Sub-Hz Metrology at APC

Hubert Halloin - APC

E-GRAAL kick-off meeting

March 9th, 2015

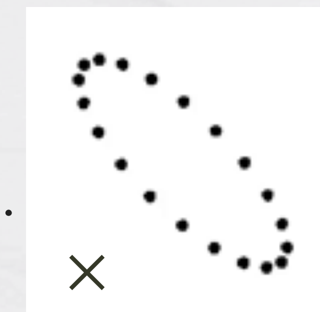
Gravitational waves ?

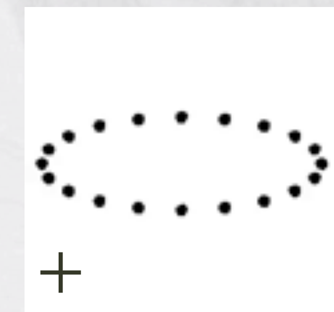
What are GW ?

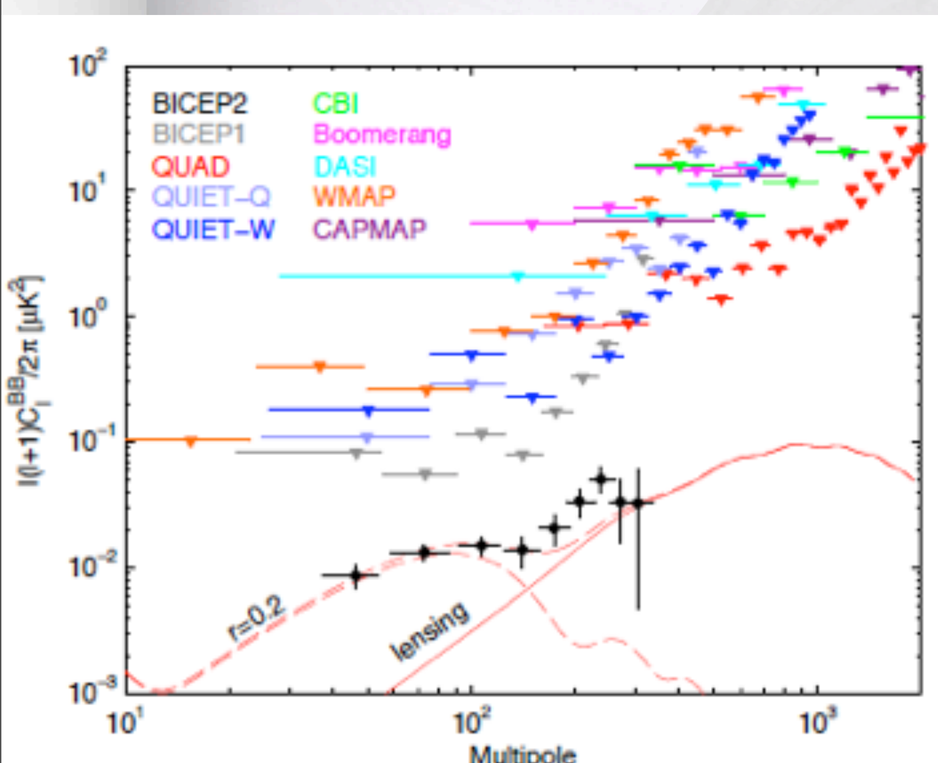
- ✓ The GW are elastic deformations of the space-time metric (GR prediction)
- ✓ Transverse, quadrupole waves
- ✓ Observational effect : Variation of the light-distance between 2 masses initially at rest.

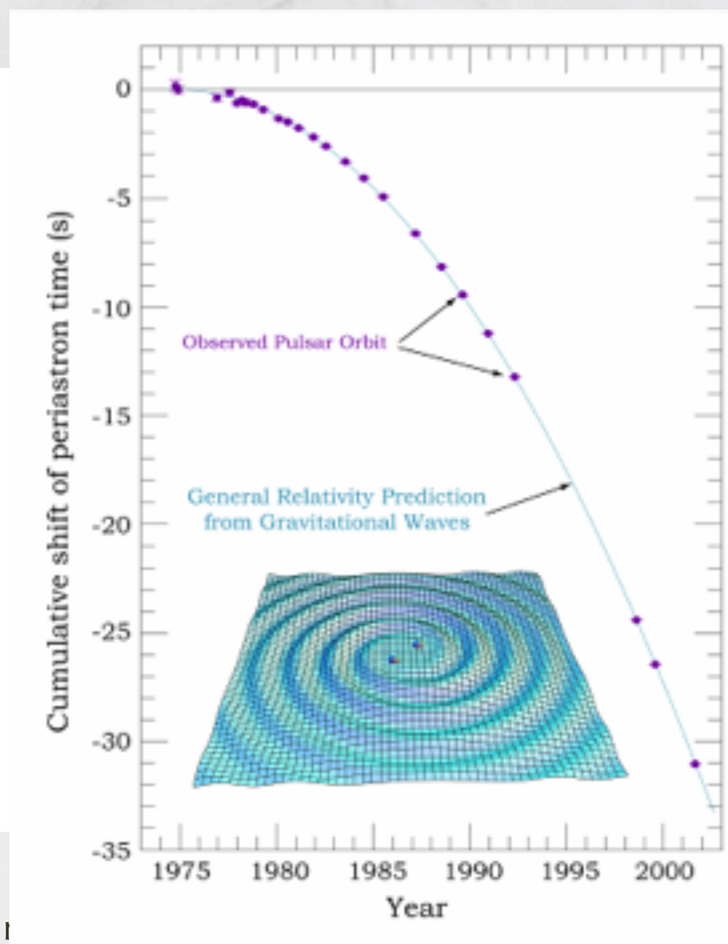
Indirect evidences (up to now …) :

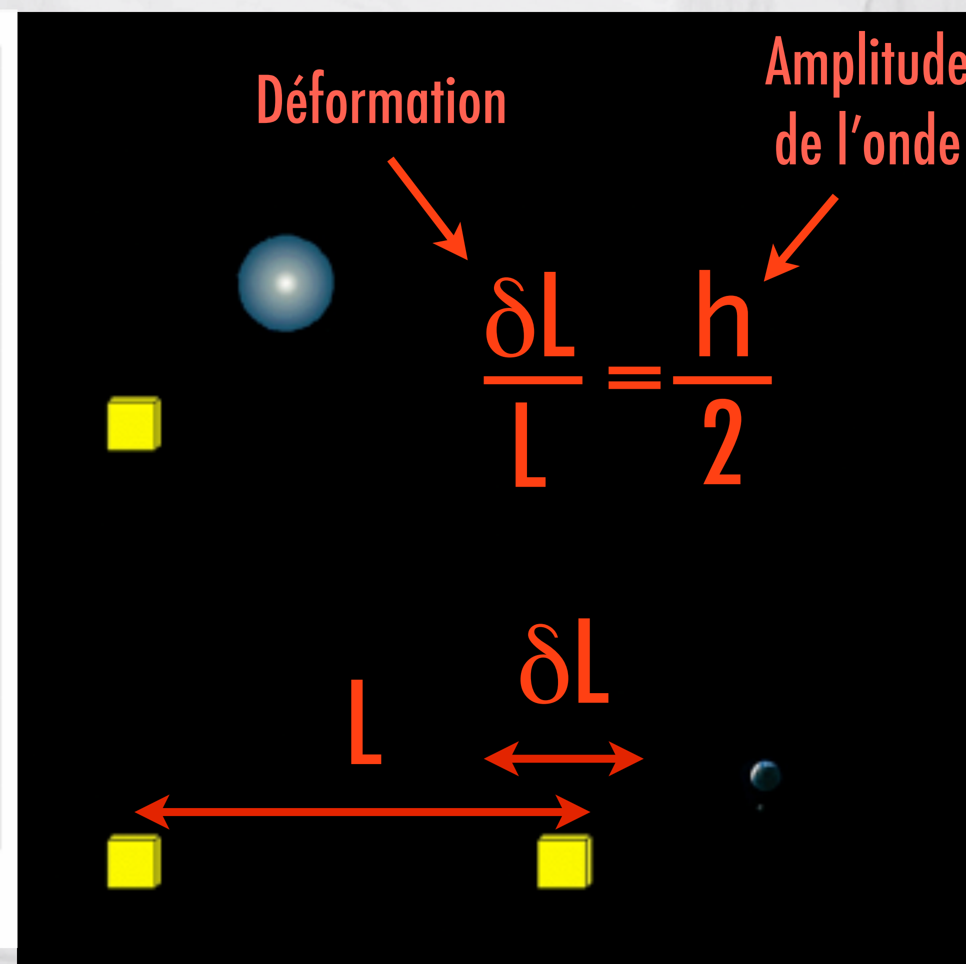
- ✓ Binary pulsars (Hulse & Taylor)
- ✓ Imprints of GW in the CMB (BICEP2) ? Probably not (yet) …











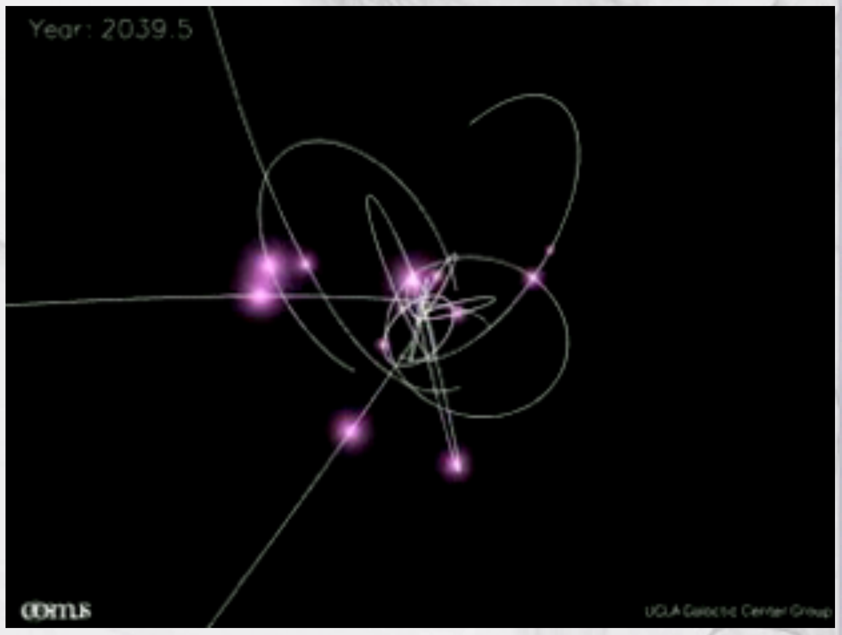
Low frequency sources of GW

Estimation of GW amplitude for a source of mass M, compacity κ, at a distance r :

$$h \approx 2\kappa \frac{GM}{rc^2} \approx \ 10 \text{ pm/Mkm } \frac{M}{M_{Soleil}} \frac{30 \text{ kal}}{r} \frac{\kappa}{0{,}001}$$

