Effectiveness of null channels as noise monitors for LISA
&
Impact of noise knowledge uncertainty on SGWB parameter estimation

LISA CONSORTIUM

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DA challenges for SGWB 2023, CERN

Effectiveness of null channels as noise monitors for LISA

M.Muratore in collaboration with O. Hartwig (SYRTE, Observatoire de Paris), D. Vetrugno , S. Vitale, W. J. Weber (Universita di Trento)

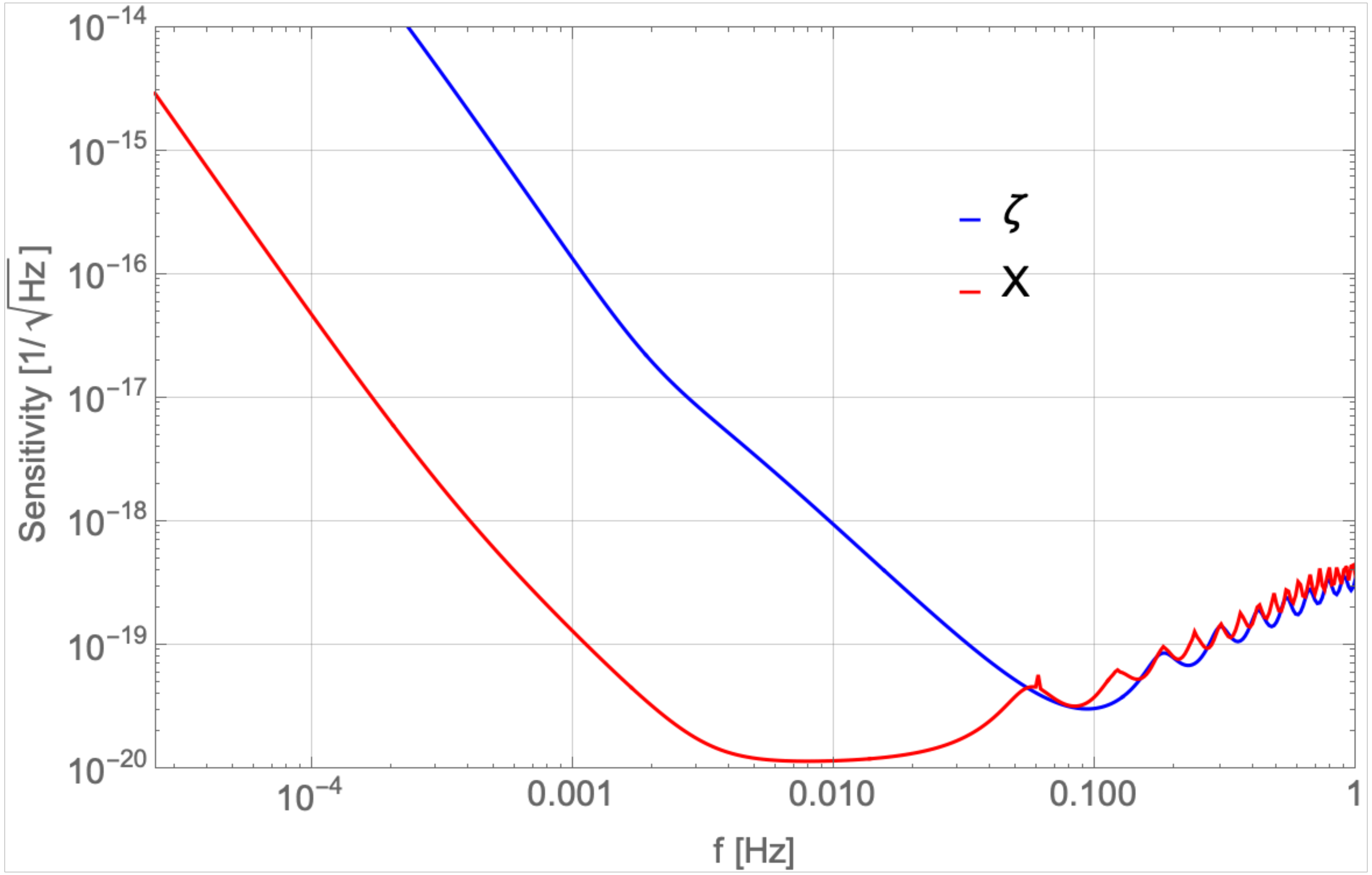
Noise knowledge for LISA

Why do we care?

- 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

✖ Candidate: the 'null' TDI channel

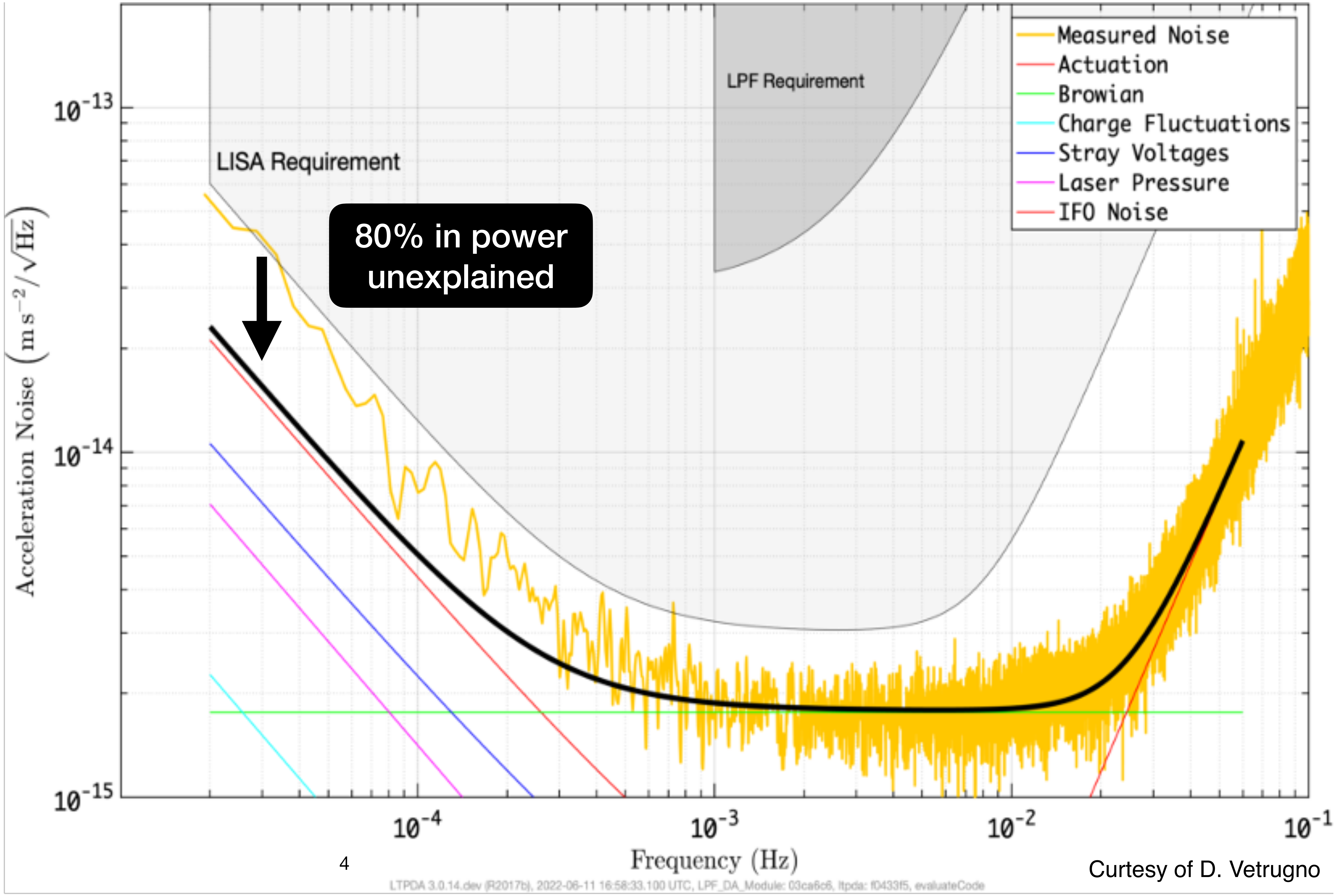
- Goals here:
  - ✳Understand how well we can constrain the noise in X with ζ
  - ✳Understand the impact of noise knowledge uncertainty on SGWB parameter estimation



- Up to ~50 mHz, ζ has suppressed GW response wrt. X
- At high frequencies, response is similar

Noise example: TM motion in LISA Pathfinder

- Total noise model for TM noise in LPF is sum of several physical effects
  - Different effects have different driving parameters, which can be different for the 6 test masses
- At low frequency, large part of 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, noise model should allow for significant **freedom in noise shape & amplitude**



Curtesy of D. Vetrugno

LISA Observables

Single link measurements

- LISA will monitor distance fluctuations between the 6 TMs housed in the 3 S/C

- Simple model for these single-link measurements:

$$\eta_{12}(t) \sim H_{12}(t) + x^g_{21}(t-\tau) + x^g_{12}(t) + x^m_{12}(t)$$

- $H_{12}(t)$: Pathlength change from GW

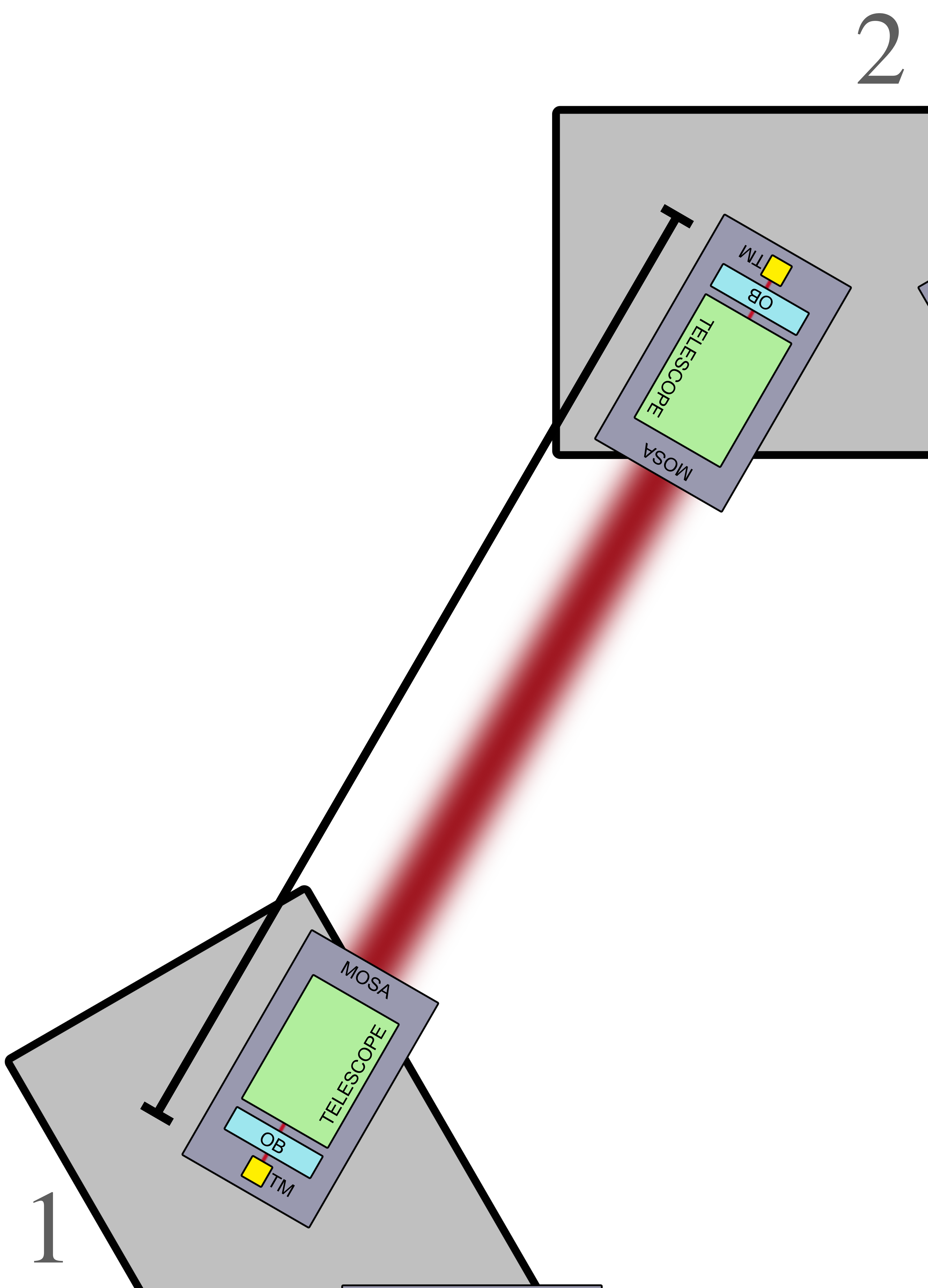
- $x^g_{ij}(t)$: TM deviation from geodesic motion

