GW Observatory II
LISA

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School on Gravitational Waves for Cosmology and Astrophysics

Benasque - Spain

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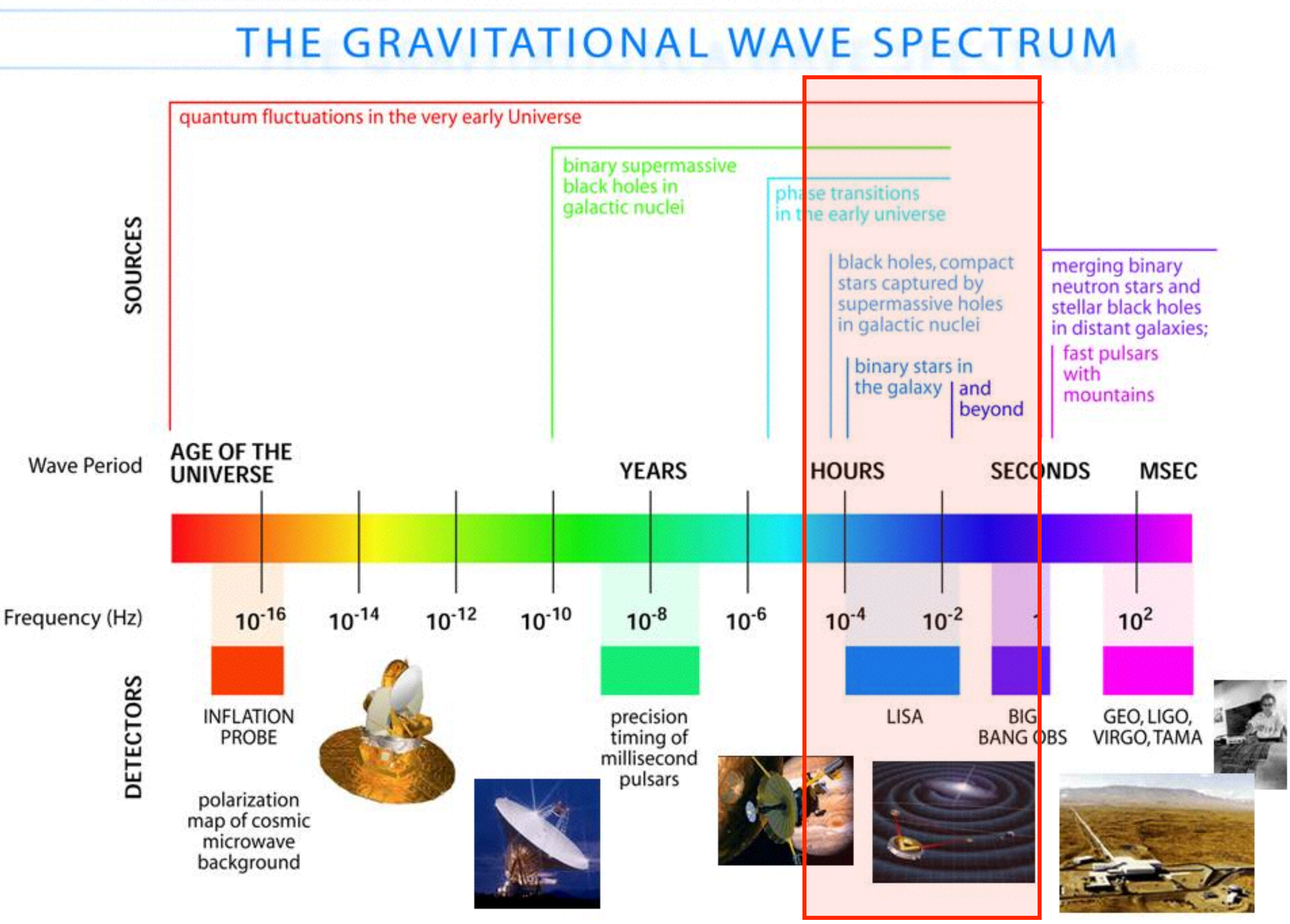
Structure of the lectures

- DA I: Statistic basis for DA: Likelihood, frequentist/Bayesian
- GW Obs I: History, response to GW
- DA II: 3 main classes of signal, parameter estimations, Fisher Matrix
- GW Obs II: LISA: LISAPathfinder, noises, ...
- DA III: LISA DA: Global analaysis, MBHB, stochastic, ...
- GW Obs III: LIGO
- GW Obs IV: PTA
- DA IV: PTA data analysis

Overview

- Context and history
- LISA design
- Time Delay Interferometry
- LISAPathfinder
- Noise sources
- Sensitivity
- Orbital motion

Context and history


THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
102
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

History of LISA

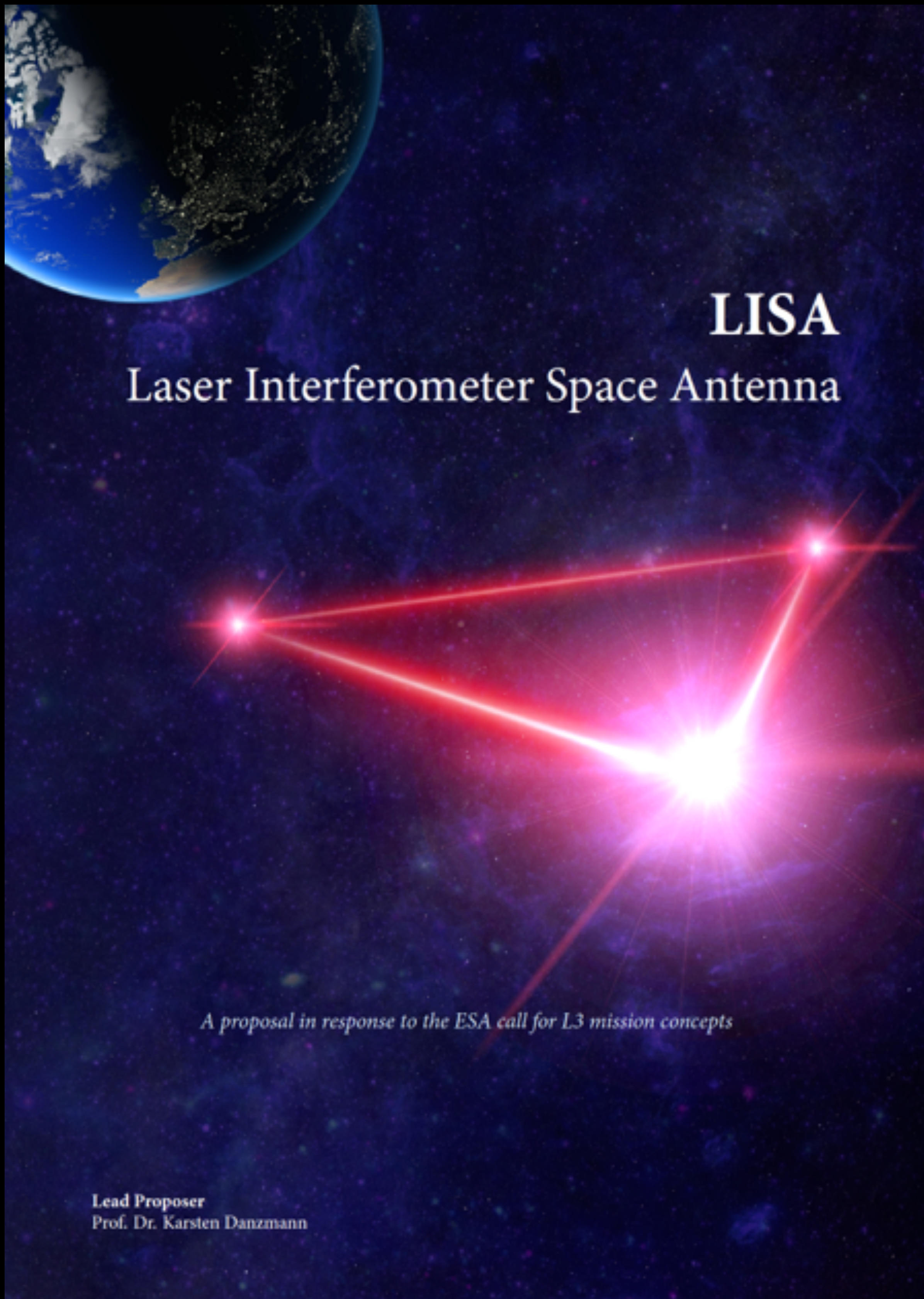
- 1978: first study based on a rigid structure (NASA)
- 1980s: studies with 3 free-falling spacecrafts(US)
- 1993: proposal ESA/NASA: 4 spacecrafts
- 1996-2000: pre-phase A report
- 2000-2010: LISA and LISAPathfinder: ESA/NASA mission
- 2011: NASA stops => ESA continue: reduce mission
- 2012: selection of JUICE L1 ESA
- 2013: selection of ESA L3 : « The gravitational Universe »
- 2015-2016: success of LISAPathfinder + detection GWs

LISA à l'ESA

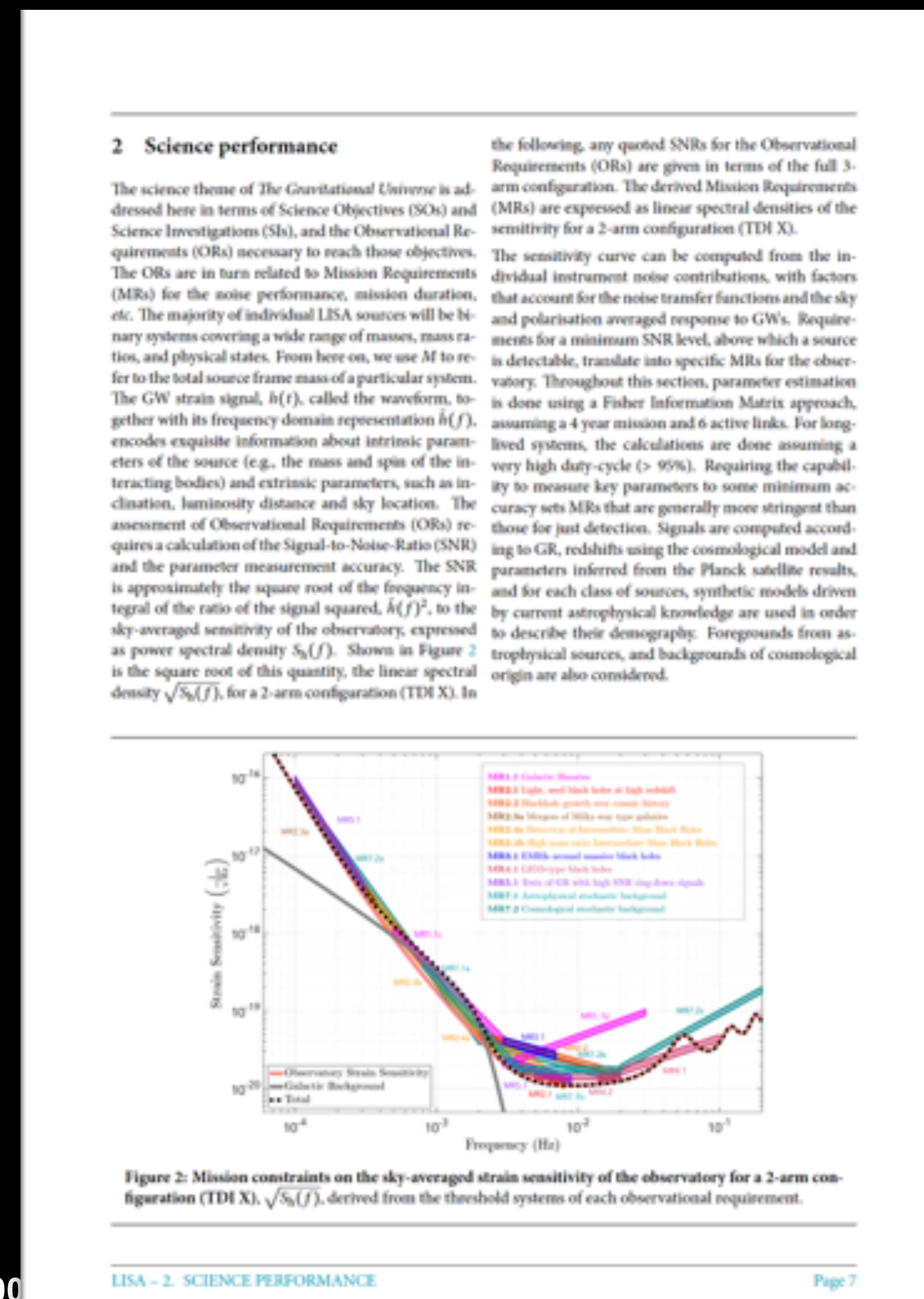
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- Juin 2017 : « mission proposal assessed » by SPC
- 2017→2019 : competitive phase A : 2 companies compete
- 2019→2020 : B1: start industrial implementation
- 2020-2021 : mission adoption
- During about 8.5 years : construction
- 2030-... : launch Ariane 6.4
- 4 years of nominal mission
- Possible extension to 10 years

→ GW observations !

« The LISA Proposal »



https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf



2 Science performance

The science theme of *The Gravitational Universe* is addressed here in terms of Science Objectives (SOs) and Science Investigations (SIs), and the Observational Requirements (ORs) necessary to reach those objectives. The ORs are in turn related to Mission Requirements (MRs) for the noise performance, mission duration, *etc.* The majority of individual LISA sources will be binary systems covering a wide range of masses, mass ratios, and physical states. From here on, we use M to refer to the total source frame mass of a particular system. The GW strain signal, $h(t)$, called the waveform, together with its frequency domain representation $\tilde{h}(f)$, encodes exquisite information about intrinsic parameters of the source (e.g., the mass and spin of the interacting bodies) and extrinsic parameters, such as inclination, luminosity distance and sky location. The assessment of Observational Requirements (ORs) requires a calculation of the Signal-to-Noise-Ratio (SNR) and the parameter measurement accuracy. The SNR is approximately the square root of the frequency integral of the ratio of the signal squared, $\tilde{h}(f)^2$, to the sky-averaged sensitivity of the observatory, expressed as power spectral density $S_h(f)$. Shown in Figure 2 is the square root of this quantity, the linear spectral density $\sqrt{S_h(f)}$, for a 2-arm configuration (TDI X). In the following, any quoted SNRs for the Observational Requirements (ORs) are given in terms of the full 3-arm configuration. The derived Mission Requirements (MRs) are expessed as linear spectral densities of the sensitivity for a 2-arm configuration (TDI X).

The sensitivity curve can be computed from the individual instrument noise contributions, with factors that account for the noise transfer functions and the sky and polarisation averaged response to GWs. Requirements for a minimum SNR level, above which a source is detectable, translate into specific MRs for the observatory. Throughout this section, parameter estimation is done using a Fisher Information Matrix approach, assuming a 4 year mission and 6 active links. For long-lived systems, the calculations are done assuming a very high duty-cycle (> 95%). Requiring the capability to measure key parameters to some minimum accuracy sets MRs that are generally more stringent than those for just detection. Signals are computed according to GR, redshifts using the cosmological model and parameters inferred from the Planck satellite results, and for each class of sources, synthetic models driven by current astrophysical knowledge are used in order to describe their demography. Foregrounds from astrophysical sources, and backgrounds of cosmological origin are also considered.

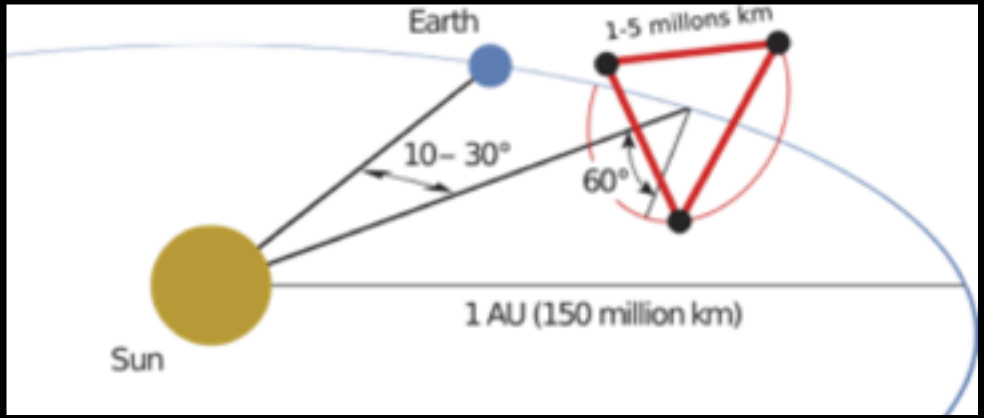
Figure 2: Mission constraints on the sky-averaged strain sensitivity of the observatory for a 2-arm configuration (TDI X), $\sqrt{S_h(f)}$, derived from the threshold systems of each observational requirement.

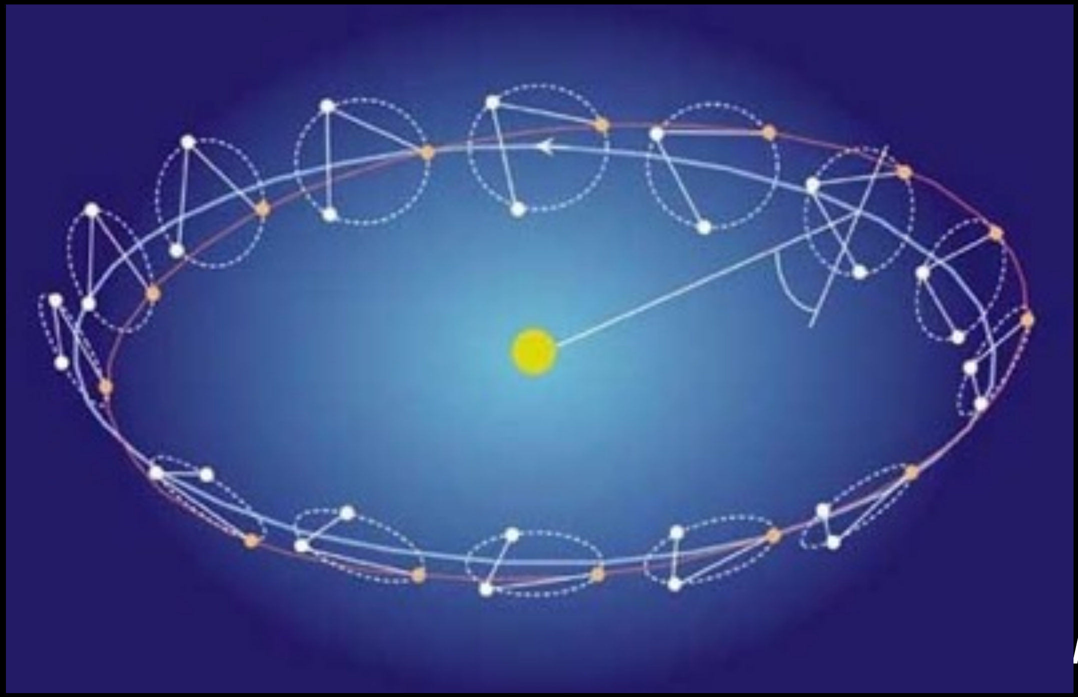
LISA – 2. SCIENCE PERFORMANCE Page 7

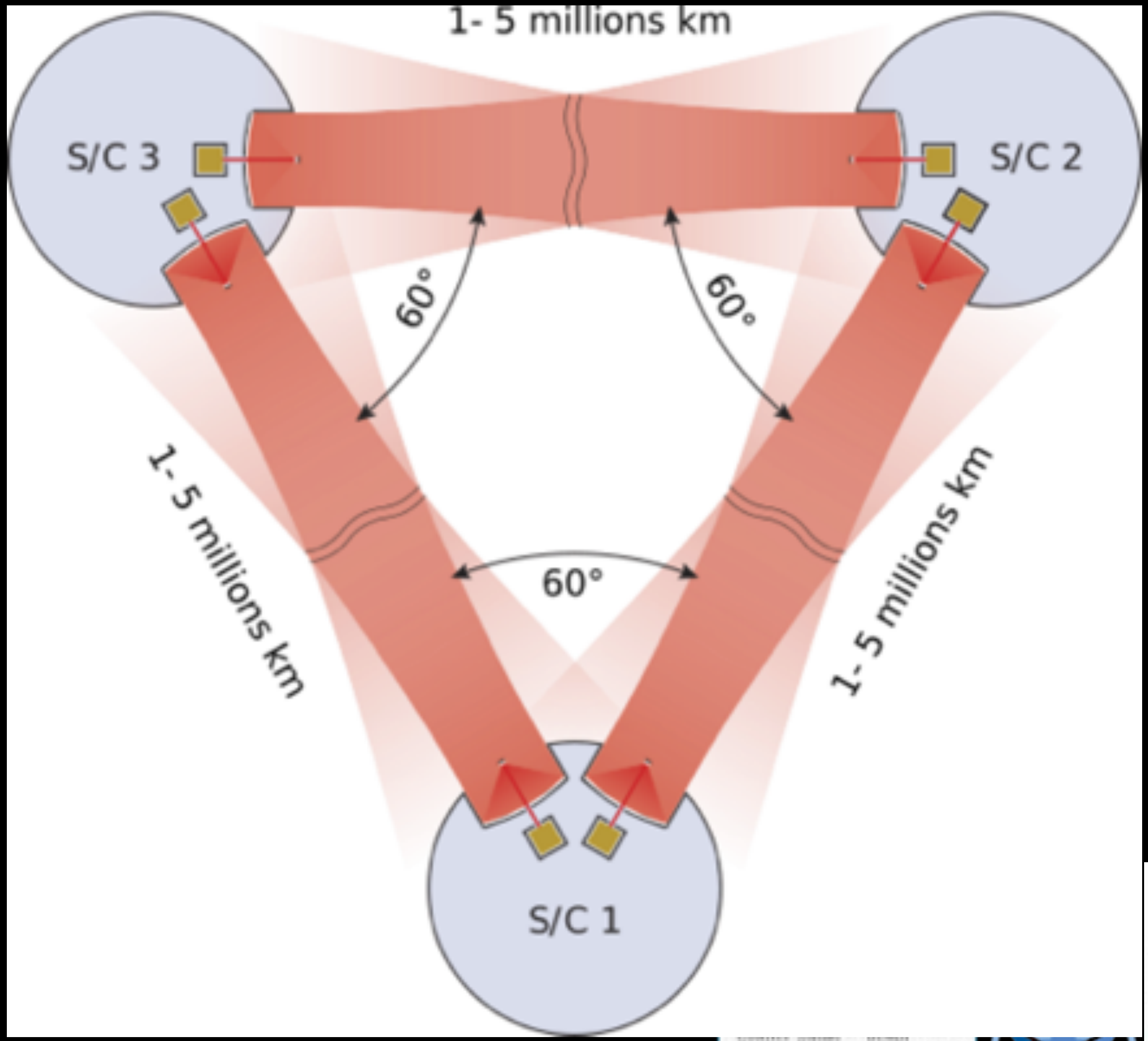
LISA design

LISA

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from few millions kilometers (2.5 Mom in the proposal L3)
- Goal: detect relative distance changes of 10^{-21}: few picometers

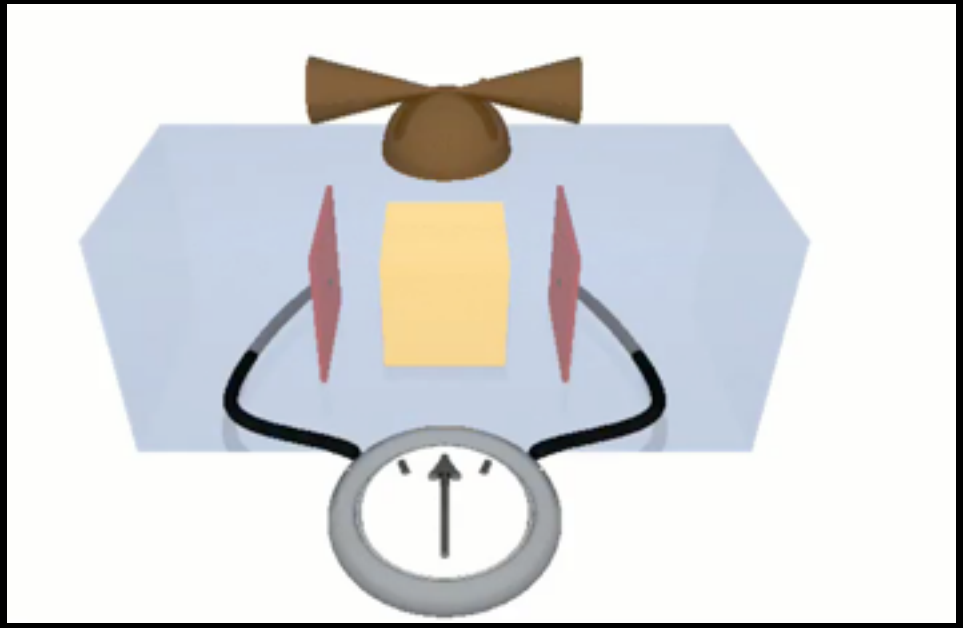


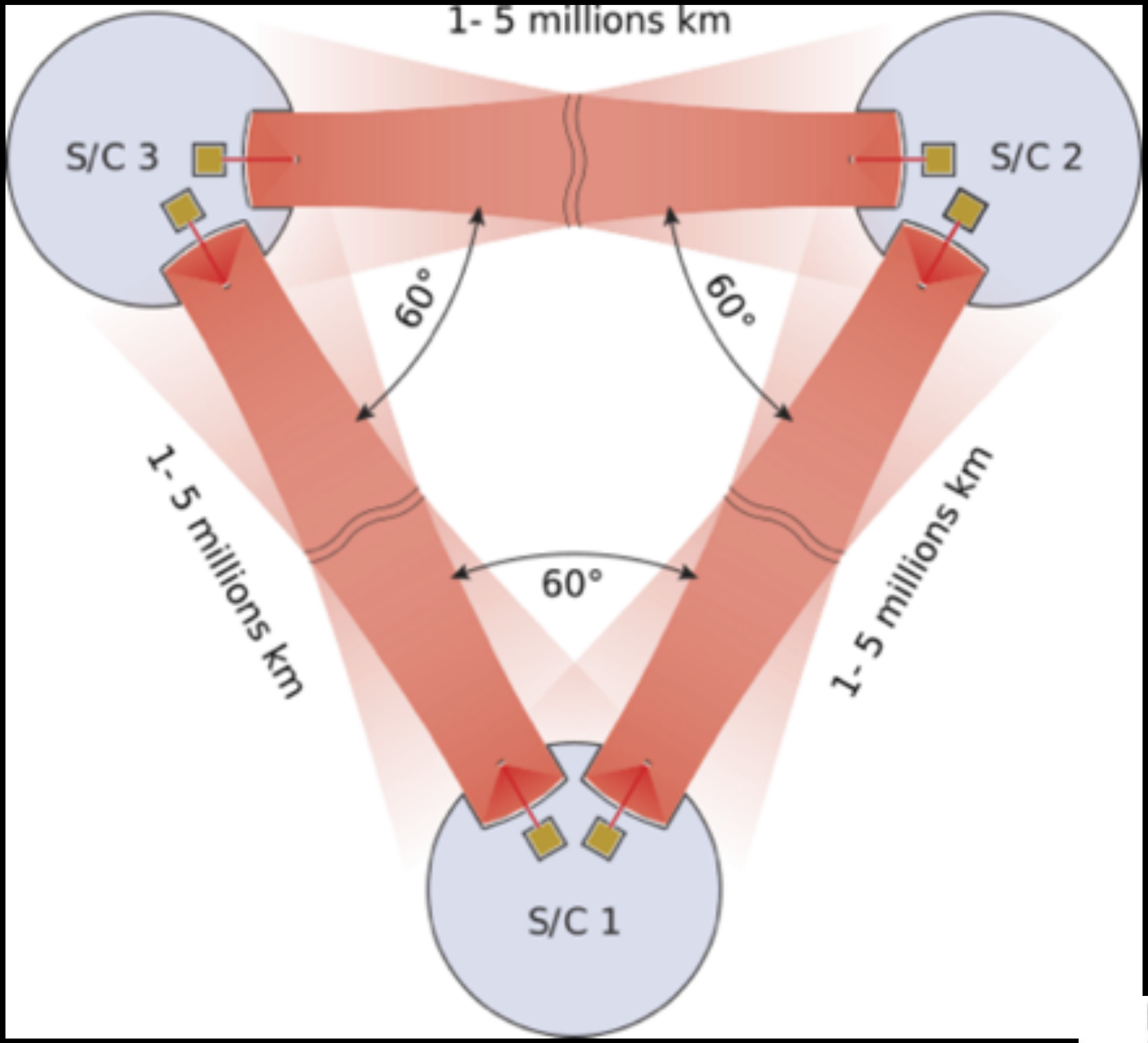




LISA

- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing





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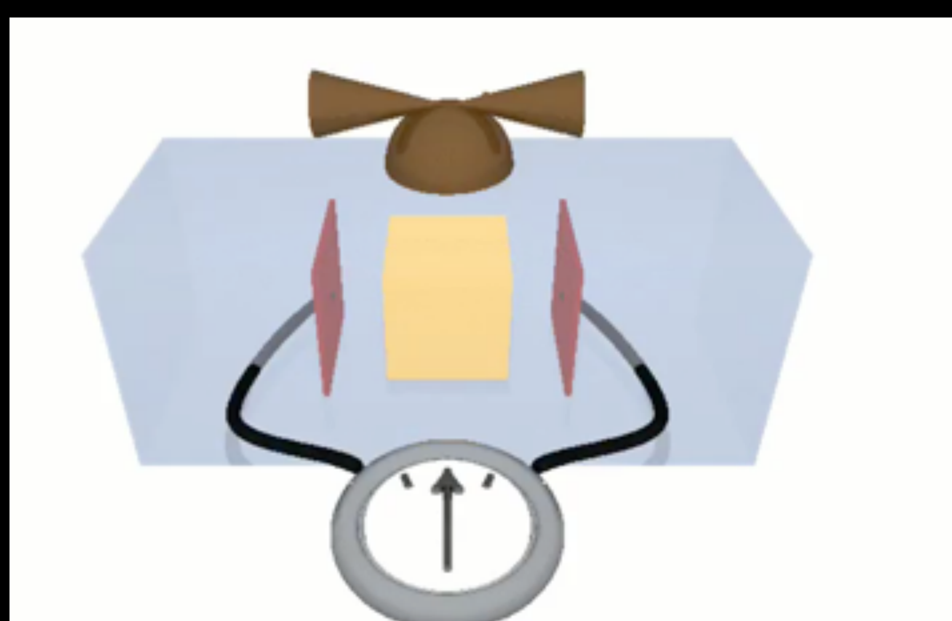

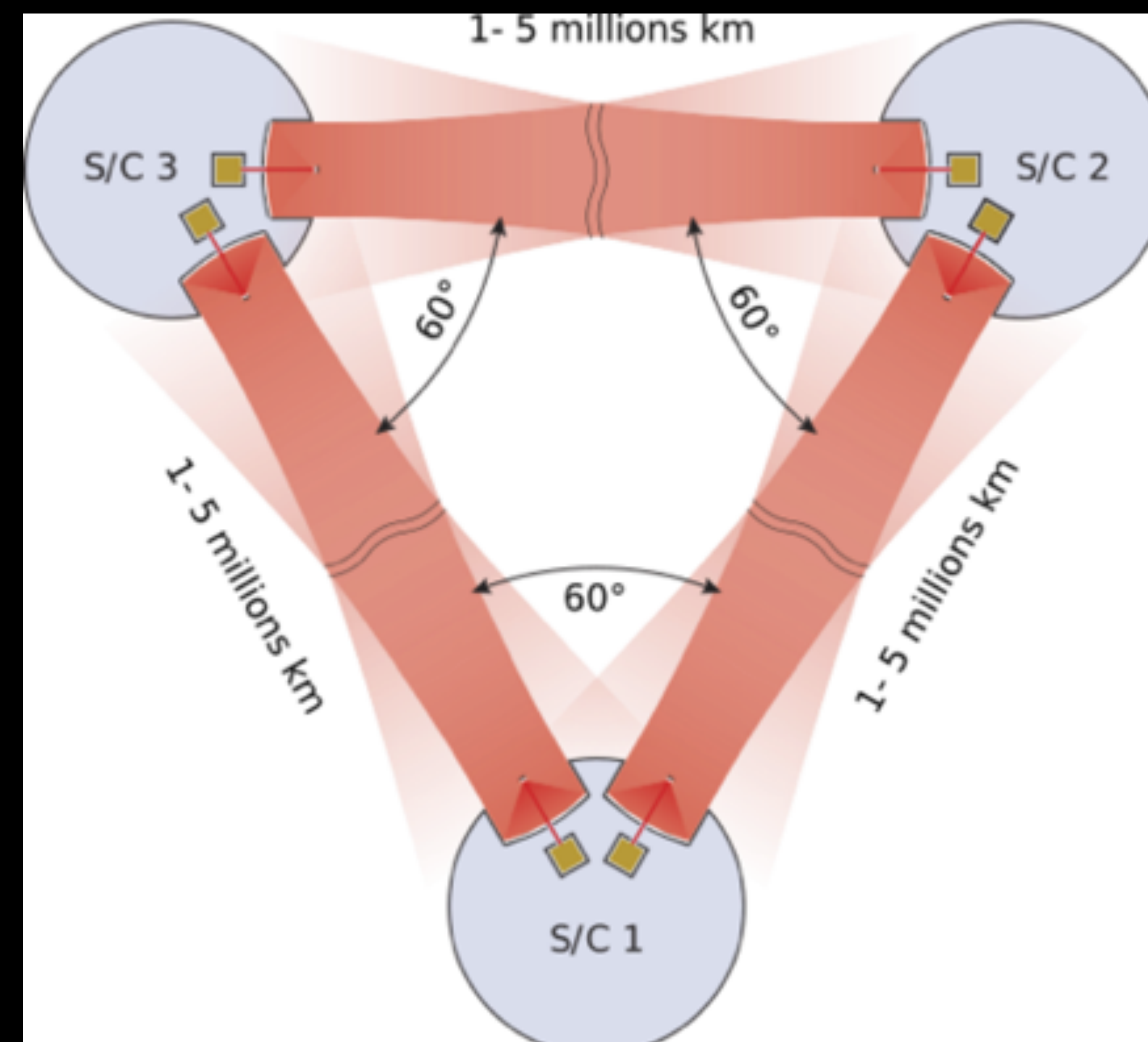

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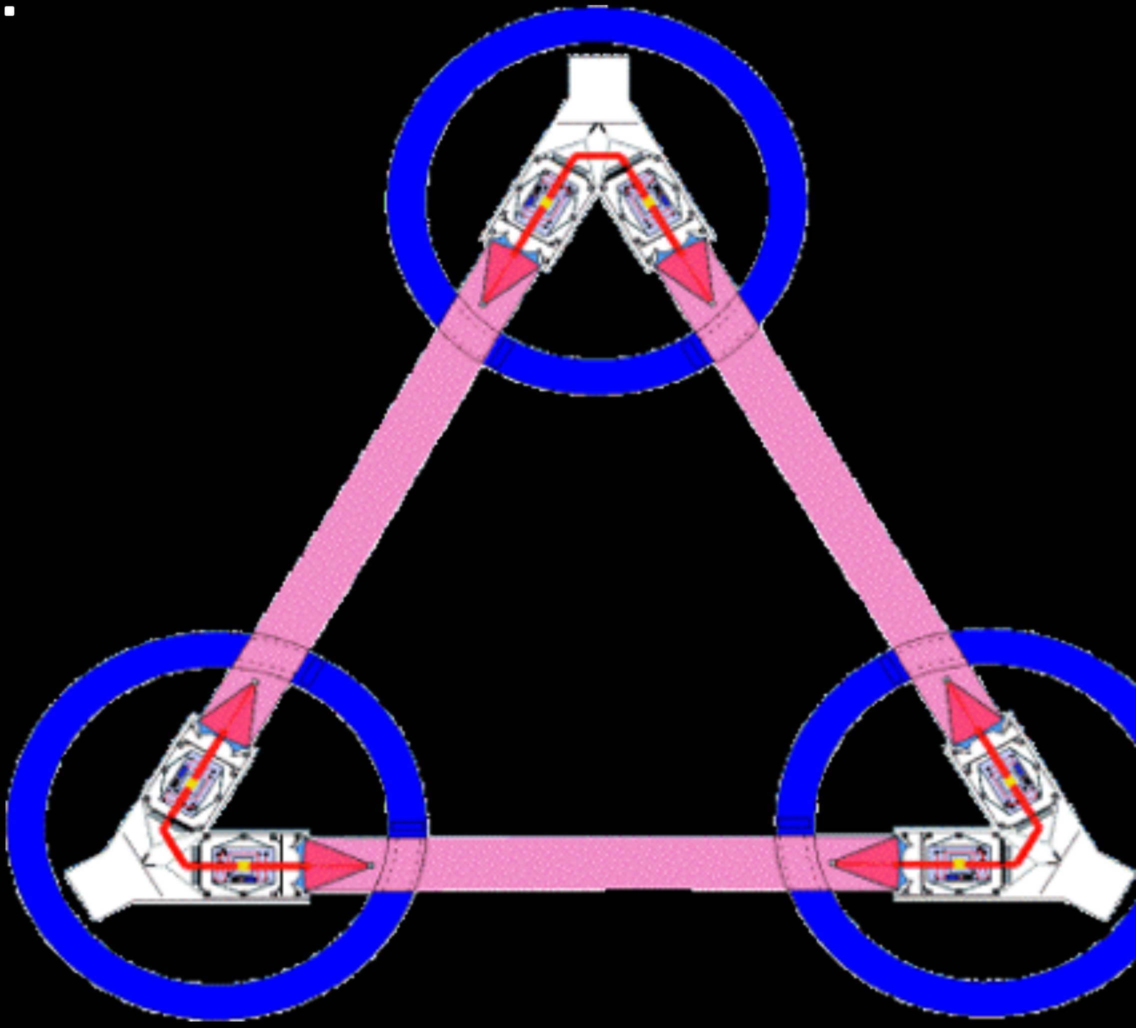
LISA : Measurements

- Problem with 2.5×10^9 m : A laser beam cannot make a round trip because too much intensity is lost.
  - 100pW received for 1 Watt emitted.
- Measurement with one arm and interference between two incoherent lasers in phase :
  - Distant laser
  - Local laser.
- 6 measurements ... at least!



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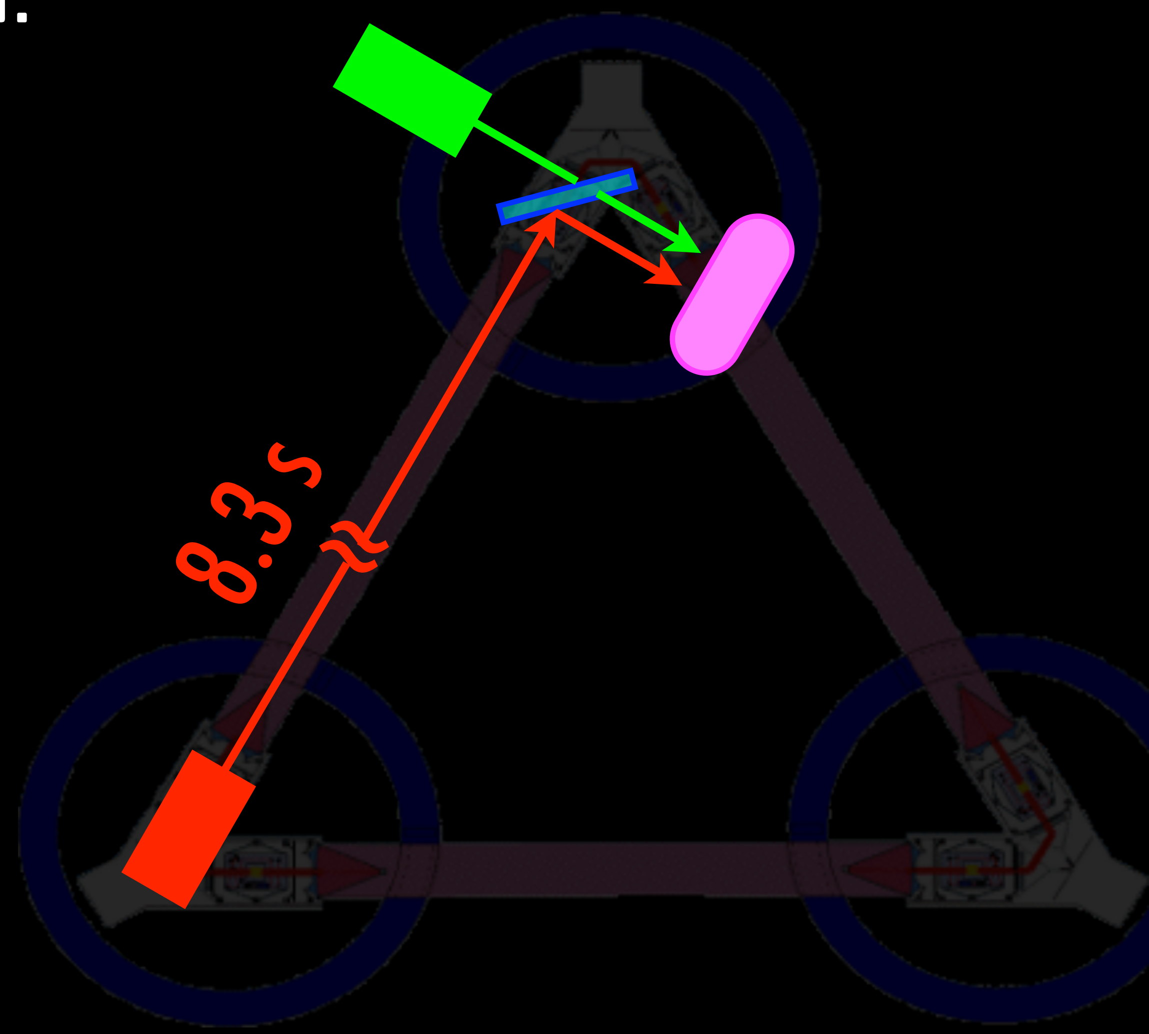

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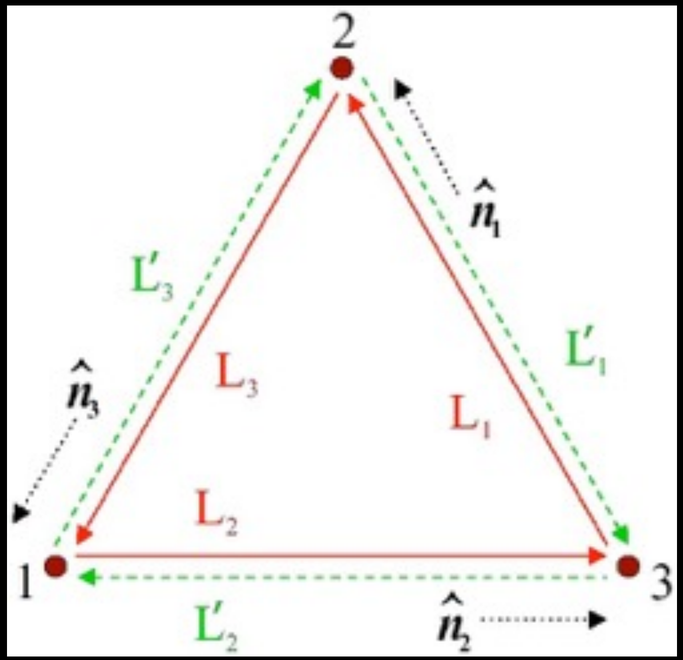
LISA : Measurements (old design)

- Phase shift between the two beams measured by phasemeter.
- Beams from an external spacecraft, are delayed :
  - delay operator D_i^{real} : $D_i^{real}\; x(t) = x\left(t - \frac{L_i^{real}}{c}\right).$
- The measurement :

$$s_1 = s_1^{GW} + s_1^{ShotNoise} + D_3^{real}\; p'^{lasernoise}_2 - p_1^{lasernoise} - 2\delta^{Acc.Noise}$$



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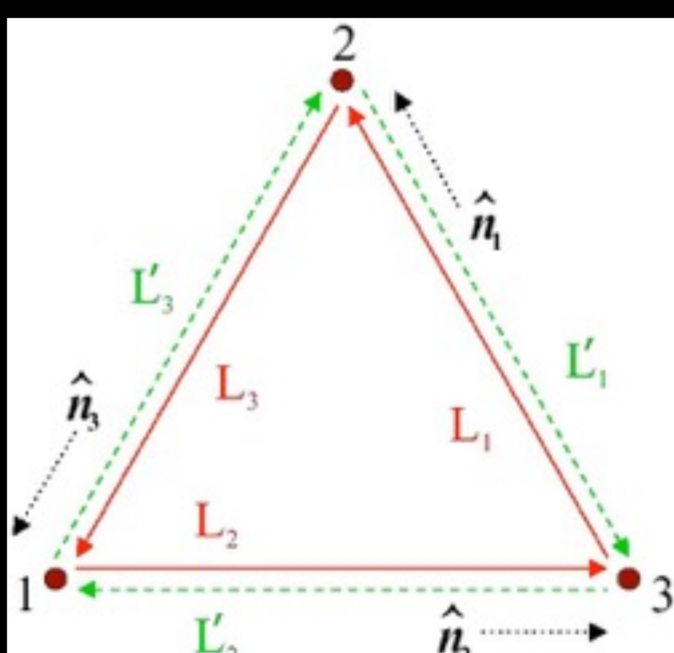

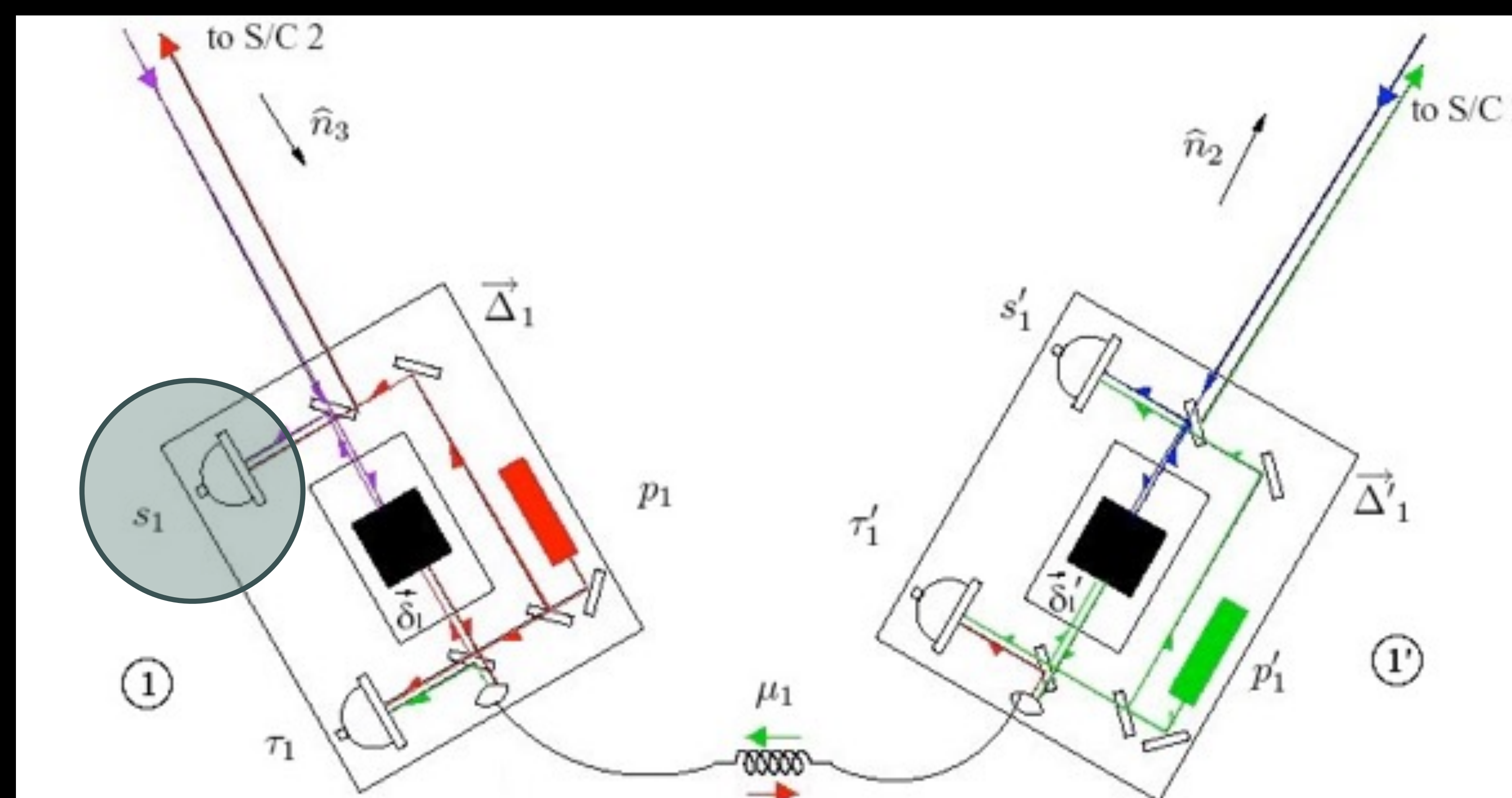

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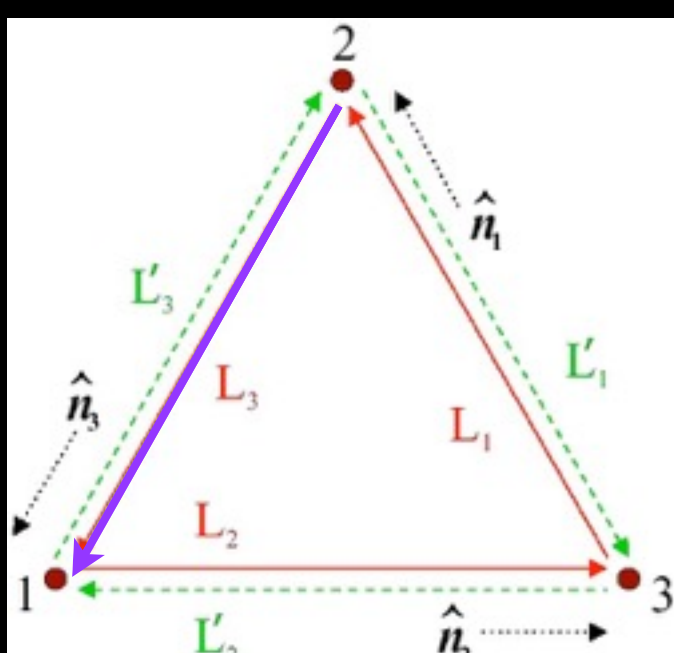

