A review on the astrophysical stochastic gravitational wave signals in the LISA band

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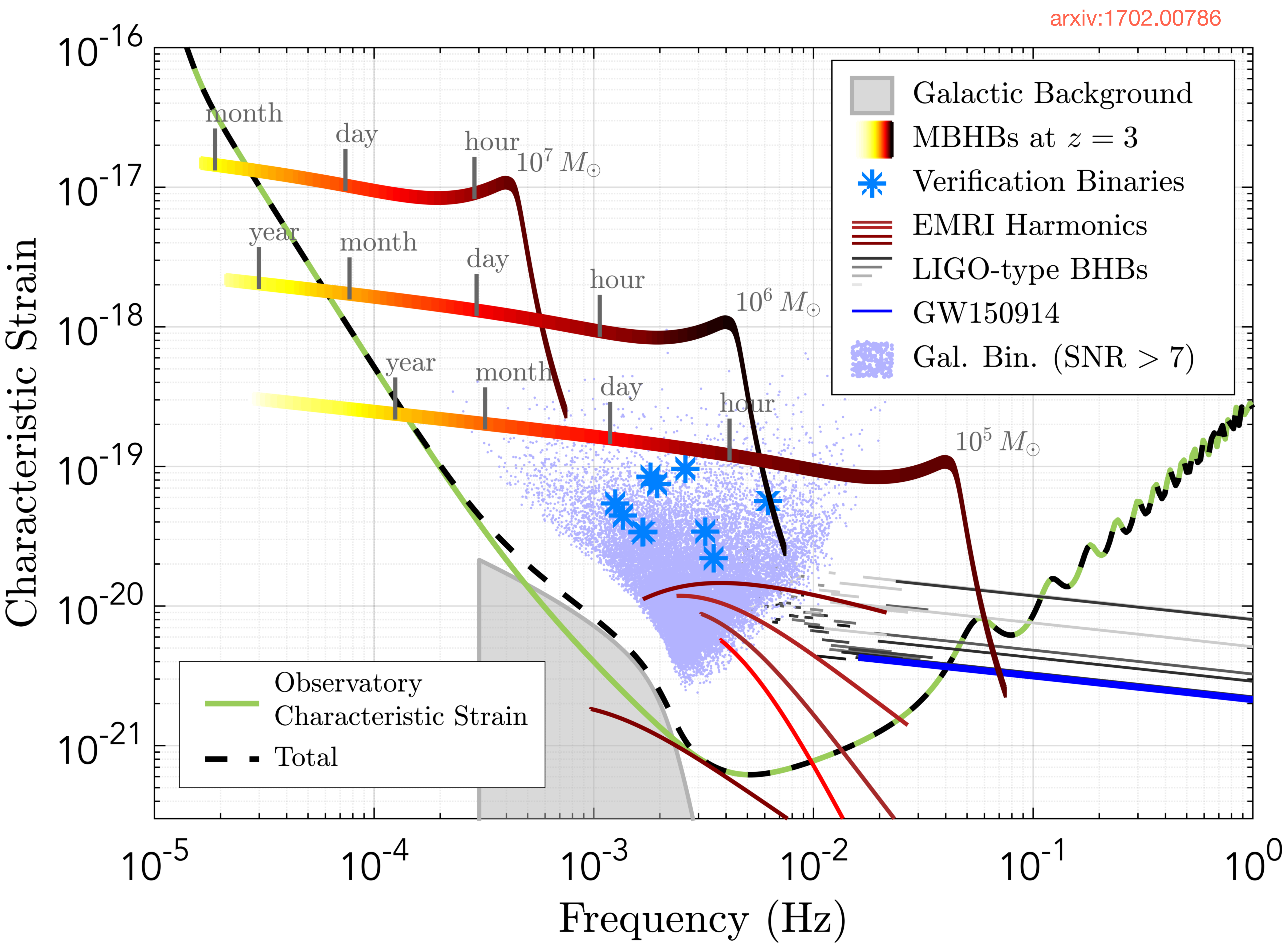
Stochastic signals of Astrophysical origin

Important, because

- They will give us a lot of information about underlying population models.
- Challenge data analysis effort
  - Contribute to the noise, affect total *noise knowledge*.
- Complicates the search for signals of Cosmological origin.

- We will make a summary of what we expect for LISA.
- Discuss possible implications to Data Analysis.



arxiv:1702.00786
Characteristic Strain
Frequency (Hz)
10-16
10-17
10-18
10-19
10-20
10-21
10-5
10-4
10-3
10-2
10-1
100
month
day
hour
107 M⊙
year
month
day
hour
106 M⊙
year
month
day
hour
105 M⊙
Galactic Background
MBHBs at z = 3
Verification Binaries
EMRI Harmonics
LIGO-type BHBs
GW150914
Gal. Bin. (SNR > 7)
Observatory
Characteristic Strain
Total

So, LISA ☞ signal dominated, and

here is *a* list of potential sources:

- Compact Galactic binaries (GBs)
- Stellar Origin Black Hole binaries (SOBHBs)
- Supermassive Black Hole Binaries (SMBHBs)
- Extreme Mass Ratio Inspirals (EMRIs)
- Cosmological signals.

How to get down to the residuals?

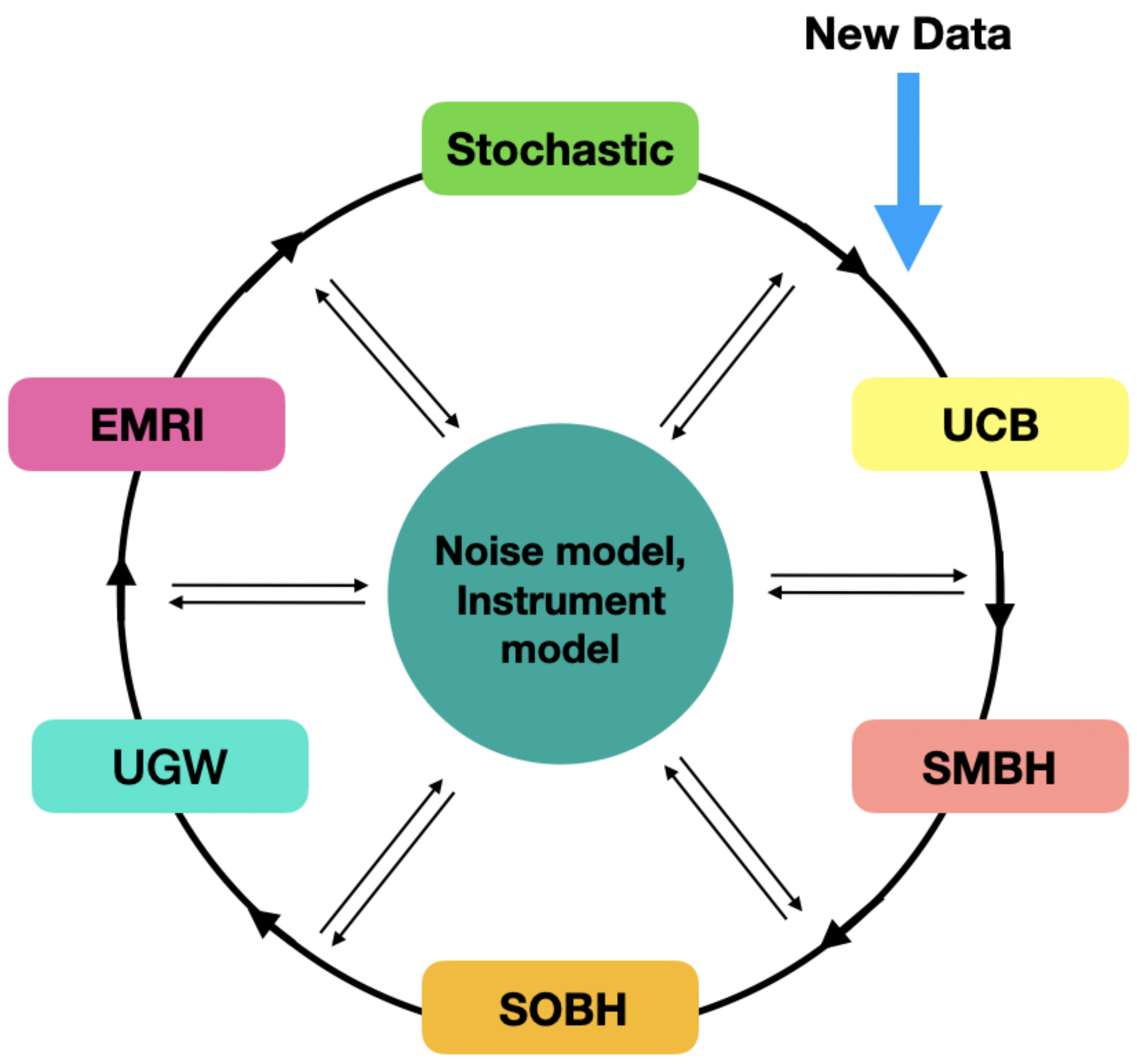
Simulate both the population signals & LISA data analysis.

For different types of astrophysical sources we need to

1. Get the different population models.
2. Simulate wave-forms in the LISA band.
3. Perform data analysis, and get resolved sources and stochastic signals.

Global fit

A necessary scheme for LISA data analysis

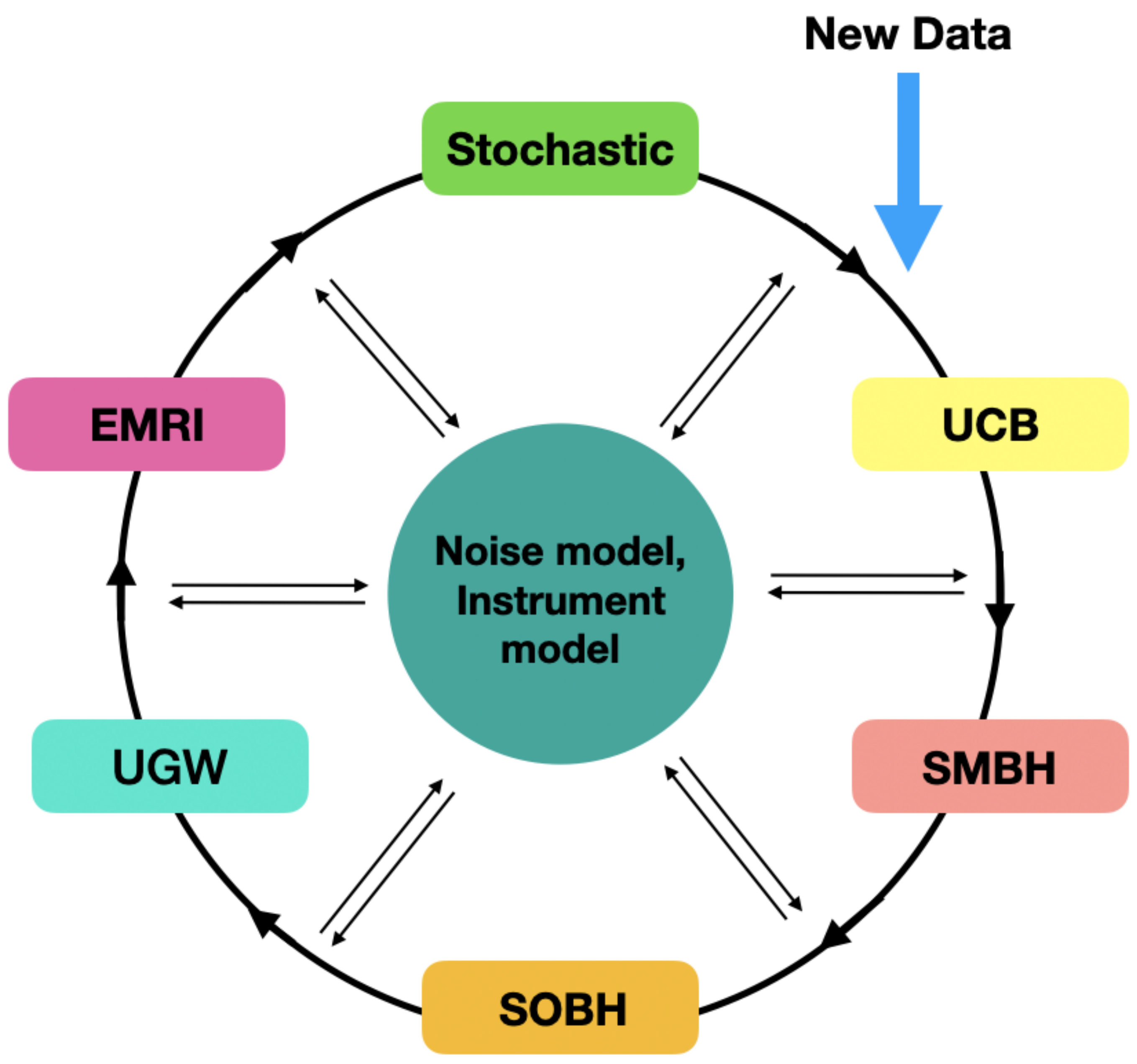


Littenberg+ 2021

- Many types of sources.
- Iterate among them, try to search in the data.
- Pass residuals around
- Update our instrument knowledge.

Global fit

A necessary scheme for LISA data analysis



Littenberg+ 2021

- Many types of sources.
- Iterate among them, try to search in the data.
- Pass residuals around
- Update our instrument knowledge.

- So far we are based to matched filtering, and costly MCMC algorithms.
- Forbid us from exploring scenarios of different populations yielding stochastic signals.

Q. Baghi: LISA data analysis: from measurements to discoveries

O Hartig: On the effectiveness of null TDI channels as instrument noise monitors in LISA

M Muratore: Impact of the noise knowledge uncertainty for the science exploitation of cosmological and astrophysical stochastic gravitational wave background with LISA

M Lilley: Stochastic gravitational wave background reconstruction for a non-equilateral and unequal-noise LISA constellation

R Rosati: Recovering Primordial Stochastic Gravitational Wave Backgrounds in the LISA Global Fit

H Inchauspé: Doppler-boosted anisotropies of SGWB and LISA: a lever of separation from instrumental and confusion noise.

“Simulating” the Data Analysis of LISA

Instead we can “simulate” the LISA data analysis…

Using a scheme based on simple SNR criteria.

- Iterative process, “loose” criteria about the detection of each source, i.e. a SNR limit.
- For example, we define a SNR0, for which if a given source surpasses it, then we subtract it. Basically loop over the known catalogue.

