Towards a complete L0-L2 pipeline

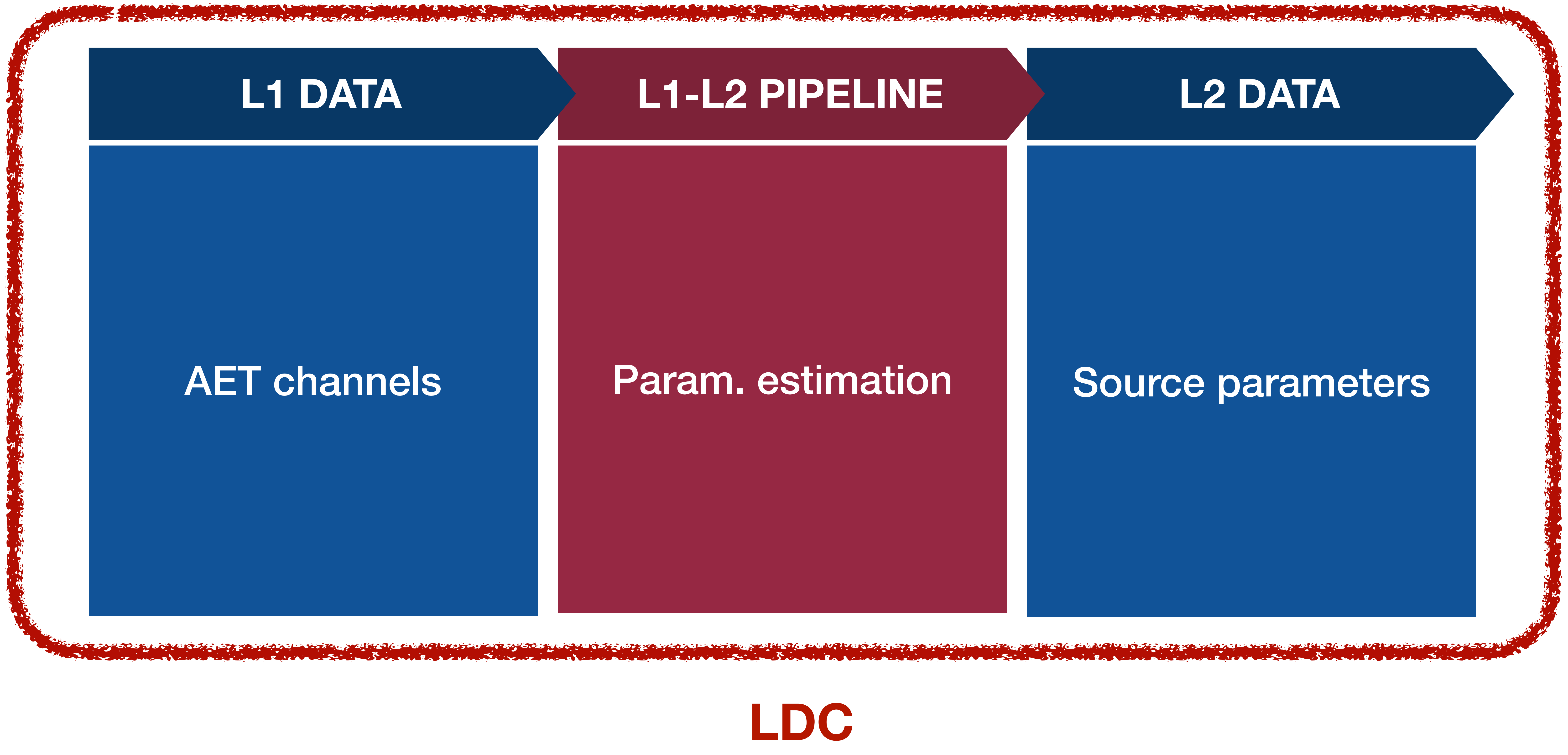
Progress in simulation, processing and analysis

SYRTE l'Observatoire de Paris | PSL

University of Glasgow

Jean-Baptiste Bayle and Olaf Hartwig – 2022 LIDA (Toulouse)

LISA Data Analysis Pipeline



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

LISA Data Analysis Pipeline

L0 SIMULATION

Orbits
GW response
Instrument
Ground tracking
…

L0/L0.5 DATA

Science data
Ground tracking
Housekeeping data

L0-L1 PIPELINE

Laser noise red.
Other noise (clock, spacecraft motion, tilt to length, etc.) reduction
Reference frame transformation

L1 DATA

TDI channels in global ref. frame (XYZ, AET, …)
Reconstructed orbits in global ref. frame
Noise models

L1-L2 PIPELINE

Param. estimation

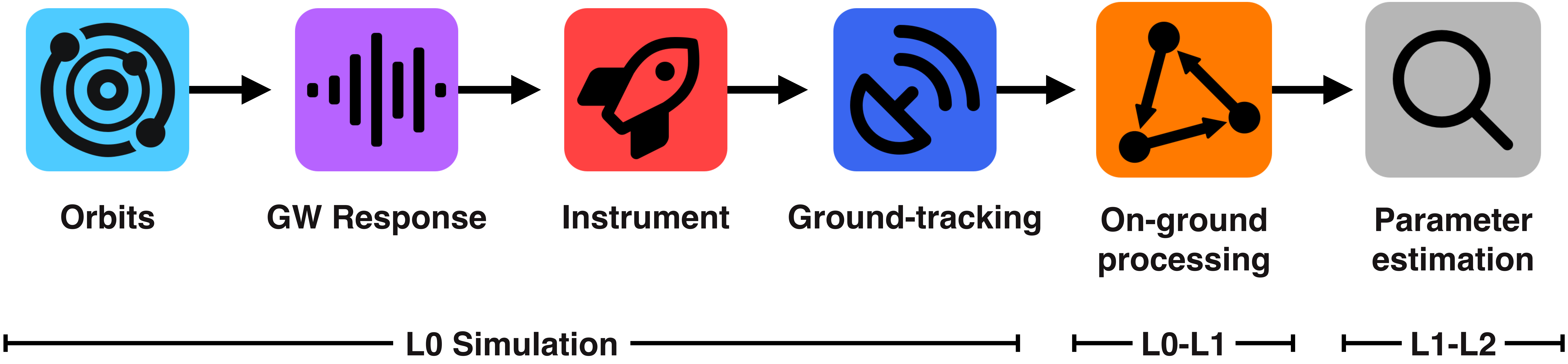
L0-L2 DEMONSTRATION PIPELINE

Context

- **Activity requested by ESA & LISA Consortium**
  - FMT Task 4.5 started only a few months ago
  - Preparation for mission adoption over summer 2023
  - Deliverables are a demonstration pipeline and some figures of merits (Before june?)
- Participants
  - University of Glasgow (Jean-Baptiste Bayle, Christian Chapman-Bird, Graham Wohan)
  - SYRTE (Olaf Hartwig, Aurelien Hees, Marc Lilley, Peter Wolf)

Method

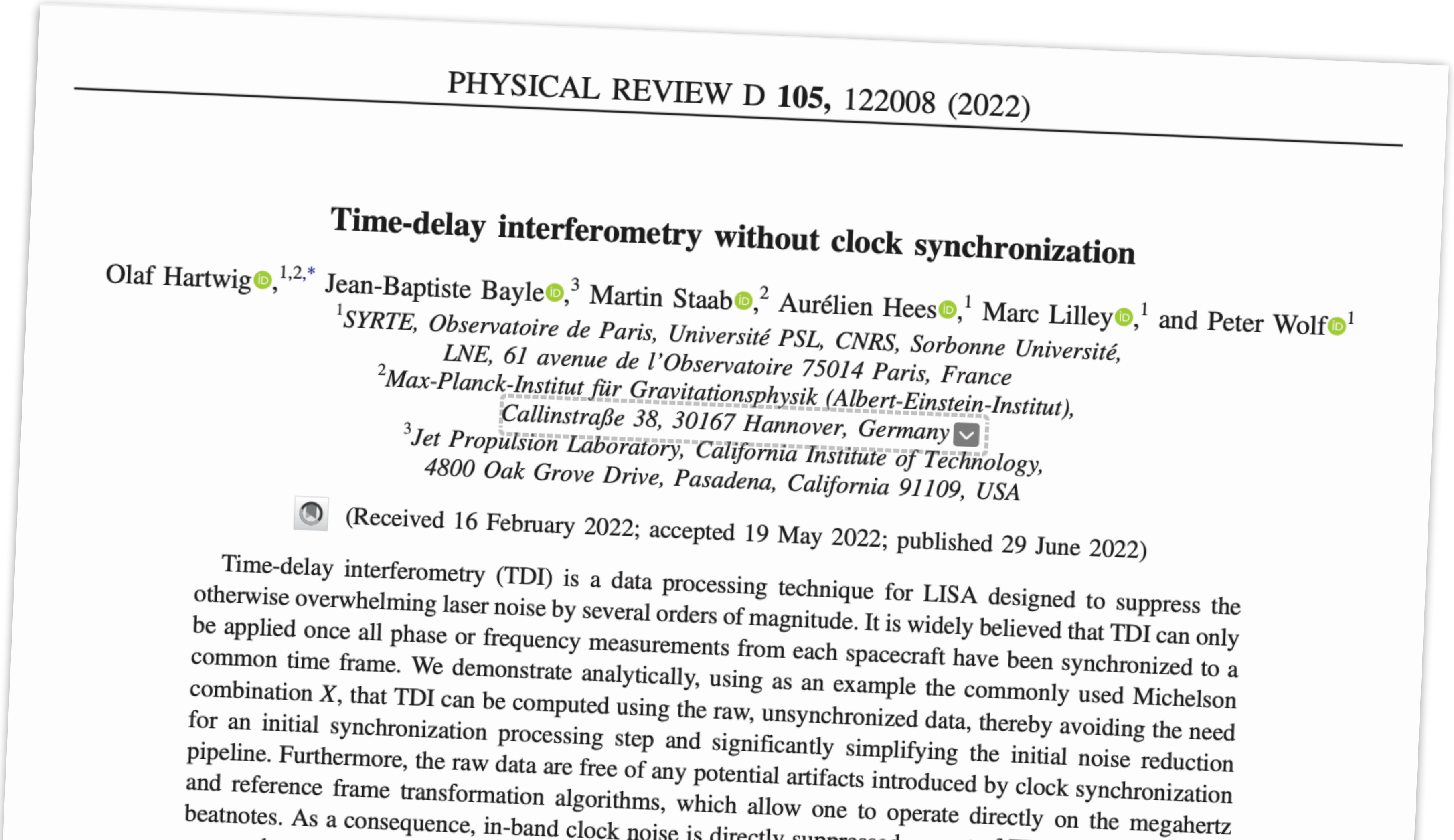
- Build a pipeline with various processing blocks



- Assemble the blocks and builds performance metrics

Method

- Processing blocks exist in multiple versions (various configurations)
  - Start with simplified configurations
  - Increase model faithfulness (and processing accordingly) and assess metric variations
- Short timeframe, so restrict the activity to
  - Rather simple target configuration
    - Well separated loud Galactic binary sources
    - Current best simulation model of the instrument
    - Processing derived from 10.1103/PhysRevD.105.122008
    - Parameter estimation based on LDC
  - Identify impactful effects (and try to mitigate them?)


PHYSICAL REVIEW D **105**, 122008 (2022)

Time-delay interferometry without clock synchronization

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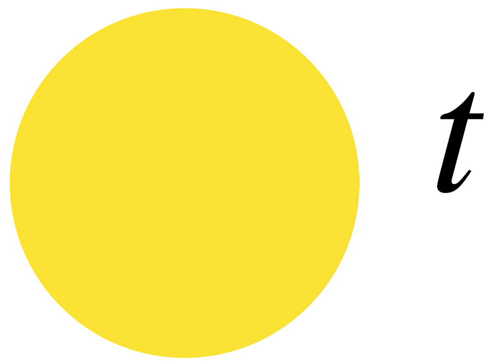
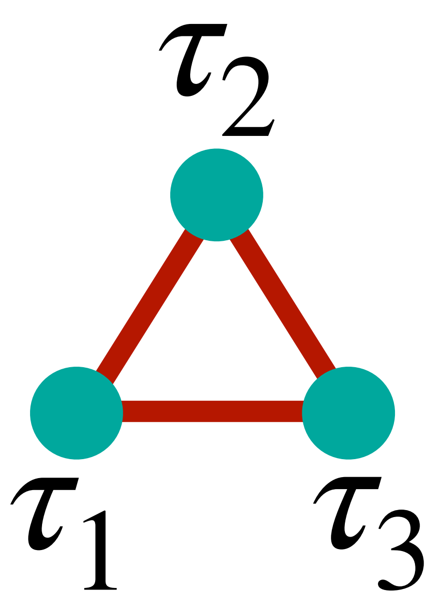
Time-delay interferometry (TDI) is a data processing technique for LISA designed to suppress the otherwise overwhelming laser noise by several orders of magnitude. It is widely believed that TDI can only be applied once all phase or frequency measurements from each spacecraft have been synchronized to a common time frame. We demonstrate analytically, using as an example the commonly used Michelson combination X, that TDI can be computed using the raw, unsynchronized data, thereby avoiding the need for an initial synchronization processing step and significantly simplifying the initial noise reduction pipeline. Furthermore, the raw data are free of any potential artifacts introduced by clock synchronization and reference frame transformation algorithms, which allow one to operate directly on the megahertz beatnotes. As a consequence, in-band clock noise is directly

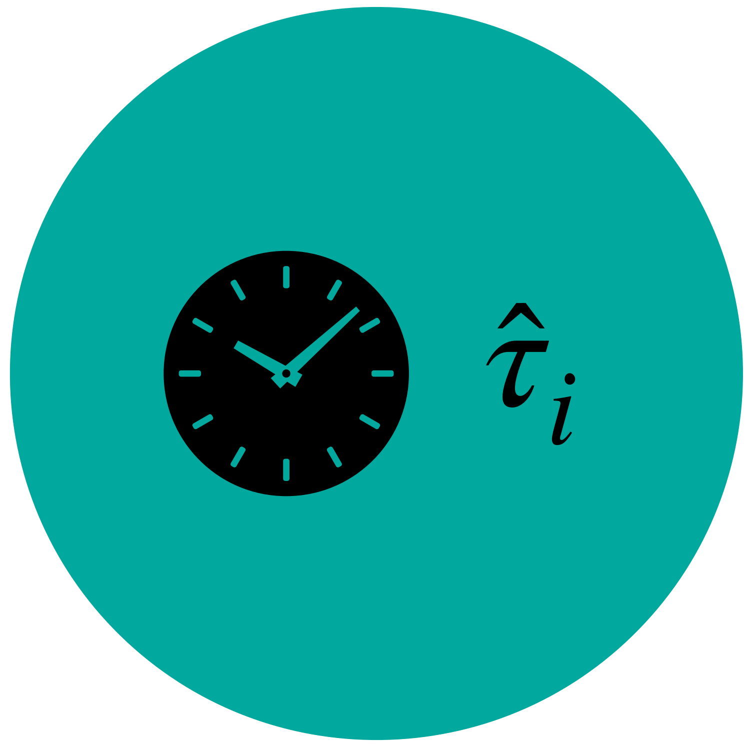
L0 Simulation

Timescales

- **Global TCB time t**
  - Defined as time shown of a perfect clock sitting at Solar system barycenter
  - Global timescale, used for orbits and GW strain
- **One proper time τ_i for each spacecraft i ($i = 1,2,3$)**
  - Defined as time shown by a *perfect* clock sitting in spacecraft i
  - Related to t (and each other) by General Relativity
  - Used to describe physics inside one spacecraft
- **One onboard clock time $\hat{\tau}_i$ for each spacecraft i ($i = 1,2,3$)**
  - Defined as time shown by the *actual* clock sitting in spacecraft
  - Differs from τ_i by instrumental imperfections
  - Only timescales directly accessible by the satellites



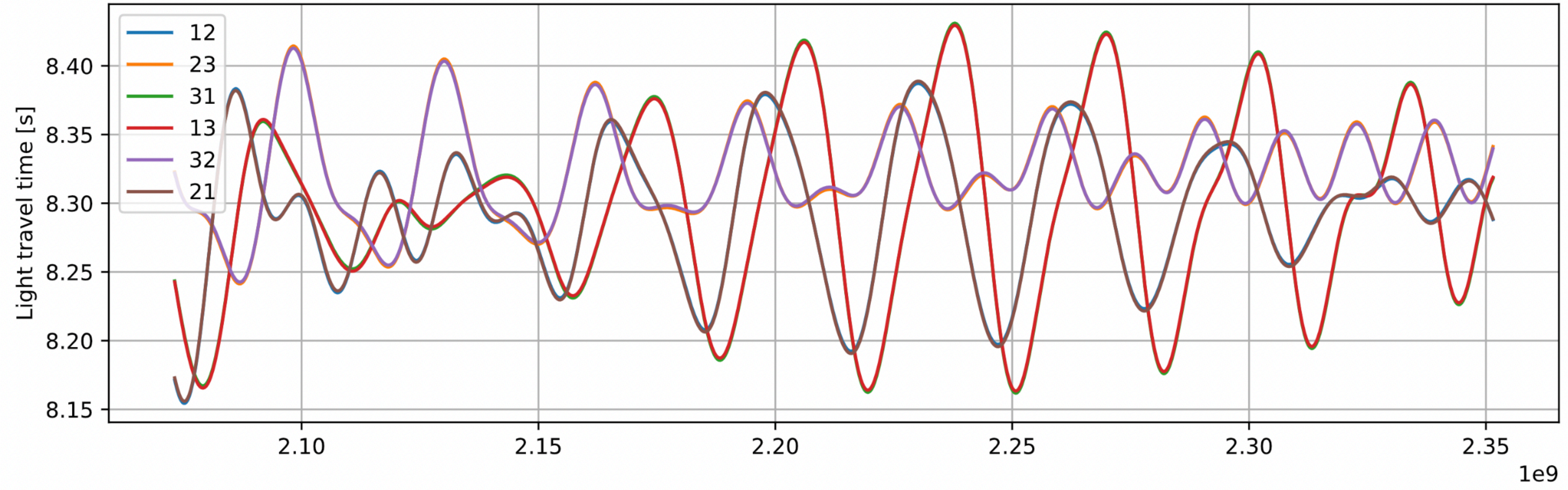




Orbits

- Use ESA numerically optimized orbits
- Interpolate spacecraft state vectors and compute necessary quantities (e.g., light travel times and relativistic relationships between reference frames) with

Bayle, Jean-Baptiste, Hees, Aurélien, Lilley, Marc, & Le Poncin-Lafitte, Christophe. (2022). LISA Orbits (2.0). Zenodo. https://doi.org/10.5281/zenodo.6412992



GW Response

- Compute frequency shift due to gravitational waves measured on each optical bench (link responses) in the spacecraft proper time frames with

  Bayle, Jean-Baptiste, Baghi, Quentin, Renzini, Arianna, & Le Jeune, Maude. (2022). LISA GW Response (1.1). Zenodo. https://doi.org/10.5281/zenodo.6423436

- Model fully described described in documentation
  - Deformation induced on link 12 is $H_{12}(t) = h_+^{\mathrm{SSB}}(t)\xi_+(\hat{\mathbf{u}}, \hat{\mathbf{v}}, \hat{\mathbf{n}}_{12}) + h_\times^{\mathrm{SSB}}(t)\xi_\times(\hat{\mathbf{u}}, \hat{\mathbf{v}}, \hat{\mathbf{n}}_{12})$
  - Reception time t_1 of a photon emitted at t_2 is $t_1 \approx t_2 + \frac{L_{12}}{c} - \frac{1}{2c}\int_0^{L_{12}} H_{12}(\mathbf{x}(\lambda), t(\lambda))\,\mathrm{d}\lambda$
  - We substitute and differentiate to obtain the frequency shift

$$y_{12}(t_1) \approx \frac{1}{2\left(1 - \hat{\mathbf{k}}\cdot\hat{\mathbf{n}}_{12}(t_1)\right)} \left[H_{12}\left(t_1 - \frac{L_{12}(t_1)}{c} - \frac{\hat{\mathbf{k}}\cdot\mathbf{x}_2(t_1)}{c}\right) - H_{12}\left(t_1 - \frac{\hat{\mathbf{k}}\cdot\mathbf{x}_1(t_1)}{c}\right)\right]$$

  - Resample to proper times $\hat{\tau}_1(t)$ using orbits

Instrument Simulation

- Simulation model available in a paper *in prep*. and the LISA Instrument Simulation Model document (available here for the consortium members)

  Bayle, Jean-Baptiste, Hartwig, Olaf, & Staab, Martin. (2022).
  LISA Instrument (1.1.1). Zenodo. https://doi.org/10.5281/zenodo.7071251

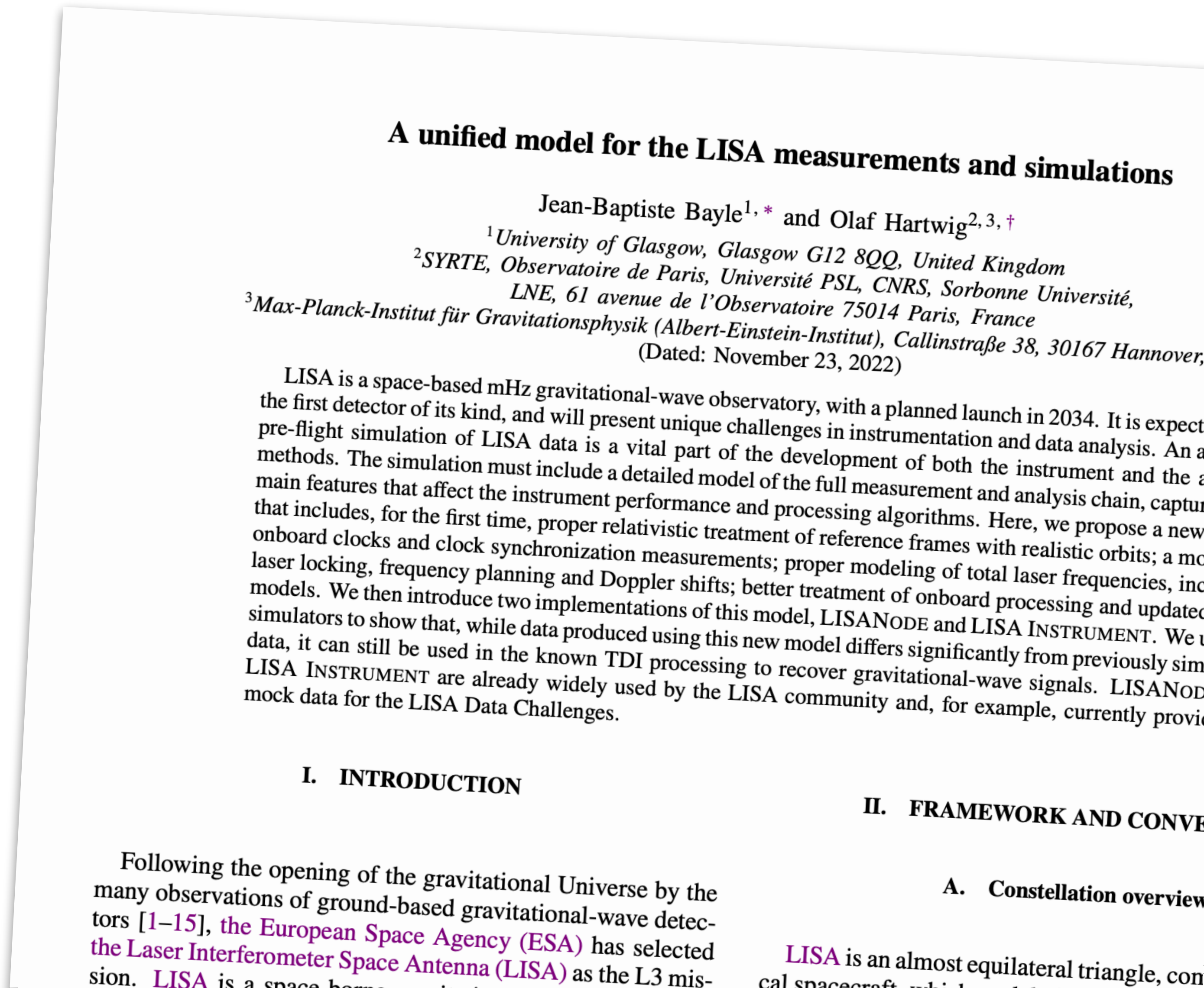
- Instrumental simulation includes

  Optics (modulation and propagation of laser beams, main interferometric measurements and auxiliary measurements)

  Dynamics (motion of spacecraft and test masses) – currently limited

  Onboard processing (digital sampling, filtering and downsampling)

- Two sampling rates
  - Measurements telemetered at 4 Hz
  - Physics simulated at 16 Hz (inputs upsampled during simulation)



A unified model for the LISA measurements and simulations

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(Dated: November 23, 2022)

LISA is a space-based mHz gravitational-wave observatory, with a planned launch in 2034. It is expect the first detector of its kind, and will present unique challenges in instrumentation and data analysis. An a pre-flight simulation of LISA data is a vital part of the development of both the instrument and the a methods. The simulation must include a detailed model of the full measurement and analysis chain, captu main features that affect the instrument performance and processing algorithms. Here, we propose a new that includes, for the first time, proper relativistic treatment of reference frames with realistic orbits; a mo onboard clocks and clock synchronization measurements; proper modeling of total laser frequencies, inc laser locking, frequency planning and Doppler shifts; better treatment of onboard processing and update models. We then introduce two implementations of this model, LISANode and LISA Instrument. We u simulators to show that, while data produced using this new model differs significantly from previously sim data, it can still be used in the known TDI processing to recover gravitational-wave signals. LISANod LISA Instrument are already widely used by the LISA community and, for example, currently provi mock data for the LISA Data Challenges.

