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

LISA data analysis: from classical methods to machine learning, 24 November 2022

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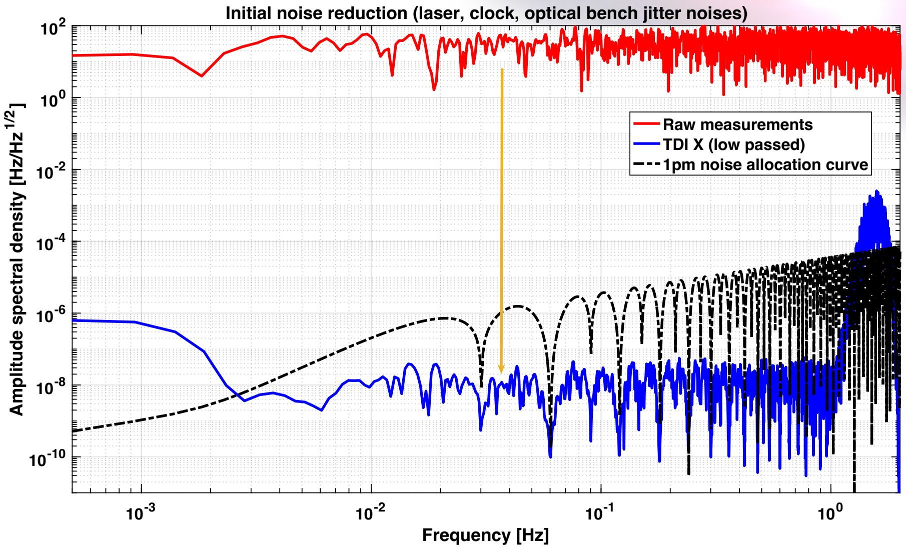
The LISA noise a quick recap

- **The LISA noise is dominated by laser frequency noise** that we need to reduce via the post-processing TDI
- **Many TDI's combinations** can be formed as the GW sensitive **Michelson X**
  (Revisitation of time delay interferometry, June 2020 CQG 37(18) DOI:10.1088/1361-6382/ab9d5b, Muratore et al.)
- **Post-processing via the initial noise reduction pipeline L0-L1 to** reduce clock, TTL, spacecraft jitter noises etc (see Olaf & JB talk)
- Secondary noises: **TM acceleration noise and optical metrology noise**



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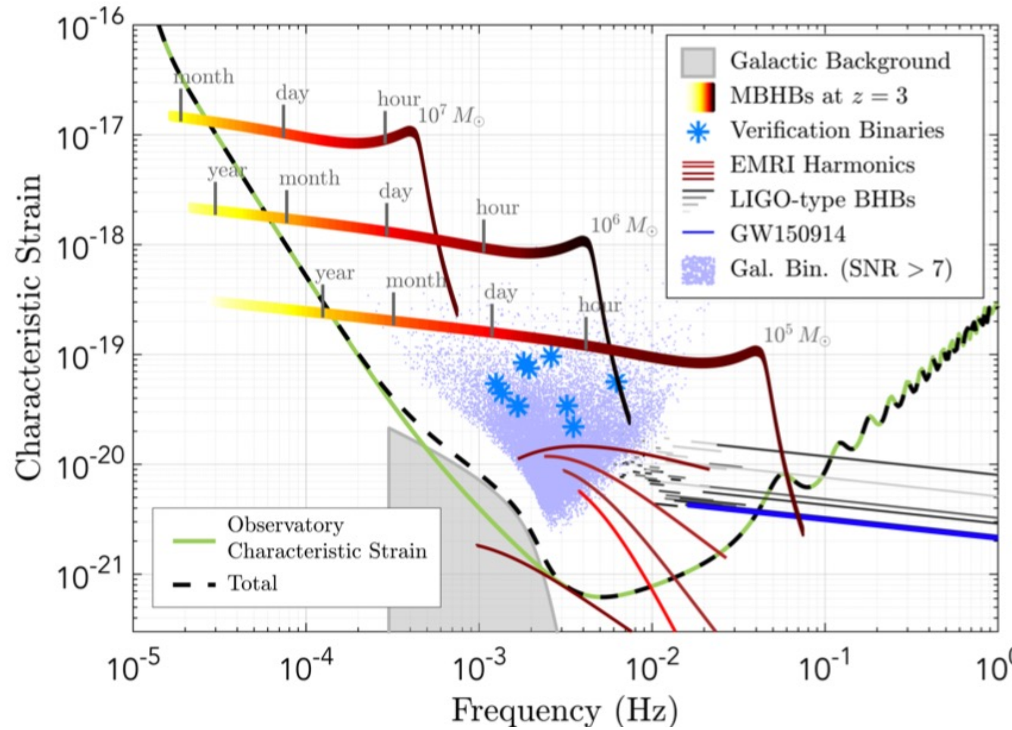
1 TDI X first generation

Stochastic Gravitational Wave Background with LISA

- Why do we need to know the instrumental noise?
- For the high SNR individual sources, it does not make a big difference
- But it is important for the SGWB
- We need to distinguish SGWB from instrumental noise in the sensitive channels (X / A)
- LISA cannot use cross-correlation with other detectors