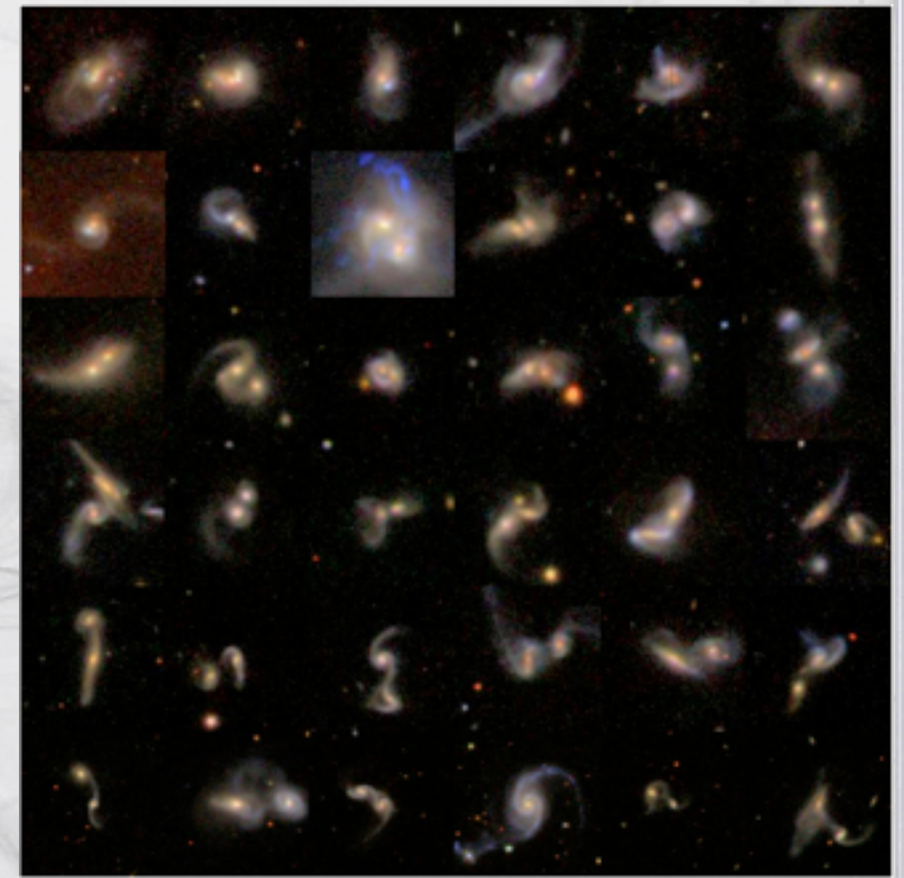
$$f \approx \sqrt{\frac{G\rho}{\pi}} \approx 2 \text{ Hz } \frac{M_{Soleil}}{M} \left(\frac{\kappa}{0{,}001}\right)^{3/2}$$

- ✓ Very massive and compact objects (super-massive BH, white dwarfs binaries, etc.) can produce significant signals
- ✓ Can be detected at very large distance (h scales as 1/r ...)
- ✓ But these sources are within the mHz to Hz range (cannot be observed by earth-based interferometers)...

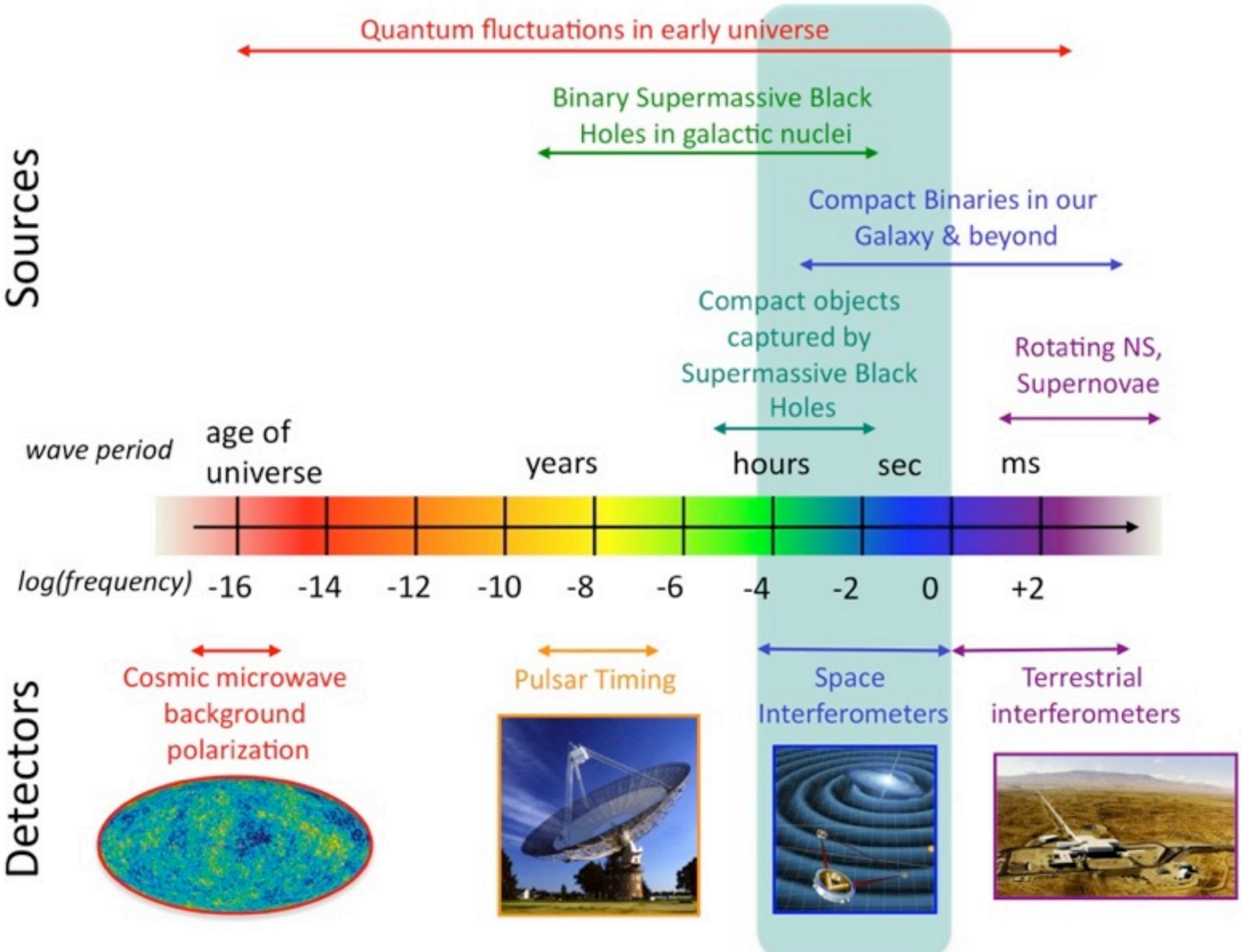


Typical example : SMBH coalescence

- ✓ M=10^6 M_{sol}, z=1, κ=0,5 => h≈10^{-18} (1 nm/Mkm), f≈10 mHz
- ✓ Liu et al., 2011 : ~3,5 % of AGNs @z=0,1 are interacting (SDSS survey)



