Cosmology with LISA

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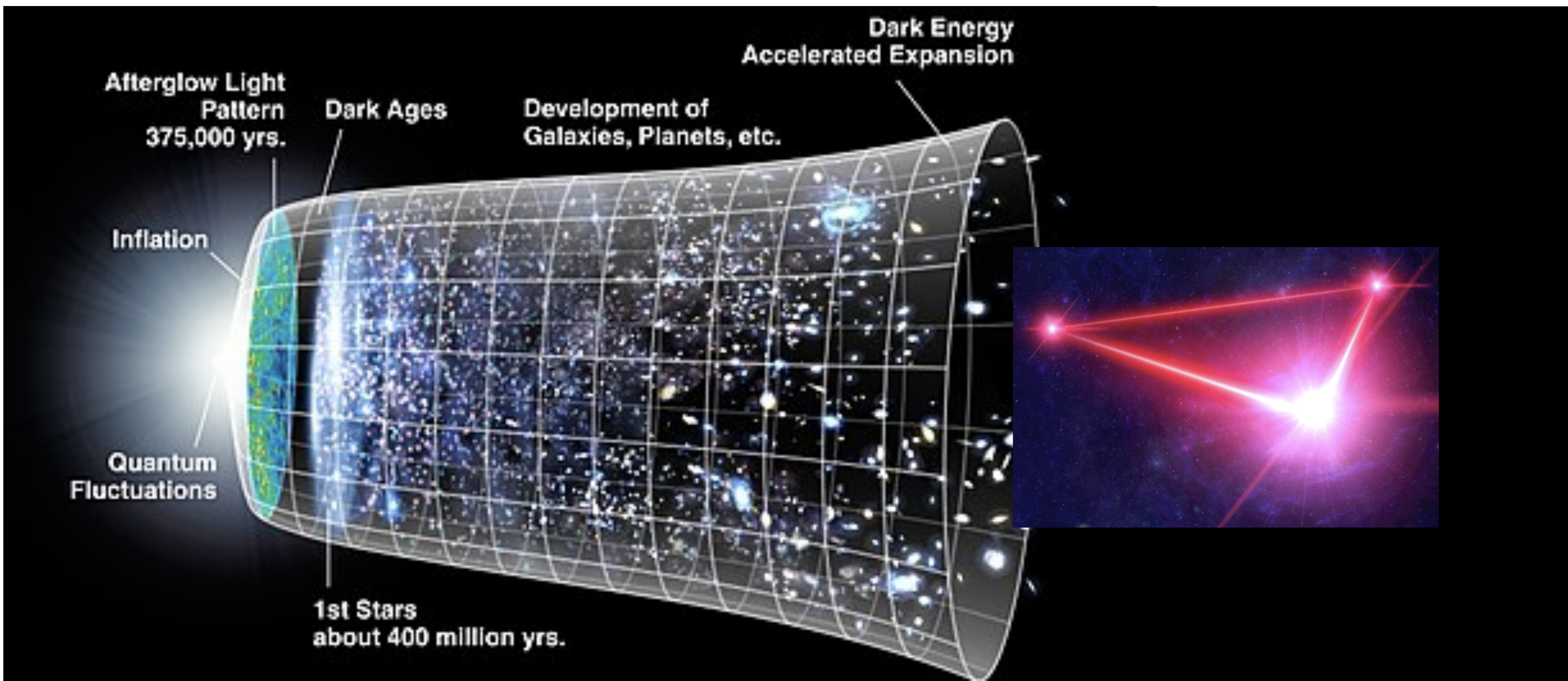
CERN & University of Geneva



Summary

- LISA has been initially conceived as a GW astrophysics observatory, it has not been designed to do cosmology

- However, it can provide new information on a variety of scales: from the Galaxy to Hubble scales, from the present time to the very early universe -> therefore it can be used as a cosmological observatory as well

- LISA can test the *late time universe* through the observation of the GW emission from compact binaries, and measure cosmological parameters

- LISA can test the *very early universe* through the detection of a stochastic GW background and therefore, indirectly, test high energy physics scenarios

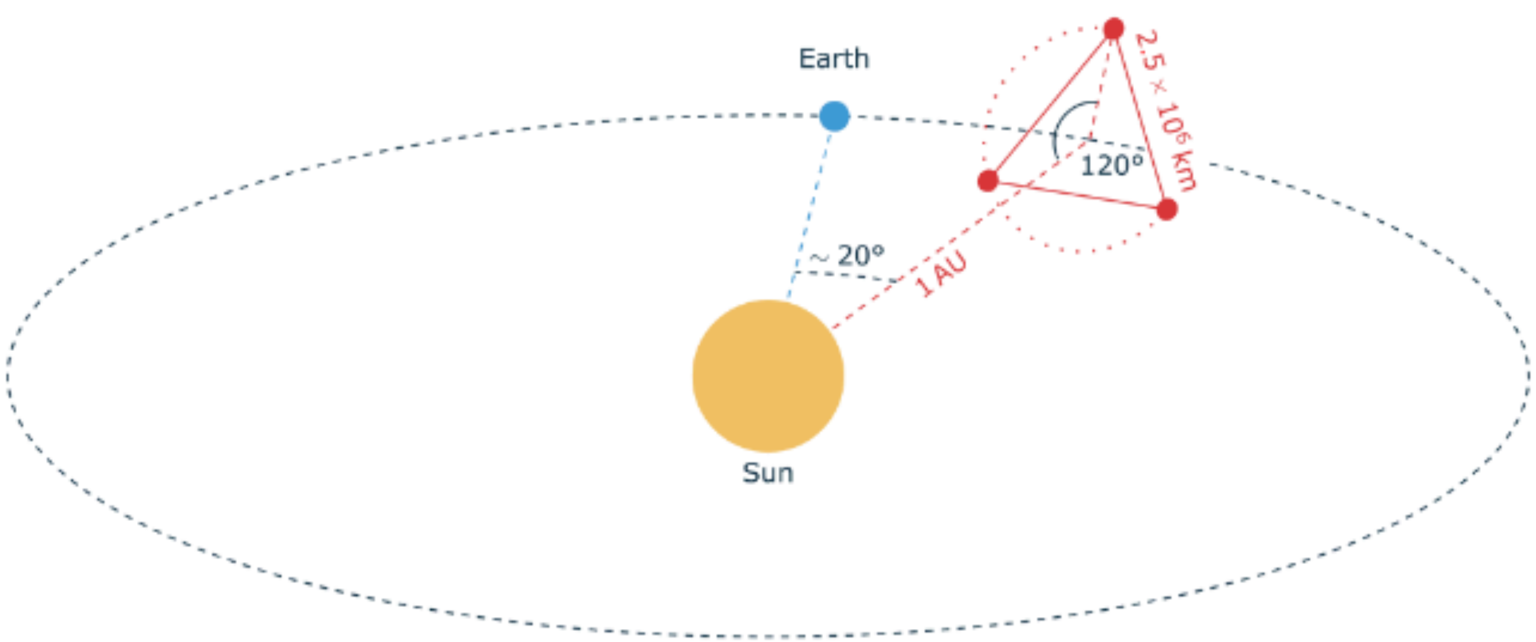
- Provided we fully address the challenges presented by LISA data analysis

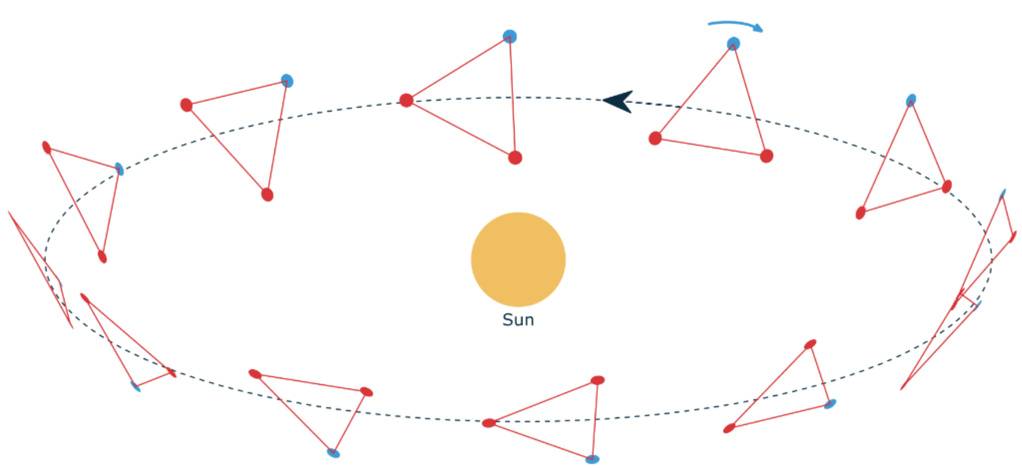
LISA: Laser Interferometer Space Antenna

GW detector in space:

- no seismic noise
- much longer arms than on Earth: 2.5 million km

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$



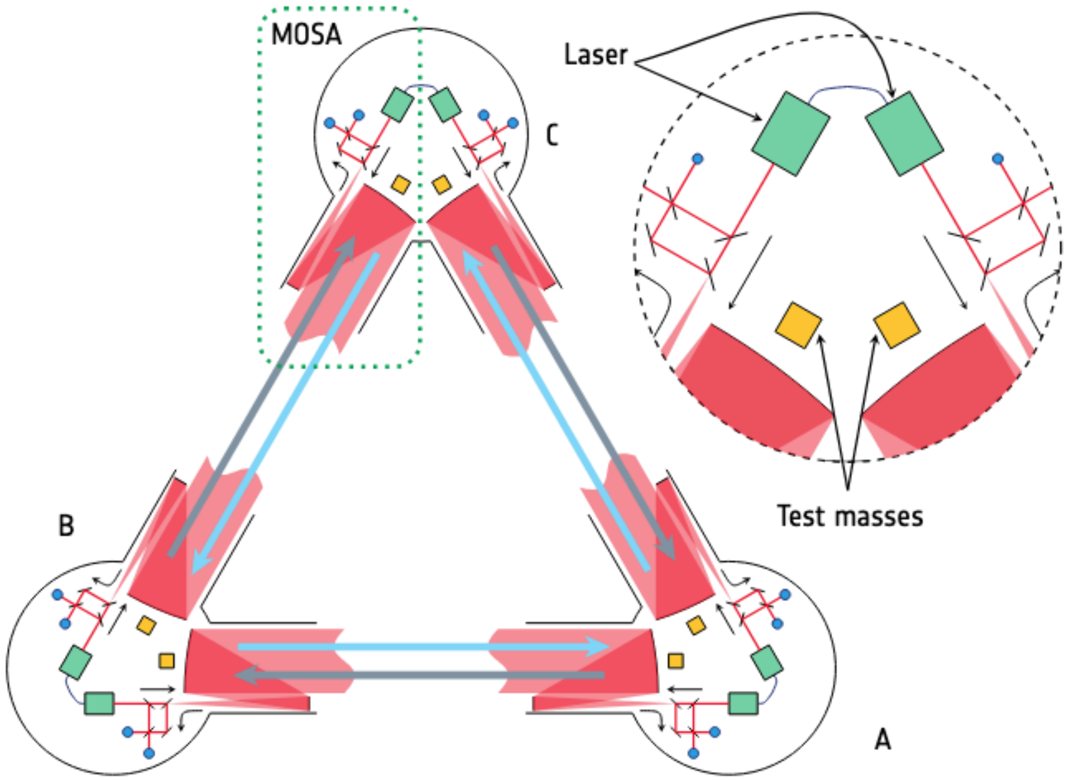


it is a survey instrument:

no pointing
continuous sky observation

LISA Red Book arXiv:2402.07571

LISA: Laser Interferometer Space Antenna

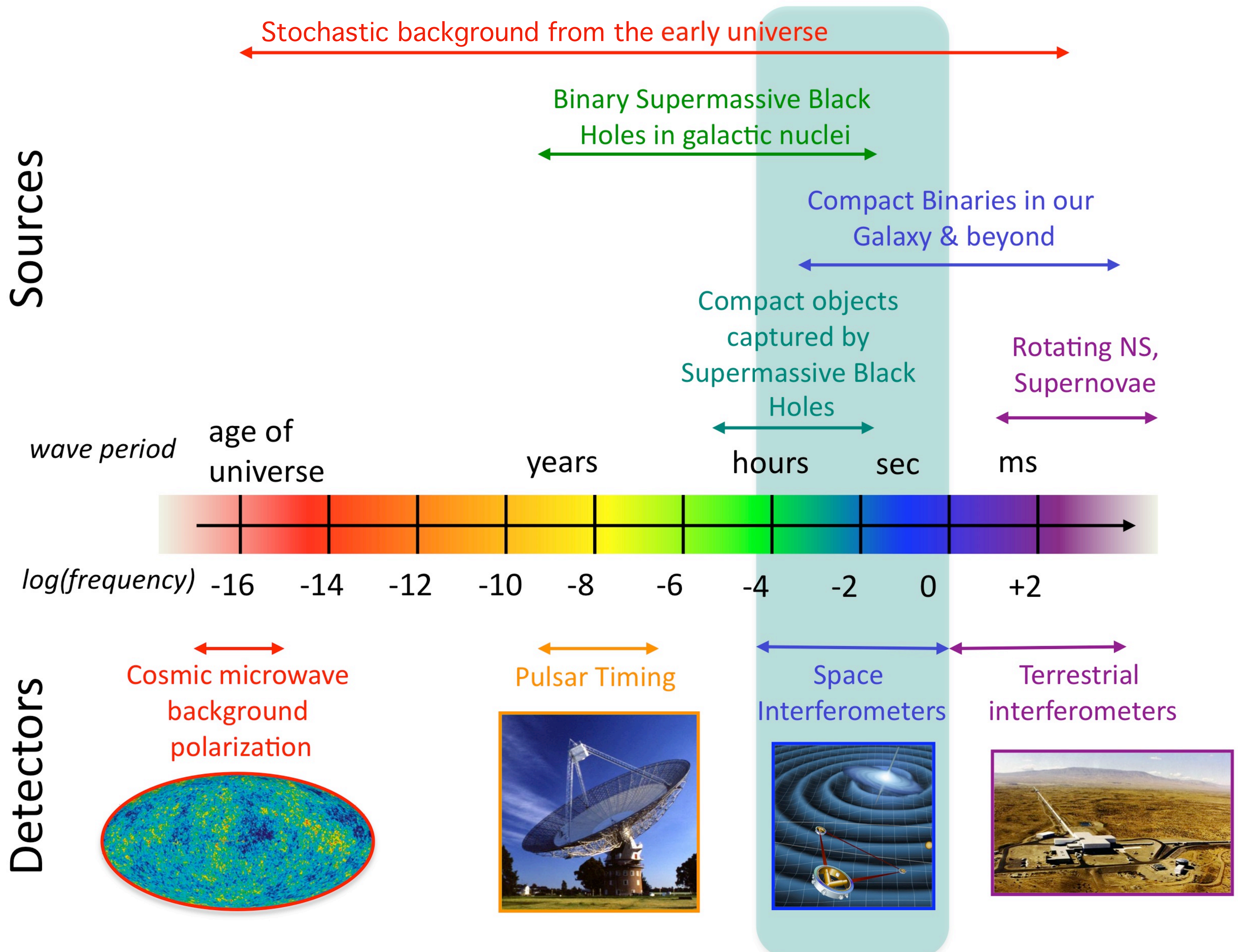


- Two masses in free fall per spacecraft
- Objective: measure relative distance changes of 10^{-21} on 2.5 million km arms -> picometer displacement of masses
- Several sources of noise: laser, clocks, acceleration…
- Laser frequency noise reduced via Time Delay Interferometry

Schedule:

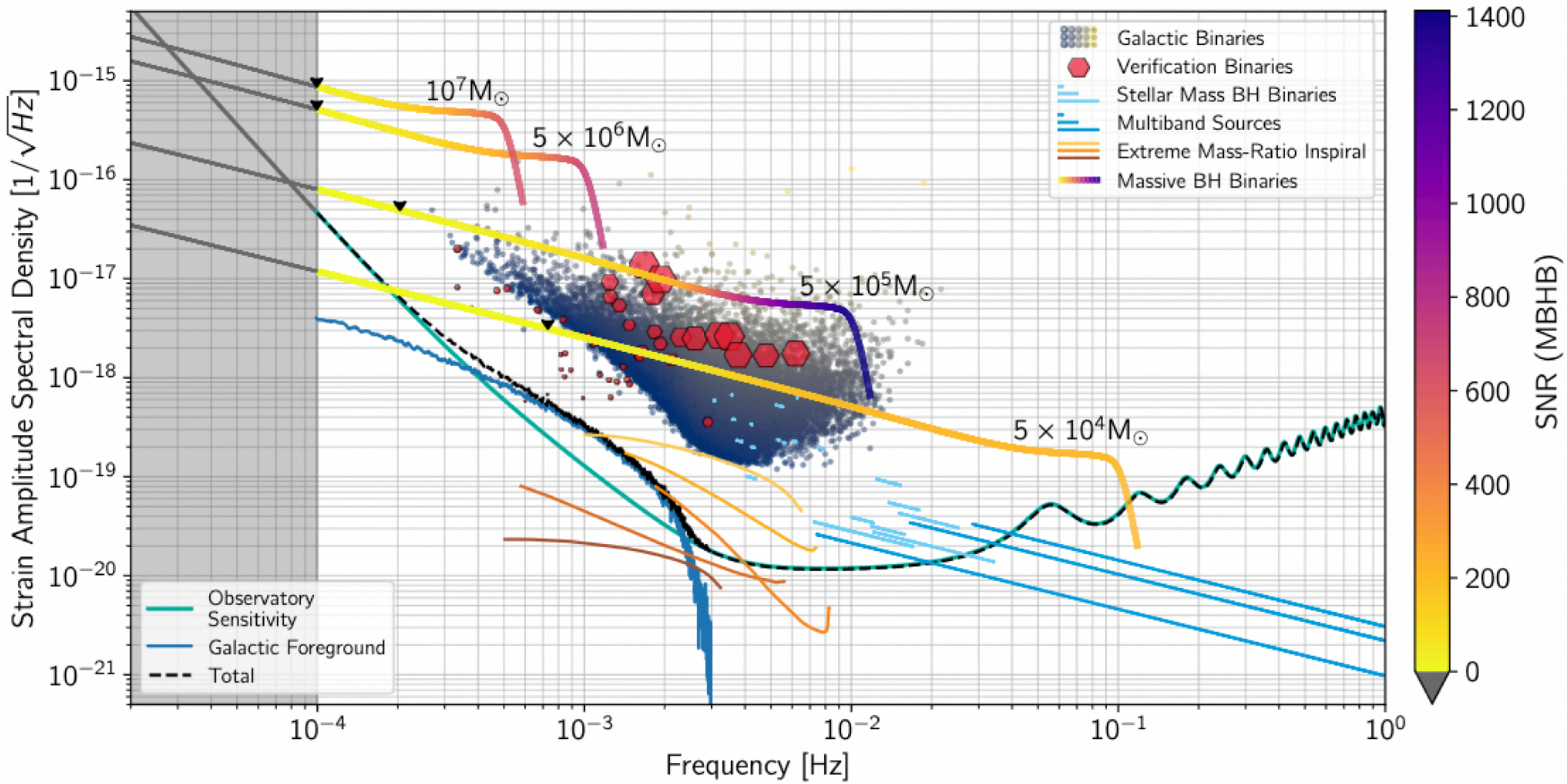
- February 2024: ESA mission adoption, science Red Book
- ~10 years: mission construction (definition, construction, integration, test, validation)
- ~2035: launch (Ariane 6) + 1.5 years to get to orbit, 6-12 months for commissioning
- nominal mission duration ~4 years
- cost: ~1.5 B€
- ESA LISA Science Team in place
- Data analysis preparation started by the DDPC and NGS
- Reboot of the LISA Consortium happening now

The Gravitational Wave Spectrum



NASA Goddard Space Flight Center

What *we expect* LISA to detect
(It's a new window!)



LISA Red Book arXiv:2402.07571

What *we expect* LISA to detect
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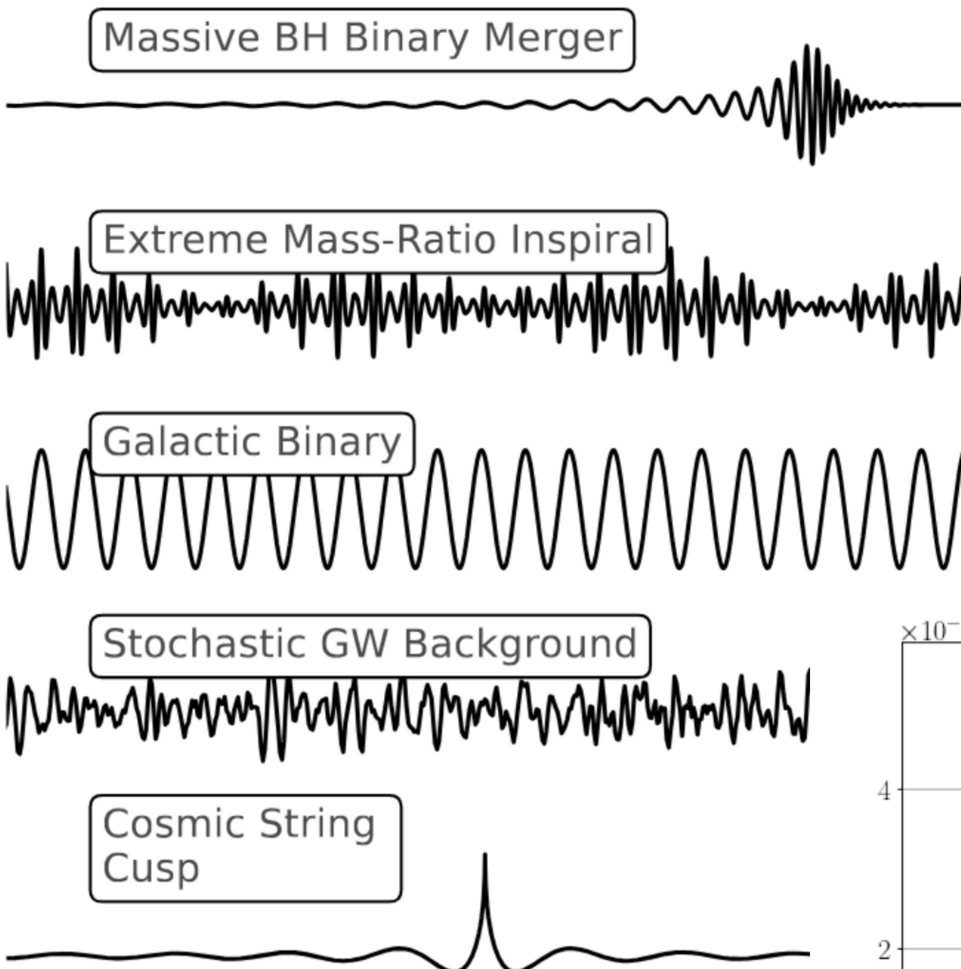
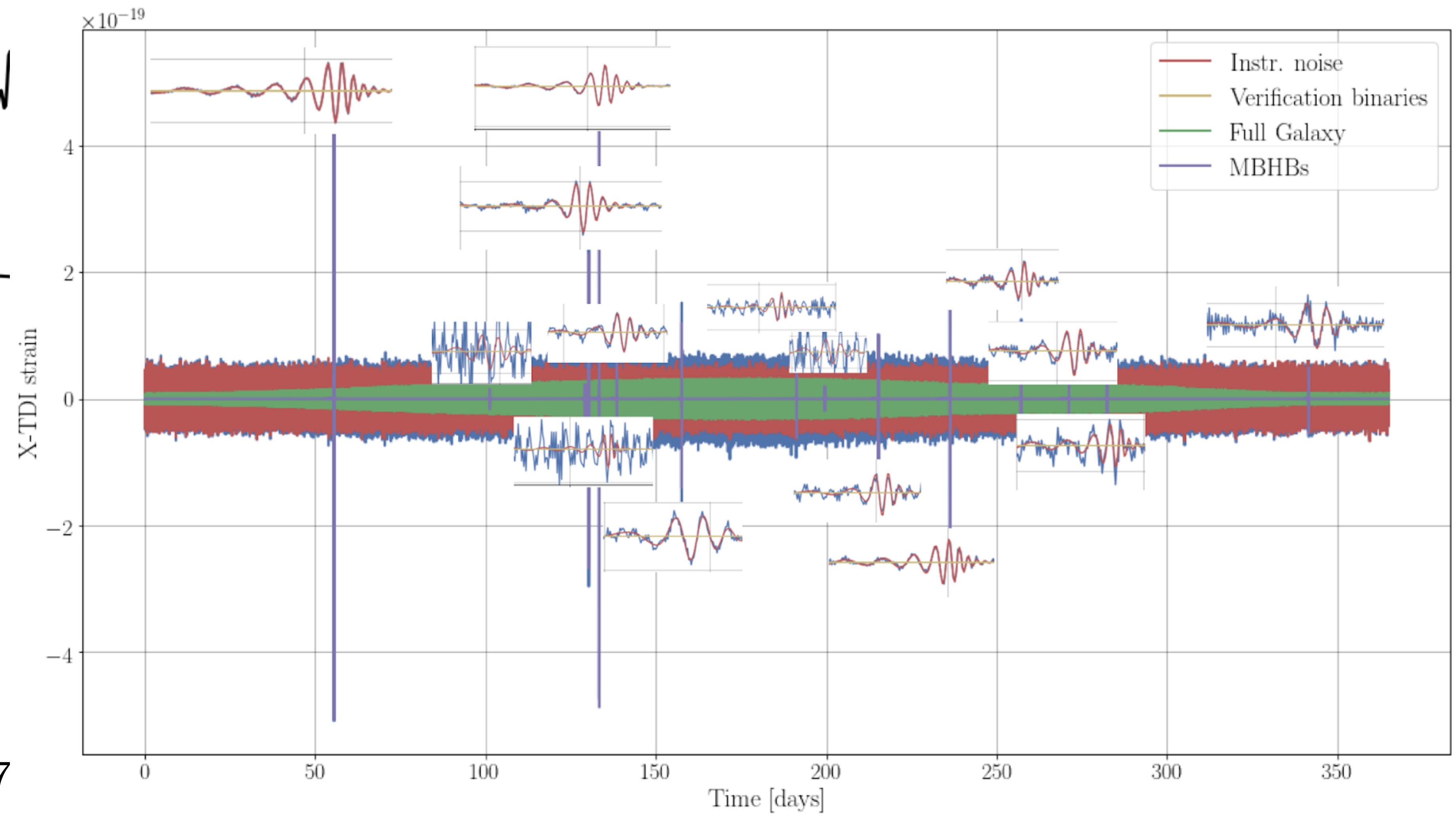


