Impact of noise knowledge uncertainties on detecting SGWB with LISA

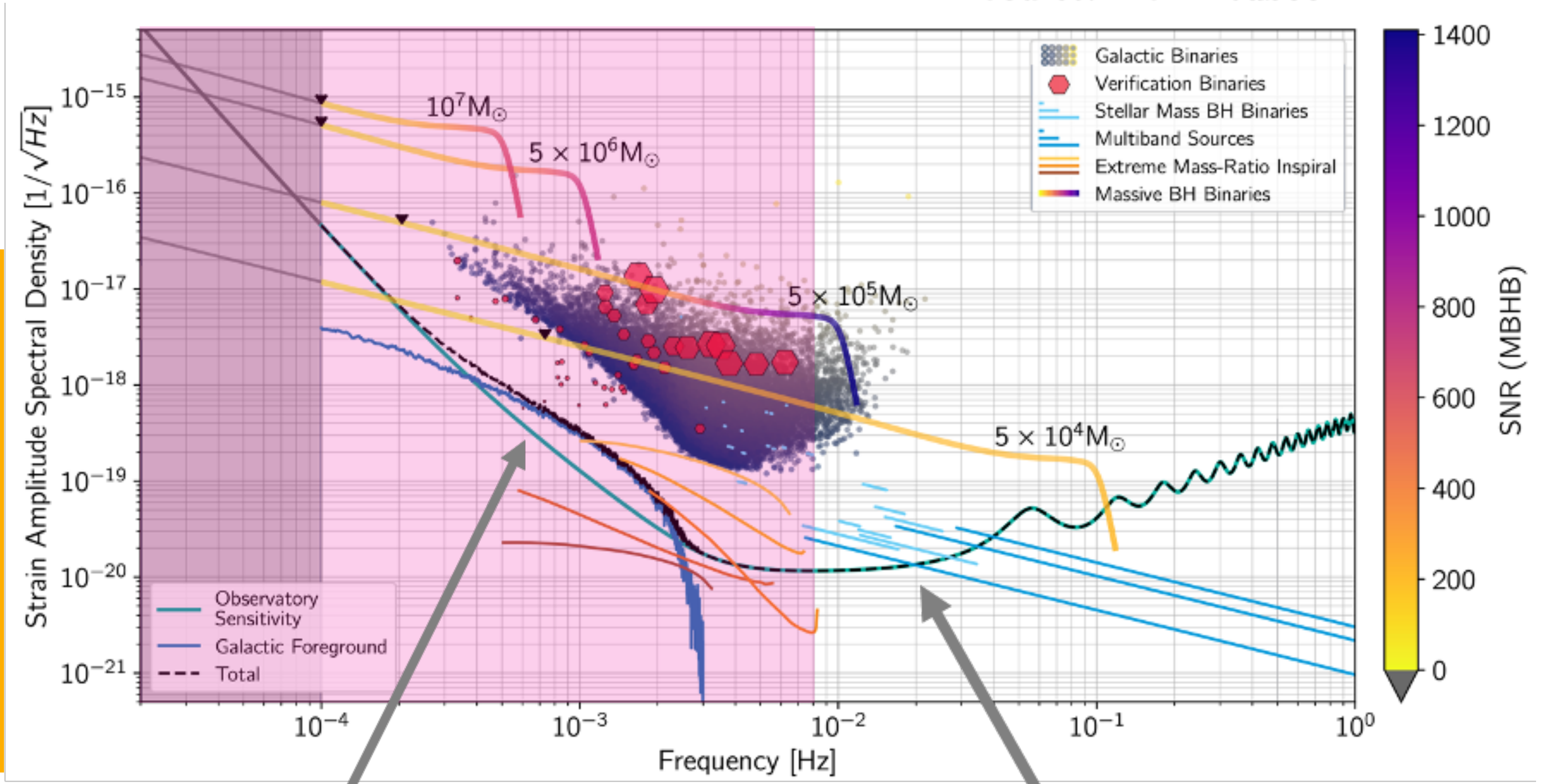
Martina Muratore, LISA Astrophysics WG meeting, Garching, 7/11/2024

Image curtesy of O.Hartwig

What does mean LISA noise?

Source: LISA Redbook

Acceleration noise	Metrology noise
• Actuation noise • Brownian noise • Stray Electrostatics Noise • Magnetic noise • Radiation pressure Noise • Temperature Force Noise • Gravitational Noise • TM-SC/MOSA coupling Force Noise	• Read-out • Laser noise • Clock noise • Spacecraft jitter • Tilt-to-Length



$3\ fm/s^2/Hz^{1/2}$

Acceleration noise (tested by the LISA-Pathfinder (LPF) technology demonstration mission)

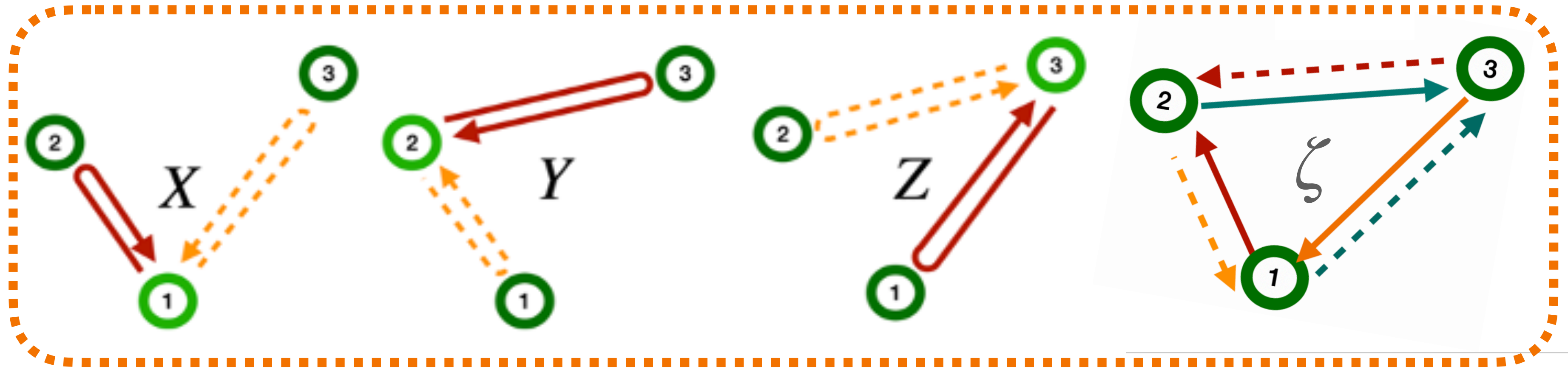
[arXiv:2112.07490]

$15\ pm/Hz^{1/2}$

Metrology noise (after noise reduction)

Noise knowledge for LISA

Why do we care?



$$A = \frac{Z - X}{\sqrt{2}},$$

$$E = \frac{X - 2Y + Z}{\sqrt{6}}$$

- Methods for SGWB detection often **rely** on accurate (sometimes perfect) knowledge of the instrumental noise

