Data processing, waveform modeling & data analysis for space-based GW detectors

LISA activities at SYRTE

Adrien Bourgoin

On behalf of the
« *theory and metrology* » group

API « Ondes gravitationnelles et objets compacts »

Meudon, 10 novembre 2023

Space-based detector

Introduction to LISA

- LISA w.r.t. ground-based detectors
- Science and sources
- LISA mission

Gravitational Wave Observatories

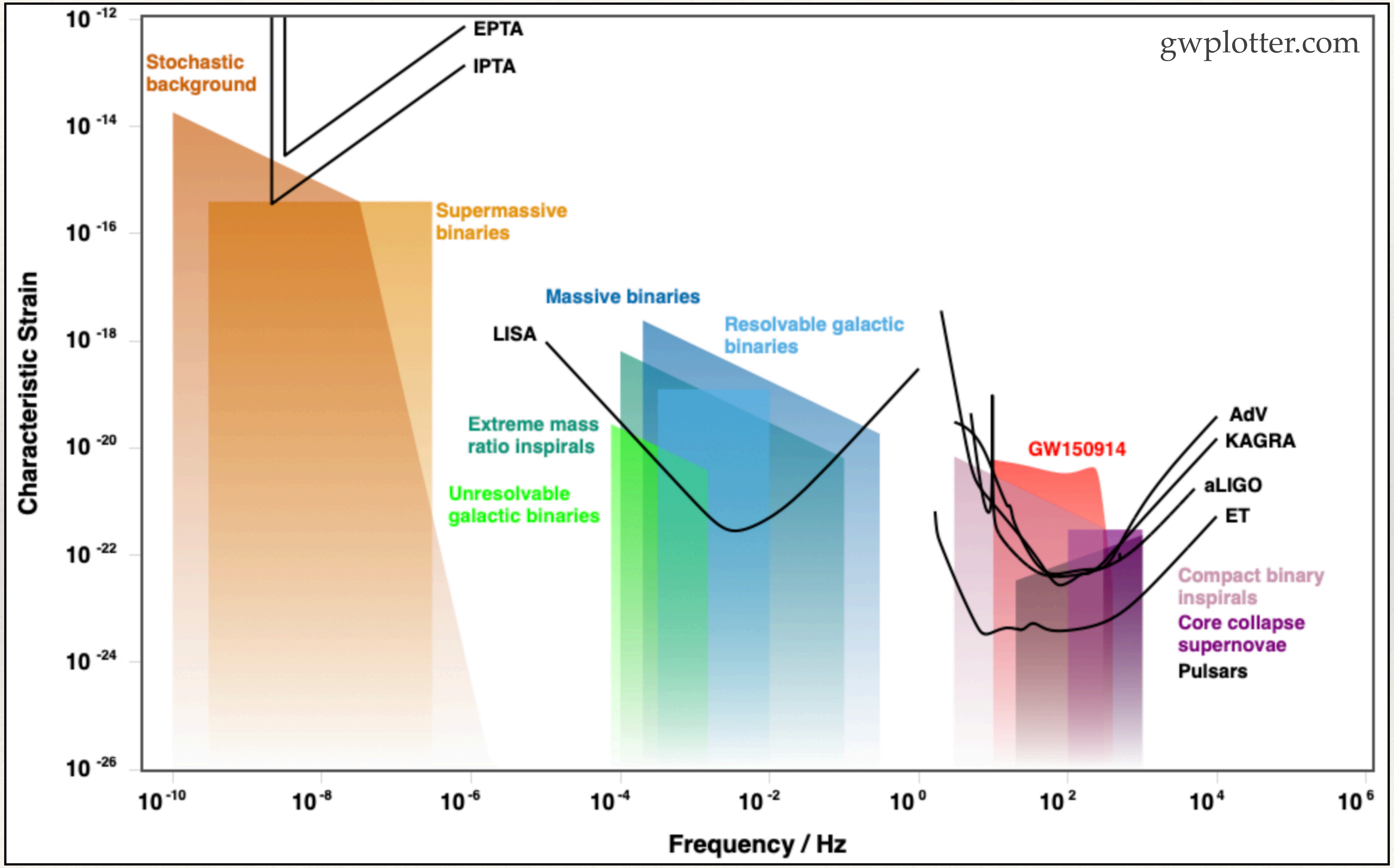
A new window for Astrophysics

Since 2015

- *Observatories:* LIGO, Virgo, Kagra, EPTA, NANOGrav
- *First detection:* GW150914
- *Upgrade:* aLIGO, AdVirgo, with sensitivity x2 for 2023
- *Number of Events:* ~100
- *Sources:* Stellar Mass BHs mergers, NSs mergers, and *supermassive BHs*?

Next future

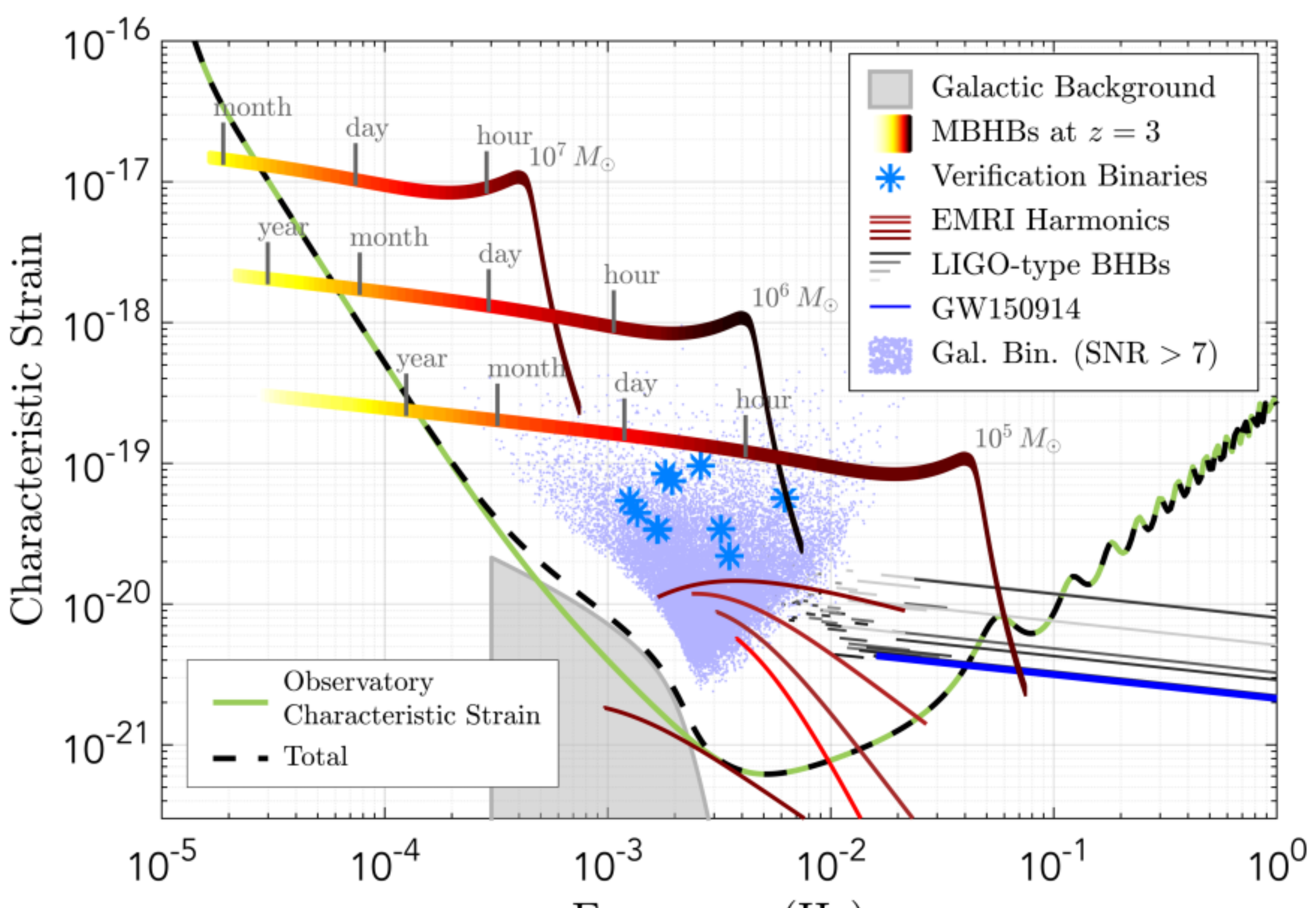
- *Observatories:* ET, LISA
- *Sources:* Super massive BHs mergers, Stellar mass BHs in-spirals, Galactic Binaries in-spirals, EMRIs



Sources in LISA band

What type of science to do with LISA?

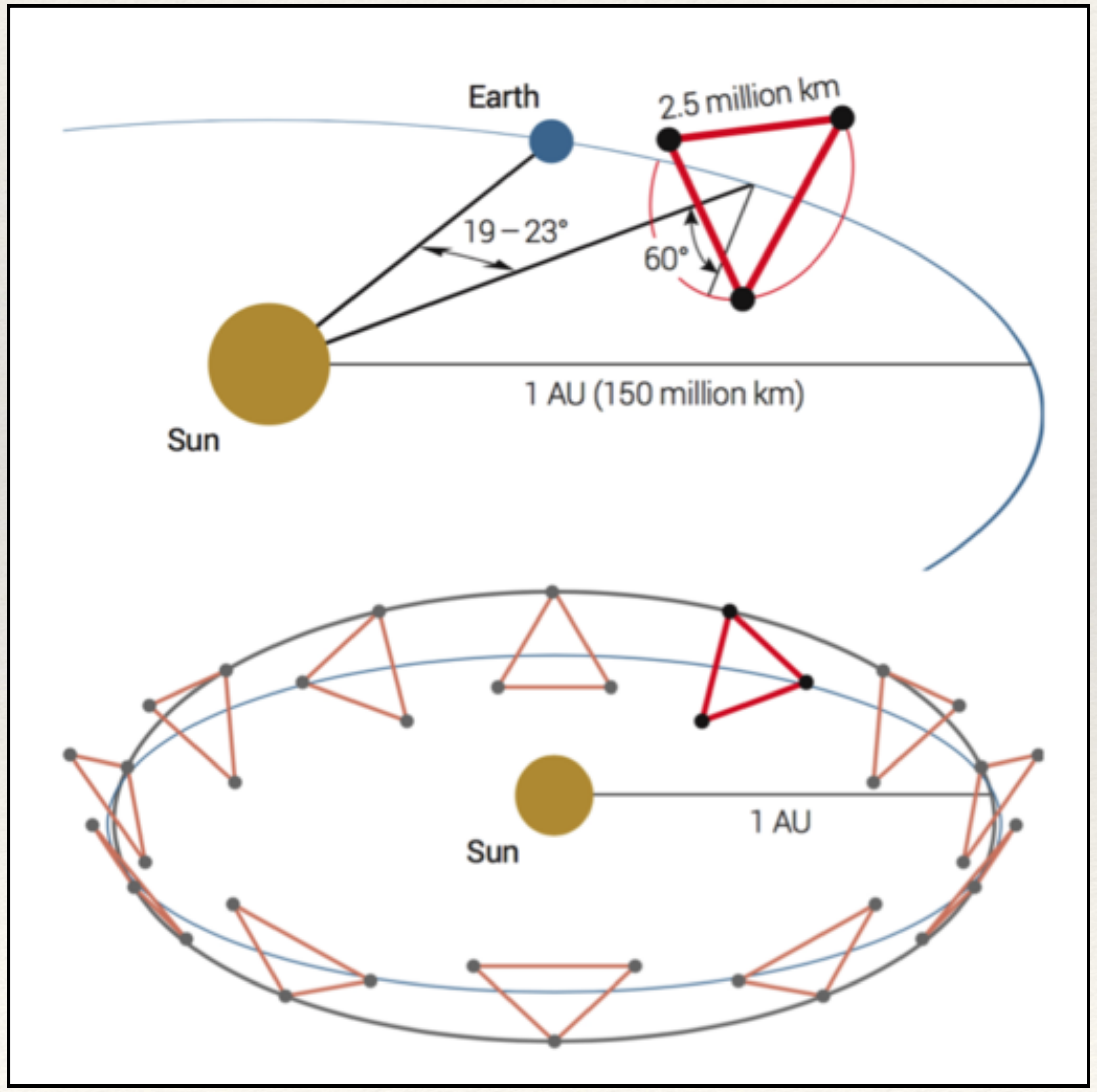
- Astrophysics
  - Super massive Black Holes (BHs) mergers
  - Stellar mass BHs inspirals, binary of WD/NS in-spirals
  - Extreme Mass Ratio Inspiral (EMRI)
- Cosmology
  - Hubble constant, w or w/o EM counterparts
  - Inflation, phase transitions, cosmic strings
- Fundamental Physics
  - Test of GR, Lorentz symmetry breaking
  - Constraints of cosmological scenario

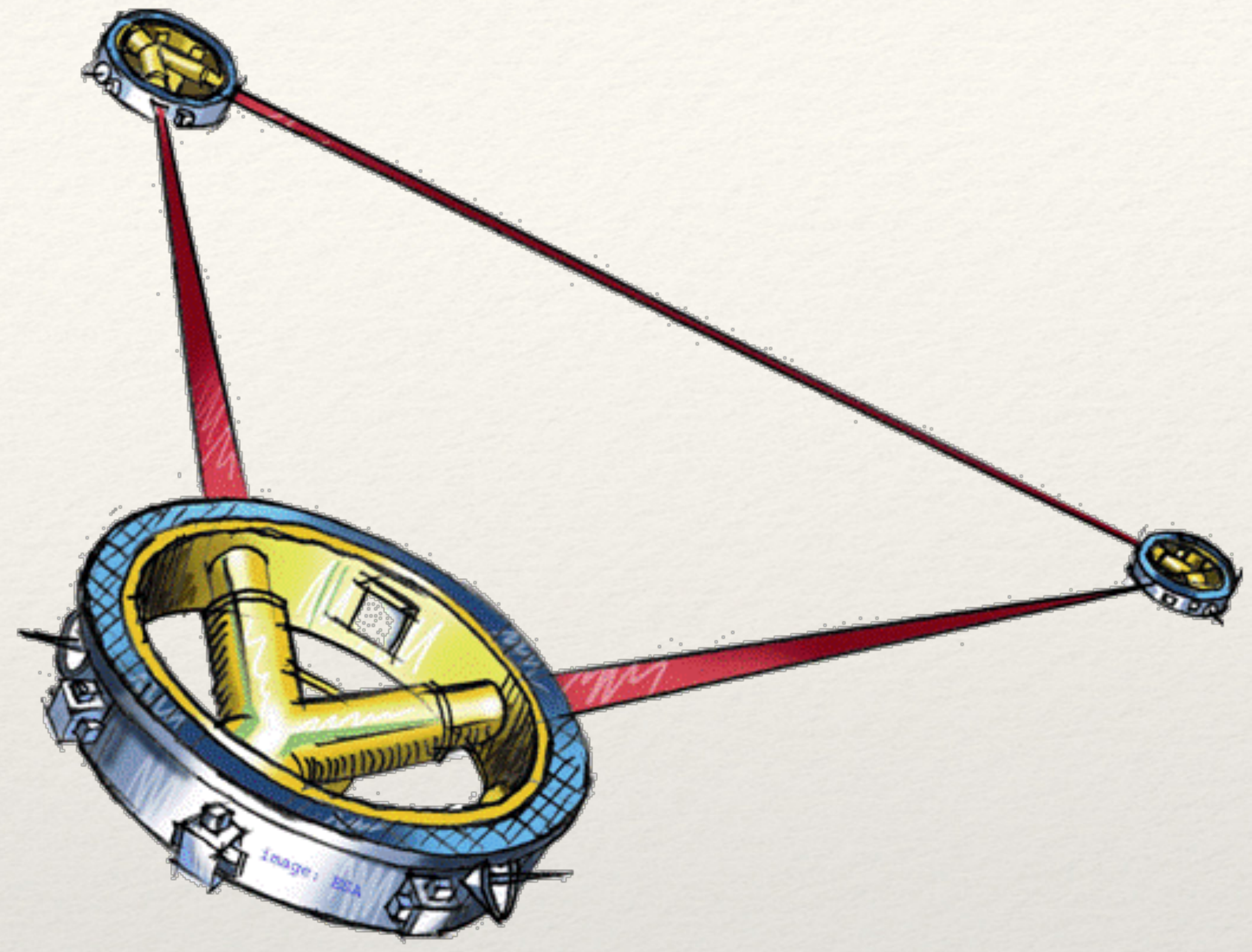


[Amaro-Seoane *et al.*, 2017]

