Overview of LISA

Gravitational wave orchestra Annecy, 19-09-2024, Martina Muratore

Image courtesy of O.Hartwig

Talk overview

- LISA mission overview
- Time Delay Interferometry to reduce laser noise
- TDI null channels as instrument noise monitors
- SGWB in the global fit

- LISA mission overview

Mission overview

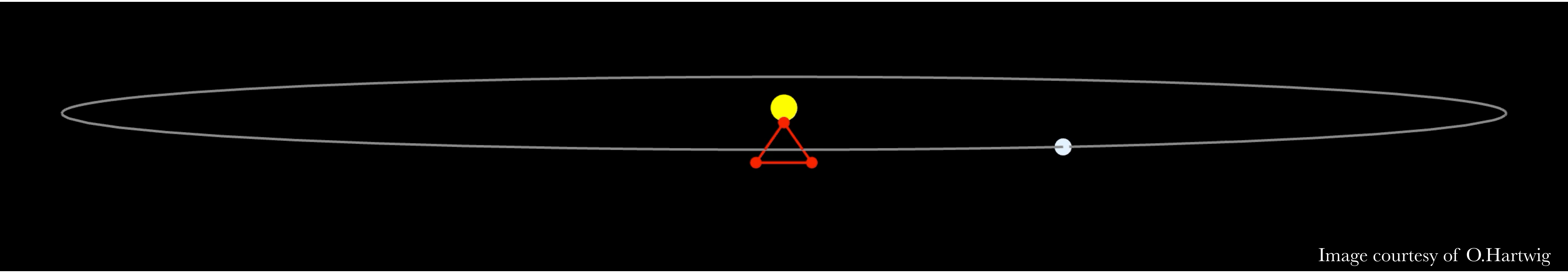
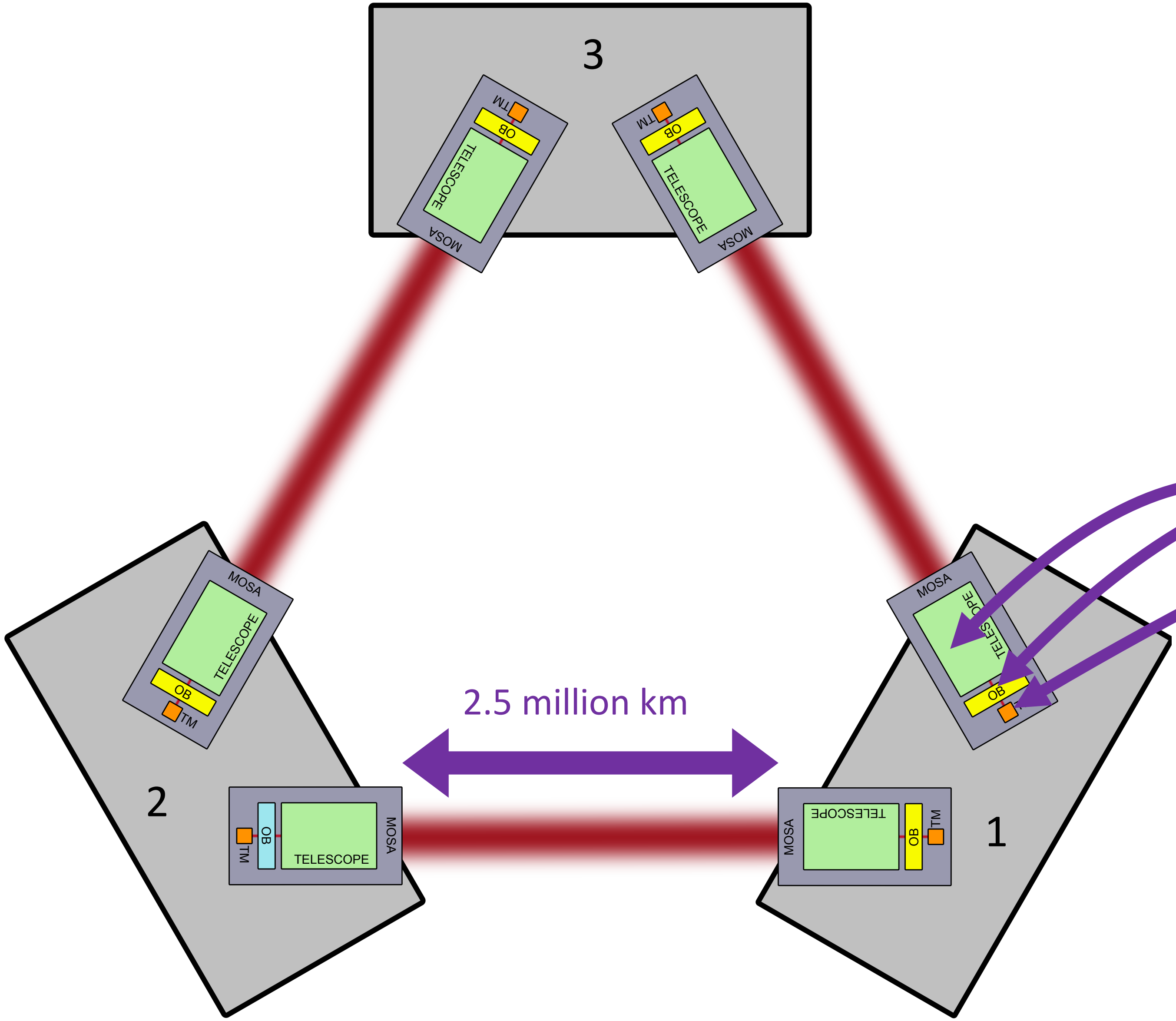


Image courtesy of O.Hartwig

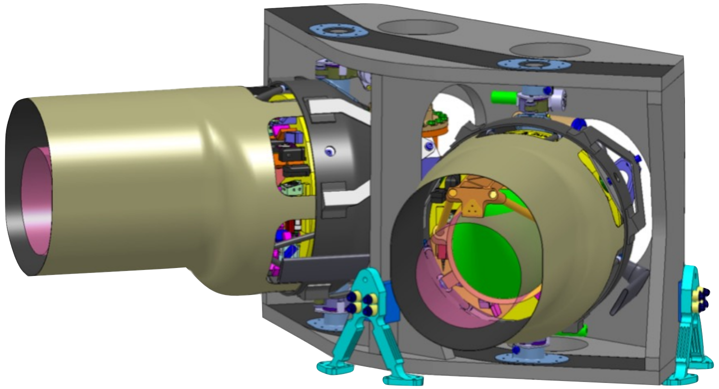
- 3 drag-free satellites, separated by $2.5x10^6$ km continuously exchange laser beams
- The constellation forms an *almost* equilateral triangle which trails the Earth by 20° and is tilted by an angle of 60° from the ecliptic plane

LISA constellation

Slide courtesy of O. Harwig

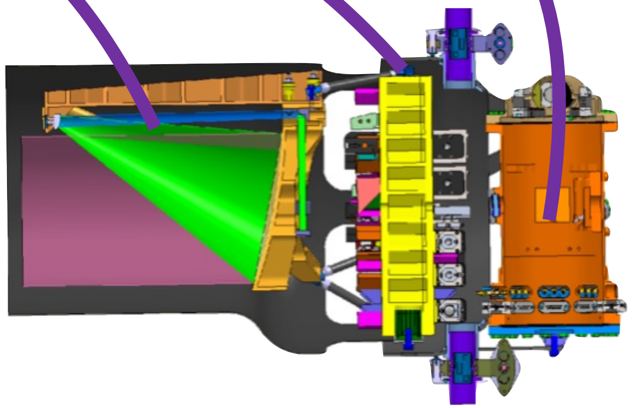


Payload strawman conceptual design. Images courtesy of Airbus D&S GmbH, Friedrichshafen.



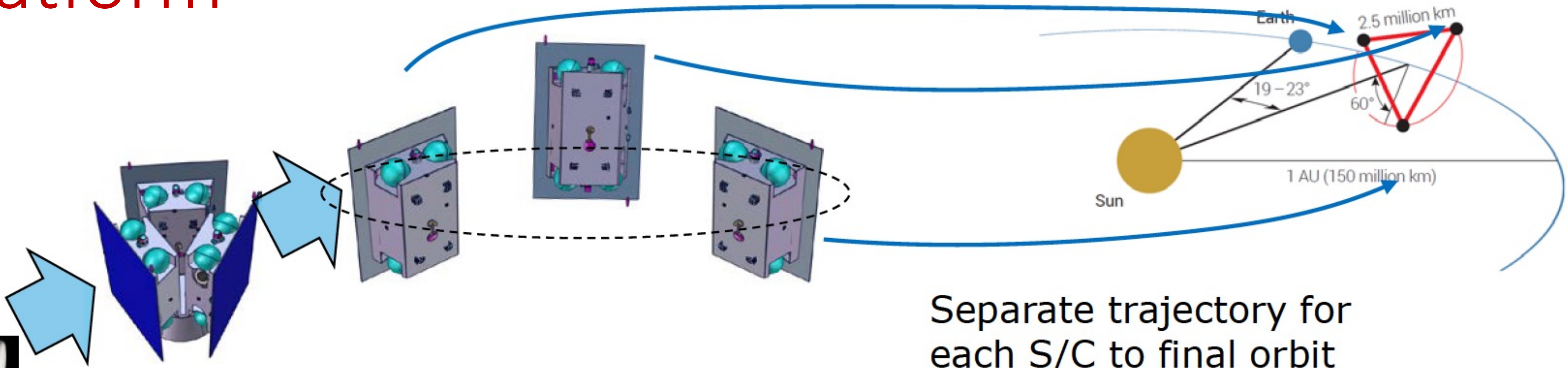
Source: L3 proposal

Movable optical sub-assembly (MOSA)



Source: L3 proposal

LISA Platform



Separate trajectory for
each S/C to final orbit

Separation of the stack
right after launch

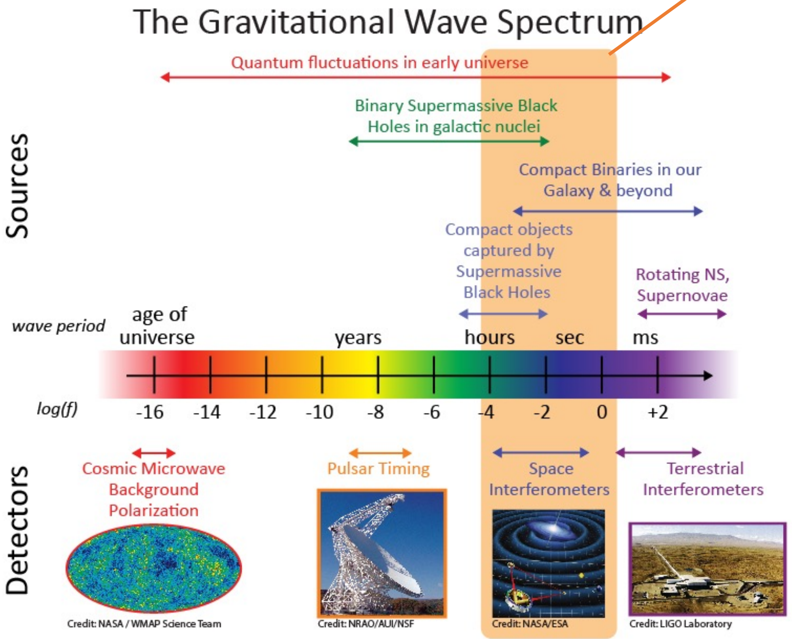

LISA-CDF-IFP-2017

Launch in stacked
configuration
Direct injection into escape
trajectory

○ LISA was adopted by ESA last January 2024 and the launch is scheduled for 2035

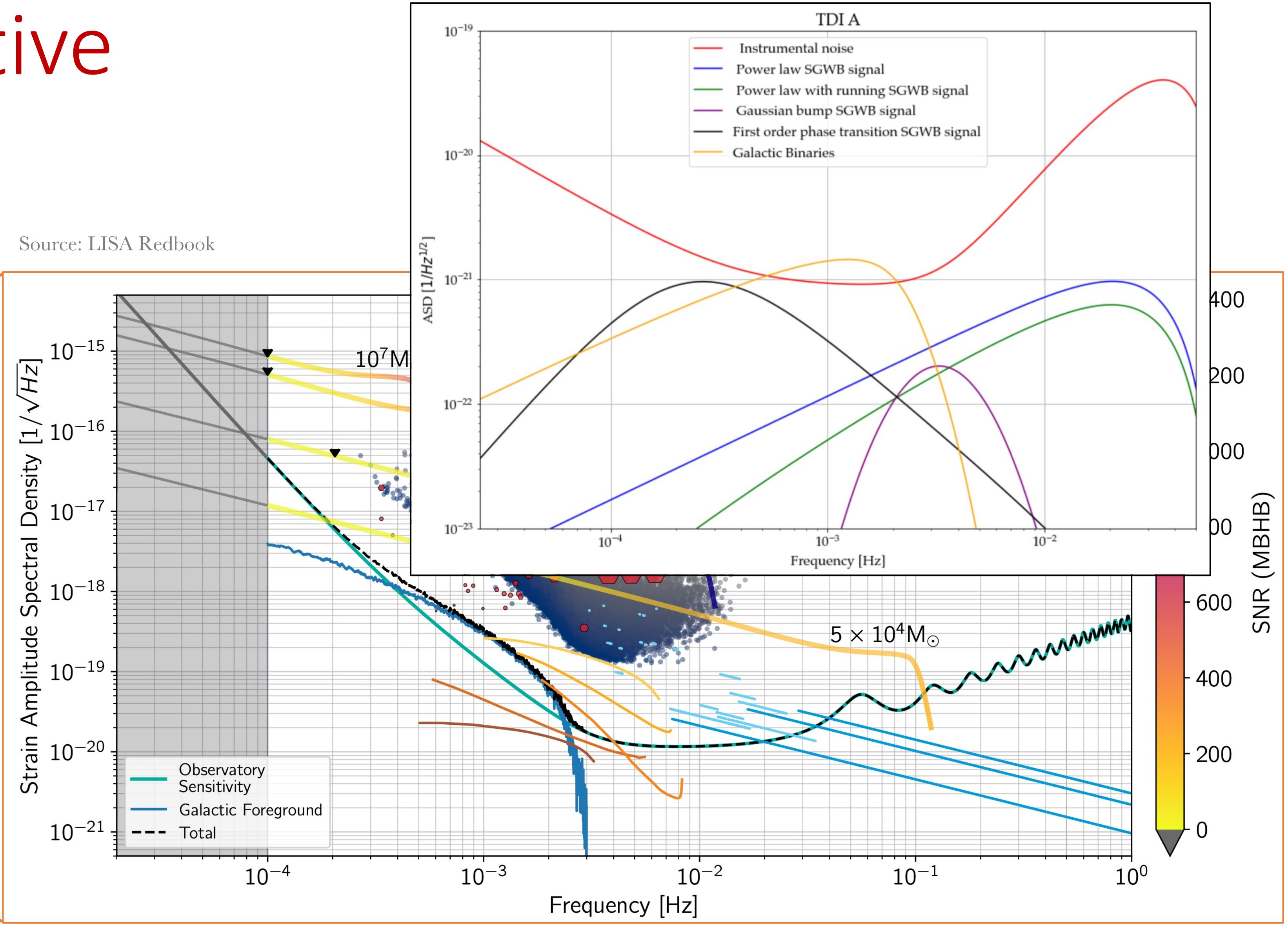
○ Each satellite will follow a heliocentric orbit

LISA science objective

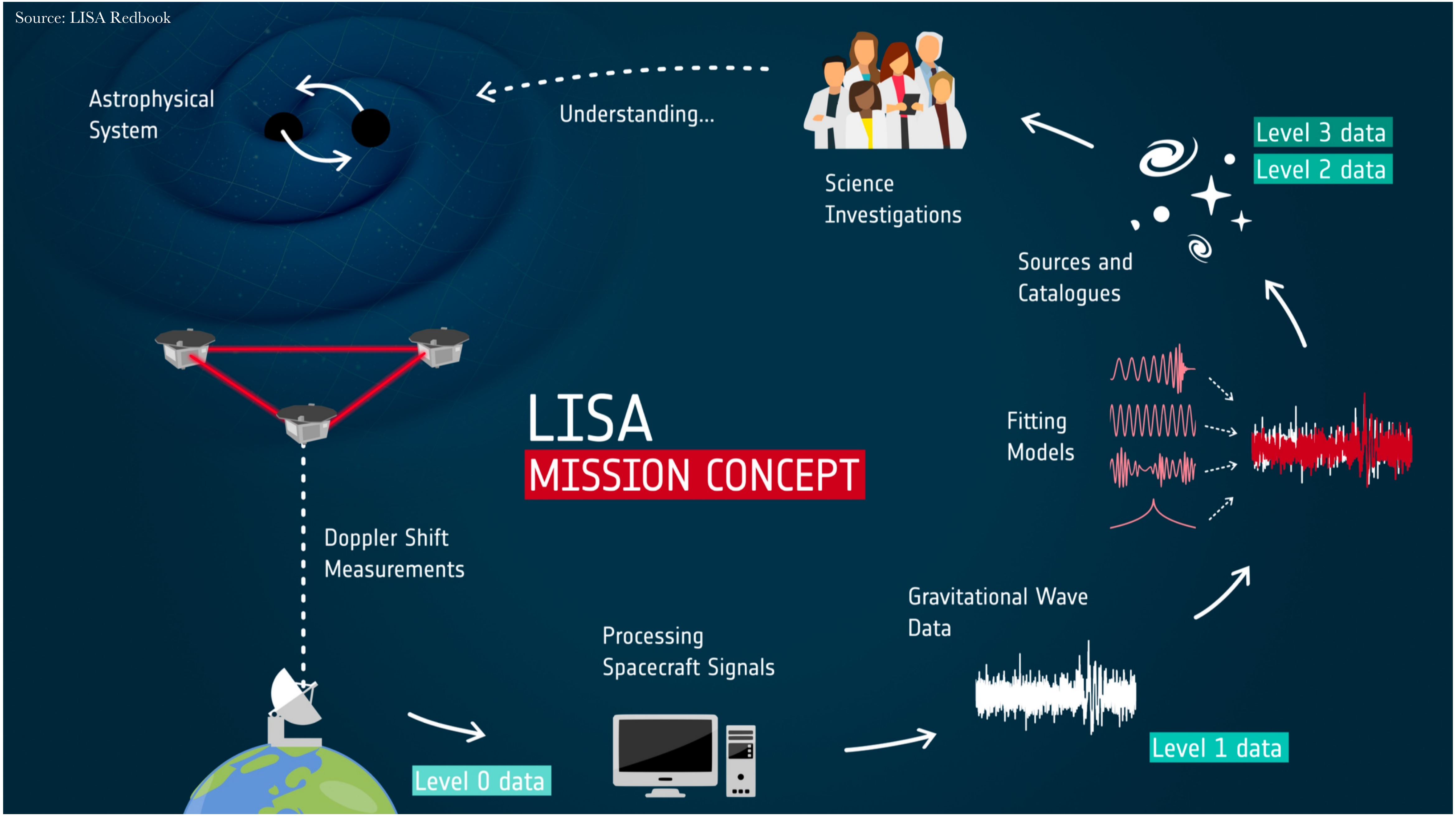


Credis: NASA Goddard Space Flight Center.

Source: LISA Redbook



Source: LISA Redbook



LISA
MISSION CONCEPT

Astrophysical System

Understanding...