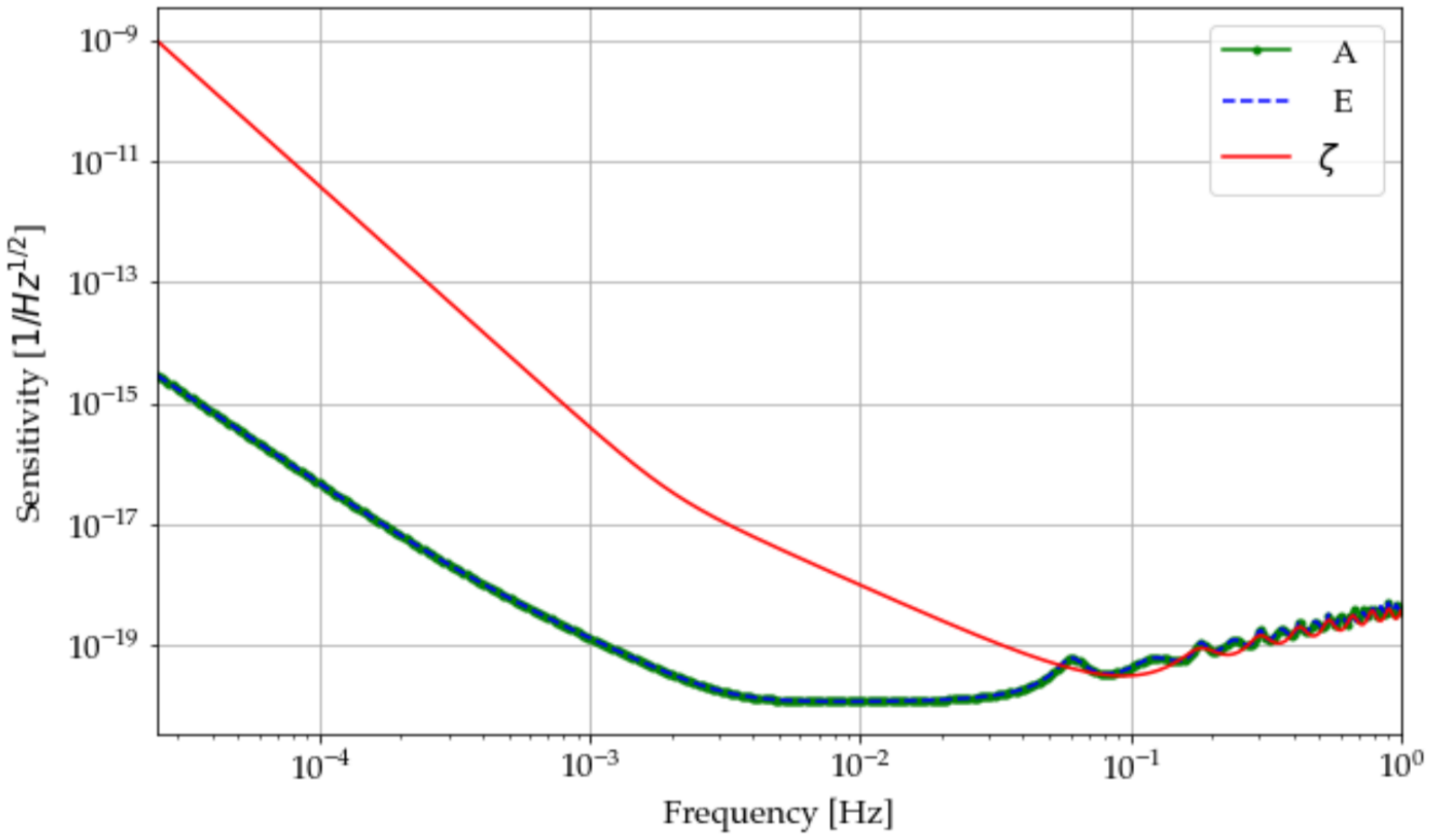
- LISA is the first mission of its kind, cannot be fully tested end-to-end on ground and signal cannot be turned off

  - **A-priori noise knowledge must be expected to be poor**

- LISA **cannot use cross-correlation** with other detectors, such that ‘intrinsic’ noise monitors are desirable

  - Candidates **‘null’ TDI channel** (ζ)

M. Muratore, O. Hartwig, D. Vetrugno, S. Vitale, W.J. Weber, Phys. Rev. D 107, 082004

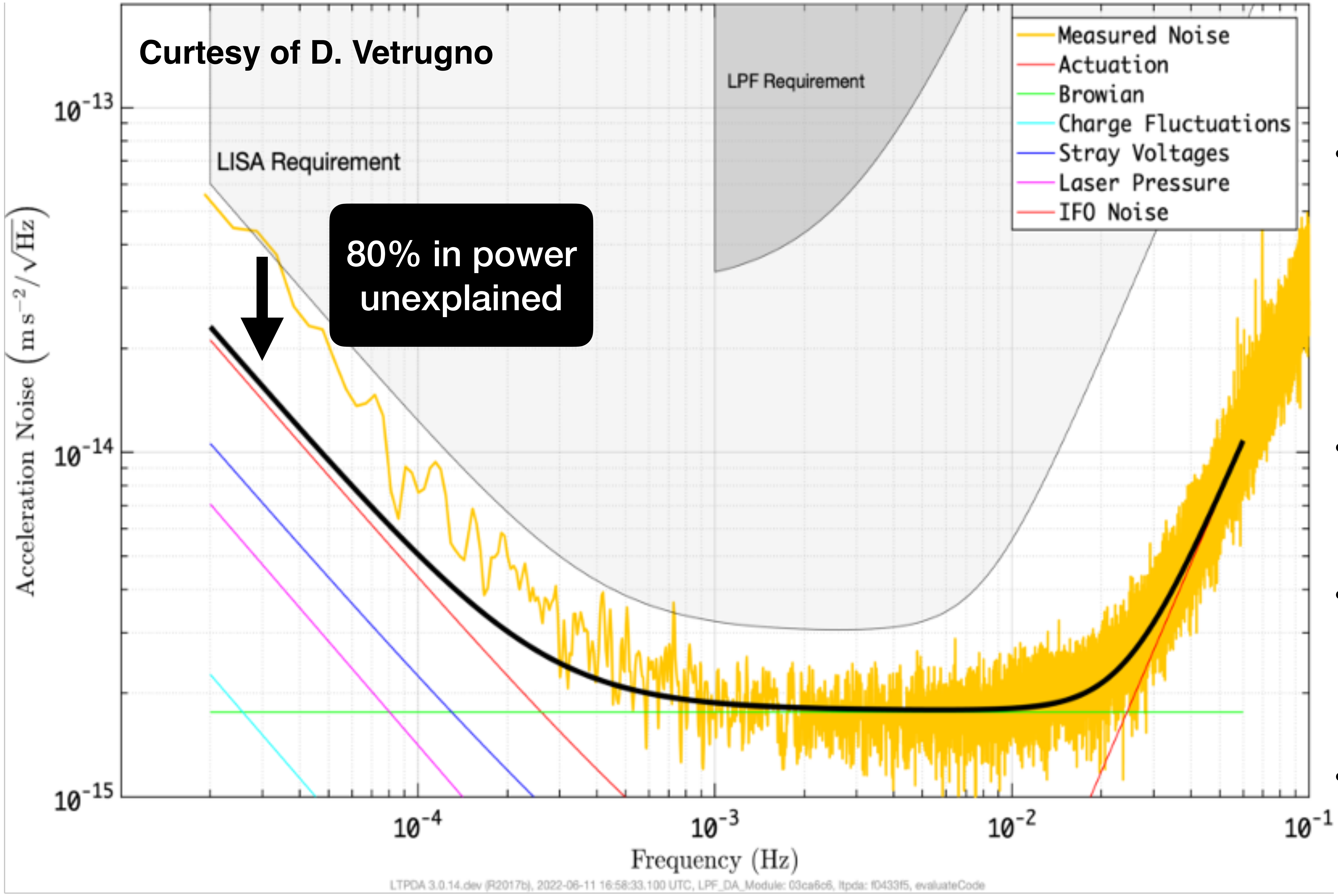


M. Muratore, D. Vetrugno, S. Vitale, and O. Hartwig Phys. Rev. D 105, 023009

- Quantify the **impact of noise knowledge uncertainty** on SGWB parameter estimation