The LISA mission

- 3 S/C in heliocentric orbits, **2.5 millions km** apart
- Strain sensitivity at the level of 10^{-21}
- Launch around **2035** for 1 yr commissioning and **4 yr science**
- Adoption by ESA in **January 2024**

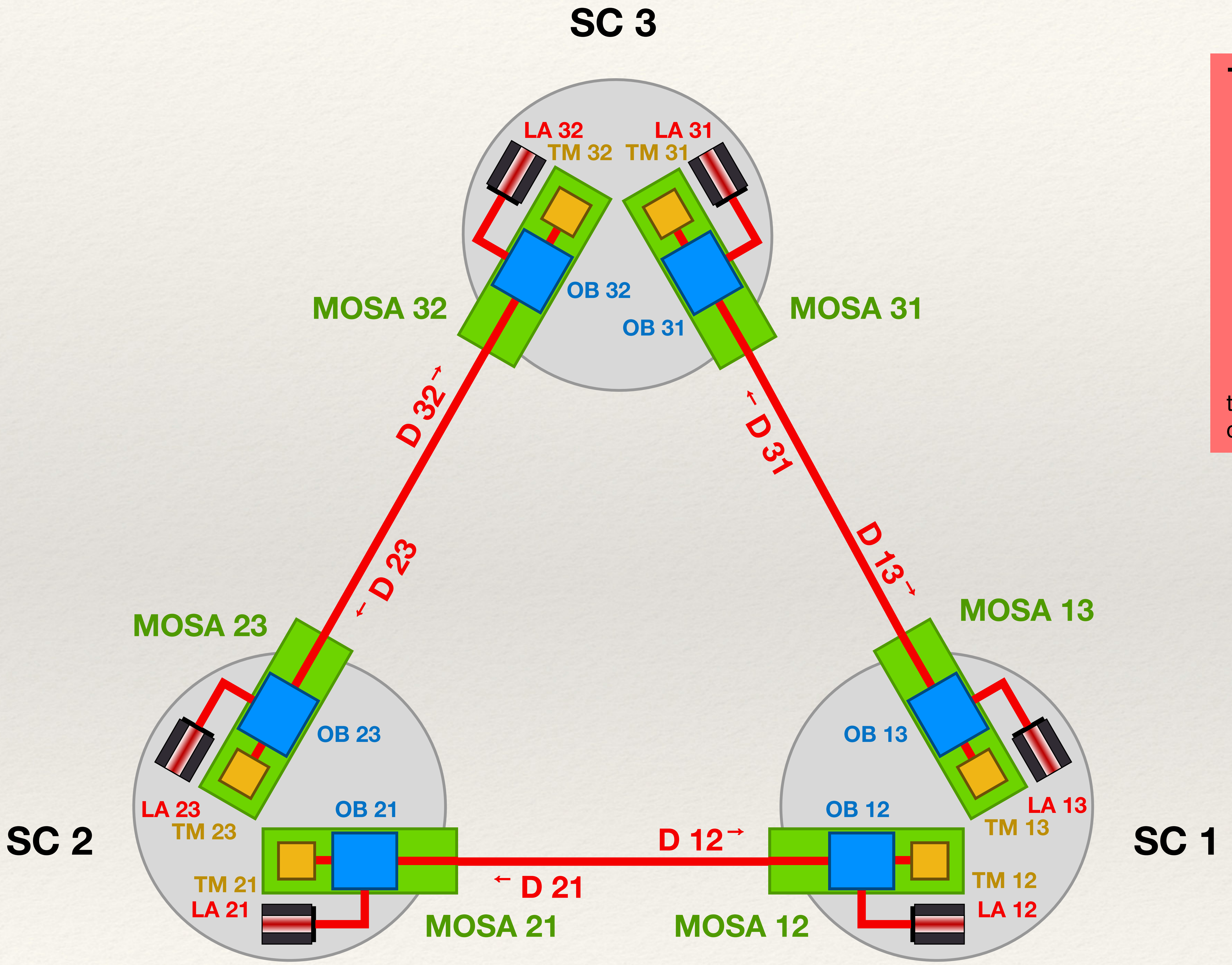


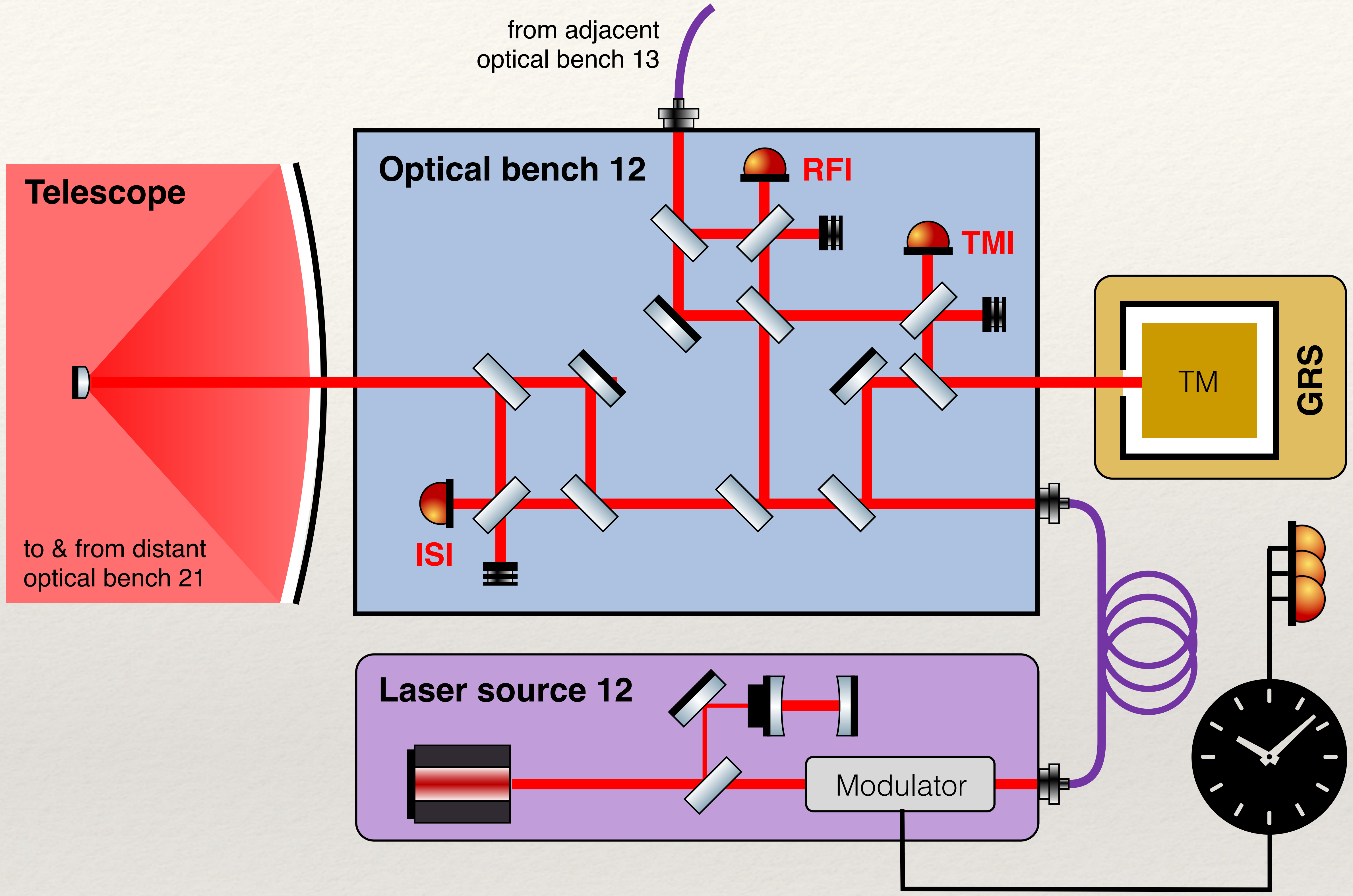


- Main **noises** mitigated in ground processing (**Time Delay Interferometry**)
  - Test masses acceleration noise
  - Optical metrology system noise
  - Tilt-to-length
  - Clock noise
  - S/C jitter
  - Laser frequency noise

LISA setup

Optical bench onboard each S/C





- 3 interferometric signals per optical bench:
  - Inter S/C interferometer (ISI)
  - Reference interferometer (RFI)
  - Test mass interferometer (TMI)
- Clock error imprinted onto laser beam

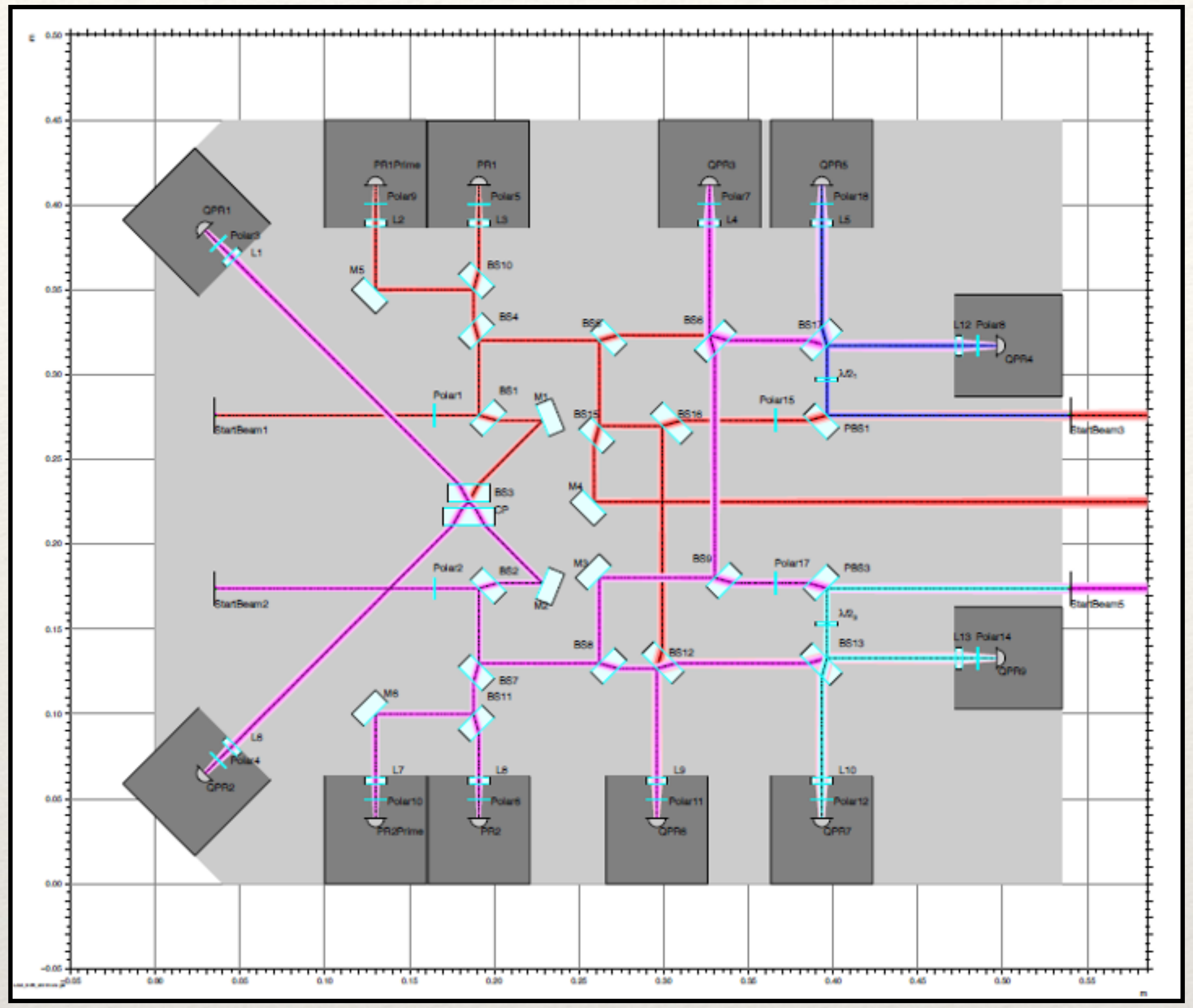
Testing performances of LISA's optical bench on ground