Science Investigations

Level 3 data

Level 2 data

Sources and Catalogues

Fitting Models

Doppler Shift Measurements

Gravitational Wave Data

Processing Spacecraft Signals

Level 0 data

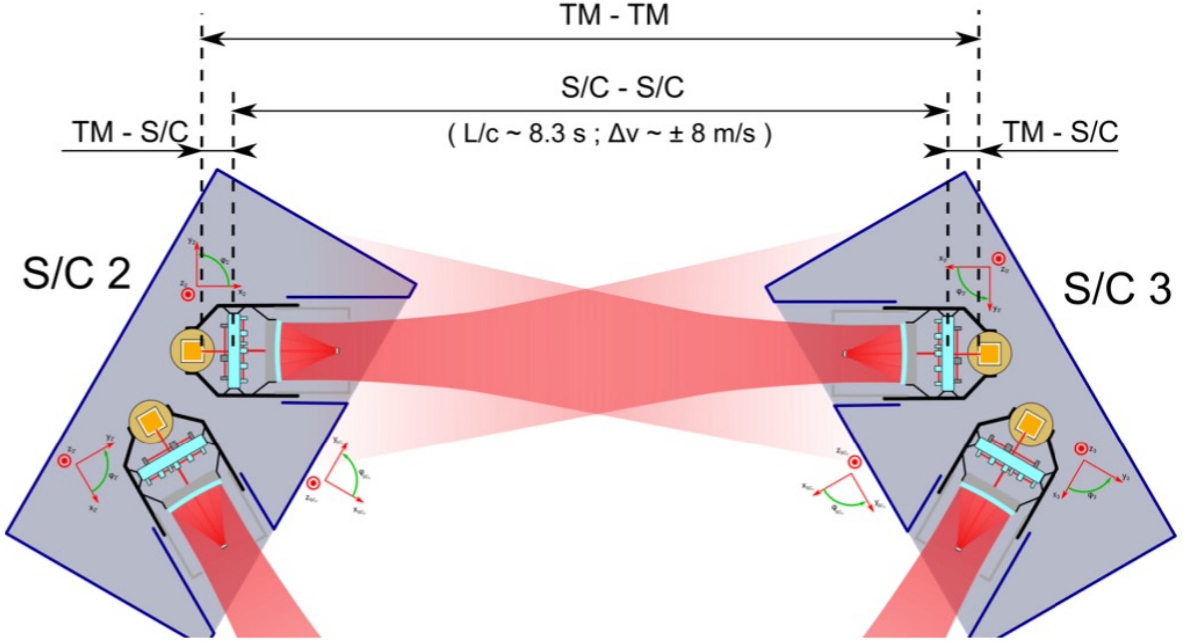
Level 1 data

○ Noise and Time Delay Interferometry

(To my knowledged from 2019….)

- M.Muratore, Phd. Time delay interferometry for LISA science and instrument characterisation,
- Olaf Hartwig,: Phd. Instrumental modelling and noise reduction algorithms for the Laser Interferometer Space Antenna.
- Staab, Martin Benedikt: Phd. Time-delay interferometric ranging for LISA: Statistical analysis of bias-free ranging using laser noise minimization.
- Quang Nam Dam , Phd. Simulations and associated data analysis for realistic LISA configuration,
- Jean-Baptiste Bayle. Phd. Simulation and Data Analysis for LISA (Instrumental Modeling, Time-Delay Interferometry, Noise-Reduction Performance Study, and Discrimination of Transient Gravitational Signals)

LISA measurement chain (L0 data)



LISA PDD

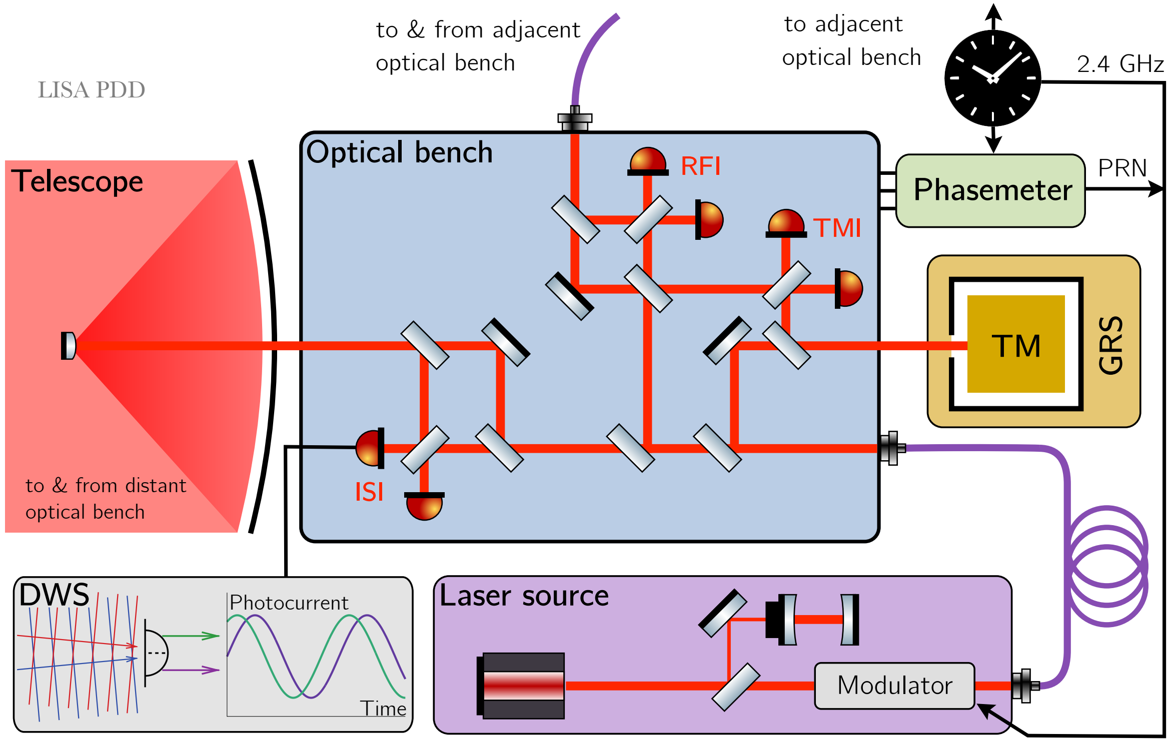


image curtesy of O.Hartwig

- LISA measures the relative proper motion of free-falling test masses (TM) inside spacecraft (SC) and the **GW signal is observed as picometer fluctuations in such distance**

What does mean LISA noise? (L1 data)

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

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

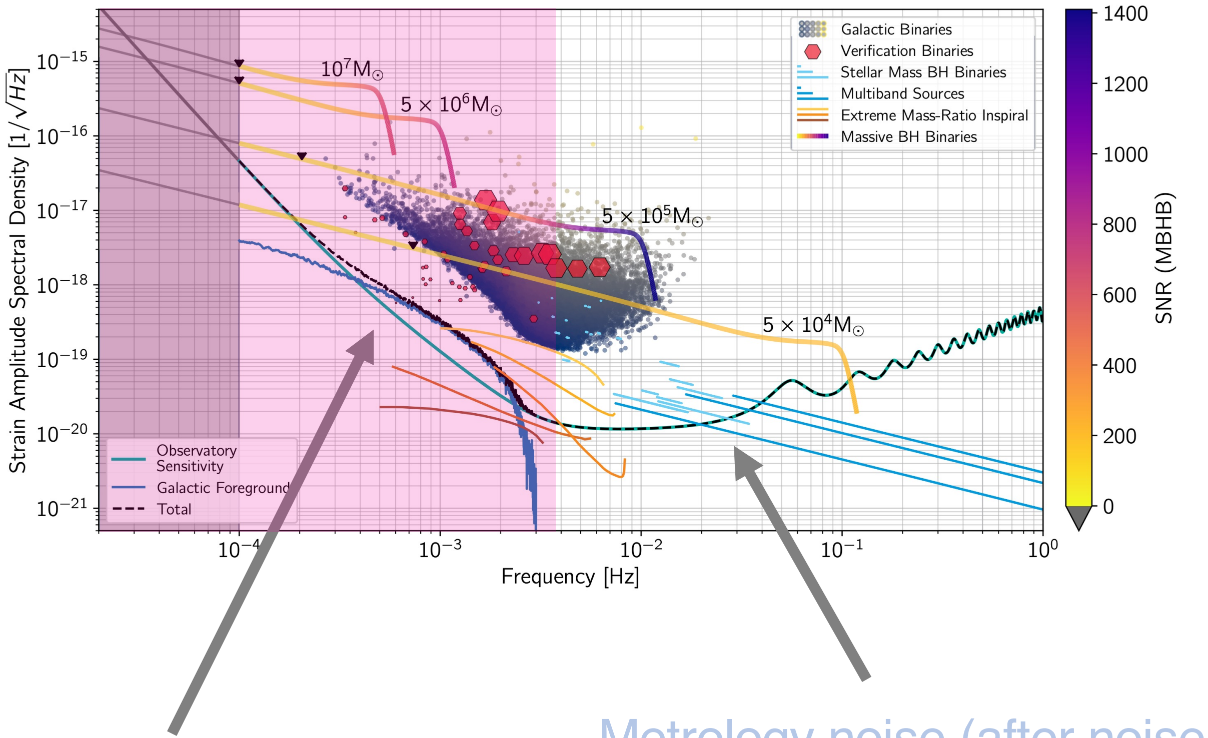
Free-falling test mass

- Actuation noise
- Brownian noise
- Stray Electrostatics Noise
- Magnetic noise
- Radiation pressure Noise
- Temperature Force Noise
- Gravitational Noise
- TM-SC/MOSA coupling Force Noise

Metrology

- Read-out
- Laser noise
- Clock noise
- Spacecraft jitter
- Tilt-to-Length

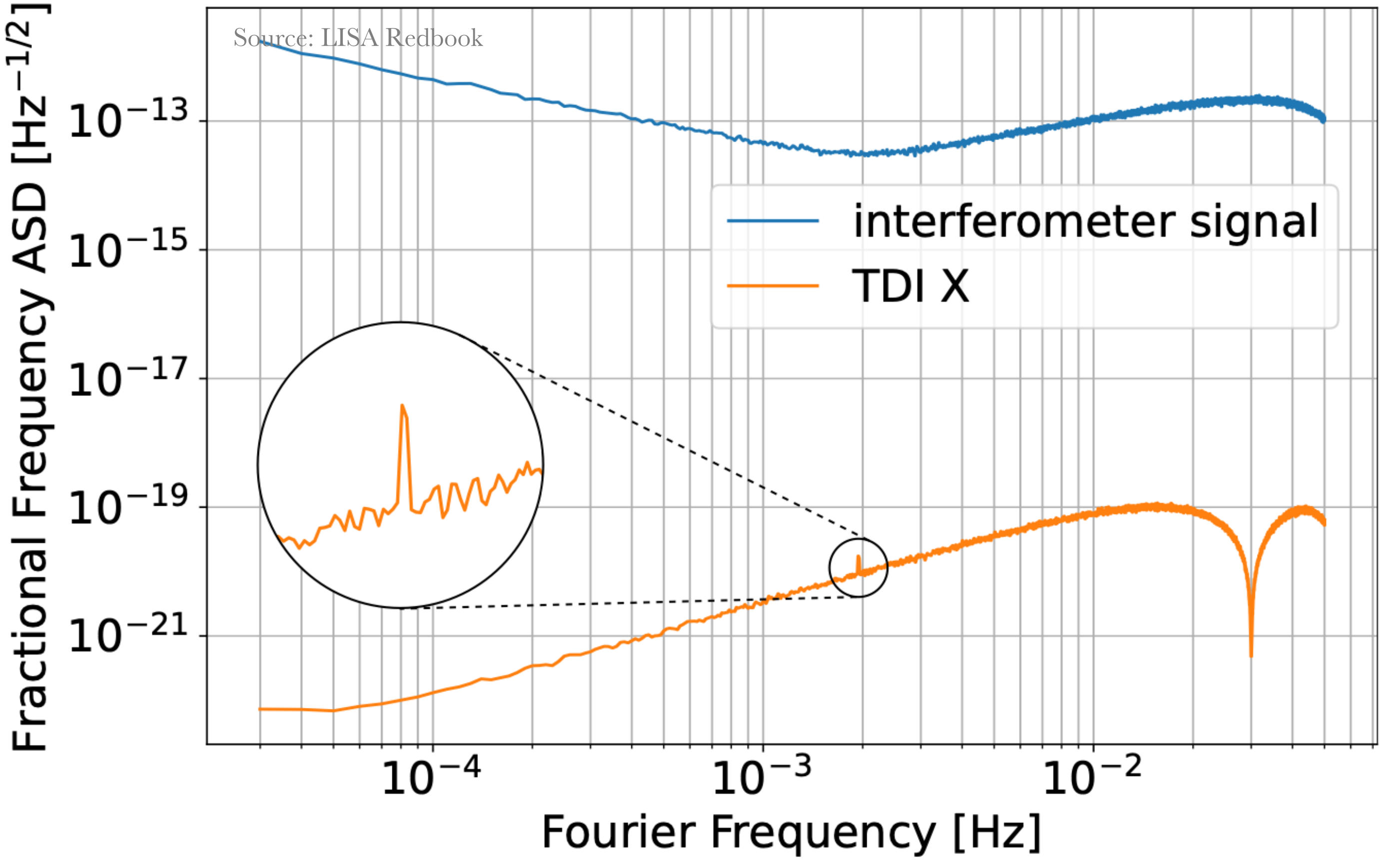
Source: LISA Redbook



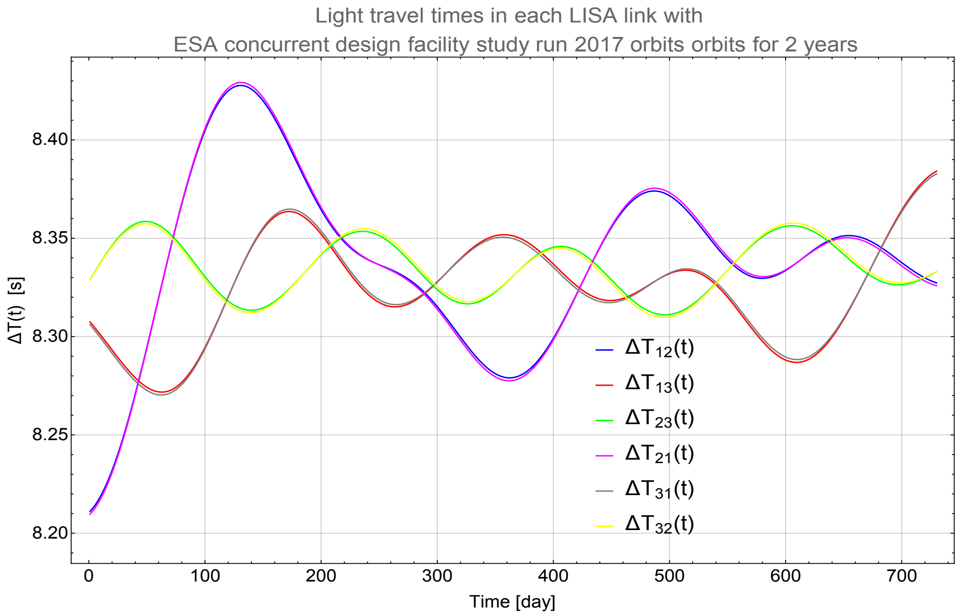
Acceleration noise

Metrology noise (after noise reduction)

The (nightmare of) laser frequency noise



- Laser frequency noise completely covers the GW signal. $\left(\sim\frac{10^{-13}}{\sqrt{Hz}}\ vs\ \frac{10^{-21}}{\sqrt{Hz}}\right)$



Laser noise cancellation in LVK interferometers equal arm-lengths (stable laser / ideal case)

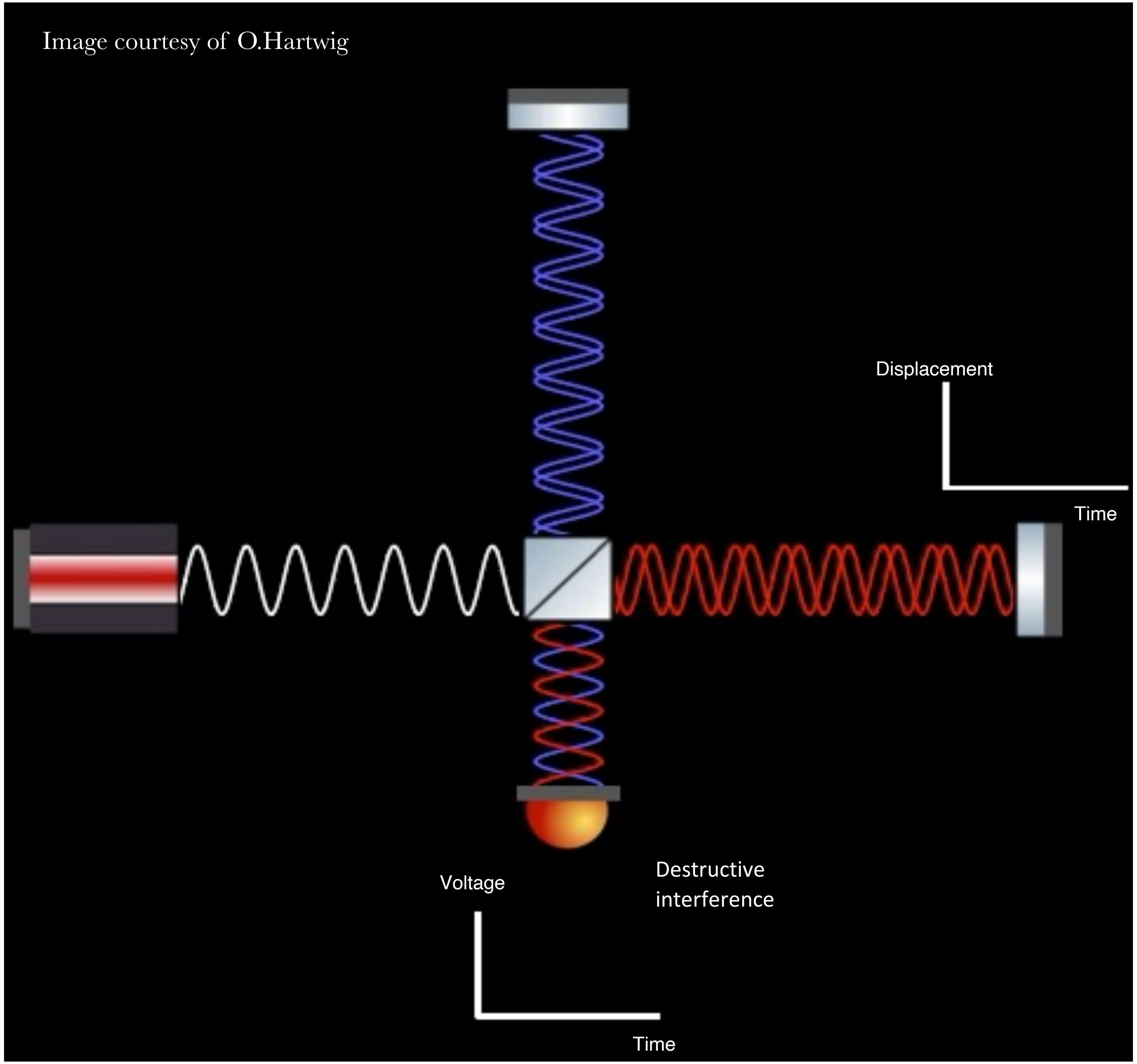


Image courtesy of O.Hartwig

Laser noise cancellation in LVK interferometers equal arm-lengths (stable laser/ ideal case)