LISA Data Challenge
Sangria dataset

Courtesy of N. Karnesis, N. Korsakova, A. Petiteau

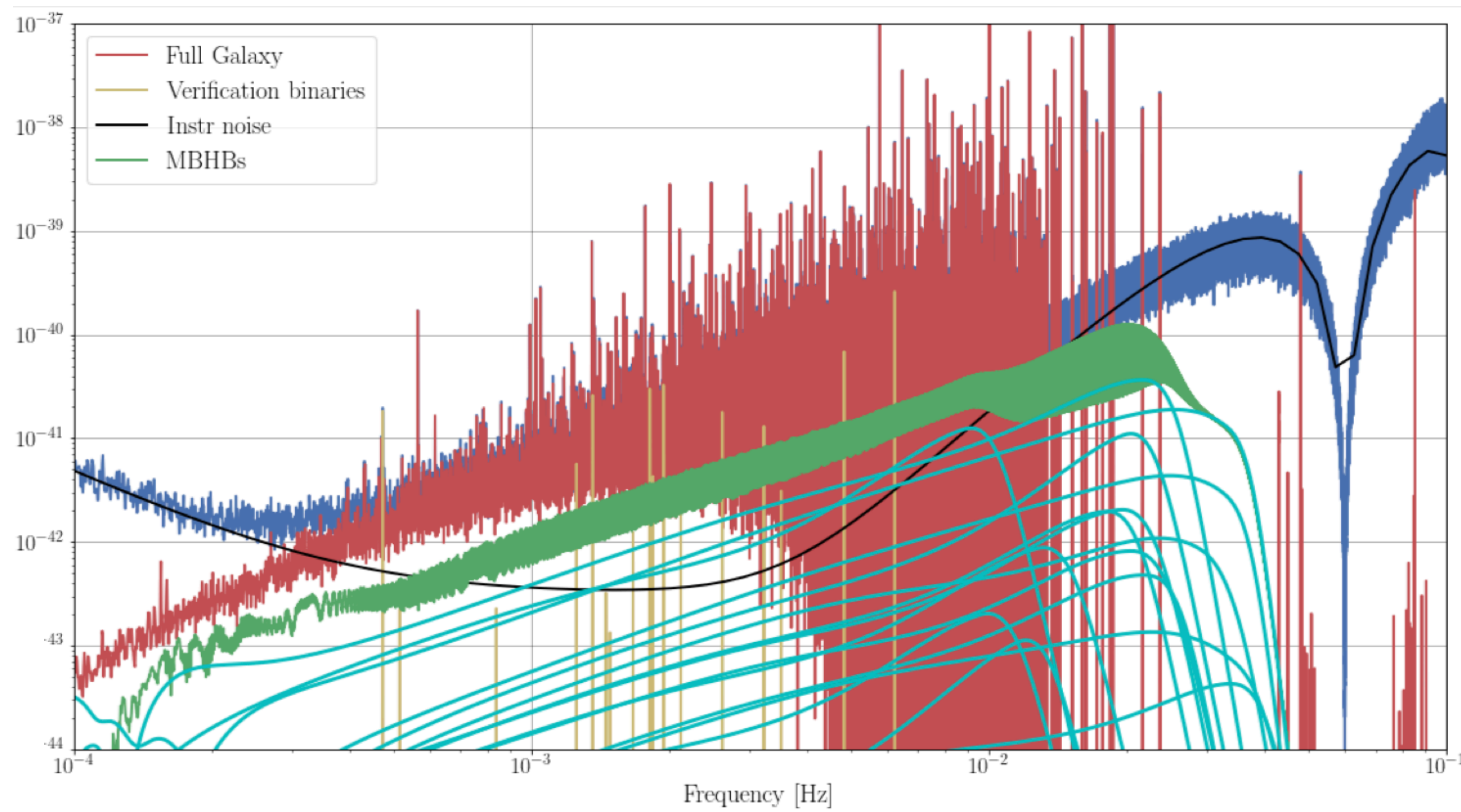


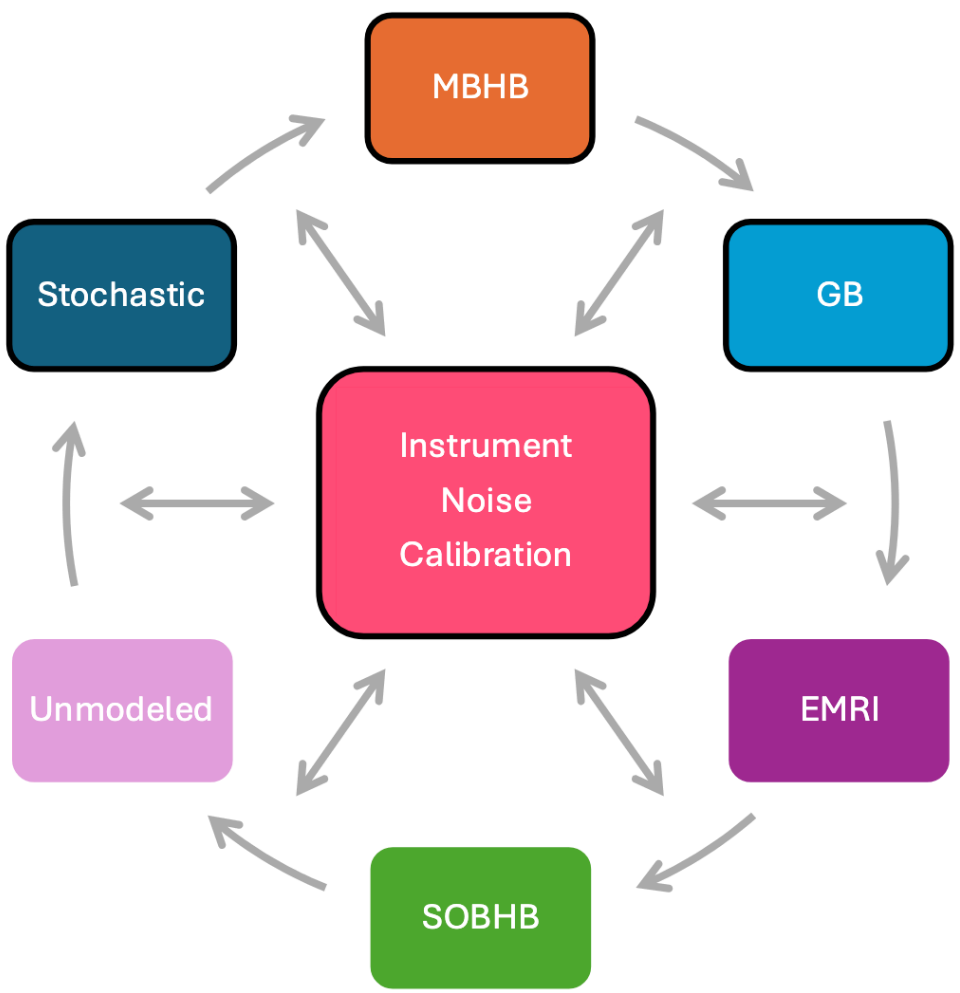
LISA Red Book arXiv:2402.07

What *we expect* LISA to detect

Challenges for data analysis

- Large number of overlapping sources
- Confusion noises from unresolved sources
- One doesn't cross-correlate like LVK
- How well will we know the instrumental noise?
- Artefacts: gaps in the data, glitches…



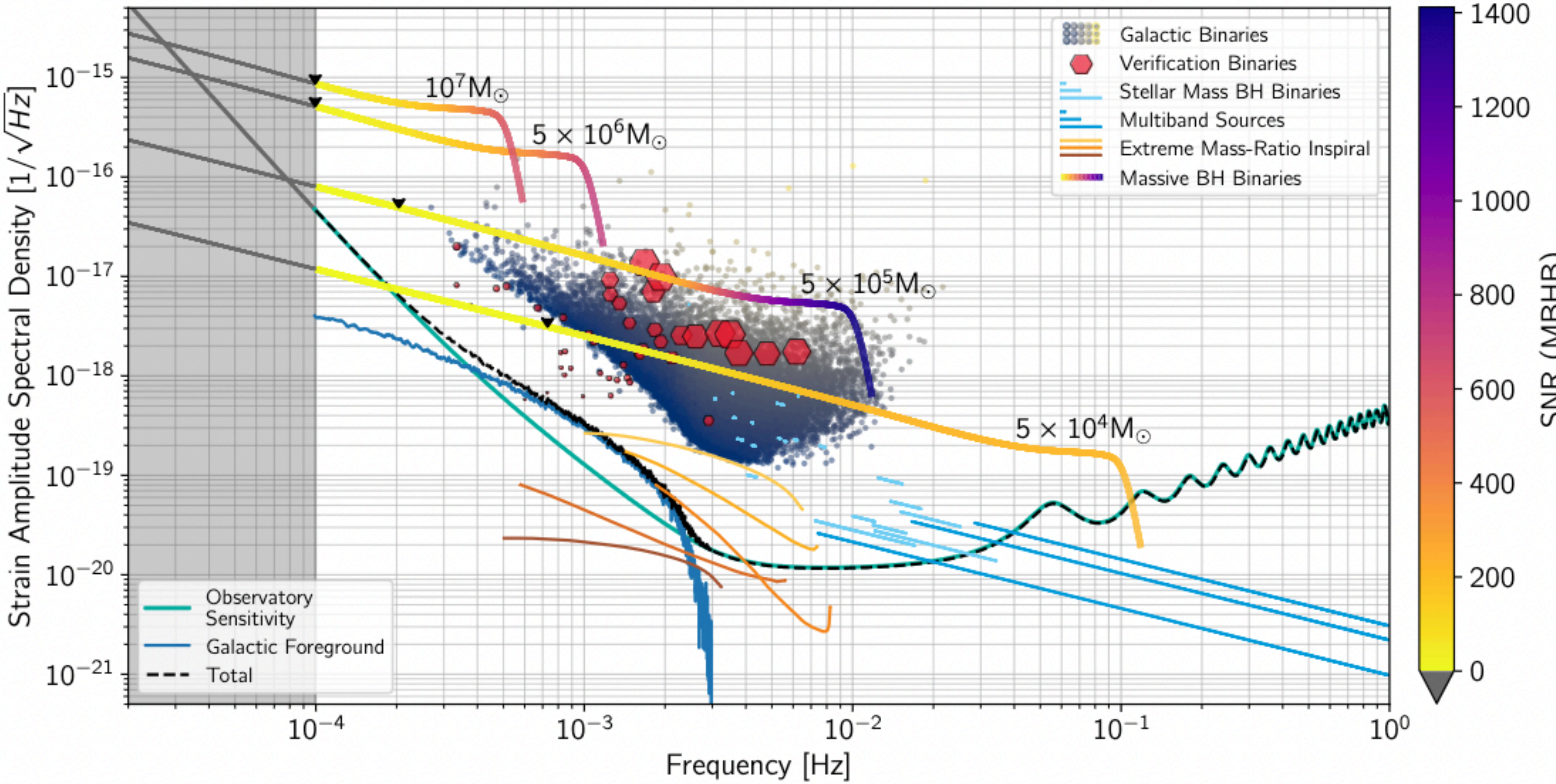


"Global fit" procedure

- Iterative identification of each source type
- At each iteration, better characterisation of sources
- Treatment of residuals from imperfect sources subtraction: noise, stochastic signals

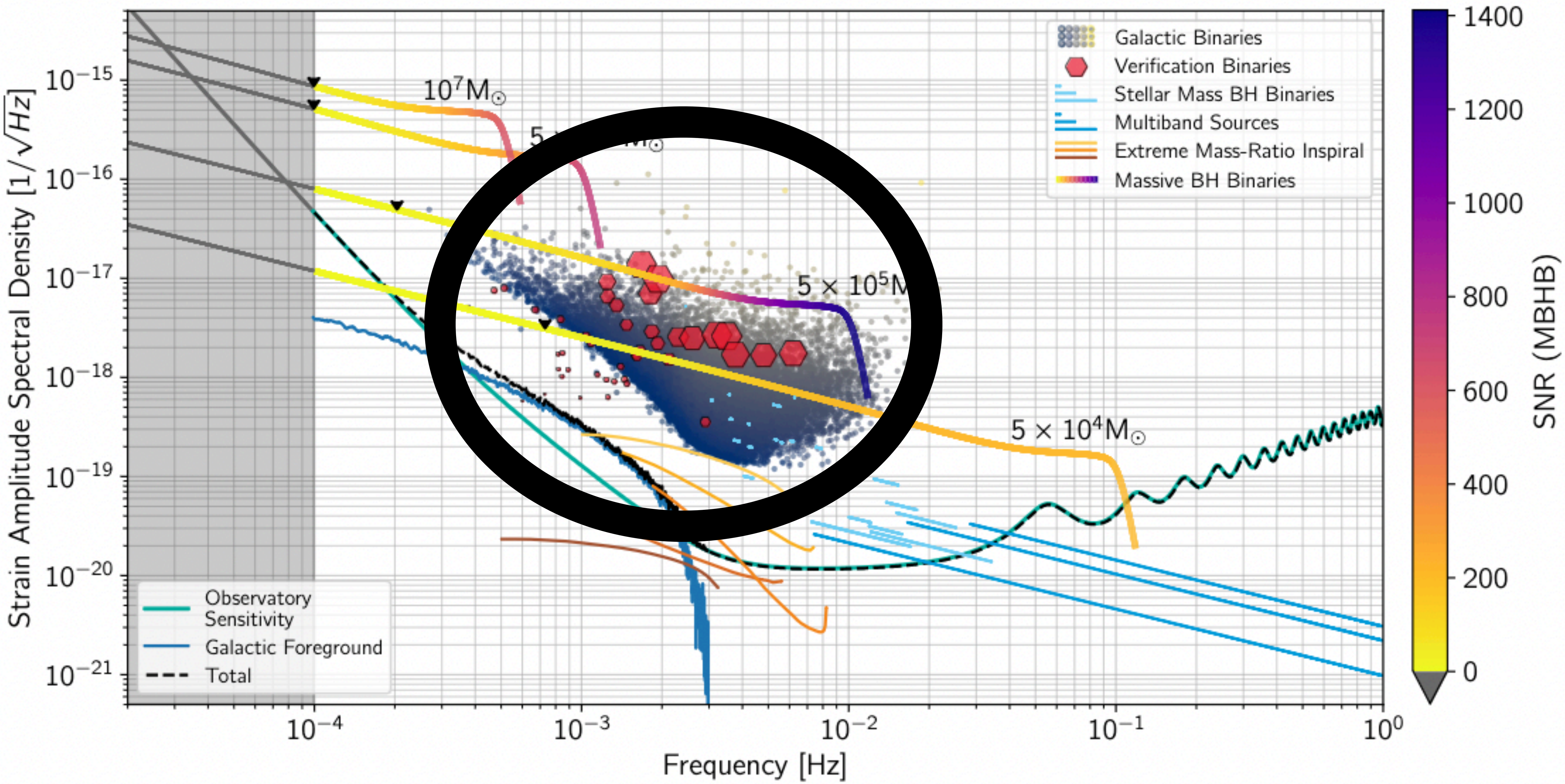
Deng et al, arXiv:2501.10277
Rosati & Littenberg, arXiv:2410.17180
Katz et al, arXiv:2405.04690
Littenberg & Cornish, arXiv:2301.03673

Proceed source-type by source-type and highlight mainly their use for **cosmology**



- Sources that can be used to probe the late-time universe expansion
- Possibility of detecting a stochastic signal from the early universe
- Sources that generate foregrounds masking stochastic signals (and also other sources)

Compact binaries in the galaxy



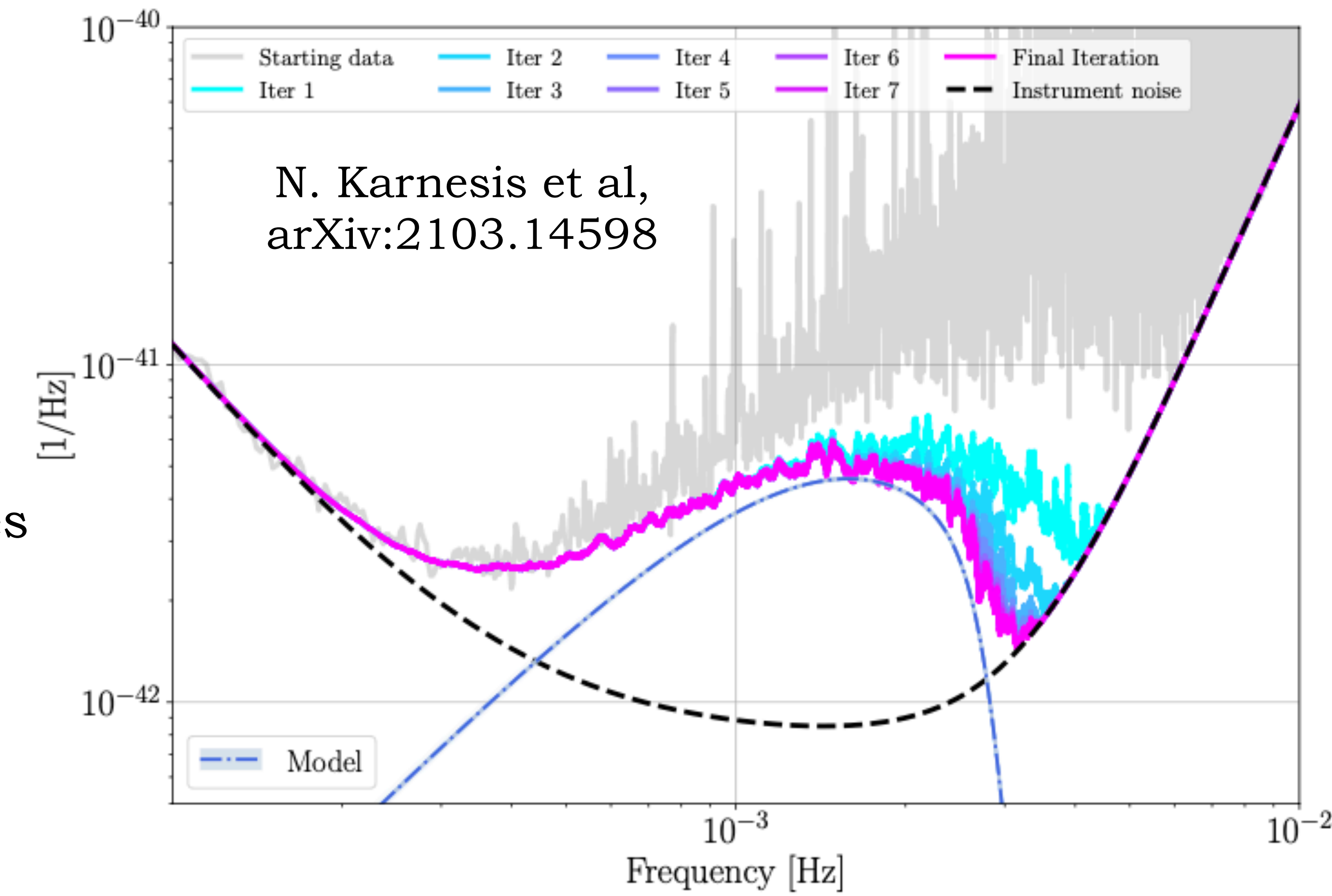
- Most are in the inspiral phase: quasi-monochromatic, permanent GW signal
- ~ 25000 sources are expected with SNR 7-1000

$$M_c = 1\,M_\odot \quad \tau = 10^5\,\mathrm{y} \longrightarrow f = 3\,\mathrm{mHz}, \quad \dot{f} = 10^{-16}\,\mathrm{Hz/sec}$$

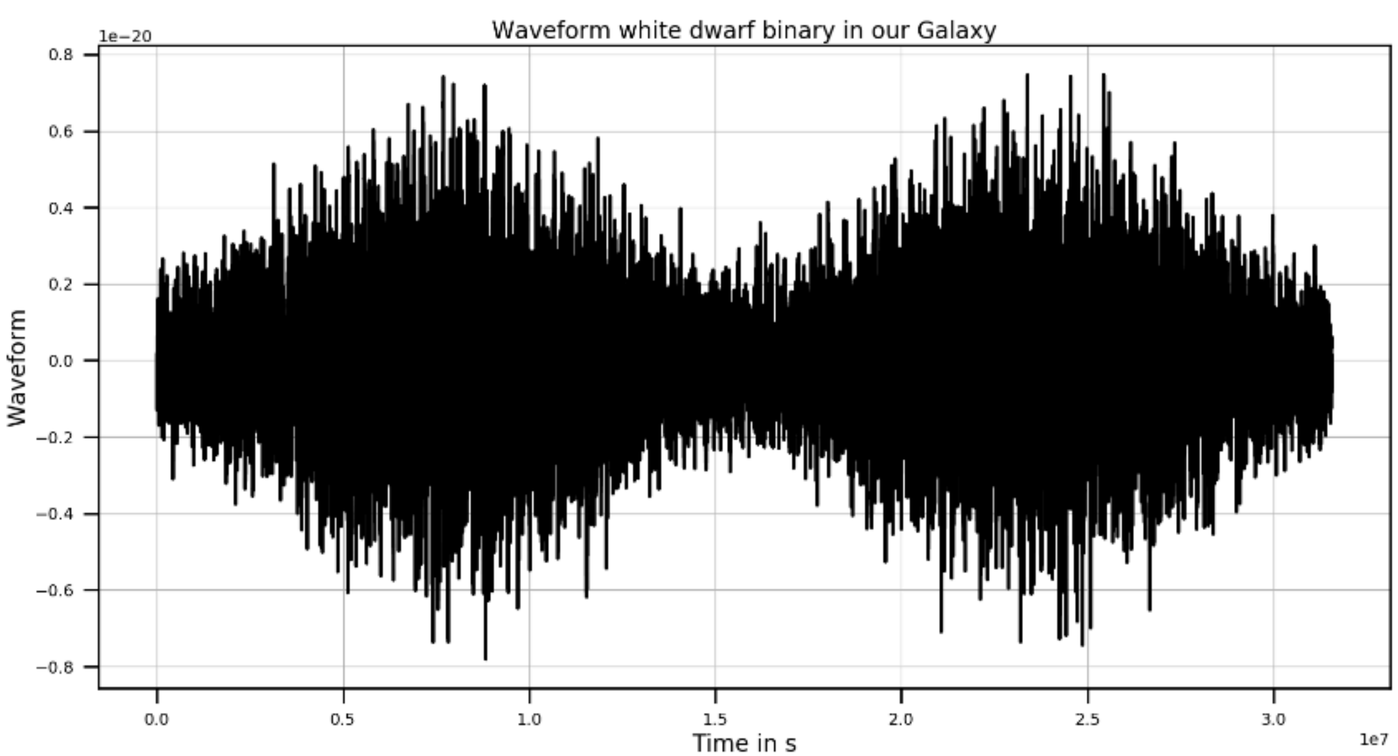
Compact binaries in the galaxy

Important for **cosmology** only as a ***confusion noise***: yearly modulated, foreground stochastic signal

