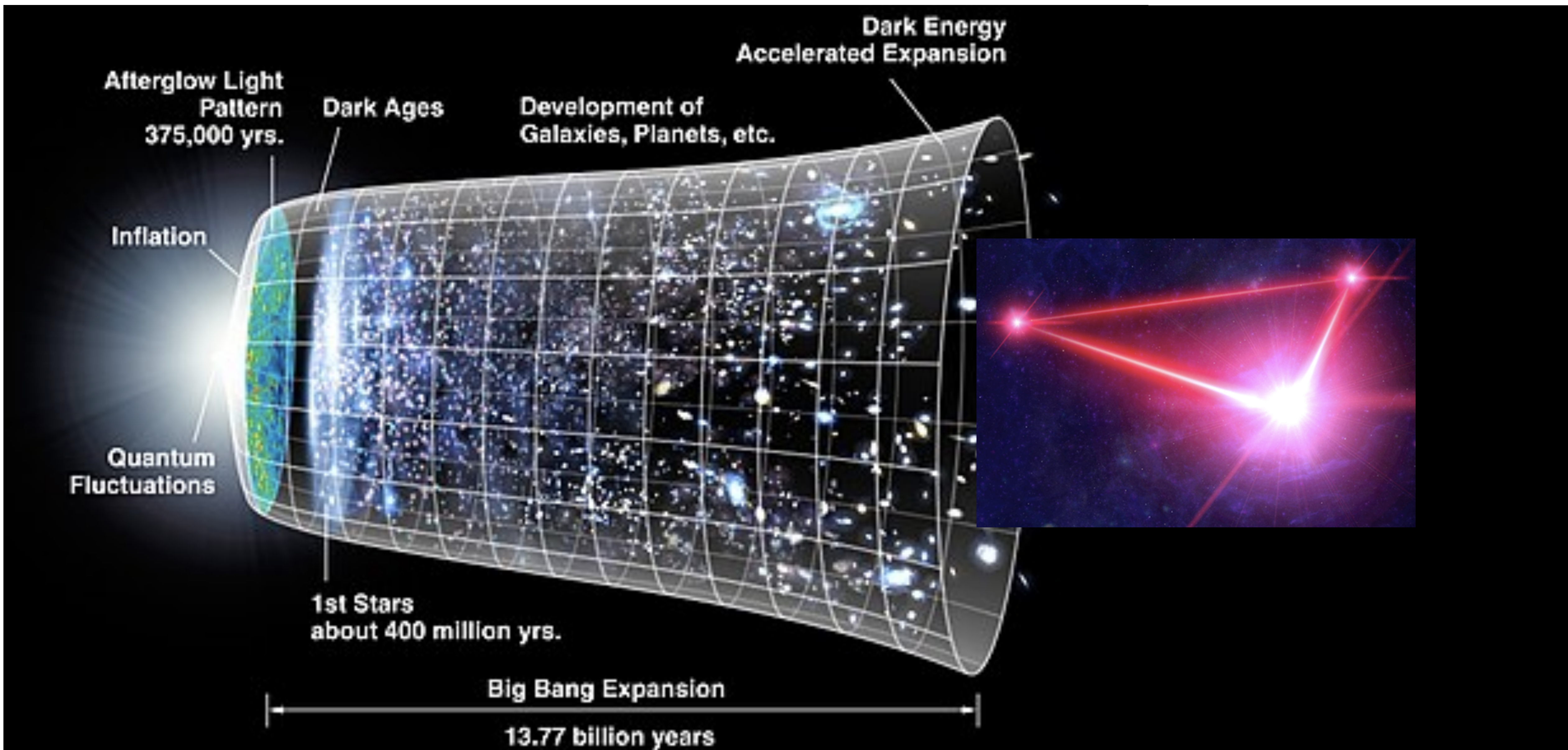
Cosmology with LISA and related Figures of Merit

Chiara Caprini
CERN & University of Geneva



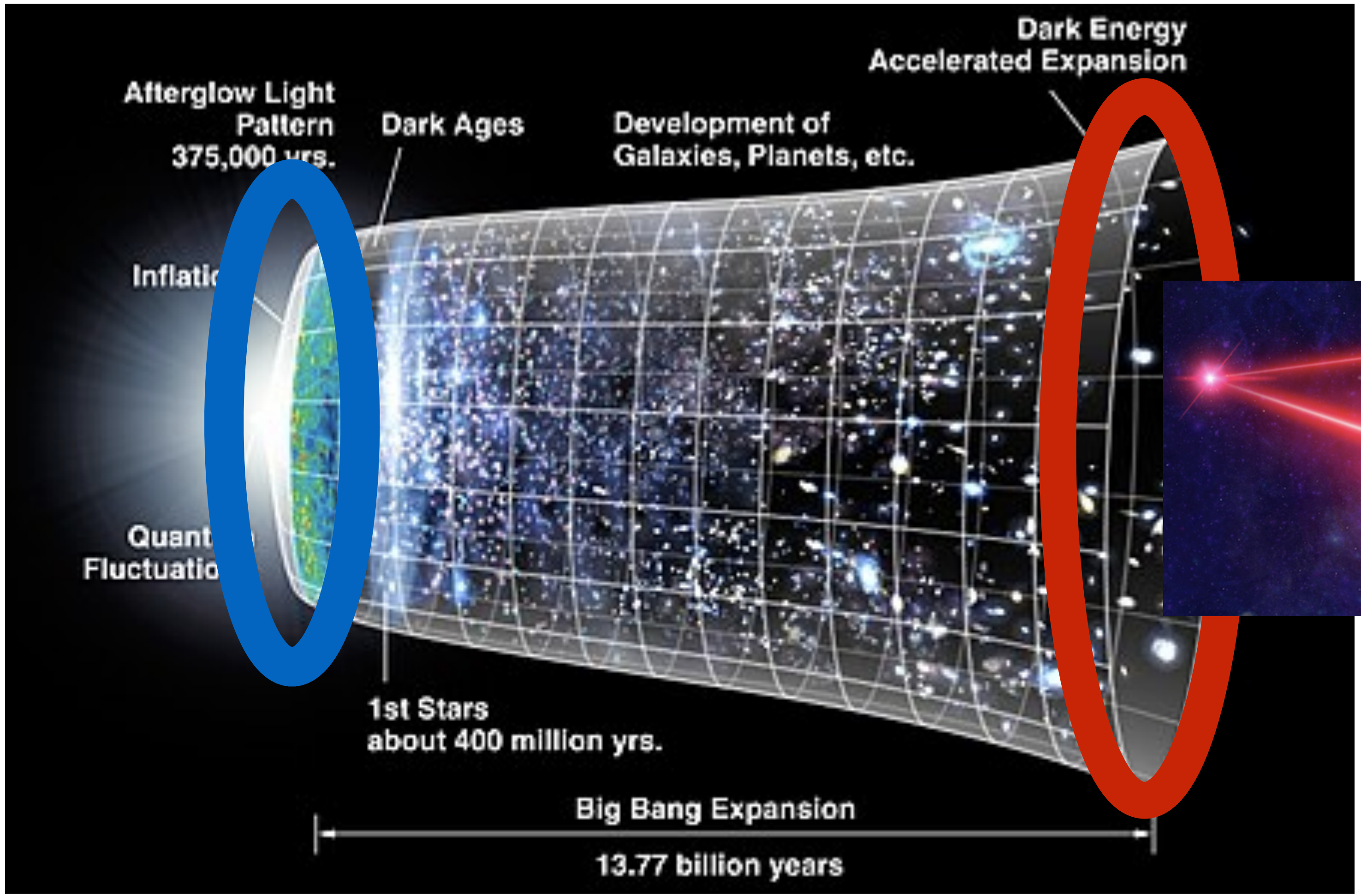
Summary

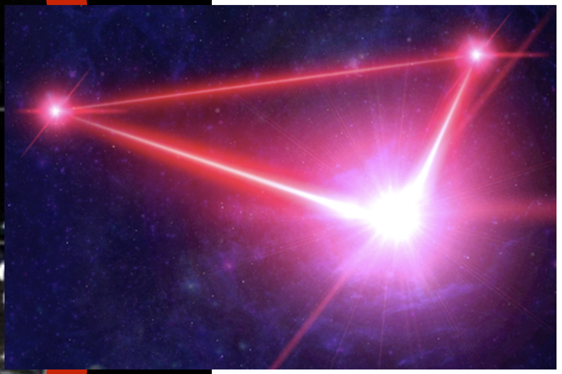
- LISA has been initially conceived as a GW Astrophysics observatory, it has not been designed to do Cosmology

- However, it can provide information on a variety of scales: from Galactic 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 *very early universe* through the detection of stochastic GW backgrounds and therefore, indirectly, test high energy physics phenomena

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

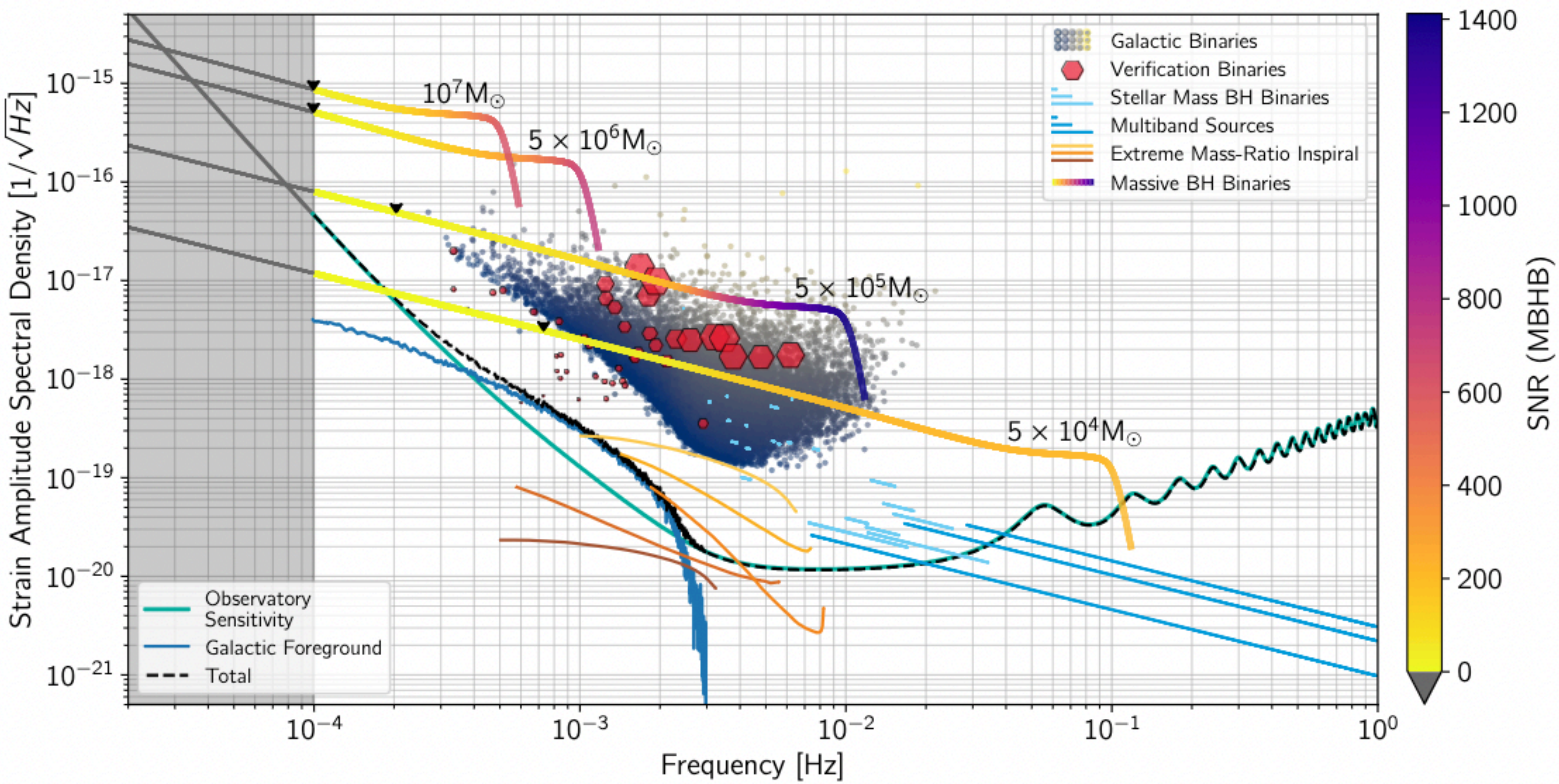




The rest of the talk: proceed source-type by source-type highlighting their use for **Cosmology**

- 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 other sources

LISA Red Book arXiv:2402.07571



The rest of the talk: proceed source-type by source-type highlighting their use for **Cosmology**

+

Present the **LISA Figures of Merit** for the cosmology-related Science Objectives