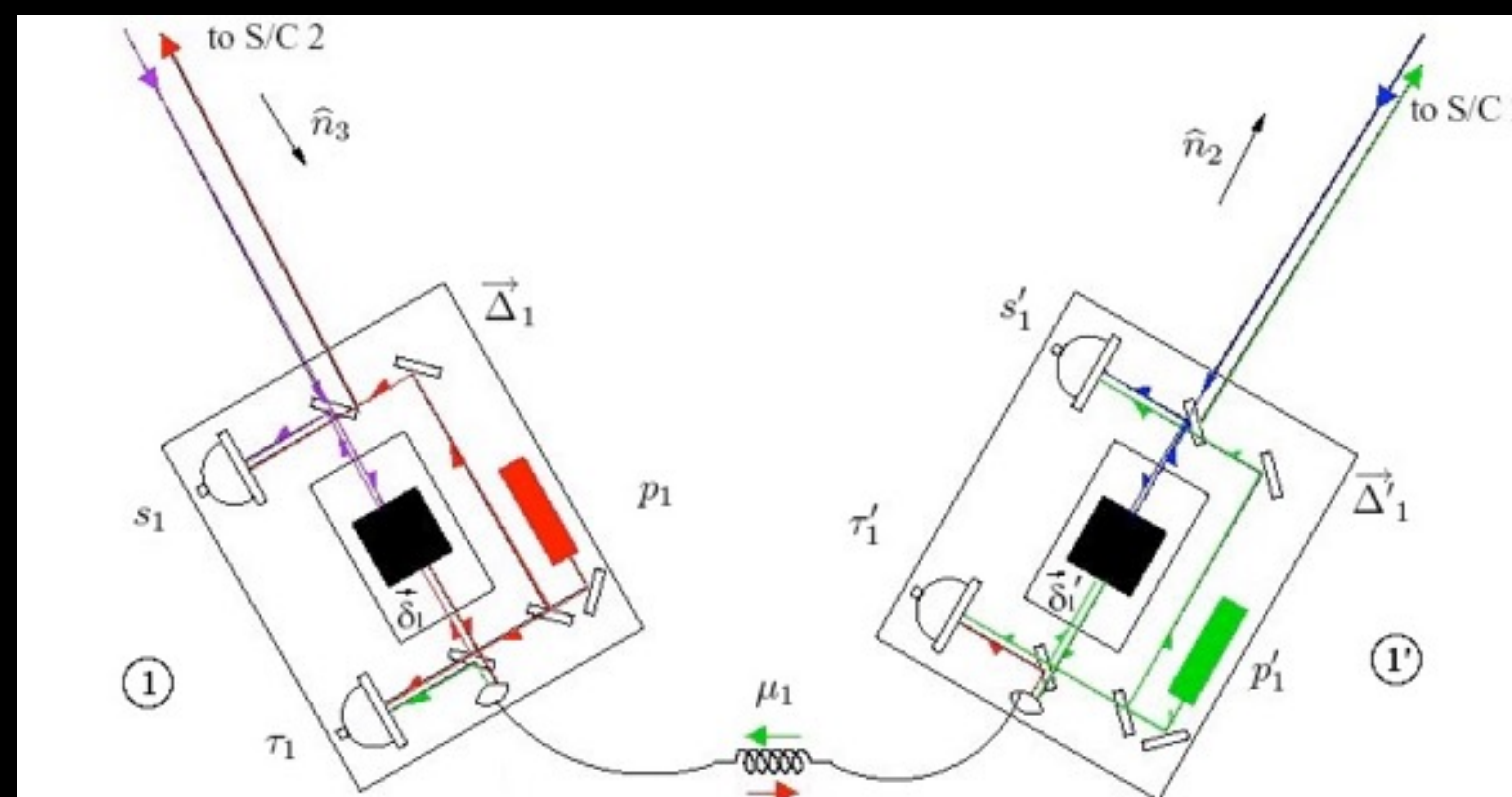

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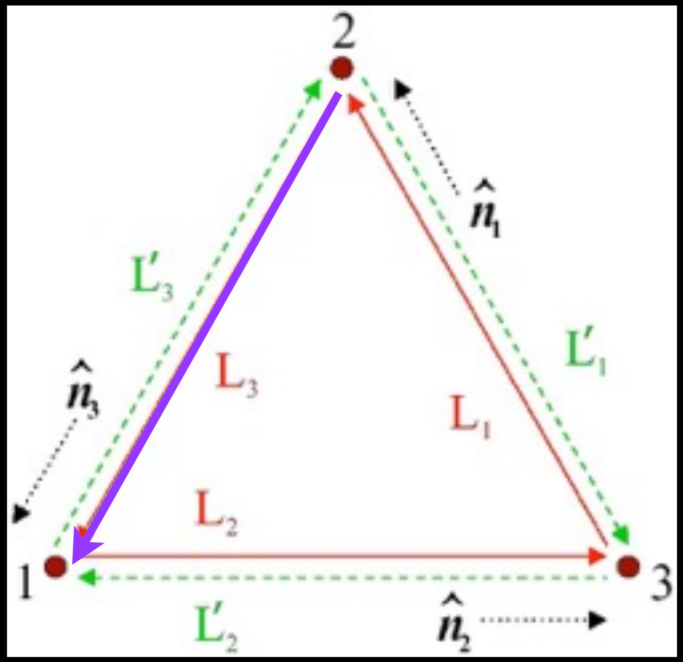

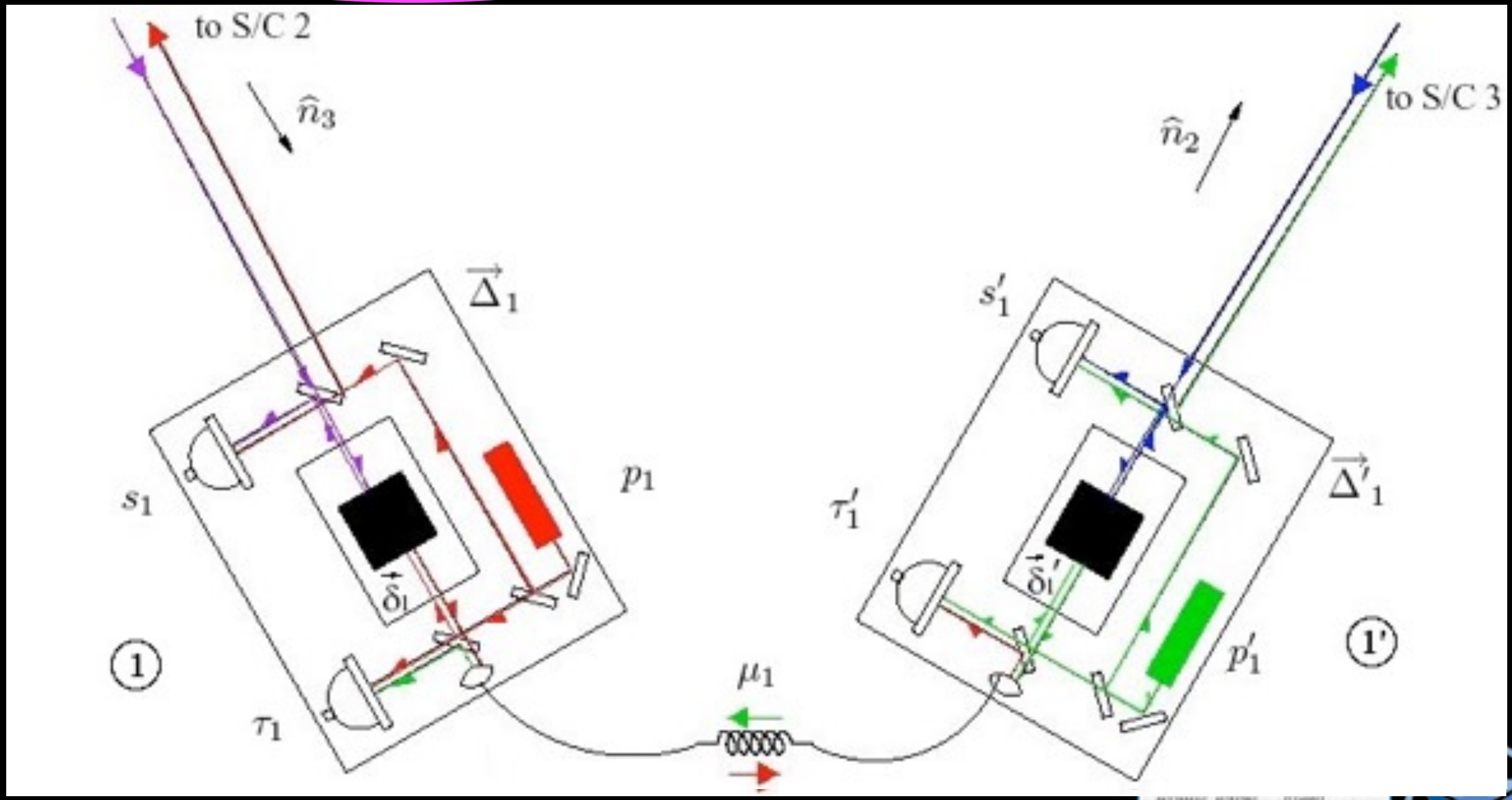

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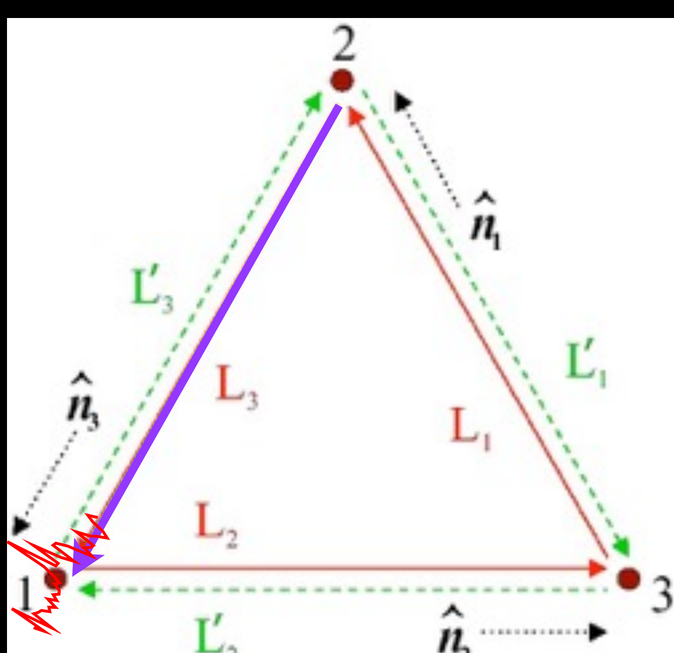

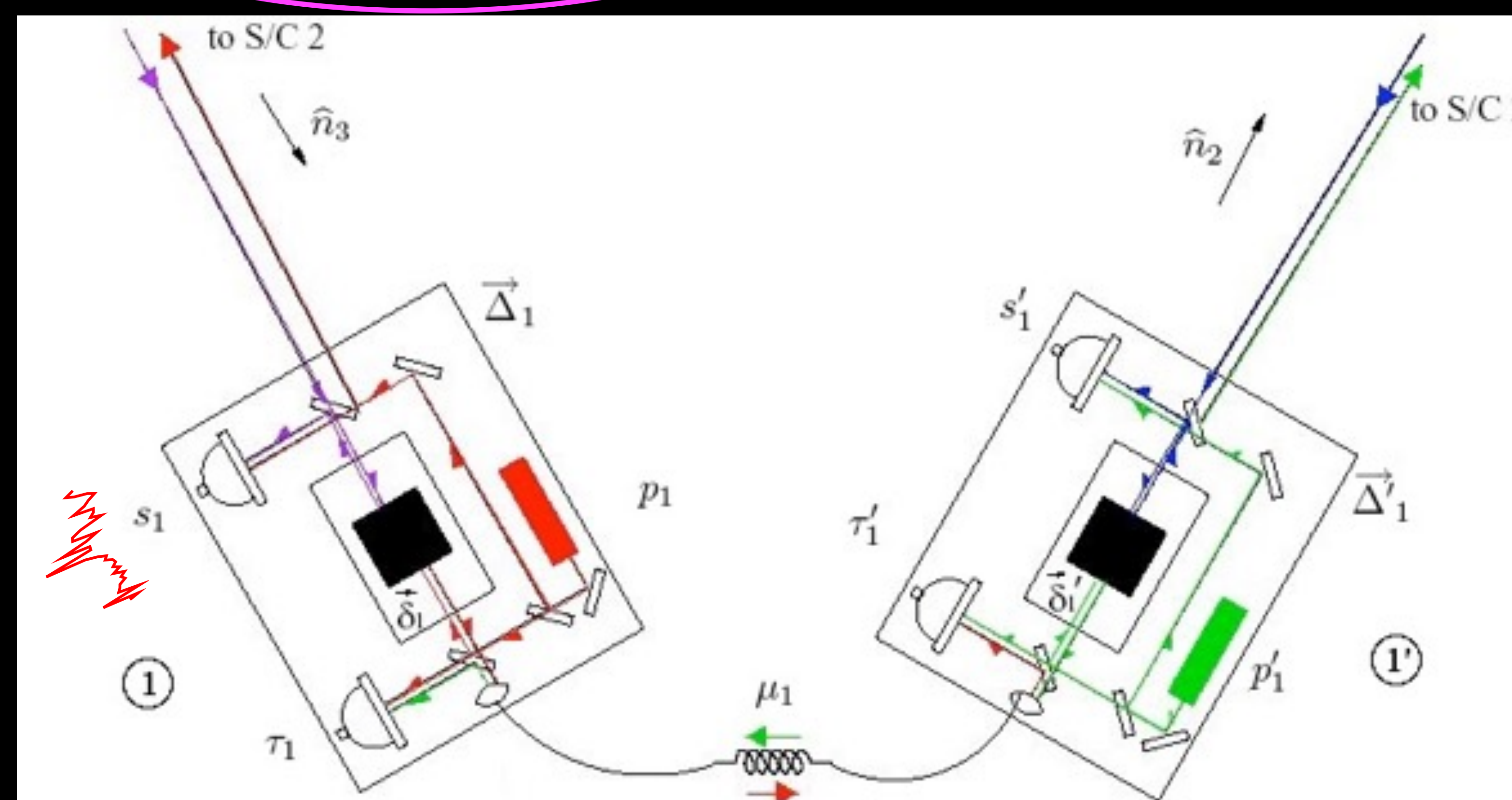

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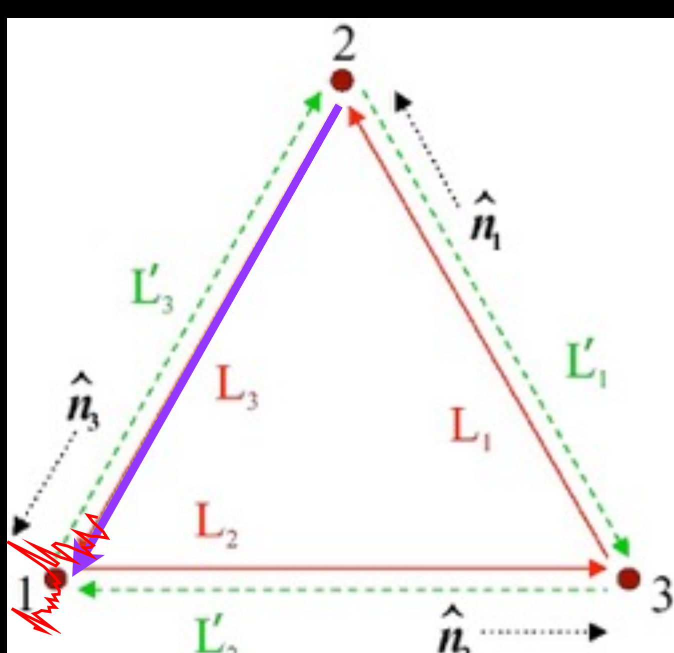

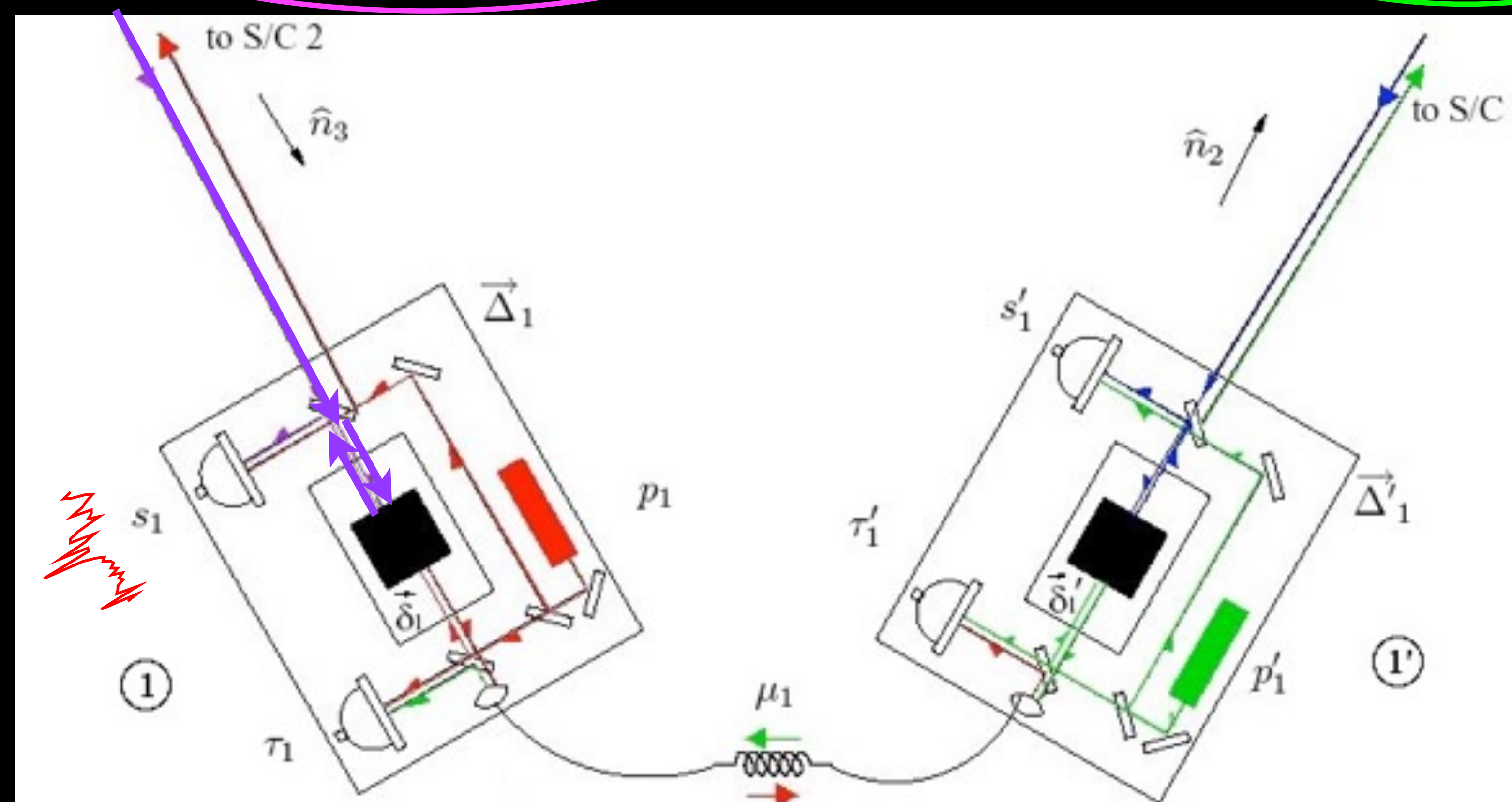

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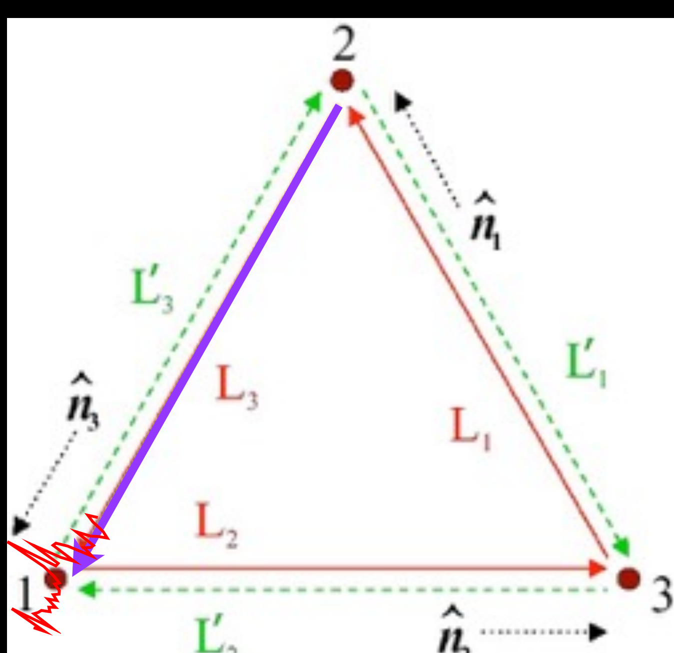

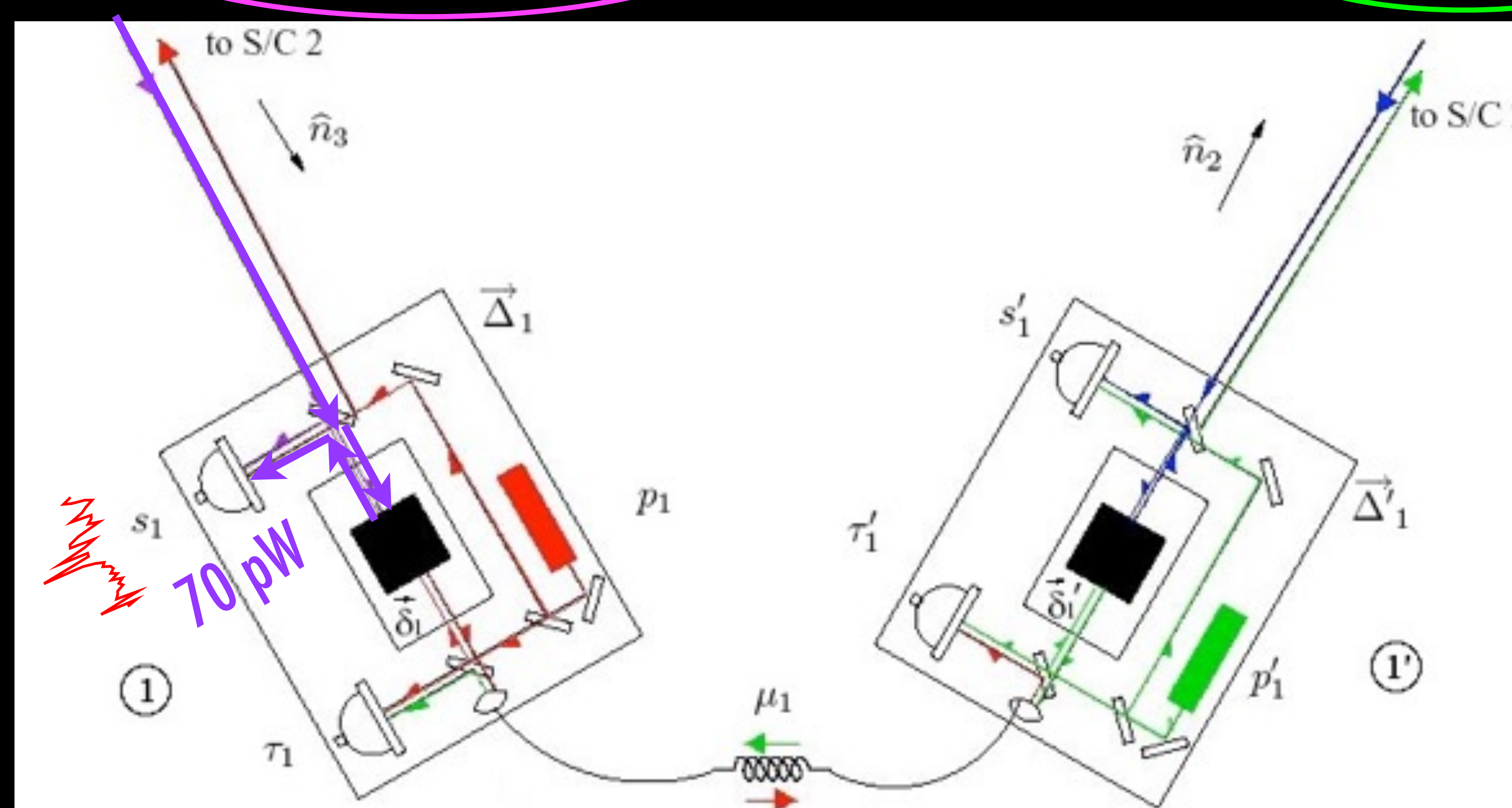

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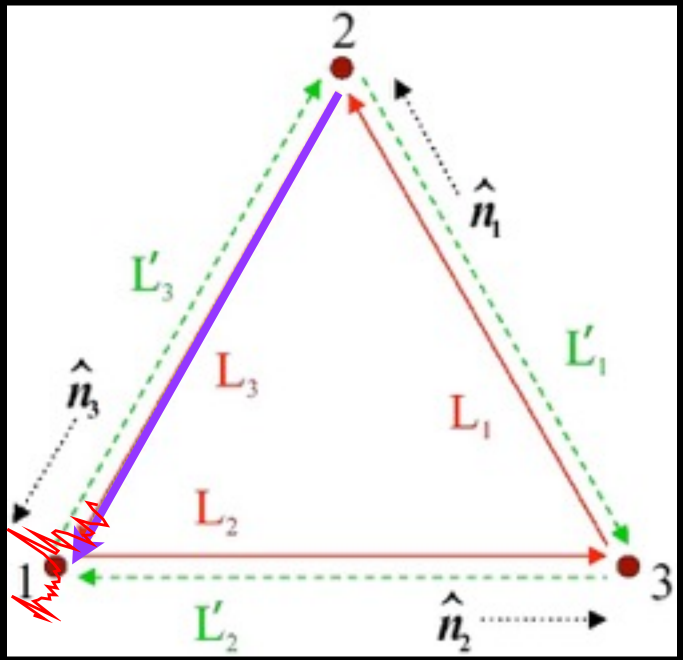

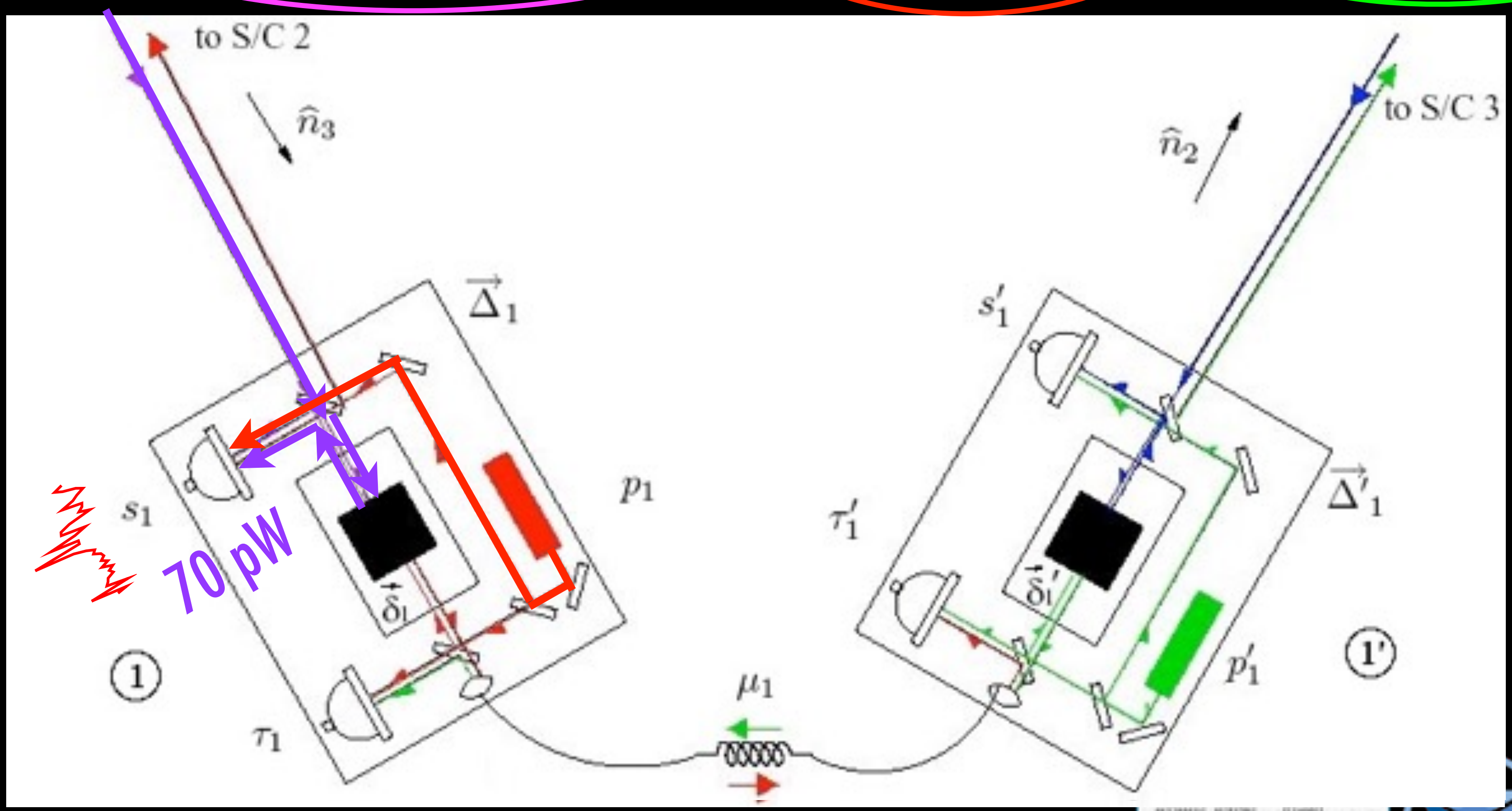

Time Delay Interferometry

eliminating laser noise but keeping the GW signal

- Pre-processing of the science data,

Tinto & Durandhar, Revue *Living Rev. Rel. 8 p 4* (2005)
Durandhar, Nayak & Vinet, *PRD 65 102002* (2002)

- Combinations of delayed measurements to reduce laser noise:

$$-s'_2(t) = p'_2(t)$$

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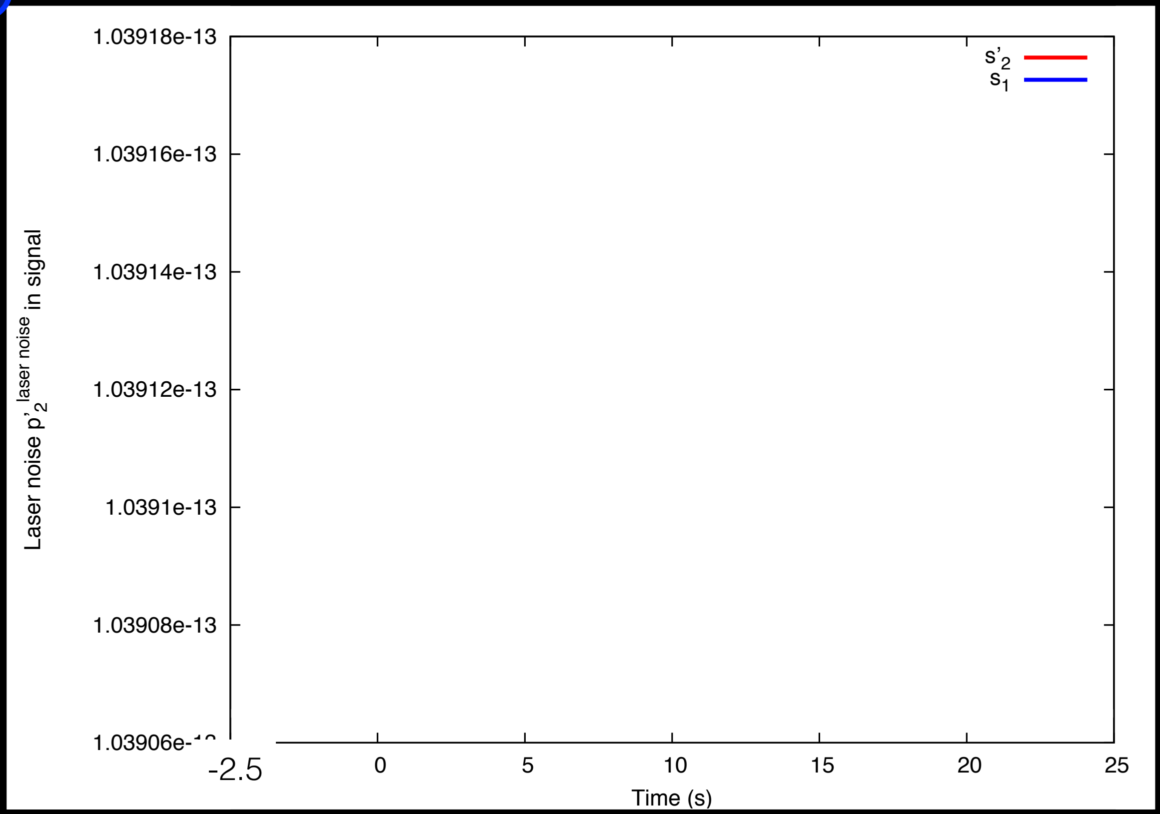

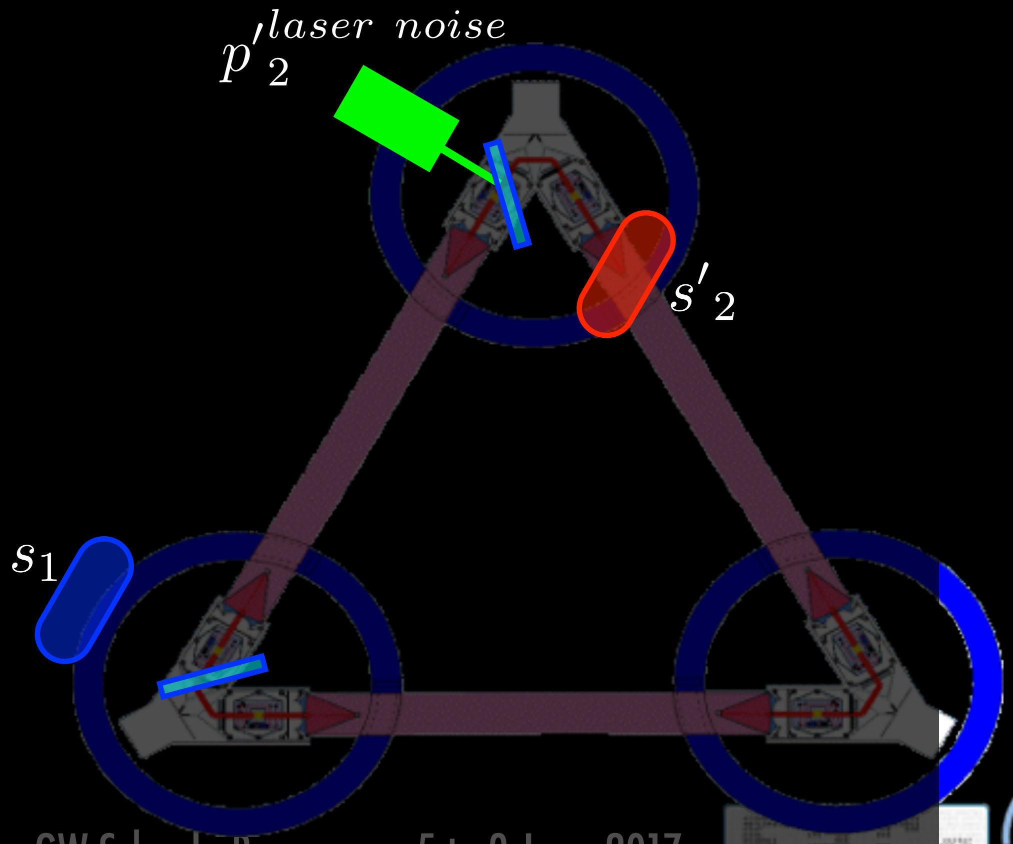

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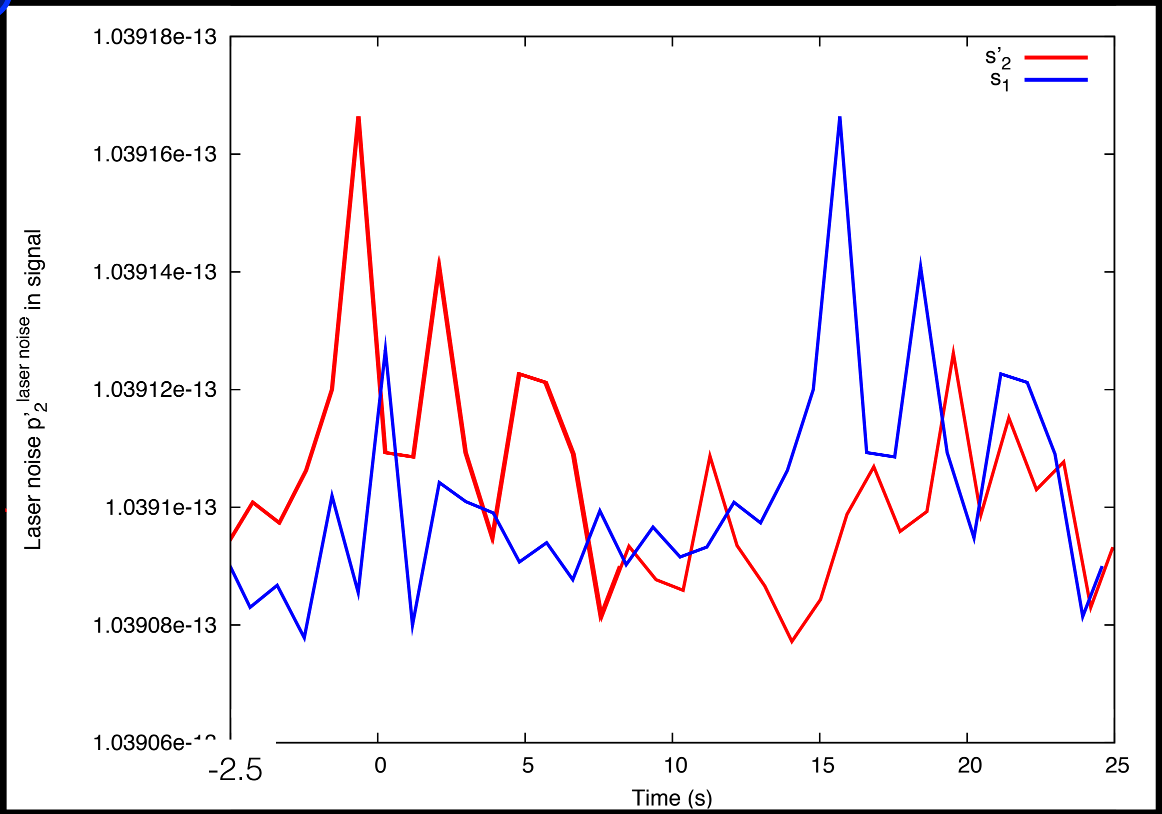

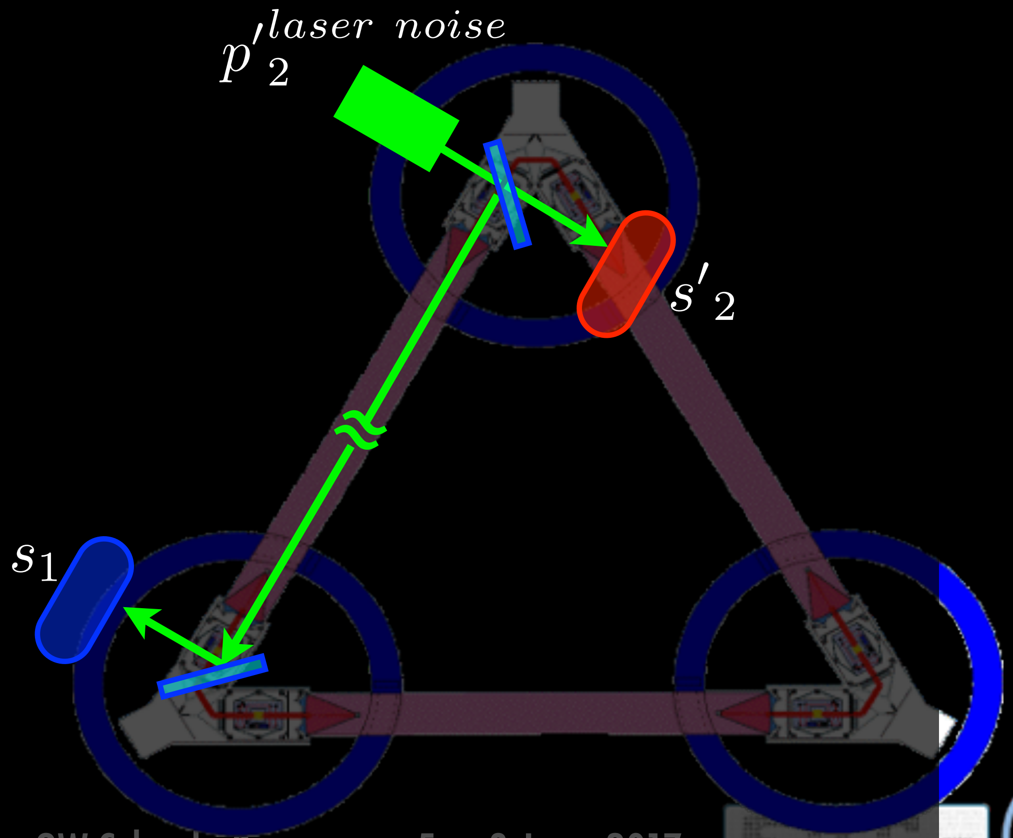

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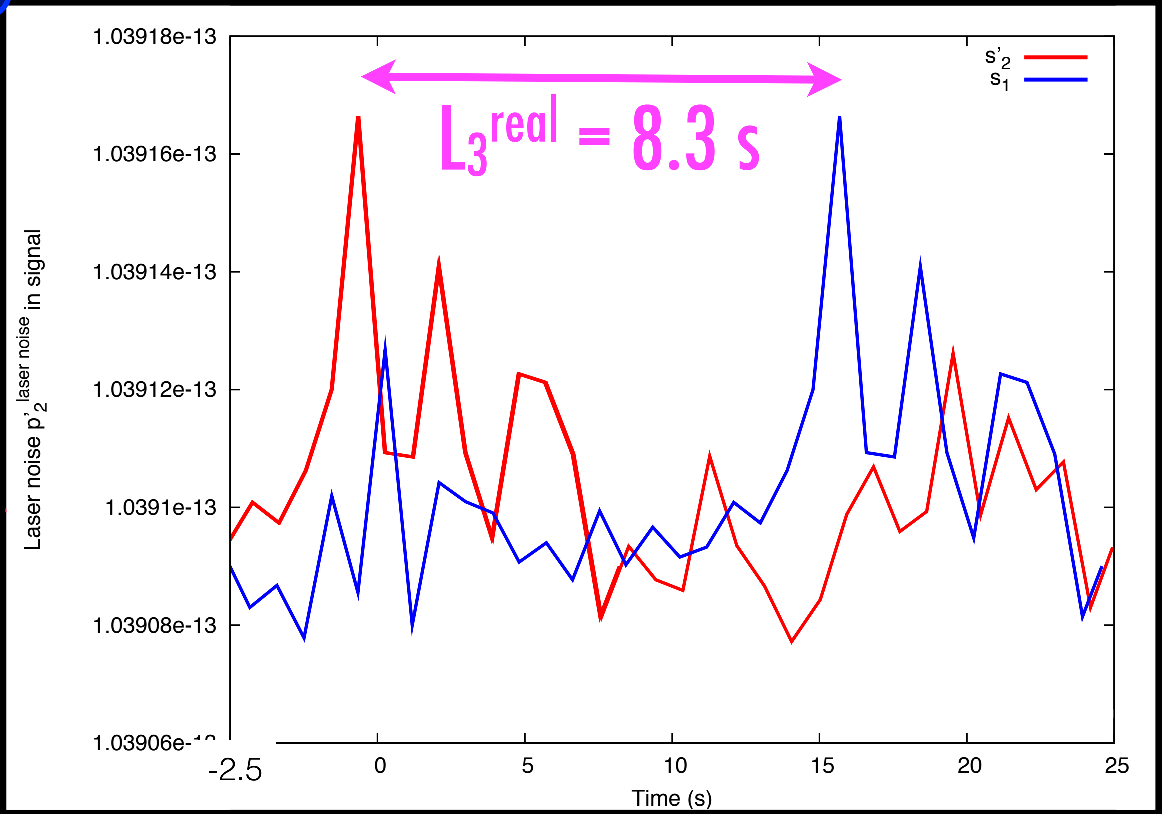

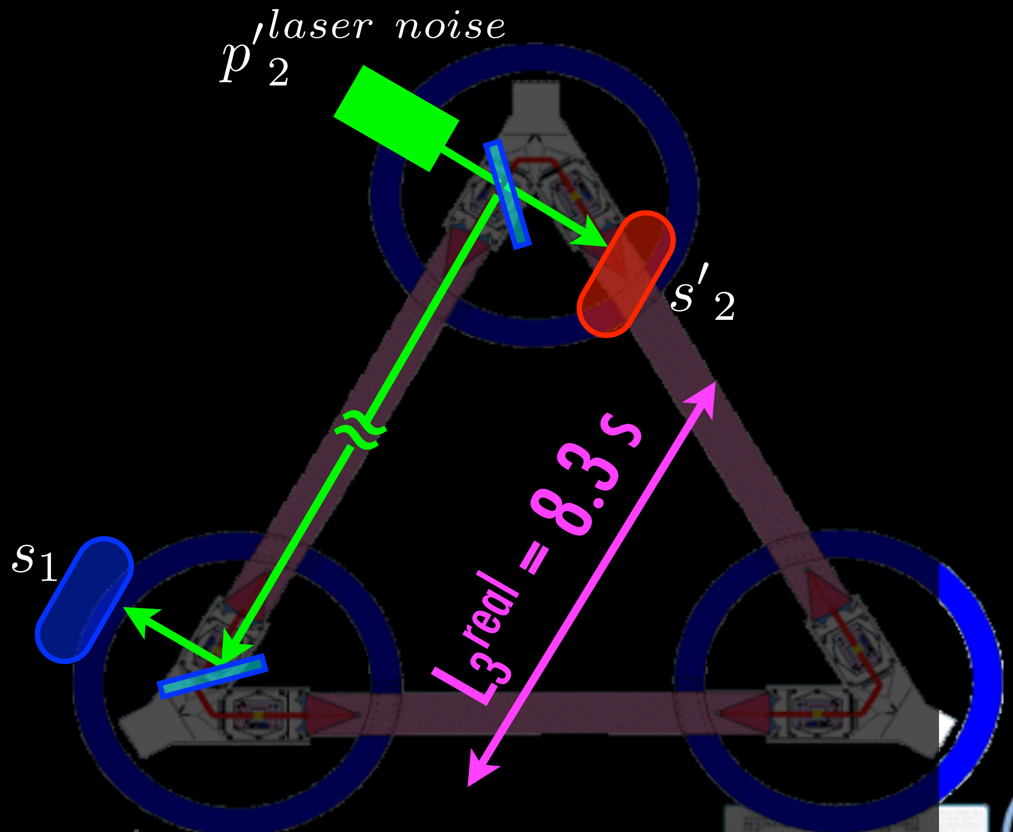

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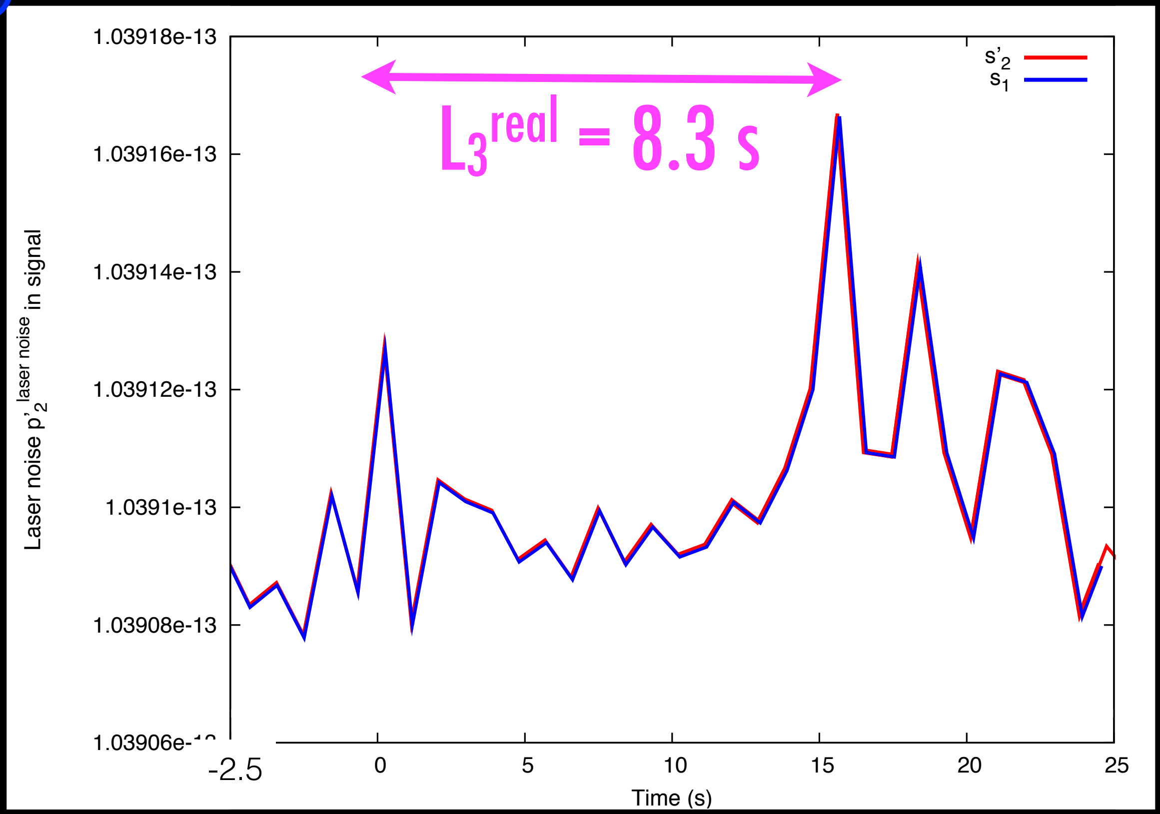

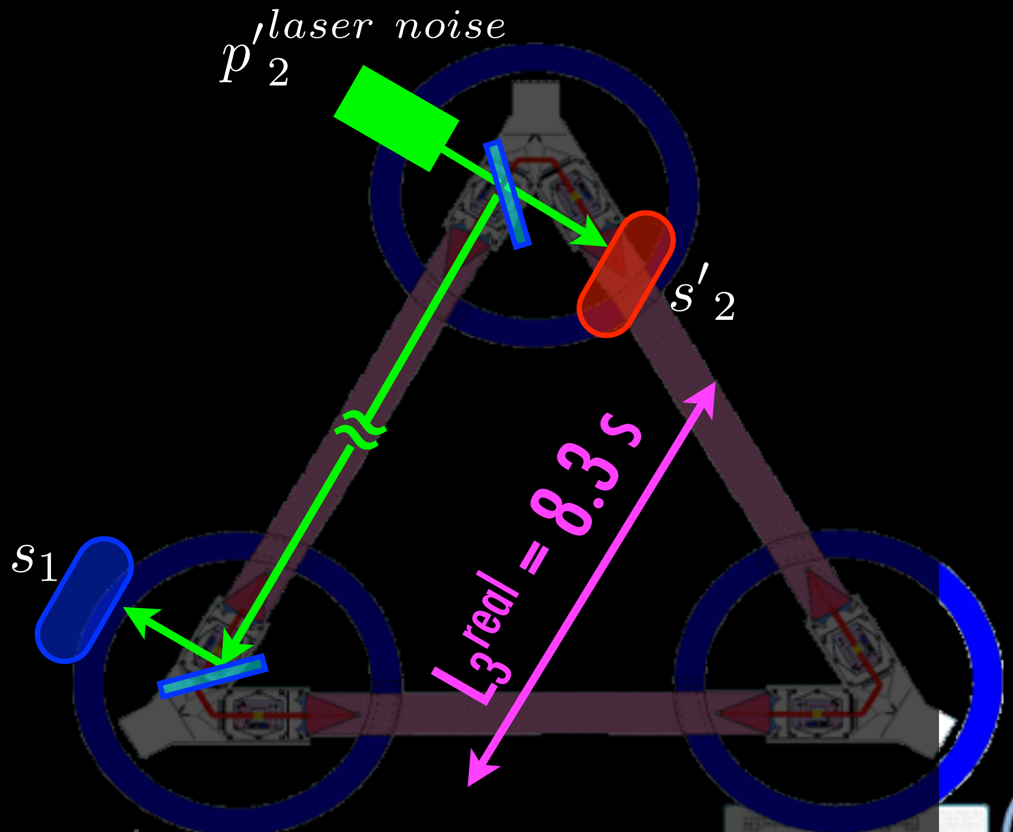

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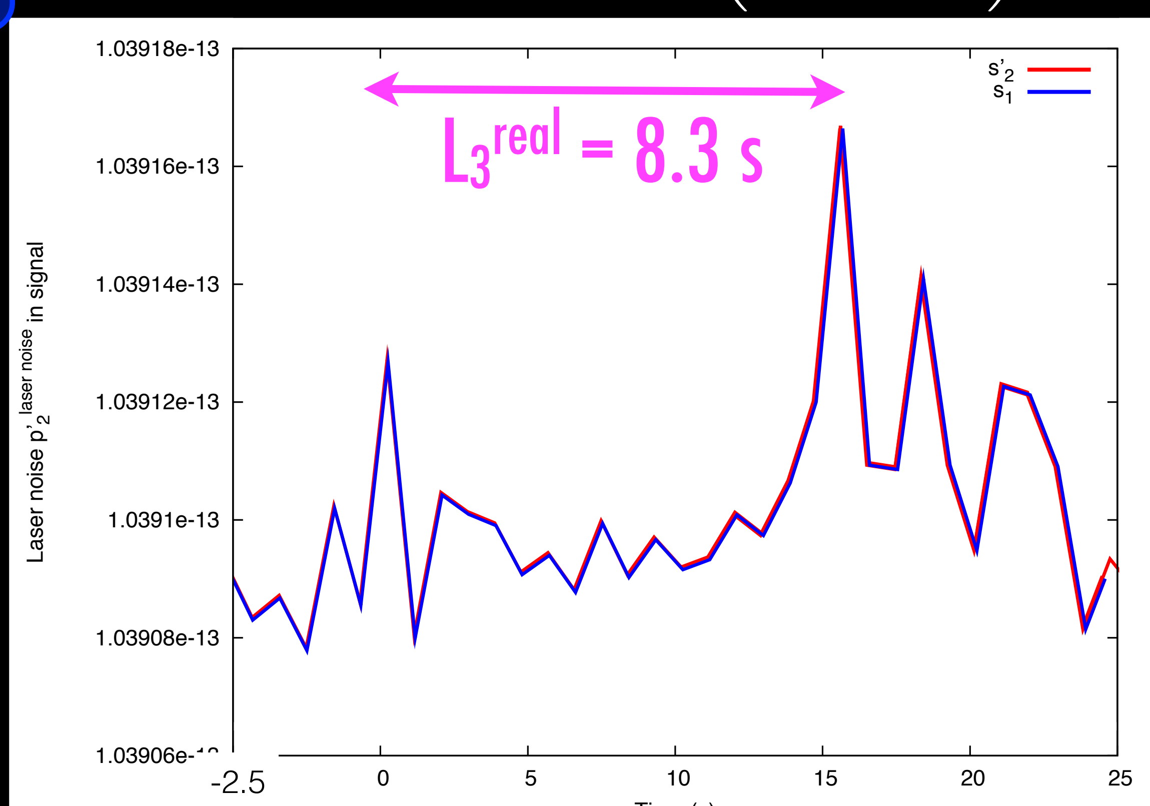