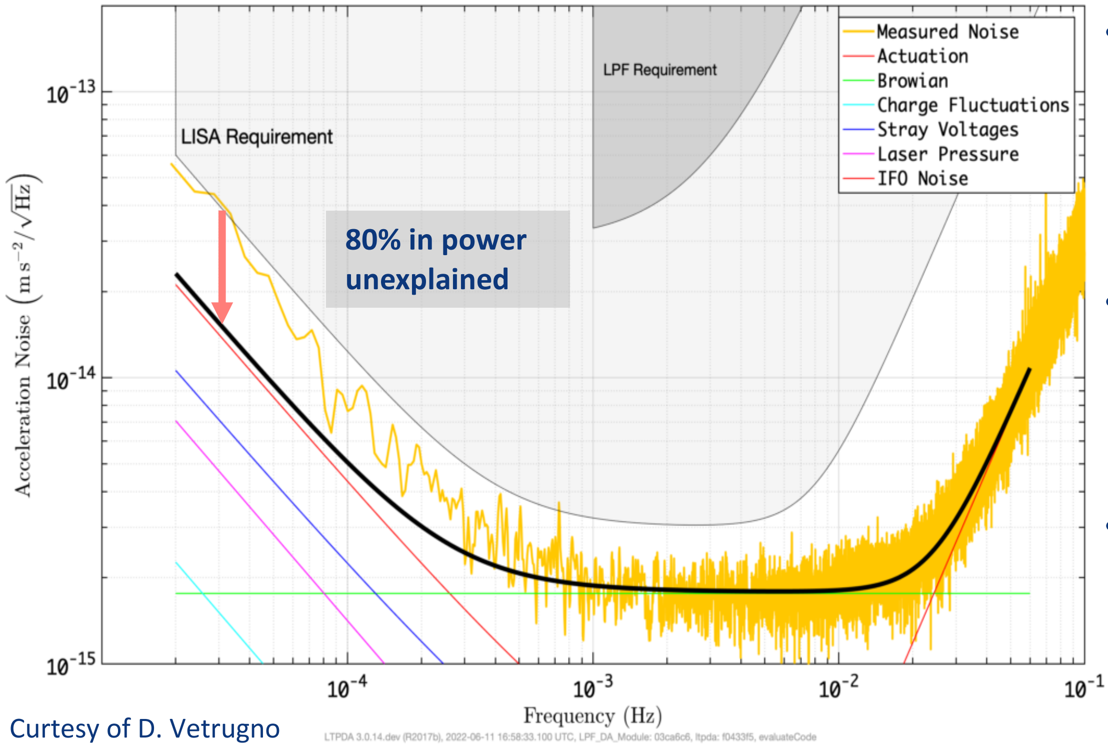
Null channels to estimate the noise (in-flight calibration)

- Pre-flight modelling

- Look for TDI combinations that have *suppressed* sensitivity to gravitational wave (GW) signals but still carry some information on the instrumental noise and calibrate the noise in flight

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

Pre-flight modelling: Modeled forces do not fully explain noise



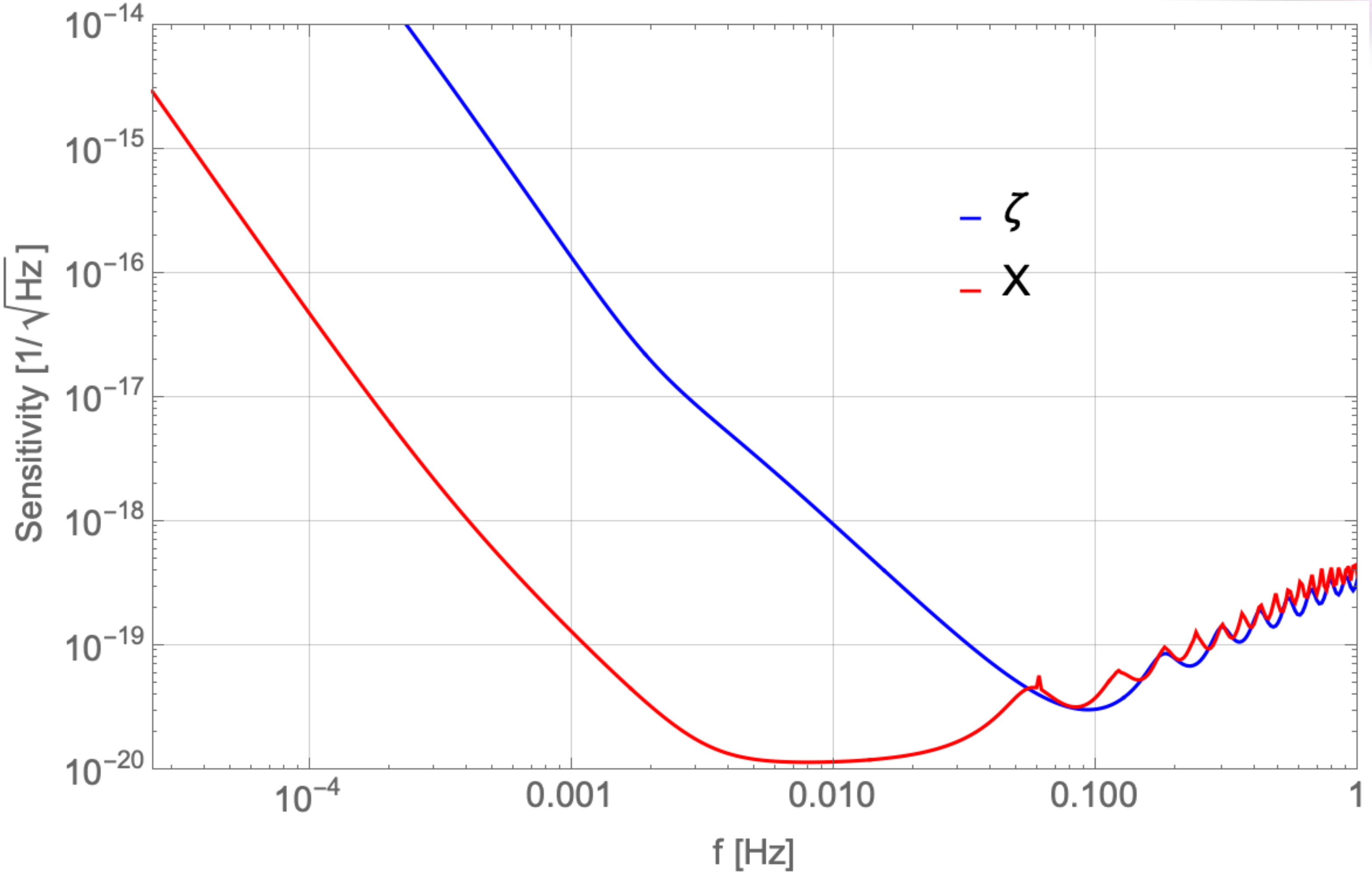
Curtesy of D. Vetrugno

- Various key parameters of the LISA noise (**DC residual forces, magnetic field gradients, residual stray electrostatic fields, optical alignments, among others)**, are all designed to be ideally zero
- but with uncertainties that make their residual contribution **both difficult to predict and likely different among the different LISA TM or optical readouts**
- Existing noise model consists of many components which depend on physical parameters which cannot be measured directly (e.g., the Brownian force noise or the optical interferometry shot noise)

LISA instrument **cannot be tested end-to-end** on ground, few examples:

- TM acc. noise, expected to dominate the budget $< 1mHz$ but it cannot be measured to the accuracy required
- Long ifo arm cannot be measured end-to-end