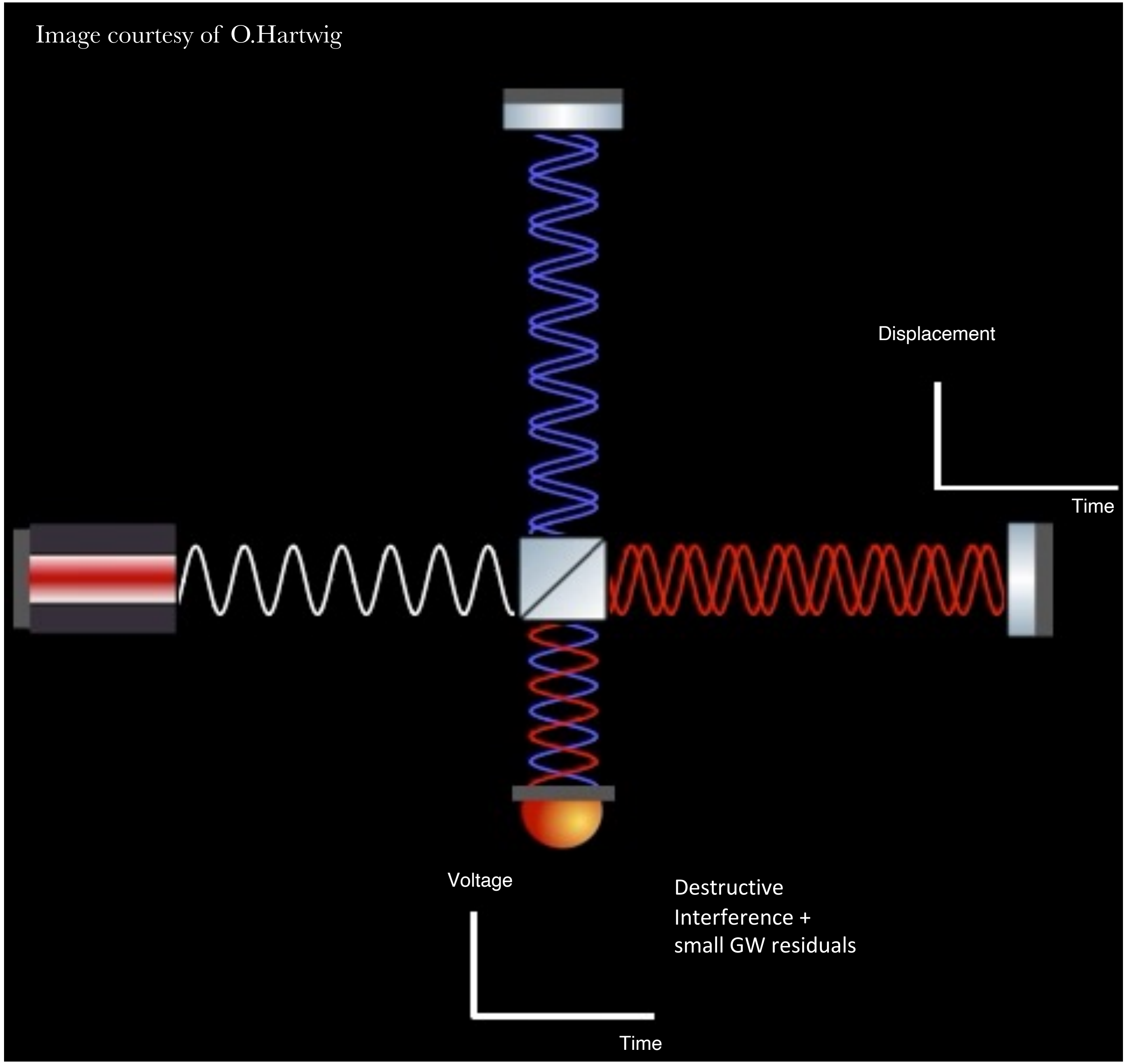


Image courtesy of O.Hartwig

Laser noise cancellation in LVK interferometers unequal arm-lengths (stable laser/ ideal case)

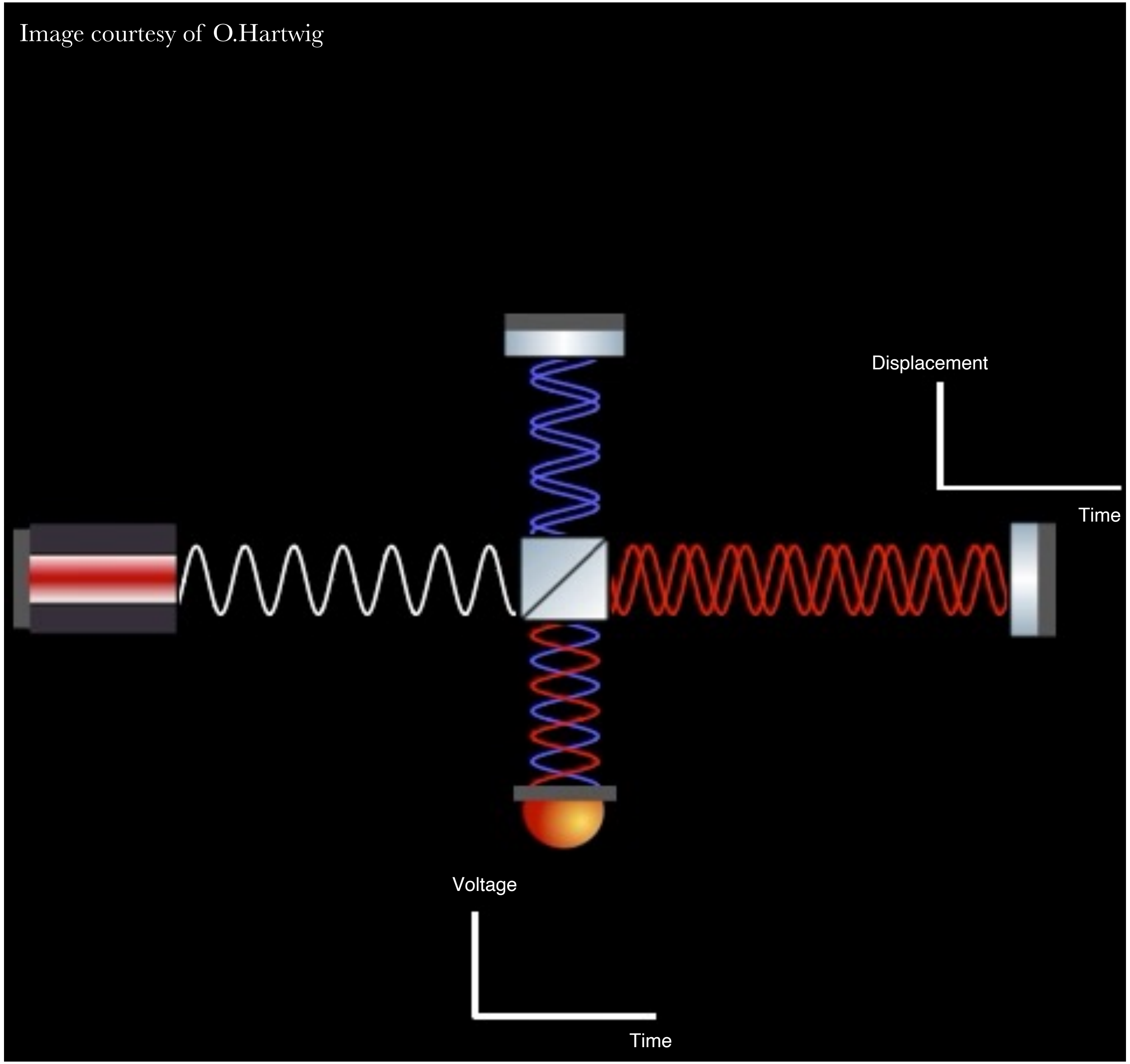
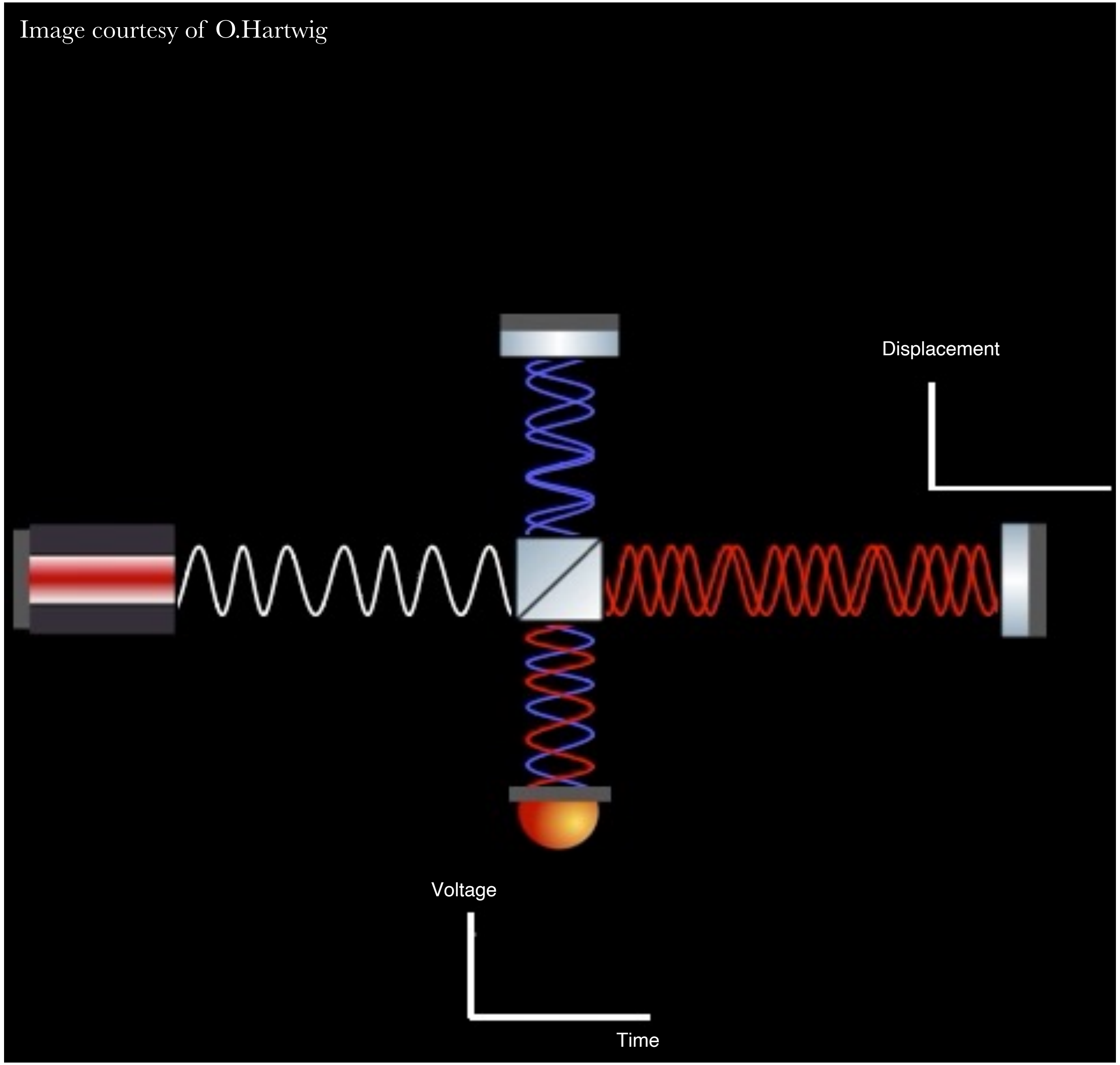
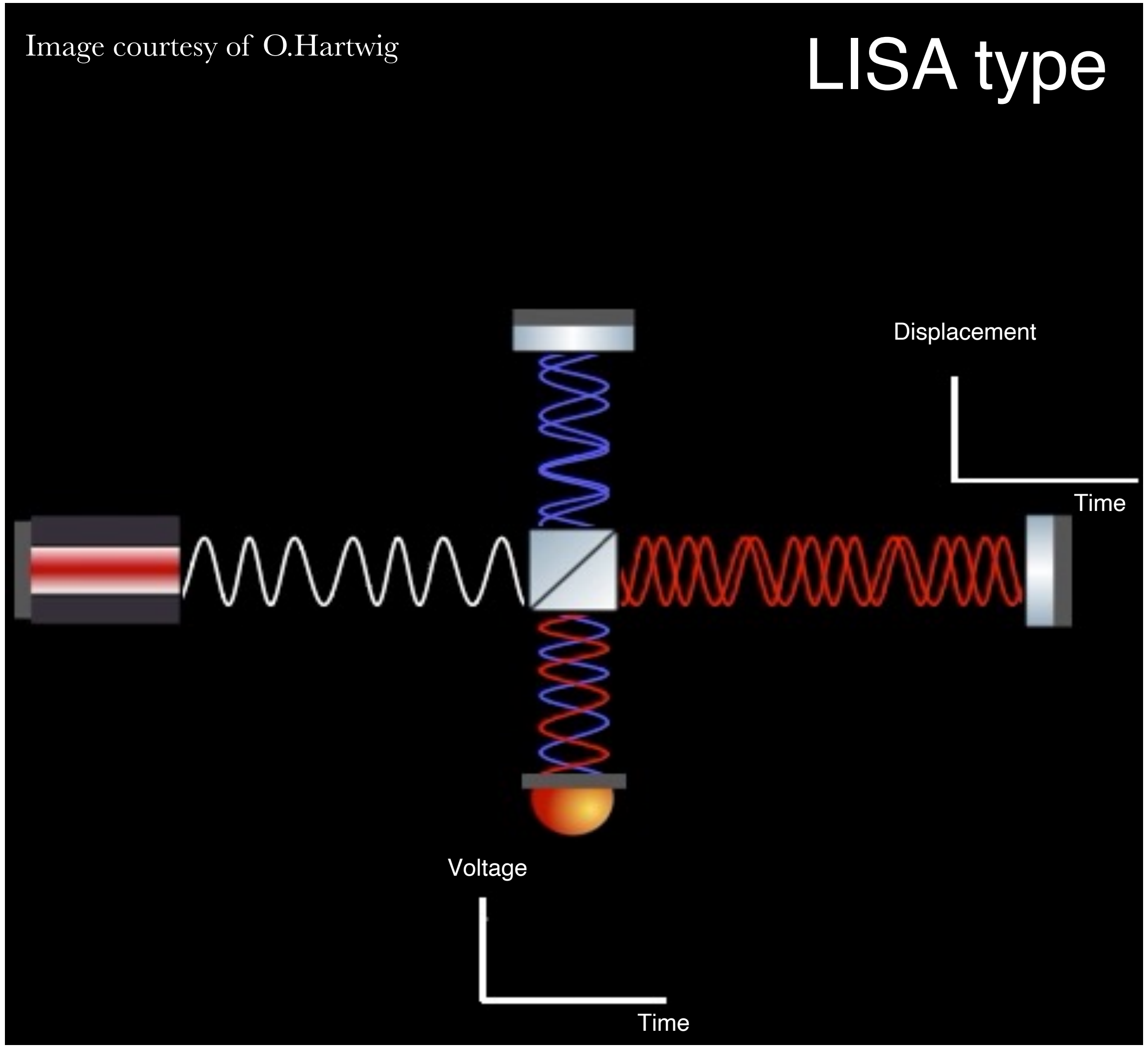


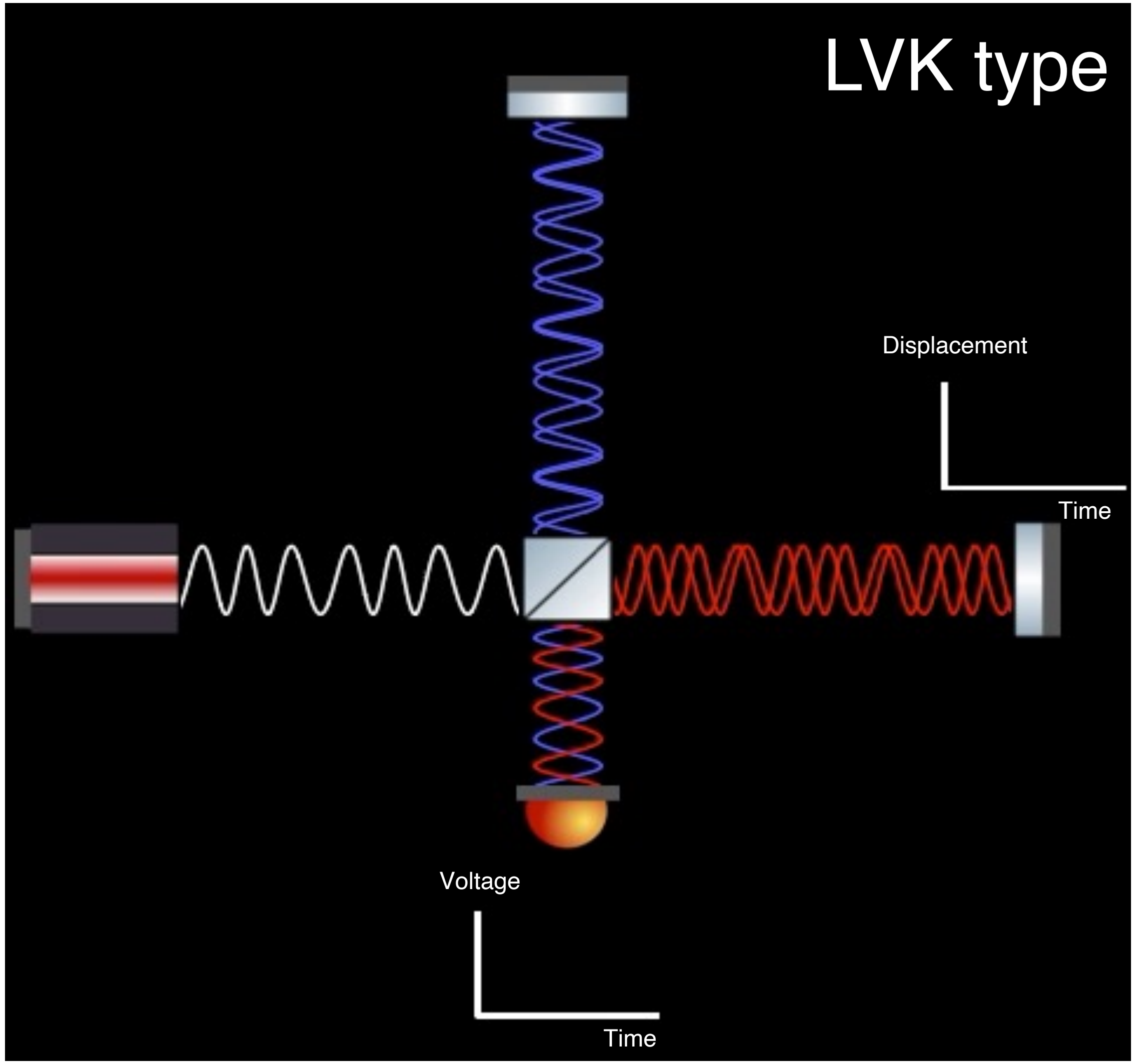
Image courtesy of O.Hartwig

Laser noise **non-cancellation** in LISA **unequal** arm-lengths (**non-stable** laser)