The Gravitational Wave Spectrum

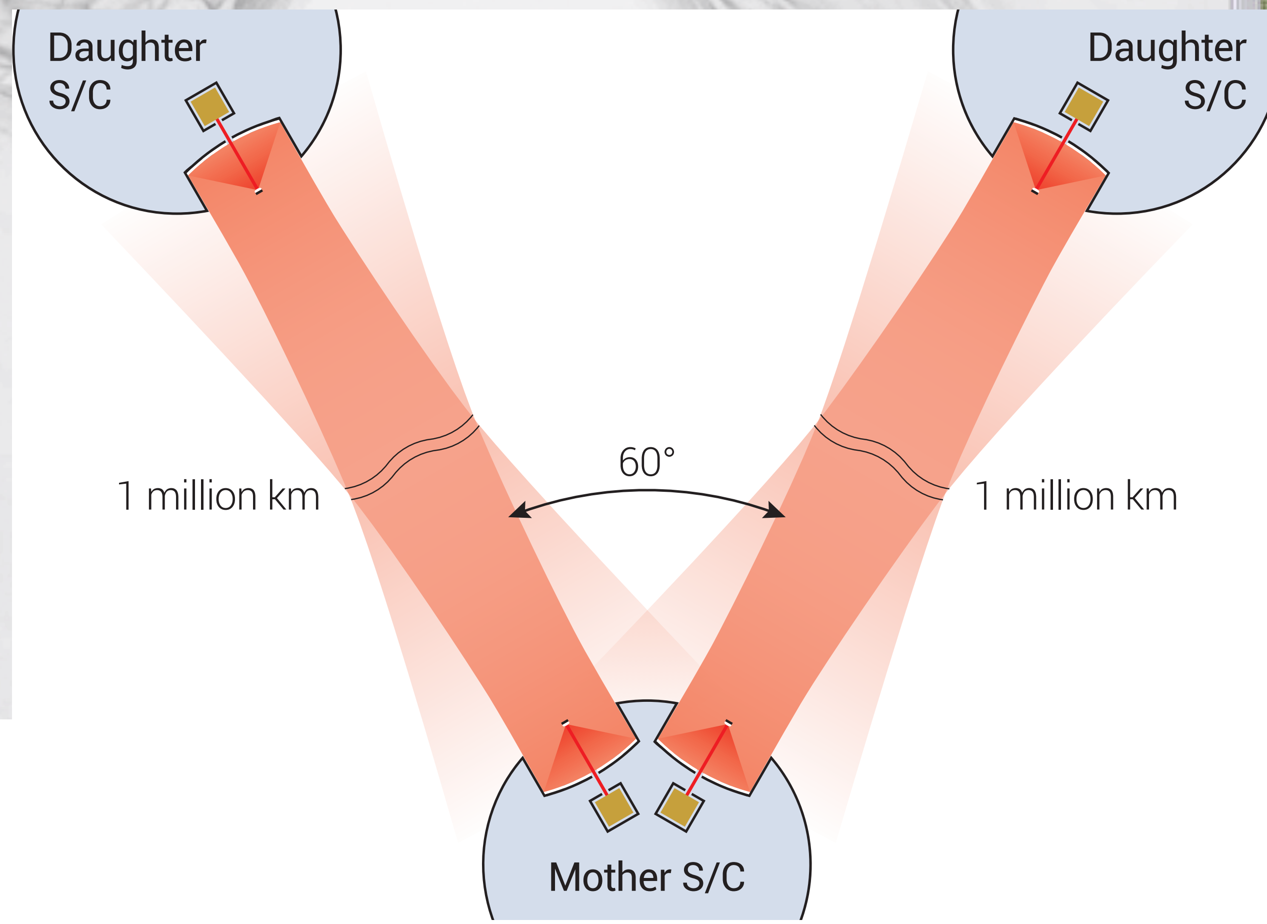


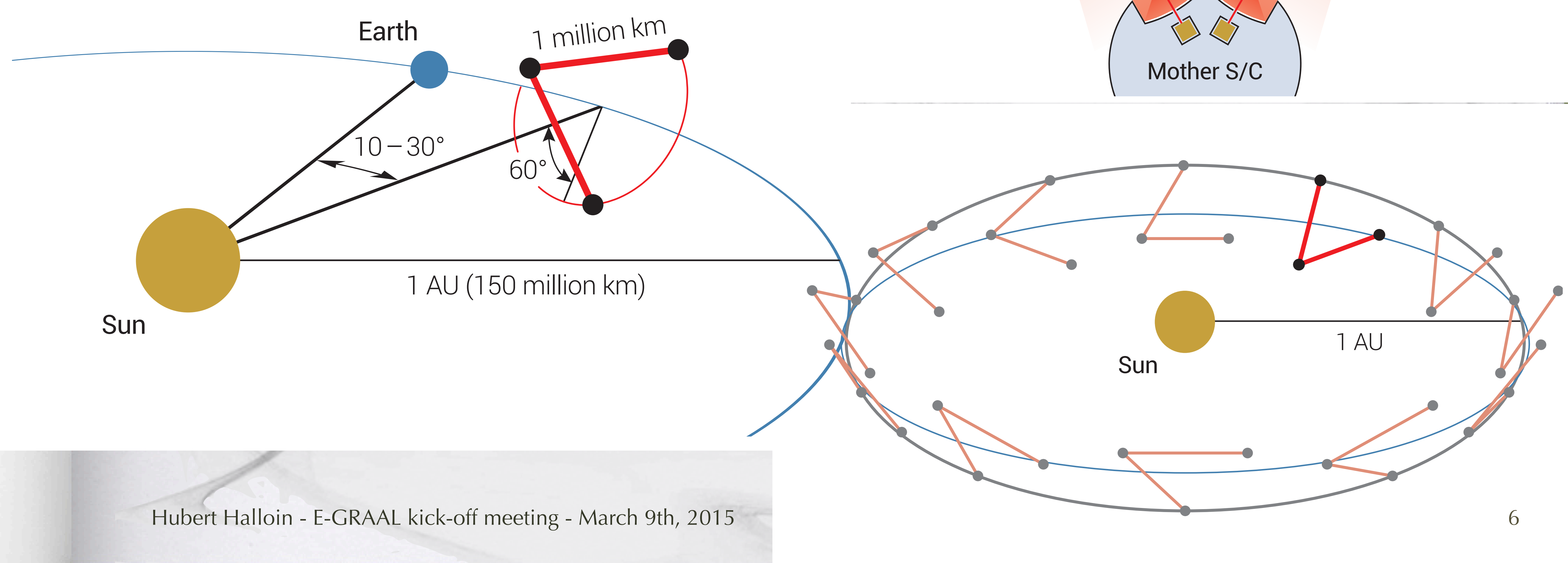
eLISA

eLISA

Detection principle :

- ✓ 4 inertial masses (2/bras)
- ✓ arm length : 1 000 000 km
- ✓ ~1W laser emitted by the 'mother' towards the 'daughters' and sent back after phase locking and frequency shifting
- ✓ long distance metrology thanks to heterodyne interferometry (carrier frequency ~5-15 MHz)
- ✓ detection bandpass : 0.1 mHz to 1 Hz



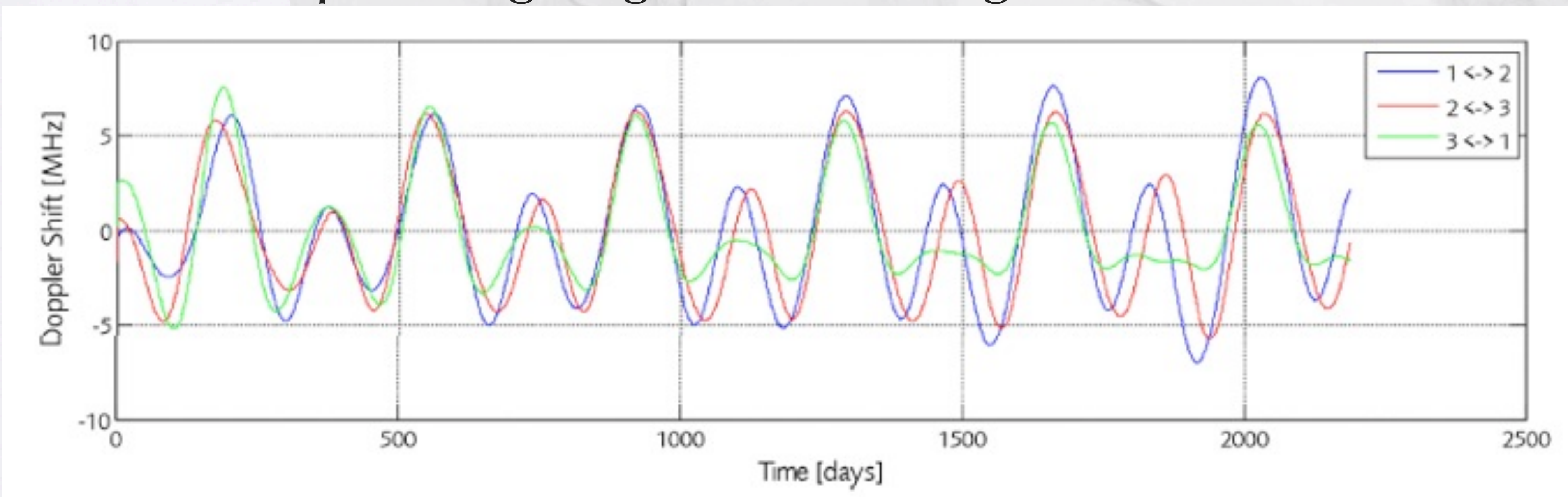


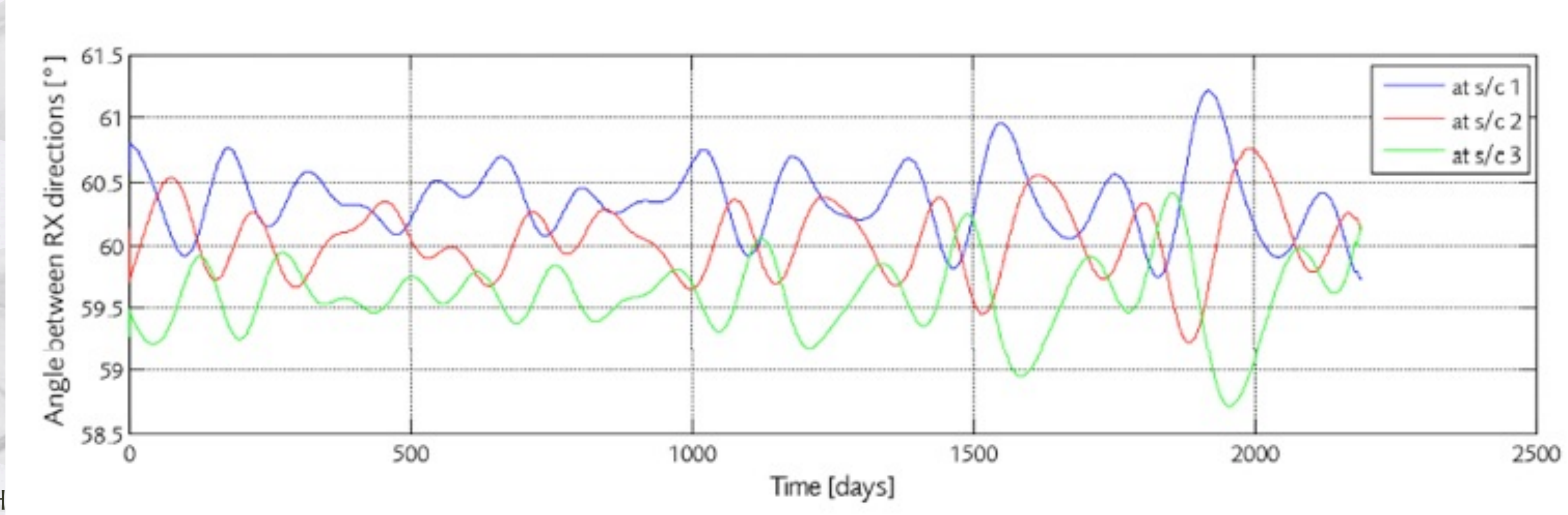
dimanche 8 mars 15

Orbits

Variation of the inter-spacecraft distances :

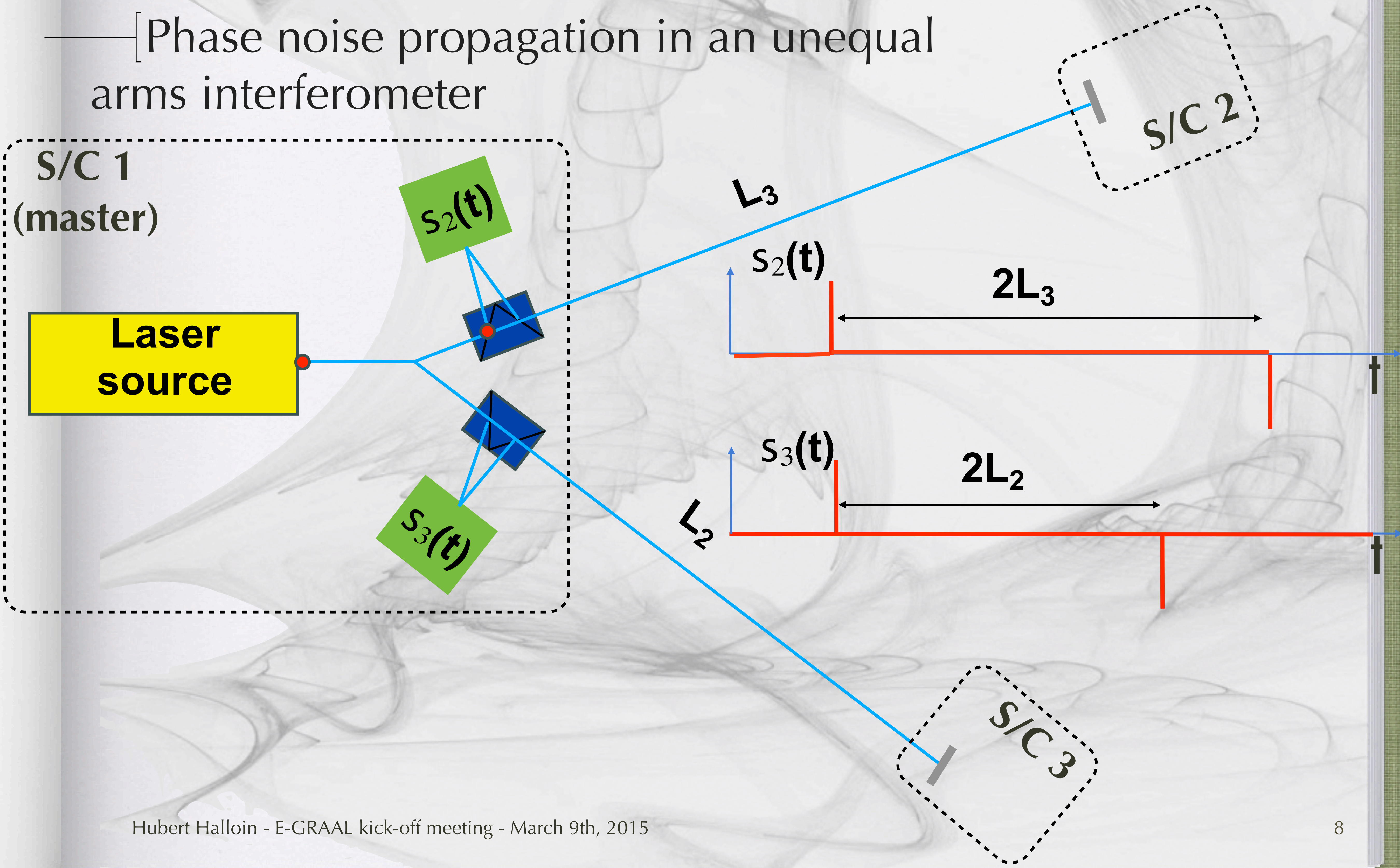
- ✓ Doppler effect
- ✓ variable pointing angles (breathing)