Noise example

Test-mass (TM) motion in LISA Pathfinder: designed and flown to test LISA free-fall with LISA hardware



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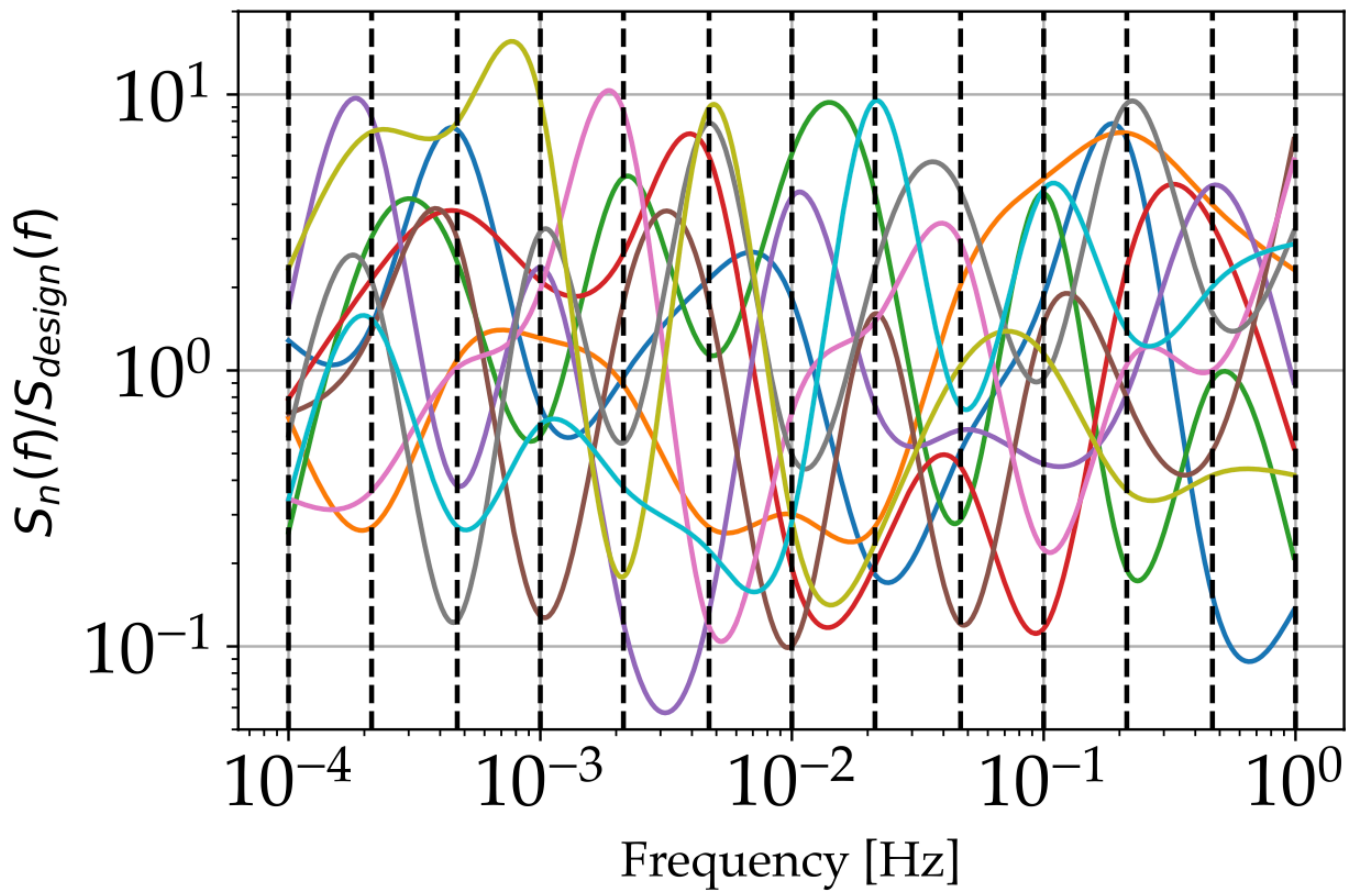
- **The total noise model for TM noise in LPF is the sum of several physical effects**
  - *Different effects have different driving parameters, which can be different for the 6 test masses*
- At **low frequencies**, large part of the noise model is **still un-explained**
- Some parameters for higher frequencies are **inferred from the observed noise level** (e.g., residual gas pressure)
- Given these uncertainties, the noise model should allow for significant **freedom in noise shape & and amplitude**

How do we model the noise then in LISA?

One possibility: spline to model noise uncertainty

- We use cubic splines to model noise knowledge uncertainty *(at the TDI level)*
- **Generic, slowly varying, fluctuations** in the noise power (PSD) and cross spectral density (CSD)
- We consider equality spaced **13 knots**
- We allow for 1 order of magnitude variation in the noise PSD/CSD



Martina Muratore et al. Phys. Rev. D **109**, 042001

Example: Fisher analysis for Power law signal

(e.g. stellar-origin black hole binaries)

$$h^2\Omega_{\rm GW}(f) \approx A\left(\frac{f}{f_p}\right)^n$$

- $h^2\Omega_{gw}(f)$ is the energy density of the signal

  $h^2\Omega_{\rm GW}(1\,{\rm mHz}) = 3.78\times10^{-13}$

- f_p is the pivot frequency of 3mHz ,
- n is the slope of the GW signal
- A is the amplitude of the GW signal