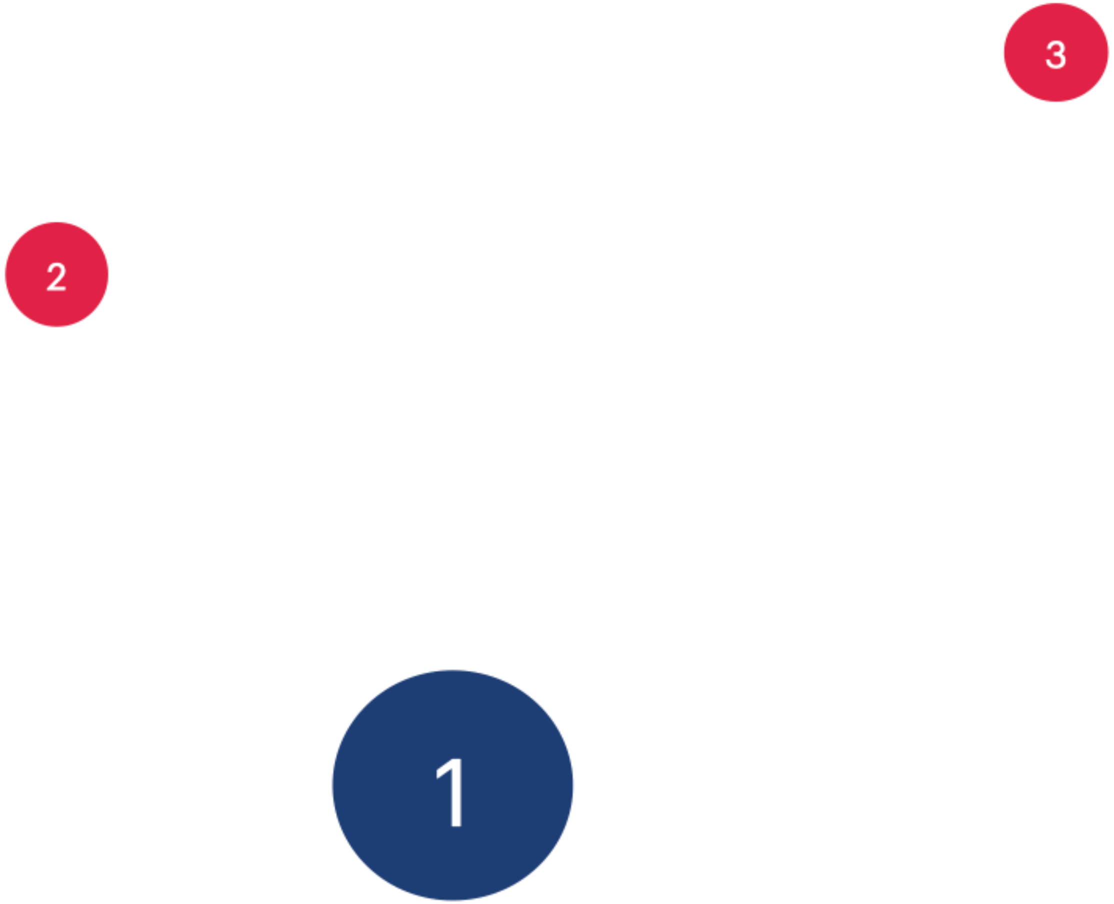


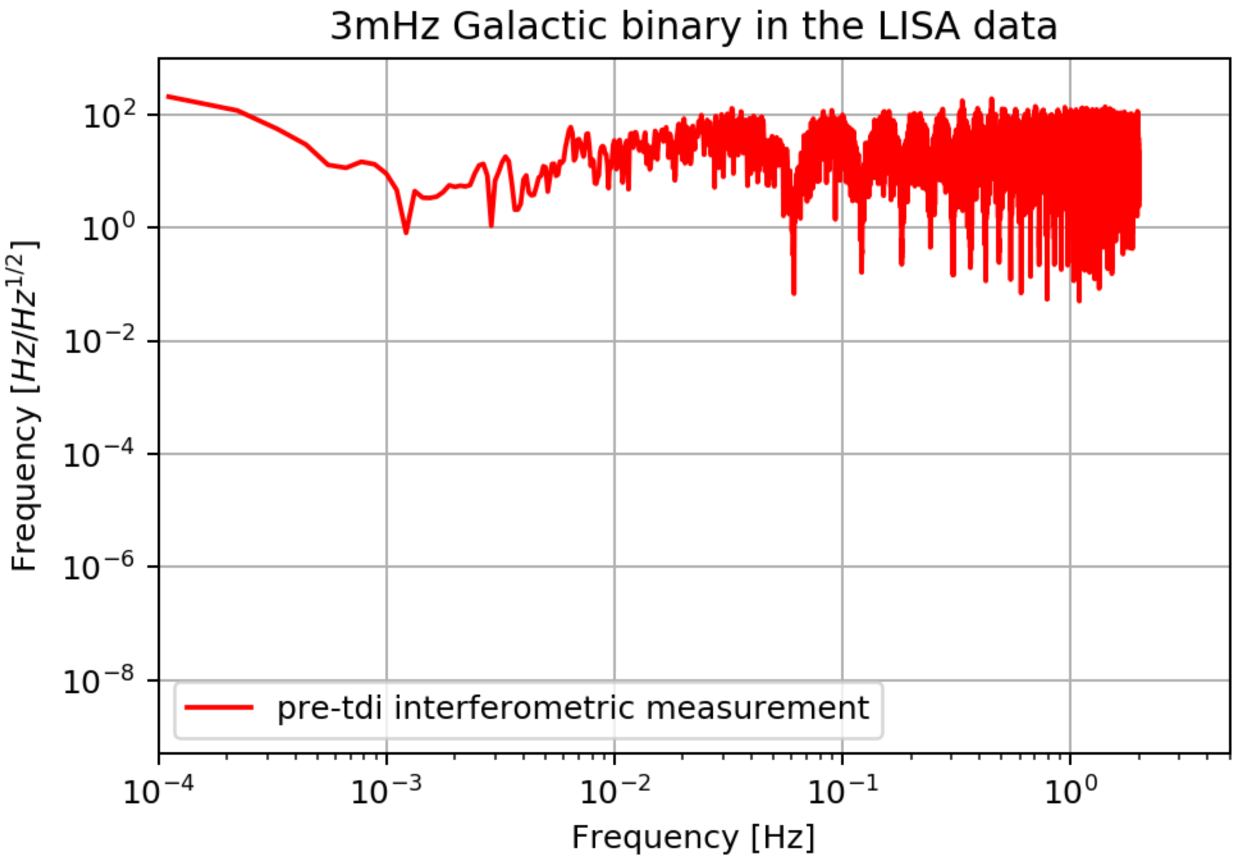
Laser noise cancellation LISA vs. LVK





Michelson 0 gen. interferometer





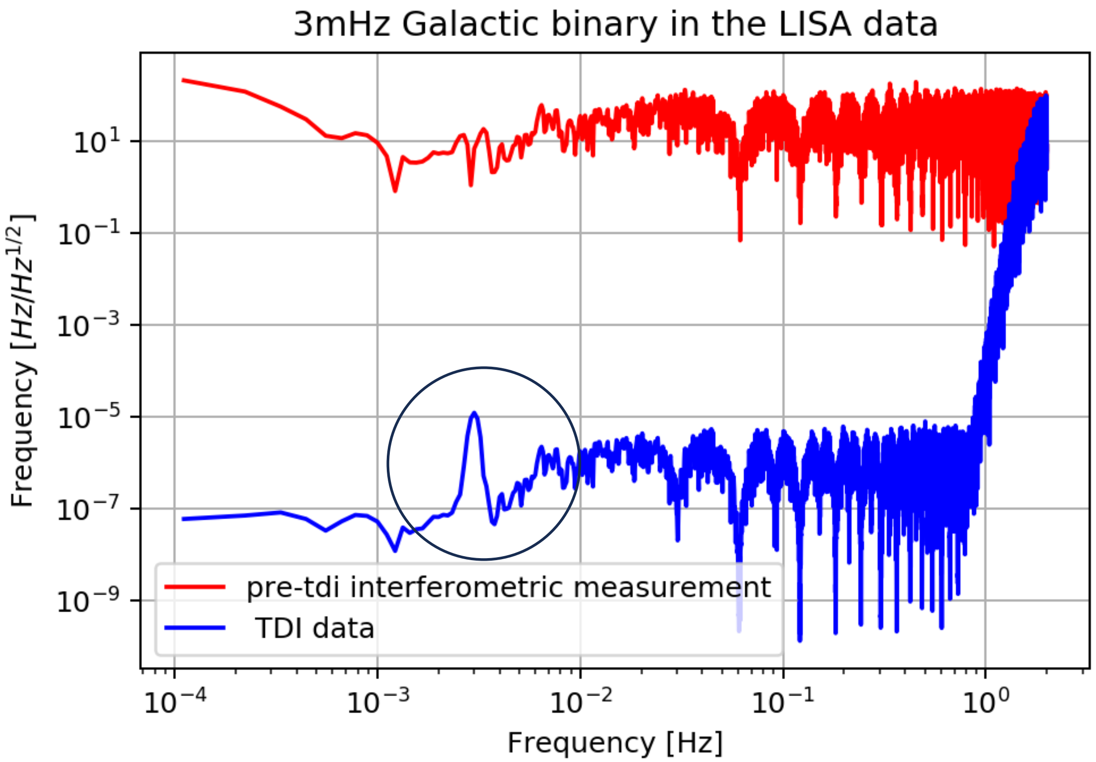
Credit: PyTDI [Bayle, Jean-Baptiste, Hartwig, Olaf, & Staab, Martin] and GW response simulations [Bayle, Jean-Baptiste, Baghi,Quentin,Renzini Arianna & Le Jeune, Maude]

Time Delay Interferometry (TDI)

3

- First proposed in [Tinto et al., 1999]
- Cancel laser noise by constructing an equal arm interferometer in post-processing
- In practice: delays realised by interpolating 4 Hz data [Shaddock et al., 2004]

2



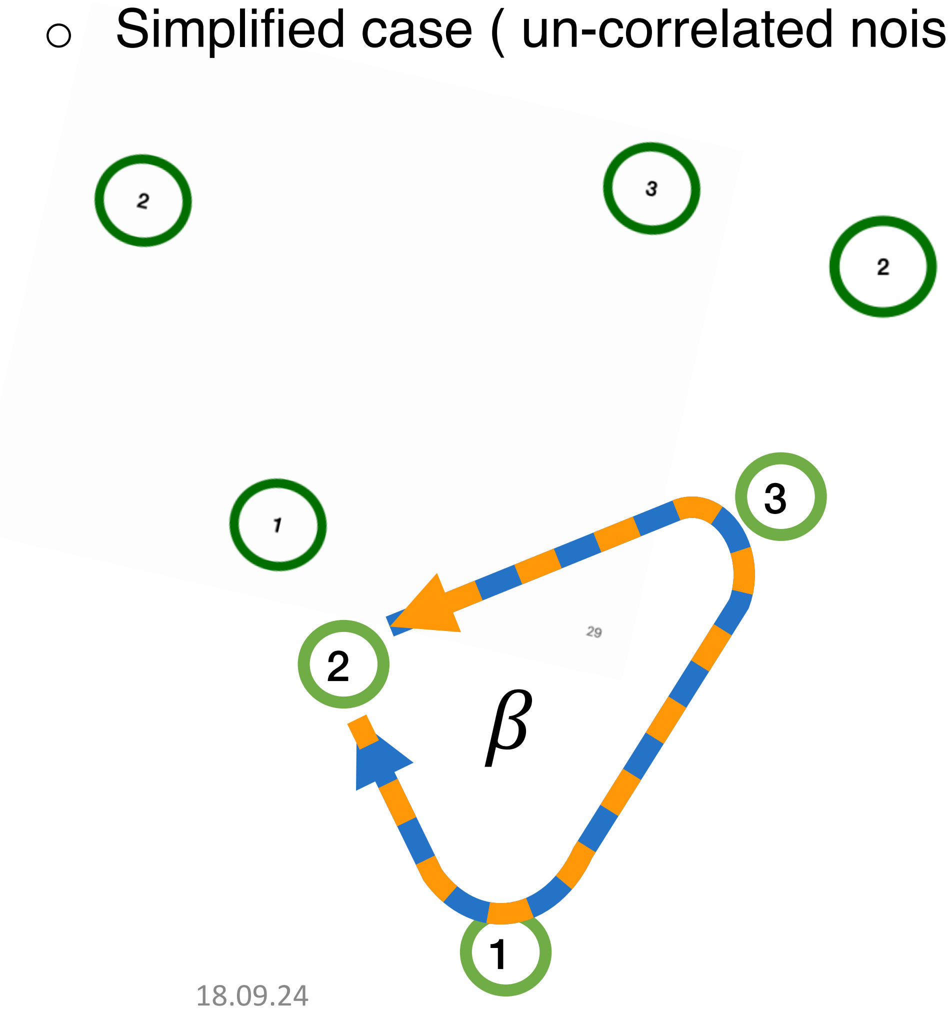
1

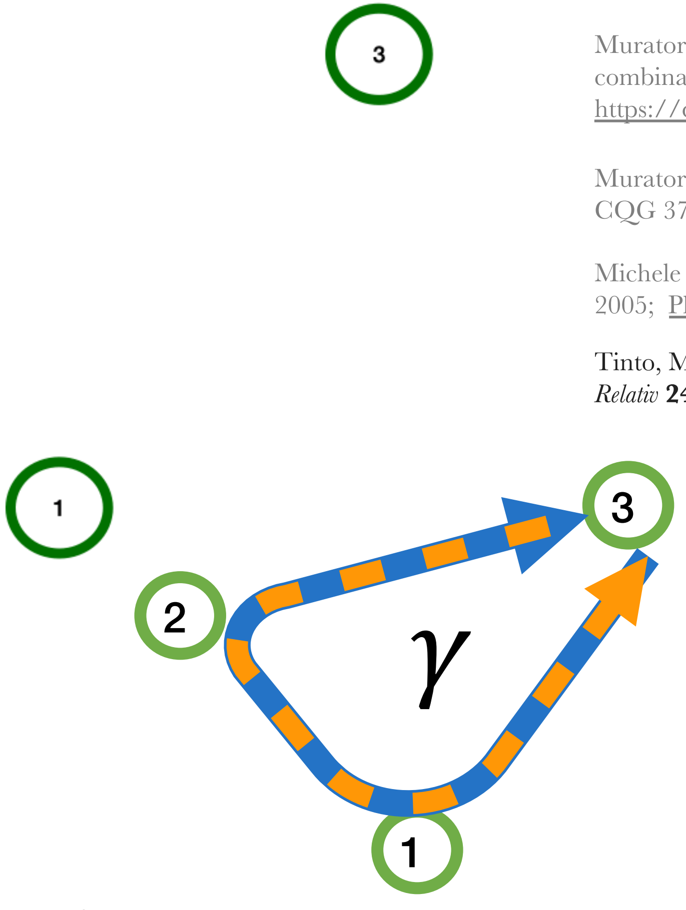
This is an example of constant arm lengths (1st generation TDI)

Many TDI variables

*Images courtesy of O.Hartwig

- 34 Core combinations, which represent 210 distinct variables
- For a static constellation all TDI variables can be build from 4 generators [Dhurandhar et al., 2002]
- Simplified case (un-correlated noise) 3 orthogonal channels can be form





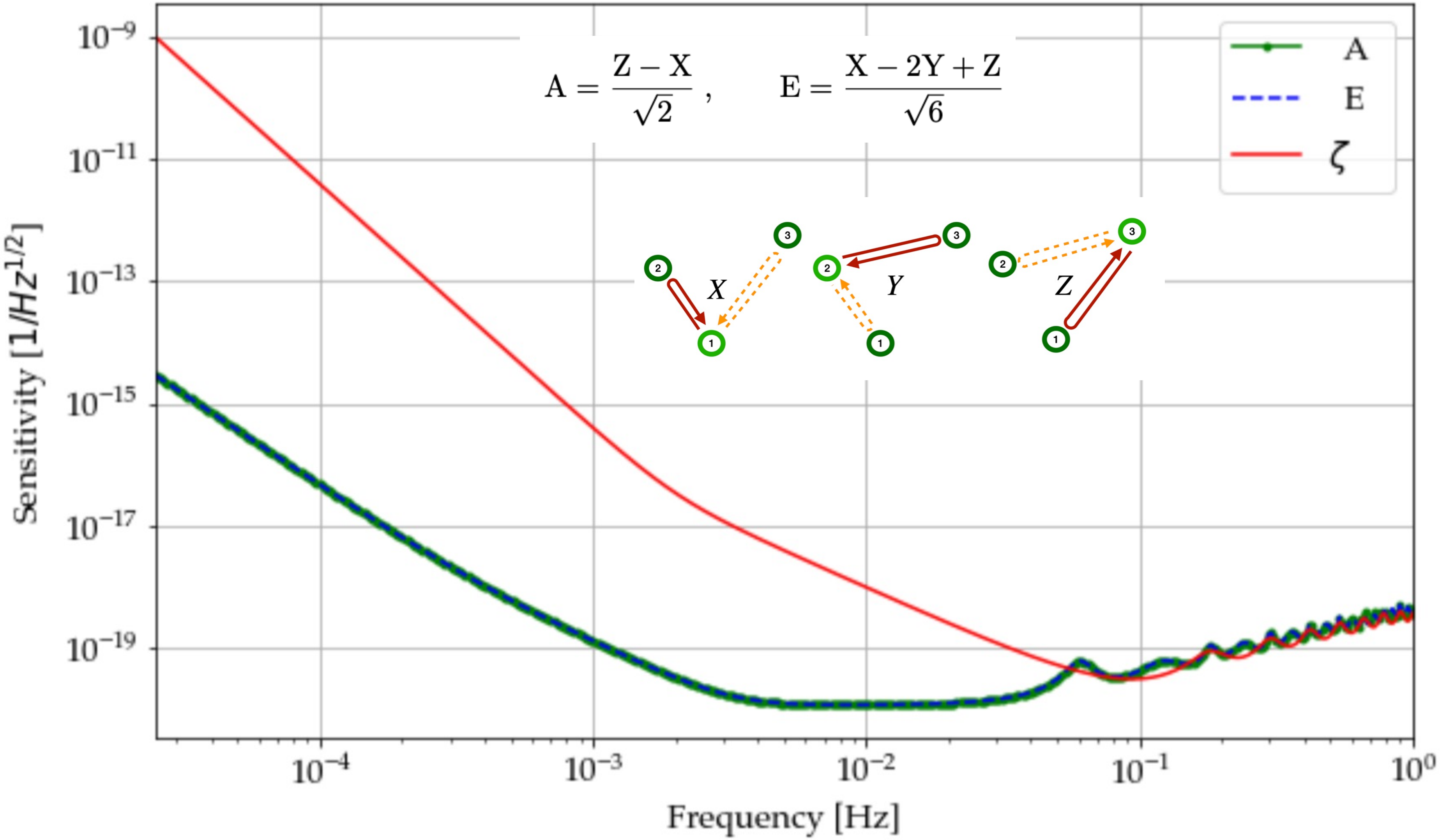
Muratore and Hartwig, Characterization of Time Delay Interferometry combinations for the LISA instrument noise, https://doi.org/10.48550/arXiv.2111.00975

Muratore et al, Revisitation of time delay interferometry, June 2020 CQG 37(18) DOI:10.1088/1361-6382/ab9d5b

Michele Vallisneri. Phys. Rev. D **72**, 042003 – Published 12 August 2005; Phys. Rev. D **76**, 109903 (2007)

Tinto, M., Dhurandhar, S.V. Time-delay interferometry. *Living Rev Relativ* **24**, 1 (2021). https://doi.org/10.1007/s41114-020-00029-6

Sensitivities of TDI channels to GW



Null channels to estimate instrumental noise

- Correlation with other detectors is not possible for LISA (no independent TDI channels !)
- Distinguish Stochastic GW background from instrumental noise require a good knowledge of this one
- The LISA detector is supposed to be signal dominated (no direct measurement of the noise !)
- Look for TDI combinations that have *suppressed* sensitivity to GW signals but still carry some information on the instrumental noise

Can we infer the noise from the null channels ?