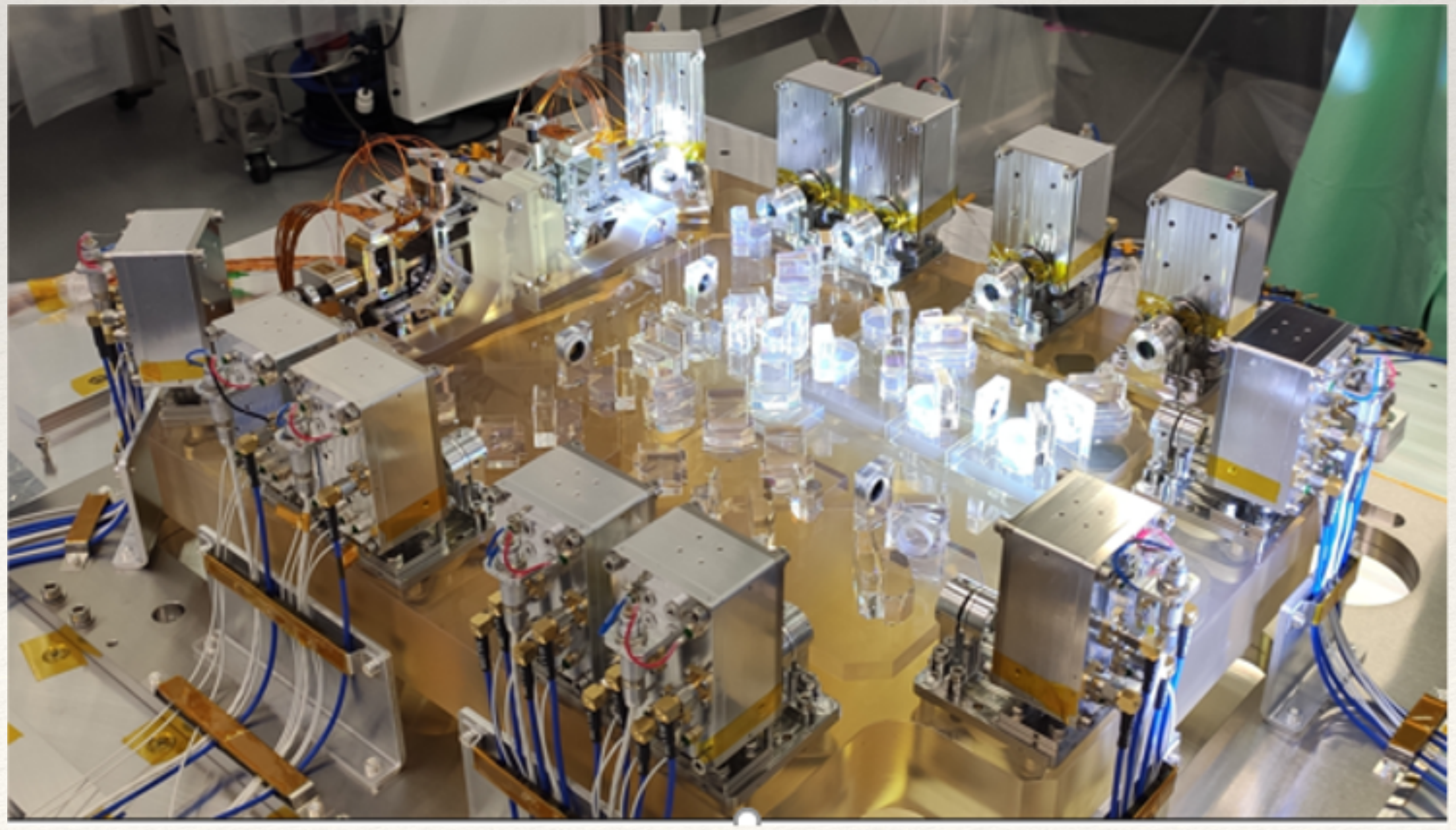
Hardware ground testing

- Interferometric Detection System (**BSim**)
- Optical Test System (**SLOGSE**)
- ZIFO testing **phasemeter** and **laser stability**

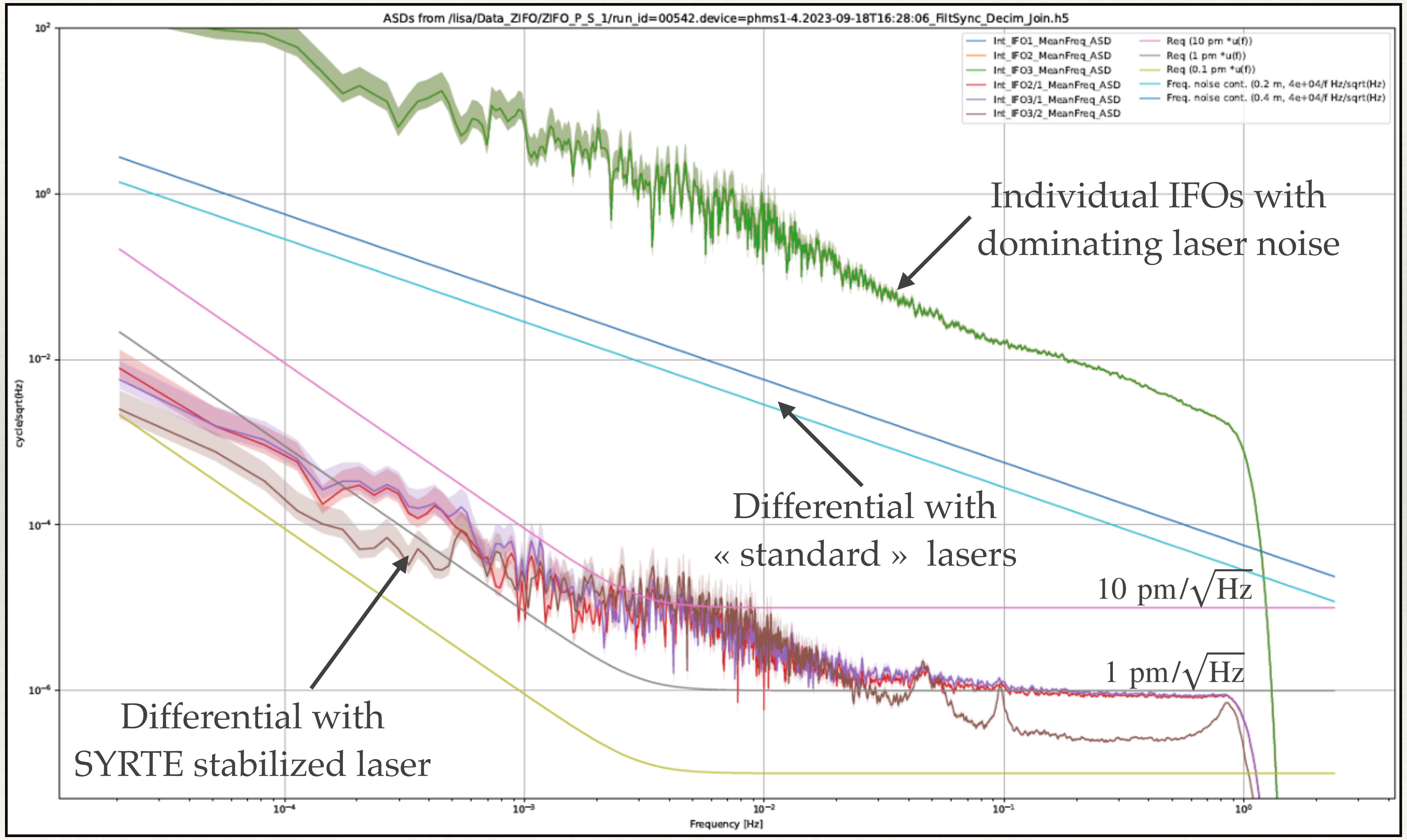
ZIFO @ LAM

O. Acef, A. Mehlman, B. Pointard & P. Wolf





LISA test bench with SYRTE iodine stabilized laser system



From L0 to L1 and L0 to L2 (end-to-end)

Data processing pipelines

- From raw data to science
- Tests of pipelines L0 to L1 and L0 to L2

L0.5 to L1: interface between material and science

A. Hees, M. Lilley & P. Wolf

L0.5 data:

- Telemetered data: scientific and auxiliary
- S/C orbitography + time couples
- Instrument knowledge

L0.5 to L1:

- Apply several corrections to the raw data
- Combine raw data to reduce various noise sources (laser, TTL, clocks, …)
- Identify misbehavior of the instrument, possibly identify artefacts, assess data quality
- …

L1 data (ready to « use »):

- TDI time series expressed in BCRS
- Inter S/C BCRS distance
- S/C ephemeris
- Quality flags
- First estimates of noise model
- …

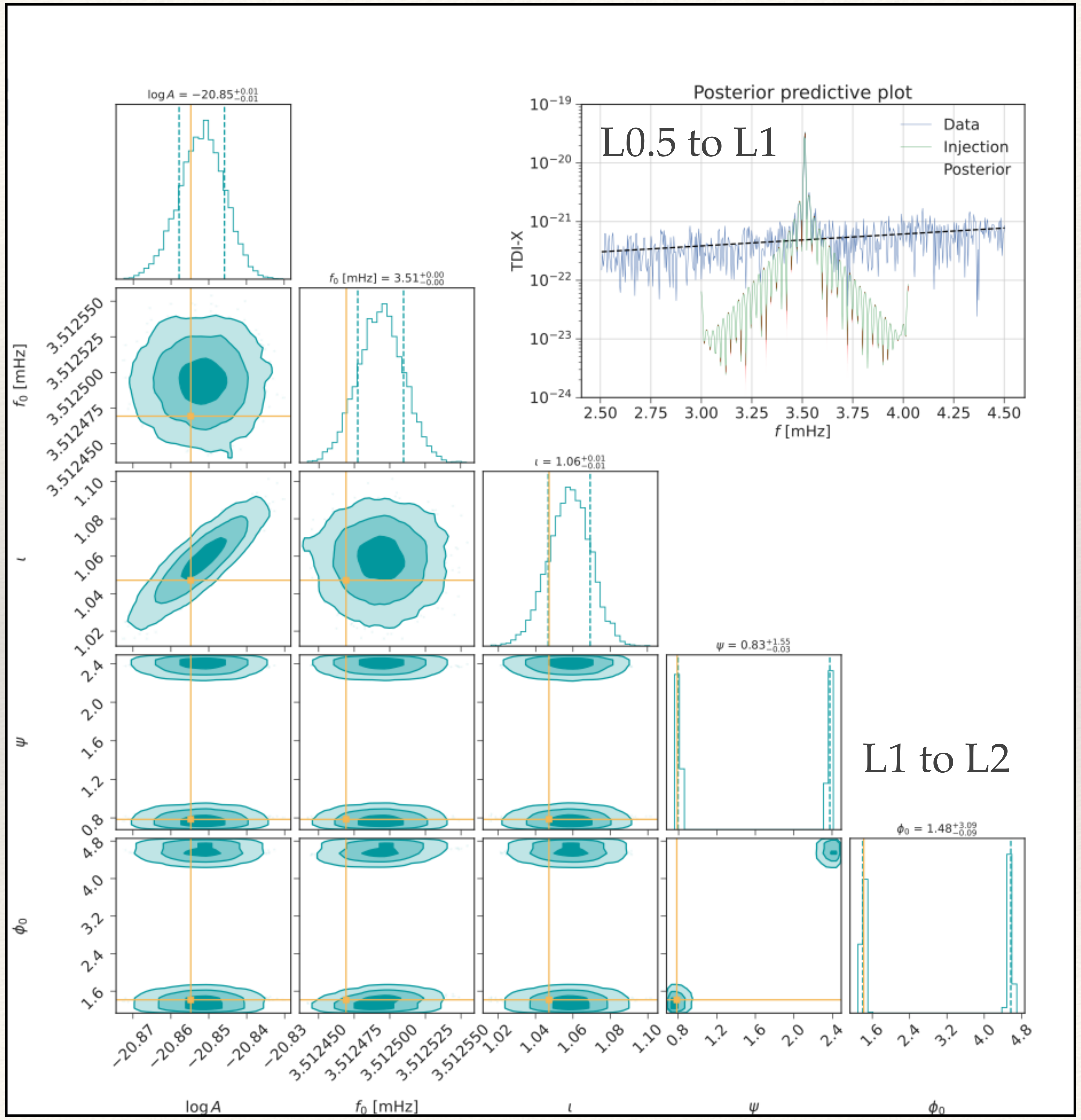
- Deal with the « technicalities » related to the instrument to produce data that can be directly used to search for GWs
- SYRTE responsible for the development of the L0.5 to L1 pipeline (with Univ. Glasgow)

Recent results for MAR

A. Hees, M. Lilley & P. Wolf

- Simulation of realistic L0.5 data (with 1 GB)
- Development of a *first full* L0 to L1 pipeline
- L1-L2 parameter estimation
    - @ L1 level :
        - Is the remaining noise well understood and modeled ?
        - Is the signal present in the data ? Can it be modeled ?
    - @ L2 level:
        - Are the recovered parameters OK w.r.t. injected ones?

Successful results obtained
[detailed report submitted to MAR]