NK+ 2021,
Digman & Cornish 2022
S Nissanke+ 2011
Crowder & Cornish 2007
Timpano+ 2006

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Using a scheme based on simple SNR criteria.

- Iterative process, "loose" criteria about the detection of each source, i.e. a SNR limit.
- For example, we define a SNR0, for which if a given source surpasses it, then we subtract it. Basically loop over the known catalogue.
- Fast.
- Generic! Applicable to virtually any type of source (being careful though)
- Idealized:
  - ▼ No source overlap problem.
  - ▼ Perfect subtraction ☞ perfect residuals.
  - ▼ Noise is ideal as well.

NK+ 2021,
Digman & Cornish 2022
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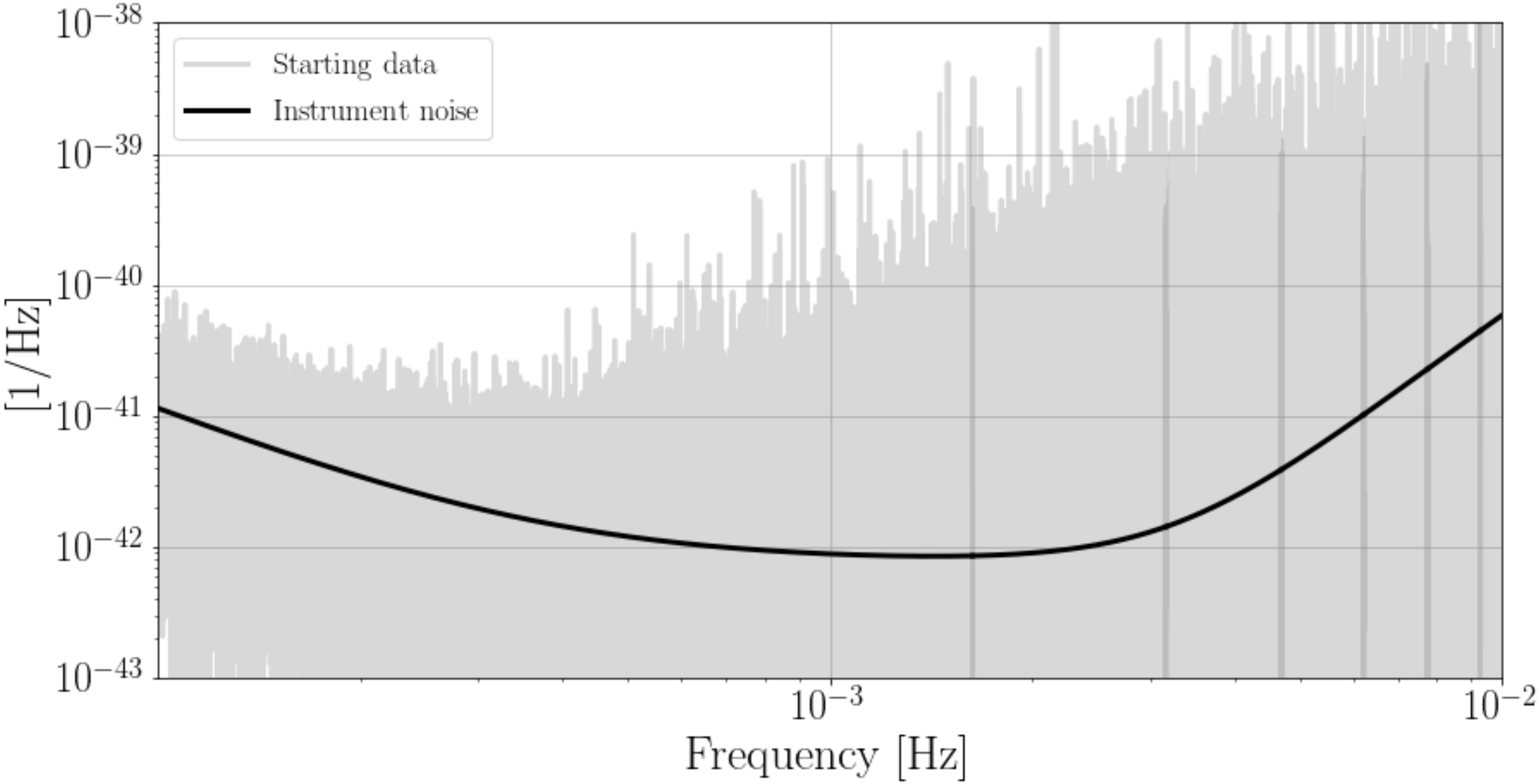
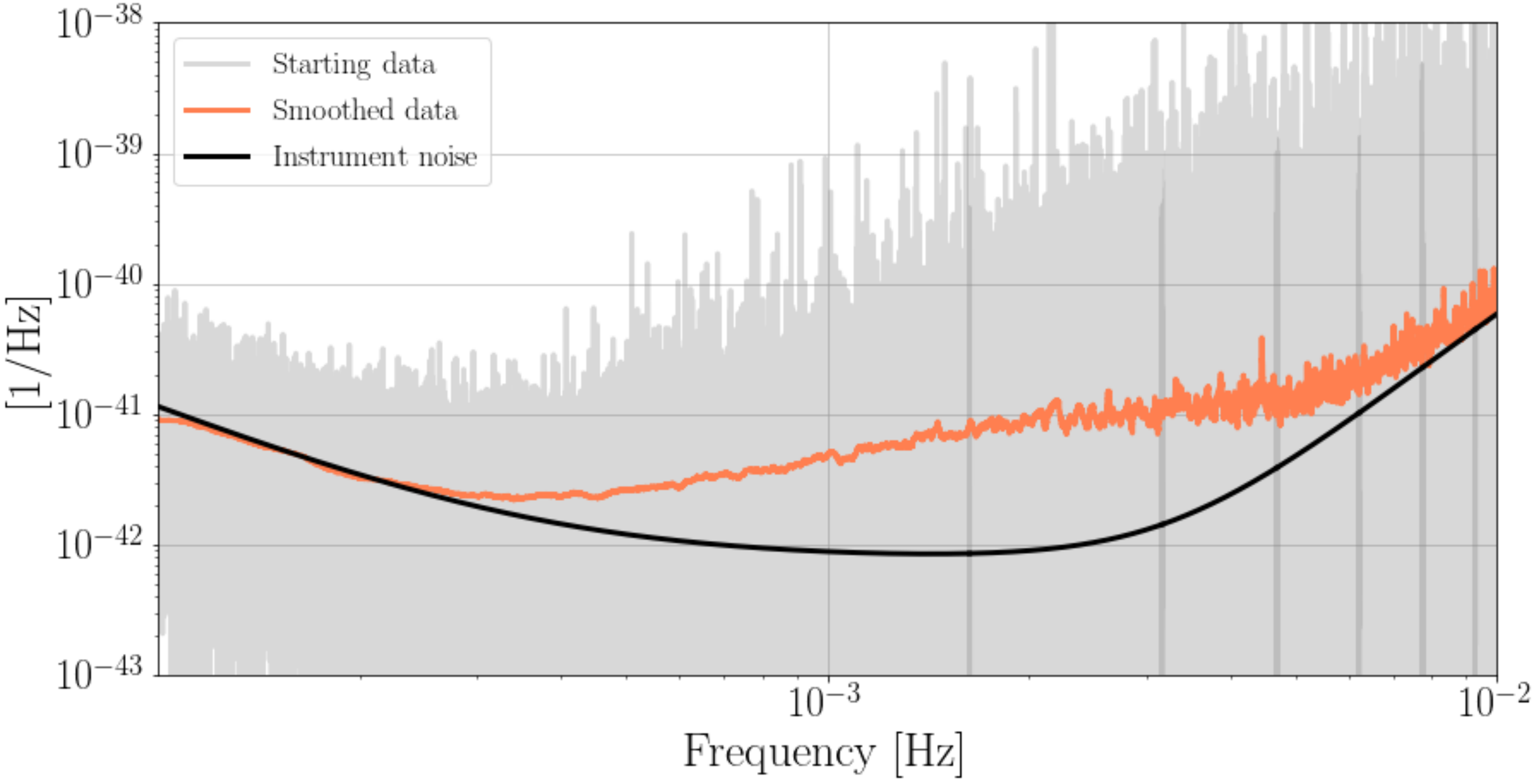
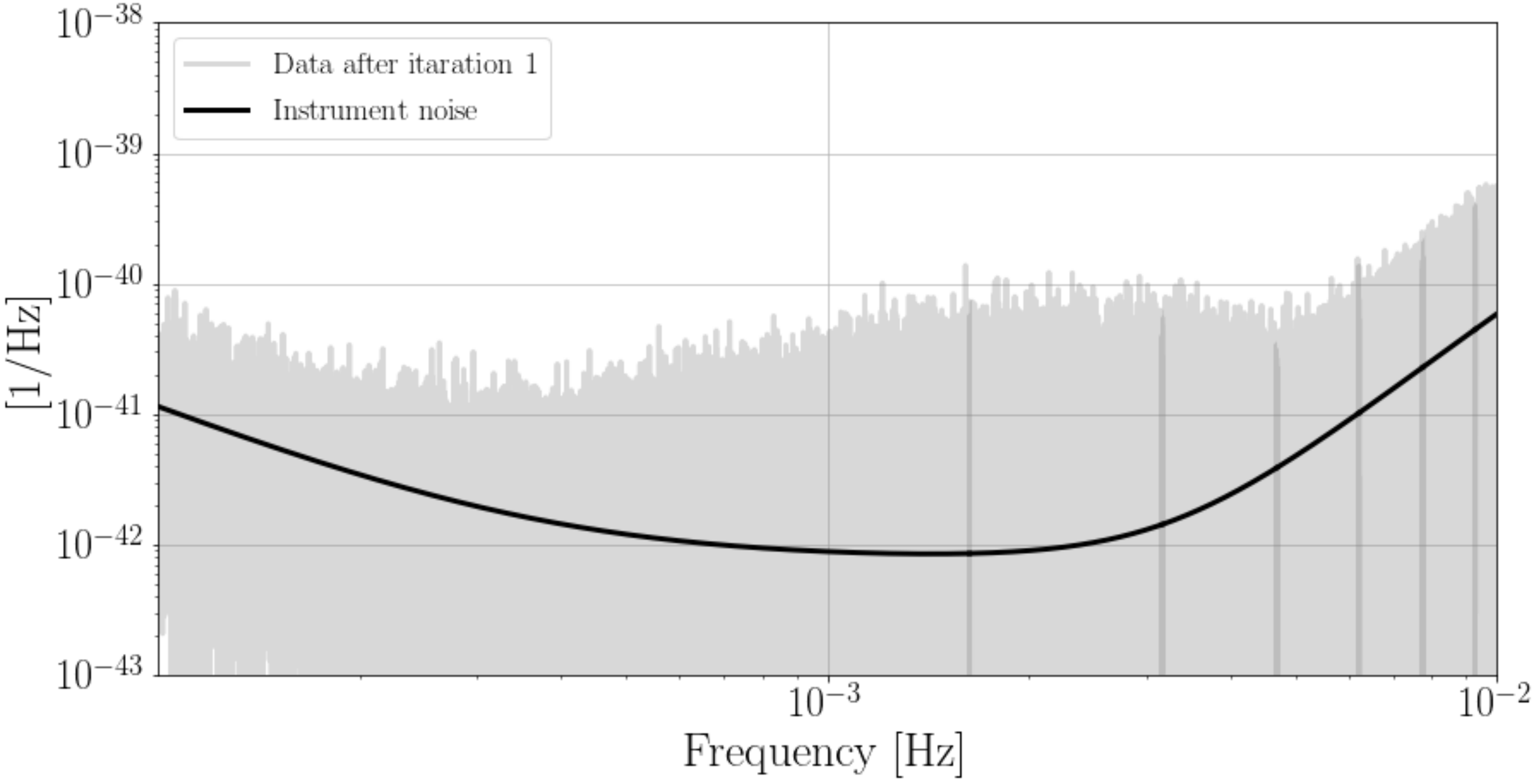
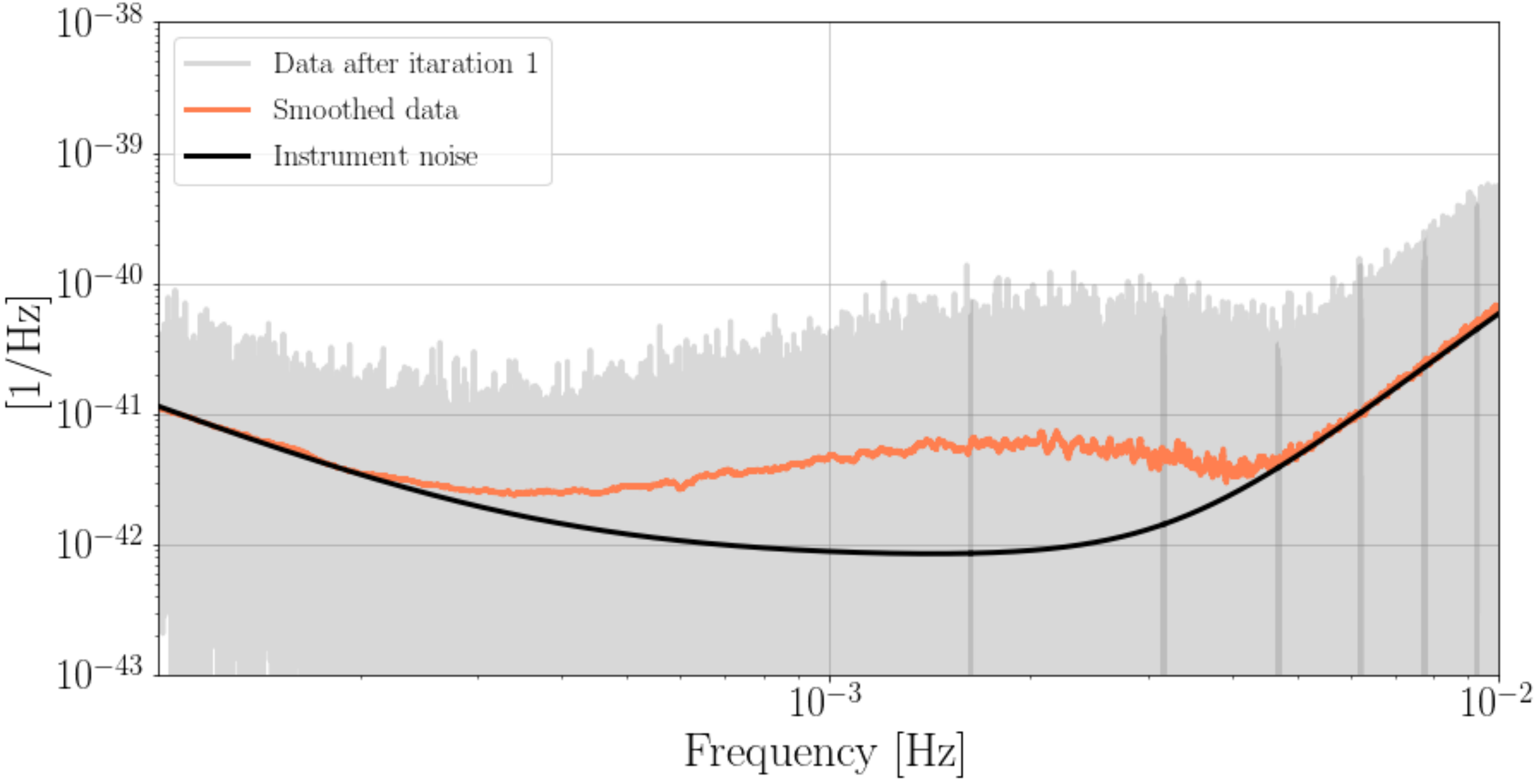