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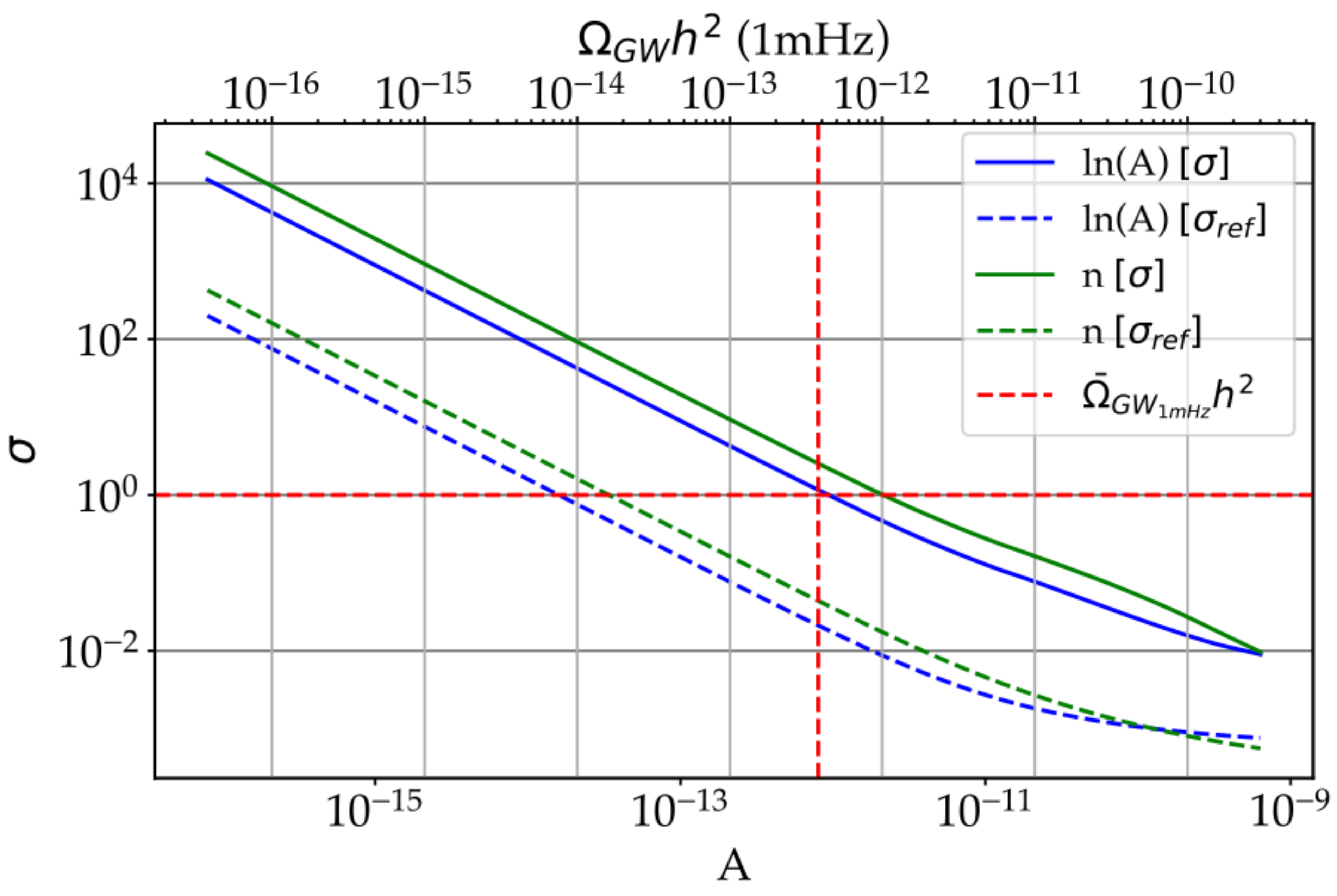

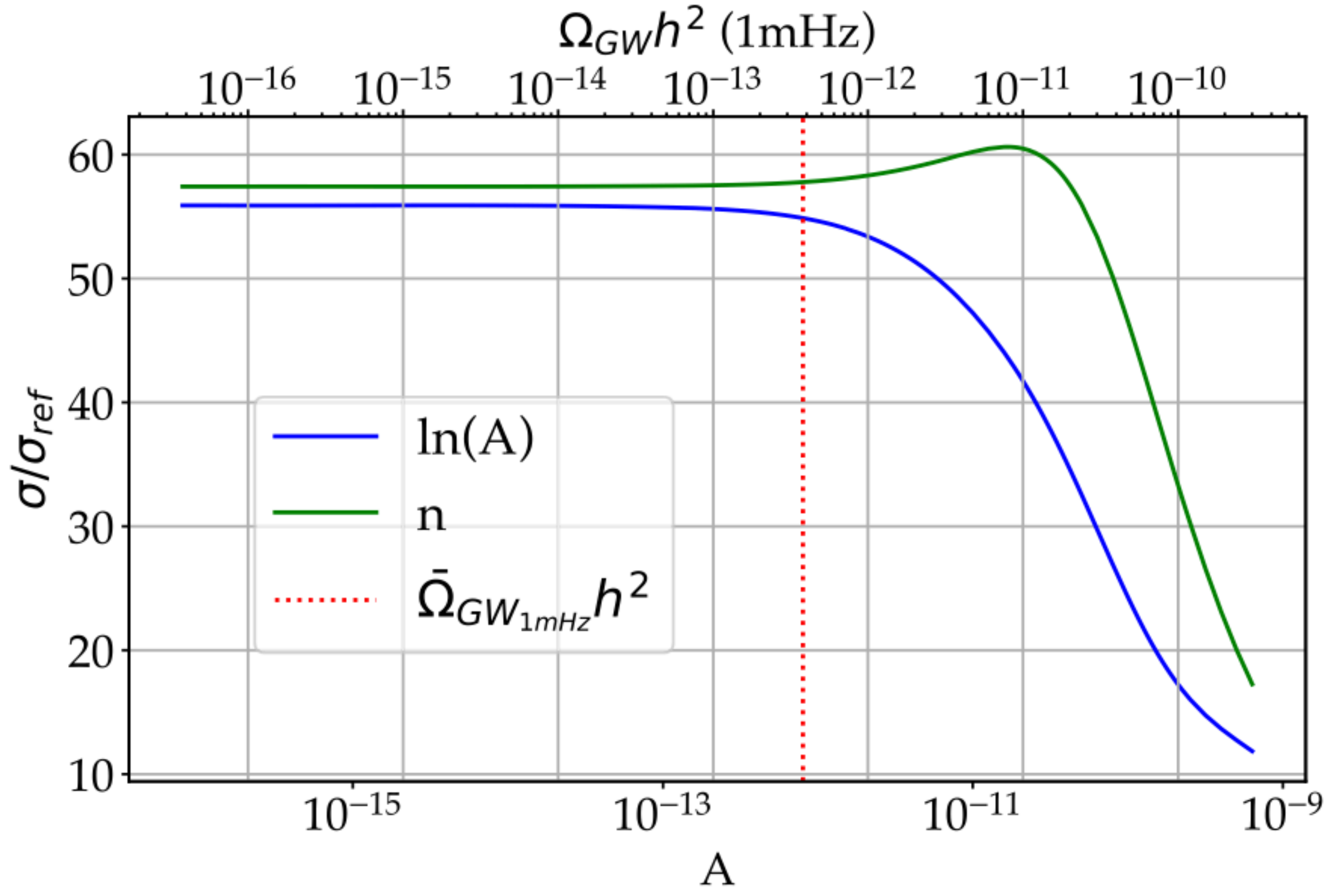

Can we put requirements on the LISA noise ?

- **Fix the background amplitude and vary** the variance of the **Gaussian prior** on the instrumental noise spline model to examine its impact on parameter estimation

- Above the noise requirement threshold, there is **little difference** between having **partial knowledge** and **no knowledge of the noise** (within the instrumental noise variations modeled here)

- It is **unrealistic** to expect that a noise requirement within **the 1%–10% range could be met**