Waveform modeling and preparation for L2

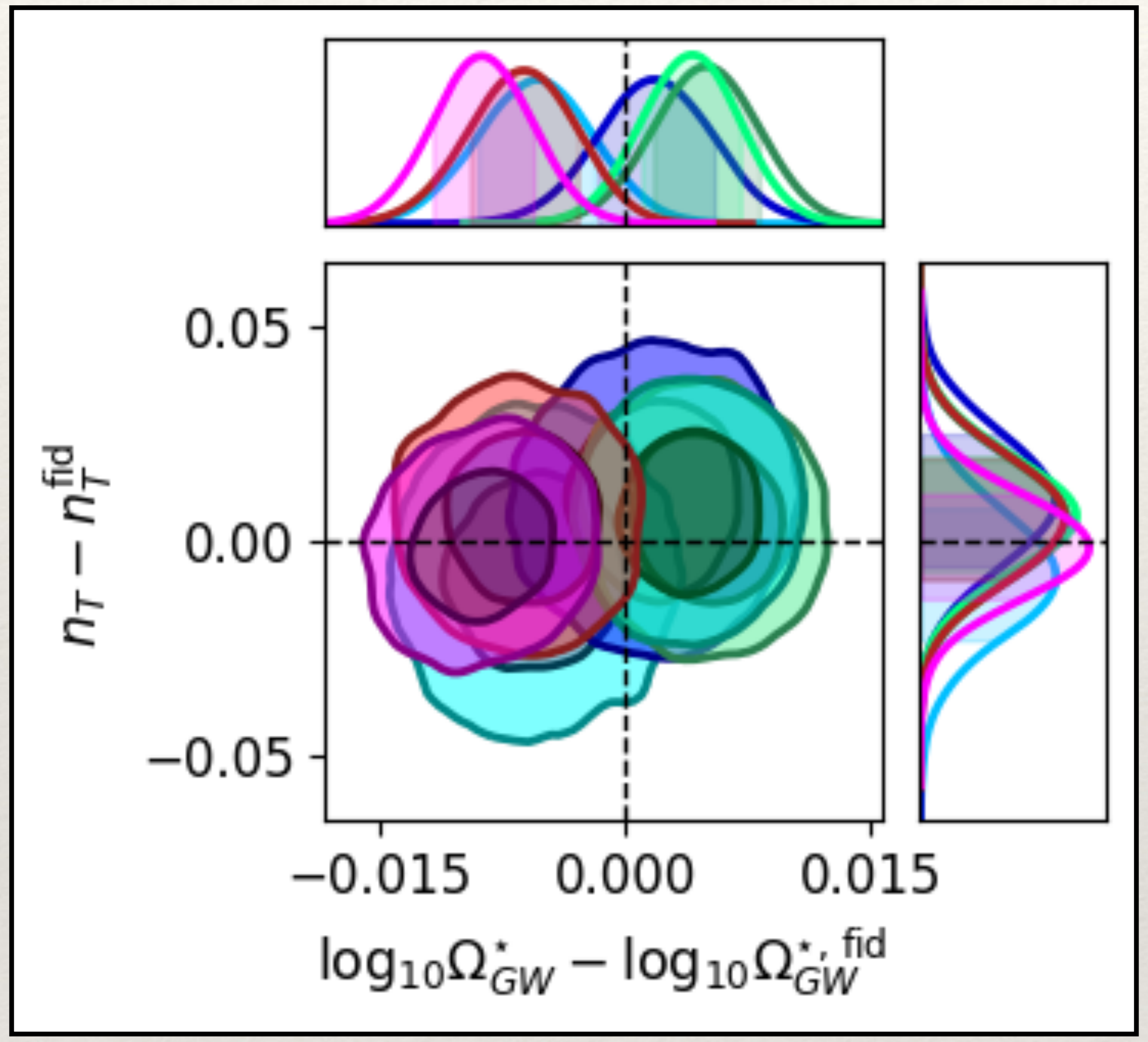
Scientific exploitation activities

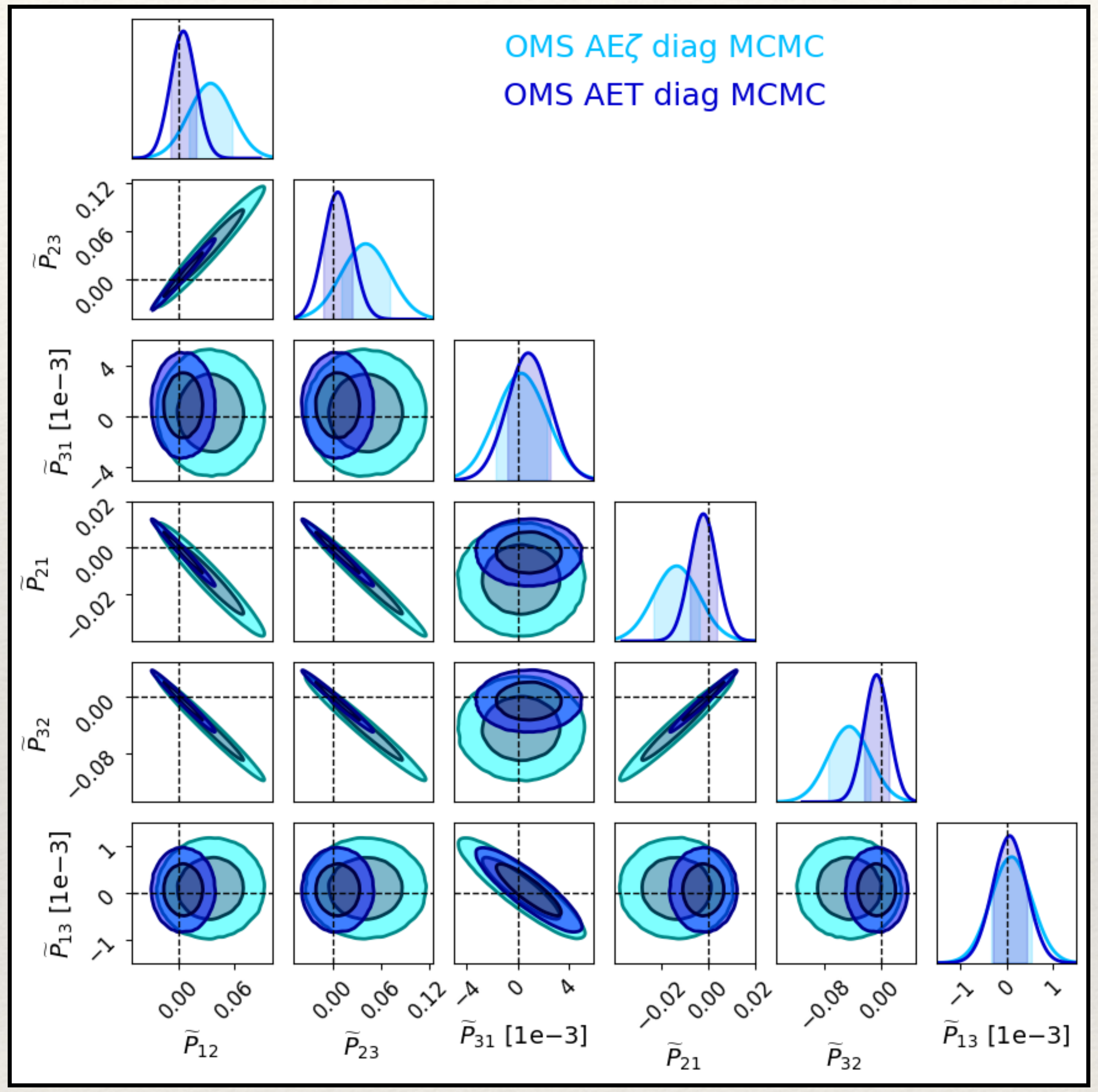
- Stochastic GW background
- GBs and magnetism
- Hierarchical triple systems
- GBs and the SME

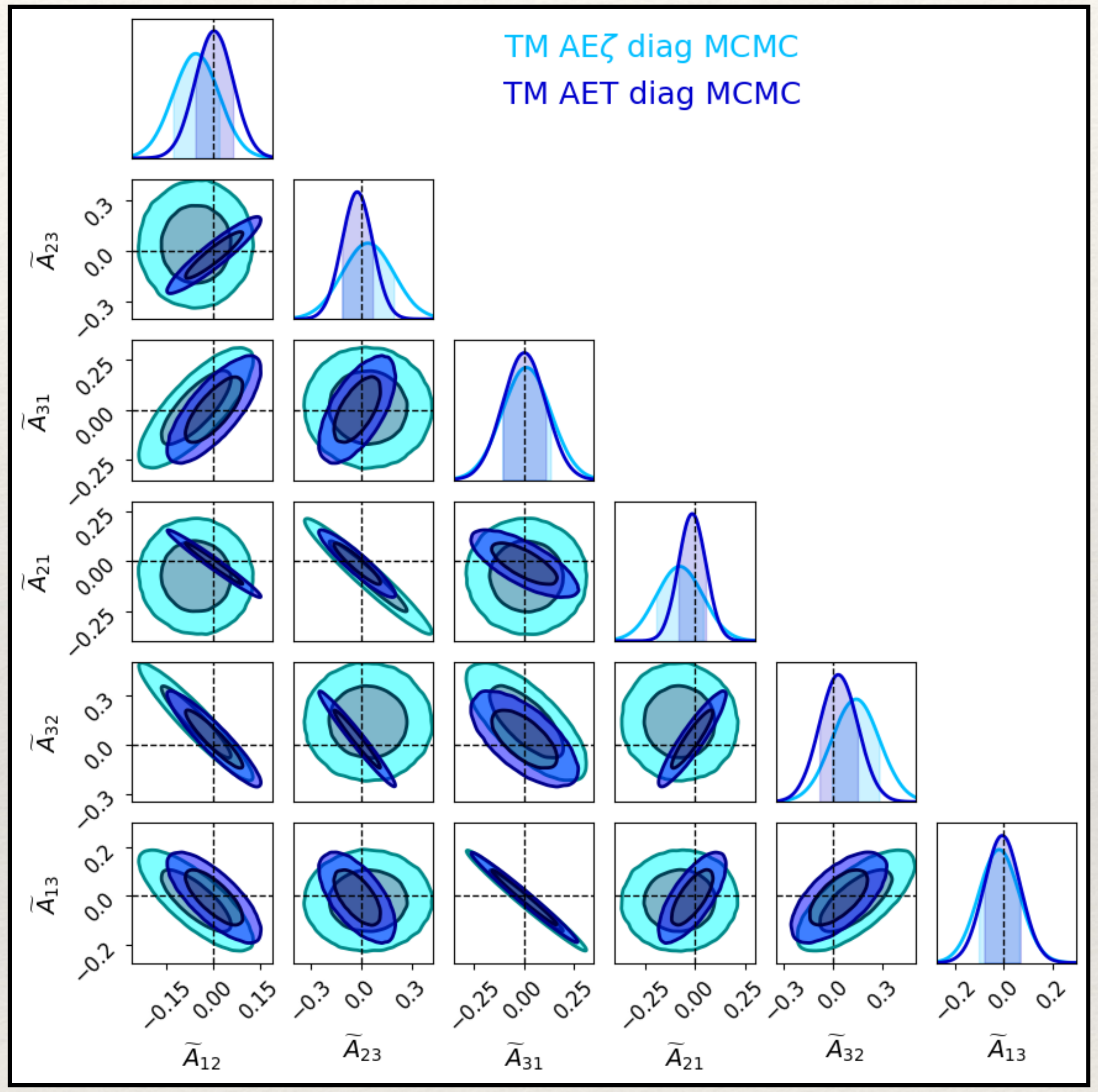
SGWB reconstruction (1/3)

A. Hees, M. Lilley & X. Roux

One goal of LISA is the detection of *cosmological SGWB*. But with the uncertainty in the instrumental noise, and the large freedom in the shape of the SGWB, fully agnostic component separation methods would be ideal







Impact of the choice of TDI variables on parameter reconstructions [Hartwig *et al.*, 2023]

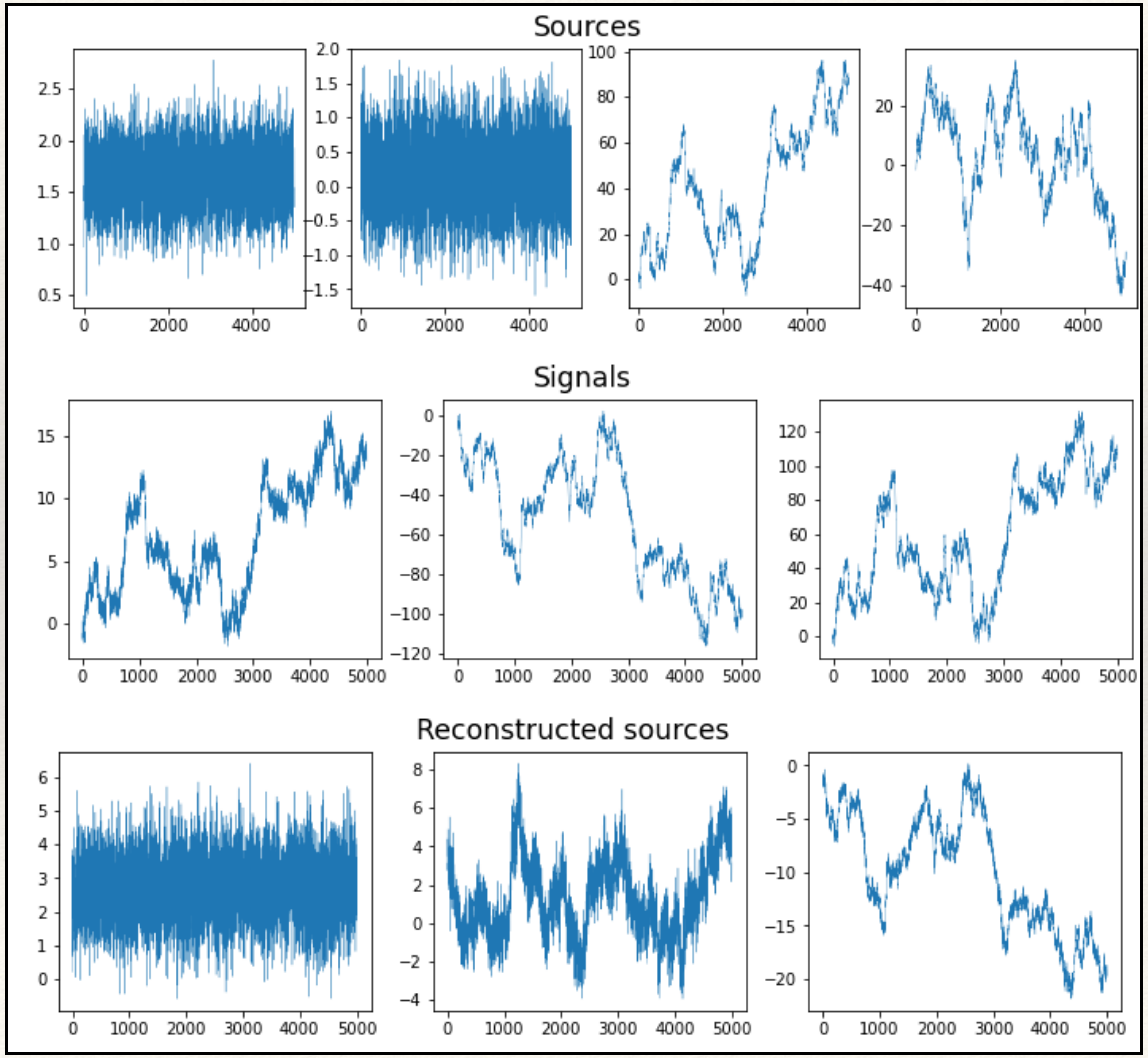
Analysis using MCMC and Fisher analysis demonstrate that (known signal and noise spectral shapes):

- Reconstruction of the SGWB signal is robust to the choice of TDI variables no matter the inclusion/exclusion of cross-correlations between channels (*left panel*).
- When neglecting cross-correlations between channels, the choice of TDI variables is important (*right panels*).

SGWB reconstruction (2/3)

A. Hees, M. Lilley & X. Roux

Separating non-stationary signals from stationary ones using *stationary subspace analysis* (Xavier's internship)



In this example:

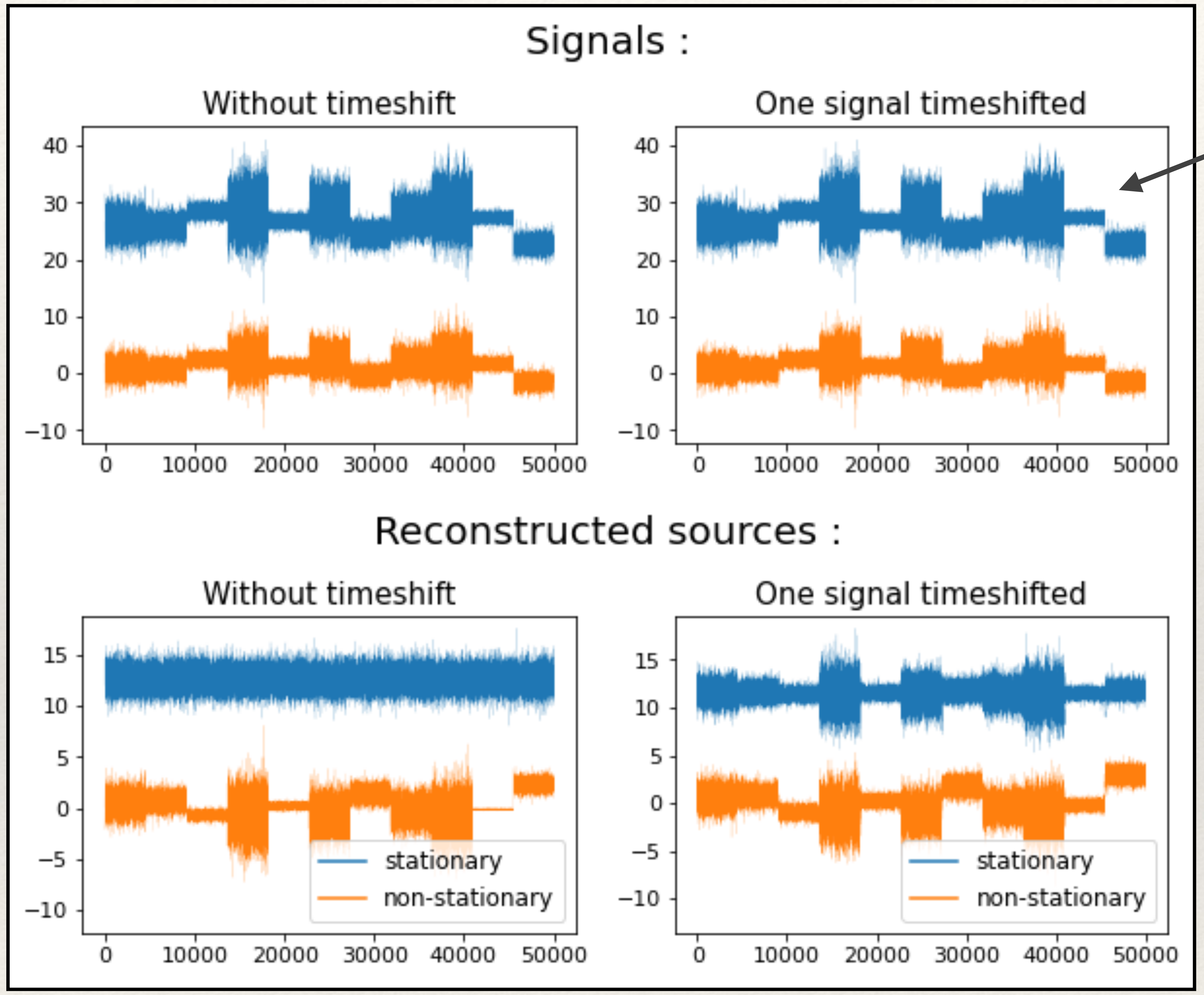
- $n^t = 4$ sources combined into $m = 3$ signals
- $n^s = 2$ stationary sources
- $n^{ns} = 2$ non-stationary sources
- The method can reconstruct $m - n^{ns} = 1$ stationary sources