I. INTRODUCTION

Following the opening of the gravitational Universe by the many observations of ground-based gravitational-wave detectors [1–15], the European Space Agency (ESA) has selected the Laser Interferometer Space Antenna (LISA) as the L3 mission. LISA is a space-base...

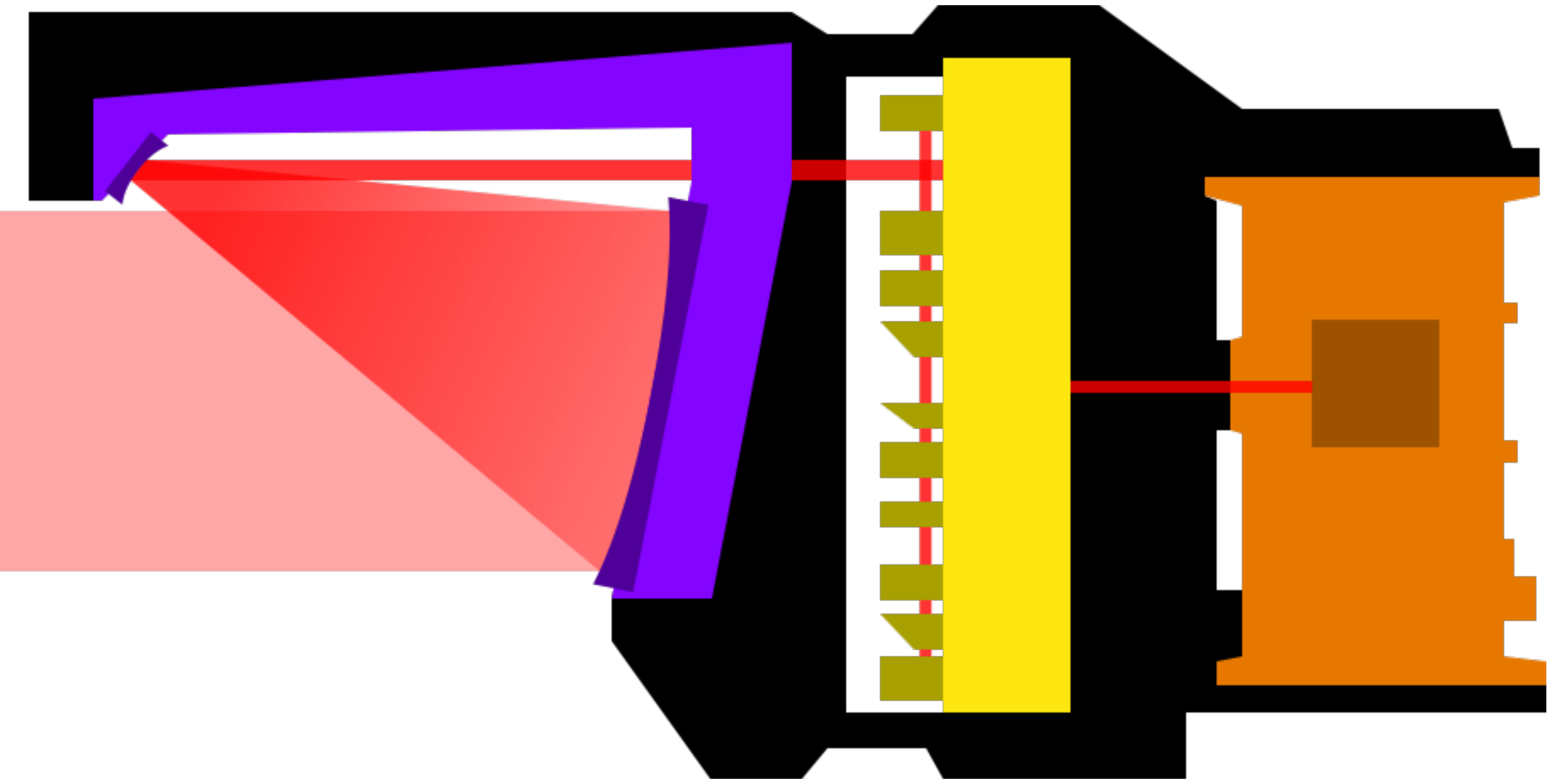
II. FRAMEWORK AND CONVE...

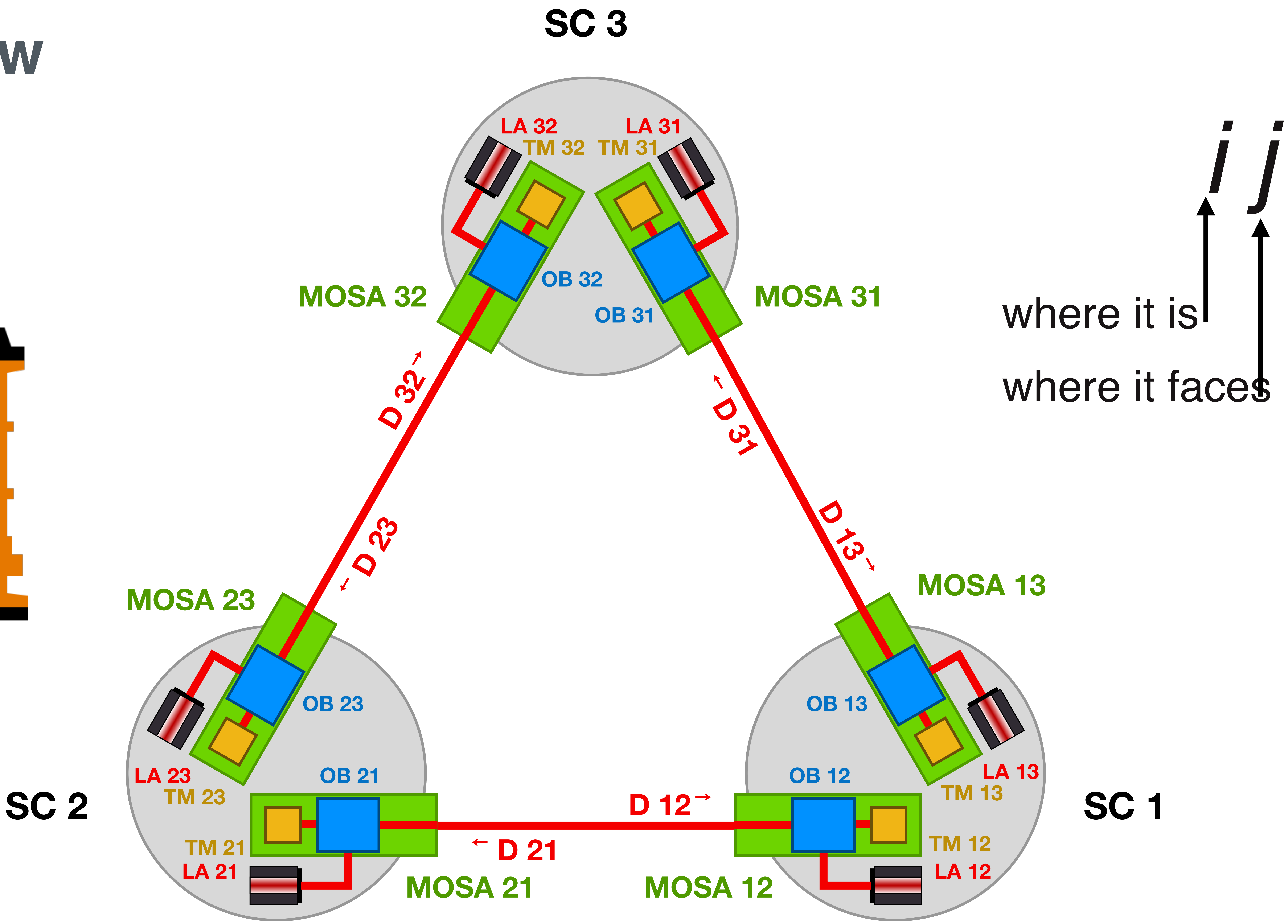
A. Constellation overview

LISA is an almost equilateral triangle, con... cal spacecraft...

Instrument Simulation

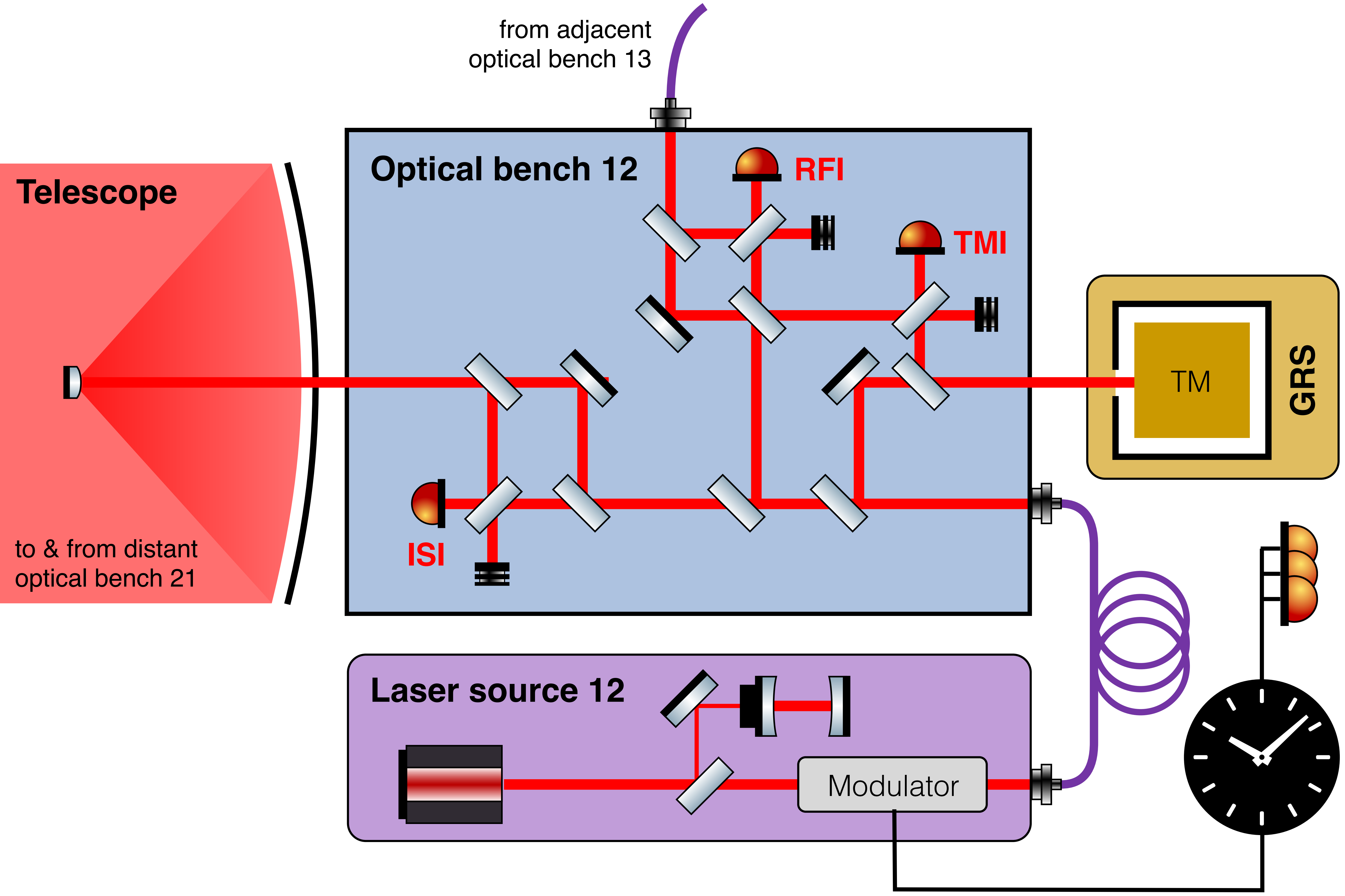
Constellation Overview





Instrument Simulation

Optical Bench Overview



- 3 main interferometric signals recorded on each optical bench
  - **Inter-spacecraft interferometer** (ISI)
  - **Reference interferometer** (RFI)
  - **Testmass interferometer** (TMI)
- Interferometer data sampled according to onboard clock
- Modulate laser beams using clock signal to correct for sampling errors during L0-L1 processing

Instrument Simulation

Laser Beams

- Electromagnetic field $E(\tau) = E_0(\tau)\cos(2\pi\Phi(\tau))$
- GW signals encoded in the oscillating part of the field
- Simulate total frequencies $\nu(\tau) = \dot{\Phi}(\tau)/2\pi$ – *not just strain*!

$$\nu(\tau) = \nu_0 + \nu^o(\tau) + \nu^\epsilon(\tau)$$

total instantaneous frequency → $\nu(\tau)$

central frequency → ν_0
constant 281.6 THz

frequency offsets → $\nu^o(\tau)$
freq. plan, Dopplers, etc.
$\approx 10\,\mathrm{MHz}$

frequency fluctuations → $\nu^\epsilon(\tau)$
Noises, GW, etc.
$\approx 100\,\mathrm{Hz} + 100\,\mathrm{nHz}$

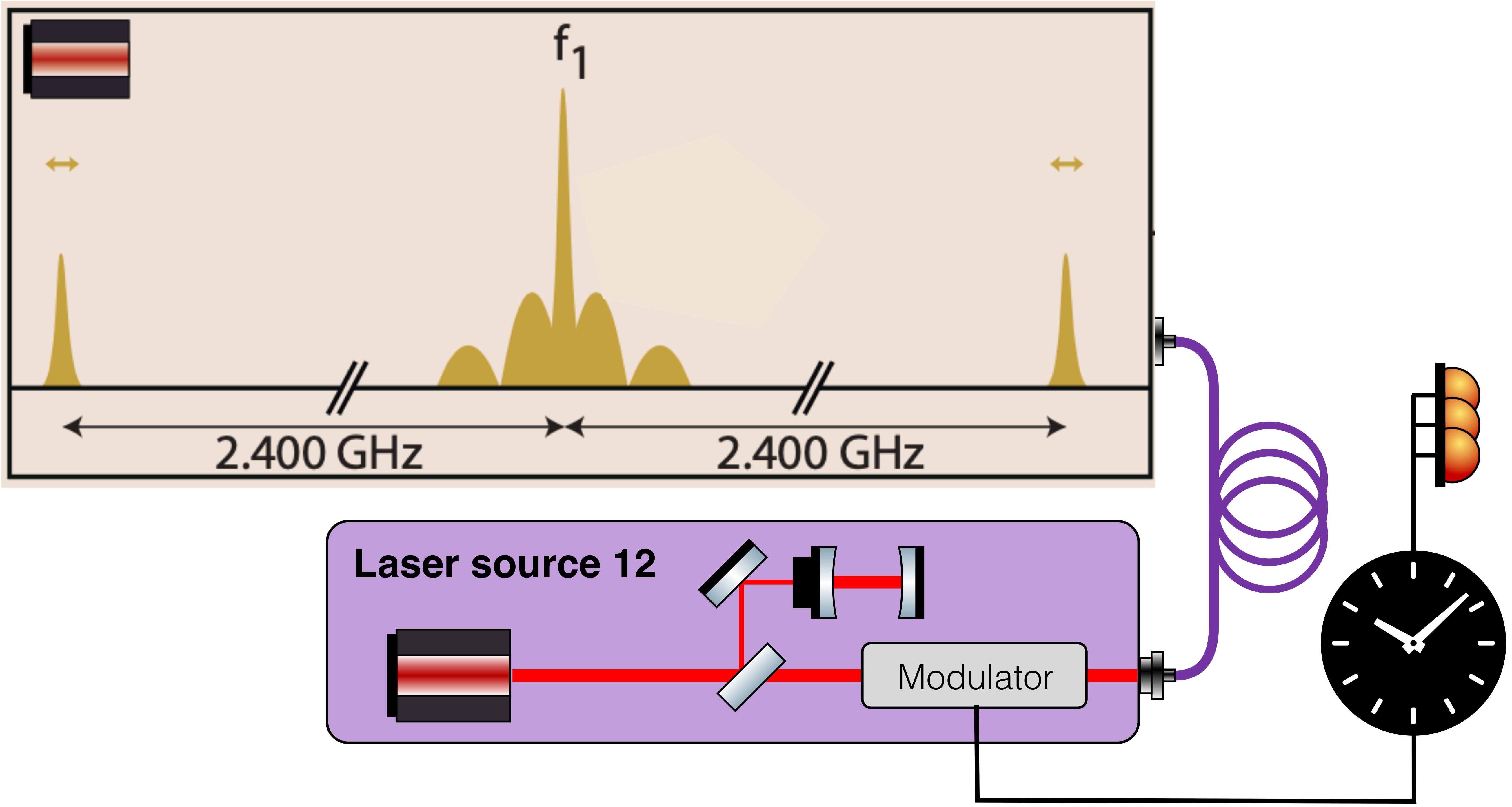
Instrument Simulation

Beam Modulation

- Onboard clocks used to sample data, therefore contribute to *phase errors*
- Phase modulation used to measure the in-band part of this clock noise

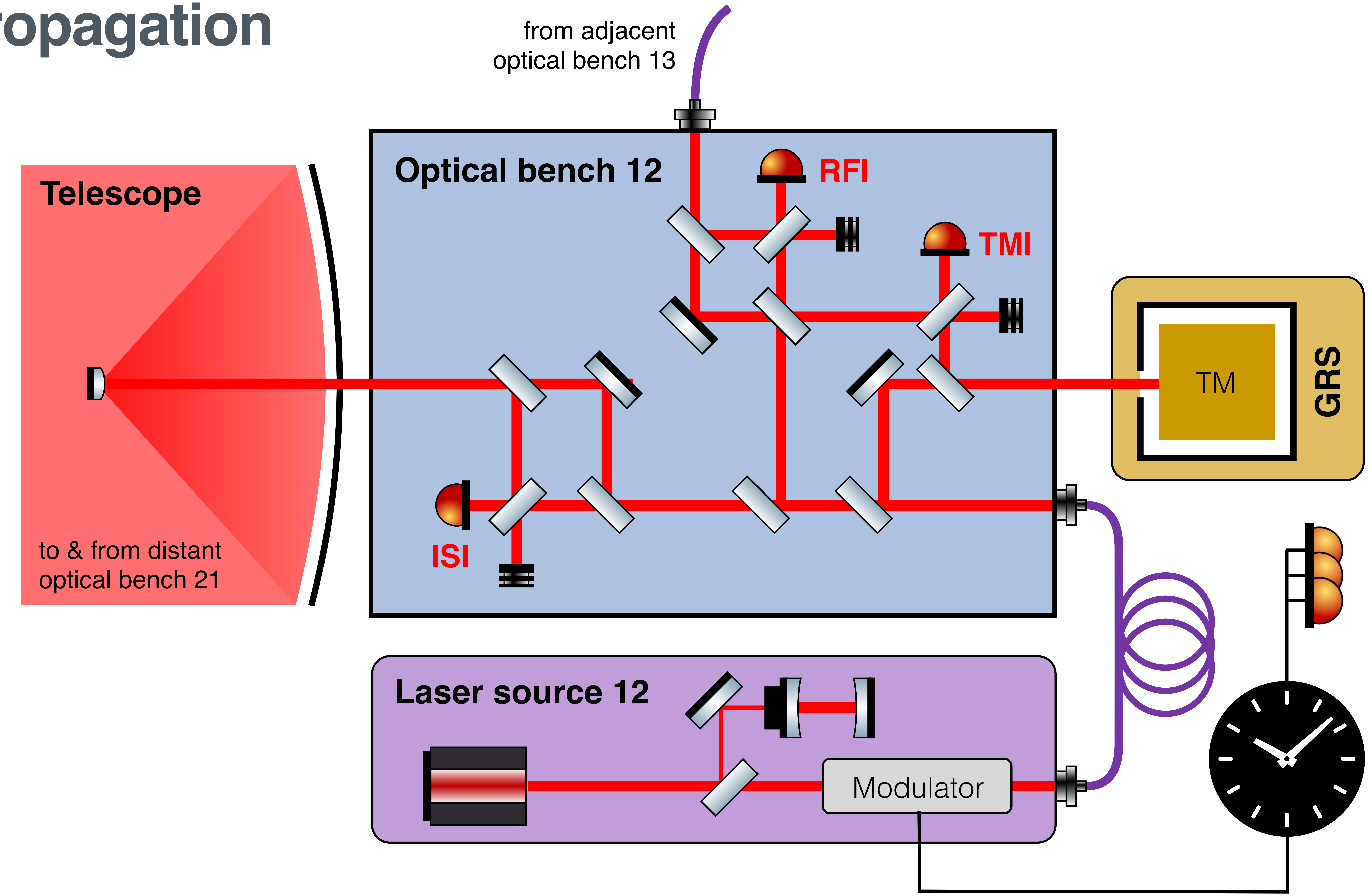
$$\mathrm{E}(\tau) = E_0 e^{j2\pi(\Phi_c(\tau)+m\Phi_m(\tau))}$$