- Modelled starting from Galaxy models by iterative subtraction of loud sources
- Can also be non-Gaussian
  Buscicchio et al arXiv:2420.08263



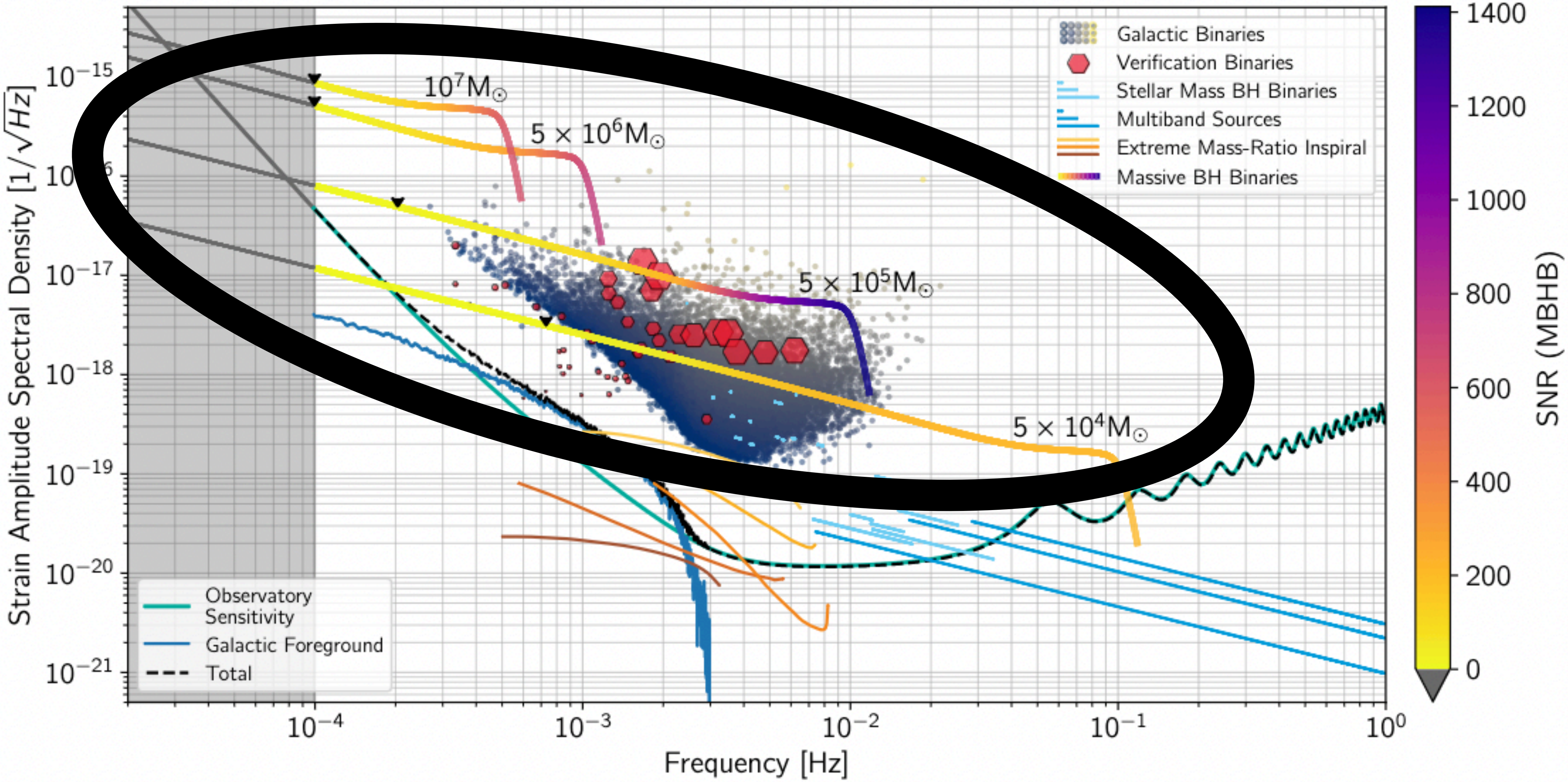
G. Boileau et al, arXiv:2105.04283



How to distinguish it from a stochastic background:

- Can be taken into account using a multi-parameter spectral template
  e.g. Kume et al arXiv:2410.10342
- Or one can exploit the time modulation
  e.g. Hindmarsh et al arXiv:2406.04894

Massive black hole binaries

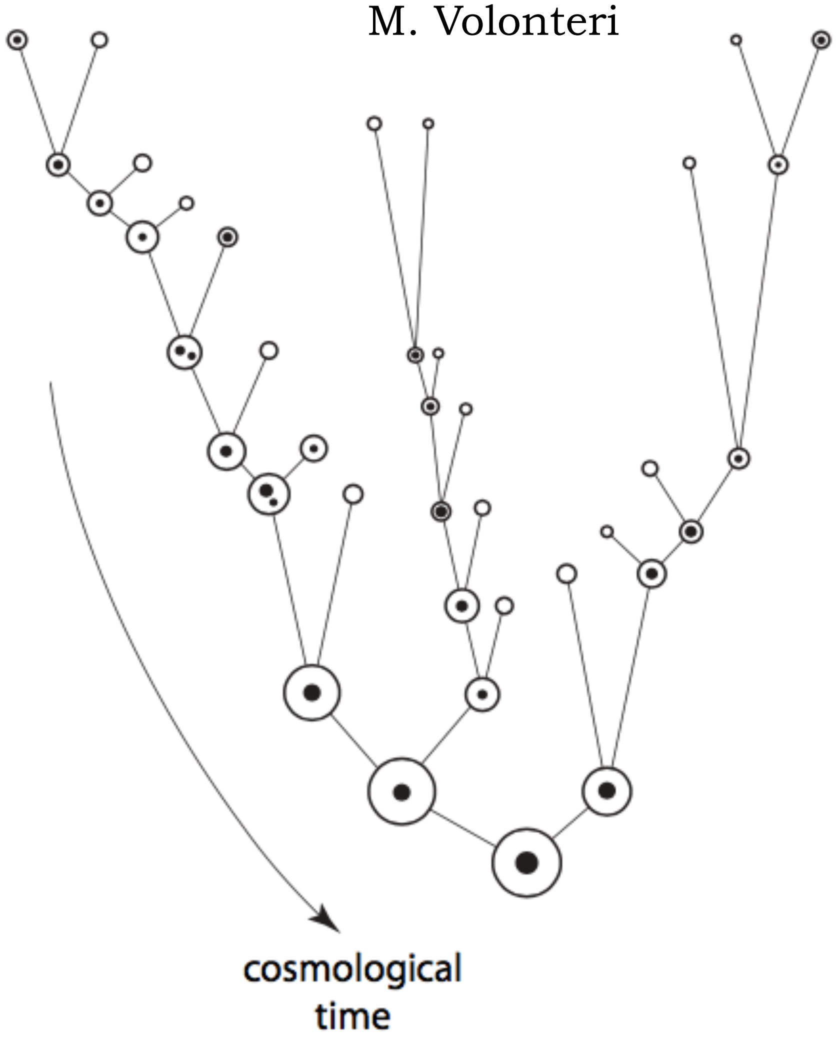


The loudest LISA sources (other than unexpected ones)

Massive black hole binaries

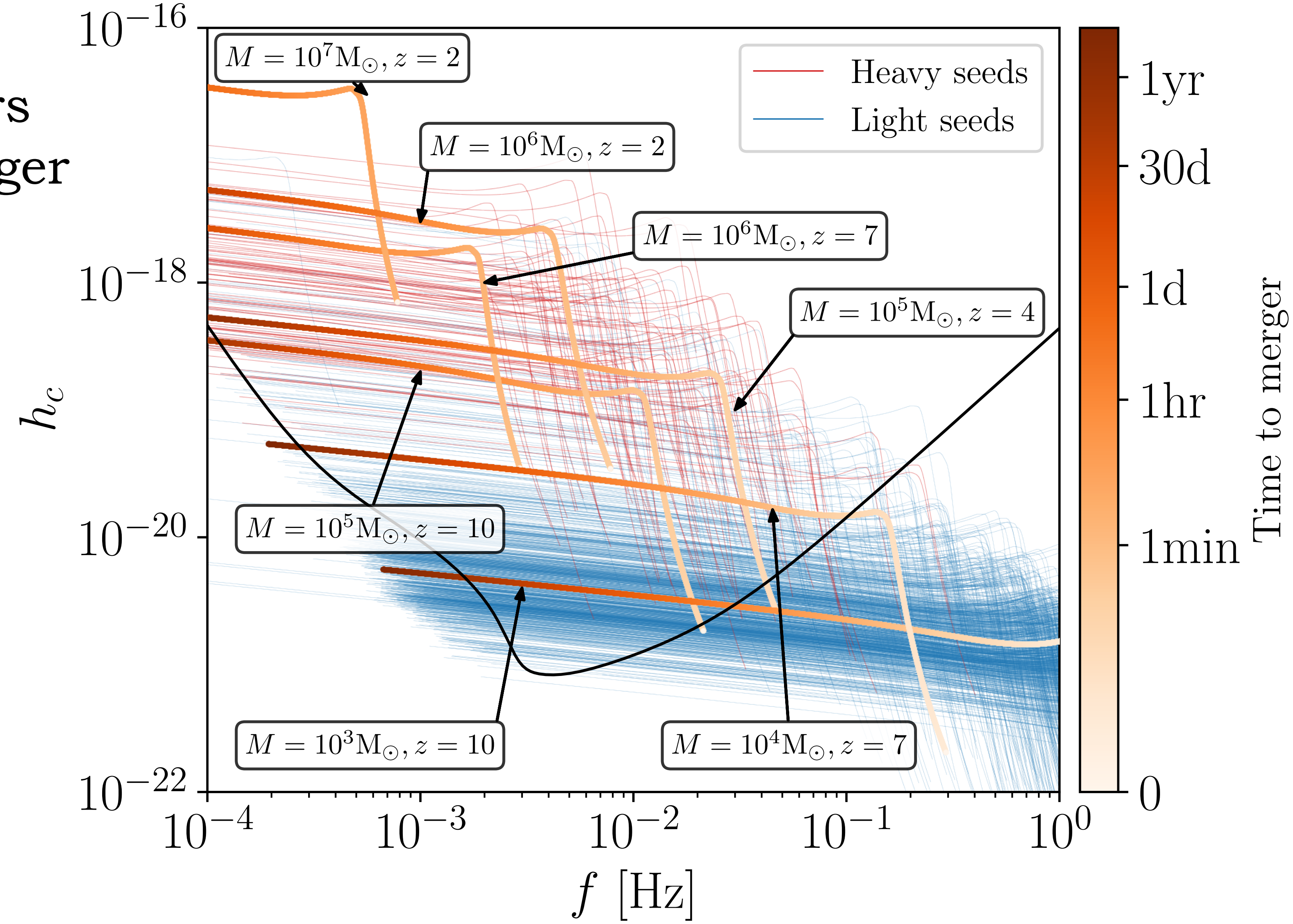
- MBH are indirectly observed in the centre of many galaxies. Galaxies collide -> MBH must exist in binaires

image:
M. Volonteri



Massive black hole binaries

- MBH are indirectly observed in the centre of many galaxies. Galaxies collide -> MBH must exist in binaires
- MBHB from 10^4 $M_\odot$ to 10^7 $M_\odot$: LISA detects the inspiral, merger, ringdown
- Signal duration: from few hours to several months prior to merger



LISA Red Book arXiv:2402.07571

Massive black hole binaries

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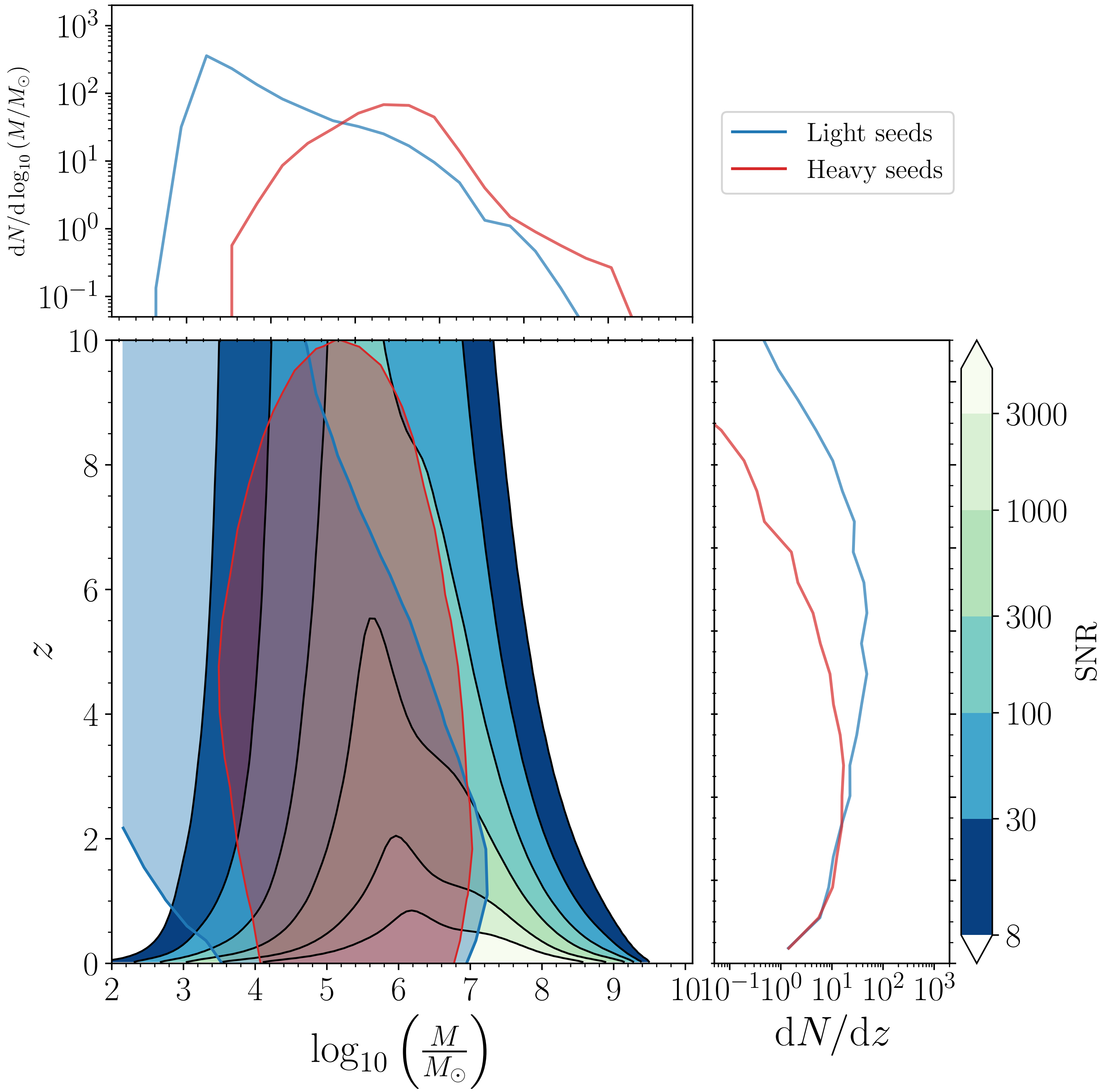
- MBHB from $10^4\,M_\odot$ to $10^7\,M_\odot$: LISA detects the inspiral, merger, ringdown
- Signal duration: from few hours to several months prior to merger
- SNR up to few thousands
- Measured up to z ~ 20!
- Expected rates from few to 100 per year (depending on model)
- LISA will probe MBH formation and growth (accretion, mergers…)

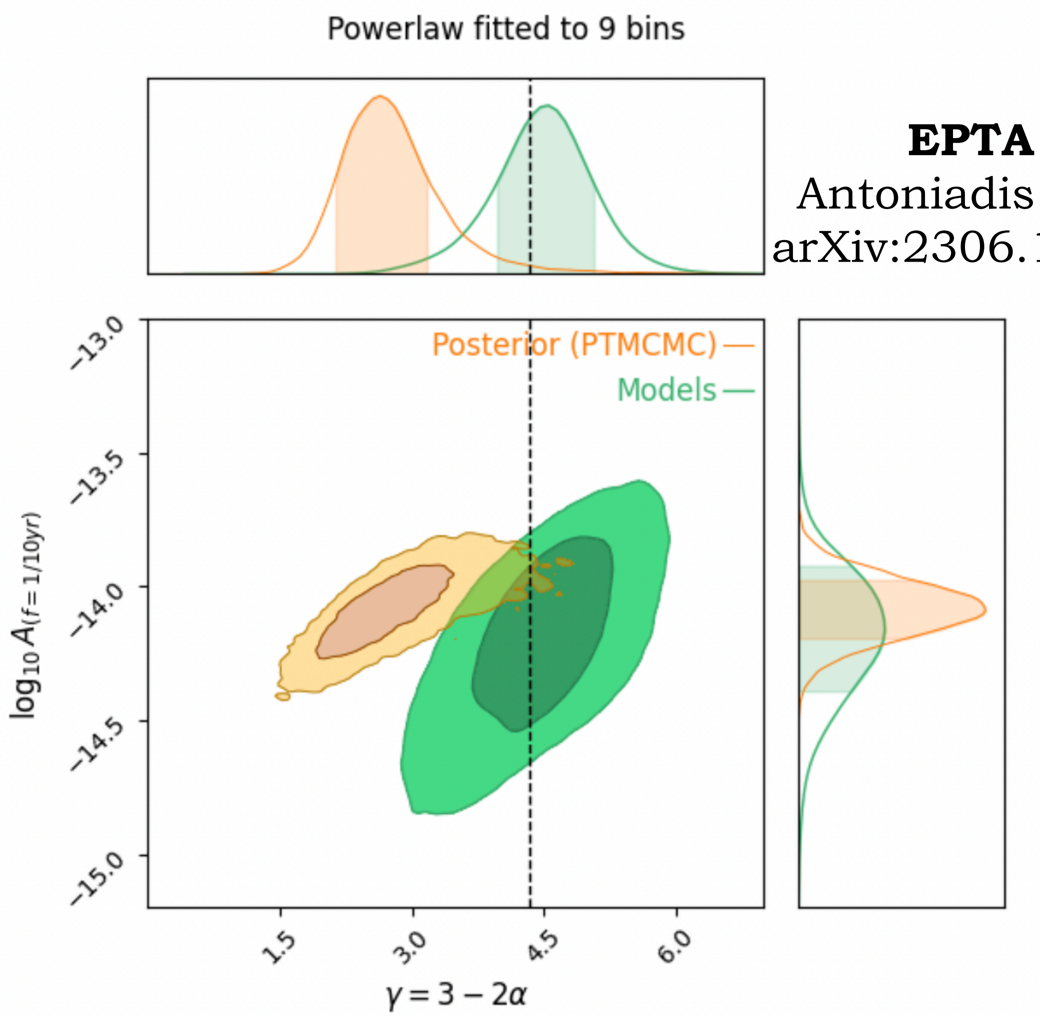


LISA Red Book arXiv:2402.07571

Massive black hole binaries

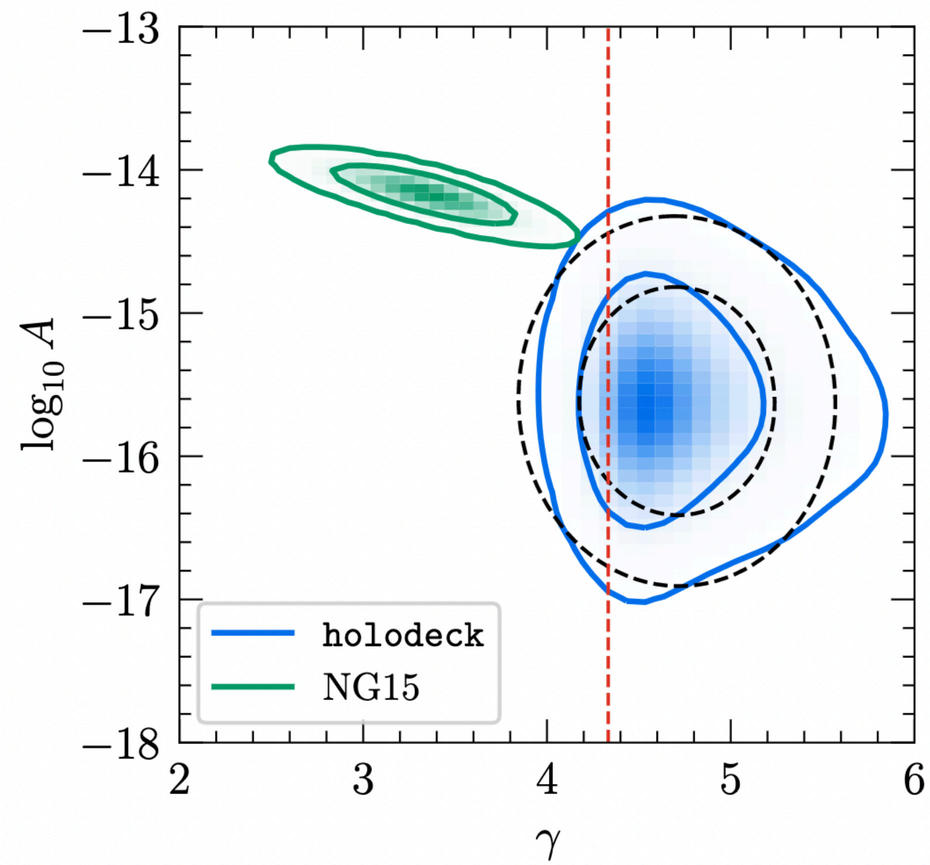
- LISA can be complementary to PTA observations in masses, redshift…
- JWST sees SMBHs up to very high redshift z ~ 11…

e.g. Toubiana et al arXiv:2410.17916



EPTA
Antoniadis et al arXiv:2306.16227

NANOGrav
Afzal et al arXiv:2306.16219



Cosmology:

- **EM counterparts and coincident GW detection:** MBHB are expected to have counterparts if they occur in gaseous disks at the centre of galaxies (very uncertain rate)

Massive black hole binaries

MBHB can be used as bright sirens to measure cosmological parameters

$$h_+(\tau,\theta,\varphi) = \frac{4}{d_L(z)}(G\,\mathcal{M}_c)^{5/3}[\pi f(\tau)]^{2/3}\left(\frac{1+\cos^2\theta}{2}\right)\cos(2\Phi(\tau))$$

$$h_\times(\tau,\theta,\varphi) = \frac{4}{d_L(z)}(G\,\mathcal{M}_c)^{5/3}[\pi f(\tau)]^{2/3}\,\cos\theta\,\sin(2\Phi(\tau))$$