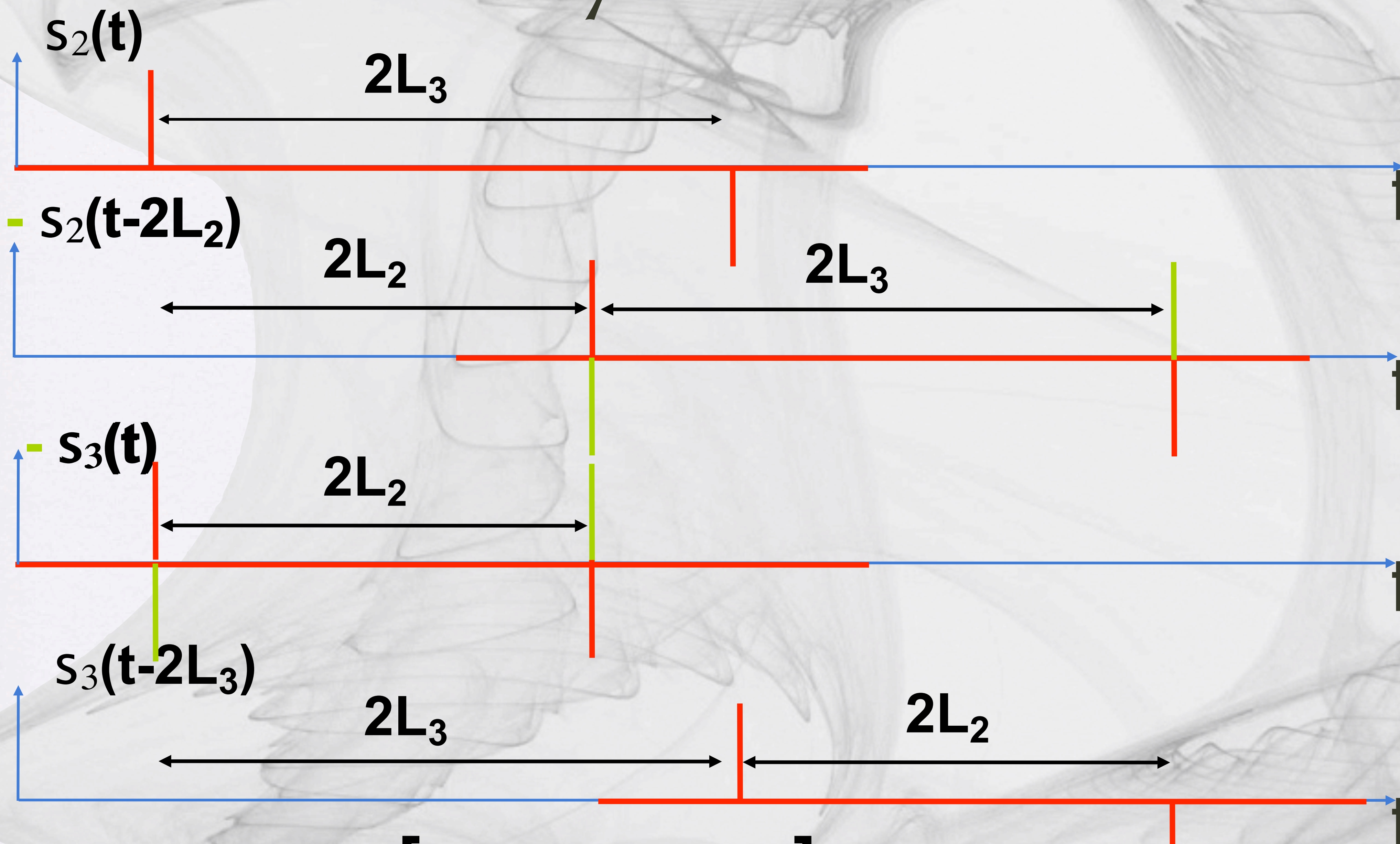


Time Delay Interferometry

- Phase noise propagation in an unequal arms interferometer



Time Delay Interferometry



$$s_2(t) + s_3(t-2L_3) - [\, s_3(t) + s_2(t-2L_2) \,] = 0 \ldots$$

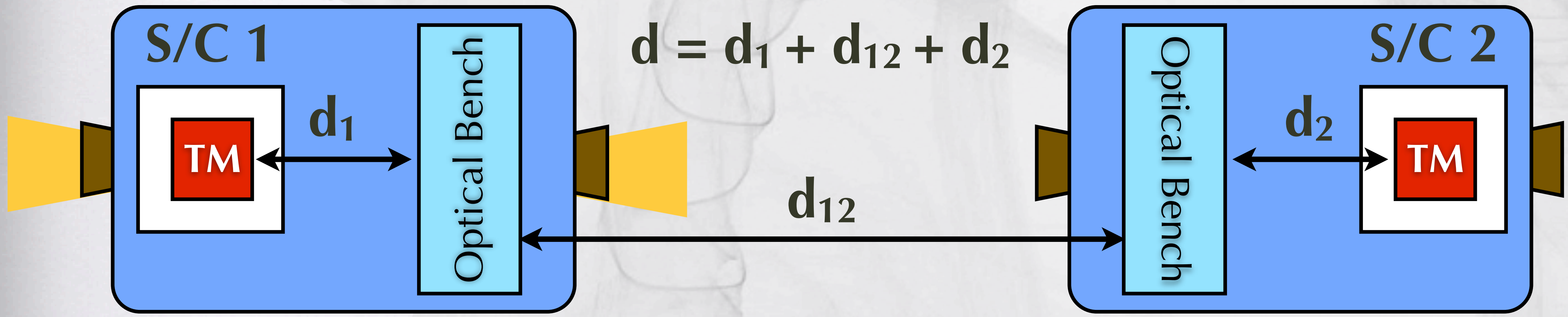
$\Rightarrow$ **Cancellation of the laser noise ...**

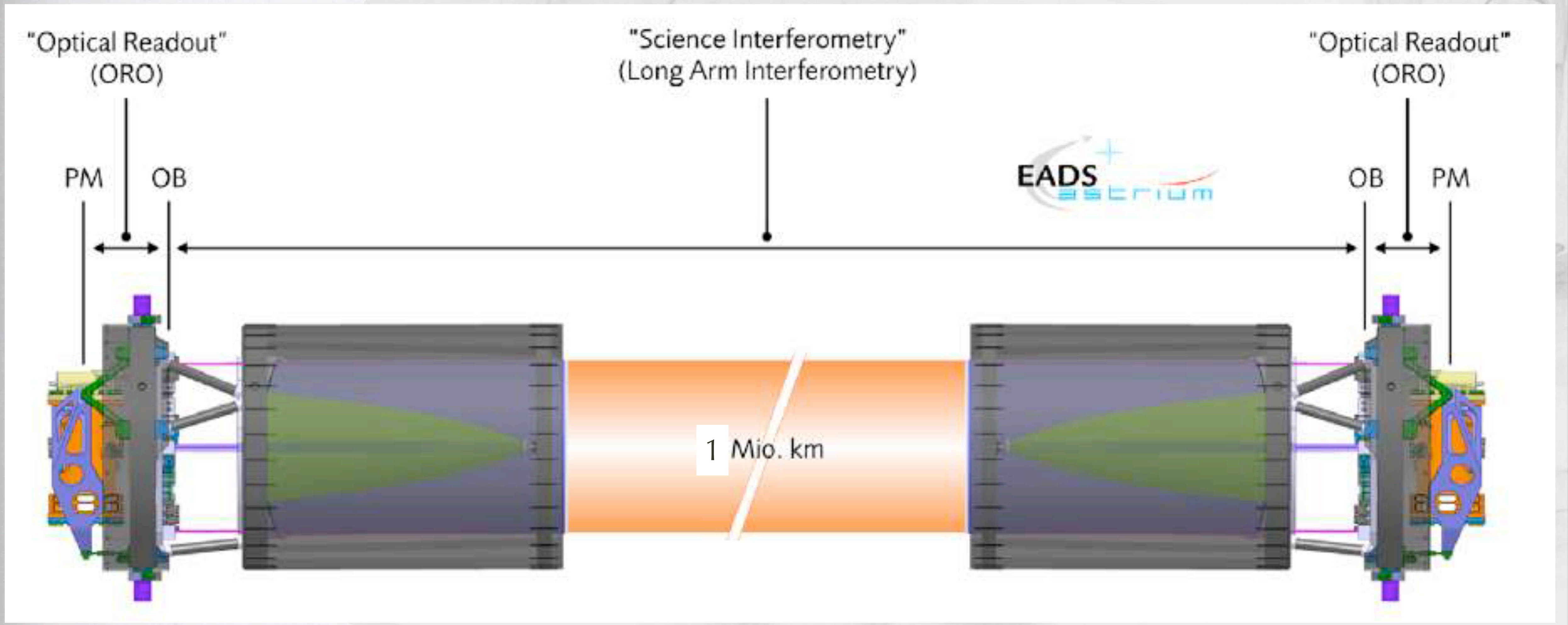
Also modifies the detector response to GW

The cancellation is perfect only if the distances L_2 and L_3 are perfectly known

eLISA interferometric link

- 3 separate measurements (heterodyne interferometry)