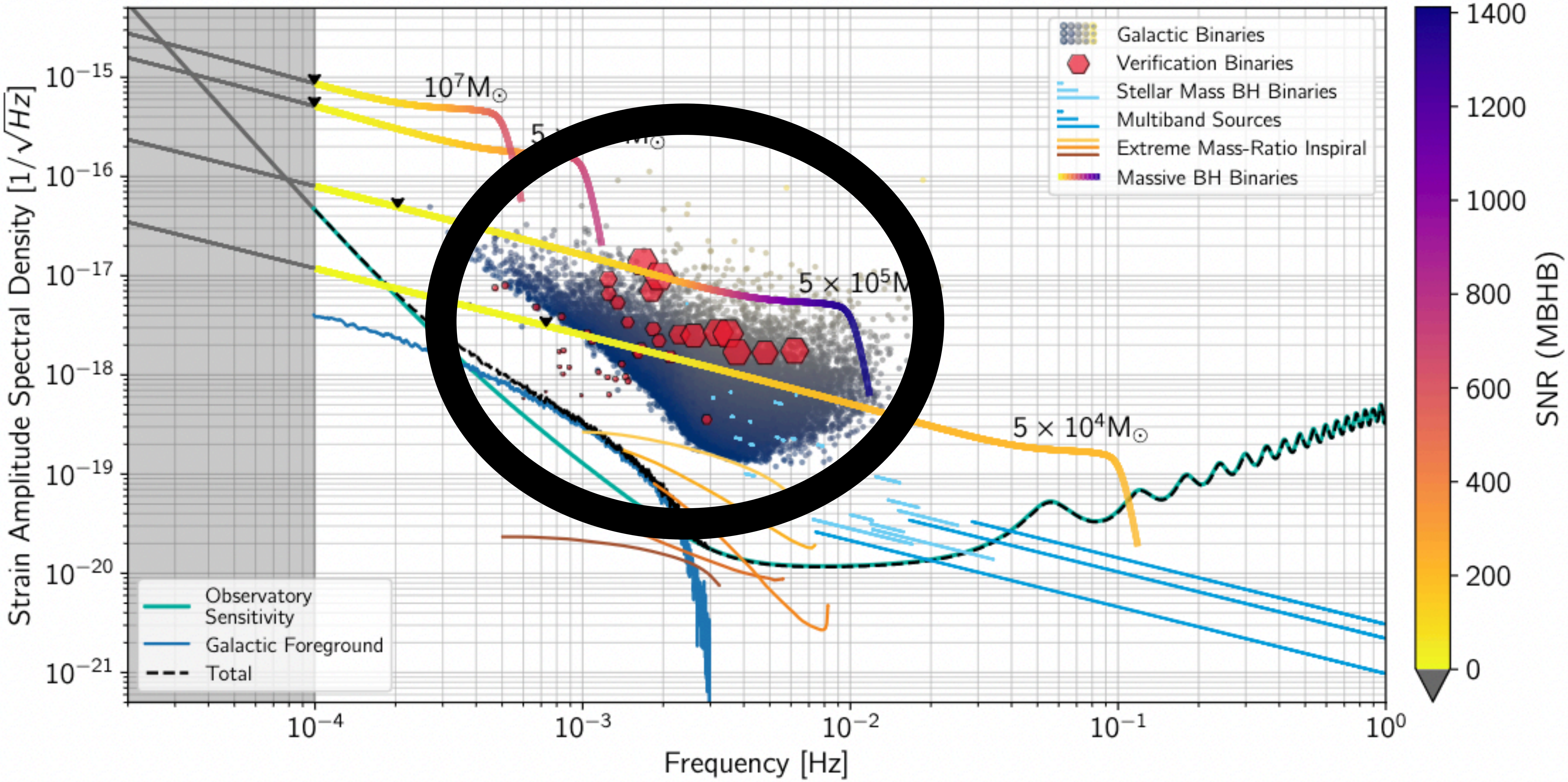
The LISA community (old Science Investigation Work Package + scientists in the Consortium) had developed a set of Figures of Merit to assess LISA ability to achieve its science objectives

FoMs are tools designed to evaluate the impact of changes in sensitivity on the scientific performance of the LISA detector

The LISA Science Team is reviewing and selecting them as part of its work

A paper, hopefully complemented with pipelines, will come out soon:
S. Babak et al, in preparation
coordinated by R. Buscicchio and A. Mangiagli

Compact binaries in the galaxy

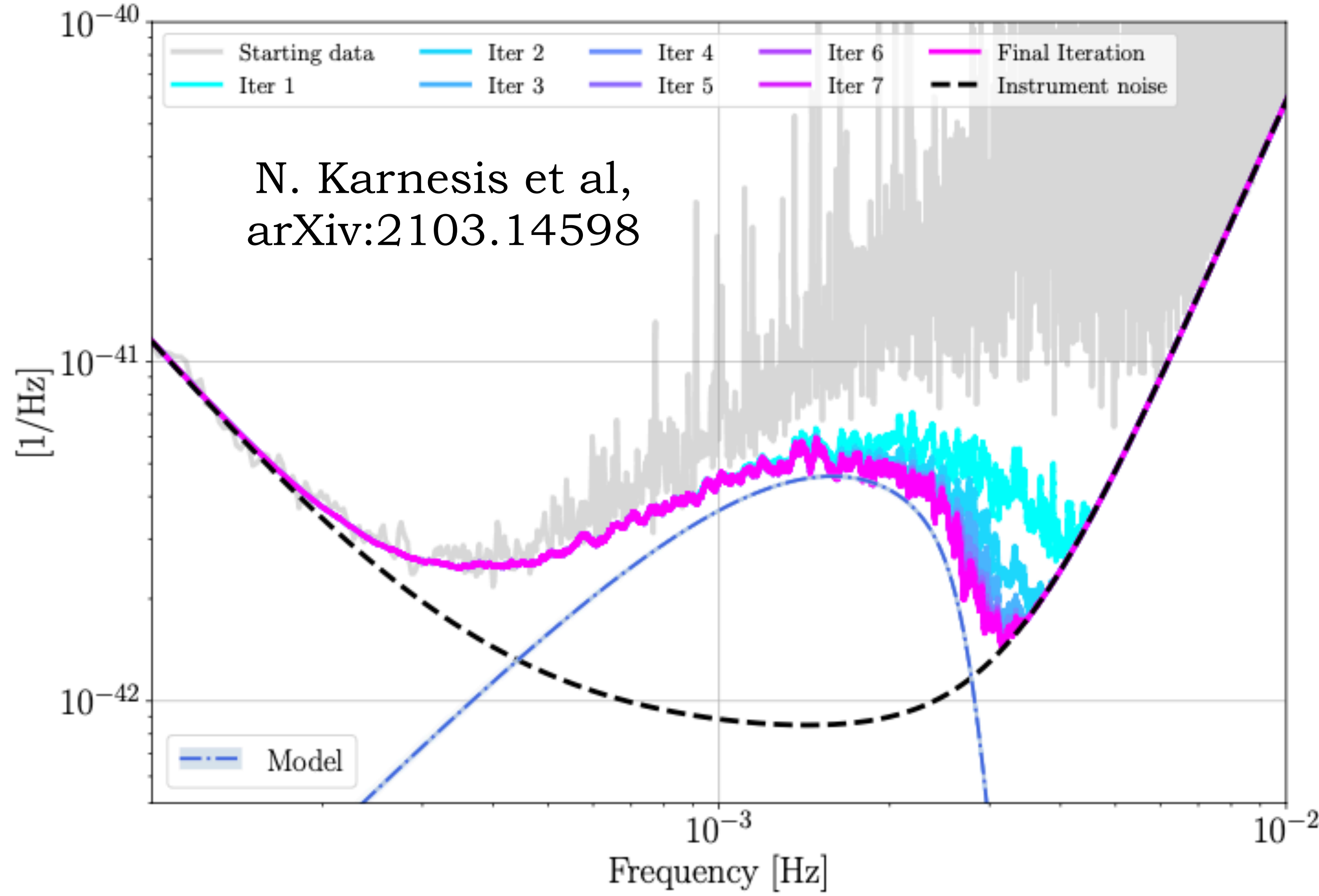


Important for **cosmology** only as a ***confusion noise***:
yearly modulated, foreground stochastic signal

Compact binaries in the galaxy

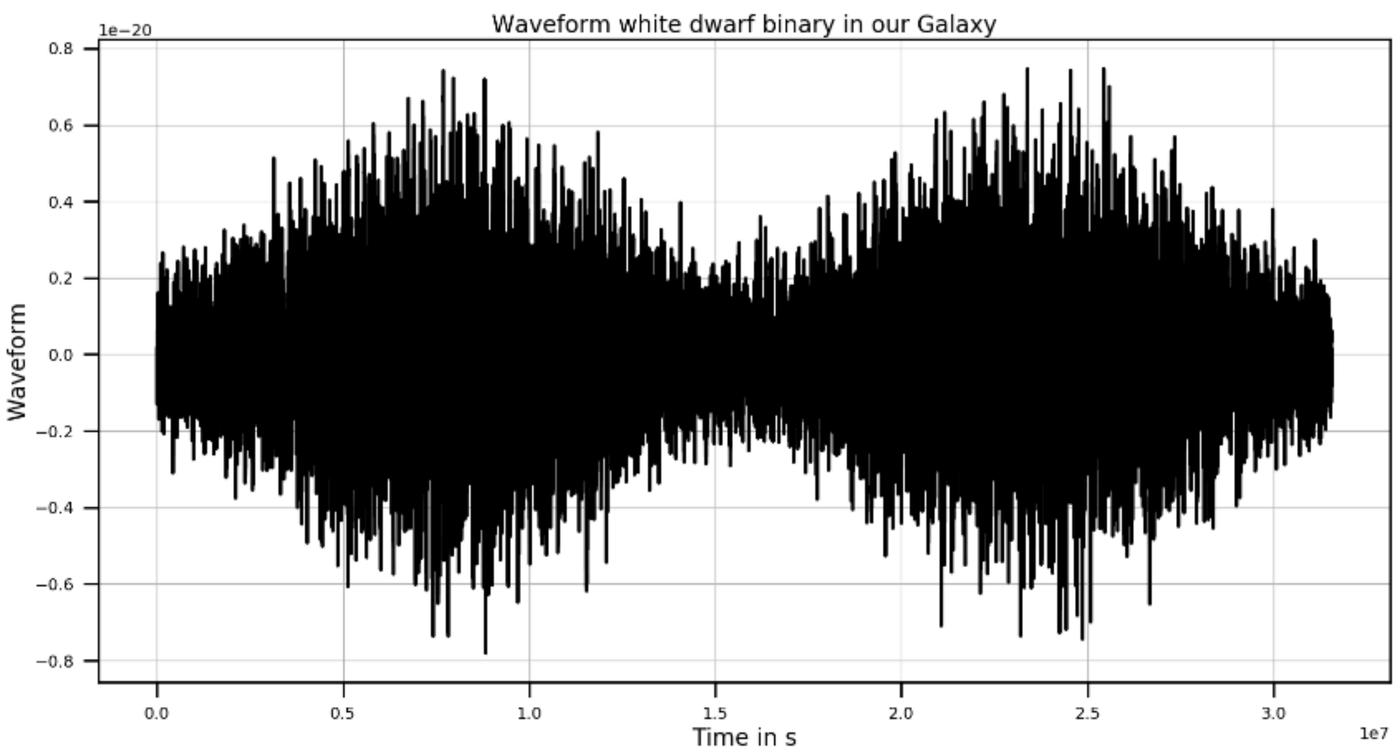
How to distinguish the galactic foreground from a possible stochastic background from the early universe?

- Fitting a multi-parameter spectral template
  e.g. Kume et al arXiv:2410.10342



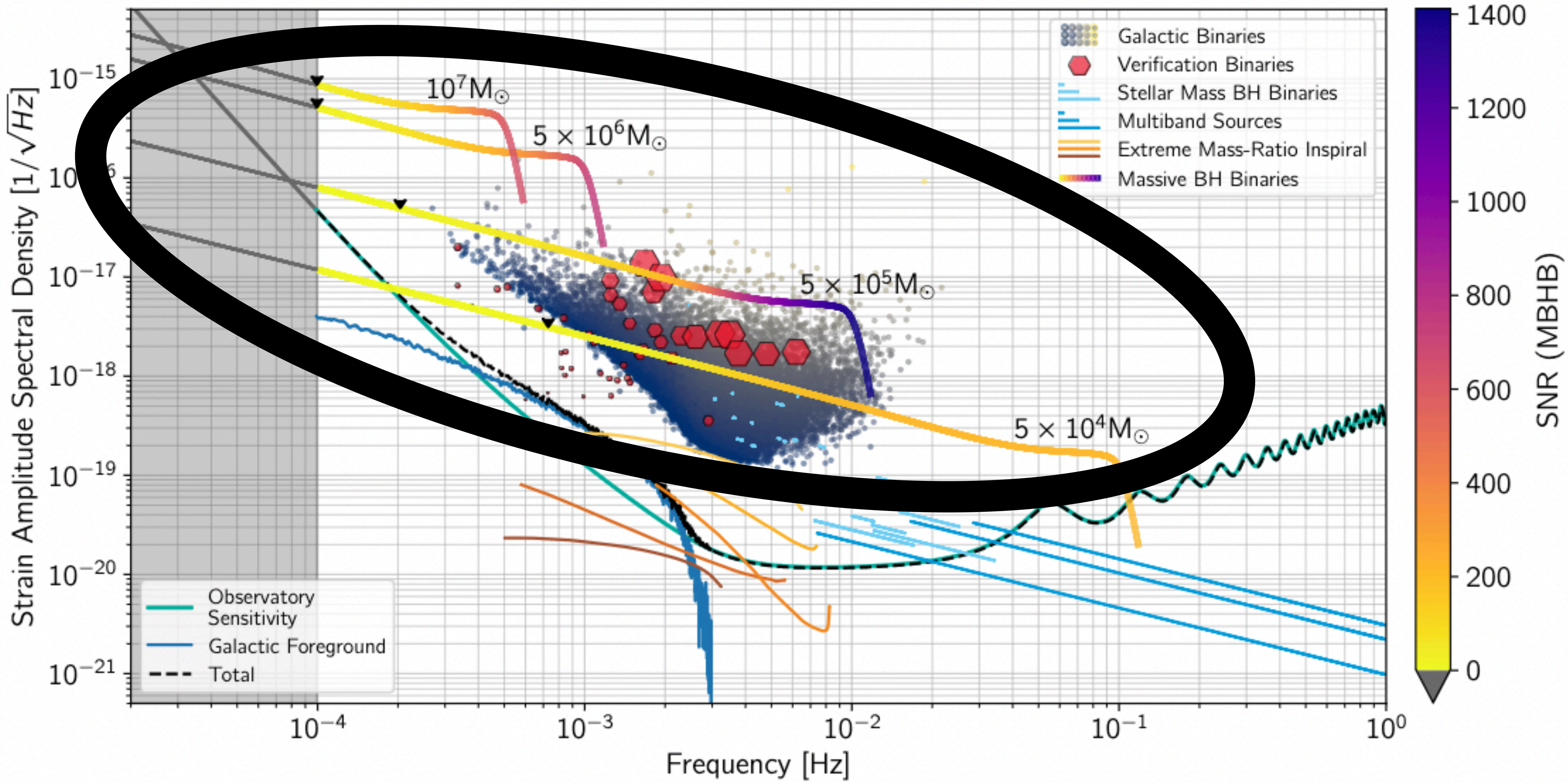
N. Karnesis et al, arXiv:2103.14598

G. Boileau et al, arXiv:2105.04283



- Exploiting its time modulation
  e.g. Hindmarsh et al arXiv:2406.04894
  Buscicchio et al arXiv:2511.03604