- Modeled as "independent" sideband beams (expansion with Bessel functions)



Instrument Simulation

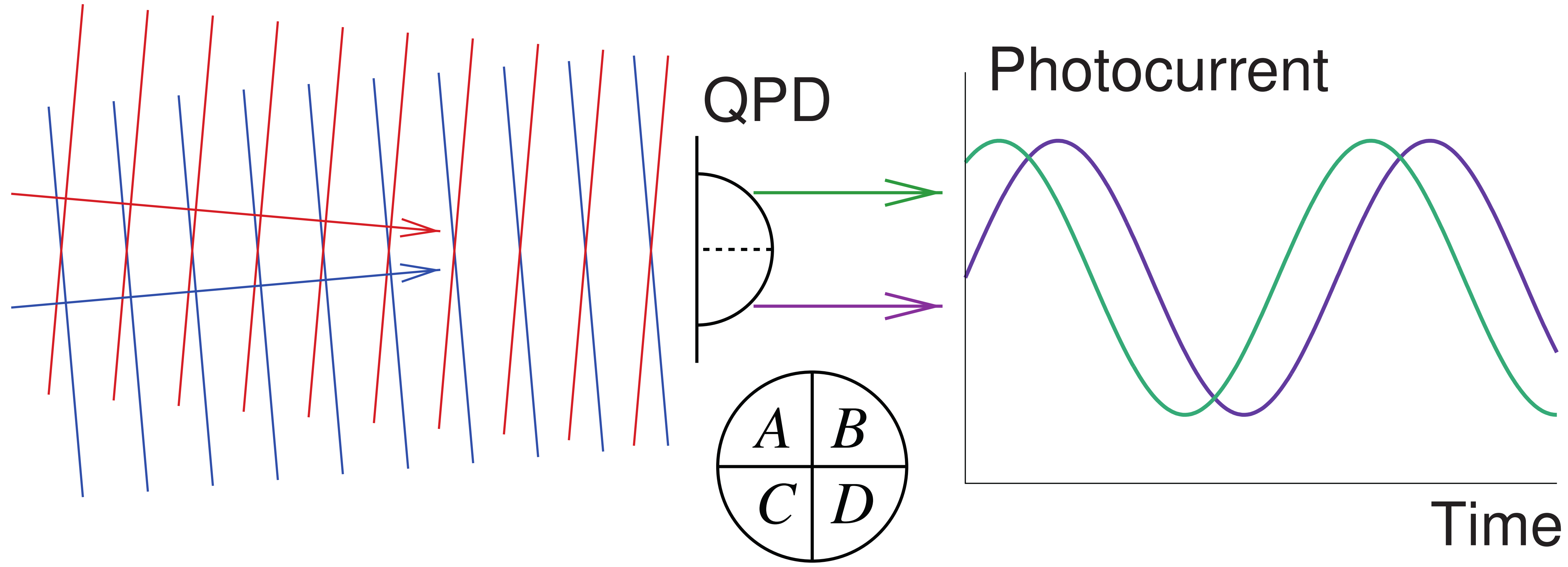
Beam Propagation

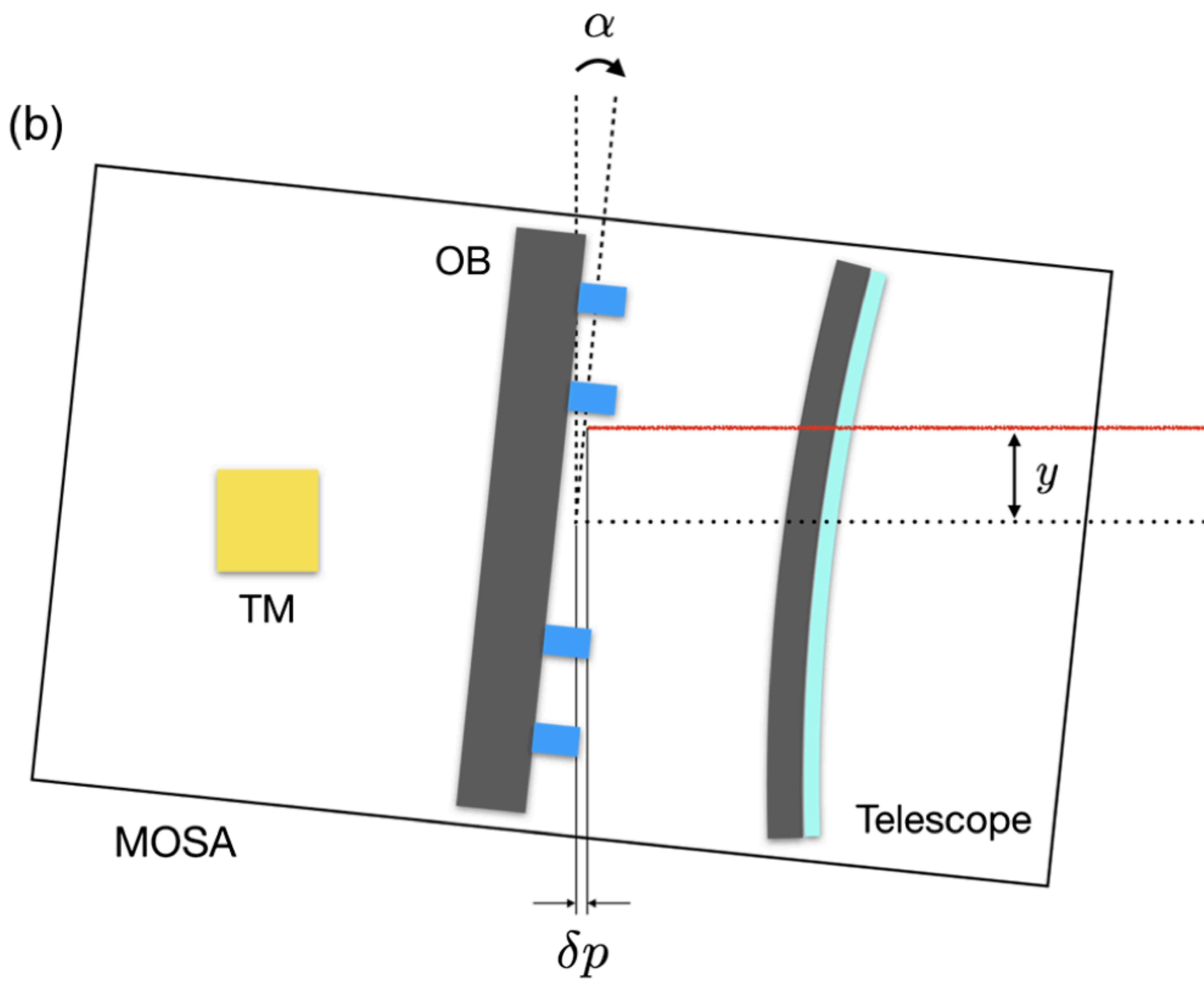


Instrument Simulation

Tilt to Length (TTL)

- **Tilt to length couples beam tilts and optical element misalignment to pathlength changes**
- Linear model with a set of 24 coefficients relating tilt angles to pathlength changes
- DWS allows to measure angular tilts of 2 beams by combining outputs of a quadrant photodiode





Paczkowski et al. (2022). 10.1103/PhysRevD.106.04200

Instrument Simulation

Inter-spacecraft Propagation

- Phase is a frame invariant quantity, so total phase is equal at reception and emission
- Signals propagated between spacecraft using **proper pseudoranges (PPRs)**, which include **light travel times** and conversion factor between spacecraft proper times
- In addition,
  - GWs cause a tiny ($\approx 10^{-20}\,\mathrm{s}$) additional modulation of the PPR
  - Additional Doppler shifts with frequency data

$$\nu_{ij\leftarrow ji}(\tau) = \frac{\mathrm{d}}{\mathrm{d}\tau}\Phi_{ji}(\tau - d_{ij}(\tau) - H_{ij}(\tau)) = (1 - \dot{d}_{ij}(\tau) - \dot{H}_{ij}(t))\nu_{ji}(\tau - d_{ij}(\tau))$$

PPRs

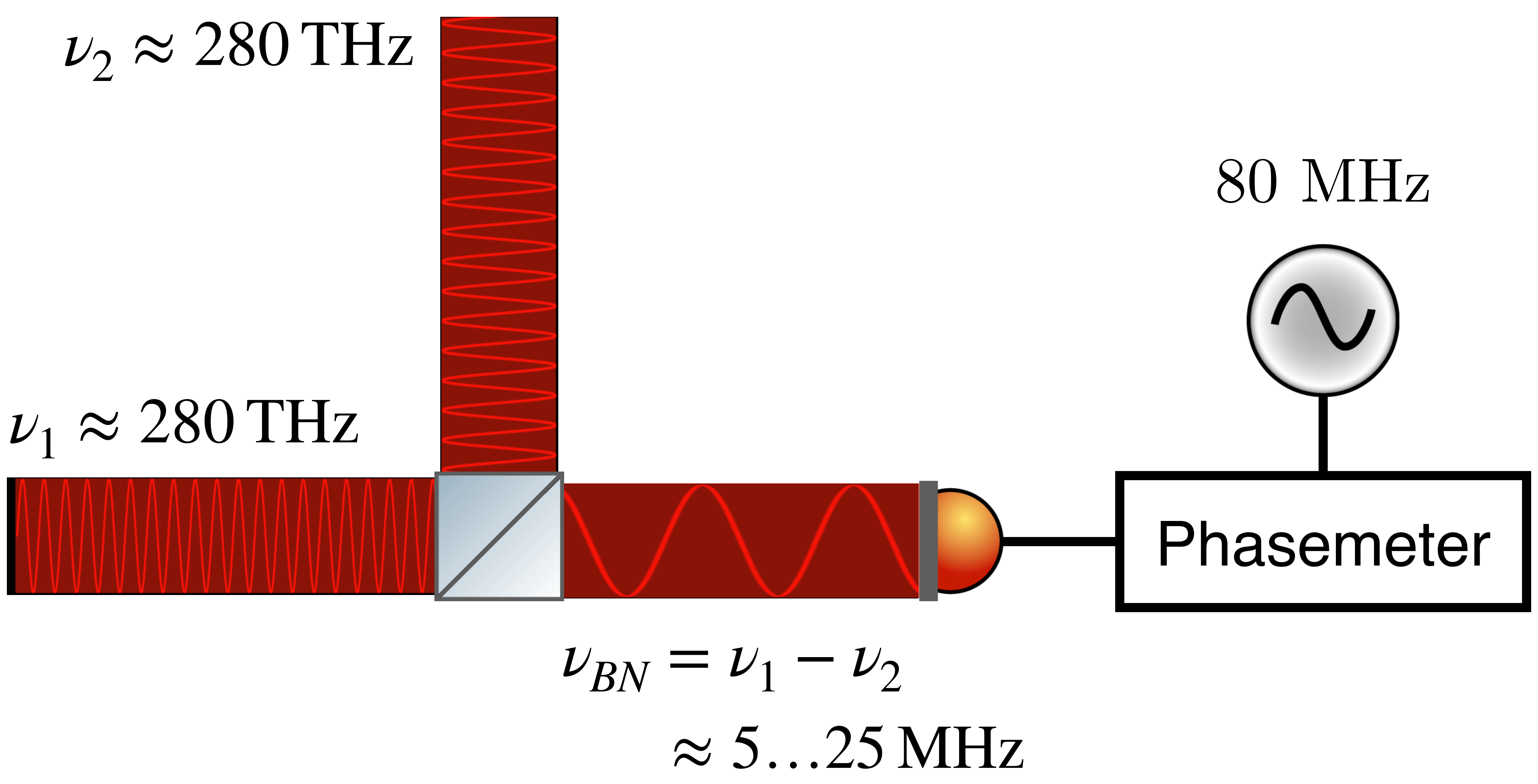
total instantaneous frequency

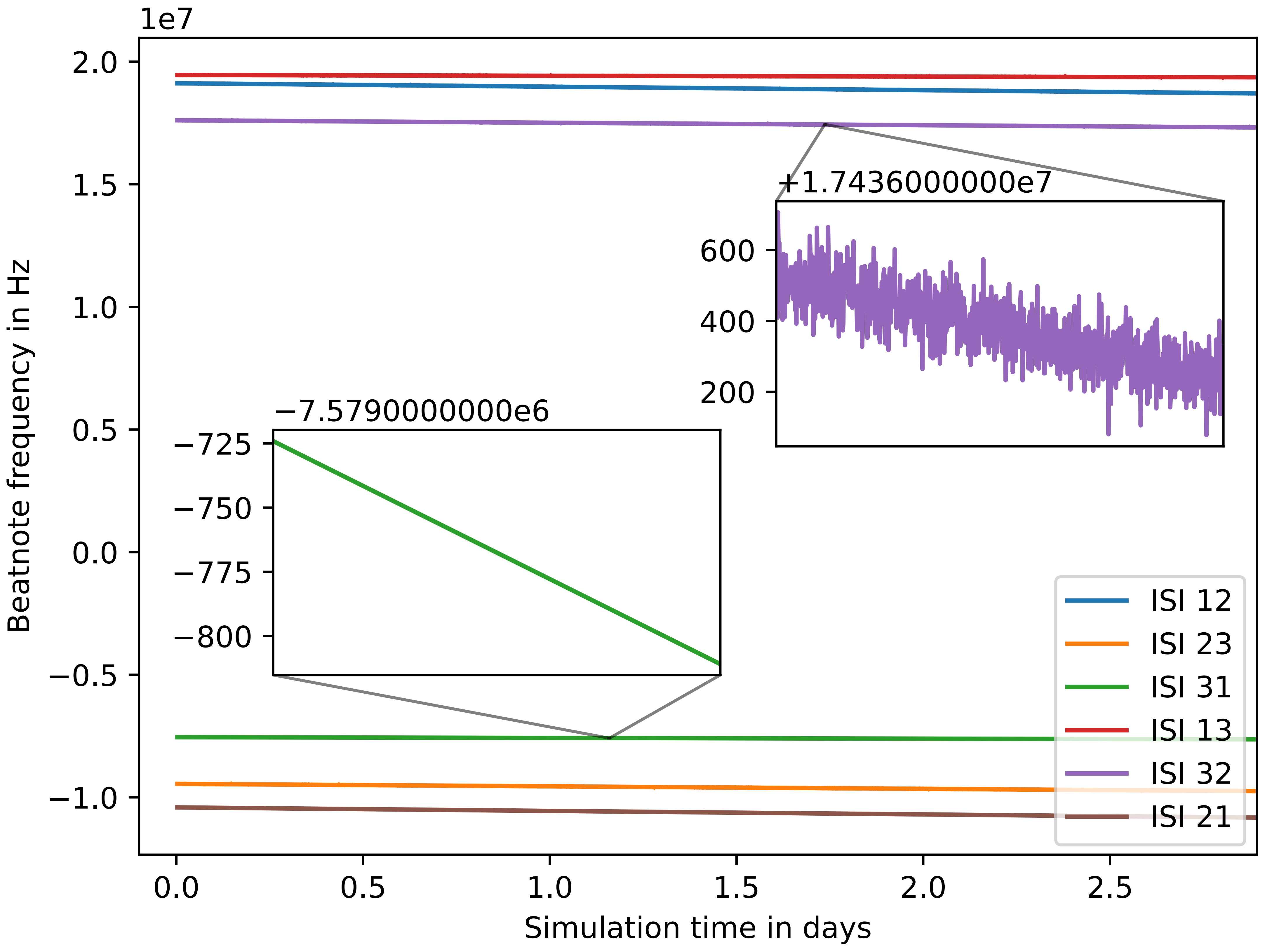
Doppler shift

Instrument Simulation

Interferometry & Readout

- LISA uses heterodyne interferometry and GW is encoded as μ-cycle phase fluctuation in MHz beatnotes (in frequency)
- Beatnotes recorded according to local clock

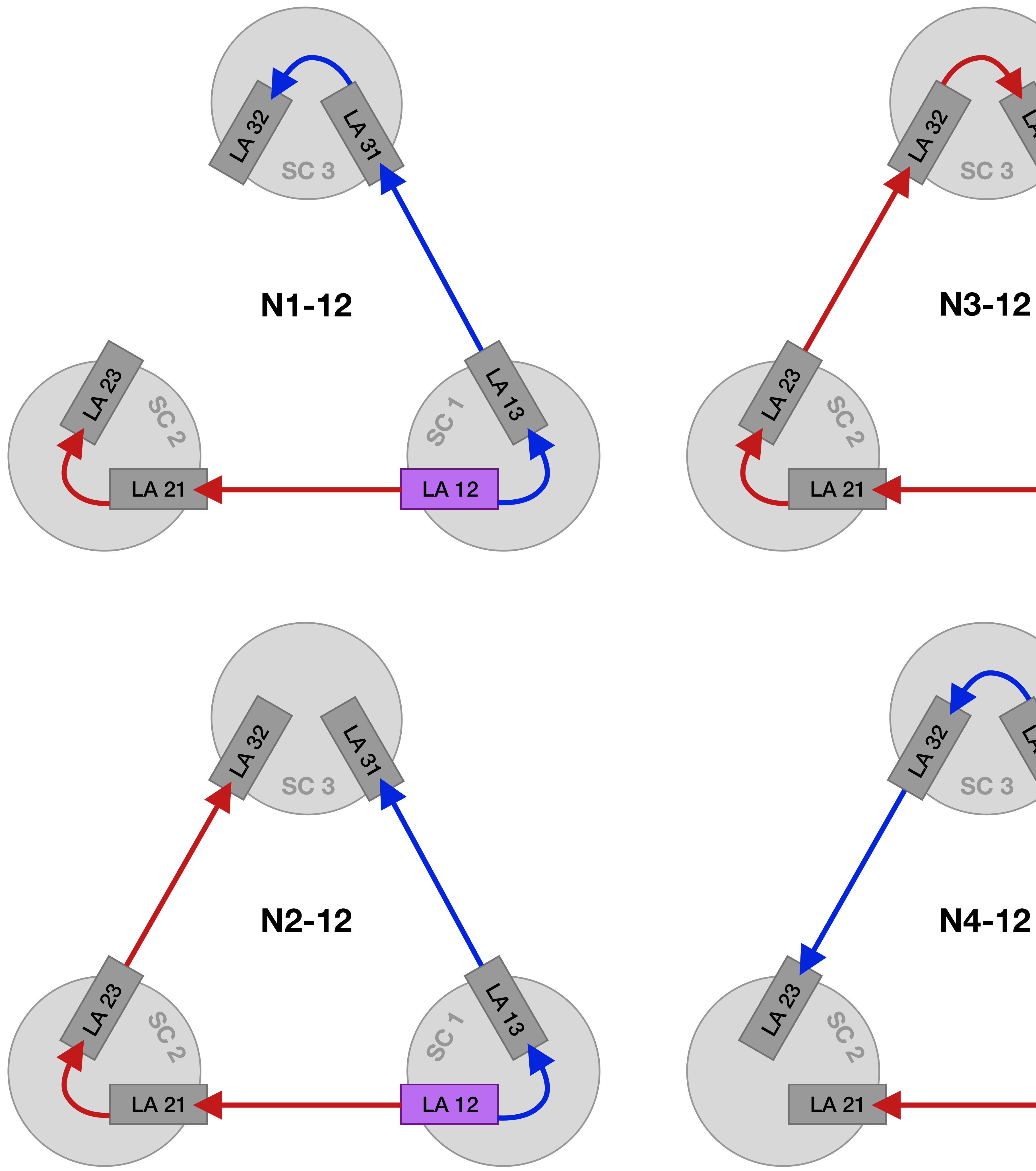




Instrument Simulation

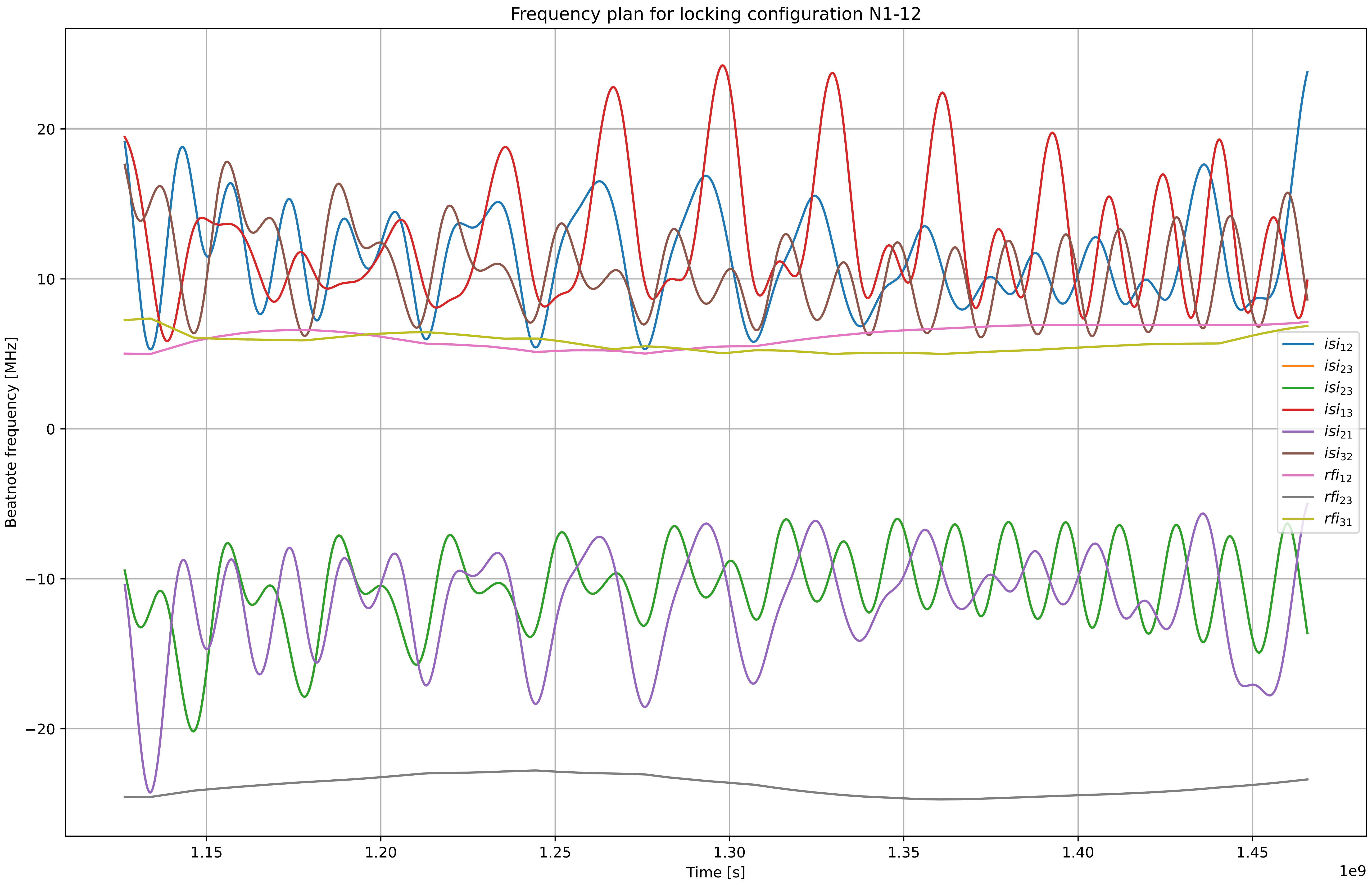
Laser Locking & Frequency Plan

- All beatnotes should fall into the phasemeter validity frequency range (5 to 25 MHz)
  - Doppler shifts frequencies by 10s of MHz
  - Solution: lock lasers (many configurations possible) with an optimized precomputed frequency plan
- Frequency plan optimized numerically by G. Heinzel
- As a consequence, noises are distributed over different beatnotes