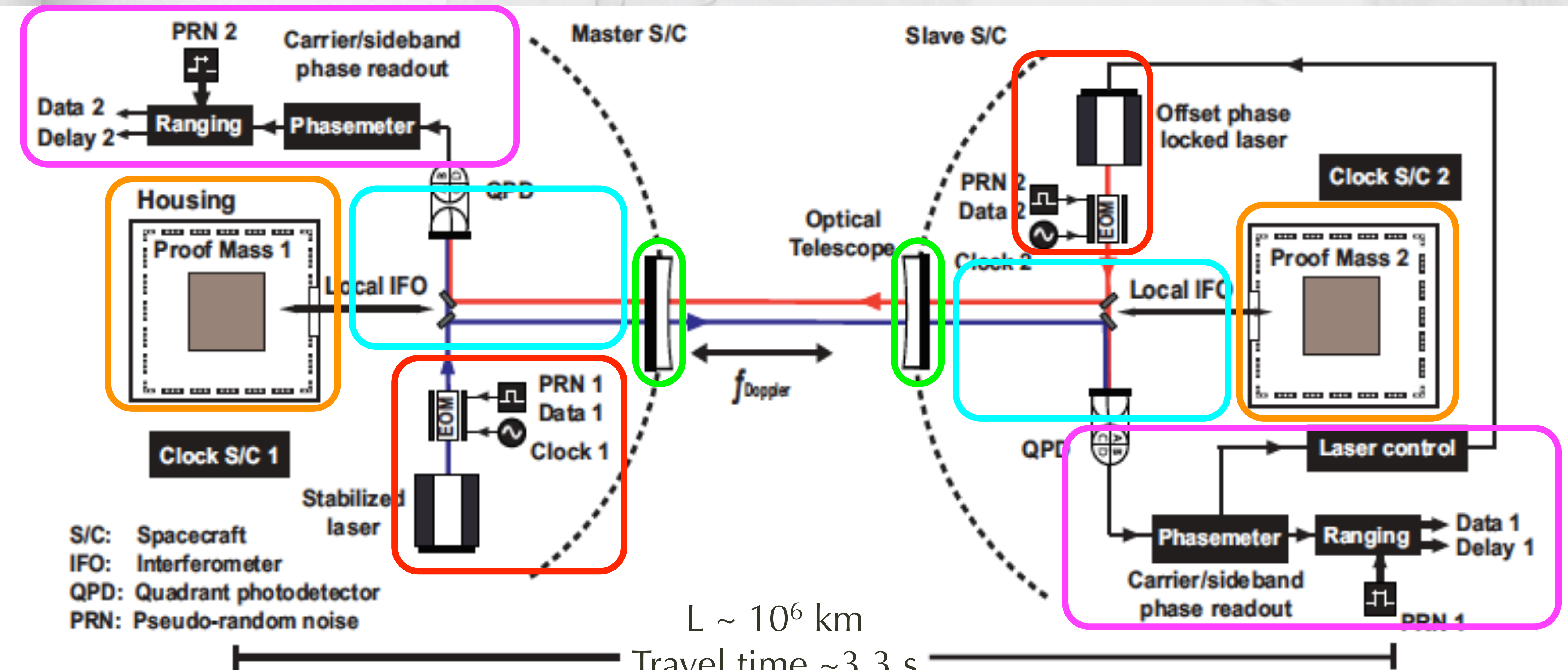




Some more details ...

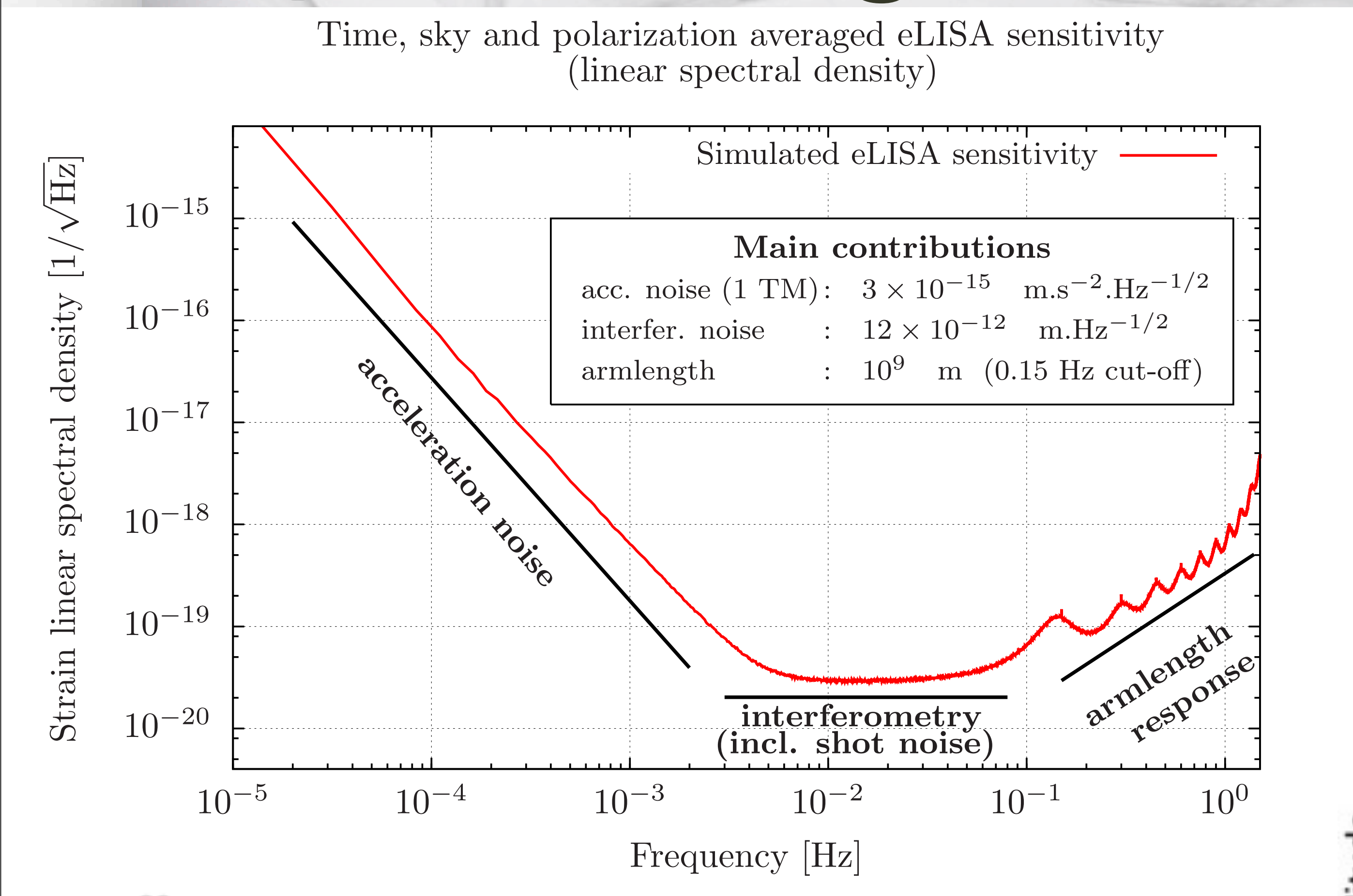
Main payload elements

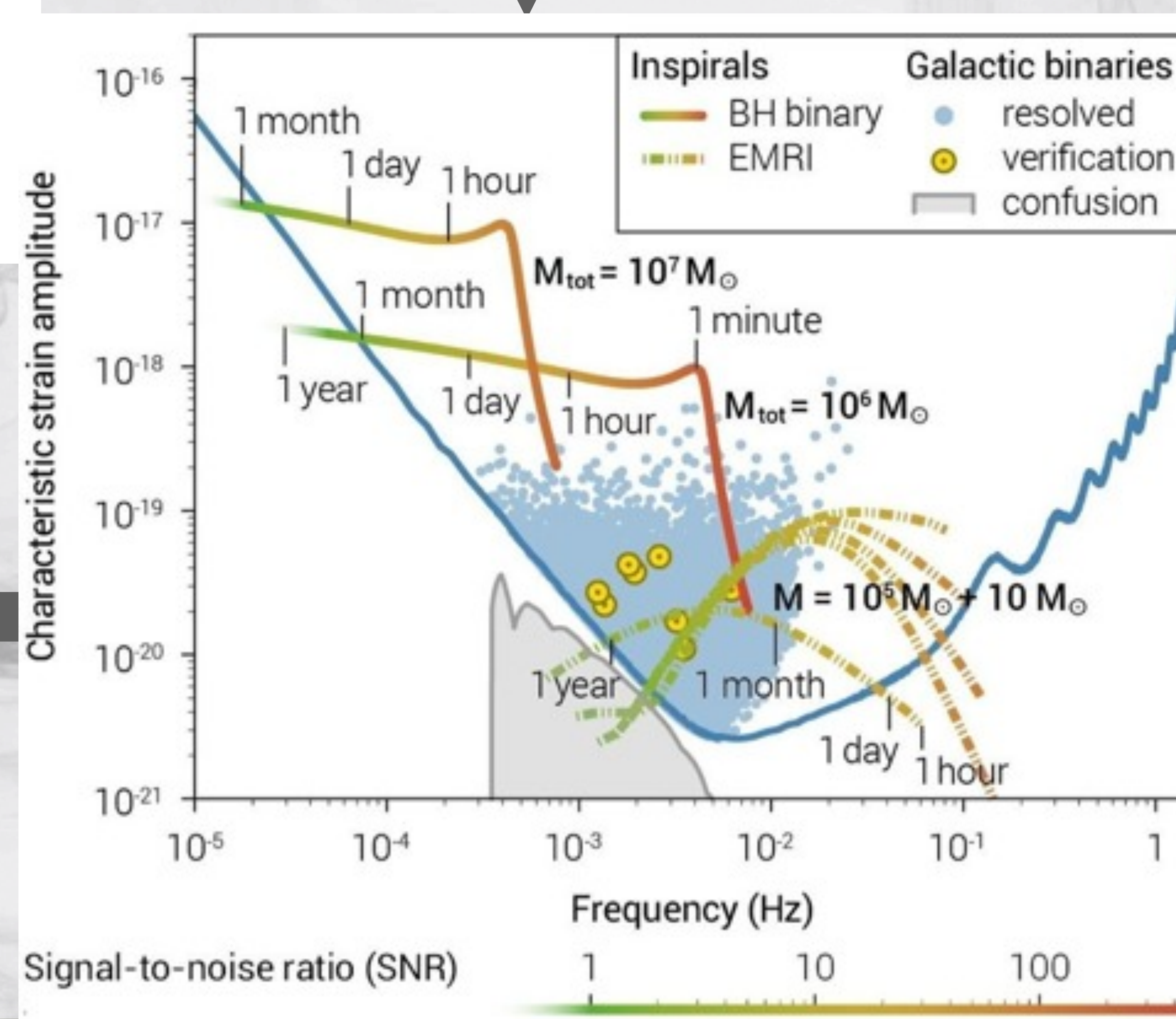
- ✓ Gravitational Reference System (GRS)
- ✓ Zerodur Optical Bench
- ✓ Phase & frequency extraction (Phasemeter)
- ✓ Telescope
- ✓ Laser source

