LISA data modeling and data analysis @SYRTE

"Theory and metrology group", SYRTE, Paris Observatory

LISA data analysis in France meeting, Caen, May 19th 2022

SYRTE l'Observatoire de Paris | PSL

SYstèmes de Référence Temps-Espace

The SYRTE theory and metrology group in a nutshell

Main lines of research:

- Providing an accurate modeling (or simulation tools) for laboratory experiments (quantum sensors), astrophysical observations, space-mission, etc…
- Develop new way/tools to analyze data for lab experiments, astrophysical observations, …
- Develop and perform new tests of fundamental physics using lab experiments, astrophysical observations, space mission

Examples: modeling for time/frequency transfer, modeling for Gaia, MICROSCOPE data analysis, development of ACES, GNSS Galileo data analysis and redshift test, search for Dark Matter using atomic sensors, Lunar Laser Ranging tests of fundamental physics, etc…

Scientists involved in LISA modeling / DA

Postdocs:

- A. Bourgoin (CNES postdoc)
- O. Hartwig (postdoc funded by CNES)

Permanent researchers

- M.-C. Angonin
- A. Hees
- C. Le Poncin-Lafitte
- M. Lilley
- P. Wolf

None of us is working full-time on LISA!

+ currently 3 stagiaires (I. Urso, S. Aoulad Lafkih, C. Aykroyd)
+ new PhD's in September (?)

Our expertise at SYRTE

- Expertise relatively unique within our group:
  - Expertise in relativistic modeling
  - Expertise in data analysis for time/frequency transfer, clock synchronization
  - Expertise in dealing with space mission data analysis (MICROSCOPE, ACES, Gaia, …)
  - Expertise in parts of the technology used in LISA (clocks, lasers, …)
  - Participation in AIVT activities (Lasers, tests and test-bench design)
  - Expertise in phenomenology of alternative theories of gravitation and dark matter models
  - Good vision of the scientific outputs of LISA

Currently 4 axes of research are being explored

Our team is (relatively) new in the LISA DA (< 2 years)

1. Study of Galactic Binaries: improved waveform modeling and related data analysis, tests of fundamental physics
   presentation by Adrien Bourgoin

2. L0 – L1 data preprocessing: development of new methods and impact on LISA scientific objectives
   presentation by Olaf Hartwig

3. Study of a methodology to extract the stochastic background from the stochastic source of noises
   presentation by Marc Lilley

4. Observations of stars orbiting Sgr A* and fundamental physics tests
   presentation by Aurelien Hees

Projects driven by our scientific interests, may evolve with time

LISA Data Analysis

Gravitational waves radiated by magnetic Galactic Binaries and detection by LISA

A. Bourgoin[1,2], E. Savalle[3], C. Le Poncin-Lafitte[1], S. Mathis[2], and M.-C. Angonin[1]

[1]SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Paris, France.
[2]Département d'Astrophysique-AIM, CEA/IRFU/DAp, CNRS/INSU, Université Paris-Saclay, Universités de Paris, Gif-sur-Yvette, France.
[3]CEA Paris-Saclay University, IRFU/DPhP, Gif-sur-Yvette, France.

May 19th, 2022

CGB (Compact Galactic Binaries)

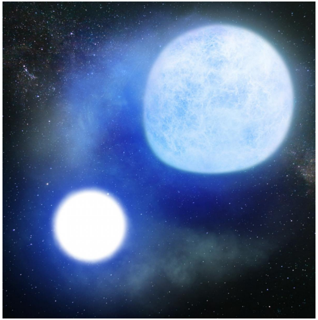


Illustration of a CGB system in tidal interaction.

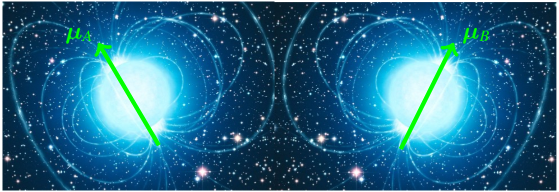


Illustration of a CGB system in magnetic interaction.

Physical properties

Binaries of **White Dwarfs**, **Neutron Stars**, and stellar-mass **black holes**, in various combinations, and within the galaxy.

- **White Dwarfs** (WD), **Neutron Stars** (NS),
- **Radius**: $R_{\mathrm{WD}} \sim R_{\oplus}$ $R_{\mathrm{NS}} \sim 10$ km
- **Mass**: $M_{\mathrm{WD}} \lesssim M_{\odot}$ $M_{\mathrm{NS}} \gtrsim M_{\odot}$
- **Density**: $\rho_{\mathrm{WD}} \sim 1\ \mathrm{t/cm^3}$ $\rho_{\mathrm{NS}} \sim 10^9\ \mathrm{t/cm^3}$
- **Compacity** ($\Xi = GM/c^2R$):

$$\Xi_{\mathrm{WD}} \sim 10^{-3} \qquad \Xi_{\mathrm{NS}} \sim 10^{-1}$$

- **LISA frequency** ($\Phi = 10^{-1}$ Hz to $\Phi = 10^{-4}$ Hz):

$$a \sim 10^4 - 10^6\ \mathrm{km}$$
$$P \sim 1\ \mathrm{min} - 10\ \mathrm{h}$$

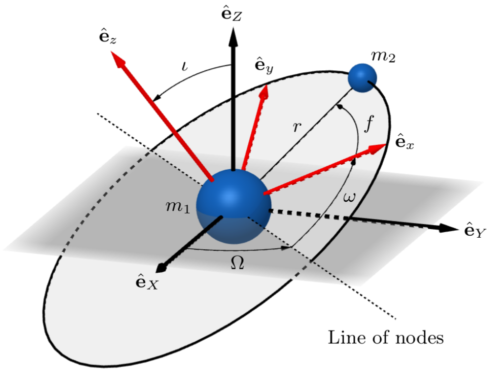
- **Magnetic fields** ($< 20\%$ WD and $< 10\%$ NS):

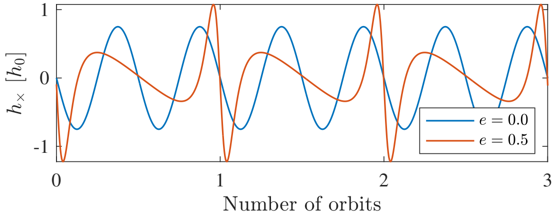
$$\boxed{B_{\mathrm{WD}} \sim 10^6 - 10^9\ G} \qquad \boxed{B_{\mathrm{NS}} \sim 10^{14} - 10^{15}\ G}$$

- **Magnetic moments** ($\mu \propto BR^3$):

$$\boxed{\mu_{\mathrm{WD}} \sim 10^{30} - 10^{33}\ \mathrm{A \cdot m^2}} \qquad \boxed{\mu_{\mathrm{NS}} \sim 10^{29} - 10^{30}\ \mathrm{A \cdot m^2}}$$

GW emitted by a binary system





Keplerian orbit

Circular orbit ($e = 0$) $\Longrightarrow$ monochromatic (freq $= 2n$)

Eccentric orbit ($e \neq 0$) $\Longrightarrow$ multi-frequency

Modulation depends on (ι, Ω, ω).