Massive black hole binaries



Cosmology: EM counterparts and coincident GW detection

MBHBs are expected to have counterparts if they occur in gaseous disks at the centre of galaxies

Massive black hole binaries

MBHBs can be used as bright standard sirens to measure cosmological parameters

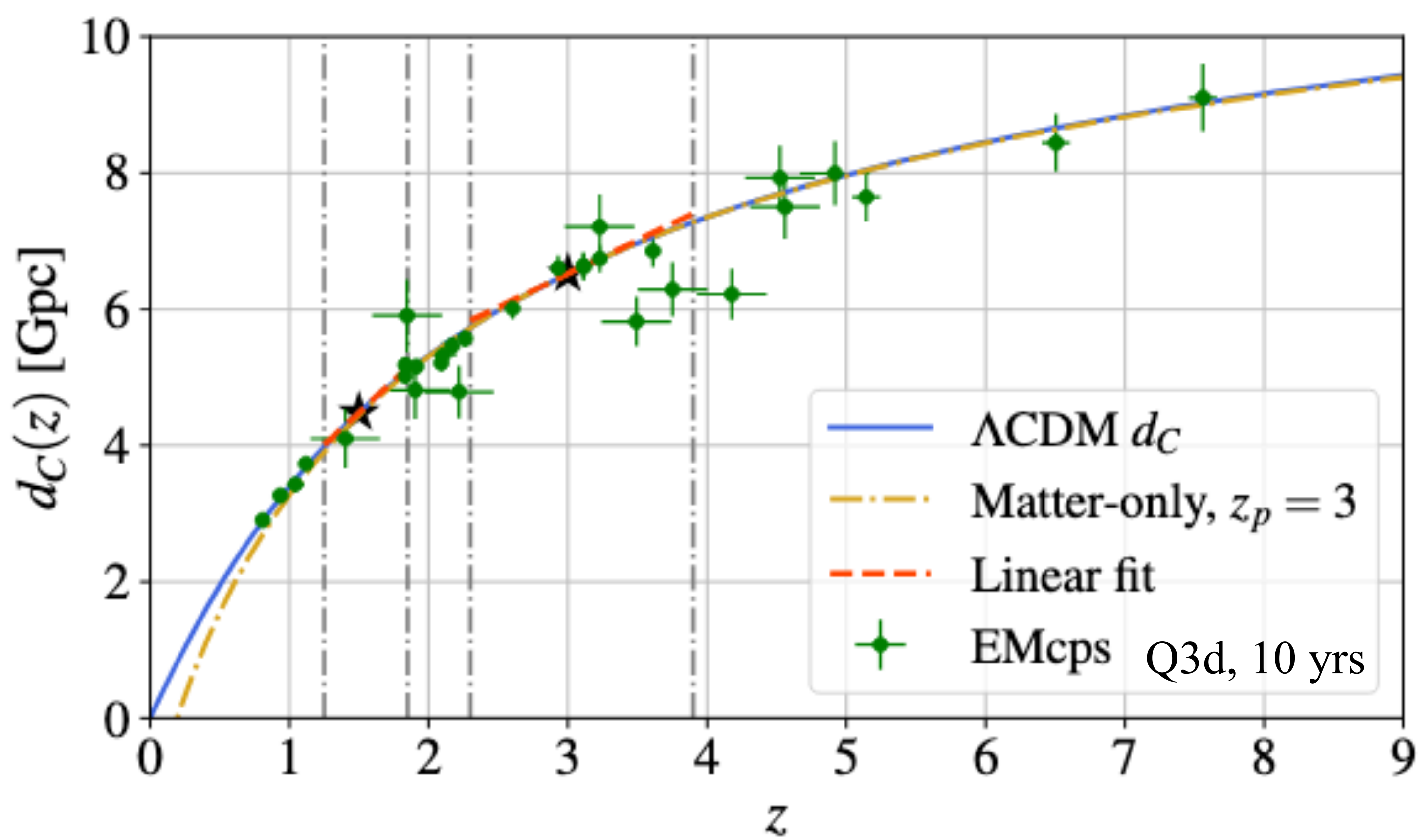
An electromagnetic counterpart to the MBHBs is necessary because the GW measurement alone does not provide a measurement of the redshift, only of the luminosity distance

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

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

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

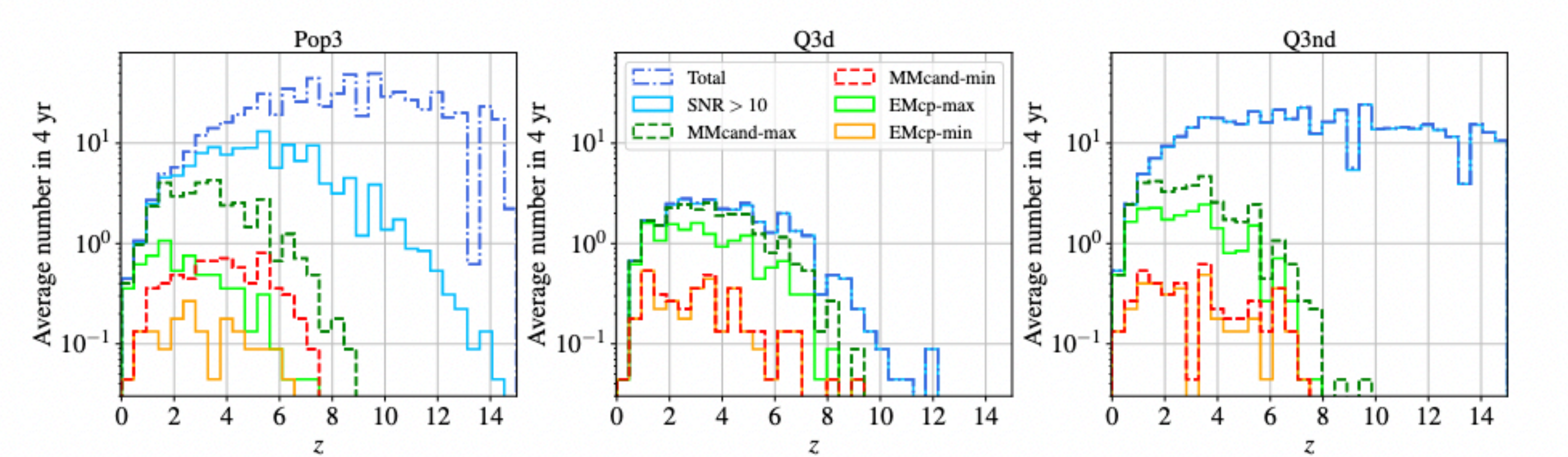
Redshifted chirp mass
degeneracy among the redshift and the true chirp mass



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

Massive black hole binaries

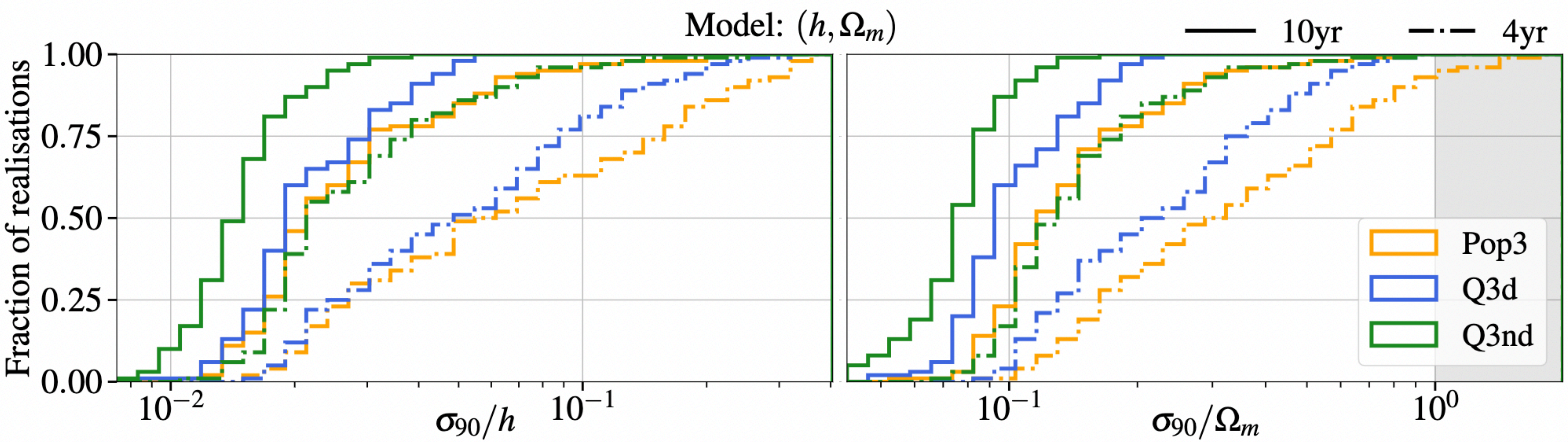
- LISA detection provides **error on sky localisation and d_L** (but one must account for weak lensing error)
- **Model of the EM counterpart and of its detection strategy** provides the sky localisation and the redshift error (optical, radio, X-ray…)
- The number of EM counterparts depends on the MBHB astrophysical generation model and on the EM detection channel
- The events cluster at high redshift 2 < z < 5 -> **COSMOLOGY AT HIGH REDSHIFT**



	Rubin	SKA+ELT			Athena+ELT				
		Isotropic flare	Γ2	Γ10	Catalogue $F_{X,\,lim}$ = 4e-17	Catalogue $F_{X,\,lim}$ = 2e-16	Eddington $F_{X,\,lim}$ = 4e-17	Eddington $F_{X,\,lim}$ = 2e-16	
	$\Delta\Omega = 10\,deg^2$				$\Delta\Omega = 0.4\,deg^2$	$\Delta\Omega = 2\,deg^2$	$\Delta\Omega = 0.4\,deg^2$	$\Delta\Omega = 2\,deg^2$	
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

The uncertainty of cosmological measurement with MBHB bright sirens is difficult to forecast because the errors are dominated by **statistical fluctuations in the realisations**



- **LISA forecast constraints on H_0**: 5% in 4 years, 2% in 10 years

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

complementary to standard cosmological probes

Massive black hole binaries

- **We have explored high redshift models:**

1. Assuming matter only

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

e.g. at redshift $z = 4$:
10% error on Hubble parameter (6% in 10 years)
3% on luminosity distance (1.5% in 10 years)
in 50% of the universe realisations

2. Cubic polynomials spline interpolation of luminosity distance
(model independent)

e.g. at redshift $z \leq 3$:
10% error on Hubble parameter (2% in 10 years)
5% on luminosity distance (1% in 10 years)
in 50% of the universe realisations

Massive black hole binaries

Figures of merit associated with science objective 6 “Probe the rate of expansion of the universe” featuring MBHBs

1. Number of MBHBs: model independent

FoM6.1: Number of MBHBs detectable with SNR ≥ 10 and sky-localisation at merger $\Delta\Omega \leq 10\,\mathrm{deg}^2$	
Threshold	Motivation
> 10	The $D_{\mathrm{L}} - z$ relation can be fully reconstructed
> 4 and < 10	To reconstruct the $D_{\mathrm{L}} - z$ relation we need at least 4 points (of which 3 EMcp).
> 1 and < 4	Limited possibility to reconstruct the $D_{\mathrm{L}} - z$ relation.
< 1	Prevent follow-up observations and a GW170817-like analysis.