The method is indeed able to retrieve the stationary signal

SGWB reconstruction (3/3)

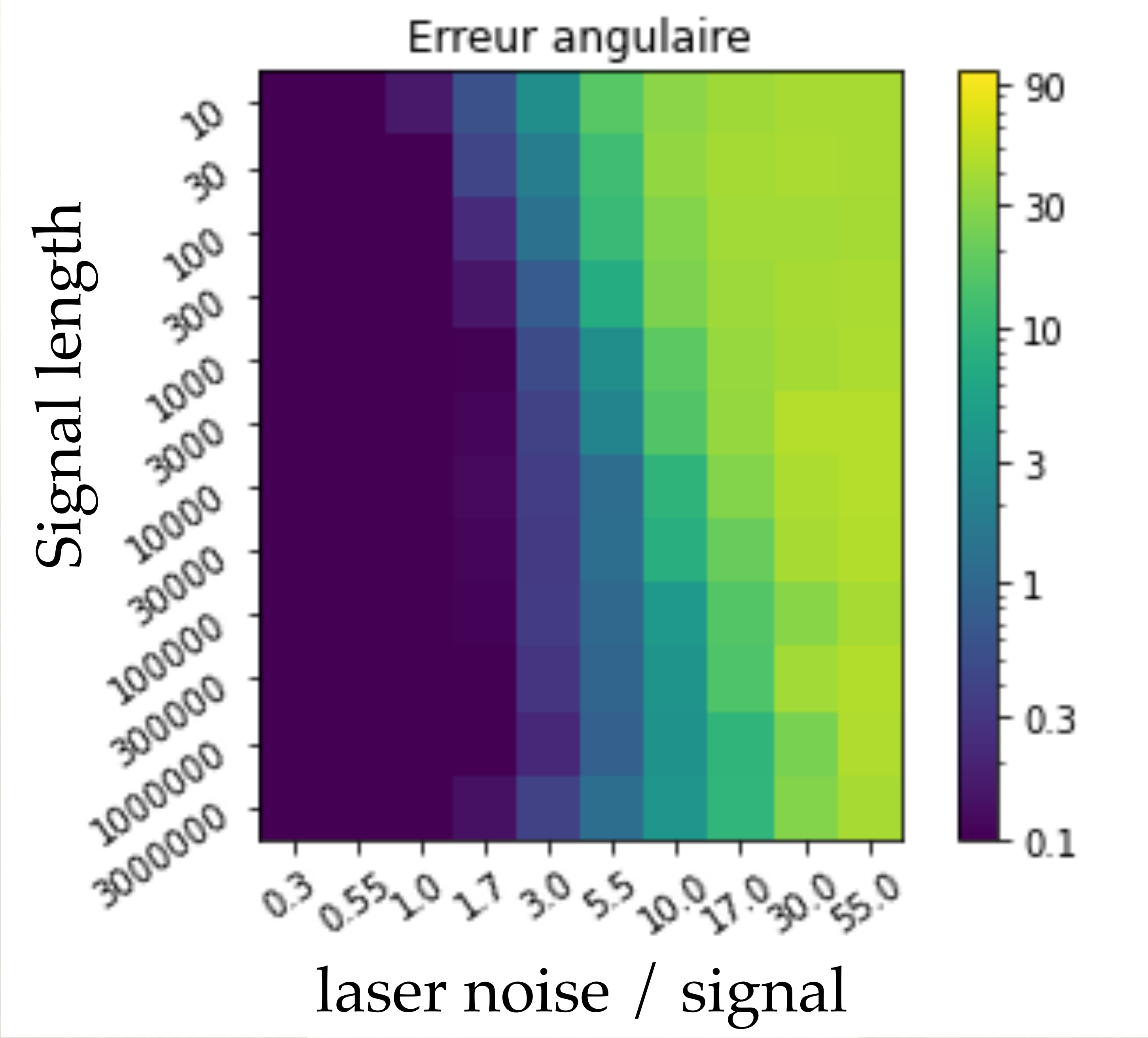
A. Hees, M. Lilley & X. Roux

Does the *stationary subspace analysis* still works on a simplify TDI?



Timeshifted by tenth of units

We can attempt to apply the method before TDI. In this case it works only for large time series and artificially small laser noise



In this example, we use 2 sources to generate 2 signals:

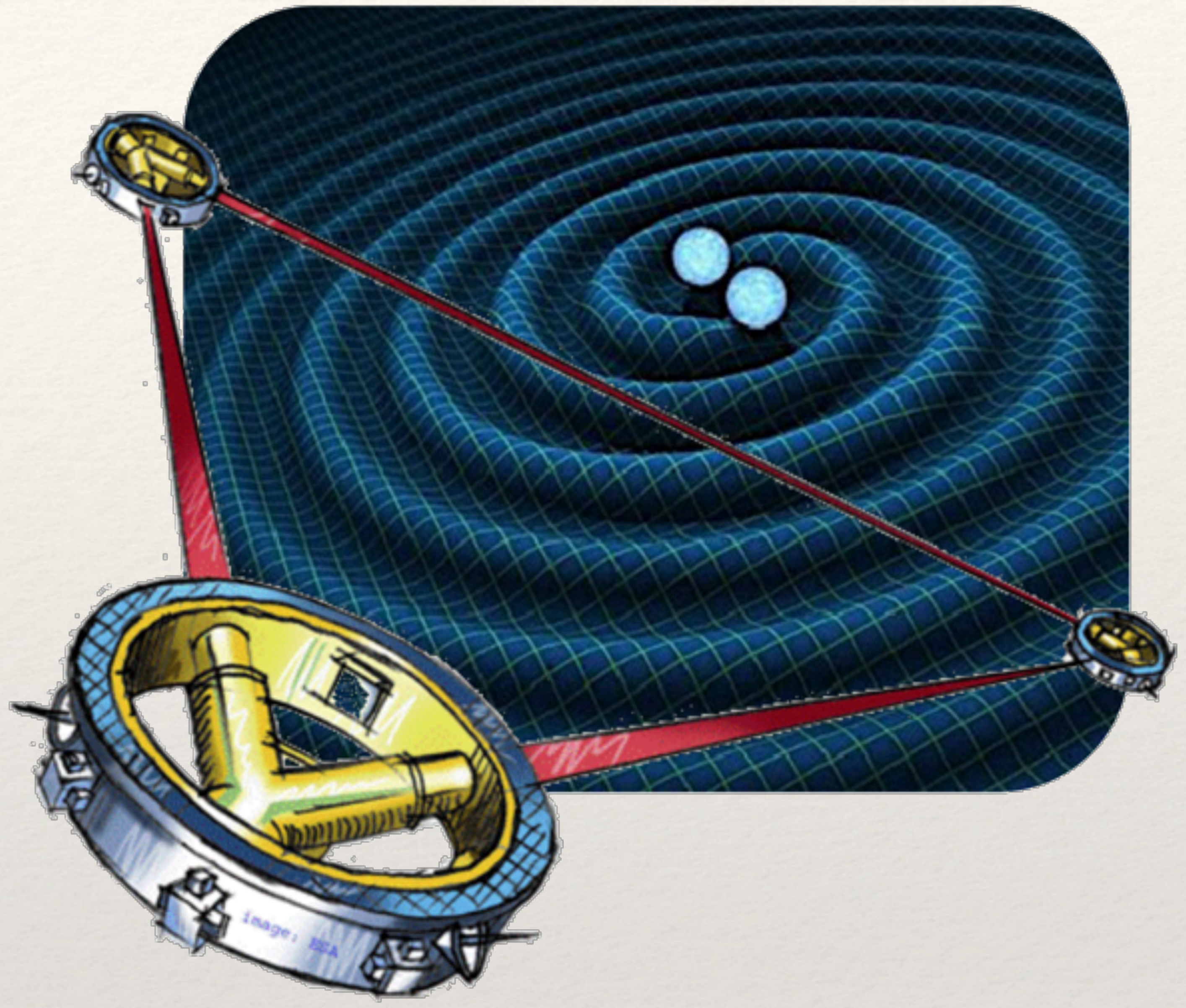
- If we don't introduce a TDI-type delay on one of the 2 signals, the method is *successful*
- If we introduce a TDI-type delay in one of the 2 signals, the method is *unsuccessful*

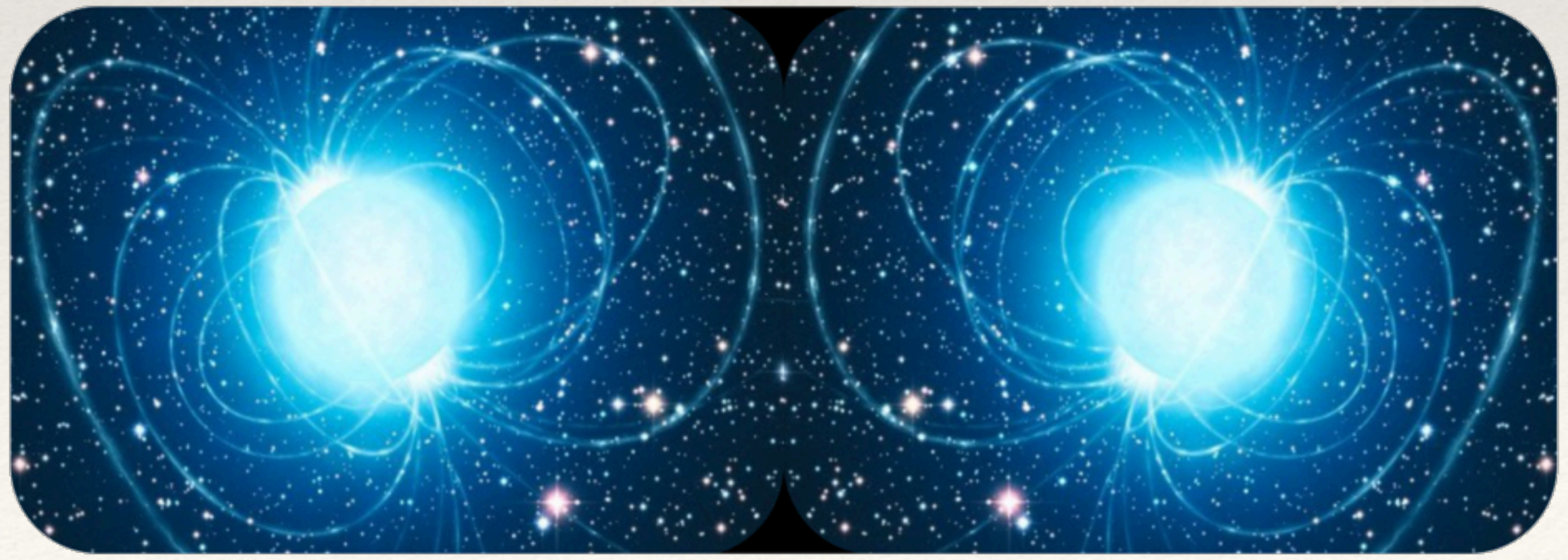
Future work :

- Time frequency domain
- Machine learning approach

WD and NS binaries

- Degenerate stars: White Dwarf (WD) and Neutron Star (NS)
- Existence of WD-WD, WD-NS, and NS-NS binaries
- Number of binary systems in the galaxy: 30 - 60 millions
- GW signal (from 0.1 mHz to 1 Hz):
  - Orbital period: few h to several ms
  - Slow in-spiral regime up to 0.1 Hz (*quasi-monochromatic*)
  - Coalescence detected at frequencies ~ 100 Hz (ground-based detectors)
- Existence of *known* systems (EM spectrum) within the mHz regime
  - *Tens* of « verification binaries » and *hundred* pulsars [Sathaprakash *et al.*, 2012]
  - Guaranteed sources $\Longrightarrow$ Calibration of the instrument
- Rate of detections
  - 25 000 resolvable galactic sources for LISA (SNR > 6)
  - 10^5 NS-NS/yr as far as $z \sim 5$ for ET
- Physics of these objects may change their expected GW signal
  - $B_{\rm WD} \sim 10^9$ G and $B_{\rm NS} \sim 10^{15}$ G



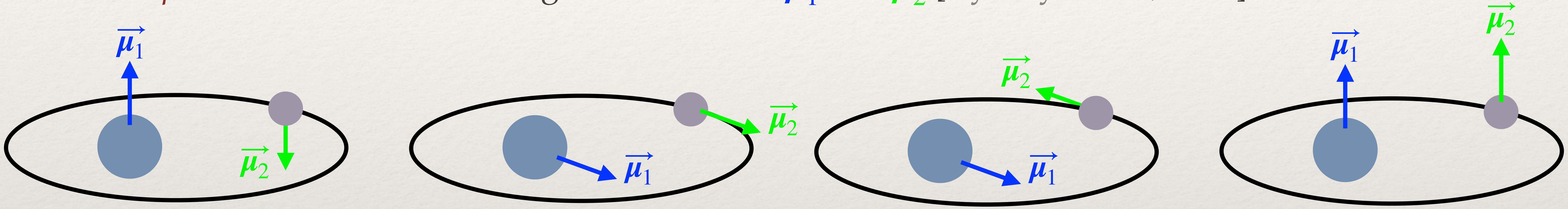


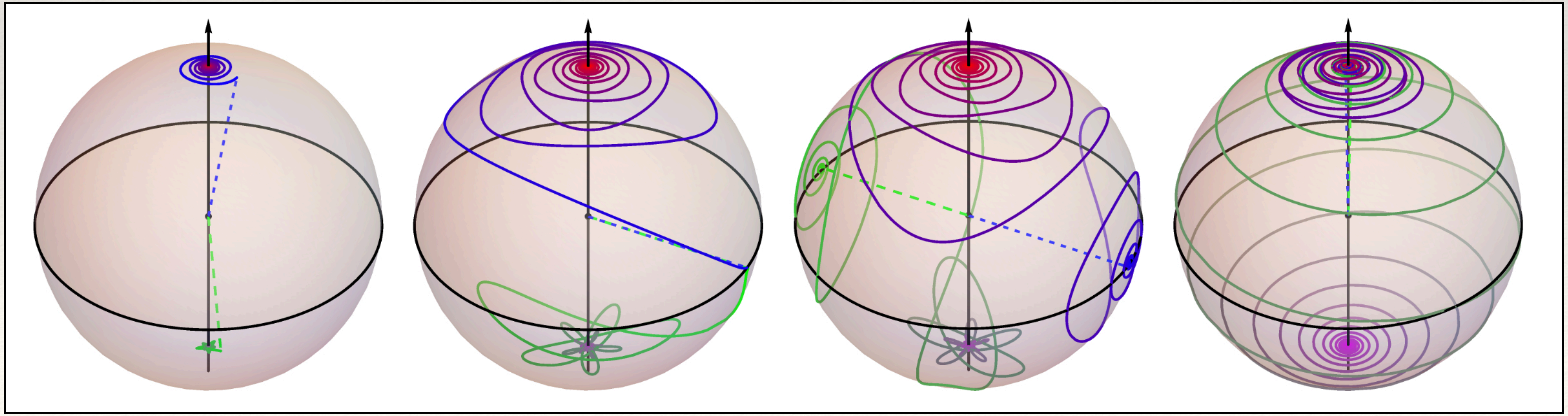
Secular stability of GBs' magnetic moment

