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

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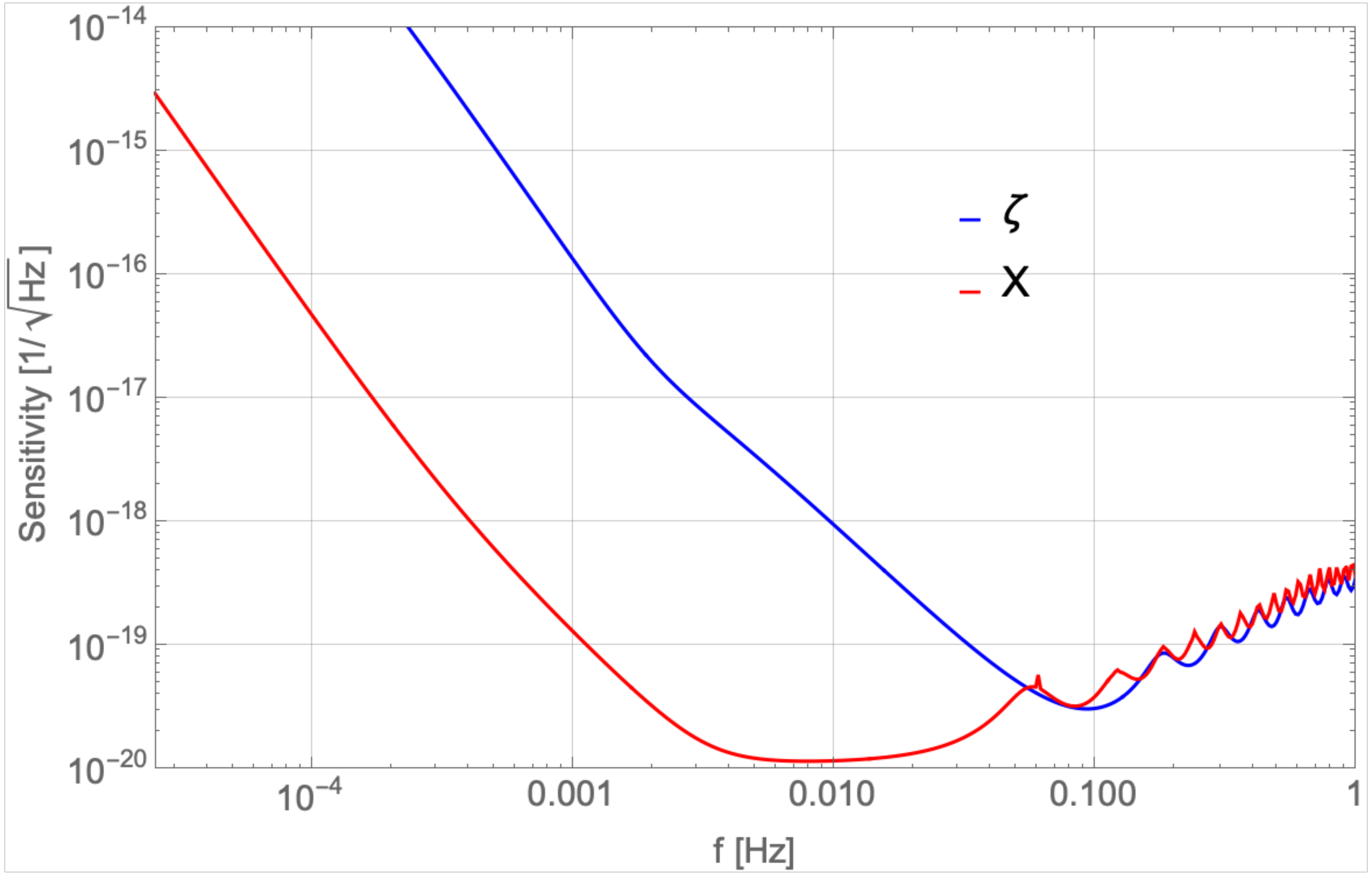
Noise knowledge for LISA

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
    - Goal here: understand how well we can constrain the noise in X with ζ



