Assessing the performance of future space-based detectors:

Astrophysical foregrounds and individual sources

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LISA Astrophysics WG Meeting
MPA,Garching

Starting PhD with Astrid Lamberts,
Nelson Christensen at OCA - Nice

November 7th 2024

— Outline

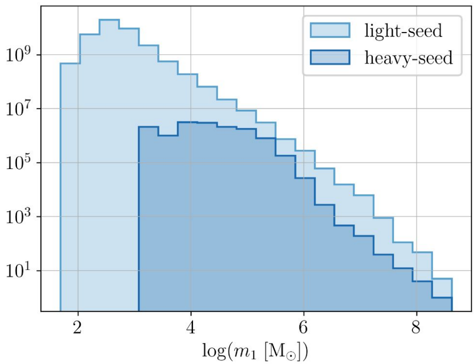
1) **Voyage 2050**: ESA's Space Science Programme for 2035-2050 missions
   ➞ Science theme "Early Universe" with gravitational waves or CMB
   ➞ Proposal for a new detector post LISA

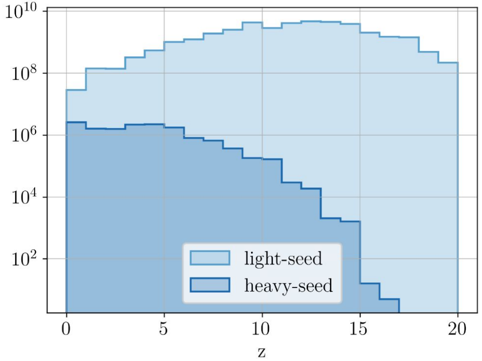
2) **Computation of GW backgrounds** :
   Stochastic GW signal from unresolvable sources, affecting the detector sensitivity

3) **Analysis of the detectable sources** :
   Extracted by the GW
   ➞ their properties can be investigated

Populations:

- Massive black hole binaries (MBHBs)
  ➞ "heavy-seed" and "light-seed"
- Extreme mass-ratio inspirals (EMRIs)
- Stellar-origin binary black holes (SOBBHs) from *Torrado*
- Galactic binaries (GB) from *Korol, Toonen*





— Mission concepts

Space-based interferometers:
3 identical spacecrafts forming an equilateral triangle that exchange laser beams

LISA:

constellation barycentre in an heliocentric orbit
arm length = 2.5 million km

Decihertz Observatory (DO) [1] :

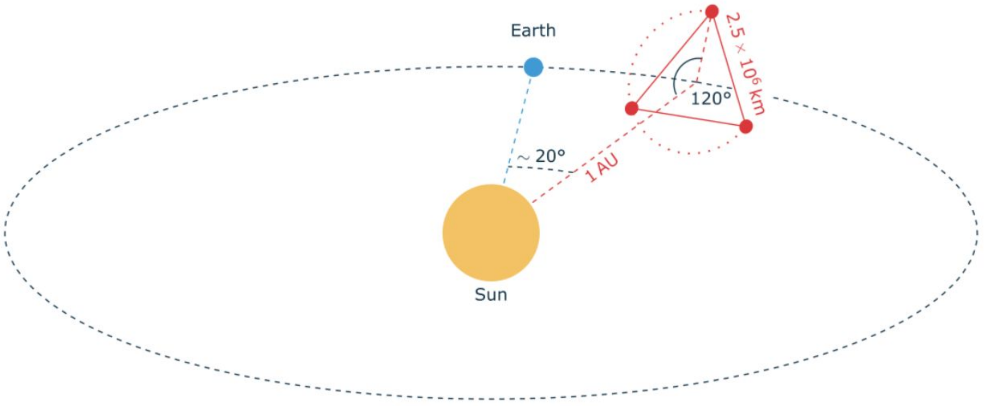
LISA-like detector in Earth-trailing orbit
arm length = 100 thousand km
(25x shorter than LISA)

[1] Sedda et al. (2021)

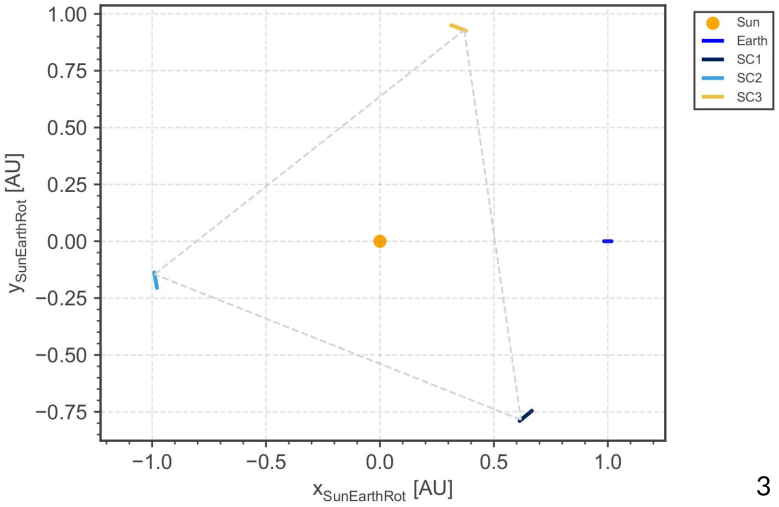
LISAmax[2] :

satellites orbiting around the Sun at 1 au
arm length = 259 million km
(100x longer than LISA)

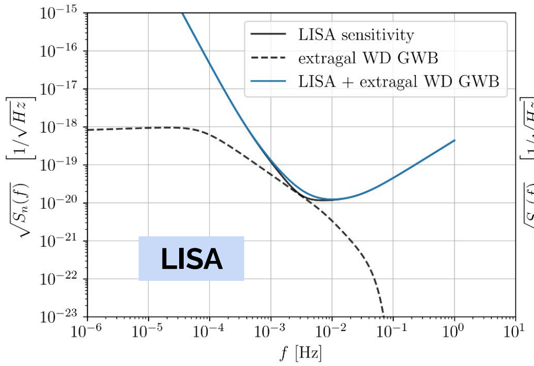
[2] Martens et al. (2023)

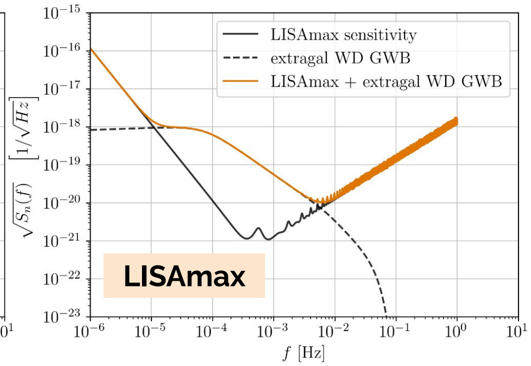


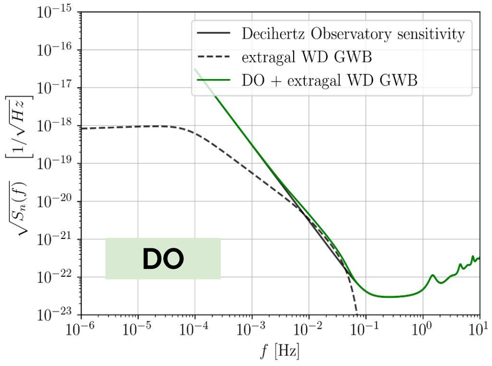
from LISA Definition Study Report



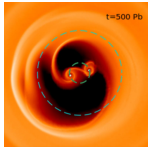
— Sensitivity curves

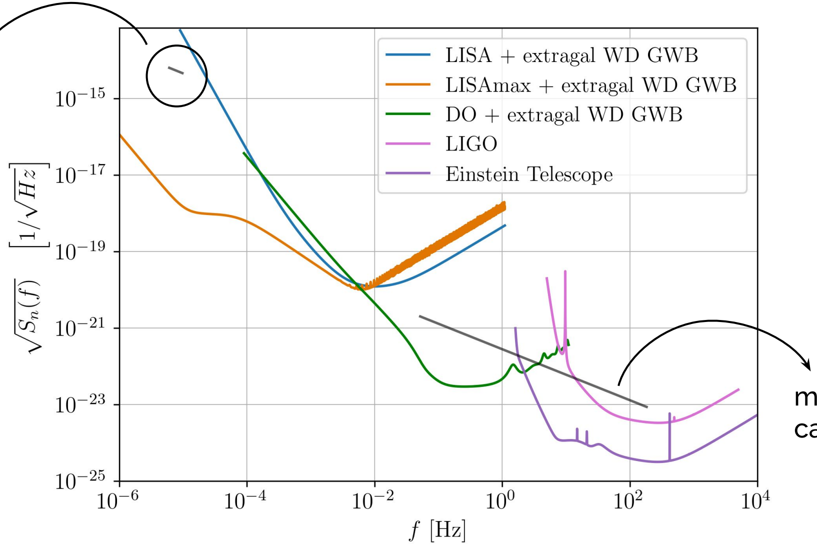






multi-messenger candidate





multi-band candidate

$$S_{n,tot}(f) = S_{n,det}(f) + S_{n,extragal}(f)$$

Instrumental sensitivity

+

Astrophysical noise

from extragalactic WD binaries [3]

[3] S. Hofman and G. Nelemans (2024)

— Iterative computation of the GW background

developed by :
Matteo Bonetti, Alice Perego

- ➔ takes as input the sensitivity curve $S_n(f)$ of 1 detector between LISA / LISAmax / Decihertz Observatory (including the noise from the GWB of extragalactic WDBs)
- ➔ takes as input the catalogues of the populations (MBHBs, EMRIs, stellar-origin BBHs and galactic binaries)

Cycle on iteration i = 0 … N:

- Iteration 0 :

