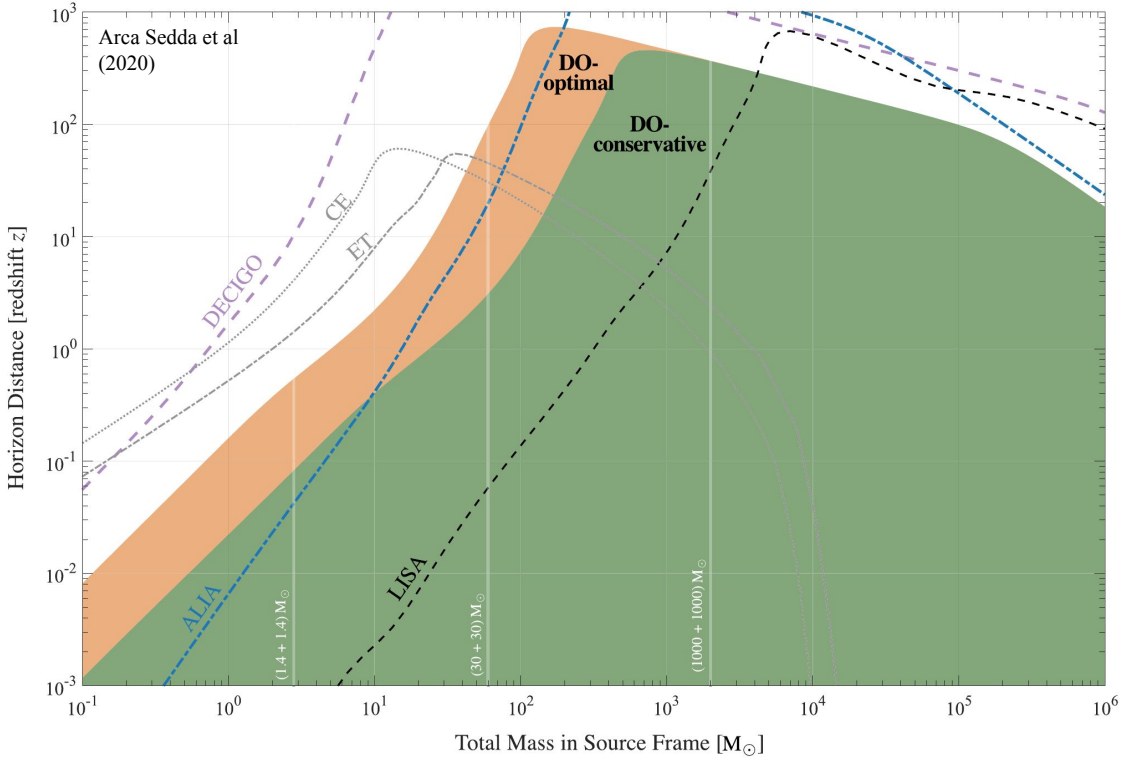
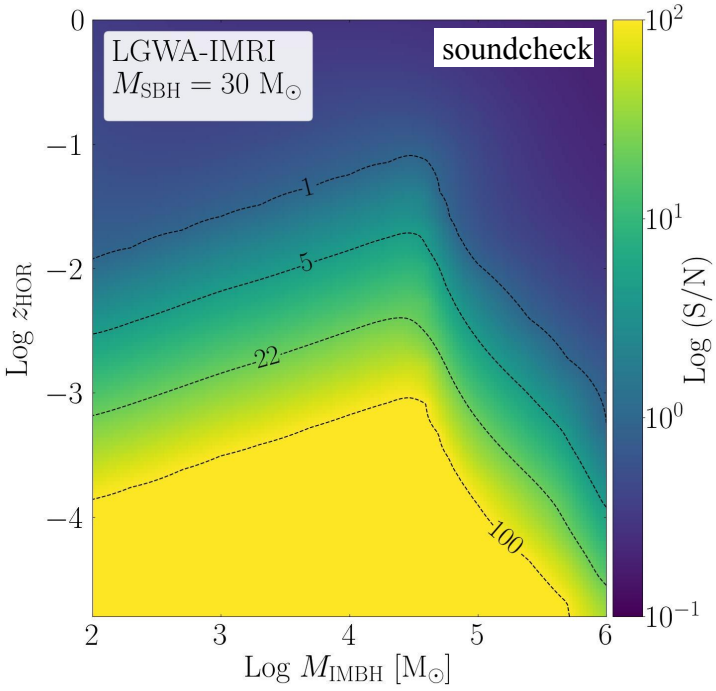
Why Decihertz?