Use null channels to characterise noise in-flight

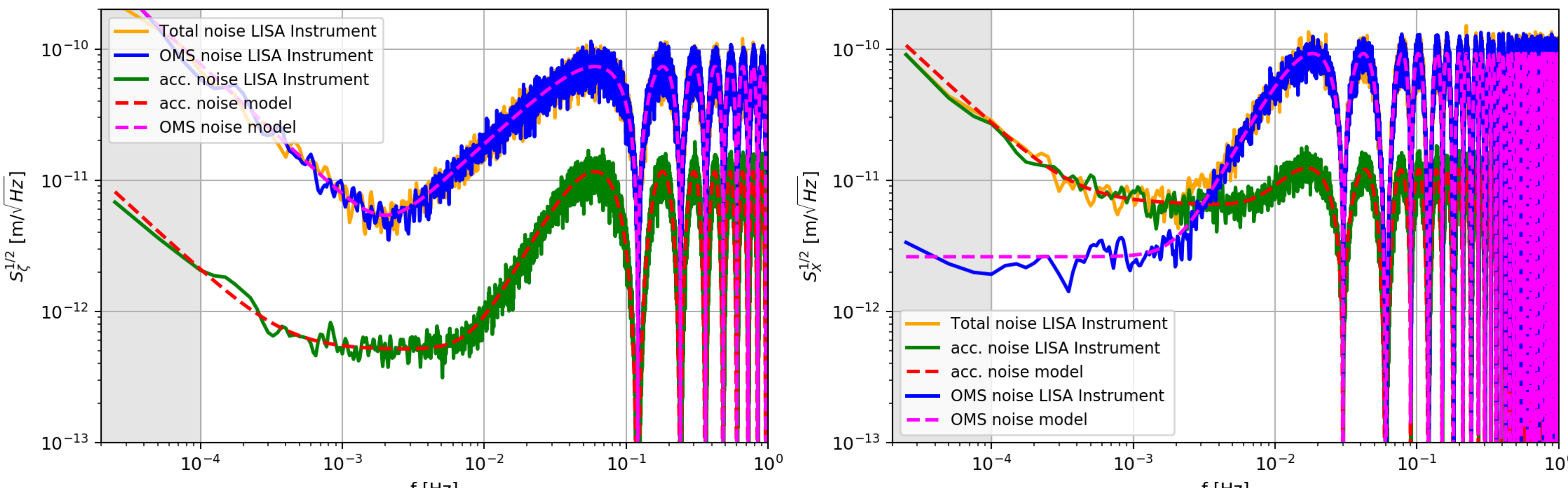


TM acceleration noise and OMS noise in TDI ζ and X

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

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

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



LISA Instrument [Bayle, Hartwig, Staab 2022]

- **The best would be to calibrate noise in-flight via null TDI combinations**

Our approach to measure the noise using the null channels

- Do not rely on any assumptions on the actual noise levels of the individual TM and OMS noise terms
- It could be evaluated at any time and it is robust against non-stationarity of the noise
- Caveat: it still does rely on assumptions on the **6 TM to be uncorrelated as well as OMS noise terms**
- Look for **upper limit on the noise for TM acc. and OMS noise for X** (equivalently for A and E) using the null channel
- **Goal:** define a detection threshold with LISA for the SGWB (we do not make any assumption on the shape of the SGWB)

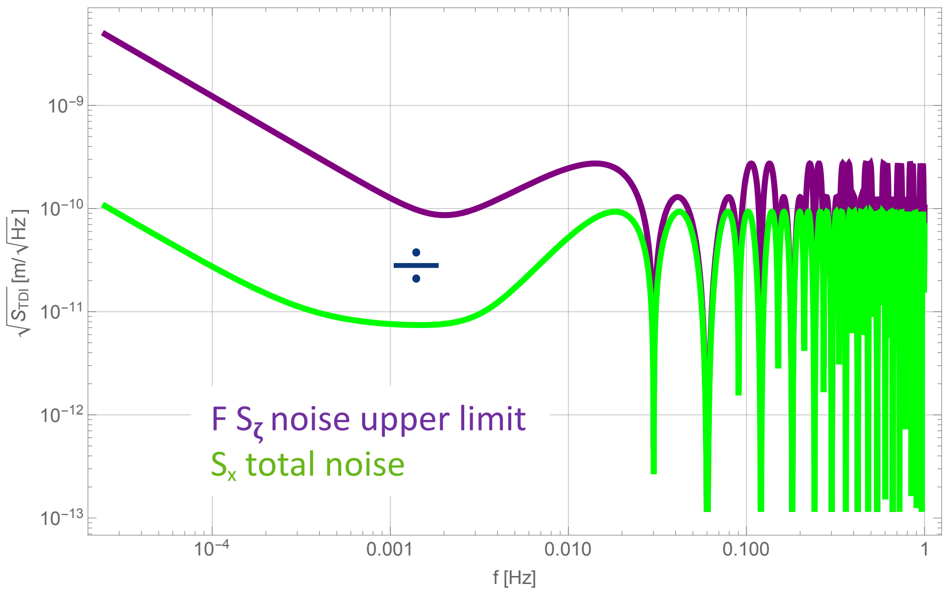
Noise upper limit for TM acc. and OMS noise for X using the null channel

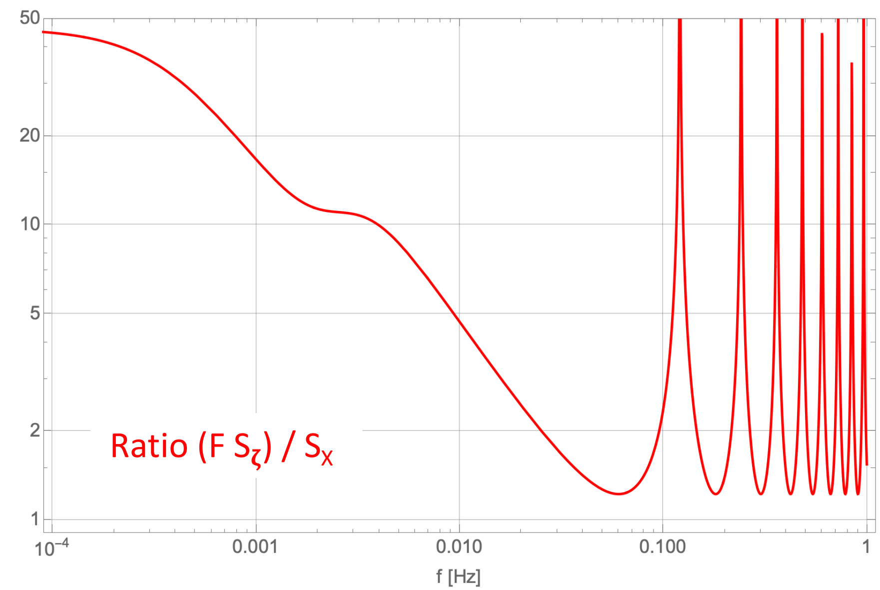
- We are looking for a function **F** such that: $F S_\zeta > S_X$
- Where: $S_X = T_g^X S_g + T_{oms}^X S_{oms}$

  $S_\zeta = T_g^\zeta S_g + T_{oms}^\zeta S_{oms}$

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

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





Note the plots are made assuming noise at the required levels and 6 uncorrelated TM and OMS !