- $x^m_{ij}(t)$: Noise from optical metrology (e.g., shot noise)

- **Remark: This is strongly simplified**

  - Each of these noises results from a superposition of different physical effects

  - Current performance model: 8 TFs for non-suppressed noise groups + complicated couplings for suppressed ones (laser, clock, TTL)

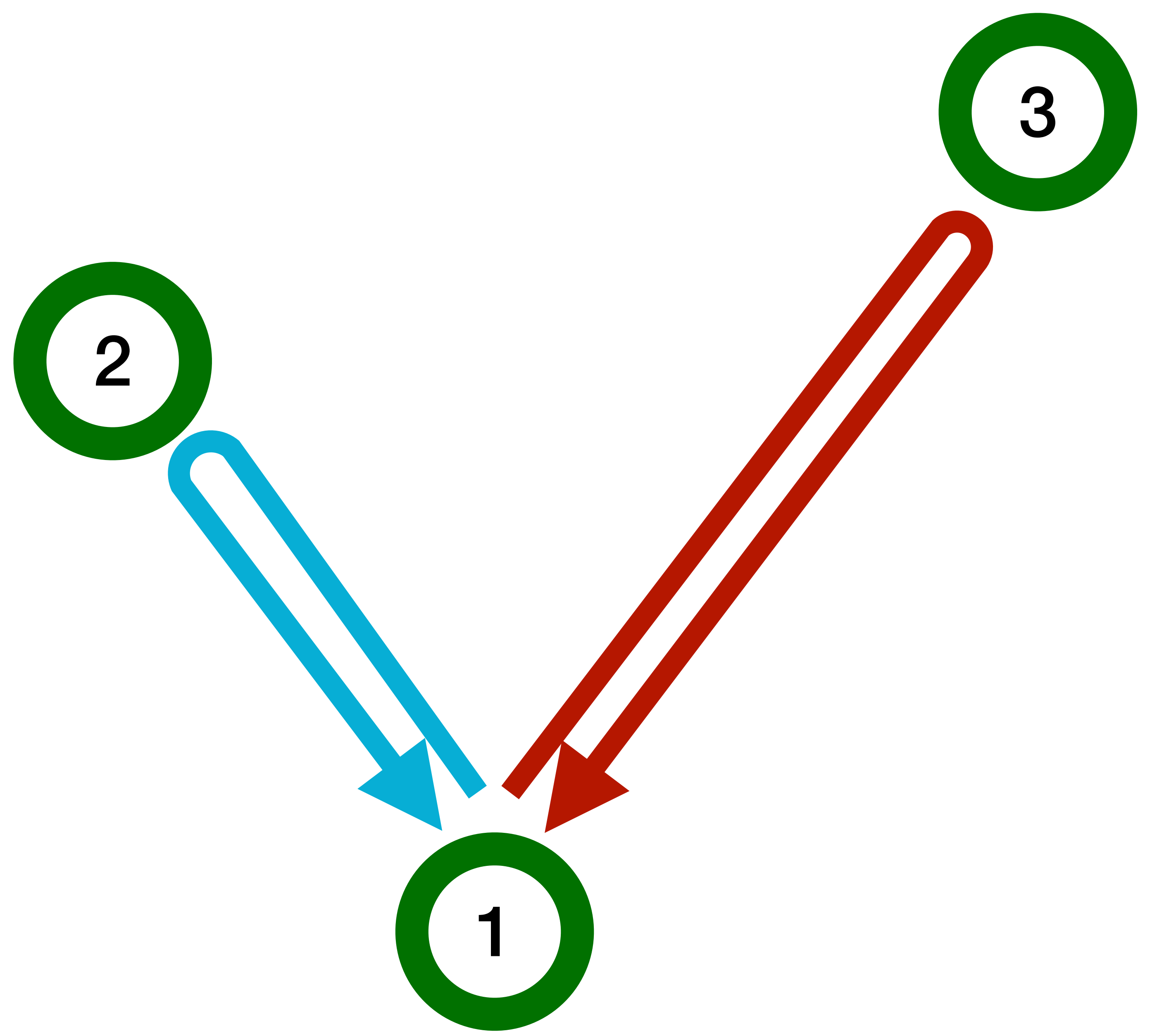


LISA Observables

*Massimo Tinto, F.B. Estabrook, and J.W. Armstrong

D. A. Shaddock, Phys. Rev. D 69, 022001 (2004) and more…

TDI channels



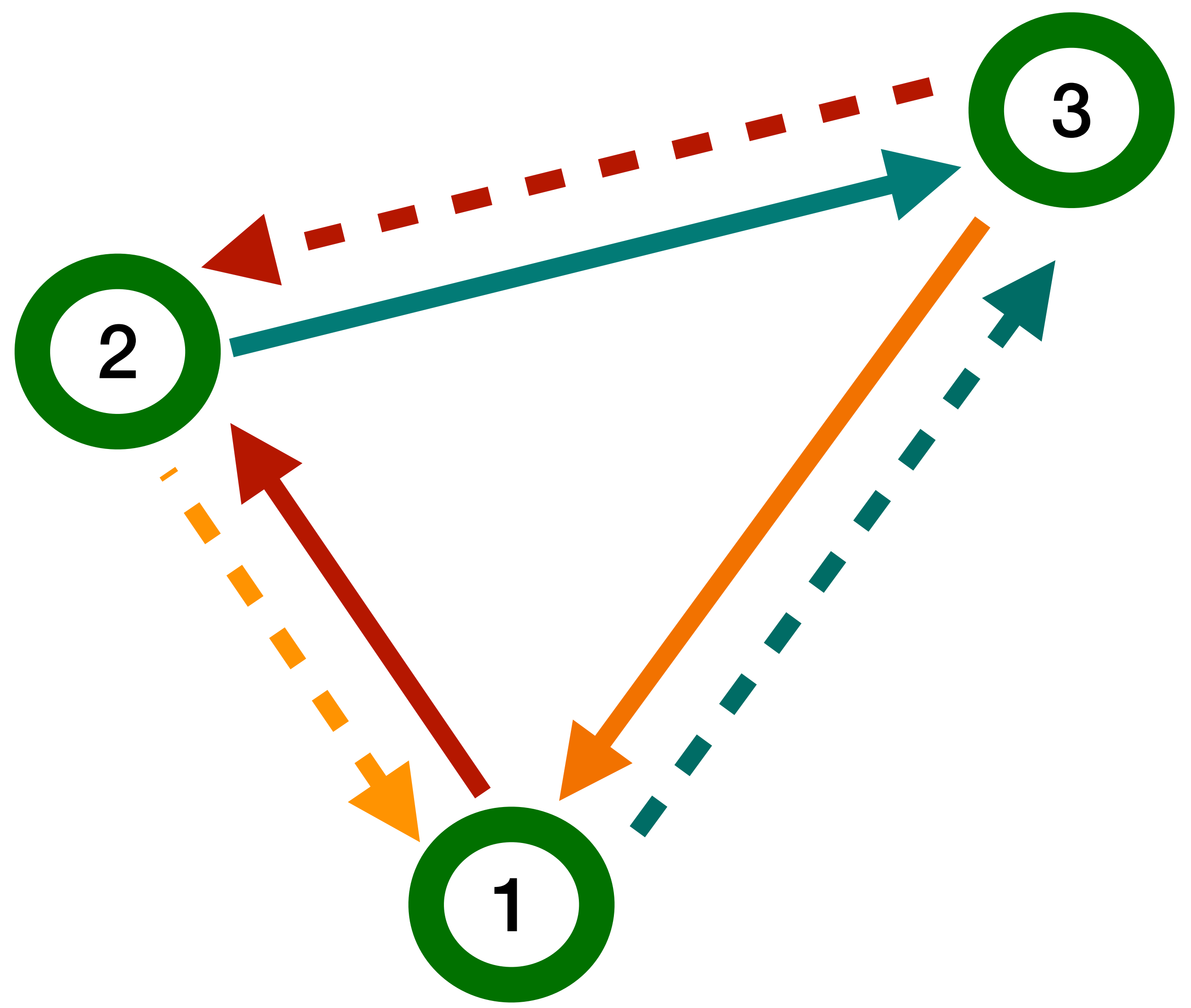
- LISA admits the construction **2 Michelson-like** channels sensitive to GWs
  - For simplicity, we focus on the single Michelson X channel:

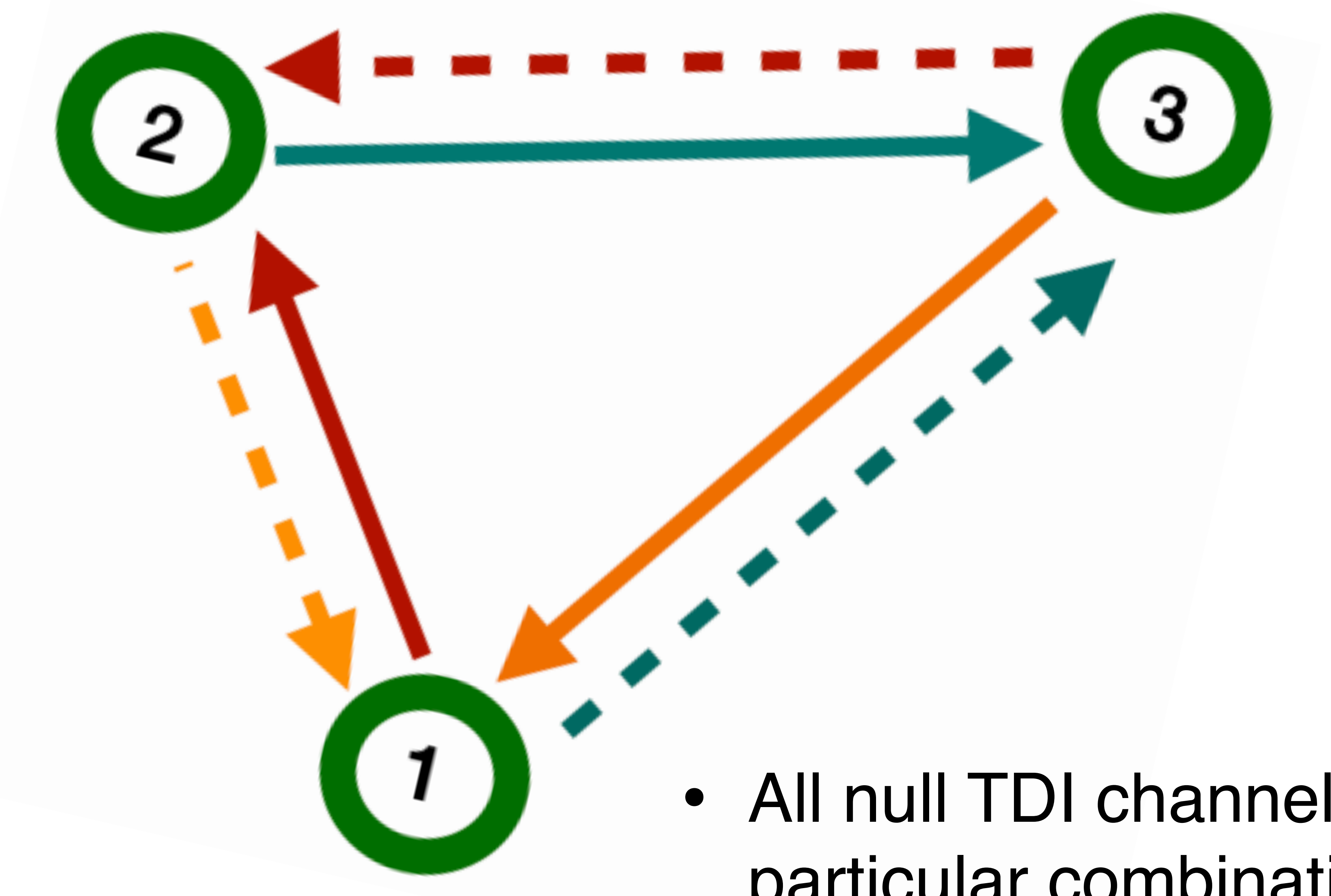
$$X \approx (1 - D^4)(1 - D^2)(\eta_{12} + D\,\eta_{21} - \eta_{13} - D\,\eta_{31})$$