M.-C. Angonin, C. Aykroyd, A. Bourgoin,
C. Le Poncin-Lafitte & S. Mathis

Part of Christopher's PhD

- From mHz to Hz effective point particles is a good approximation
- Many orbit coverage, need for a secular description of the orbital motion
- Orientation of the magnetic fields controls the orbital evolution and then the GW emission
- Find the *most probable* orientation of magnetic moments $\vec{\mu}_1$ and $\vec{\mu}_2$ [Aykroyd *et al.*, 2023]





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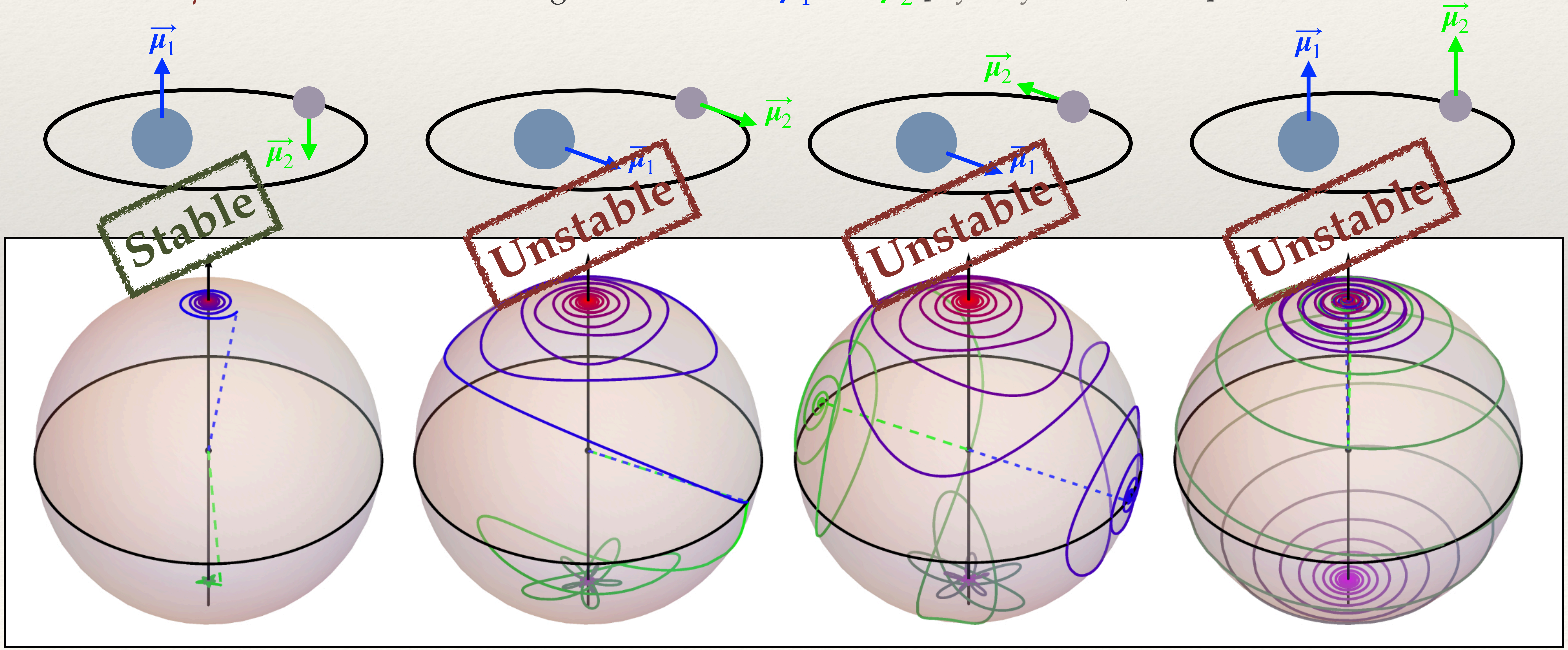


Magnetic GBs

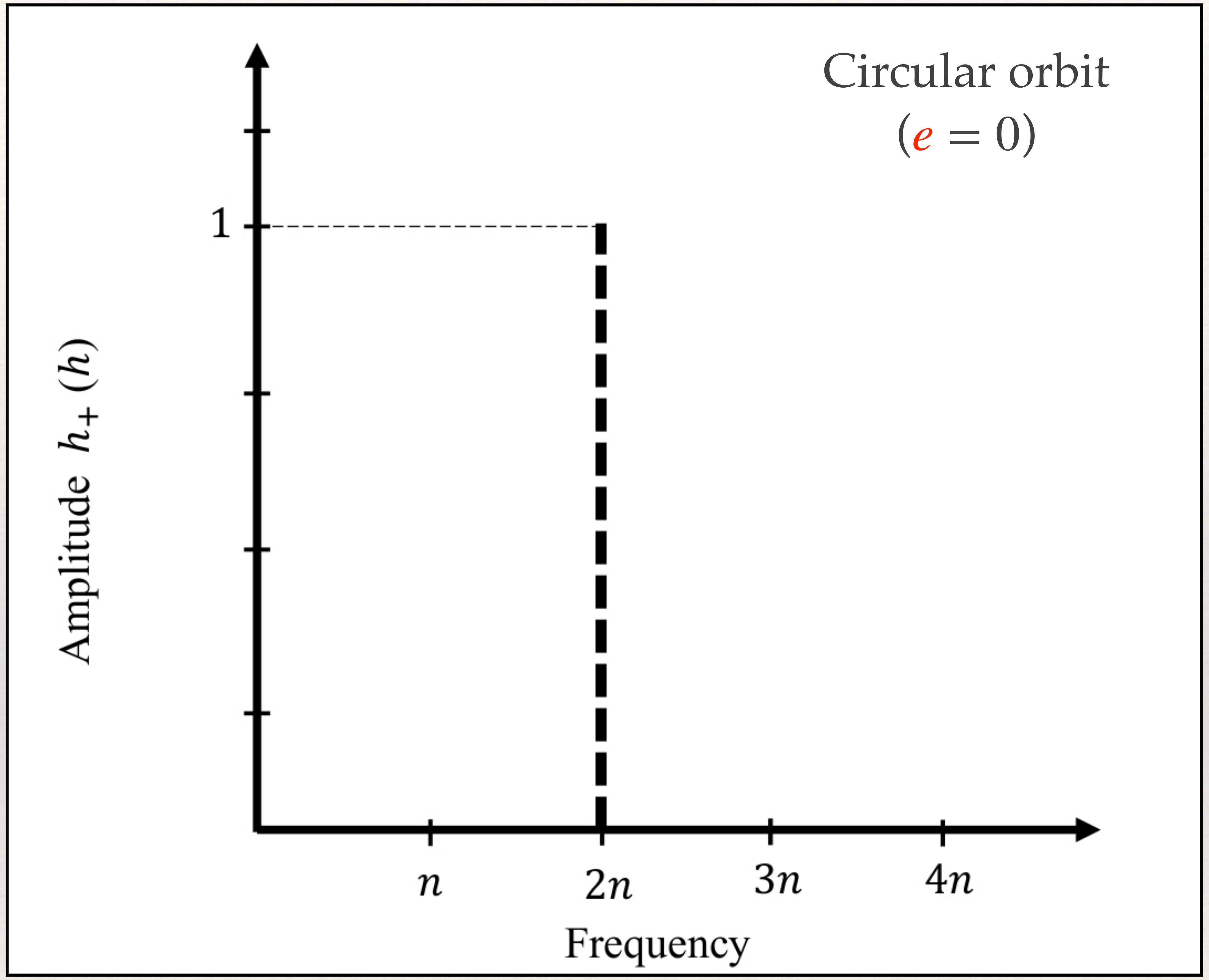
M.C. Angonin, C. Aykroyd, A. Bourgoin, C. Le Poncin-Lafitte, S. Mathis & E. Savalle

- Fourier decomposition (ℓ-th order in eccentricity):

$$h_+ - ih_\times = h(a) \sum_{k=-(\ell+2)}^{\ell+2} c_k(z,\zeta)\, e^{ikL} \quad \text{with} \quad h(a) = 2\eta \left(\frac{a}{D}\right)\left(\frac{Gm}{c^2 a}\right)^2$$

- Current GW template for WD/NS binaries
  - Circular in-spiral ($e = 0$) → one frequency
  - Two point-masses at 2.5PN → a time frequency shift
    $\Longrightarrow$ *Quasi-monochromatic*

- GW template for magnetic WD/NS binaries
  - Quasi-circular orbit ($e \neq 0$) → multi-frequency
    $\Longrightarrow$ one eccentric GB ≡ several monochromatic GB
    $\Longrightarrow$ Biais in LISA's catalog for GBs
  - Highly magnetic GBs (20% WDs > 10^6 G and 10% NSs > 10^{14} G)
    $\Longrightarrow$ Magnetism inferred from $2n$ and $3n$ frequencies



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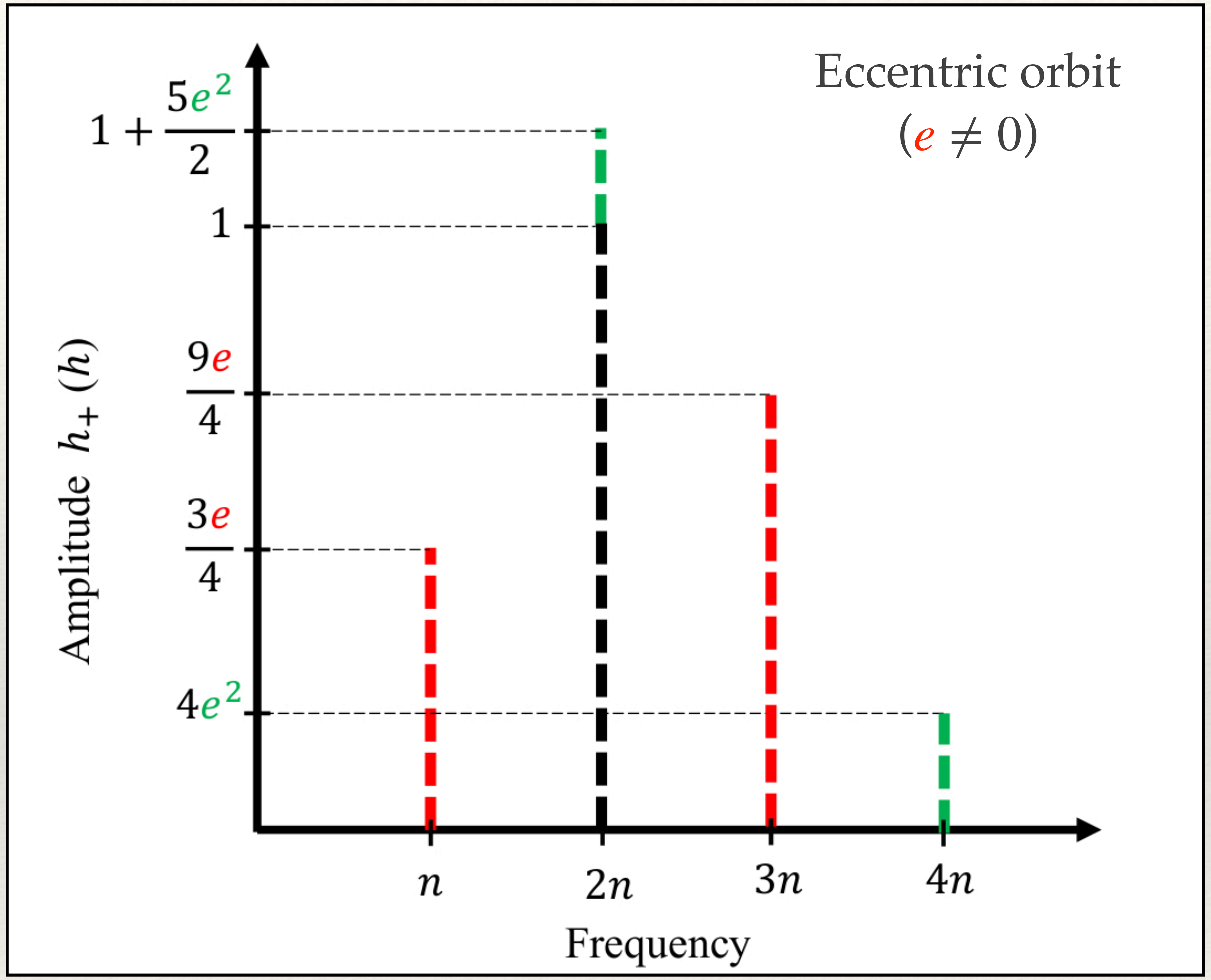