Instrument Simulation

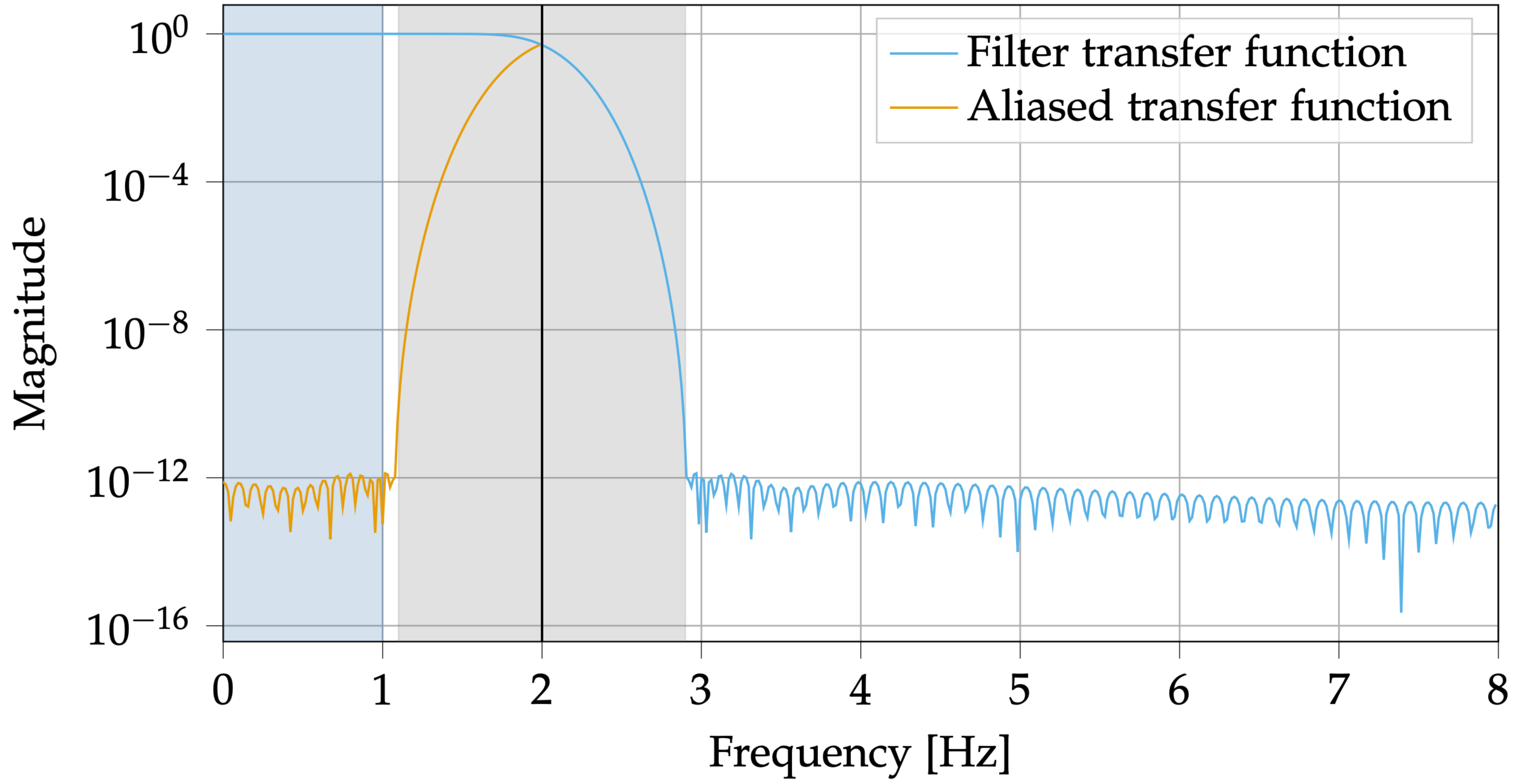
Laser Locking & Frequency Plan

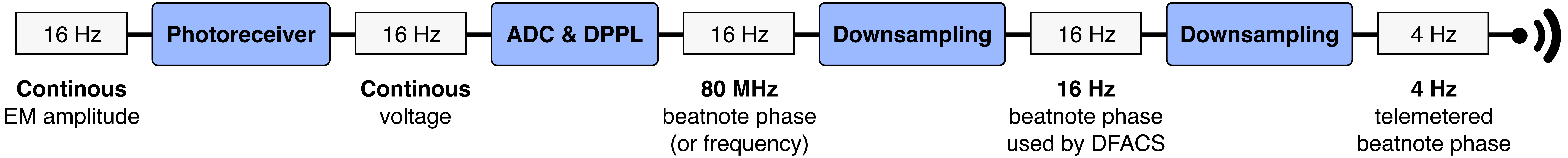


Instrument Simulation

Onboard Processing

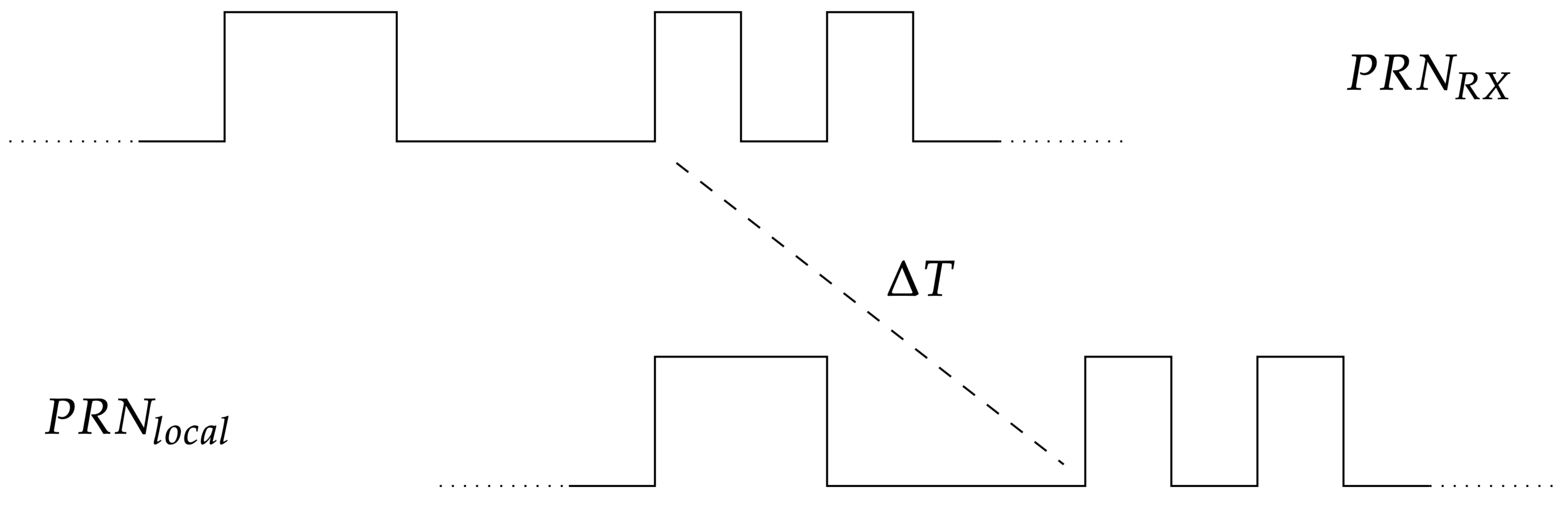
- In reality
  - Phasemeter runs at 80 MHz
  - Filtered and downsampled in several steps to final 4 Hz telemetry
- In simulation
  - Physics and phasemeter at 16 Hz
  - Single filter and decimation step to 4 Hz



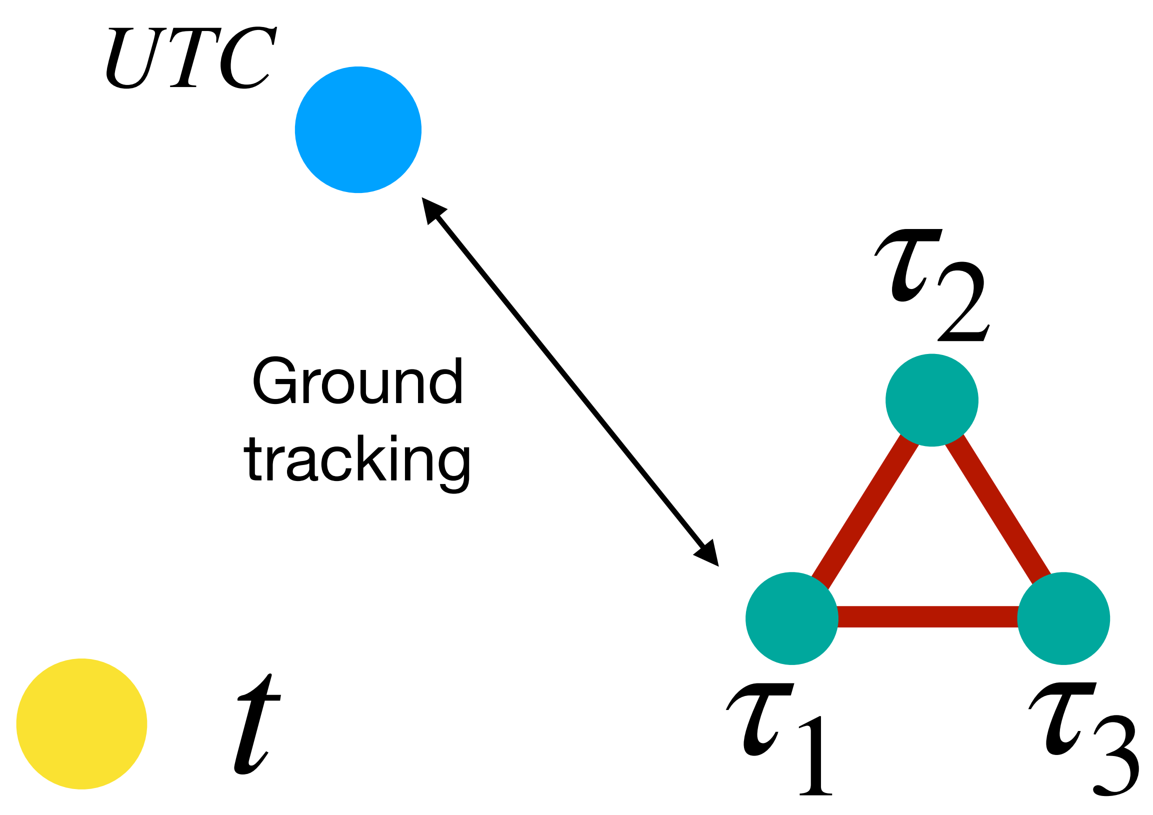


MPR & Ground Tracking

- Measured pseudoranges (MPRs)
  - Correlate signals from two distant clocks
  - Include photon light travel time and transformation between clock times $\Delta T = \hat{\tau}_i - \hat{\tau}_j$ (and any correlation errors)



- Ground tracking provides estimates of
  - Spacecraft positions with 2-50 km accuracy (direction dependent) and spacecraft velocities with 10 cm/s accuracy
  - Time correlations between clocks and a global time frame (here UTC) better than ms accuracy



L0 Data Overview

- Science data
  - 3 interferometer data (carrier and sideband) on the 6 optical benches
  - Measured pseudoranges (MPRs)
  - Differential waveform sensor (DWS) measurements
  - Other quantities not simulated currently (GRS, etc).
- Ground-tracking
  - Reconstructed orbits
  - Time correlations (clock times as a function of a global reference frame)
- Housekeeping and calibration stuff (lots of ’em)

L0-L1 Processing

LISA Data Analysis Pipeline

0 SIMULATION

Orbits
GW response
Instrument
round tracking
…

L0/L0.5 DATA

Science data
Ground tracking
Housekeeping data

L0-L1 PIPELINE

Laser noise red.
Other noise (clock, spacecraft motion, tilt to length, etc.) reduction
Reference frame transformation

L1 DATA

TDI channels in global ref. frame (XYZ, AET, …)
Reconstructed orbits in global ref. frame
Noise models

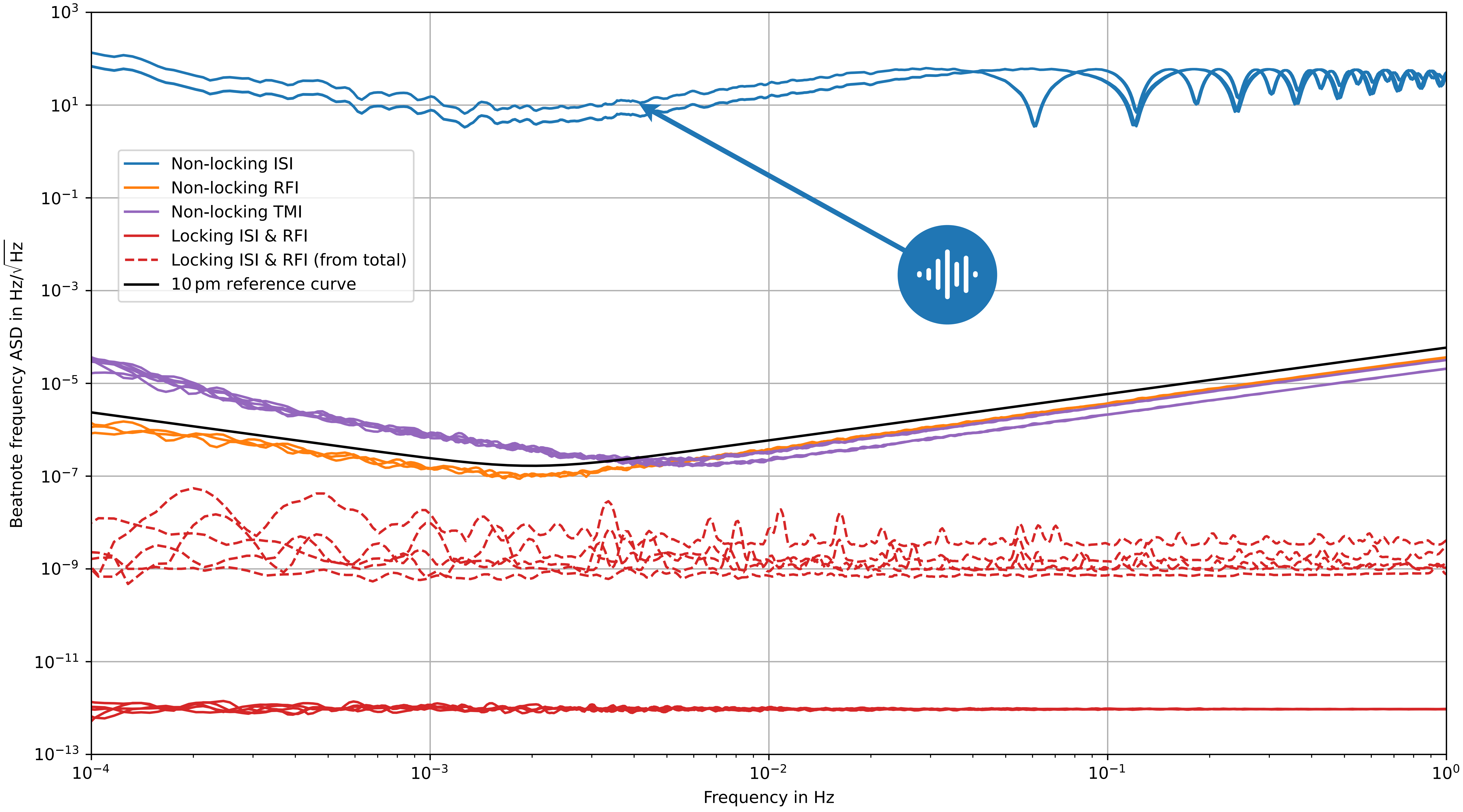
L1-L2 PIPELINE

Param. estimation

L2

Source p

L0 Data Overview



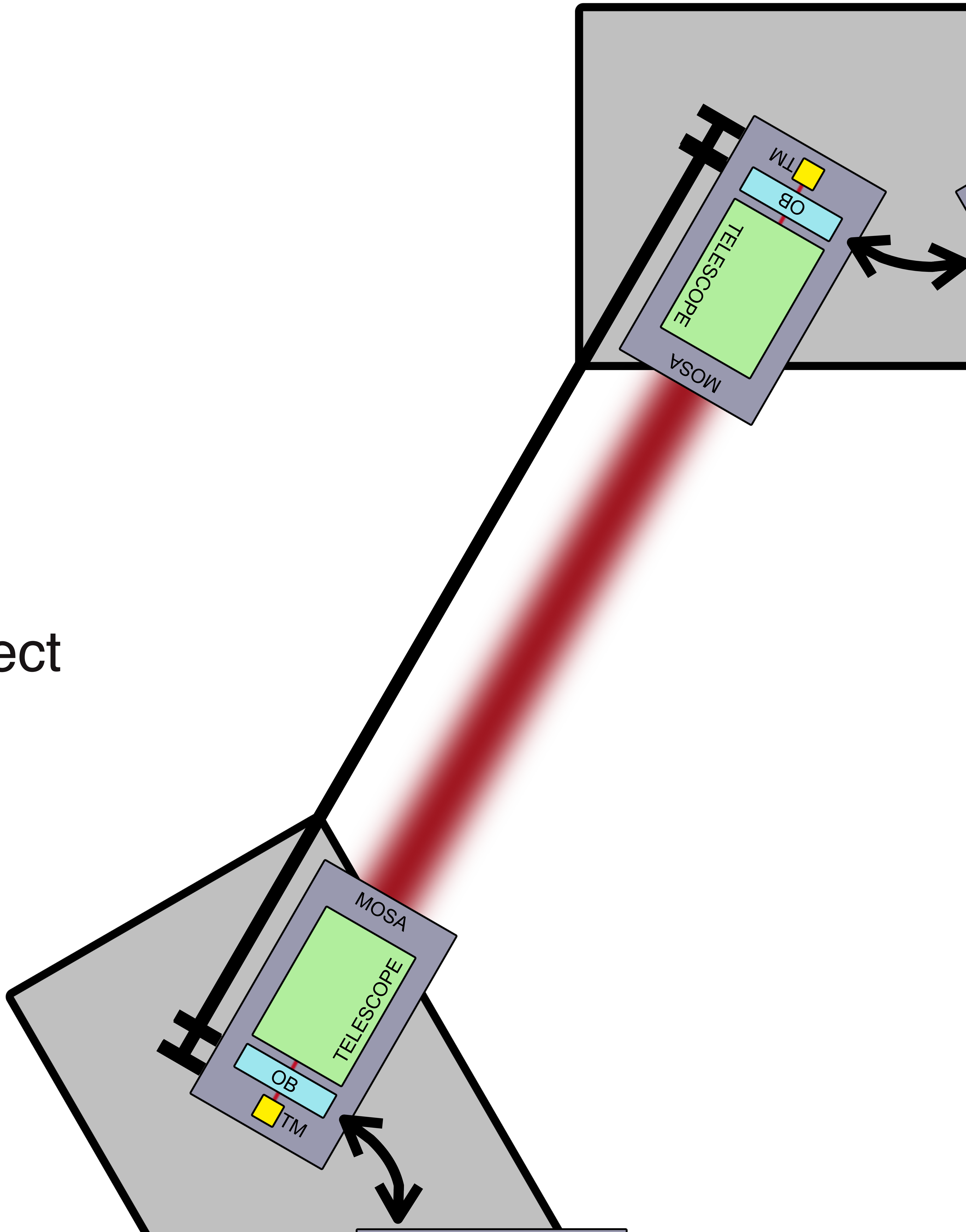
One Recipe (Amongst Others)

Here, L0-L1 pipeline for total frequency
Phase data will also be available, TBD if we gain anything in PE from using it…