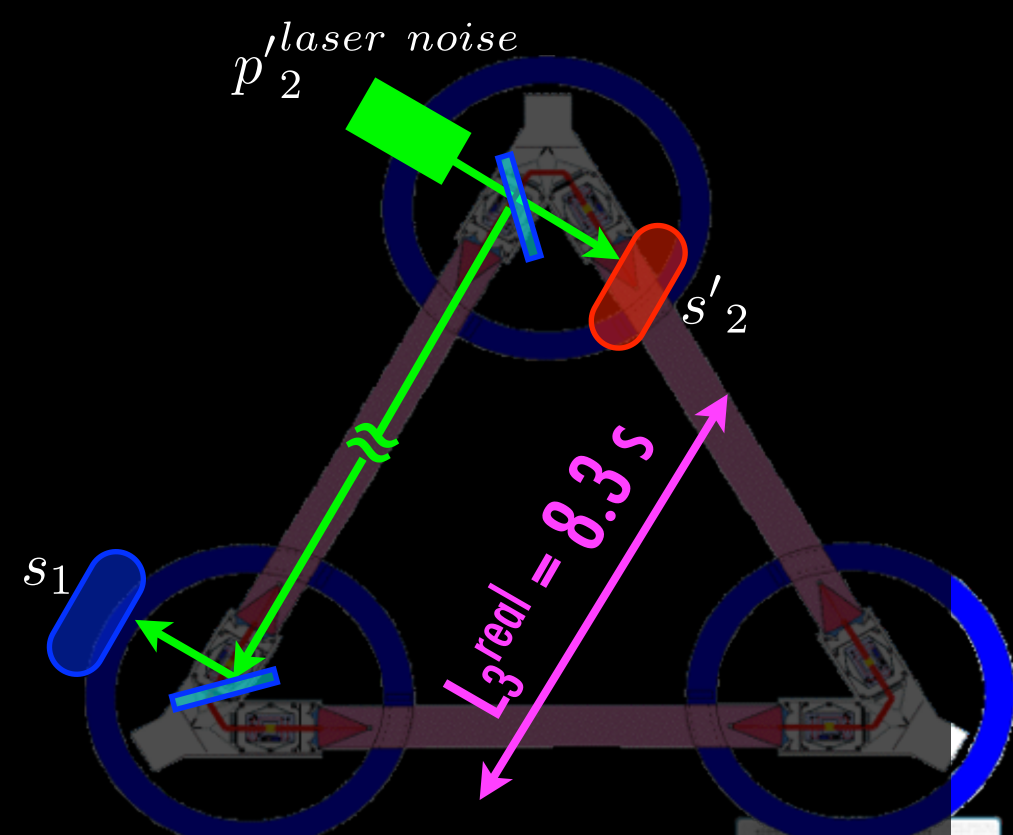

Time Delay Interferometry

TDI requires :

- knowledge of delays : $L_i^{TDI} = L_i^{real}$
- interpolation due to the sampling of phasemeter signal

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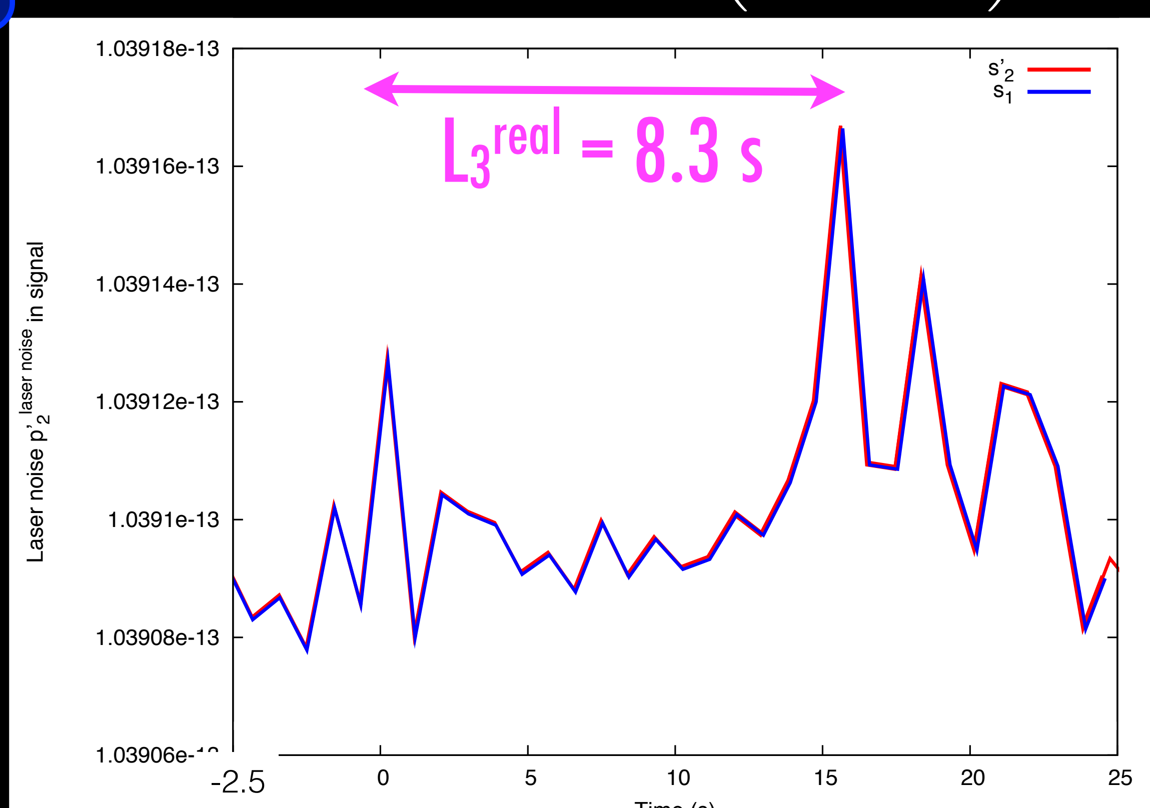
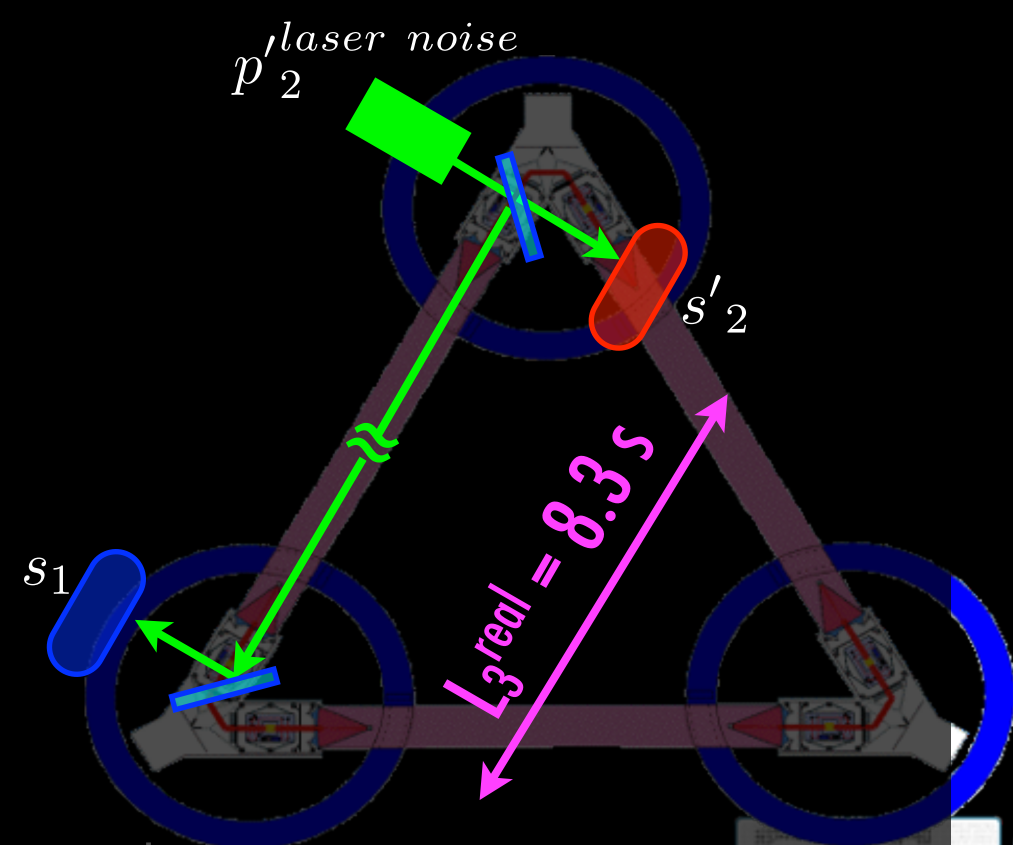
$$\begin{aligned} s_1(t) \;&+\; D_3^{TDI}\, s'_2(t) \\ &= D_3^{real} p'_2 - D_3^{TDI} p'_2 \\ &\simeq 0 \end{aligned}$$





Time Delay Interferometry

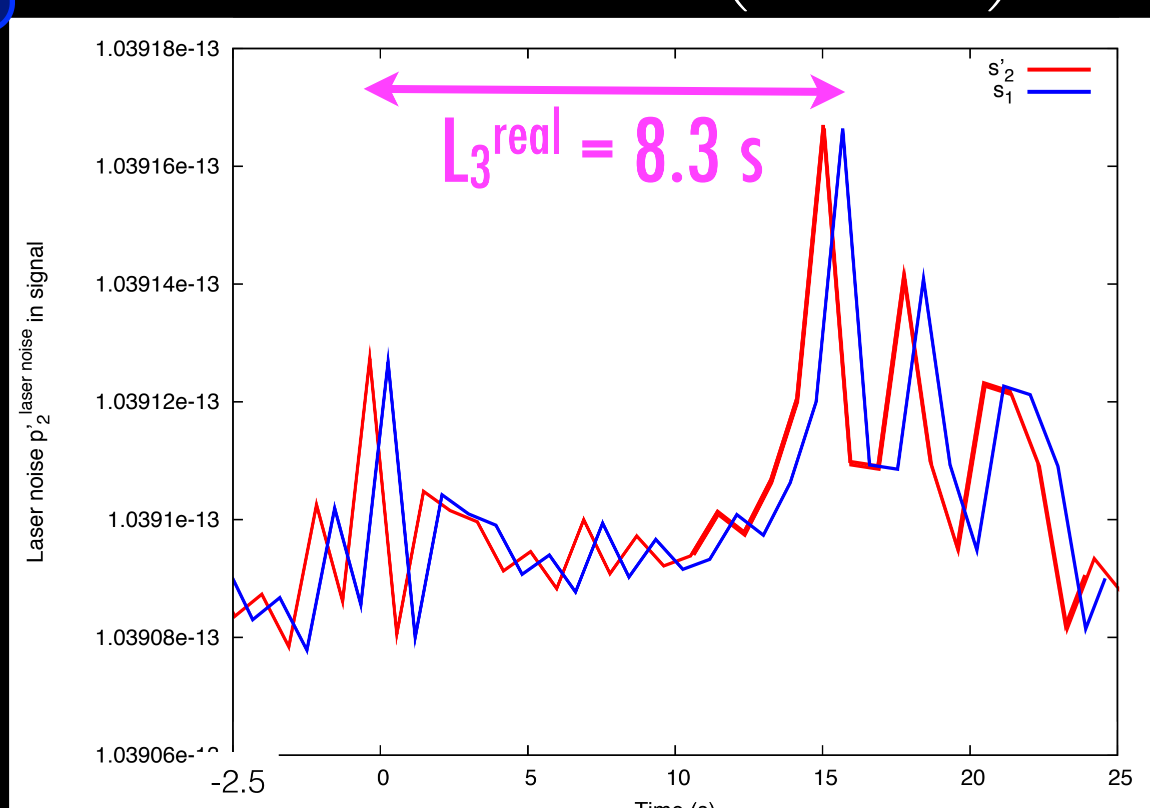
TDI requires :

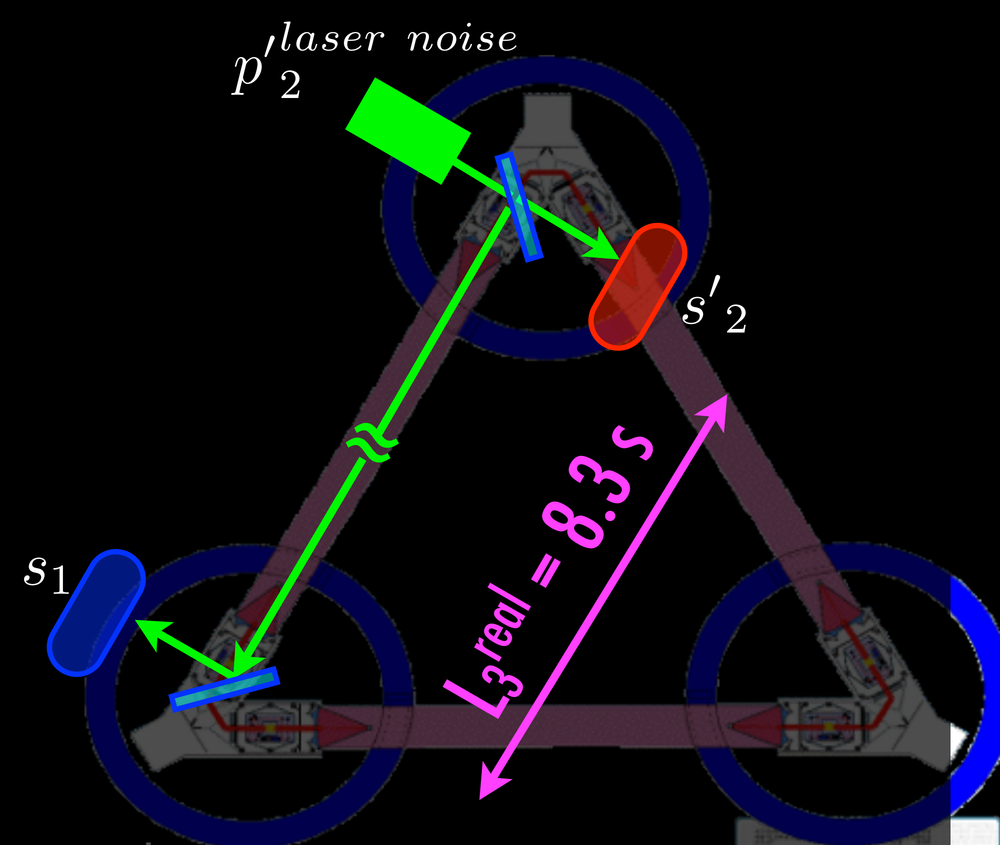
- knowledge of delays : $L_i^{TDI} = L_i^{real}$
- interpolation due to the sampling of phasemeter signal

$$-D_3^{TDI}\ s'_2(t) = -D_3^{TDI} s'_2 = p'_2\left(t - \frac{L_3^{TDI}}{c}\right)$$

$$s_1(t) = D_3^{real} p'_2(t) = p'_2\left(t - \frac{L_3^{real}}{c}\right)$$

$$\begin{aligned} s_1(t) \ &+ \ D_3^{TDI}\ s'_2(t) \\ &= \ D_3^{real} p'_2 - D_3^{TDI} p'_2 \\ &\simeq \ \text{residual laser noise} \end{aligned}$$





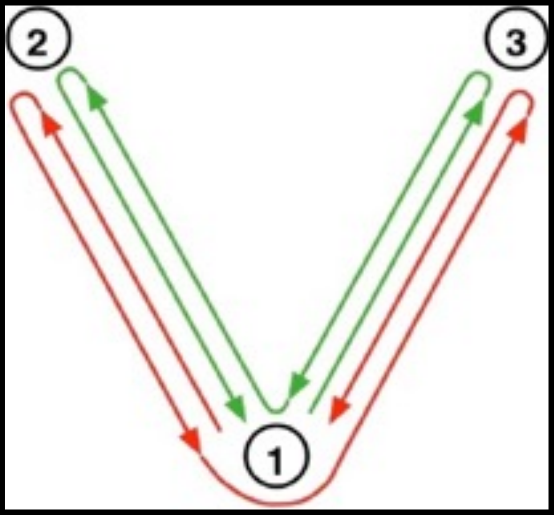
Time Delay Interferometry

- Time Delay Interferometry:

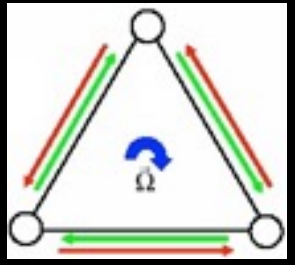
Tinto & Durandhar, Revue *Living Rev. Rel. 8 p 4* (2005)
Durandhar, Nayak & Vinet, *PRD 65 102002* (2002)
Vallisneri, *gr-qc/0504145* (2005)

- Combine delayed measurements to reduce laser noises, optical bench noises, ... ?
- Algebraic development: many combinations (generators)

$$
\begin{aligned}
X &= -s_1 - D_3\ s'_2 - D_3 D_{3'}\ s'_1 - D_3 D_{3'} D_{2'}\ s_3 \\
&\quad + s'_1 + D_{2'}\ s_3 - D_{2'} D_2\ s_1 - D_{2'} D_2 D_3\ s_3 \\
&\simeq 0
\end{aligned}
$$



- Different precisions level
  - 1st generation: rigid formation of LISA : $D_{i'}\, s = D_i\, s$,
  - generation 1.5: Sagnac effect : $D_{i'}\, s \neq D_i\, s$ but $D_j D_i\, s = D_i D_j\, s$,
  - 2nd generation: flexing and Sagnac effect : $D_j D_i\, s \neq D_i\ D_j\, s$



Time Delay Interferometry

- **TDI generation 1**

$$X_{1st} = \left(1 - D_2^2, 0, -D_2 + D_2 D_3^2, -1 + D_3^2, D_3 - D_2^2 D_3, 0\right)$$

- **TDI generation 1.5**

$$X_{1.5} = (1 - D_2 D'_2, 0, -D'_2 + D'_2 D'_3 D_3, -1 + D'_3 D_3, D_3 - D_2 D'_2\ D_3, 0)$$

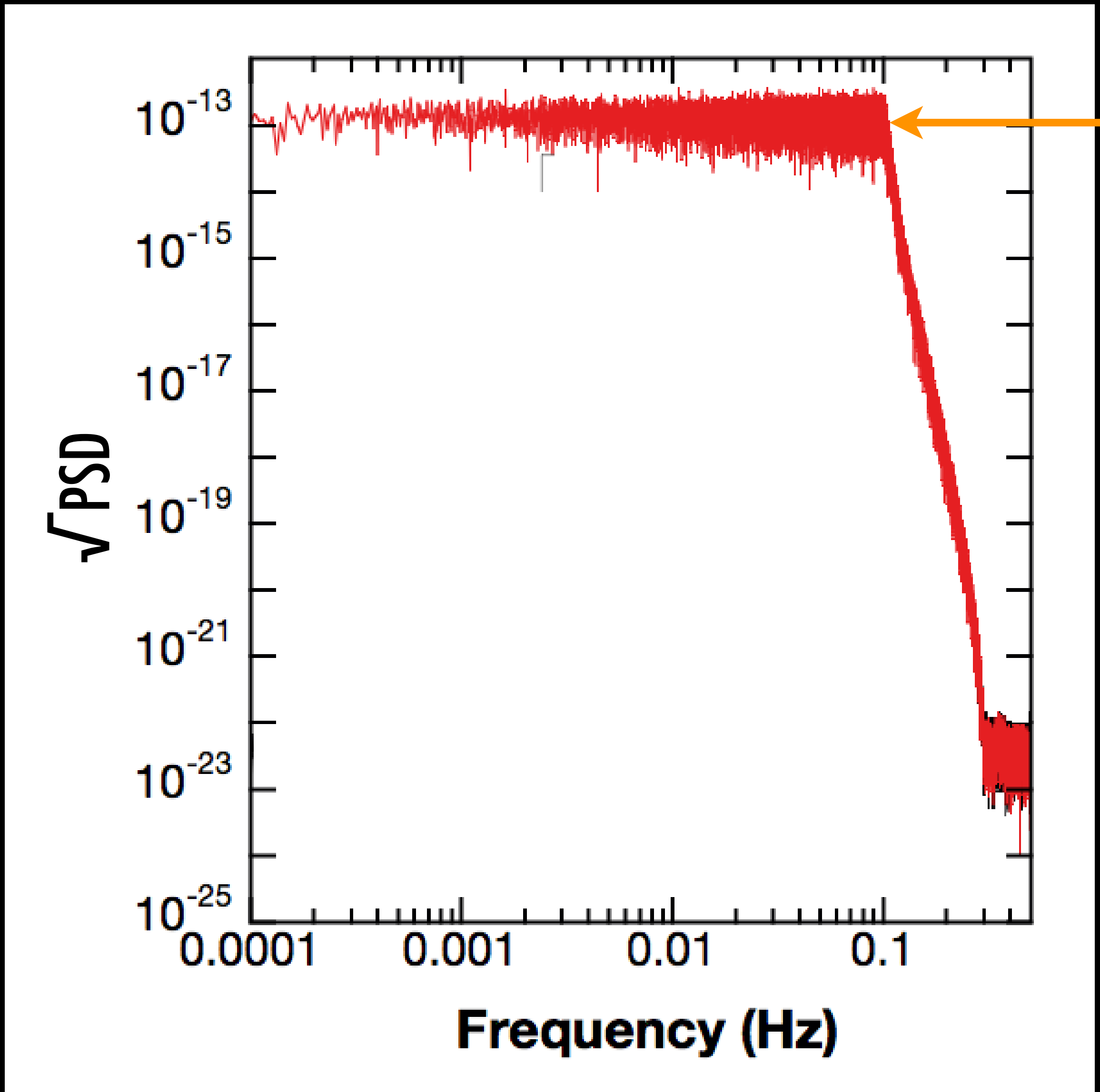
- **TDI 2nd generation: until 7 delay operators combined**

$$\begin{aligned} X_{2nd} = (&1 + D_3 D'_3 D'_2 D_2 D'_2 D_2 - D'_2 D_2 - D'_2 D_2 D_3 D'_3, \\ &0, \\ &D_3 D'_3 D'_2 + D_3 D'_3 D'_2 D_2 D'_2 - D'_2 - D'_2 D_2 D_3 D'_3 D_3 D'_3 D'_2, \\ &D_3 D'_3 + D_3 D'_3 D'_2 D_2 - 1 - D'_2 D_2 D_3 D'_3 D_3 D'_3, \\ &D_3 + D_3 D'_3 D'_2 D_2 D'_2 D_2 D_3 - D'_2 D_2 D_3 - D'_2 D_2 D_3 D'_3 D_3, \\ &0) \end{aligned}$$

Time Delay Interferometry

- Reduction of laser noises by 8 orders of magnitude !

A GW is hidden here !



Phasemeter
(cut off due to the filter required for digitalization of signal)

Petiteau & al, Phys. Rev. D (2008)

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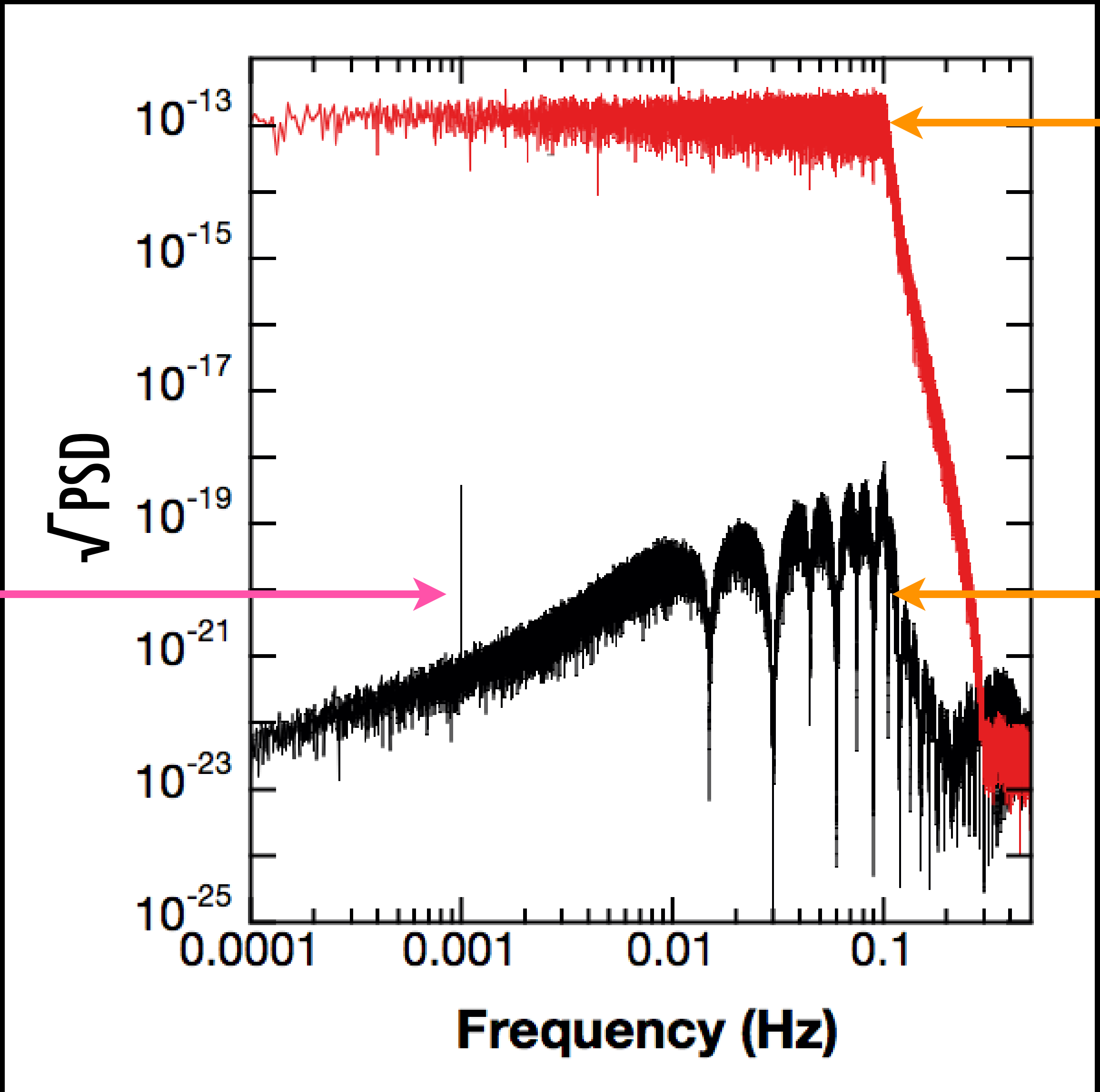

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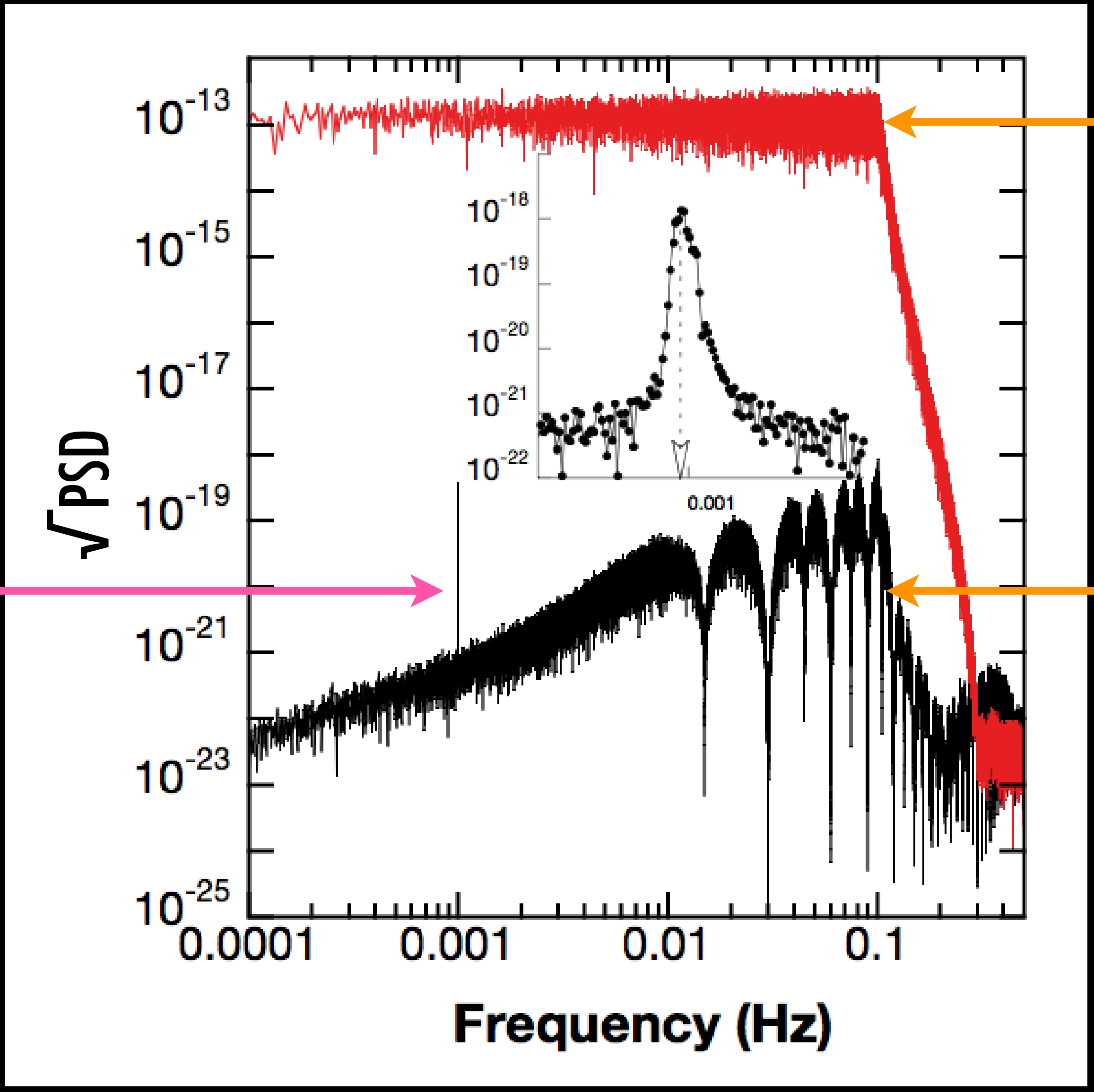

Phasemeter
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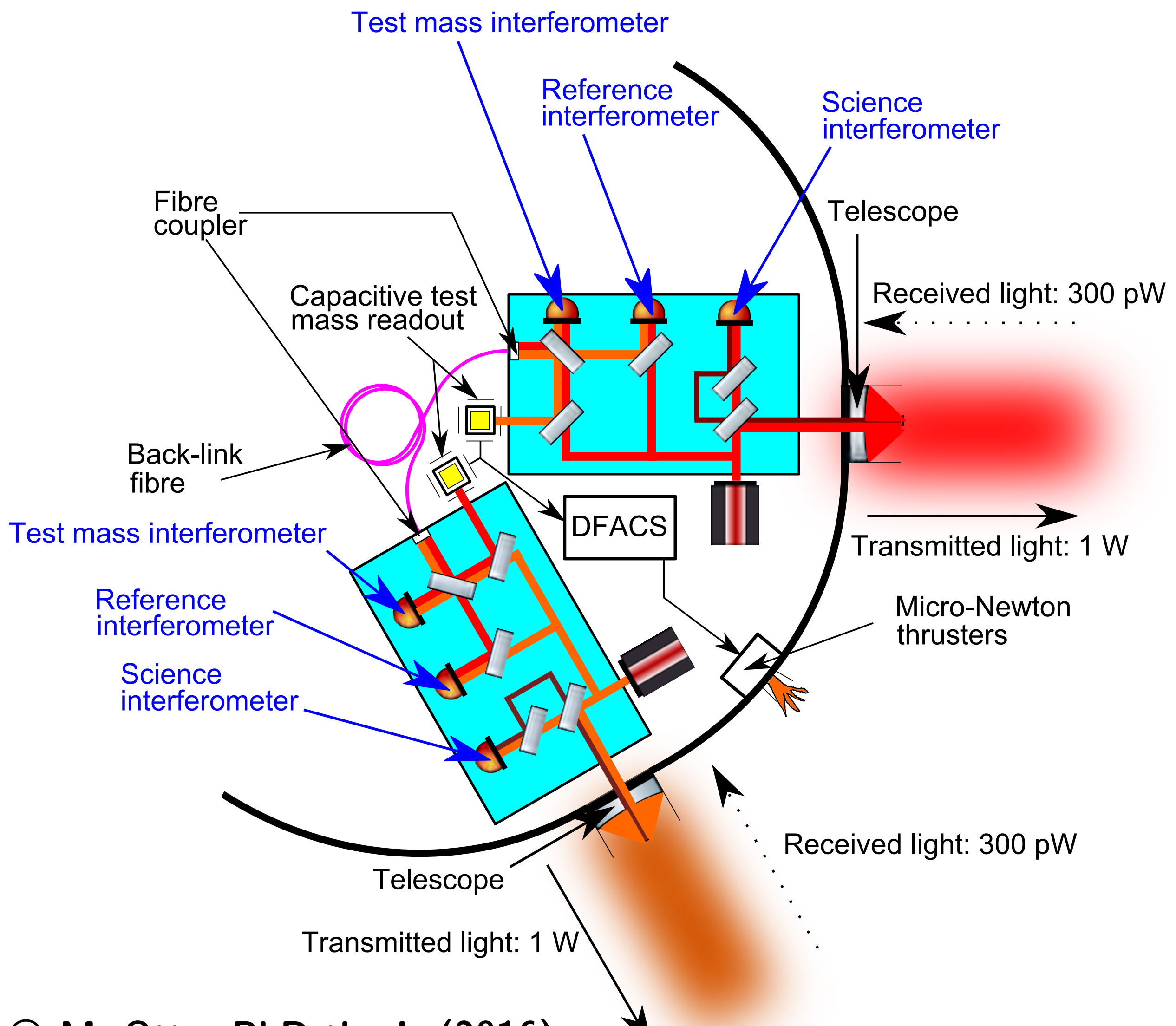
TDI Michelson

Petiteau & al, Phys. Rev. D (2008)

François Arago Centre

Current design

- Exchange of laser beam to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts



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- Noises sources:
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Acceleration noise (see LPF)
  - Read-out noises

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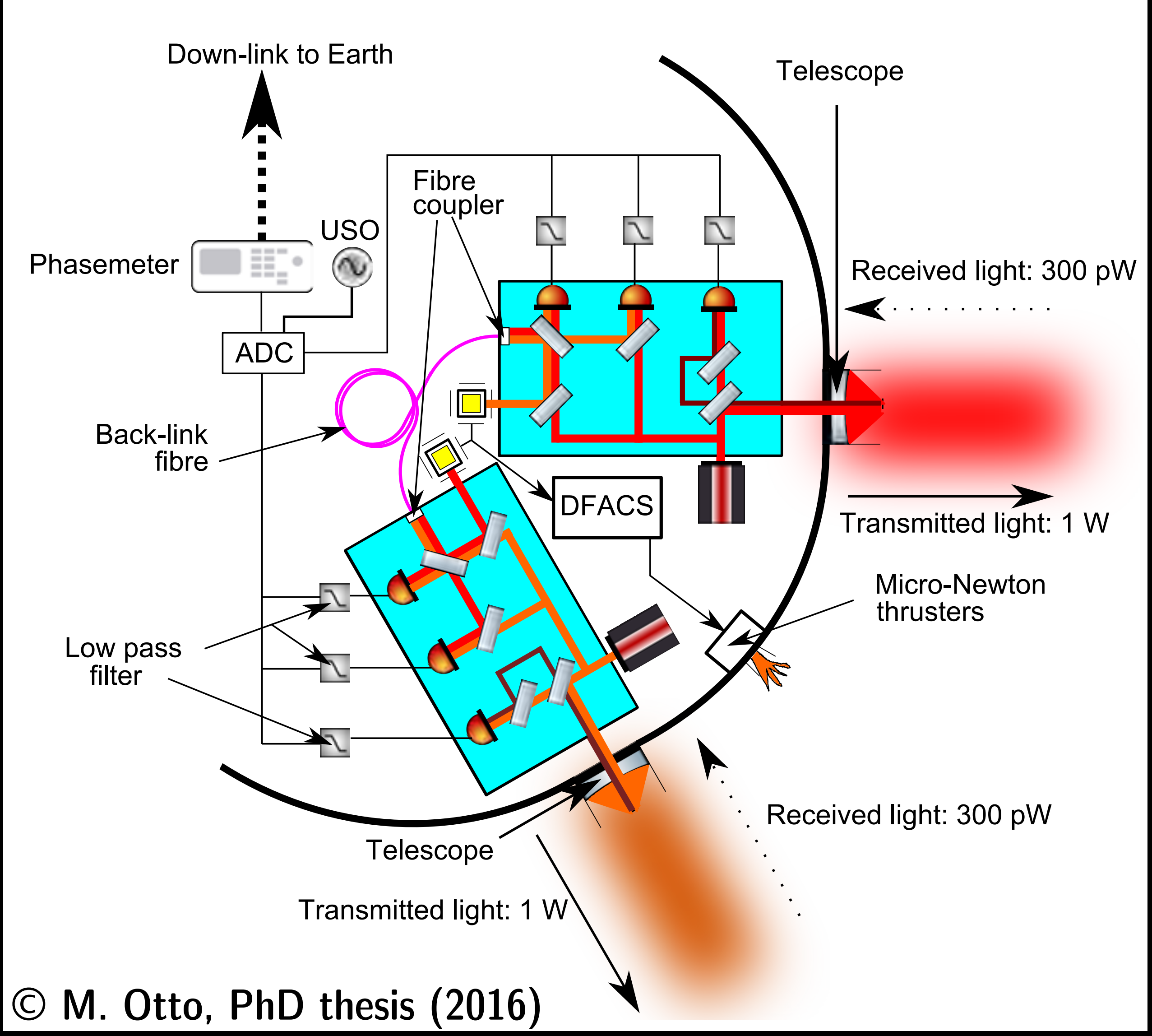

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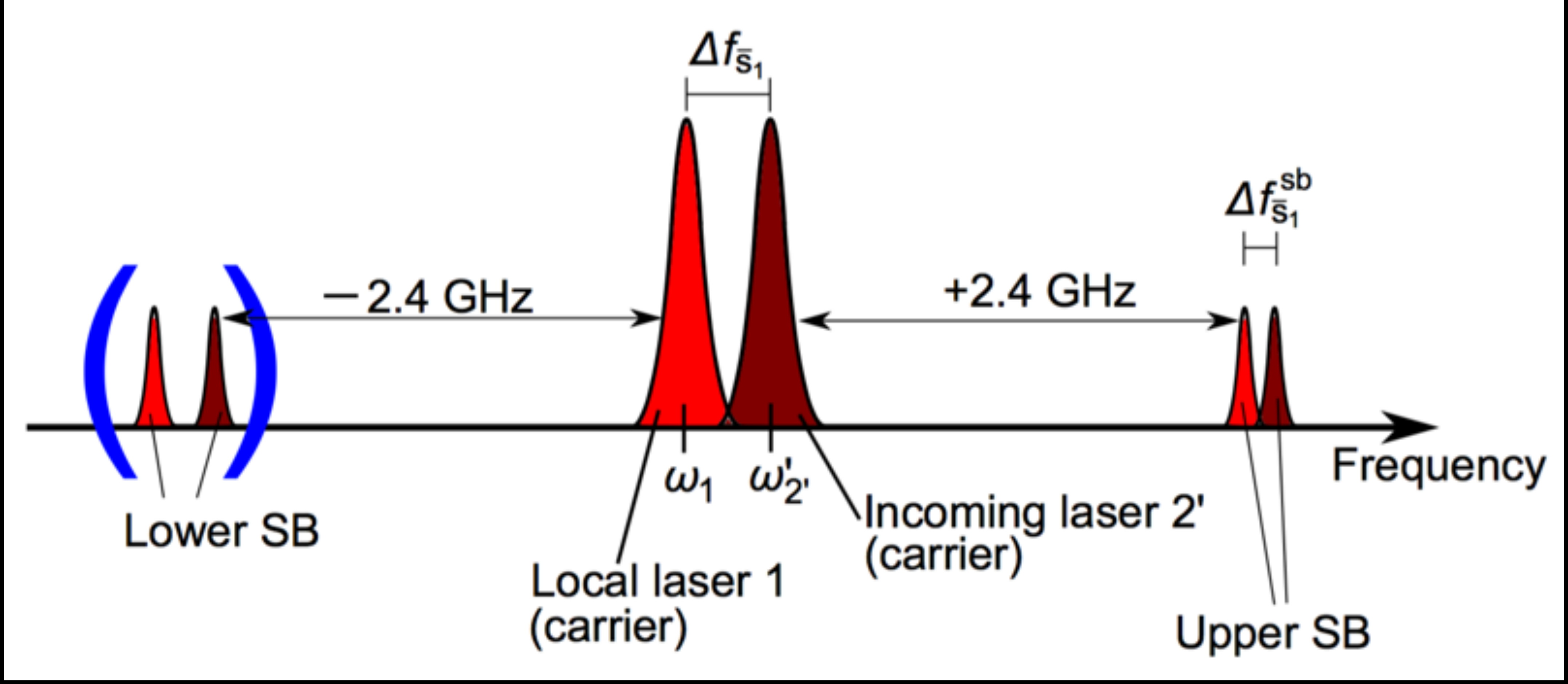
- Noises sources:
  - Laser noise : 10^{-13} (vs 10^{-21})
  - Clock noise (3 clocks)
  - Acceleration noise (see LPF)
  - Read-out noises

Current design

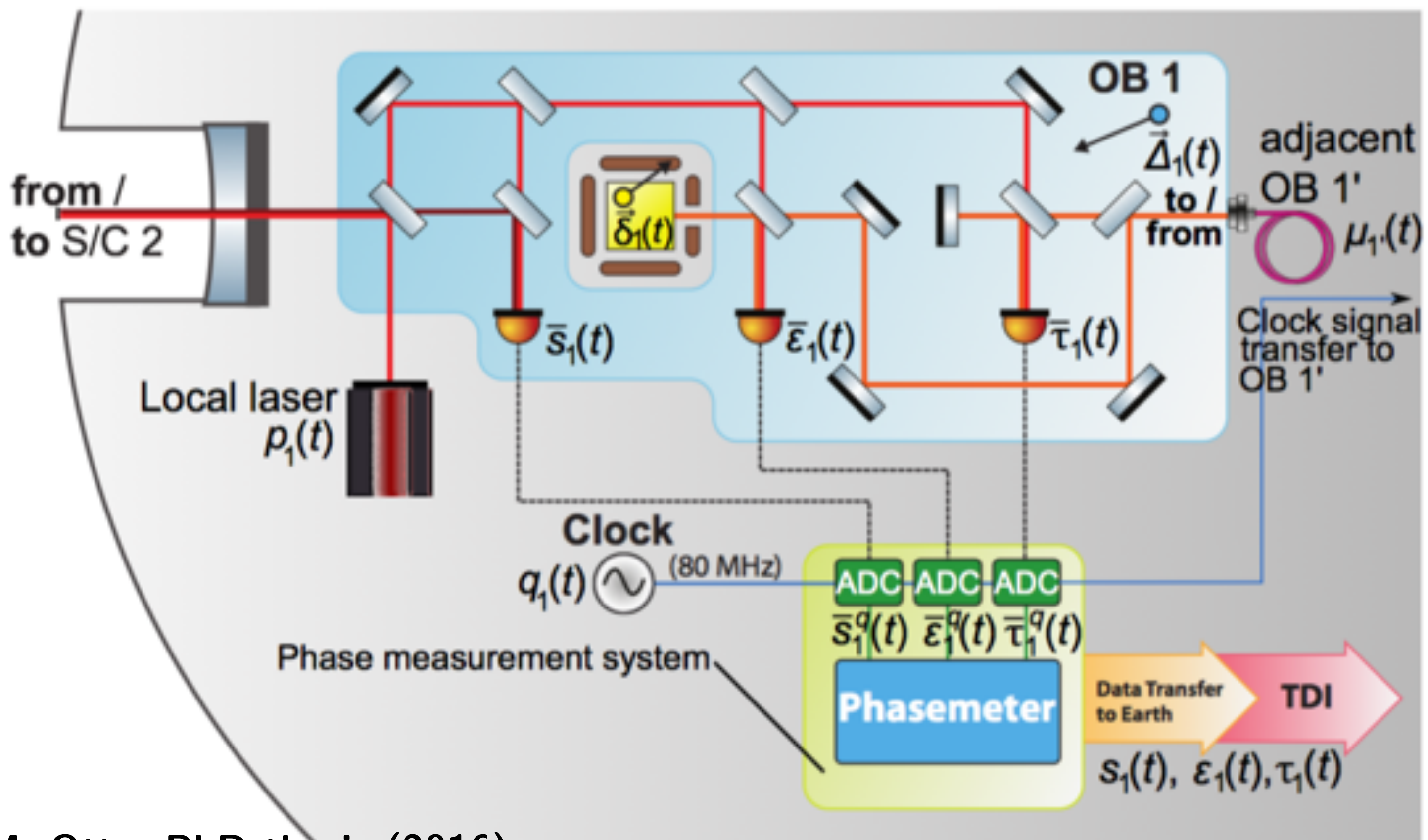
- Use sidebands to transfer clock noise
- Modulation of laser with a pseudo-random code to measure the absolute distance at a precision of 30cm.