  Cycle on the populations j = 1 … 4
  - computes the GWB signal of all the sources $h_c(f)$

  ➔ prints the sum $h_c(f)$ as the total GW background

- Iteration 1 … N :

  Cycle on the populations j = 1 … 4
  - computes the SNR of all of the sources based on $S_n(f)$ + GWB computed at previous step
  - computes the GWB signal of the sources with SNR < threshold $h_{c,\mathrm{unres}}(f)$

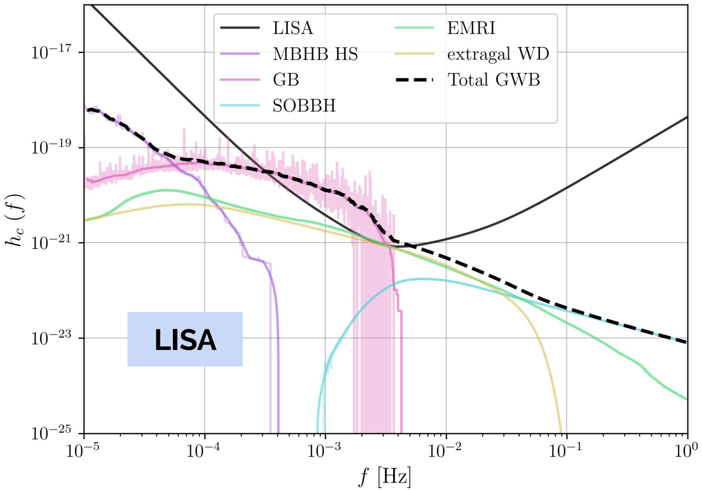
  ➔ prints the sum $h_{c,\mathrm{unres}}(f)$ as the unresolved GW background

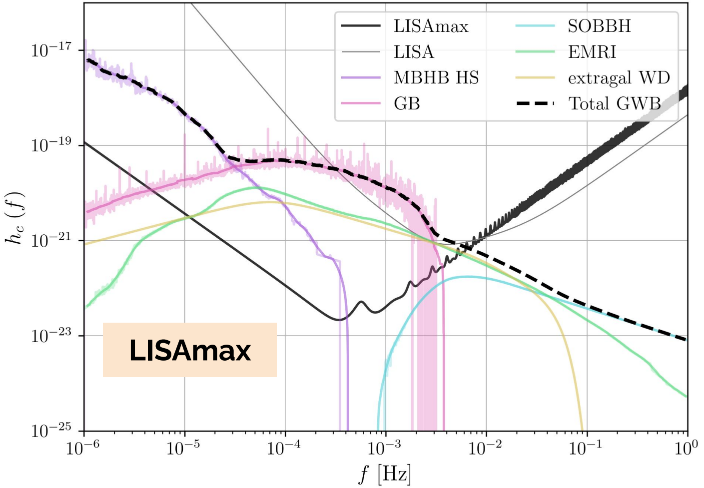
— "Heavy-seed" (HS) Scenario

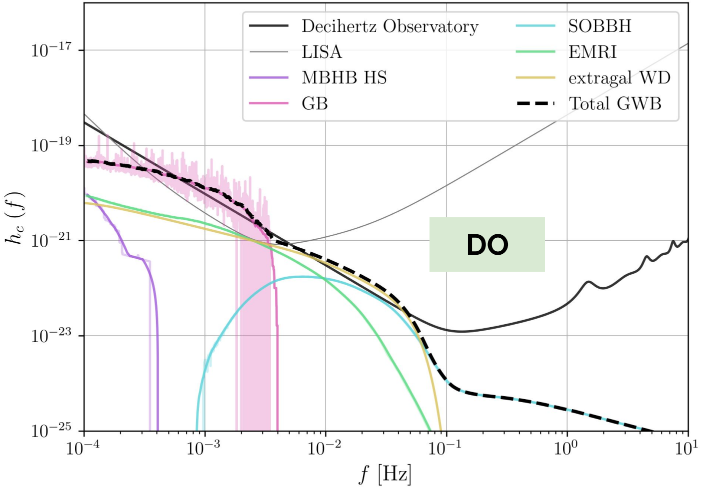
Main astrophysical foregrounds :

- LISA : affected by **GBs**
- LISAmax : affected by **MBHBs** + **GBs**
- DO : affected (slightly) by **GBs** + **extragal WDs**

→ reduces the GWB of EMRIs and SOBBHs







— “Light-seed” (LS) Scenario

Main astrophysical foregrounds :

- LISA : affected by **GBs**
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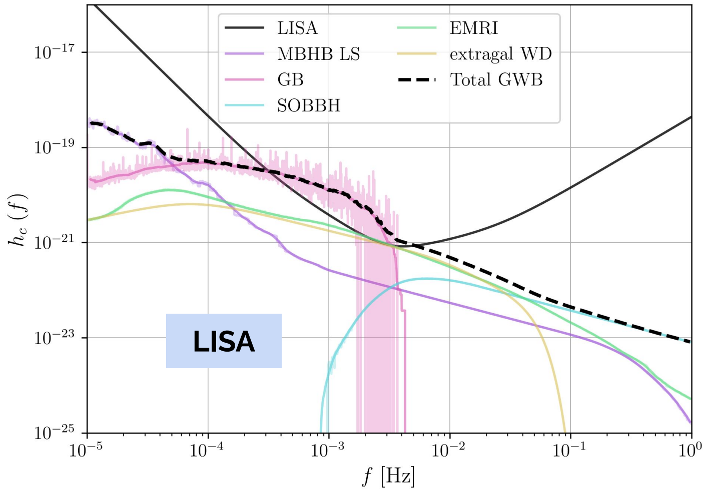
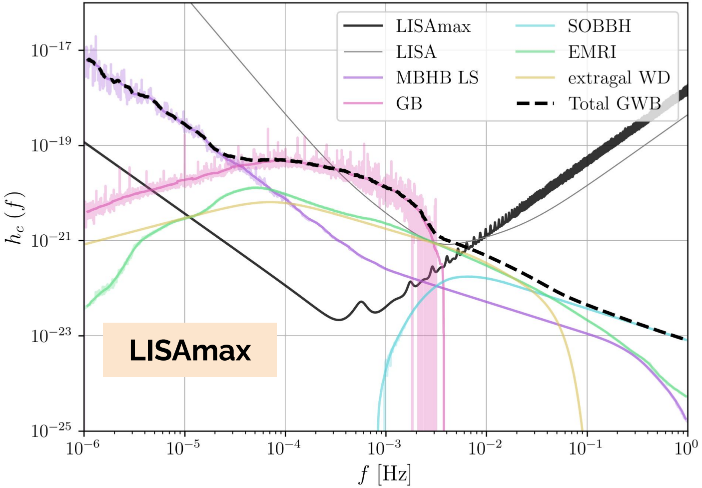
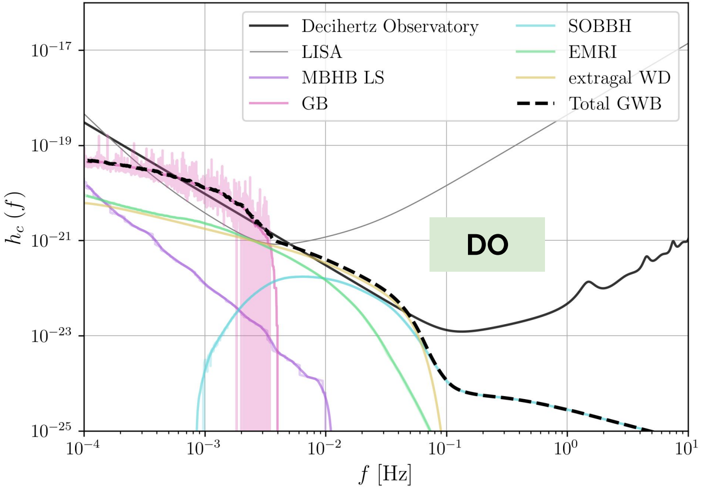