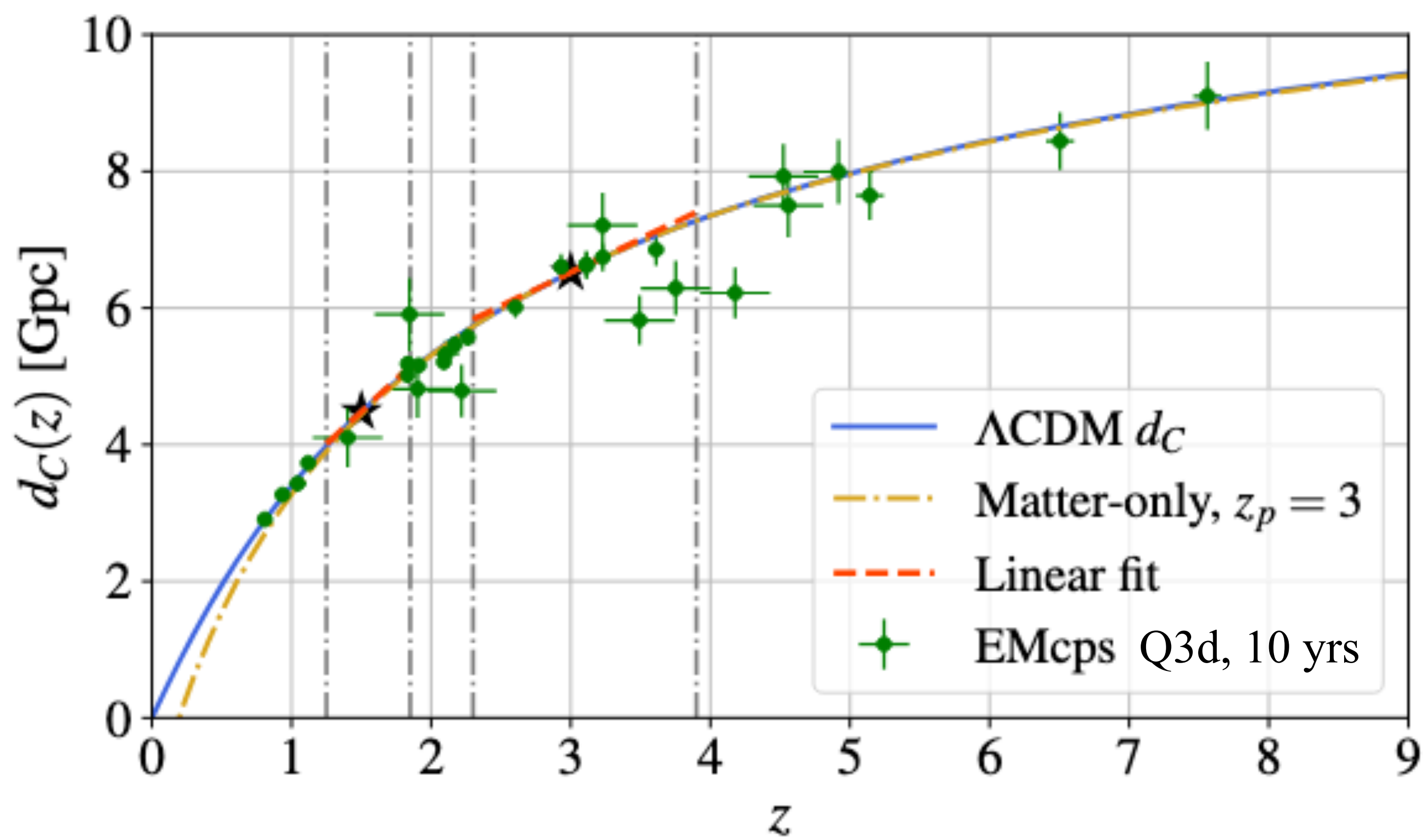
$$\mathcal{M}_c = (1+z)M_c$$

$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

Redshifted chirp mass
degeneracy among the redshift and the true chirp mass

- Measurement of the luminosity distance: no calibration needed, EASY AND DIRECT

- Measurement of the redshift: IMPOSSIBLE BY GW EMISSION ONLY



Mangiagli et al arXiv:2312.04632

Massive black hole binaries

MBHB can be used as bright sirens to measure cosmological parameters

- In order to infer the redshift from the detection of an EM counterpart of the MBHB one must select events with good sky localisation (few!)
- The nature of the EM counterpart at merger is unclear
- Weak lensing (and peculiar velocity) error affect the measurement of d_L

Our approach

- Step 0: simulated catalogues of massive BH binaries (E. Barausse)

- Step 1: LISA parameter estimation (error on sky localisation and d_L)
  - Bayesian code LISAbeta (S. Marsat)

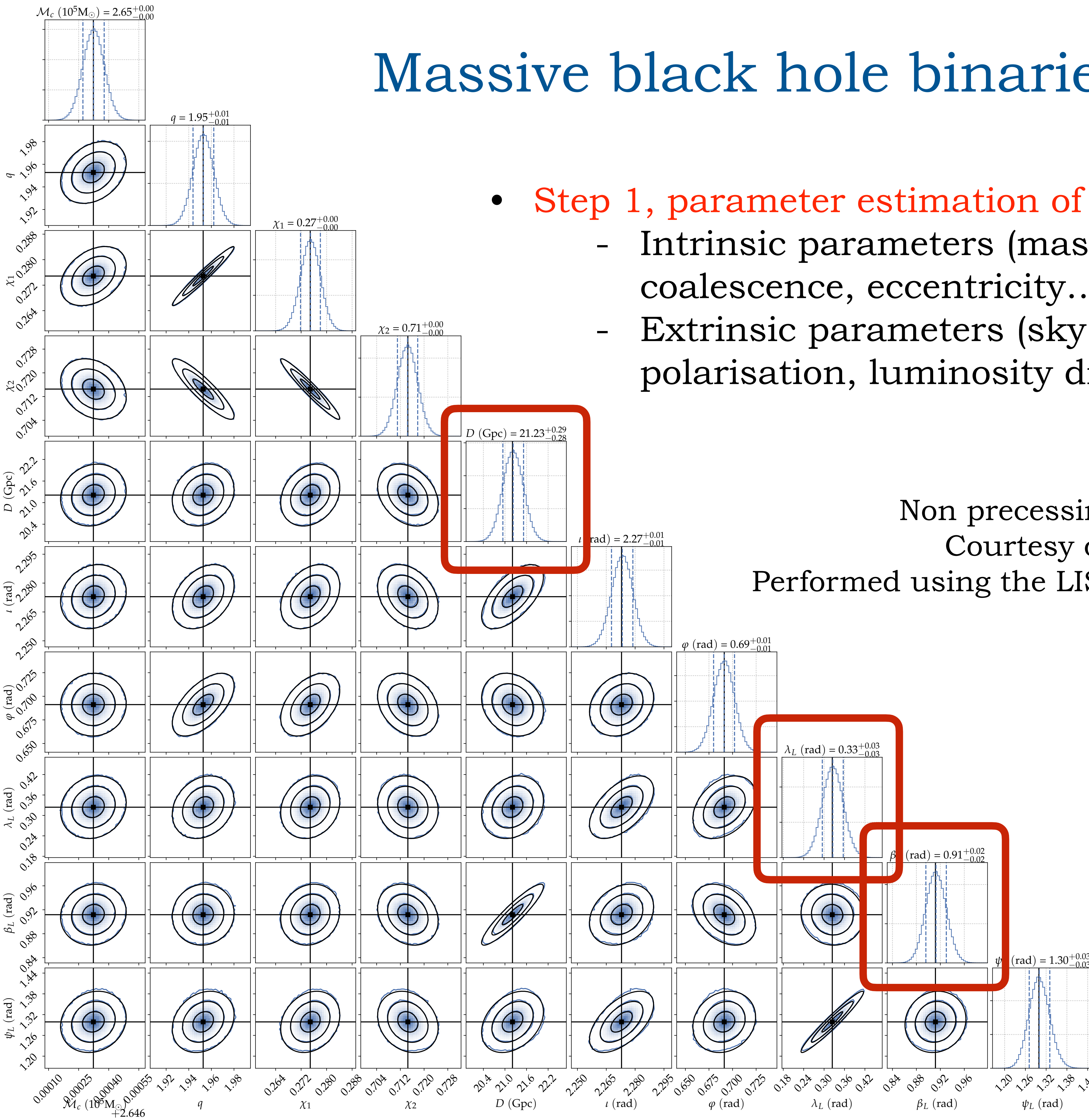
- Step 2: model of the EM counterpart and detection strategy (redshift error)
  - Detection of the host galaxy with LSST
  - Localisation of a radio counterpart with SKA and detection of the host galaxy with ELT (for the redshift information)
  - Localisation of a X-ray counterpart with Athena and detection of the host galaxy with ELT (for the redshift information)

- Step 3: construction of the Hubble diagram

Tamanini et al, arXiv:1601.07112
Mangiagli et al, arXiv:2207.10678
Mangiagli et al arXiv:2312.04632

Massive black hole binaries

- Step 1, parameter estimation of MBHB systems:
  - Intrinsic parameters (masses, spins, phase at coalescence, eccentricity…)
  - Extrinsic parameters (sky position, inclination, polarisation, luminosity distance…)

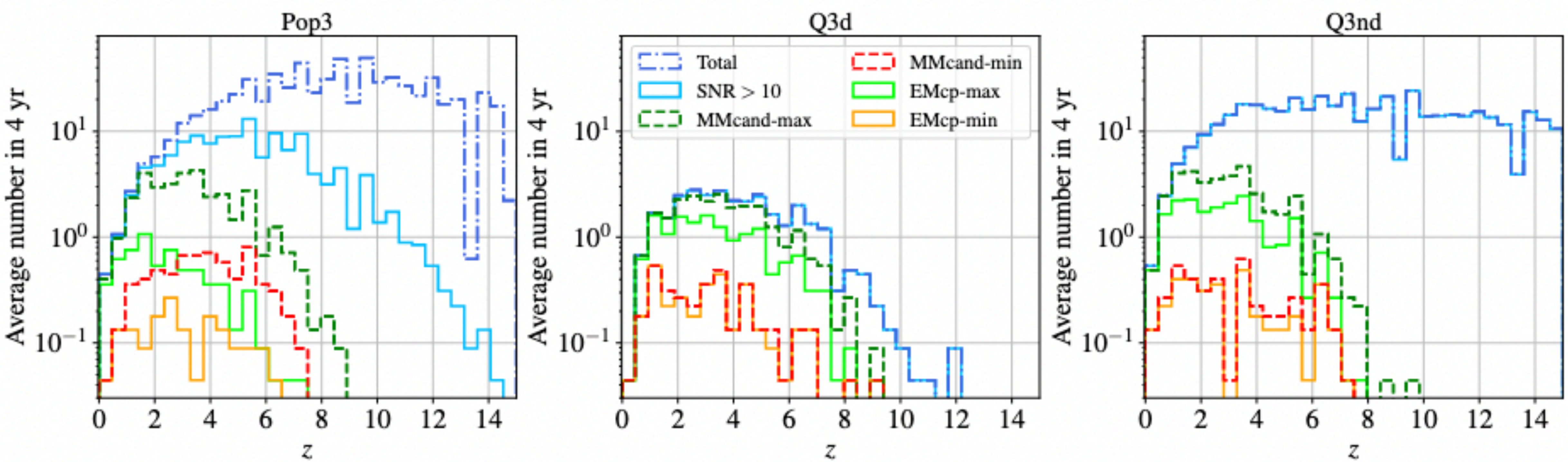


Non precessing circular binary
Courtesy of A. Mangiagli
Performed using the LISAbeta code, S. Marsat et al

Massive black hole binaries

- Step 2, construction of the EM counterpart and its detection strategy:

- After applying the sky localisation cut, the number of standard sirens is quite low
- It depends heavily on the MBHB astrophysical generation model and on the EM detection channel
- The events cluster at high redshift 2 < z < 5



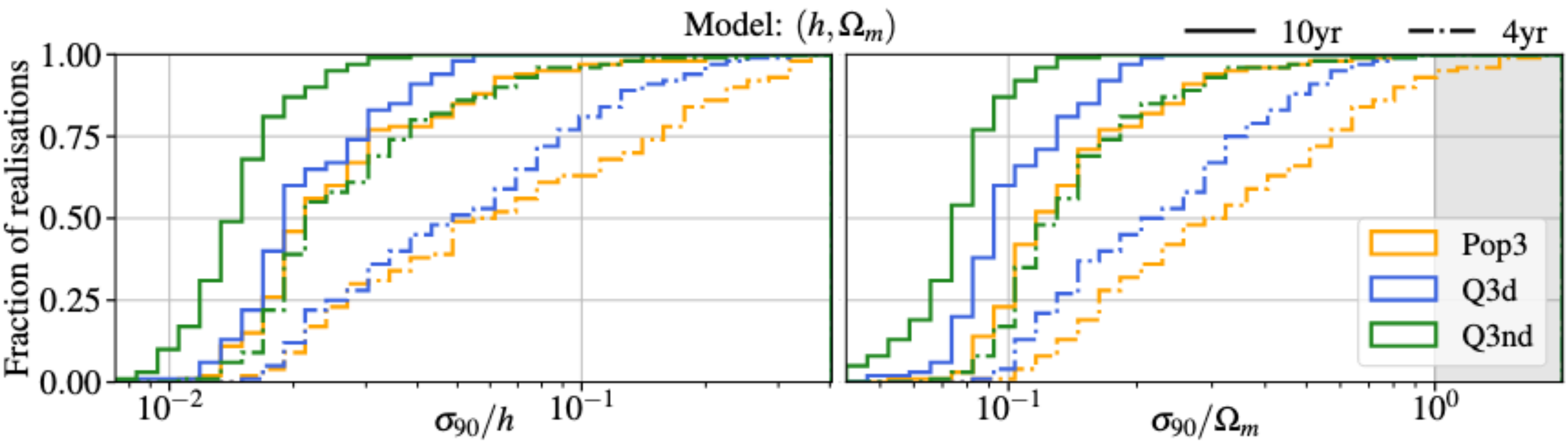
	Rubin	SKA+ELT			Athena+ELT				
		Isotropic flare	Γ2	Γ10	Catalogue $F_{X,\,\mathrm{lim}} = 4\text{e-}17$	Catalogue $F_{X,\,\mathrm{lim}} = 2\text{e-}16$	Eddington $F_{X,\,\mathrm{lim}} = 4\text{e-}17$	Eddington $F_{X,\,\mathrm{lim}} = 2\text{e-}16$	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	
No-obsc.	0.84	6.4	1.51	0.04	0.49	0.27	1.02	0.84	Pop3
	3.07	14.8	2.71	0.04	2.67	1.38	3.87	2.13	Q3d
	0.53	20.3	3.2	0.04	0.58	0.31	4.4	3.24	Q3nd
Obsc.	0.13	6.4	1.51	0.04	0.04	0.04	0.13	0.17	Pop3
	0.75	14.8	2.71	0.04	0.22	0.13	0.18	0.09	Q3d
	0.35	20.3	3.2	0.04	0.18	0.04	0.27	0.31	Q3nd

Massive black hole binaries

Step 3: the uncertainty of cosmological measurement with MBHB standard sirens is difficult to forecast!

Since the number of EM counterparts is low for the nominal mission duration (4 years), the errors (high) are dominated by statistical fluctuations in the **realisations**
The constraints also depend much on the MBHB formation channel

- **LISA forecast constraints on H0 and Ω_m**



relative errors on h of $\lesssim 5\%$ in 4 yrs and $\lesssim 2\%$ in 10 yrs for at least 50% of the realisations.

Massive black hole binaries

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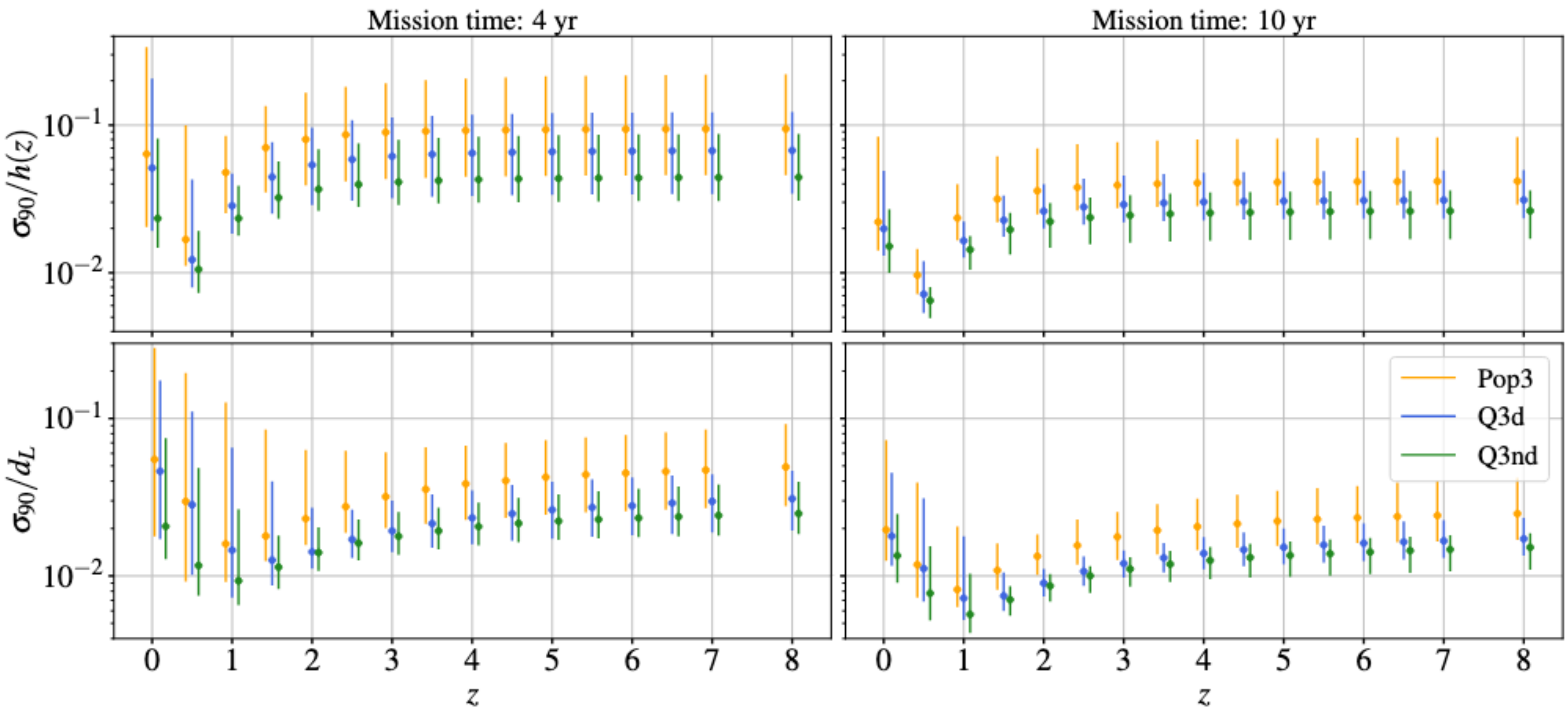
- **But at higher redshift it gets better...**

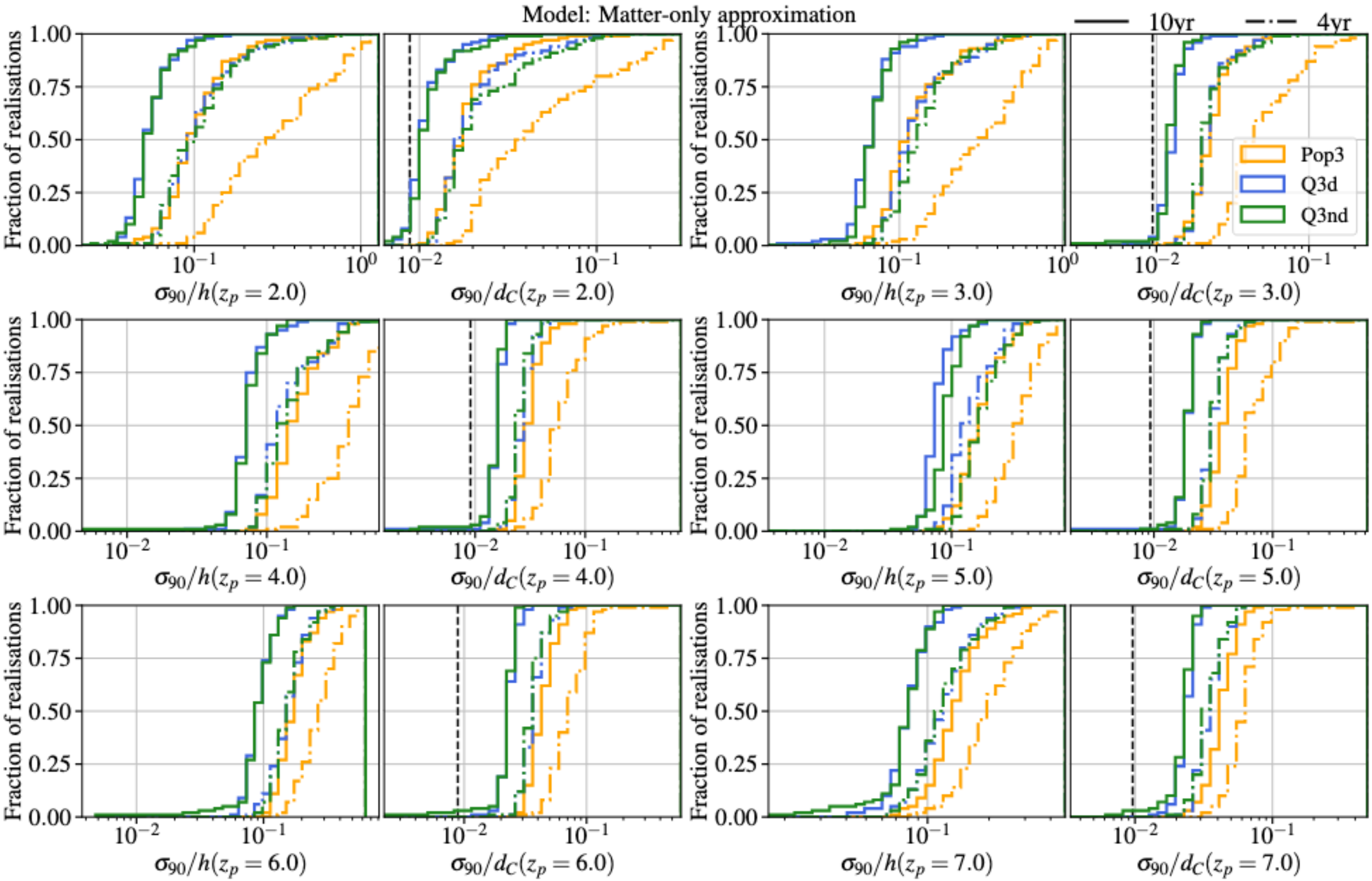
(obtained simply from transformation)



Massive black hole binaries

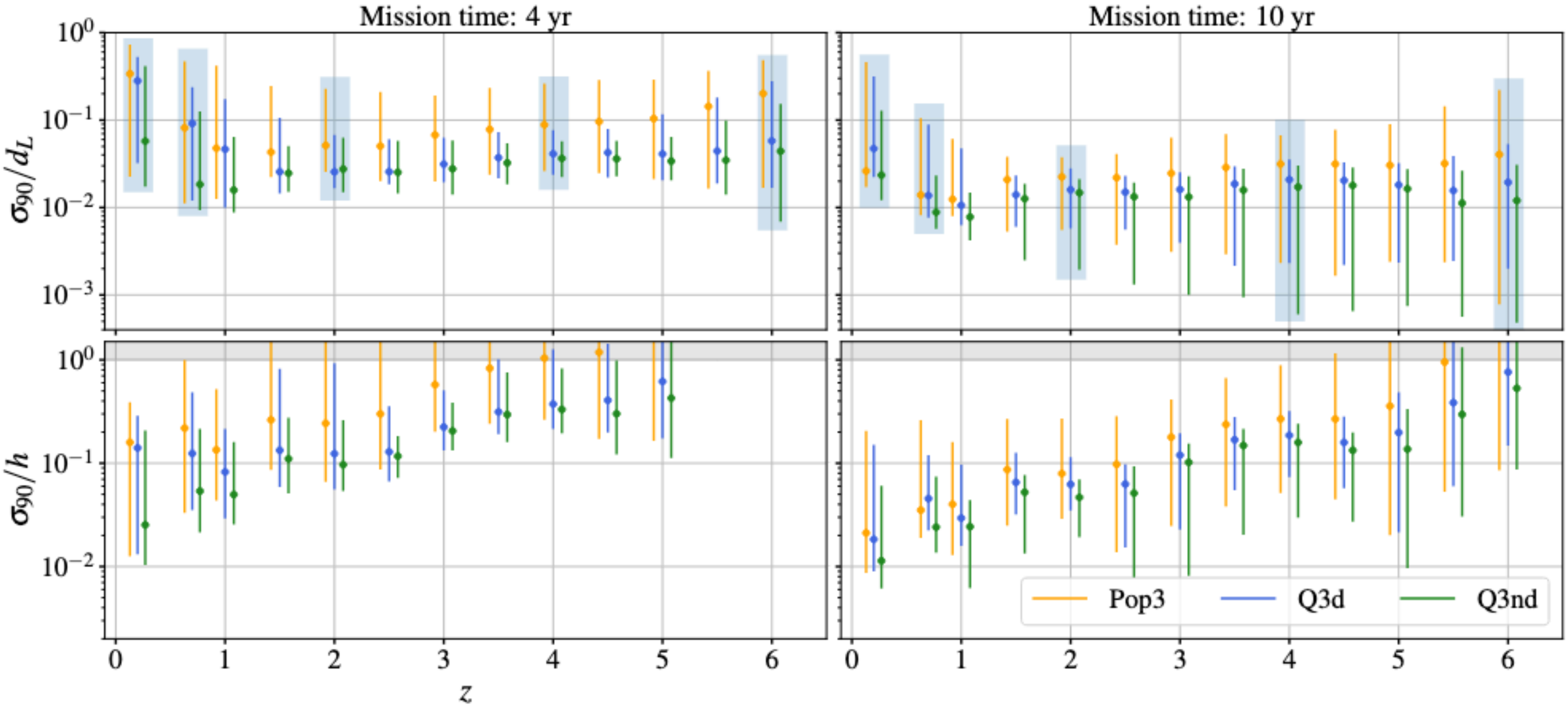
- **So we have explored high redshift models:**
  1. Assuming matter only

$$d_C(z) = d_C(z_p) + 2(1+z_p)H^{-1}(z_p)\left(1 - \frac{\sqrt{1+z_p}}{\sqrt{1+z}}\right)$$