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

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

  - Remark: some noise correlations cancel in ζ but not in X!



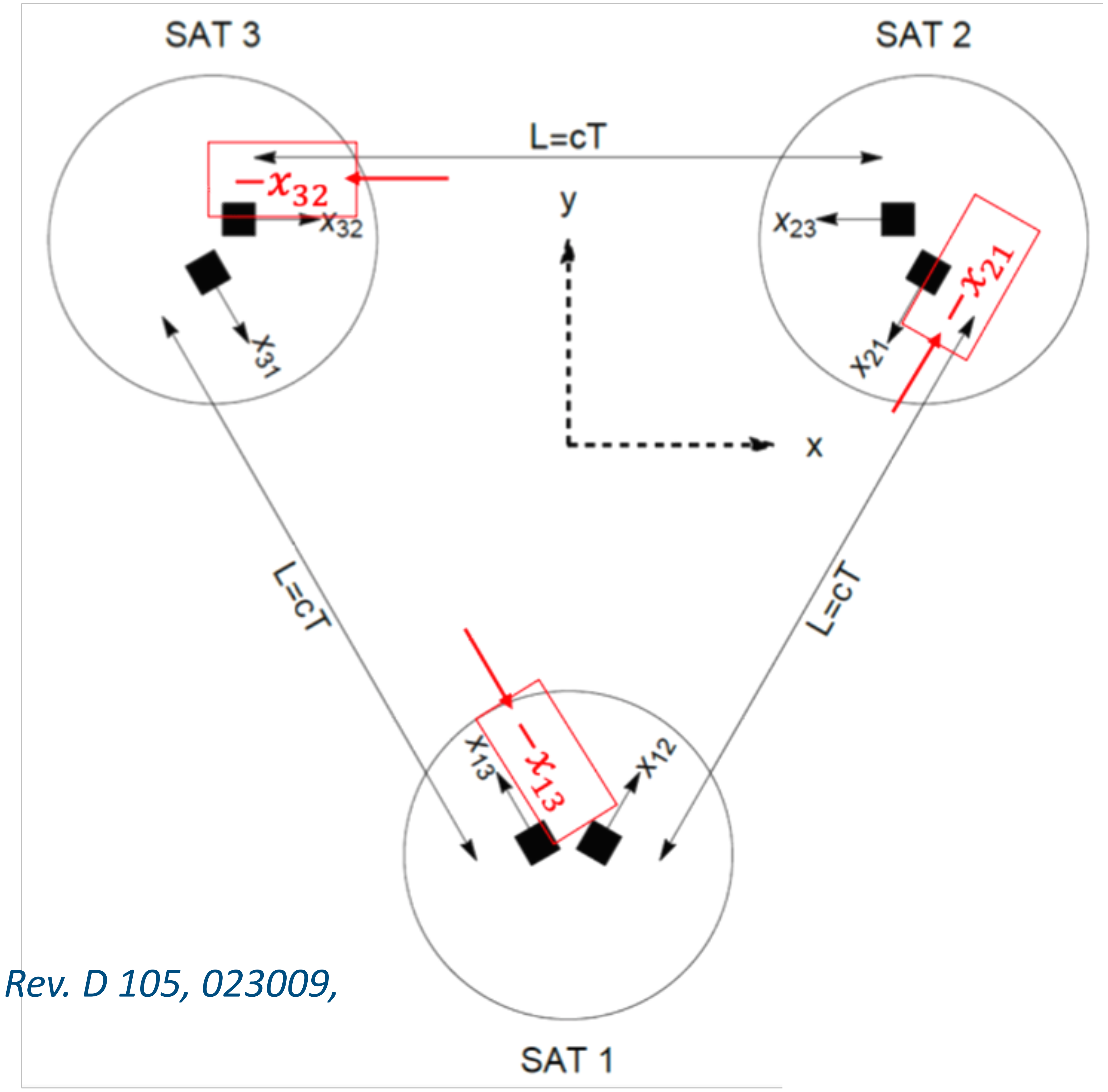


All null-combinations behave like a *Sagnac interferometer* sensitive to the rigid rotation of the constellation

- All null TDI channels are only sensitive to a particular combination of the six TMs

$$g(1,2,t-nT)-g(2,1,t-nT)$$
$$+g(2,3,t-nT)-g(3,2,t-nT)$$
$$+g(3,1,t-nT)-g(1,3,t-nT)$$

- **All combinations** that subtract simultaneous counter-propagating beams **always suppress not only GW but also TM acc. noise**



Time Delay Interferometry combinations as instrument noise monitors for LISA. Phys. Rev. D 105, 023009, M. Muratore et al.

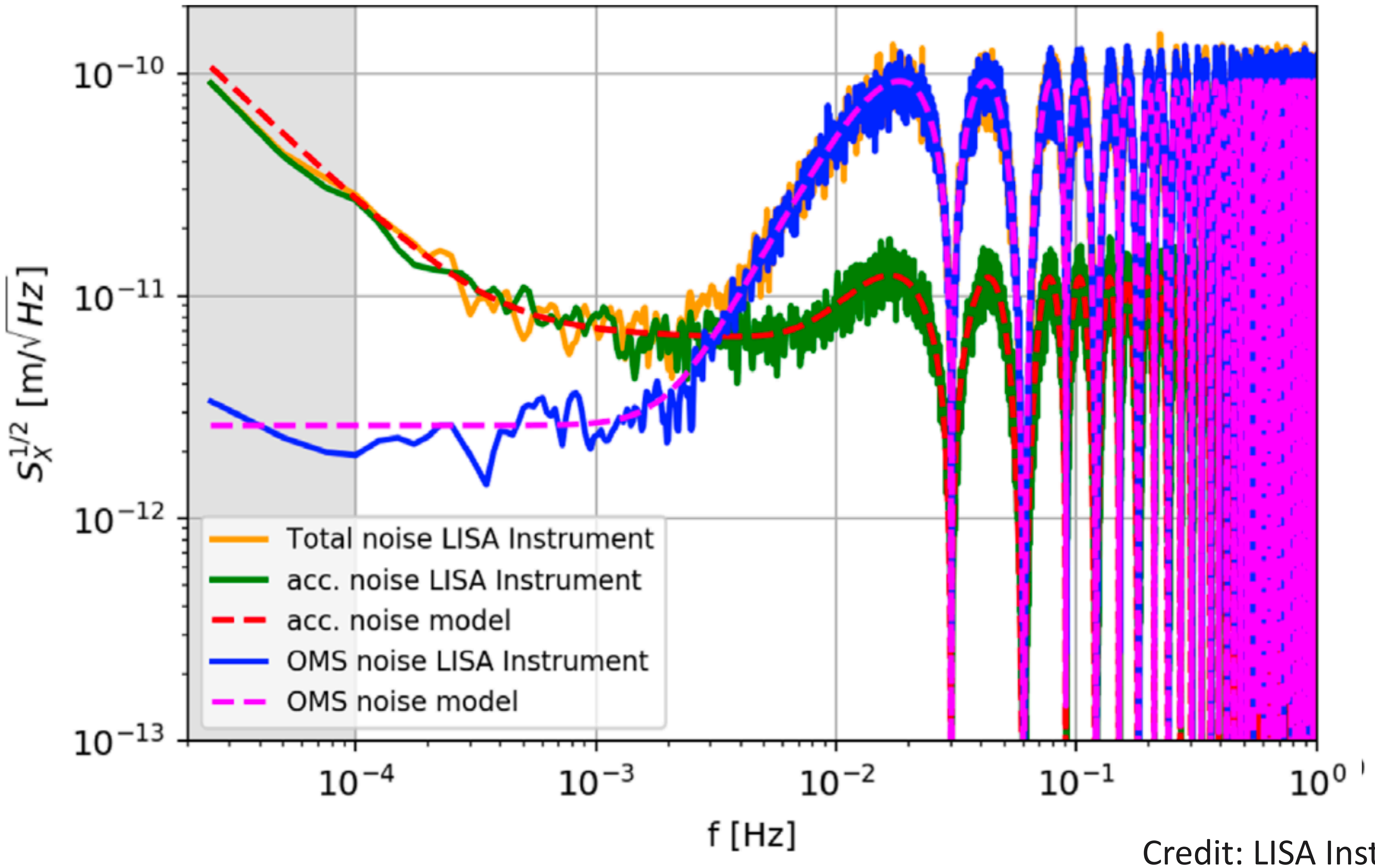
Noise assumptions to check the effectiveness of null channels as noise monitors