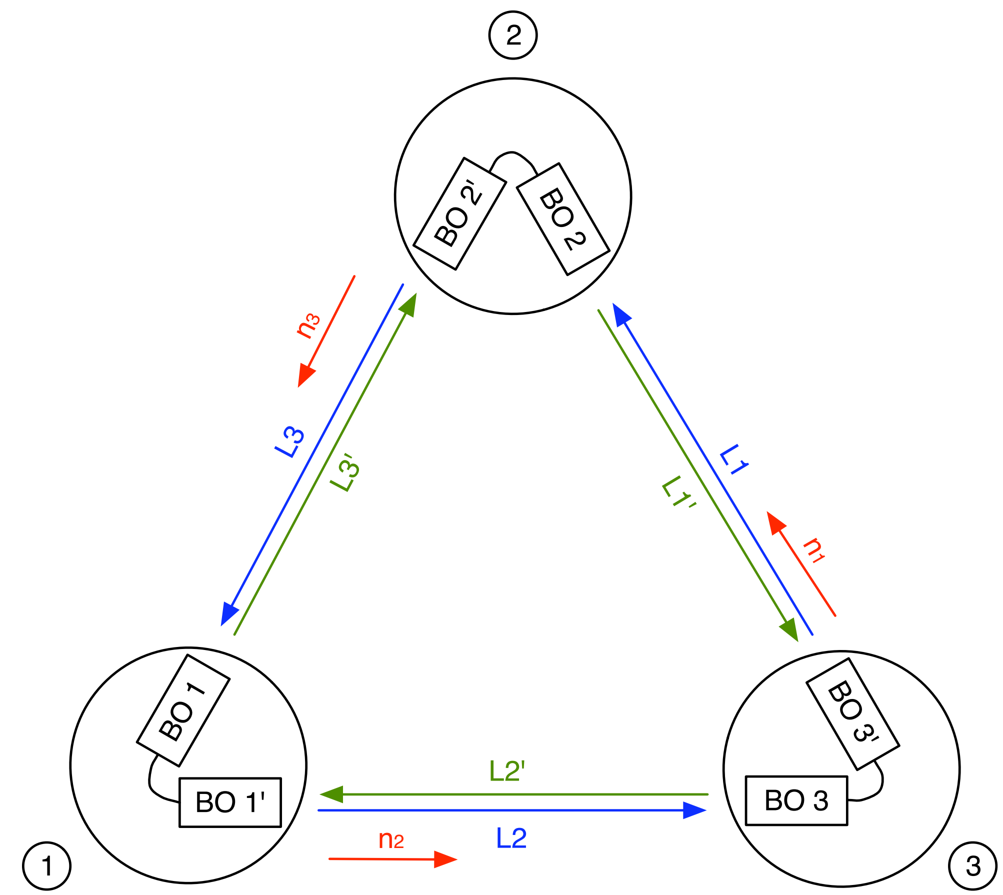


Current design

- s_i^c : scientific interferometer measurement at the carrier frequency,
- s_i^{sb} : scientific interferometer measurement at the sideband frequency,
- τ_i : reference interferometer measurement
- ϵ_i : test-mass interferometer measurement
- θ_i^j : factor to track of the sign of the phasemeter input
- h_i : gravitational wave signal on the link
- p_i : laser noise
- Δ_i : optical bench displacement noise projected along the arm :

$$\Delta_i = 2\pi\vec{\Delta}_i.\vec{n}_{i'+2} \quad \text{and} \quad \Delta_{i'} = -2\pi\vec{\Delta}_{i'}.\vec{n}_{i+1}$$





Current design

- δ_i : test mass displacement noise projected along the arm (acceleration noise):

$$\delta_i = 2\pi\vec{\delta}_i.\vec{n}_{i'+2} \quad \text{and} \quad \delta_{i'} = -2\pi\vec{\delta}_{i'}.\vec{n}_{i+1} \tag{10}$$

- $N_i^{ro,s}$, $N_i^{ro,\tau}$, $N_i^{ro,\epsilon}$ $N_i^{ro,sb}$: Read-out noises, i.e. all noises from the photodiode to the output of the phasemeter
- $N_i^{opt,s}$, $N_i^{opt,\tau}$, $N_i^{opt,\epsilon}$ $N_i^{opt,sb}$: Optical noise, i.e. all noises on the two interfering beams before the photodiode of the scientific interferometer at the carrier frequency
- μ_i : noise of the back link optical fiber from optical bench i to optical bench i'
- q_i : noise of the clock of spacecraft i
- a_i : translation factor of the clock noise for the scientific interferometer at the carrier frequency :

$$a_i = \frac{|f_{i'+1\to i} - f_i|}{f_{PT,i}} \quad \text{and} \quad a_{i'} = \frac{|f_{i+2\to i'} - f_{i'}|}{f_{PT,i}} \tag{11}$$

- b_i : translation factor of the clock noise for the reference interferometer and the test-mass interferometer :

$$b_i = \frac{|f_{i'} - f_i|}{f_{PT,i}} \quad \text{and} \quad b_{i'} = \frac{|f_i - f_{i'}|}{f_{PT,i}} \tag{12}$$

- c_i : translation factor of the clock noise for the scientific interferometer at the sideband frequency :

$$c_i = \frac{|f^{sb}_{i'+1\to i} - f^{sb}_i|}{f_{PT,i}} \quad \text{and} \quad c_{i'} = \frac{|f^{sb}_{i+2\to i'} - f^{sb}_{i'}|}{f_{PT,i}} \tag{13}$$

The $x_{;\mathbf{i}}$ correspond to the application of a **real** delay :

$$x_{;\mathbf{i}}(t) \equiv \mathcal{D}_\mathbf{i} x(t) \equiv x\left(t - \frac{\mathbf{L_i}(t)}{c}\right) \tag{14}$$

Current design

- Optical bench 1 :

$$s_1^c(t) = \theta_1^{2'} \left[h_1 + p_{2';\mathbf{3}} - p_1 + \frac{\Delta_{2';\mathbf{3}}}{\lambda_{2'}} - \frac{\Delta_1}{\lambda_{2'}} + N_1^{opt,s} \right] + a_1 q_1 + N_1^{ro,s}$$

$$\tau_1(t) = \theta_1^{1'} \left[p_{1'} - p_1 + \mu_{1'} + N_1^{opt,\tau} \right] + b_1 q_1 + N_1^{ro,\tau}$$

$$\epsilon_1(t) = \theta_1^{1'} \left[p_{1'} - p_1 + 2 \left(\frac{\delta_1}{\lambda_{1'}} - \frac{\Delta_1}{\lambda_{1'}} \right) + \mu_{1'} + N_1^{opt,\epsilon} \right] + b_1 q_1 + N_1^{ro,\epsilon}$$

$$s_1^{sb}(t) = \theta_1^{2'} \left[h_{1'} + p_{2';\mathbf{3}} - p_1 + m_{2'} q_{2;\mathbf{3}} - m_1 q_1 + \frac{\Delta_{2';\mathbf{3}}}{\lambda_{2'}} - \frac{\Delta_1}{\lambda_{2'}} + N_1^{opt,sb} \right] + c_1 q_1 + N_1^{ro,sb}$$

- Optical bench 1'

$$s_{1'}^c(t) = \theta_{1'}^{3} \left[h_{1'} + p_{3;\mathbf{2'}} - p_{1'} - \frac{\Delta_{3;\mathbf{2'}}}{\lambda_3} + \frac{\Delta_{1'}}{\lambda_3} + N_{1'}^{opt,s} \right] + b_{1'} q_1 + N_{1'}^{ro,s}$$

$$\tau_{1'}(t) = \theta_{1'}^{1} \left[p_1 - p_{1'} + \mu_1 + N_{1'}^{opt,\tau} \right] + b_{1'} q_1 + N_{1'}^{ro,\tau}$$

$$\epsilon_{1'}(t) = \theta_{1'}^{1} \left[p_1 - p_{1'} + 2 \left(-\frac{\delta_{1'}}{\lambda_1} + \frac{\Delta_{1'}}{\lambda_1} \right) + \mu_1 + N_{1'}^{opt,\epsilon} \right] + b_{1'} q_1 + N_{1'}^{ro,\epsilon}$$

$$s_{1'}^{sb}(t) = \theta_{1'}^{3} \left[h_{1'} + p_{3;\mathbf{2'}} - p_{1'} + m_3 q_{3;\mathbf{2'}} - m_{1'} q_1 - \frac{\Delta_{3;\mathbf{2'}}}{\lambda_3} + \frac{\Delta_{1'}}{\lambda_3} + N_{1'}^{opt,sb} \right] + c_{1'} q_1 + N_{1'}^{ro,sb}$$

TDI with current design

M. Otto, PhD thesis (2016)

- Intermediate TDI: first step
  - Step 1: Combine science and test mass interferometers

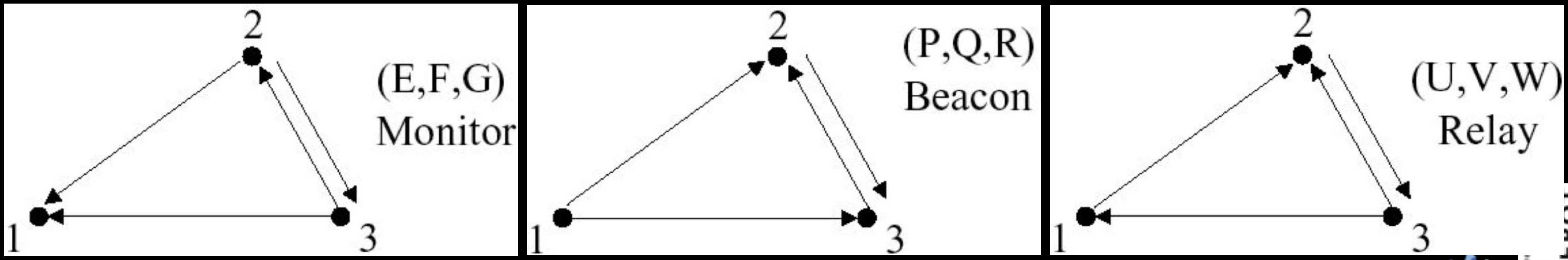
    => Suppression of optical bench displacement noises
  - Step 2: Combine with reference interferometers

    => Suppression of 3 free running laser noises
  - Step 3: Combine with sidebands

    => Clock noise removable
- Then apply on the results of step 3 the regular TDI combination. With real orbits you need at least the generation 2

TDI generators

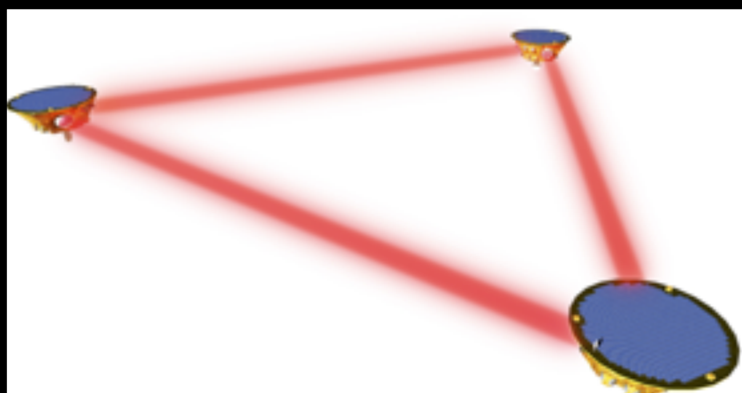
- With 6 links, there is a large numbers of possible TDI combinations: generators
- Usual ones:
  - X, Y, Z: Michelson equivalent
  - A, E: the 2 noises uncorrelated channel = equivalent to 2 independent detectors
  - T: "Sagnac" or "null channel": very weak response to GW



LISAPathfinder

LISAPathfinder

- Technological demonstrator for LISA

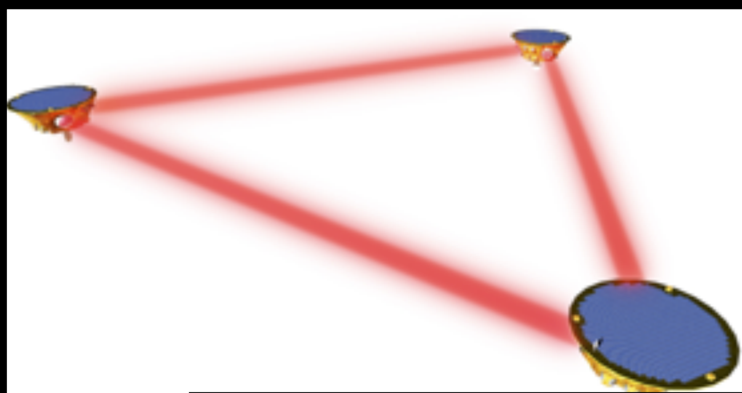


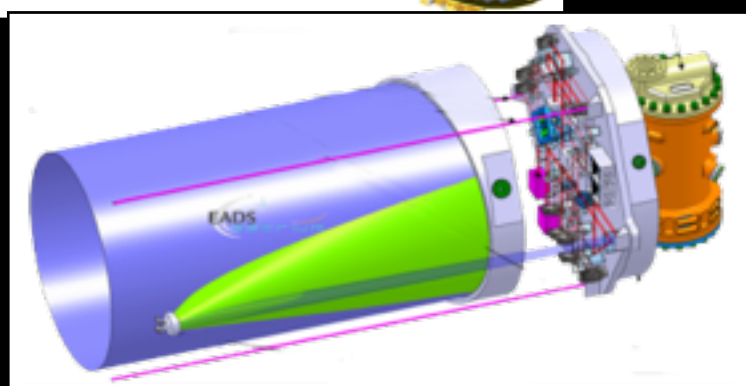
LISA :

- 3 spacecraft separated by millions of km
- Role of each spacecraft is to protect the fiducial test masses from external forces

LISAPathfinder

- Technological demonstrator for LISA





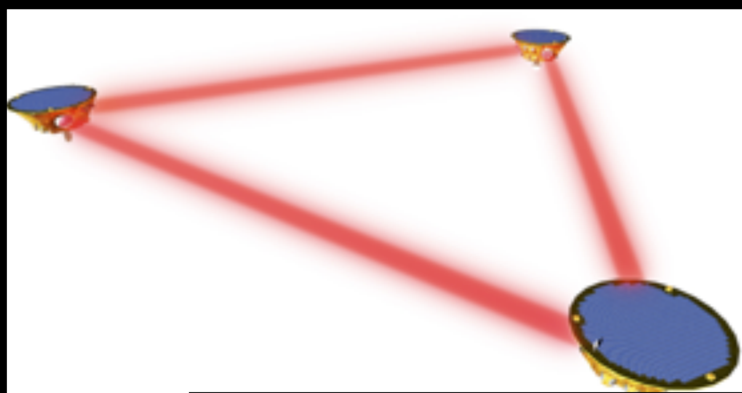
LISA :

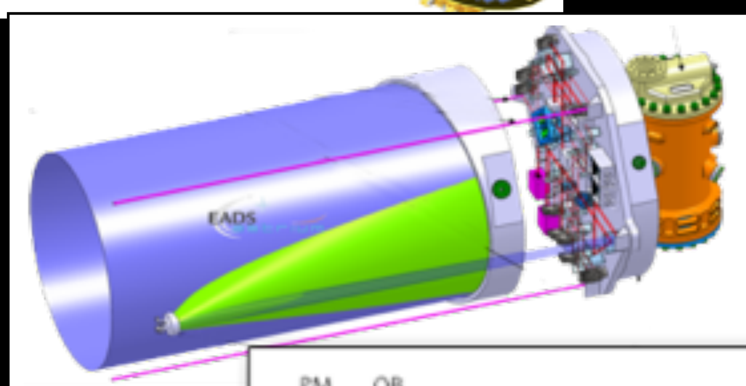
Locally measure distance from TM to SC using:

- Laser interferometry along sensitive axis (between SC)
- Capacitive sensing on orthogonal axes
- TM displacement measurements are used as input to DFACS which controls position and attitude of SC respect to the TM

LISAPathfinder

- Technological demonstrator for LISA





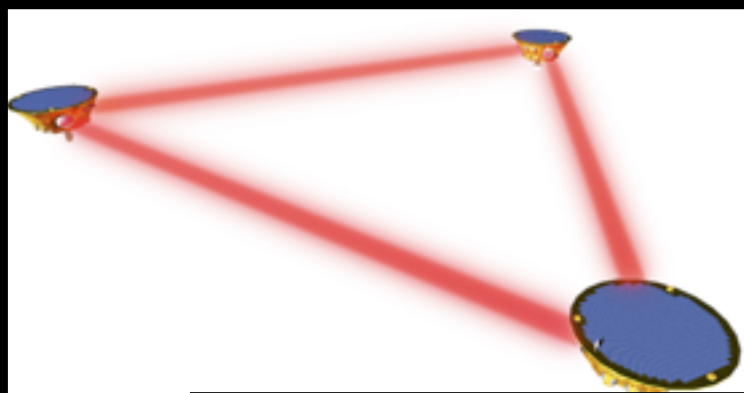
LISA :

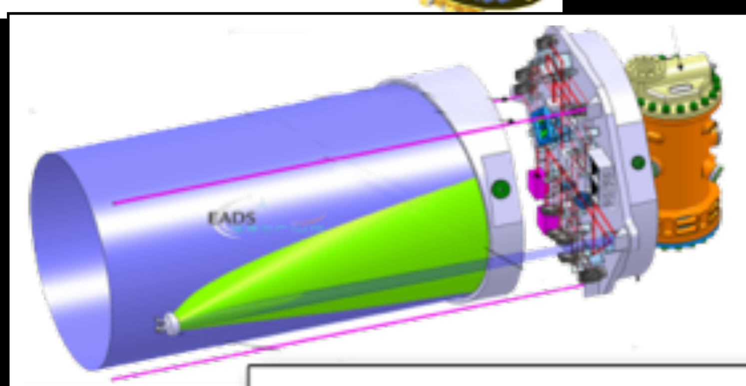
- Measure distance along using laser interferometry

(TM1 → SC1) + (SC1 → SC2) + (SC2 → TM2)

LISAPathfinder

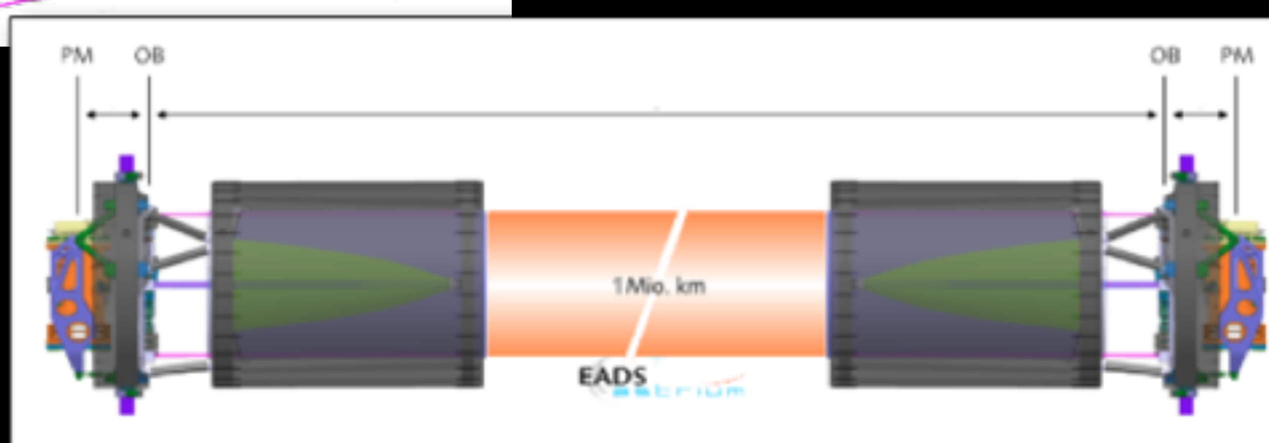
- Technological demonstrator for LISA

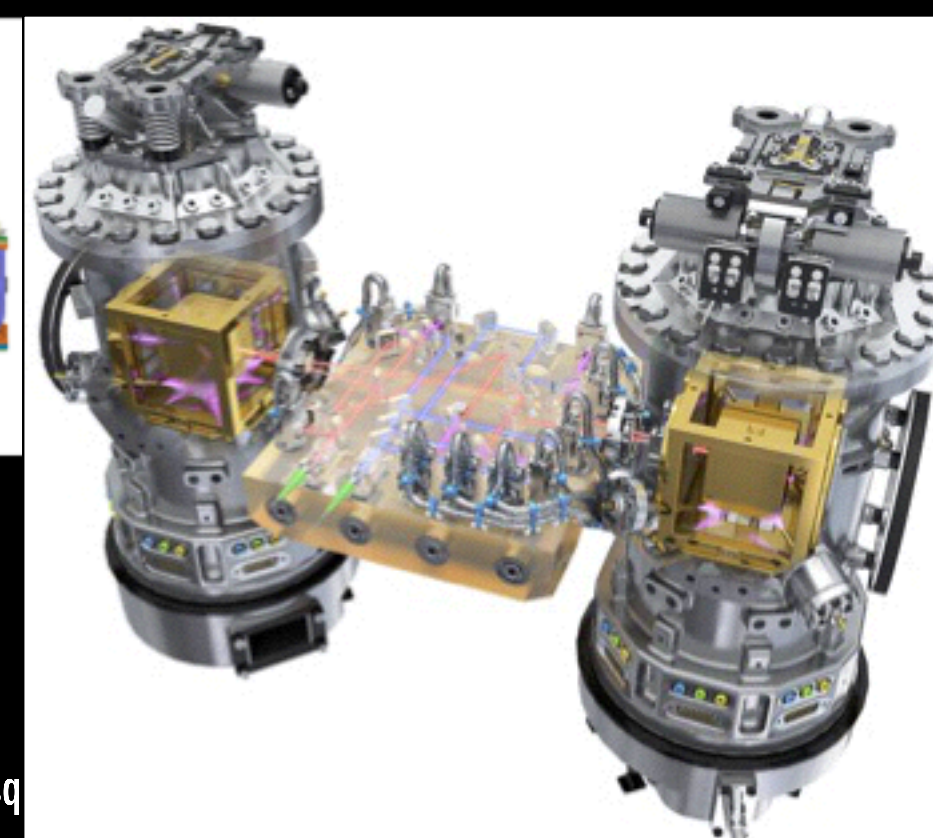




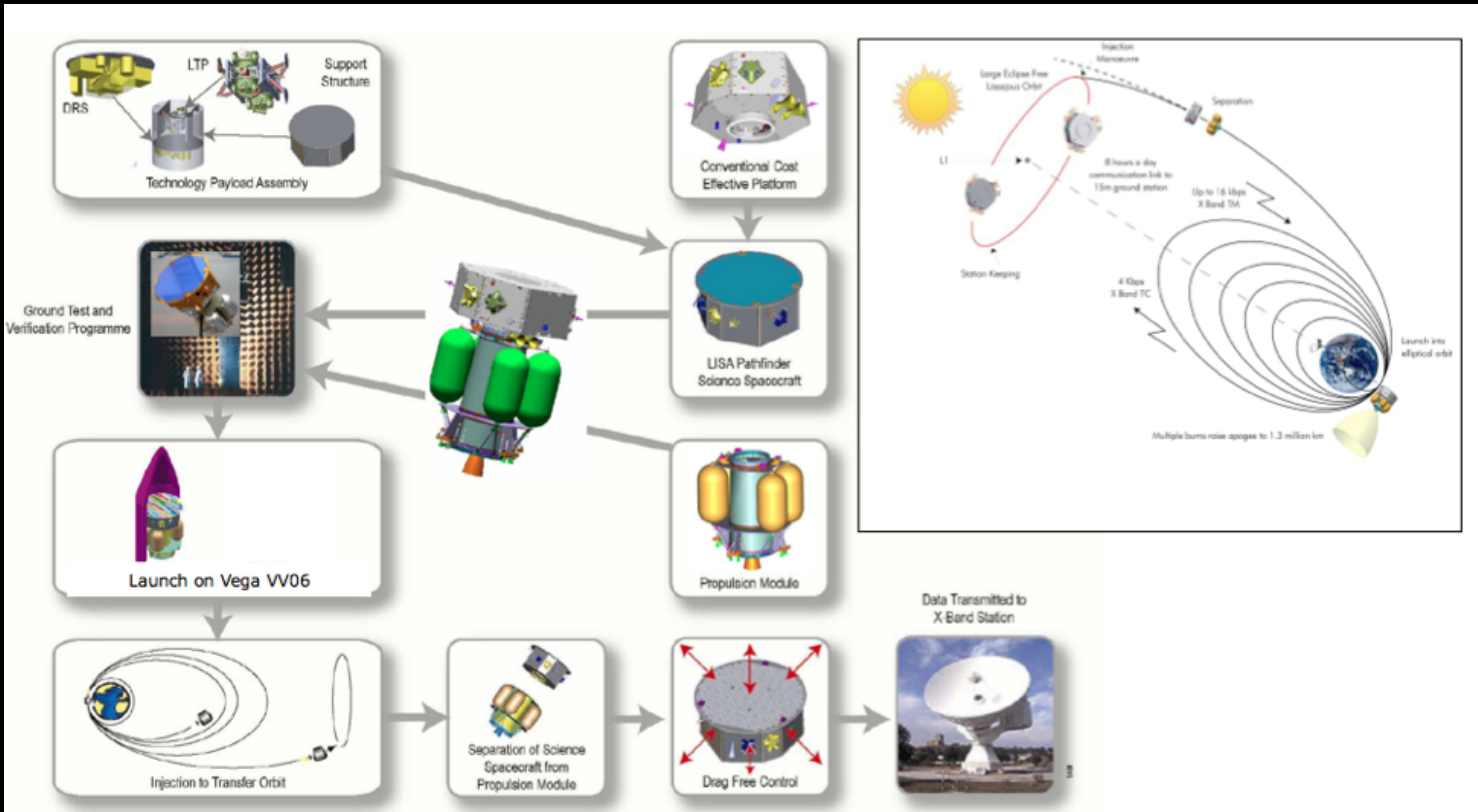
LISAPathfinder:

- 2 test masses / 2 inertial sensors
- Laser readout of TM1→SC and TM1→TM2
- Capacitive readout of all 6 d.o.f. of TM
- Drag-Free and Attitude Control System
- Micro-newton thrusters

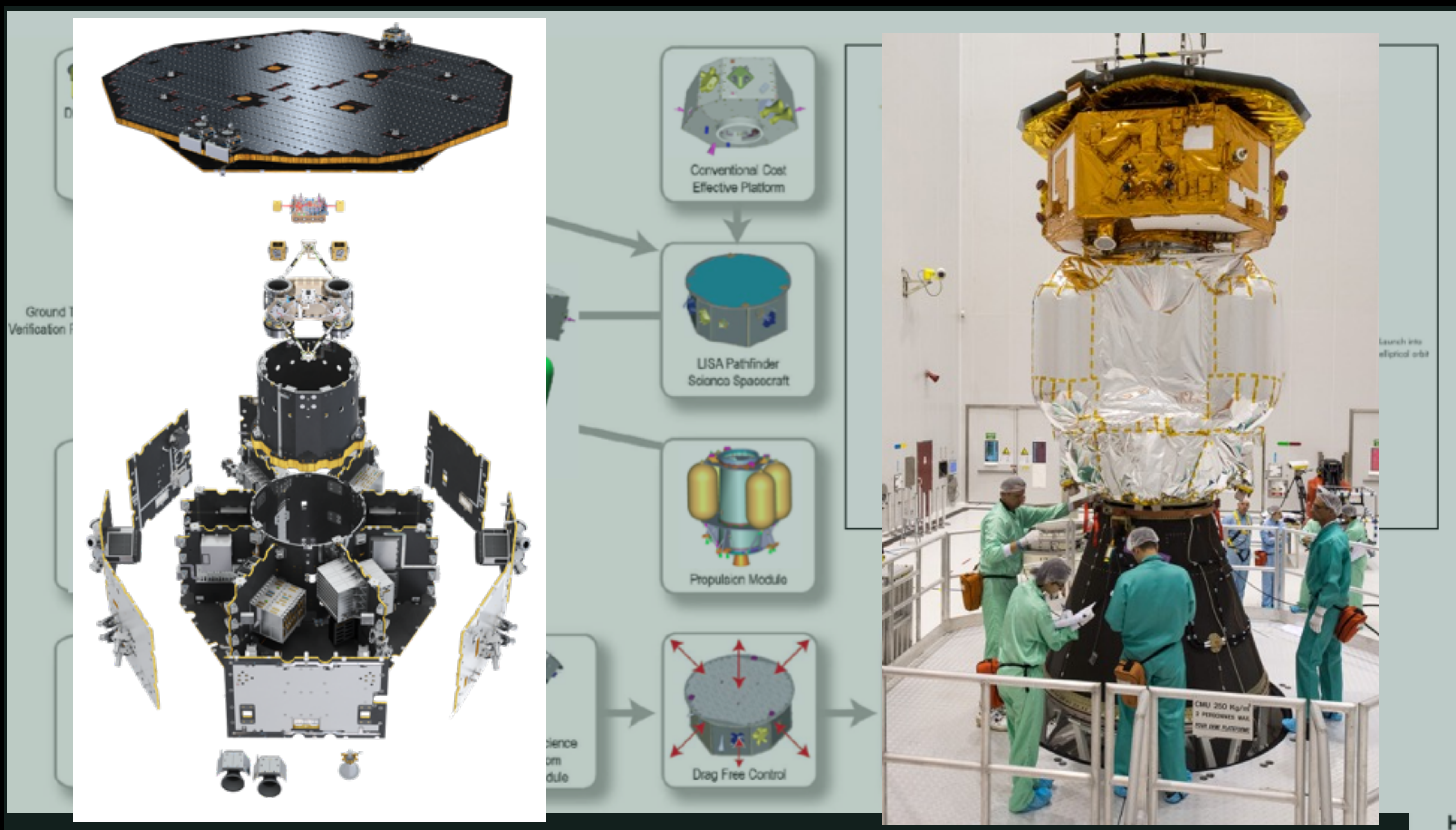




LISAPathfinder timeline



LISAPathfinder timeline

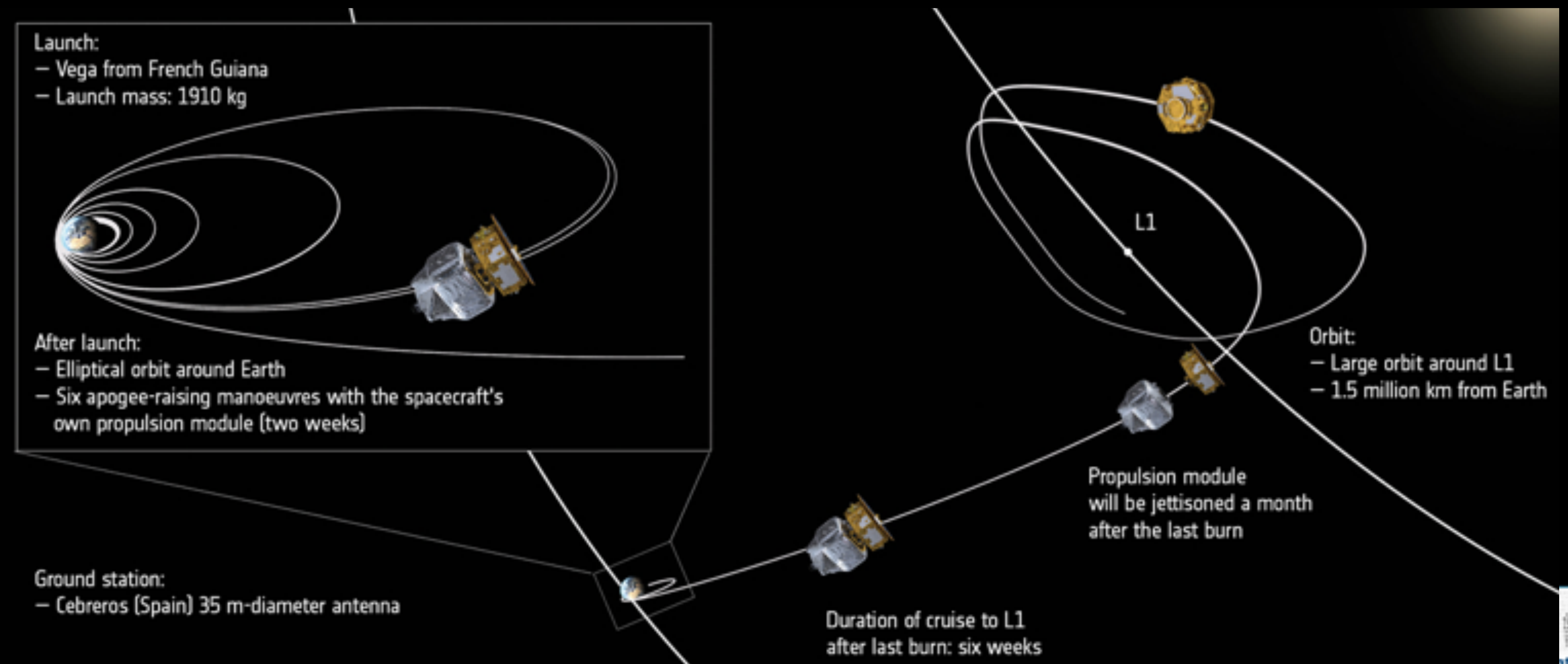


LISAPathfinder timeline

François Arago Centre

LISAPathfinder timeline

- 3/12/2015: Launch from Kourou
- 22/01/2016: arrived on final orbit & separation of propulsion module
- 17/12/2015 → 01/03/2016: commissioning
- 01/03/2016 → 27/06/2016: LTP operations (Europe)
- 27/06/2016 → 11/2016: DRS operations (US) + few LTP weeks
- 01/12/2016 → 31/06/2017: extension of LTP operations



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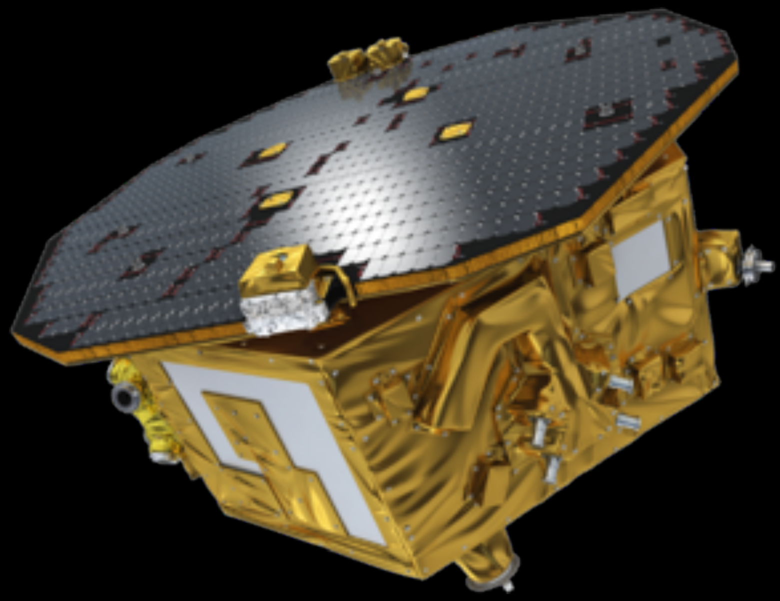
Last command: 18/07/2017



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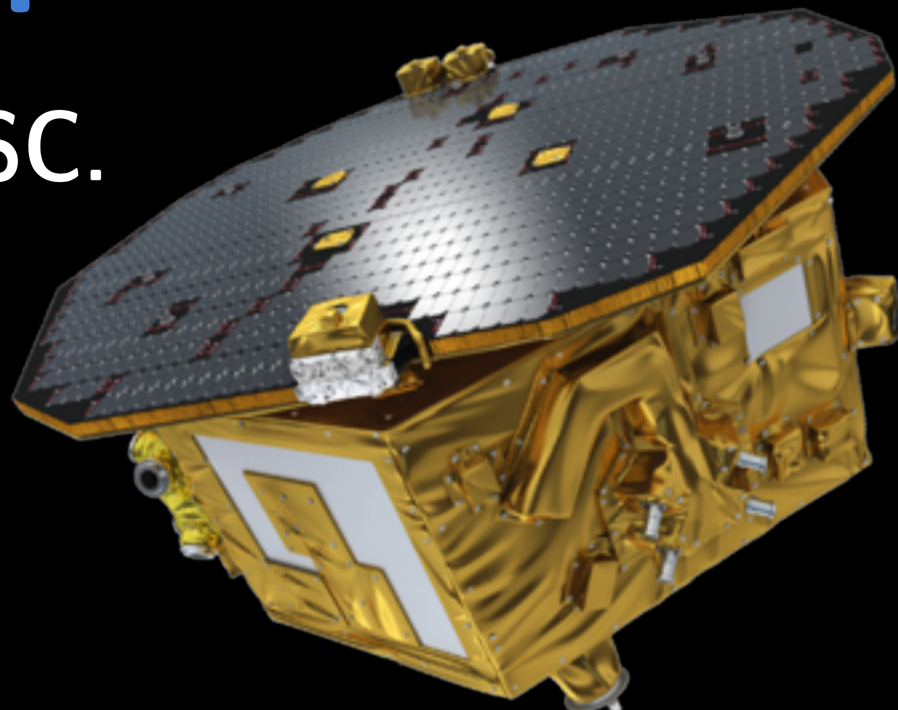
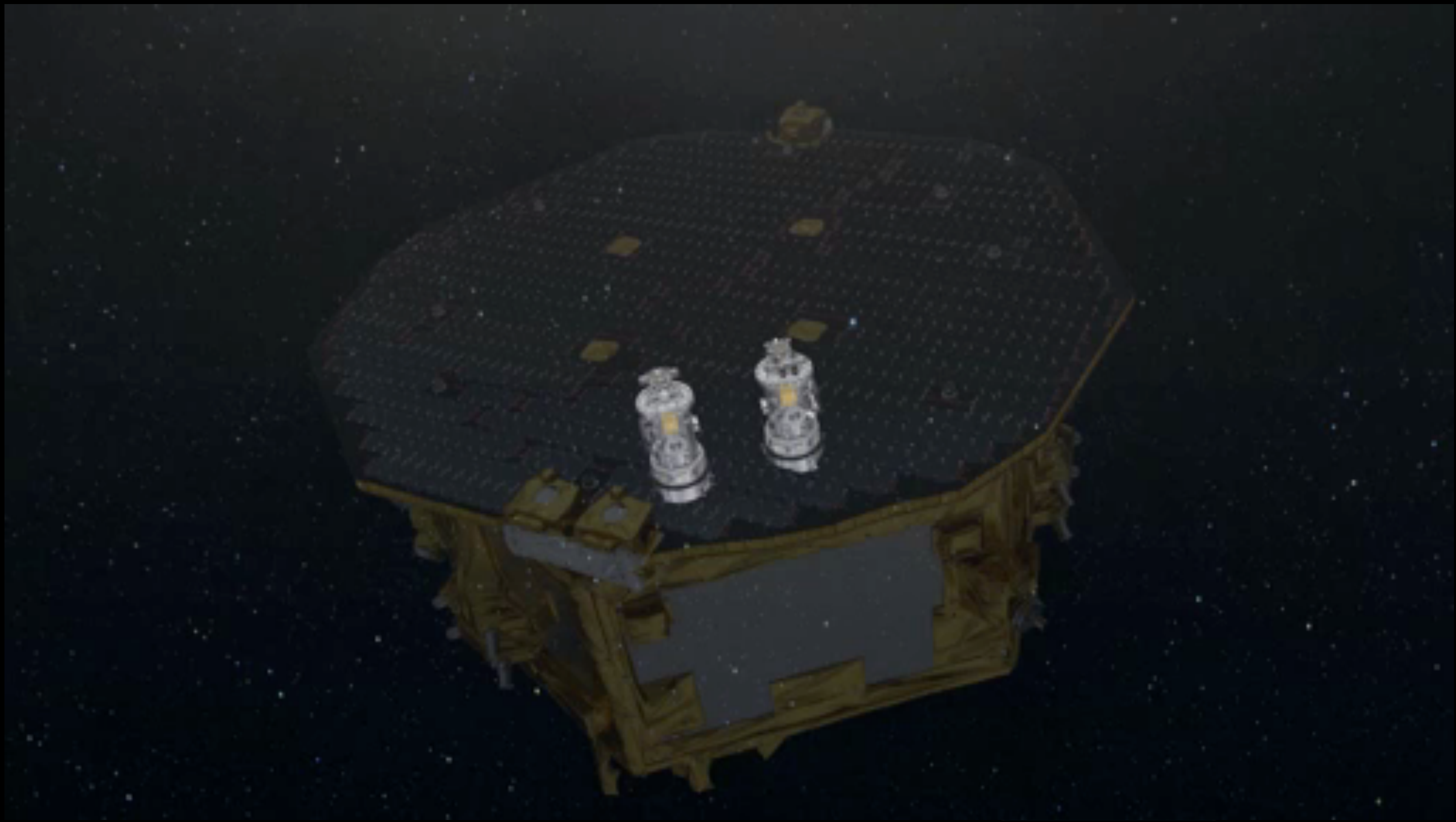


- Basic idea: Reduce one LISA arm in one SC.
- LISAPathfinder is testing :
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters



LISAPathfinder

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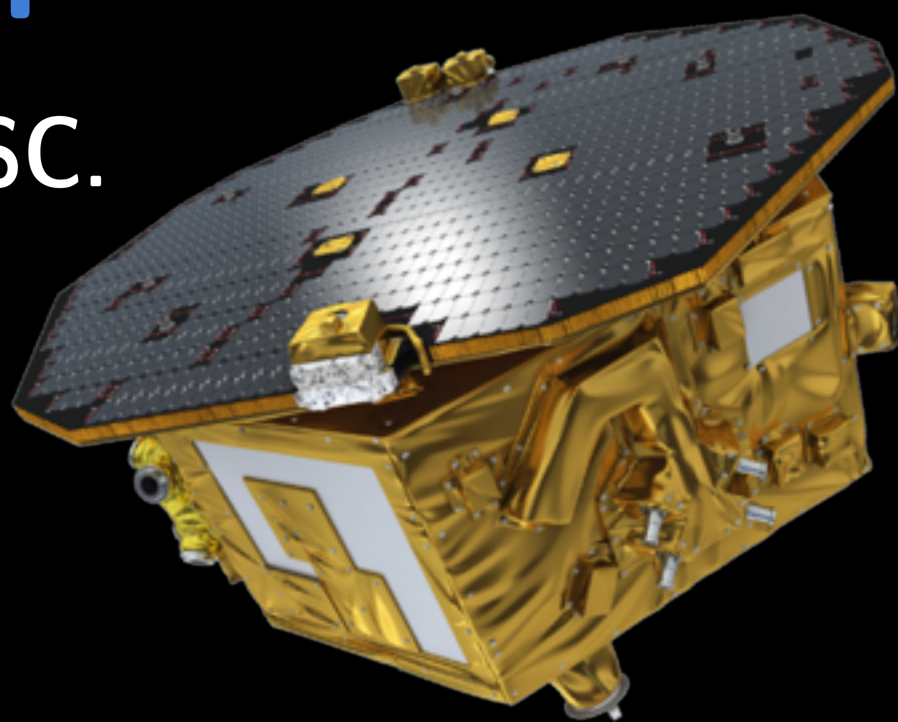

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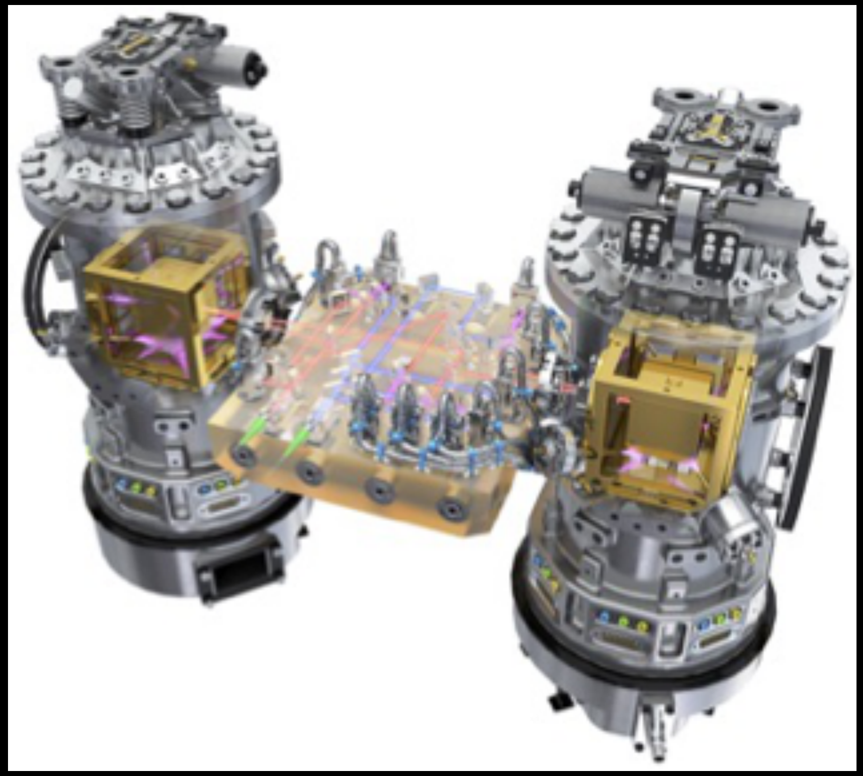
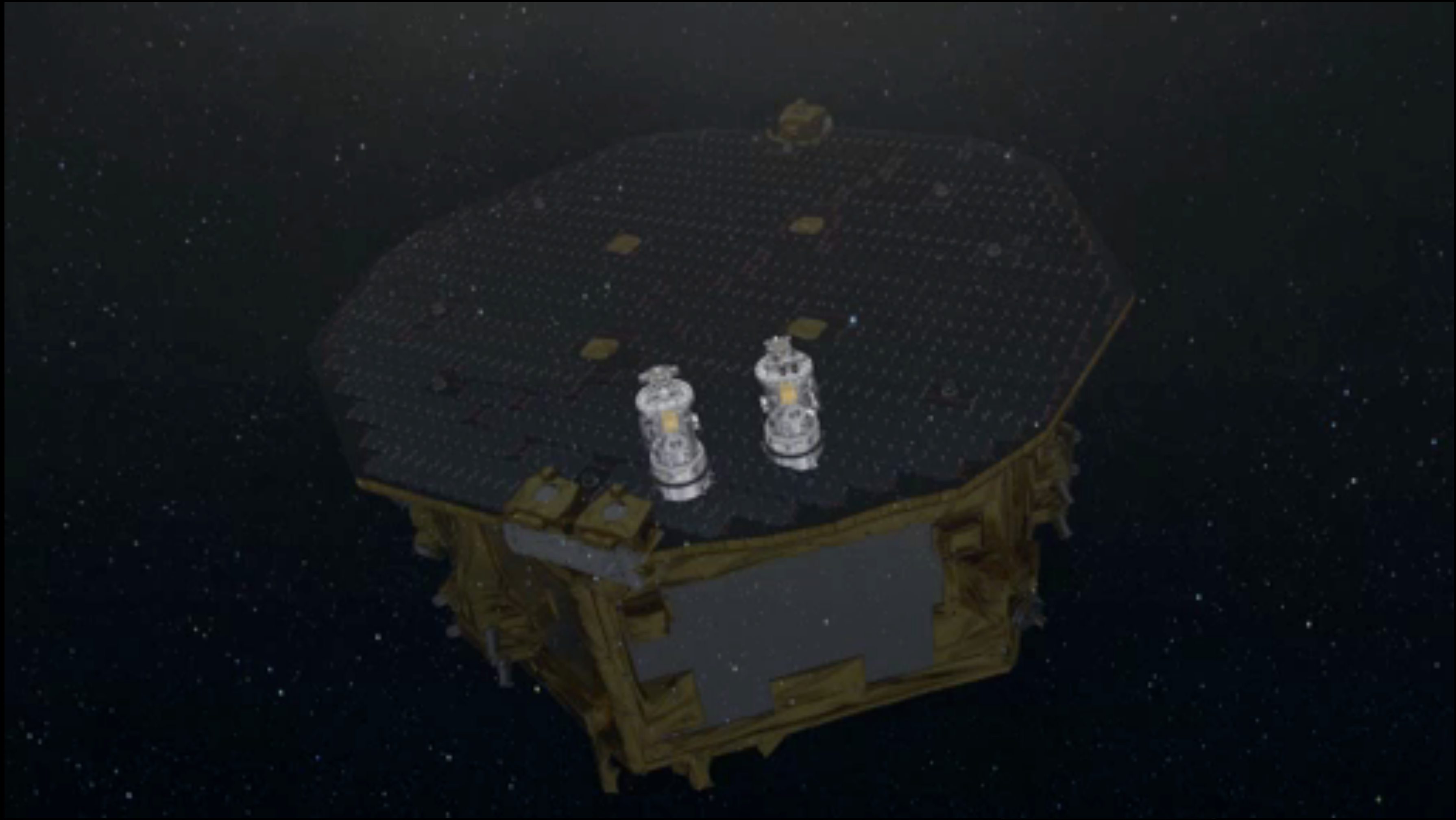
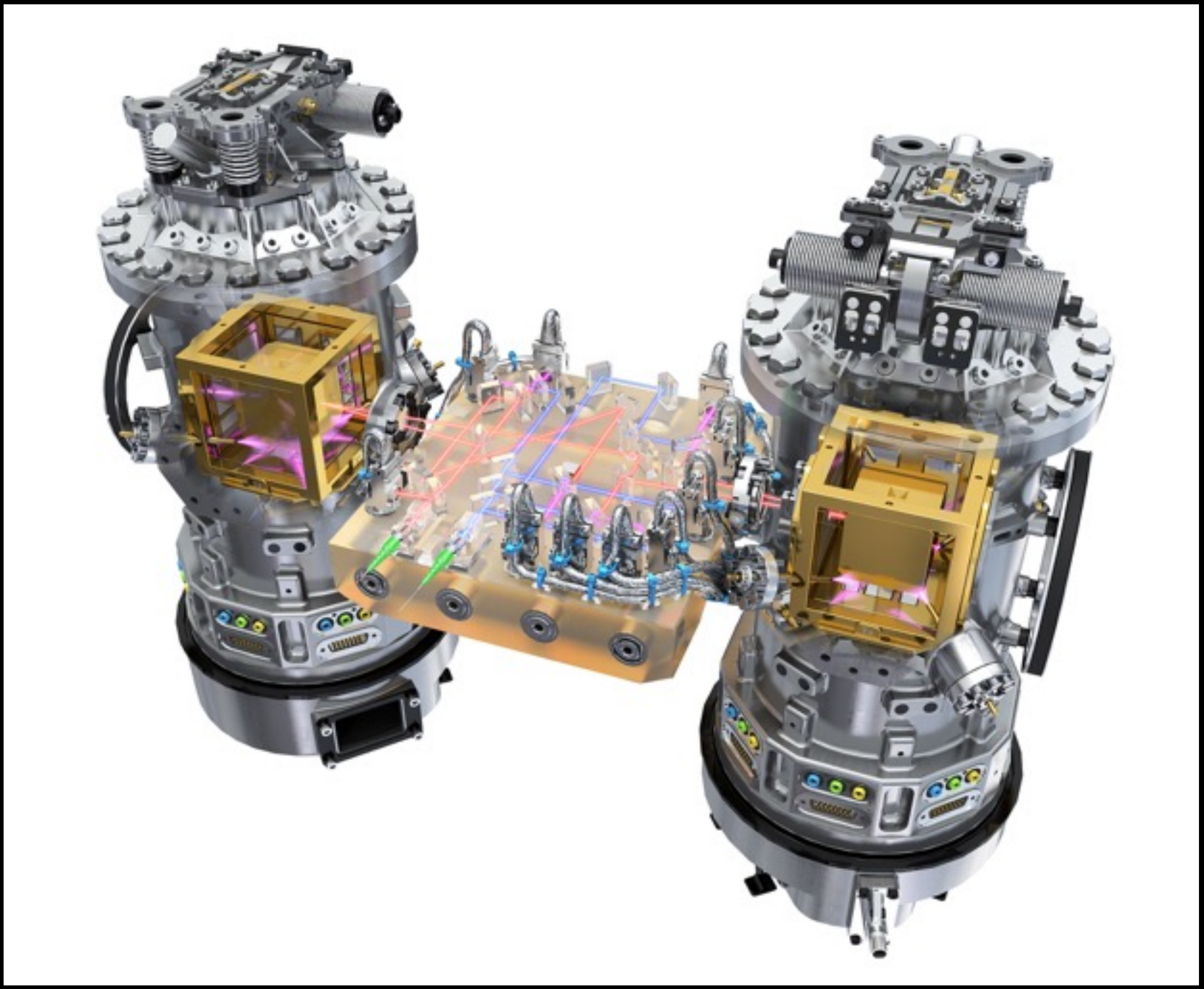


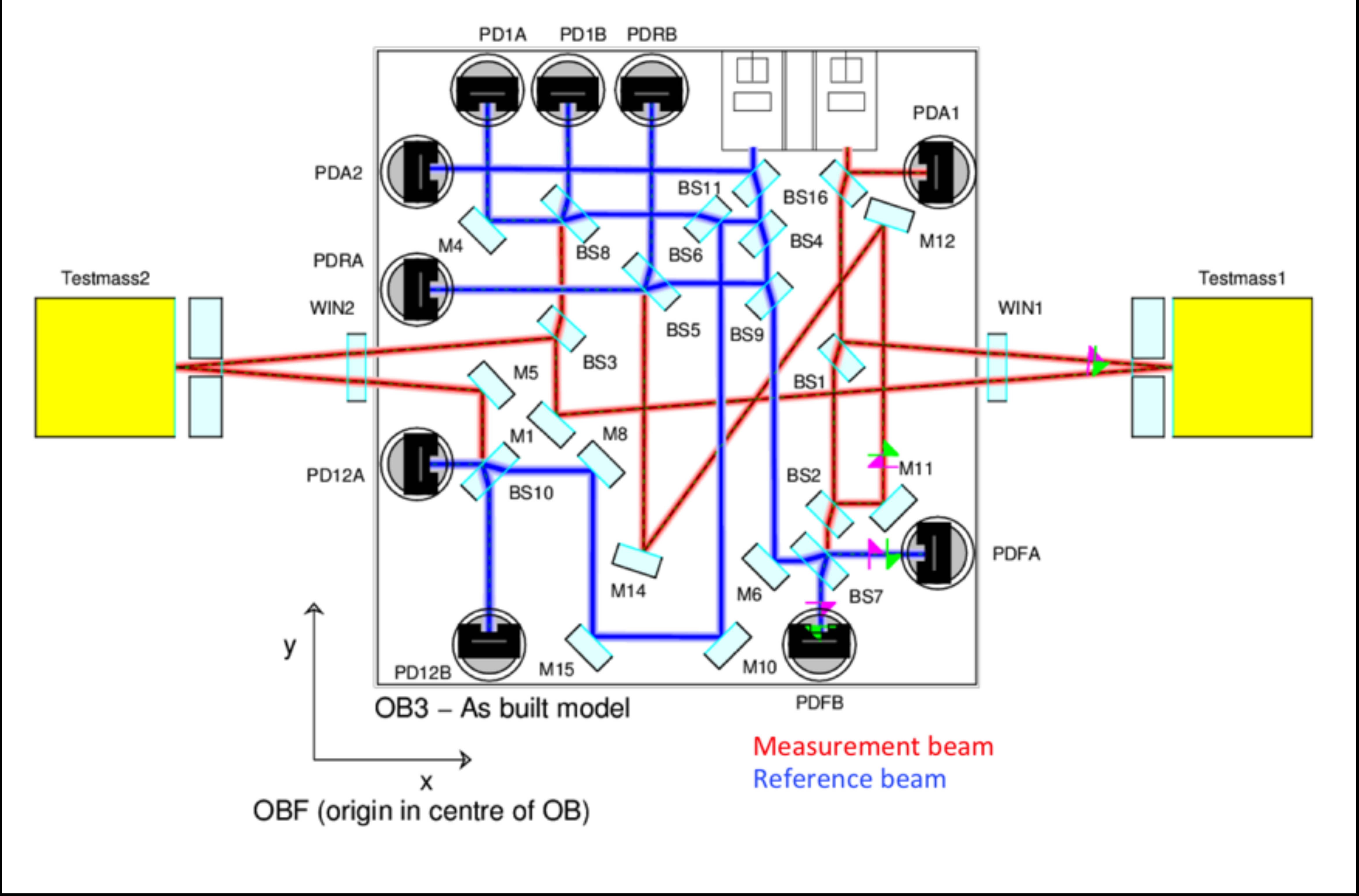


The instrument - LTP

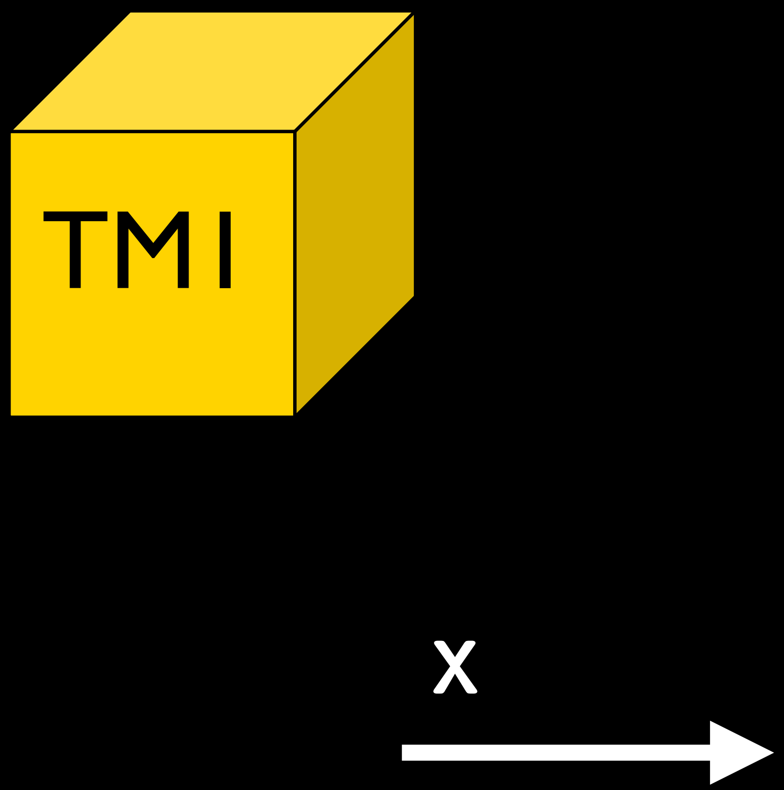


- Gravitational Reference Sensor
- Optical Bench
- Lampe UV
- Laser
- Compensation mass
- Under vacuum
- Caging Mechanism
- Thermal and magnetic monitoring