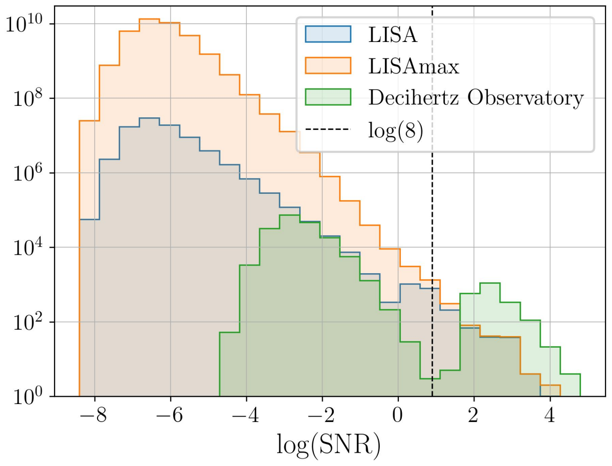


Properties of the resolved sources

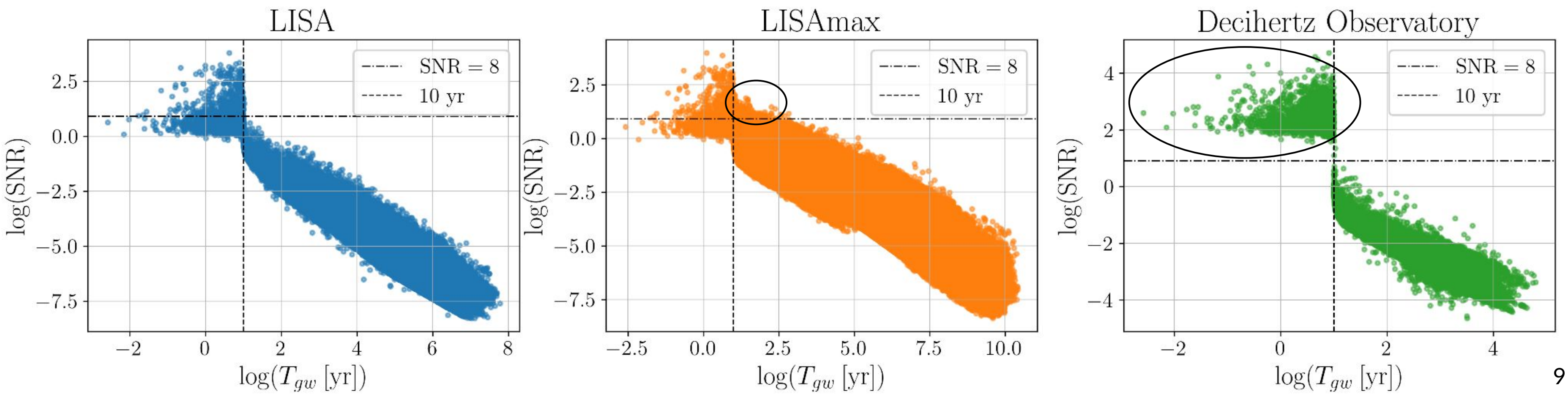
— MBHBs from light-seed model

Total number of sources : 3.8 x 10^{10}

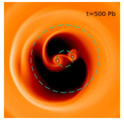
- LISA : ~ 500 ➞ some of the mergers
- LISAmax : ~700 ➞ some of the mergers
  + some sources far from merger
- DO : ~2000 ➞ all the mergers



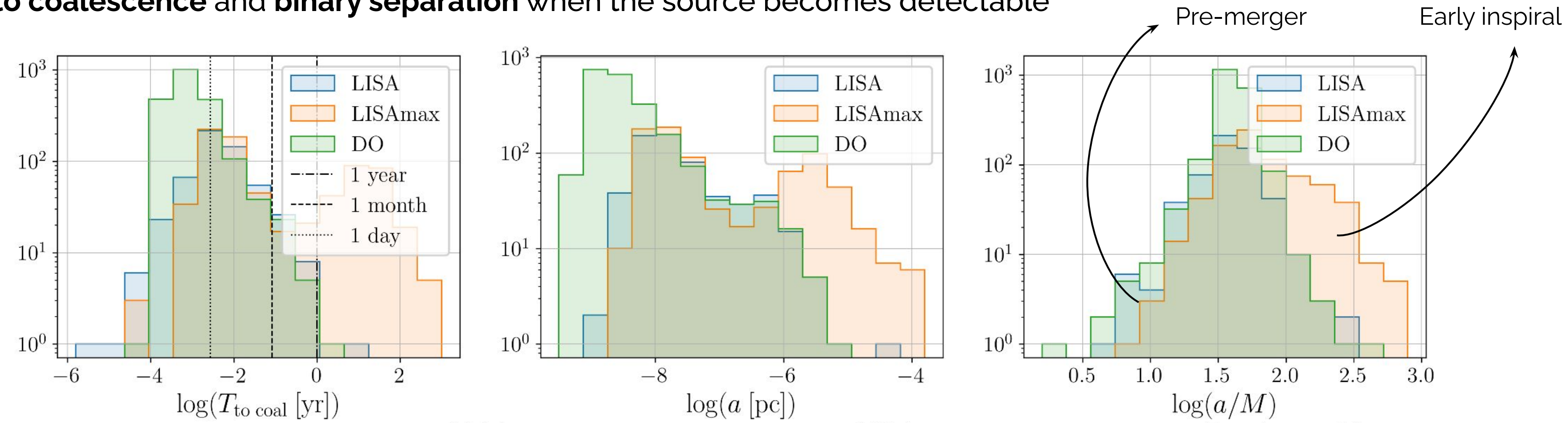
SNR and **Coalescence time**



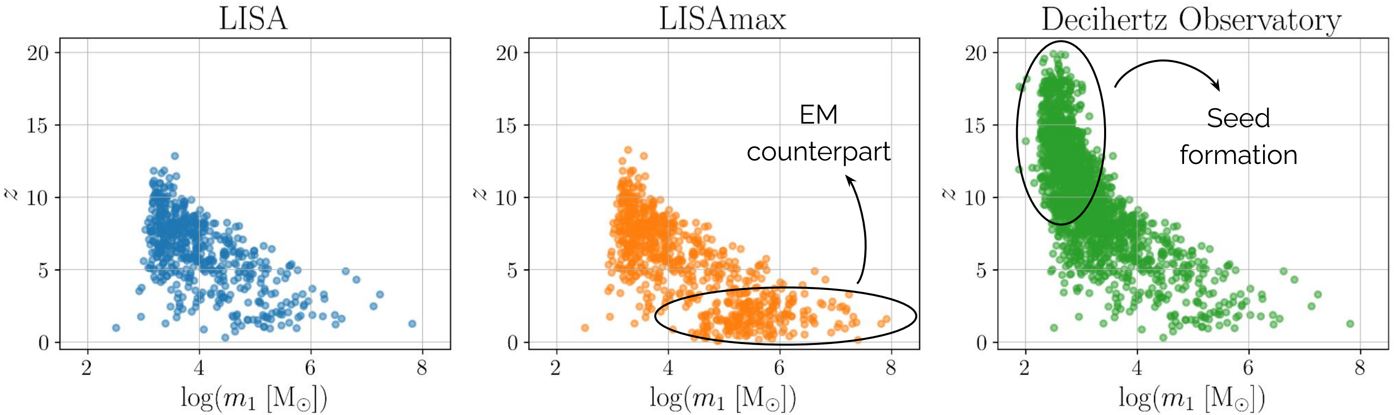
— MBHBs from light-seed model



Time to coalescence and **binary separation** when the source becomes detectable



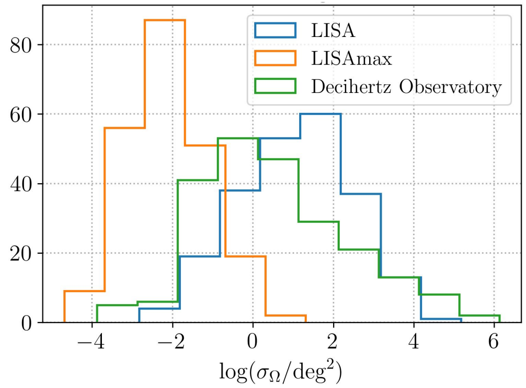
Mass and **redshift**

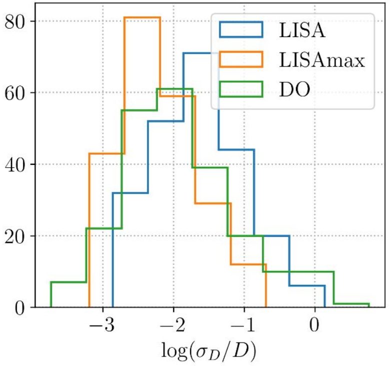


— Parameter estimation:

LISAmax in the HS scenario

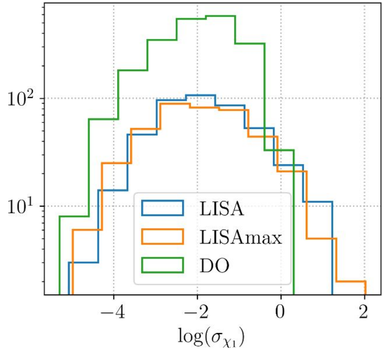
- detects the source in the inspiral phase
  ➞ the signal stays in band for a longer time
  ➞ good accuracy on **total mass *M*,**
  luminosity distance *D*
  ➞ optimal **sky localization** down to ~ arcmin²

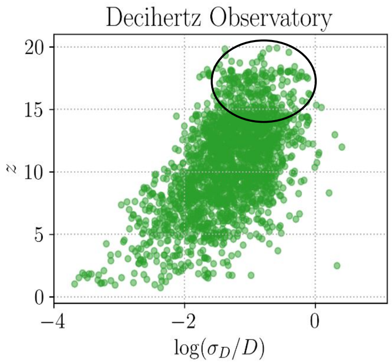




Decihertz Observatory in the LS scenario

- lower noise curve where most mergers happen
  ➞ good accuracy on **spins** χ_1, χ_2
  ➞ higher SNR
  ➞ better accuracy on **distance D**
  and **sky localisation** than HS scenario



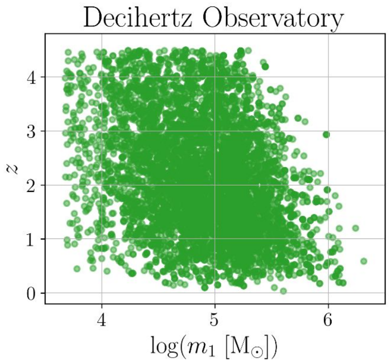


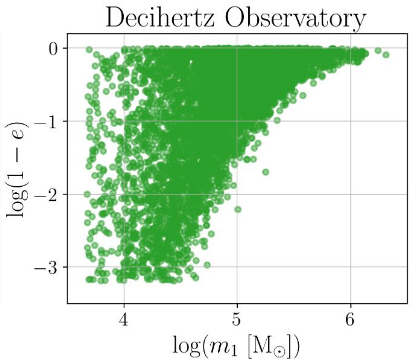
— EMRIs and SOBBHs

EMRIs

Total number of sources : 10^6

- LISA : ~500
- LISAmax : ~750
- DO : ~7000

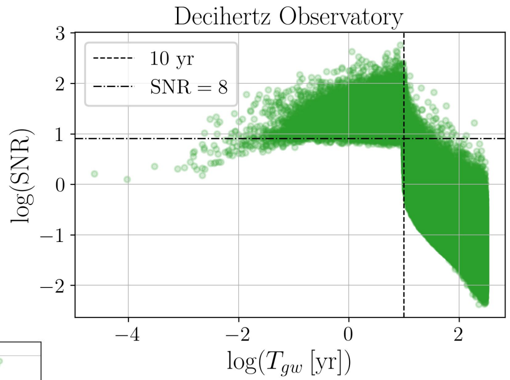


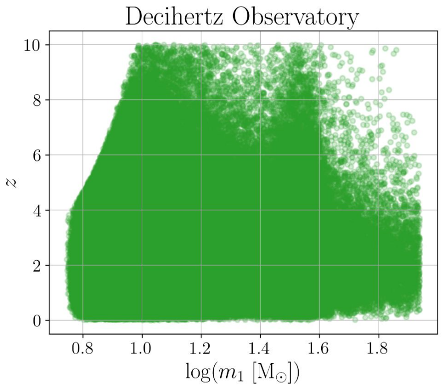


SOBBHs

Total number of sources : ~2.6 x 10^7

- LISA : a few
- LISAmax : a few
- DO : ~9 x 10^5





— Summary:

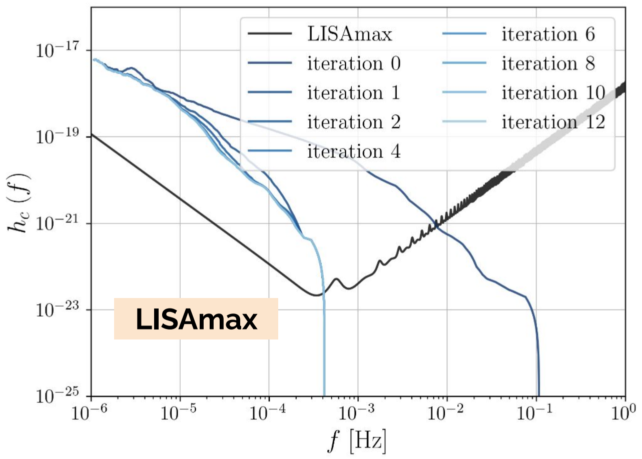
LISAmax	Decihertz Observatory
- MBHBs **very far from merger** at low z ➞ insights about MBHB formation and evolution ➞ fully-coupled with gas ➞ **EM counterpart** - merging MBHBs with **high SNR in the early inspiral** ➞ superior precision in the sky localization ➞ multi-messenger astronomy and cosmography	- lightest MBHBs up to very **high z** ➞ insights about MBH formation and accretion - stellar-origin BHBs ➞ LVK sources but in the early inspiral ➞ **multi-band observations** ➞ even higher redshift ➞ **redshift evolution** of the population - EMRIs with high eccentricity and light central MBH
- affected by **astrophysical foregrounds** (MBHBs and Galactic binaries)	- **lowers the astrophysical GWB** below the instrumental noise

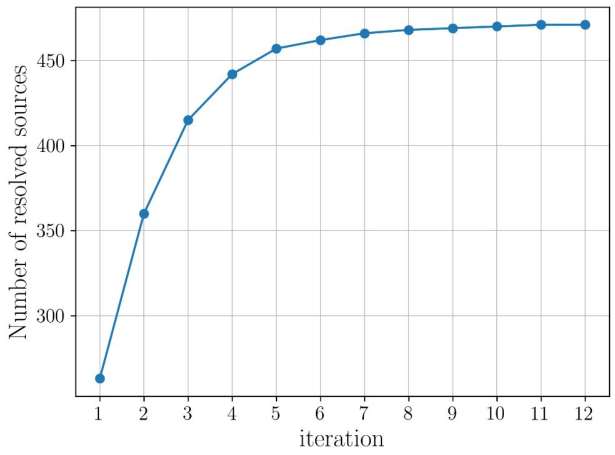
Thank you!

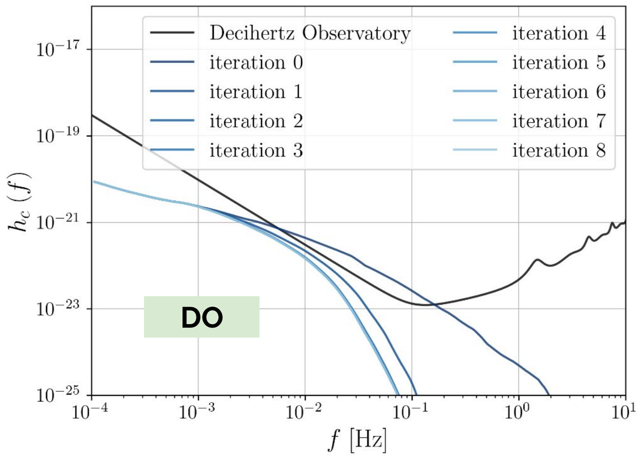
Backup slides

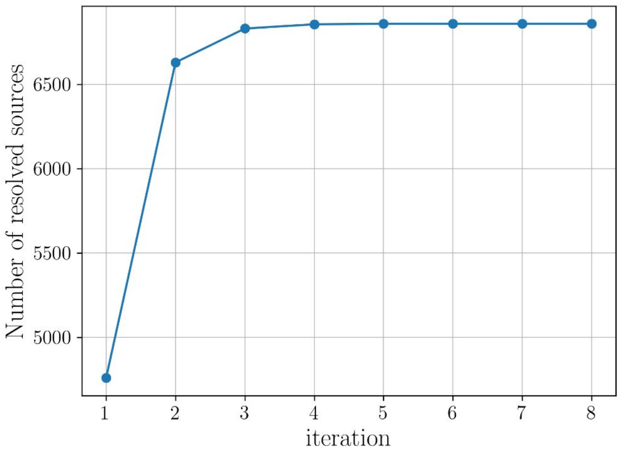
— Iterative computation of the GW background

GW background of MBHBs in HS scenario









GW background of EMRIs

— Source signals

Source 1

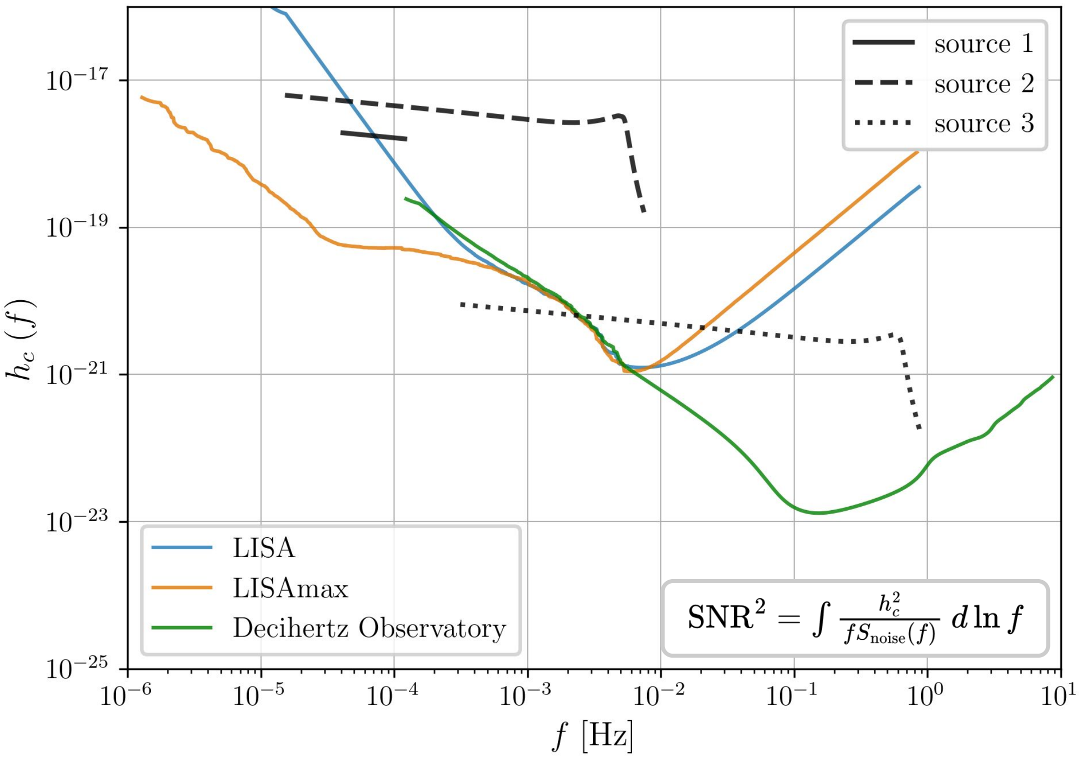
- $M_1 \sim 10^6\ M_\odot$, z = 1.6
- T_{coal} = 10.6 years → non merging source
- detected only by LISAmax with SNR ~ 40

Source 2

- $M_1 \sim 10^5\ M_\odot$, z = 4.5
- T_{coal} = 4.5 years
- detected by all 3 detectors

Source 3

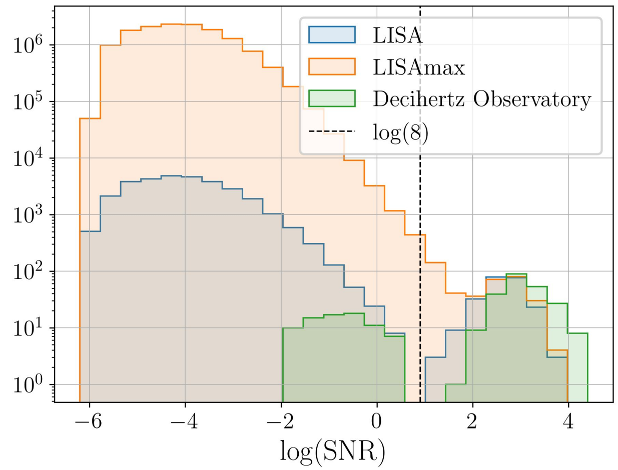
- $M_1 \sim 10^3\ M_\odot$, z = 15.6
- T_{coal} = 5.5 years → merging source
- detected only by Decihertz Observatory with SNR ~ 300