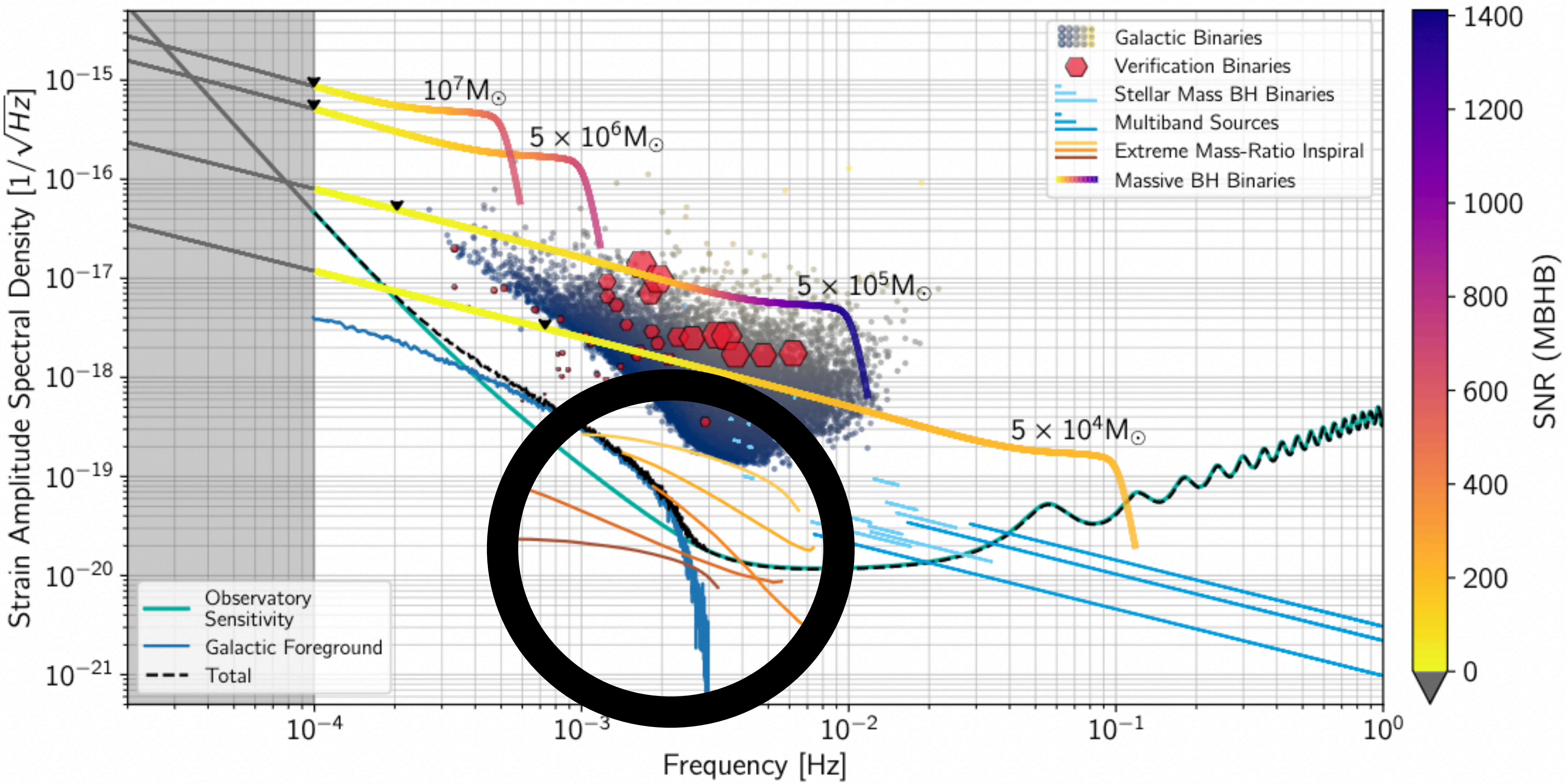
2. Error on H_0: exploring the Hubble tension

FoM6.3: Median relative error on h_0 at 90% credible interval, i.e. σ_{90}/h_0	
Threshold	Motivation
$\sigma_{90}/h_0 < 1\%$	Potential to solve the Hubble tension
$1\% < \sigma_{90}/h_0 < 10\%$	Allow to achieve the scientific goals. LVK achieves $\sim 14\%$ relative error on h_0 at 1σ with GW170817 [172]
$10\% < \sigma_{90}/h_0 < 30\%$	LVK achieves $\sim 37\%$ relative error on h_0 at 2σ with GW170817 [172]
$\sigma_{90}/h_0 > 30\%$	No or only marginal improvement compared to current LVK results

3. Error on $H(z=3)$: complementarity with future probes

FoM6.4: Median relative error on $h(z_p = 3)$ at 90% credible interval, i.e. $\sigma_{90}/h(z_p = 3)$	
Threshold	Motivation
$\sigma_{90}/h(z_p = 3) < 5\%$	Competitive with future probes at the same redshift (see Fig. 2 in [176])
$5\% < \sigma_{90}/h(z_p = 3) < 50\%$	Potential to probe the matter-dominated region of the Universe
$50\% < \sigma_{90}/h(z_p = 3) < 100\%$	The science goal is only marginally achieved
$\sigma_{90}/h(z_p = 3) > 100\%$	The science goal cannot be achieved

Extreme mass ratio inspirals



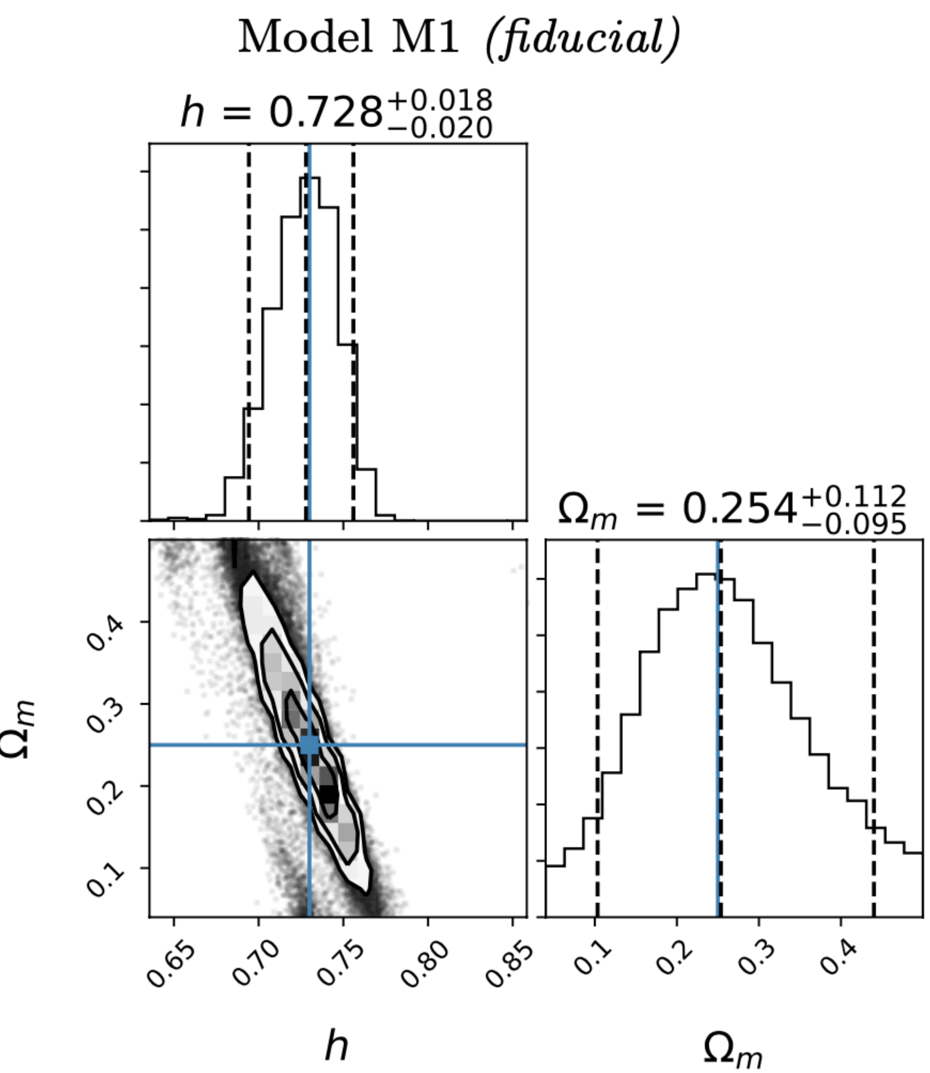
Cosmology: they can produce a dangerous (depending on the event rates) foreground stochastic signal

and they can be used as **dark sirens**

Extreme mass ratio inspirals

Dark sirens: sources for which no EM counterpart is expected, the redshift is inferred with a **statistical method**

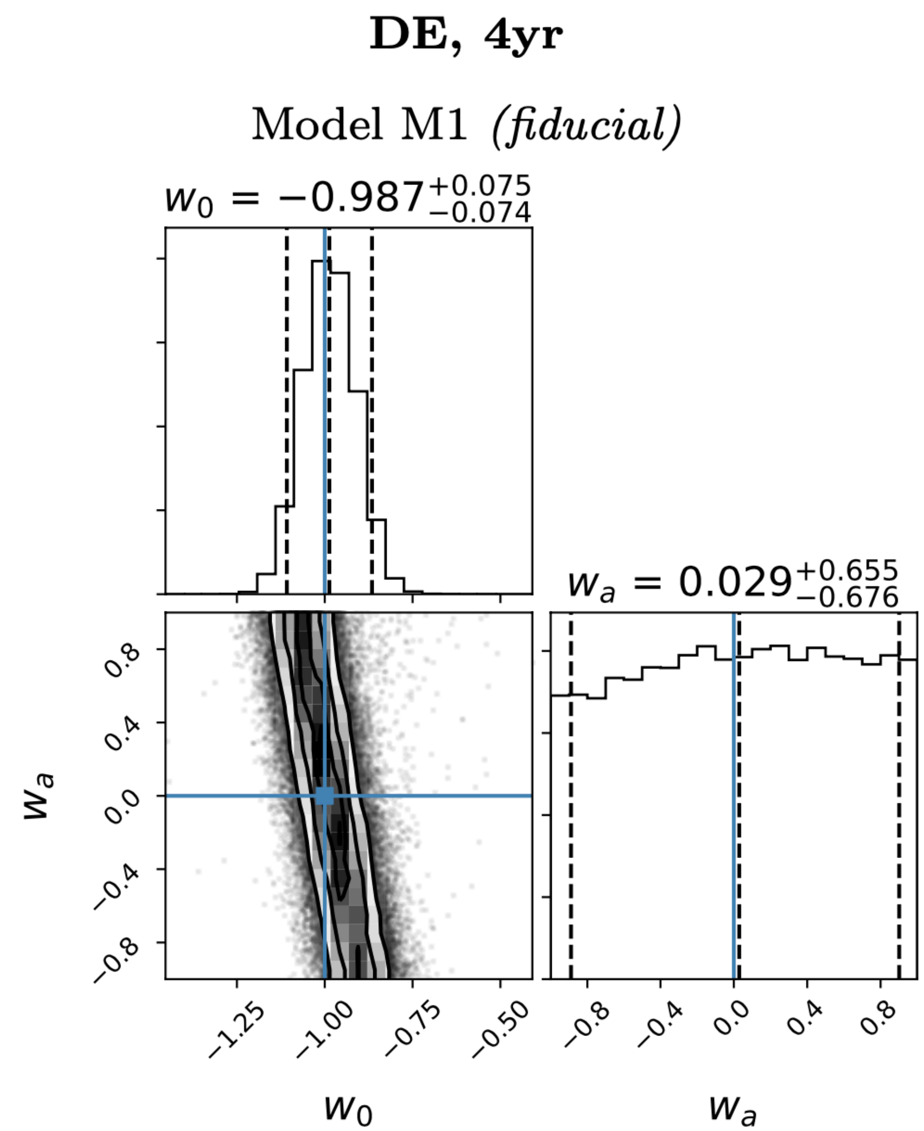
- EMRIs with SNR>100 can be used to infer cosmological parameters: the results depend on the rates



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

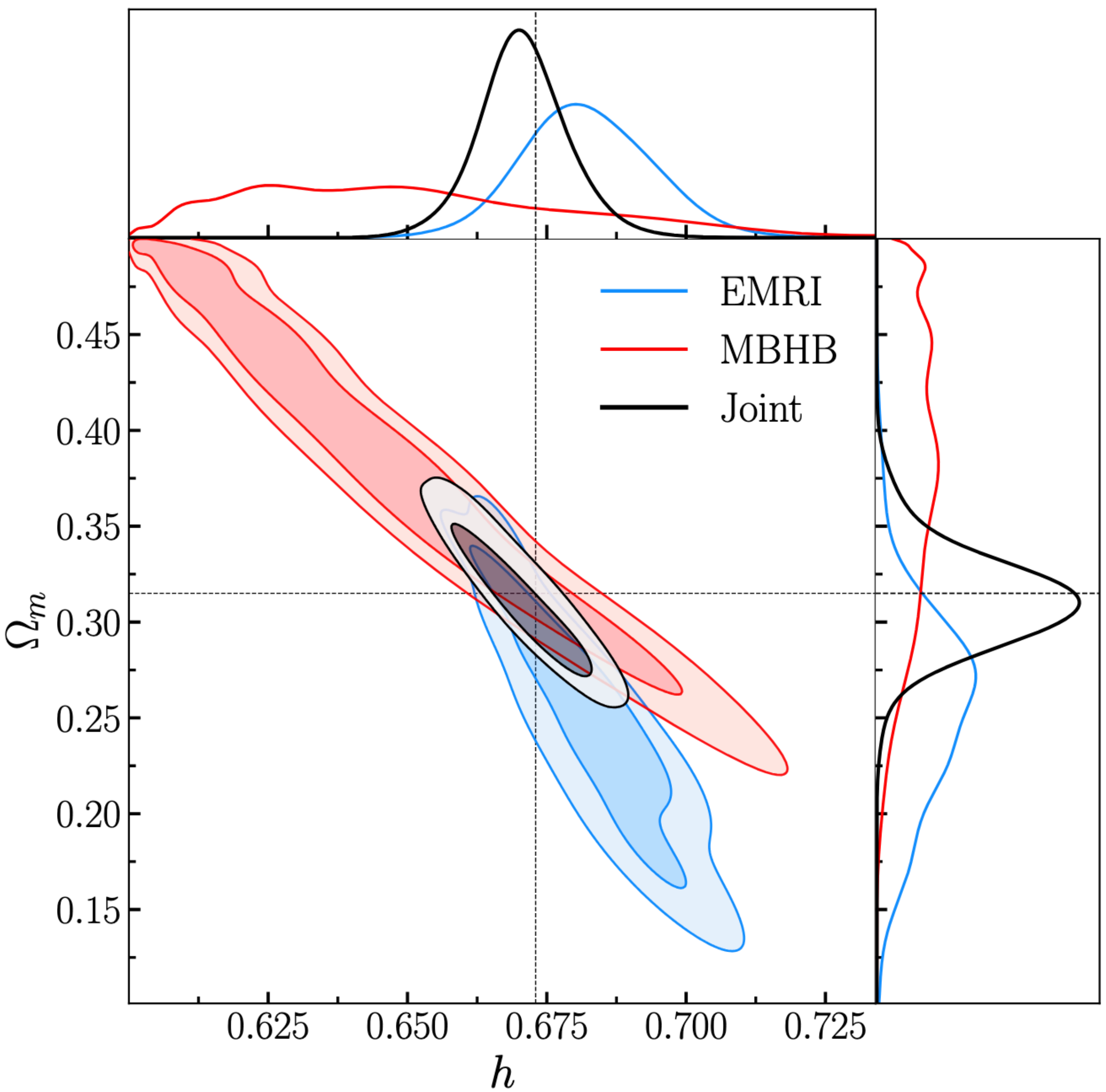
Figure of merit associated with science objective 6
"Probe the rate of expansion of the universe" featuring EMRIs