Optical bench

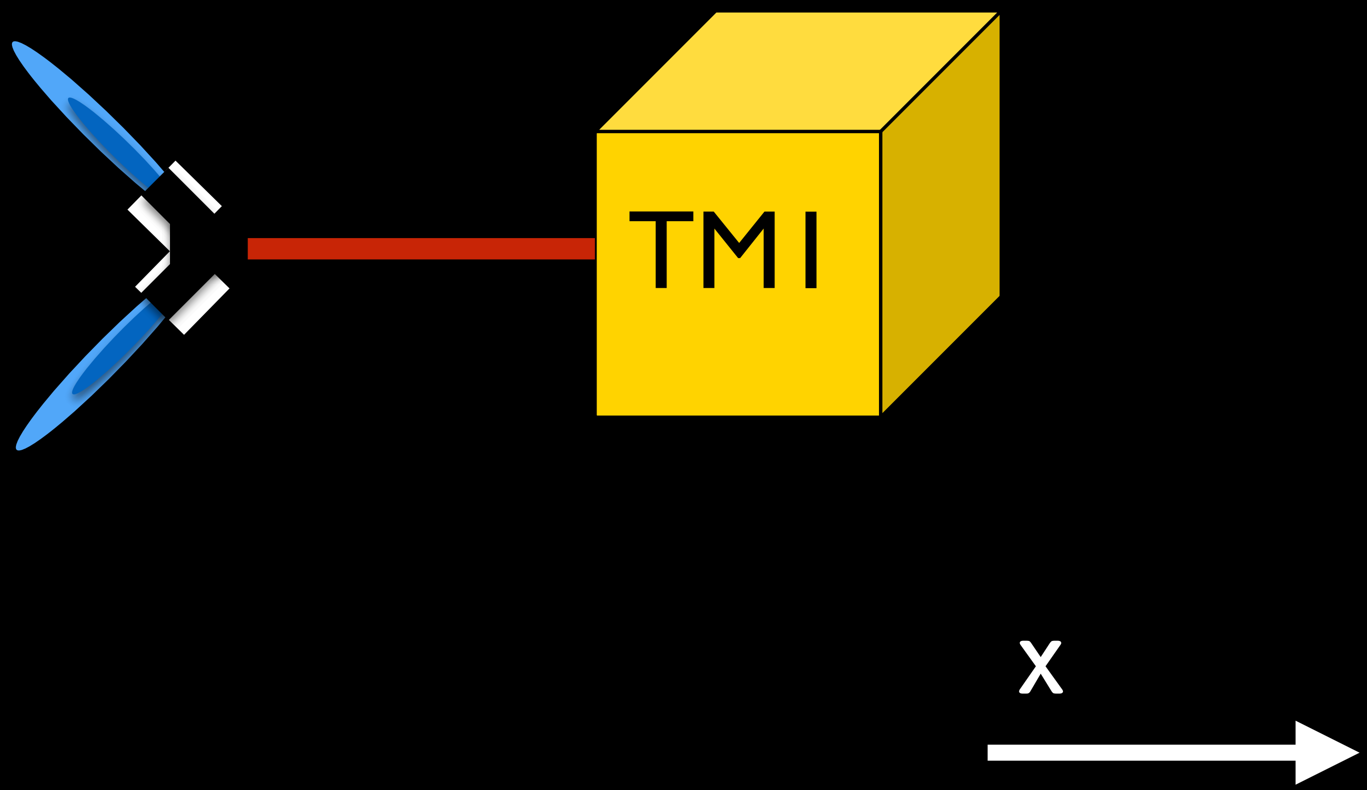


The measurement - deltaG



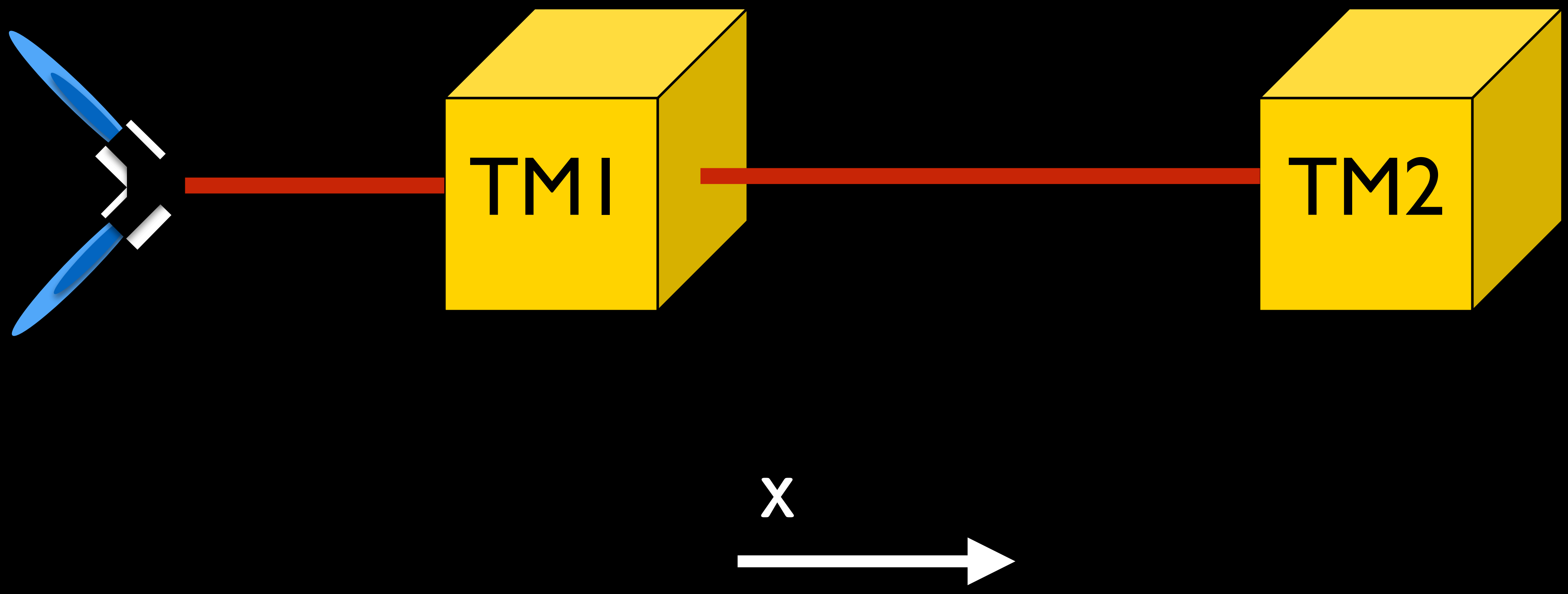
by Joseph Martino

The measurement - deltaG



by Joseph Martino

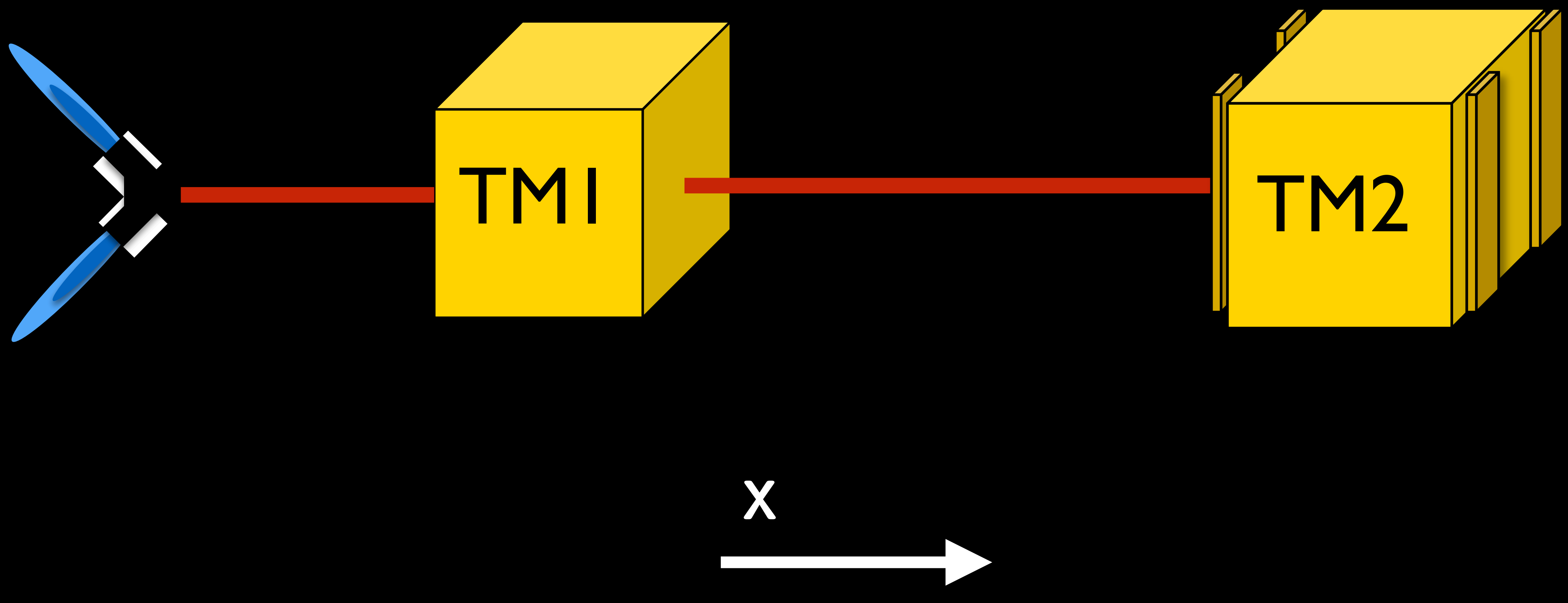
The measurement - deltaG



by Joseph Martino

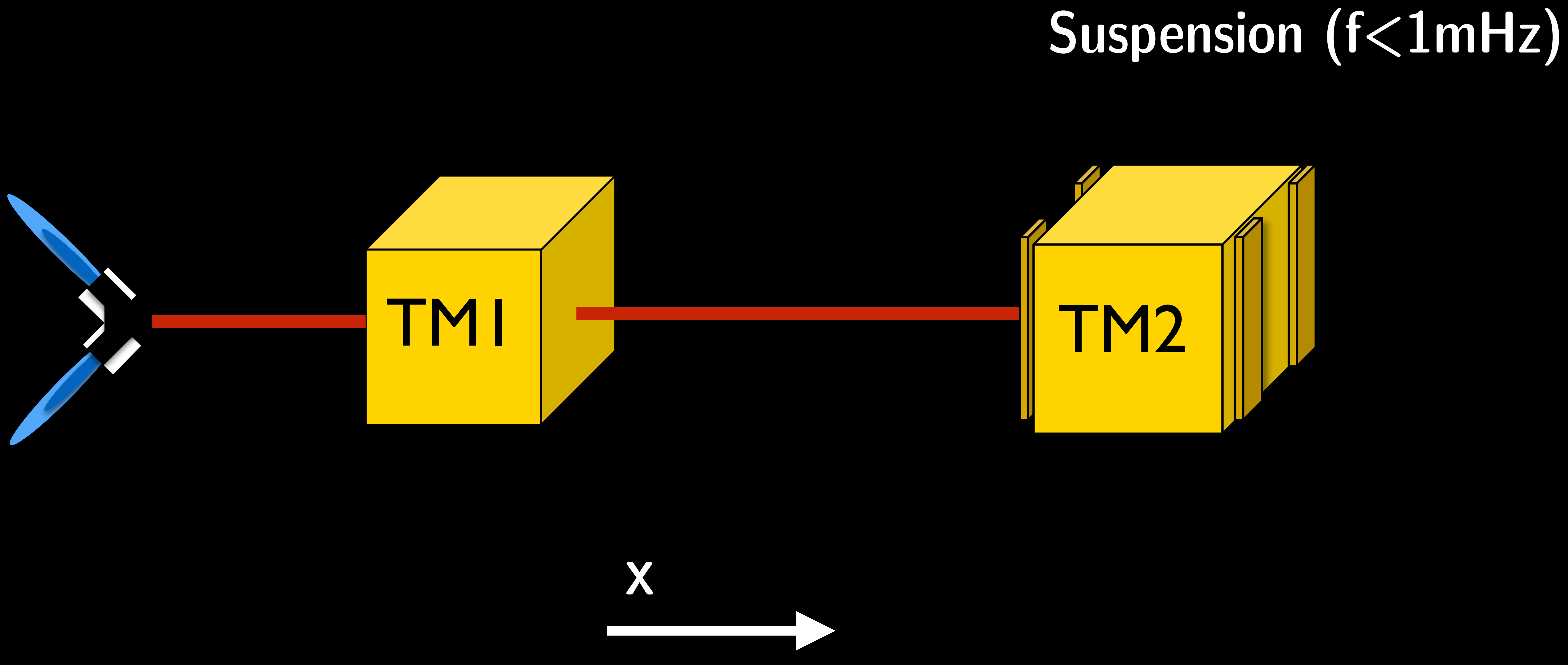
The measurement - deltaG

Suspension (f<1mHz)



by Joseph Martino

The measurement - deltaG

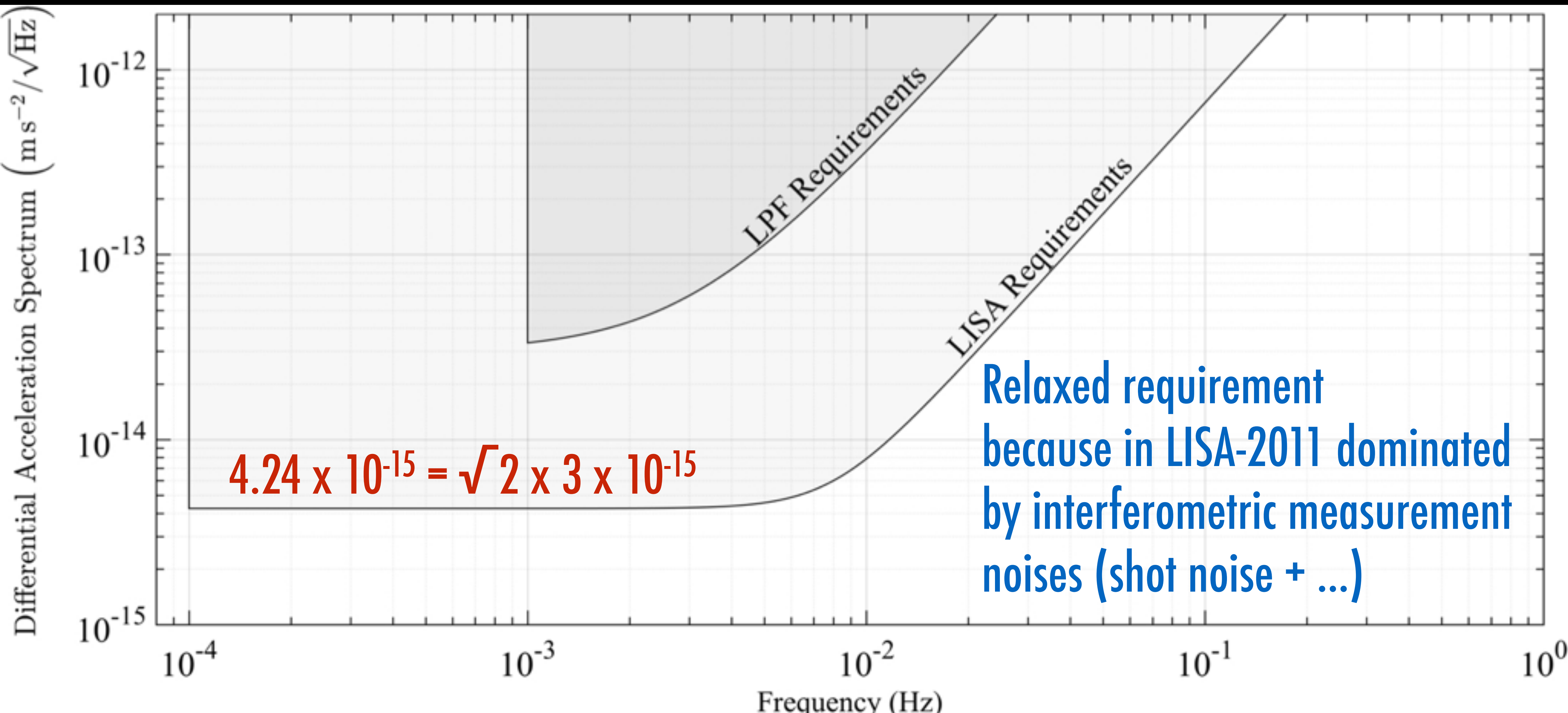


$$\text{deltaG} = d^2(o12)/dt^2 - \text{Stiff} * o12 - \text{Gain} * Fx2$$

by Joseph Martino

Requirements: LPF vs LISA

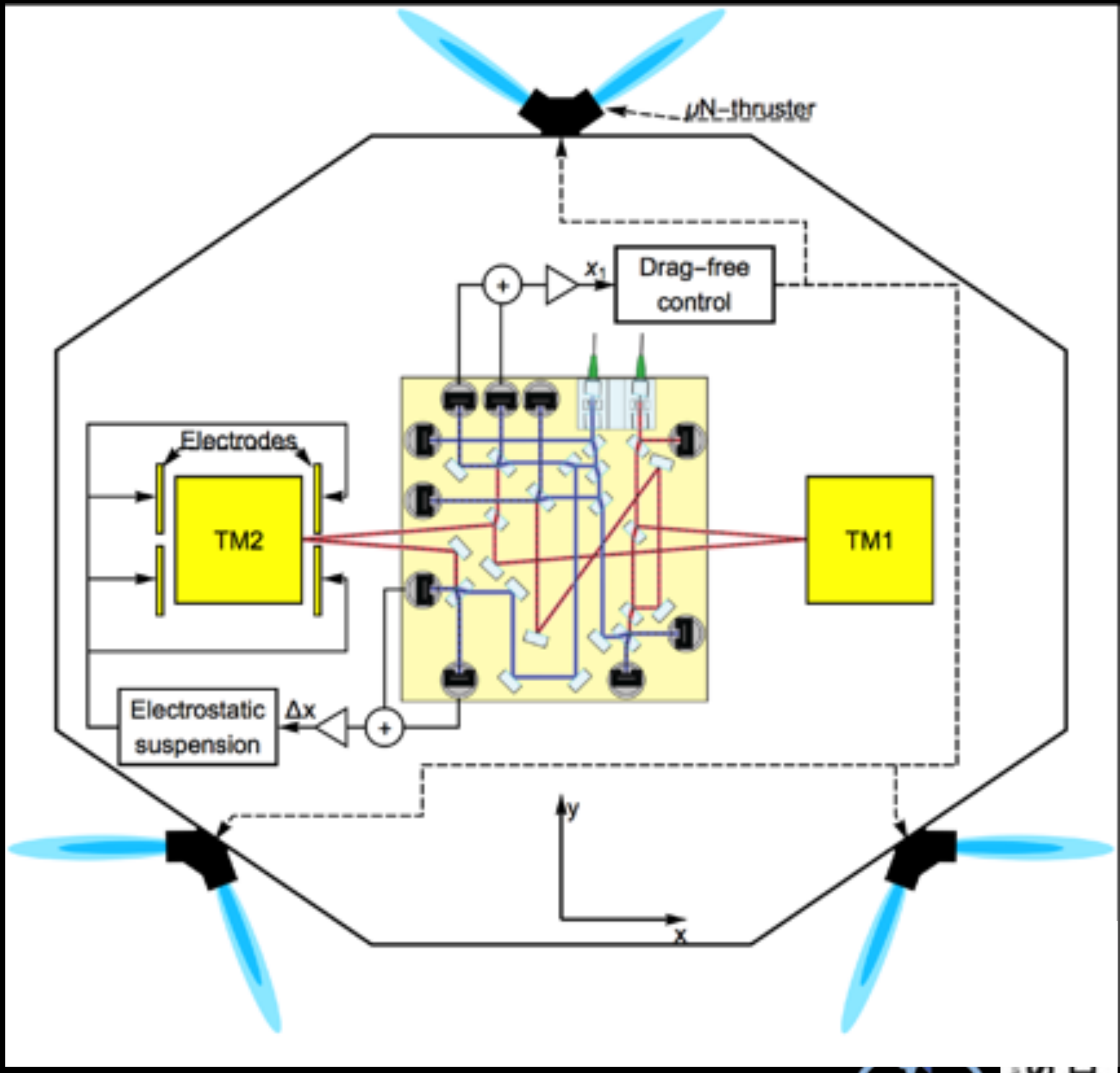
- Main LISAPathfinder (LPF) measurement : Δg : differential acceleration between the 2 test-masses



Requirements: LPF vs LISA

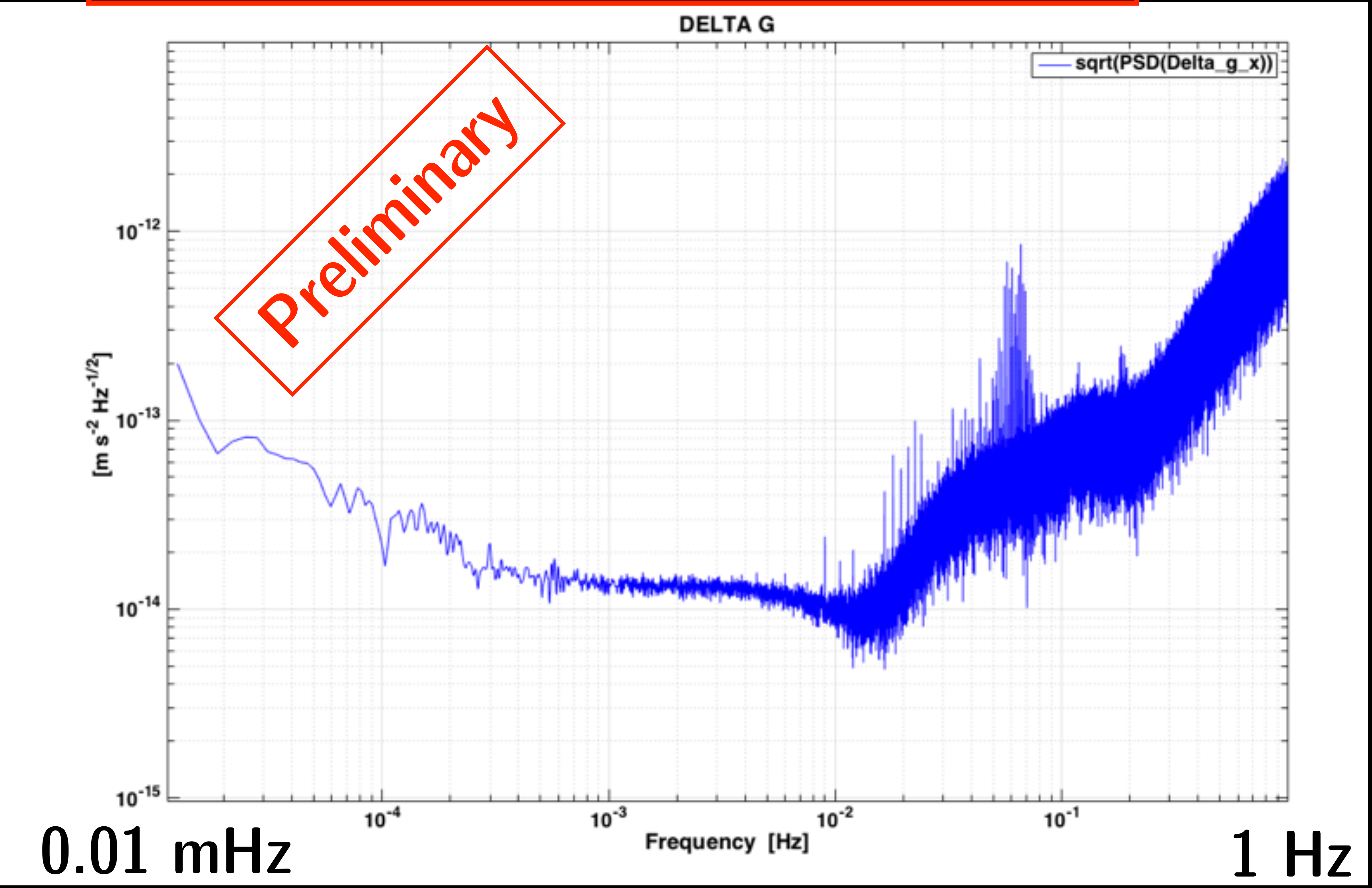
Why the LISAPathfinder requirements are restricted compare to LISA ones ?

- We understand limitations with LISAPathfinder and correct for them in LISA
- Short arm limitation :
  - Gravitational field not perfectly flat => constant electrostatic actuation on test- mass 2
- f > 1 mHz : limit duration of industrial testing
- Industrial margin



Δg - raw

- Differential acceleration Test Mass1 - Test Mass2
- $\Delta g = \boxed{d^2(o12)/dt^2 - \text{Stiff} * o12 - \text{Gain} * Fx2}$



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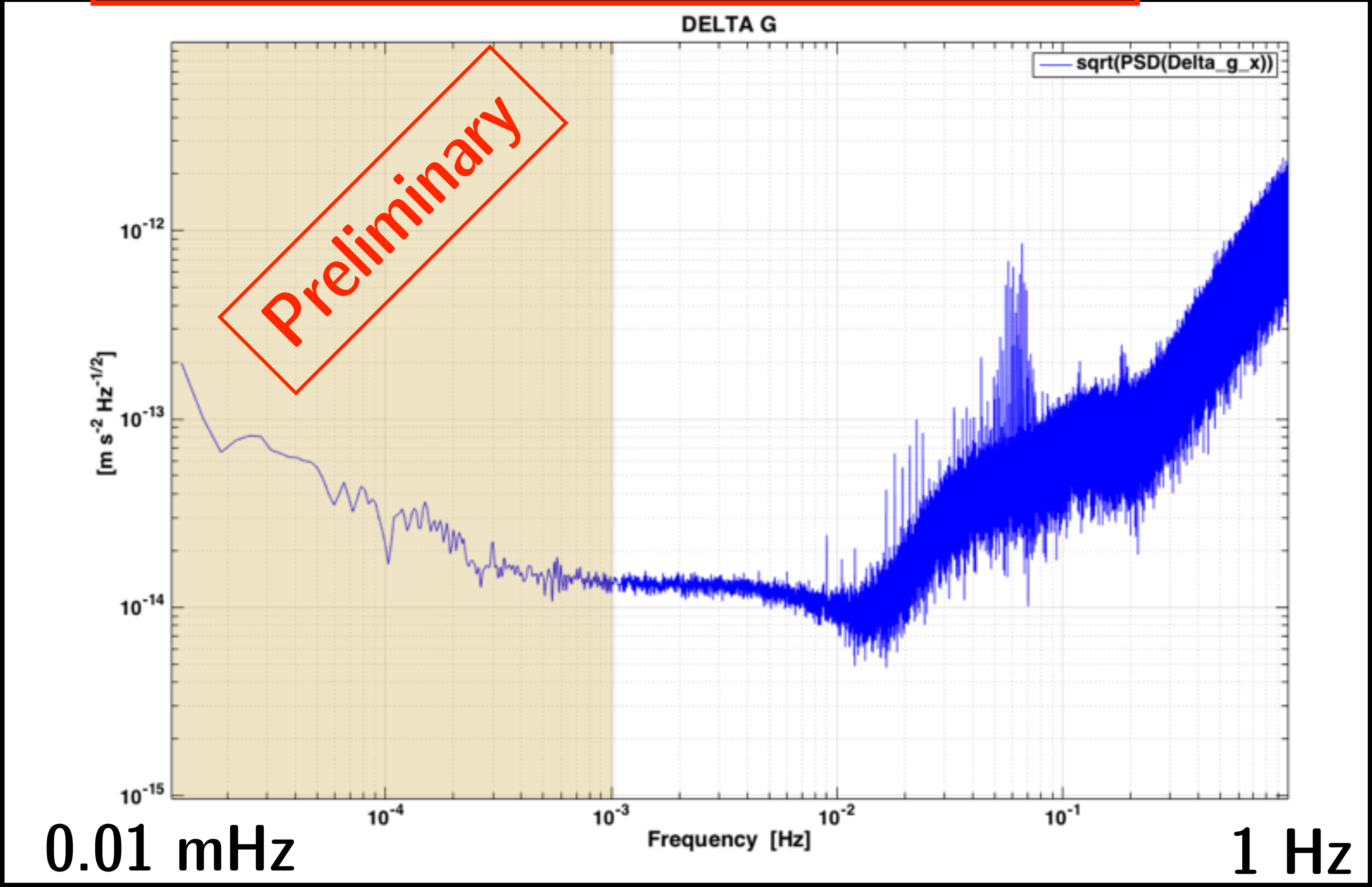
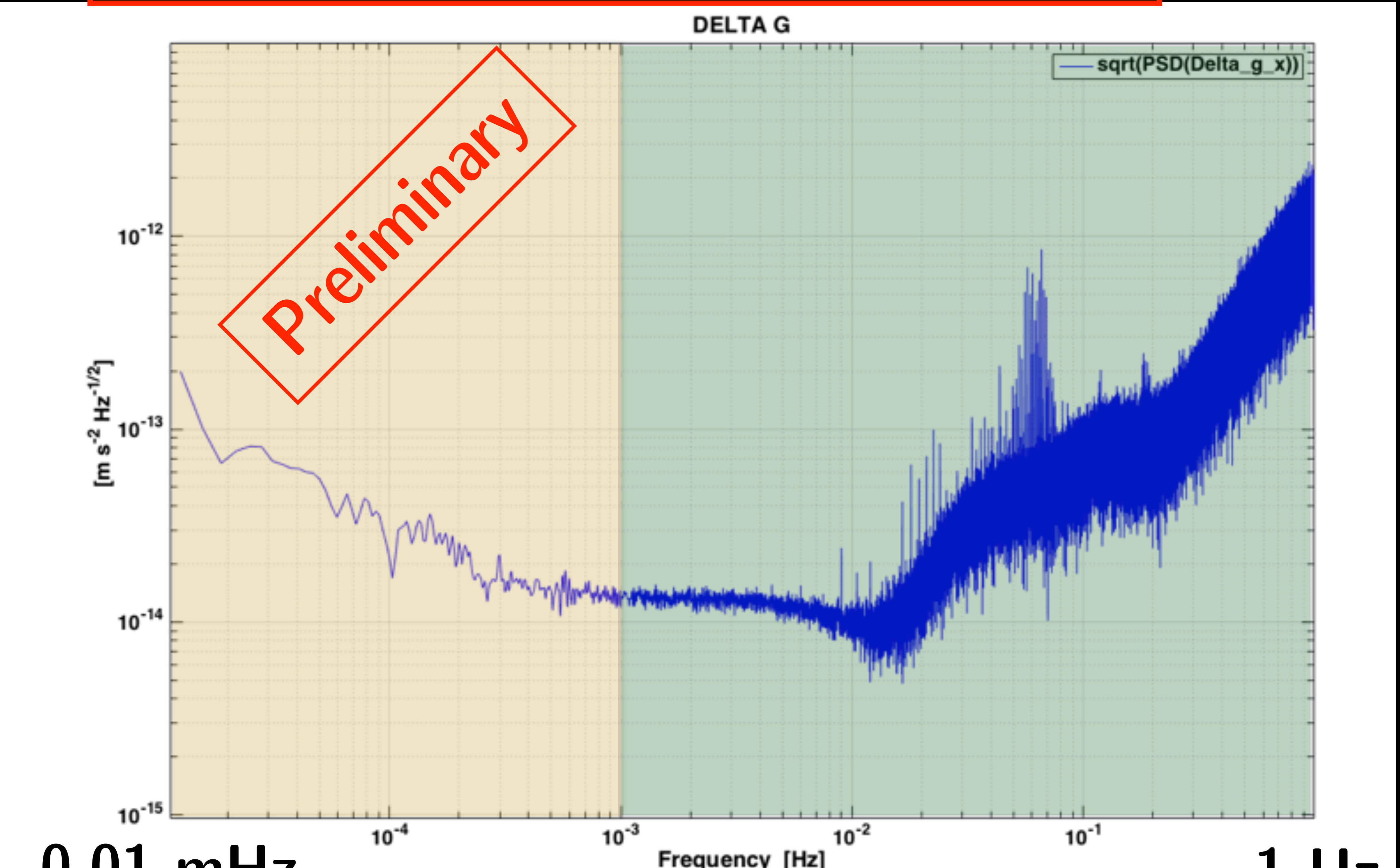
Δg - raw

- Differential acceleration Test Mass1 - Test Mass2
- $\Delta g = \boxed{d^2(o12)/dt^2 \text{ - Stiff * } o12 \text{ - Gain * } Fx2}$



Δg - raw

- Differential acceleration Test Mass1 - Test Mass2
- $\Delta g = \boxed{d^2(o12)/dt^2 - Stiff * o12 - Gain * Fx2}$



0.01 mHz

1 Hz

by Joseph Martino

François Arago Centre

System-Identification

- Measure gains and stiffness
- $\Delta g = d^2(o12)/dt^2$ - Stiff * o12 - Gain * Fx2

by Joseph Martino

Centrifugal Forces

$$\vec{\Omega} \times \vec{\Omega} \times \vec{r}$$

by Joseph Martino

Angle Decorrelation - Euler Forces

by Joseph Martino

$$\Delta\vec{g}_{\mathrm{tang}} = \vec{g}_{\mathrm{tang},2} - \vec{g}_{\mathrm{tang},1}$$
$$= (\vec{r}_2 - \vec{r}_1) \times \dot{\vec{\Omega}}$$

Angle Decorrelation - Euler Forces

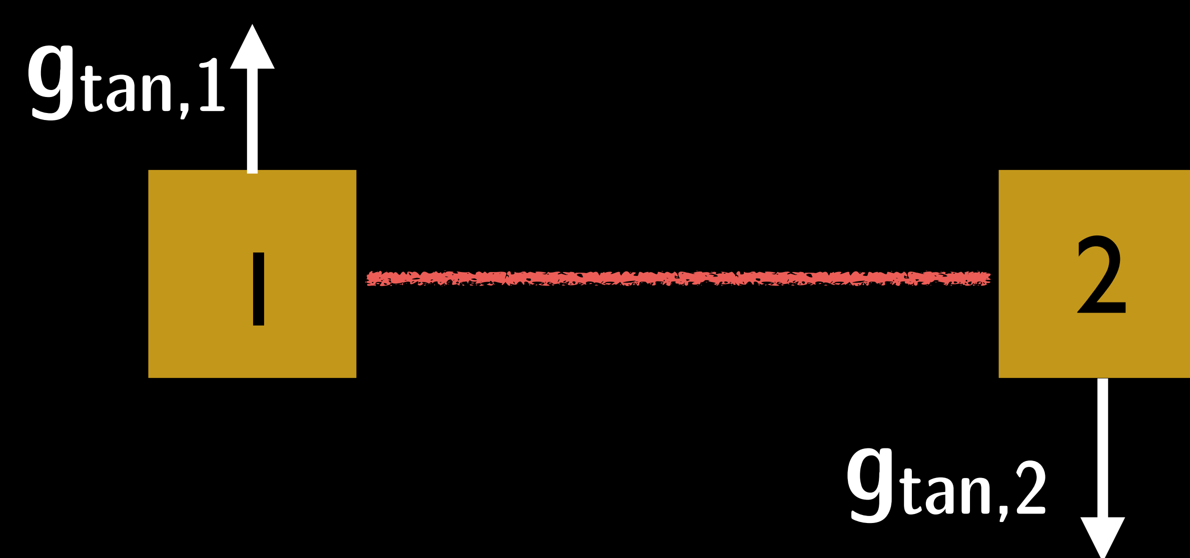
by Joseph Martino

$$\Delta\vec{g}_{\mathrm{tang}} = \vec{g}_{\mathrm{tang},2} - \vec{g}_{\mathrm{tang},1}$$
$$= (\vec{r}_2 - \vec{r}_1) \times \dot{\vec{\Omega}}$$

Angle Decorrelation - Euler Forces

by Joseph Martino

$$\Delta\vec{g}_{\rm tang} = \vec{g}_{\rm tang,2} - \vec{g}_{\rm tang,1}$$
$$= (\vec{r}_2 - \vec{r}_1) \times \dot{\vec{\Omega}}$$

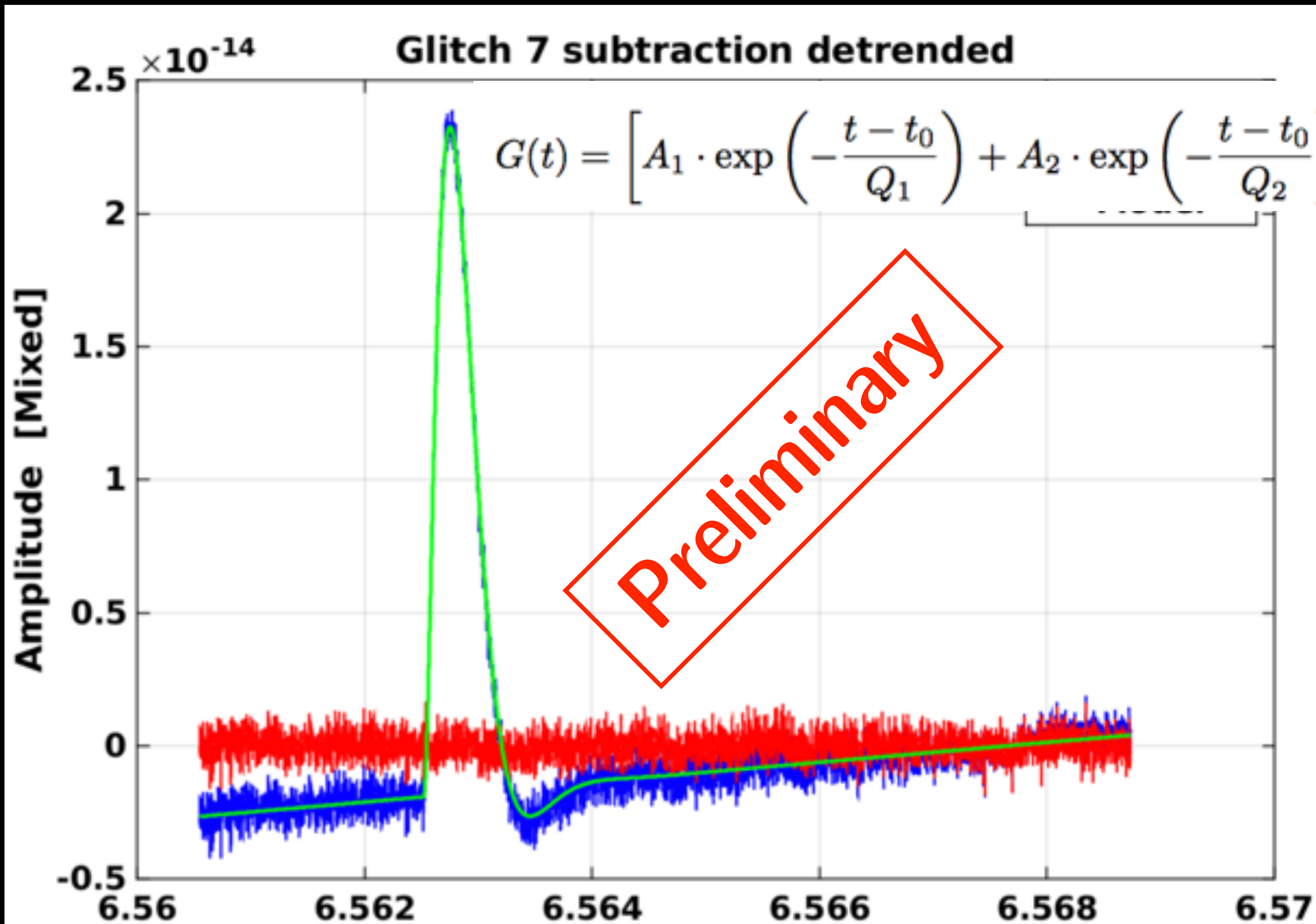


de-Glitch

Preliminary

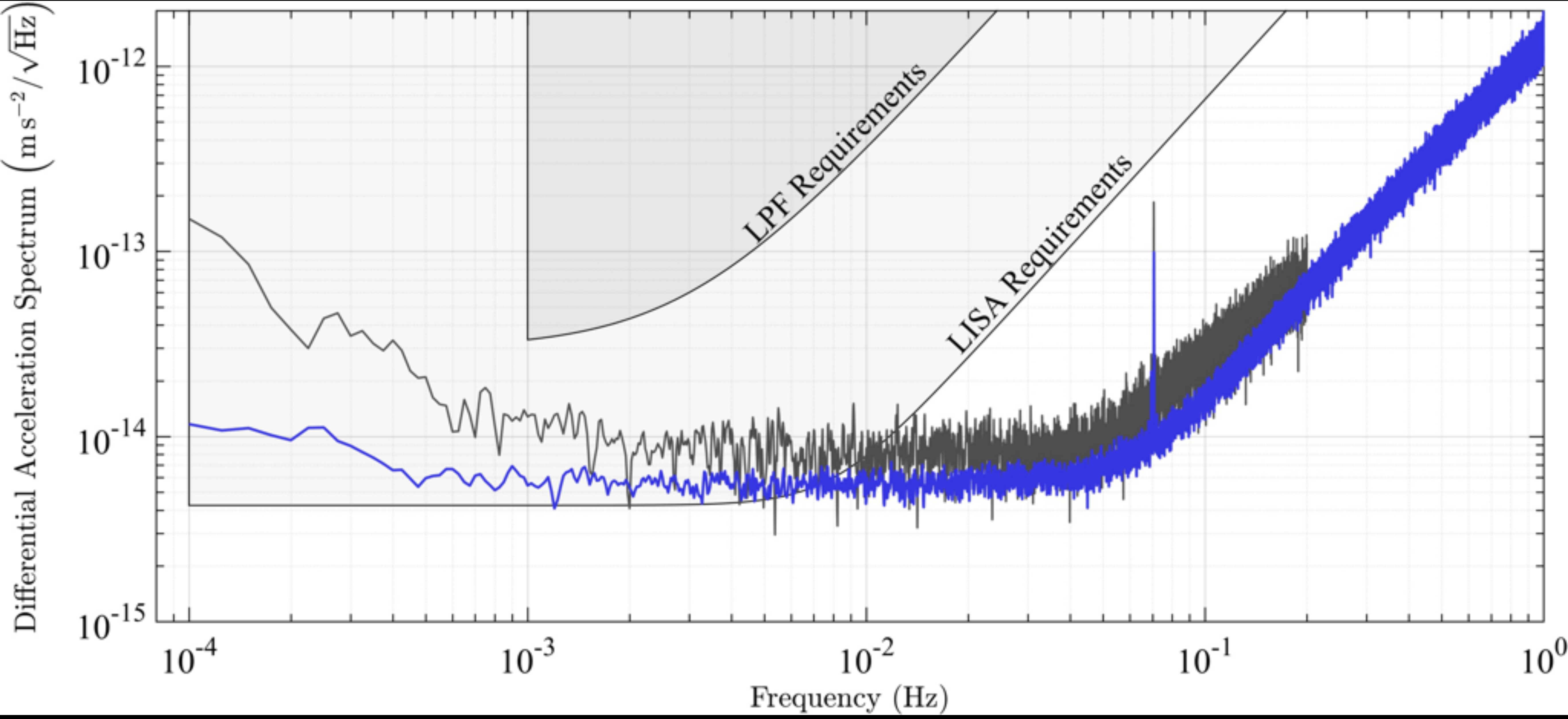
de-Glitch

$$G(t) = \left[A_1 \cdot \exp\left(-\frac{t-t_0}{Q_1}\right) + A_2 \cdot \exp\left(-\frac{t-t_0}{Q_2}\right) + A_3 \cdot \exp\left(-\frac{t-t_0}{Q_3}\right)\right] * \left[1 - \exp\left(-\frac{t-t_0}{Q_0}\right)\right]^{\alpha}$$



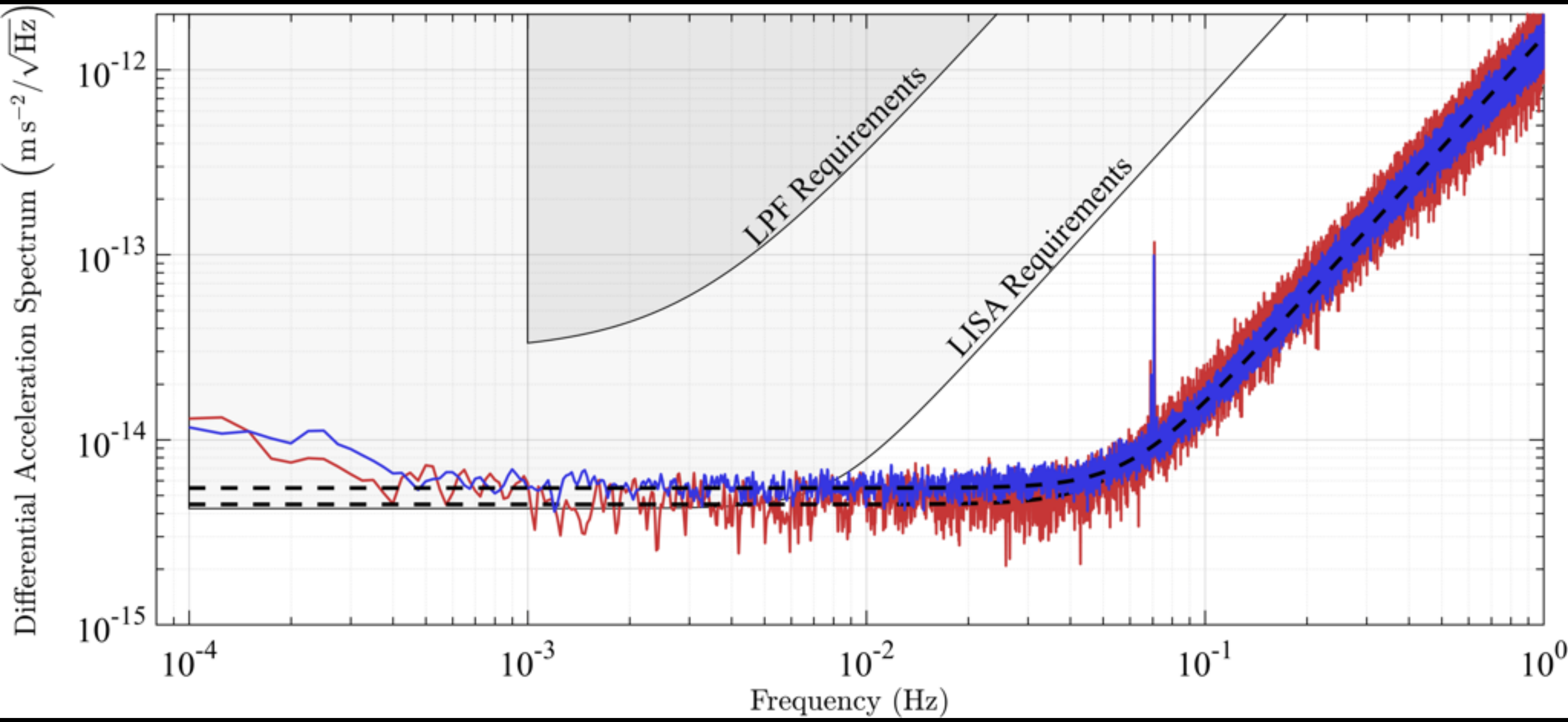
First results

M. Armano et al. PRL 116, 231101 (2016)



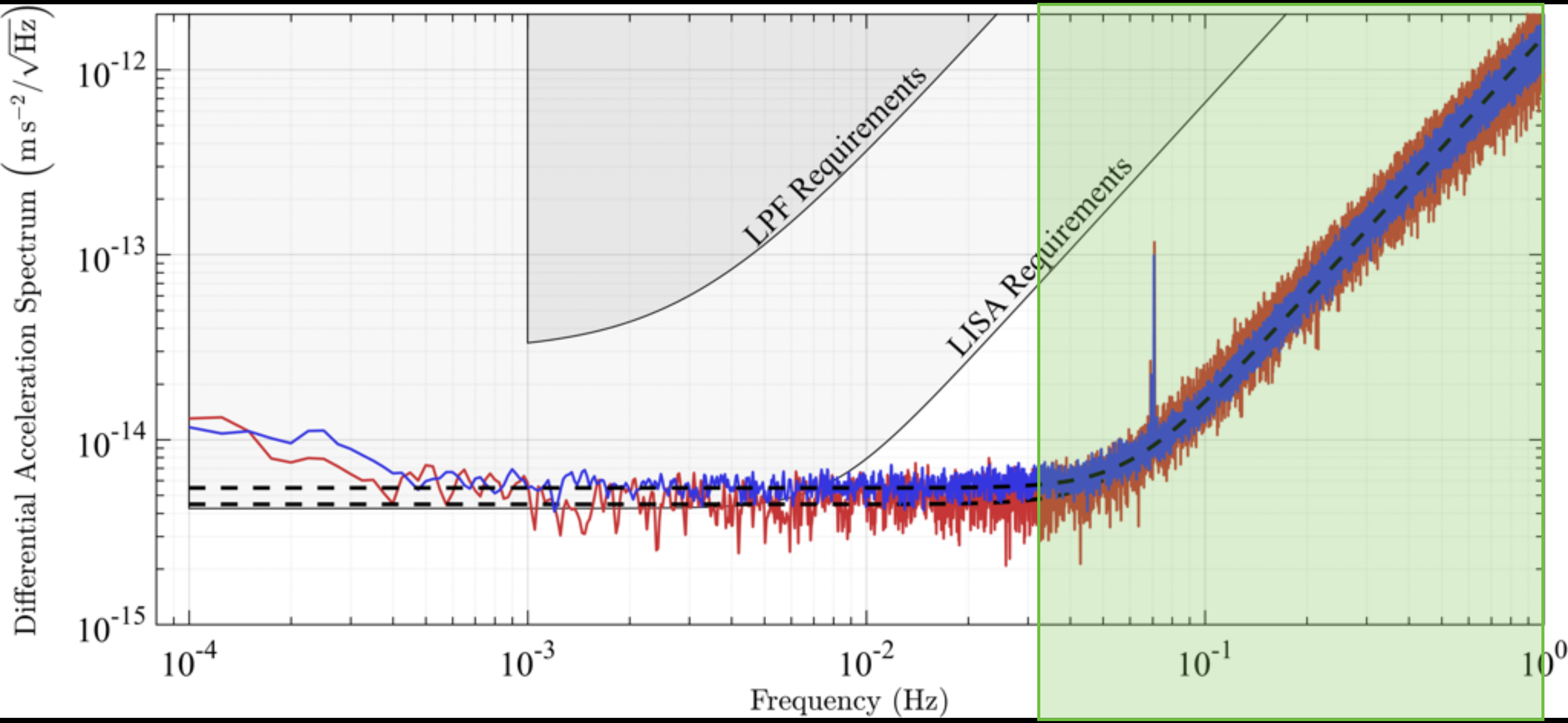
First results

M. Armano et al. PRL 116, 231101 (2016)



First results

M. Armano et al. PRL 116, 231101 (2016)

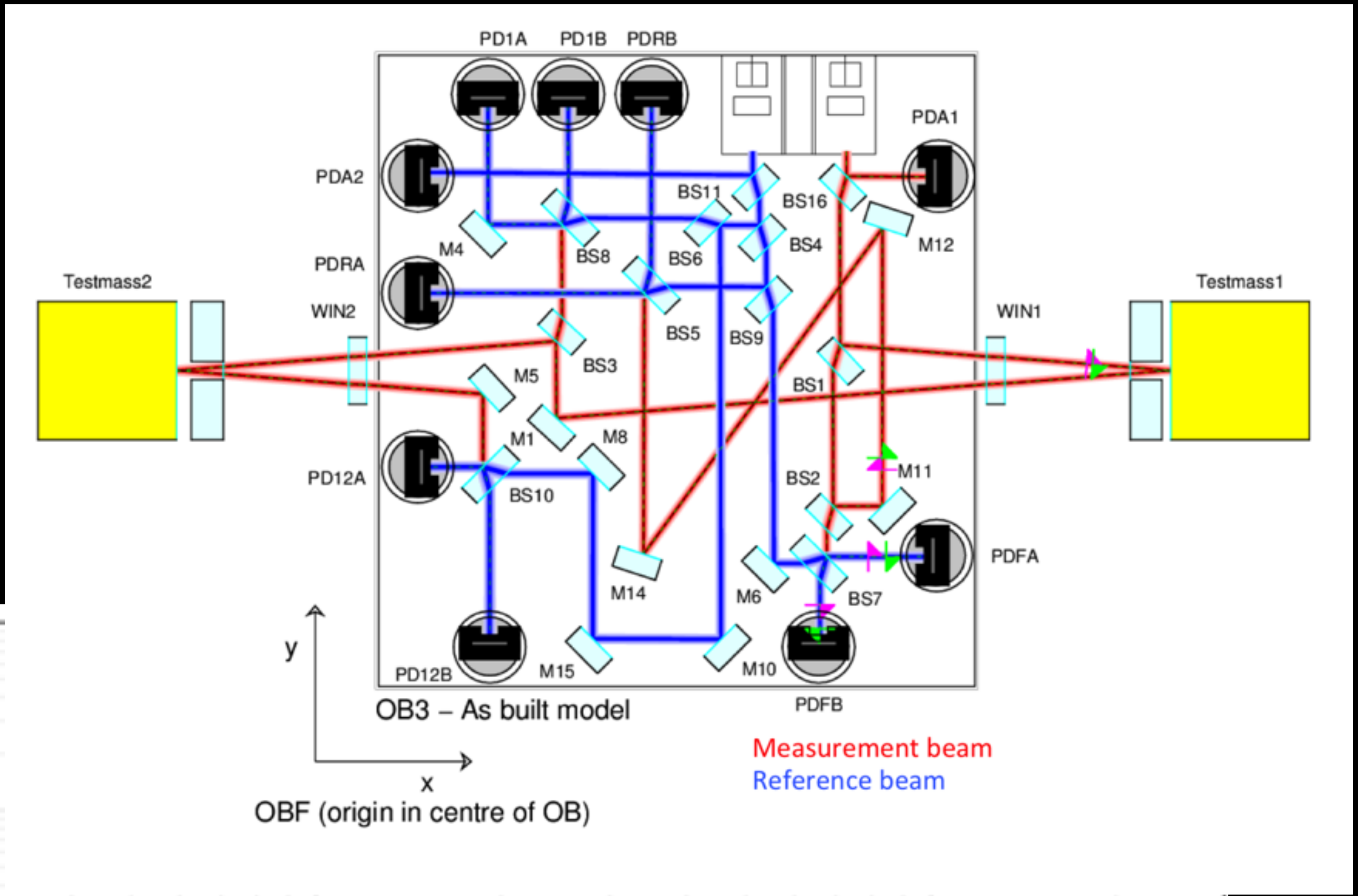


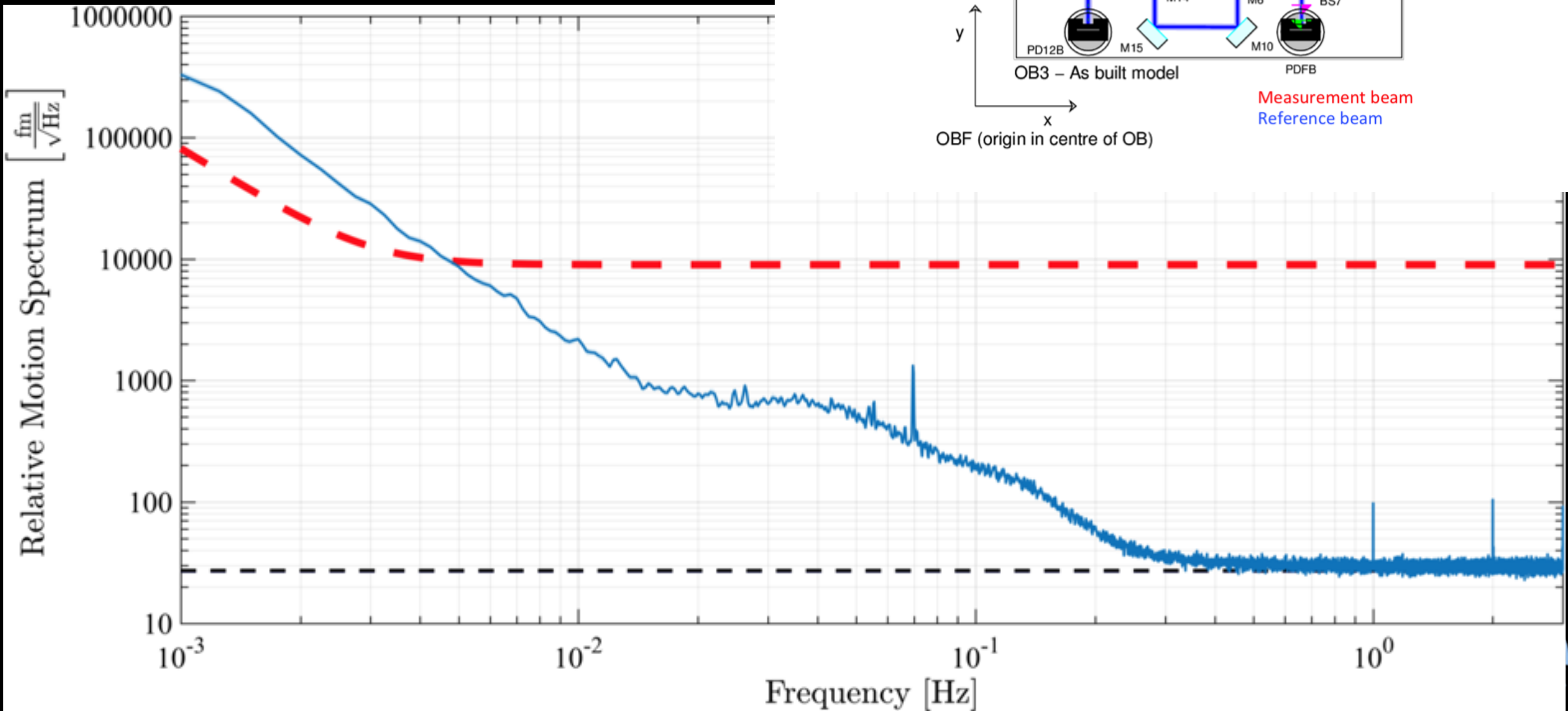
Interferometric noise

Not real test-mass motion

High frequency limit

- Optical measurement system:
  - Interferometric precision: 30 fm.Hz$^{-1/2}$
  - Orientation of test-masses