Starting data
Instrument noise
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
[1/Hz]
10^{-3}
10^{-2}
Frequency [Hz]



Starting data
Smoothed data
Instrument noise
[1/Hz]
Frequency [Hz]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-3}
10^{-2}


Data after itaration 1
Instrument noise
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
[1/Hz]
10^{-3}
10^{-2}
Frequency [Hz]



Data after itaration 1
Smoothed data
Instrument noise
[1/Hz]
10^{-38}
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10^{-43}
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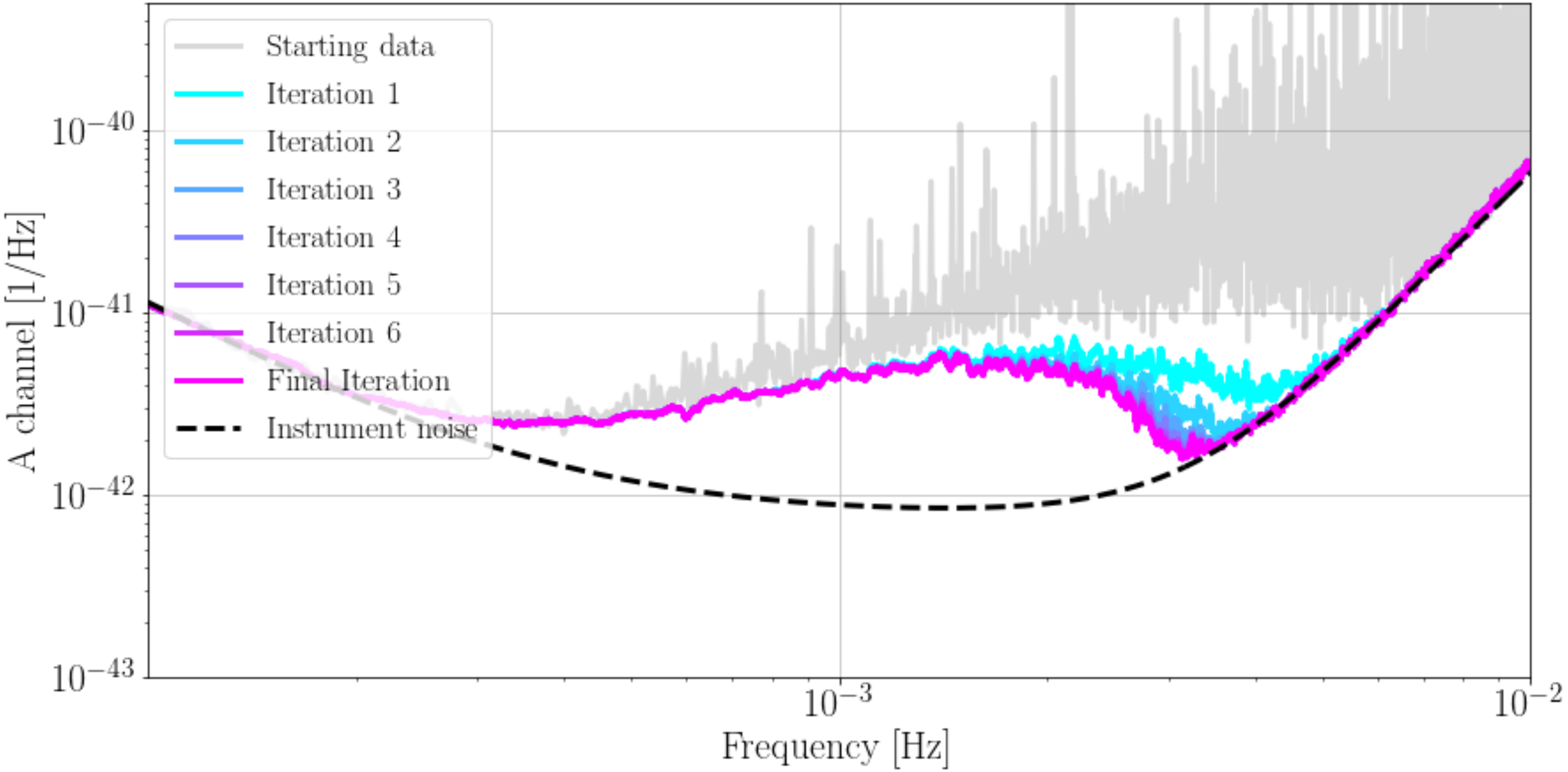
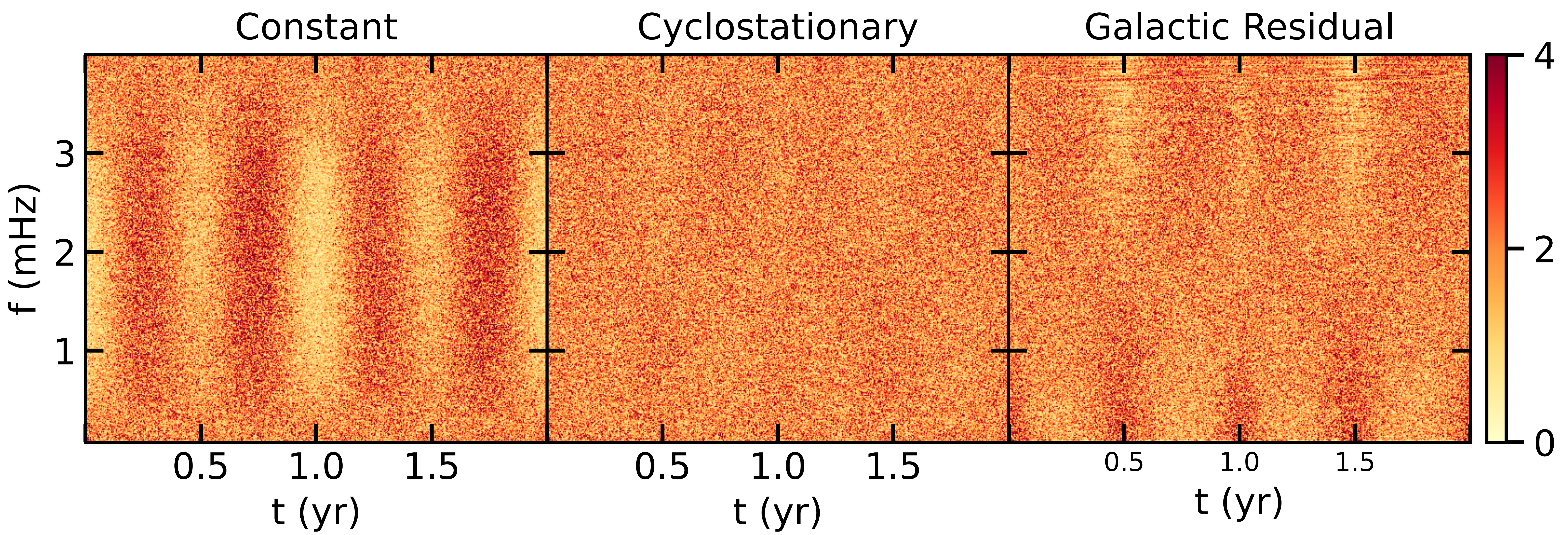
Frequency [Hz]



Starting data
Iteration 1
Iteration 2
Iteration 3
Iteration 4
Iteration 5
Iteration 6
Final Iteration
Instrument noise
10^{-40}
10^{-41}
10^{-42}
10^{-43}
A channel [1/Hz]
10^{-3}
10^{-2}
Frequency [Hz]

Pros and cons of this method

- ▲ Fast & Generic.
- ▲ Can combine multiple populations from source types.
- ▼ Has drawbacks, i.e. Idealized (unrealistic noise & simplifying assumptions).
- ▶ Improvements have been proposed [Digman & Cornish 2022].



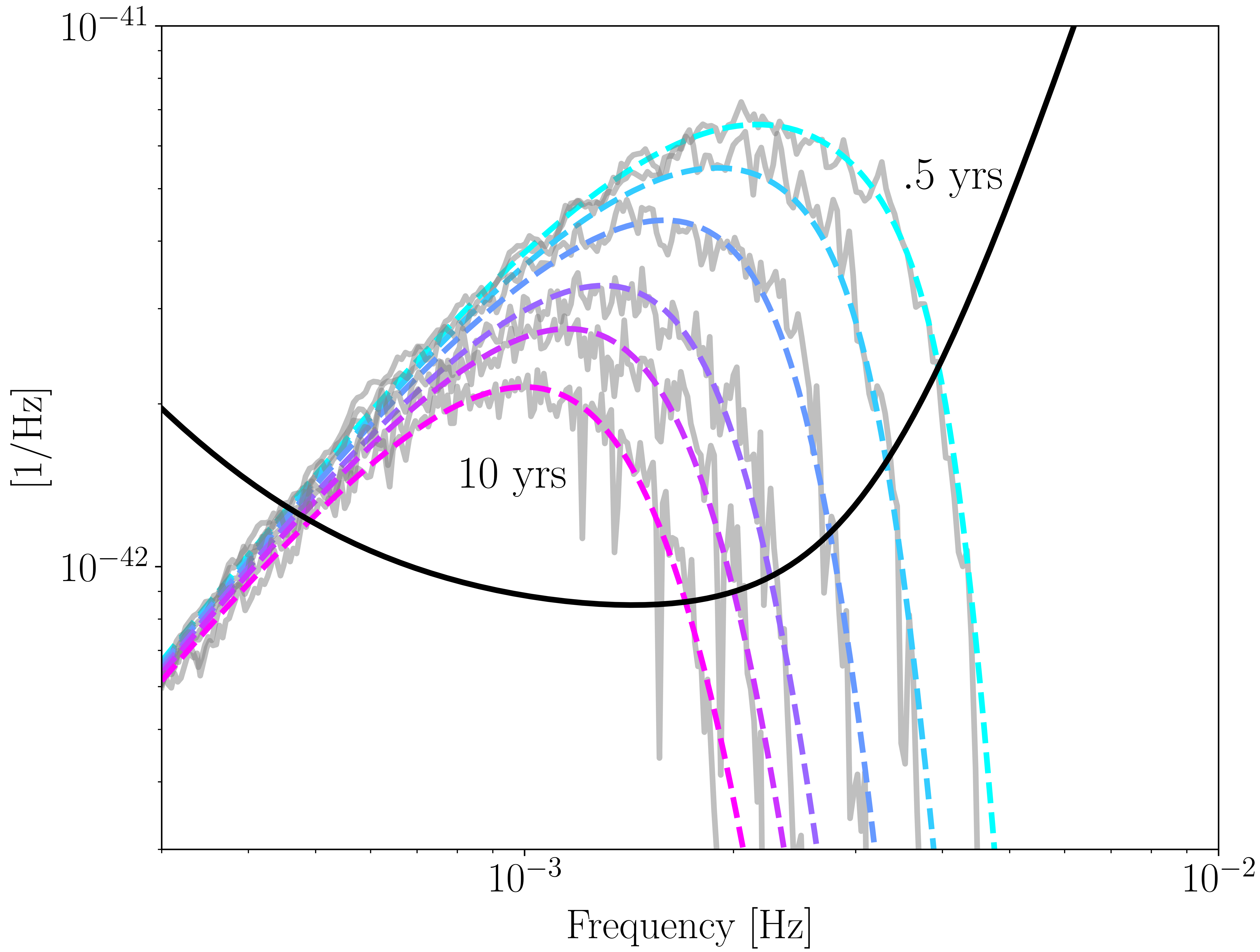
A. Compact Galactic Binaries

A.0. On the Galactic binaries

- Compact binaries with orbital period ~<1 hr.
- Mostly WD-WDs, but other objects there as well!
- Multi-messenger laboratories.
- Potential Triplets detections.
  [Danielski+ 2019, Tamanini & Danielski 2019, Katz+ 2022]