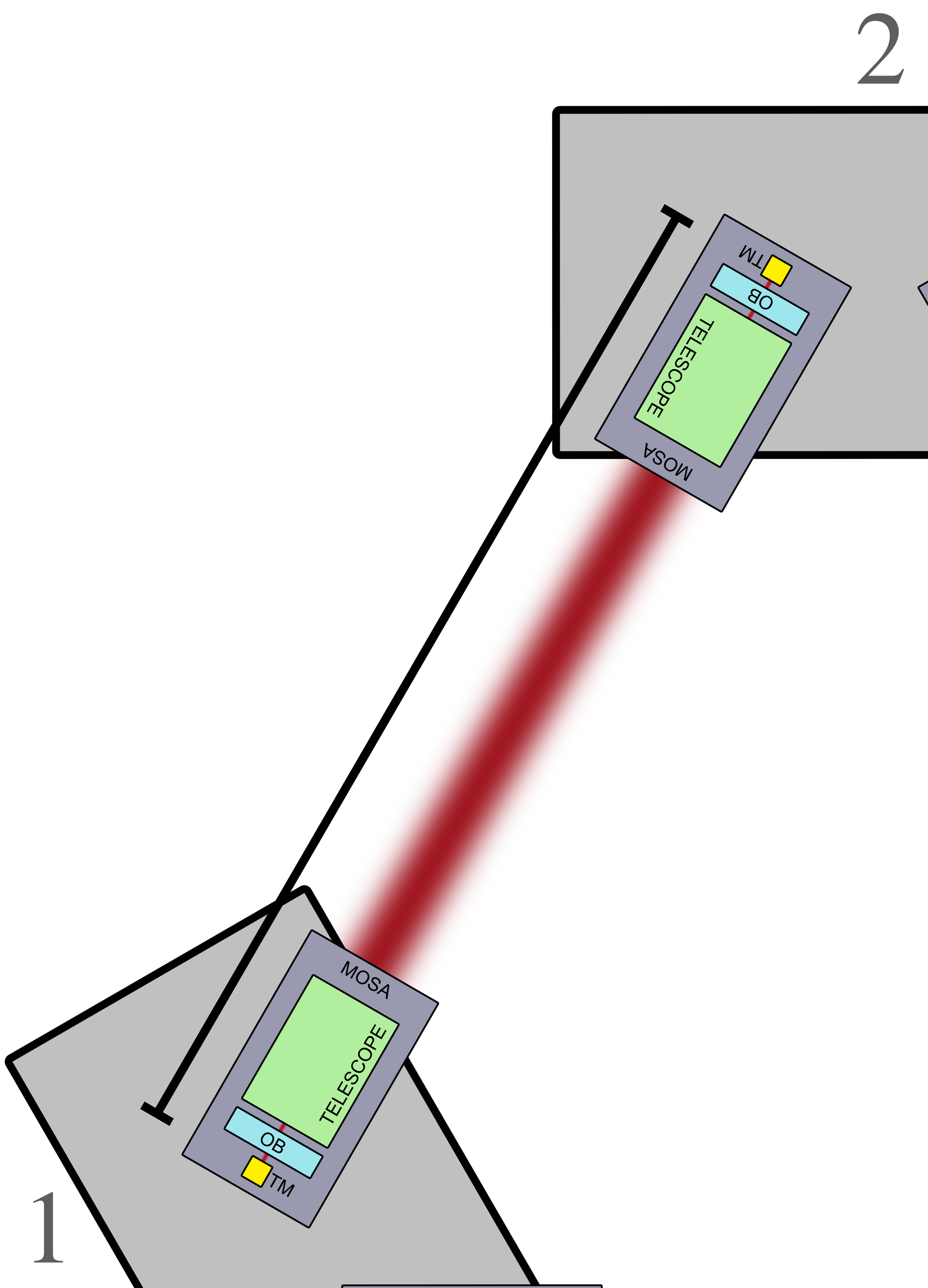
LISA Observables

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:

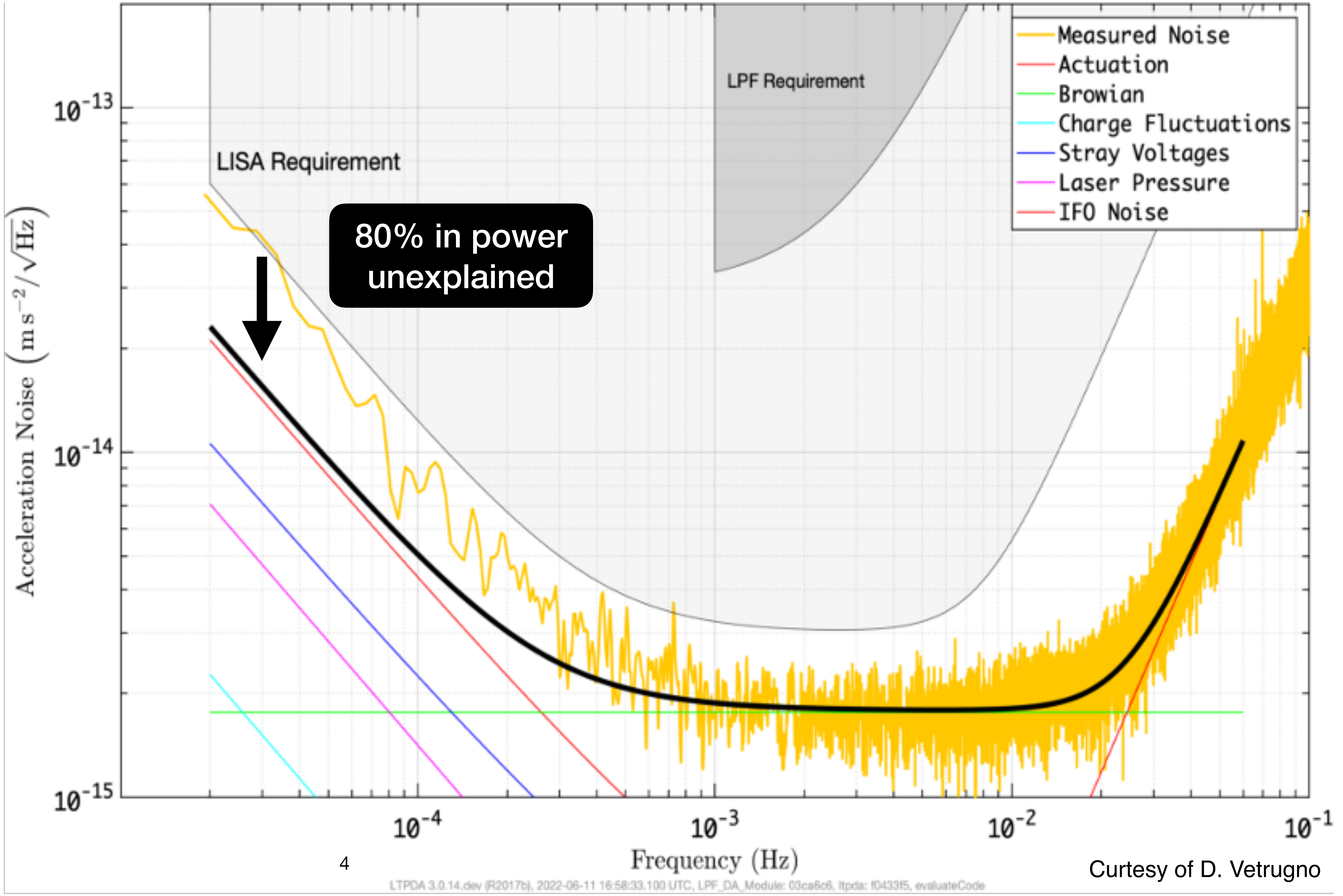
$$\eta_{12}(t) \sim H_{12}(t) + x^g_{21}(t-\tau) + x^g_{12}(t) + x^m_{12}(t)$$

- $H_{12}(t)$: 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)