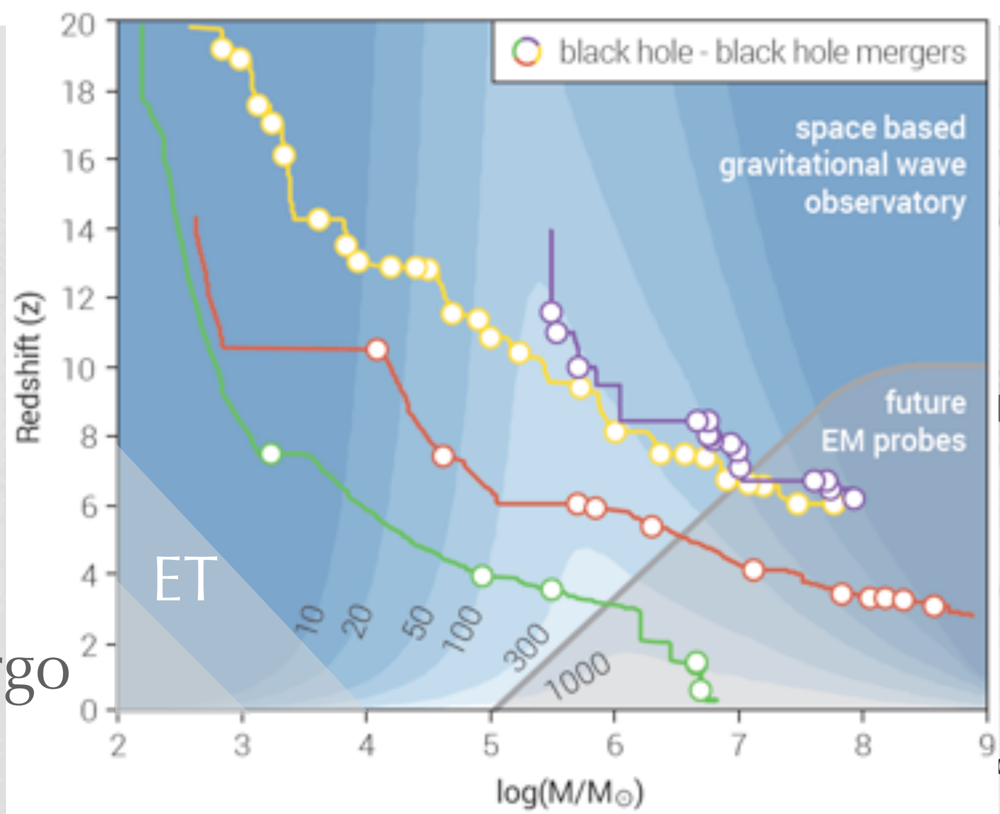


Esteban et al., «Experimental demonstration of weak-light laser ranging and data communication for LISA.», *Optics Express*, **2011**, vol. 19 p. 15937

Limiting noises and performance







Virgo

LISA Pathfinder

LISA Pathfinder

The LISA Pathfinder satellite will test key-technologies for eLISA :

- ✓ Residual noise in differential acceleration (i.e. drag-free performance) :

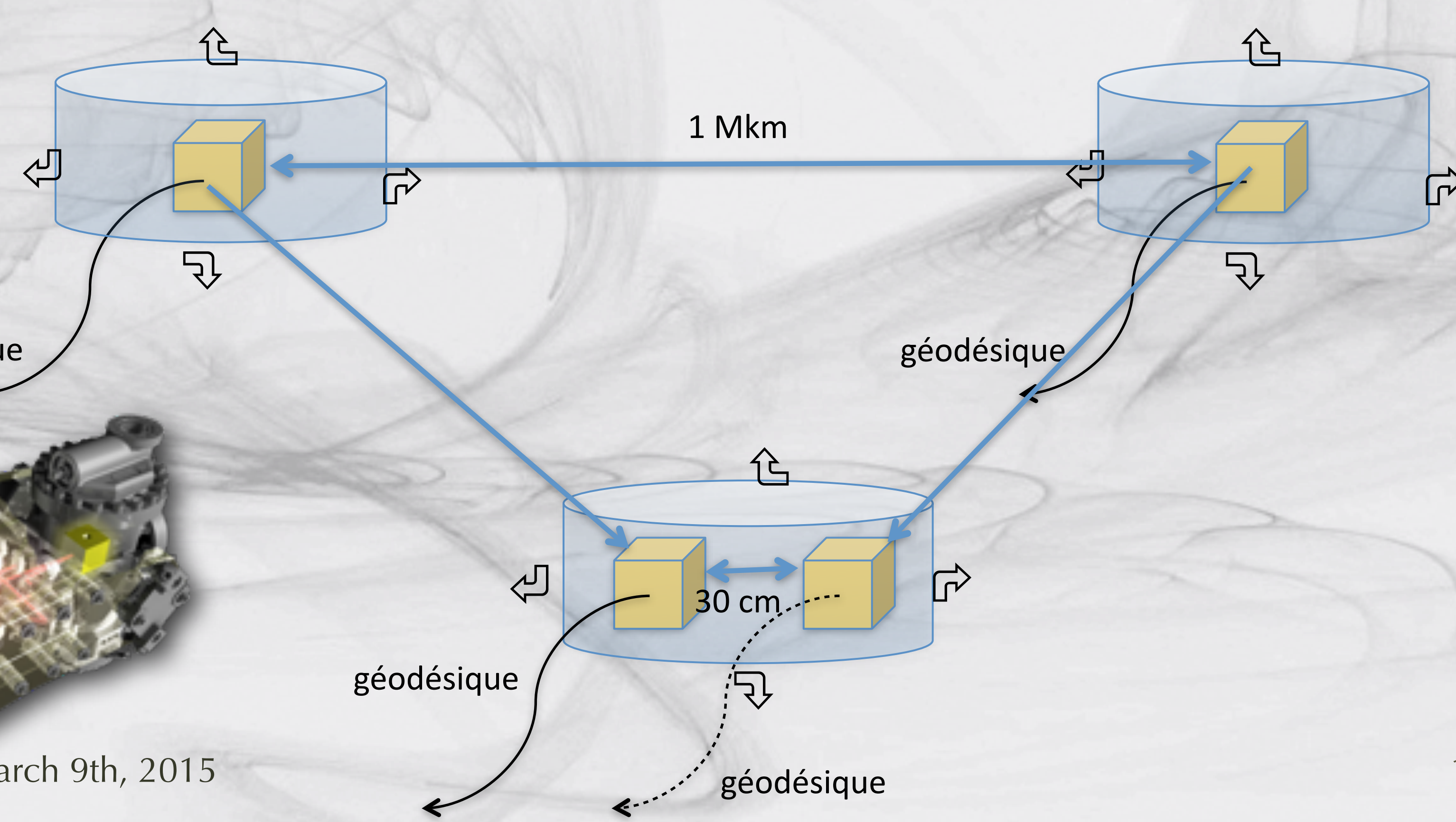
$$S_a^{\frac{1}{2}}(f) \leq 3 \times 10^{-14} \left[1 + \left(\frac{f}{3\,\mathrm{mHz}}\right)^4\right]^{\frac{1}{2}} \mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$$

- ✓ Displacement noise :

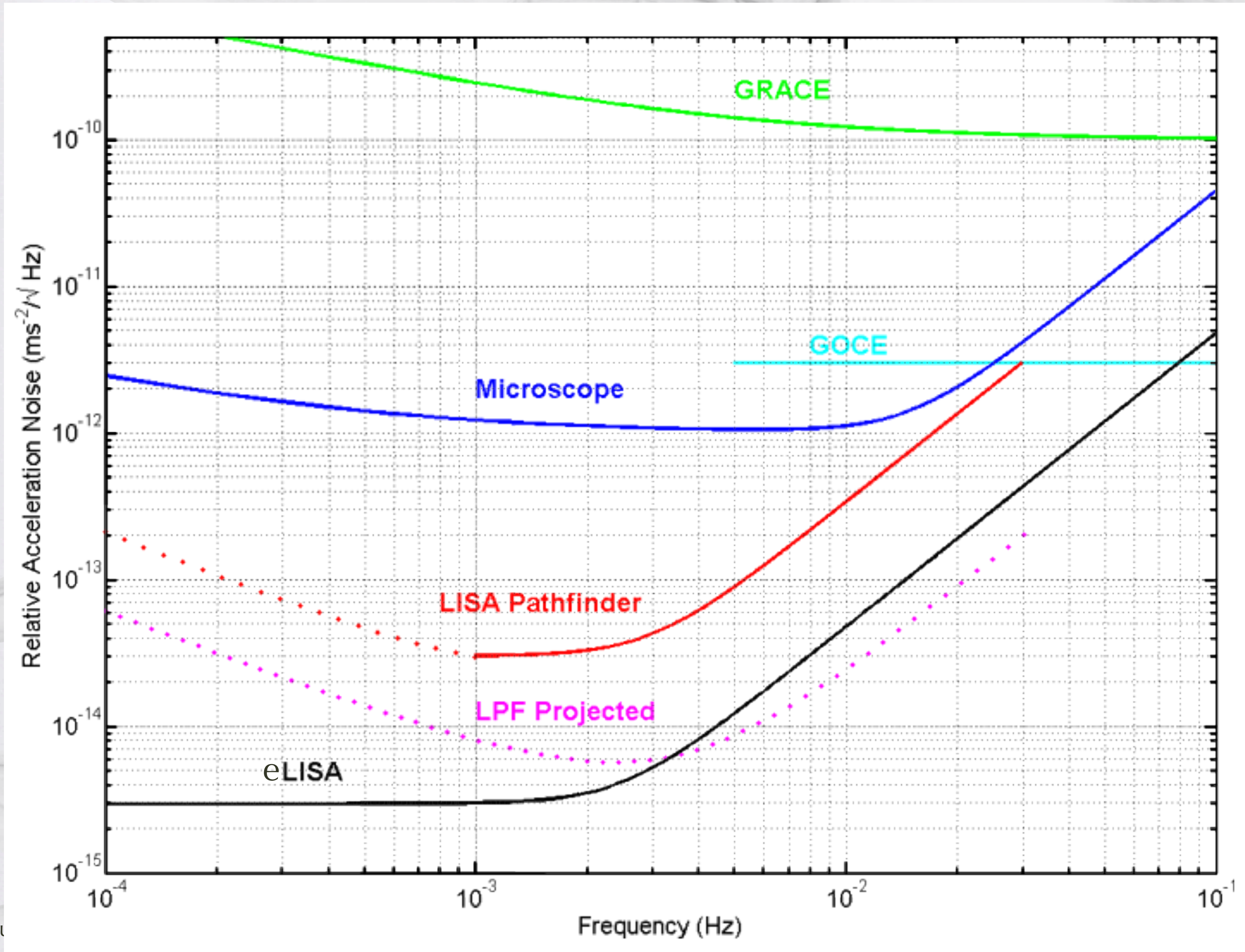
$$S_{oms}^{\frac{1}{2}}(f) \leq 9.1 \times 10^{-12} \left[1 + \left(\frac{3\,\mathrm{mHz}}{f}\right)^4\right]^{\frac{1}{2}} \mathrm{m}/\sqrt{\mathrm{Hz}}$$