Massive black hole binaries

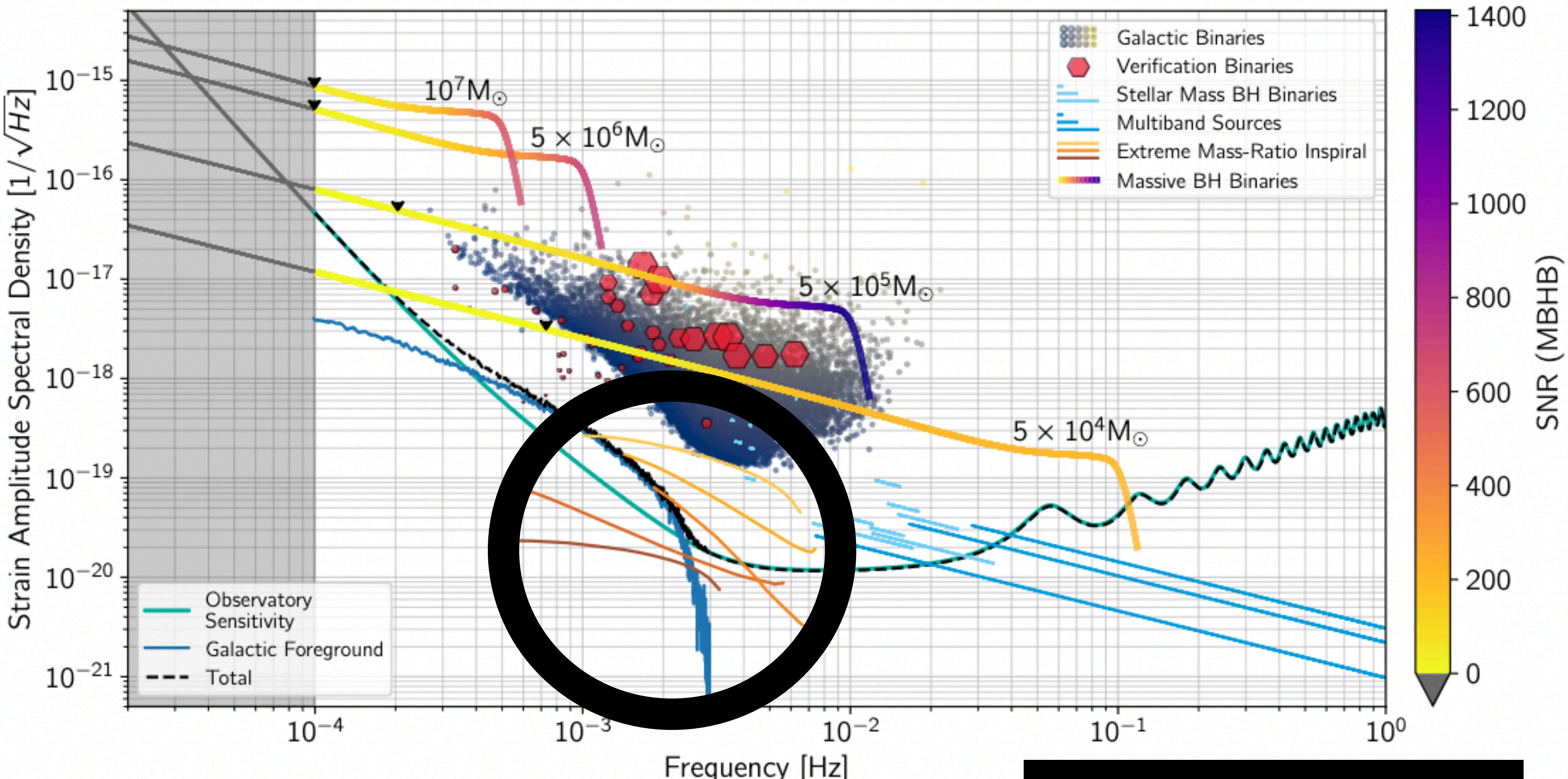
- **So we have explored high redshift models:**
  2. Cubic polynomials spline interpolation of luminosity distance
  (model independent)



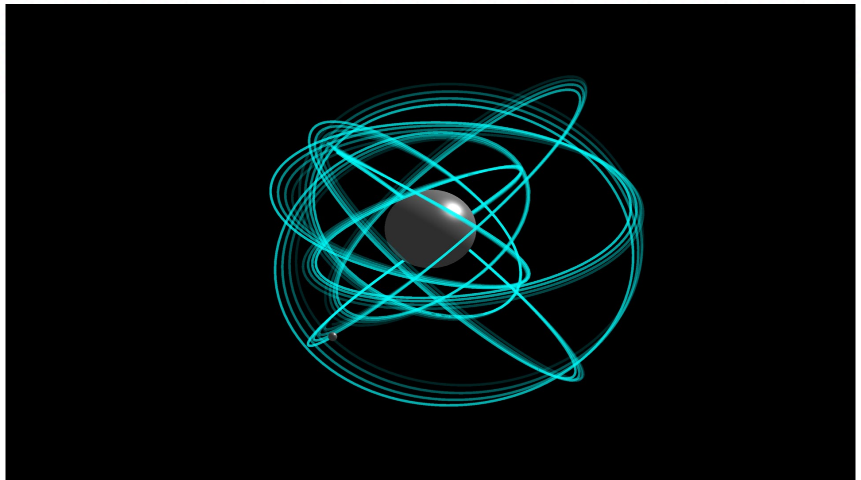
(several other models less interesting or less performant)

Mangiagli et al arXiv:2312.04632

Extreme mass ratio inspirals



Binaries for which the masses of the two objects are very different $10^{-7} < q < 10^{-4}$

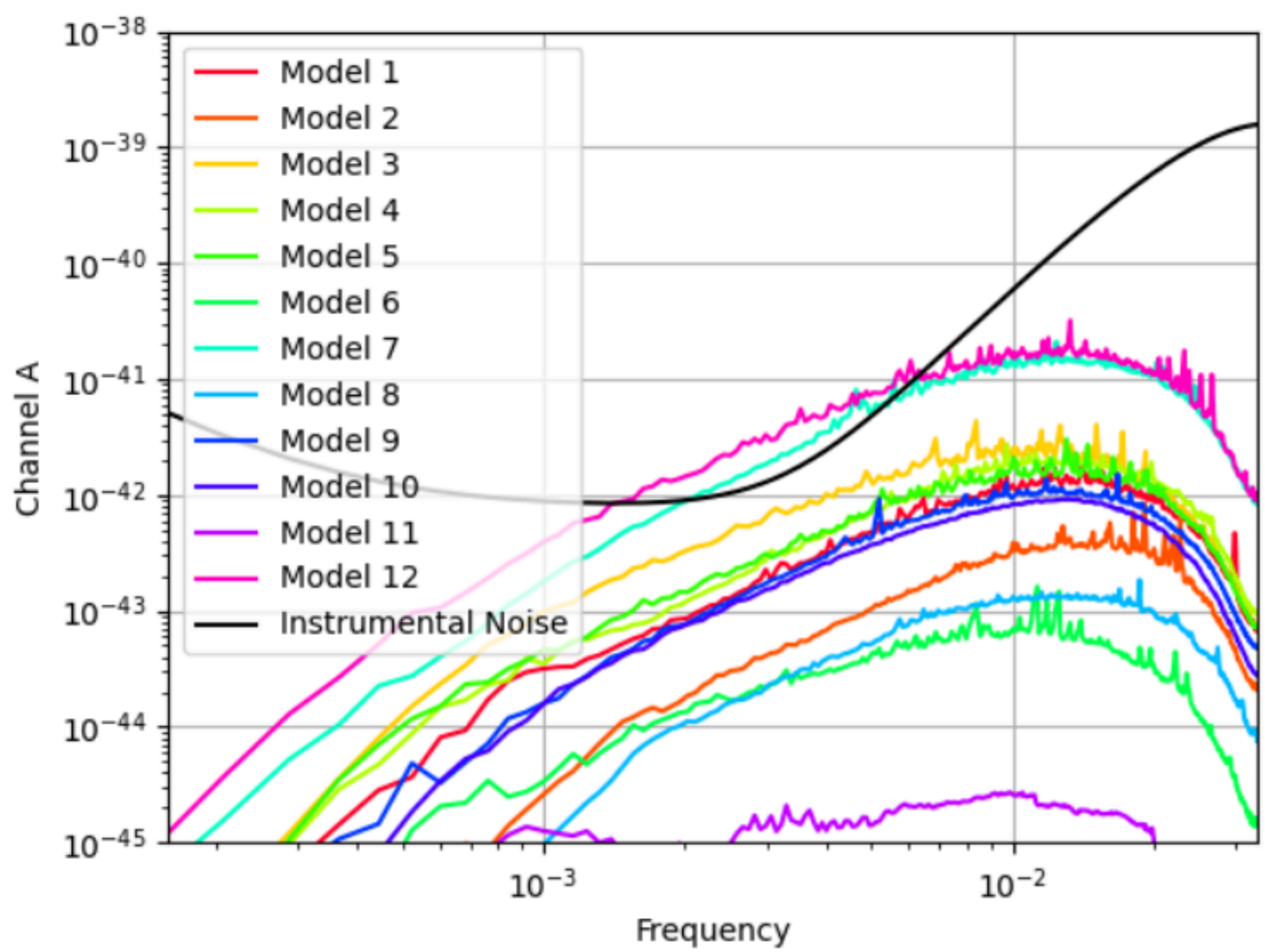


Extreme mass ratio inspirals

- The waveforms are complex and the rates are highly uncertain
- The SNR can be as high as few hundreds
- They remain in band for a long time, longer as q decreases
- They offer the opportunity to map the full BH population of the Universe
- And to study the environment of galaxy centres (including the Milky Way)
- They can be used to perform tests of General Relativity
- They can give rise to an **unresolved foreground**

The level of the **foreground** depends on the EMRI rate, that depend on the astrophysical formation model (mass function, spin distribution, mass-luminosity relation…)

Pozzoli et al arXiv:2302.07043
Piarulli et al arXiv:2410.08862

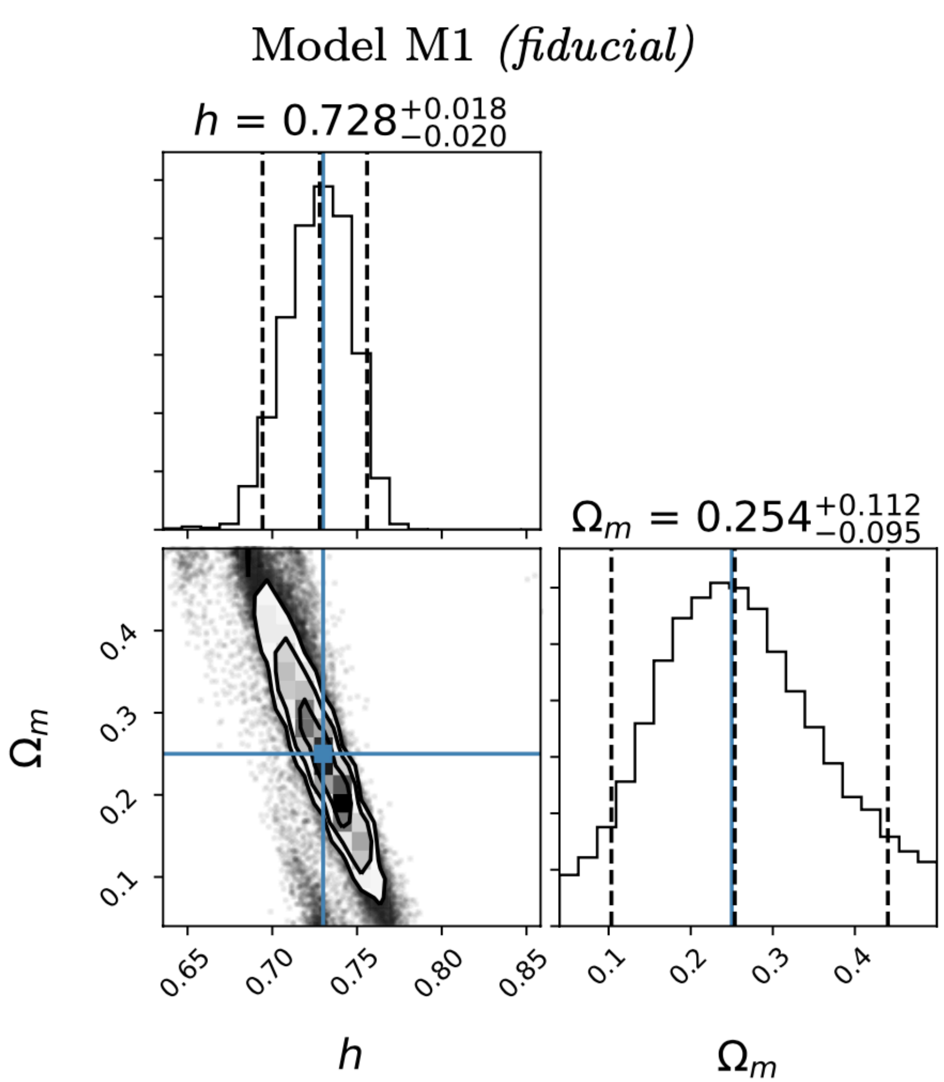


Extreme mass ratio inspirals

Cosmology: dark sirens

Dark sirens: sources for which no EM counterpart is expected, **statistical method** cross-correlation with galaxy catalogues to infer the redshift from the luminosity distance measurement

- EMRIs with SNR>100 can be used for cosmology: results depend on the rates, which are uncertain

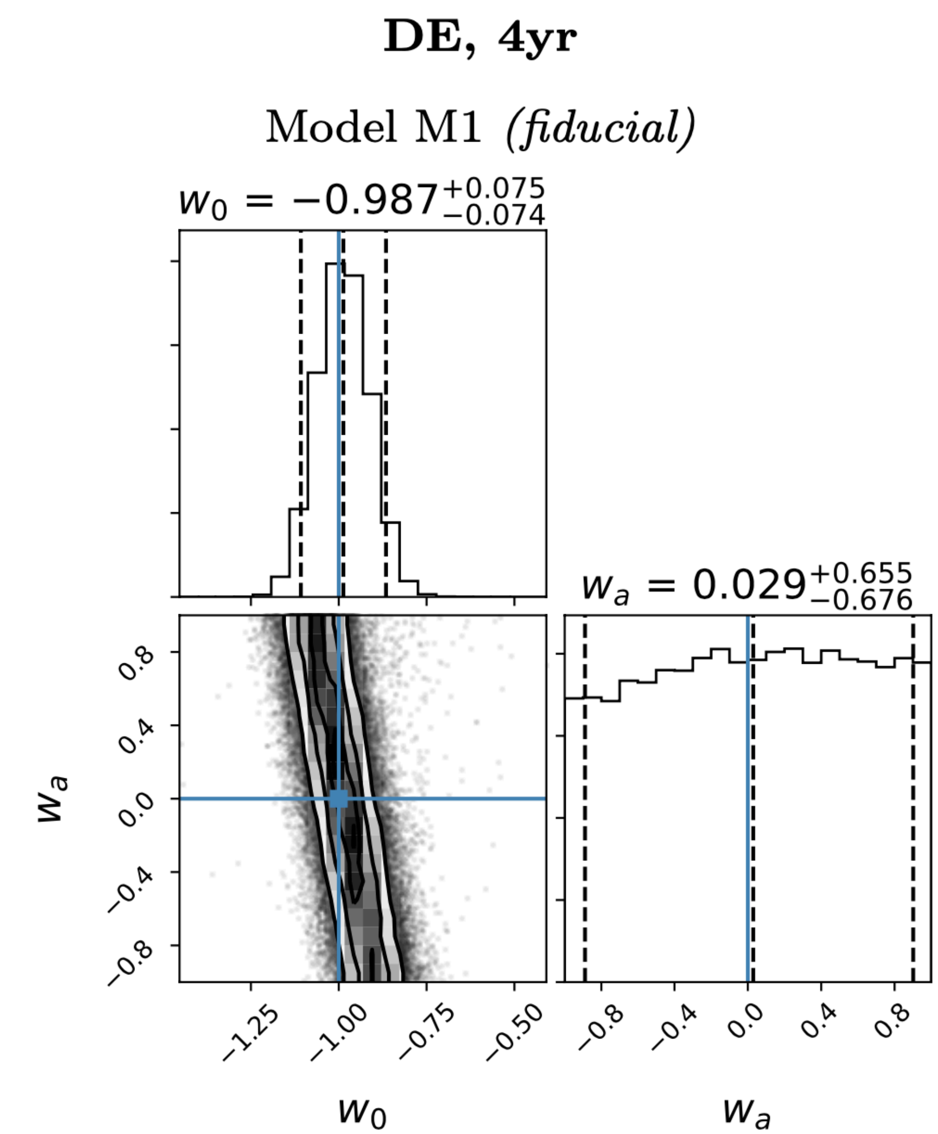


A 4-year LISA mission can provide:

3% constraints on H_0

7% constraints on w_0

Laghi et al, arXiv:2102.01708



Extreme mass ratio inspirals

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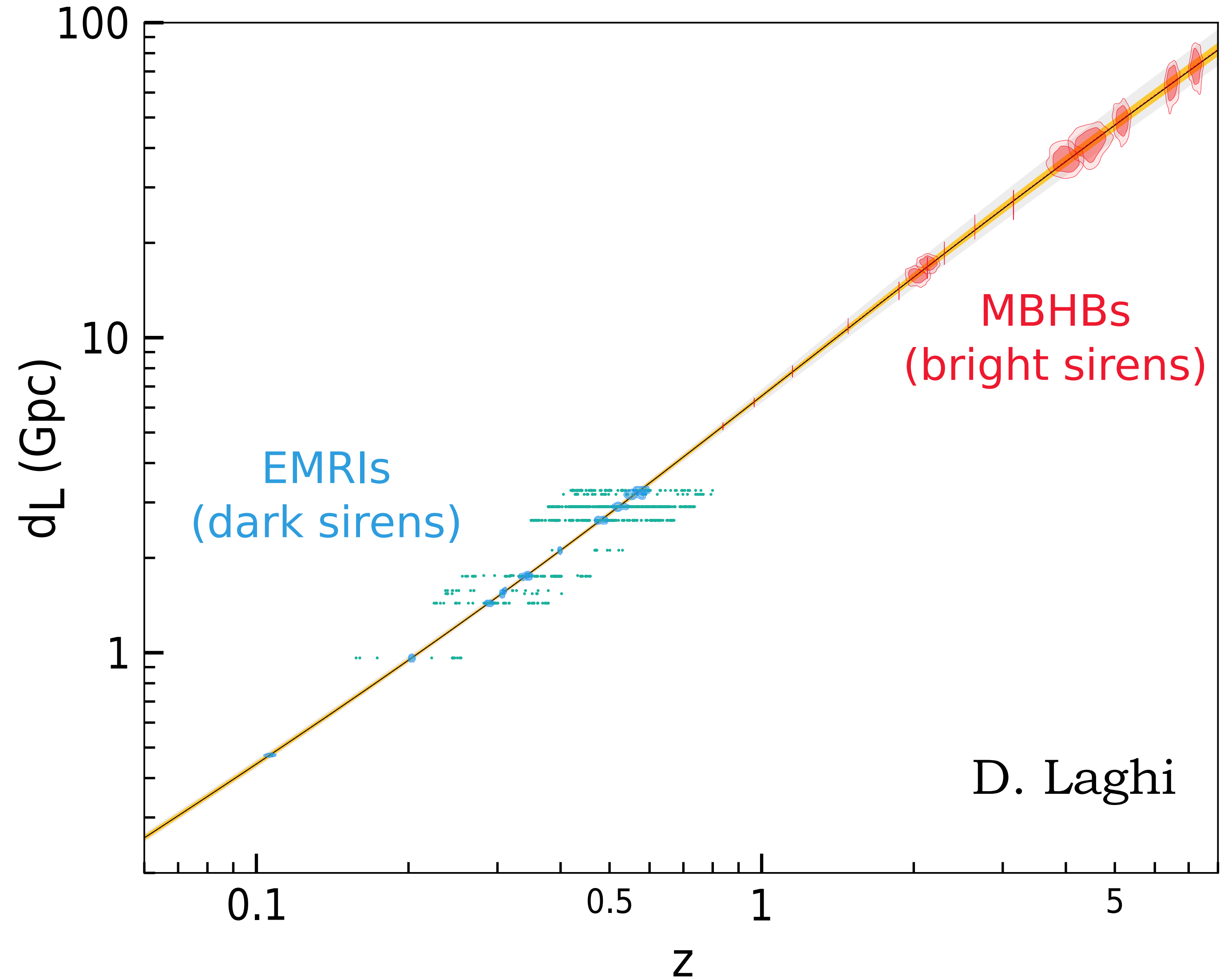
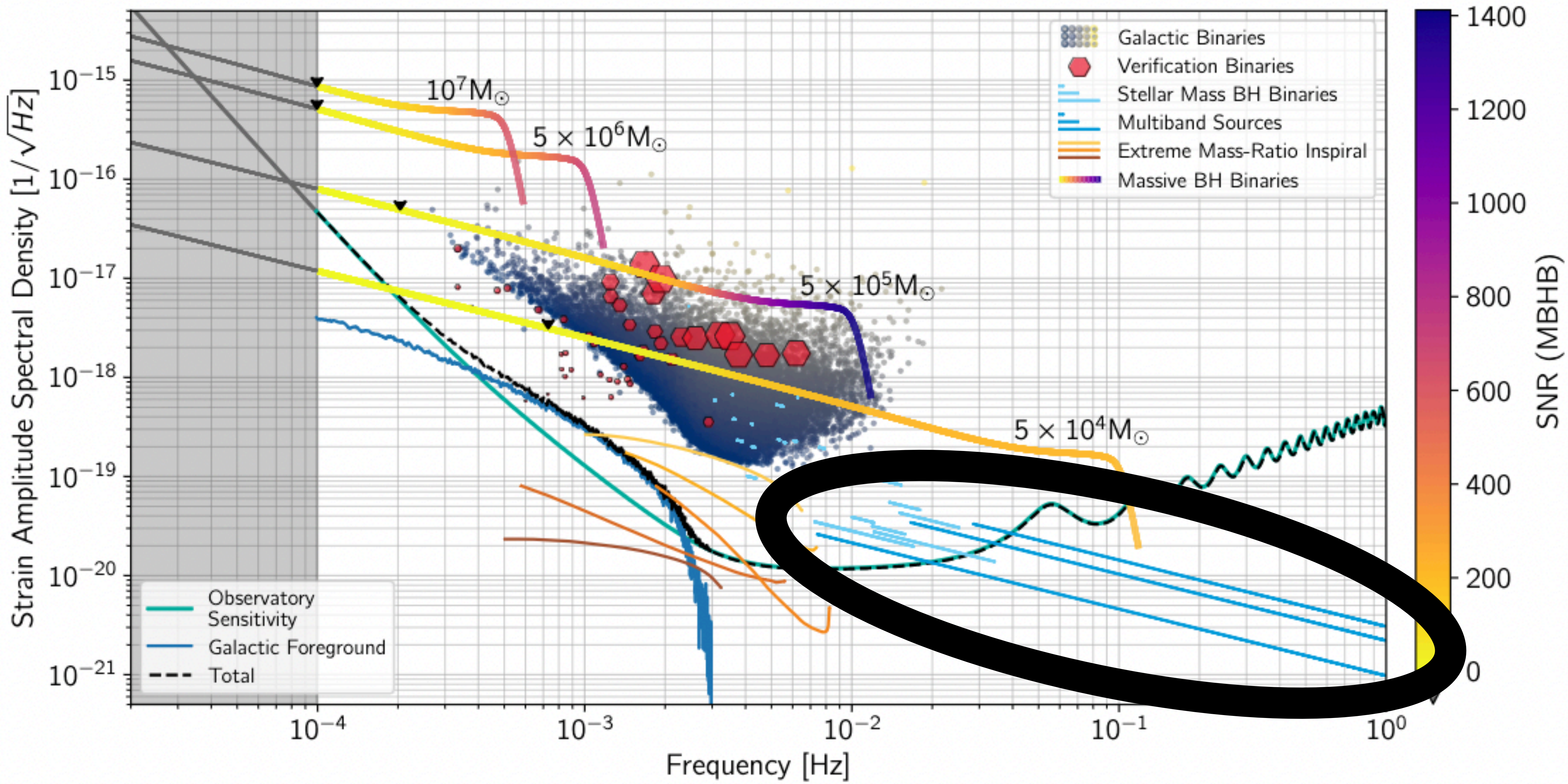
The full potential of LISA is not yet assessed (Laghi et al, work in progress)