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

Noise assumptions in our study

Single link measurements

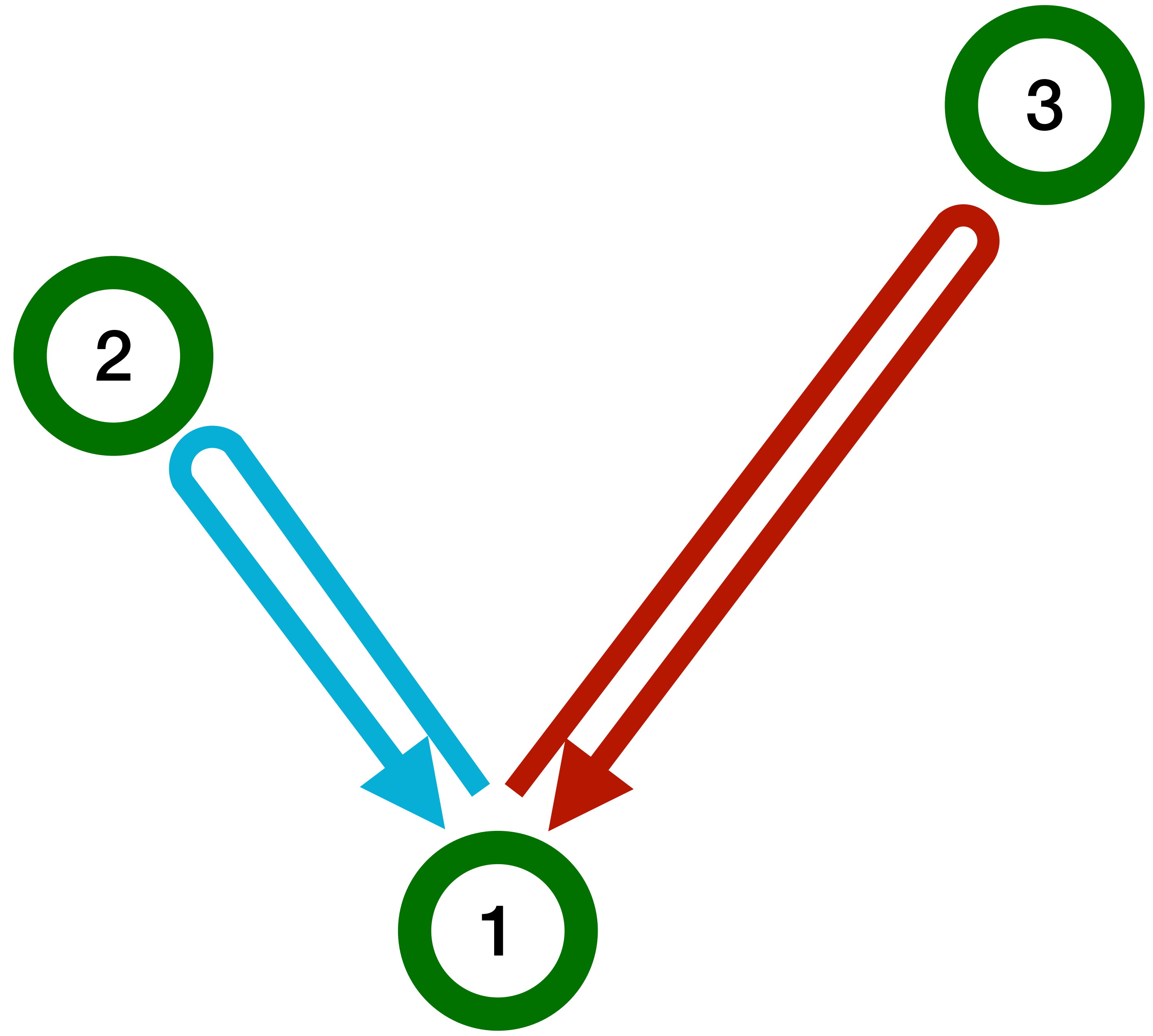
- No assumptions on any spectral shape or amplitude
  - But for evaluating plots: assume noise levels from requirements
- $H_{ij}(t)$: Assume response to isotropic SGWB with PSD S_h
- $x^g_{ij}(t)$: Assume motion of different TMs to be fully uncorrelated, with PSDs $S^{disp}_{g_{ij}}$
  - In reality, 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

TDI channels

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

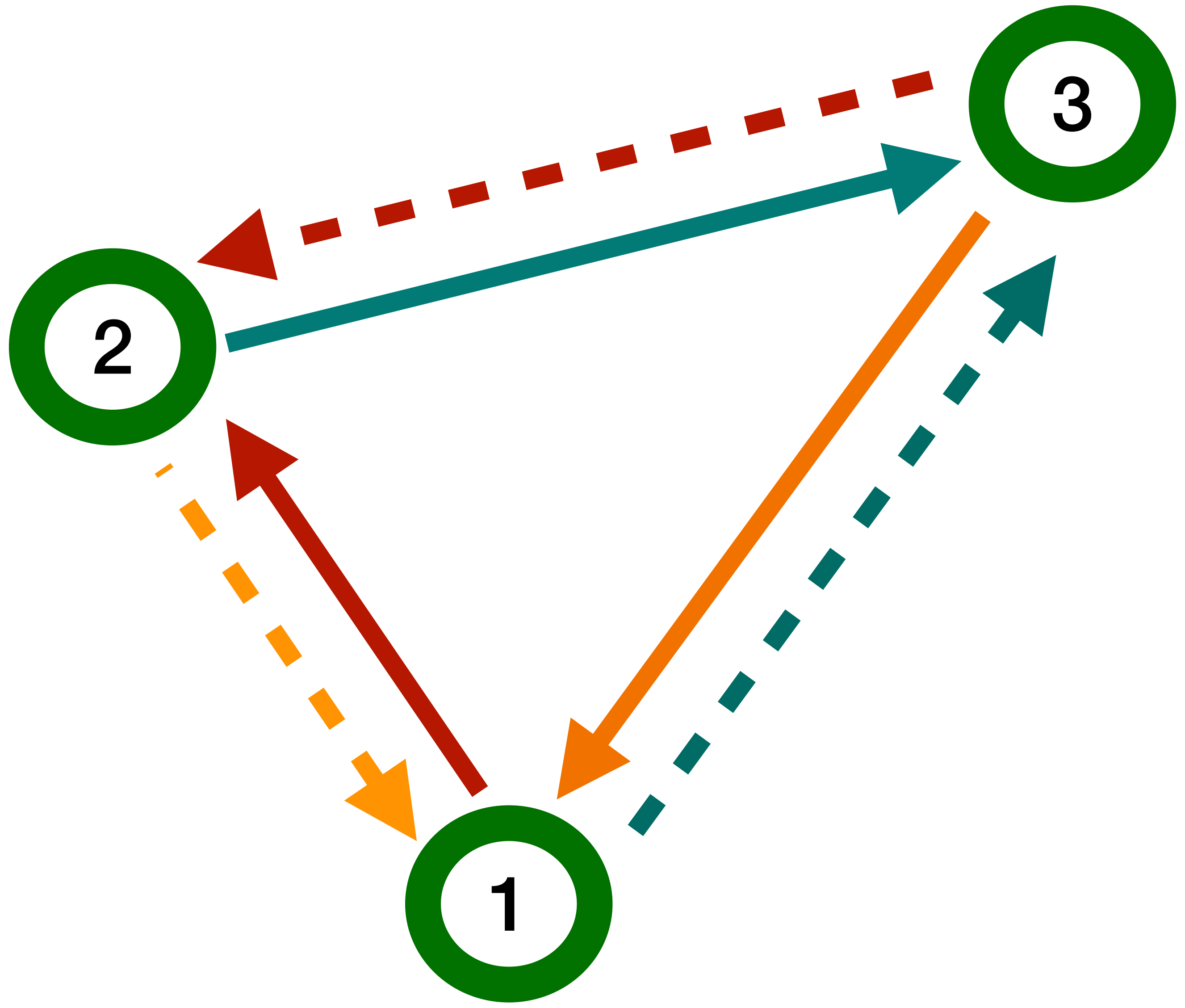
$$X \approx (1 - D^4)(1 - D^2)(\eta_{12} + D\,\eta_{21} - \eta_{13} - D\,\eta_{31})$$