Strain amplitude depends on the shape (a).

$$\boxed{h = 2\eta \left(\frac{a}{D}\right)\left(\frac{Gm}{c^2 a}\right)^2}$$

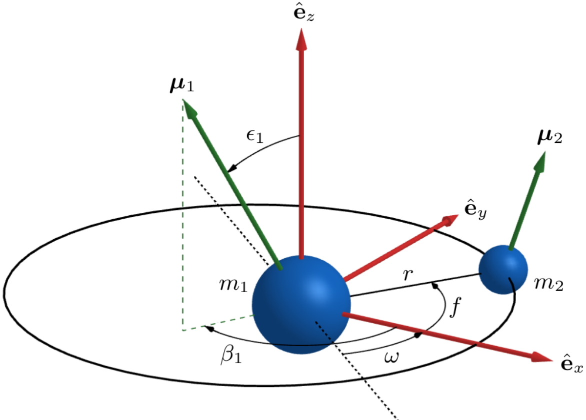
- D: distance to the field point, i.e., $D = |\boldsymbol{x}|$,
- m: total mass, i.e., $m = m_1 + m_2$,
- η: symmetric mass ratio, i.e., $\eta = m_1 m_2 / m^2$

CGB and LISA

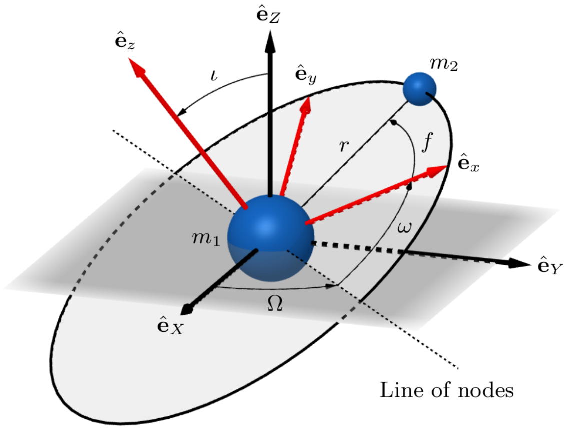
- Within the LDC (quasi-monochromatic sources):

$$\boxed{h_+(t) = -h(1 + \cos^2 \iota)\cos(\phi + \Phi t + \dot{\Phi} t^2),}$$

- **How does internal physics modify this picture?**



- Magnetic moments: $\boldsymbol{\mu}_1$ and $\boldsymbol{\mu}_2$
- Obliquities of the magnetic moment $\boldsymbol{\mu}_1$: ϵ_1, ϵ_2
- Precession angles of the magnetic moment $\boldsymbol{\mu}_1$: β_1, β_2



- **Semi-major axis**: a

$$\boxed{a(t) = a_0 + \dot{a}_{\mathrm{GR}}\, t}$$

- **Mean longitude**: $L = \varpi + M$

$$\boxed{L(t) = L_0 + \widetilde{L}_{\mathrm{M}}(t) + (n_0 + \dot{L}_{\mathrm{GR}} + \dot{L}_{\mathrm{M}})t - \frac{3n_0}{4}\frac{\dot{a}_{\mathrm{GR}}t^2}{a_0}}$$

- **Eccentricity vector**: $z = e\, \mathrm{e}^{\mathrm{i}\varpi}$

$$\boxed{z(t) = e_0 \exp\left(\frac{\dot{e}_{\mathrm{GR}}\, t}{e_0}\right) \exp\big(\mathrm{i}\varpi(t)\big)}$$

- **Inclination vector**: $\zeta = \sin\left(\frac{\iota}{2}\right) \mathrm{e}^{\mathrm{i}\Omega}$

$$\boxed{\zeta(t) = \zeta_0 + \widetilde{\zeta}_{\mathrm{M}}(t)}$$

- **Longitude of the pericenter**: $\varpi = \Omega + \omega$

$$\boxed{\varpi(t) = \varpi_0 + \widetilde{\varpi}_{\mathrm{M}}(t) + (\dot{\varpi}_{\mathrm{GR}} + \dot{\varpi}_{\mathrm{M}})t}$$

Zeroth-order in eccentricity: $\boxed{h_+^{(0)}(t) = -h_0(1+\cos^2\iota_0)\cos\left(\phi^{(0)} + \Phi^{(0)}t + \dot{\Phi}^{(0)}t^2\right)}$

where the **main frequency** $\left(\Phi^{(0)}\right)$ and the **frequency shift** $\left(\dot{\Phi}^{(0)}\right)$ are given by

$$\Phi^{(0)} = 2n_0\left(1 + \frac{\dot{L}_{\mathrm{GR}}}{n_0} + \frac{\dot{L}_{\mathrm{M}}}{n_0}\right), \qquad \dot{\Phi}^{(0)} = -\frac{3n_0}{2}\frac{\dot{a}_{\mathrm{GR}}}{a_0},$$

where

$$\boxed{\frac{\dot{L}_{\mathrm{M}}}{n_0} = \left(\frac{3\mu_0}{4\pi G}\right)\left(\frac{1}{\eta m^2}\right)\left(\frac{\mu_1\mu_2}{a_0{}^2}\right)\frac{\left(1+\sqrt{1-e_0{}^2}\right)}{(1-e_0{}^2)^2}\cos\epsilon_{10}\cos\epsilon_{20}}$$

$\Longrightarrow$ **Magnetism must be used for physical interpretation** of the **main frequency** $\left(\Phi^{(0)}\right)$, if

$$\frac{\sigma_{\Phi^{(0)}}}{\Phi^{(0)}} < \frac{\dot{L}_{\mathrm{M}}}{n_0}, \quad \text{i.e., if} \quad \boxed{\frac{\sigma_{\Phi^{(0)}}}{\Phi^{(0)}} < 6.8\times 10^{-7}} \quad \text{for } \Phi^{(0)} = 10^{-1}\text{ Hz and WD-WD with } B_1 = B_2 = 10^9\text{ G.}$$

$\Longrightarrow$ Uncertainty for **verification binaries** between 10^{-6} to 10^{-9} !

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Impact of magnetism on GW mode polarizations

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Impact of magnetism on GW mode polarizations

First-order in eccentricity: $\boxed{h_+^{(1)}(t) = -\frac{9}{4}e_0 h_0(1+\cos^2\iota_0)\cos\left(\phi^{(1)} + \Phi^{(1)}t + \dot{\Phi}^{(1)}t^2\right) + \dots}$

where the **secondary frequency** $\left(\Phi^{(1)}\right)$ and the **frequency shift** $\left(\dot{\Phi}^{(1)}\right)$ is given by

$$\Phi^{(1)} = 3n_0\left(1 + \frac{3\dot{L}_{\rm GR} - \dot{\varpi}_{\rm GR}}{3n_0} + \frac{3\dot{L}_{\rm M} - \dot{\varpi}_{\rm M}}{3n_0}\right), \qquad \dot{\Phi}^{(1)} = -\frac{9n_0}{4}\frac{\dot{a}_{\rm GR}}{a_0},$$

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$$\frac{3\Phi^{(0)}}{2} - \Phi^{(1)} = \dot{\varpi}_{\rm M} + \dot{\varpi}_{\rm GR}, \qquad \text{with} \qquad \dot{\varpi}_{\rm M} \propto \frac{\mu_1\mu_2}{{a_0}^{7/2}}.$$