FoM6.2.1: Number of EMRIs detectable with SNR ≥ 100 and $z < 1$	
Threshold	Motivation
> 100	Ability to estimate σ_{68}/h_0 at $\lesssim 1\%$ [56]
> 5 and < 100	Ability to estimate σ_{68}/h_0 at $\sim 1\% - 5\%$ [56]
> 1 and < 5	Ability to estimate σ_{68}/h_0 only at $\gtrsim 5\%$ [56]
< 1	Prevent the possibility to conduct the dark siren analysis

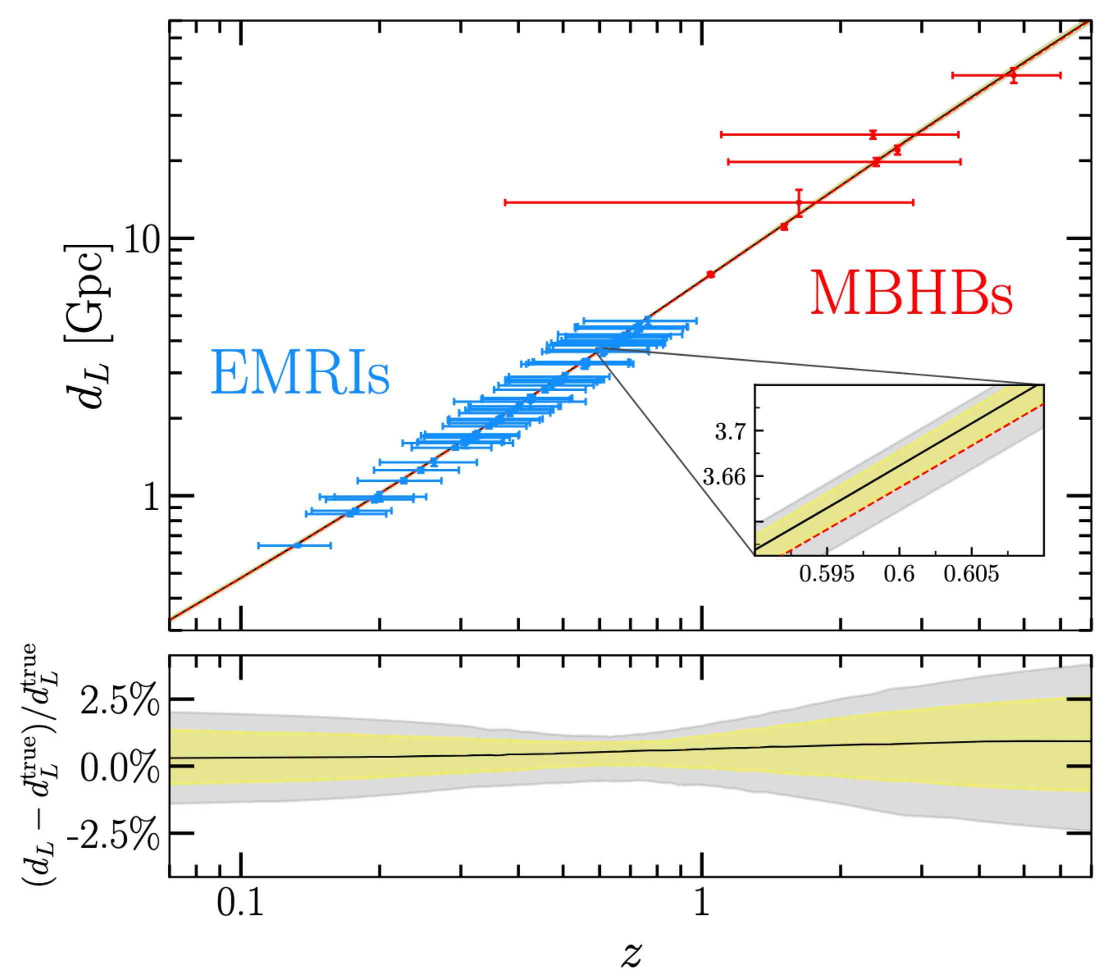
4. Error on H_0: exploring the Hubble tension

The full potential of LISA to probe cosmological parameters comes from combining the two classes of sources, at low and high z

Laghi et al, arXiv:2603.23612



Source	$\langle N \rangle$	ΛCDM (2D) h[%]	ΛCDM (2D) Ω_m[%]	ΛCDM (1D) h[%]	ΛCDM (1D) Ω_m[%]	DE (2D) w_0[%]
4 yr						
EMRI	60	2.0	25	0.6	7.9	9.3
MBHB	6	4.3	19	1.3	6.5	14
EMRI+MBHB	66	1.2	9.4	0.5	3.9	7.2
10 yr						
EMRI	156	1.0	8.6	0.2	1.5	5.9
MBHB	16	1.5	9.1	0.5	3.2	7.6
EMRI+MBHB	172	0.6	4.7	0.3	1.2	4.9



No FoM, computationally too expensive

Extra galactic white dwarf binaires

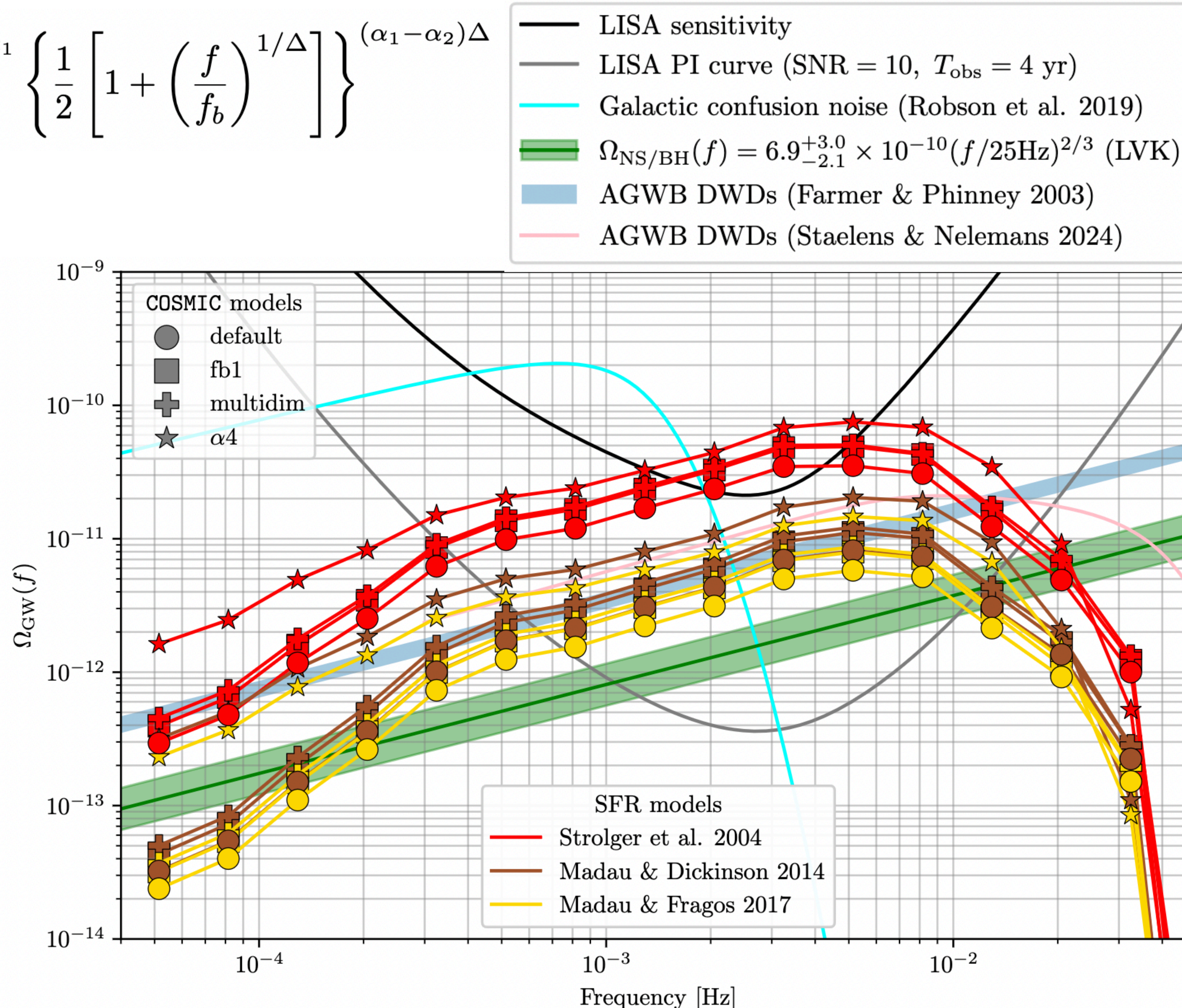
Cosmology: they produce a dangerous (stationary and isotropic) foreground

$$\Omega_{\mathrm{WDex}}(f) = A_{\mathrm{WDex}} \left(\frac{f}{f_b}\right)^{-\alpha_1} \left\{\frac{1}{2}\left[1 + \left(\frac{f}{f_b}\right)^{1/\Delta}\right]\right\}^{(\alpha_1-\alpha_2)\Delta}$$

$$A_{\mathrm{WDex}}(3\,\mathrm{mHz}) = \mathcal{O}(10^{-11})$$

Hofman & Nelemans,
arXiv:2407.10642

Boileau et al,
arXiv:2506.18390



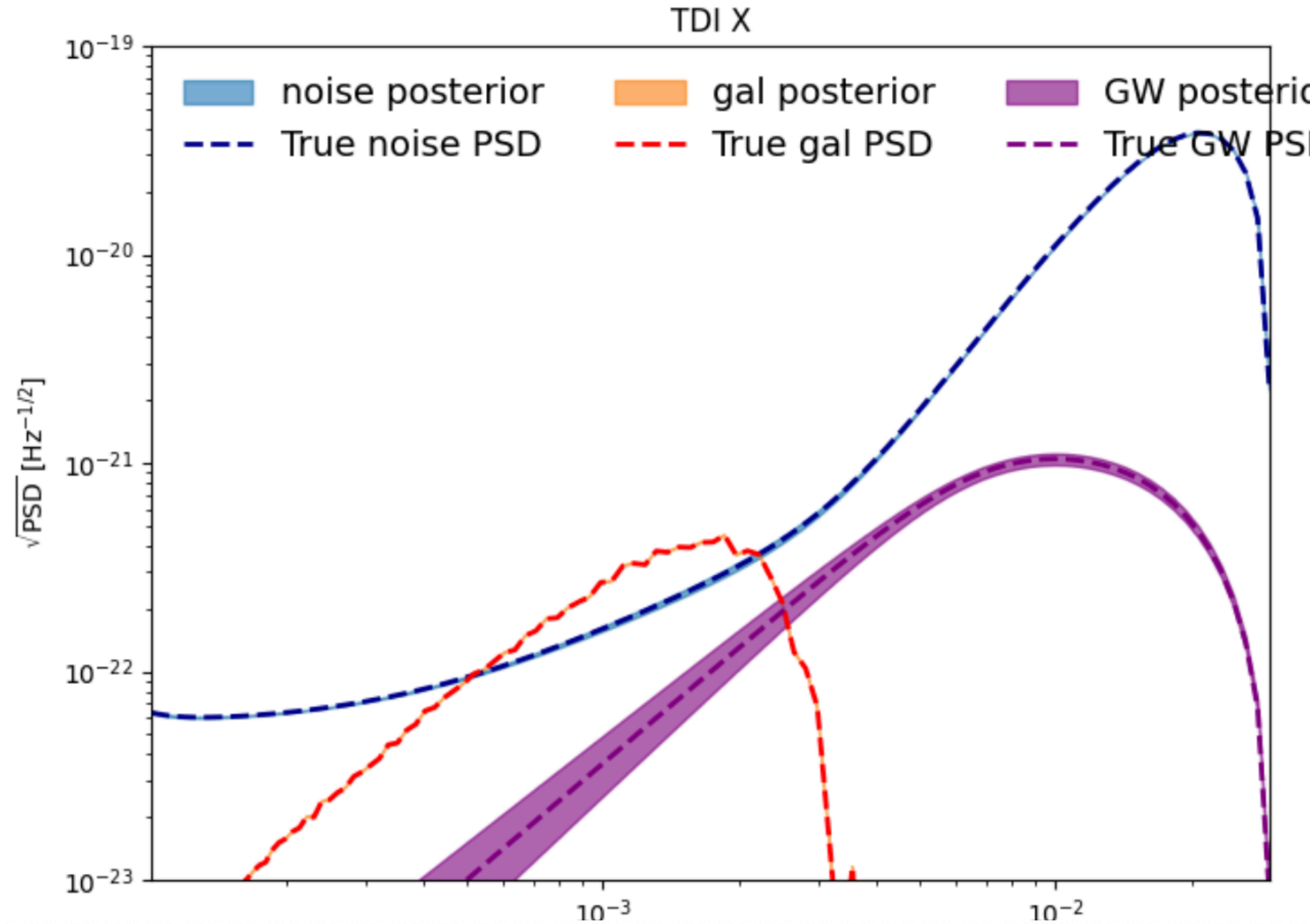
Extra galactic white dwarf binaires

Figures of merit associated with science objective 7 “Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics”