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

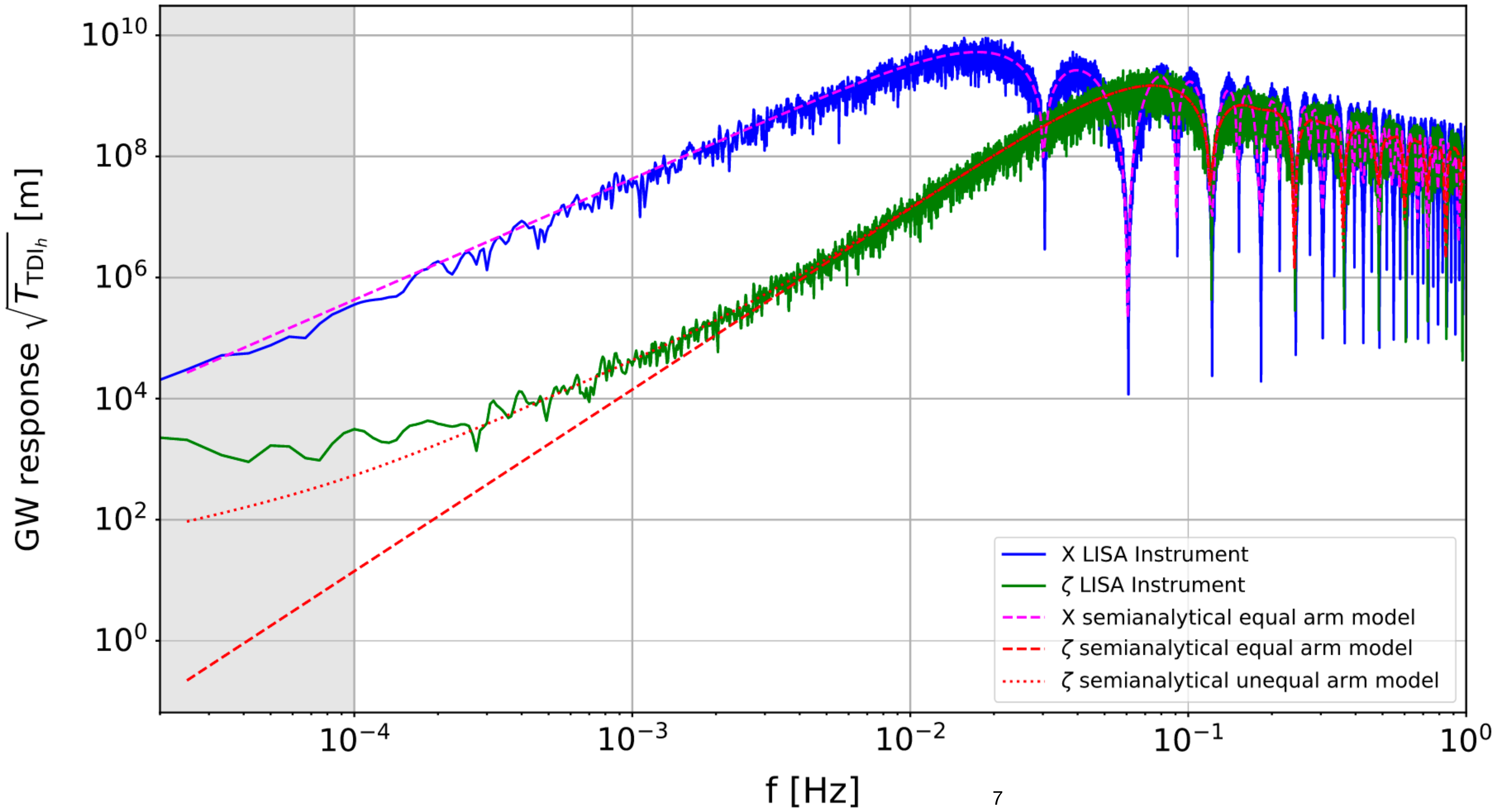
$$\zeta \approx (1 - D)(\eta_{12} - \eta_{13} + \eta_{23} - \eta_{21} + \eta_{31} - \eta_{13})$$