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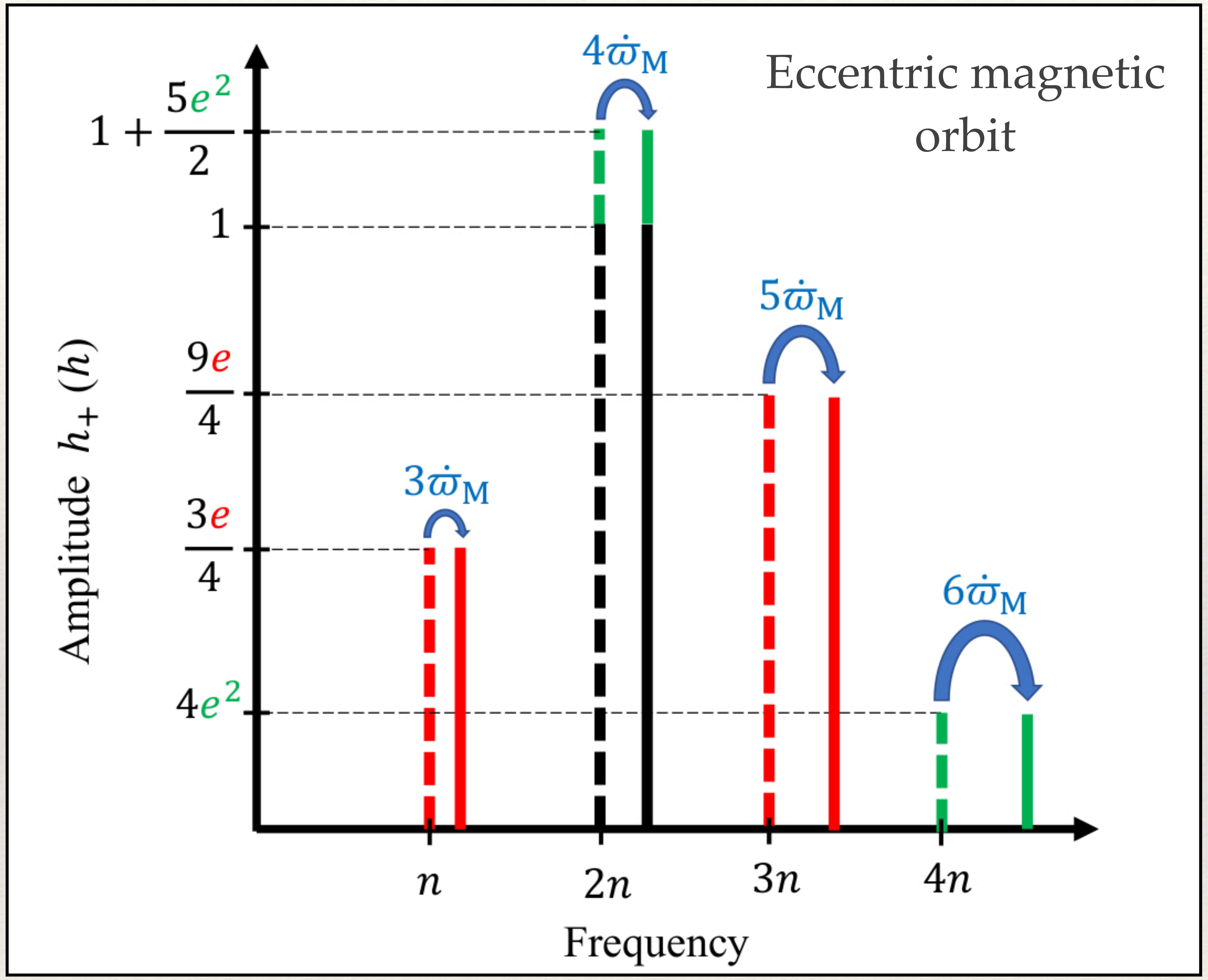

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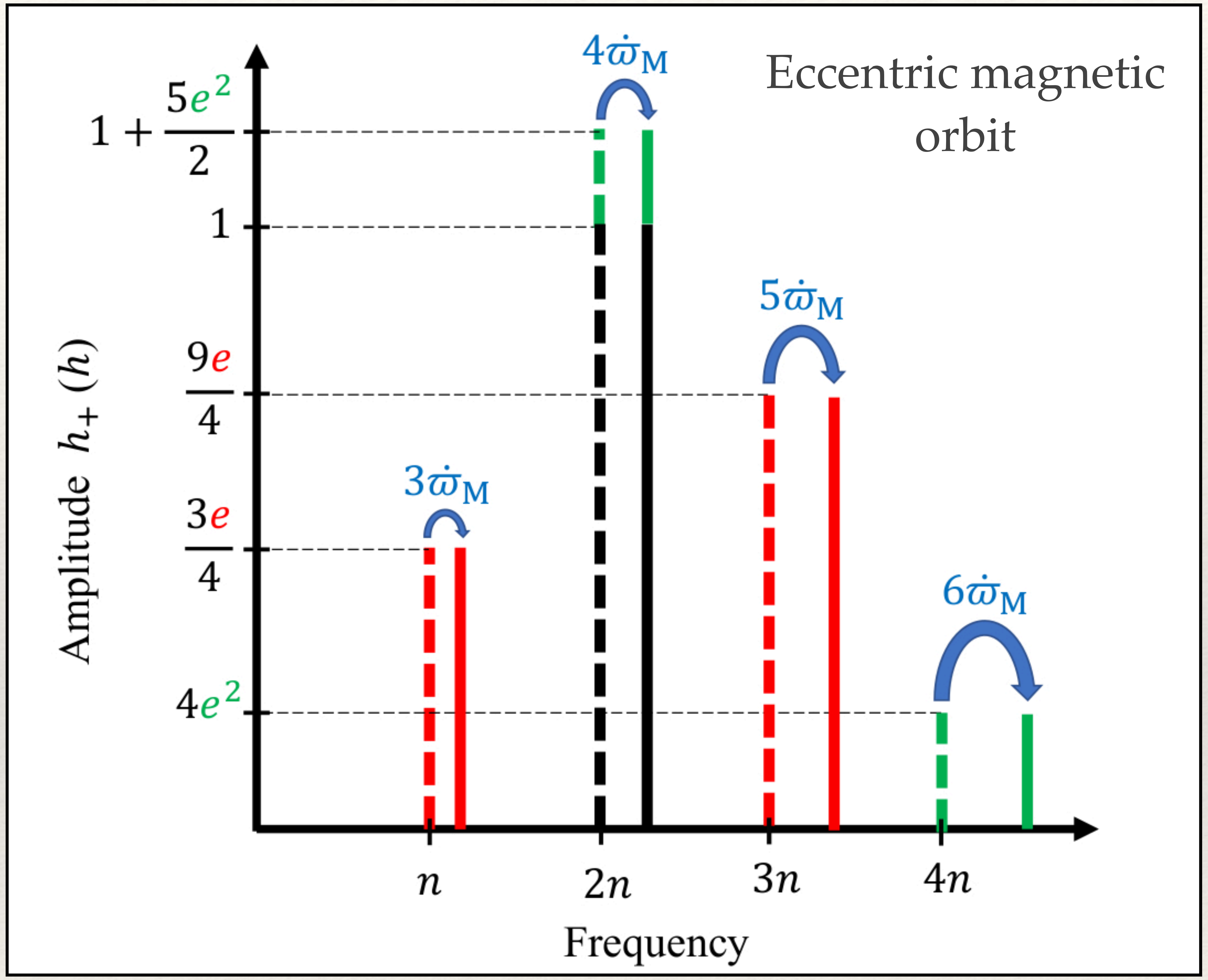


Monochromatic picture not allowing for a complete scientific interpretation of LISA data

[Savalle *et al.*, 2023]

Measuring frequency shift is like measuring mag. energy since $\dot{\varpi}_M \propto \bar{U}_M$

[Bourgoin *et al.*, 2022]

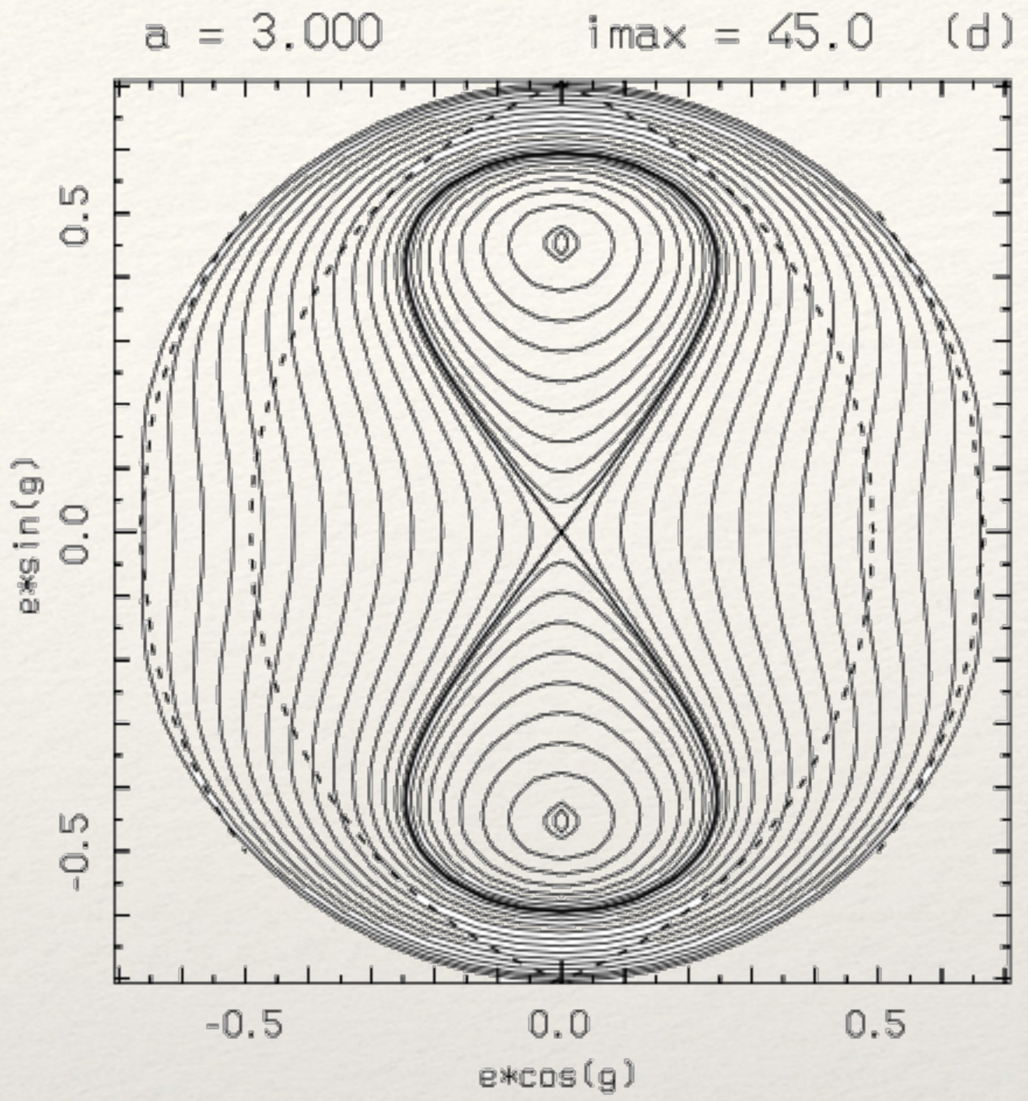
Hierarchical triple systems

A. Bourgoin, F. Destrier & A. Hees

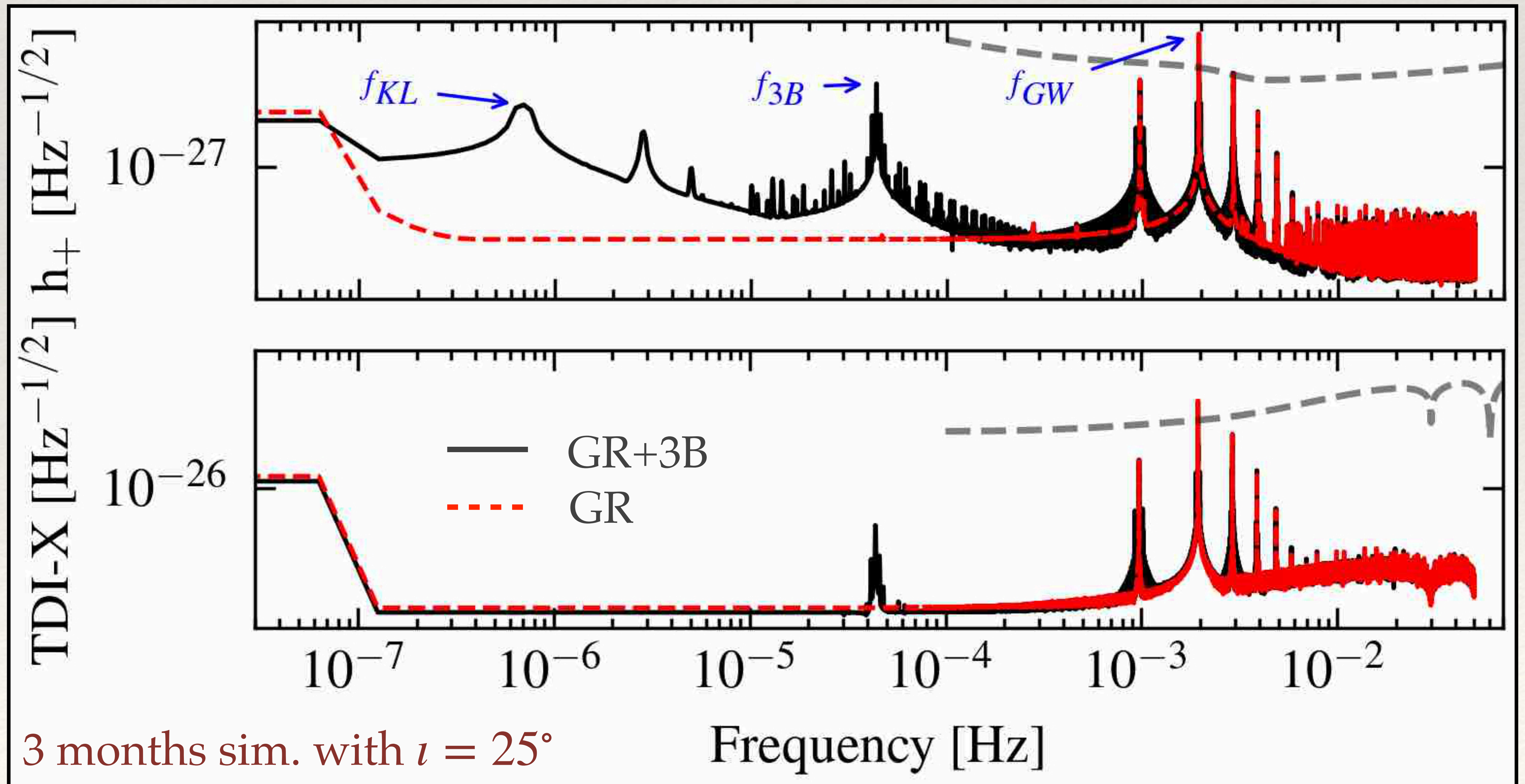
- Main ideas
  - How SgrA* impact GW emitted by a binary system?
  - Can we learn something on the 3B from data?
  - What impact on binary's parameters if 3B not modeled?