Estimating correlated noise with the null channels

- Intermediary TDI variables:

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

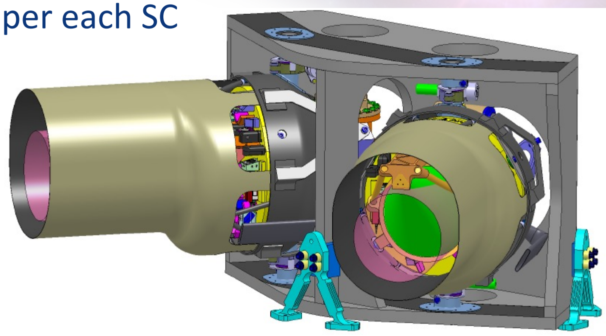
TM acc. noise — OMS noise

- 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)*

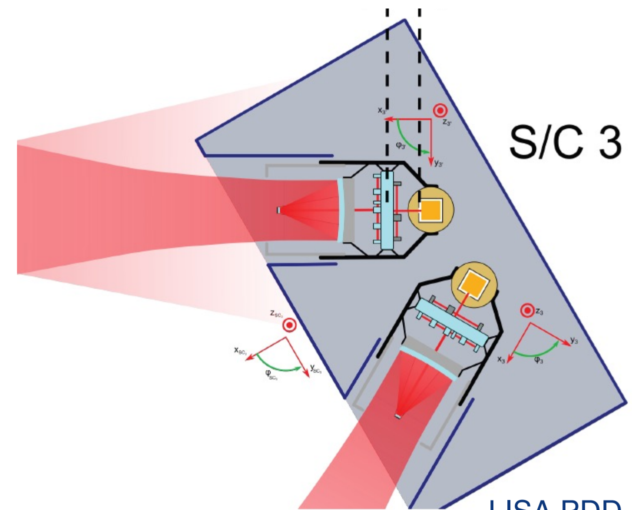
$$\zeta = (1-D)\left(\eta_{12} - \eta_{13} + \eta_{23} - \eta_{21} + \eta_{31} - \eta_{32}\right)$$

- **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



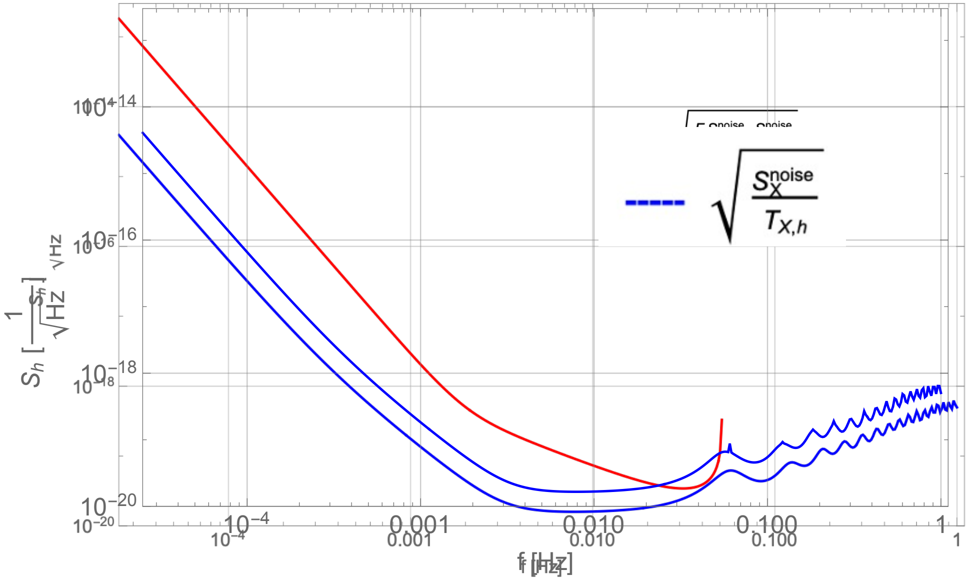
Payload strawman conceptual design. Images courtesy of Airbus D&S GmbH, Friedrichshafen. LISA proposal

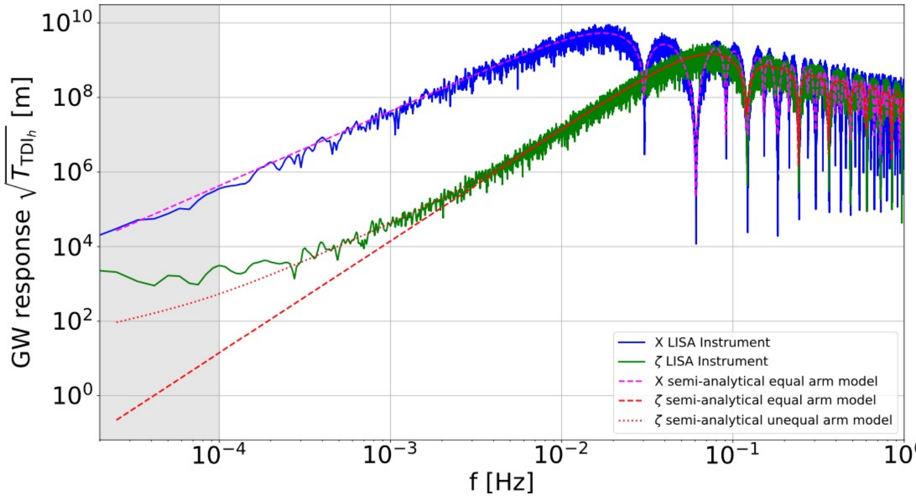


LISA PDD

Detection threshold and upper limit (assuming known noise levels) on SGWB

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





LISA GW Response [Bayle]

- In reality we can define an upper bound on GW signal: $S_h \leq S_X^{meas}/T_{X_h}$
- and a lower bound on GW signal: $$S_h \geq \frac{S_X^{meas} - F S_\zeta^{meas}}{T_{X_h} - F T_{\zeta_h}}, \qquad \text{valid if } T_{X_h} > F T_{\zeta_h}.$$

Summary

- **Use the null channel to estimate the level** at which two of the main noise sources**, uncorrelated TM and OMS noise, will affect** the GW sensitive **X channel**.
  - the results of this analysis suggests that between 30-100 mHz we have a noise estimate below a factor 4 of the promised detector noise power a limit

- We could only identify a **SGWB if it becomes significantly larger** than our noise estimate (detection threshold)
  - Given the large uncertainties in the range of possible stochastic background levels, the results shown here might proof useful.