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



LISA Observables

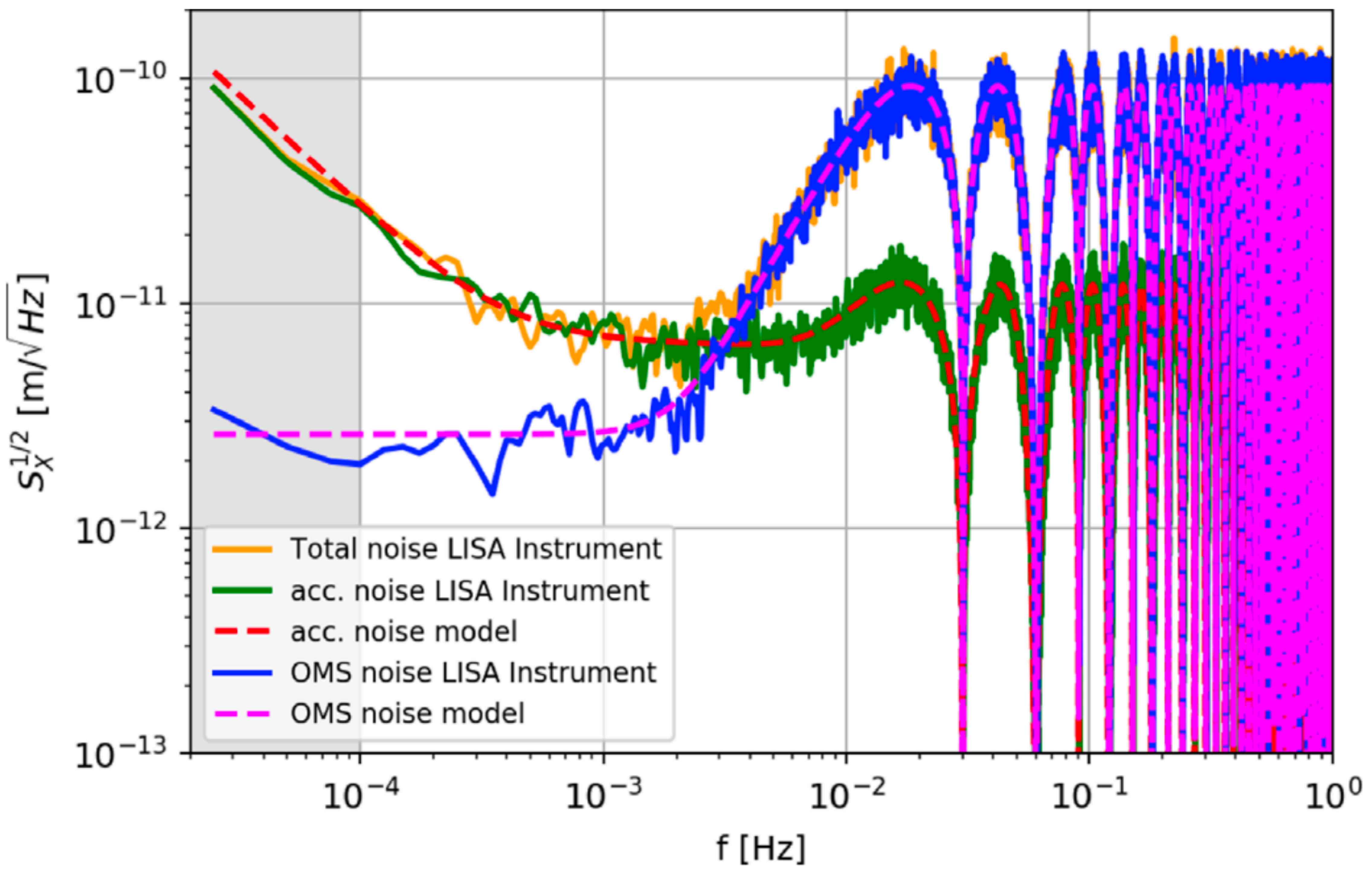
GW response to isotropic SGWB

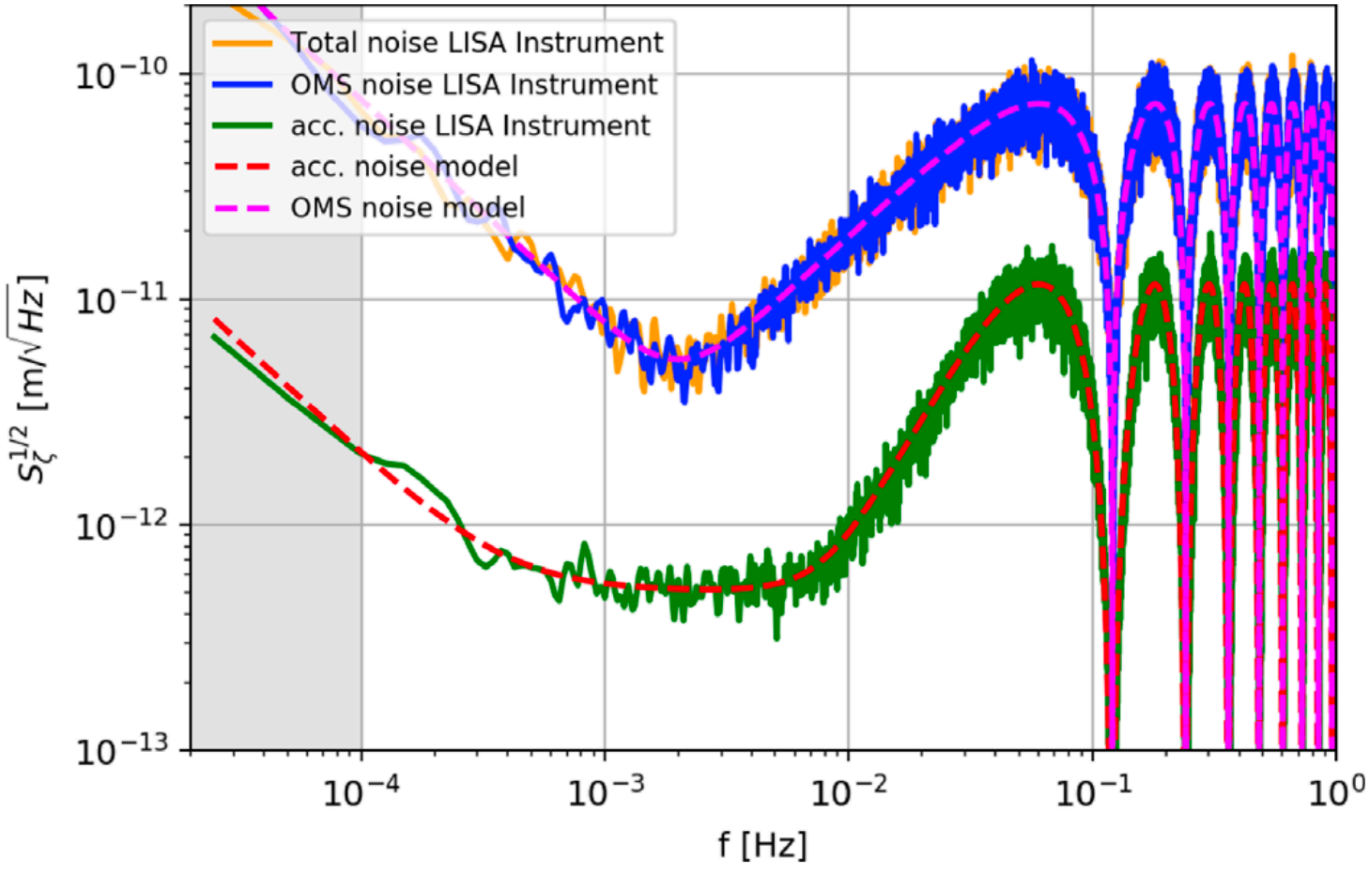


- Up to ~50 mHz, ζ has suppressed GW response wrt. X
- At high frequencies, response is similar

LISA Observables

Noise response