- Celestial mechanics [Morbidelli, 2011]
  - Kozai-Lidov resonances (quadrupole term)
    - ➡ Increase of e for $\iota > \iota_{crit}$
  - *Single average* orbit (binary's period) ≠ usual *double average*
    - ➡ Period of 3B still present
  - 2.5PN Eqs. of motion for the binary
    - ➡ Radiative part present

- GW signal
  - Perturbing acceleration in the quadrupole formula
  - Source frame within the GW wavelength zone
  - Impact on LISA observable: TDI



[Destrier, 2023]



3 months sim. with $\iota = 25°$

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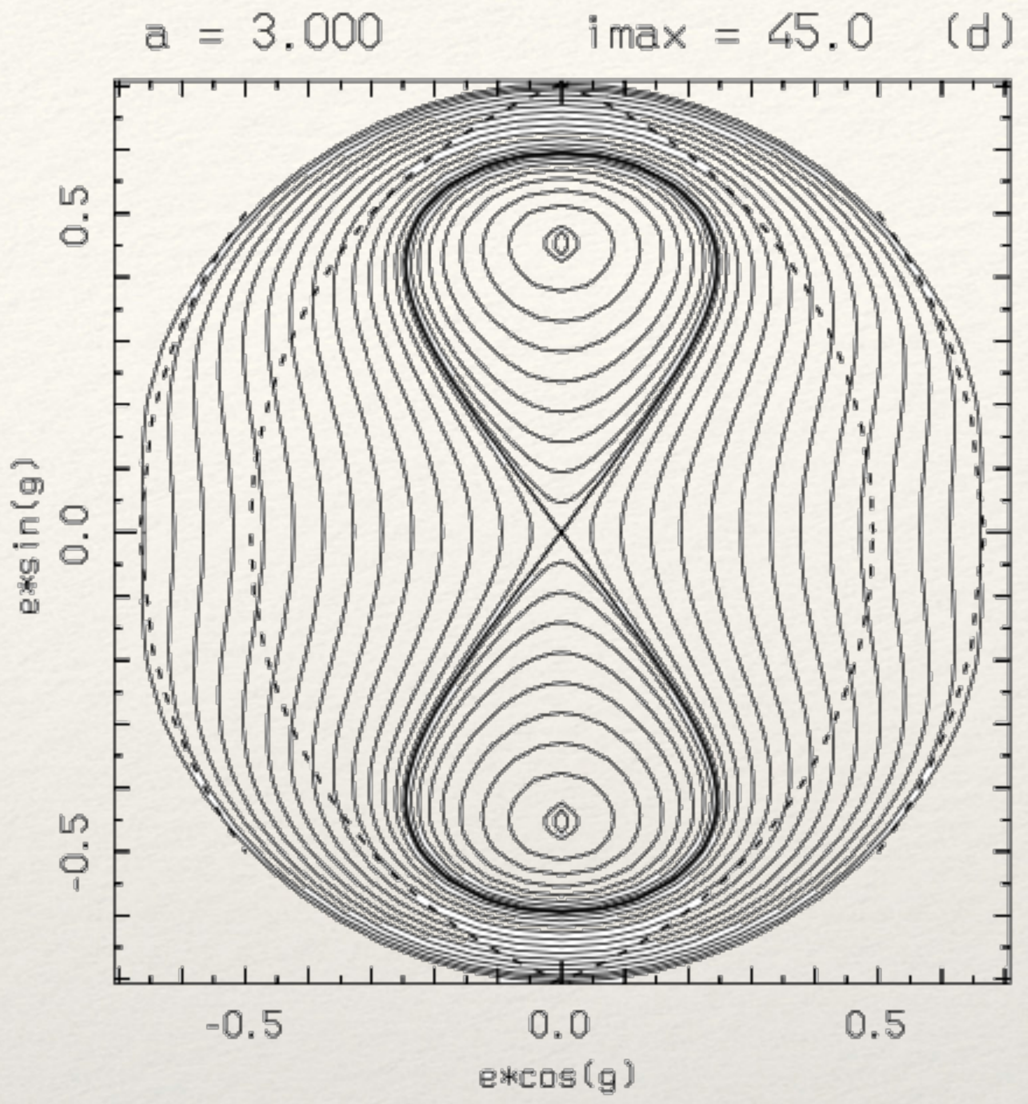
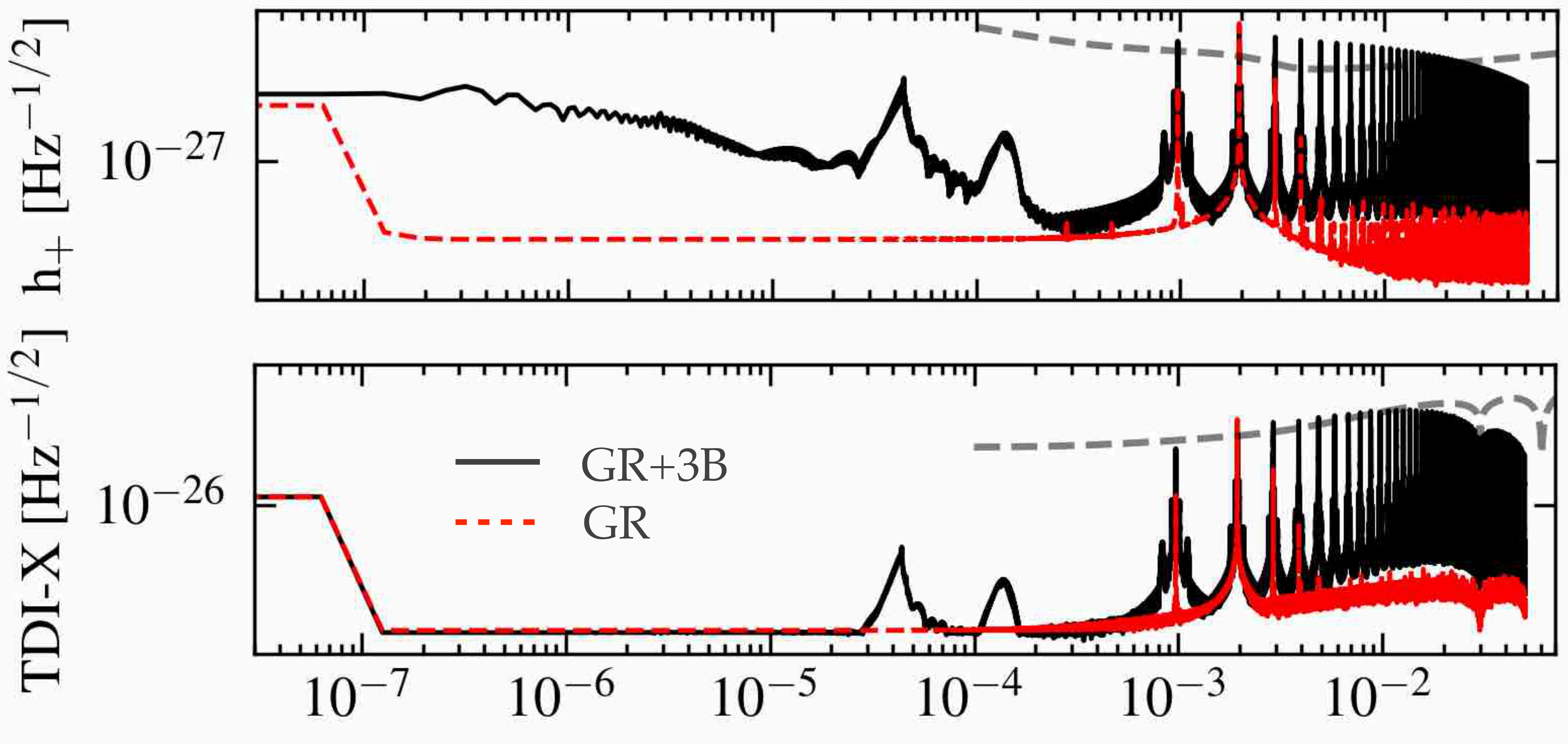


[Destrier, 2023]



3 months sim. with $\iota = 60°$

Lorentz Symmetry with GBs

M.-C. Angonin, S. Aoulad Lafkih,
C. Le Poncin-Lafitte & N. A. Nilsson

Study the possible *violations of the LS* in the generation of GWs by GBs and CMB polarizations

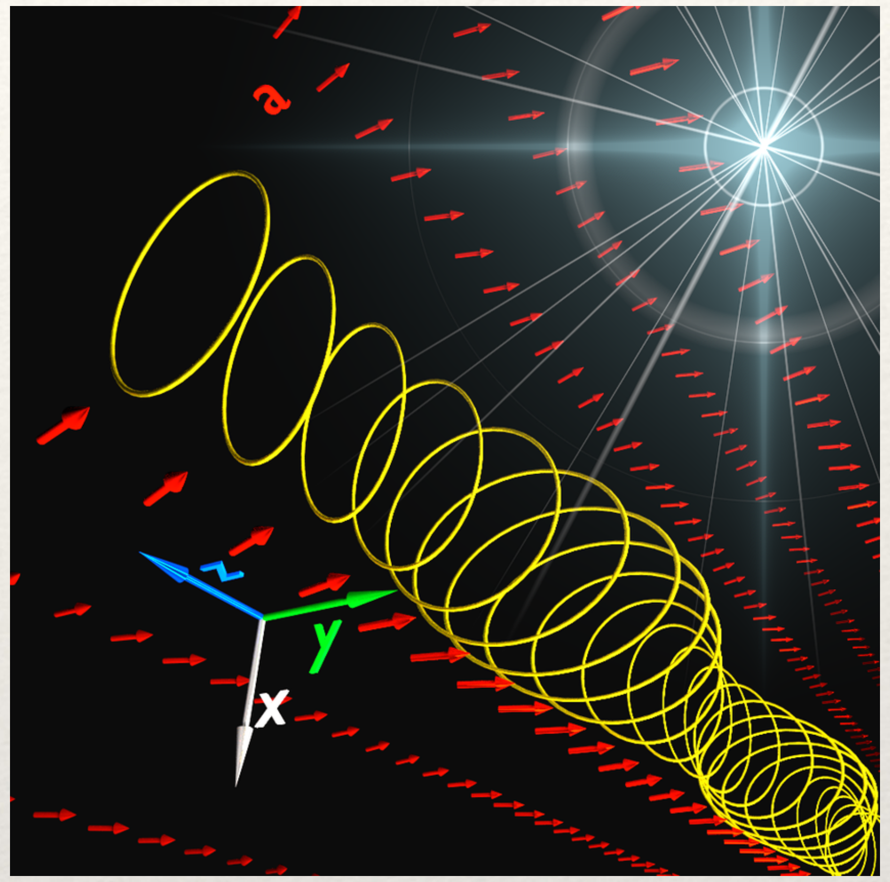
- The *Standard Model Extension* (SME) framework to test LS violations

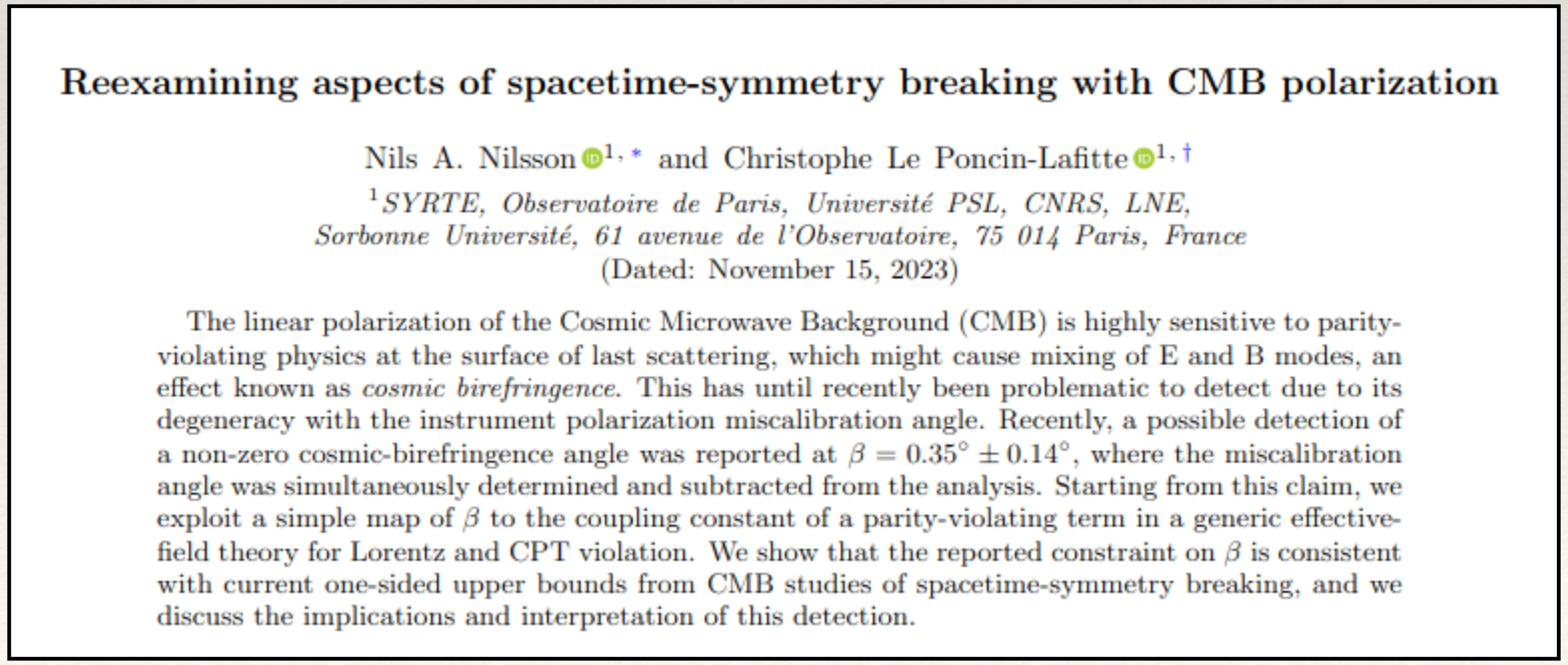
- Modeling GWs within the SME framework (minimal sector)

- Solving wave equations with SME coefficients u, s, and t (Samy's PhD & Albin's postdoc)
  - At first post-Newtonian order [Nilsson *et al.*, 2023; arXiv:2307.13302]
  - Some difficulties:
    - Using regularization method for divergent integrals
    - Non-decreasing term with distance
    - Terms $\propto \mathscr{R}$ (near zone size) remaining

- Constraining additional polarizations [Bailey *et al.*, 2023; arXiv:2307.13374]

- Signal of parity violation in the CMB can be related to spacetime symmetry breaking





Reexamining aspects of spacetime-symmetry breaking with CMB polarization

Nils A. Nilsson[1,*] and Christophe Le Poncin-Lafitte[1,†]
[1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, LNE, Sorbonne Université, 61 avenue de l'Observatoire, 75 014 Paris, France*
(Dated: November 15, 2023)

The linear polarization of the Cosmic Microwave Background (CMB) is highly sensitive to parity-violating physics at the surface of last scattering, which might cause mixing of E and B modes, an effect known as *cosmic birefringence*. This has until recently been problematic to detect due to its degeneracy with the instrument polarization miscalibration angle. Recently, a possible detection of a non-zero cosmic-birefringence angle was reported at $\beta = 0.35^\circ \pm 0.14^\circ$, where the miscalibration angle was simultaneously determined and subtracted from the analysis. Starting from this claim, we exploit a simple map of β to the coupling constant of a parity-violating term in a generic effective-field theory for Lorentz and CPT violation. We show that the reported constraint on β is consistent with current one-sided upper bounds from CMB studies of spacetime-symmetry breaking, and we discuss the implications and interpretation of this detection.

Summary: LISA activities at SYRTE

Hardware ground testing

- IDS (BSim)
- OTS (SLOGSE)
- ZIFO

Mission adoption
(2024)

Scientific exploitations

- SGWB
- GB + magnetism
- Triple systems
- GB + SME

Launch
(2035)

Data processing pipelines

- L0 to L1
- L1 to L2

SYRTE l'Observatoire de Paris | PSL

SYstèmes de Référence Temps-Espace