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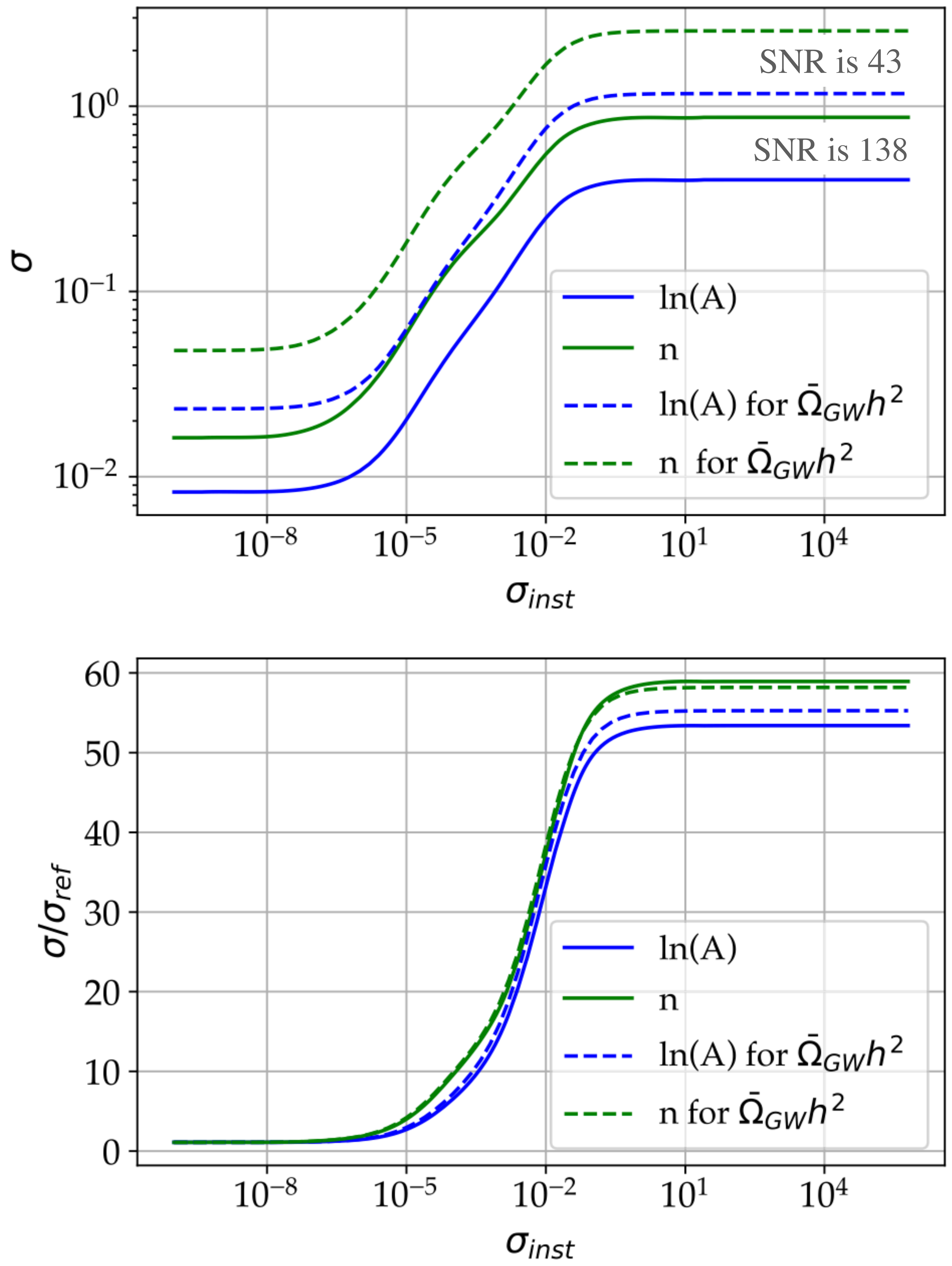
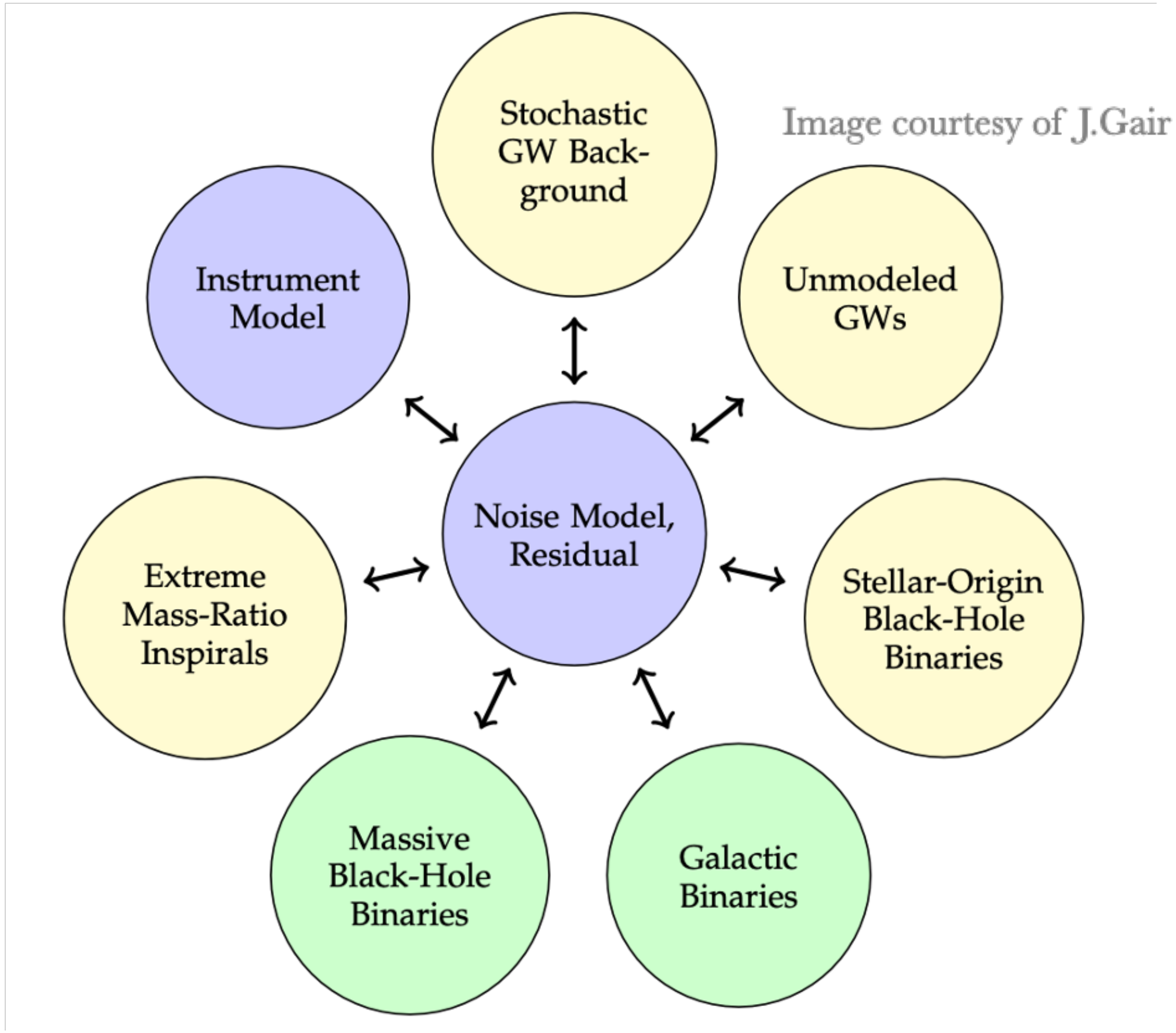


Conclusion

- Do not *strictly/blindly* rely on noise models, we need to be as **flexible and agnostic as possible in our analysis**
- We observe about 2 **orders of magnitude degradation in the accuracy of the estimation** of SGWB signal parameters due to noise knowledge uncertainties
- Thinking of **putting requirement on the noise** 'level/shape' **is unfeasable**

Searching SGWB sources in the LISA data

- **Global fit:** numerous sources are always present and need to be fitted simultaneously
- A **large number** of sources and source type
- We **do not have a direct measurement of the noise** but needs to be inferred from the data
- Non-stationarities, gaps, spectral lines, glitches
- Many galactic binaries (GBs) would be resolved but many will remain unresolvable and be part of the (astrophysical) noise
- **We cannot use 'noise monitor' channel** to distinguish b/w GW signals and noise