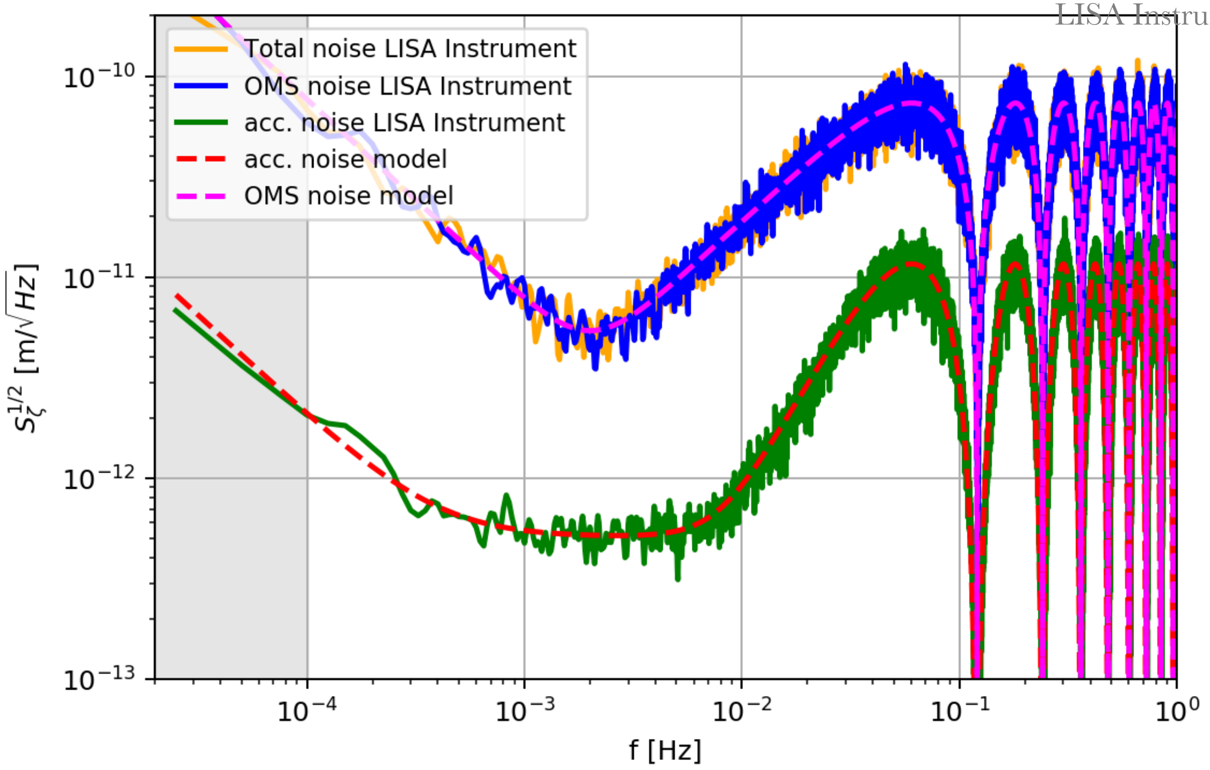
Muratore et al., On the effectiveness of null TDI channels as instrument noise monitors in LISA e-Print: 2207.02138

Raphael Flauger et al JCAP01(2021)059

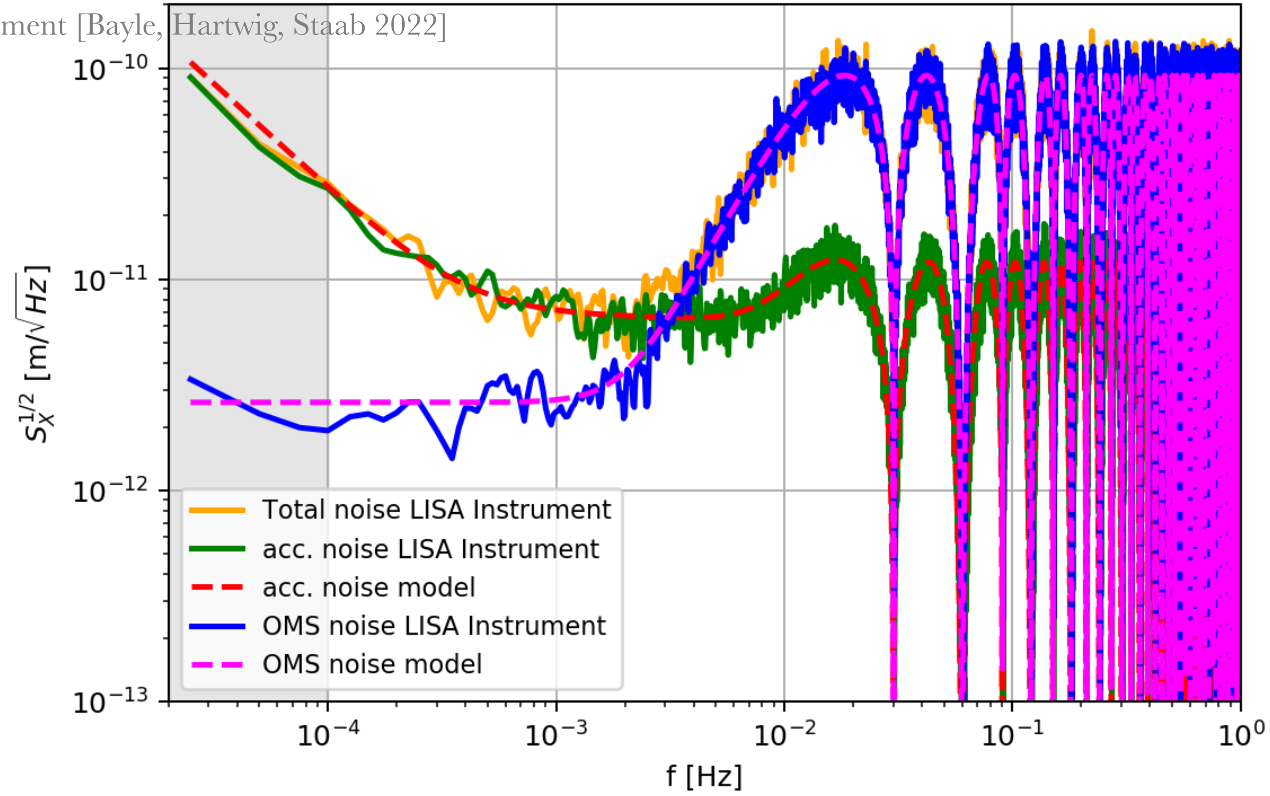
$$S_X^{noise} \approx 64\tau^4\omega^4\left(4\sum_{ij\in\mathcal{I}_X} S_{g_{ij}}^{disp} + \sum_{ij\in\mathcal{I}_X} S_{oms_{ij}}\right)$$

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

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

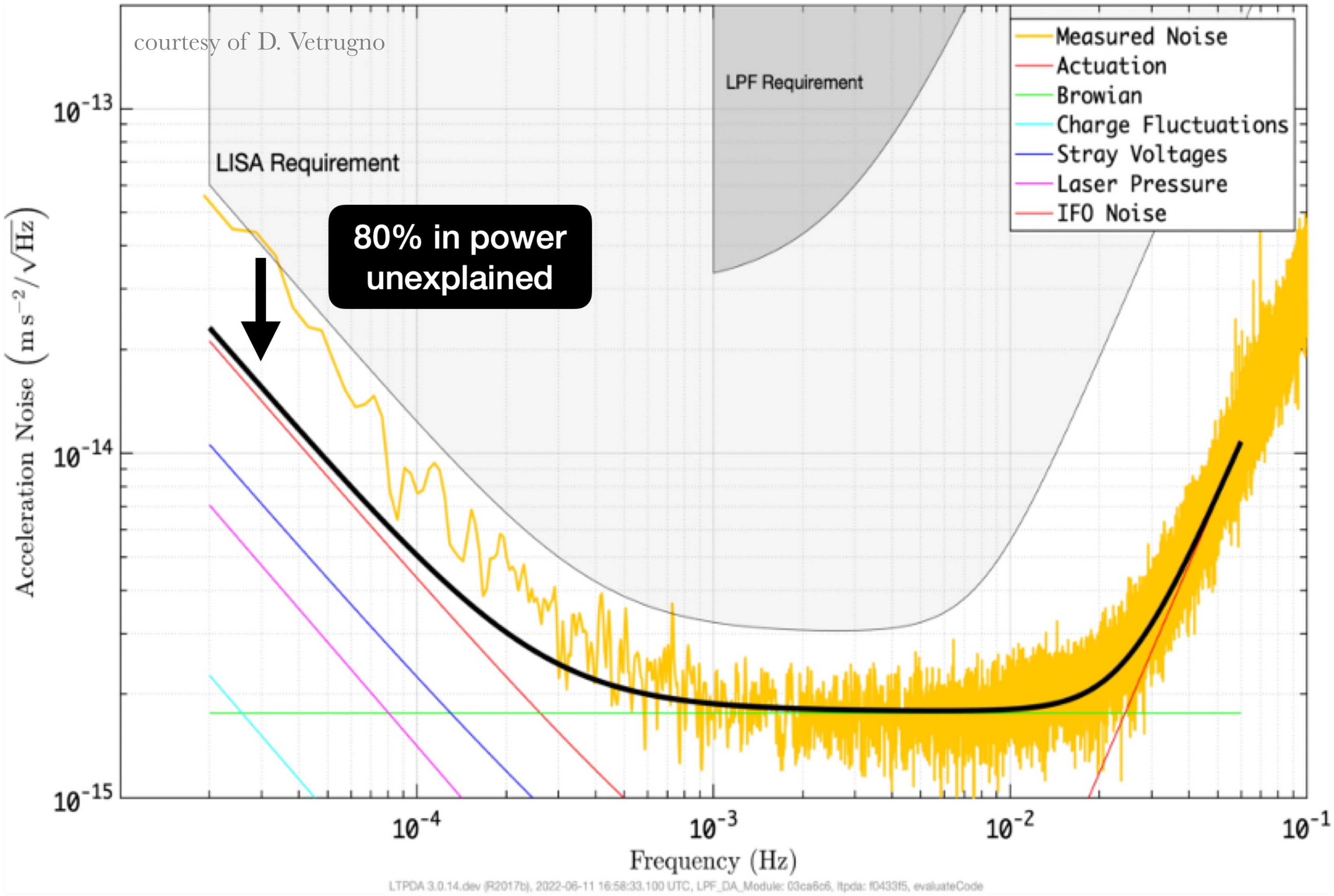


LISA Instrument [Bayle, Hartwig, Staab 2022]



Can we rely on noise models for data analysis ?

- Noise example: TM motion in LISA Pathfinder



*Slide courtesy of O.Hartwig and J. Bayle

LISA data analysis pipeline

L0/L0.5 DATA	L0-L1 PIPELINE	L1 DATA	L1-L2 PIPELINE	L2 DATA
Science data Ground tracking Housekeeping data	Laser noise red. Other noise (clock, spacecraft motion, tilt to length, etc.) reduction Reference frame transformation	TDI channels in global ref. frame (XYZ, AET, …) Reconstructed orbits in global ref. frame Noise models	Param. estimation	Source parameters

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
- SGWBs -- if not loud -- will be residuals

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

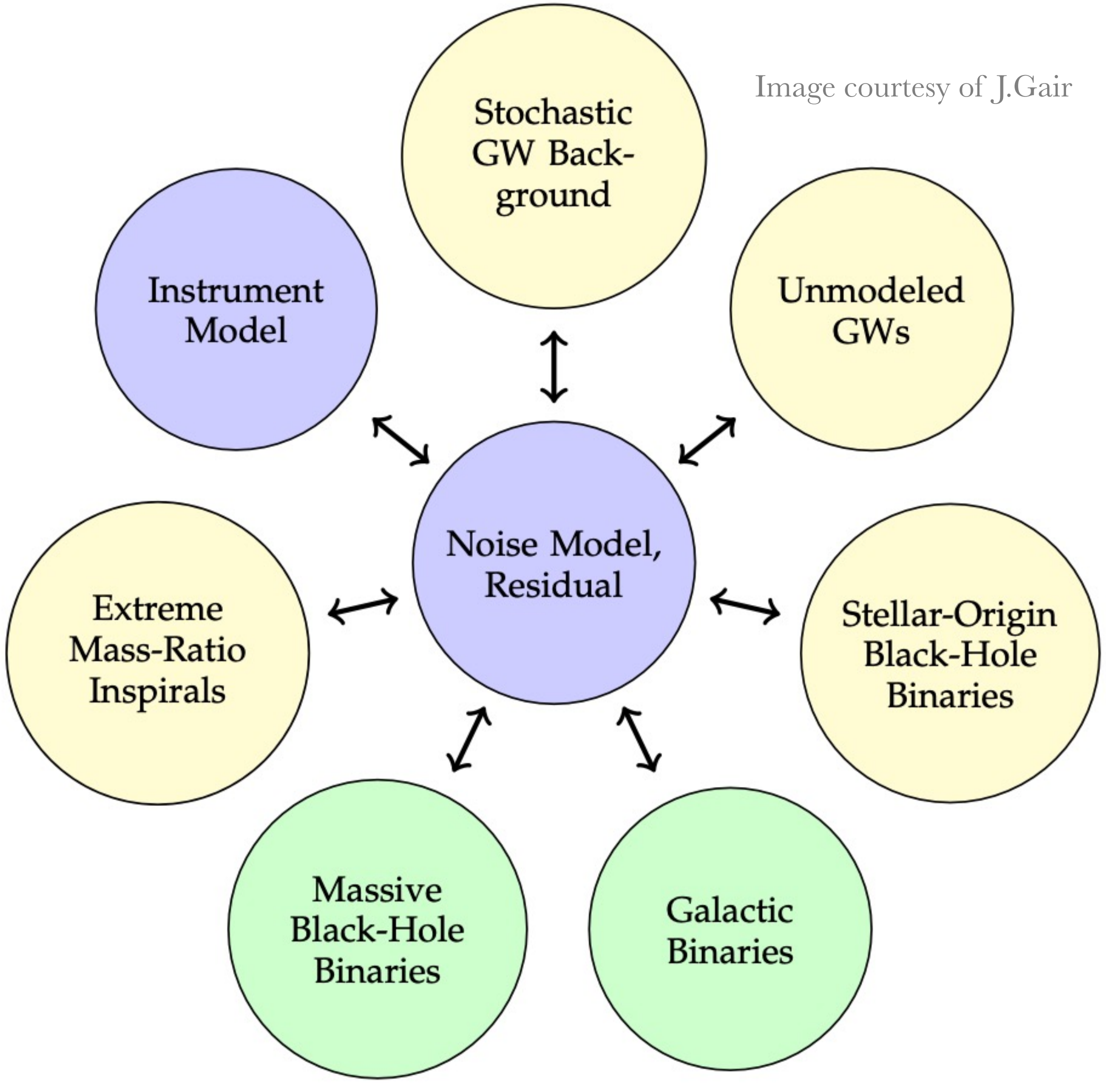
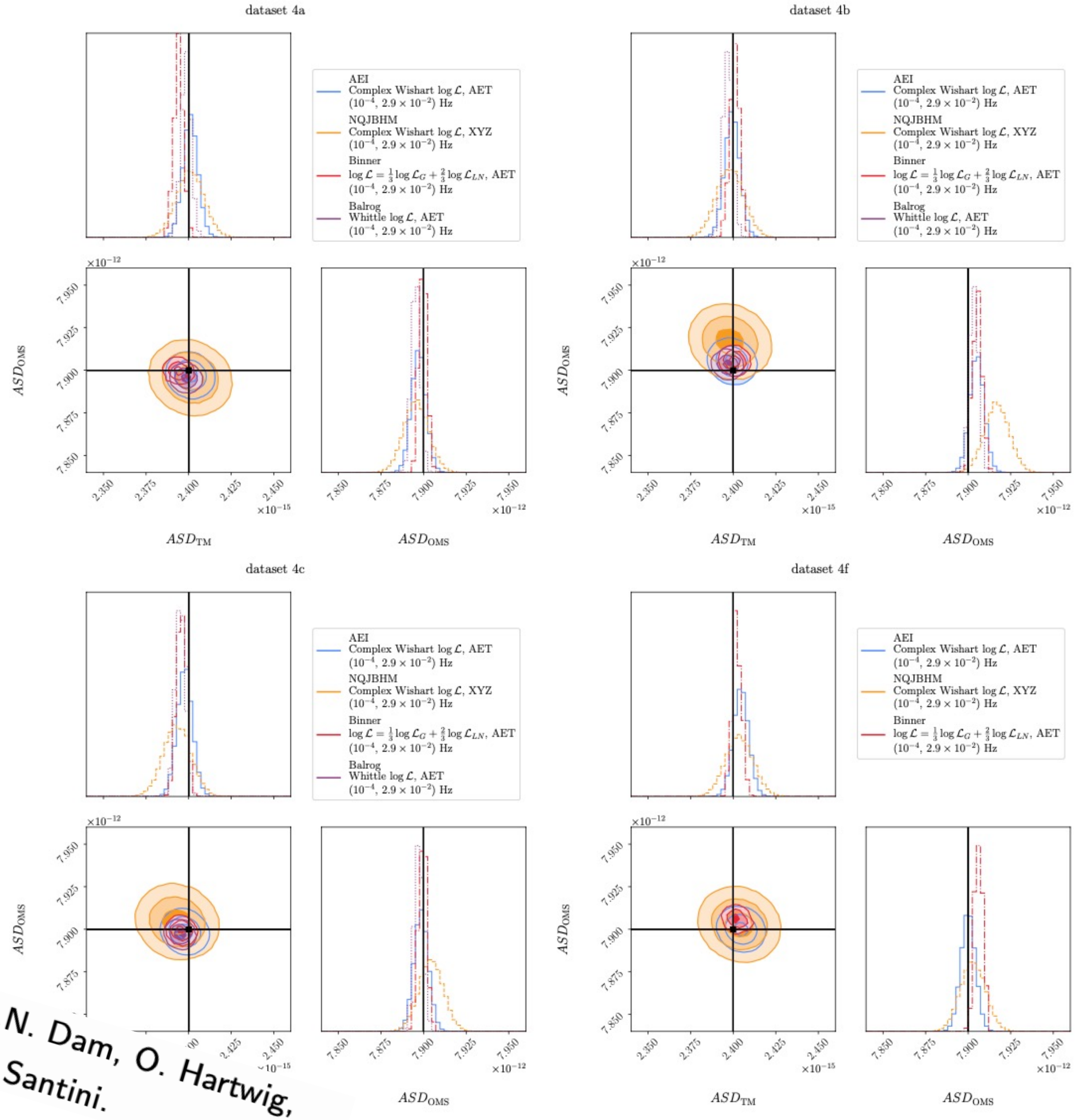


Image courtesy of J.Gair

Joining the efforts

- Different methodology to solve the problem
- A unified pipeline for SGWB parameter estimations
- Provide a block for global fit

In collaboration with: Q. Baghi, J.B. Bayle, R. Buscicchio C. Caprini, Q.N. Dam, O. Hartwig, J. Gair, N. Karnesis, M. Muratore, G. Nardini, F. Pozzoli, A. Santini.



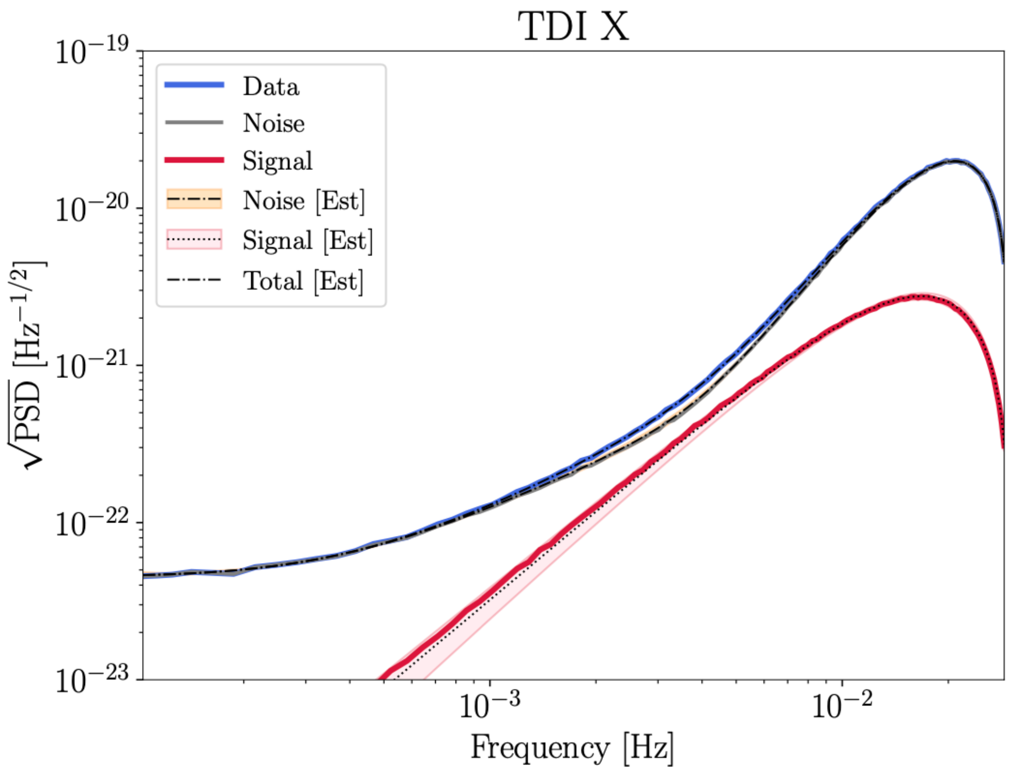
- Noise-agnostic searches using splines but with signal template