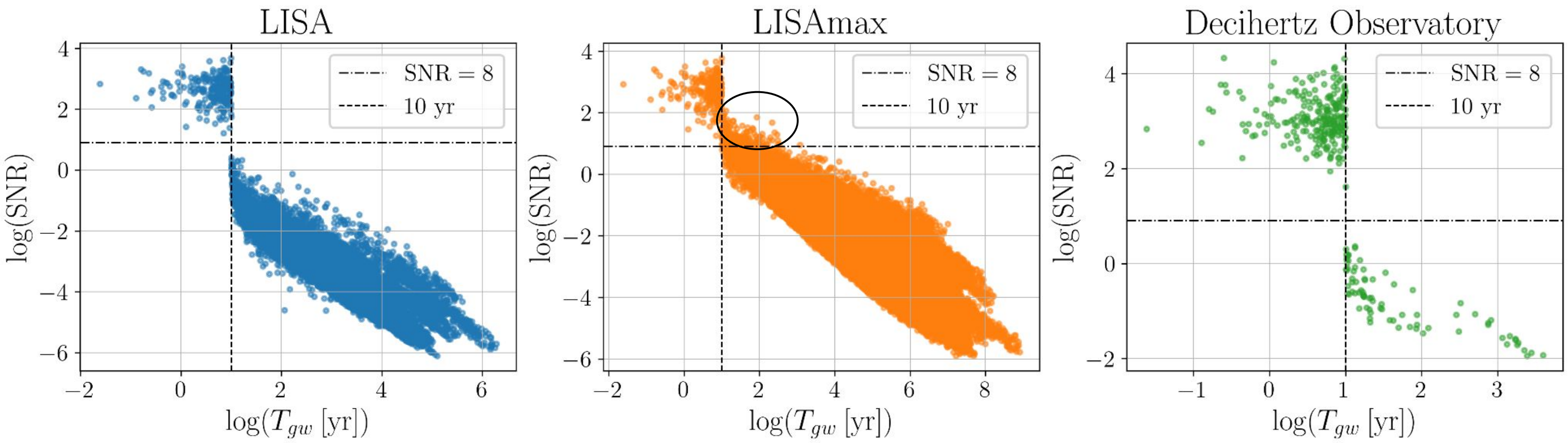
— MBHBs from heavy-seed model

Total number of sources : 1.4 x 10^7

- LISA : ~200 ➞ all the mergers
- LISAmax : ~450 ➞ all the mergers
  + some sources far from merger
- DO : ~200 ➞ all the mergers