A.1. On DWDs

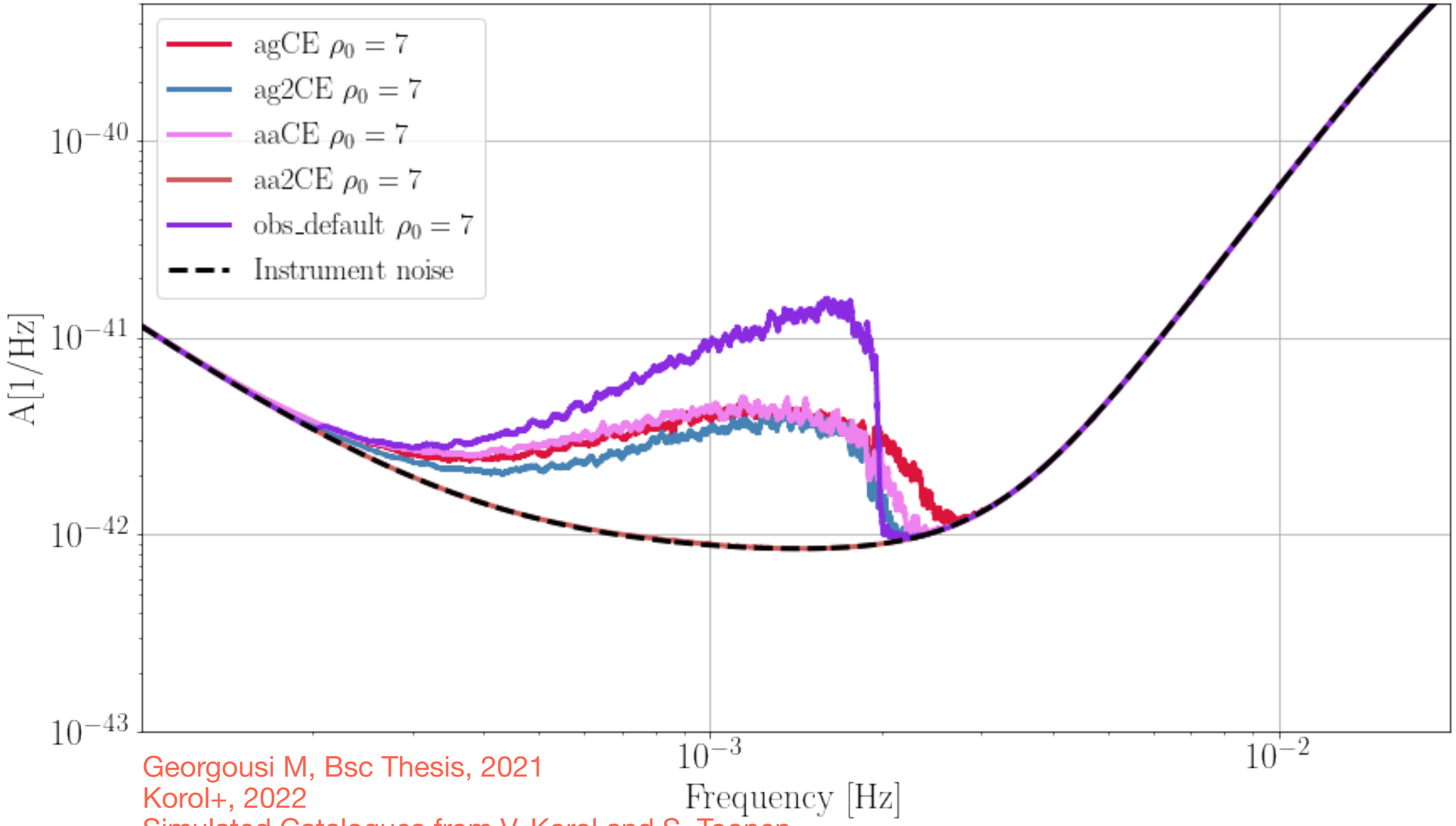
- Depending on the population model, we resolve O(10^4) sources.
- More data ☞ more resolvable sources.
- Cyclo-stationary stochastic signal.
- Main reason we need the global fit!
- Spectral shape: information about properties of Galaxy, and its evolution history.
- Background from Extragalactic WD binaries?
[Korol+ 2020, Farmer & Phinney 2003]



NK+ 2021

A.1. On DWDs

- Very important: Spectral shape depends on the underlying population model!



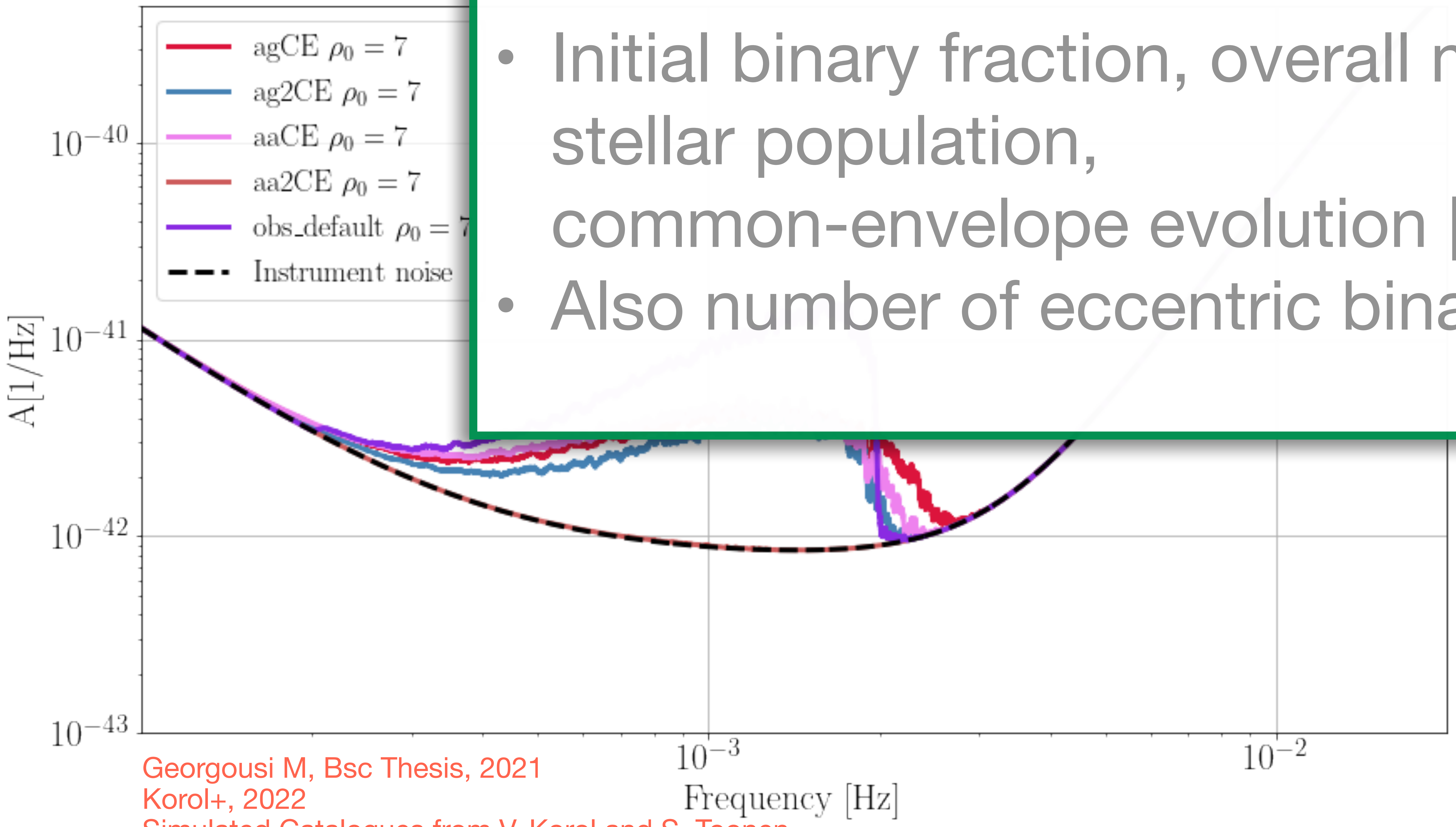
Georgousi M, Bsc Thesis, 2021
Korol+, 2022
Simulated Catalogues from V. Korol and S. Toonen

A.1. On DWDs

- Very important: Spectral s

Spectral shape depends on population!

- Initial binary fraction, overall mass, stellar population, common-envelope evolution […]
- Also number of eccentric binaries?



Georgousi M, Bsc Thesis, 2021
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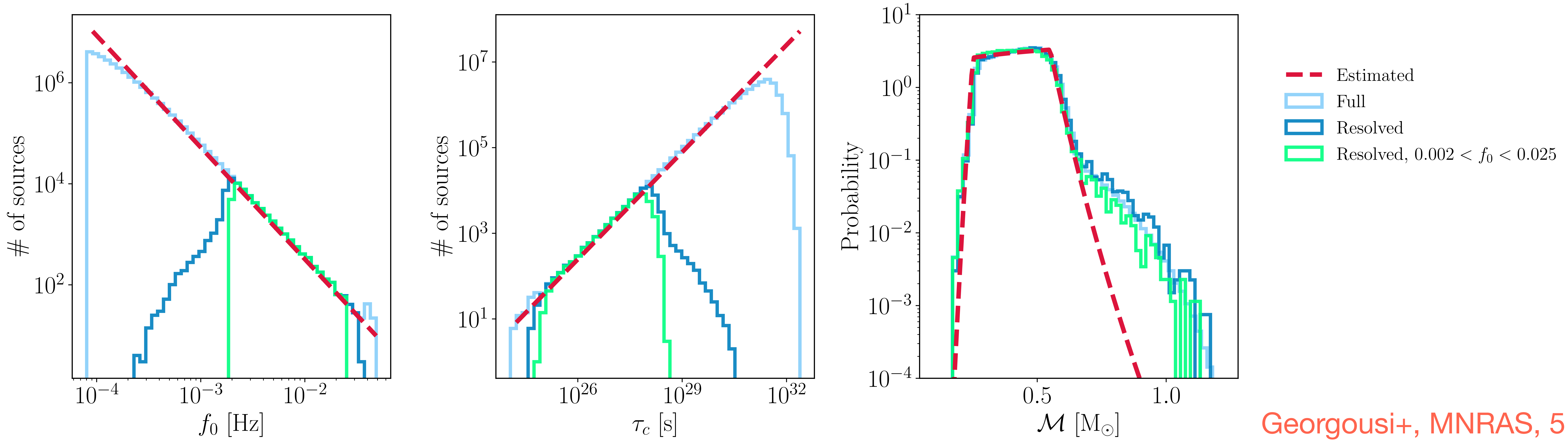
A.1. On DWDs

- Use resolved sources and a hierarchical Bayesian analysis to get information about the population properties.

$$p(\vec{\theta}, \vec{\beta}|d) = \frac{\mathcal{L}(d|\vec{\theta})\,p(\vec{\theta}|\vec{\beta})\,p(\vec{\beta})}{p(d)}$$



Georgousi+, MNRAS, 519, 2, 2023
Adams+, PRD, 86, 124032, 2012

B. Stellar-mass Black Holes

B. On the stellar-mass black holes

- LVK data has already given us a plethora of such sources.
- This is a good starting point for extrapolating to LISA.
- What we can to then is

1. Take the given population model(s)
2. Estimate the confusion signal of LISA, given the uncertainties from LVK.
3. Do a forecast on the resolvable sources.

B. On the stellar-mass black holes

- Two ways to actually get an estimate of the foreground signal

  1. Analytically

  2. Numerically

Babak+, arXiv:2304.06368, 2023

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- Two ways to actually get an estimate of the foreground signal

  1. Analytically

  2. Numerically

$$\Omega_{\mathrm{GW}}(f)h^2 = \frac{8\pi^{5/3}}{9}\frac{h^2}{H_0^2}f^{2/3}\int_0^\infty \mathrm{d}\mathcal{M}p(\mathcal{M}\,(m_1,m_2))\,\mathcal{M}^{5/3}\int_0^\infty \mathrm{d}R(z)\frac{(1+z)^{2/3}}{H(z)}$$

Babak+, arXiv:2304.06368, 2023
E. S. Phinney, 2001

B. On the stellar-mass black holes

- Two ways to actually get an estimate of the foreground signal

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$$\Omega_{\rm GW}(f)h^2 \propto f^{2/3}$$

And the population details tune the amplitude.

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  2. Numerically

$$\Omega_{\rm GW}(f)h^2 \propto f^{2/3}$$

Perigois+ 2022
Phinney 2001
Sesana+ 2016
Perigois+ 2021

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- Two ways to actually get an estimate of the foreground signal

    1. Analytically

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- Two ways to actually get an estimate of the foreground signal

  1. Analytically

  2. Numerically

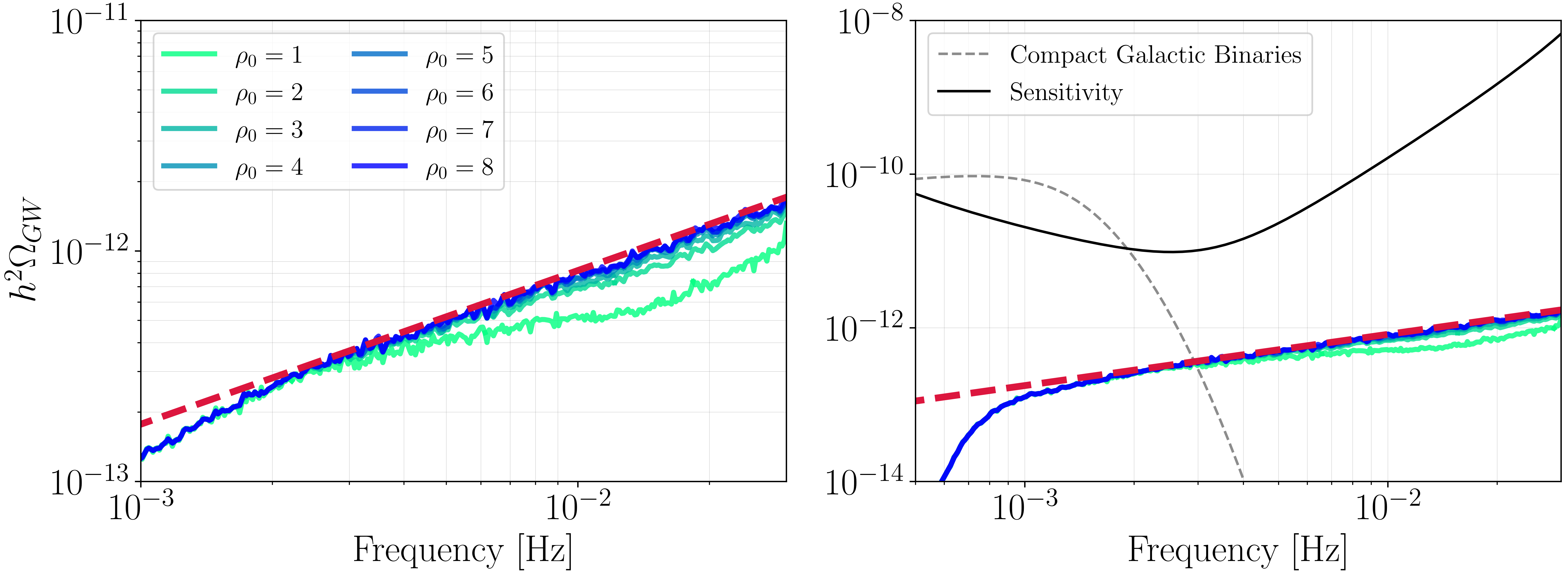
     - Choose an observational time (4 years).
     - Simulate catalogues (up to a z maximum, for practical reasons).
     - Use PhenomHM waveforms.
     - Set an SNR threshold for the detectable sources, and follow the iterative scheme.