Characterise astro foreground to disentangle from possible cosmo background

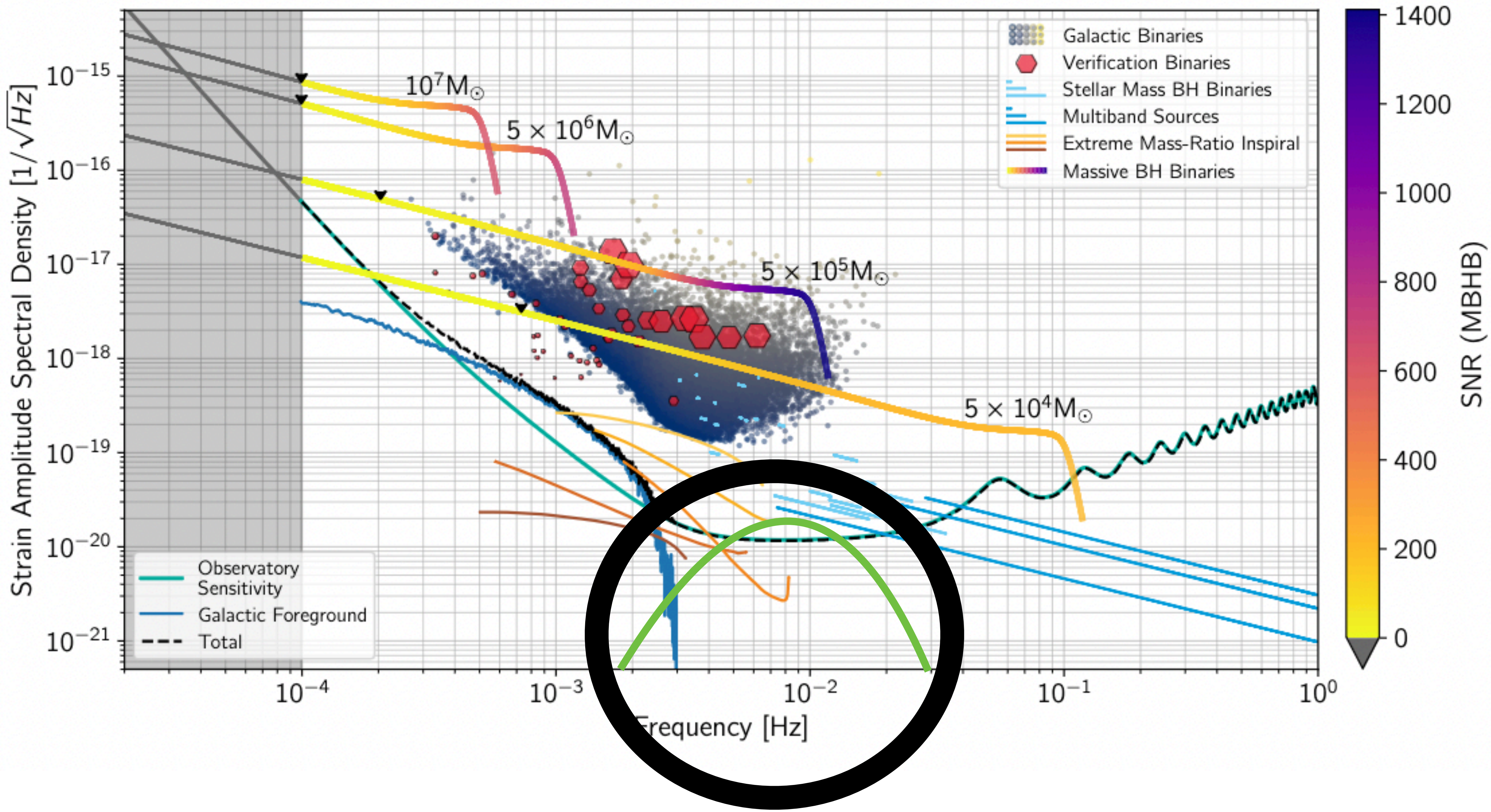
The foreground has a parametric model, while the instrument noise is modelled with a spline

LISA Red Book arXiv:2402.07571
Baghi et al, 2302.12573
See also:
Muratore et al, arXiv:2308.01056
Pozzoli et al, arXiv:2311.12111
Santini et al, arXiv:2507.06300



SI 7.1: Astrophysical extra-galactic foreground characterization	
Threshold	Motivation
$\delta A_{\mathrm{WDex}}/A_{\mathrm{WDex}} < 7\%$ and $\delta\alpha_1/\alpha_1 < 20\%$	Excellent reconstruction of the foreground
$7\% \leq \delta A_{\mathrm{WDex}}/A_{\mathrm{WDex}} \leq 14\%$ and $20\% \leq \delta\alpha_1/\alpha_1 \leq 30\%$	The error on the amplitude allows to distinguish between all population synthesis scenarios within the Madau-Dickinson star formation rate
$14\% < \delta A_{\mathrm{WDex}}/A_{\mathrm{WDex}} < 60\%$ and $30\% < \delta\alpha_1/\alpha_1 < 50\%$	The error on the amplitude allows to characterise the default or $\alpha 4$ models only and the spectral index is measured
$\delta A_{\mathrm{WDex}}/A_{\mathrm{WDex}} \geq 60\%$ and $\delta\alpha_1/\alpha_1 \geq 50\%$	characterisation of the foreground signal no longer possible

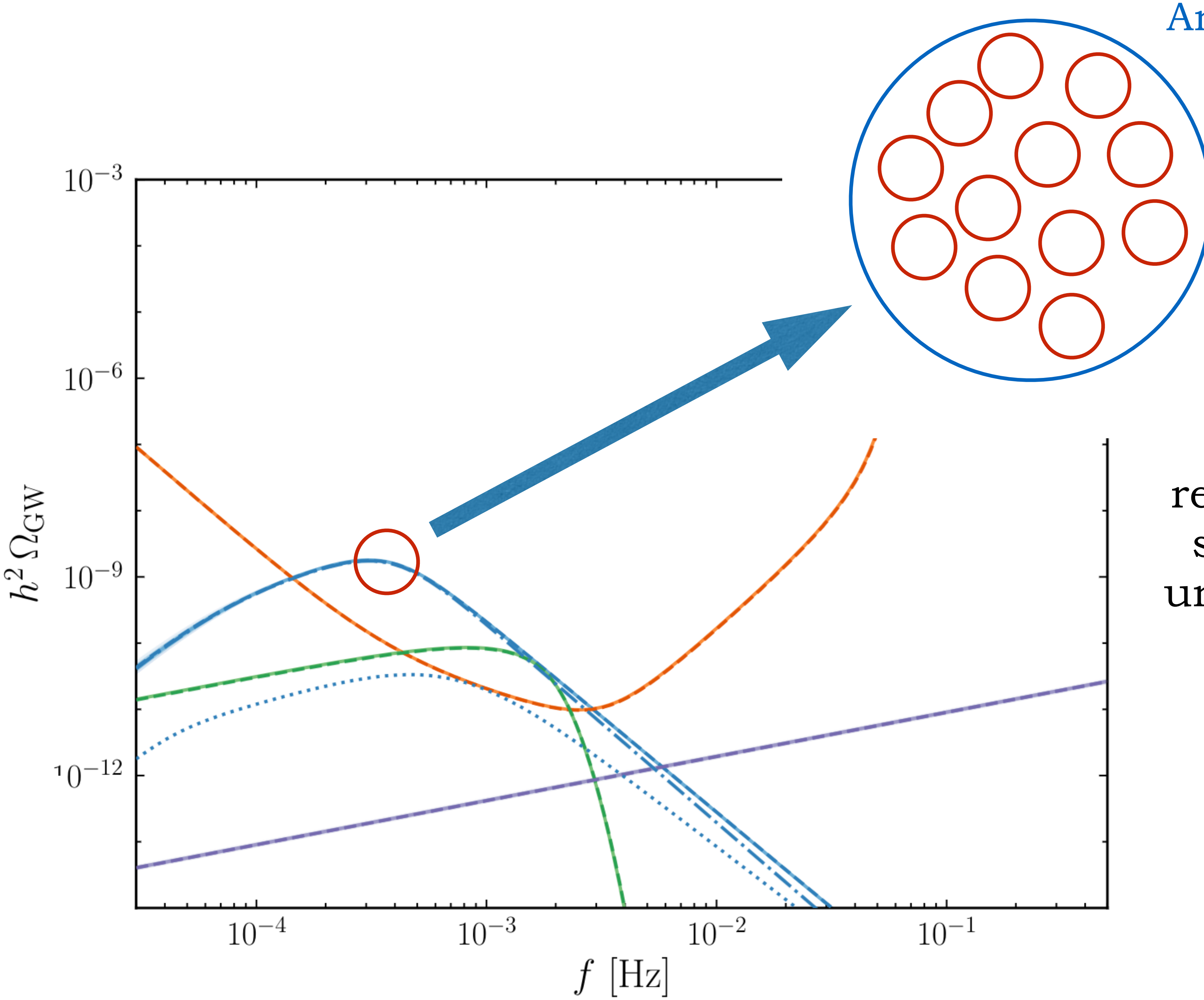
The stochastic GW background from the early universe



the dream of **cosmology**

The stochastic GW background from the early universe

The LISA detector today detects the GW signal sourced in very many
causally disconnected regions in the early universe
This produces an uncorrelated, stochastic signal



Angular size of the full sky: 360°
Detector resolution: ~10°

Angular size of the correlated regions: 10^{-12}°

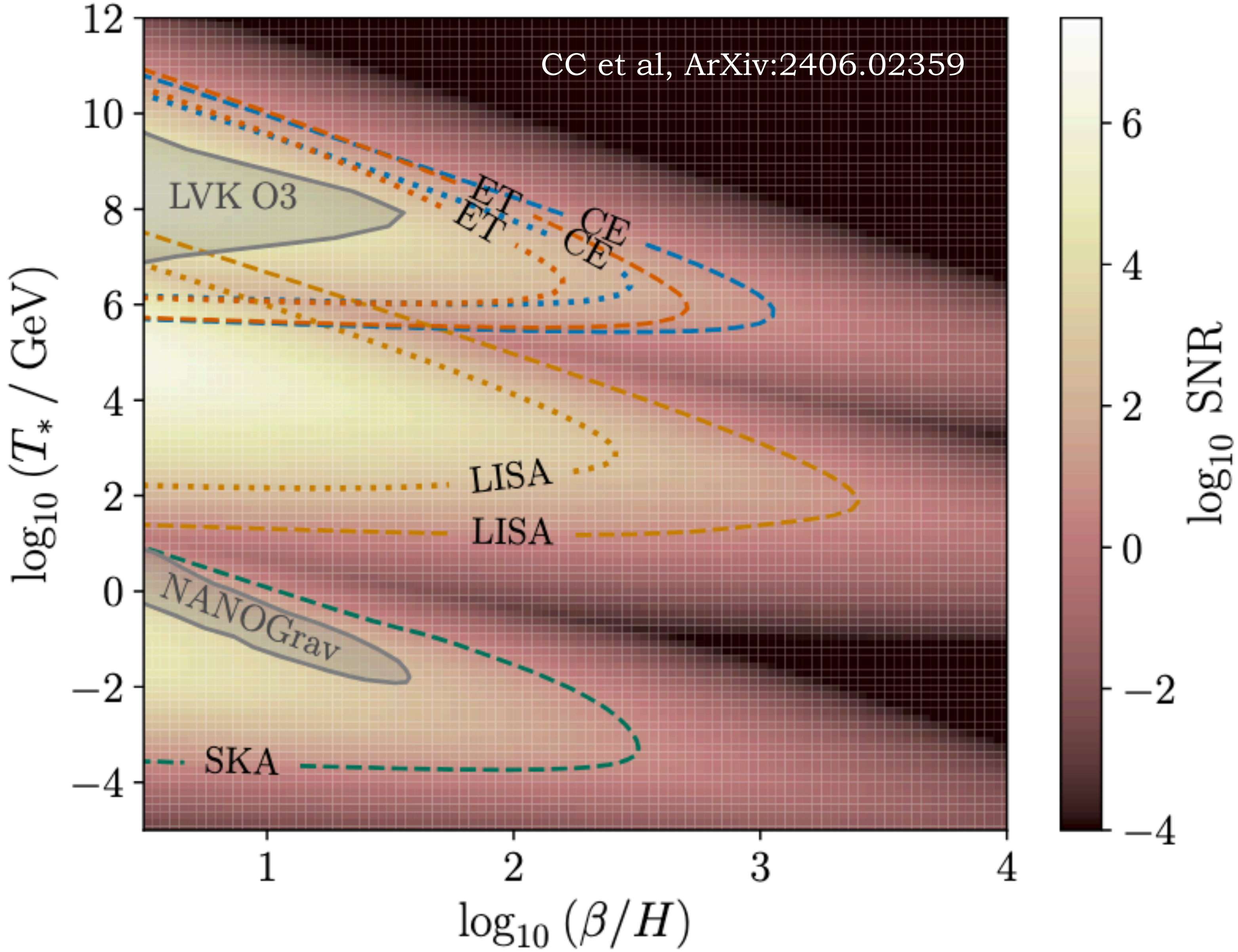
The size of the correlated region, connected with the GW source operating in the early universe, determines the signal characteristic frequency