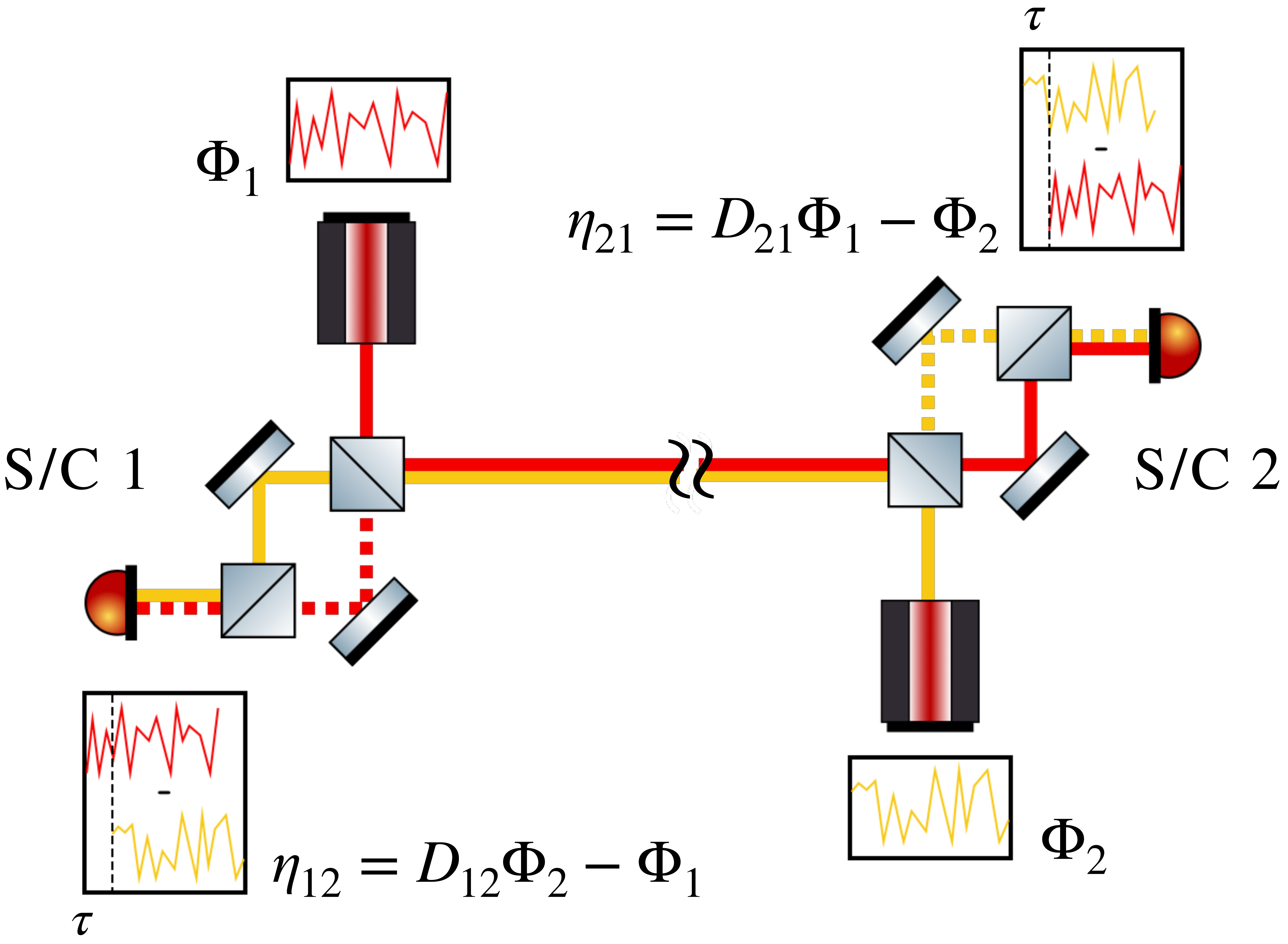
1. Accurate estimation of the pseudoranges
   - Merge ground-tracking, MPRs and sidebands to provide accurate and low-noise estimates
   - Compute light travel times for response function
2. Construct test-mass-to-test-mass measurements to reduce spacecraft motion
3. Reduce tilt-to-length using DWS measurements
4. Correct for laser and clock noise using TDI
5. Synchronize TDI variable to a global reference frame using time correlations
6. Compute AET channels (if actually useful for PE)

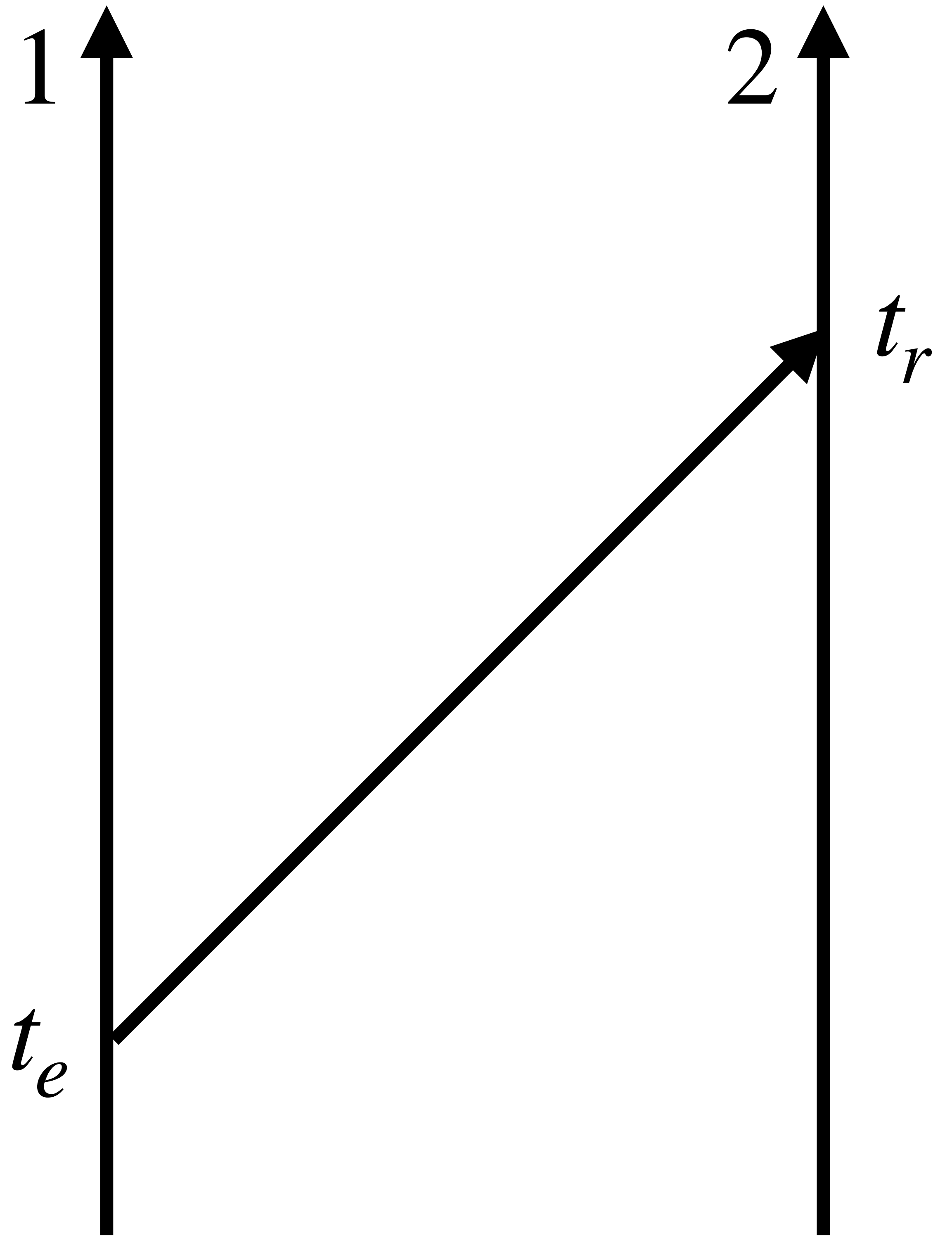
Single-Link Corrections

- **We want to monitor the TM-to-TM measurement**
- 3 Interferometers on each optical bench
  - Inter-spacecraft interferometer (ISI)
  - Test-mass interferometer (TMI)
  - Reference(interferometer (RFI)
- Combined in early processing step to synthesize direct TM-to-TM measurement, with 1 laser per spacecraft
- Then subtract TTL via DWS measurements
  - Coupling coefficients are estimated using dedicated calibration experiments (under investigation)



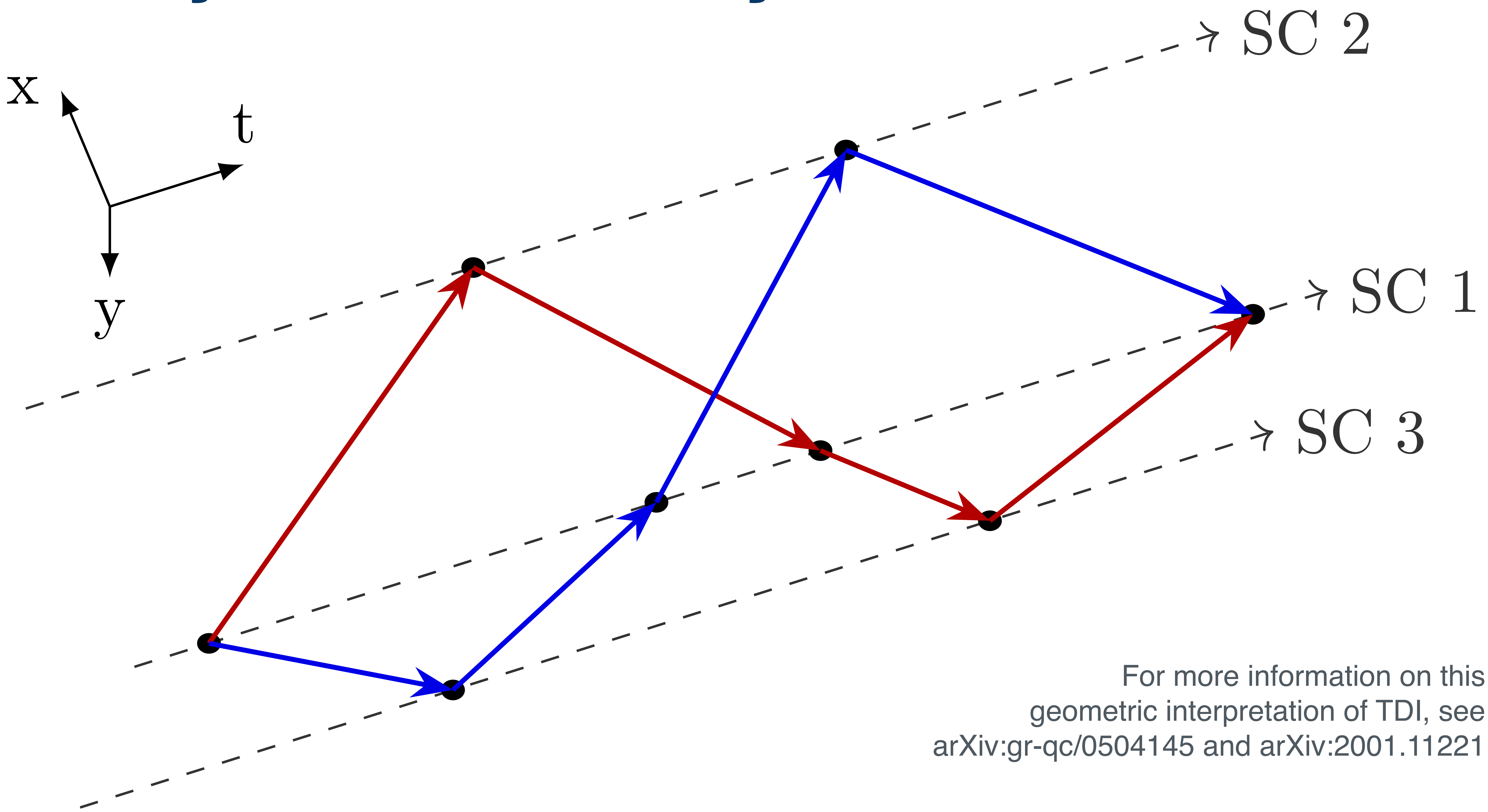
Simplified LISA Link





$$\Phi_1(t_e) \equiv D_{21}\Phi_1(t_r) \\ = \Phi_1(t_r - d_{21}(t_r))$$

Time-Delay Interferometry

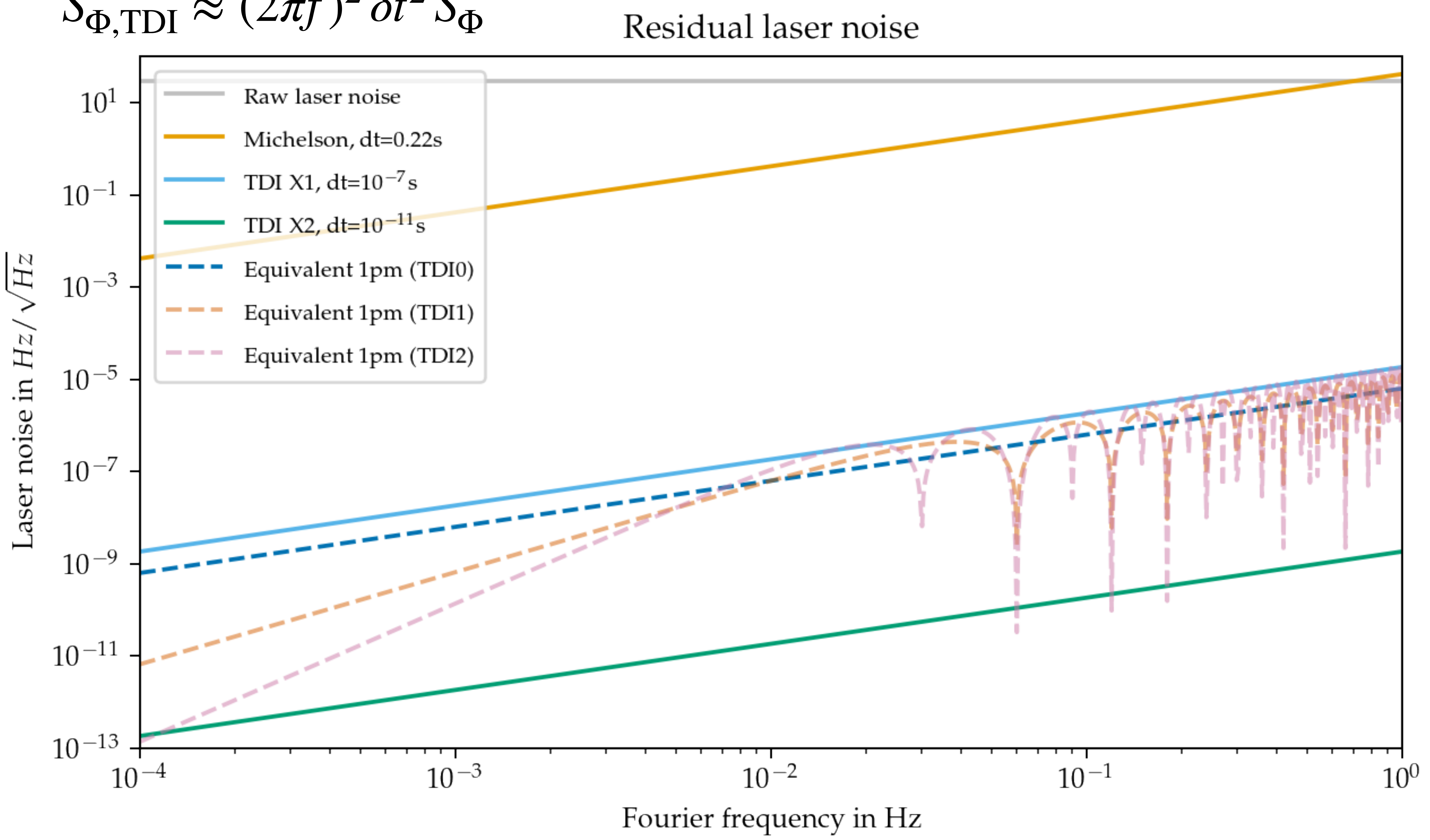


For more information on this geometric interpretation of TDI, see arXiv:gr-qc/0504145 and arXiv:2001.11221

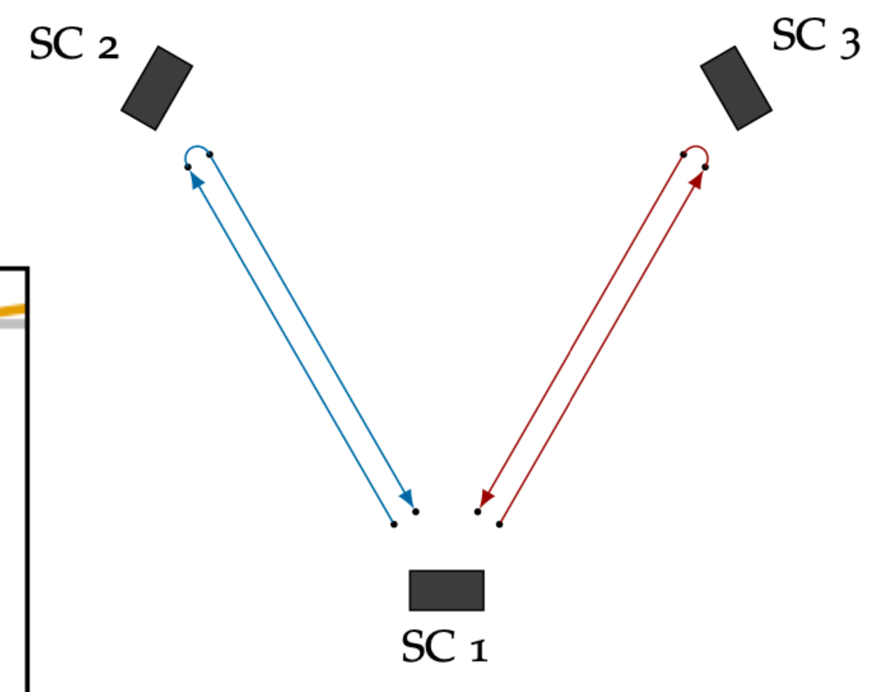
Laser Noise Residual

… Assuming Realistic Orbits

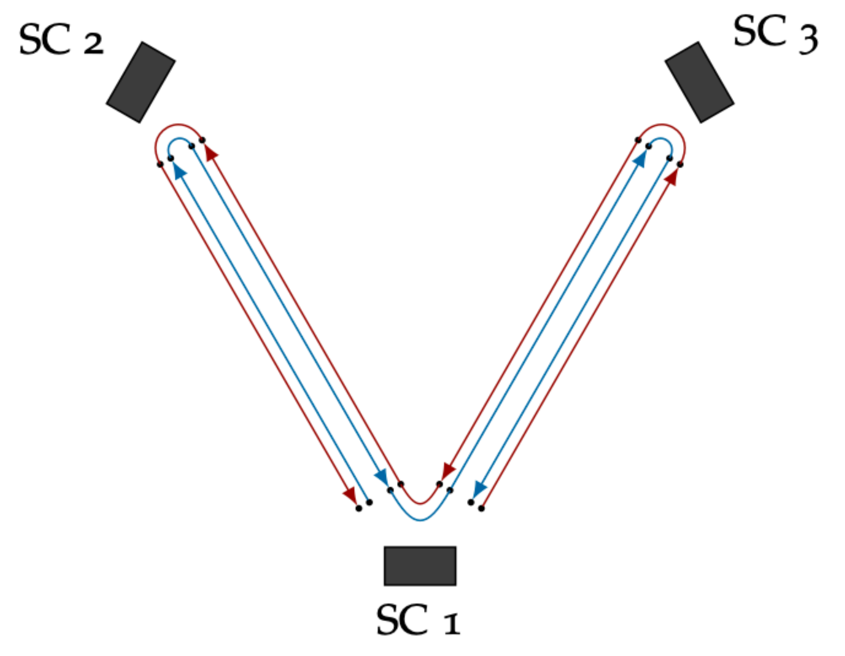
$$S_{\Phi,\mathrm{TDI}} \approx (2\pi f)^2\, \delta t^2\, S_\Phi$$



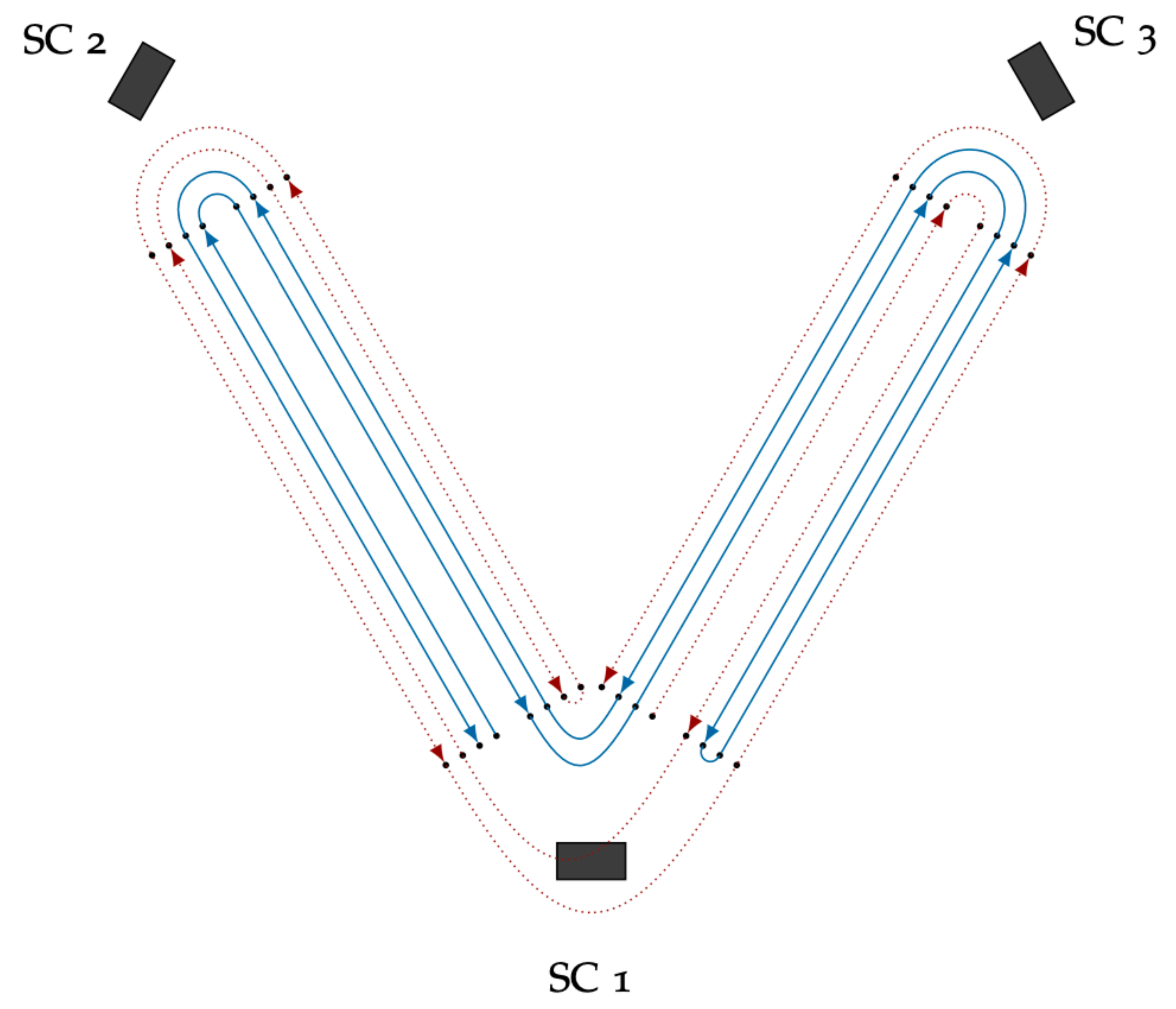
Average light travel times with ESA orbits: $d_A \approx 8.3\,\mathrm{s}$, $\dot{d}_A \approx 10^{-9}$ and $\ddot{d}_A \approx 10^{-15}\,\mathrm{s}^{-1}$