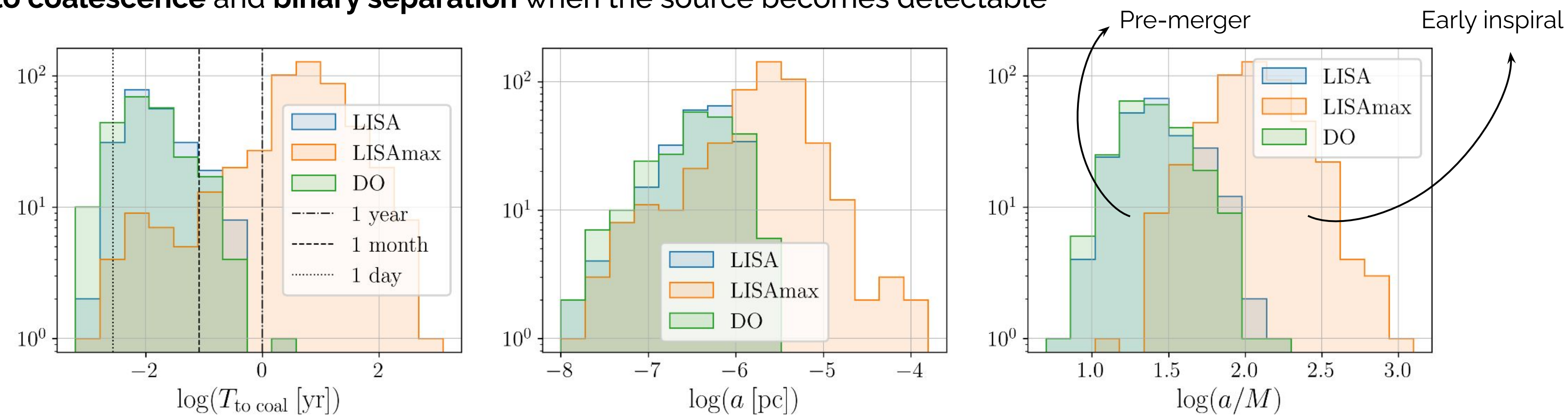


SNR and **Coalescence time**

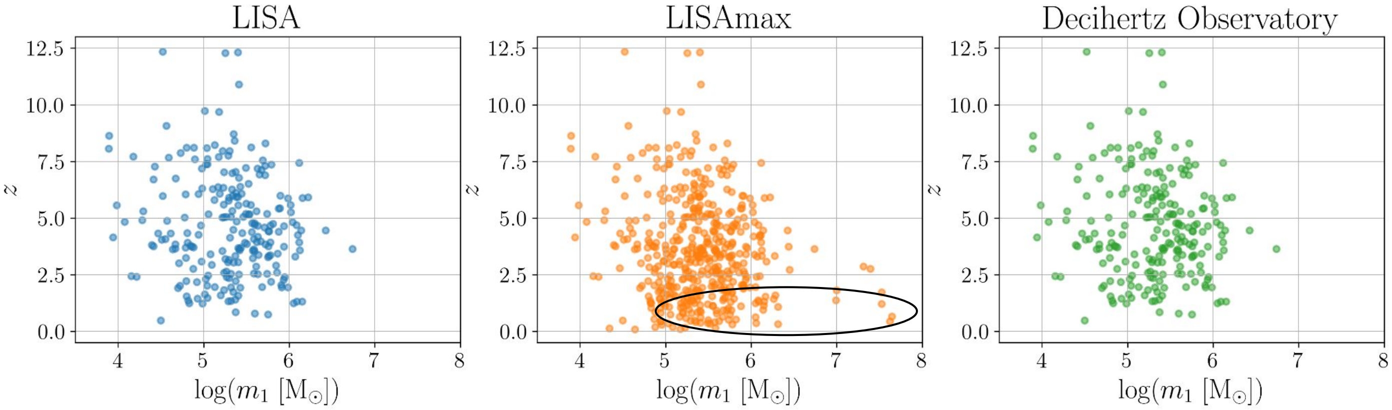


— MBHBs from heavy-seed model

Time to coalescence and **binary separation** when the source becomes detectable



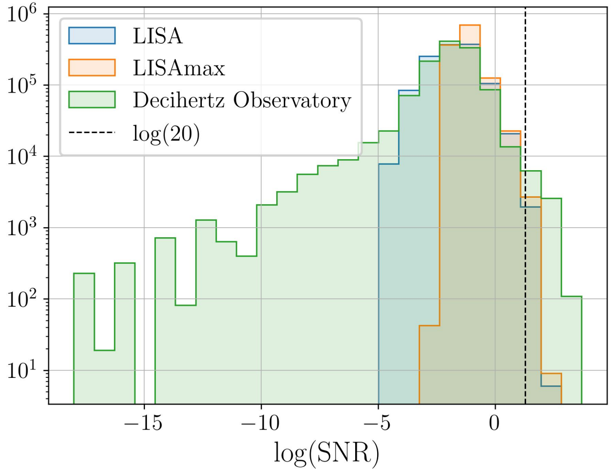
Mass and **redshift**



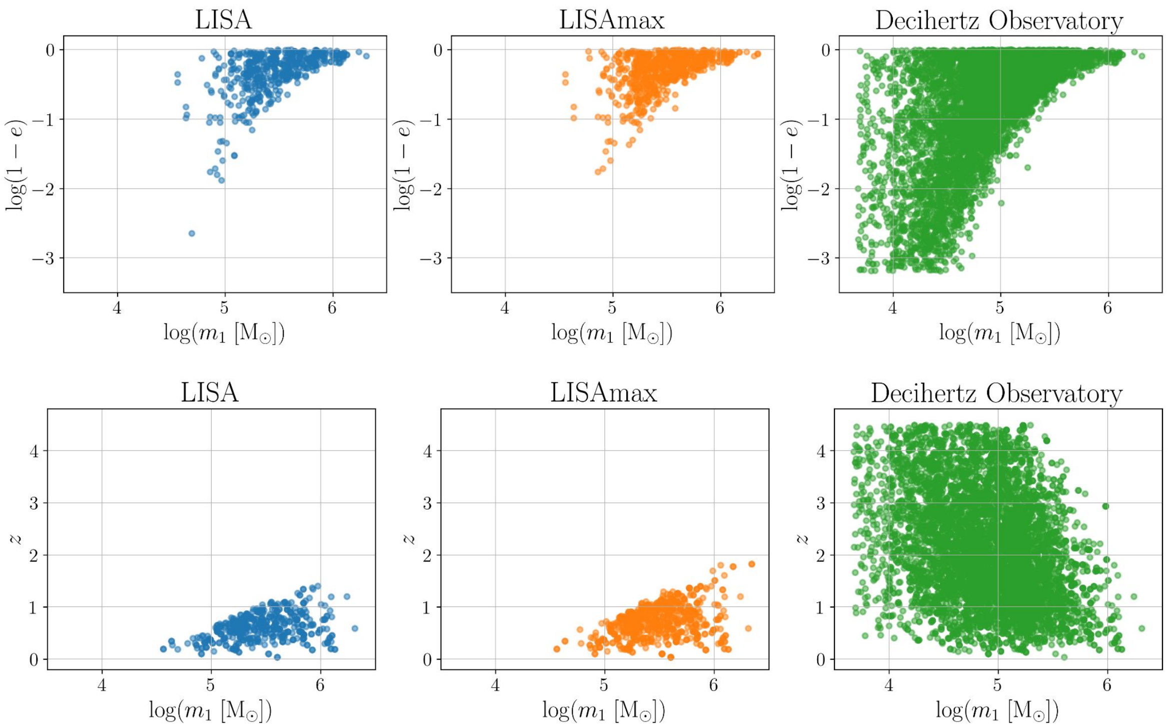
— EMRIs

Total number of sources : 10^6

- LISA : ~500
- LISAmax : ~750
- DO : ~7000

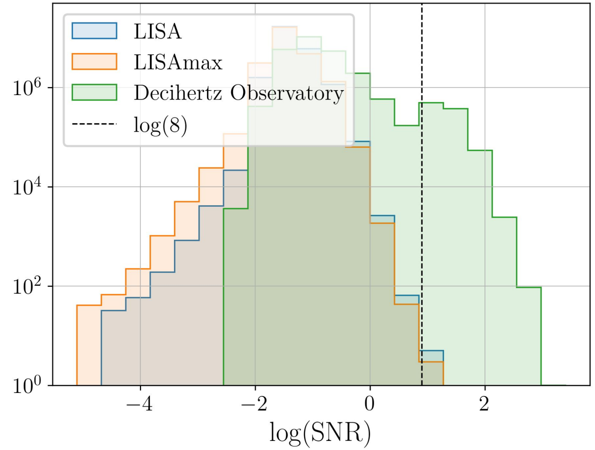


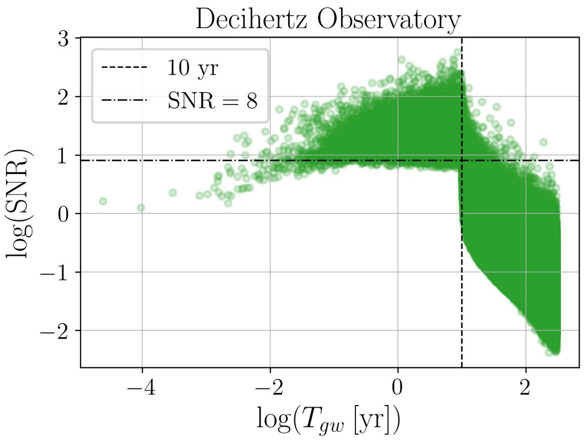
Mass, **eccentricity** and **redshift**



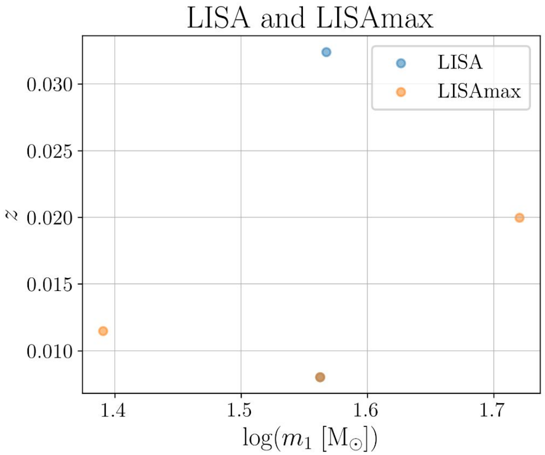
— Stellar-origin BBHs

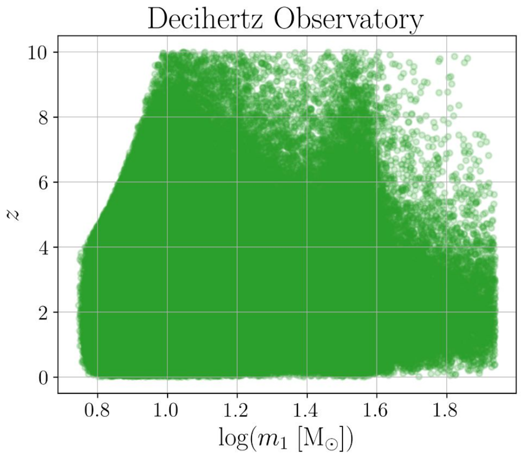
Total number of sources : ~2.6 x 10^7
- LISA : a few
- LISAmax : a few
- DO : ~9 x 10^5





Mass and **redshift**

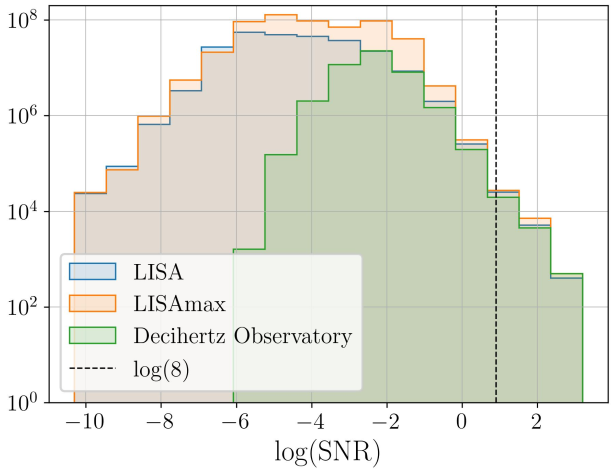




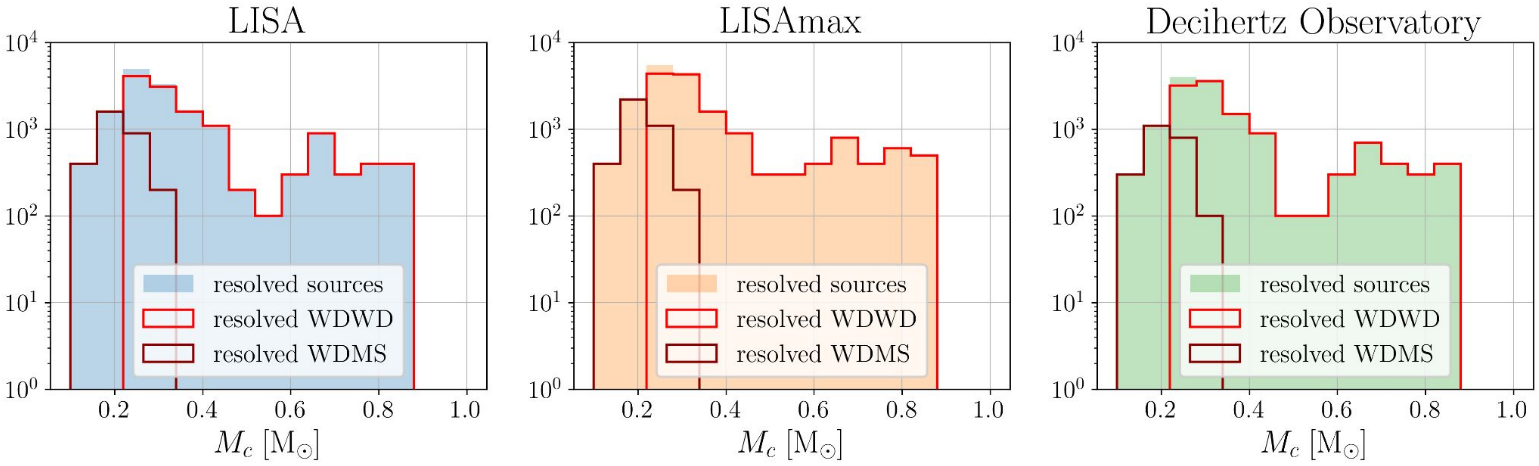
— Galactic binaries

Total number of sources : ~7 x 10^8

- LISA : ~14000
- LISAmax : ~18000
- DO : ~16000



Chirp mass



N.B.
- Inclination-polarisation averaged waveforms
- sky-averaged PSD noise

— SNR and GWB computation

- **Signal to noise ratio** (SNR)
  - ➞ strength of a signal in respect to the detector noise $$\mathrm{SNR}^2 = \int \frac{h_c^2}{f S_{\mathrm{noise}}(f)}\, d\ln f$$
  - ➞ $h_c^2(f)$ is the **characteristic strain** of the signal:

    MBHBs ➞ inspiral-merger-ringdown waveform from PhenomC

    SOBBHs, GBs ➞ inspiral post-newtonian formula $$h_c^2(f) = \frac{2}{3}\frac{G^{5/3}(\pi)^{2/3}M_c^{5/3}f^{-1/3}}{c^3\pi^2 d^2}$$