Discoveries waiting in the deci-Hz band: IMBHs (?)

How many IMBH-BH mergers in the LGWA reach?

SNR ~ 5-22 → z = 0.001-0.005 → D_L = (4.4 - 22) Mpc

$N_{MW}(D_L) = 4\pi/3\ (2.26)^{-3}\ (D_L/\mathrm{Mpc})^3\ 0.0116$ (Kopparapu+08,Abadie+10)

From Arca Sedda, Amaro-Seoane, Chen 21:

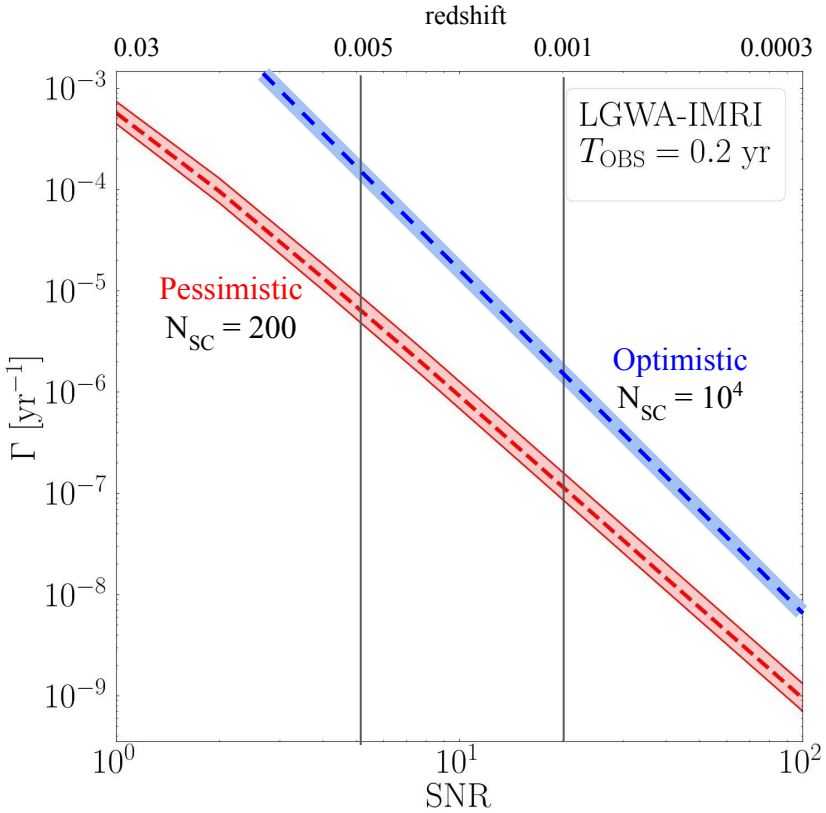
$N_{SC} = 0.08\ (\ M_{MW} / M_{SC}\ )$ (Bastian+08)

$N_{IMBH} = N_{SC}\ f_{IMBH}\ N_{MW}(D_L)$

T_{IMBH} ~ 1 Gyr

For LGWA (soundcheck):

Rate = N_{IMBH} / T_{IMBH} ~ (2 x 10^{-6} - 0.00024) yr^{-1} (optimistic N_{IMBH})



Discoveries waiting in the deci-Hz band: IMBHs (?)

Detecting IMBHs via GWs can enlighten us about the nature of IMBHs by:

1) inferring the mass spectrum

2) measuring the IMRI rate

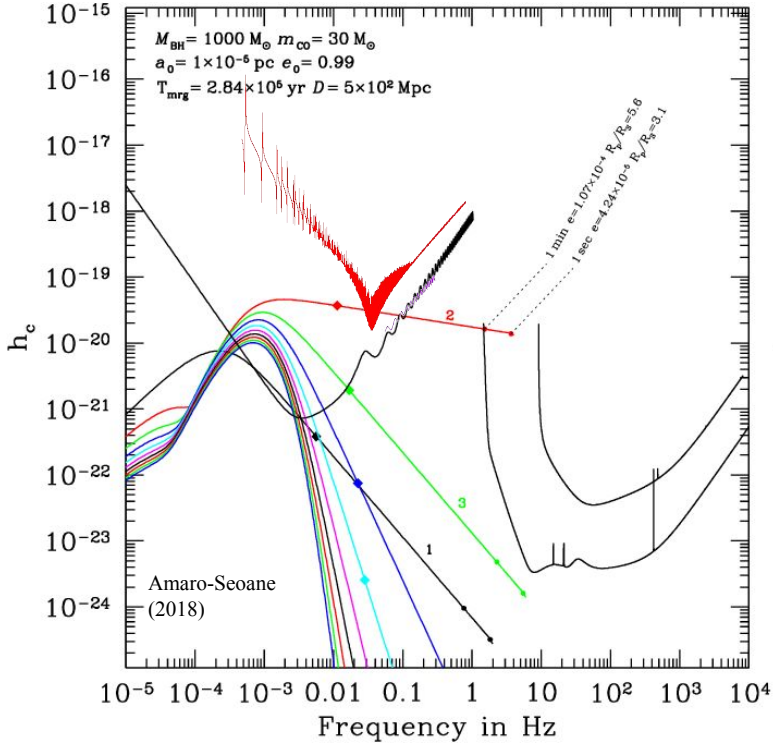
3) measuring the IMBH spin → clues about IMBH formation history

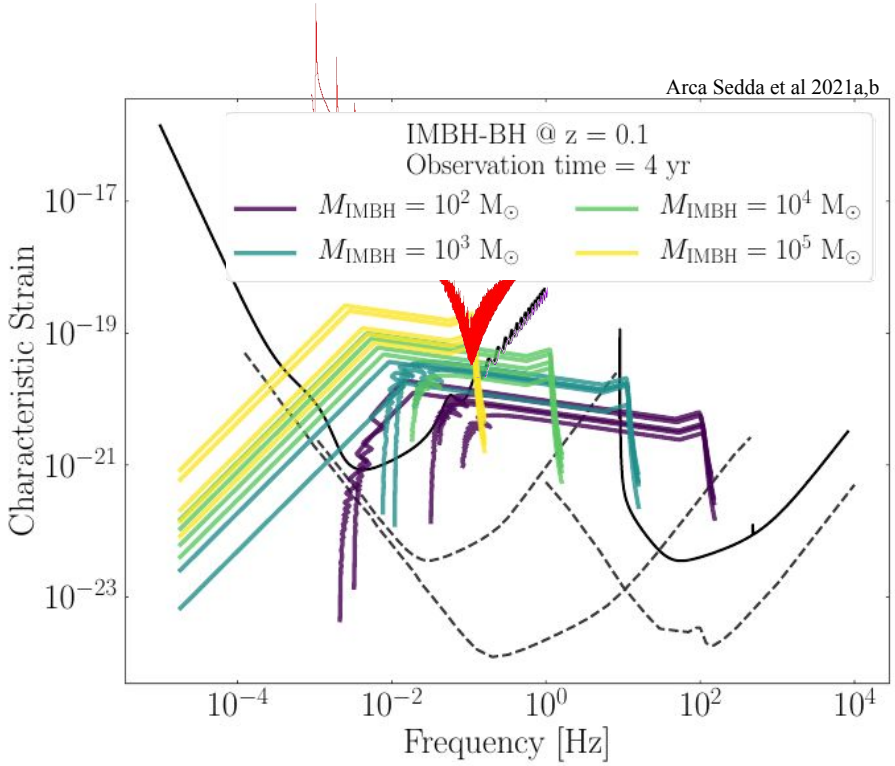
4) identifying the IMBH companion: BH, WD, NS?

5) pinpointing properties: localisation accuracy?

Discoveries waiting in the deci-Hz band: IMBHs (?)

Multiband GW Astronomy with IMBHs





Discoveries waiting in the deci-Hz band: IMBHs (?)