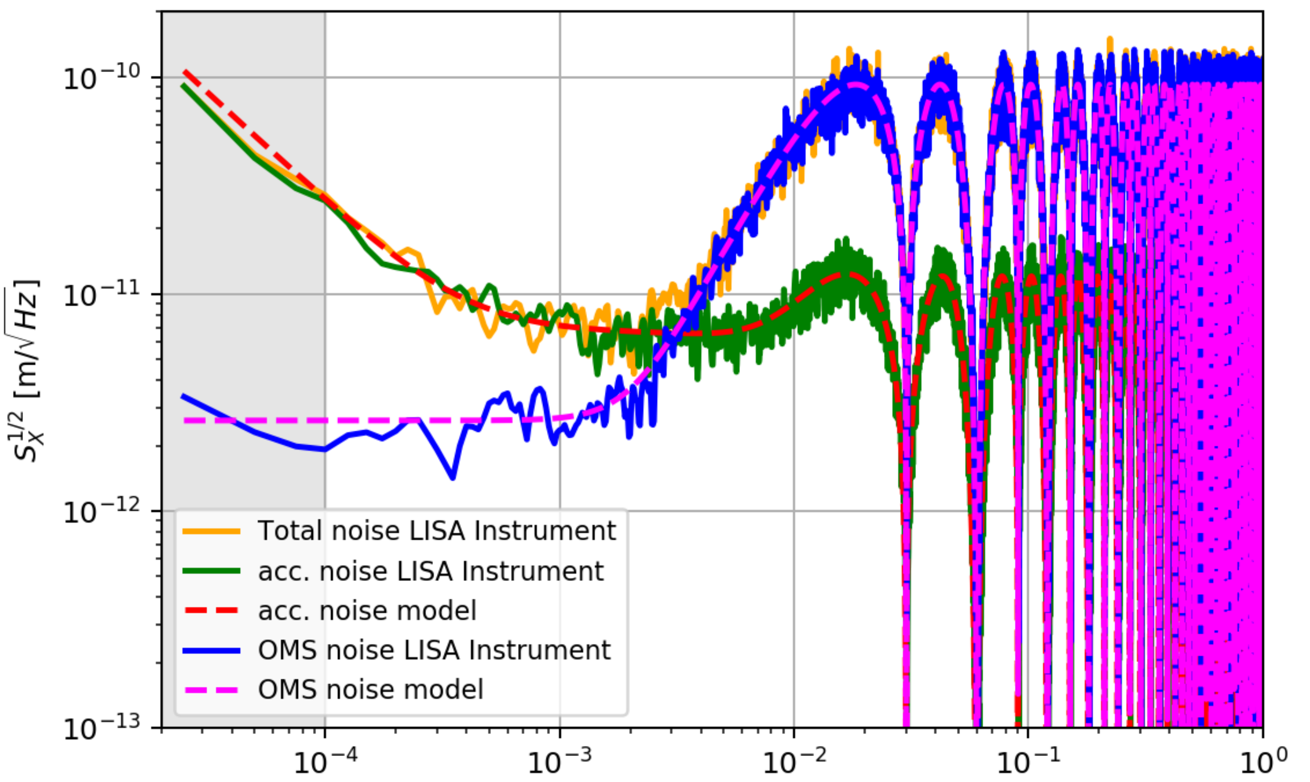
- Null channels **cannot** be used to estimate some forms of correlated noise

Discussion

- **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
- This study **is limited** as we only considered the two main noise sources, which we assumed to be fully uncorrelated.
- **Follow-up studies** could investigate other known noise sources, such as **modulation noise or effects of correlations between noises, e.g., correlated TTL and see if null channel might be of use**

Thank you for your attention

TM acceleration noise and OMS noise in TDI X



LISA Instrument [Bayle, Hartwig, Staab 2022]

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

$$S_{g_{ij}}(f) = \left(3 \times 10^{-15}\ \frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}\right)^2 \times \left(1 + \left(\frac{0.4\ \mathrm{mHz}}{f}\right)^2\right)\left(1 + \left(\frac{f}{8\ \mathrm{mHz}}\right)^4\right) \quad \left[\frac{m^2\, s^{-4}}{Hz}\right]$$

$$S_{oms_{ij}}(f) = \left(15\ \mathrm{pm}/\sqrt{\mathrm{Hz}}\right)^2 \times \left(1 + \left(\frac{2\ \mathrm{mHz}}{f}\right)^4\right) \quad \left[\frac{m^2}{Hz}\right]$$

Common assumption for noise modelling in LISA Data analysis

- Gaussian and Stationarity
- Relying on fixed, perfectly known noise spectral shapes
- Fitting is done just for amplitudes of noise parameters (one/two parameters or even more, but assuming the knowledge of spectral shapes)
- Uncorrelated noise b/w TM and OMS noise components
- *New approach by* using of splines to model the noise (see Quentin Talk)

The null-channels

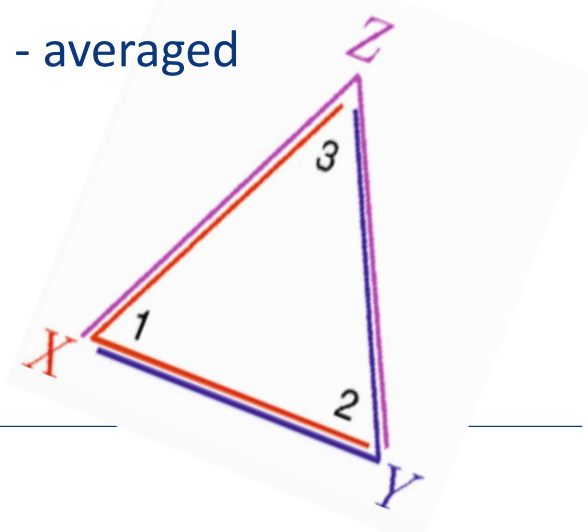
- A good proxy: find TDI combinations that have *null* sensitivity to GW when:
  - GW falls normally to the constellation plan
  - LISA is a perfect static triangle