The stochastic GW background from the early universe

$$10^{-5}\,\mathrm{Hz} < f < 0.1\,\mathrm{Hz} \quad \longrightarrow \quad 100\,\mathrm{GeV} \lesssim T_* \lesssim 10^6\,\mathrm{GeV}$$

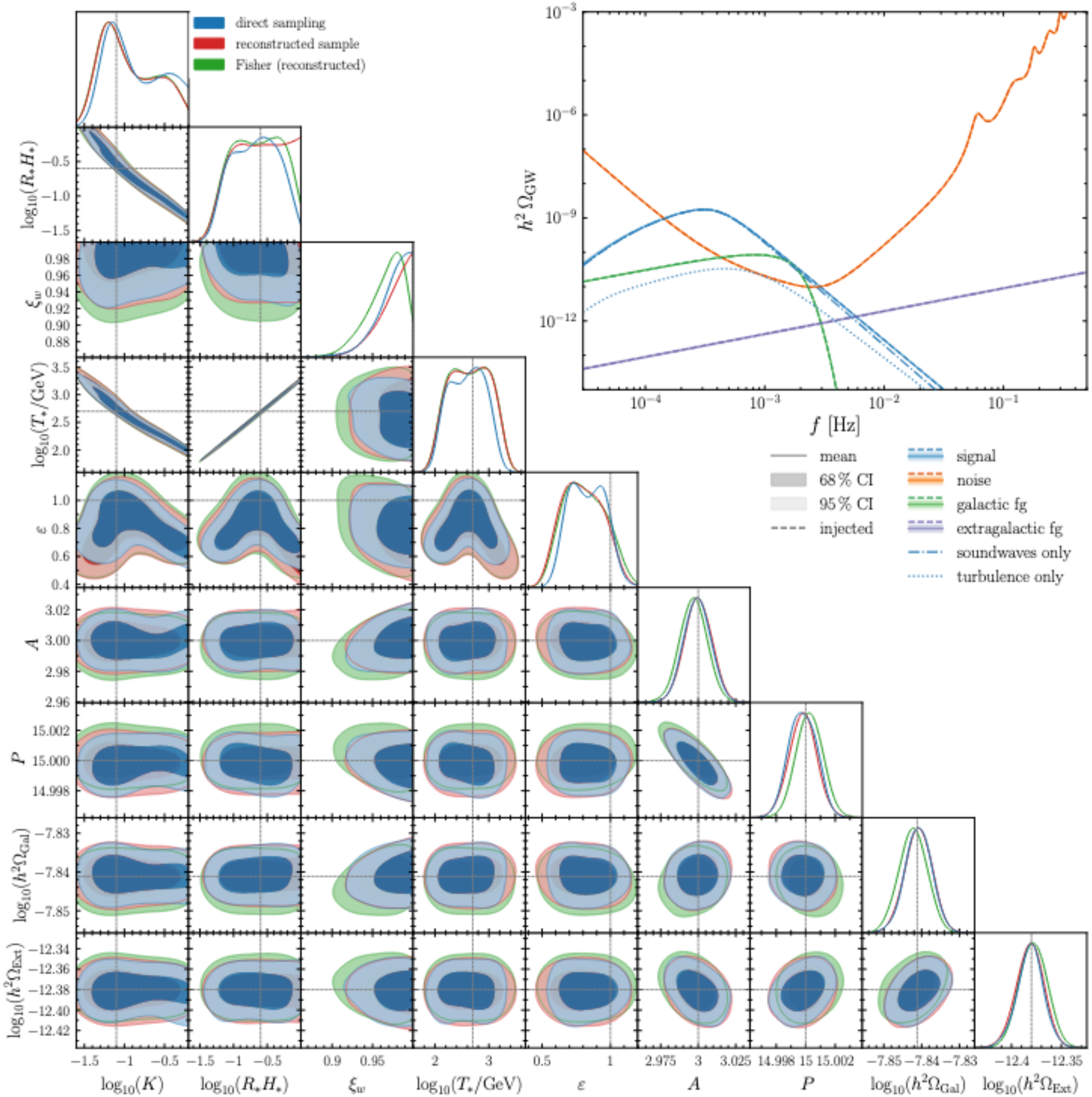
LISA offers the opportunity to probe the **EW energy scale and beyond**

test beyond standard model physics complementary to particle colliders



Parameter to which the signal amplitude is *inversely* proportional

The stochastic GW background from the early universe



Template-based reconstruction of the *thermodynamic parameters of a first order phase transition*

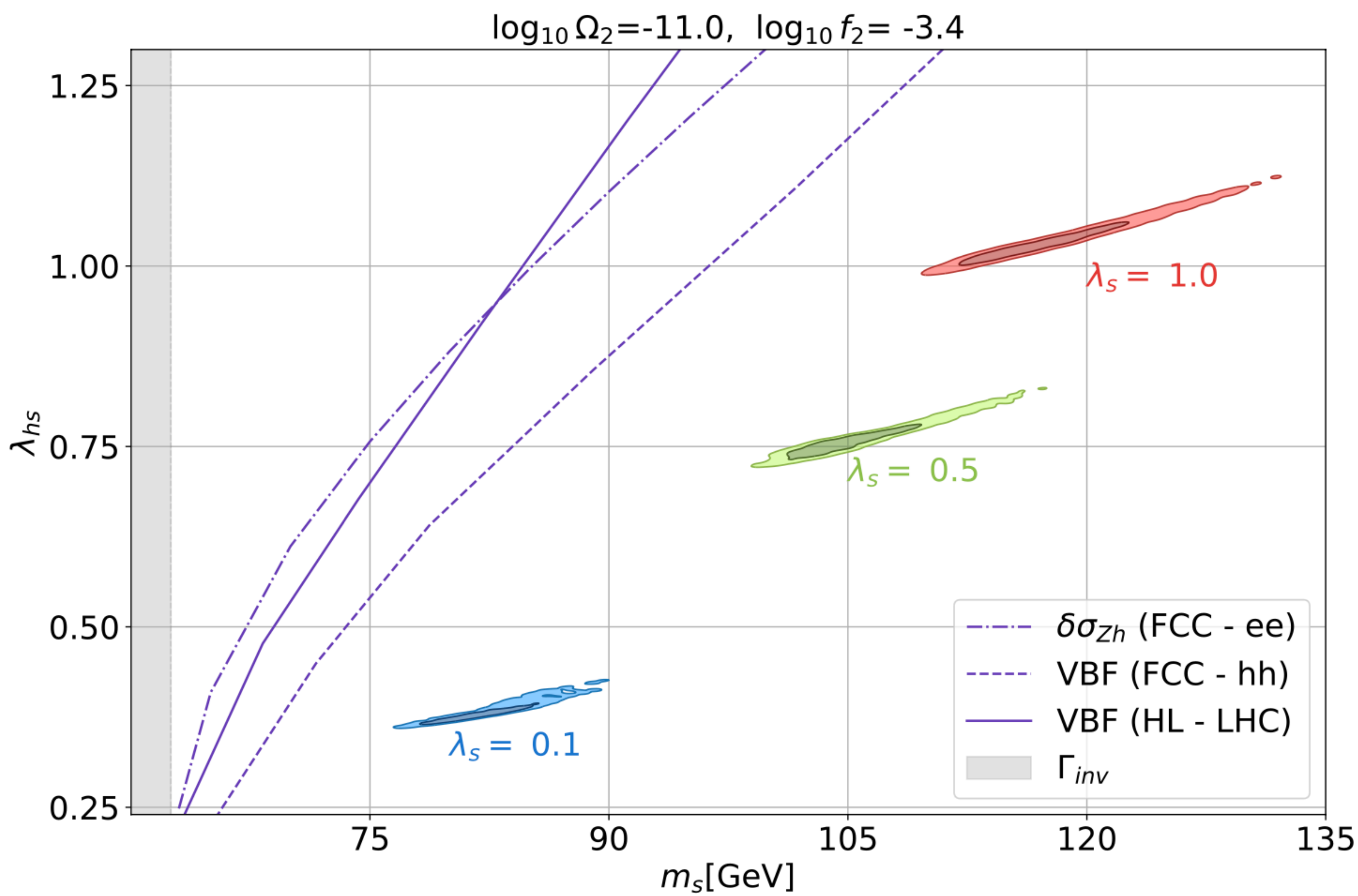
accounting for foregrounds and **assuming a two-parameters noise model**

LISA CosWG, arXiv:2403.03723

The stochastic GW background from the early universe

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

Z_2 singlet extension of the Standard Model



LISA CosWG, arXiv:2403.03723

The stochastic GW background from the early universe

Examples of possible sources of GW signals: far-reaching discovery potential

- *Inflation*:
  - quantum tensor fluctuations at second order
  - tensor modes from additional fields (scalar, gauge…)
  - preheating
  - …

- *Phase transitions in the radiation dominated era*:
  - stable topological defects
  - bubble wall collisions from a first order phase transition
  - bulk fluid motion (compressional and vortical)
  - magnetic fields
  - …

GW sourced by **anisotropic stresses**, examples:

- Scalar field gradients $\Pi_{ij} \sim [\partial_i \phi \partial_j \phi]^{TT}$
- Bulk fluid motion $\Pi_{ij} \sim [\gamma^2 (\rho + p) v_i v_j]^{TT}$
- Gauge fields $\Pi_{ij} \sim [-E_i E_j - B_i B_j]^{TT}$
- Second order scalar perturbations, Π_{ij} from a combination of $\partial_i \Psi, \partial_i \Phi$

The stochastic GW background from the early universe

Because SGWB sources are based on theories so far lacking experimental confirmation, it is impossible to make definite predictions for the signal, contrary to the case of astrophysical foregrounds

A great variety of spectral shapes from a great variety of proposals for the sources

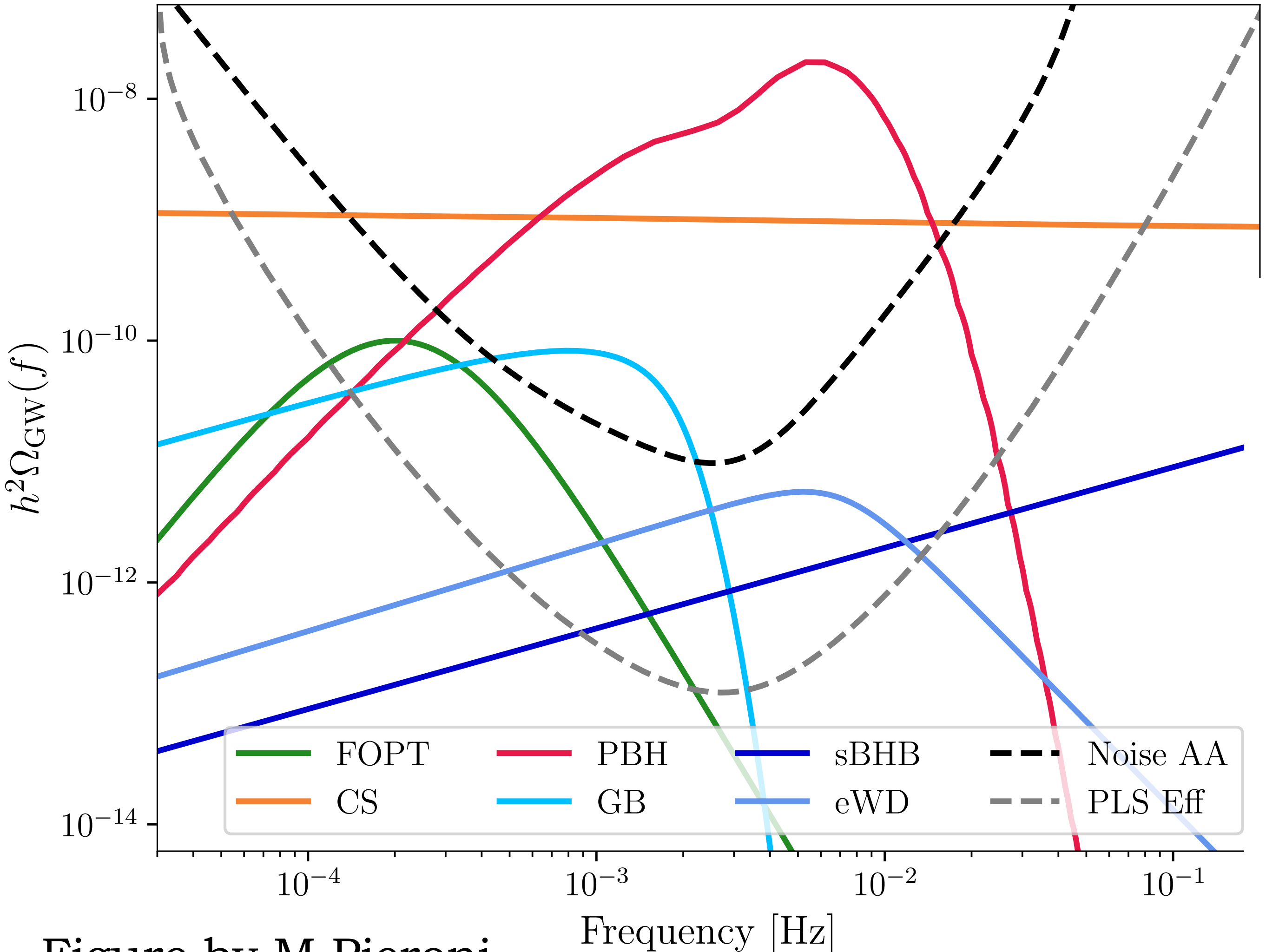
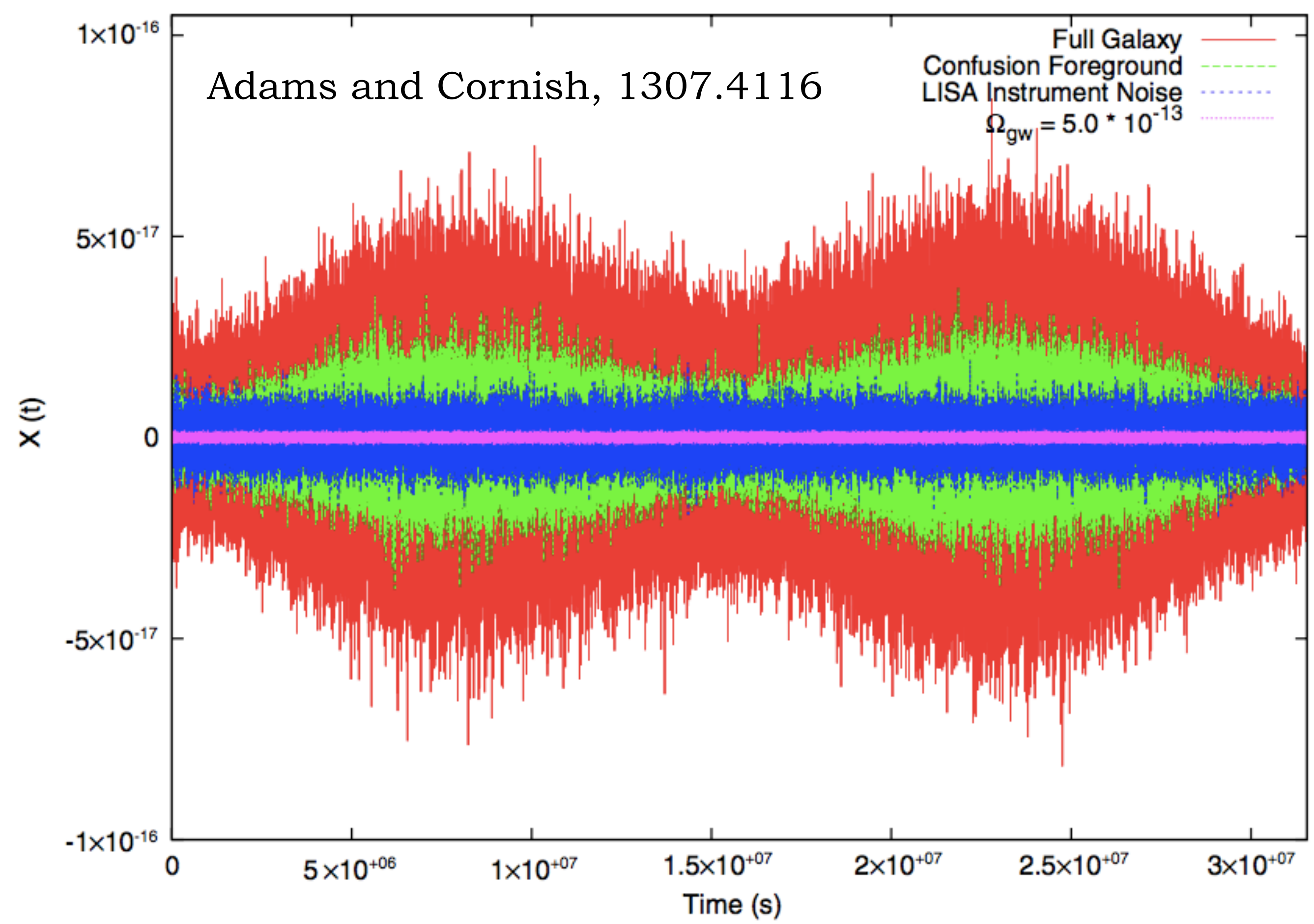