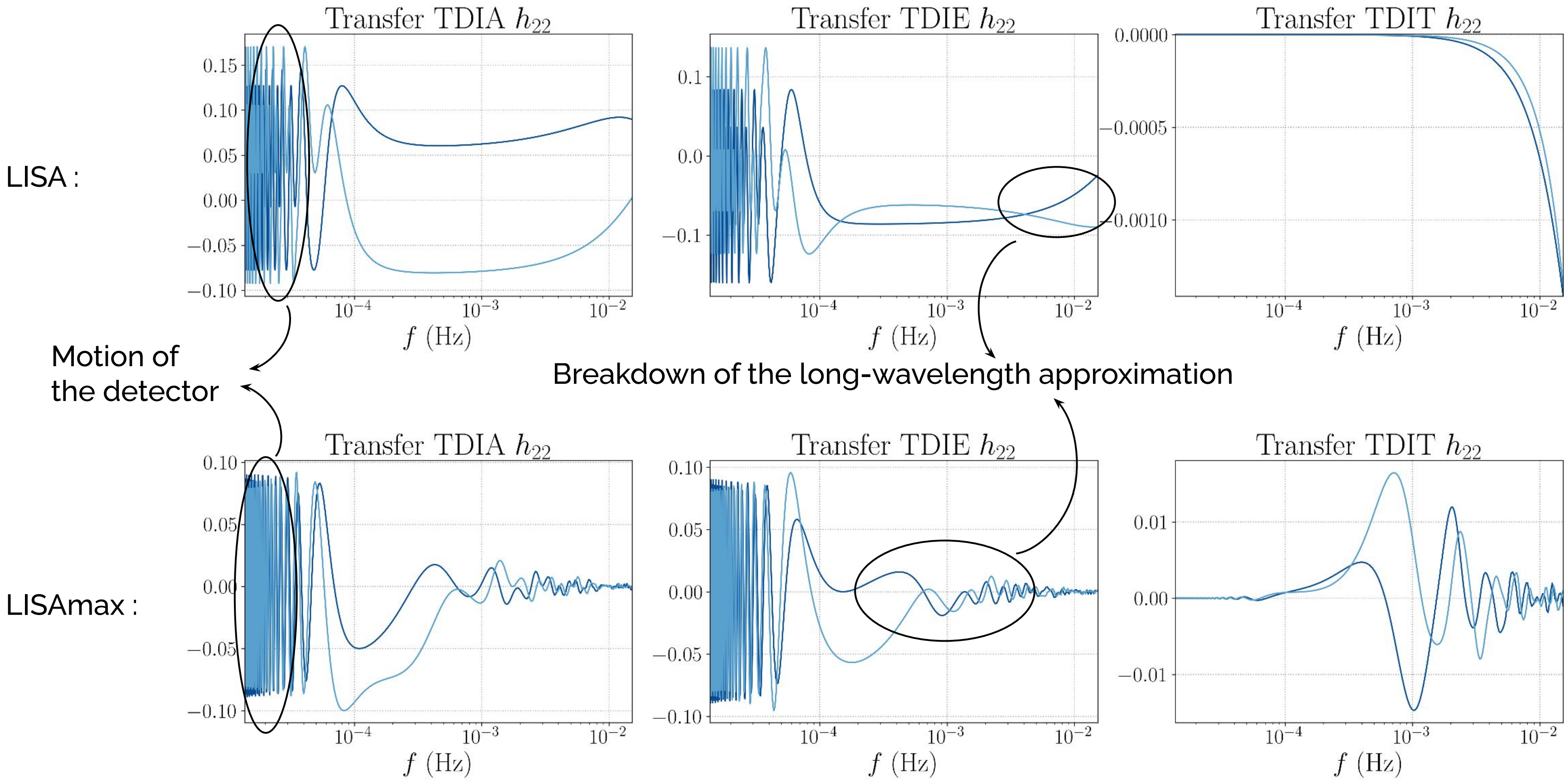
    EMRIs ➞ higher harmonics

$$h_c^2(f) = \frac{2}{3}\frac{G^{5/3}(\pi)^{2/3}M_c^{5/3}f^{-1/3}}{c^3\pi^2 d^2} \times \Phi(f)$$ with $$\Phi(f) = 2^{2/3}\sum_{n=1}^{\infty}\frac{g_n(e_n)}{n^{2/3}\mathcal{F}(e_n)}$$

- PSD of the **GW background**
  - ➞ non-evolving source ➞ contribution in a single frequency bin $h^2 \times f/\Delta f$
  - ➞ evolving source ➞ contribution on more frequency bins

$$h_{c,\mathrm{gwb}}^2(f) = \frac{1}{2}\int dz\, dM_c \frac{d^3N}{dz\ dM_c\ d\ln f_r}\frac{h_c^2(f_r)}{f T_{\mathrm{obs}}}$$

— Detector response

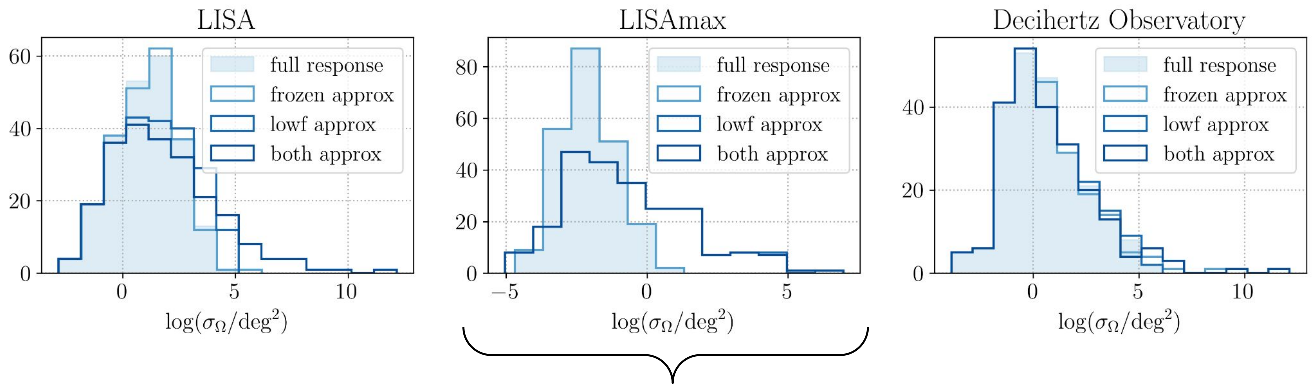


— Sky localisation

- neglecting the instrument motion
  ➞ frozen approximation of the response, no time modulations

- applying the long-wavelength approximation on the full frequency range
  ➞ low-frequency approximation on the full frequency range. The combination of these approximations reduces to the

- both approximation ➞ 2 LIGO-like interferometers with constant pattern functions

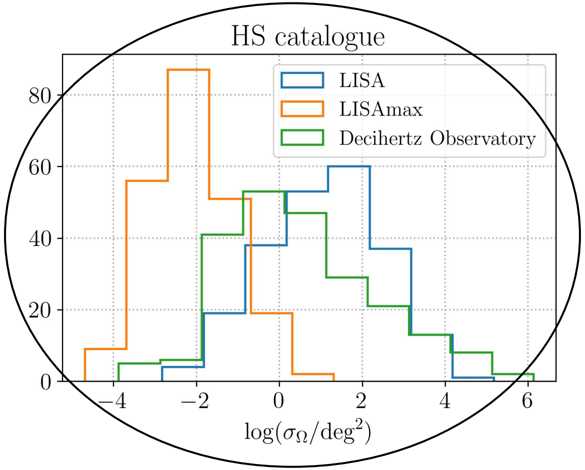


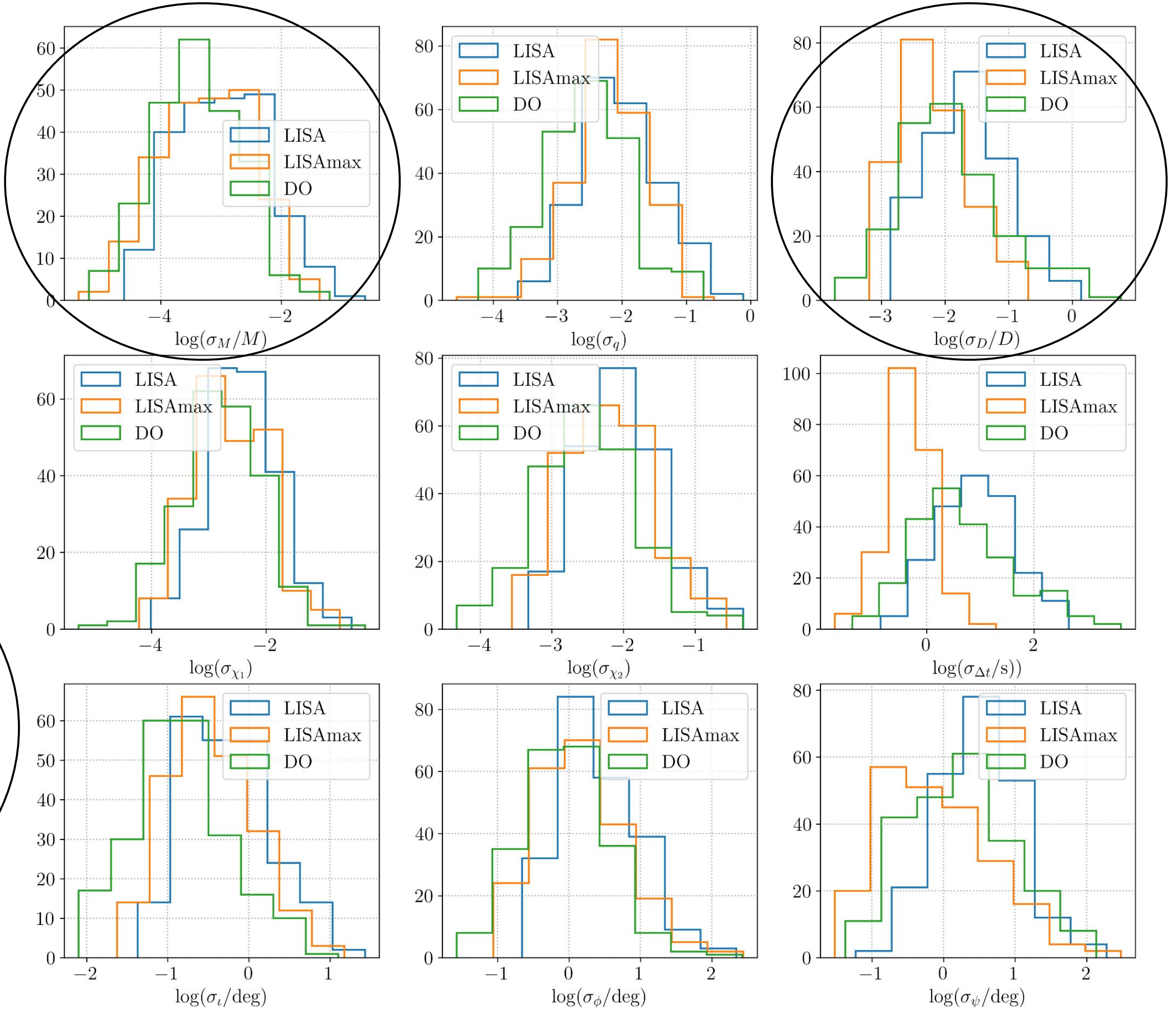
most information on the sky localisation for LISAmax is provided by the **high-frequency effects** of the response, rather than from the detector motion