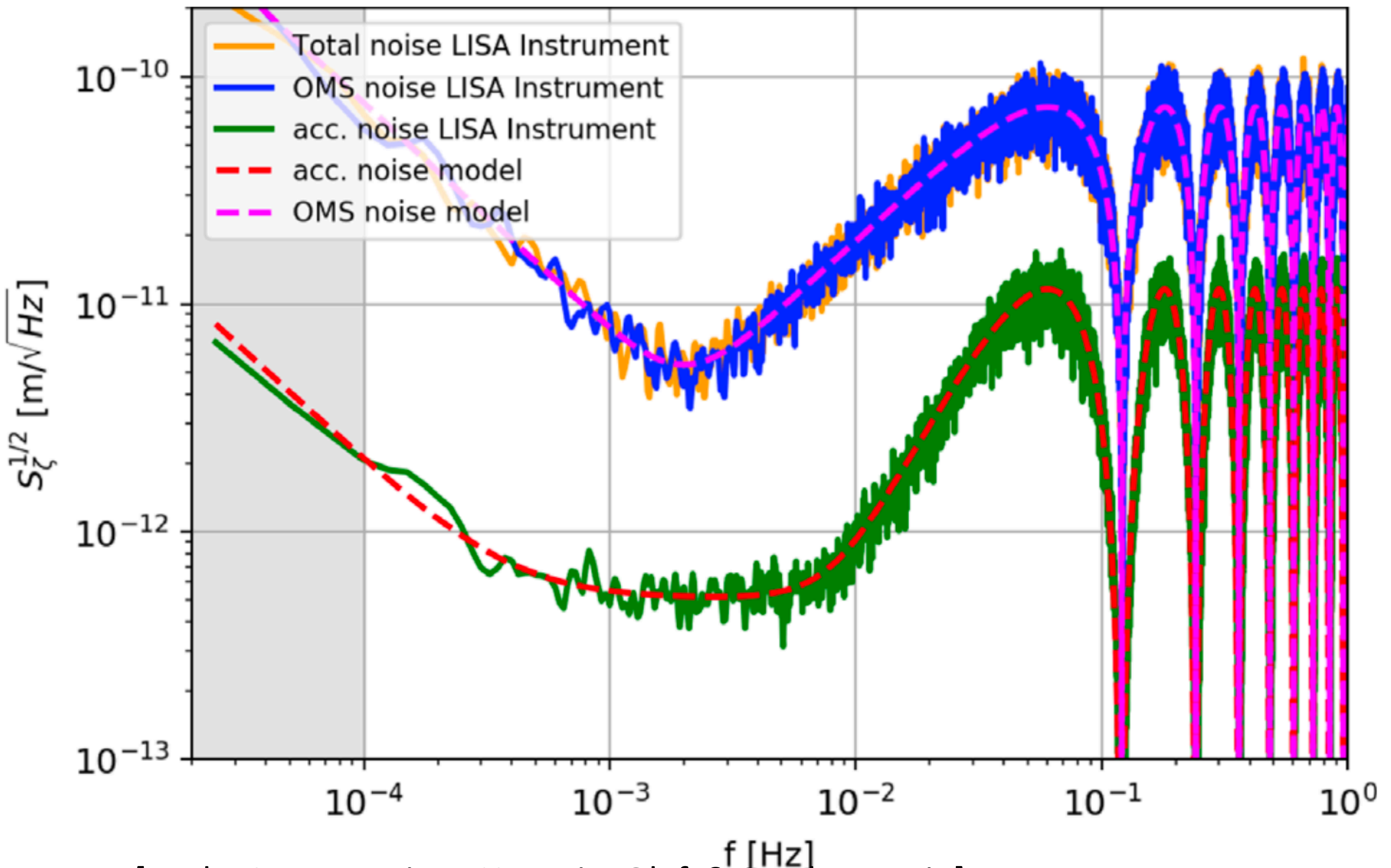
Single link measurements

- No assumptions on any spectral shape or amplitude
  - But for evaluating plots: assume noise levels from requirements
- $H_{ij}(t)$: Assume response to isotropic SGWB with PSD S_h
- $x^g_{ij}(t)$: Assume motion of different TMs to be fully uncorrelated, with PSDs $S^{disp}_{g_{ij}}$
  - In reality, TM motion in same S/C might have some correlation
- $x^m_{ij}(t)$: Assume OMS noises to be fully uncorrelated, with PSDs $S_{oms_{ij}}$
  - True for shot noise, but not the full picture

LISA Observables

Noise response





Credit: LISA Instrument [Bayle, Jean-Baptiste, Hartwig, Olaf, & Staab, Martin]

$$S_{X_g} = \underbrace{256\sin^4(\tau\omega)\cos^2(\tau\omega)}_{T_{X_g}}\left(\left(S_{g_{12}}^{\text{disp}} + S_{g_{13}}^{\text{disp}}\right)\cos^2(\tau\omega) + S_{g_{21}}^{\text{disp}} + S_{g_{31}}^{\text{disp}}\right),$$

$$S_{X_{\text{oms}}} = \underbrace{64\sin^4(\tau\omega)\cos^2(\tau\omega)}_{T_{X_{\text{oms}}}}\left(S_{\text{oms}_{12}} + S_{\text{oms}_{13}} + S_{\text{oms}_{21}} + S_{\text{oms}_{31}}\right)$$

$$S_{\zeta_g} = \underbrace{16\sin^4\left(\frac{\tau\omega}{2}\right)}_{T_{\zeta_g}}\left(S_{g_{12}}^{\text{disp}} + S_{g_{13}}^{\text{disp}} + S_{g_{21}}^{\text{disp}} + S_{g_{23}}^{\text{disp}} + S_{g_{31}}^{\text{disp}} + S_{g_{32}}^{\text{disp}}\right)$$

$$S_{\zeta_{\text{oms}}} = \underbrace{4\sin^2\left(\frac{\tau\omega}{2}\right)}_{T_{\zeta_{\text{oms}}}}\left(S_{\text{oms}_{12}} + S_{\text{oms}_{13}} + S_{\text{oms}_{21}} + S_{\text{oms}_{23}} + S_{\text{oms}_{31}} + S_{\text{oms}_{32}}\right)$$

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

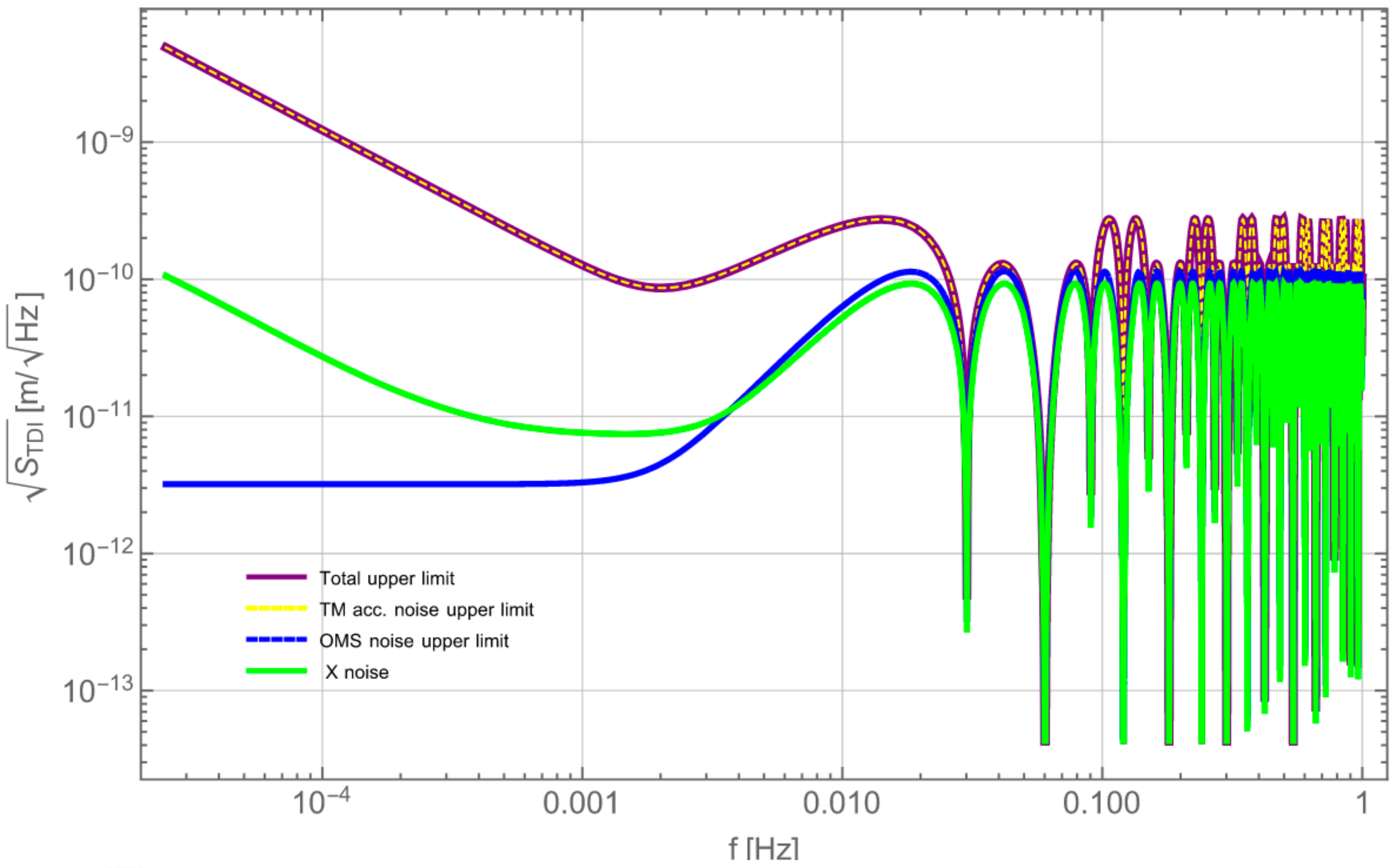
Noise upper limits

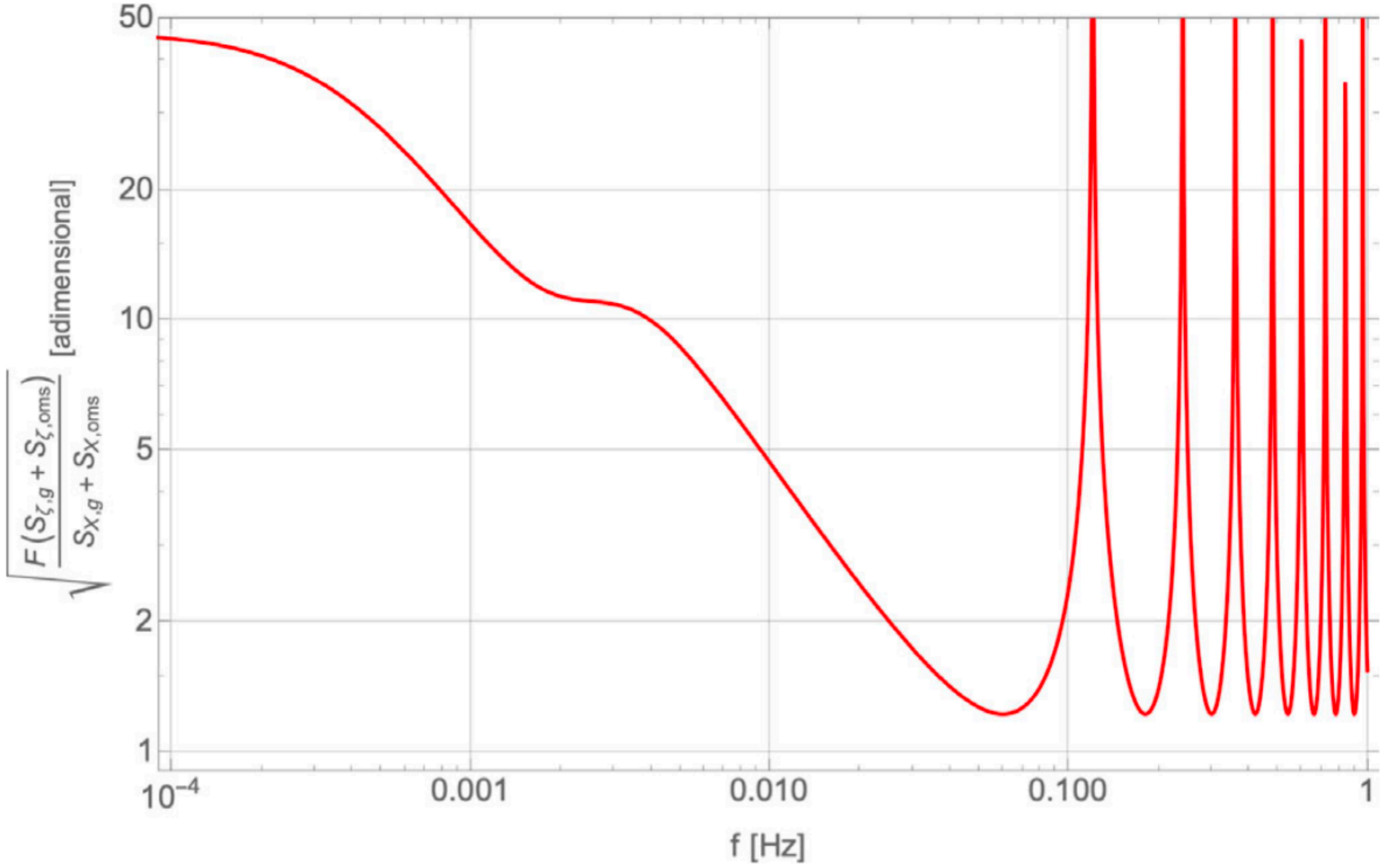
- OMS noise is dominating ζ at all frequencies
- We can still derive an upper bound on the noise in X by finding a function satisfying

$$F(S_{\zeta_{\mathrm{oms}}} + S_{\zeta_g}) \geq S_{X_{\mathrm{oms}}} + S_{X_g}$$