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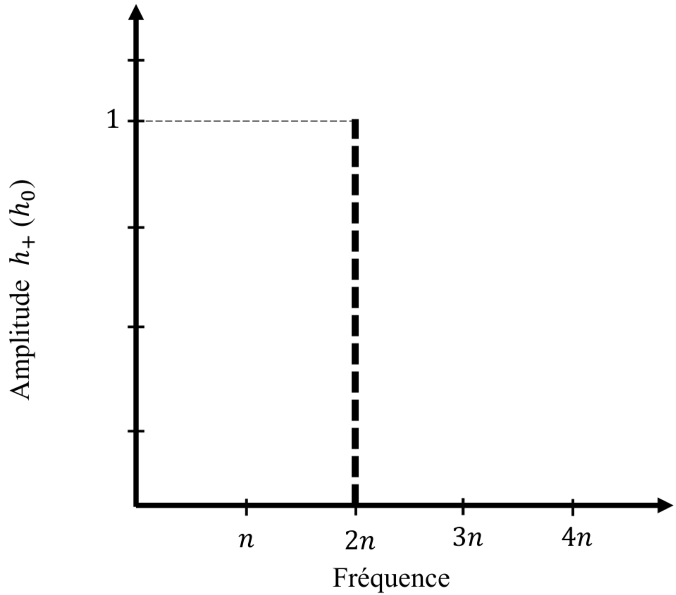
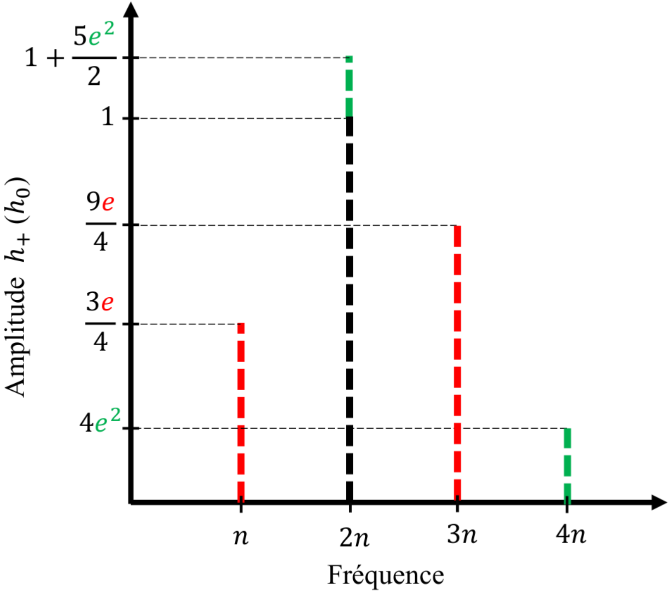
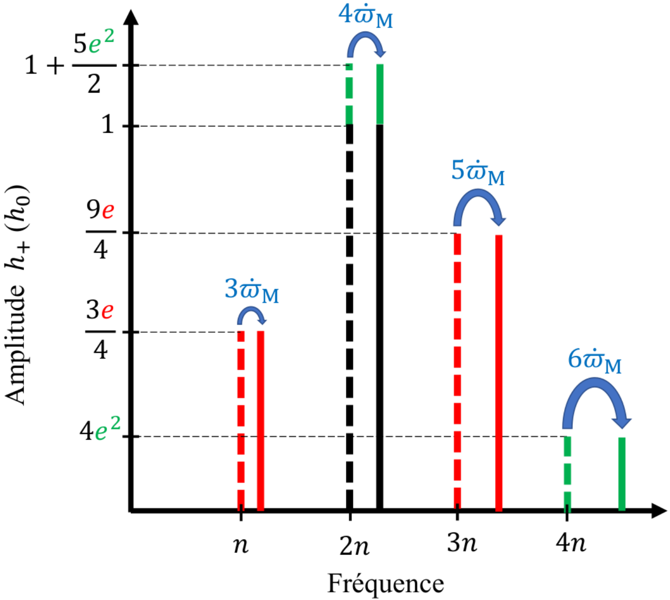
Summary: no eccentricity no magnetism

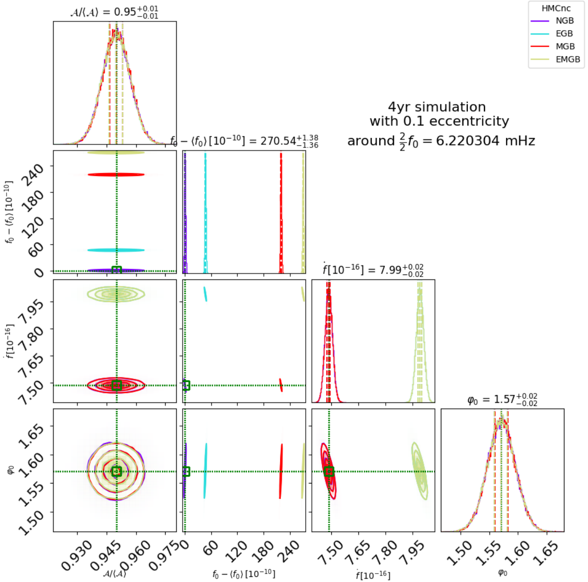


Summary: eccentricity with magnetism

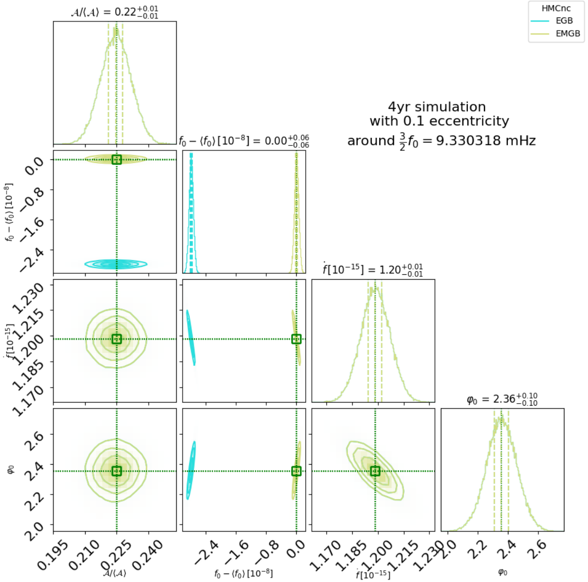



$4\dot{\varpi}_M$
$5\dot{\varpi}_M$
$3\dot{\varpi}_M$
$6\dot{\varpi}_M$
$1+\frac{5e^2}{2}$
1
$\frac{9e}{4}$
$\frac{3e}{4}$
$4e^2$
Amplitude h_+ (h_0)
n
$2n$
$3n$
$4n$
Fréquence

Recovering a multi-frequency signal (main frequency $2n$)



Recovering a multi-frequency signal (first harmonic $3n$)



Perspectives (Waveform for Galactic Binaries considering internal physics)

- More details in arXiv 2201.03226 (accepted in PRD).
- Eccentric and magnetic waveform retrieval (LDC tools)
  $\Longrightarrow$ e.g., with HM Cancri ($e = 0.1$, see McNeil *et al.*, 2020)
  $\Longrightarrow$ Combination between harmonics at $3n$ and $2n$ for magnetism.
  Collaboration SYRTE and CEA DPhP (E. Savalle)
- Non-adiabatic MHD interaction e.g., unipolar induction mechanism.
  $\Longrightarrow$ Requires only one magnetic body.
  $\Longrightarrow$ Loss of energy that can compete with 2.5PN terms.
  $\Longrightarrow$ Secular deformations of the orbit.
  Collaboration SYRTE and CEA DAp (A. Strugarek)
- Dynamical tides and MHD interaction.
  $\Longrightarrow$ Magneto-gravito-inertial-waves.
  $\Longrightarrow$ Toward a coherent vision (internal structure, magnetism, and dynamics) of CGB.
  Ph.D. C. Aykroyd at SYRTE and CEA DAp
- Lorentz Invariance with Galactic Binaries
  $\Longrightarrow$ Use SME framework to produce waveforms taking into account LI breakings
  $\Longrightarrow$ Inverse problem with Bayesian method; study the precision level we can determine SME parameters

X-INREP

Independent verification of the L0-L1 pipeline

O. Hartwig, A. Hees, M. Lilley, P. Wolf

Long-term plan

- Develop independent L0-L1 pipeline we can run ourselves
  - No intention of developing ‘professional grade’ software with full documentation, error handling, etc.
  - Instead, focus on exploring alternative algorithms and obtain full understanding of the L0-L1 processing chain
- Once real L0 data is available, process it and make L1 results openly available (within Consortium agreed limits)
- Compare the L1 results to those from other INReP implementation(s)
- Use them for further scientific analysis (L1 -> L2)