B. On the stellar-mass black holes

- Two ways to actually get an estimate of the foreground signal

  1. Analytically

  2. Numerically



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- How detectable will this stochastic signal be with LISA?

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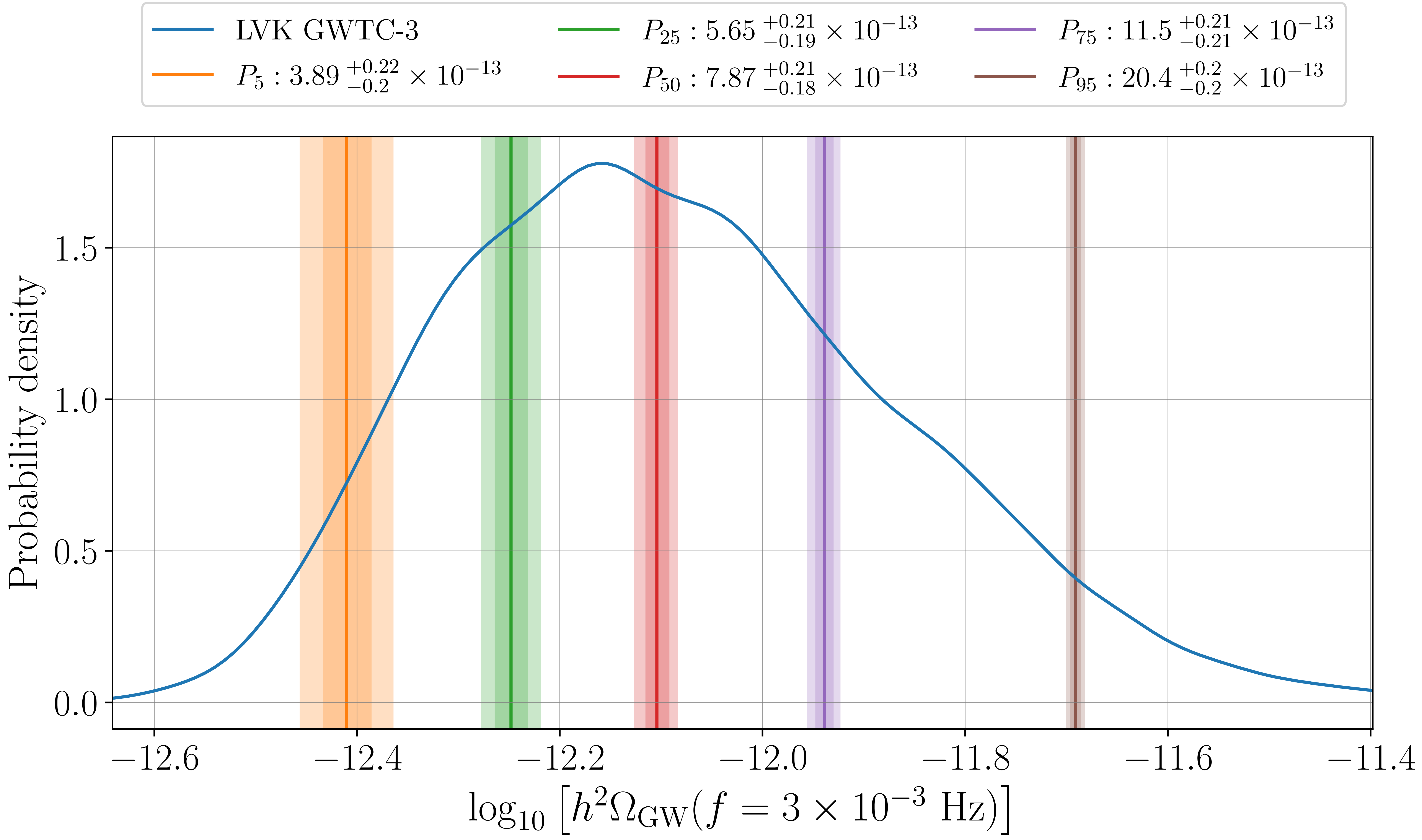

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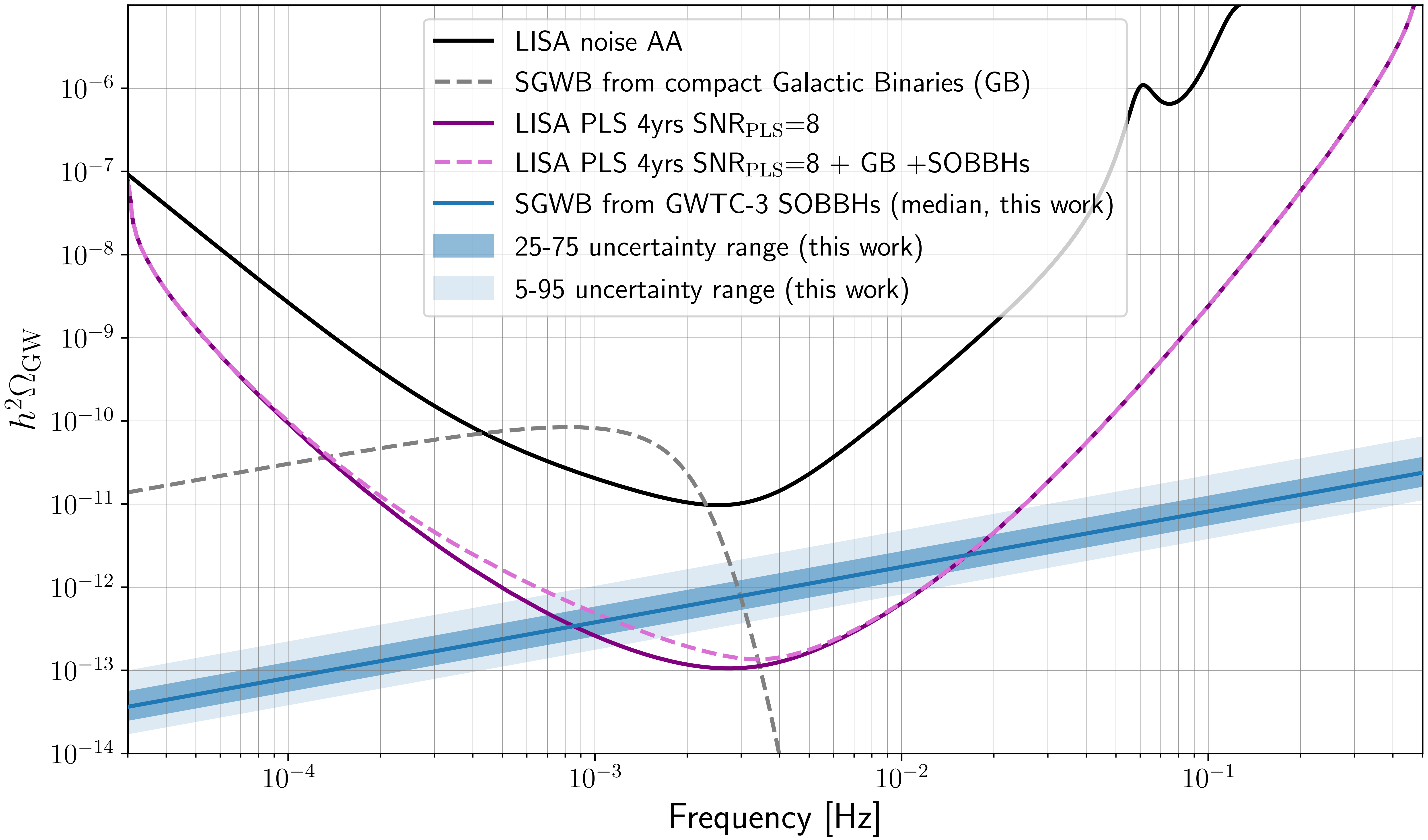

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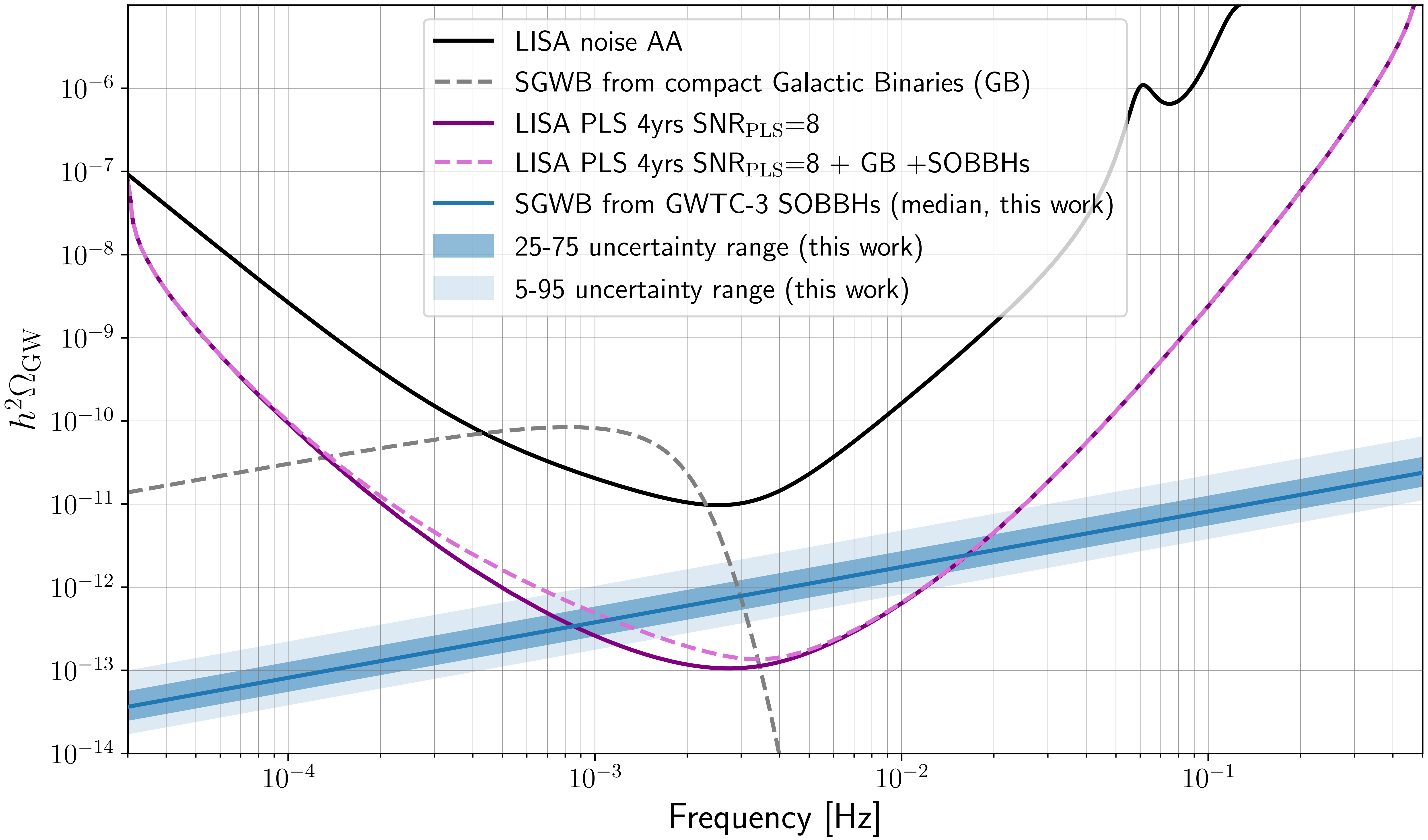
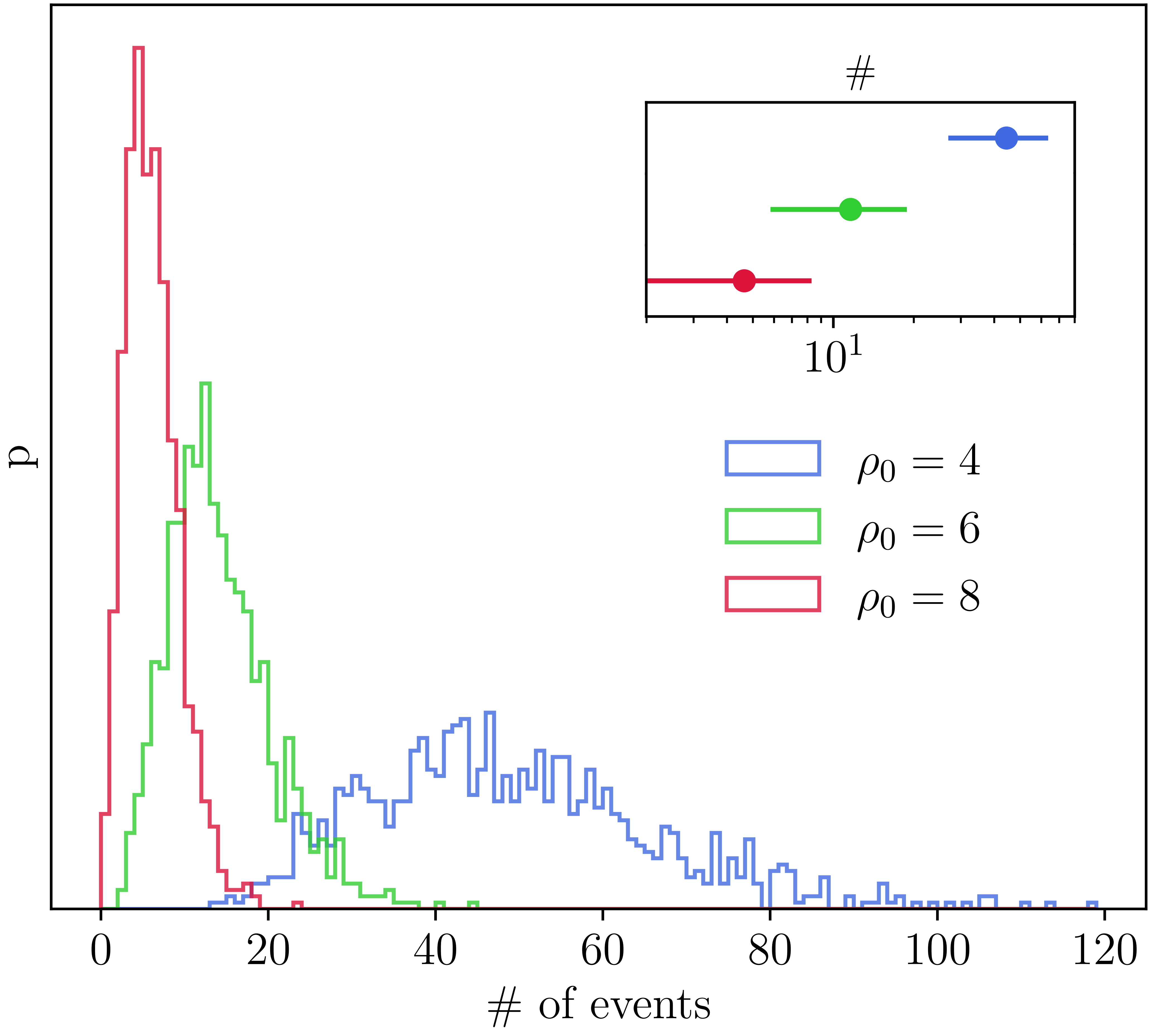


B. On the stellar-mass black holes

- What about the detectable sources?