Q. Baghi, N. Karnesis et al.

Baghi et al. https://doi.org/10.48550/arXiv.2302.12573

- SGWB template search with a two-component spline for the noise model

	Injection	Analysis
Noise	Yes	Spline model
Signal	Yes	Parametric power law



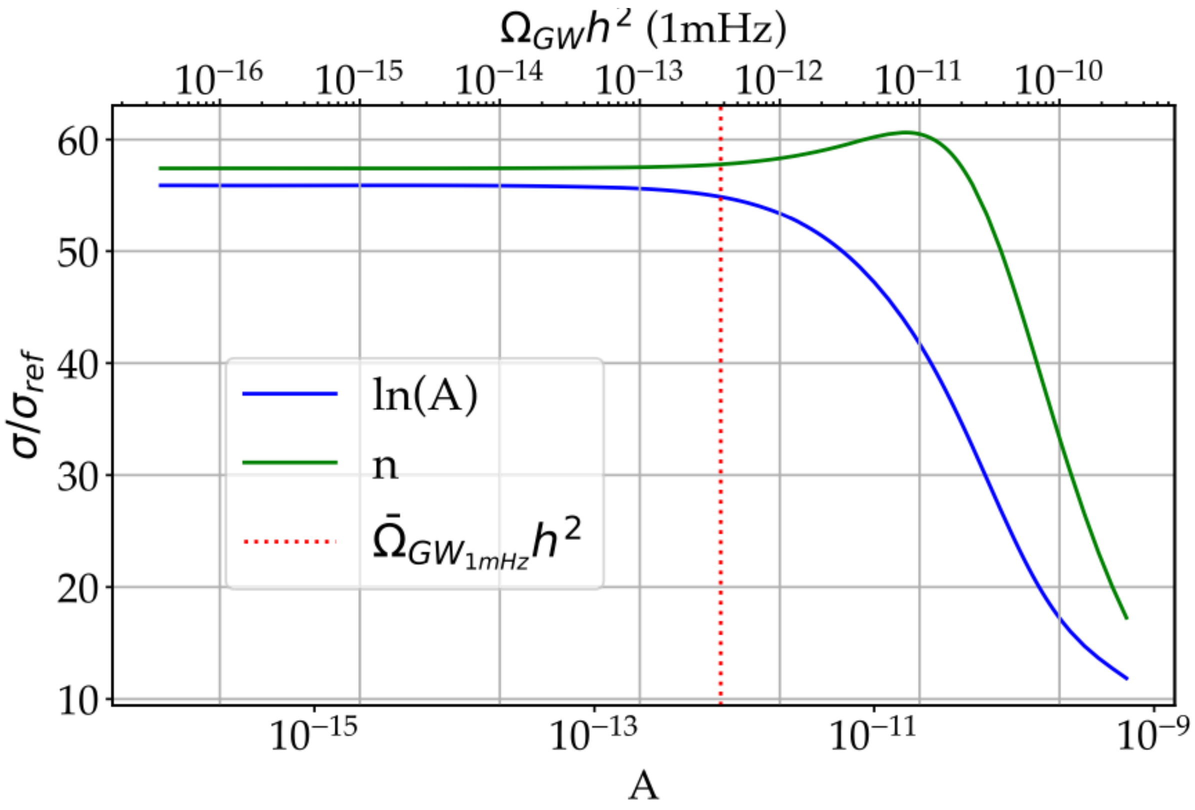
Preliminary

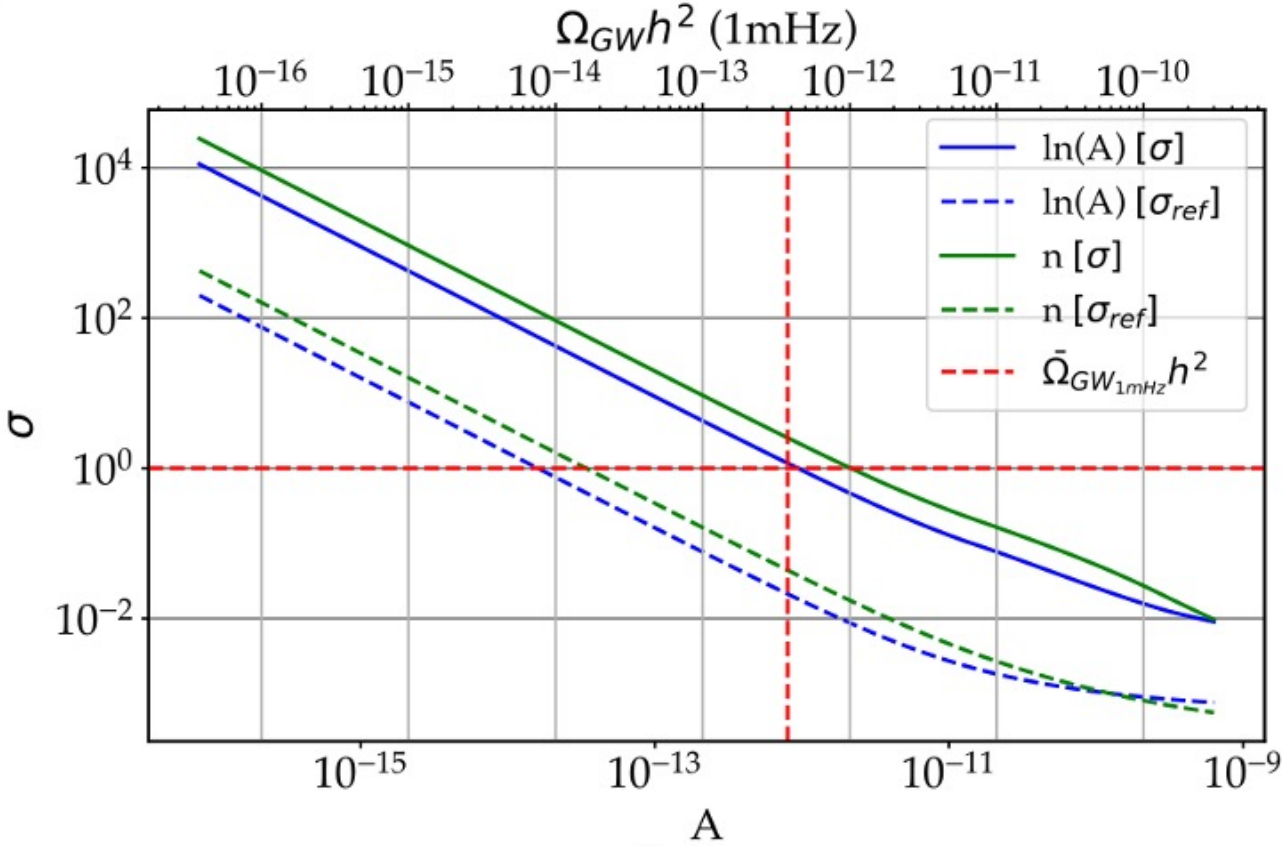
$$\log \mathscr{B}_{10} = \log \frac{Z(H_1)}{Z(H_0)}$$
$$= 31.86 \pm 0.05$$

Impact of noise knowledge uncertainty of SGWB parameter estimation

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

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





A. Santini et al.(noise and signal-agnostic search with spline)

We test our pipeline by analyzing a mock dataset made by a realization of the LISA instrumental noise and an SGWB realization drawn from a power-law energy density, $h^2\Omega(f) = A\, f^n$. To generate data consistent with a background from **SOBH** binaries, we set $A = 3.4 \times 10^{-13}$, $n = 2/3$.

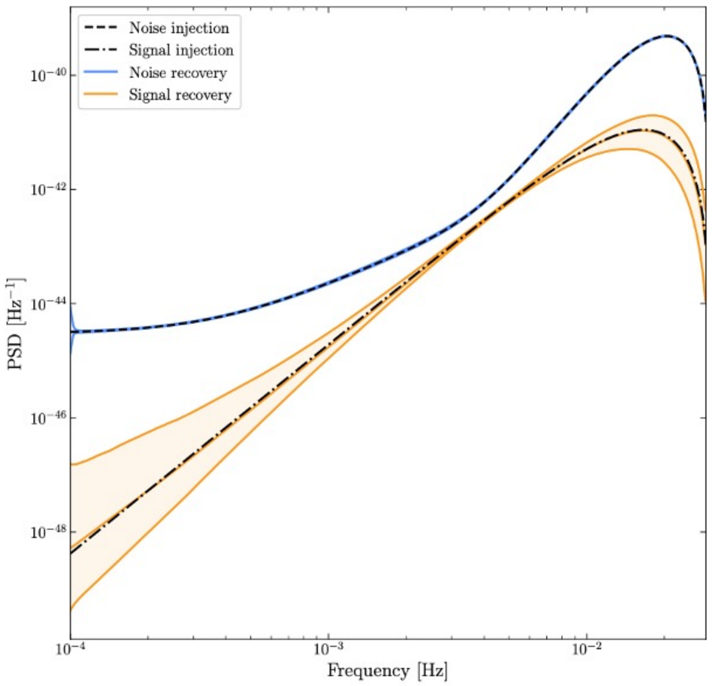


Figure 1: Injected and reconstructed PSDs for the two components. Filled contours represent 90% credible intervals.

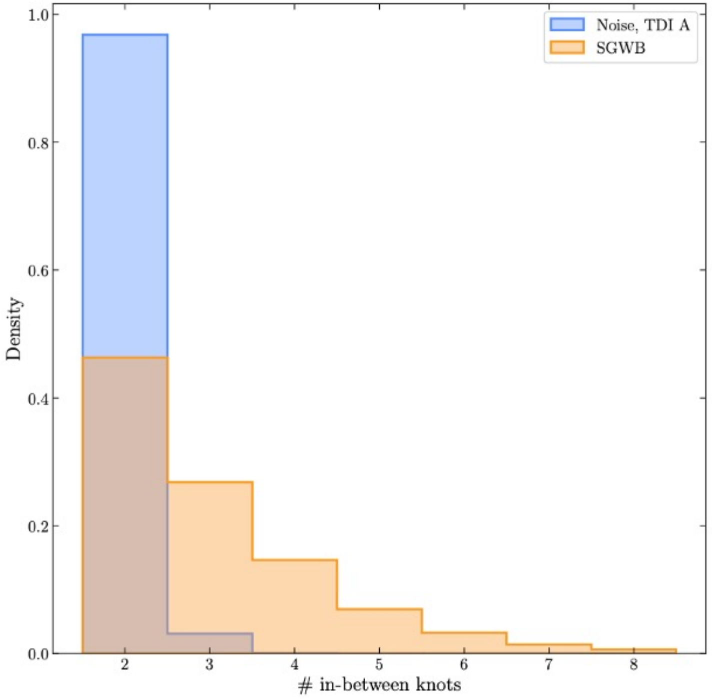
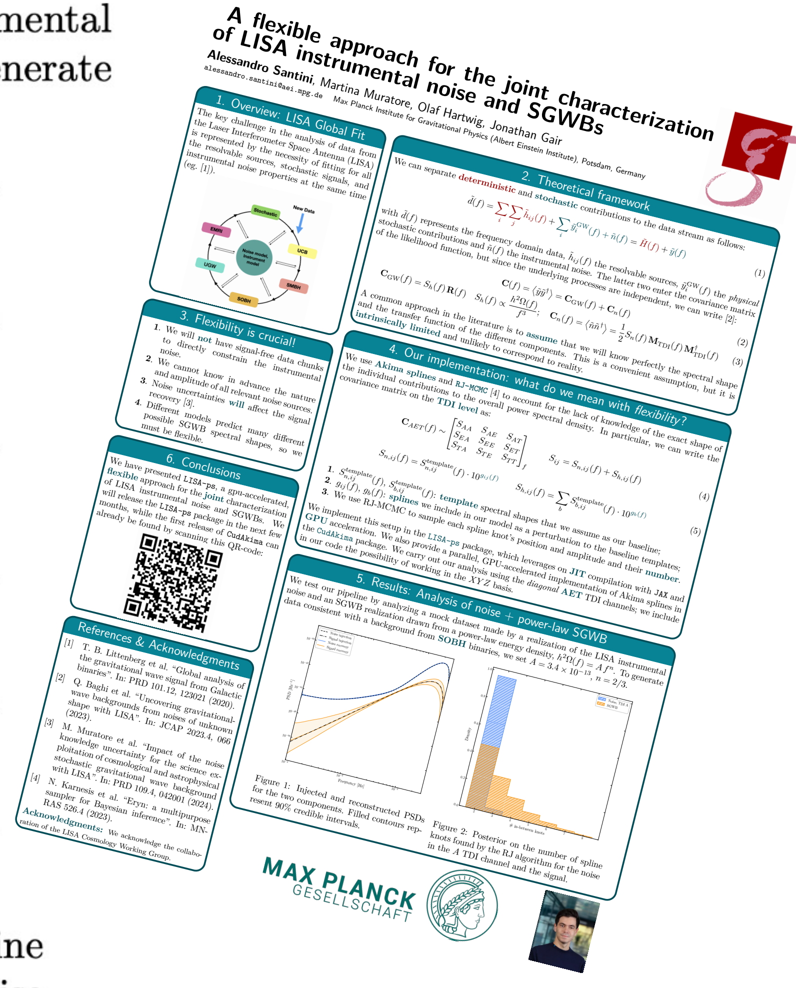


Figure 2: Posterior on the number of spline knots found by the RJ algorithm for the noise in the A TDI channel and the signal.



A flexible approach for the joint characterization of LISA instrumental noise and SGWBs

Alessandro Santini, Martina Muratore, Olaf Hartwig, Jonathan Gair

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1. Overview: LISA Global Fit

The key challenge in the analysis of data from the Laser Interferometer Space Antenna (LISA) is represented by the necessity of fitting for all the resolvable sources, stochastic signals, and instrumental noise properties at the same time (eg. [1]).

3. Flexibility is crucial!

1. We will **not** have signal-free data chunks to directly constrain the instrumental noise.
2. We cannot know in advance the nature and amplitude of all relevant noise sources.
3. Noise uncertainties **will** affect the signal recovery [3].
4. Different models predict many different possible SGWB spectral shapes, so we must be flexible.

6. Conclusions

We have presented `LISA-ps`, a gpu-accelerated, **flexible** approach for the **joint** characterization of LISA instrumental noise and SGWBs. We will release the `LISA-ps` package in the next few months, while the first release of `CudAkima` can already be found by scanning this QR-code:

References & Acknowledgments

[1] T. B. Littenberg et al. "Global analysis of the gravitational wave signal from Galactic binaries". In: PRD 101.12, 123021 (2020).

[2] Q. Baghi et al. "Uncovering gravitational-wave backgrounds from noises of unknown shape with LISA". In: JCAP 2023.4, 066 (2023).

[3] M. Muratore et al. "Impact of the noise knowledge uncertainty for the science exploitation of cosmological and astrophysical stochastic gravitational wave background with LISA". In: PRD 109.4, 042001 (2024).

[4] N. Karnesis et al. "Eryn: a multipurpose sampler for Bayesian inference". In: MNRAS 526.4 (2023).

Acknowledgments: We acknowledge the collaboration of the LISA Cosmology Working Group.

2. Theoretical framework

We can separate **deterministic** and **stochastic** contributions to the data stream as follows:

$$\tilde{d}(f) = \sum_i \sum_j \tilde{h}_{ij}(f) + \sum_i \tilde{y}_i^{\mathrm{GW}}(f) + \tilde{n}(f) = \tilde{H}(f) + \tilde{y}(f) \quad (1)$$

with $\tilde{d}(f)$ represents the frequency domain data, $\tilde{h}_{ij}(f)$ the resolvable sources, $\tilde{y}_i^{\mathrm{GW}}(f)$ the *physical* stochastic contributions and $\tilde{n}(f)$ the instrumental noise. The latter two enter the covariance matrix of the likelihood function, but since the underlying processes are independent, we can write [2]:

$$\mathbf{C}(f) = \langle \tilde{y}\tilde{y}^\dagger \rangle = \mathbf{C}_{\mathrm{GW}}(f) + \mathbf{C}_n(f) \quad (2)$$

$$\mathbf{C}_{\mathrm{GW}}(f) = S_h(f)\,\mathbf{R}(f) \quad S_h(f) \propto \frac{h^2\Omega(f)}{f^3}; \quad \mathbf{C}_n(f) = \langle \tilde{n}\tilde{n}^\dagger \rangle = \frac{1}{2} S_n(f)\,\mathbf{M}_{\mathrm{TDI}}(f)\,\mathbf{M}^\dagger_{\mathrm{TDI}}(f) \quad (3)$$

A common approach in the literature is to **assume** that we will know perfectly the spectral shape and the transfer function of the different components. This is a convenient assumption, but it is **intrinsically limited** and unlikely to correspond to reality.

4. Our implementation: what do we mean with *flexibility*?

We use **Akima splines** and `RJ-MCMC` [4] to account for the lack of knowledge of the exact shape of the individual contributions to the overall power spectral density. In particular, we can write the covariance matrix on the **TDI level** as:

$$\mathbf{C}_{AET}(f) \sim \begin{bmatrix} S_{AA} & S_{AE} & S_{AT} \\ S_{EA} & S_{EE} & S_{ET} \\ S_{TA} & S_{TE} & S_{TT} \end{bmatrix}_f \qquad S_{ij} = S_{n,ij}(f) + S_{h,ij}(f) \quad (4)$$

$$S_{n,ij}(f) = S^{\mathrm{template}}_{n,ij}(f) \cdot 10^{g_{ij}(f)} \qquad S_{h,ij}(f) = \sum_b S^{\mathrm{template}}_{b,ij}(f) \cdot 10^{g_b(f)} \quad (5)$$

1. $S^{\mathrm{template}}_{n,ij}(f)$, $S^{\mathrm{template}}_{b,ij}(f)$: **template** spectral shapes that we assume as our baseline;
2. $g_{ij}(f)$, $g_b(f)$: **splines** we include in our model as a perturbation to the baseline templates;
3. We use RJ-MCMC to sample each spline knot's position and amplitude and their **number**.

We implement this setup in the `LISA-ps` package, which leverages on **JIT** compilation with `JAX` and **GPU** acceleration. We also provide a parallel, GPU-accelerated implementation of Akima splines in the `CudAkima` package. We carry out our analysis using the *diagonal* **AET** TDI channels; we include in our code the possibility of working in the XYZ basis.

5. Results: Analysis of noise + power-law SGWB

We test our pipeline by analyzing a mock dataset made by a realization of the LISA instrumental noise and an SGWB realization drawn from a power-law energy density, $h^2\Omega(f) = A\, f^n$. To generate data consistent with a background from **SOBH** binaries, we set $A = 3.4 \times 10^{-13}$, $n = 2/3$.

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Figure 2: Posterior on the number of spline knots found by the RJ algorithm for the noise in the A TDI channel and the signal.

MAX PLANCK GESELLSCHAFT

Image courtesy of A. Santini

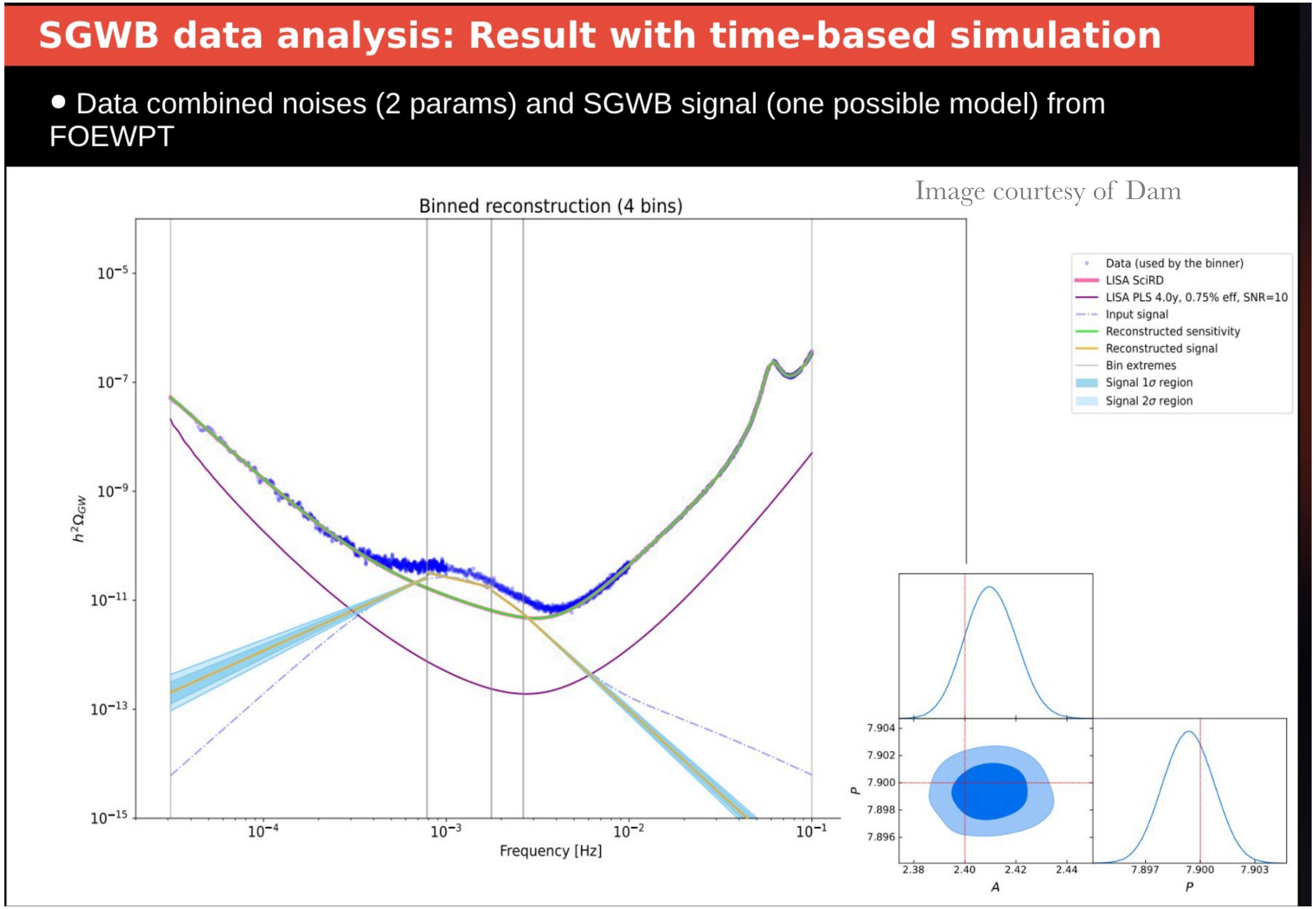
- Signal-agnostic searches using splines but with noise template

Q. N. Dam et al.

Flauger, R., Karnesis, N., Nardini, G., Pieroni, M., Ricciardone, A., & Torrado, J. (2021). Improved reconstruction of a stochastic gravitational wave background with LISA. Journal of Cosmology and Astroparticle Physics, 2021(01), 059

- **SGWBinner:** search SGWB signal for each bin (small equal log-frequency intervals) as a single
  power law, assuming they are independent for every bin.