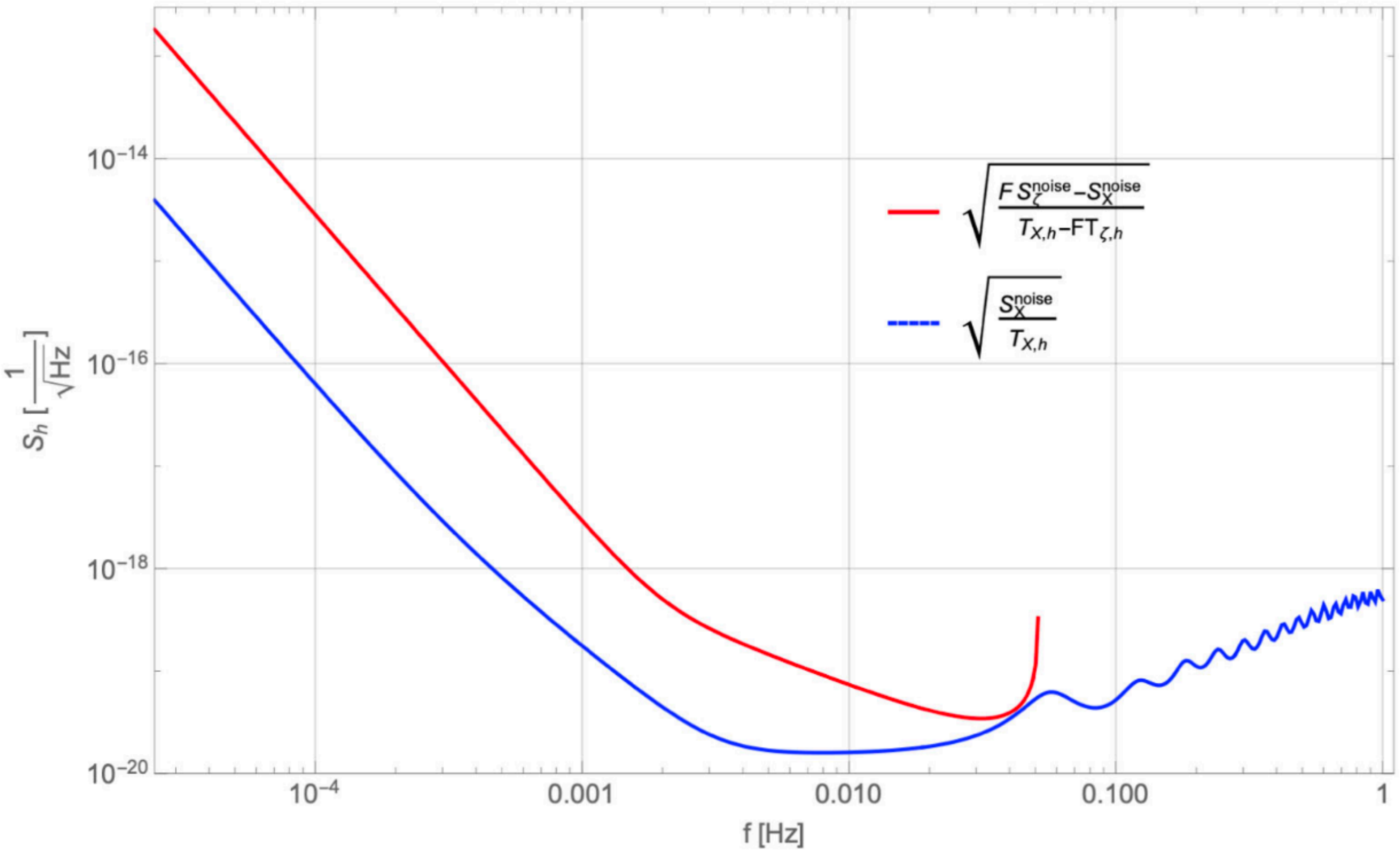
- We can take the larger of the two TFs to scale the noise

$$F = \mathrm{Max}(T_{X_{\mathrm{oms}}}/T_{\zeta_{\mathrm{oms}}}, T_{X_g}/T_{\zeta_g}) = 256\cos^4\left(\frac{\omega\tau}{2}\right)\cos^2(\omega\tau)$$





SGWB upper limit + detection threshold



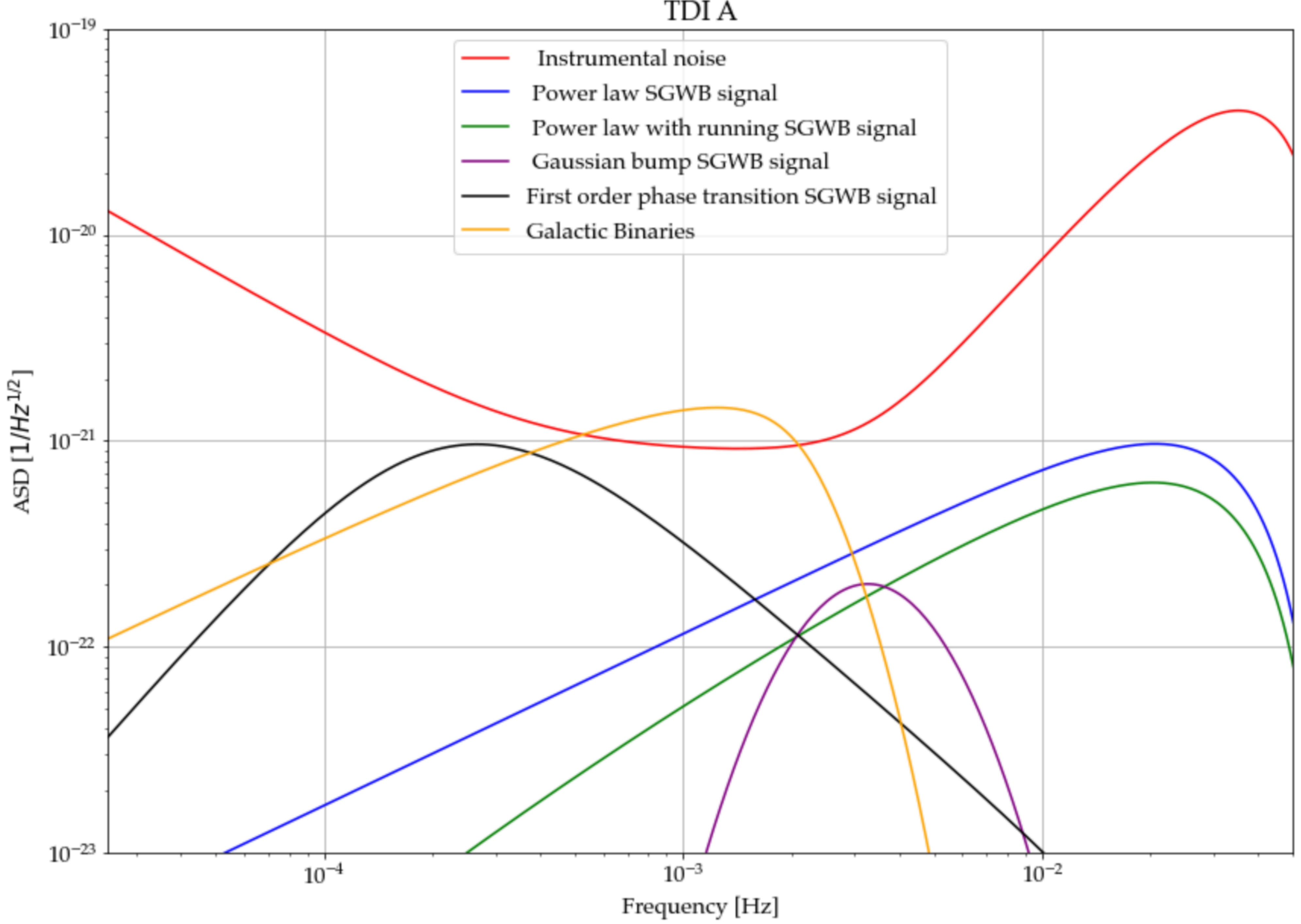
- SGWB upper limit: we will know it's below the observed noise level
- Considering just these noises, we can use the upper bound + the known response to **identify a strong SWGB**
- Reminder: **plots evaluated with noise levels from SciRD**, but method is **fully agnostic** to noise levels.

Impact of noise knowledge uncertainty on SGWB parameter estimation

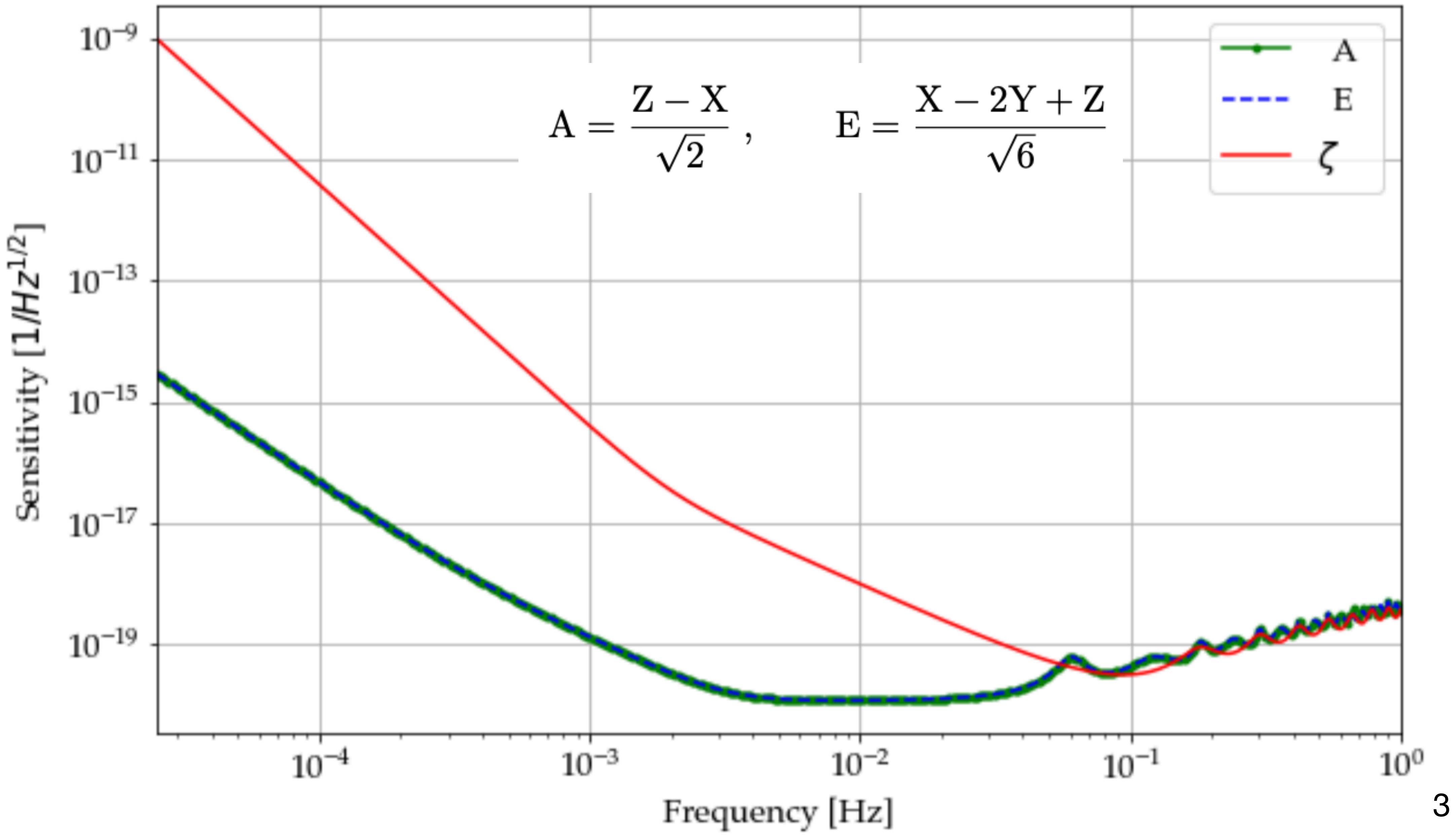
M. Muratore in collaboration with J.Gair and L. Speri (AEI Potsdam)