By combining the redshift-distance measurement from EMRIs and MBHBs one can improve the measurement possibly to sub-% level on H_0 and few % on $\boldsymbol{\Omega}_M$



- spectral sirens (from features e.g. in the mass distribution): not yet for LISA

Black hole binaries of tents of solar masses

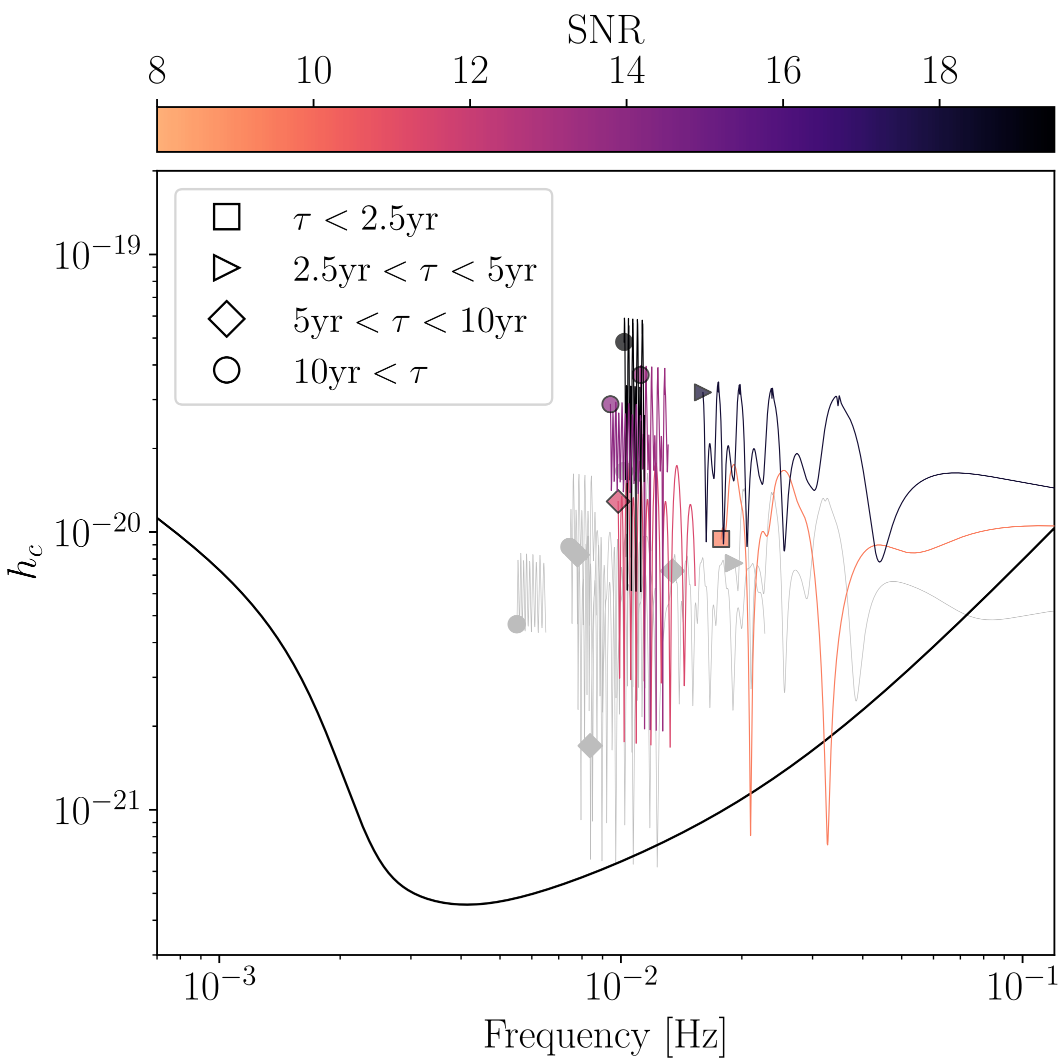


- Merging BHBs are observed regularly by Earth-based interferometers
- Earlier in the inspiral phase, they emit in the LISA band
- Most of them will be quasi-monochromatic sources during the mission duration

$$M_c = 25\,M_\odot \quad \tau = 10\,\mathrm{y} \longrightarrow f = 0.01\,\mathrm{Hz}, \quad \dot{f} = 10^{-11}\,\mathrm{Hz/sec}$$

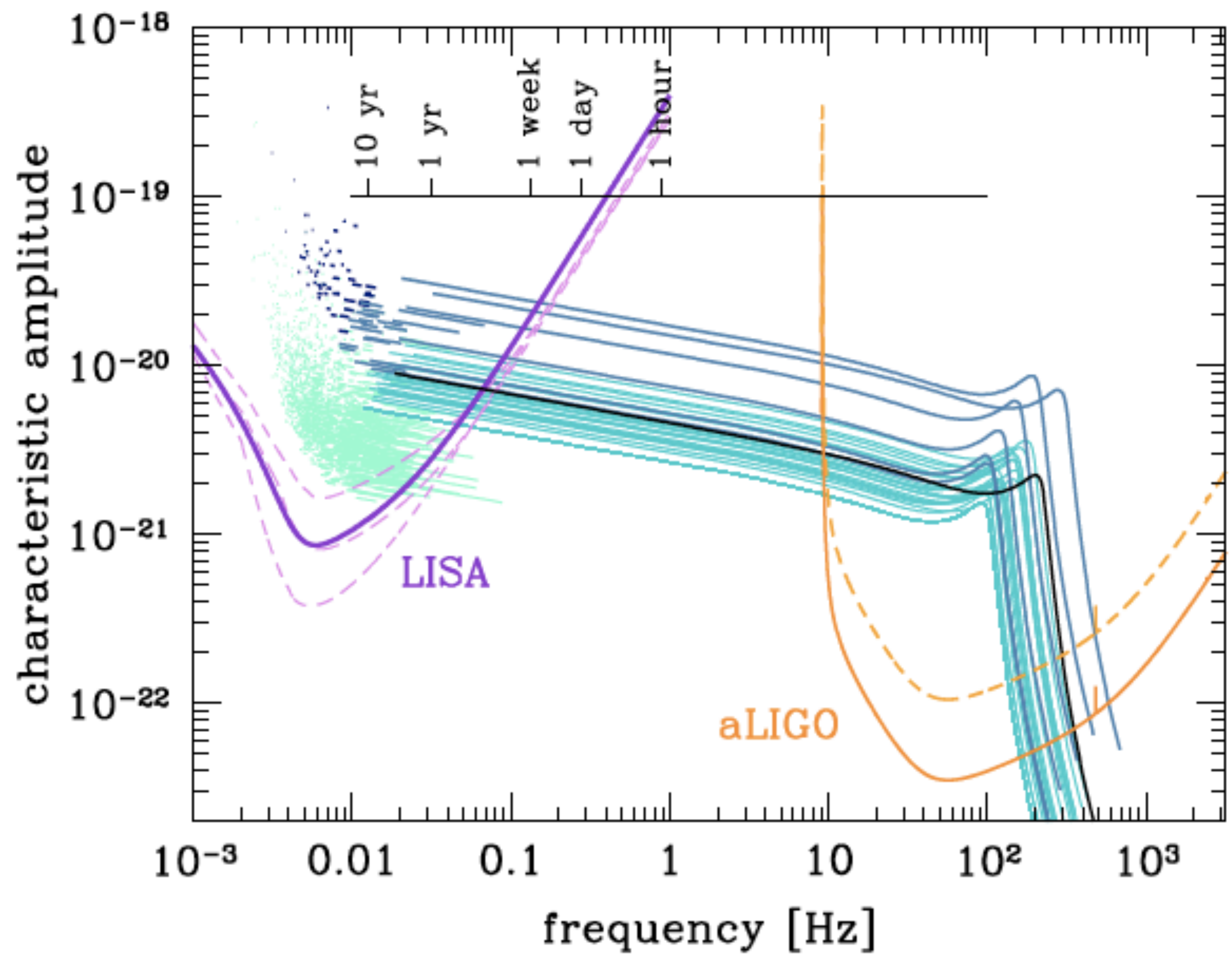
Black hole binaries of tents of solar masses

- Some of them will be caught late enough in the inspiral phase, and will evolve to merge in the Earth-based interferometer band within a reasonable number of years



Buscicchio et al arXiv:2106.05259

A Sesana arXiv:1702.04356



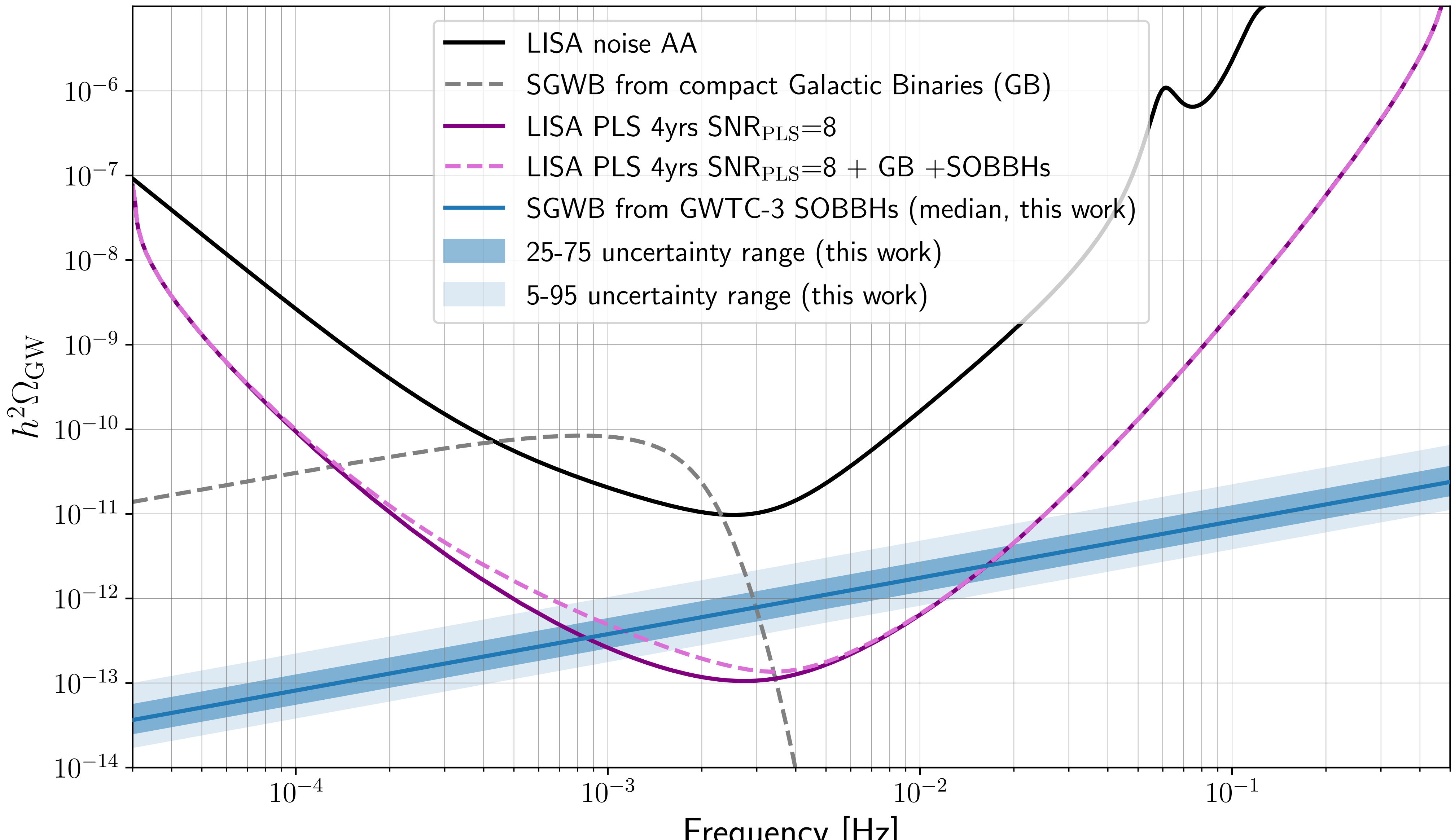
- The science that can be done with them depends on the **number of detectable sources**

Cosmology:

- ~~Dark sirens~~
- Tests of General Relativity
- **Stochastic foreground**

Black hole binaries of tents of solar masses

- The number of resolved sources can be estimated from **LVK population models**
- The rest (unresolved ones) generates a stochastic foreground
- On must estimate both at the same time via iterative subtraction
- Resolved: closer to merger and to us; foreground: distant and inspiralling
- Foreground depends on the high-z population characteristics (not probed by LVK)



S. Babak et al, arXiv:2304.06368

Lehoucq et al, arXiv:2306.09861

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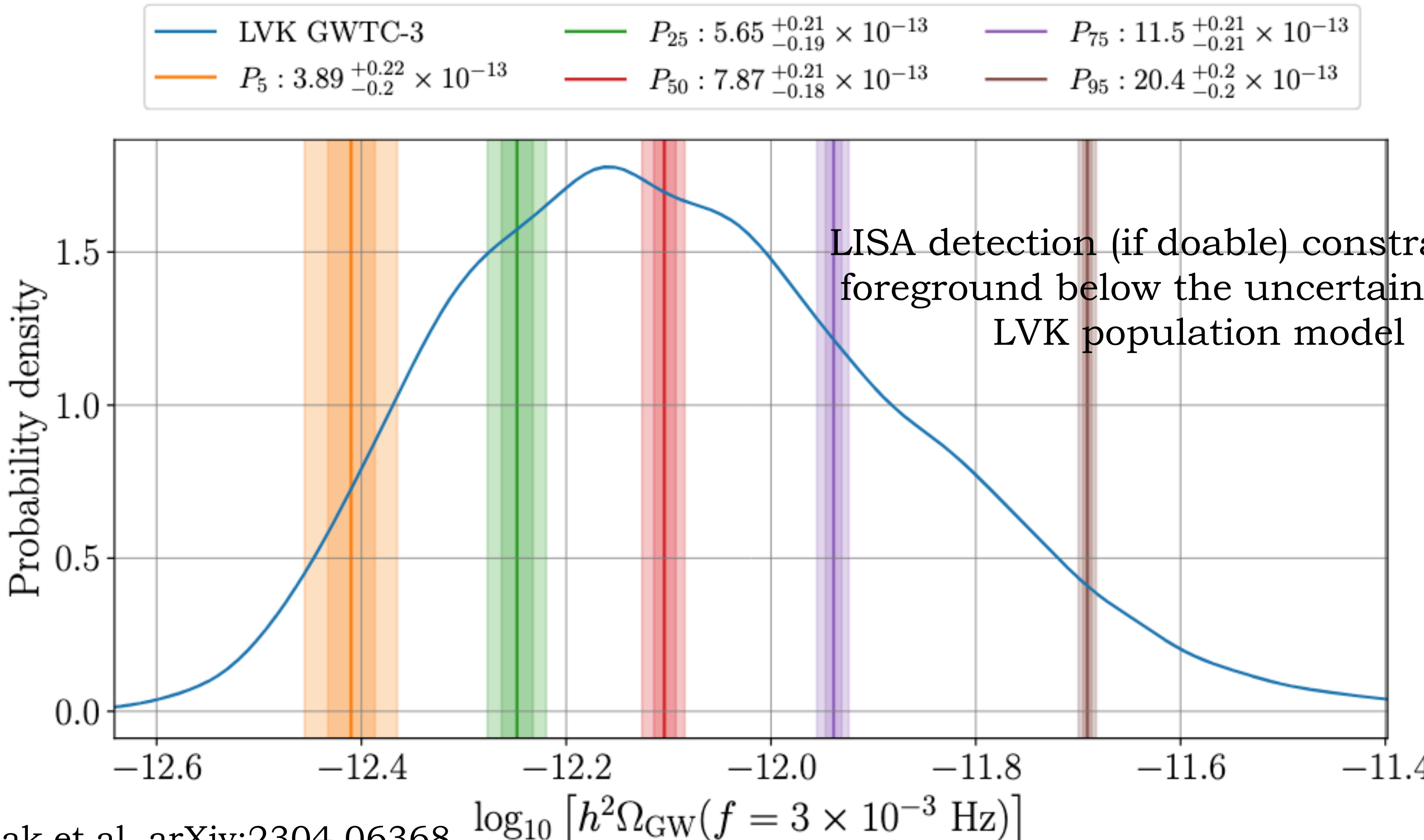

LISA detection (if doable) constrains the foreground below the uncertainty from LVK population model

S. Babak et al, arXiv:2304.06368

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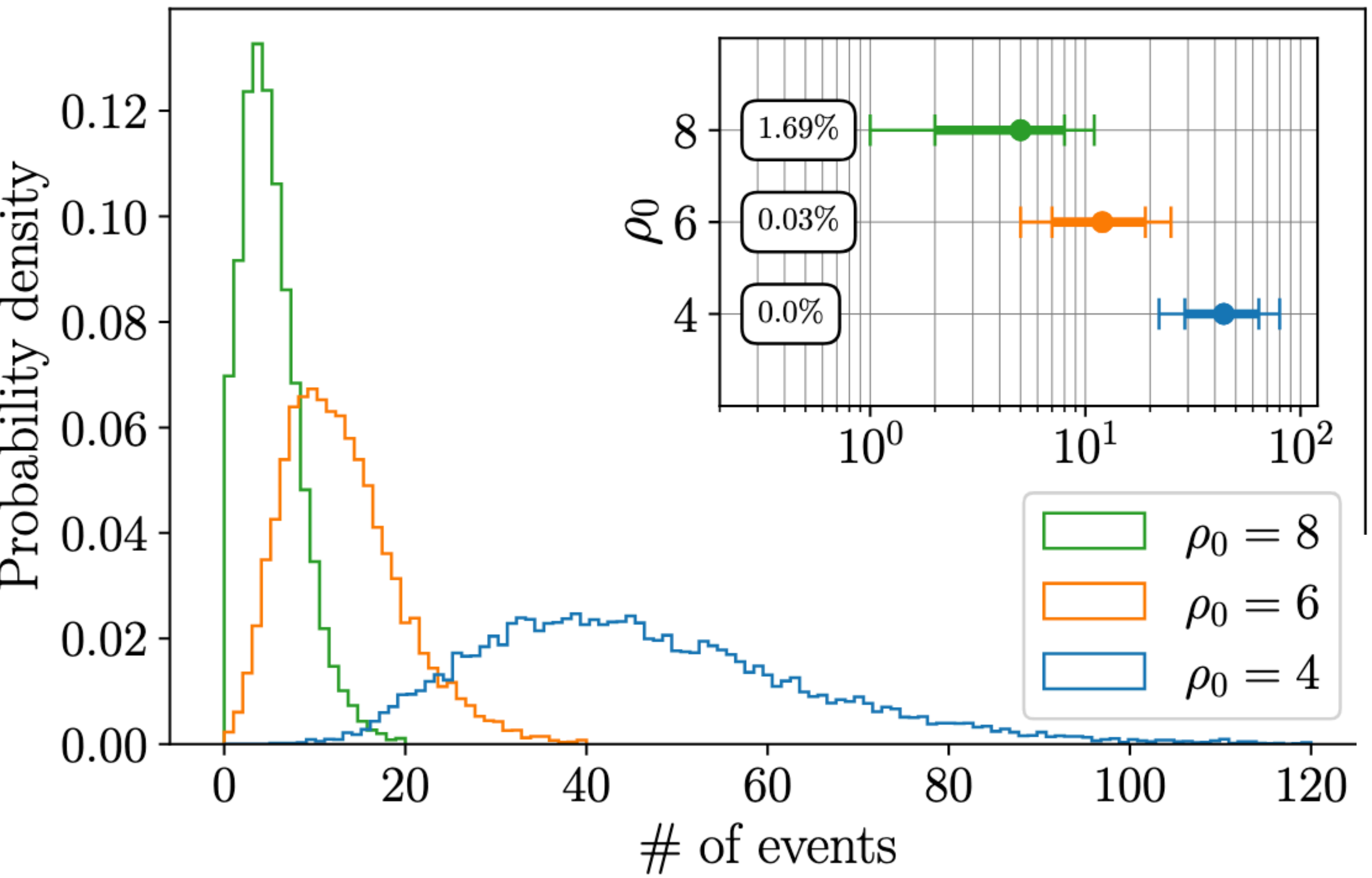
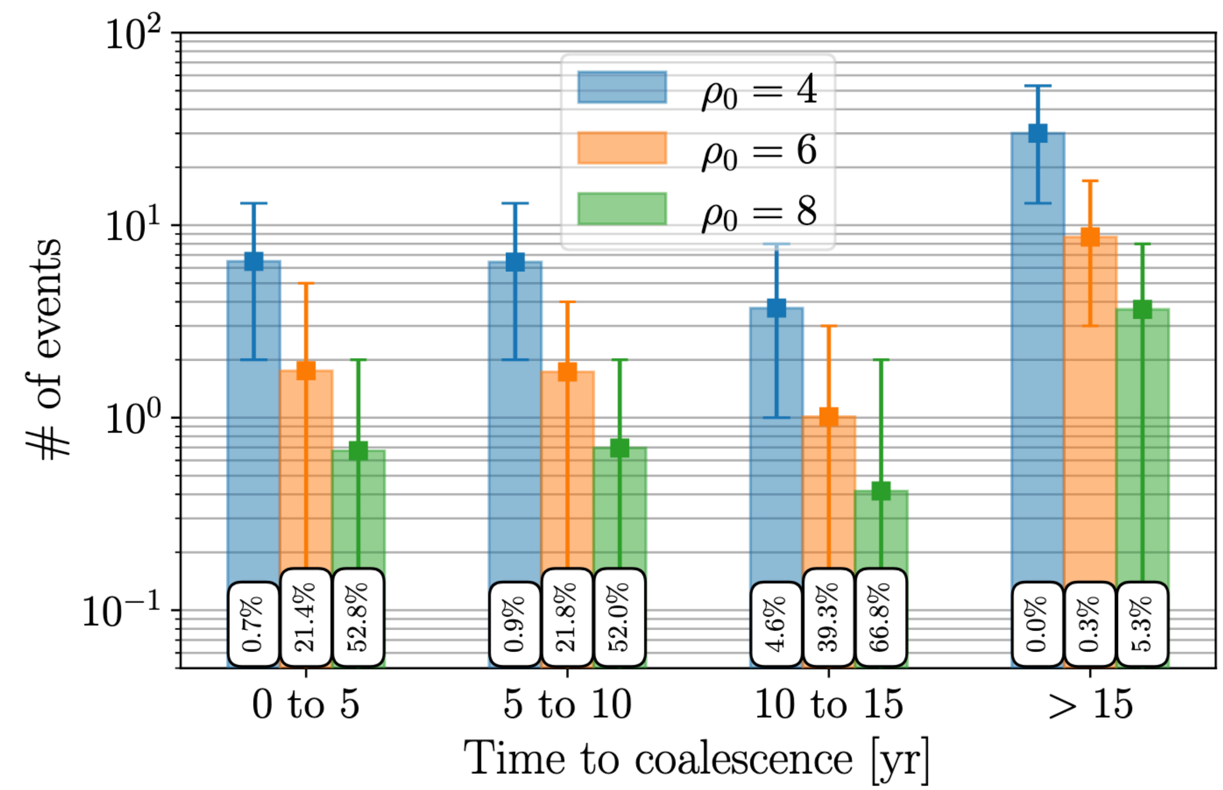
- Resolved: closer to merger and to us; foreground: distant and inspiralling
- Foreground depends on the high-z population characteristics (not probed by LVK)