1. Explore the space of all linear combinations of all possible TDI combinations, and identify its null space

2. Use this set of null-channels to measure the noise in the sensitive channels

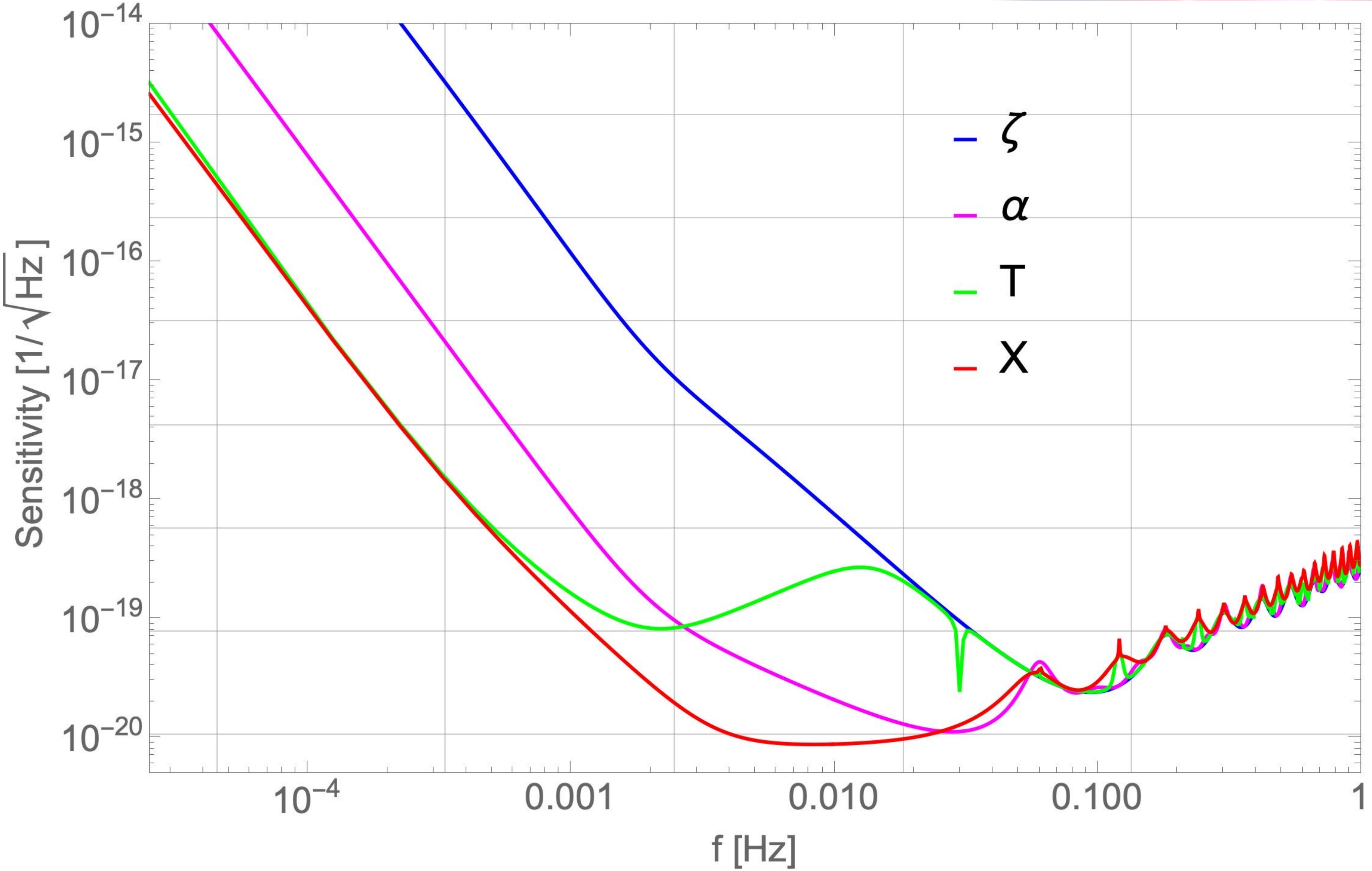
Null channel *T*: 3-element set of cyclic – permutation - averaged TDI combinations

$$T = \frac{X + Y + Z}{3}$$



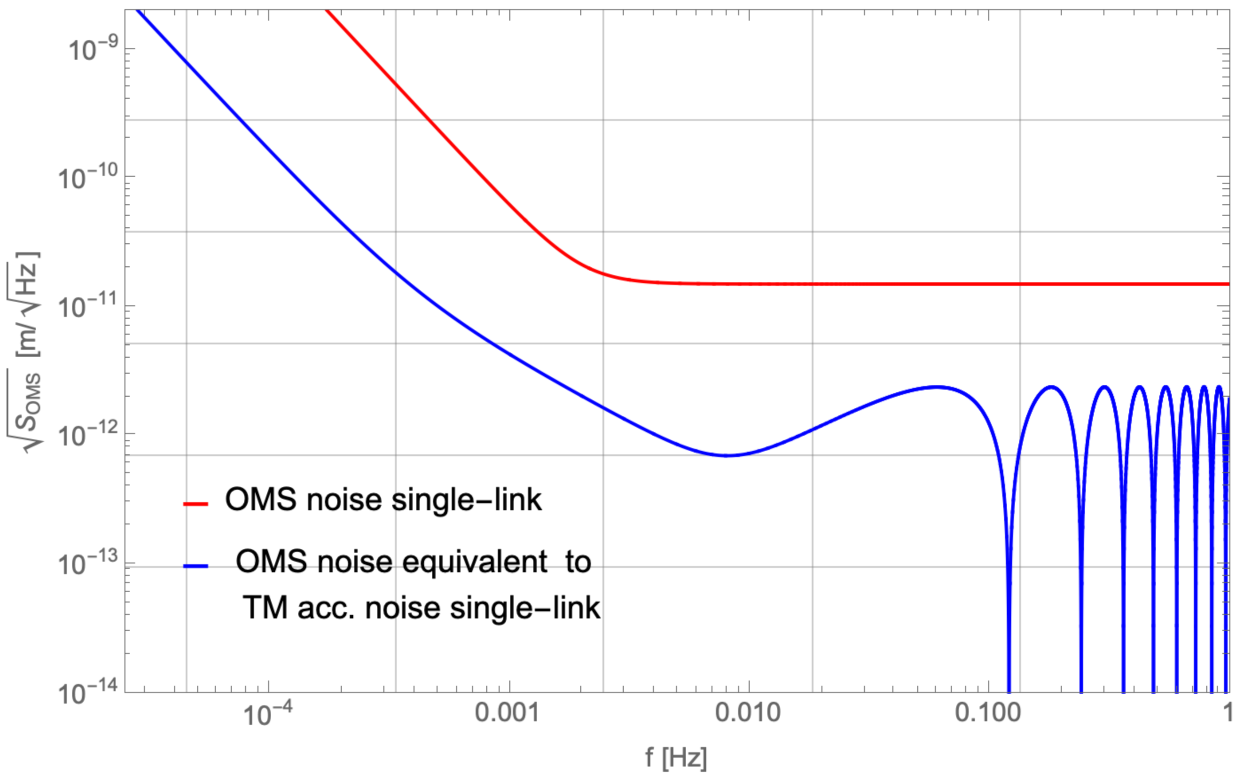
*Romano, J.D., Cornish, N.J. Detection methods for stochastic gravitational-wave backgrounds
*April 2004 Physical Review D 69(8) DOI:10.1103/PhysRevD.69.082001