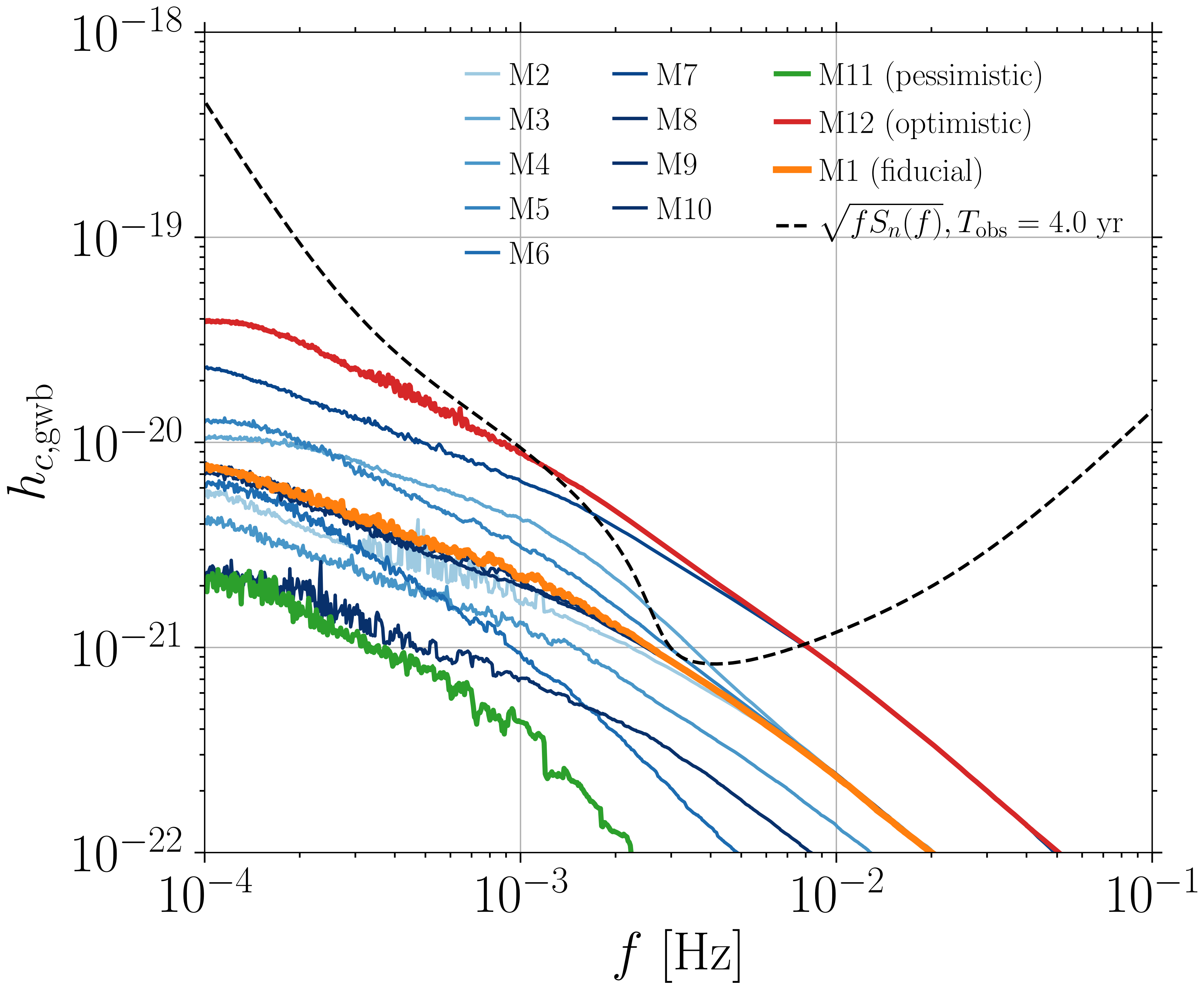


C. EMRIs

D. On Extreme Mass Ratio Inspirals

- From Bonetti & Sesana 2020 it was already shown that for some population models, we could expect a stochastic signal.
- Using simplified waveform models, estimated SNR for each harmonic.

Model	Mass function	MBH spin	Cusp erosion	M–σ relation	N_p	CO mass [$M_\odot$]	EMRI rate [yr^{-1}] Total	Detected (AKK)	Detected (AKS)
M1	Barausse12	a98	yes	Gultekin09	10	10	1600	294	189
M2	Barausse12	a98	yes	KormendyHo13	10	10	1400	220	146
M3	Barausse12	a98	yes	GrahamScott13	10	10	2770	809	440
M4	Barausse12	a98	yes	Gultekin09	10	30	520	260	221
M5	Gair10	a98	no	Gultekin09	10	10	140	47	15
M6	Barausse12	a98	no	Gultekin09	10	10	2080	479	261
M7	Barausse12	a98	yes	Gultekin09	0	10	15800	2712	1765
M8	Barausse12	a98	yes	Gultekin09	100	10	180	35	24
M9	Barausse12	aflat	yes	Gultekin09	10	10	1530	217	177
M10	Barausse12	a0	yes	Gultekin09	10	10	1520	188	188
M11	Gair10	a0	no	Gultekin09	100	10	13	1	1
M12	Barausse12	a98	no	Gultekin09	0	10	20000	4219	2279

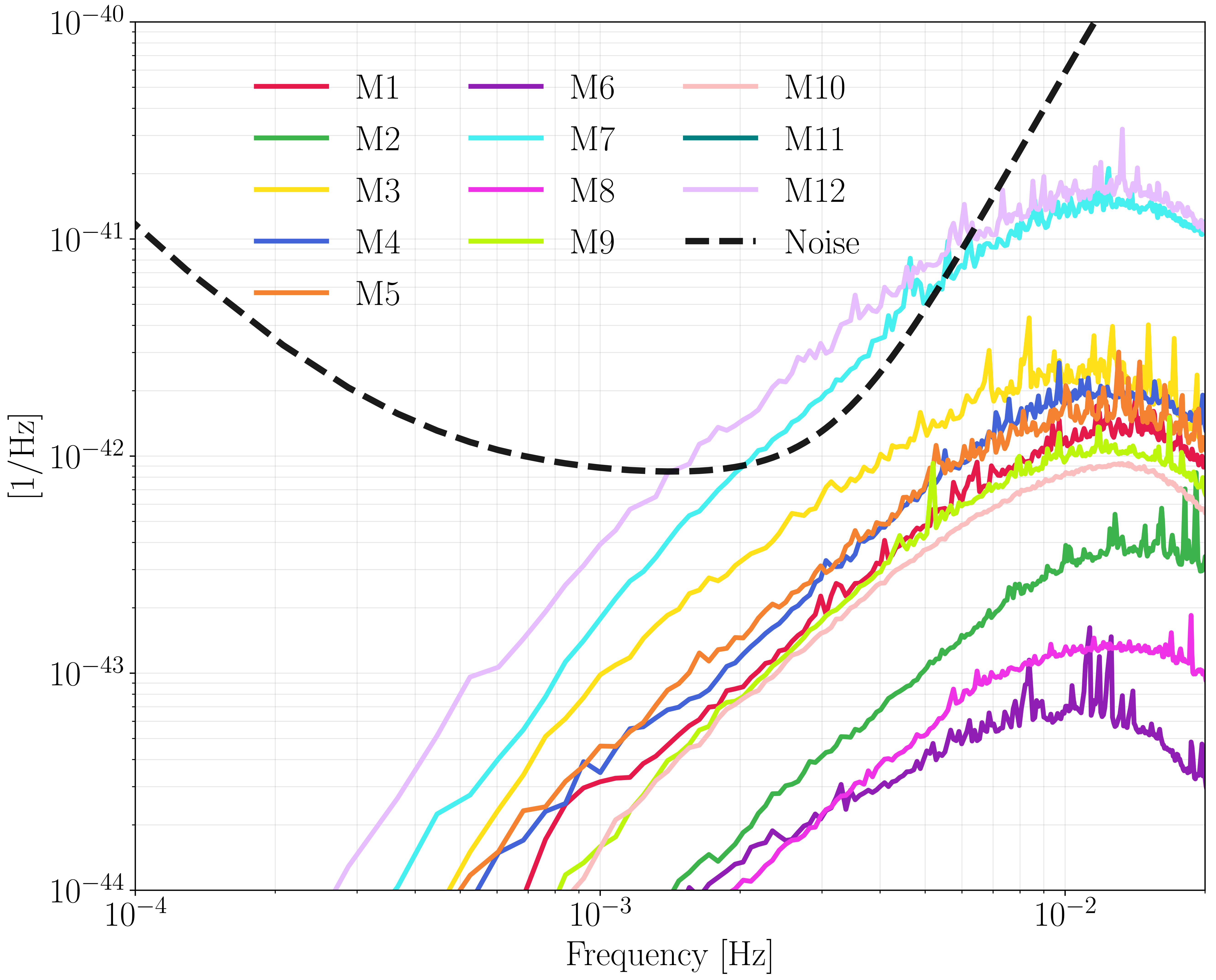


D. On Extreme Mass Ratio Inspirals

- We do as before! Simulate the population and LISA Data Analysis!
- Use the Augmented Analytic Kludge with 5PN trajectory model.
  - FEW package, [Katz+ 2021].
- Simulated all catalogues.
- Accelerate procedure: Leave out very weak signals (contribute to % level)
- Again, adopting an observation duration of 4 years, and
- assuming that sources with SNR>20 will be detectable.