- Collection of power-law signals give the overall SGWB



SGWB data analysis: Result with time-based simulation

- Data combined noises (2 params) and SGWB signal (one possible model) from FOEWPT

Image courtesy of Dam

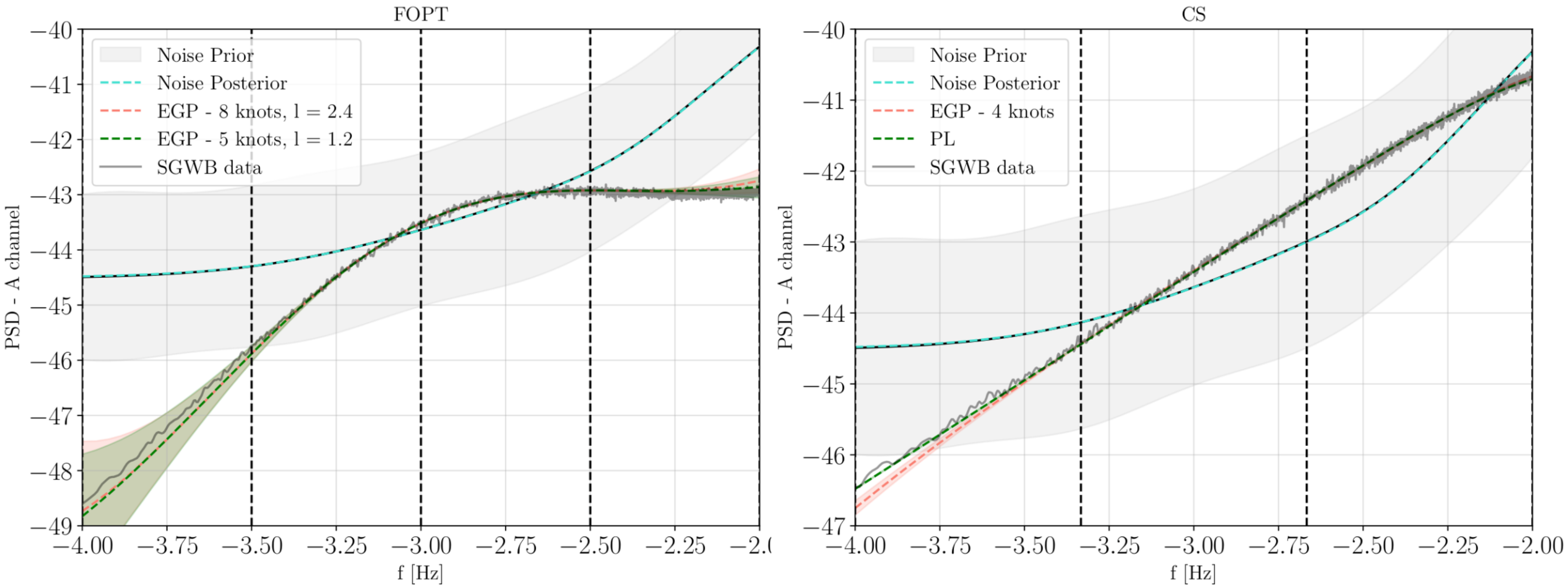
Expectation value of Gaussian process for signal and noise PSD modelling

Pozzoli, Buscicchio et al (2024)

RESULTS - APPLICATION to COSMO SOURCES

Image courtesy of Pozzoli

- GENERATION 1.5 and AET variables
- Whittle Likelihood
- Gaussian, Isotropic and stationary SGWB
- Modelling the strain:
  - •Perfect knowledge of transfer function for noise
  - •Perfect knowledge of response function to SGWB

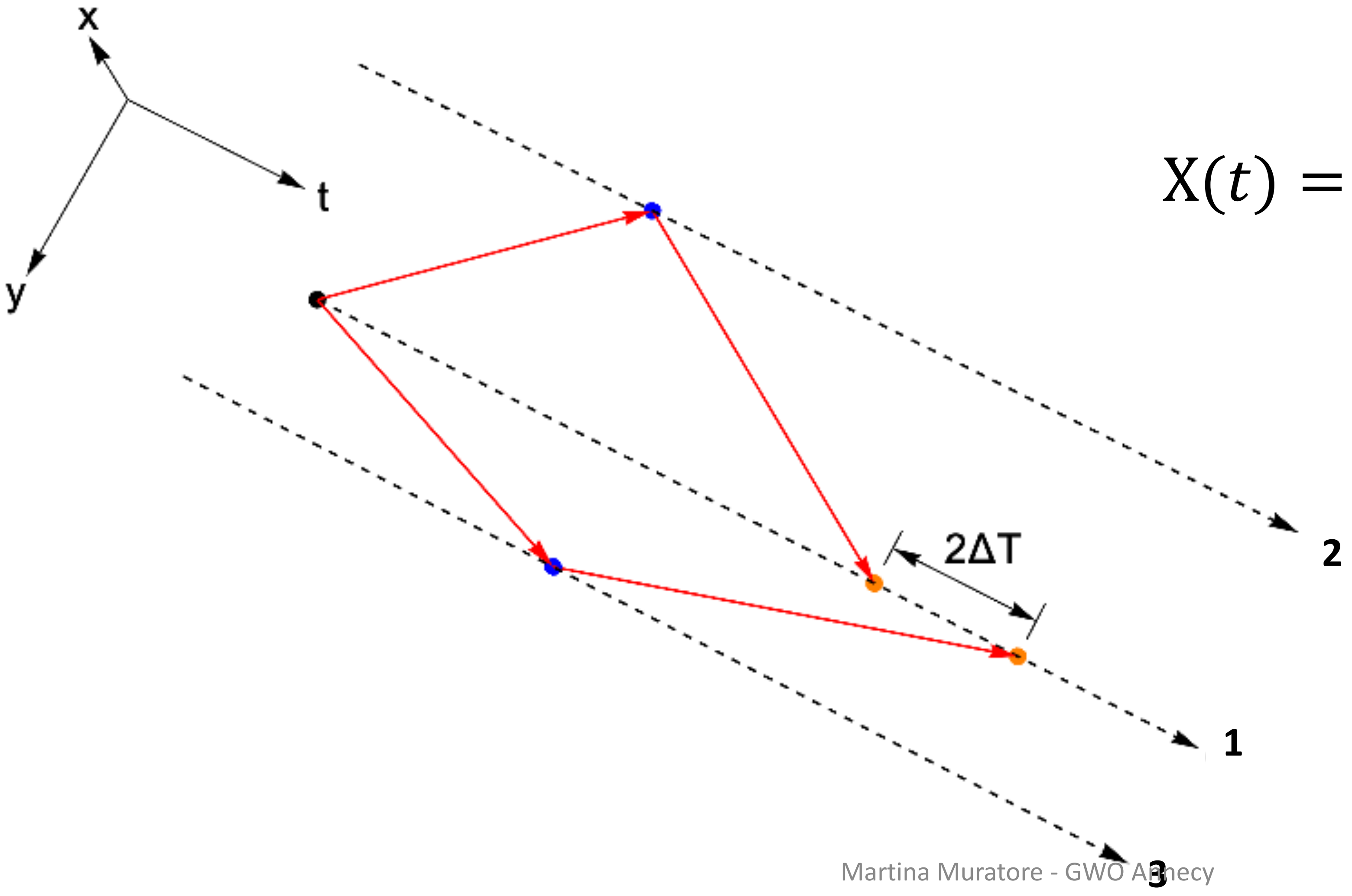


Plus much more in the literature

- Recovering a phase transition signal in simulated LISA data with a modulated galactic foreground, Tiina Minkkinen, arXiv:2406.04894
- Alvey, et al. Leveraging Time-Dependent Instrumental Noise for LISA SGWB Analysis**,** https://doi.org/10.48550/arXiv.2408.00832
- Inchaupse et al. : Observing Kinematic Anisotropies of a SGWB with LISA**,** http://arxiv.org/abs/2401.14849
- O. Hartwig, Stochastic gravitational wave background reconstruction for a nonequilateral and unequal-noise LISA constellation, Phys. Rev. D **107**, 123531
- 2010 Cornish & Adams
- Cornish and Romano SGWB Review
- Bruce Allen, https://doi.org/10.48550/arXiv.gr-qc/9604033
- ……………

Thank you for your attention

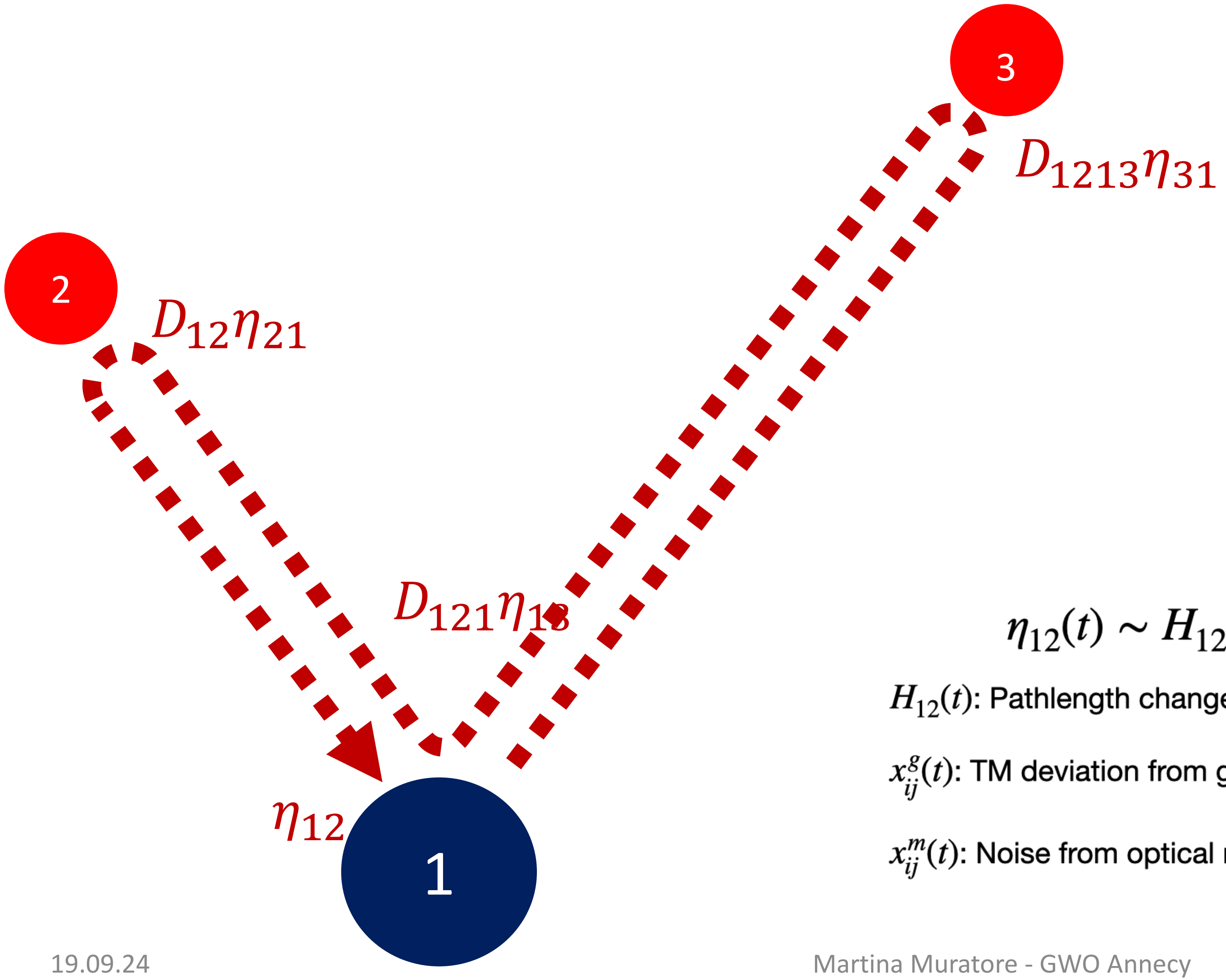
Residual laser phase noise in a space-time diagrams for unequal arms-length Michelson (zero level) interferometer



$$X(t) = \phi_1(t-2\Delta T) - \phi_1(t) \approx 2\dot{\phi}(t)\Delta T$$

1st generation TDI

Image curtesy of O. Hartwig



$$\eta_{12} + D_{12}\eta_{21} + D_{121}\eta_{13} + D_{1213}\eta_{31}$$

$$\eta_{12}(t) \sim H_{12}(t) + x_{21}^{g}(t-\tau) + x_{12}^{g}(t) + x_{12}^{m}(t)$$

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

$x_{ij}^{g}(t)$: TM deviation from geodesic motion

$x_{ij}^{m}(t)$: Noise from optical metrology (e.g., shot noise)