— PE of MBHB HS merging sources

LISAmax :

- good accuracy on **total mass *M*** and **luminosity distance *D***
- optimal **sky localization**

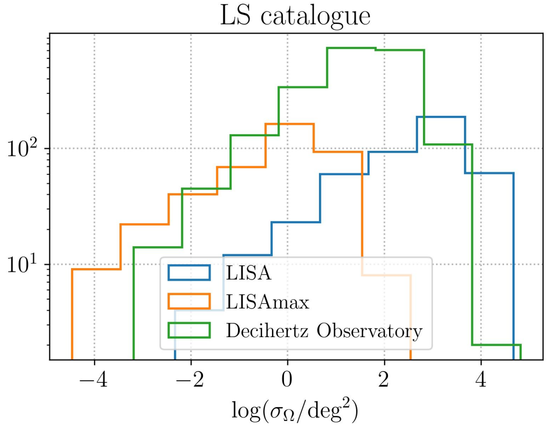


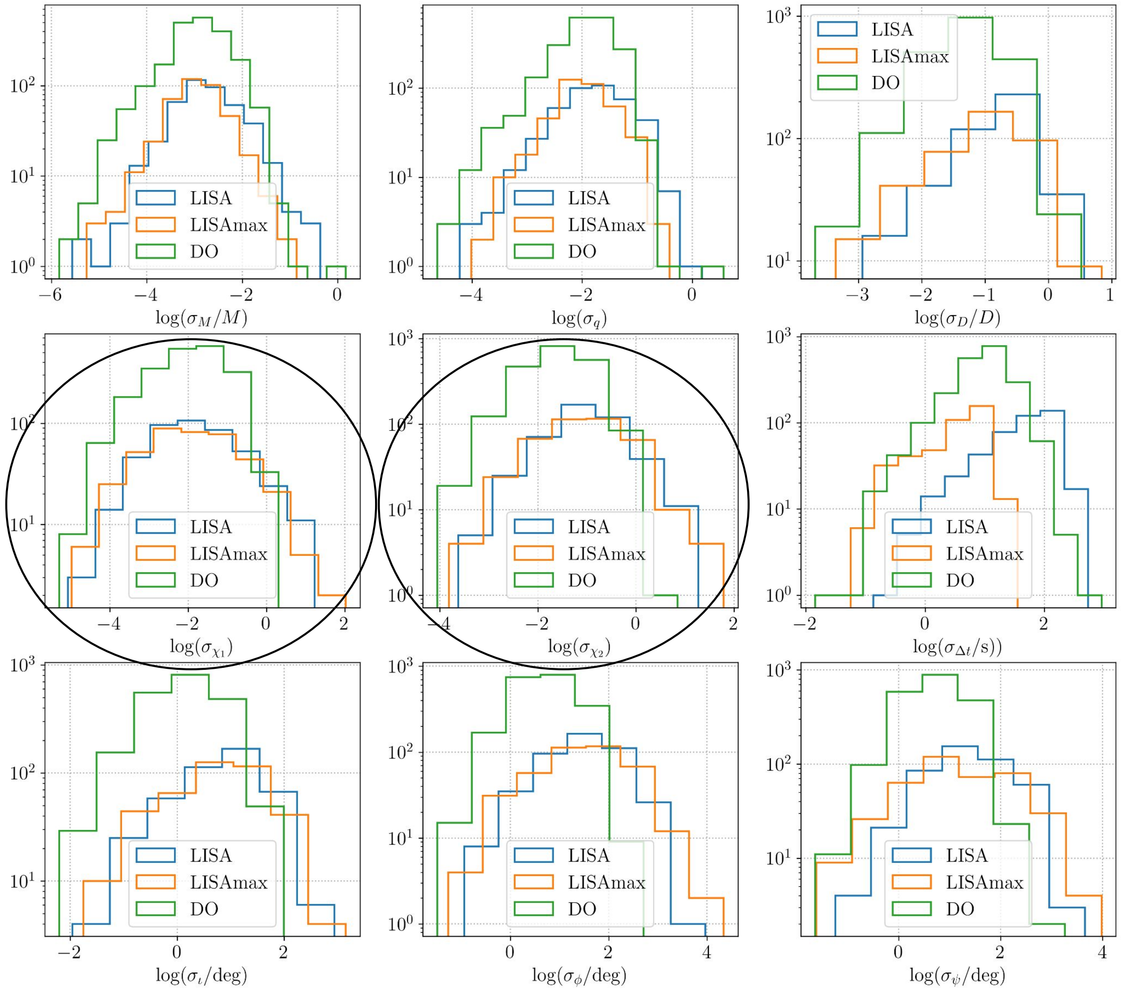


— PE of MBHB LS merging sources

Decihertz Observatory :

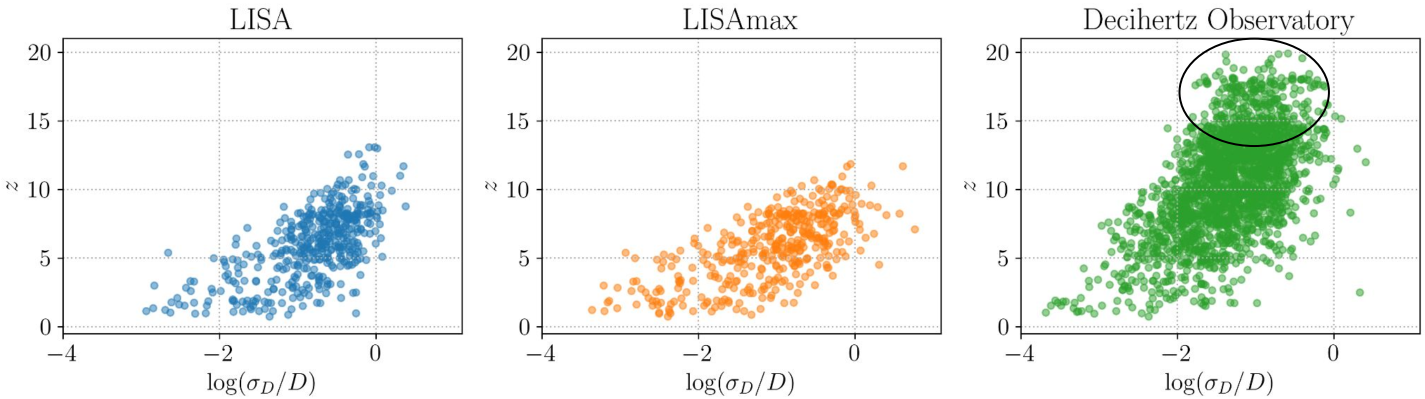
- good accuracy on **spins** χ_1, χ_2
- better accuracy on **distance D** and **sky localisation** than HS scenario



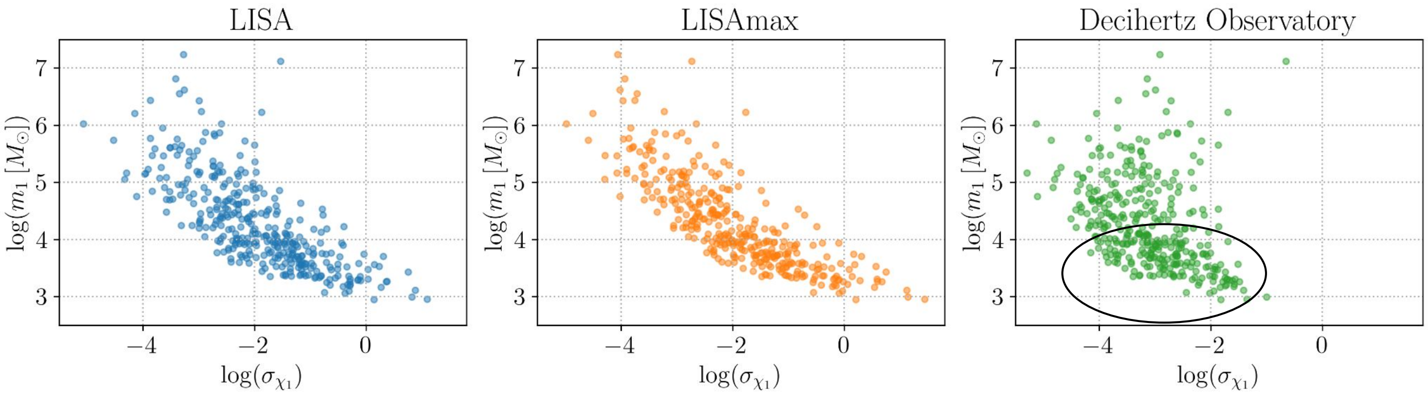


— **Accuracy on distance and spins** for Decihertz Observatory

Distance :



Primary spin:



— **Sky localization** as a function of primary mass and redshift

MBHB HS :

MBHB LS :