Use null channels to characterise noise in-flight

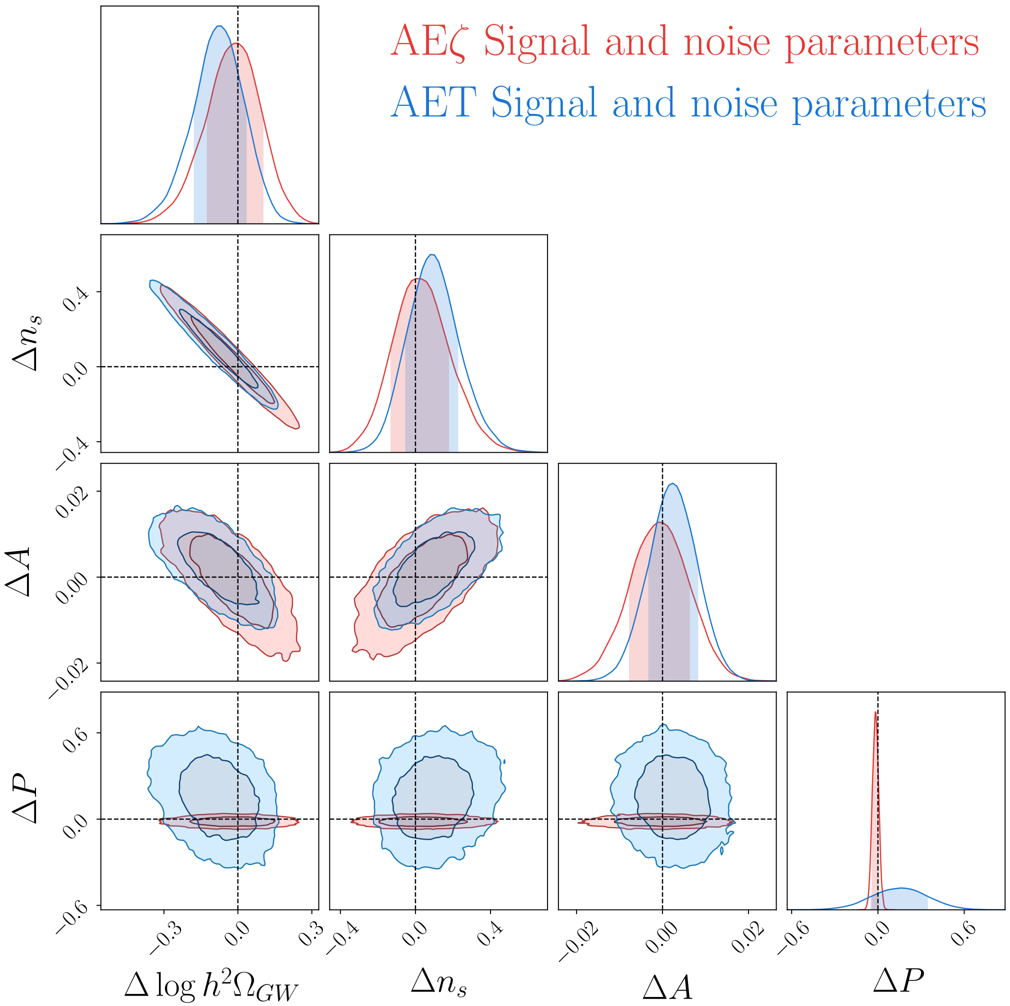


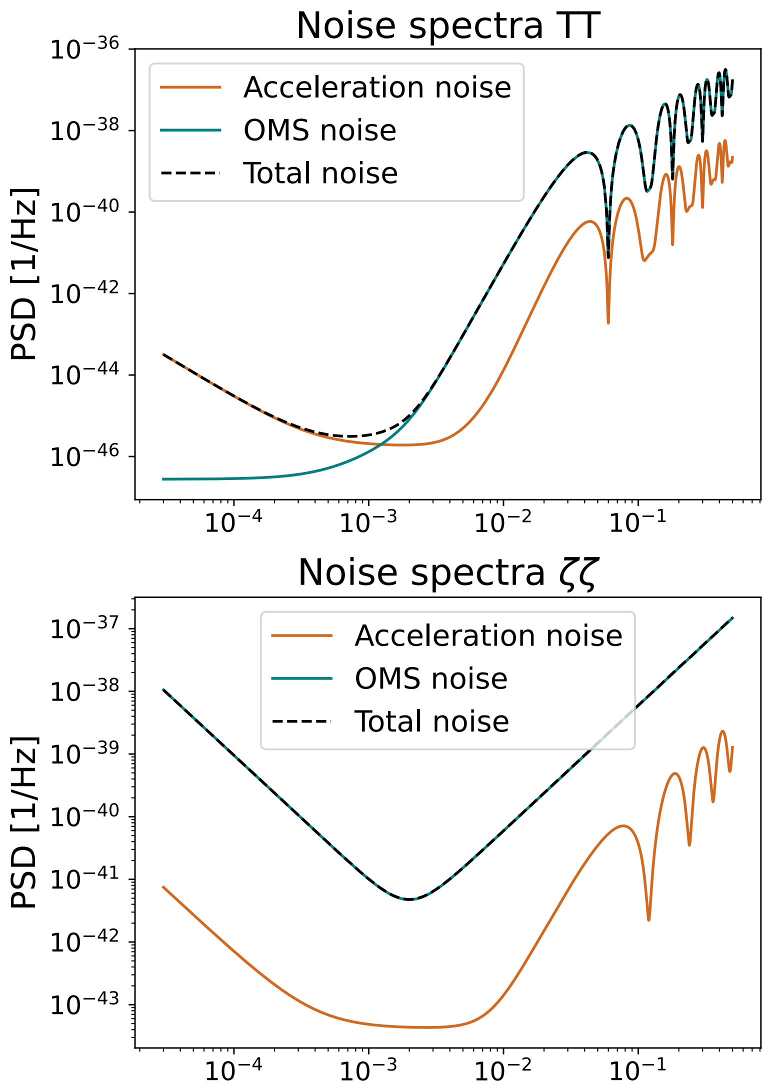
Prior noise knowledge

- In order that **ζ is also dominated by TM acc. noise** we should have the **OMS to be much better than requirement**



Signal and noise reconstruction low f (left panel), noise spectra (right panel)





Noise knowledge in LISA: preliminary discussion

- **Performance requirement** are always stated and verified as **upper limit**

- This allow instrument scientist/engineers to reach confidence by working on margin

- Working on margin:
  - Try to do the **PSD smaller than requirements**
  - If we are **below the requirement the mission is considered to be successful** otherwise **we start a debugging campaign**

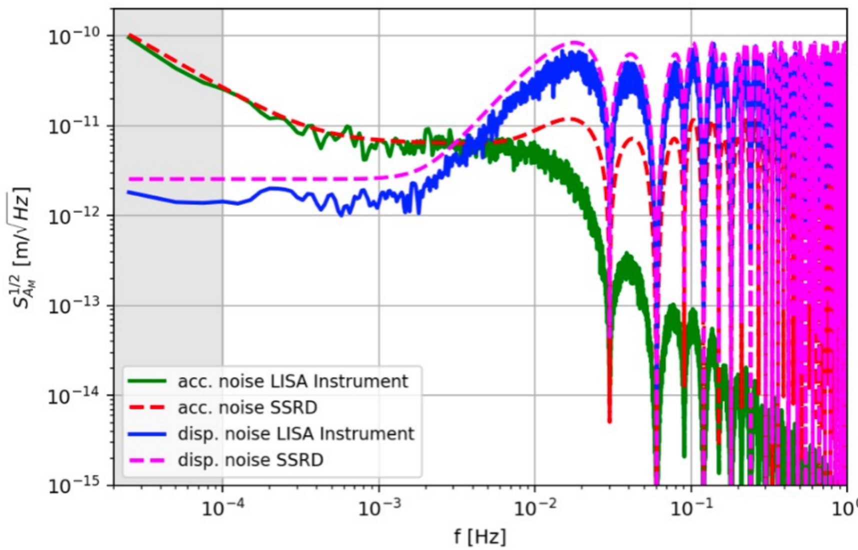