Multiband GW Astronomy with IMBHs

1) inferring the mass spectrum
2) measuring the IMRI rate
3) measuring the IMBH spin → clues about IMBH formation history
4) identifying the IMBH companion: BH, WD, NS?
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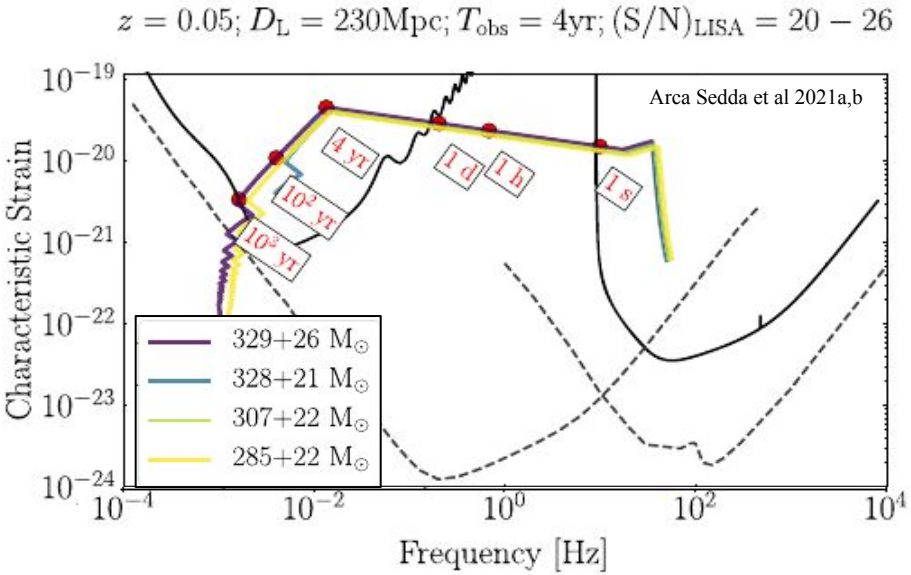

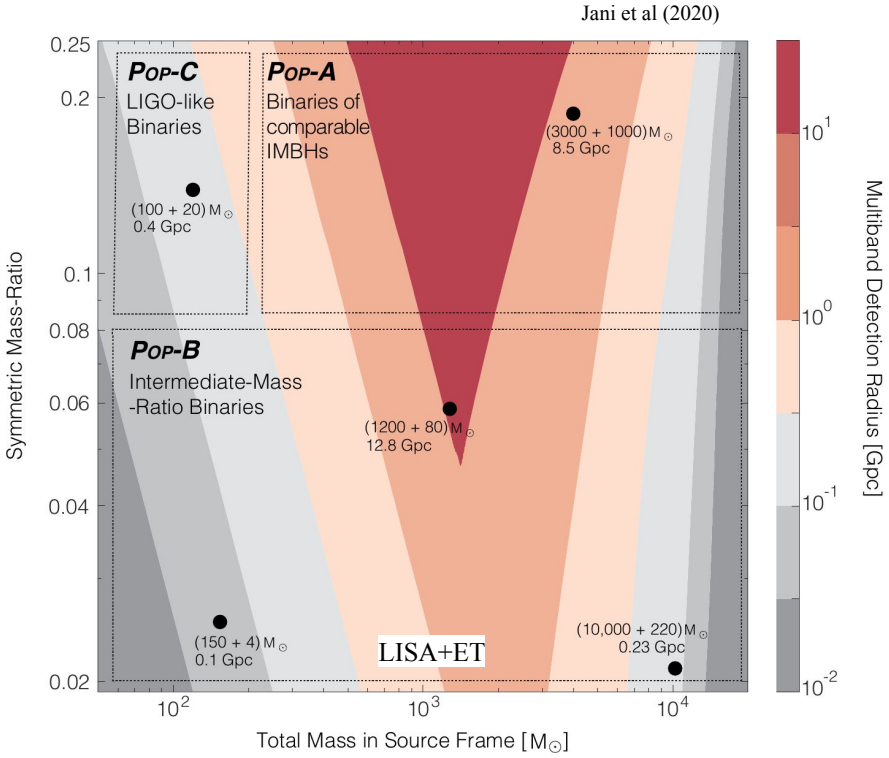

Wrap-up

#1 IMBHs may represent a missing link, but perhaps they're just the most peculiar members of the stellar BH and SMBH populations

#2 IMBHs can form in dense star clusters via multiple formation channels

#3 IMBHs can appear as GW sources called – light an heavy – IMRIs

#4 IMRI mass, mass ratio, spins, localisation can help shedding light on the true nature of IMBHs

#5 A deciHz detector is best suited for the job, as this band is where light IMRIs are loudest: IMRI rate DECIGO/LISA ~ 1000

#6 The detection rate for a LGWA Soundcheck is ~ 6×10^{-6} - 5×10^{-4} yr^{-1} for SNR < 5

#7 Having LGWA in concert with other low-, mid-, and high-frequency detectors would open the possibility to multiband IMRI detection