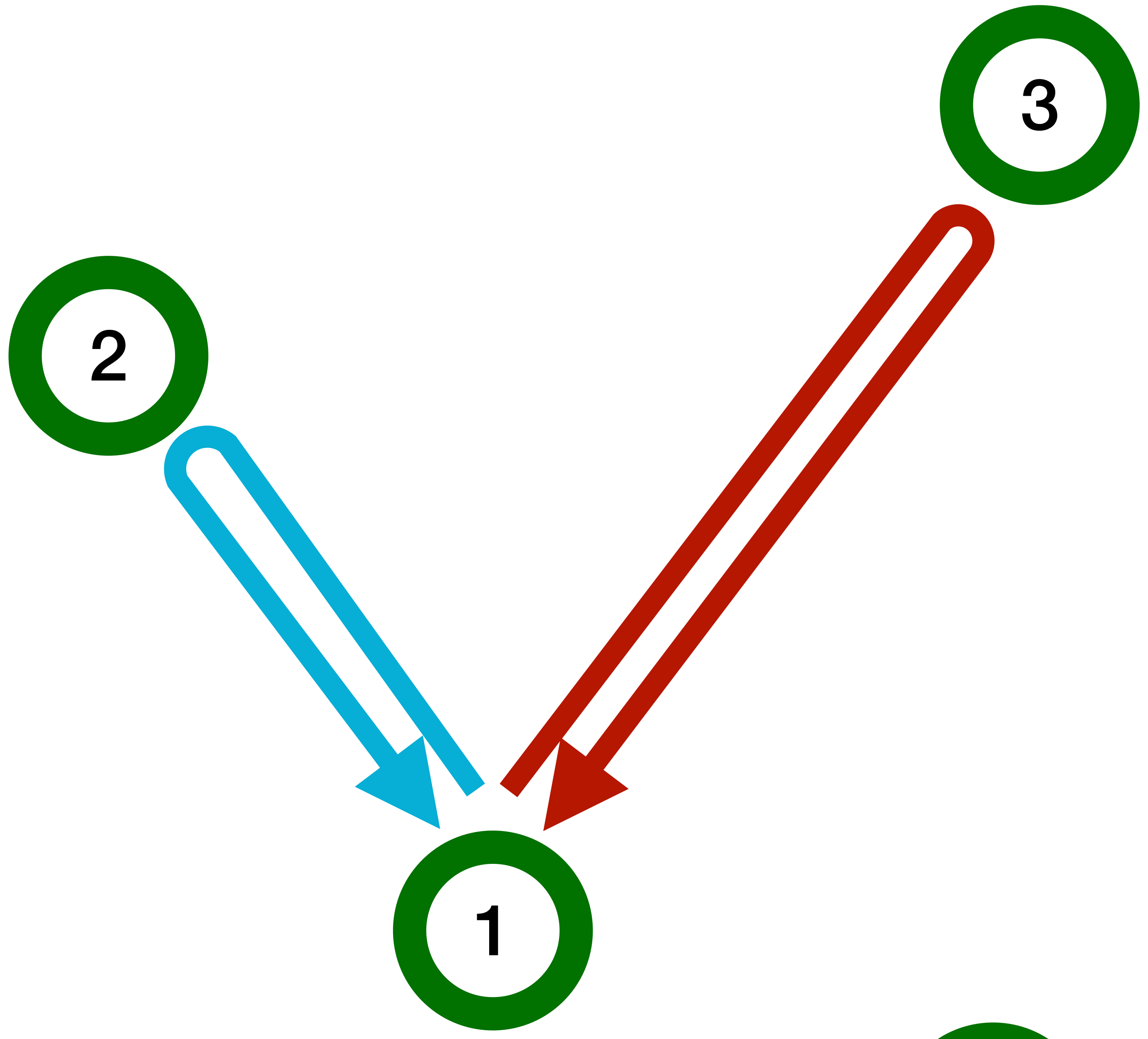
Katz et al. https://doi.org/10.48550/arXiv.2405.04690
Strub et al. https://doi.org/10.1103/PhysRevD.110.024005
Tyson B. Littenberg and Neil J. Cornish, Phys. Rev. D 107, 063004
Deng et al. , Ge-Moo-LISA Global fit

LISA Observables

TDI channels

- LISA admits the construction **2 Michelson-like** channels sensitive to GWs
  - For simplicity, we focus on the single Michelson X channel:

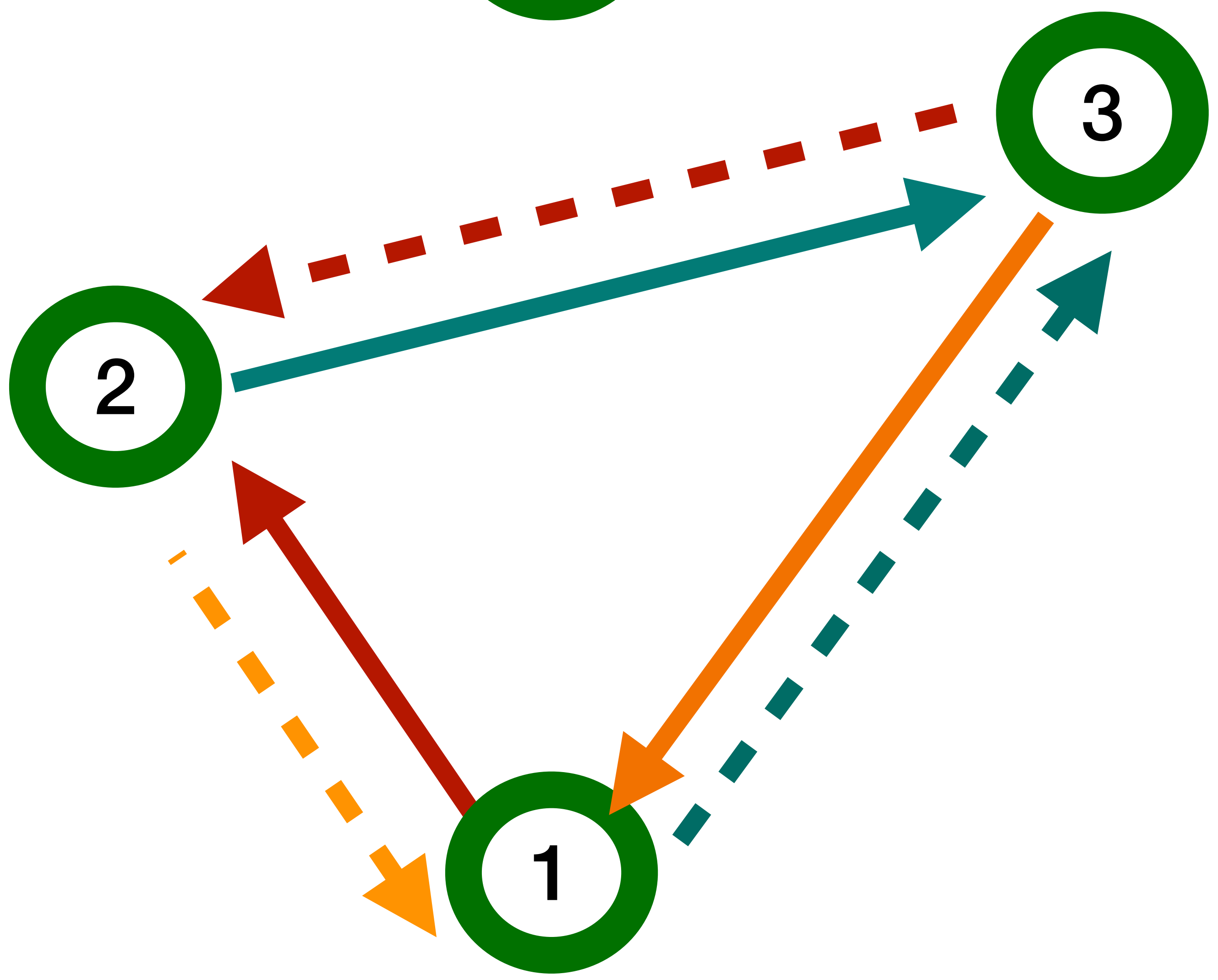
$$X \approx (1 - D^4)(1 - D^2)(\eta_{12} + D\,\eta_{21} - \eta_{13} - D\,\eta_{31})$$