Short-term plan

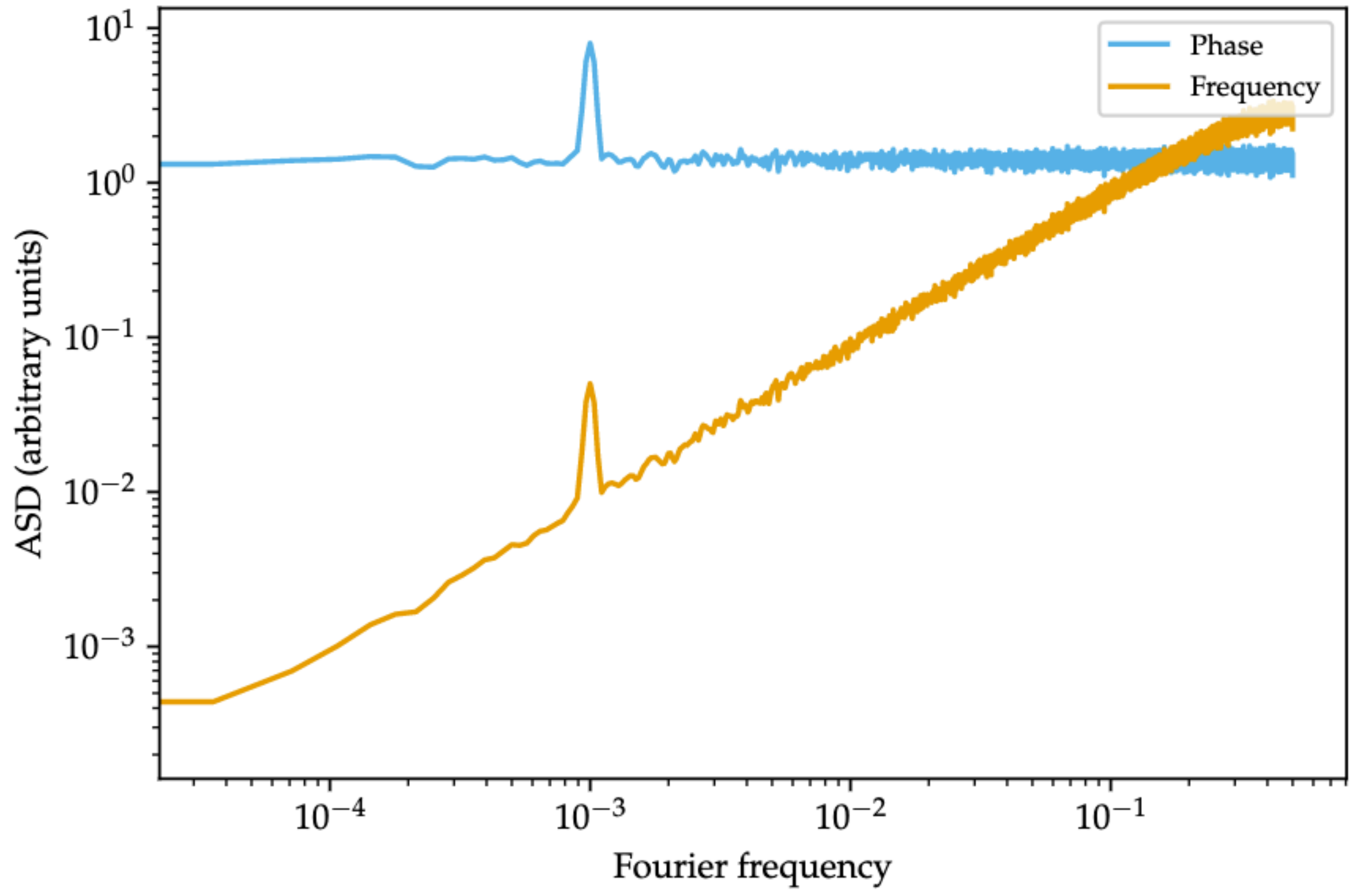
- Scientifically investigate methods and algorithms for best performance, robustness, flexibility, … of all involved processing steps.
- Test those methods with existing software (LISA-Node, LISA-Instrument, PyTDI, …)
- Develop new code where necessary and/or useful.

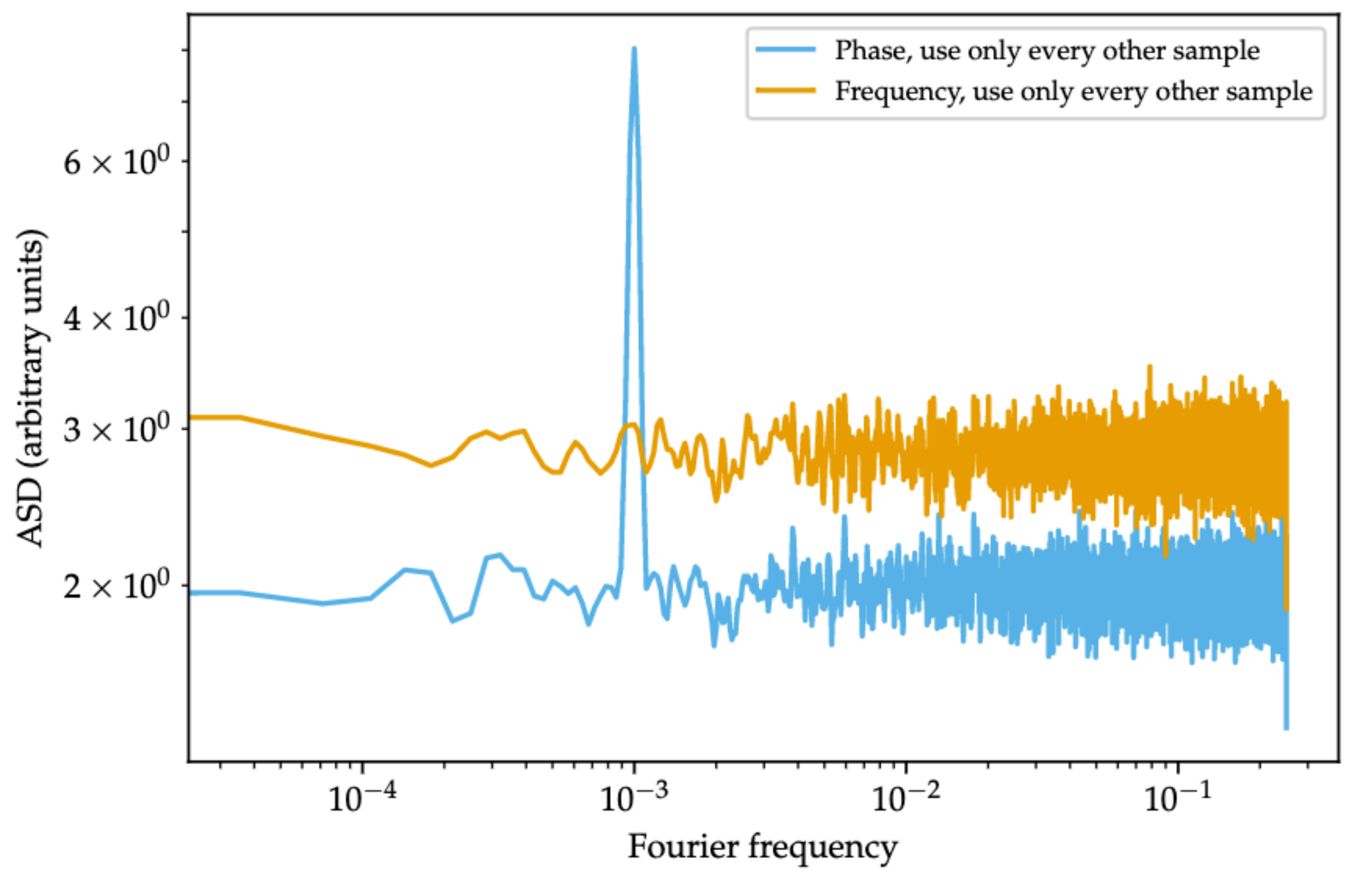
On-going: precise identification of the LISA data and necessary data preprocessing/calibration steps