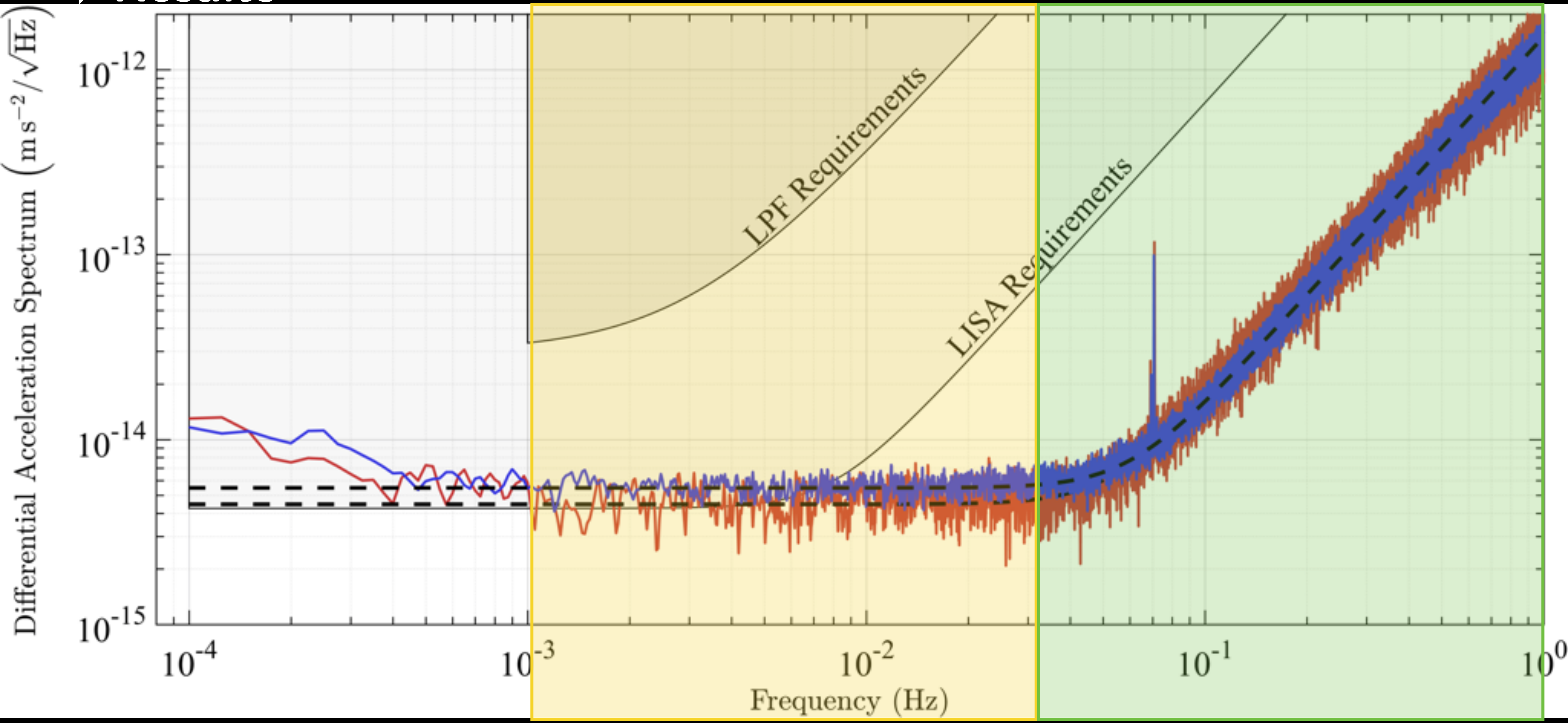




First results

M. Armano et al. PRL 116, 231101 (2016)

- Results

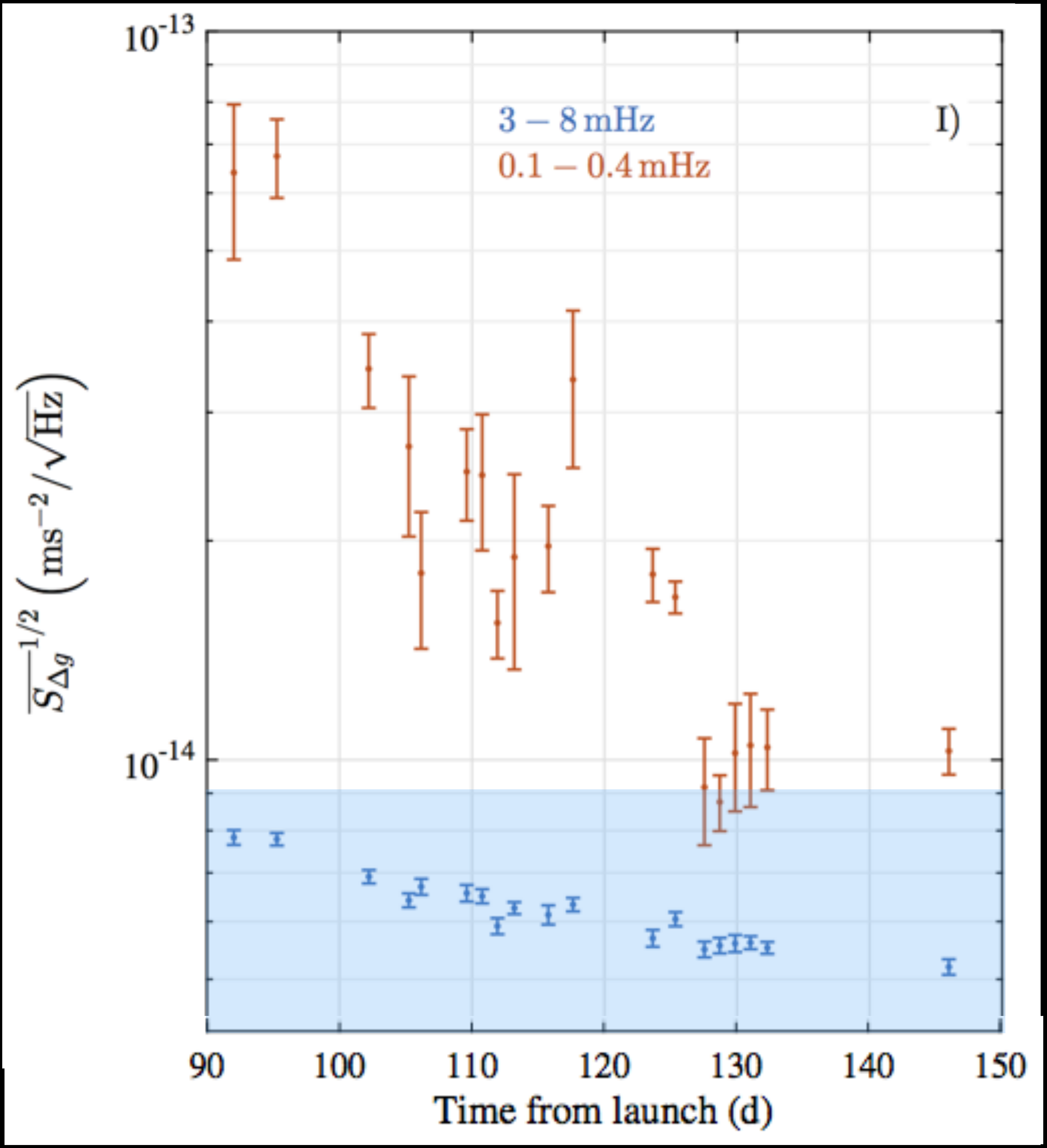


Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

Mid-frequency limit

- Noise in 1–10 mHz: brownian noise due to residual pressure:
  - Molecules within the housing hitting the test-masses
  - Possible residual outgassing
- Evolution:
  - Pressure decreases with time => constant improvement … if we don't hit something else.

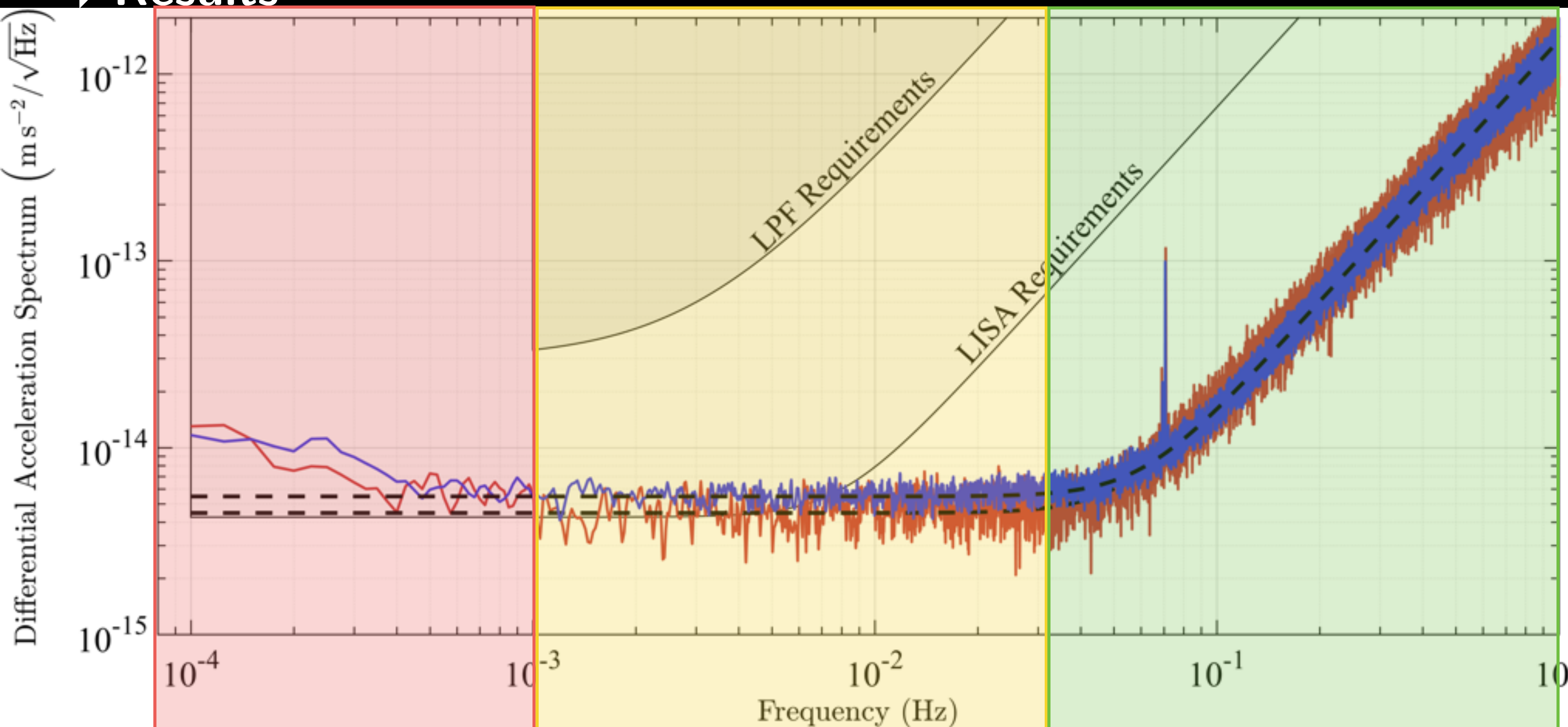


M. Armano et al. PRL 116, 231101 (2016)

First results

M. Armano et al. PRL 116, 231101 (2016)

- Results



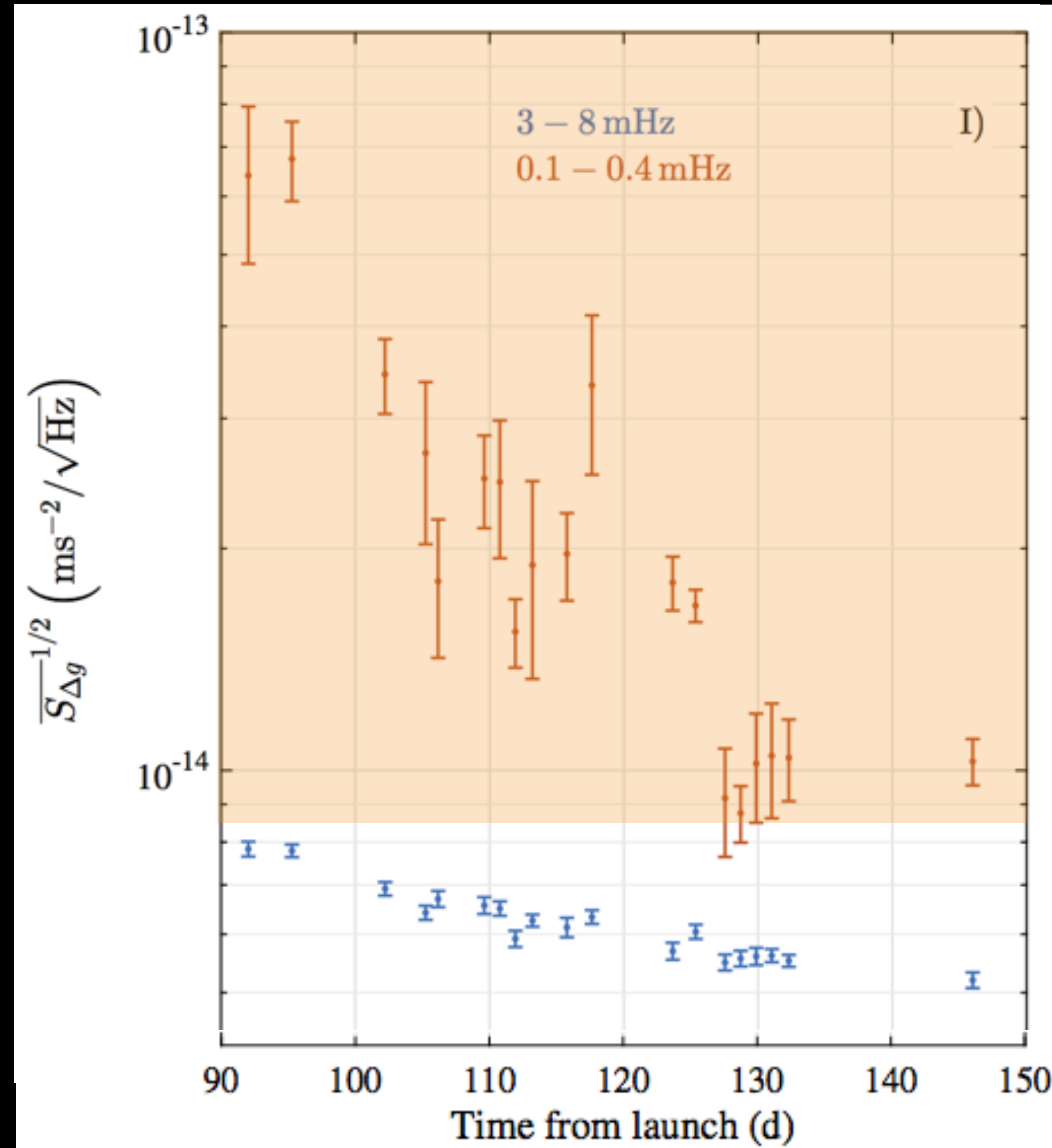
Low frequency noise: actuation noie + ...

Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion

Low-frequency limit

- Noise in 0.1 – 1 mHz: not yet understood but seems:
  - to evolve with time
  - to have 1/f slope ?
  - Temperature ? Actuation ?
- Work in progress ...
- For f < 0.1 mHz:
  - Need long noise measurements
    => mission extension



M. Armano et al. PRL 116, 231101 (2016)

Noise sources

Acceleration noise

- **Due to residual forces acting on the test-mass**
- **Obtain via LISAPathfinder measurements**

$$S_{acc}(f) = S_{acc,unmodelled} + S_{acc,brownian}$$

with

$$S_{acc,brownian} = \text{constant}$$

$$S_{acc,unmodelled}(f) = (c_{acc,red})^2 \left(\left(\frac{2 \times 10^{-5}}{f} \right)^{10} + \left(\frac{1 \times 10^{-4}}{f} \right)^{2} \right) + (c_{acc,flat})^2 \left(1 + \left(\frac{f}{8 \times 10^{-3}} \right)^{4} \right)$$

Readout noise

- Composition of a number of effects:

$$S_{ro,k,m} = \left(\frac{\lambda}{2\pi}\kappa_k\right)^2 \left(\left\langle\phi^{sn}_{r/o}\right\rangle^2 + \left\langle\phi^{rin}_{r/o}\right\rangle^2 + \left\langle\phi^{el}_{r/o}\right\rangle^2 + \left\langle\phi^{PMc}_{r/o}\right\rangle^2 + \left\langle\phi^{PMu}_{r/o}\right\rangle^2\right) \quad (10)$$

with $k = \{s, sb, \tau, \epsilon\}$ refering to the interferometers. κ_k is the inverse of the fraction of the laser power at frequency of interest :

$$\kappa_s = \frac{1}{J_0(m)^2} \quad \text{science interferometer at the carrier frequency} \quad (11)$$

$$\kappa_{sb} = \frac{1}{\sqrt{2}}\frac{f_{het}}{f_{mod}}\frac{1}{J_1(m)^2} \quad \text{science interferometer at the sideband frequency}$$

$$\kappa_\epsilon = 1 \quad \text{test-mass interferometer} \quad (12)$$

$$\kappa_\tau = 1 \quad \text{reference interferometer} \quad (13)$$

- If $k = s$ or sb => $P_1 = P_{rec}$ and $P_2 = P_{local,1}$
- If $k = \tau$ or ε => $P_2 = P_{local,1}$ and $P_2 = P_{local,2}$

Readout: shot noise

- Due to the small number of photons in the incoming beam
  - Emitted laser power: $P_{tel} = \eta_{TX} P_{laser}$
  - Received laser intensity:

$$I_{red} = \frac{\pi \; P_{tel} \; d_{tel}^2}{2 \; L_{arm}^2 \lambda_{laser}^2} \times \alpha^2 e^{-\frac{2}{\alpha^2}} \left(e^{\frac{1}{\alpha^2}} - 1 \right)^2$$

  - Received laser power on the optical bench:

$$P_{red} = \pi \left(\frac{d_{tel}}{2} \right)^2 \eta_{opt} I_{rec}$$

  - Shot noise:

$$\left\langle \phi_{r/o}^{sn} \right\rangle = M_{IMS}(f) \sqrt{\frac{q_e \left(P_1 + P_2 \right)}{R_{pd} \; \eta_{het} \; P_1 \; P_2}}$$

- P_{laser} : P_laser : laser power output
- η_{TX} : eta_TX : transmission from laser to telescope
- d_{tel} : d_tel : telescope diameter
- L_{arm} : L_arm : armlength
- λ_{laser} : lambda_laser : laser wavelength
- η_{opt} : eta_opt : optical efficiency

Readout: electronic noise

- Electronic noise associated to the photodiode

$$\left\langle \phi^{el}_{r/o} \right\rangle = M_{IMS}(f) \frac{\sqrt{N_{seg} N_{pd}}}{R_{pd}\sqrt{2}} \sqrt{\frac{\frac{4 k_B T}{R_{FB}} + I_{pd}^2 + \left(\frac{U_{pd}}{Z_{pd}}\right)^2}{\eta_{het}\ P_2\ P_1}}$$

$$Z_{pd} = \frac{1}{2\pi C_{pd} f_{het}}$$

- R_{FB} : Rfb : feedbask resistor
- T : T_preamp : temperature at the photodiode preamplifier
- I_{pd} : I_pd : input current noise
- U_{pd} : U_pd : intrinsic voltage noise
- C_{pd} : C_pd : photodiode capacitance
- f_{het} : f_het : heterodyne maximal frequency

Readout: RIN & phase meter

- RIN: Relative Intensity Noise:
  - For a balanced detection, the phase noise contribution from RIN is

$$\left\langle \phi_{r/o}^{rin} \right\rangle = \phi_{r/o}^{rin} = M_{IMS}(f) \frac{RIN_{laser}}{\sqrt{2}} \frac{\sqrt{1+(P_1/P_2)^2}}{1+P_1/P_2}$$

- Phasemeter measurement noise:
  - Correlated term: $\left\langle \phi_{r/o}^{PMc} \right\rangle = M_{IMS}(f) \phi_{r/o}^{PMc}$
  - Uncorrelated term: $\left\langle \phi_{r/o}^{PMu} \right\rangle = M_{IMS}(f) \frac{\phi_{r/o}^{PMu}}{\sqrt{N_{pd} N_{seg}}}$

Optical Path Noises

- Noises on the optical path:

$$S_{opt,k,m}(f) = \left(M(f)x_{opn}^{tel}\right)^2 \longrightarrow \text{telescope}$$

$$+ \left(M(f)x_{opn}^{pointing}\right)^2 \longrightarrow \text{pointing (tilt to length)}$$

$$+ \left(M(f)x_{opn}^{align}\right)^2 \longrightarrow \text{line of sight alignement (OB/TM)}$$

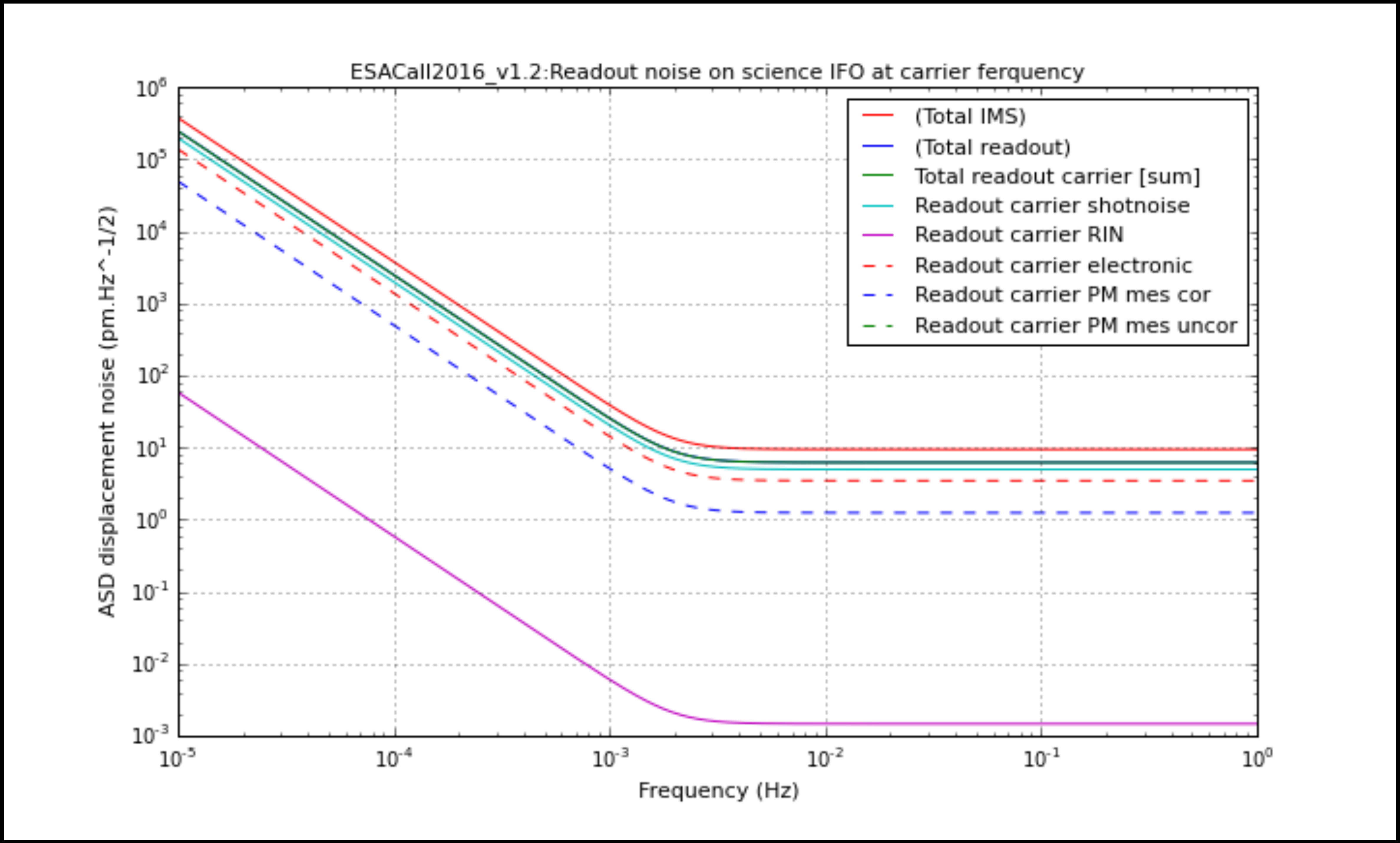
$$+ \left(M(f)x_{opn}^{SLs}\right)^2 \longrightarrow \text{stray light science interferometer}$$

$$+ \left(M(f)x_{opn}^{PAAM}\right)^2 \longrightarrow \text{PAAM}$$

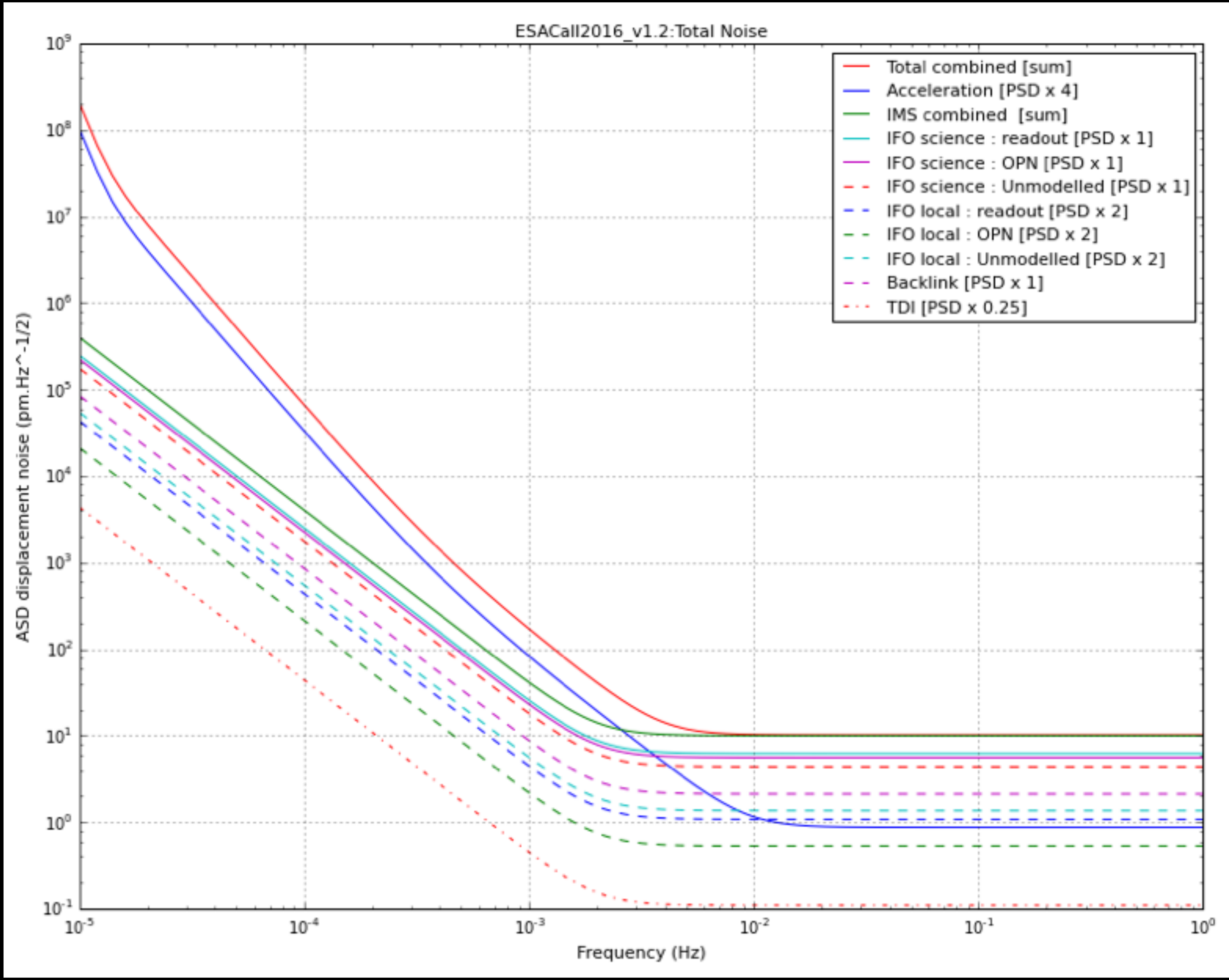
Other noises

- Unmodelled interferometer noise
- Backlink noise
- Residual laser noise after TDI

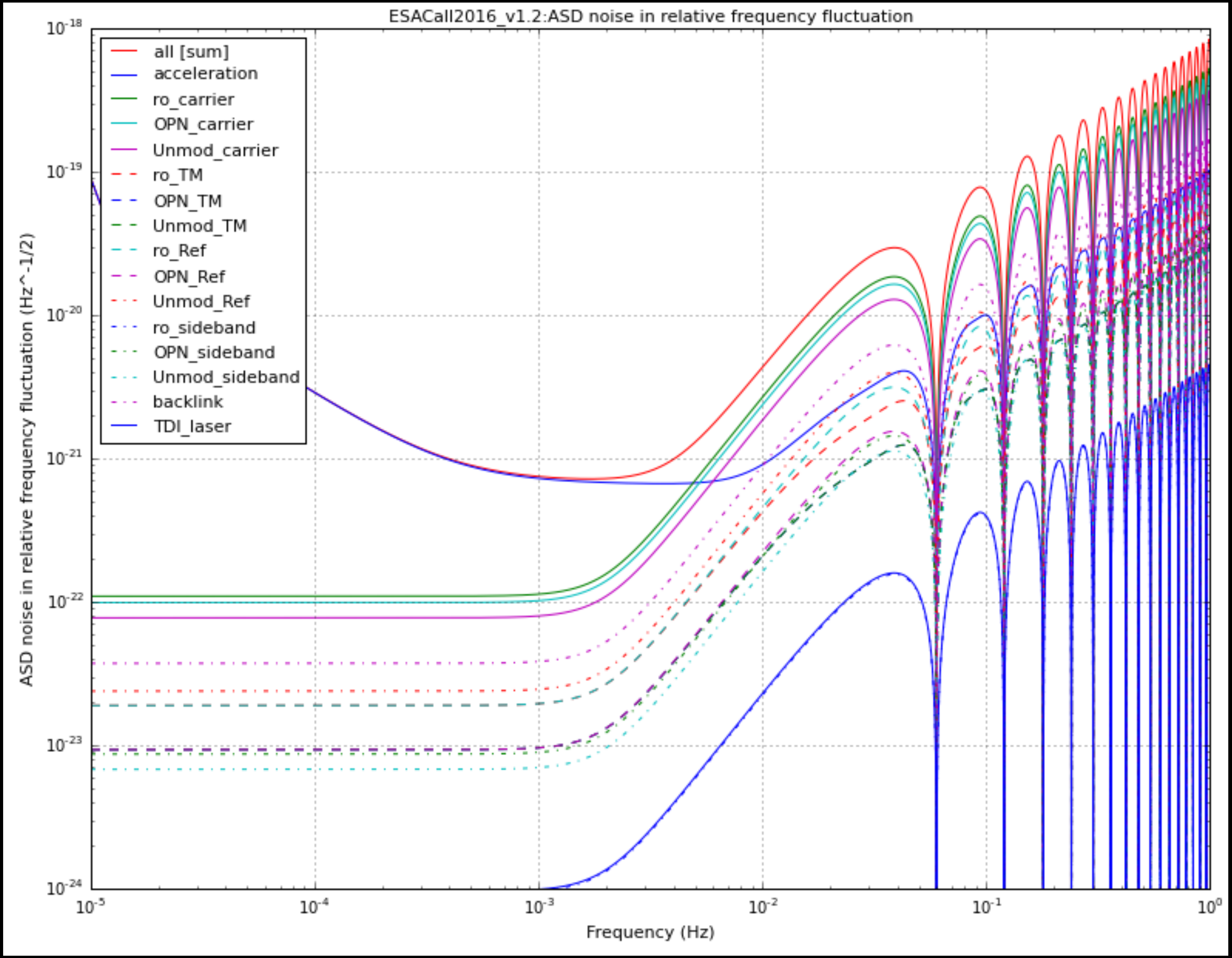
Readout noise budget



Combined on half round trip



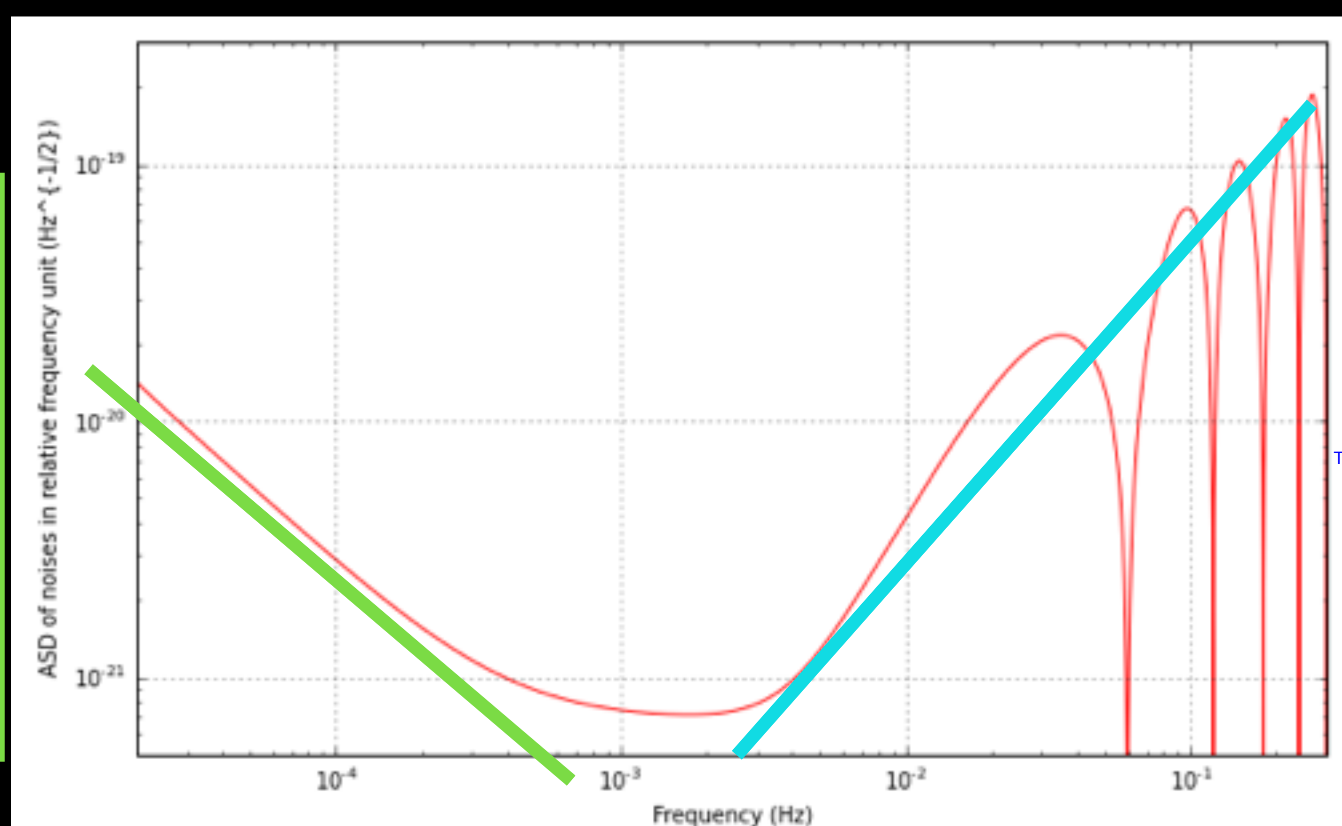
Noise budget in TDI

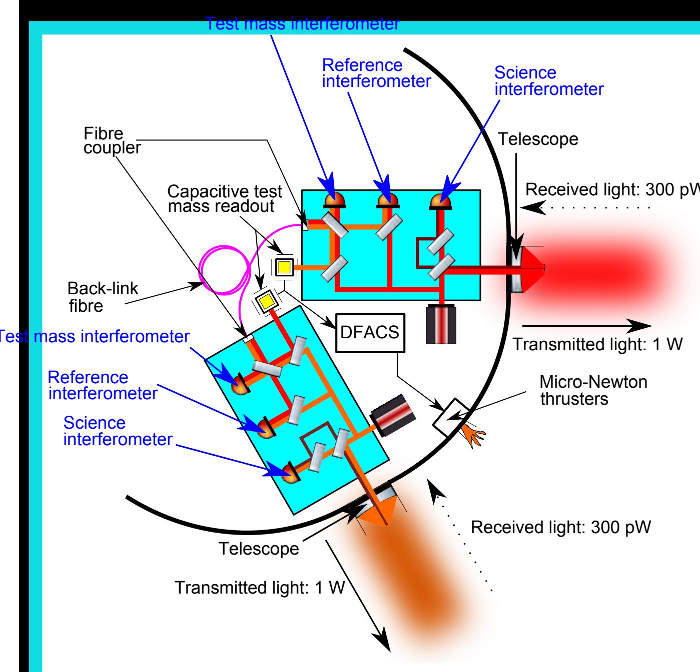


Sensitivity

Sensitivity

- Noise budget in 3 points:
  - Low frequencies: acceleration noise (unperfect free-falling of the test)
  - High frequency: interferometric measurements noise
  - Pre-processing pour réduire une partie des bruits (TDI)





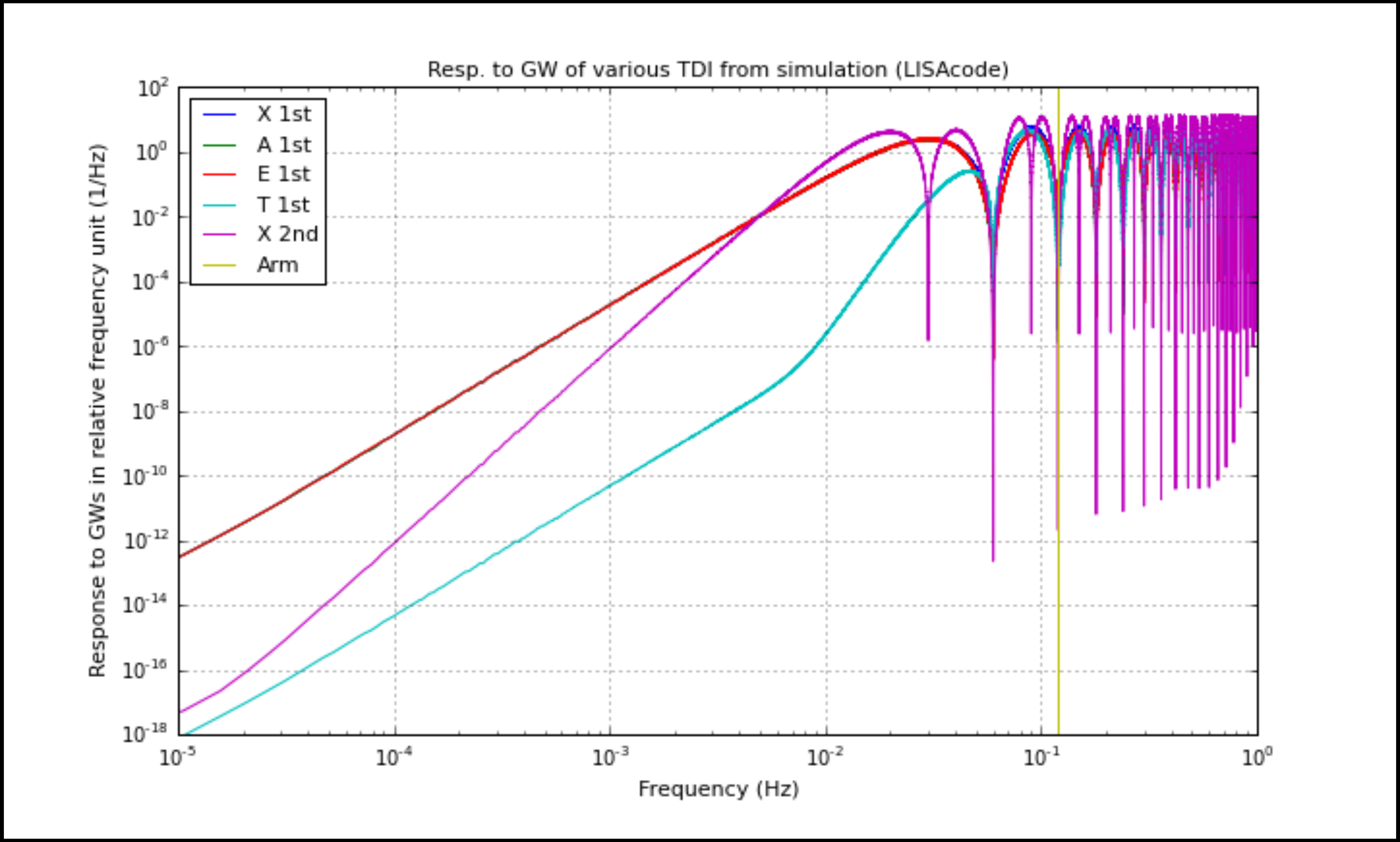
Sensitivity

- Standard sensitivity, so called "strain sensitivity" or "strain linear spectral density" is

$$S(f) = \frac{Resp_{Noise}}{Resp_{GW}} = \frac{PSD_{Noise}}{PSD_{average\ GW}}$$

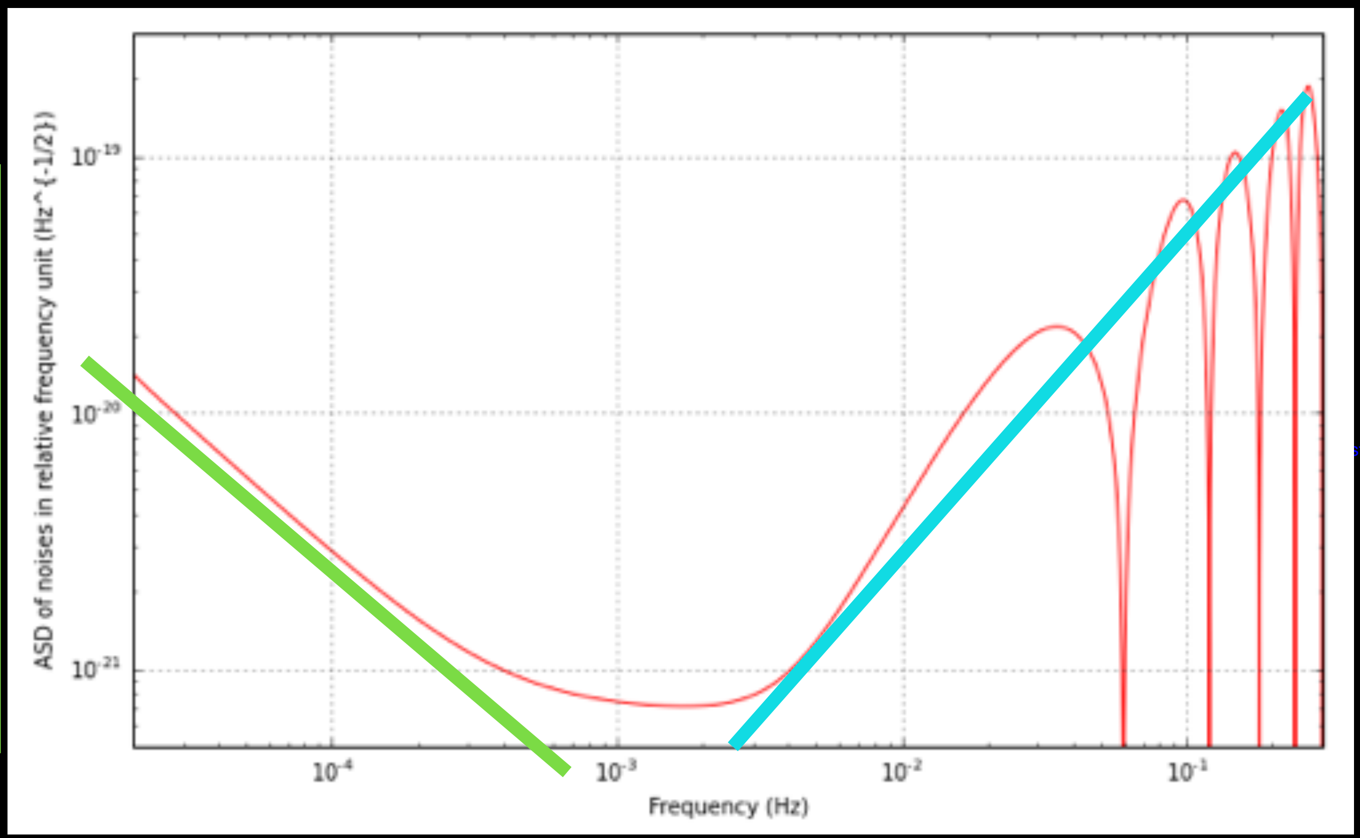
- Response to GW:
  - Depends on orbits (see later)
  - Depends on frequency partially due to TDI
  - Computation:
    - Analytic approximation
    - Using simulators: PSD of TDI X with as input 192 white stochastic GWs isotropically distributed on sky