$\Delta\tau_0 \approx 2(d_{12} - d_{13})$



$\Delta\tau_1 \approx 4d(\dot{d}_{31} - \dot{d}_{12})$



$\Delta\tau_2 = \approx d\left[(\dot{d}_{12}^2 - \dot{d}_{31}^2) - 2d(\ddot{d}_{12} - \ddot{d}_{31})\right]$

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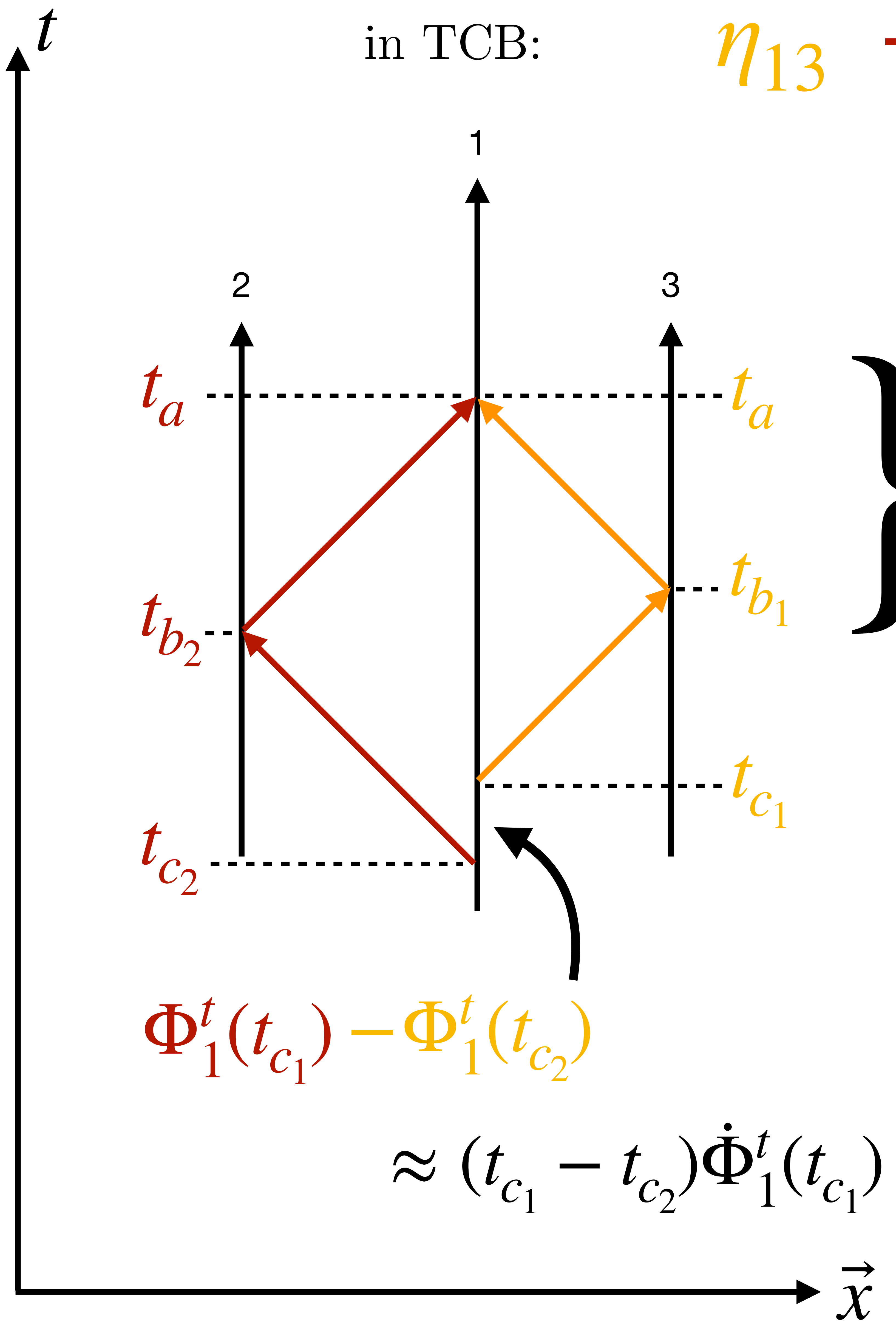
TDI with desynchronized clocks

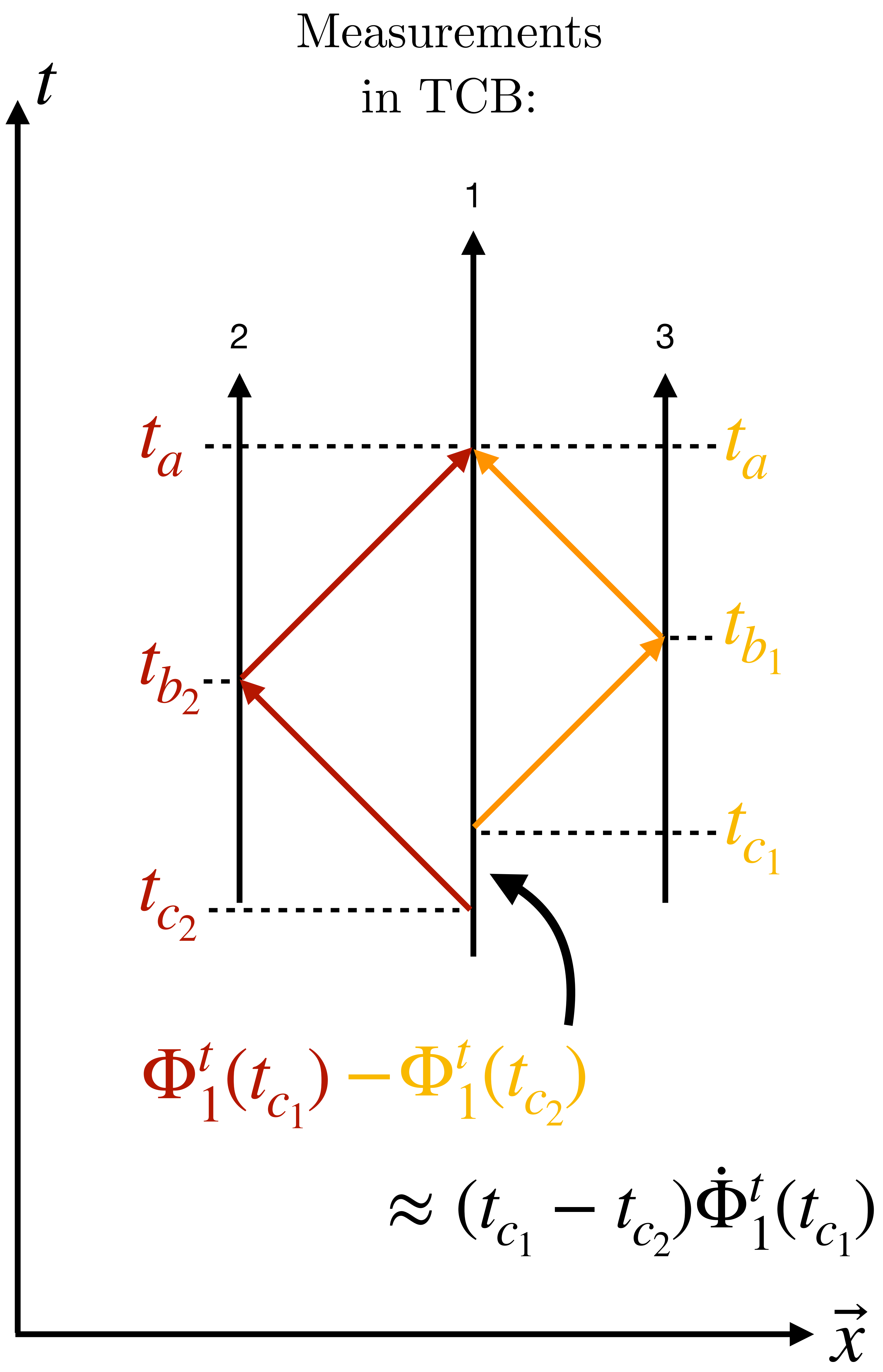
Geometric TDI with Clock Times

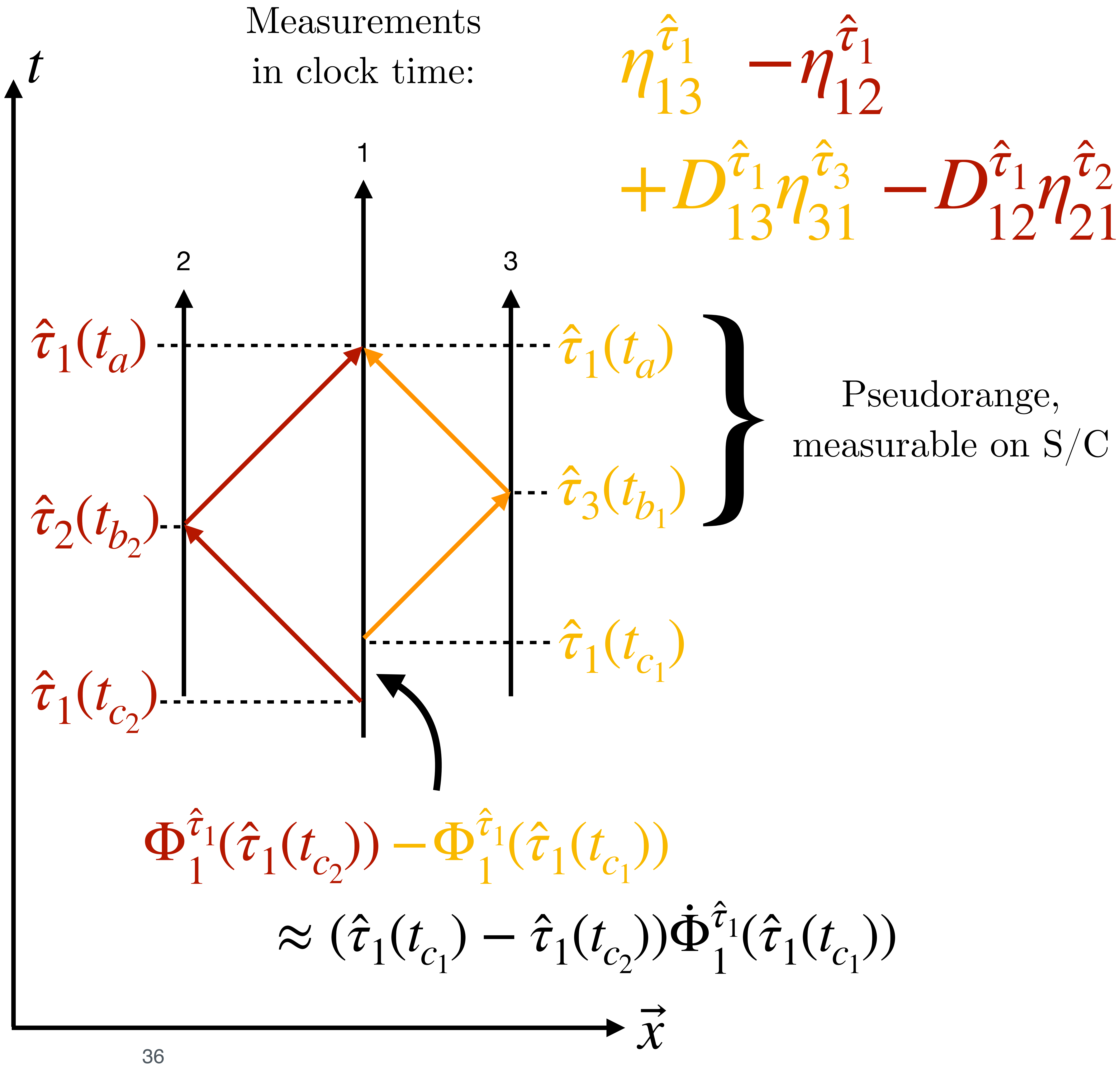
Measurements in TCB: $\eta_{13} \; -\eta_{12} \; +D_{13}\eta_{31} - D_{12}\eta_{21}$



Light travel time in TCB, Computed from S/C position estimates

Geometric TDI with Clock Times

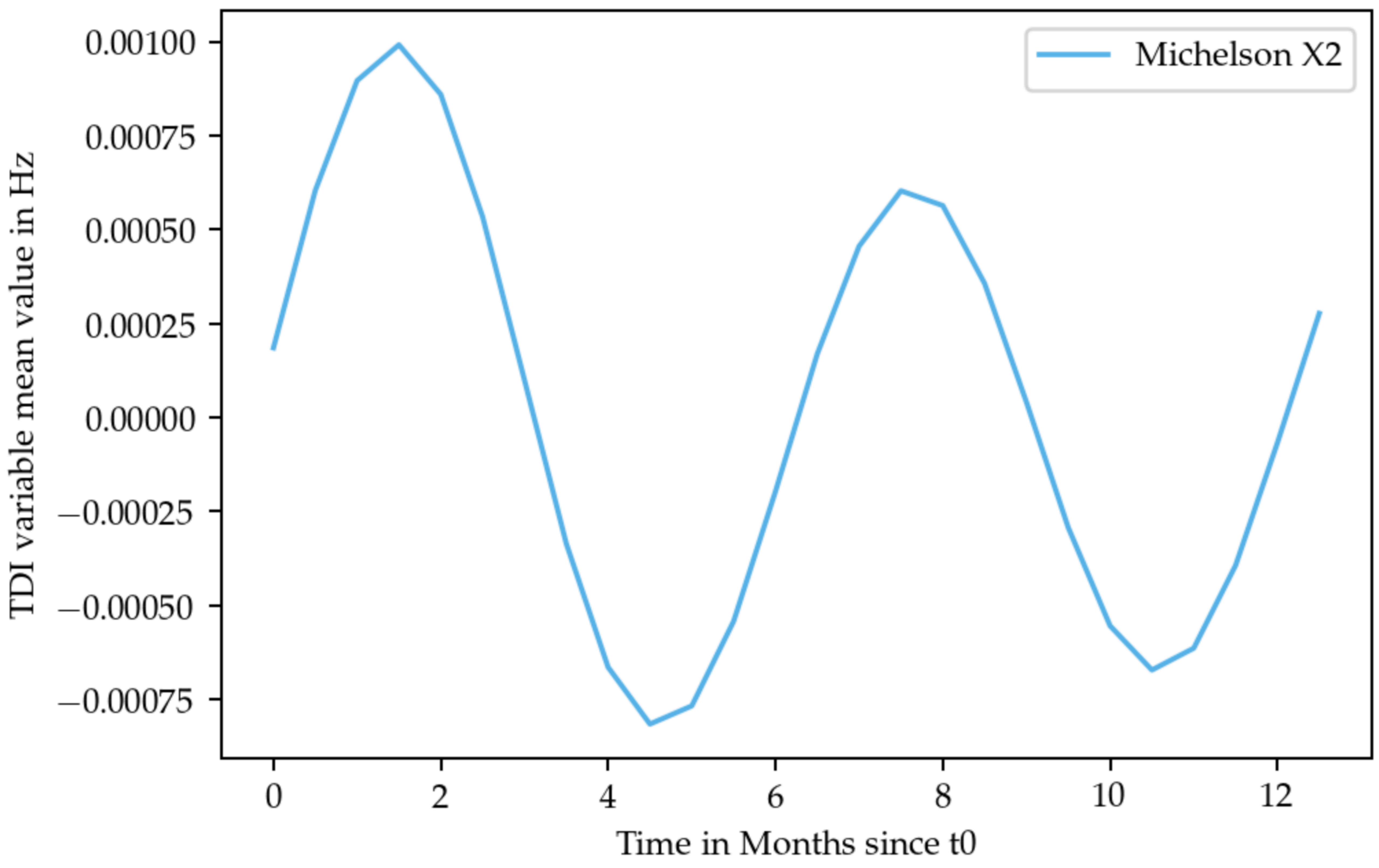




Clock Noise

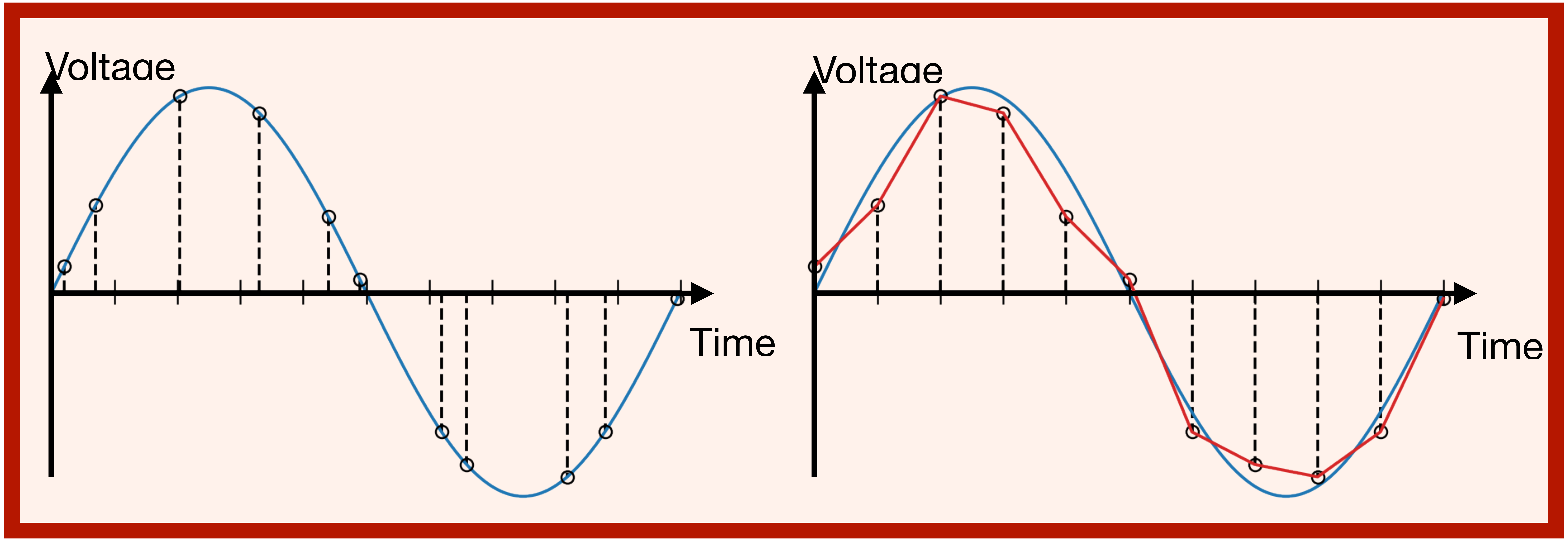
… with Perfect Pseudoranges

- We can show that we get $X^{\hat{\tau}_1}(\tau) = X^t(\tau - \delta\hat{\tau}_1(\tau)) \approx X^t(\tau) - \dot{X}^t(\tau)\delta\hat{\tau}_1(\tau)$
- The mean value of $\dot{X}^t(\tau)$ varies between $\pm 1\,\mathrm{mHz}$, with a period of 2/year
- This is 10 orders of magnitude below the previous coupling to 10 MHz beatnotes!
- Remark: noise-free variables still need to be sync. to TCB
- Remark 2: large drift can be subtracted — should we?