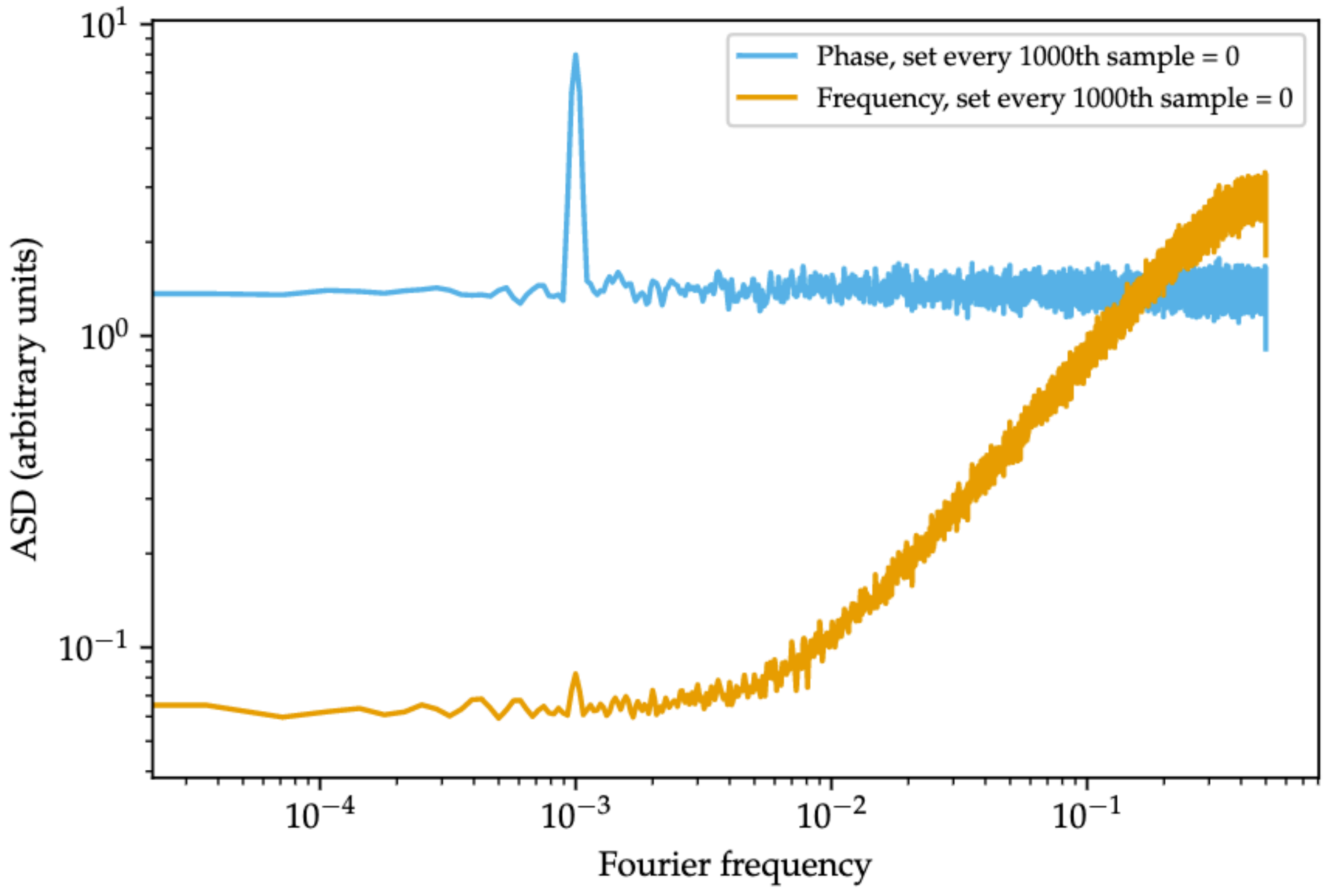
- Recent discussions with AEI (G. Heinzel, J. Esteban, etc…), CEA (A. Petiteau), SYRTE
- Identify precisely what data will be downlinked, at which frequency, how the data will be coded, what is going to be processed on-board vs. on-ground, …
- Example for Interspacecraft Interferometer:
    - Beatnote frequencies @ 4Hz + phase anchor (to reconstruct phase) @ lower rate
    - 2 times the DWS as electrical angle between quadrants @ 4 Hz + diagnostic dws @ lower rate
    - how to combine the 4 photodiodes measurements and what to downlink exactly?
    - FFT performed on-board and largest peaks + noise estimates downlinked (low rate)
    - clock UpSideBand - LowSideBand (coded using a feedforward compared to carrier) frequency @4Hz + phase anchor?
    - PRN: phase shift measured in clock cycles of 80 MHz USO
    - the I amplitude @4Hz and the Q amplitude at low rate (diagnostic) + loop gain of the PLL
    - temperature of the QPR and ePMS (needed for temperature calibration)
    - error flag @4Hz
    - ….
- Important to evaluate the data budget
- impacted by the identification of the corrections/calibrations “needed” to produce L1 data (with quality estimation)
- Similar thinking about the corrections to apply to the raw data: quality control, temperature correction, clock noise reduction, phase reconstruction, apply DWS factor, ranging processing, laser noise reduction (TDI), etc, etc…

So far: Impact of in-band gaps in phase vs. frequency

- Toy model: consider white noise at fs = 1Hz, + mHz signal, differentiate to get frequency
- Very artifical ‘gap’:
    - Remove every other sample. This is equivalent to downsampling by factor 2.
    - Aliasing barely affects signal in phase, but completely covers it in frequency
- Slightly more realistic: remove every 1000th sample (or set = 0, very similar behaviour)
- Noise becomes white (uncorrelated) at frequencies < 1/1000 Hz.
- Preliminary conclusion: raw data should be in phase, we can demonstratively lose information.
    - TBD how big the impact is on full L0-L1 pipeline in phase vs. frequency
- Toy model results summarised in TN