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

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

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

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

Noise upper limits

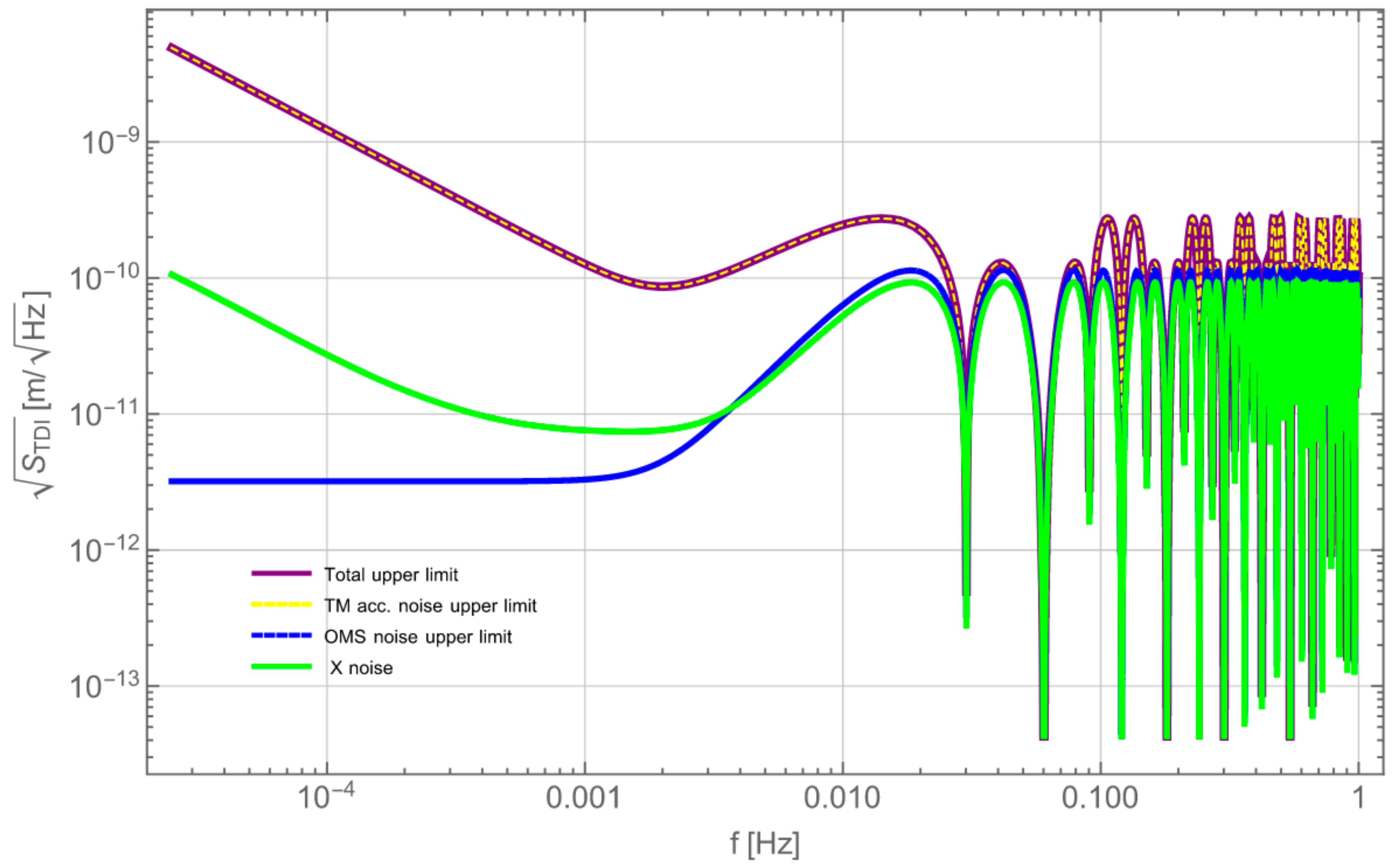
- OMS noise is dominating ζ at all frequencies