eLISA

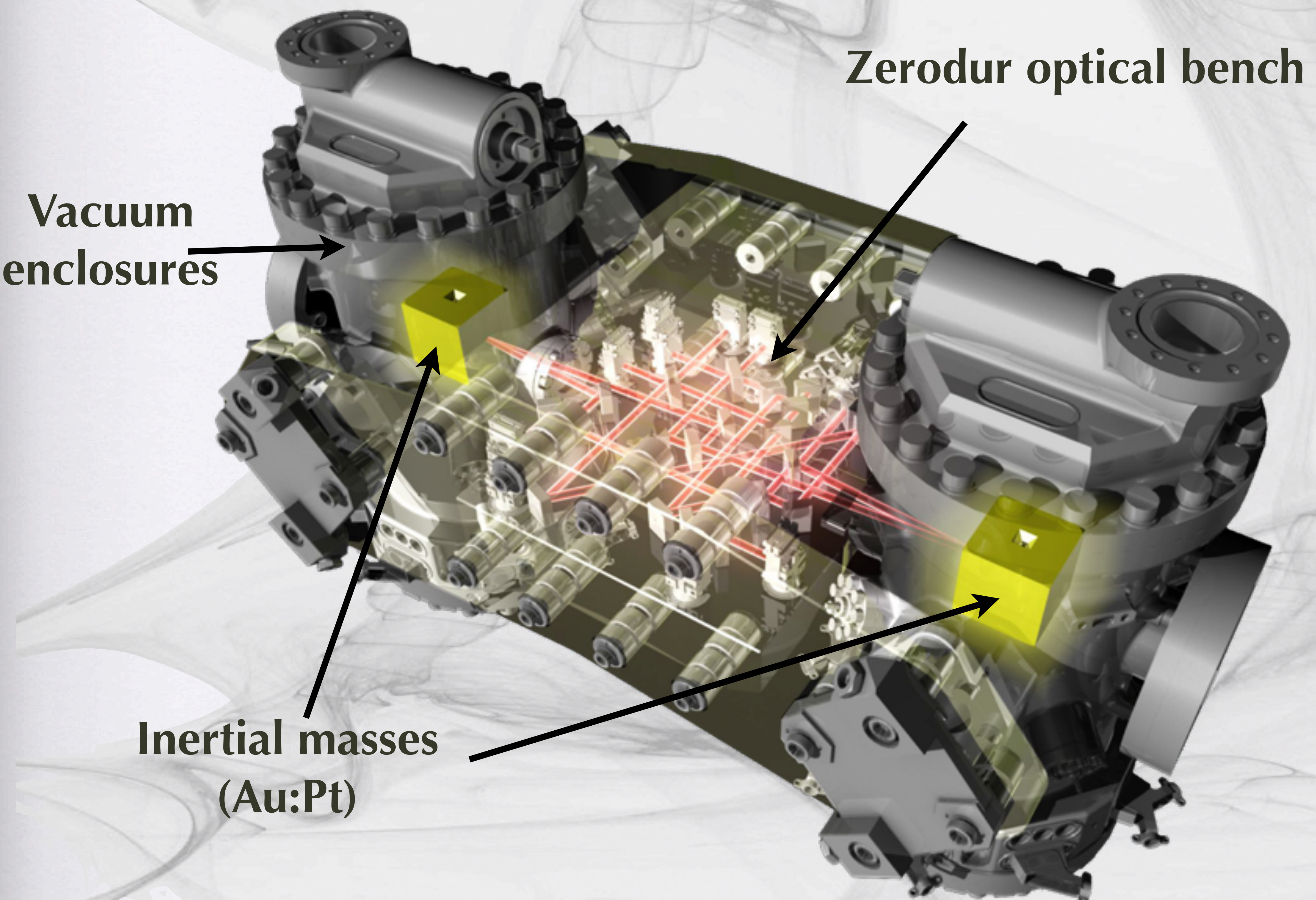
LISA Pathfinder

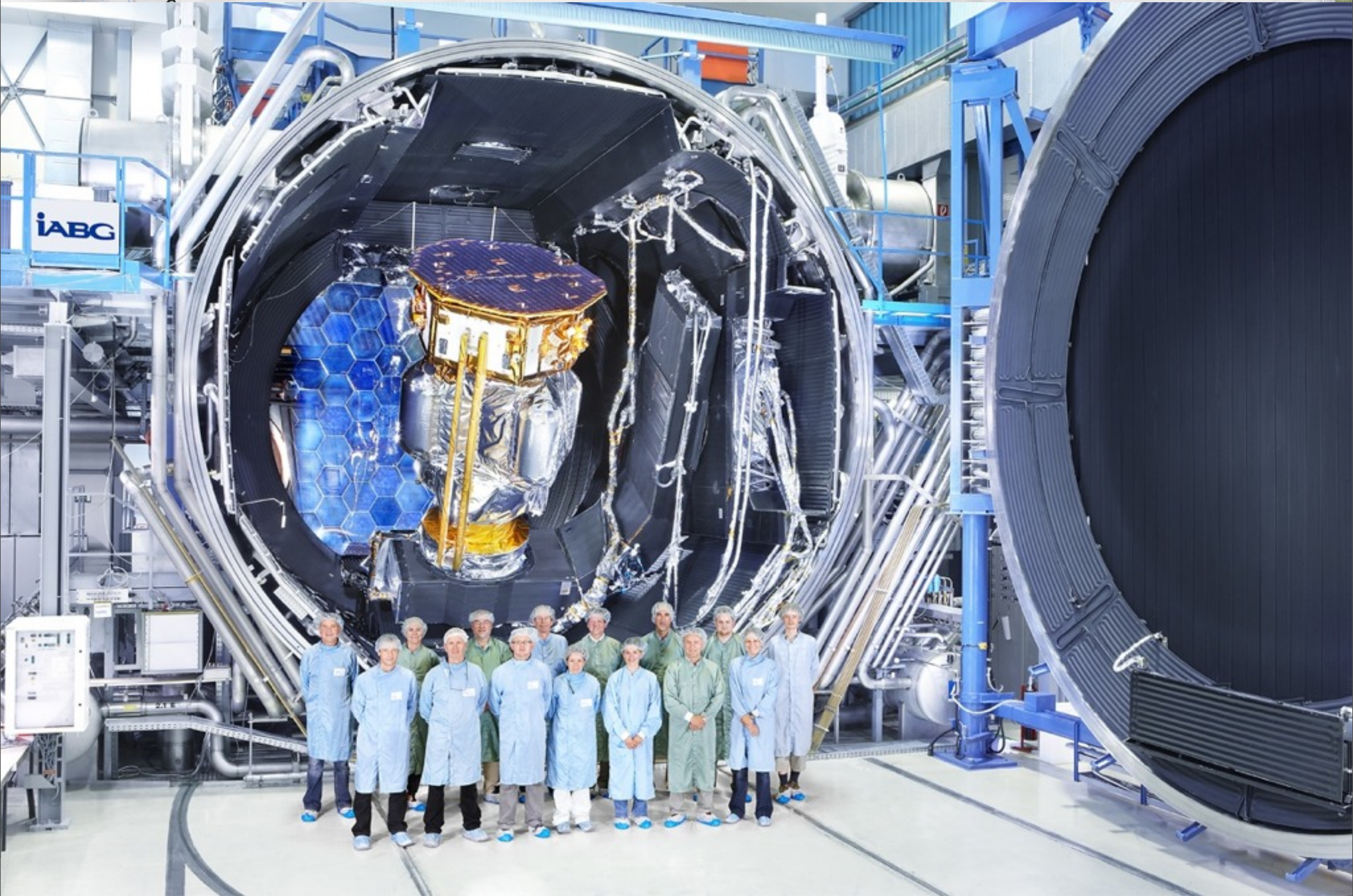


Comparison of expected performance



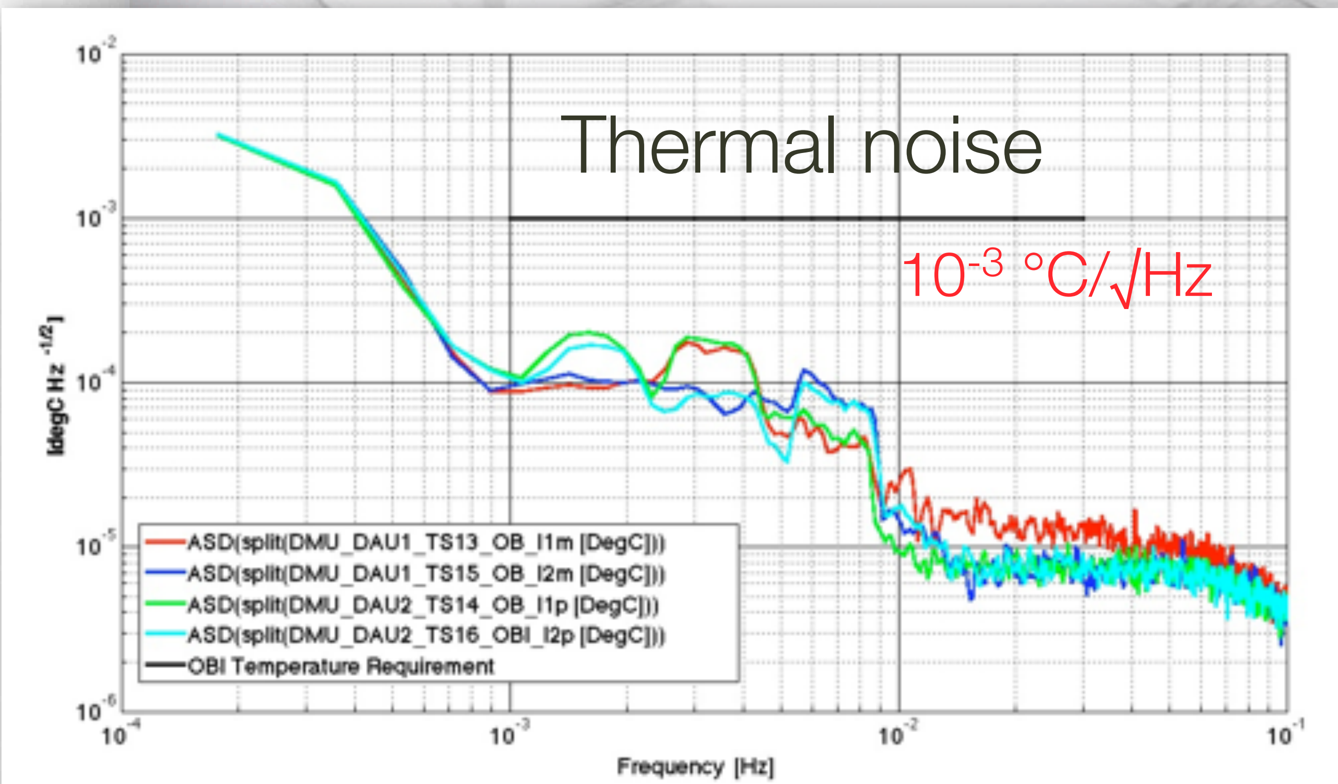
Overall layout of the LPF payload

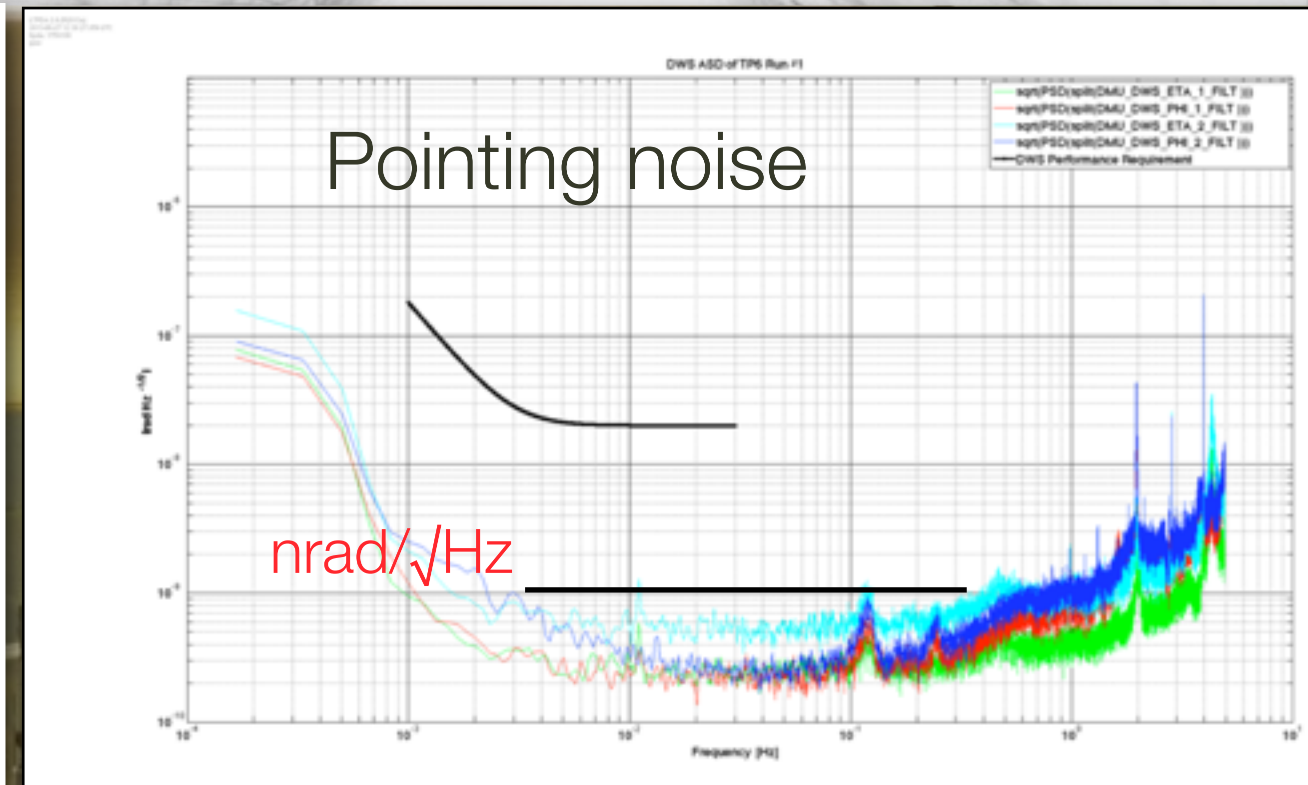


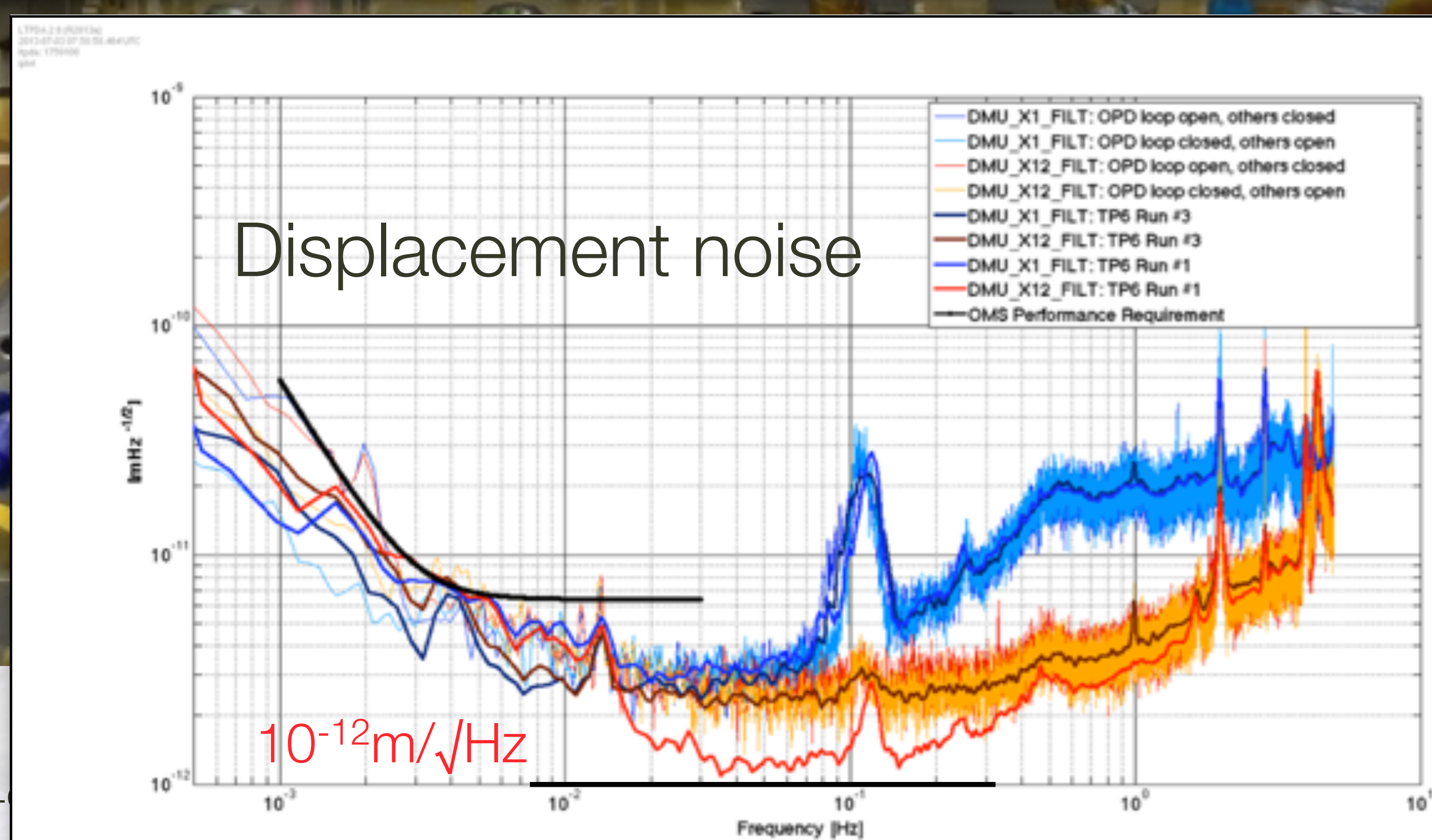

IABG

Measured performance of the optical bench