See talk by Federico Pozzoli

D. On Extreme Mass Ratio Inspirals



See talk by Federico Pozzoli

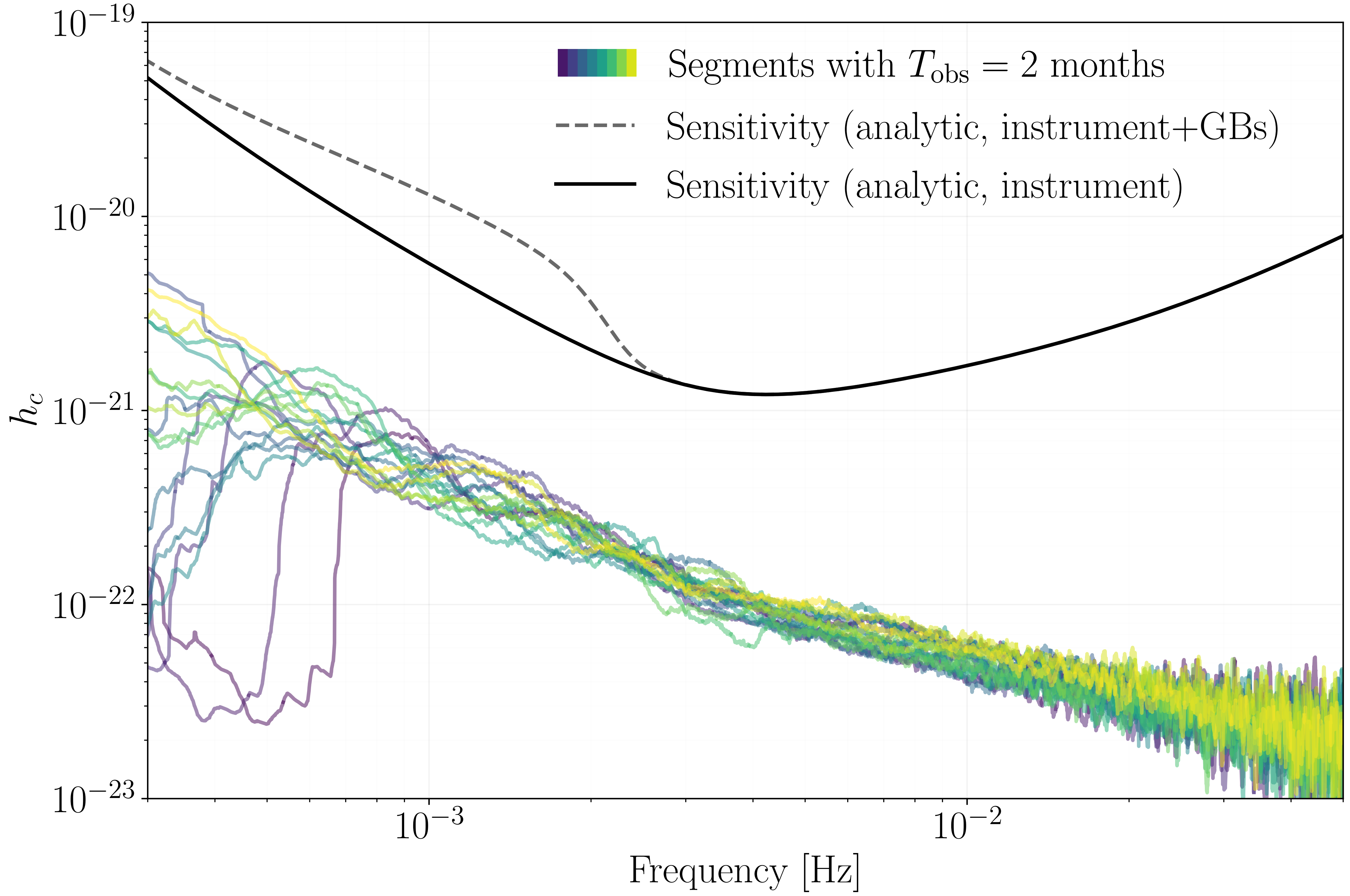
D. Massive Black Holes

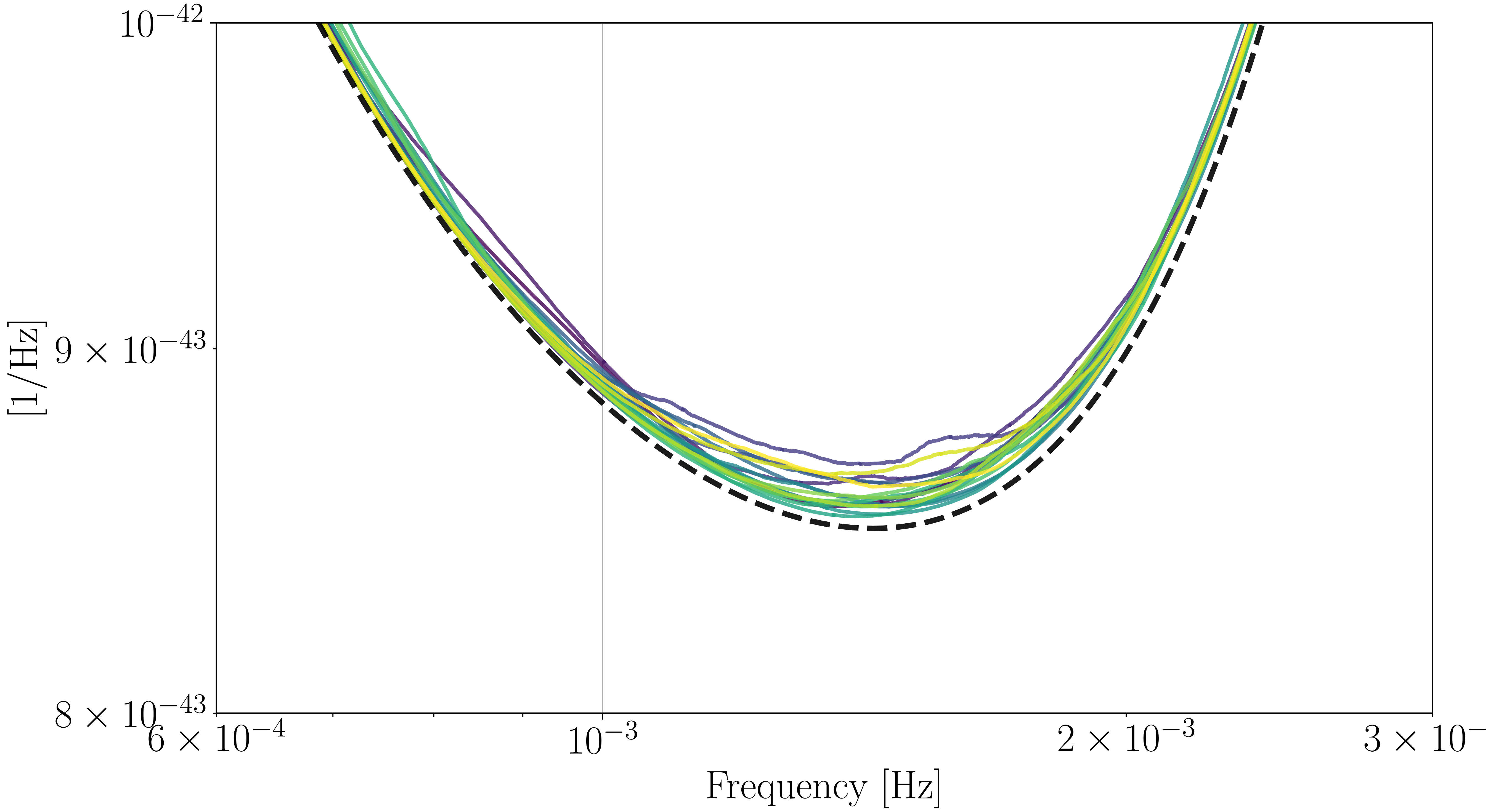
C. On the massive black holes

- To check this type of sources, we first need to consider the different population synthesis models
  - Pop III: adopts the light seeds scenario, while implementing a delay between when two host galaxies merge and when their MBHs merge.
  - Q3d: adopts the heavy seeds scenario, while also implementing a delay to merge MBHs after their host galaxies merged.
  - Q3nd: is similar to Q3d, but with no delay between the host galaxy mergers and MBH mergers.
- We do as before! Simulate the population and LISA Data Analysis!

Thesis of D. Langeroodi
Klein+ 2016, Sesana+ 2014, Barausse+ 2012

C. On the massive black holes

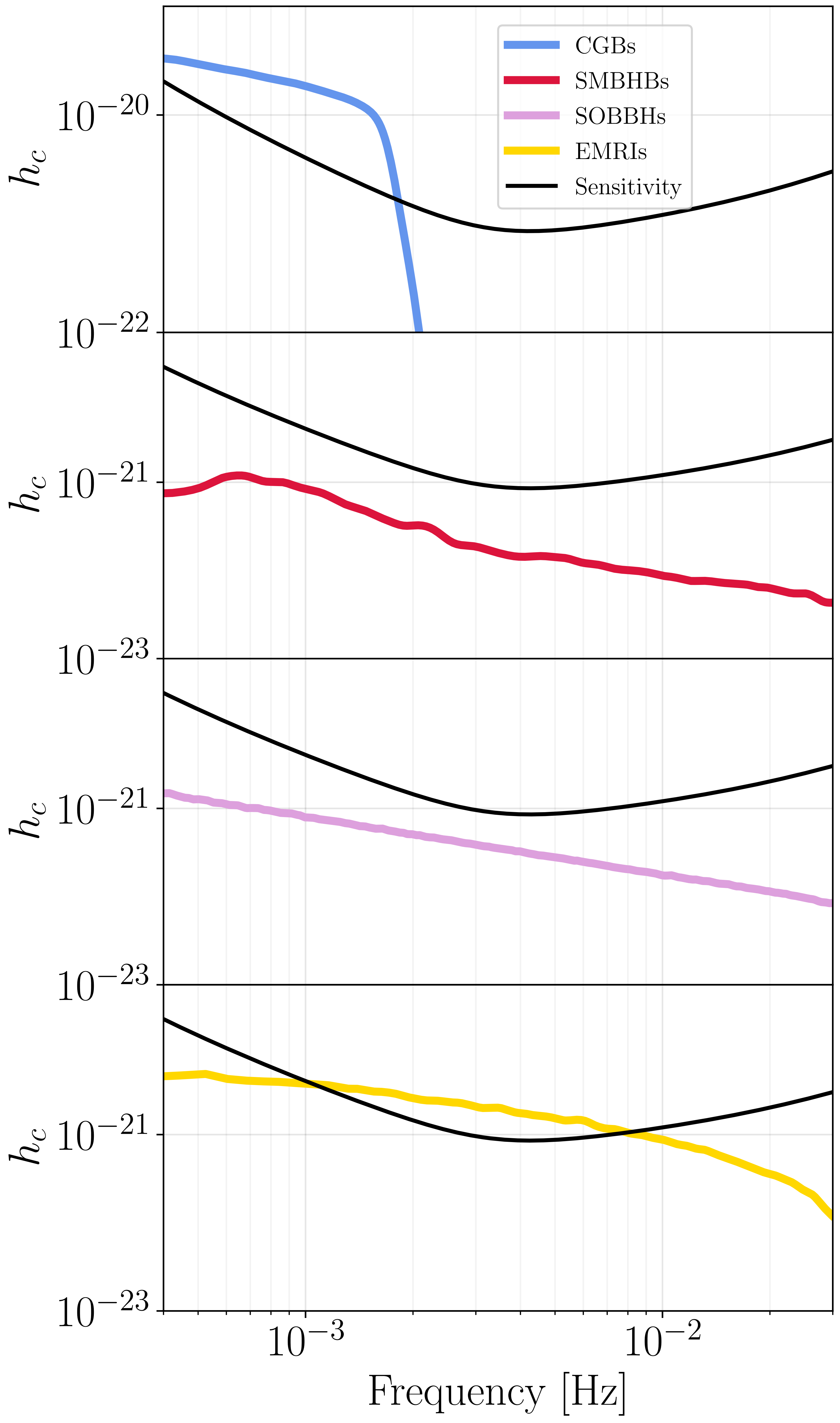


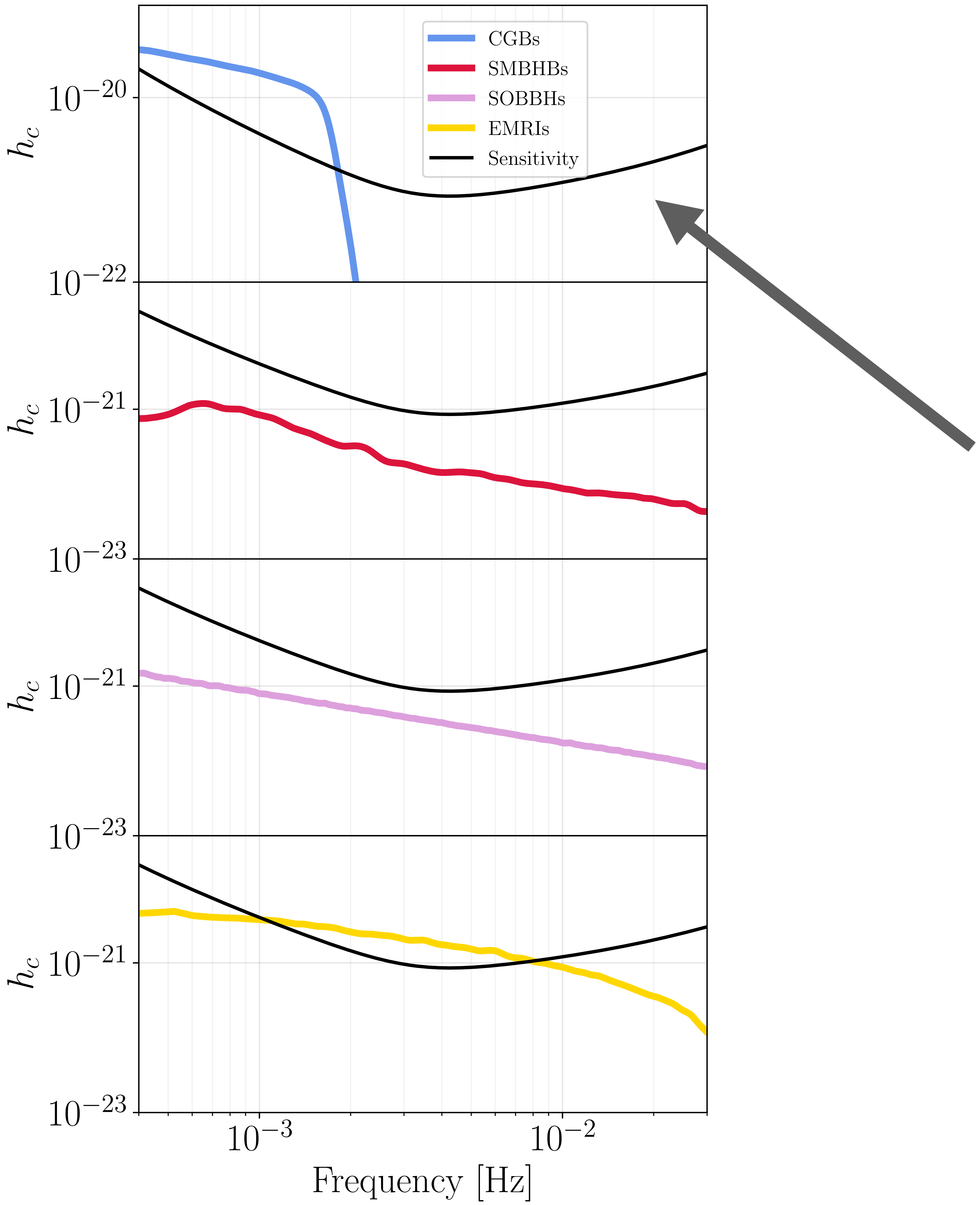


Thesis of D. Langeroodi

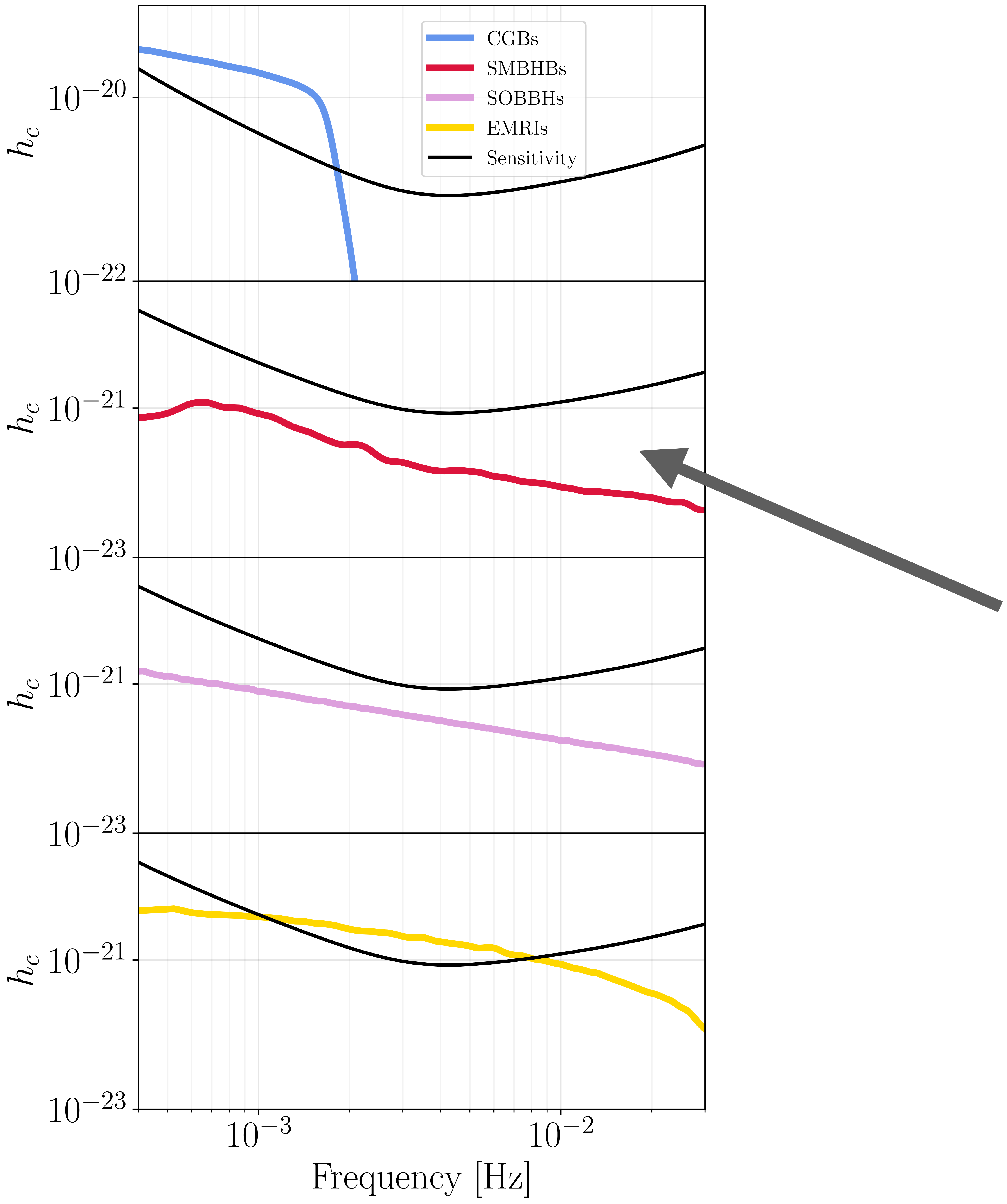
E. Adding everything together

(not cosmological signals though)