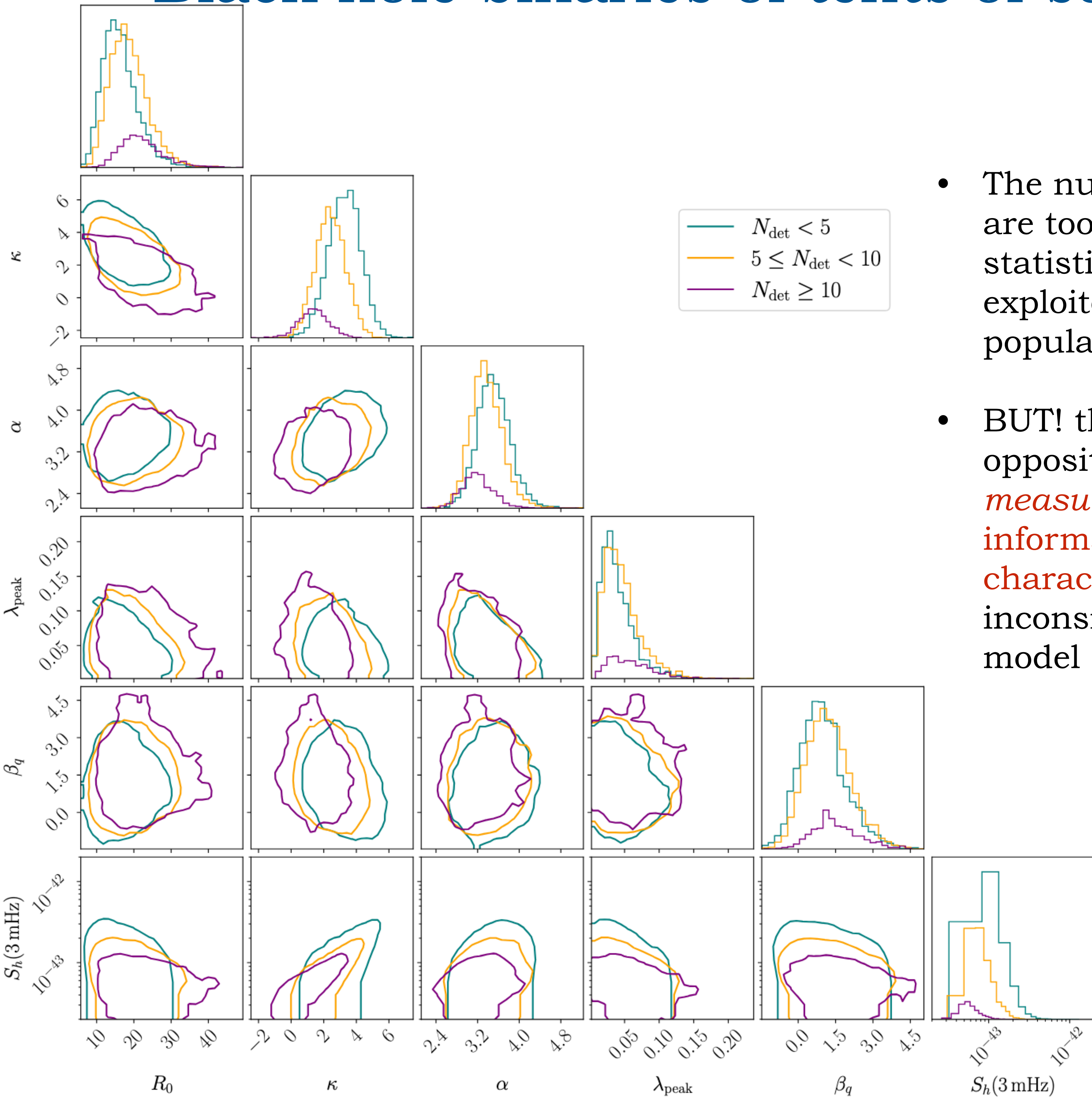


- $\mathrm{SNR_{thr}} = 8$: median 5 sources, 2% probability of no sources, 10% probability of more than 10 sources
- Multi-band sources $\tau_c \leq 15$ yrs: 1/3 of the total
- $\mathrm{SNR_{thr}} = 8$: 2^{+3}_{-2} sources but 79% of the catalogues contain at least one multi-band source



S. Buscicchio et al, arXiv:2410.18171
(See also Ruiz-Rocha et al, arXiv:2407.21161, from simulations)

Black hole binaries of tents of solar masses



- The numbers of resolved sources are too small and dominated by statistical fluctuations to be exploited to constrain the population
- BUT! the foreground has the opposite correlations, so *both measurements* can provide some information on the population characteristics, for example point to inconsistencies in the population model

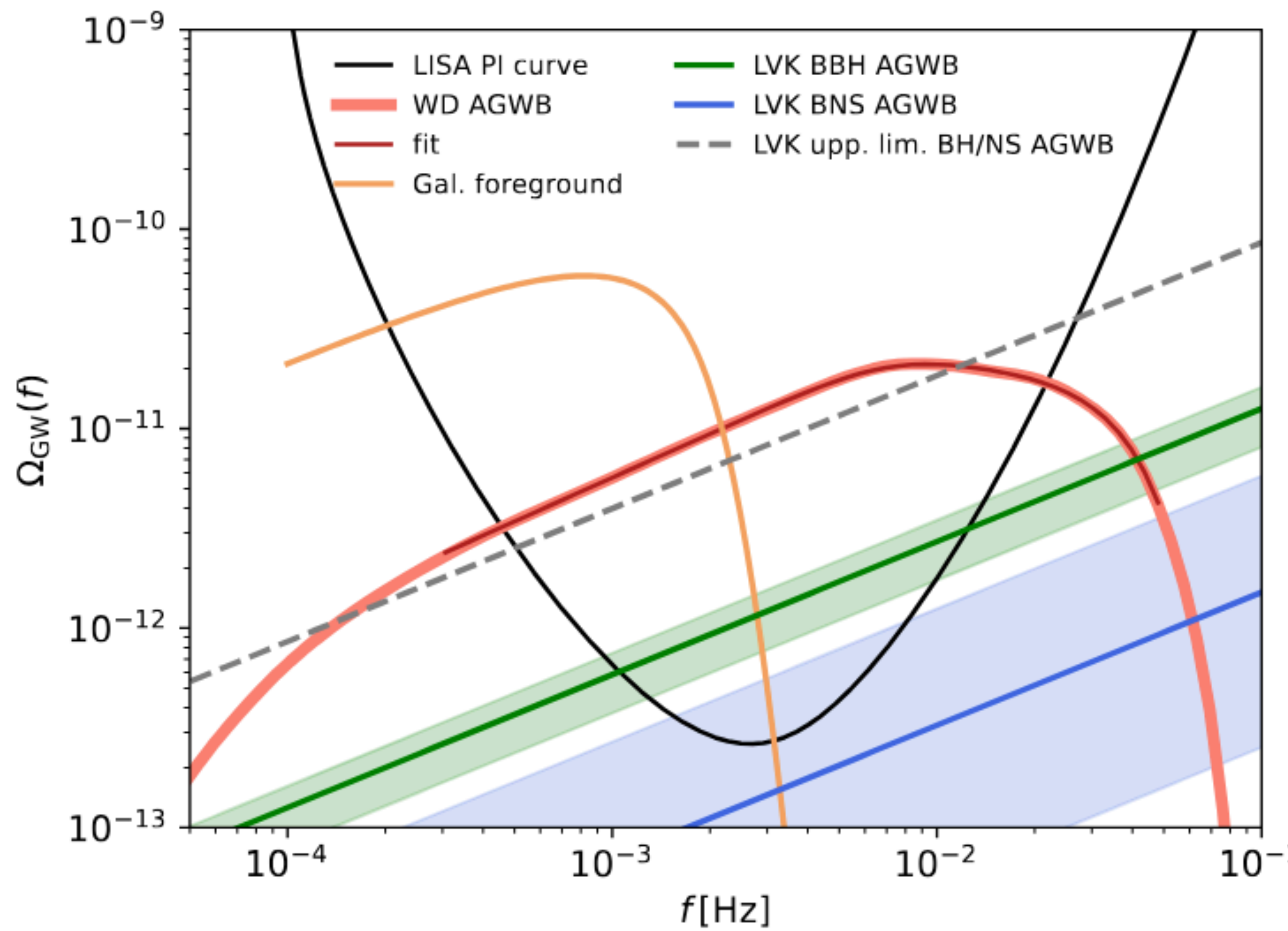
Black hole binaries of tents of solar masses

- **Higher foreground from extra-galactic white dwarf binaries!**

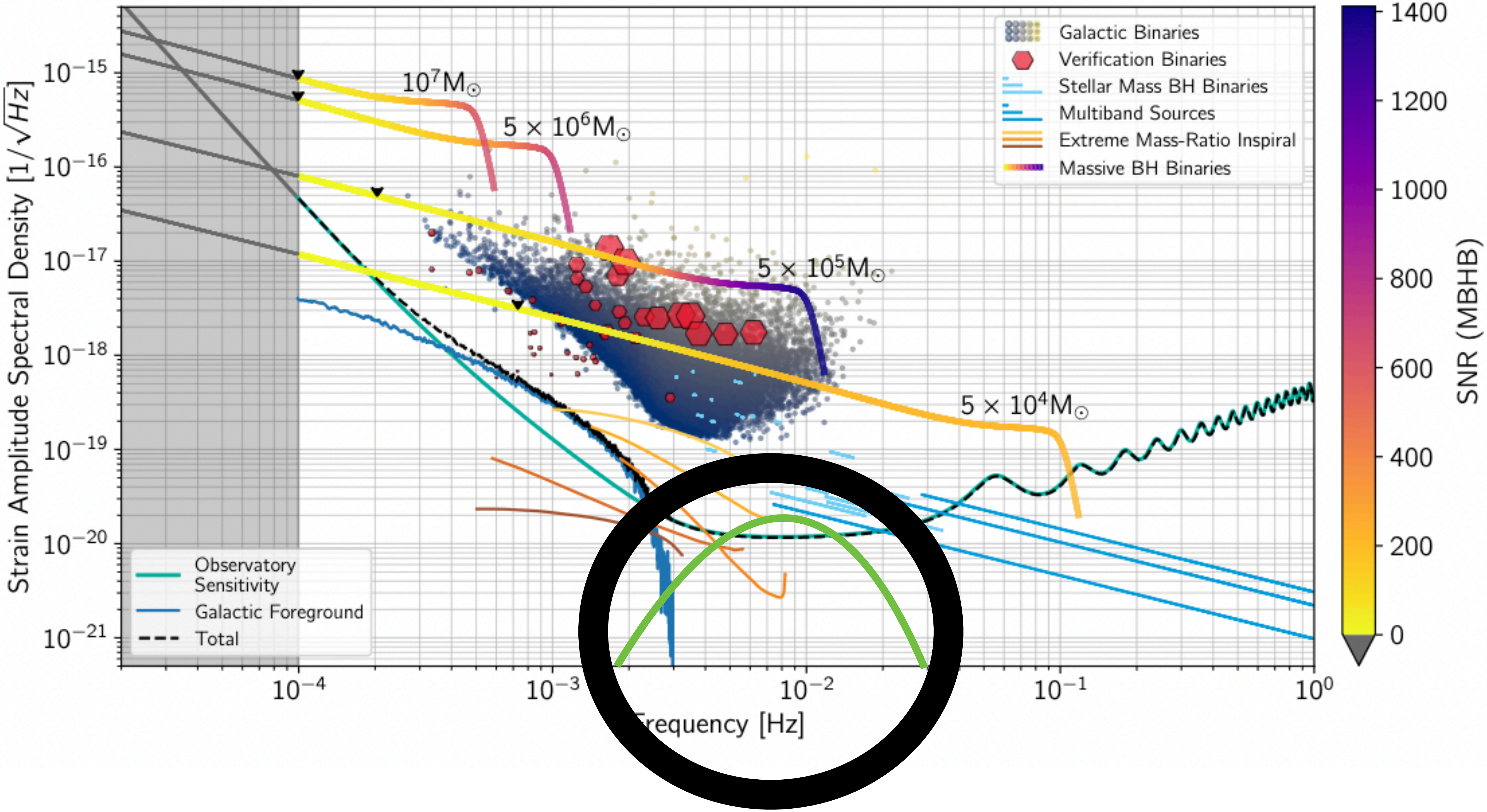
$$\Omega_{\rm WD}(3\,{\rm mHz}) \simeq 1.3 \cdot 10^{-11}$$

Staelens & Nelemans, arXiv:2310.19448
Hofman & Nelemans, arXiv:2407.10642

60% higher than previous estimates
Factor of 10 more than P_{95}



The stochastic GW background from the early universe



The stochastic GW background from the early universe

- GW emission processes in the very early universe form a **fossil radiation**, whose detection would bring direct information from very early stages of the universe evolution, to which we have no access through em radiation

- **amazing discovery potential, linked to high energy physics**

- SGWBs offer the *opportunity to test beyond standard model physics* complementary to particle colliders, clarify open problems such as the nature of Dark Matter, matter-antimatter asymmetry, GUT scale reunification, nature and characteristics of Inflation…

- Because SGWB sources are based on theories so far lacking experimental confirmation, *it is impossible to make definite predictions on the signal amplitude and spectral shape,* contrary to the case of astrophysical foregrounds

- The outstanding challenge is *how to distinguish them from the instrument noise and astrophysical foregrounds* (null channels, statistical properties of the signal…)

The stochastic GW background from the early universe

Examples of possible sources of detectable signals in the LISA band

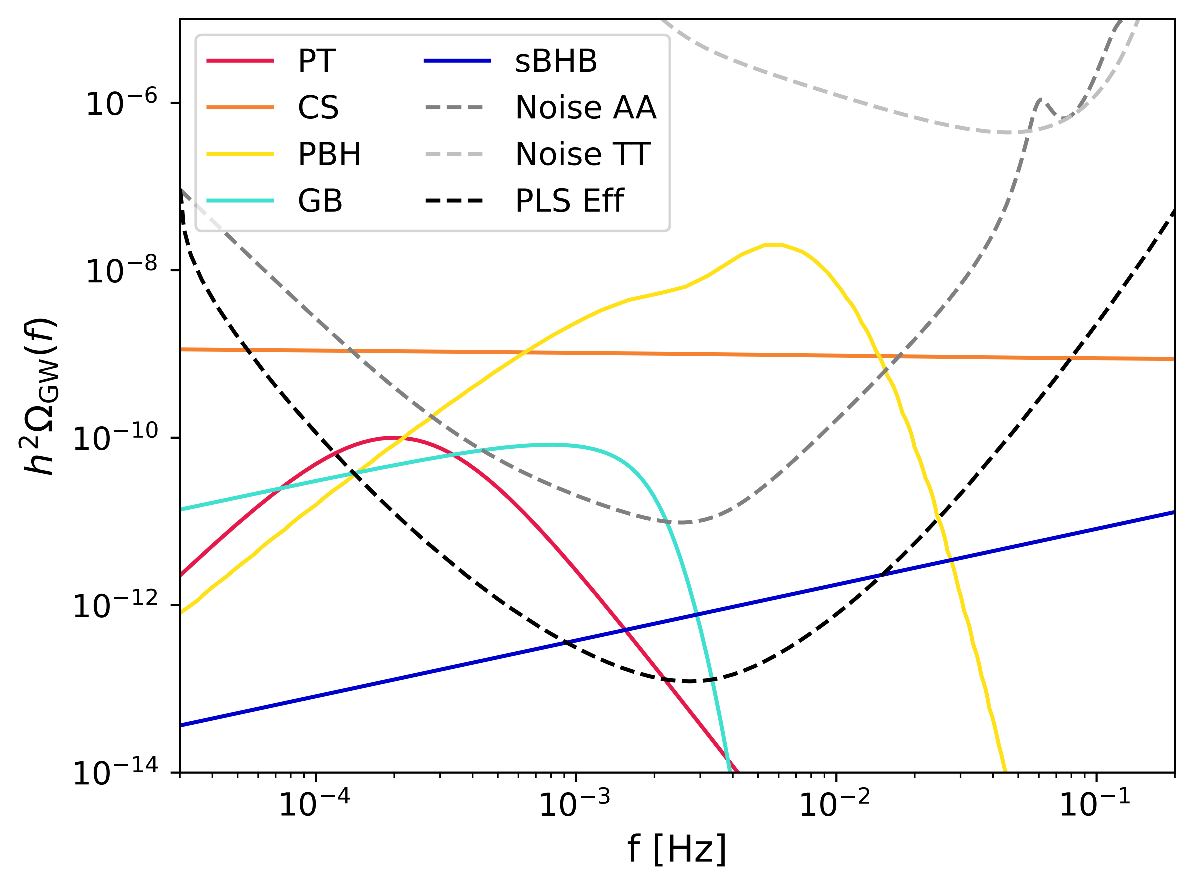
LISA CosWG, arXiv:2407.04356

- *Inflation*:
  - quantum tensor fluctuations at second order — LISA CosWG, arXiv:2501.11320
  - tensor modes from additional fields (scalar, gauge…) — LISA CosWG, arXiv:2310.19857
  - (p)reheating
  - modifications of gravity during inflation

LISA CosWG, arXiv:2405.03740

- *Other phase transitions*:
  - stable topological defects (in particular cosmic strings)
  - bubble wall collisions from a first order phase transition — LISA CosWG, arXiv:2403.03723
  - bulk fluid motion (compressional and vortical)
  - magnetic fields

LISA Red Book arXiv:2402.07571

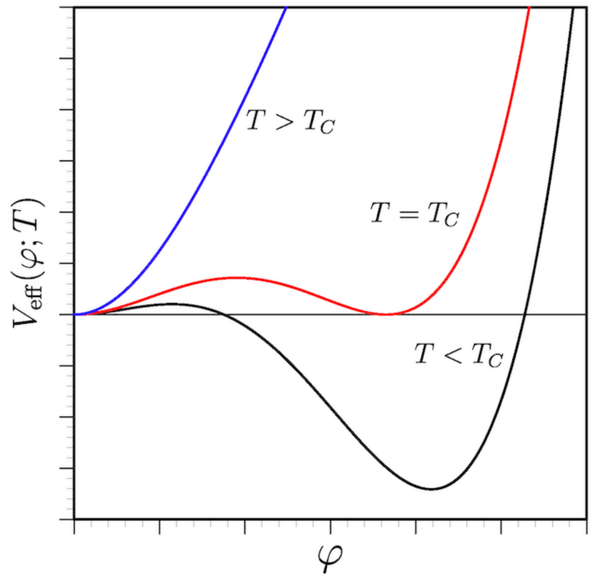


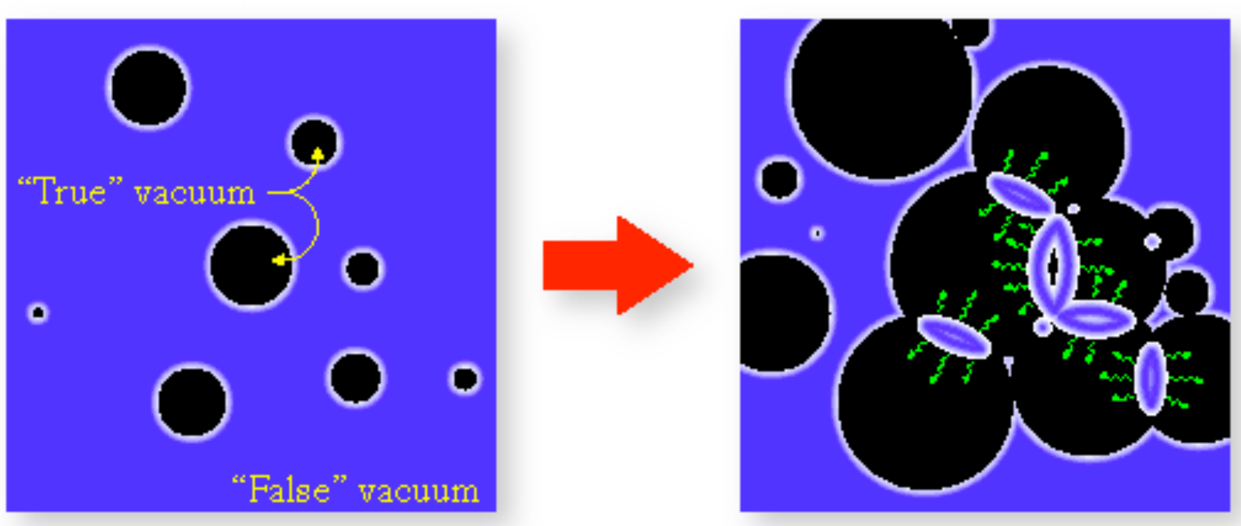
A great variety of spectral shapes depending on the source:

- Can we infer the source parameters provided we know the signal and noise spectral shape?
- Can we infer the spectral shape to reconstruct the signal origin, provided we know the noise spectral shape?
- What can we do if we don't know the noise?

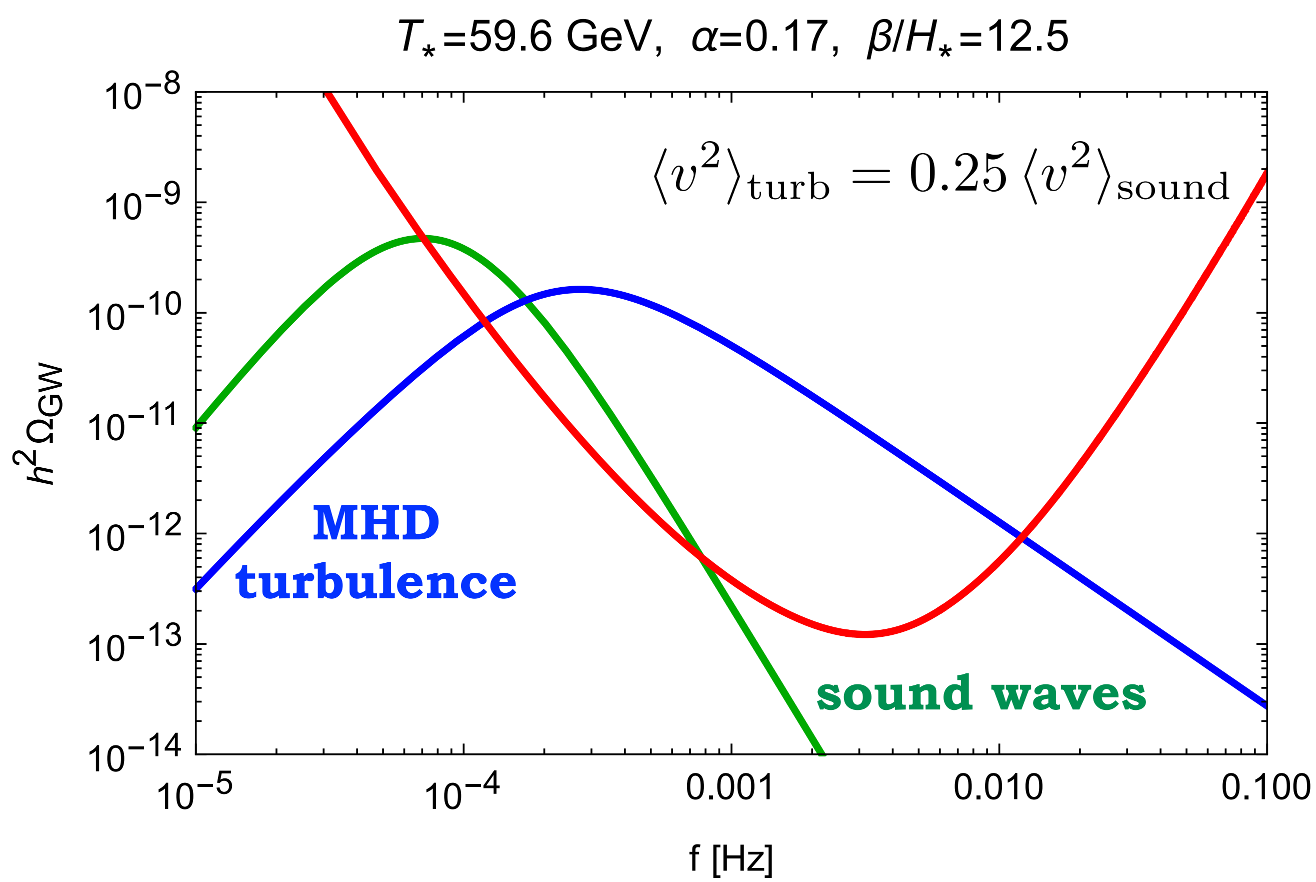
The stochastic GW background

- Strong scientific case for LISA: the **Electroweak Phase Transition ~ 100 GeV**
- Frontier between tested physics and new physics
- Can be first order in scenarios Beyond the Standard Model of particle physics
- Connections with baryon asymmetry, dark matter…
- In some BSM scenarios joint detection of the same model at LISA and HL-LHC/FCC possible
- Definite prediction of the SGWB signal not yet available: complicated non-linear problem, requiring numerical simulations