1^{st} generation TDI

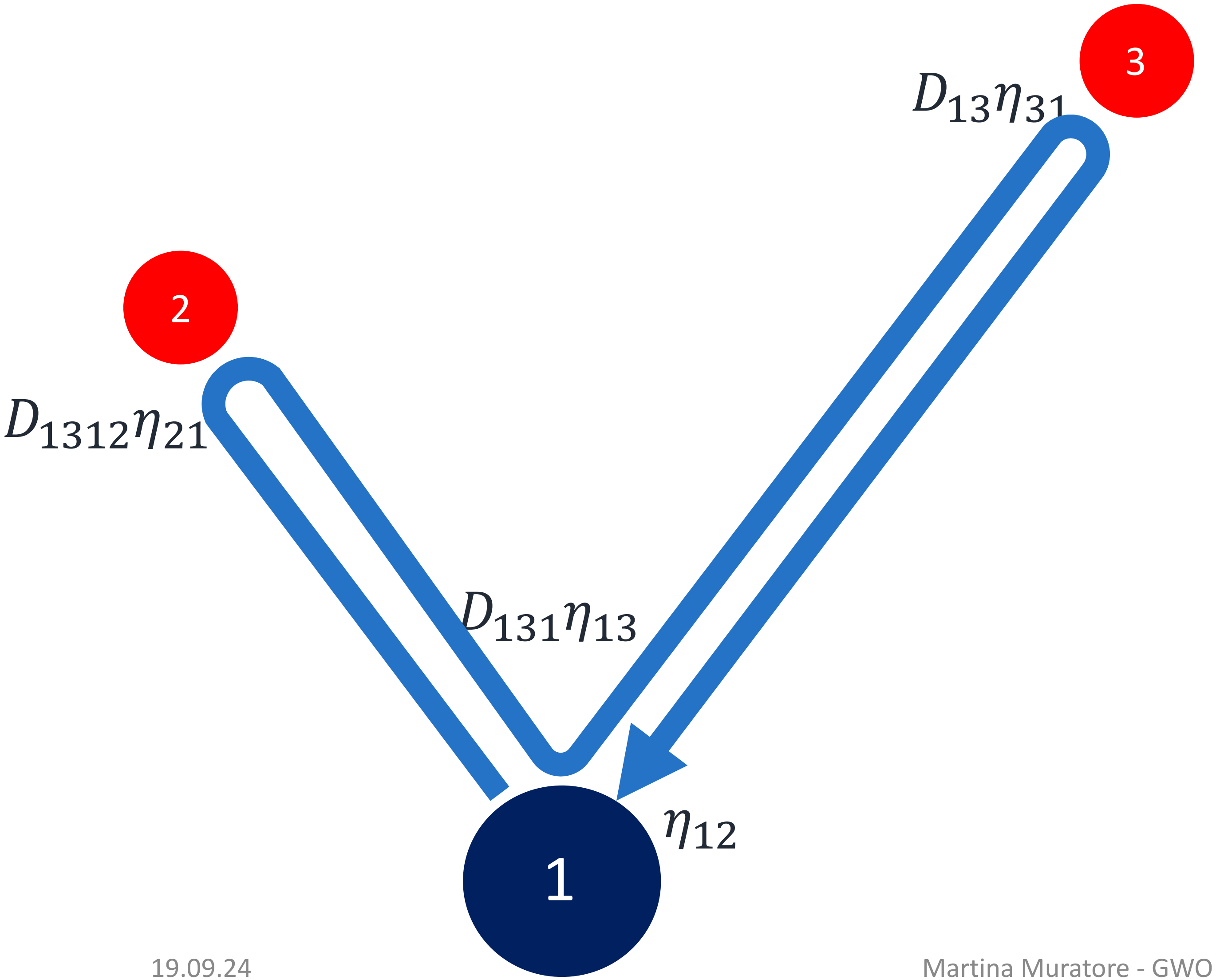


Image curtesy of O. Hartwig

$$X = \eta_{12} + D_{12}\eta_{21} + D_{121}\eta_{13} + D_{1213}\eta_{31}$$

$$- \eta_{12} - D_{13}\eta_{31} - D_{131}\eta_{13} - D_{1312}\eta_{21}$$

1st generation TDI

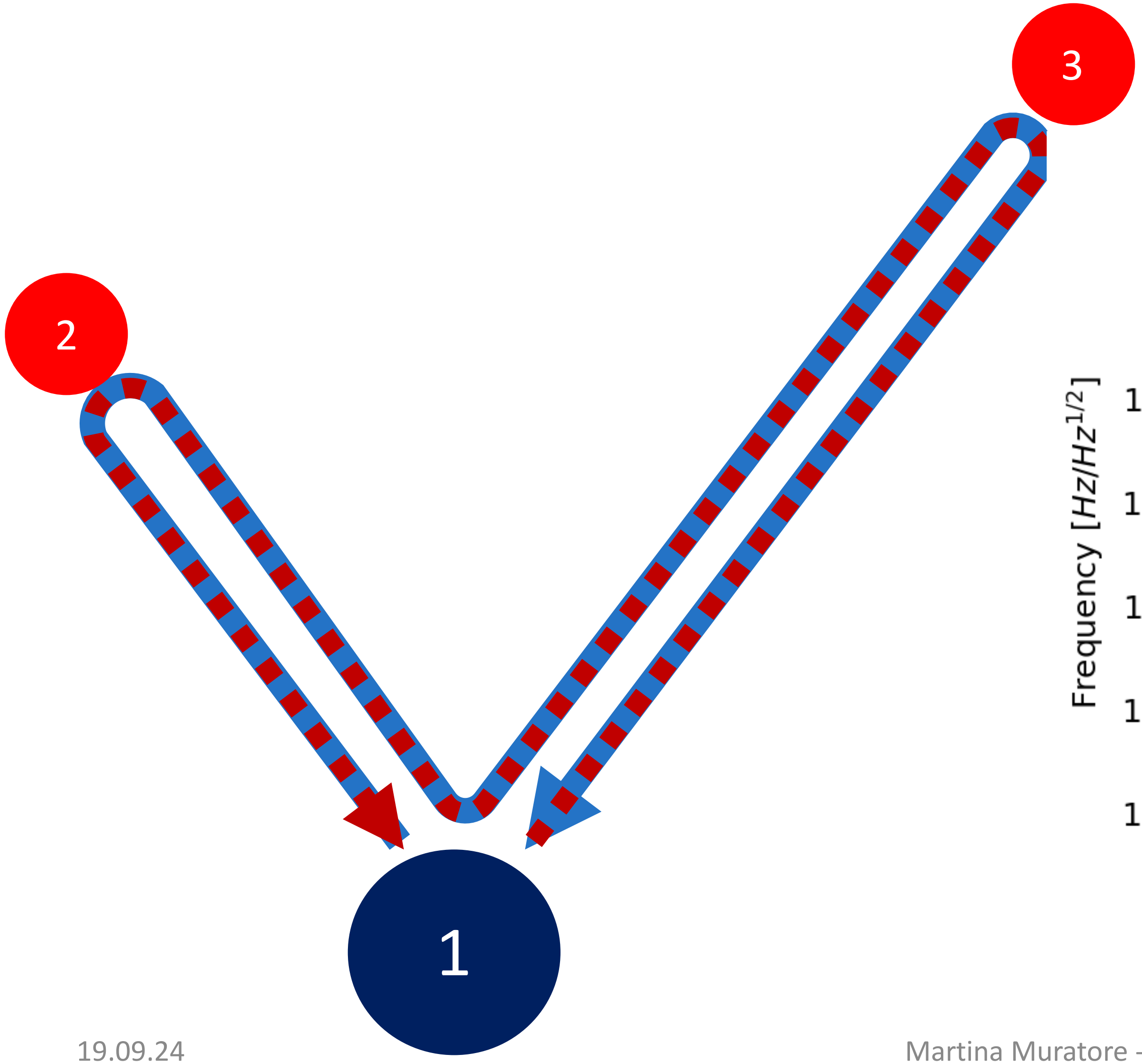
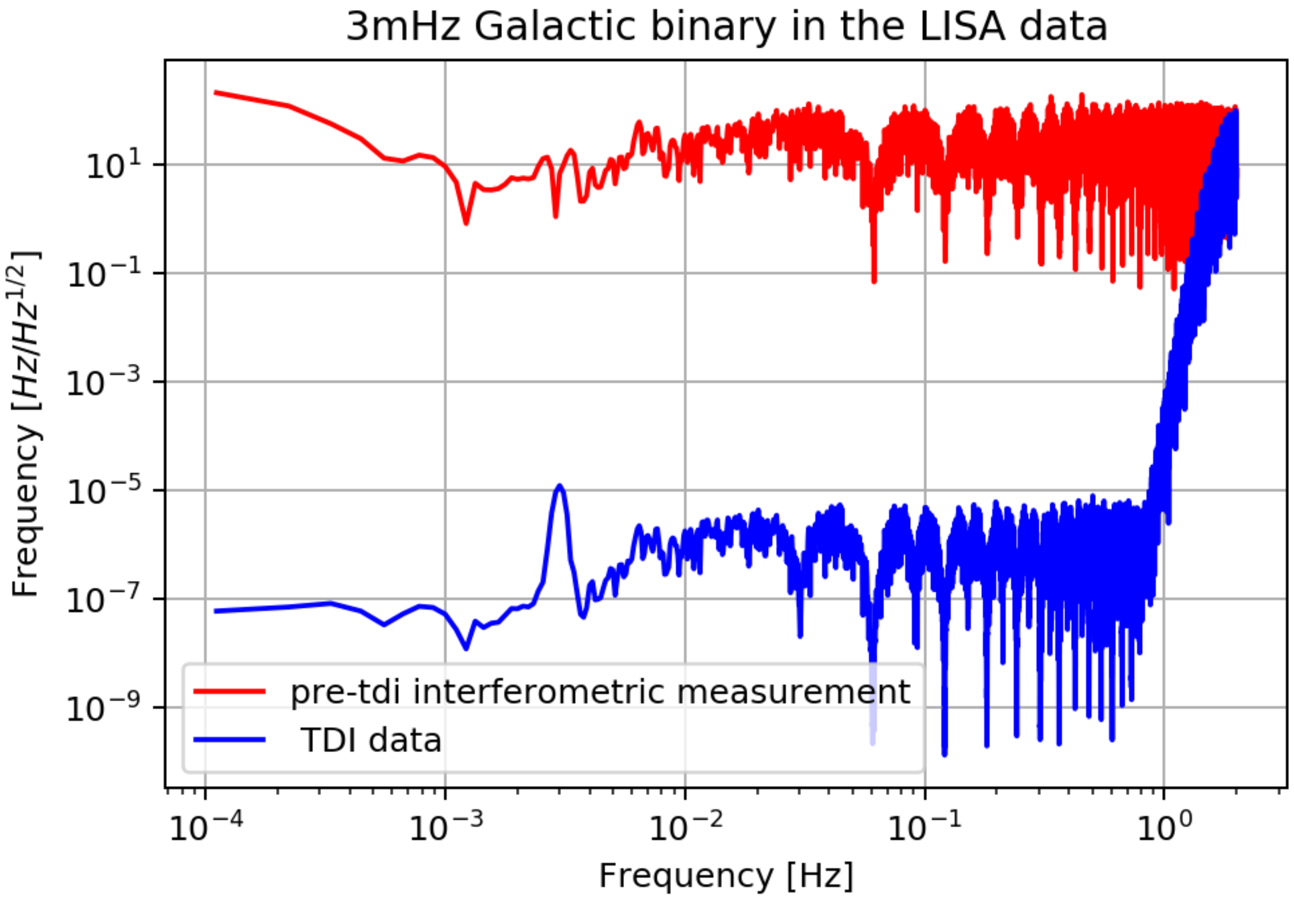


Image curtesy of O. Hartwig



The null-channels

Basic starting points

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

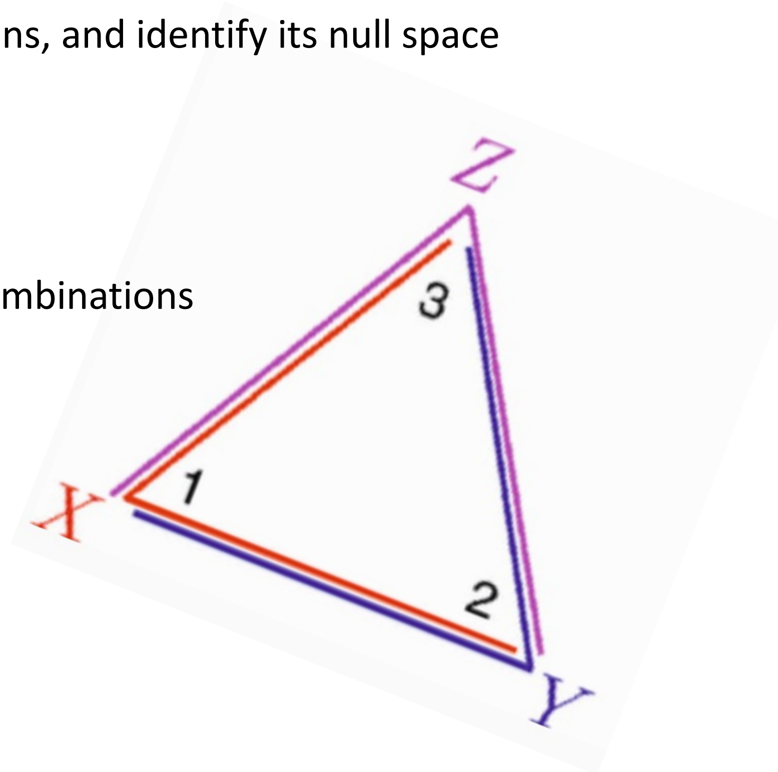
Explore the space of all linear combinations of all possible TDI combinations, and identify its null space

Use this set of null-channels to measure the acceleration noise

The null channels in the literature*

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

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



*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

What's new ?

New set of null TDI combinations $\tilde{C}_k^n$ from the 34 cyclic – permutation - averaged core TDI (slide 15)

Set of generators that looks promising to estimate instrumental noise in addition to the null-channel *T*

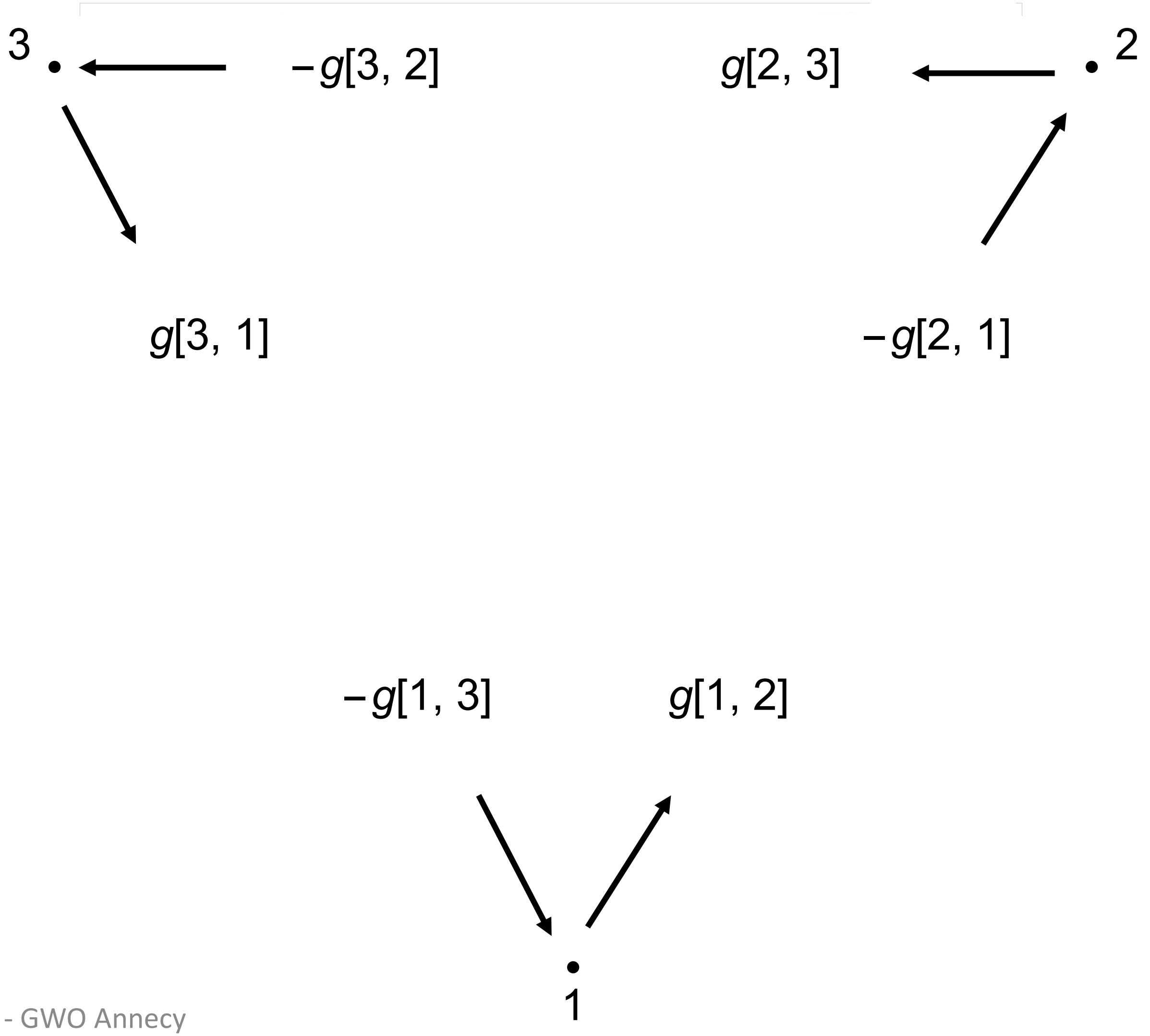
- computations in the upcoming slides…

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

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

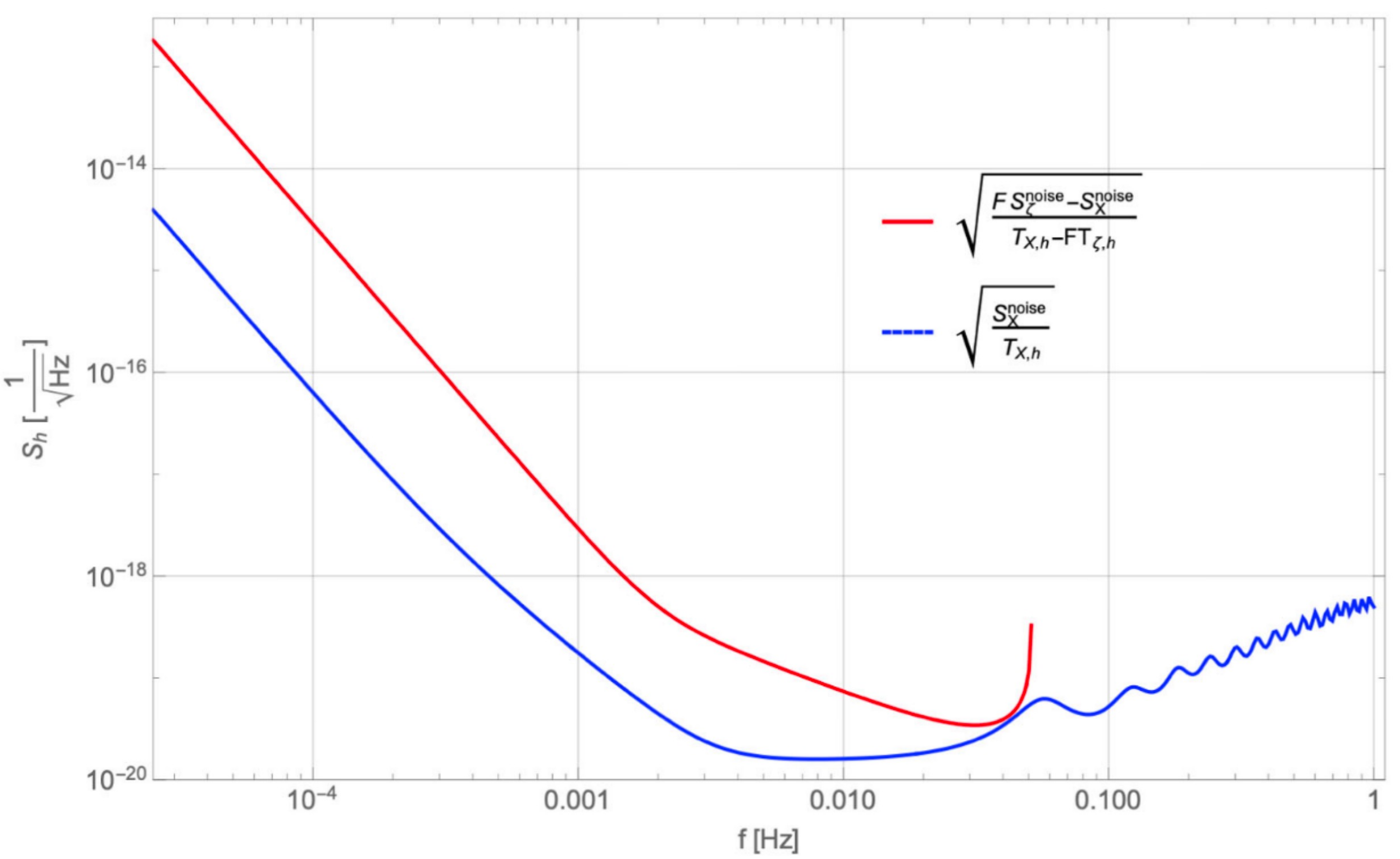
*Time dependence has been omitted for simplicity

$$G = g(1,2) - g(2,1) + g(2,3) - g(3,2) + g(3,1) - g(1,3)$$



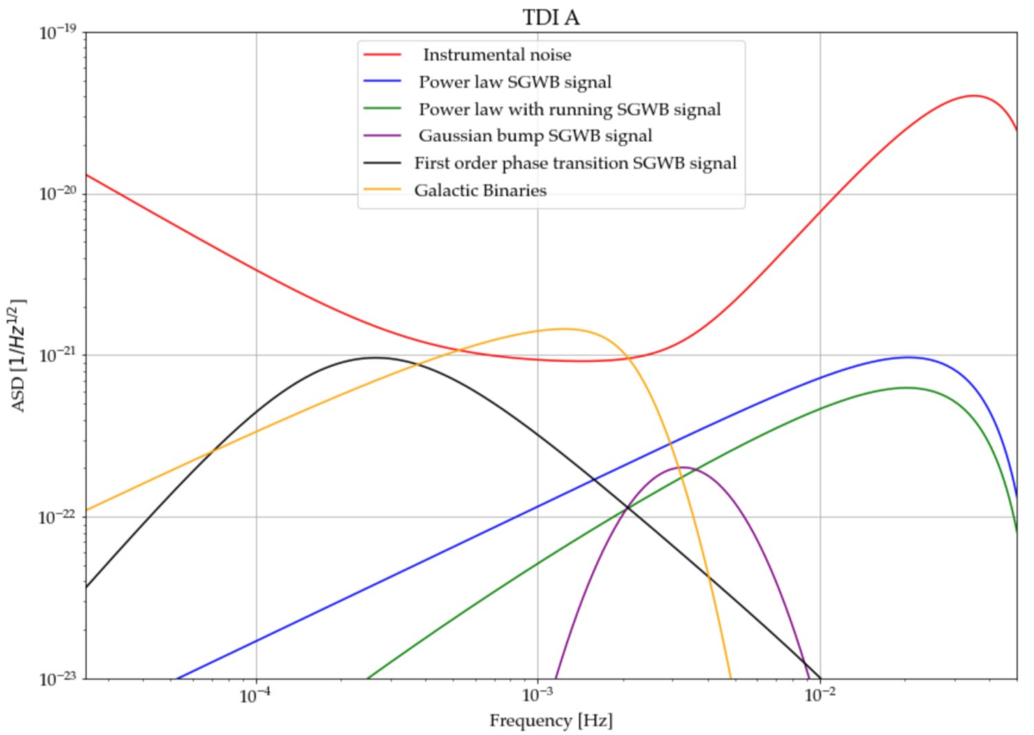
Muratore et al , Time Delay Interferometry combinations as instrument noise monitors for LISA. Phys. Rev. D 105, 023009.

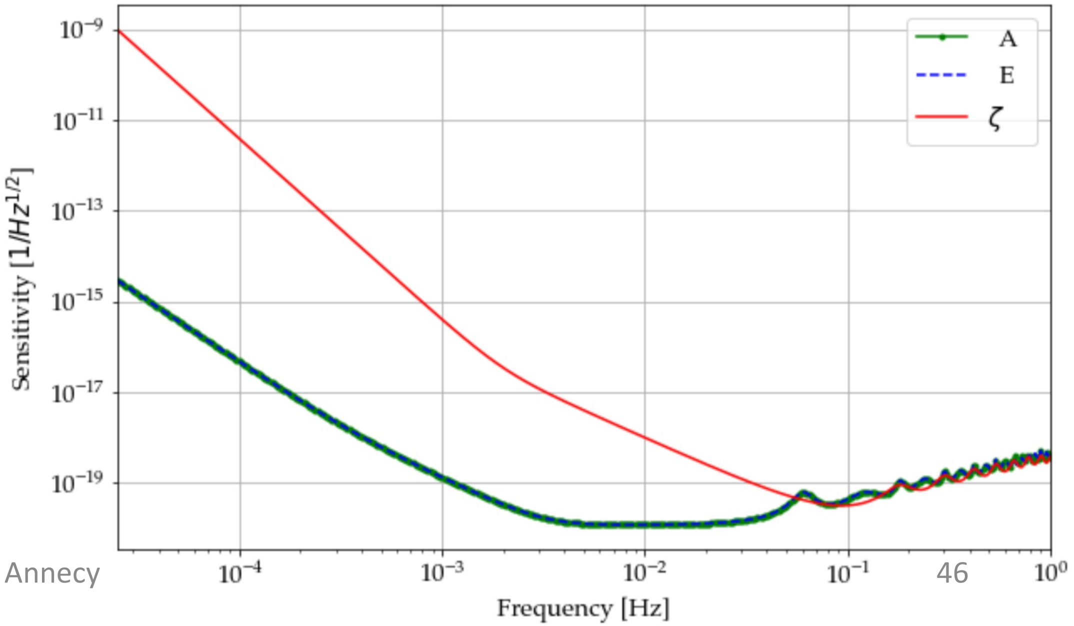
SGWB upper limit + detection threshold



Impact of noise knowledge uncertainty on SGWB estimation

- 4 SGWB signal models
- Set of 3 (first gen.) TDI channels A,E,
- 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: M. Muratore, J. Gair and L.Speri