Curtesy of Stefano Vitale

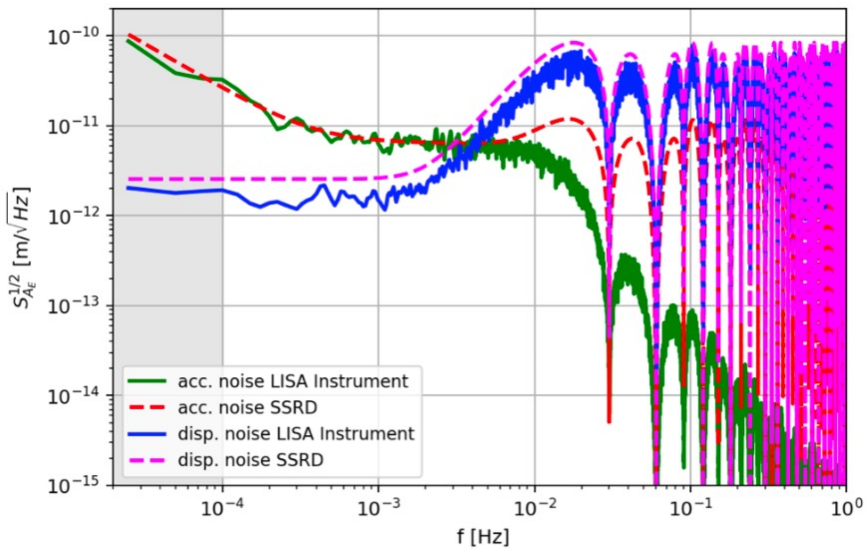
Verification by analysis and its limitation

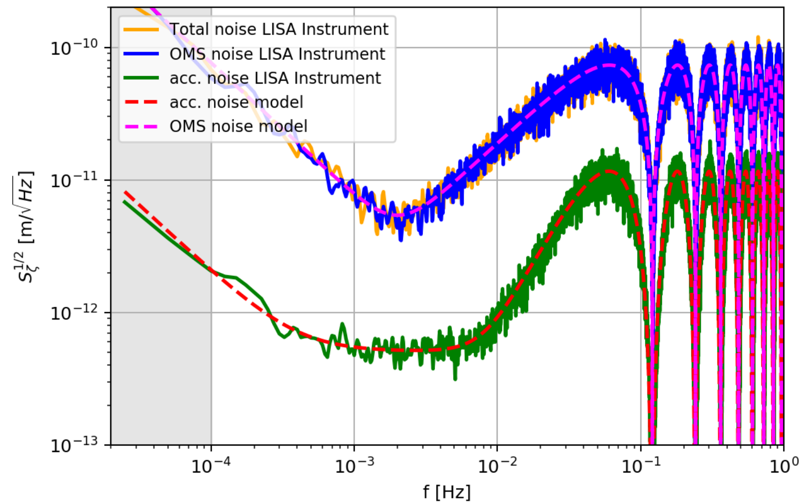
- **Performance requirement will be verified mostly by analysis** which relies on physical model for the whole instrument and its components:
  - Limitations: **Completeness and accuracy of model is always limited**, uncertainty in model parameter propagates to final results, model parameter may change in time/upon launch
  - **More risk and more margin**, significant risk of violation once in flight remains
  - **Performance can improve by trimming the system and fixing anomalies**, this shows up as an increase on the SNR

Curtesy of Stefano Vitale

Secondary noises in the orthogonal channels







LISA Instrument [Bayle, Hartwig, Staab 2022]