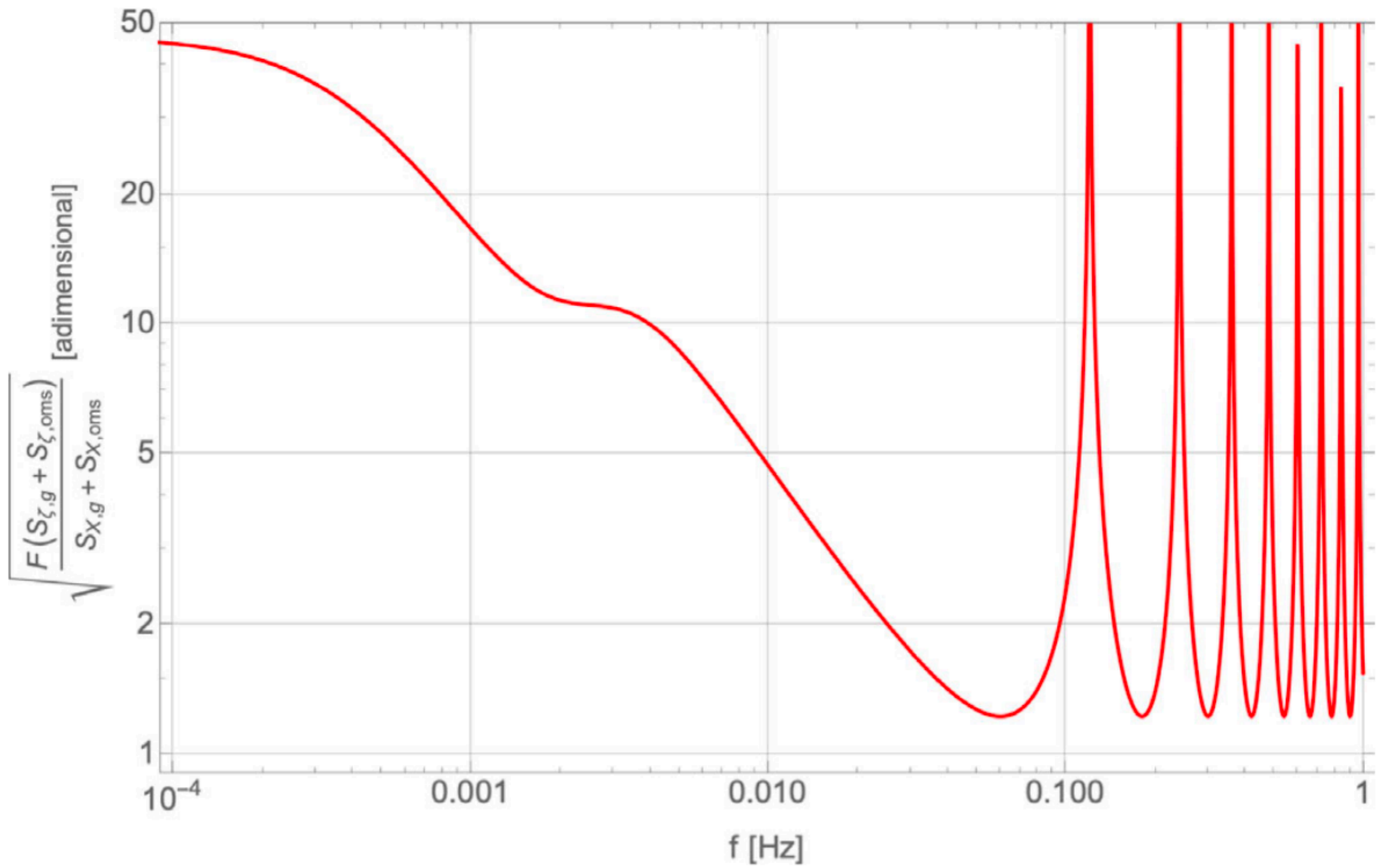
- We can still derive an upper bound on the noise in X by finding a function satisfying

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

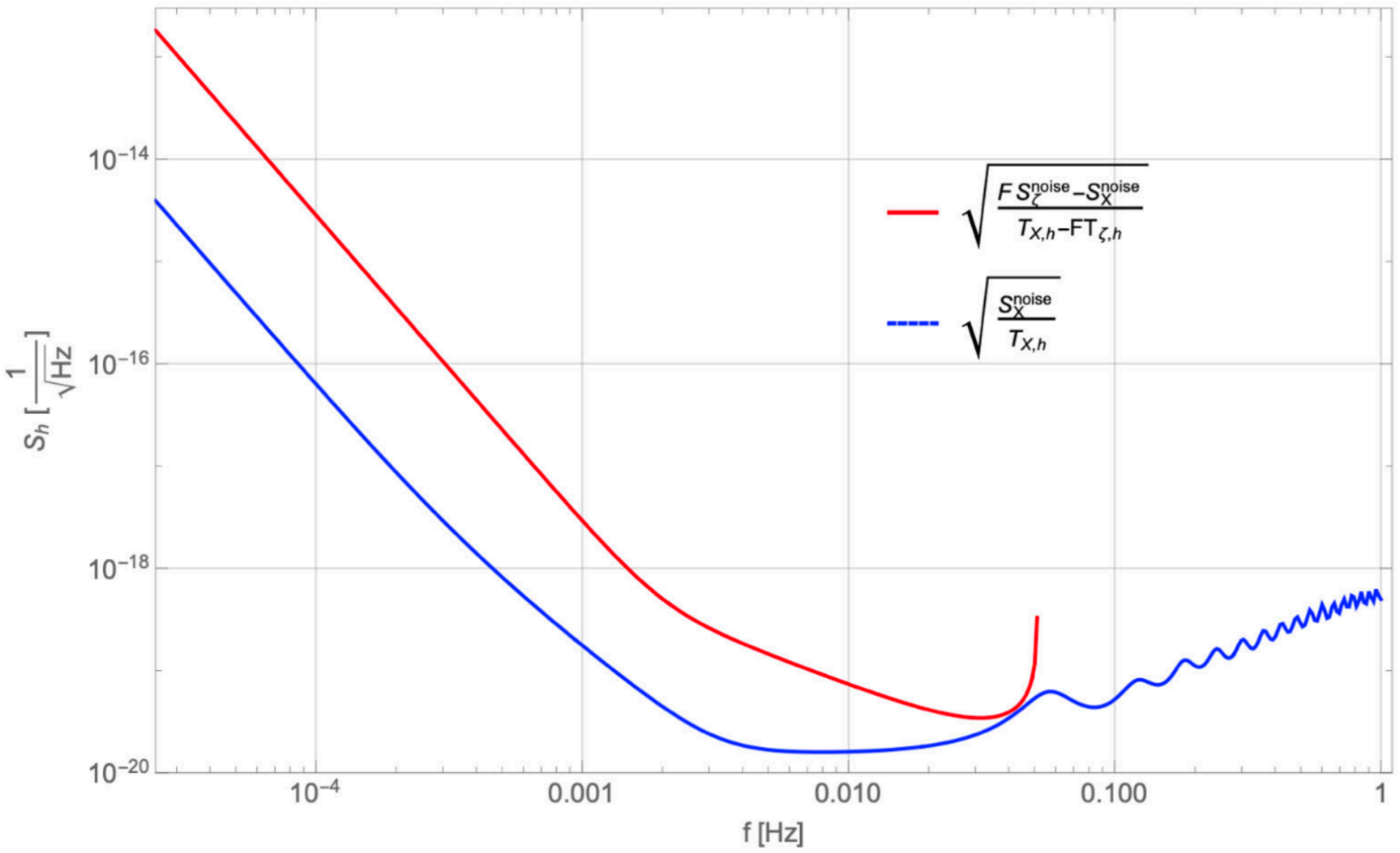
- We can take the larger of the two TFs to scale the noise