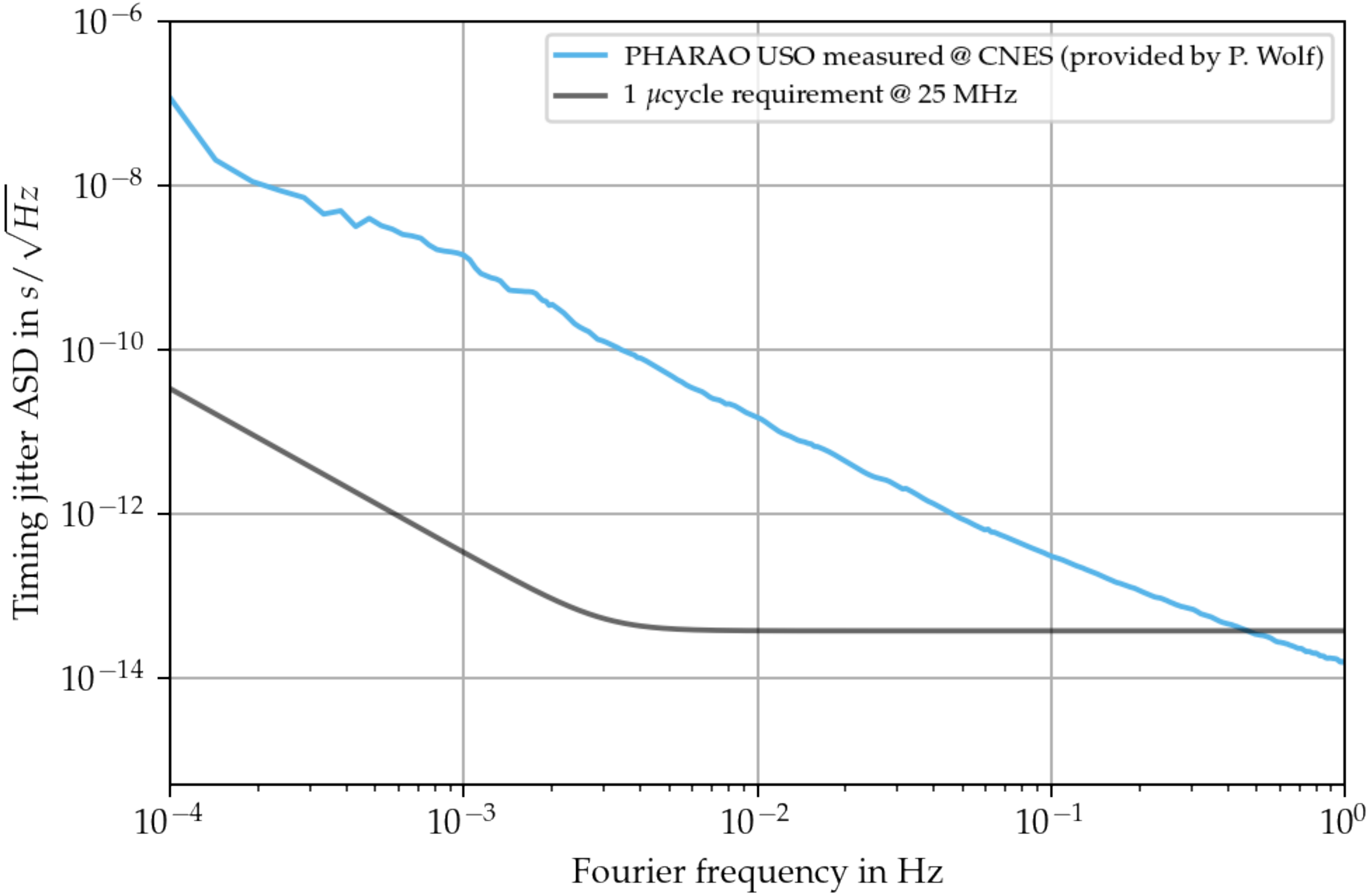
Clock Noise

… With Imperfect Pseudoranges

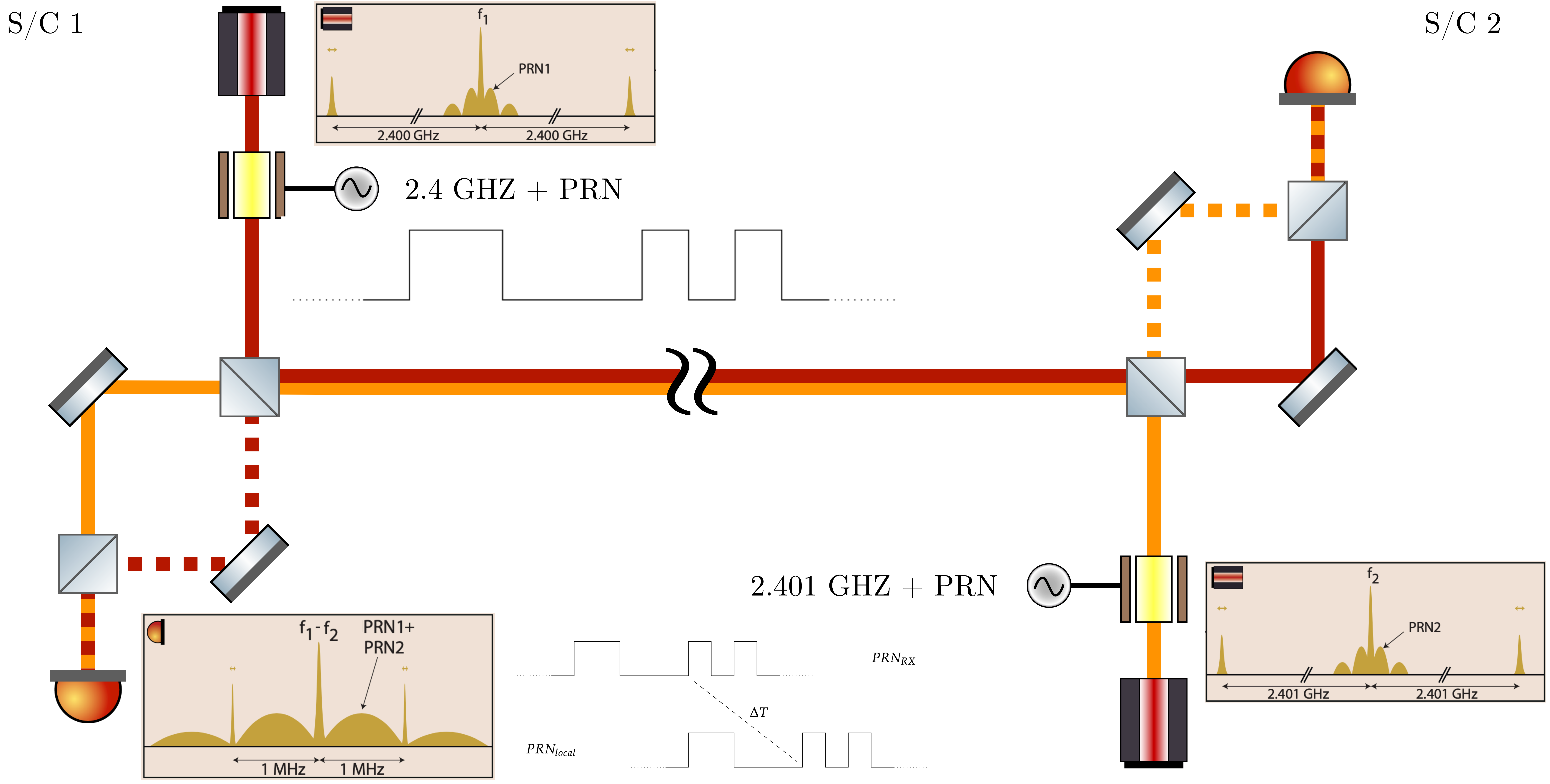


- 25 MHz beatnotes require 40 fs/sqHz timing precision for μcycle signals: clocks not good enough!
- Correct clock noise alongside laser noise by properly time-shifting each individual sample
- Any time shift applied in TDI inherits same timing requirement, if applied to total phase/frequency

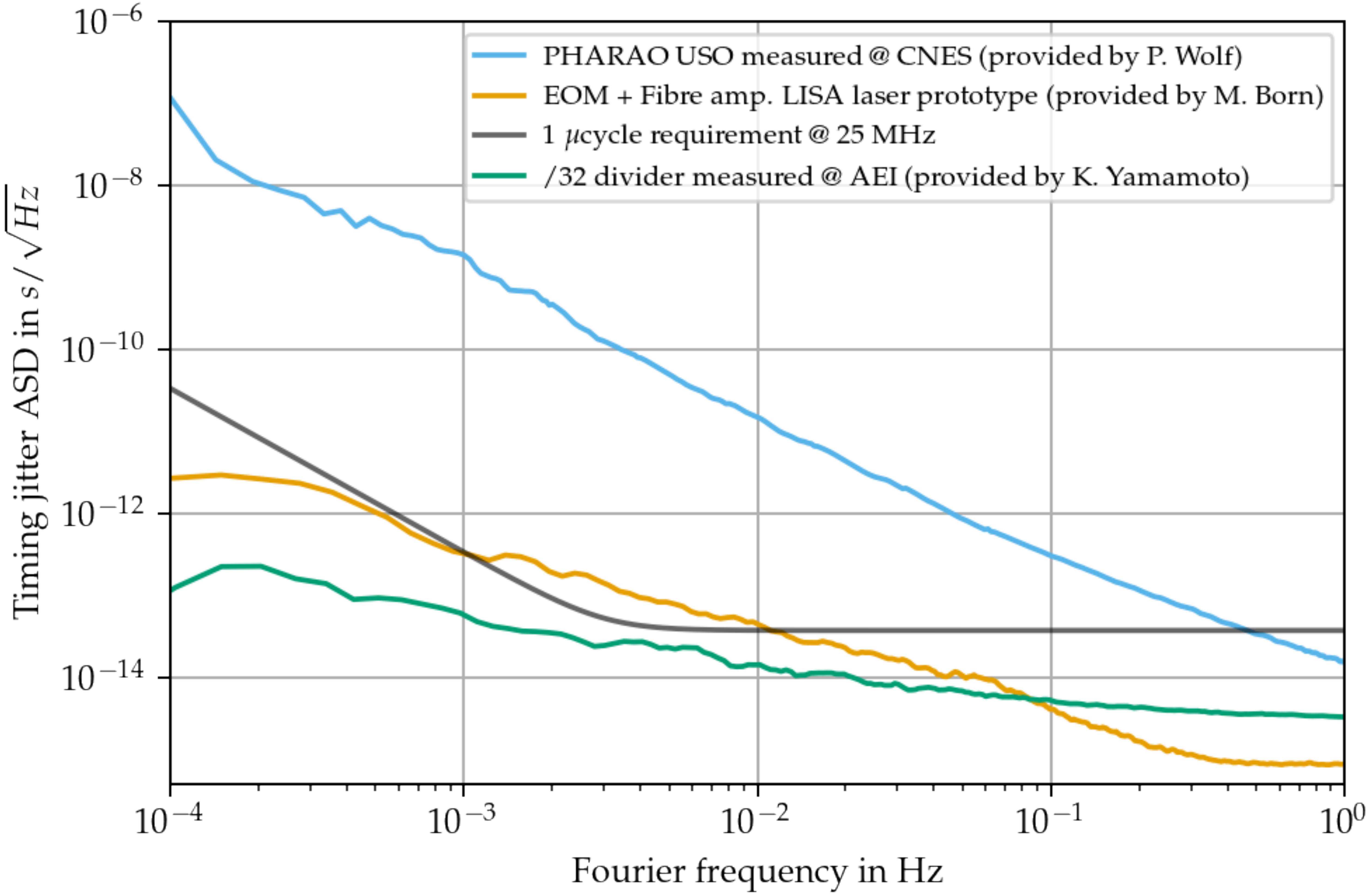
Clock comparison performance



Sideband & PRN Modulation



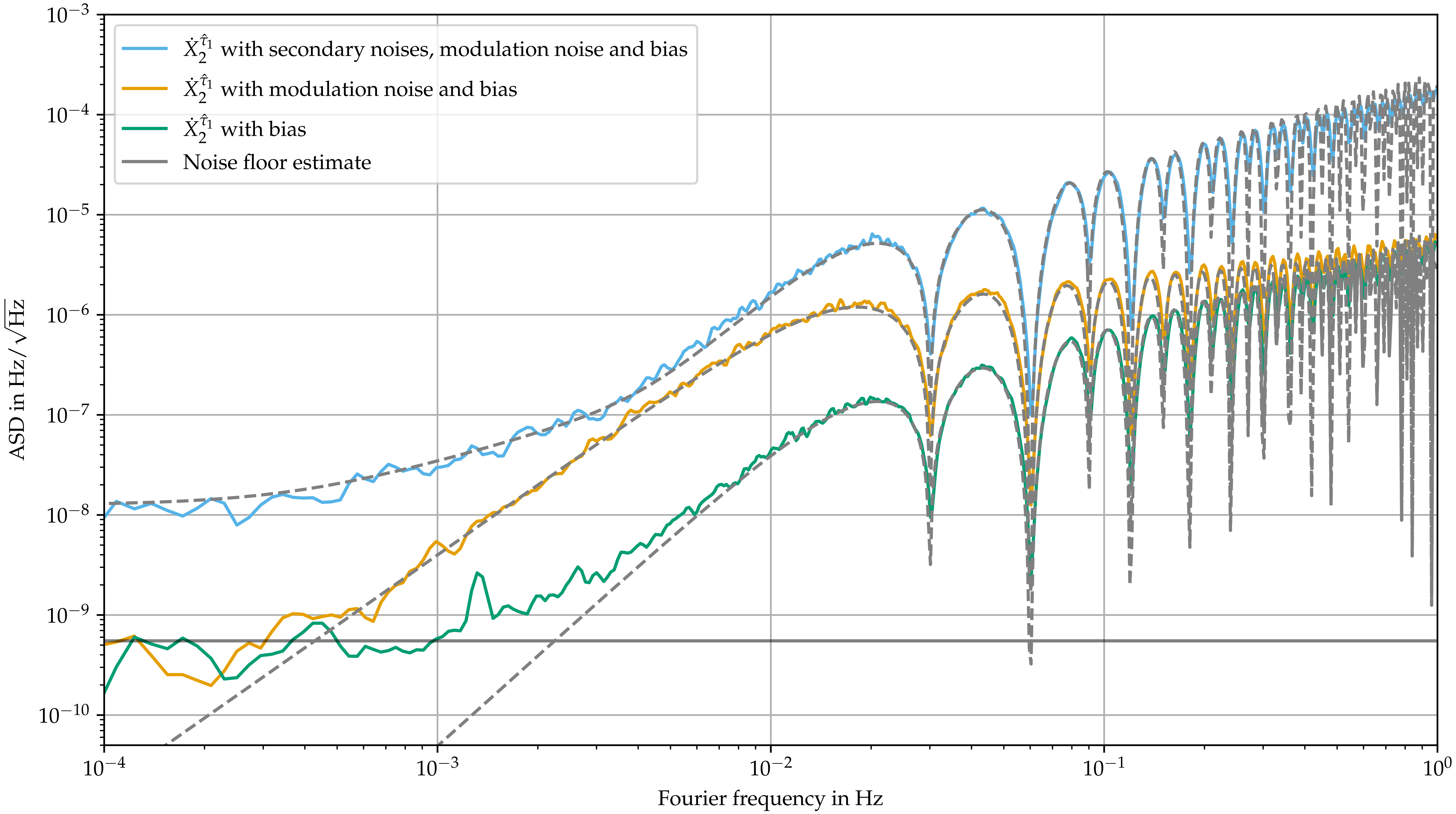
Clock Compared Performance



- PRN and sidebands allow measurement of pseudorange at $40\,\mathrm{fs\,Hz}^{-0.5}$ level
- Absolute value of pseudorange accurate to $\approx 3\,\mathrm{ns}\ (1\,\mathrm{m})$
- Clock synchronisation to globale frame accurate to $\approx 0.1\,\mathrm{ms}\ (30\,\mathrm{km})$

TDI Performance

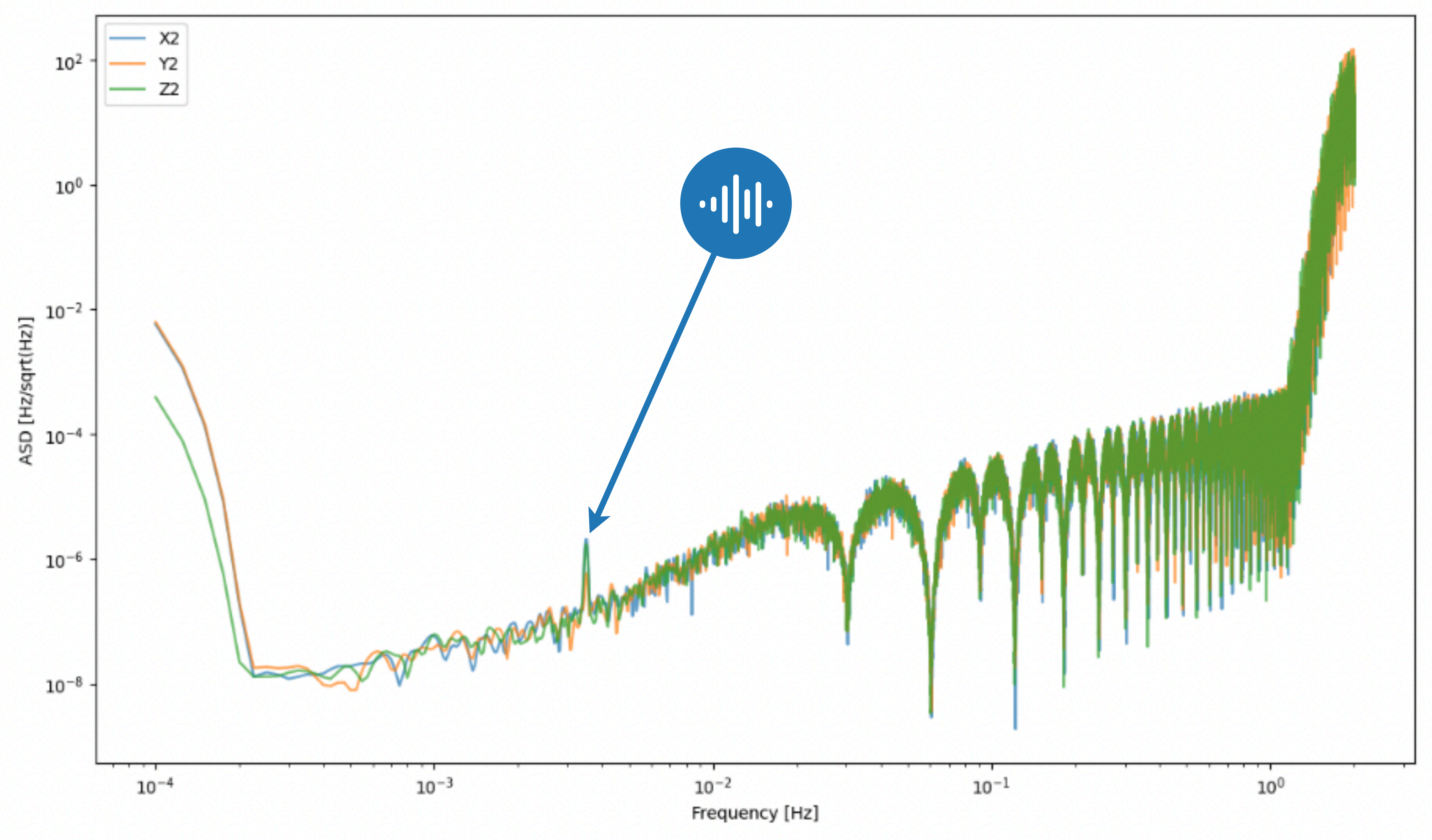
- Perform simulation with
  - Realistic orbits
  - Realistic laser, clock, sideband, PRN noises
  - Ultimately limiting secondary noises
- Performance is unaffected by large clock drifts and offsets
- Noise due to clock correction depends on the beatnote frequency and is nonstationary



Time delay interferometry without clock synchronisation, O. Hartwig, J.-B. Bayle, M. Staab, A. Hees, M. Lilley, P. Wolf. arXiv:2202.01124

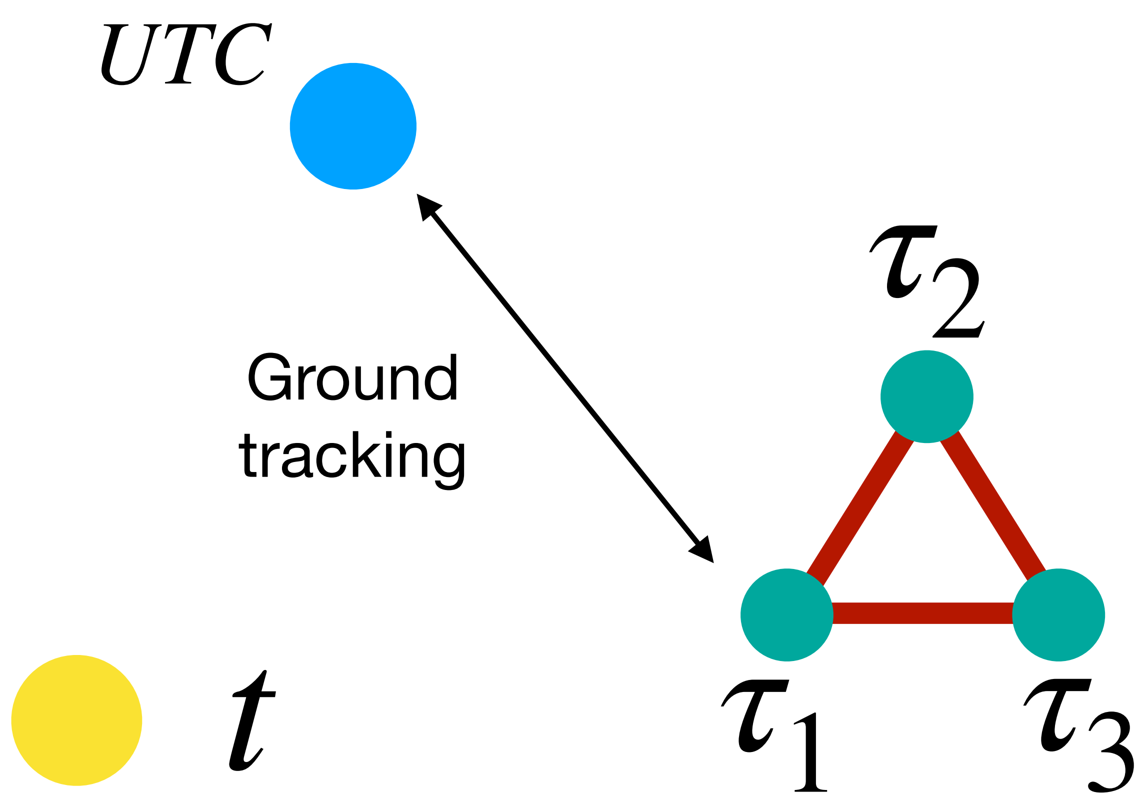
Current Outputs

- As first step, we consider a single verification binary
- Amplitude is boosted to give 4 year SNR in just 3 days
- Signal is clearly visible in TDI data



Time Synchronisation & Orbit Calculation

- After noise reduction, still need to synchronize resulting TDI channels to a global time frame at about 1ms accuracy
  - Use directly clock information from ground tracking
- For the parameter estimation, we need estimates of the orbits and light travel times to compute the response function
  - First try: directly feed-forward reconstructed orbits provided by MOC
  - Also compute LTTs directly from MOC orbits ($\approx 1\,\mathrm{ms}$ accuracy)
- Impact of these procedures is one output of this study