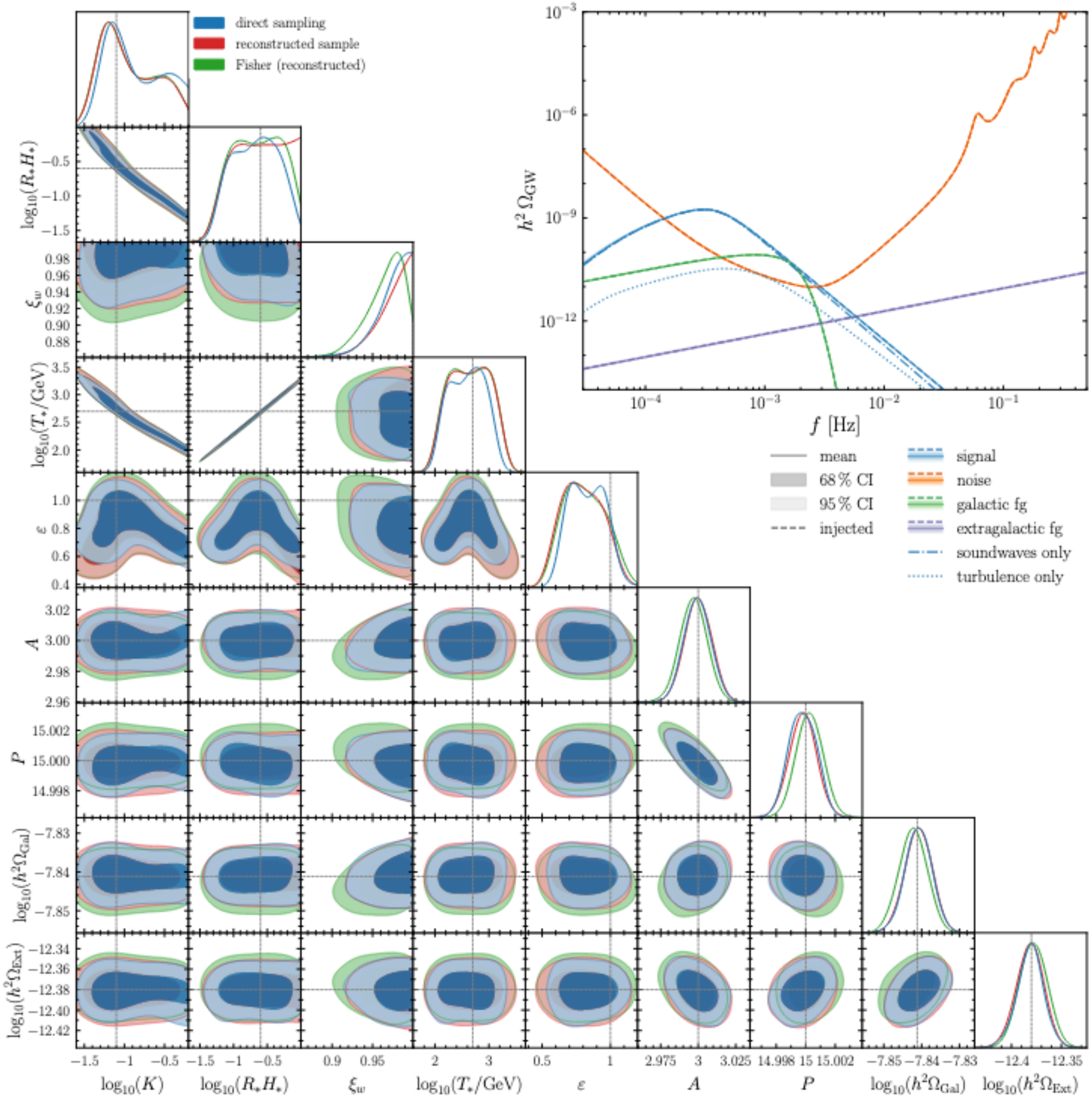




One example of GW signal from the EWPT: singlet extension of SM



The stochastic GW background



Template-based reconstruction of the *thermodynamic parameters of the first order PT* determining the SGWB signal

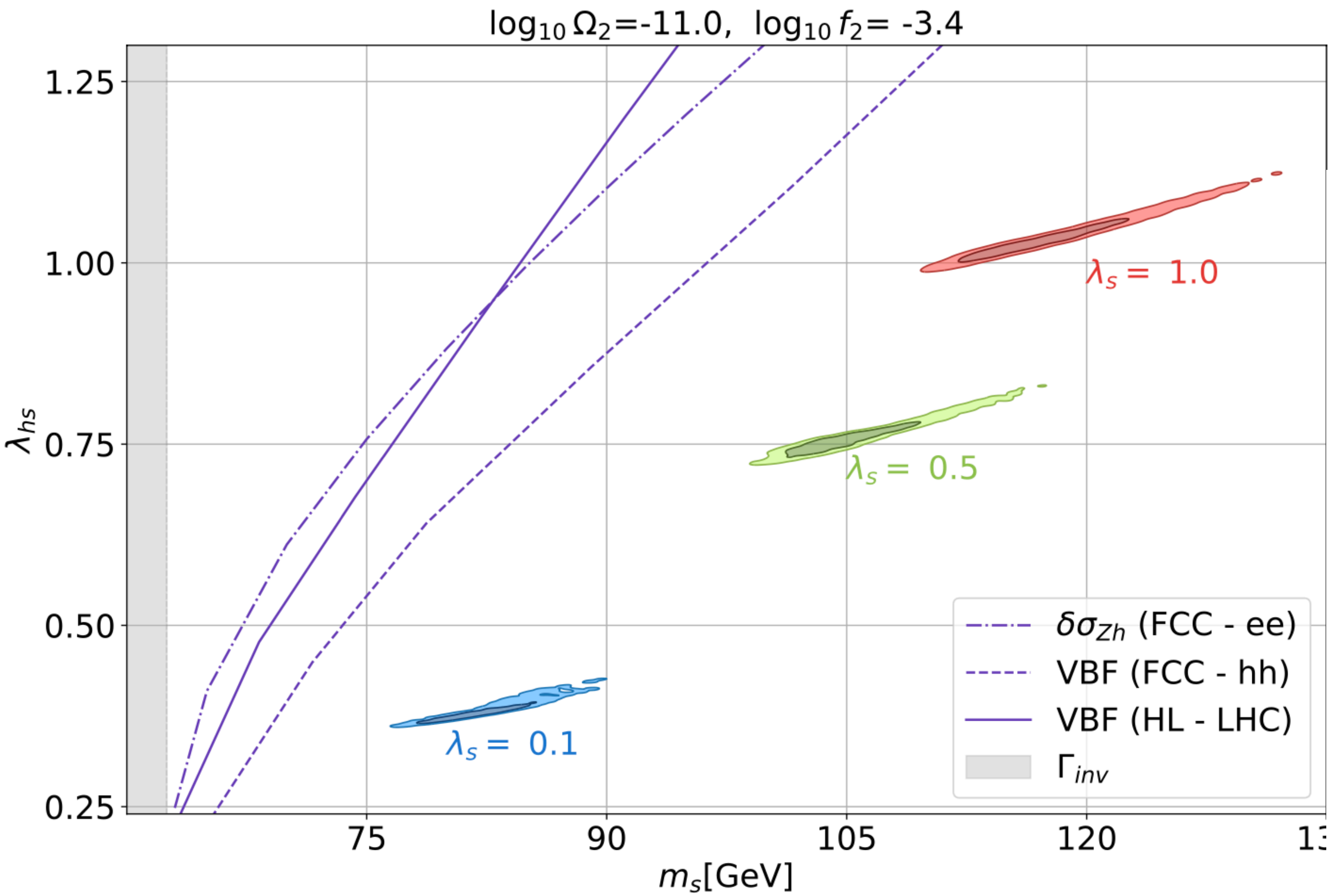
accounting for foregrounds and **assuming a two-parameters noise model**

LISA CosWG, arXiv:2403.03723

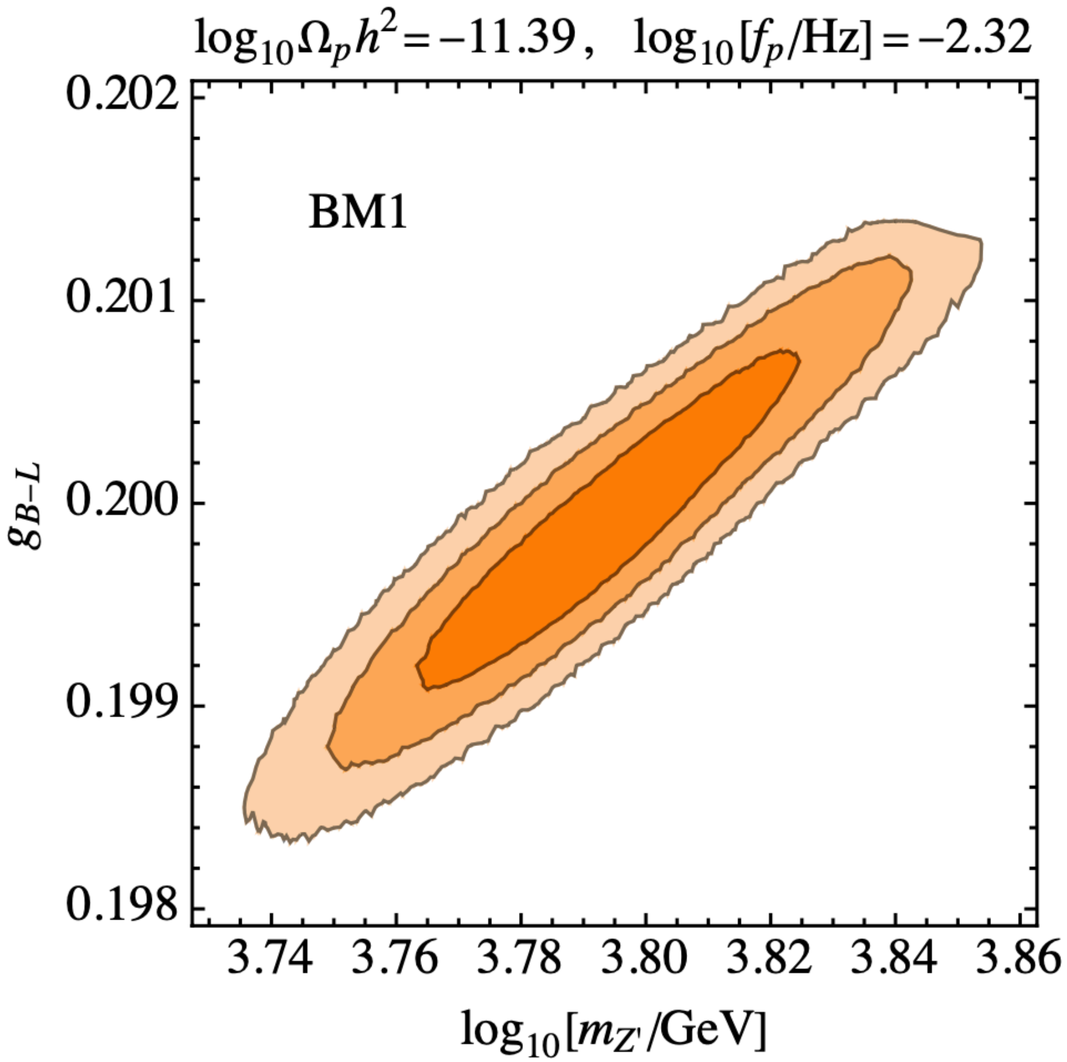
The stochastic GW background

Once the parameters of the first order PT are reconstructed from the SGWB measurement, they can be **mapped to those of the particle physics model** underlying the PT, synergizing with current and future particle physics experiments

Z_2 singlet extension of the Standard Model



U(1)$_{B\text{-}L}$ extension of the Standard Model



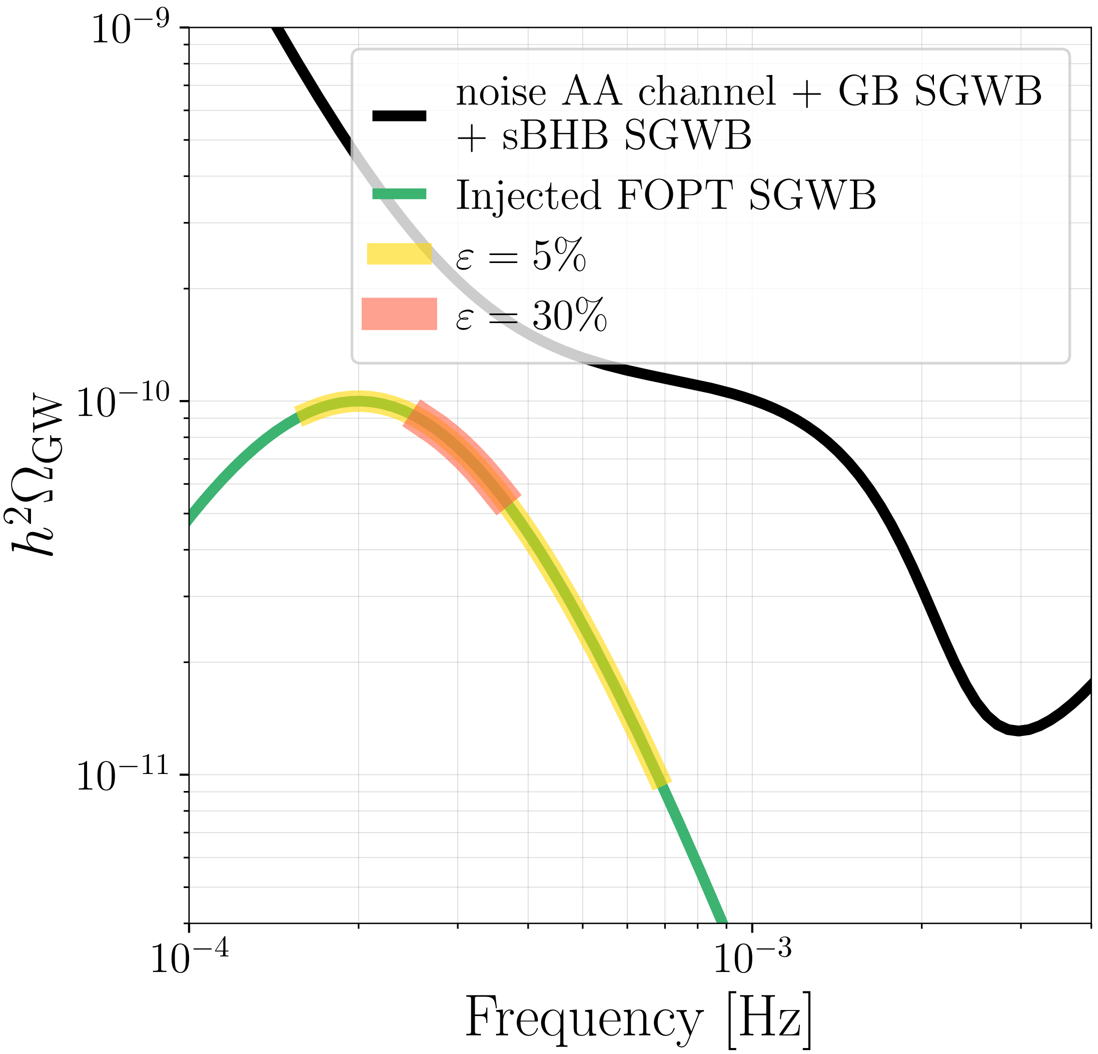
LISA CosWG, arXiv:2403.03723

The stochastic GW background

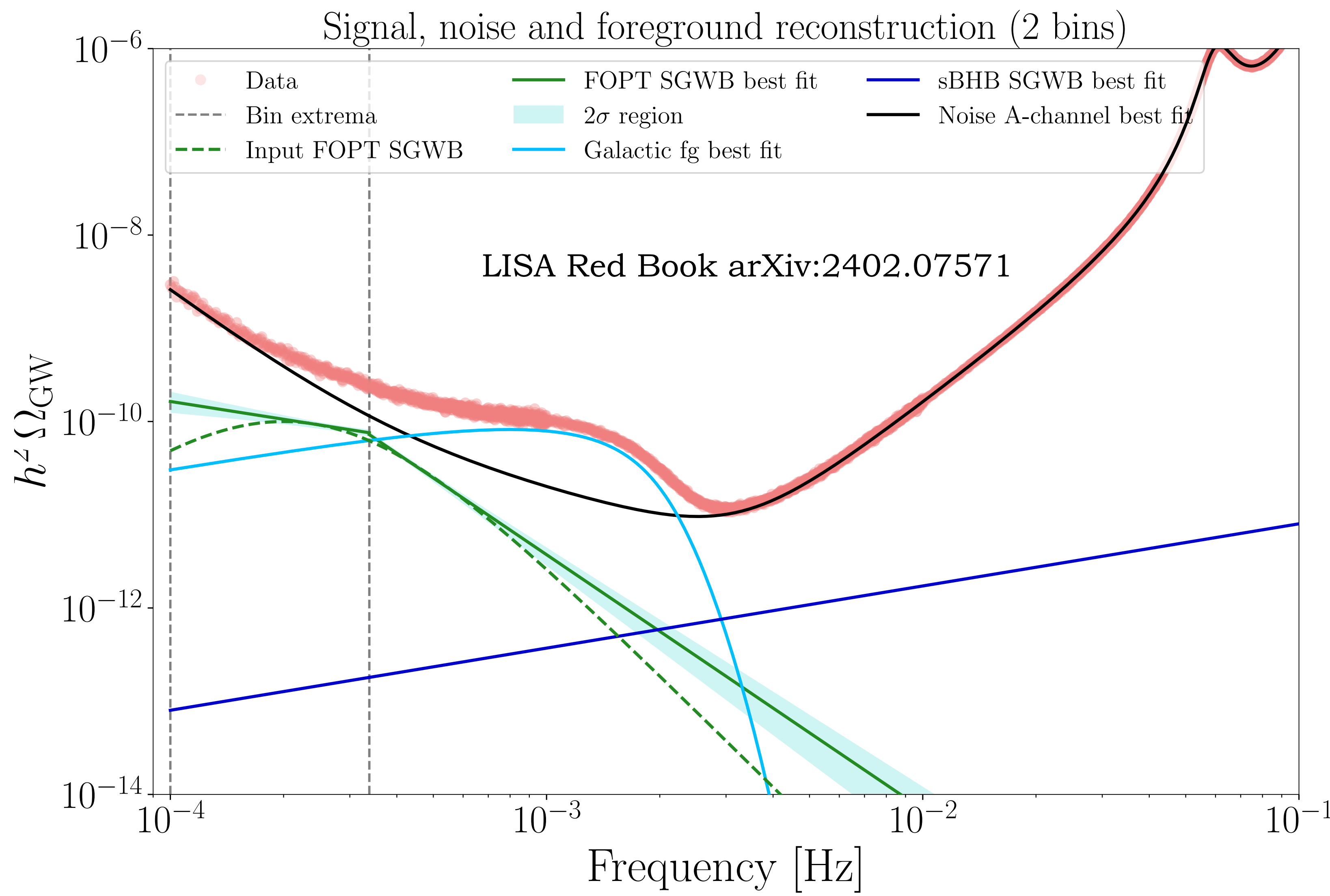
Is it possible to reconstruct the GW signal spectral shape, to identify the SGWB source, provided we know the noise spectral shape?

Signal from the singlet extension of SM setting $\quad m_s = 0.94\,\mathrm{GeV},\ \lambda_s = 1,\ \lambda_{hs} = 0.92$

N. Karnesis, arXiv:1906.09027



CC et al, arXiv:1906.09244, Flauger et al arXiv:2009.11845

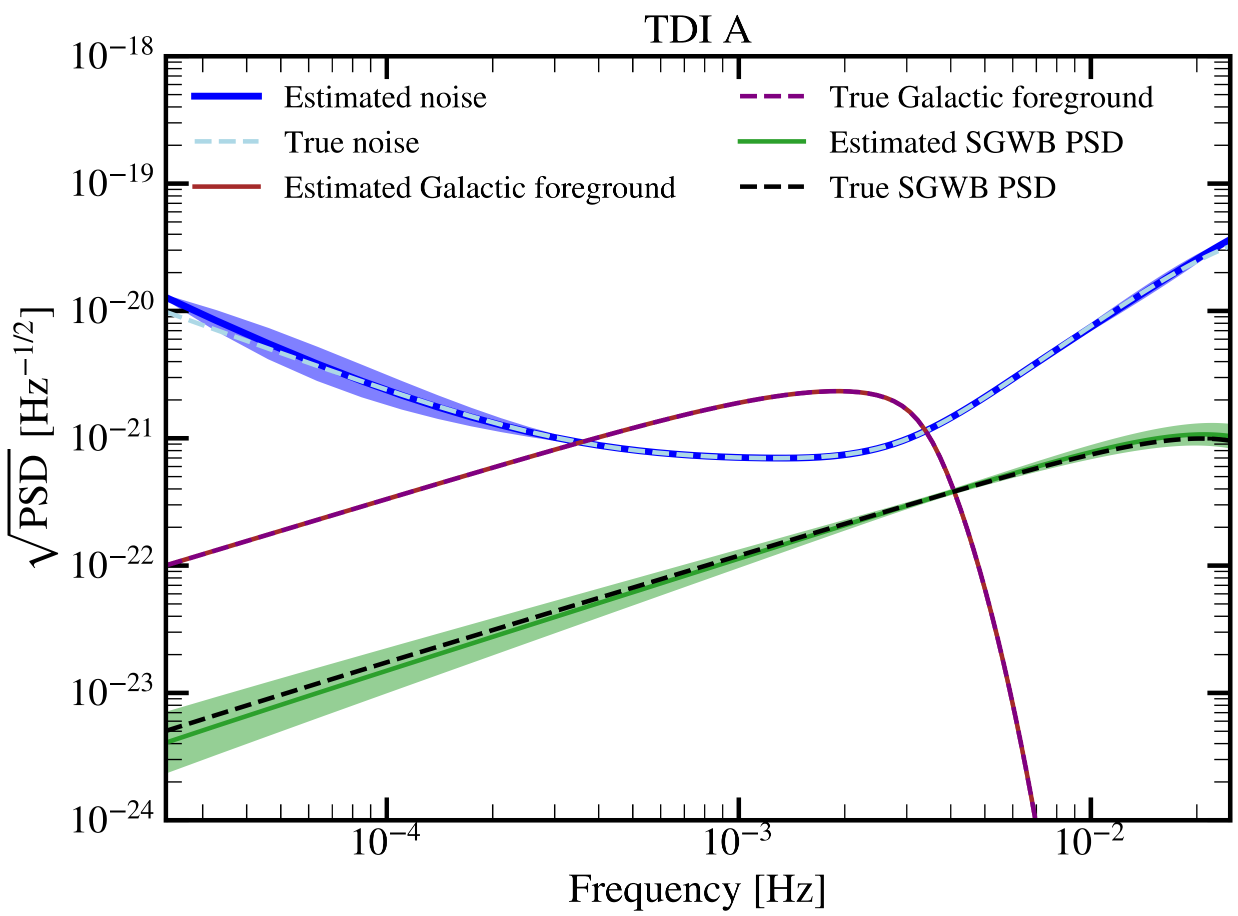


The stochastic GW background

What can we do if we don't know the noise?
Detect only known signals… astrophysical foregrounds!

- LISA detection of the foreground from *stellar mass back hole binaries*
- No assumptions on the *noise spectral shape: modelled as a spline, function of frequency*, with 6 nodes
- Include the presence of *galactic foreground*
- *Power law template* for the sBHBs SGWB: justified in this case!
- MCMC over 14 parameters

SI 7.1			
$\frac{\Delta A_{GB}}{A_{GB}}$	$\frac{\Delta A_{sBHB}}{A_{sBHB}}$	$\frac{\Delta \log f_n}{\log f_n}$	$\frac{\Delta \log A_n}{\log A_n}$
1.2 %	20 %	11 %	2 %



LISA Red Book arXiv:2402.07571
Baghi et al, 2302.12573

See also
Muratore et al, arXiv:2308.01056
Pozzoli et al, 2311.12111…

Conclusions

- For not having been designed to do cosmology, LISA performs pretty well!

Constraining late universe expansion with sirens

- Not directly competitive with standard cosmological surveys (SNIa, BAO, CMB…) at least for the nominal mission duration of about 4 years
- However, the measurement of luminosity distance is direct and independent on EM emission (different systematics)
- Potential of constraining the universe at high redshift:
  - Assuming matter only, at redshift $z=5$, 10% error on Hubble parameter and 2% on luminosity distance in 75% of the realisations
  - Assuming a model independent spline interpolation, at redshift $z<3$, 10% error on Hubble parameter and 5% on luminosity distance in 50% of the realisations
- Two categories of sources (MBHBs, EMRIs) at different redshift: possibility of combining the measurement and improve the constraints
- In the future: maybe exploit features in the mass distribution of the sources, if known?

Conclusions

- For not having been designed to do cosmology, LISA performs pretty well!

Constraining early universe and high energy physics with SGWBs

- SGWBs from the primordial universe might seem speculative but their potential to probe fundamental physics is great and amazing discoveries can be around the corner

- Physics beyond the SM: many proposals of signals, interesting constraining power

- LISA has especially three very motivated science cases (in my opinion):
    - SGWB at the EW scale, complementary to particle colliders
    - SGWB from II order perturbations when PBH can be the totality of DM
    - SGBW from cosmic strings in coincidence with PTA

- Concerning inflation, direct SGWB detection can be useful to probe another range of scales (and of the inflationary potential), much smaller than CMB

- The detection is **very** challenging!
  In general, one must control:

- Prediction/detection of spectral shapes -> the only handle to identify the SGWB origin
- Foreground from astrophysical sources -> many, high, and dependent on population uncertainties
- Decent understanding of the instrument noise -> probably absent in LISA
- Residuals from the global fit of LISA sources -> yet unknown!