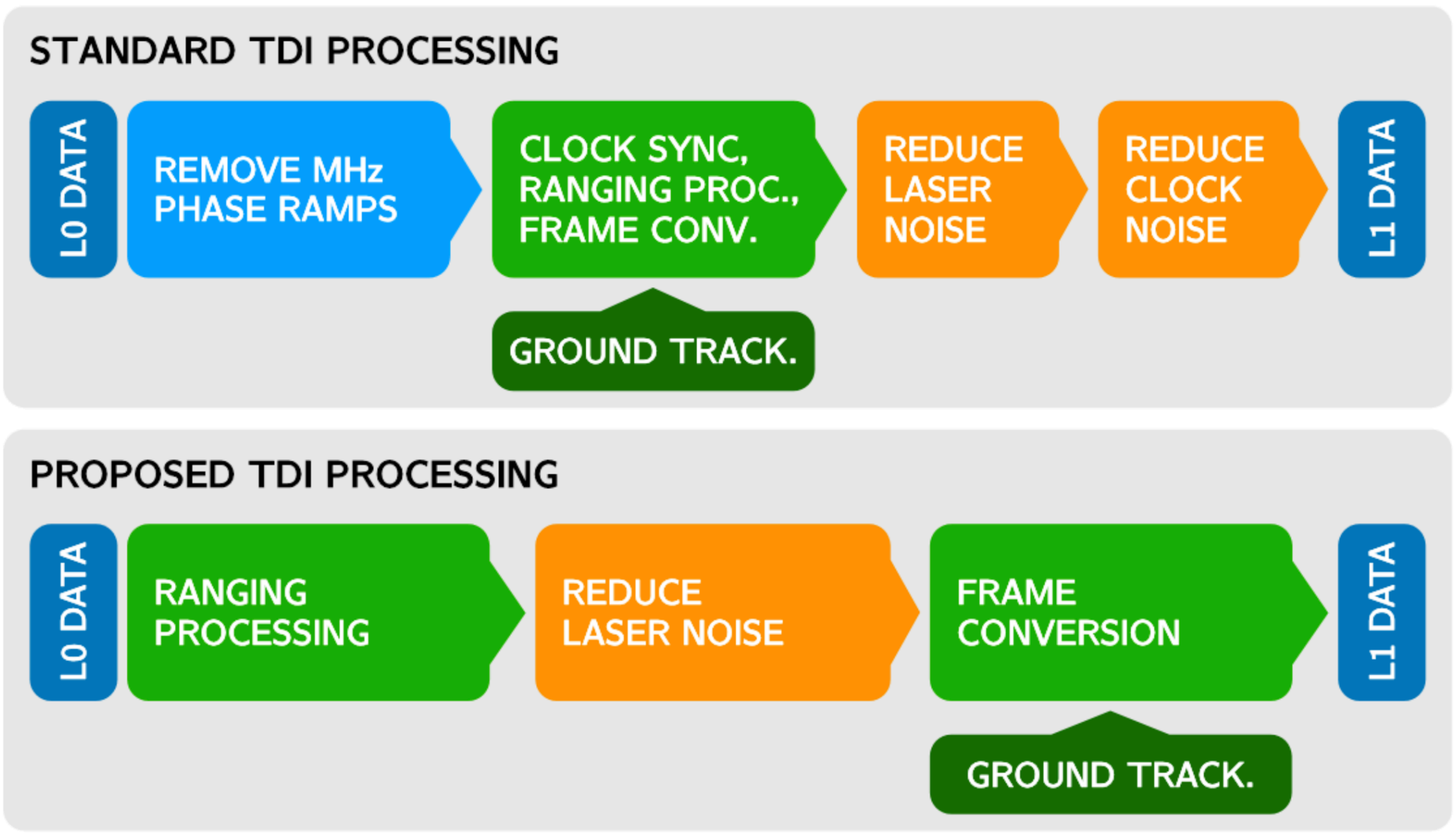


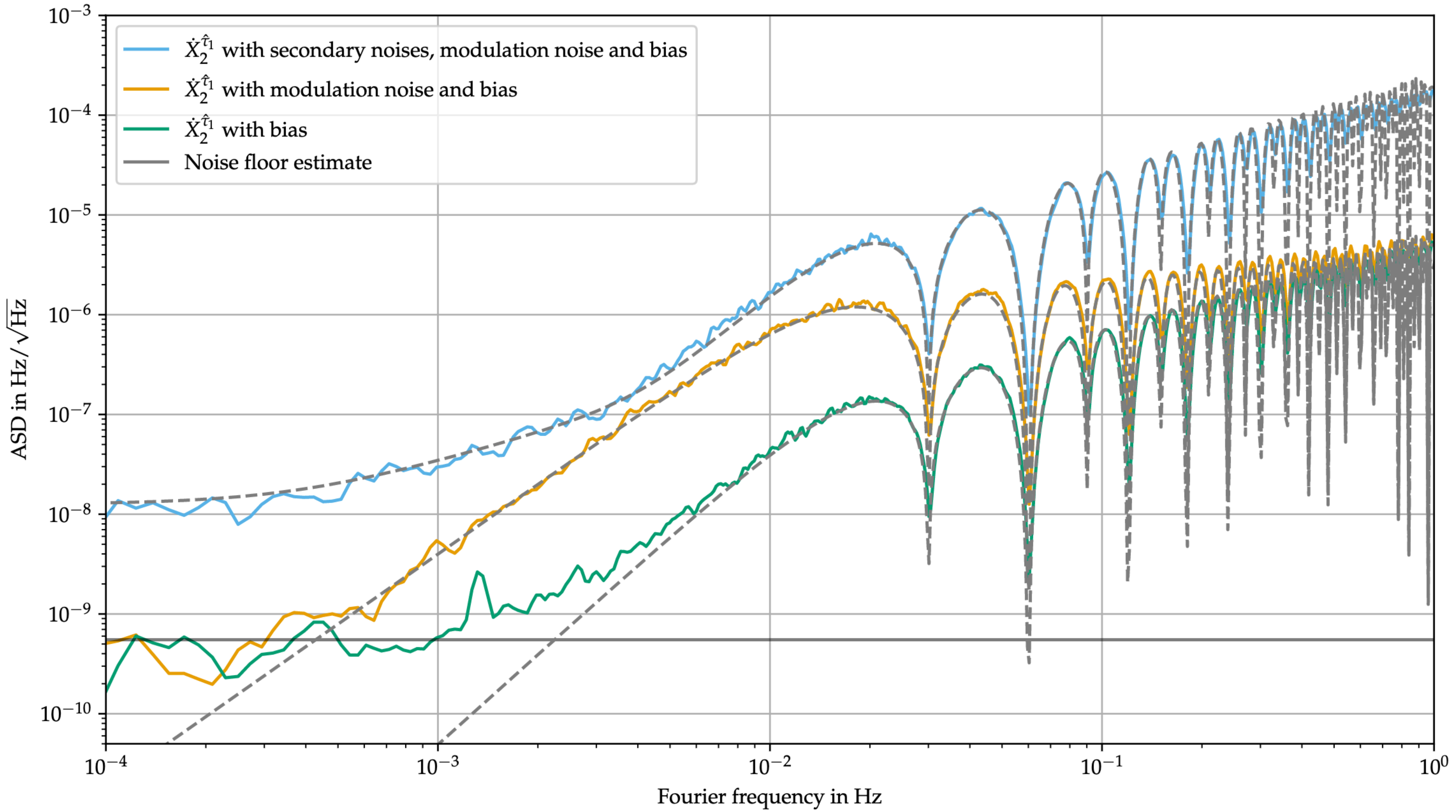




So far: TDI without clock synchronisation

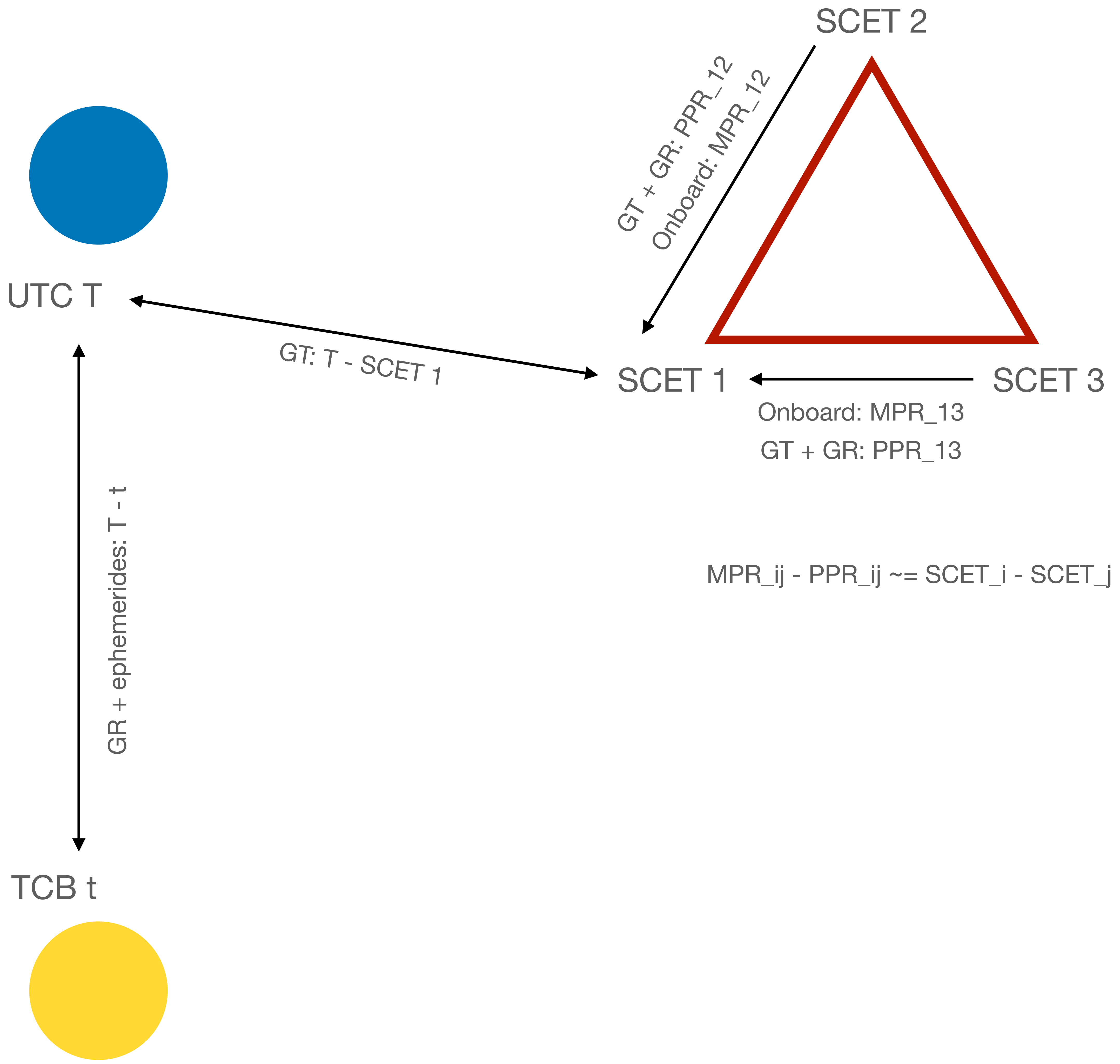
- Performed study on simplified TDI processing [arXiv:2202.01124]
- Operate directly on MHz beat notes without sync., using only on-board measurements
- Advantages:
  - Ranging processing simplifed, combine only local measurements
  - No extra clock correction step
- Less processing before TDI → less opportunities for noise to enter
- Fundamental performance limits (sideband modulation errors) enter identically to previous studies
- Possible caveat: High dynamic range, numerics more challenging (but not limiting)
- Baseline for INREP crosscheck developed at SYRTE.





Next steps: Clock sync. after TDI

- The TDI variables obtained using our method are still given by the spacecraft clocks, and need to be synchronised for astrophysical DA
- Comparatively low precision and accuracy necessary: ~1ms?
- First idea to explore very simple algorithm:
  - rely on ground-tracking data for sync. of one S/C clock to TCB. Expect contact with 1/3 S/C for 8h/24h.
  - Use orbit model from ground tracking to compute proper pseudo range + compare to measured pseudo range to get remaining two clock offsets



Next steps: Impact of L0-L1 on DA

- We plan to study the impact of the full L0-L1 pipeline on GW parameter estimation
- Current thinking:
    - Generate data using simulation tools
        - Eventually include all instrumental effects we can handle (i.e., everything currently in LISA Instrument except maybe TTL) and run full L0-L1 pipeline
        - Probably multiple datasets: e.g, establish baseline with no, or just some instrumental noises
        - Focus on simple GW signal which are ‘easy’ to analyse (TBD)
    - Run full L0-L1 pipeline
    - Compare results with different instrumental effects enabled + different pipelines

Noise characterisation and the SGWB

M. Lilley and O. Hartwig

LISA noise

- Noise characterisation is a challenging task in LISA
- Detailed noise models exist based on LISA Pathfinder & ground-based prototypes, but large uncertainties (e.g., LISA Pathfinder observed un-modelled excess-noise a factor 2-4 above the modelled part).