Figure by M Pieroni

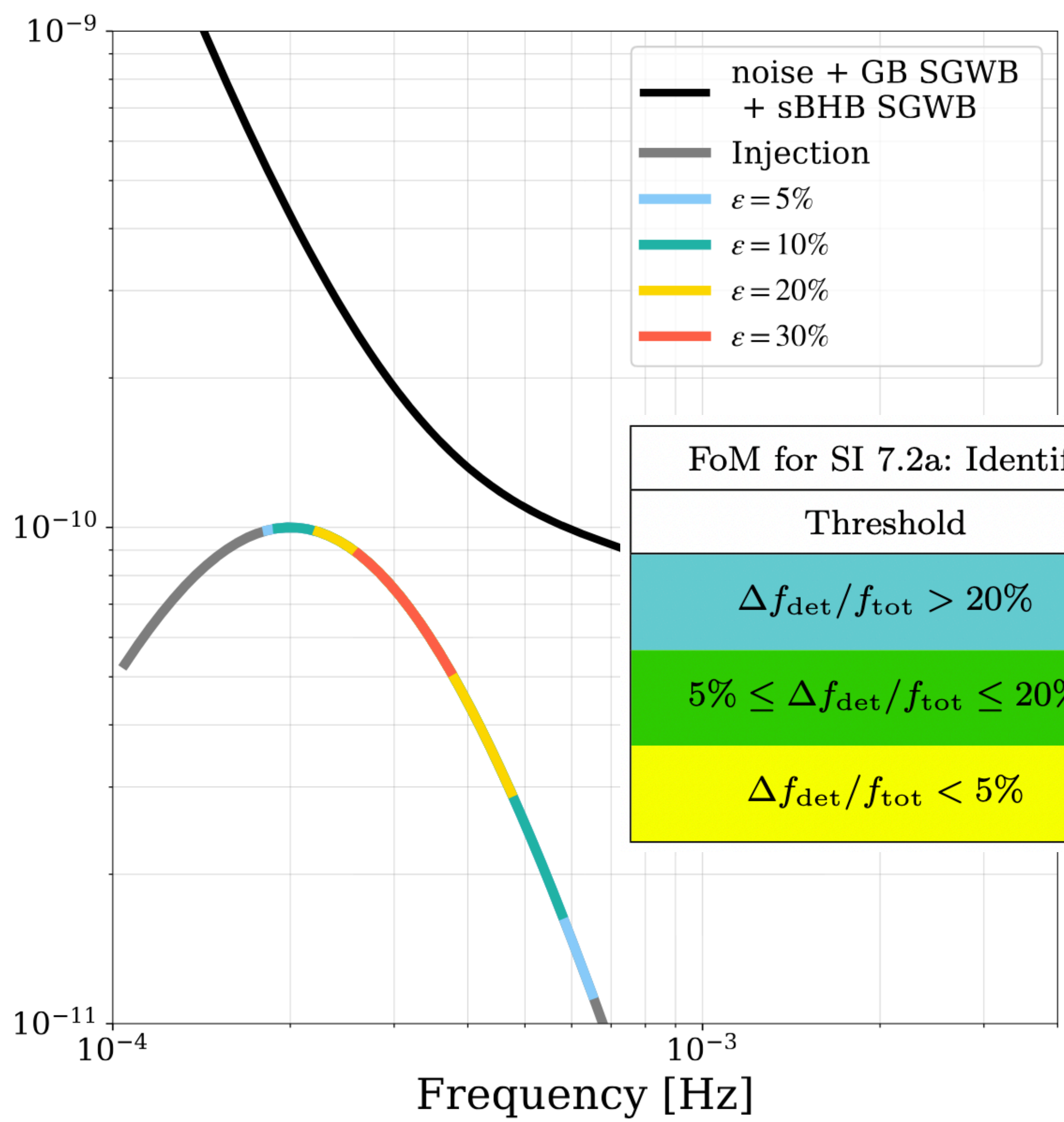
The outstanding challenge for LISA is how to distinguish them from the instrument noise and astrophysical foregrounds



The stochastic GW background from the early universe

Figures of merit associated with science objective 7 "Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics"

The presence of an "extra noise component" is recognised in the data given a noise foreground uncertainty of 20%



N. Karnesis, arXiv:1906.09027

LISA Red Book arXiv:2402.07571

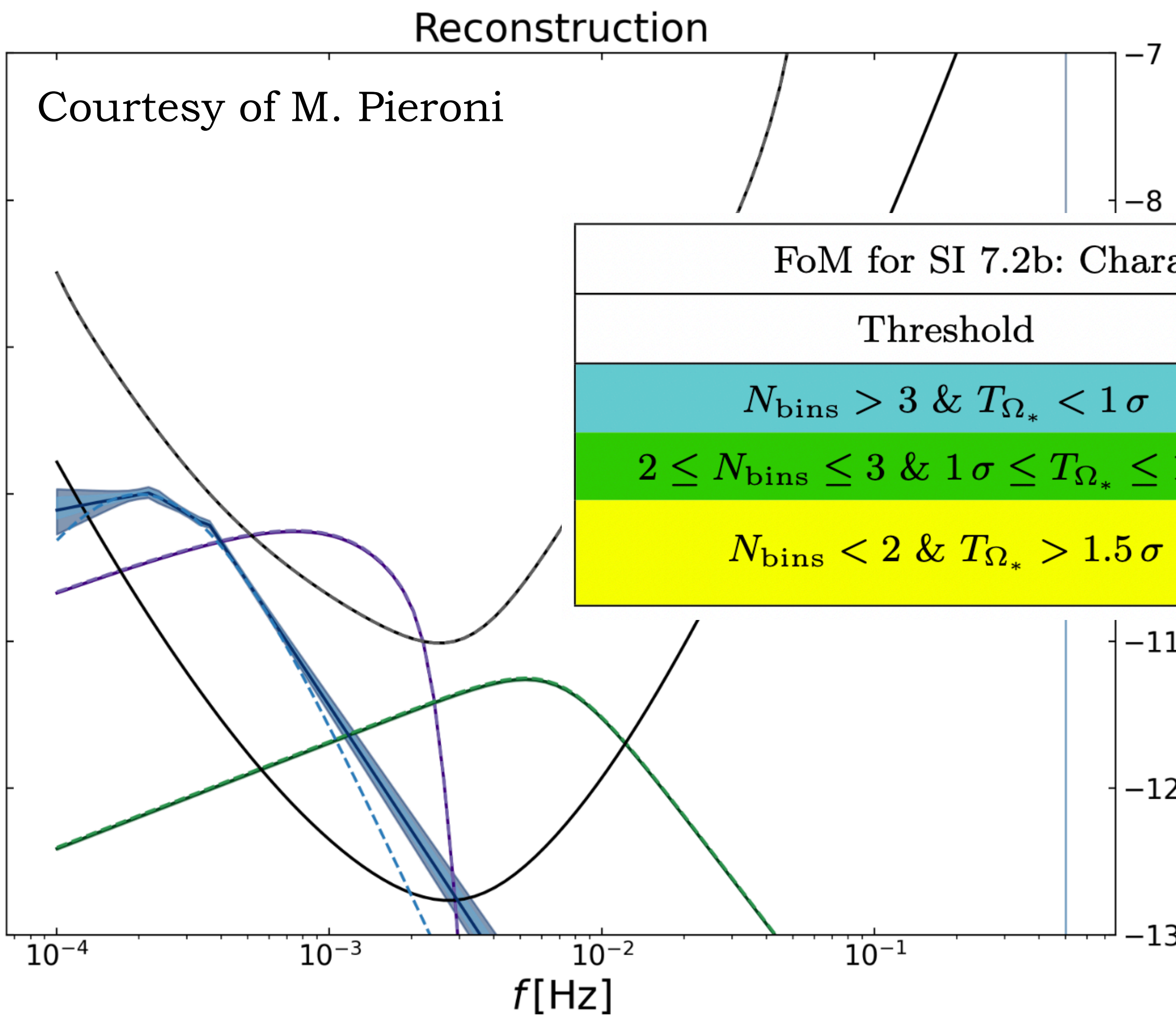
FoM for SI 7.2a: Identification of a cosmological SGWB component with 20% uncertainty on the noise + f	
Threshold	Motivation
$\Delta f_{\rm det}/f_{\rm tot} > 20\%$	The presence of the SGWB can be identified in a frequency band wide enough to allow excellent reconstruction of the spetral shape
$5\% \leq \Delta f_{\rm det}/f_{\rm tot} \leq 20\%$	The presence of the SGWB can be inferred in a frequency band wide enough to partially identify the spectral shape
$\Delta f_{\rm det}/f_{\rm tot} < 5\%$	The presence of the SGWB can be inferred in a frequency band too small to identify the spectral shape

The stochastic GW background from the early universe

Figures of merit associated with science objective 7 "Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics"

Reconstruction of the signal spectral shape to infer its origin, assuming a two-parameters noise model

LISA Red Book arXiv:2402.07571
CC et al, arXiv:1906.09244,
Flauger et al arXiv:2009.11845



FoM for SI 7.2b: Characterization of the cosmological SGWB component	
Threshold	Motivation
$N_{\rm bins} > 3$ & $T_{\Omega_*} < 1\,\sigma$	excellent reconstruction of the spectral shape
$2 \leq N_{\rm bins} \leq 3$ & $1\,\sigma \leq T_{\Omega_*} \leq 1.5\,\sigma$	reconstruction of the spectral shape possible
$N_{\rm bins} < 2$ & $T_{\Omega_*} > 1.5\,\sigma$	reconstruction of the spectral shape compromised unless the signal is a power law

Conclusions

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

Constraining late universe expansion with sirens

- Not fully competitive with standard cosmological surveys (SNIa, BAO, CMB…) but provides independent measurement (might be important in the present context of crisis)
- The luminosity distance is measured directly (different systematics) and can be constrained also at high redshift -> complementarity with cosmological probes

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 Standard Model: many proposals of signals, interesting constraining power for EW scale…

- The detection is very challenging

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