- In addition, we can construct **one 'null' channel** with suppressed GW response
  - We use the so-called ζ channel,

$$\zeta \approx (1 - D)(\eta_{12} - \eta_{13} + \eta_{23} - \eta_{21} + \eta_{31} - \eta_{13})$$

  - The orthogonal channels are: $\mathrm{A} = \dfrac{\mathrm{Z} - \mathrm{X}}{\sqrt{2}}$, $\mathrm{E} = \dfrac{\mathrm{X} - 2\mathrm{Y} + \mathrm{Z}}{\sqrt{6}}$



Can we infer the noise from the null channels ?

Muratore et al., On the effectiveness of null TDI channels as instrument noise monitors in LISA e-Print: 2207.02138

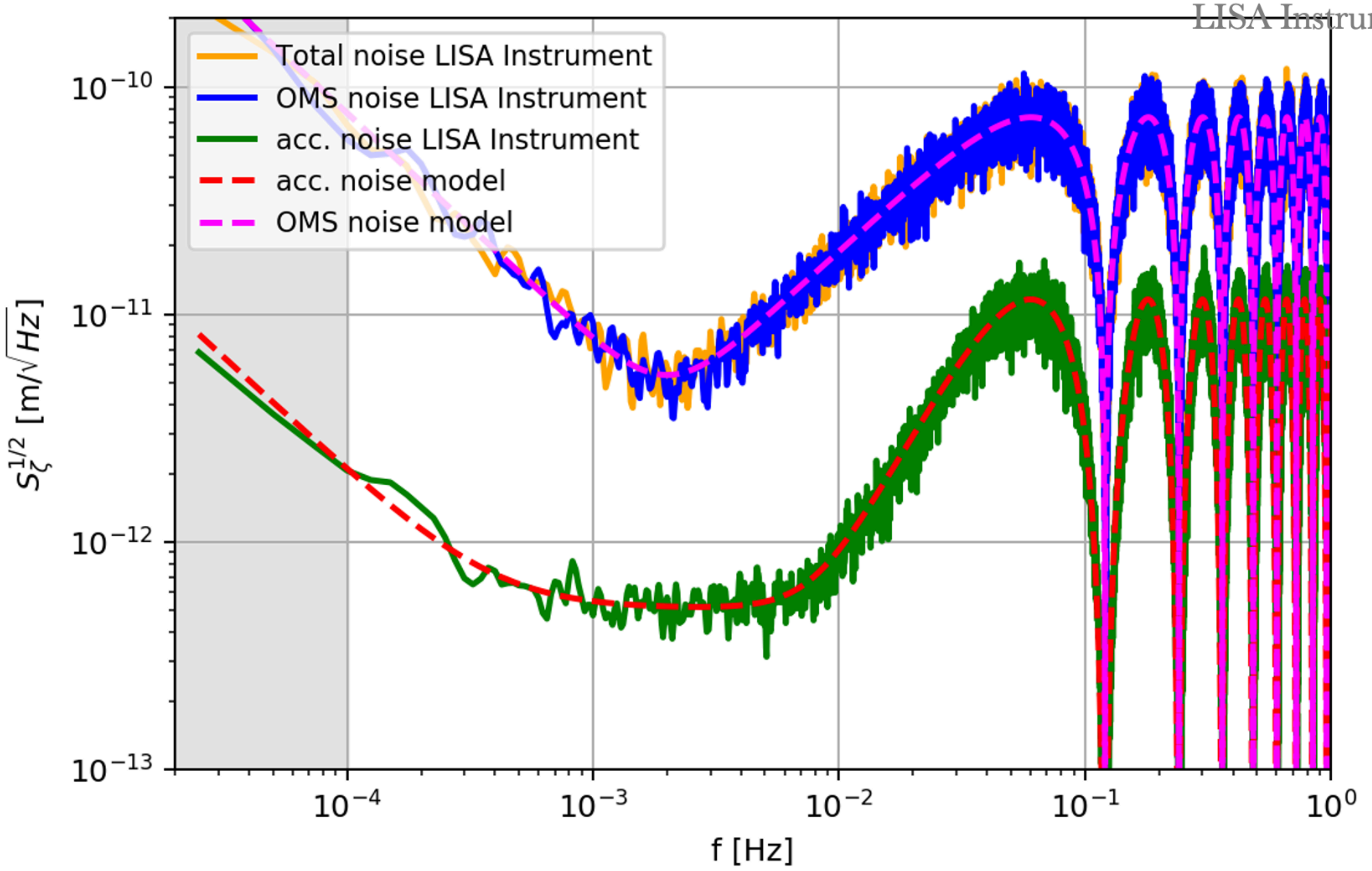
Raphael Flauger et al JCAP01(2021)059

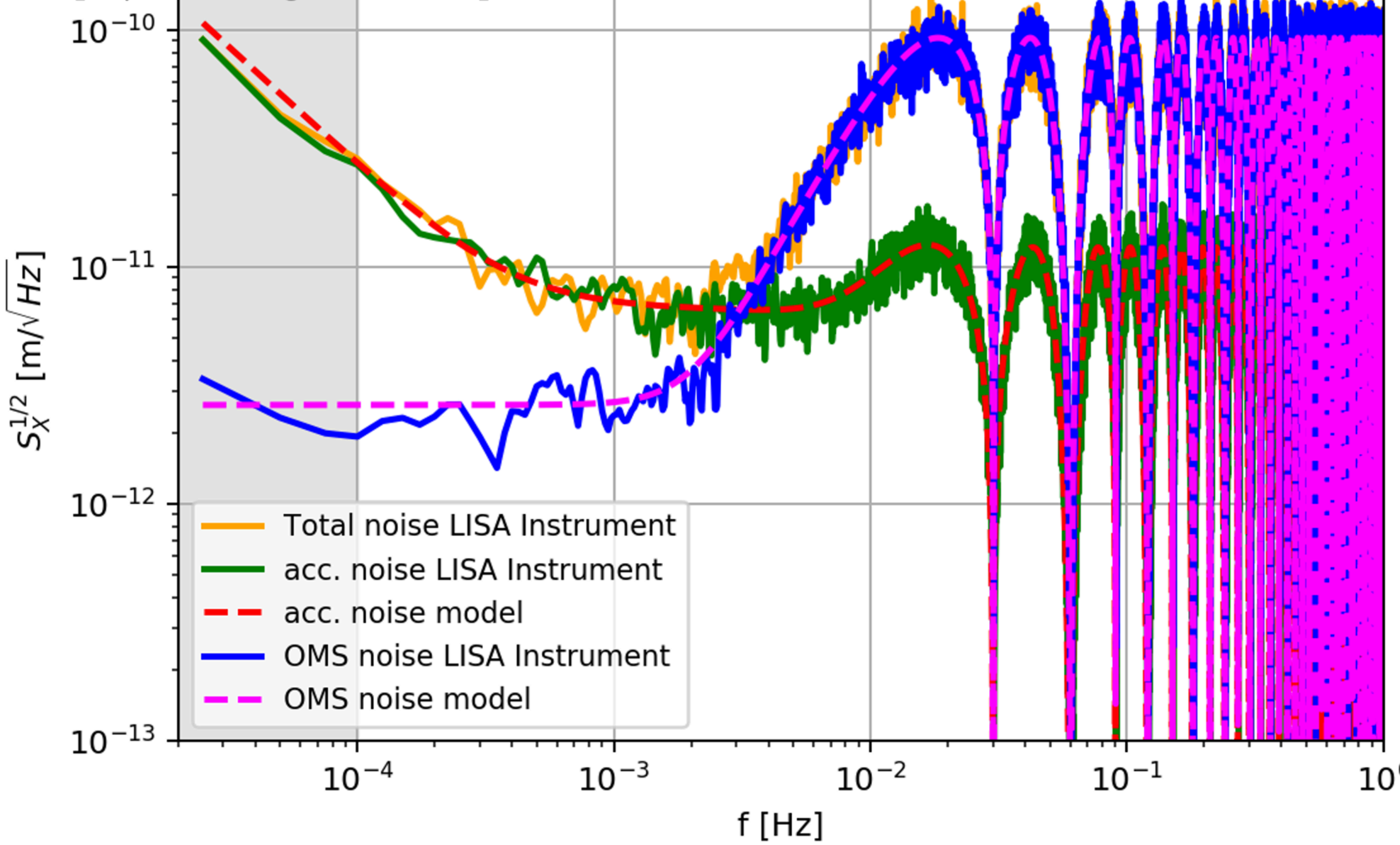
$$S_X^{noise} \approx 64\tau^4\omega^4\left(4\sum_{ij\in\mathcal{I}_X} S_{g_{ij}}^{disp} + \sum_{ij\in\mathcal{I}_X} S_{oms_{ij}}\right)$$