- We face additional challenges compared to LIGO/VIRGO:
  - Single observatory, can't use cross-correlation between detectors
  - Signal dominated at all times, except in "quasi-null" TDI channel
- The dominant noise in the "quasi-null" TDI channel is sub-dominant in other TDI channels.
- Many studies rely on (A, E, T), which are orthogonal channels only for equal and static LISA arms, and for equal and uncorrelated noises on all 3 S/C. Reality is more complex and this TDI combination may no longer be the optimal one (*see Muratore and Hartwig's work on the TDI variable ζ*).

The SGWB

- The SGWB can have many origins (<u>cosmological</u>: inflation, topological defects, etc., <u>astrophysical</u>: GBs, etc.)
- There are many uncertainties in the models and in the model parameters, at least for what concerns the cosmological SGWB.
- The overall shape of the SGWB is a superposition of unknown shapes (many are taken (under model assumptions) to be power laws, broken power laws, or other elementary shapes).

Two strategies so far

- Fix the noise model (not the noise parameters) and look for the SGWB in an agnostic way (the “binner" approach, see CWG publications).
- Fix the SGWB model (e.g. a power law) and look for the noise in an agnostic way (using the “spline” approach, Baghi, Bayle et al., work in progress)
- Currently both are implemented for A, E, T, and uncorrelated and equal noise levels on all 3 S/C.
- Ideally, one would like to remain agnostic on both (Can it be done?). Or one would like a much better handle on the noise (LIG input). Better input on the SGWB is not likely.

Our on-going work

- Work with Mauro Pieroni (“binner” code) and Martina Muratore (Trento, new TDI channels)
- Study of SNR for isotropic SGWBs for unequal fixed arms and unequal correlated noises, i.e. a more realistic set-up.
- The T channel fails and it is no longer “noise only”. (A, E, T) is very non-diagonal.
- The ζ channel is much more “noise only” and (A, E, ζ) are more diagonal
- Work-in-progress: Impact of using different TDI channels on SGWB and noise determination.
- Involved in the noise characterisation focus group lead by John Gair: benchmarking for SGWB detection.