Impact of noise knowledge uncertainty on SGWB estimation

- 4 SGWB signal models*
- Set of 3 (first gen.) TDI channels A,E, ζ
- Splines to model noise knowledge uncertainty
- Fisher parameter space:
  - 117 for the total noise + 1 for GB amplitude + n. param. for the specific GW signal model



* Source: LISA Redbook and C. Caprini private conversation



Source: M. Muratore, J. Gair and L.Speri in prep.

Splines to model PSD and CSD

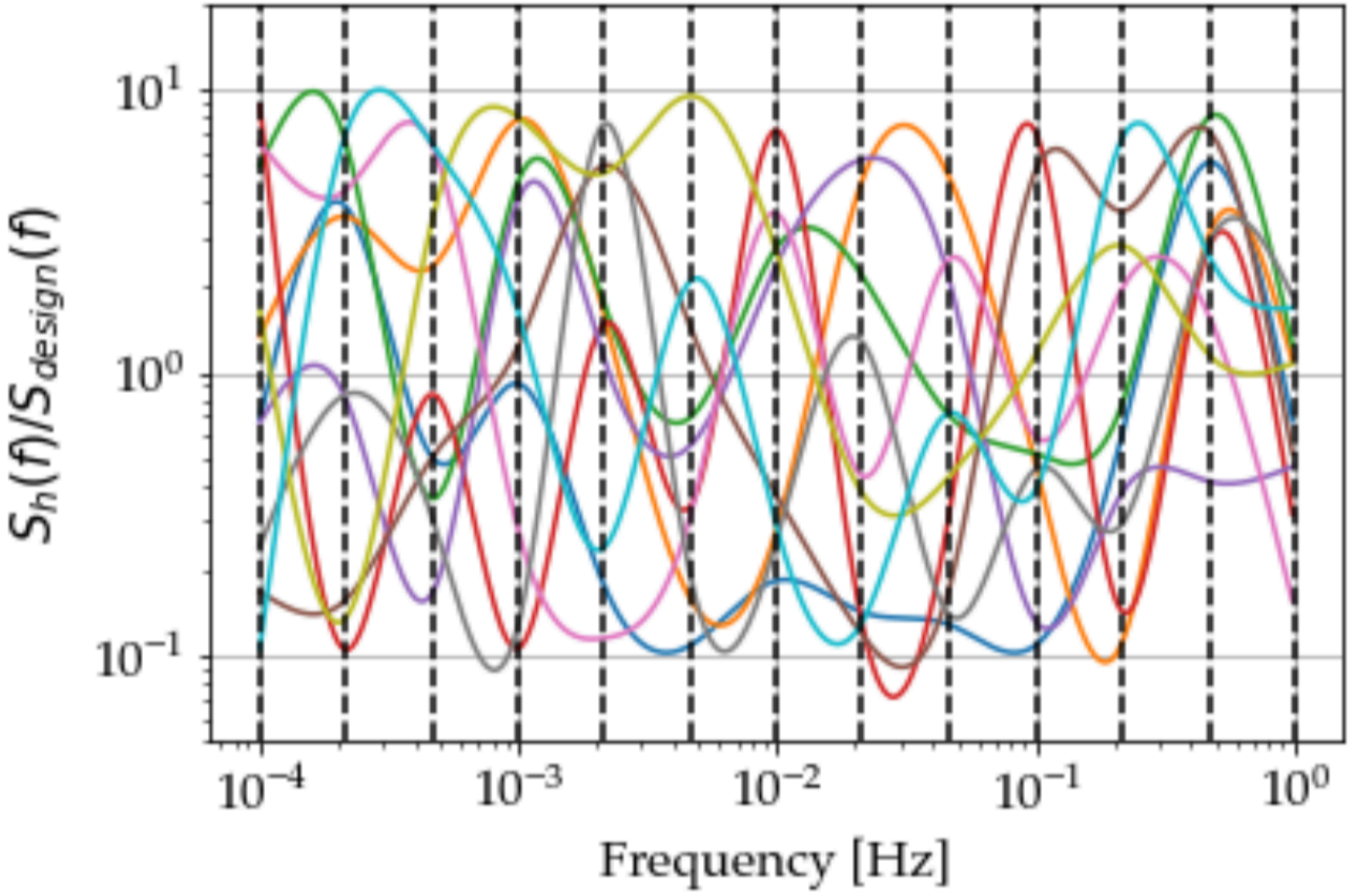
- We use splines to model the noise uncertainty generic, slowly varying, fluctuations in the PSD and CSD

$$S_{AA}(f) = \bar{S}_{AA}(f)10^{C(f|log_{10}(f_i),w_i)}$$

$$C_{AE}(f) = \sqrt{S_{AA}(f)S_{EE}(f)}\sigma_R 10^{C(f|log_{10}(f_i),w_i)}$$

$$+\sqrt{S_{AA}(f)S_{EE}(f)}I\sigma_I 10^{C(f|log_{10}(f_i),w_i)}$$

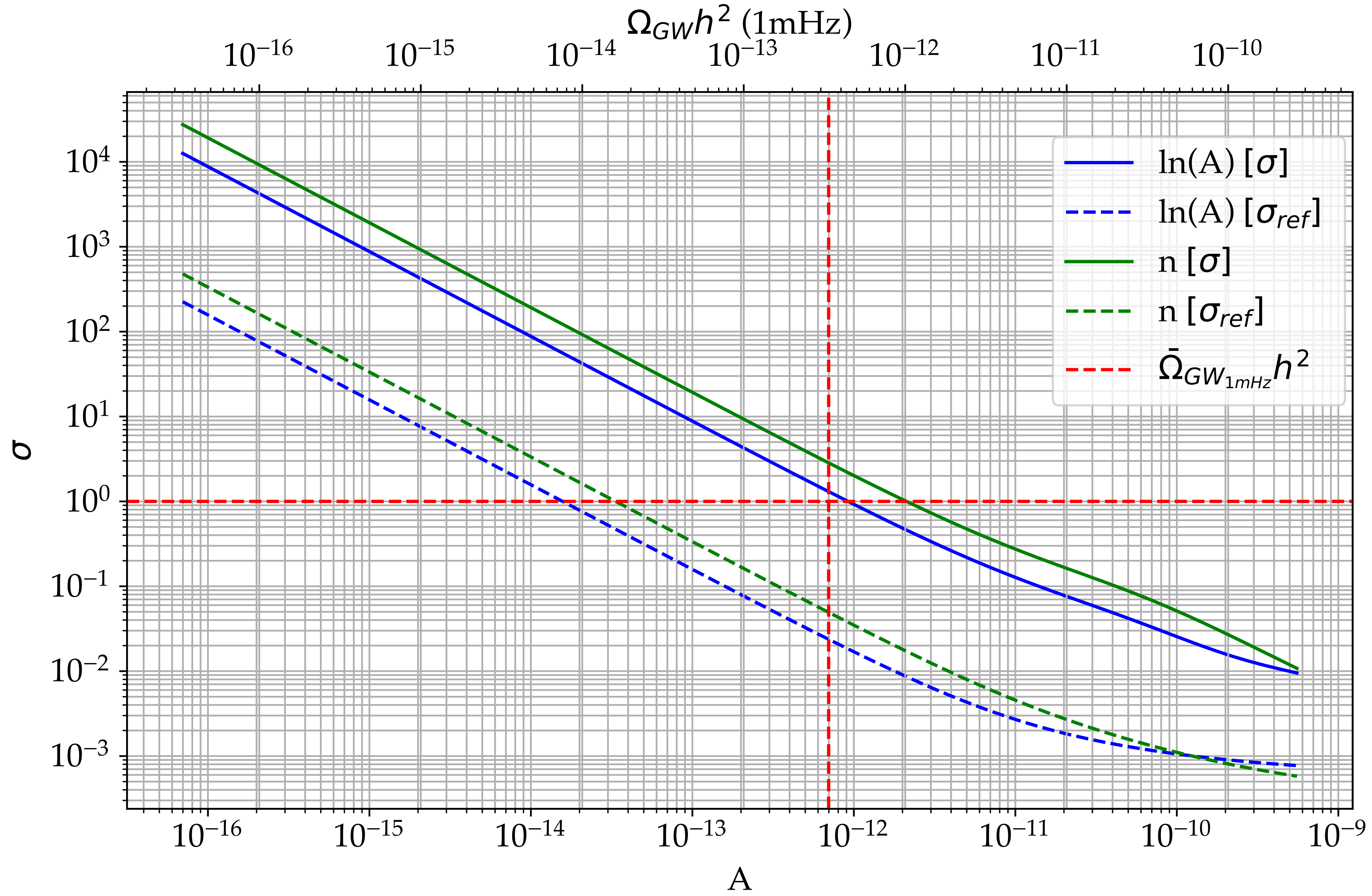
- 13 equally spaced knots [1e-4 to 1 Hz]
- The weights wi are taken to be at the reference value
- We allow for 1 order of magnitude variation in the PSD/CSD
- f is the frequency