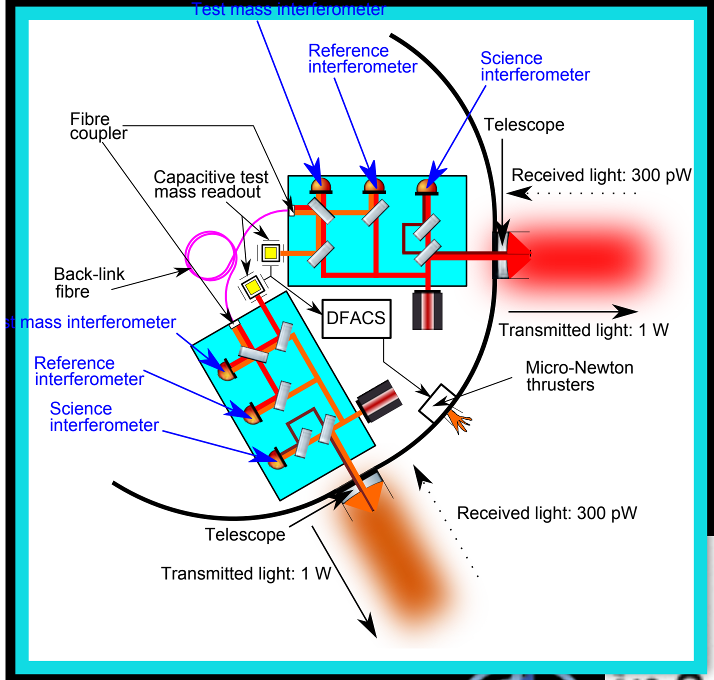
Response to GWs



Sensitivity

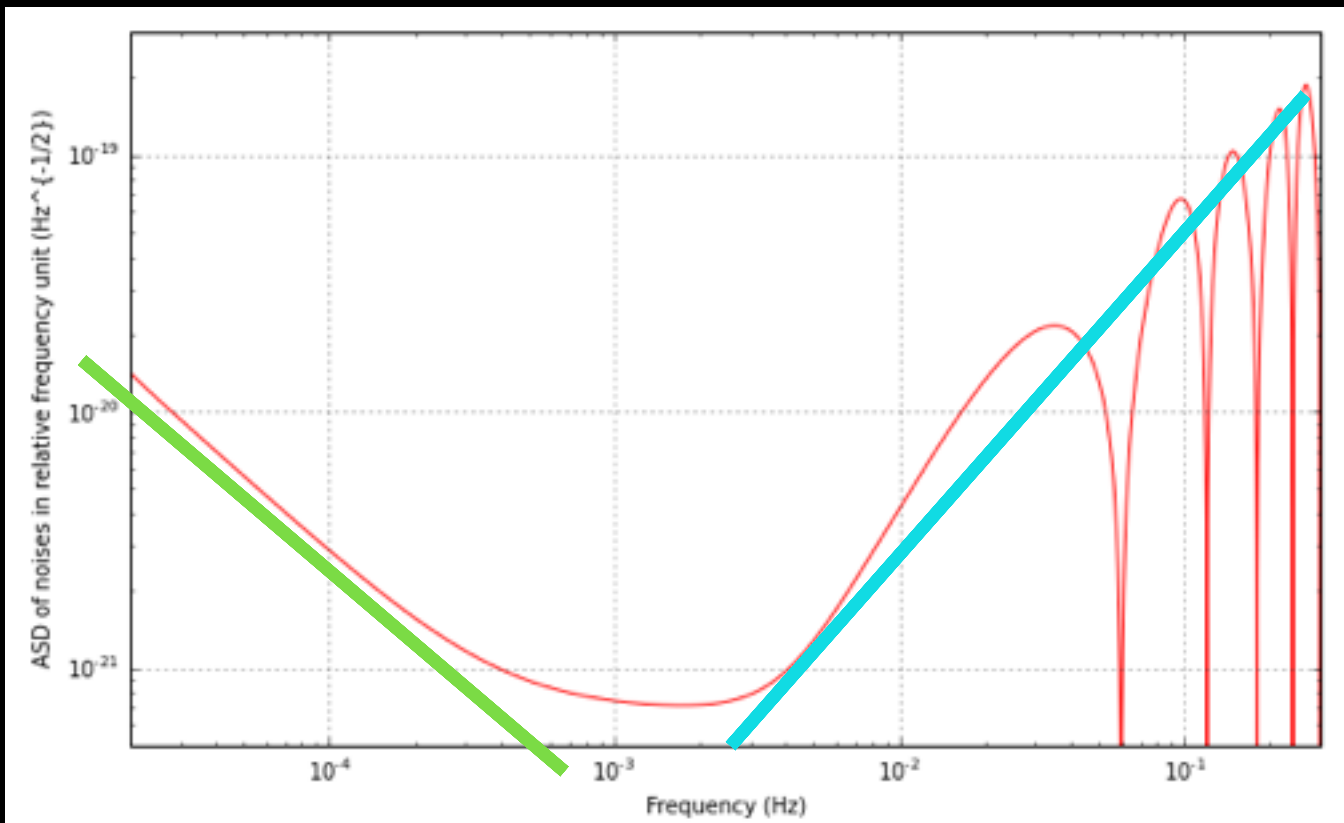
Noises



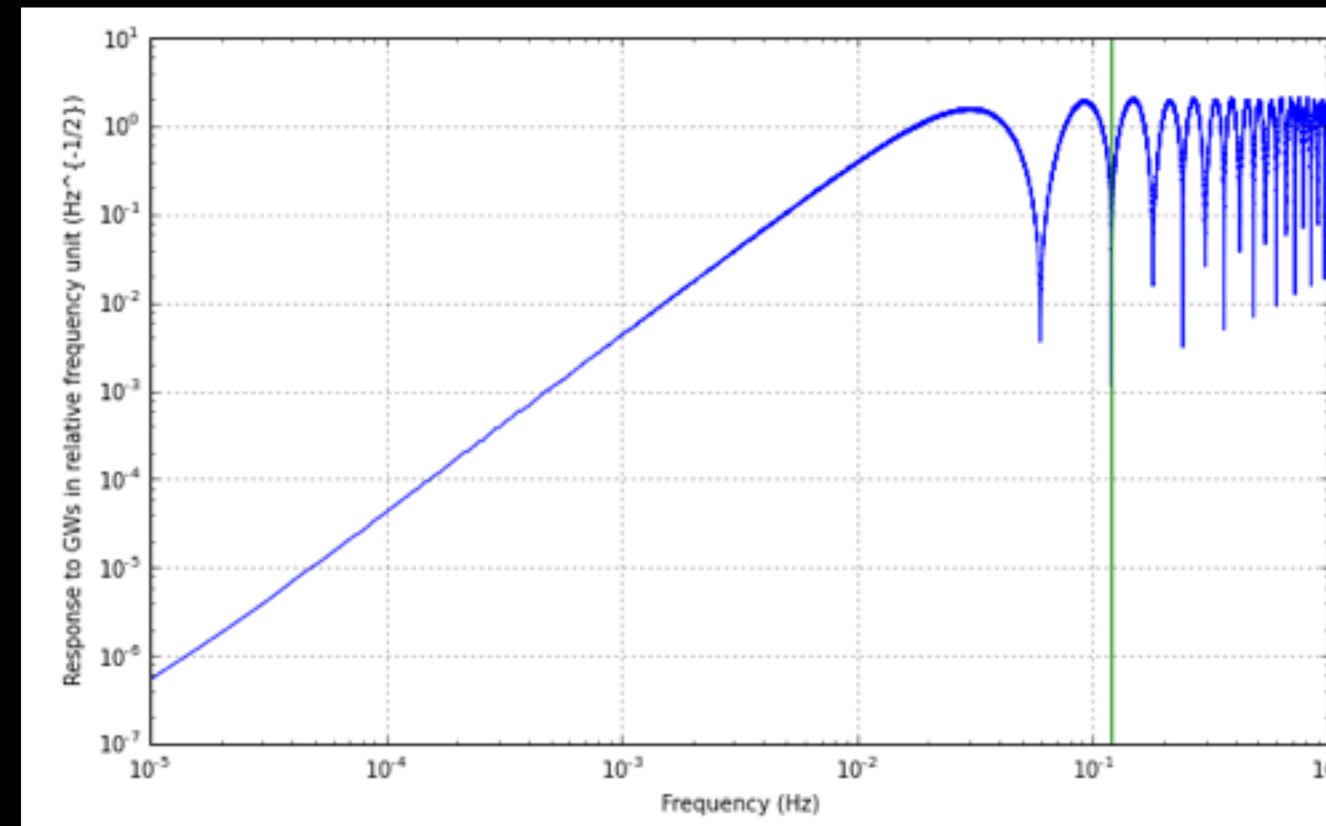


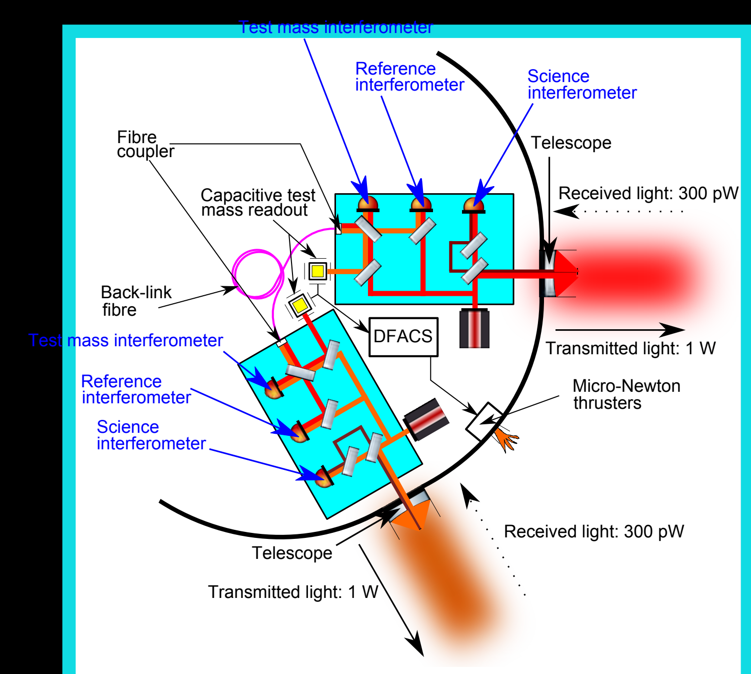
Sensitivity

Noises



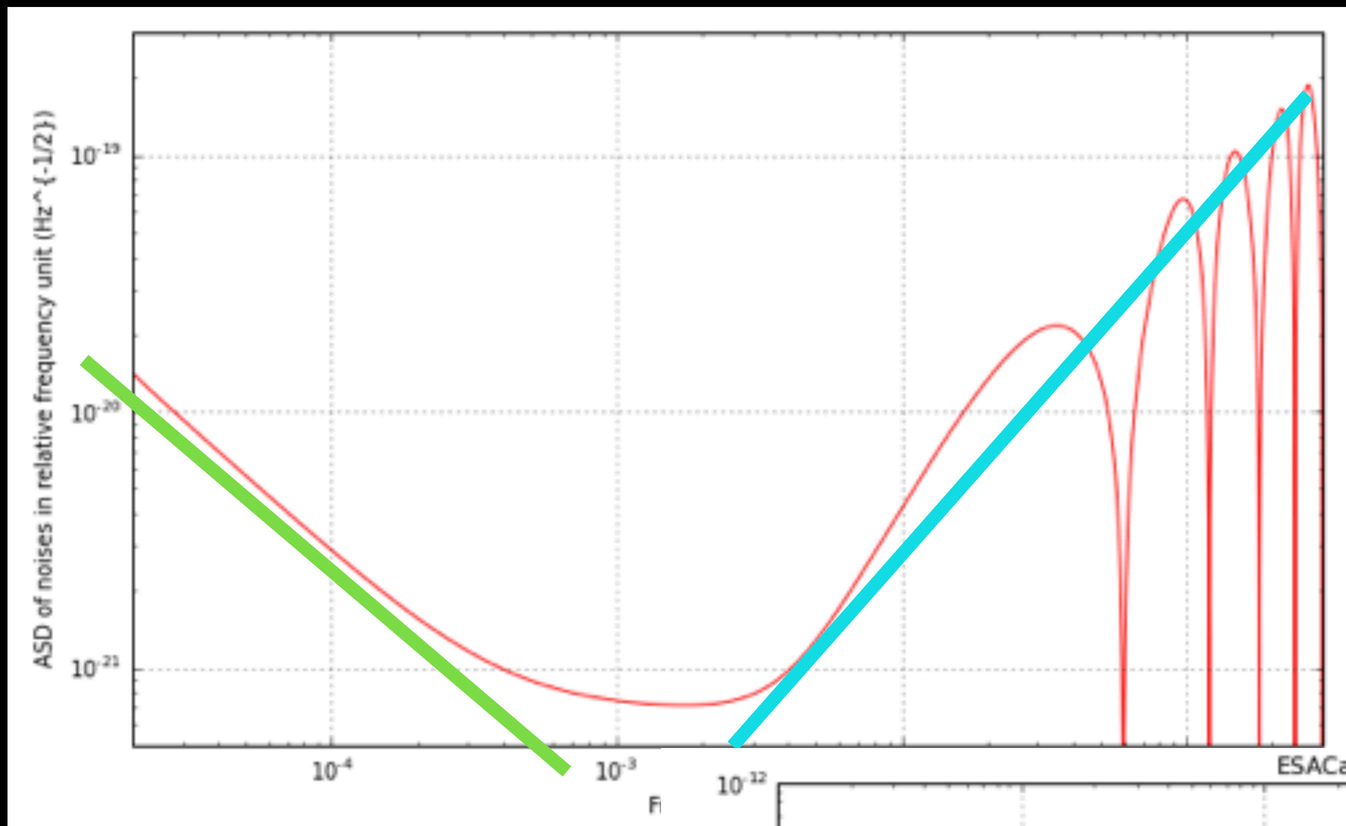
Response of the detector to GWs



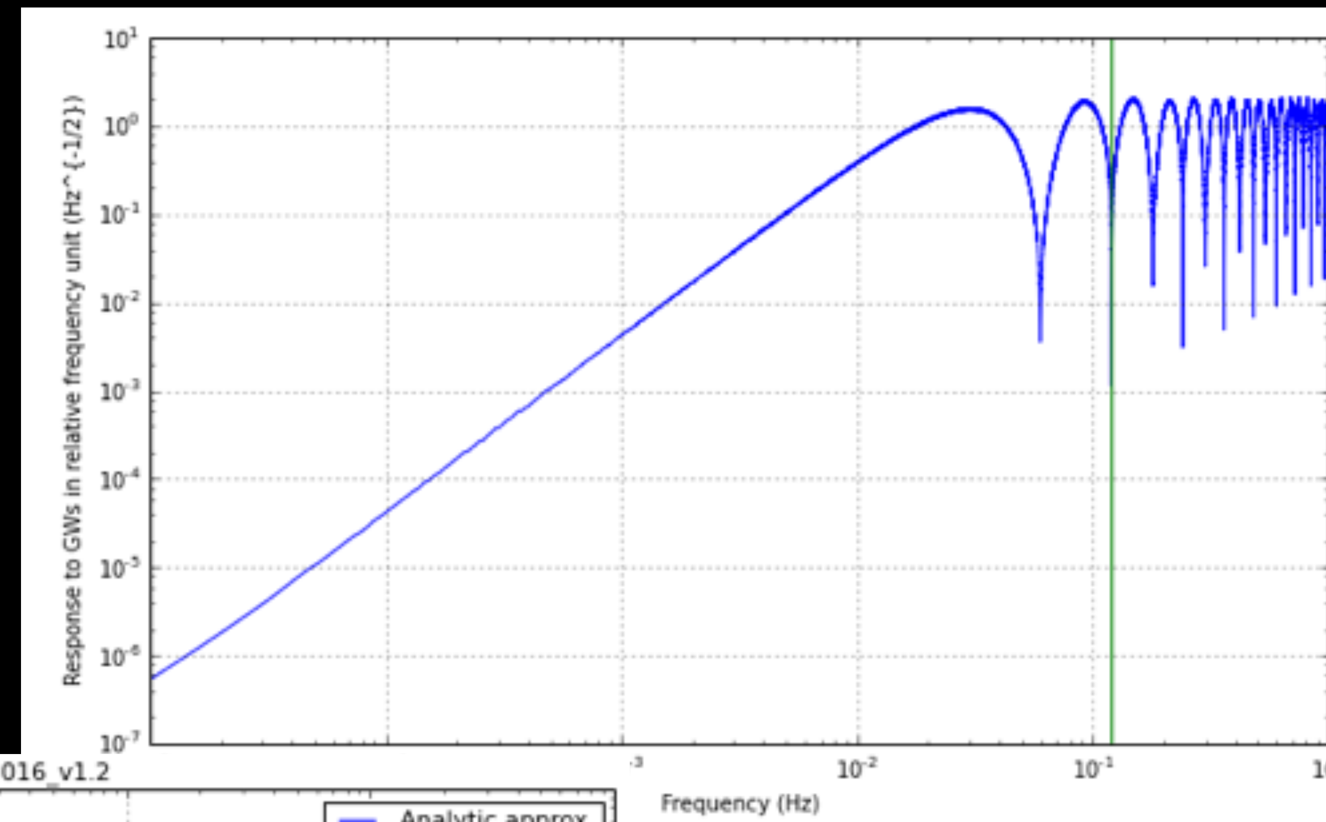


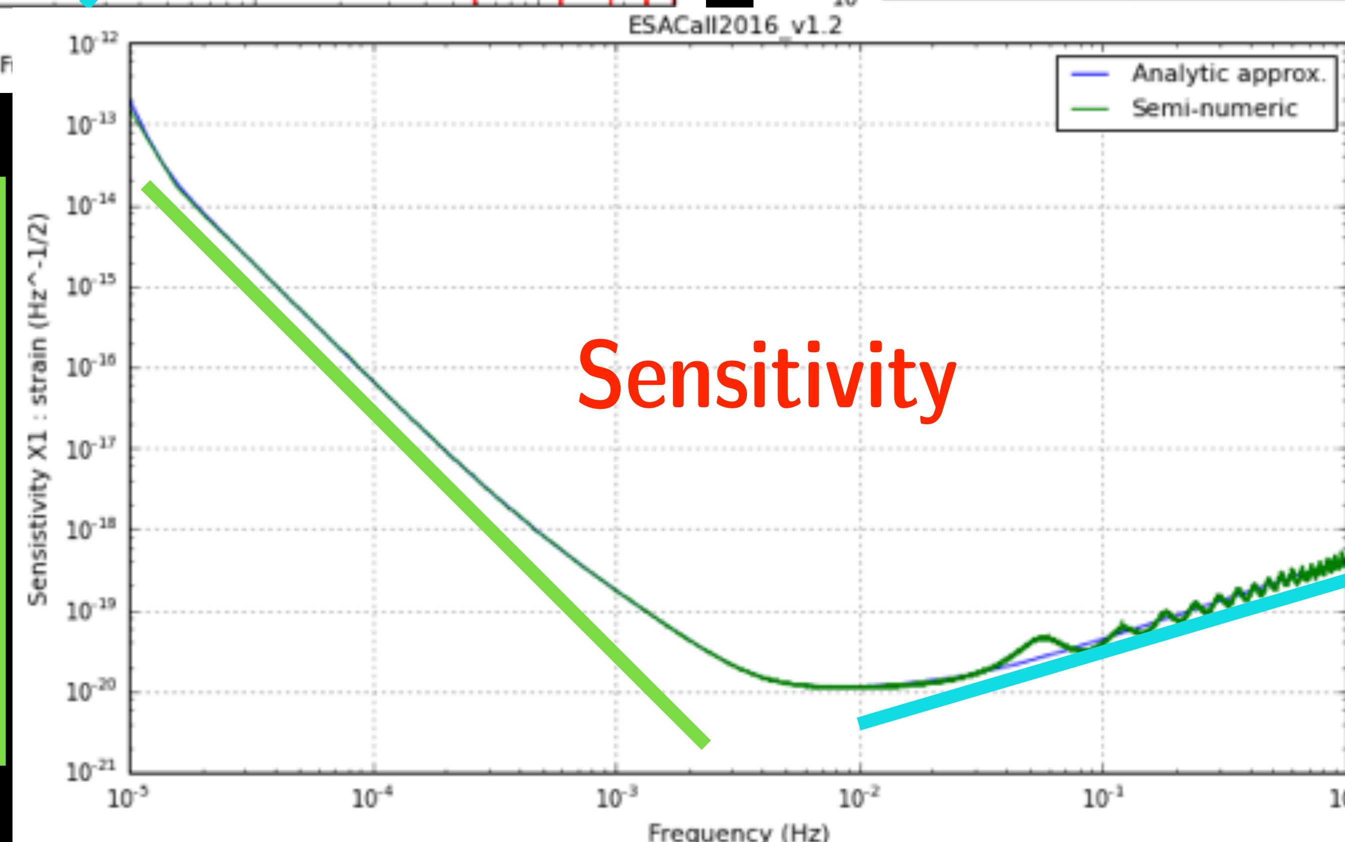
Sensitivity

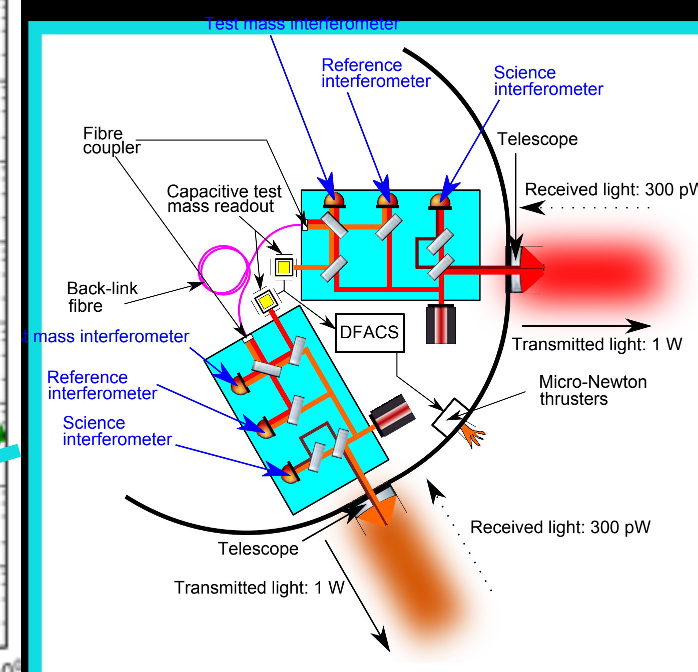
Noises



Response of the detector to GWs







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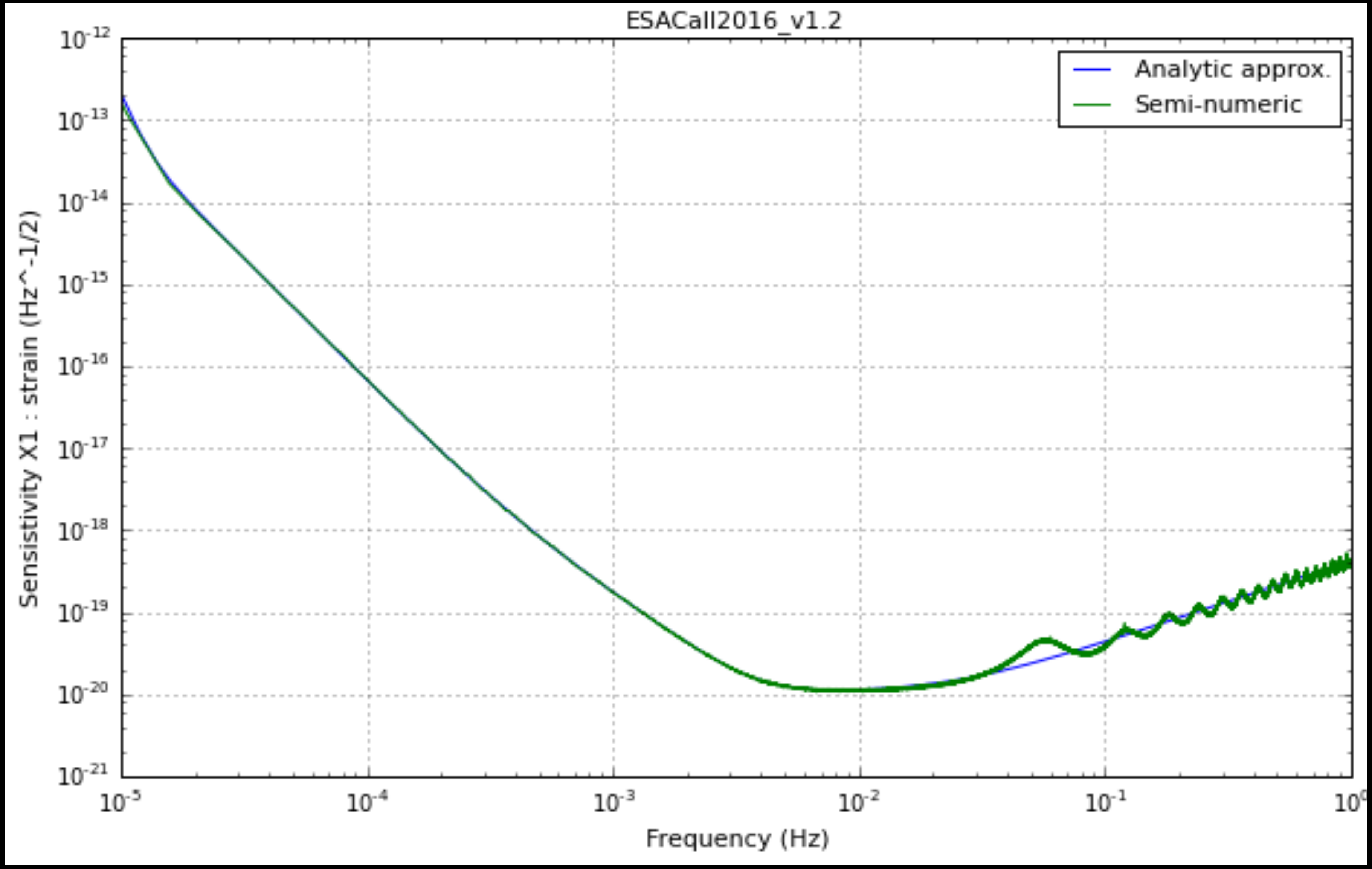
Sensitivity

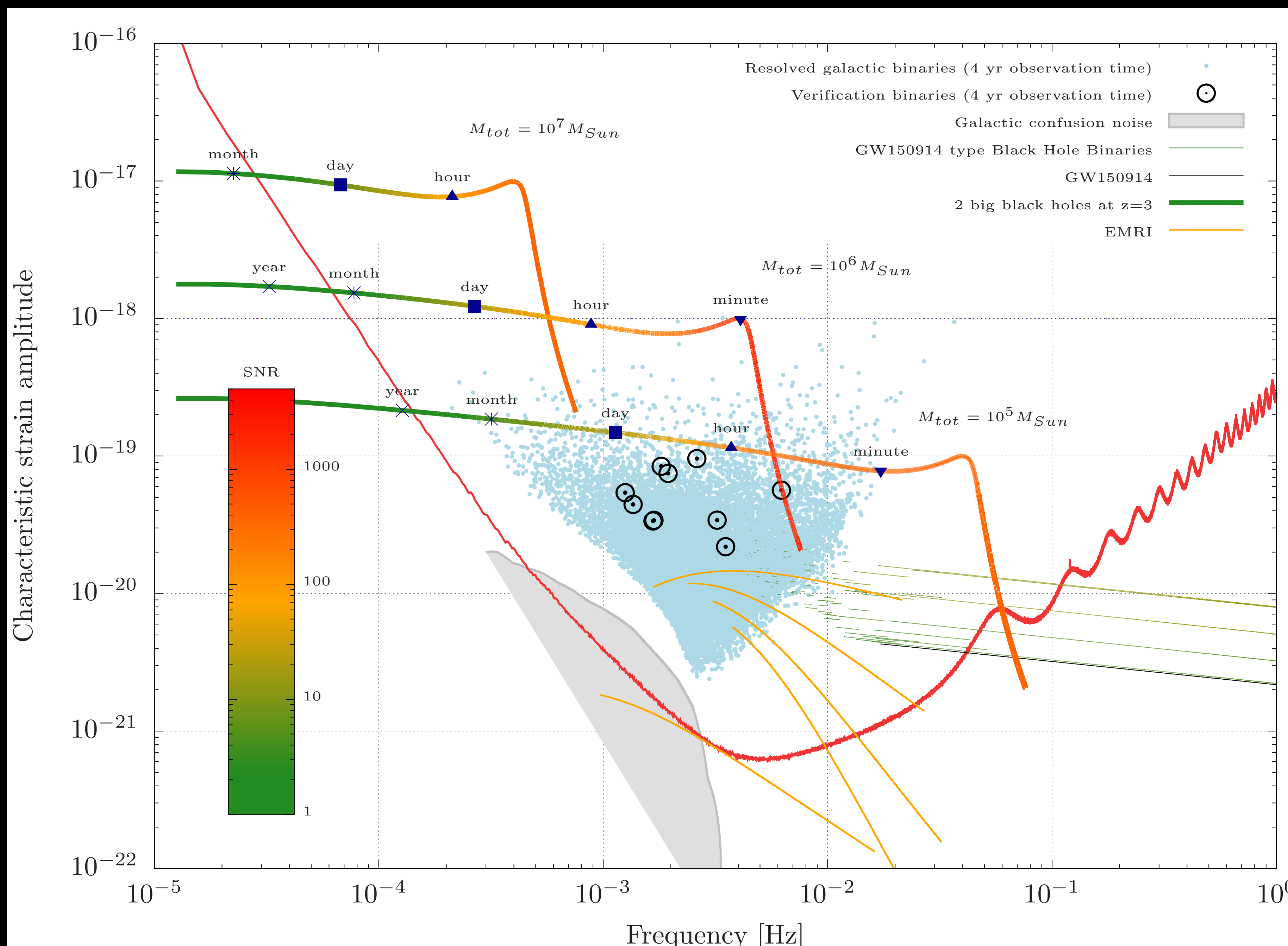
- **Analytic approximation**

$$\sqrt{S^X}(f) = \sqrt{\frac{20}{3}\left(1 + \left(\frac{f}{0.41\left(\frac{c}{2L}\right)}\right)^2\right)\frac{4S_{acc,m} + S_{IMS,m}}{L^2}}$$



Characteristic strain

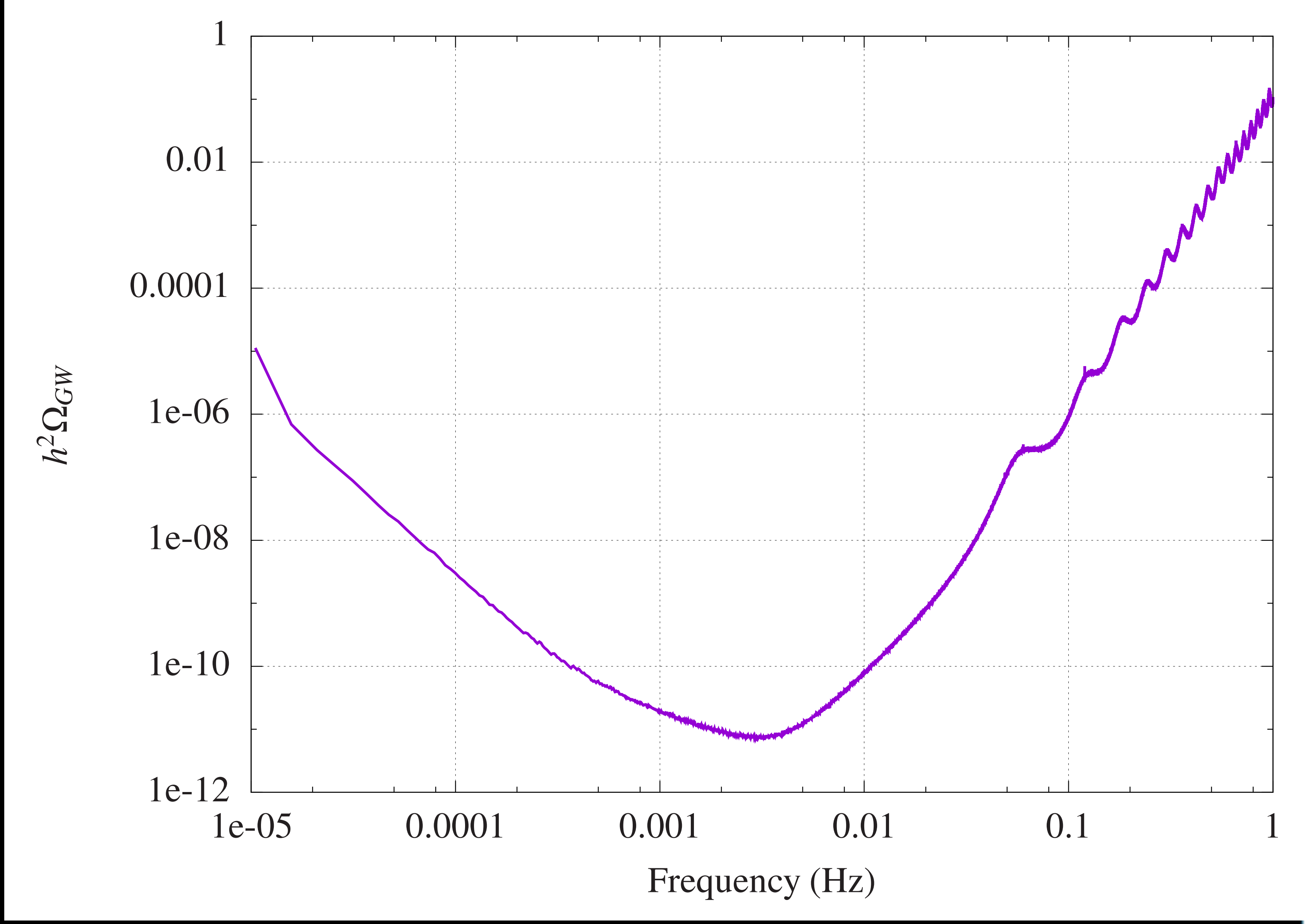
- Charceristic strain sensitivity: $S_h(f) = \sqrt{f\ S(f)}$
- Useful to compare directly with sources



Energy density sensitivity

$$h^2\Omega_{GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 S(f)$$

with $H_0 = h\ h_0$ with $h_0 = 100\ \mathrm{km.s^{-1}.Mpc^{-1}} = 3.24 \times 10^{-18}\mathrm{Hz}$.



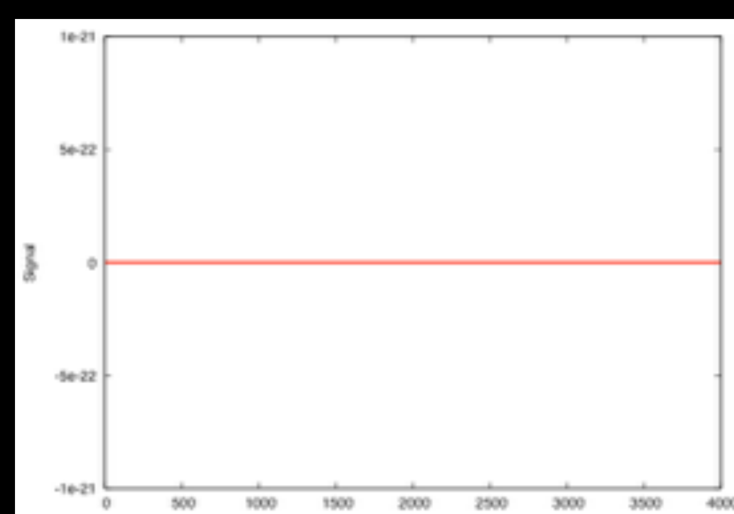
Orbital motion and finite arm

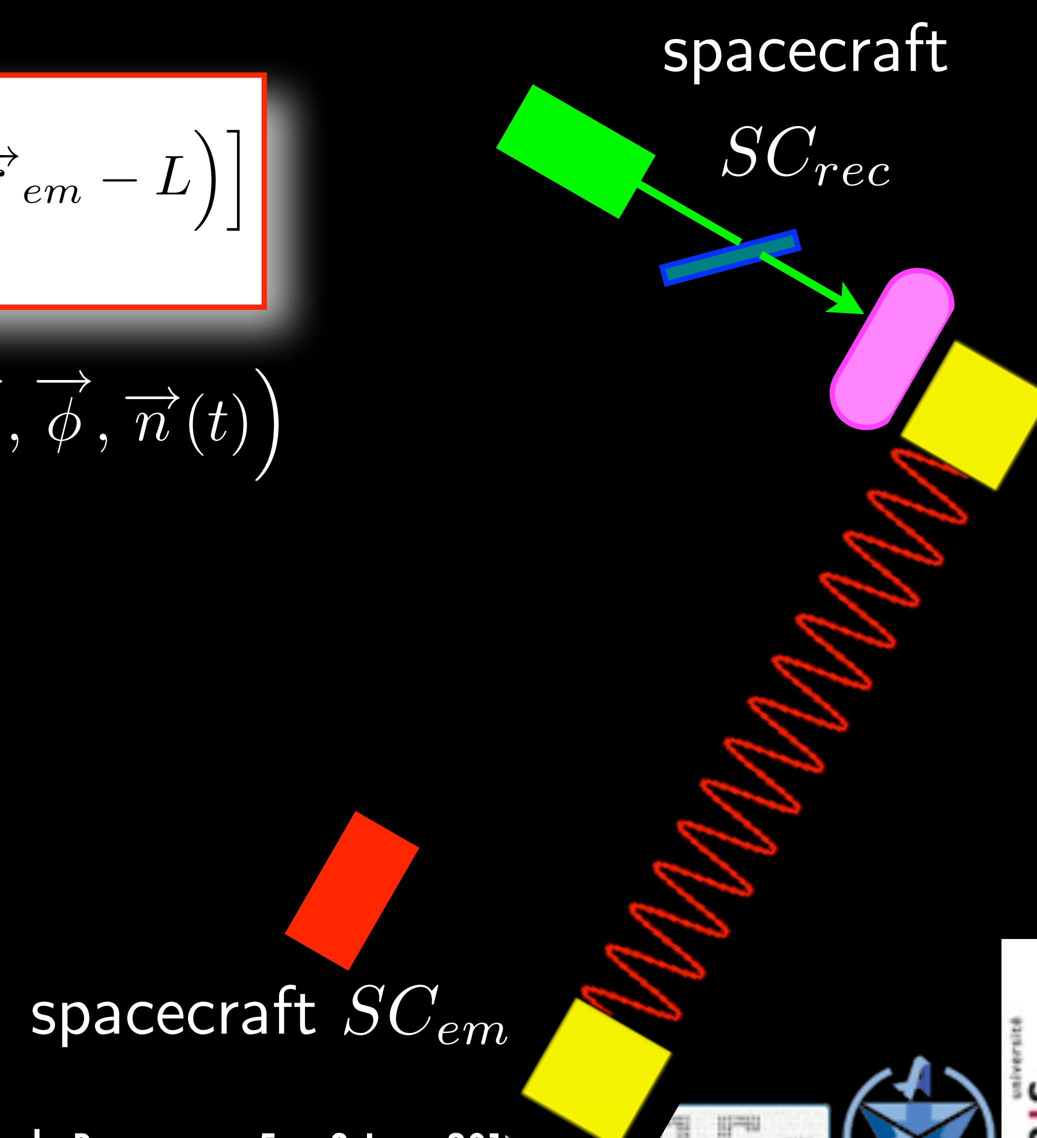
LISA : GWs detection

- Between spacecraft at r_{em} and spacecraft at r_{rec} (arm unit vector n) :
  - GW change phase of received beam
  - This phase is measured by a phasemeter
- Measurement : relative laser frequency shift :

$$\boxed{\frac{\delta\nu}{\nu_{laser}}(t) = \frac{1}{2\left(1 - \vec{k}\,.\,\vec{n}\right)}\left[H\left(t - \vec{k}\,.\,\vec{r}_{rec}\right) - H\left(t - \vec{k}\,.\,\vec{r}_{em} - L\right)\right]}$$

with $H(t) = h_{B+}(t)\,\xi_+\left(\vec{\theta}, \vec{\phi}, \vec{n}(t)\right) + h_{B\times}(t)\,\xi_\times\left(\vec{\theta}, \vec{\phi}, \vec{n}(t)\right)$





LISA : GWs detection

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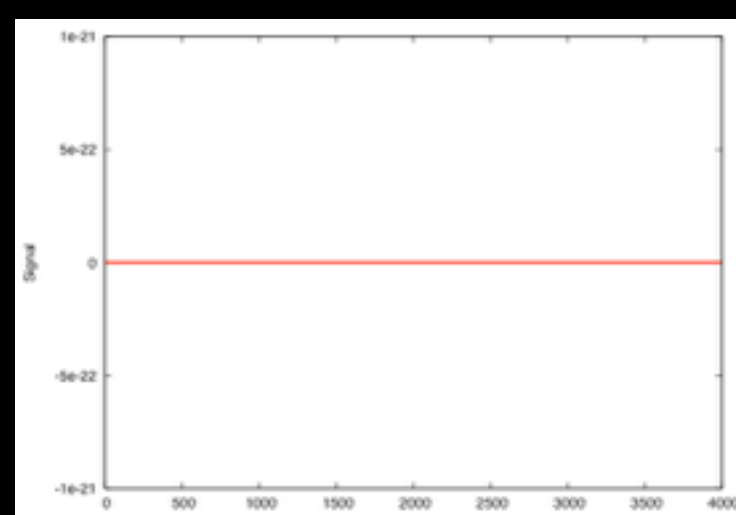
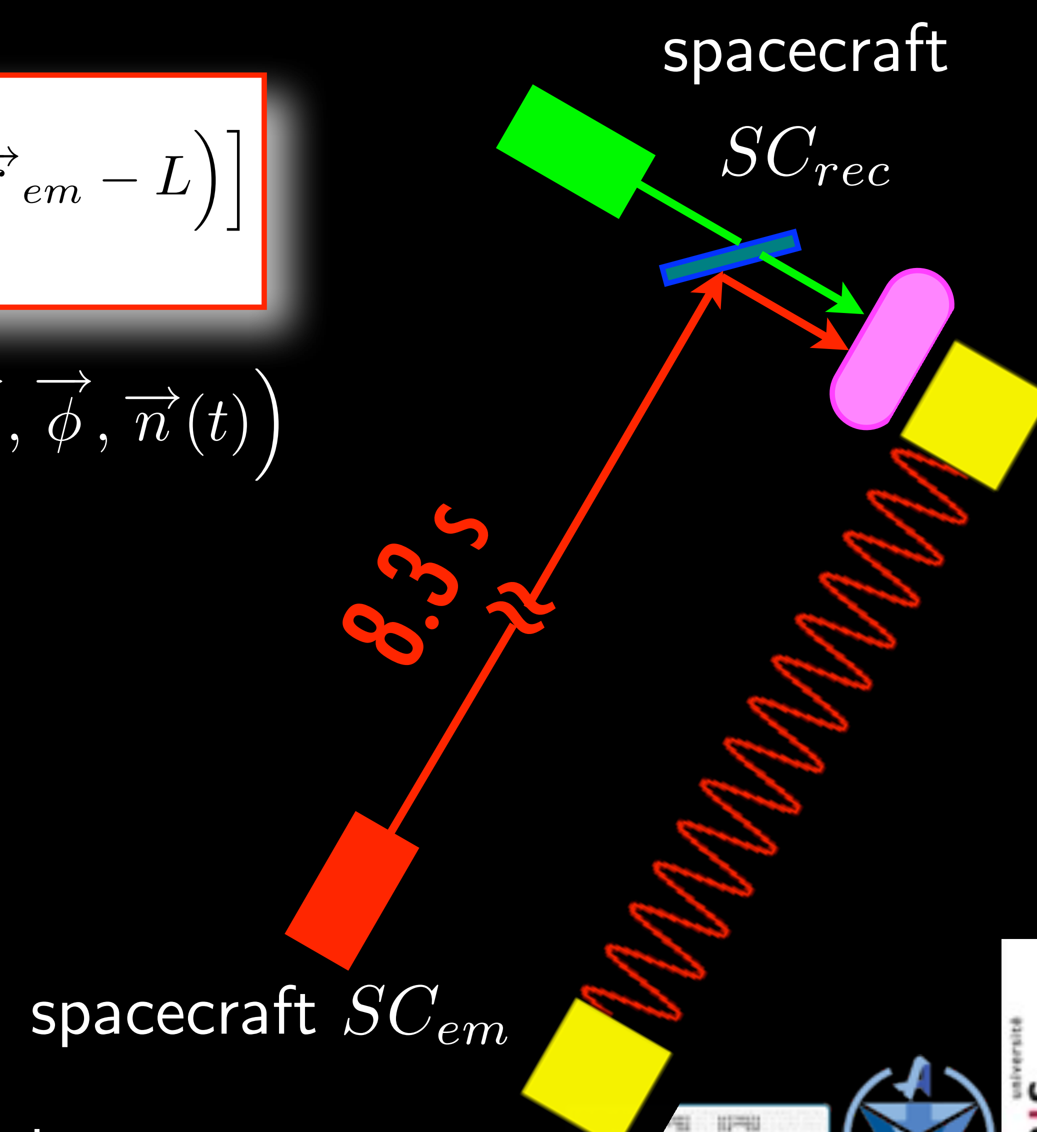
$$\boxed{\frac{\delta\nu}{\nu_{laser}}(t) = \frac{1}{2\left(1-\vec{k}\,.\,\vec{n}\right)}\left[H\left(t-\vec{k}\,.\,\vec{r}_{rec}\right) - H\left(t-\vec{k}\,.\,\vec{r}_{em} - L\right)\right]}$$

with $H(t) = h_{B+}(t)\,\xi_+\left(\vec{\theta},\vec{\phi},\vec{n}(t)\right) + h_{B\times}(t)\,\xi_\times\left(\vec{\theta},\vec{\phi},\vec{n}(t)\right)$





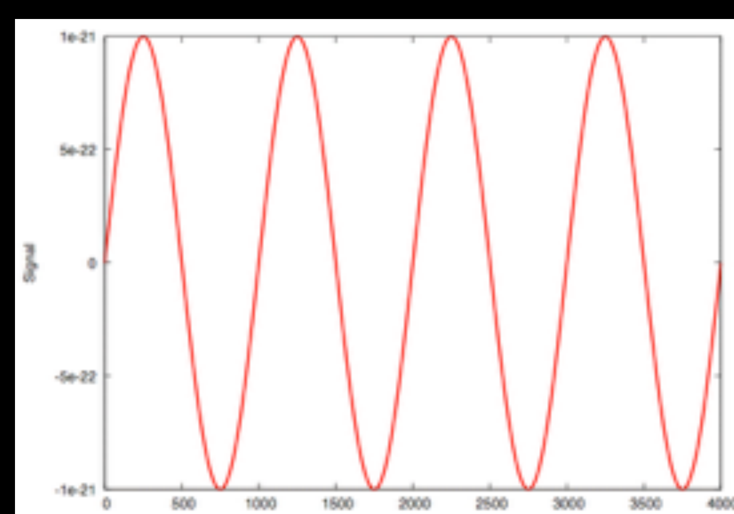
LISA : GWs detection

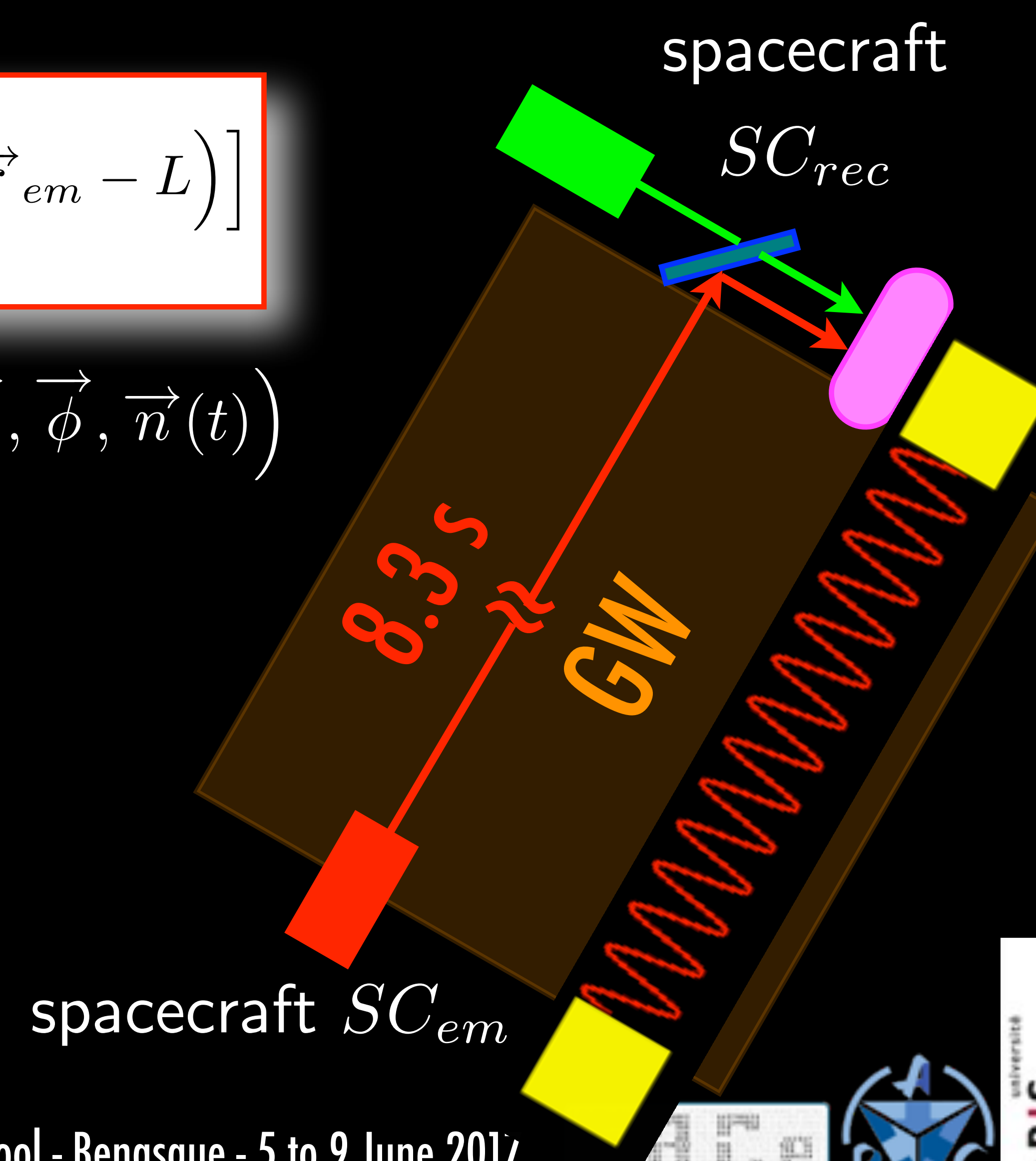
- Between spacecraft at r_{em} and spacecraft at r_{rec} (arm unit vector n) :
  - GW change phase of received beam
  - This phase is measured by a phasemeter

- Measurement : relative laser frequency shift :

$$\boxed{\frac{\delta\nu}{\nu_{laser}}(t) = \frac{1}{2\left(1-\vec{k}\,.\,\vec{n}\right)}\left[H\left(t-\vec{k}\,.\,\vec{r}_{rec}\right) - H\left(t-\vec{k}\,.\,\vec{r}_{em} - L\right)\right]}$$

with $H(t) = h_{B+}(t)\,\xi_{+}\left(\vec{\theta},\vec{\phi},\vec{n}(t)\right) + h_{B\times}(t)\,\xi_{\times}\left(\vec{\theta},\vec{\phi},\vec{n}(t)\right)$





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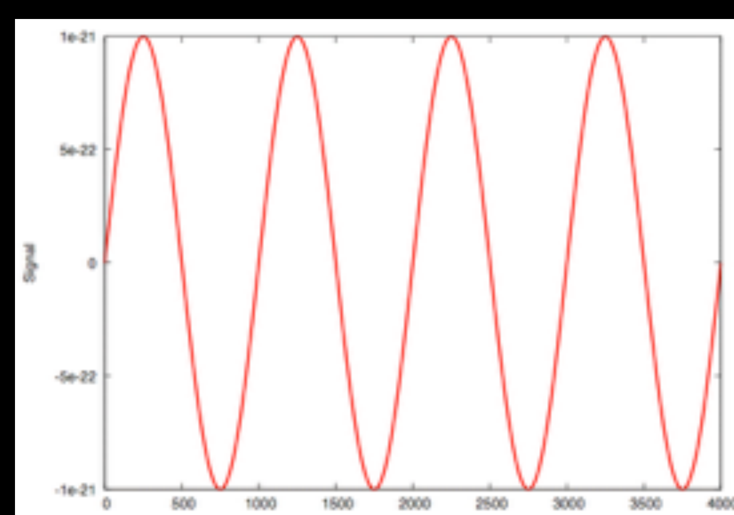
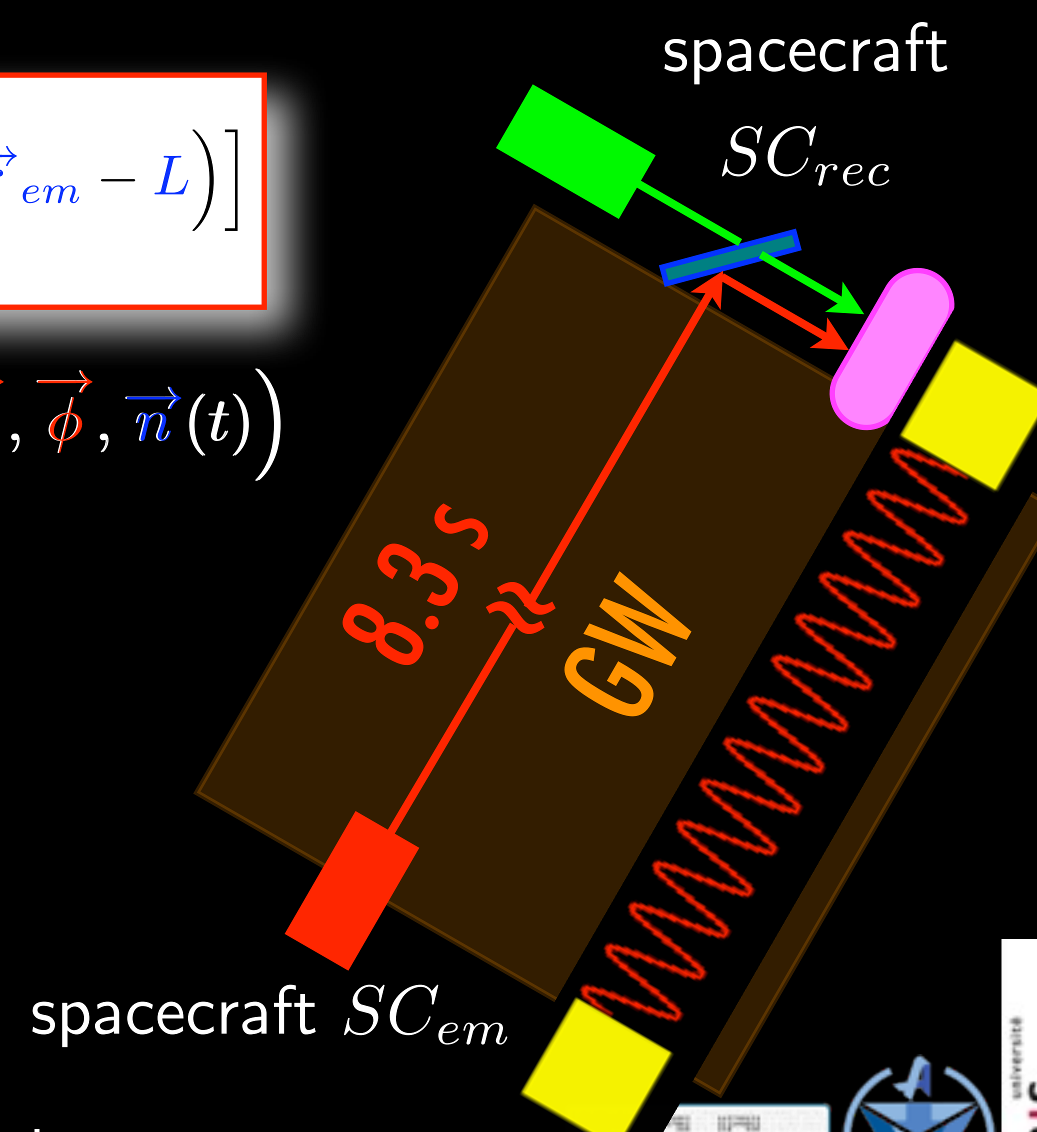
Dependency :
- amplitude of source
- position of source
- position of arm



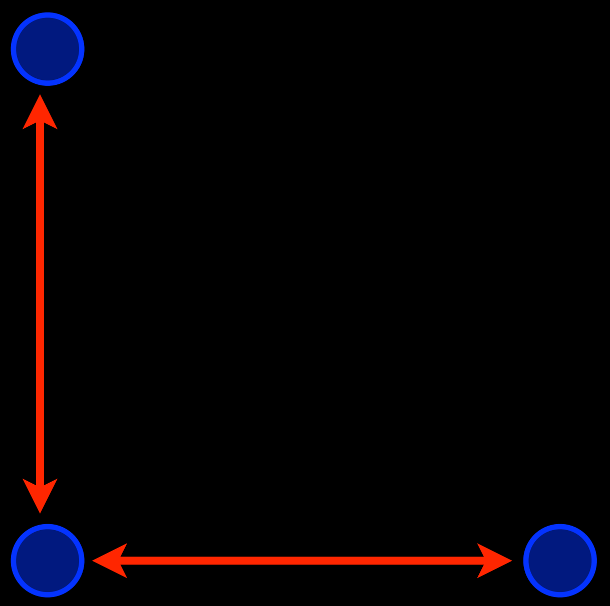


LISA

- 3 spacecraft and 6 links (2 for each arm)

  $\Longrightarrow$ 3 interferometers (one redundancy)

- Armlength = 2.5×10^9 m to detect GWs at 10^{-5} - 1 Hz



- 3 heliocentric orbits : spacecraft in free fall.
  - LISA centre follows the Earth (-20°).
  - 60° between LISA plane & ecliptic plane.
  - Variation of LISA during the year

  $\Longrightarrow$ Directional information of GWs.