GW emitted by stars orbiting SgrA* and tests of fundamental physics

"Theory and metrology group", SYRTE, Paris Observatory

LISA data analysis in France meeting, Caen, May 19th 2022

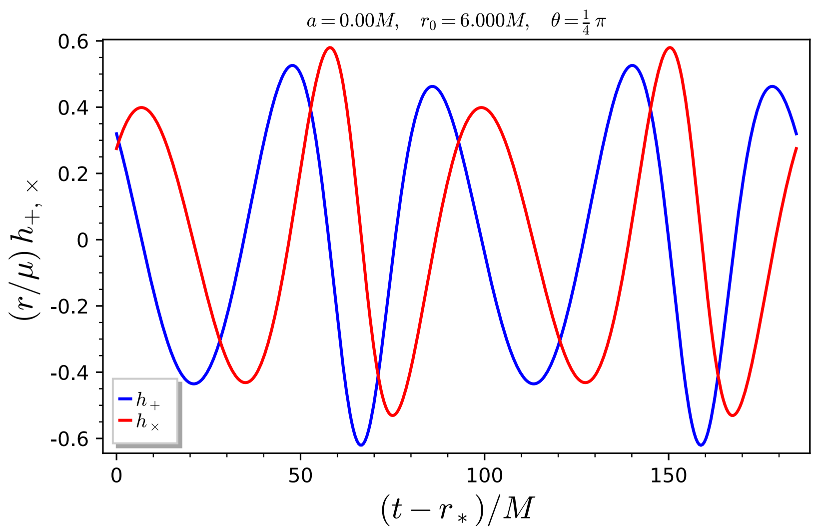
General info

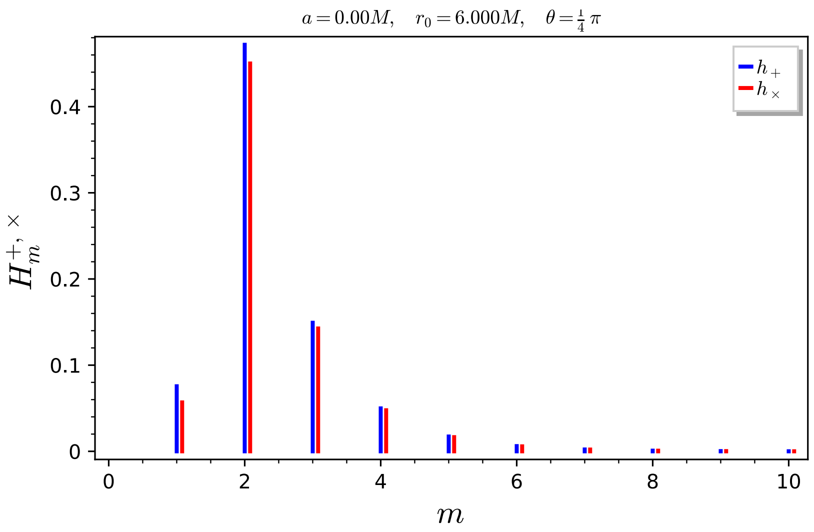
- Project started extremely recently (2 months ago)
- Scientists currently involved/interested:

  - S. Aoulad Lafkih (SYRTE)
  - E. Gourgoulhon (LUTH)
  - A. Hees (SYRTE)
  - C. Le Poncin-Lafitte (SYRTE)
  - A. Le Tiec (LUTH)
  - F. Vincent (LESIA)
- Main idea: galactic center is a highly active research area (motion of S stars, EHT image, …): what is expected from LISA?

EMRI around SgrA* as a Kerr BH

Theoretical work from LESIA/LUTH: GW emitted by a star in a equatorial circular orbit (close to ISCO: LISA band)



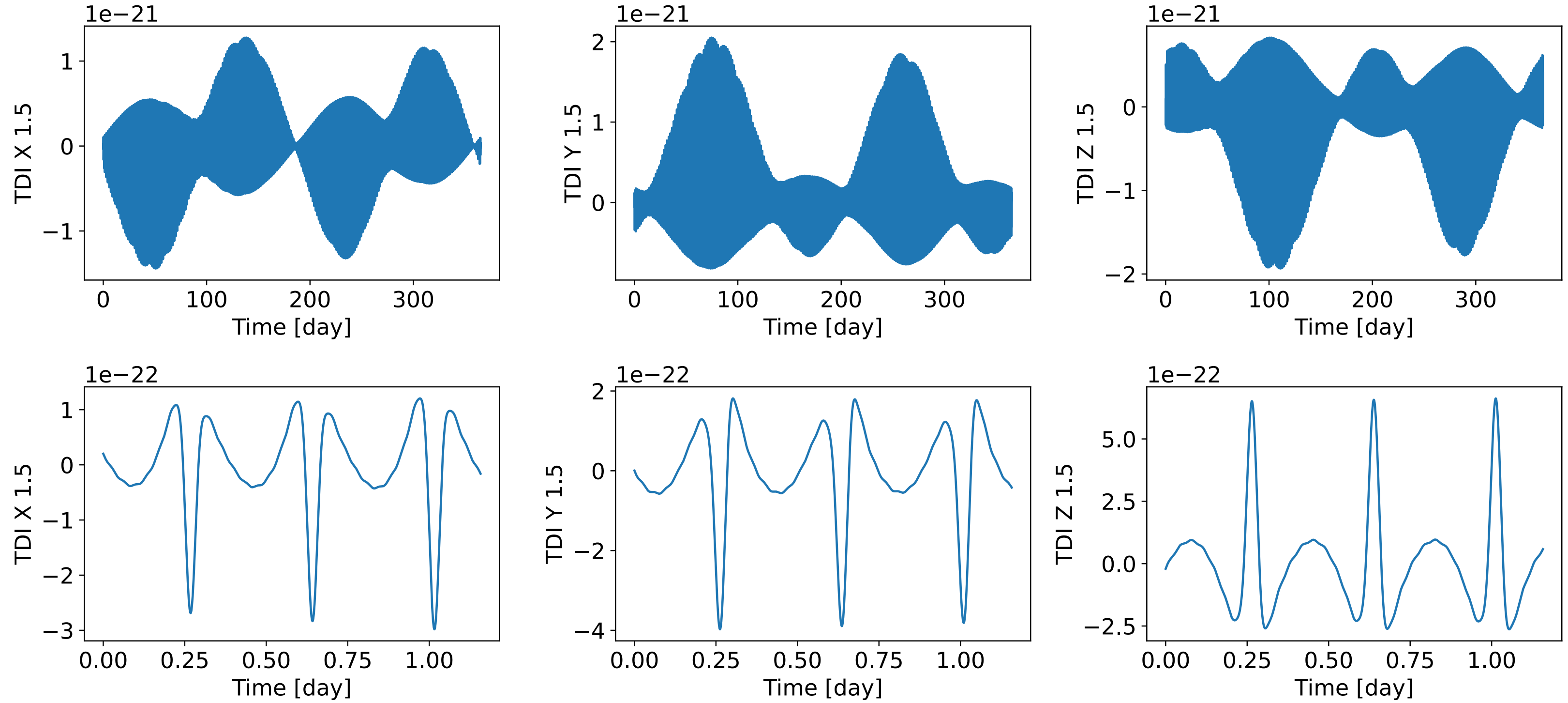


See Gourgoulhon et al, A & A, 2019

see *the kerrgeodesic_gw* sagemath package (from Eric Gourgoulhon)

EMRI around SgrA* as a Kerr BH

TDI response function for an EMRI orbiting SgrA*



Currently exploring: - how can we detect such stars? How many would be expected?

- how to differentiate them from a set of GB?
- development of an optimized fast response for this particular source. What about parameters estimation? (simplified since sky position is known)

Modified gravity

- A boson star is (still) a viable candidate for the compact object at the center of the galaxy (compact object with no horizon)
- It will impact significantly the trajectory of the surrounding stars

see Grould et al, CQG 2017

- Currently exploring: the GW emission by stars orbiting around a boson star: develop methods to produce the waveform
- Assess if such a difference can be assessed with LISA (TDI sensitivity analysis)
- Explore how this can be done in practice at the level of data analysis
- In the mid-term: consider other alternatives to the Kerr BH, other astrophysical effects (Dark Mass, etc…) and assess how LISA can play a role in GC science

Conclusion

- We are a “young” team regarding LISA DA currently exploring various projects
- Projects are developed following our scientific interest. Currently:
  - L0 – L1 data preprocessing
  - Galactic Binaries
  - Stochastic background
  - GW emitted by stars orbiting SgrA*