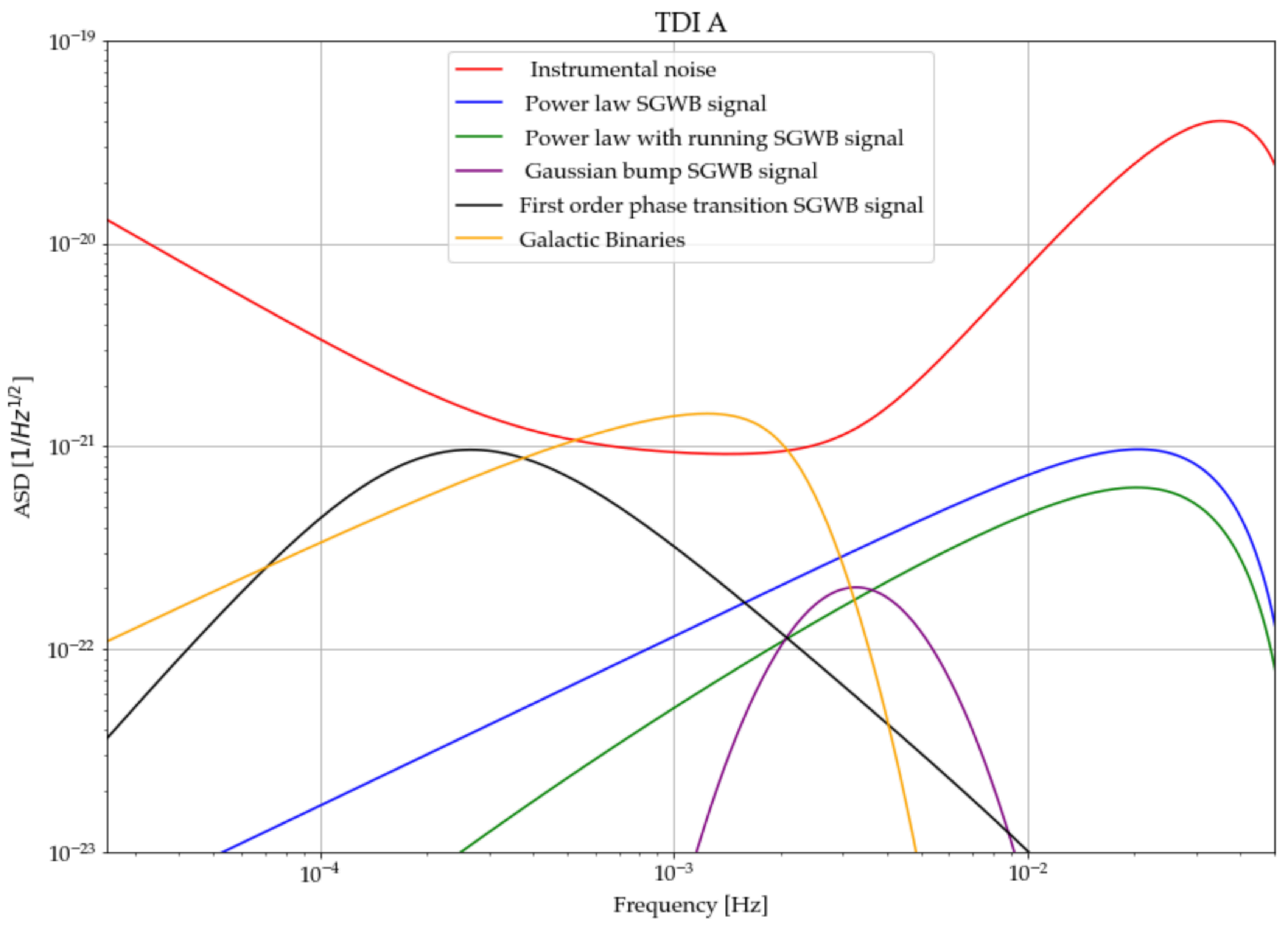
Power law SGWB from sBHB binaries with SNR 38 with 4 years of data and foreground

$$h^2\Omega_{GW}(f) \approx \underbrace{6.9 \times 10^a}_{A}\left(\frac{f}{f_p}\right)^n$$

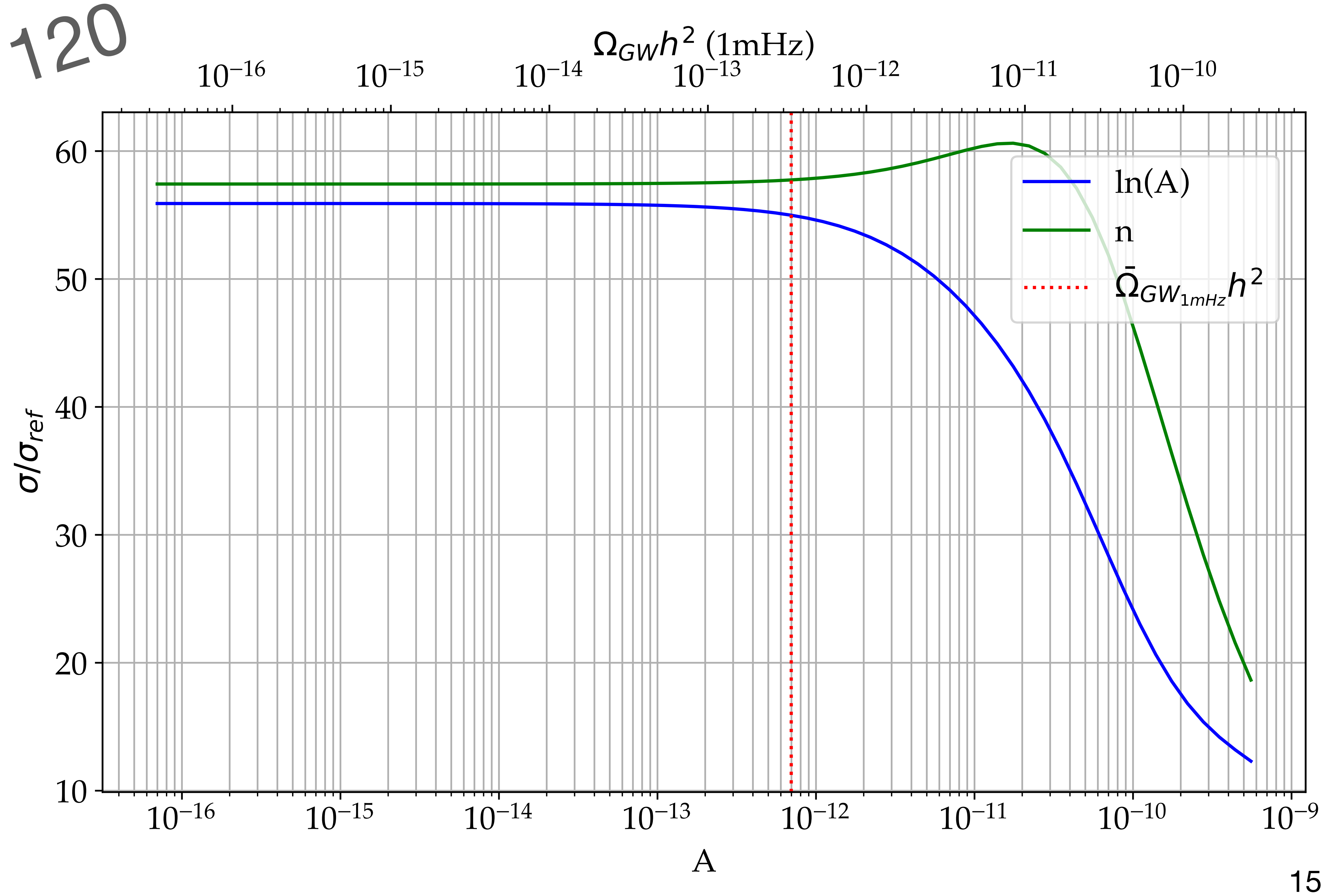
With a = -13, $n = 2/3$ and $f_p = 0.003Hz$