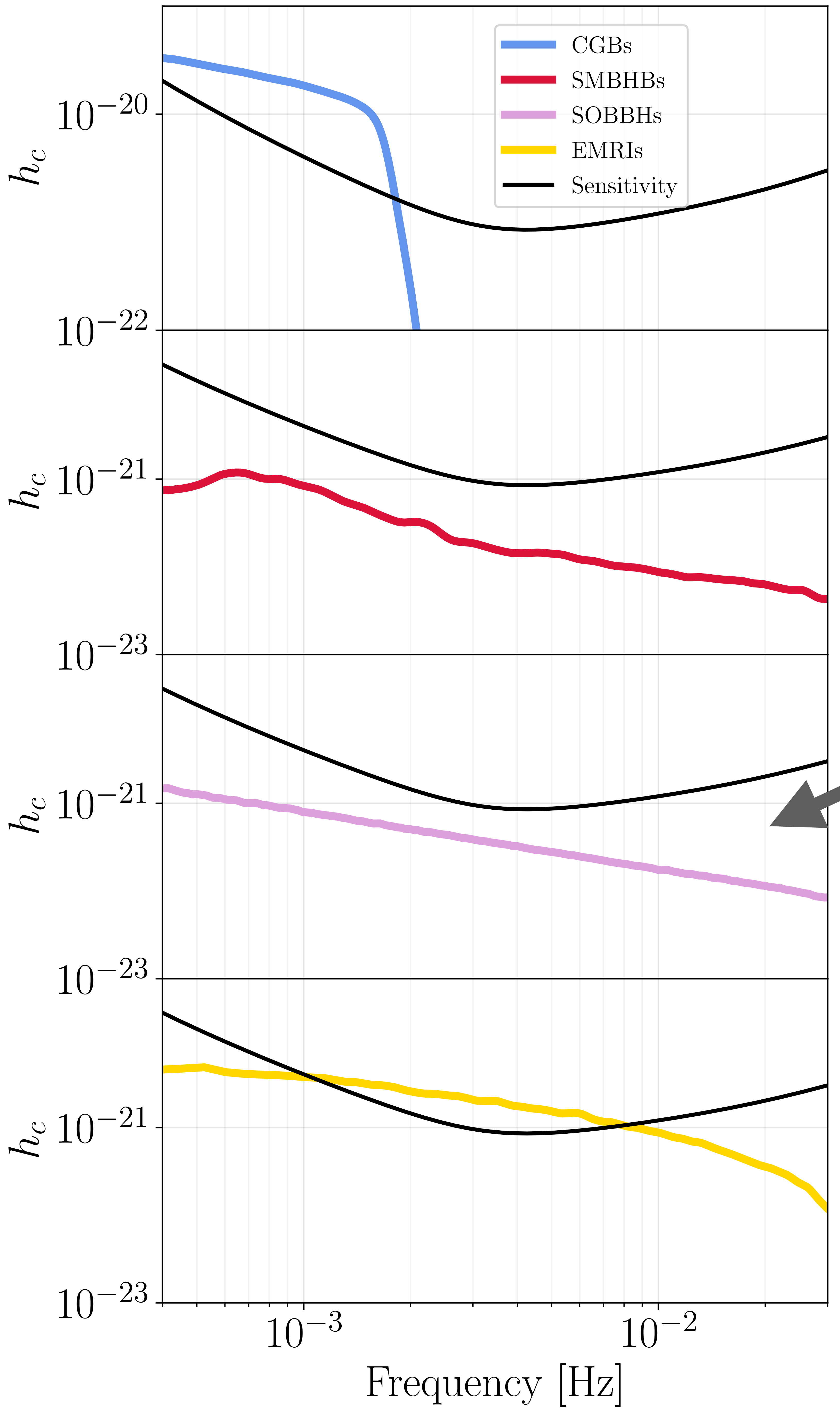

CGBs
SMBHBs
SOBBHs
EMRIs
Sensitivity
h_c
10^{-20}
10^{-22}
10^{-21}
10^{-23}
10^{-3}
10^{-2}
Frequency [Hz]



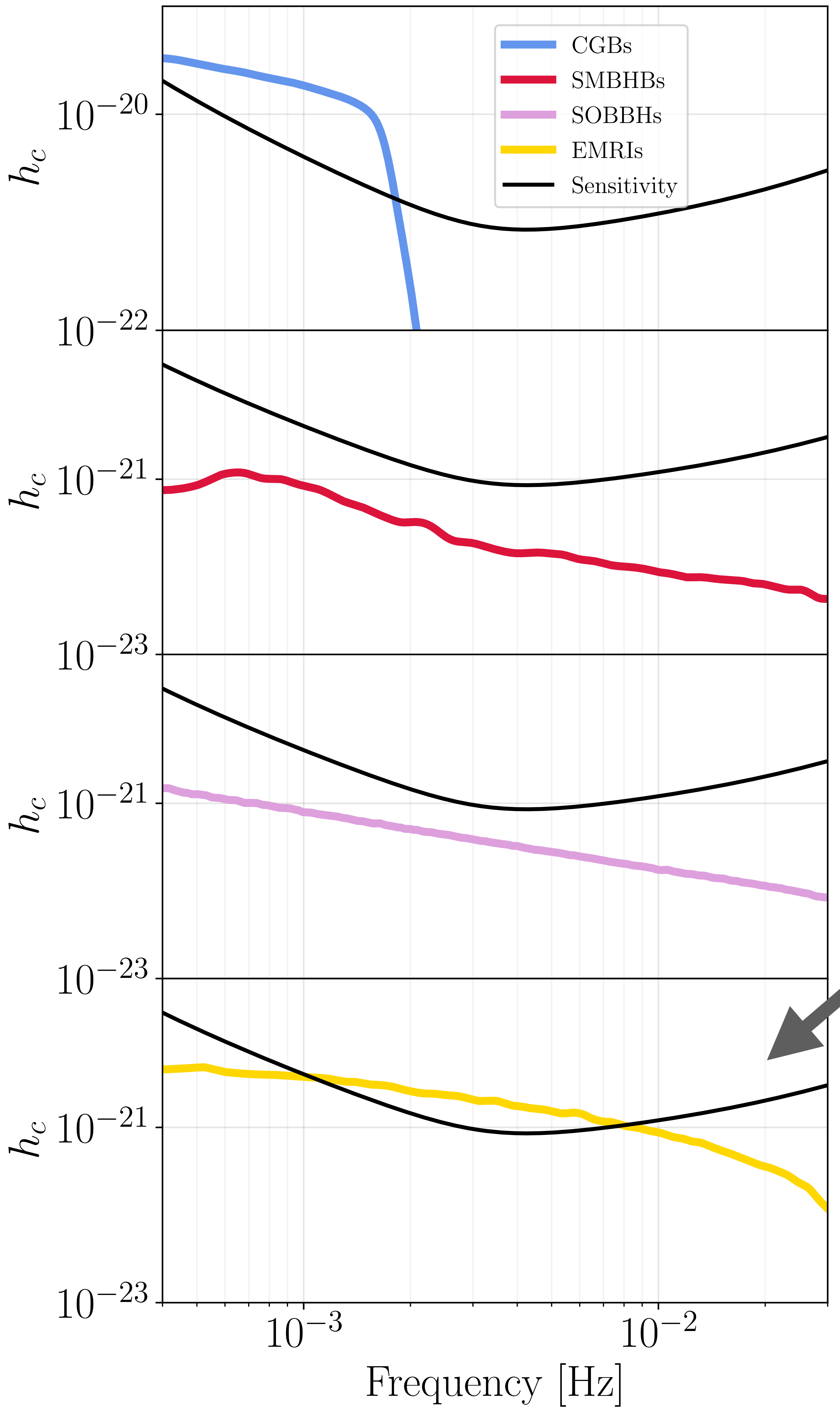
- Non-stationary (cyclo-stationary)
- Anisotropic
- Dominating below ~ 0.3 mHz
- Particular spectral shape



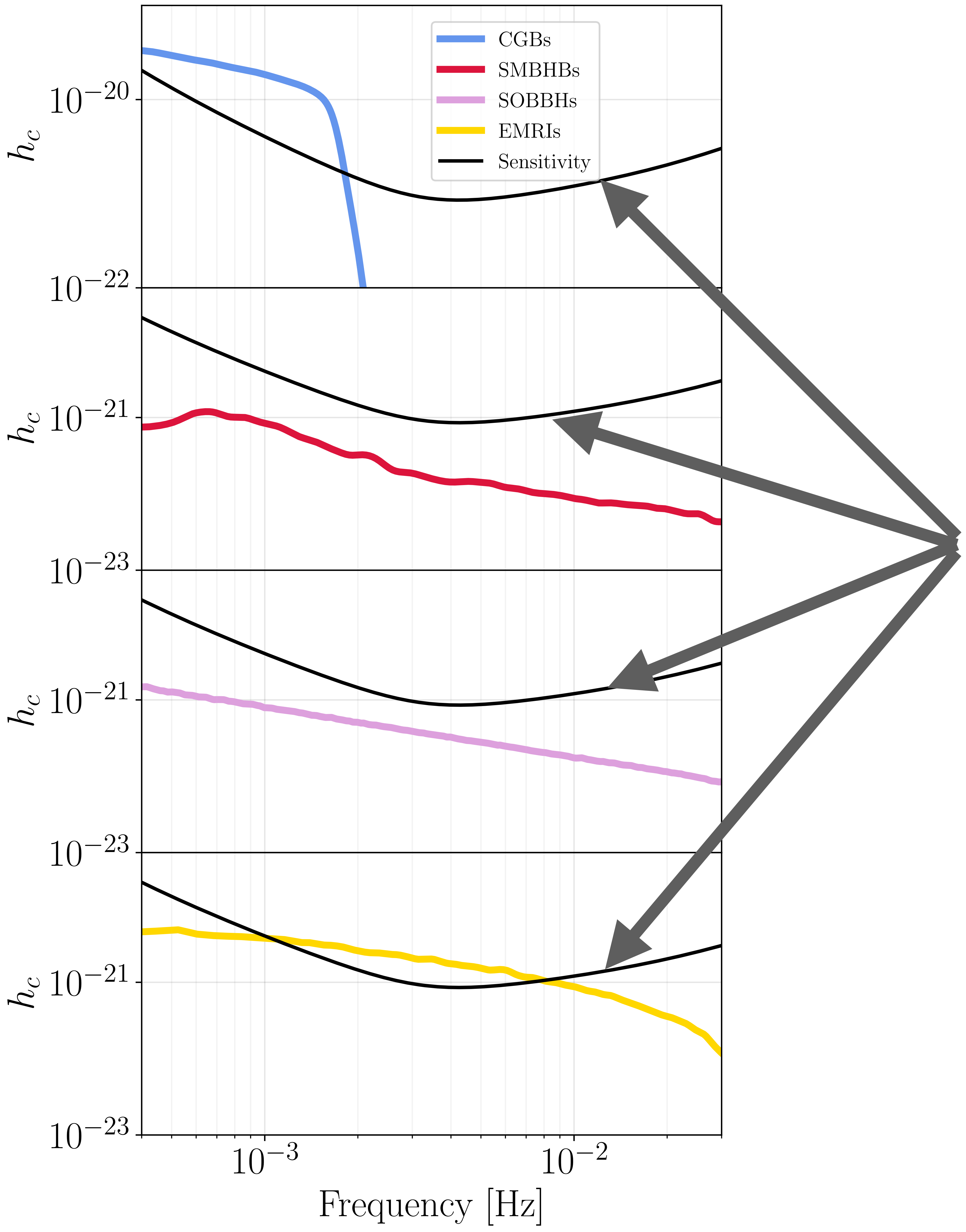
- Non-stationary
- “Pop-corn” like
- Its existence to be proven



- Stationary
- Isotropic
- Good prior on the amplitude and spectral shape.



- A lot of unknowns
- Just plotting here the most “optimistic” model



- On top of those we should add the instrumental noise properties!
- Non-stationarities: glitches, gaps, slow variations.
- Assess our level of knowledge on
  - The spectral shape
  - Overall budget (above and below!)

Summary

- Disclaimer: all these results are retrieved by assuming independent analysis for all types of sources. Future -more realistic- work should focus on a global analysis.

- We will have potential stochastic components across the band.

- This will bring implications to Data Analysis, and to the global fit.

- We need to prepare accordingly!

- Already a lot of advancements (null channels, global fit algorithms, noise modeling techniques, [see work reported in this meeting])

Έξτρα ματέριαλ