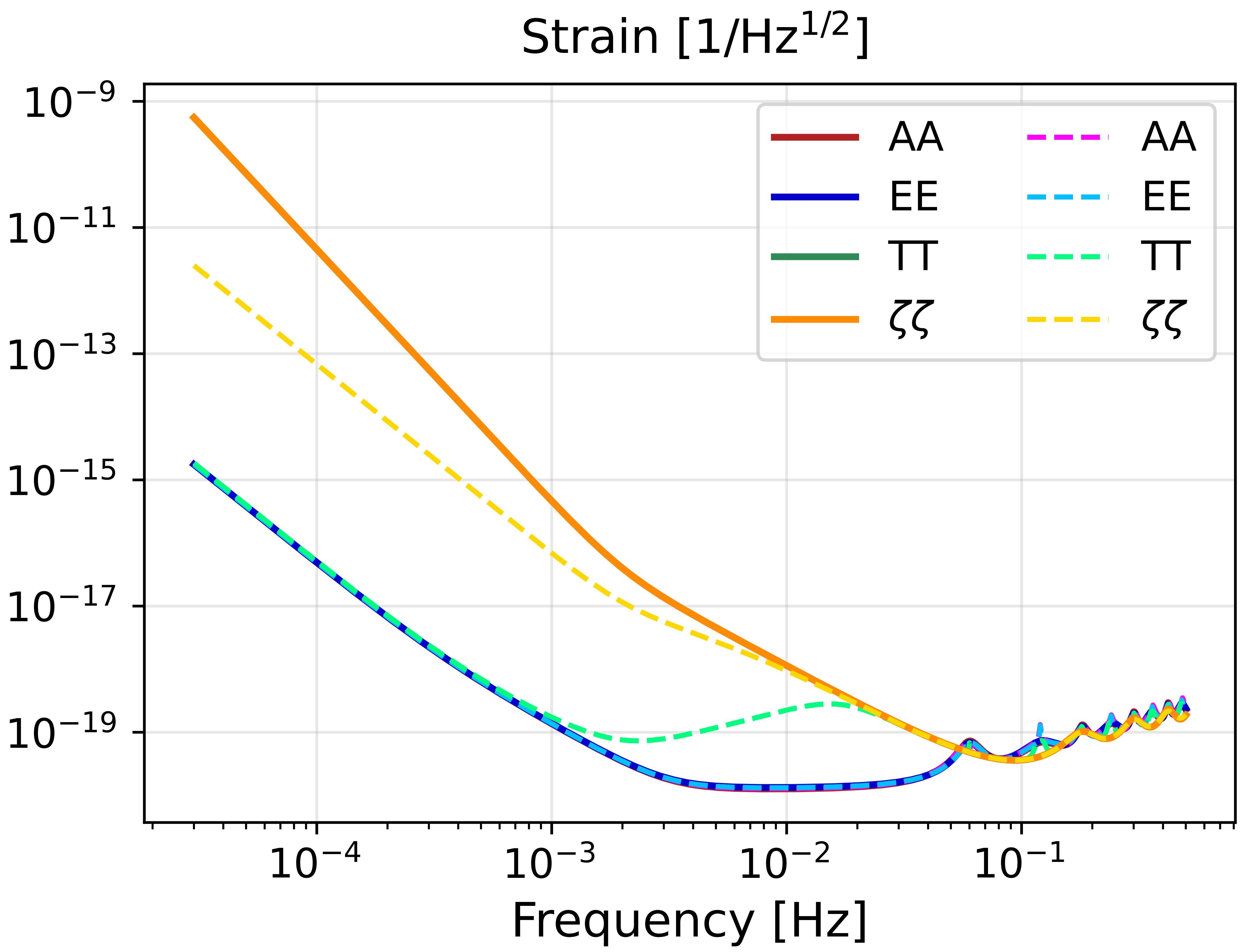
Orthogonal Channels

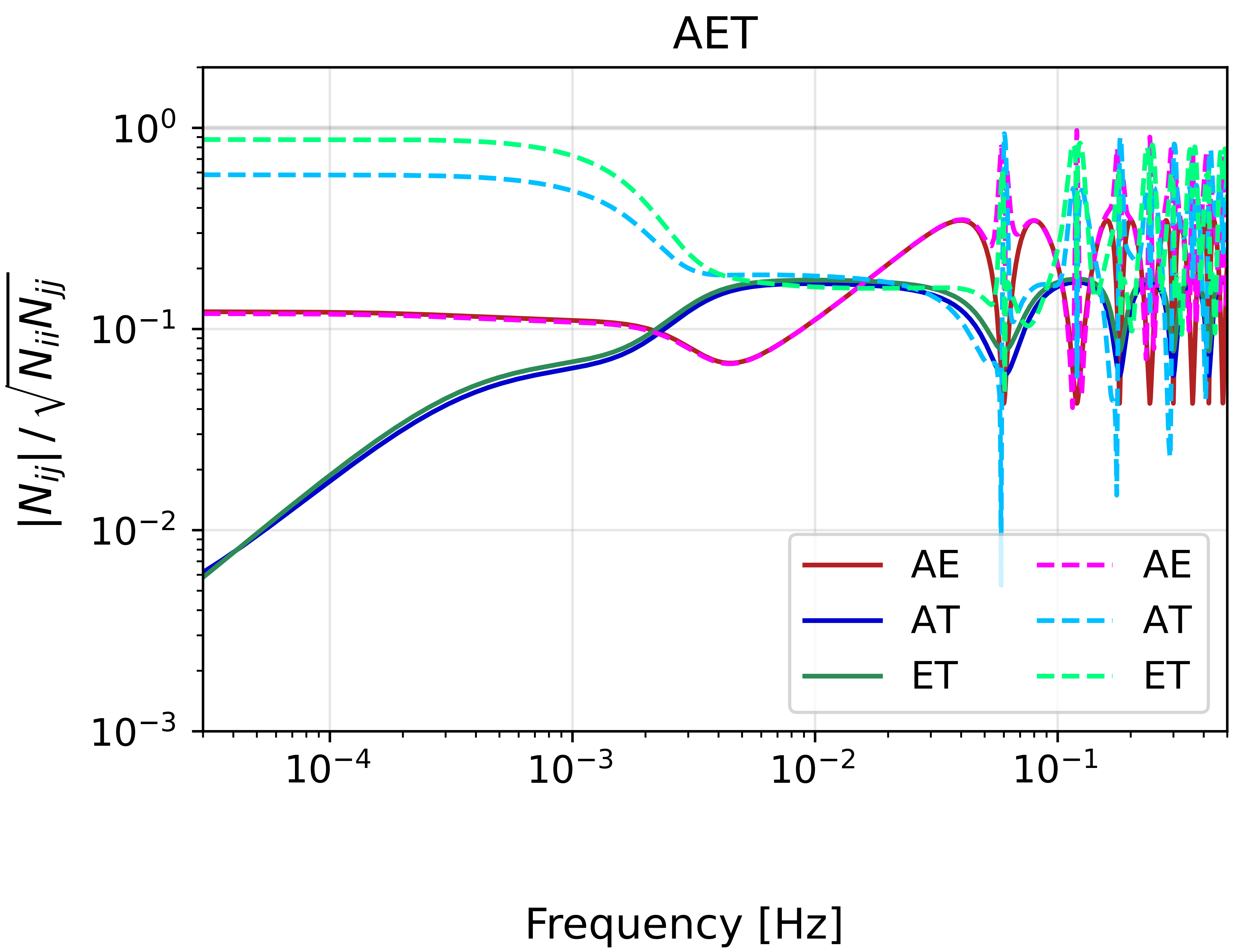
- Once synchronized, we can combine multiple channels to construct quasi-orthogonal channels. For example,

$$A = \frac{Z - X}{\sqrt{2}}, \quad E = \frac{X - 2Y + Z}{\sqrt{6}}, \quad T = \frac{X + Y + Z}{\sqrt{3}}$$

- **Warning: these are *not* orthogonal in realistic scenarios!**
  - Arm lengths and individual noise levels not equal
- Impact under investigation…
- Could use other base channels, better orthogonalization, or skip *AET* and use the full covariance matrix

Analytical Michelson



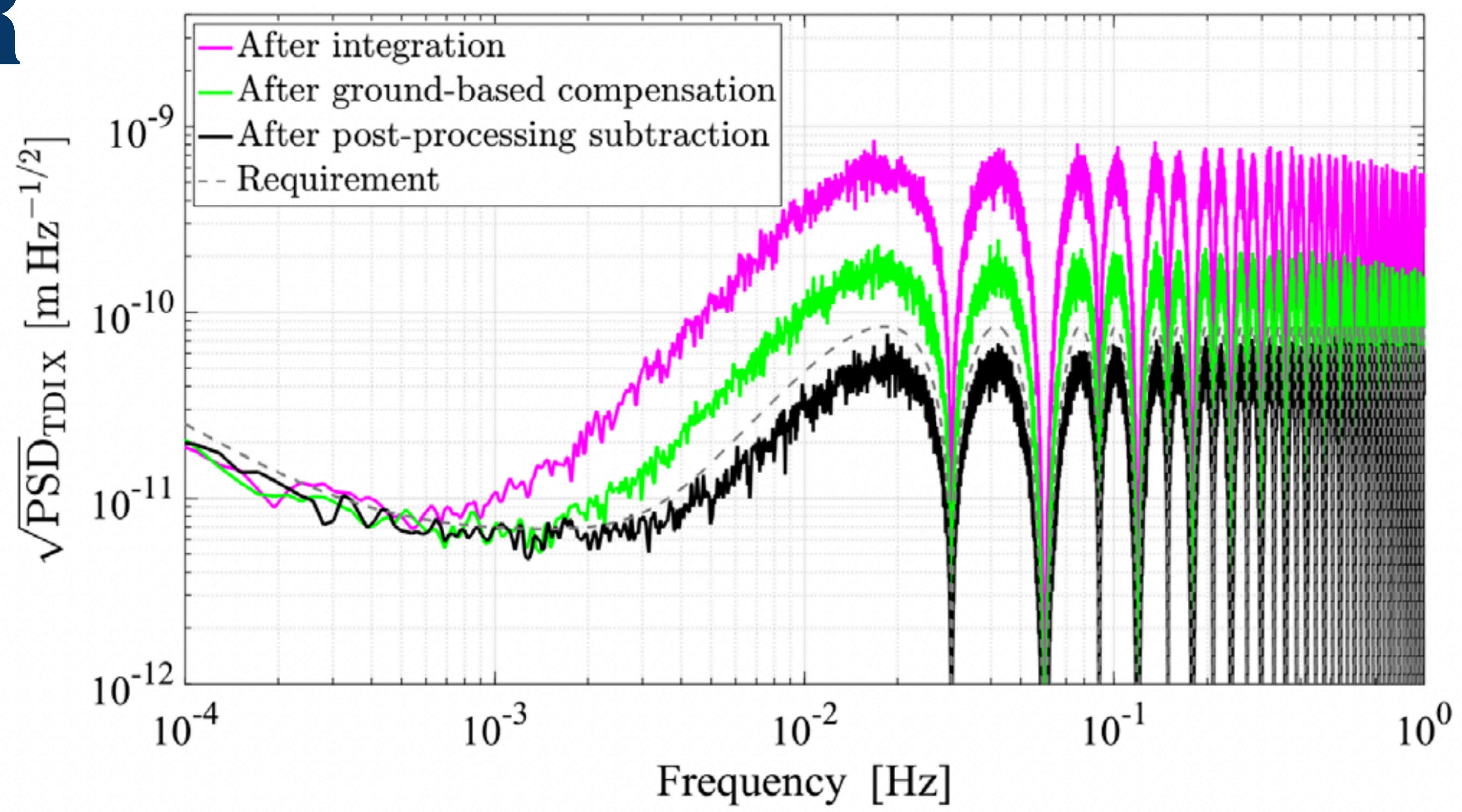


M. Pieroni, O. Hartwig, M. Lilley, M. Muratore, in prep.

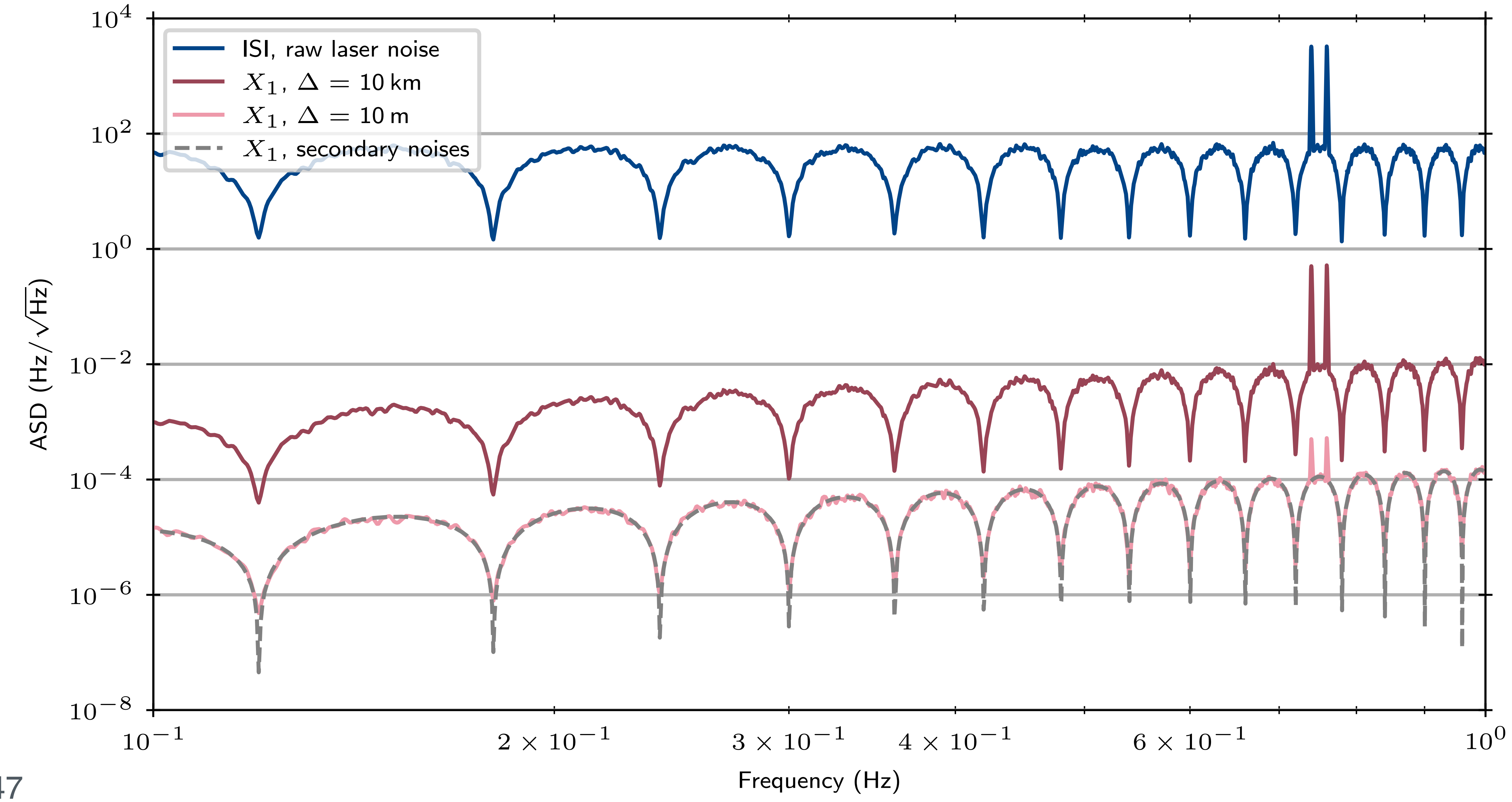
- Assume realistic (but static) arm length mismatches
- Assume noise levels drawn from normal distribution with $\sigma = 0.2$

A Word on TTL & TDIR

- Some processing steps envisioned as part of L0-L1 will require to fit some parameters to the data
- TTL coefficients are not known sufficiently well a-priori
  - Fit DWS measurement coupling factors by minimizing the noise
- Pseudorange measurements might contain additional unmodeled biases
  - Fit ranging bias by minimizing noise in TDI combinations



Paczkowski et al. 10.1103/PhysRevD.106.042005



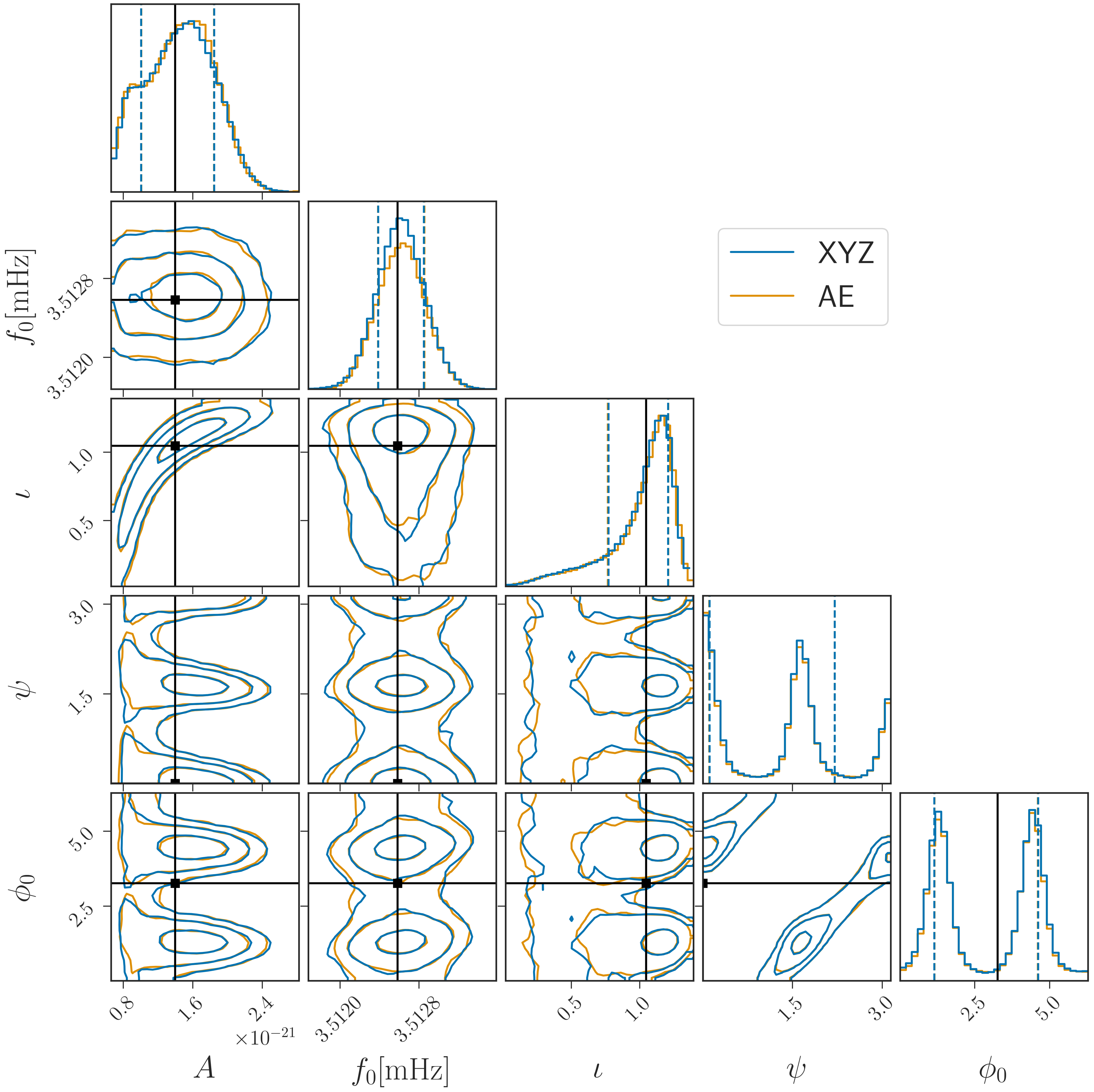
Staab et al., in prep.

L1-L2 Parameter Estimation

Thanks Christian Chapman-Bird!

Current Progress

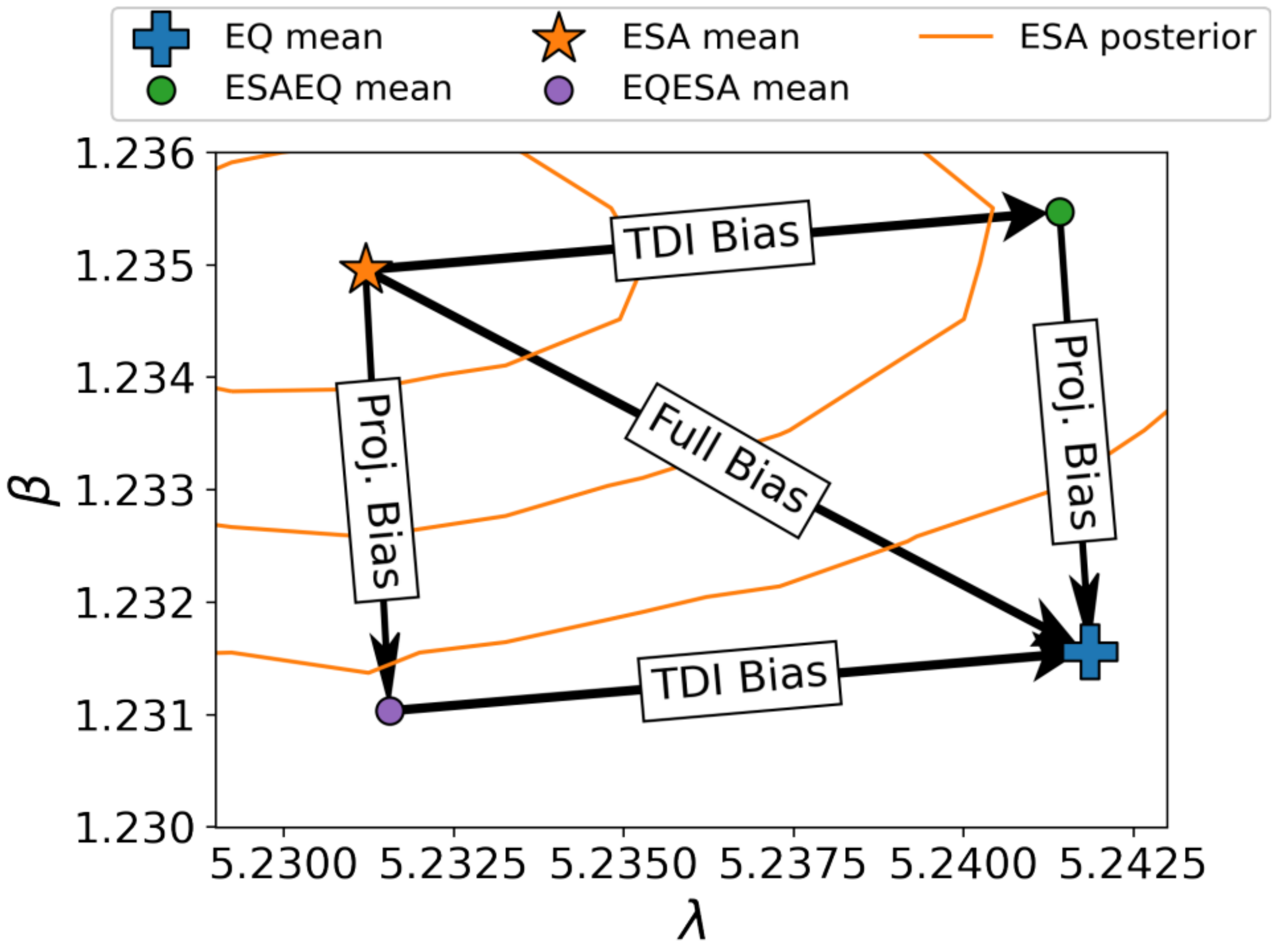
- Single galactic binary with optimal SNR of 100 for a 4-year dataset
  - For ease of testing, reduce to 3 days of data and rescale amplitude
  - Sky position fixed: "verification binary"
  - Equal-armlength orbits and aforementioned primary/secondary noise sources enabled
- Parameters are recovered well (except phase, likely an error with epochs somewhere!)
- We see good agreement between working in 2nd-generation *AE(T)* or *XYZ*, but for more realistic orbits we expect biases to emerge if diagonal covariance matrix is assumed



sampled with `nessai`

Next Steps

- Adapt the FastGB waveform model to incorporate
  - More realistic orbits, including unequal and time-varying armlengths
  - Use of orbital information obtained from ground tracking, instead of evolving a dynamical model
  - Eventually, merge these changes with existing GBGPU waveform model
- Extend simulation duration to 4 years and enable further noise sources
  - Verify that sky localisation and frequency derivative inference are performed successfully
- Experiment with various noise sources to probe the resulting impact on parameter estimation
  - Explore under which scenarios parameter estimation will incur biases



M. Katz, J.-B. Bayle, A. J. K. Chua, M. Vallisneri, 10.1103/PhysRevD.106.103001

Conclusion & Outlook

Conclusion & Outlook

- Many analysis methods to extract source parameters under development
- These methods often rely on simplifying assumptions, not necessarily reflecting the full complexity of the LISA data
- We work on checking (some of) these assumptions by building a (more) realistic simulation-processing-analysis pipeline
- We go from simple configurations (close to current LDC) and slowly add realistic features and processing elements to check that they do not break anything
- Activity started by defining the target configuration and run the pipeline with a simple configuration – PE works (mostly) as expected!