* Source: LISA Redbook

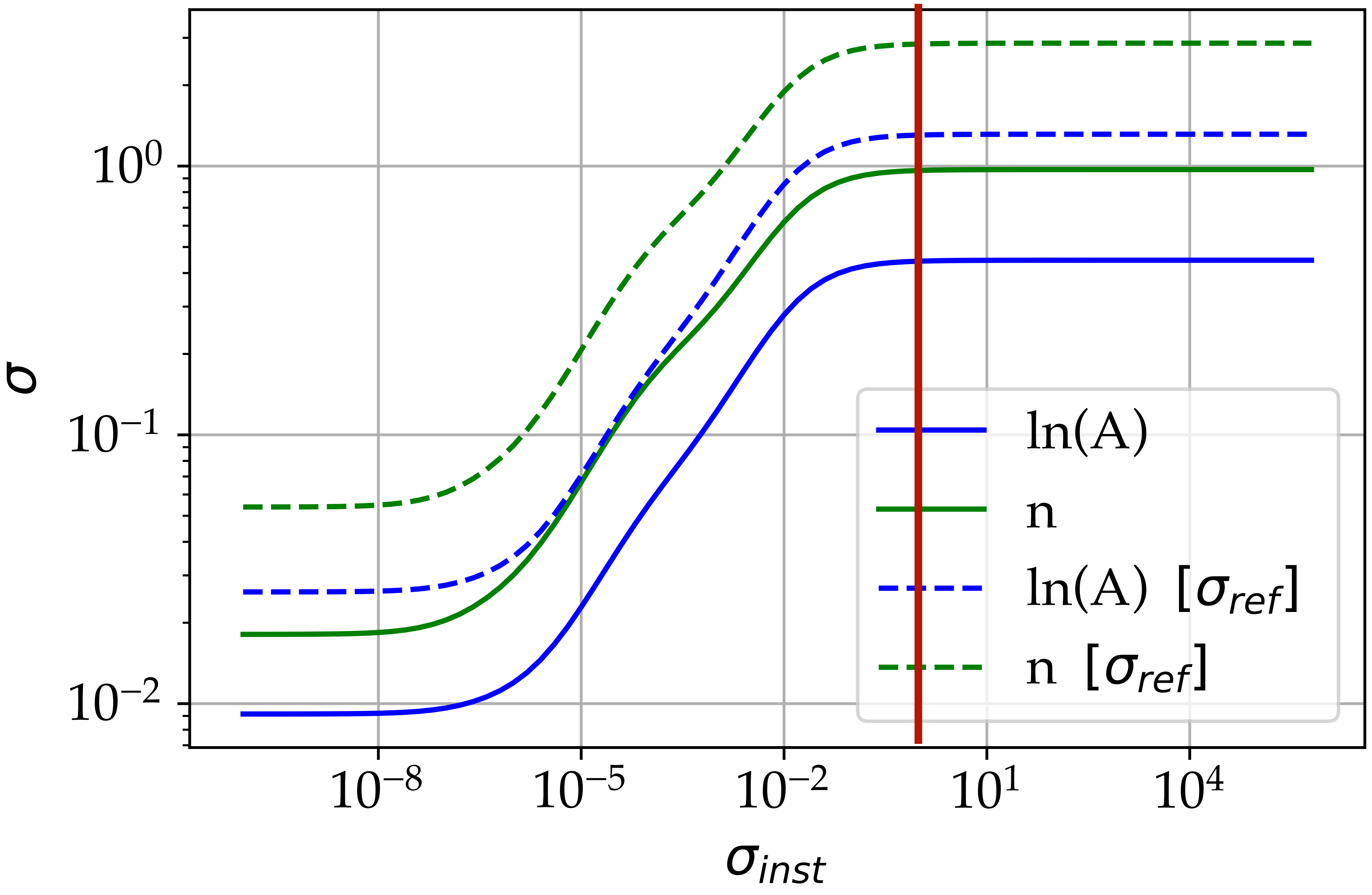


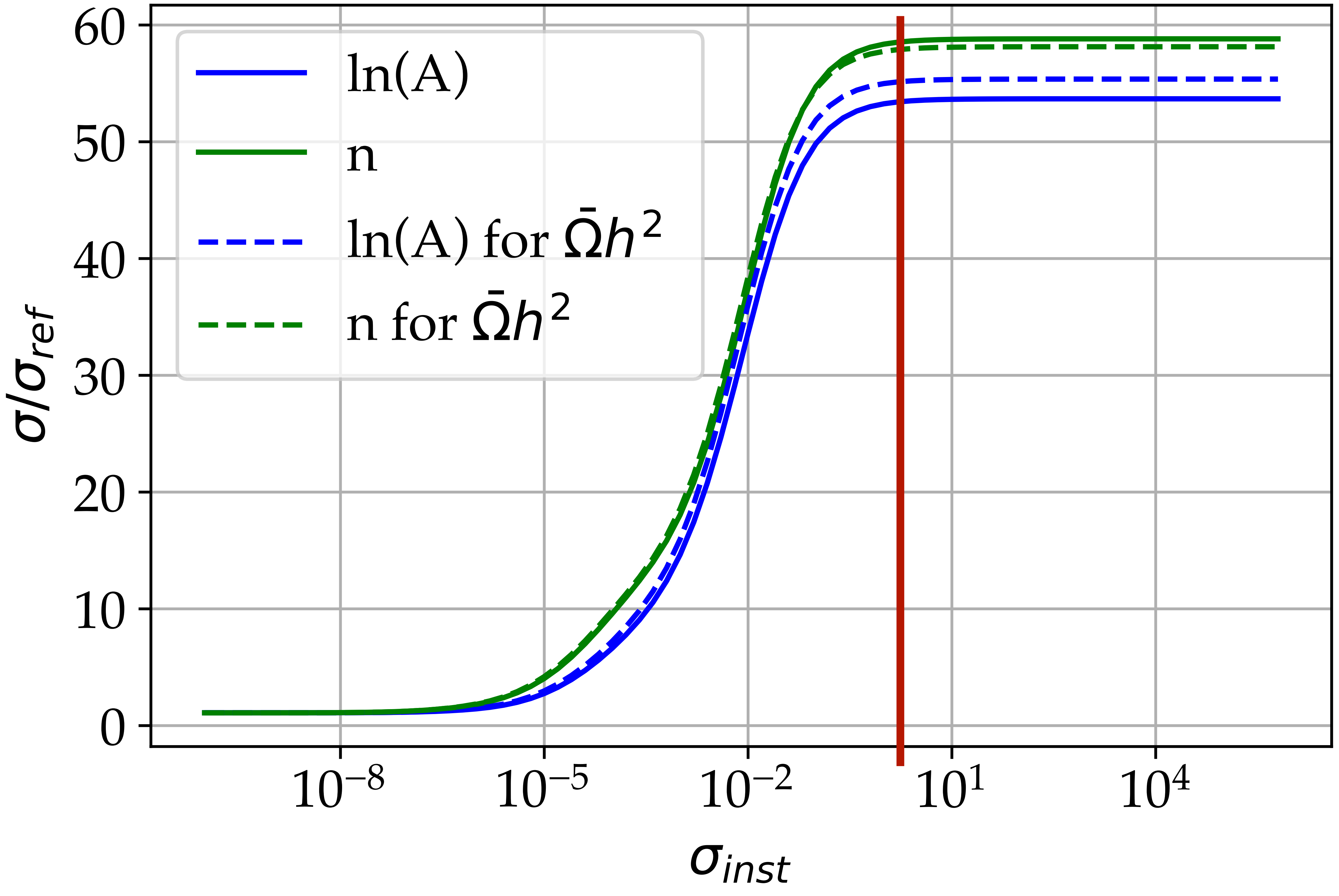
The fisher is 120 x 120



Putting requirement on the noise ?

- We now vary the prior uncertainty on the spline weights from very small to very big to see the impact on PE (with GB)





Conclusions

- Two dominant noise sources, uncorrelated TM and OMS noise, appear very differently in null- and sensitive channels - **different noise transfer functions are important**
- Assuming requirement noise levels, **noise upper bound** from null channel **is poor** at low frequency (factor 50)
  - At higher frequency, between 30-100 mHz, we have a noise estimate below a factor 4 of the promised detector noise power a limit
- We could only **distinguish a SGWB** if it becomes significantly larger than the instrumental noise
- Null channels are **completely insensitive** to some forms of correlated noise

Conclusion and few ‘’caveats”

- LISA noise will be driven by multitude of physical parameters (some will be known, some might be completely unknown)
- **The LISA data analysis,** particularly in the search for a stochastic GW background, **should be as robust as possible to ignorance of the noise model**
- **Efforts to characterize the noise based on in-flight observables should be exploited** as much as possible
- In case of **generic, slowly varying, fluctuations in the PSD and CSD things are measurable and we have modelled SGWBs** but the precision decreases by 2/3 order of magnitude

Estimating correlated noise with the null channels

- Intermediary TDI variables:

$$\eta_{ij}(t) = x^{g}_{ji}(t-\tau) + x^{g}_{ij}(t) + x^{m}_{ij}(t).$$

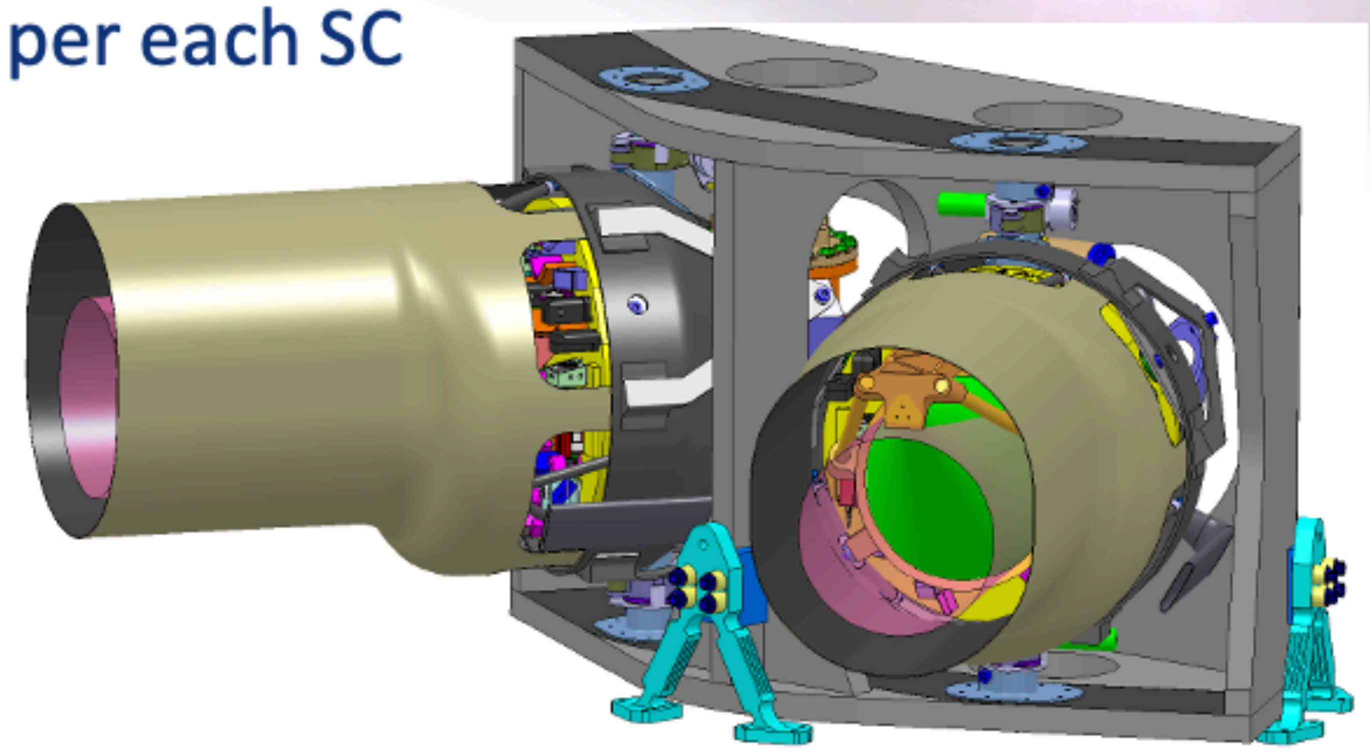
TM acc. noise — OMS noise

- It is instructive to consider the expression for ζ in the equal-armlength limit with ***D = 1-L and D*** $\boldsymbol{\eta_{ij}} = \boldsymbol{\eta_{ij}}$ *(t-L)*

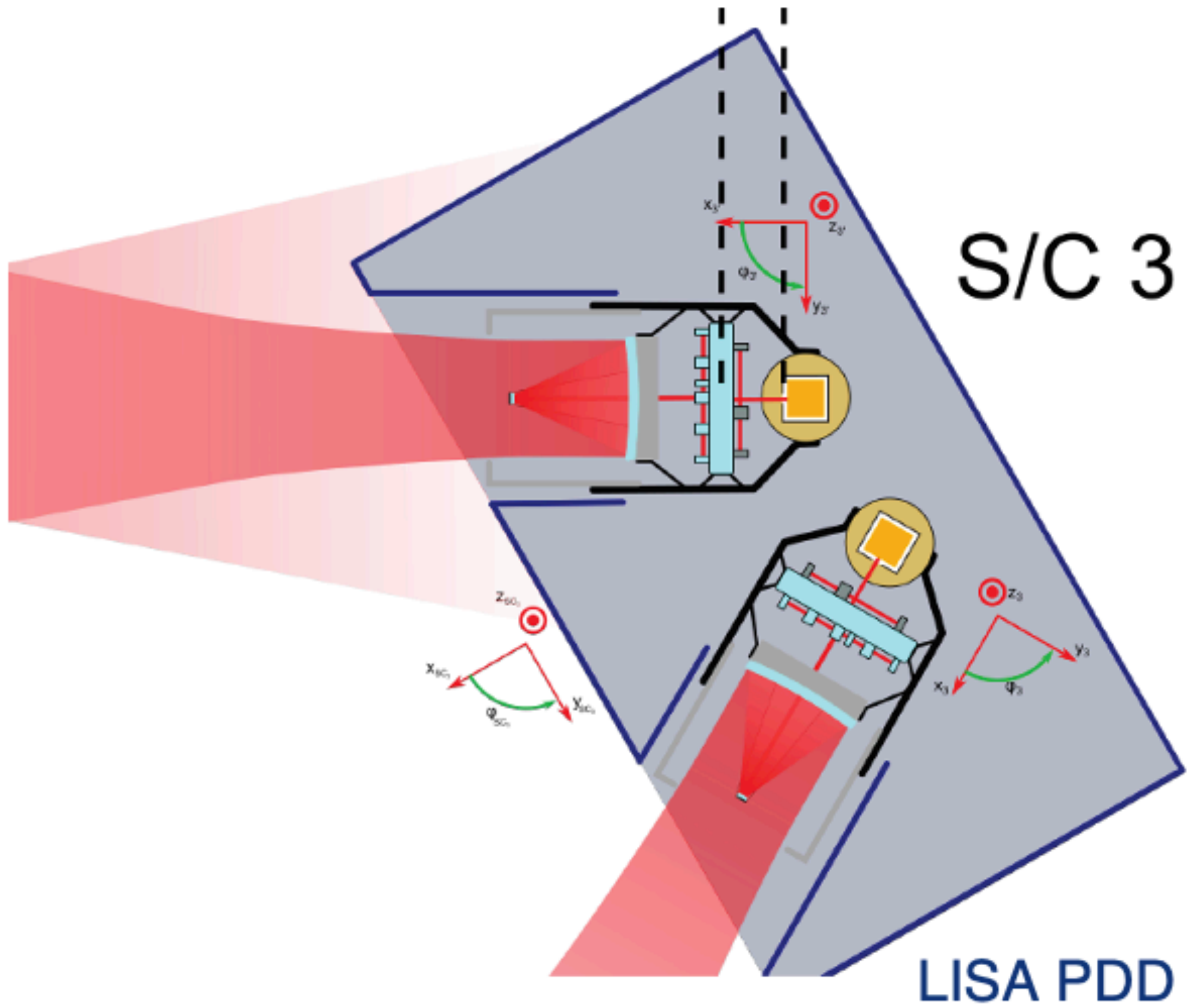
$$\zeta = (1-D)\,(\eta_{12} - \eta_{13} + \eta_{23} - \eta_{21} + \eta_{31} - \eta_{32})$$

- **ζ is insensitive to correlated noise entering equally in the two single-link measurements** recorded on-board a single spacecraft (e.g. correlated TM acc. noise)

- 2 Movable optical sub-assembly (MOSA) per each SC



Payload strawman conceptual design. Images courtesy of Airbus D&S GmbH, Friedrichshafen. LISA proposal



LISA PDD