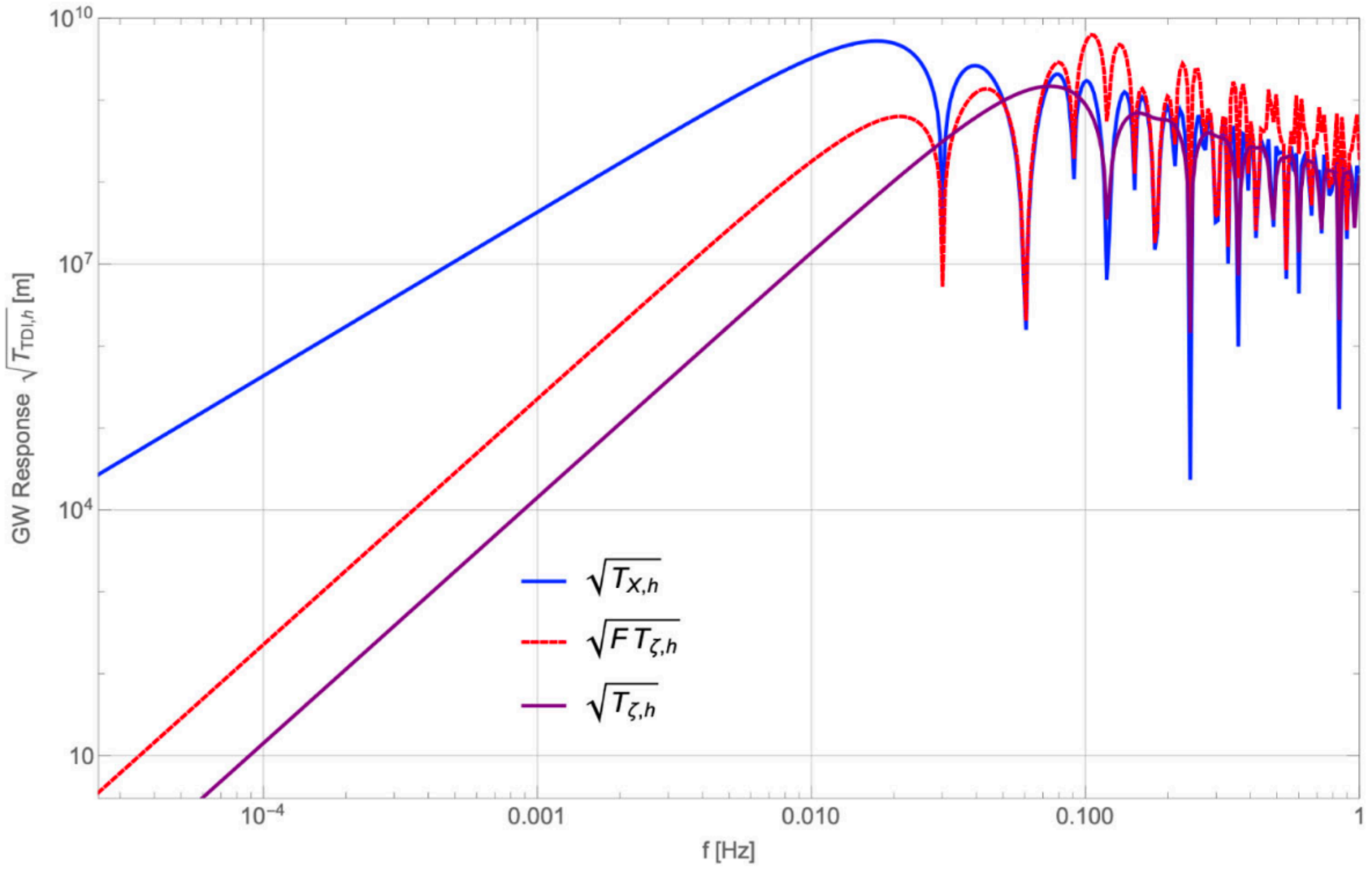
$$F = \mathrm{Max}(T_{X_{\rm oms}}/T_{\zeta_{\rm oms}}, T_{X_g}/T_{\zeta_g}) = 256\cos^4\left(\frac{\omega\tau}{2}\right)\cos^2(\omega\tau)$$





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.

Limits of our study

- Optimistic:
  - Only considered the **two main noise sources**, which we assumed to be fully uncorrelated
  - No proper statistical analysis, assume **perfect measurement** of PSDs
- Pessimistic:
  - Only considered **one sensitive channel** (instead of two)
  - No proper statistical analysis, but just a **noise upper bound** absorbing some terms
  - No use of other characteristics of the noise or signal, like non-stationarity, anisotropy, …

Conclusions 1

- 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

Conclusions 2

- 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
  - Still, given the large uncertainties in the range of possible stochastic background levels, the results shown here might proof useful.
- Null channels are **completely insensitive** to some forms of correlated noise