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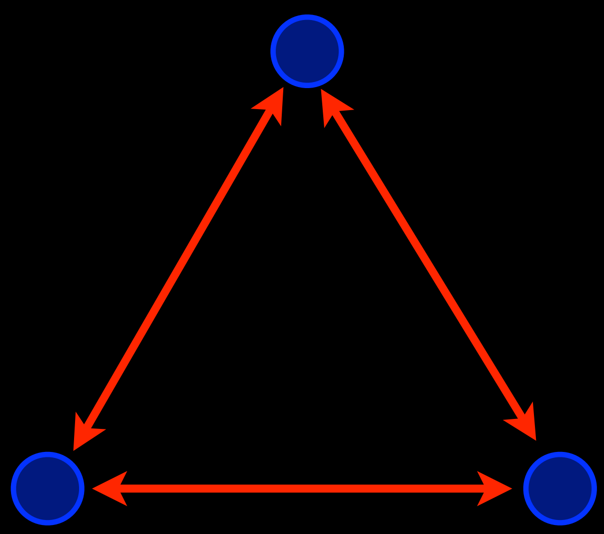

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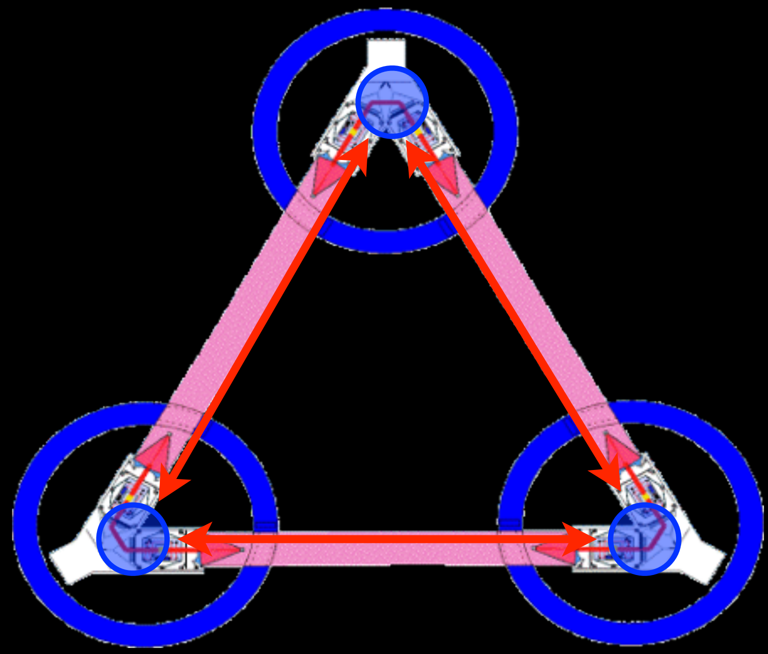

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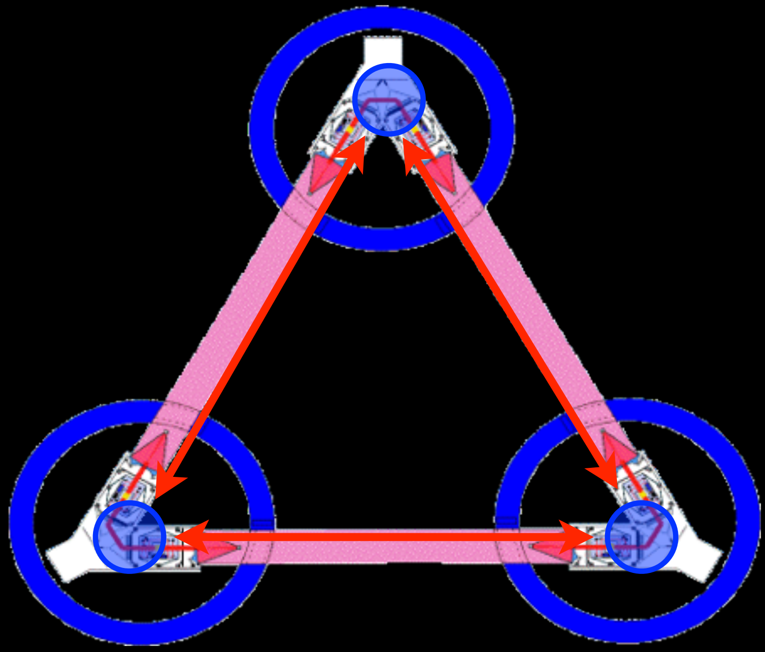

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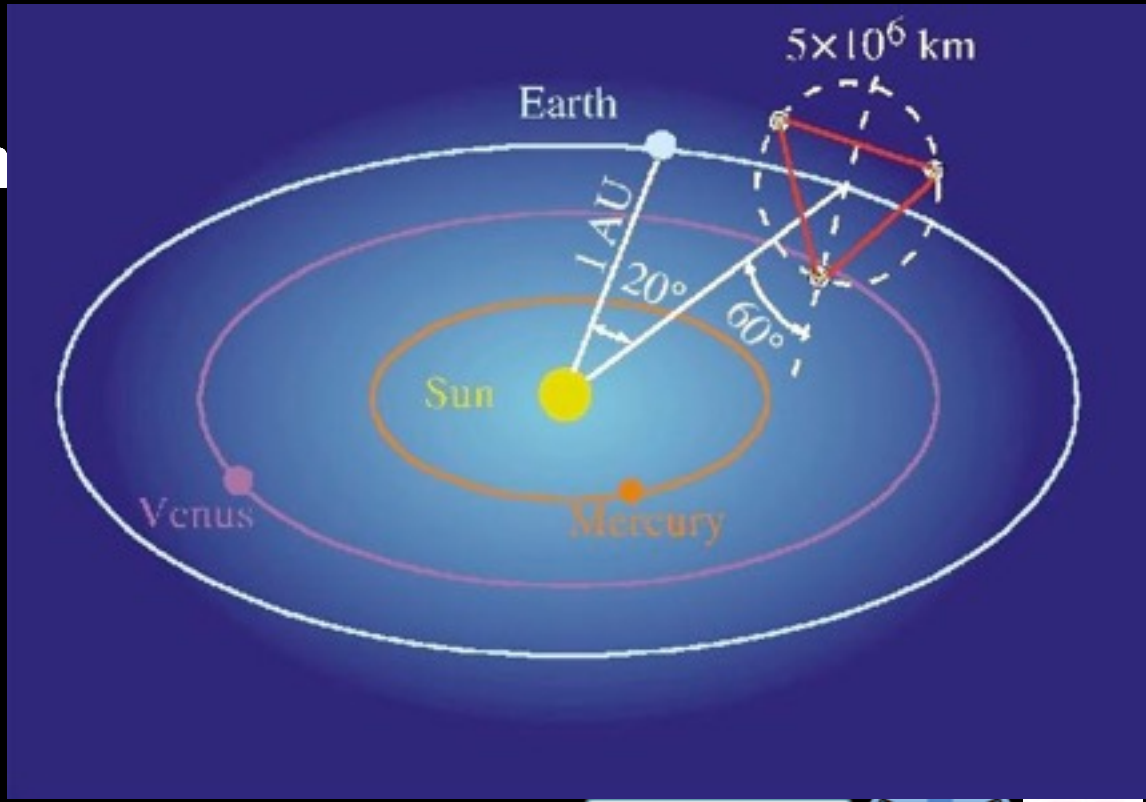

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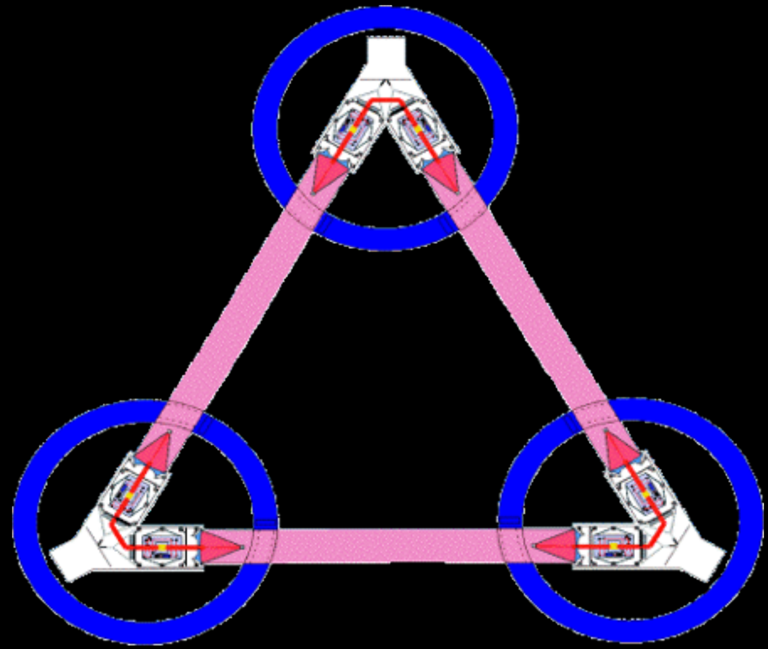
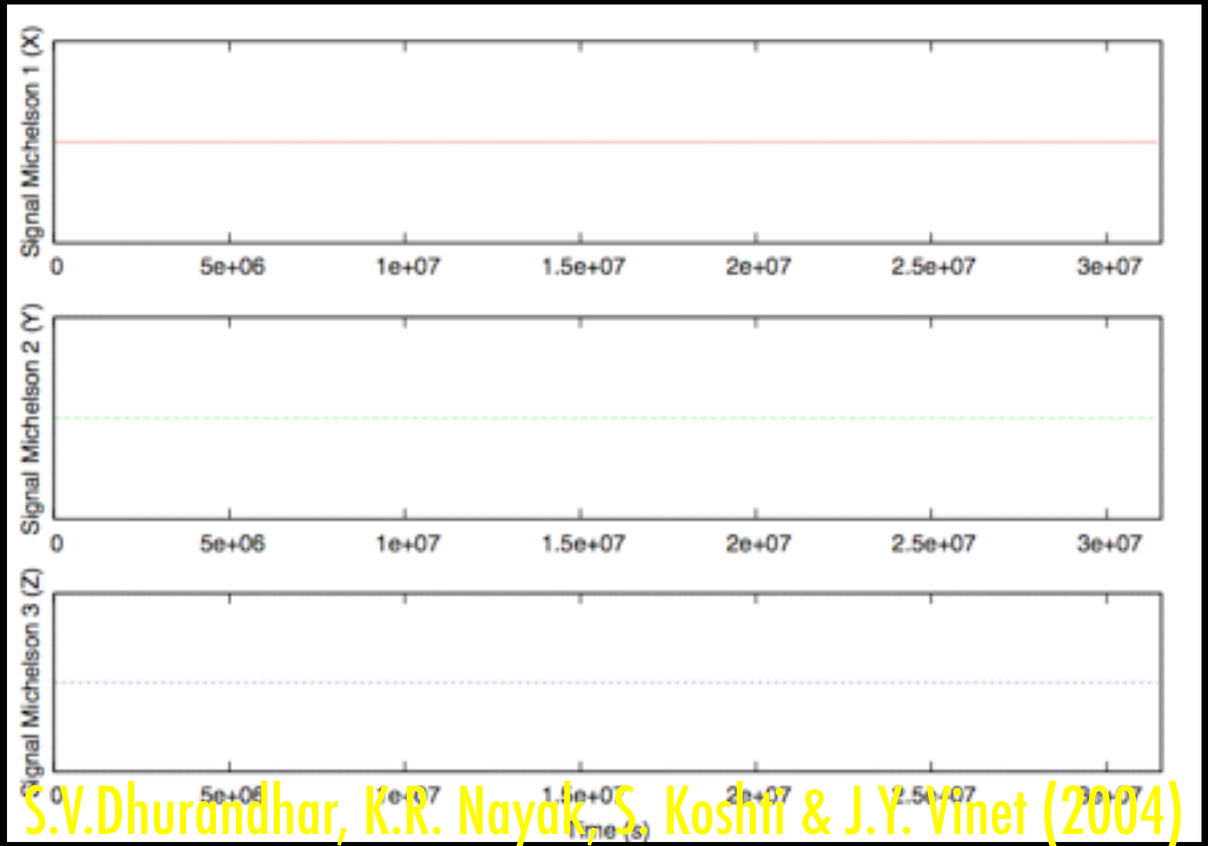
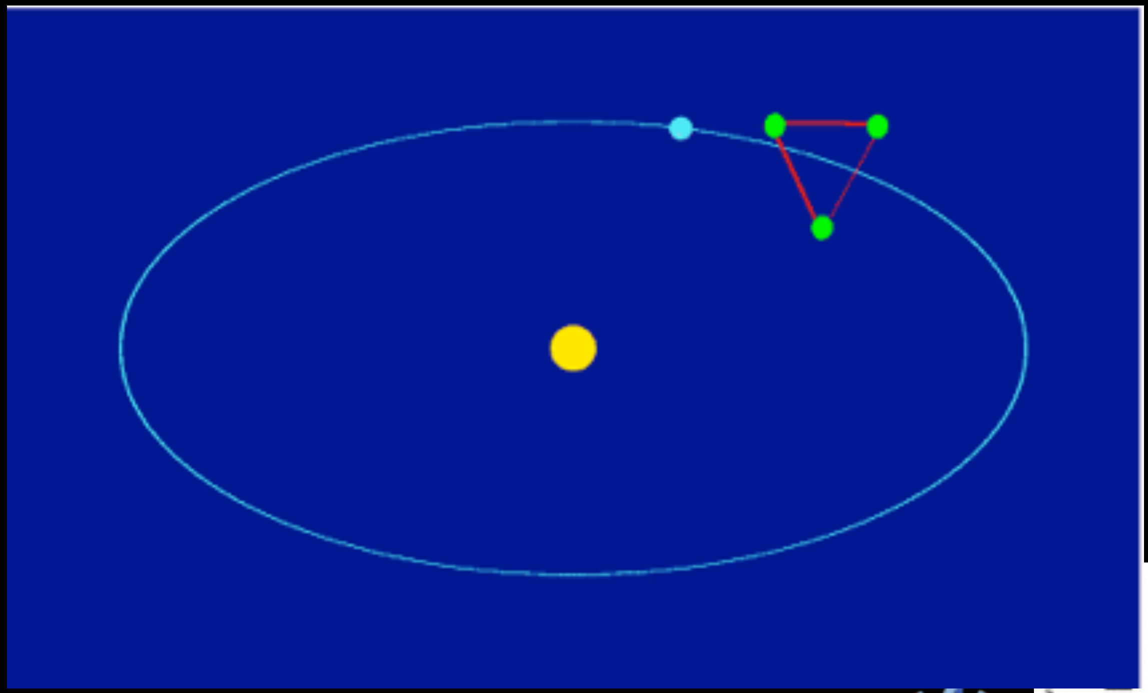




S.V.Dhurandhar, K.R. Nayak, S. Koshti & J.Y. Vinet (2004)



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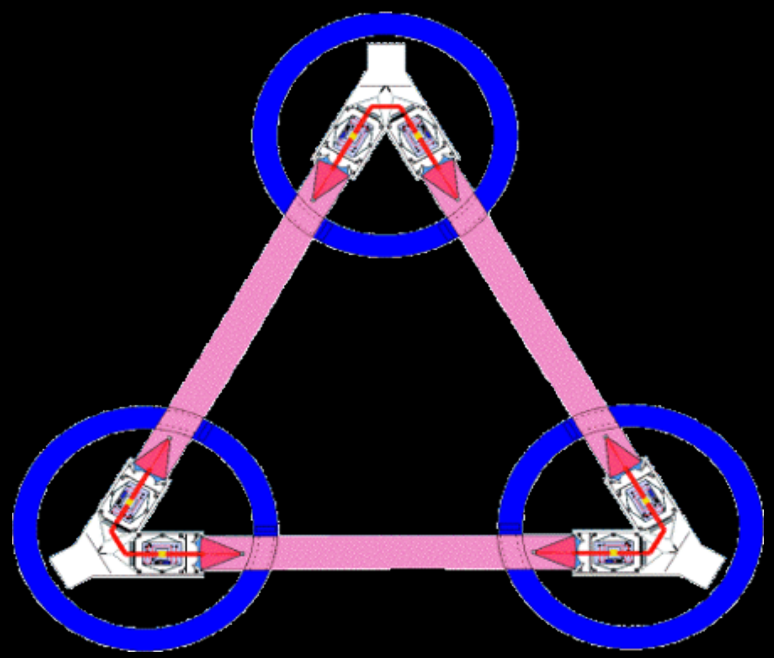

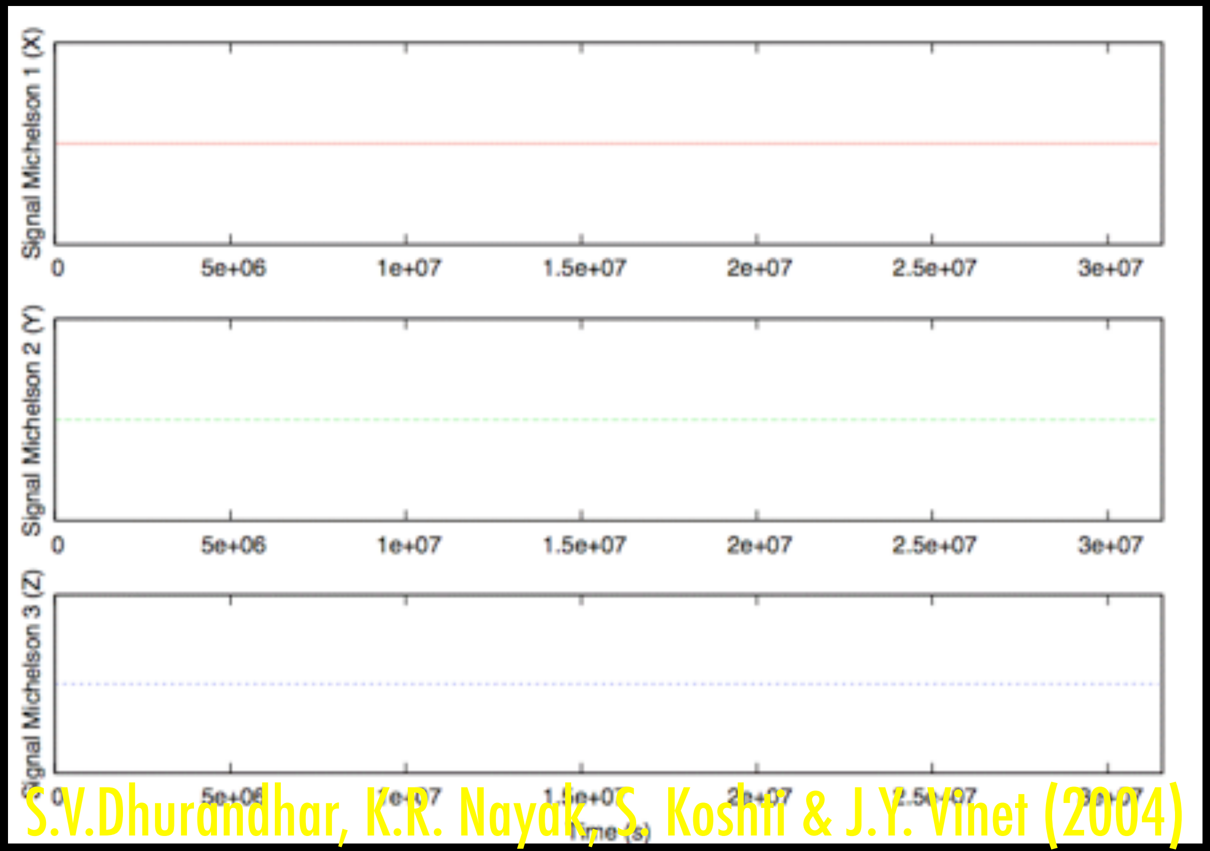

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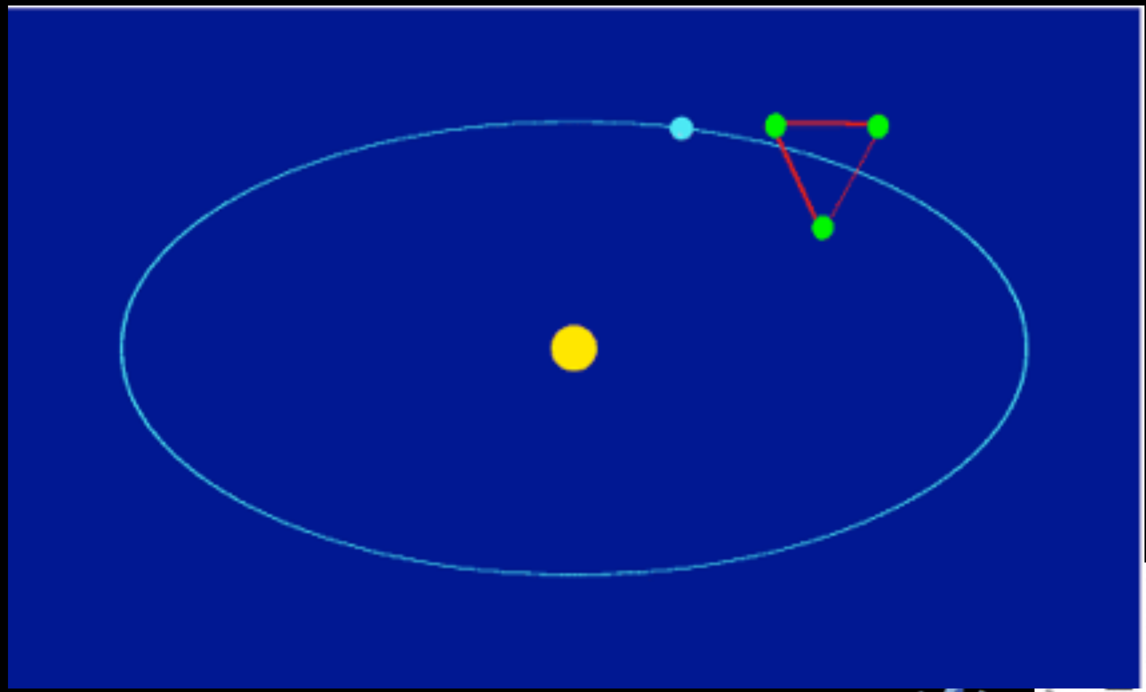

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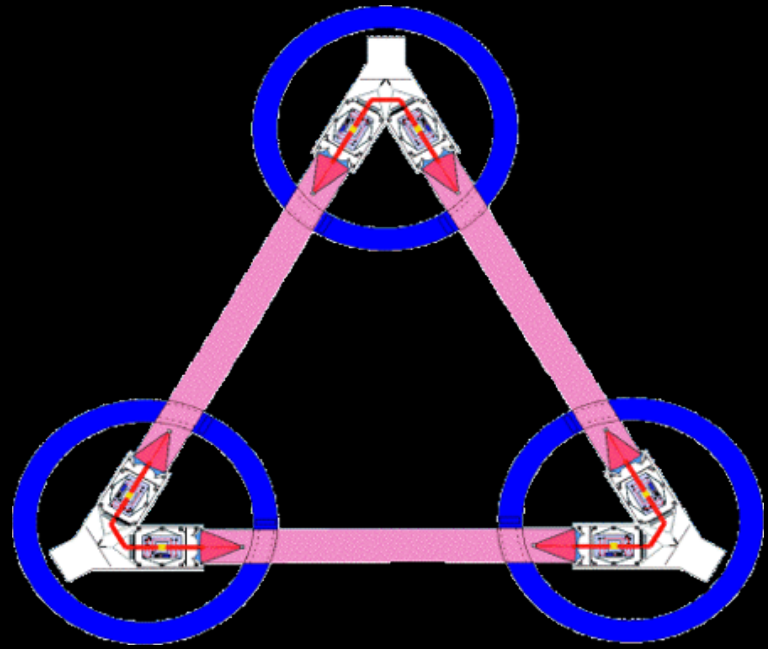
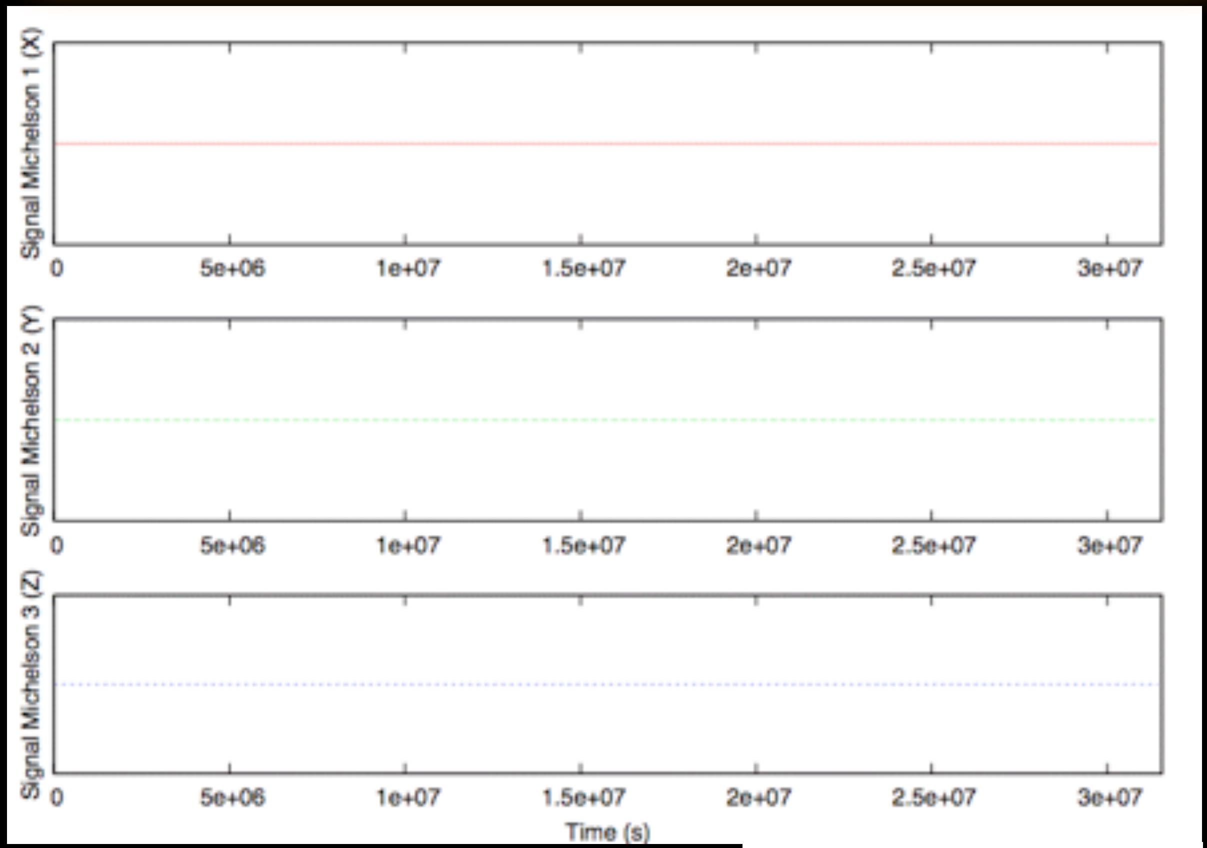
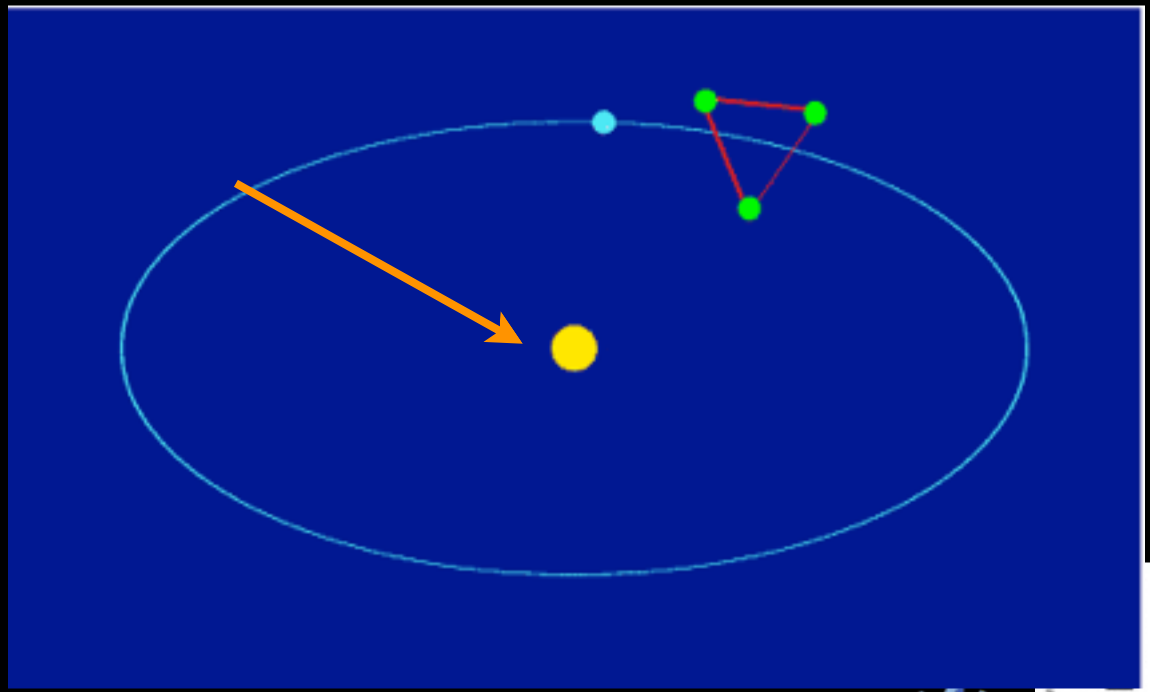


Modulation of wave amplitude



computed by LISACode



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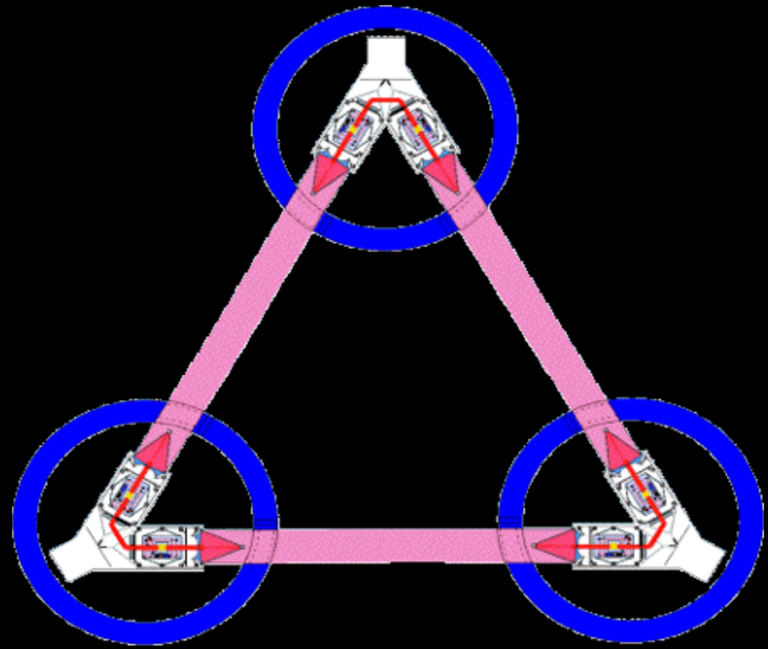

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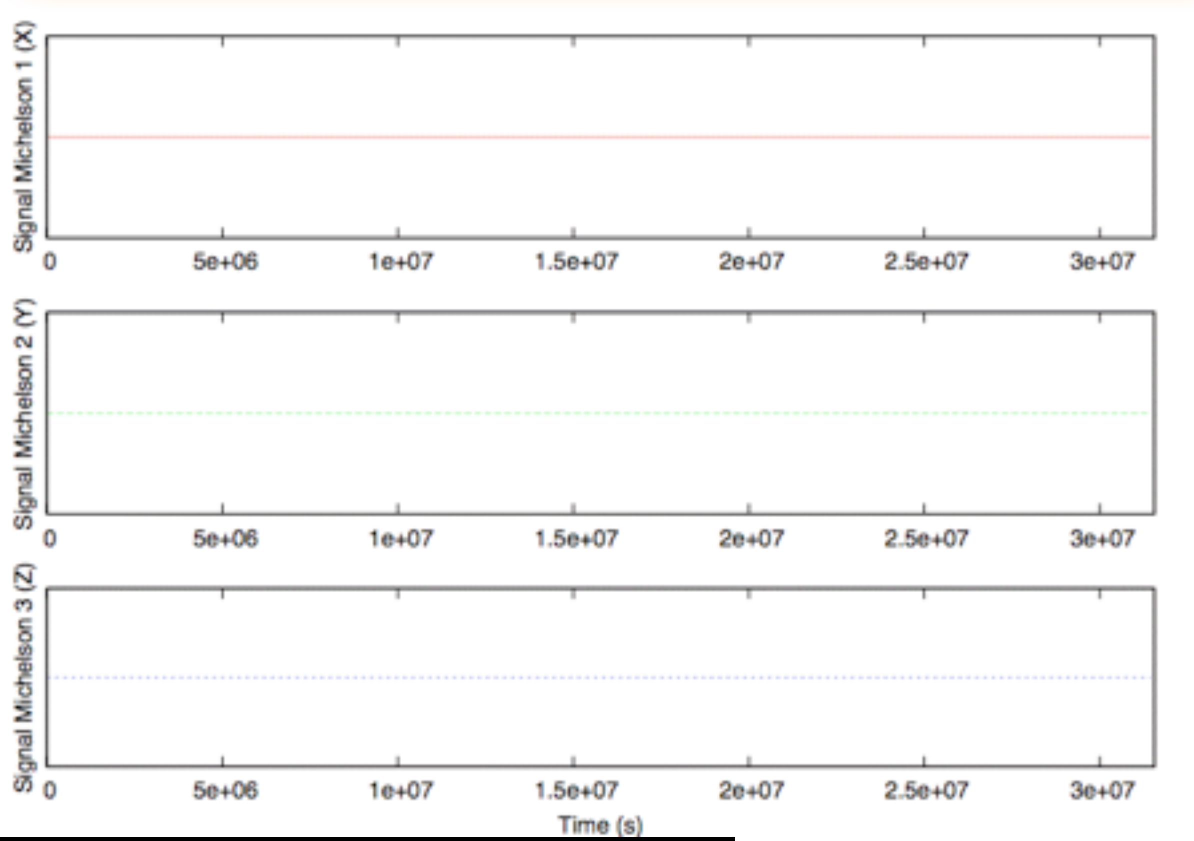

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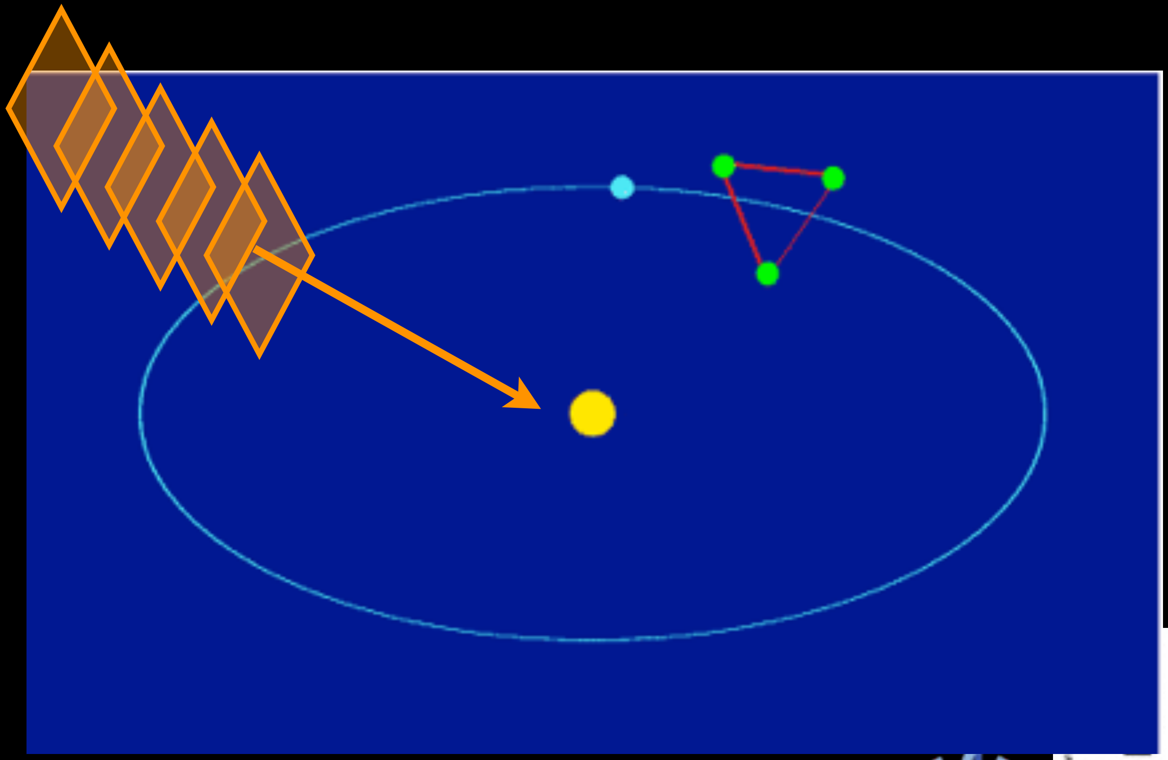

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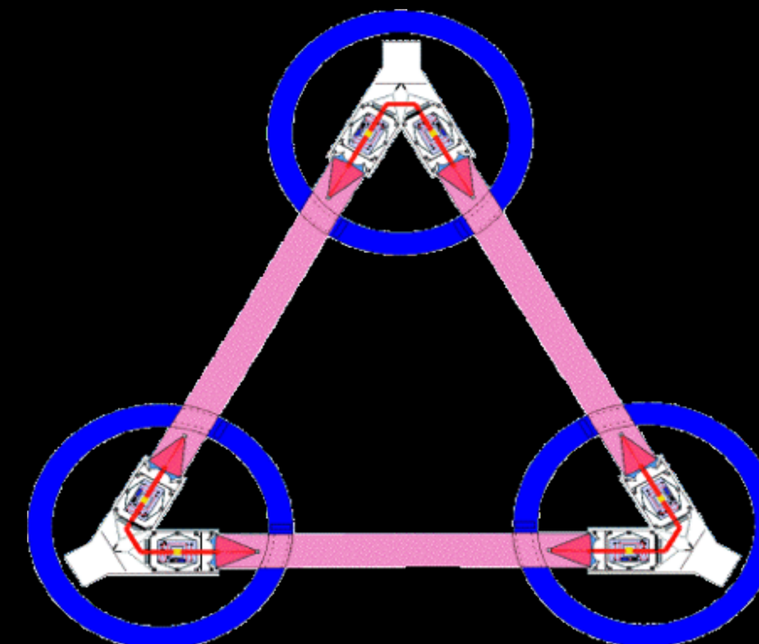

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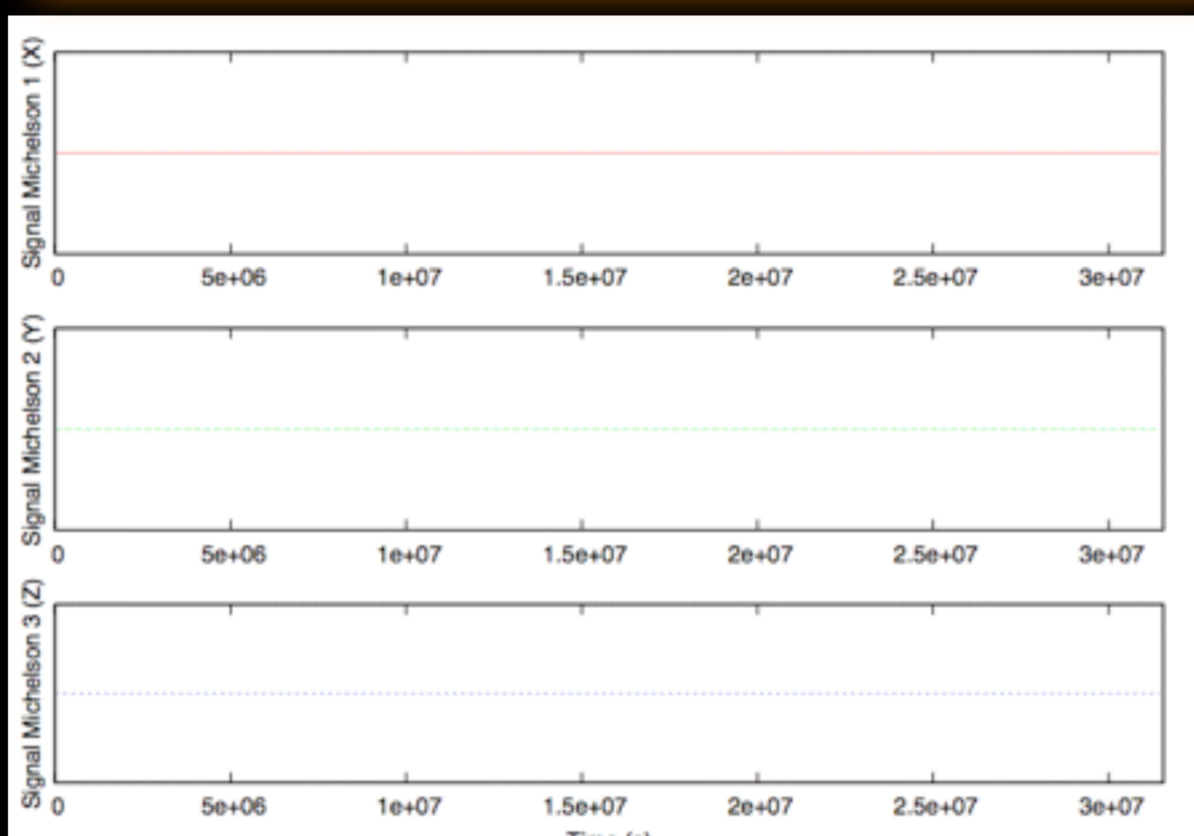

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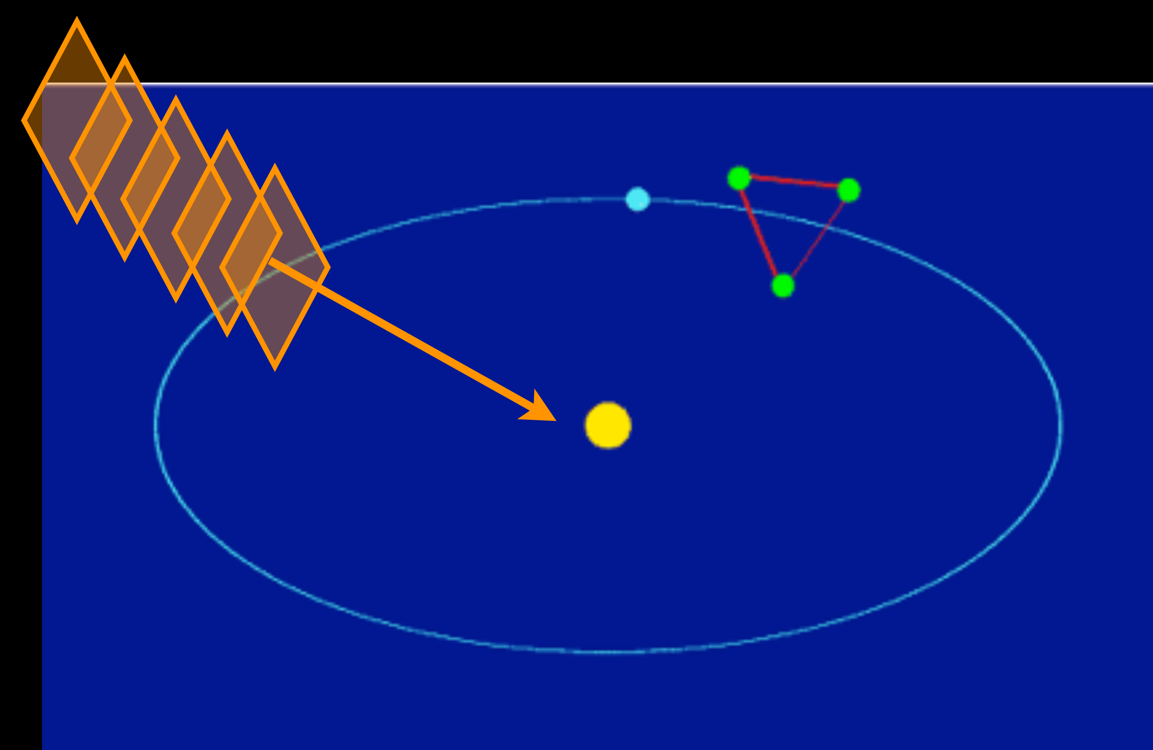
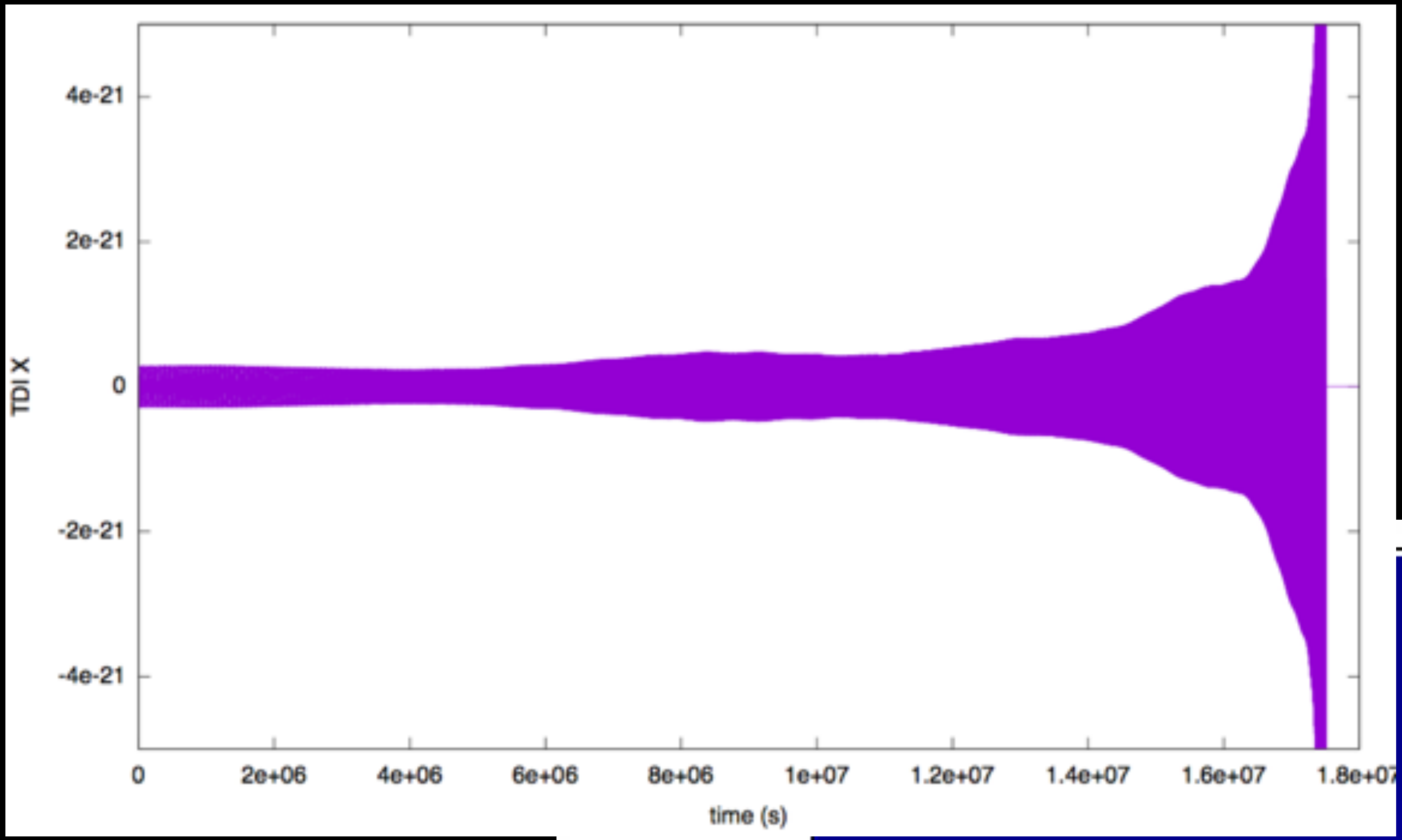
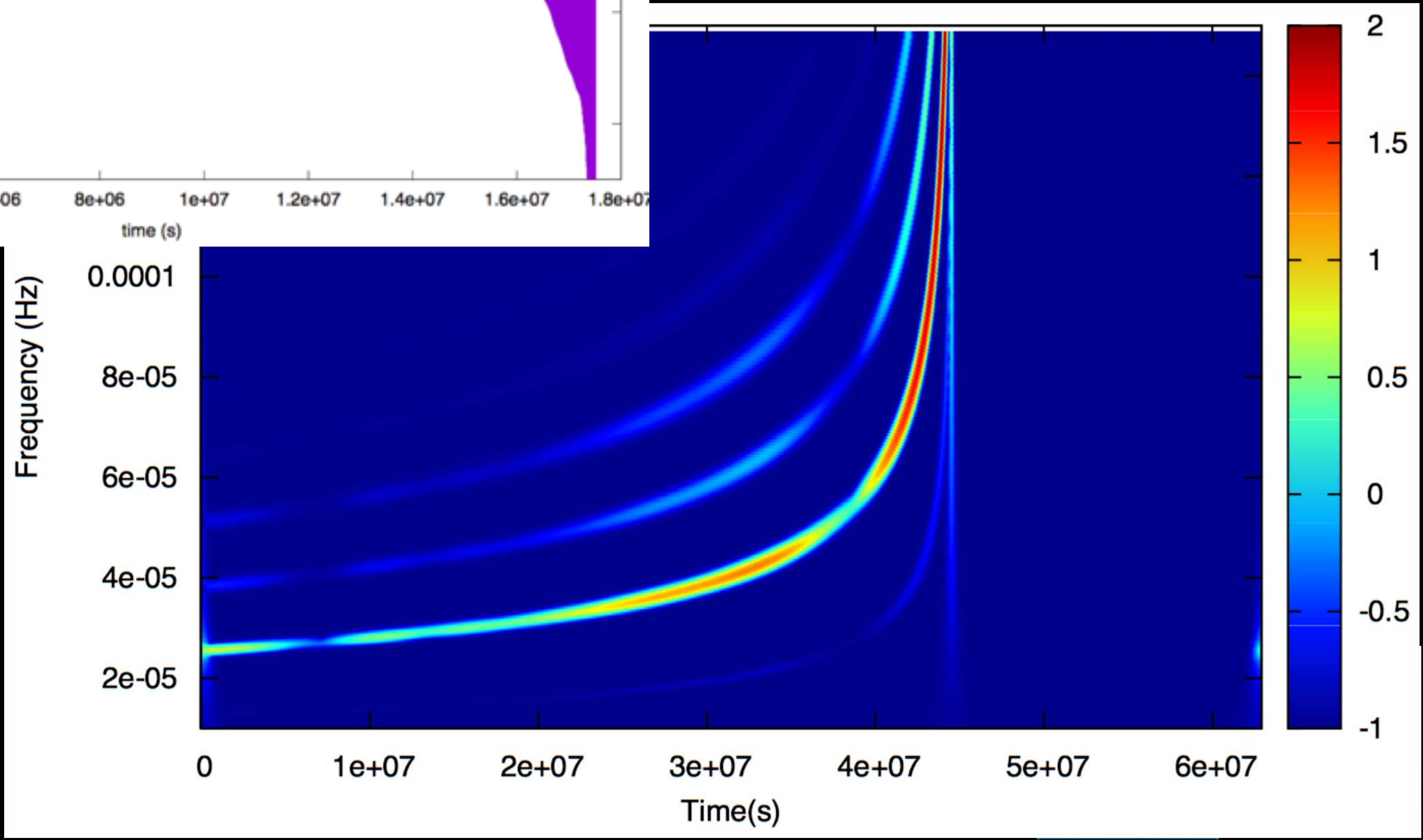


Modulation - sky position





Modulation - sky position

- Survey type instrument:
  - no pointing
  - observe “all sky every time”
- Depending on the source power and duration, the angular could go until 1 deg^2
- ... but better resolution on other parameters!

Next :

DA II (Neil)

&

LISA DA (Antoine)

Thank you