$$S_\zeta^{noise} \approx \tau^2\omega^2\left(\tau^2\omega^2\sum_{ij\in\mathcal{I}_\zeta} S_{g_{ij}}^{disp} + \sum_{ij\in\mathcal{I}_\zeta} S_{oms_{ij}}\right)$$

*Currently assumed noise level for the so-called secondary noises arXiv:2108.01167

LISA Instrument [Bayle, Hartwig, Staab 2022]

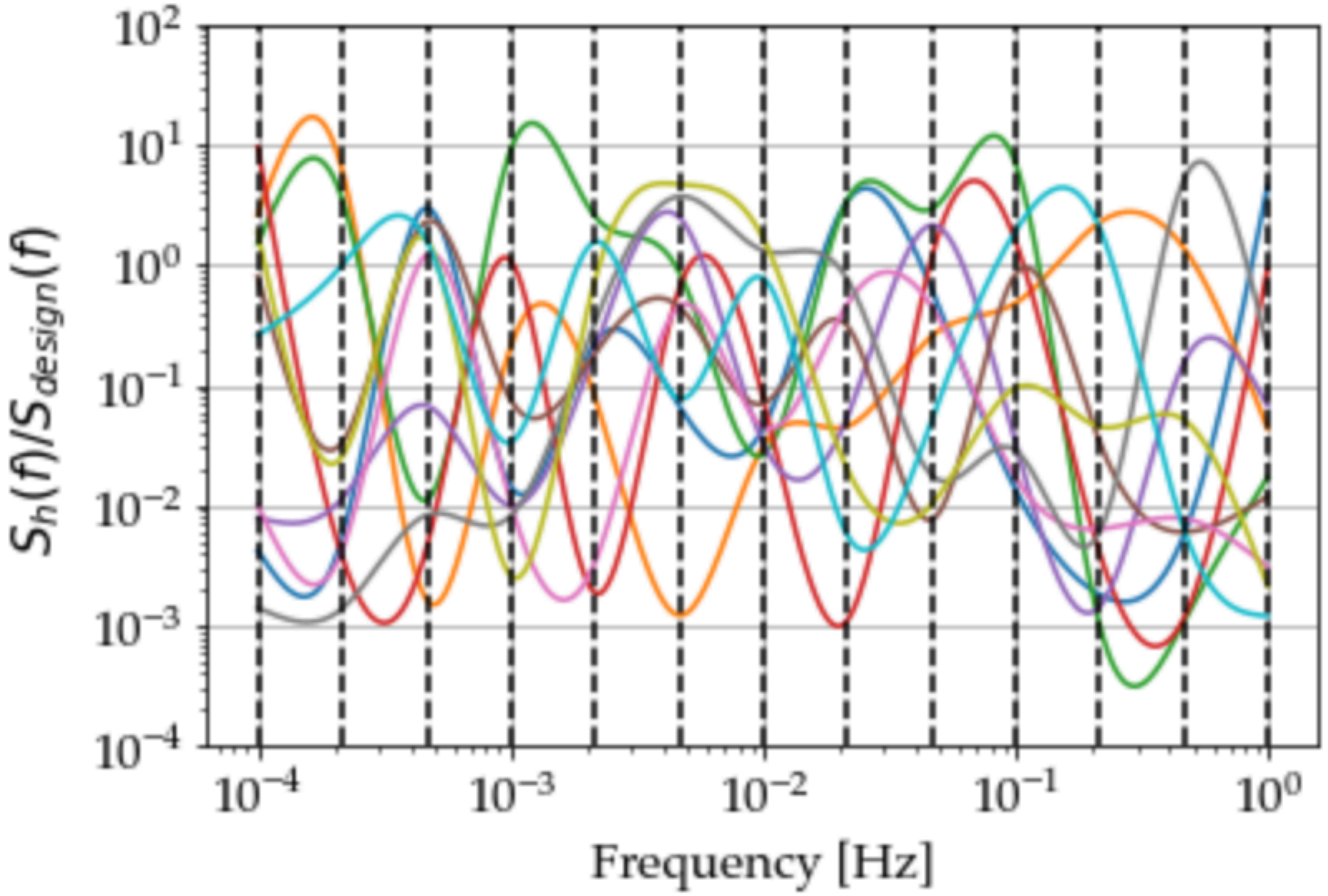




Splines to model PSD

- We use splines to model the noise uncertainty **generic, slowly varying, fluctuations in the PSD and CSD**

$$S_n(f\,|\,\vec{\lambda}) = \bar{S}_{des}(f)10^{C(f|\vec{\lambda})}$$



- $C(f\,|\,\vec{\lambda})$ *is a natural cubic spline in log10(f)*
- *k are 13 equally spaced knots [1e-4 to 1 Hz] whose value is specified by* $\vec{\lambda}$
- *Reference values of the weight is zero*
- *We allow for 1 order of magnitude variation in the PSD/CSD*
- *f is the frequency*
- $\bar{S}_{des}(f)$ *is the reference PSD of the TDI A,E or* ζ