Measured performance of the optical bench





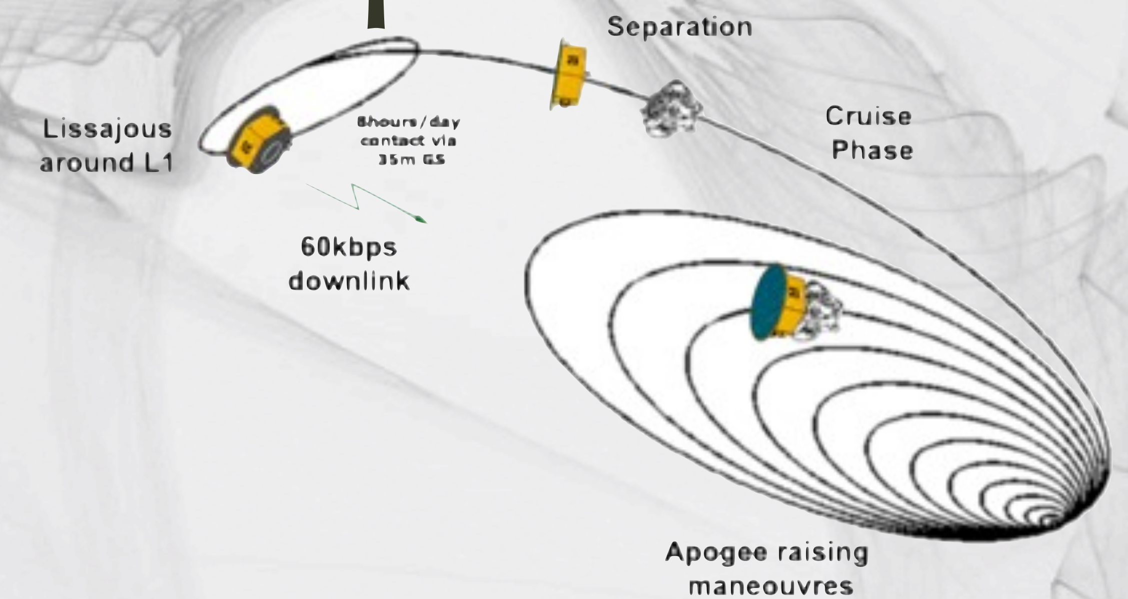


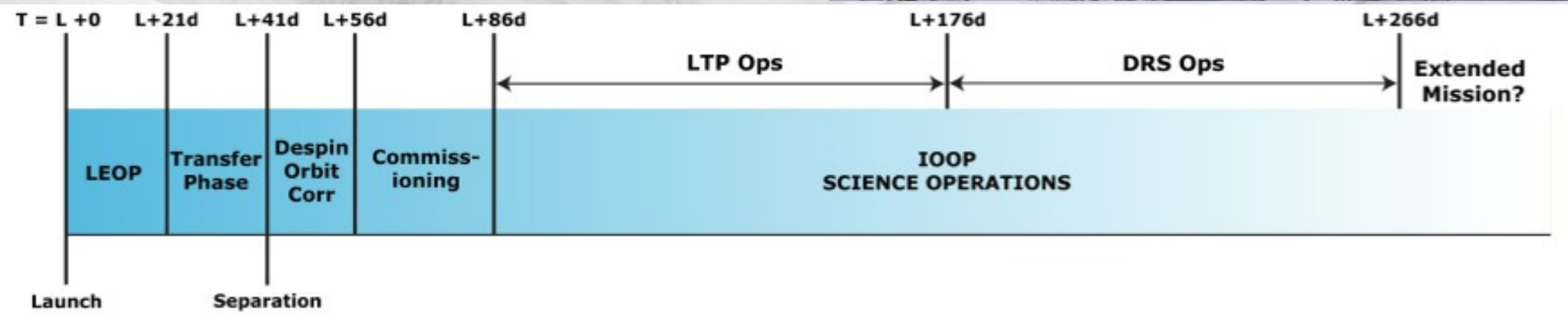
LPF launch and operations

- Expected launch in september 2015 with the VEGA launcher (from Kourou)

- Final positioning at the L1 Lagrange point (Sun-Earth system)

- Nominal duration for the science mission of 6 months (+3 months for cruise and commissioning)



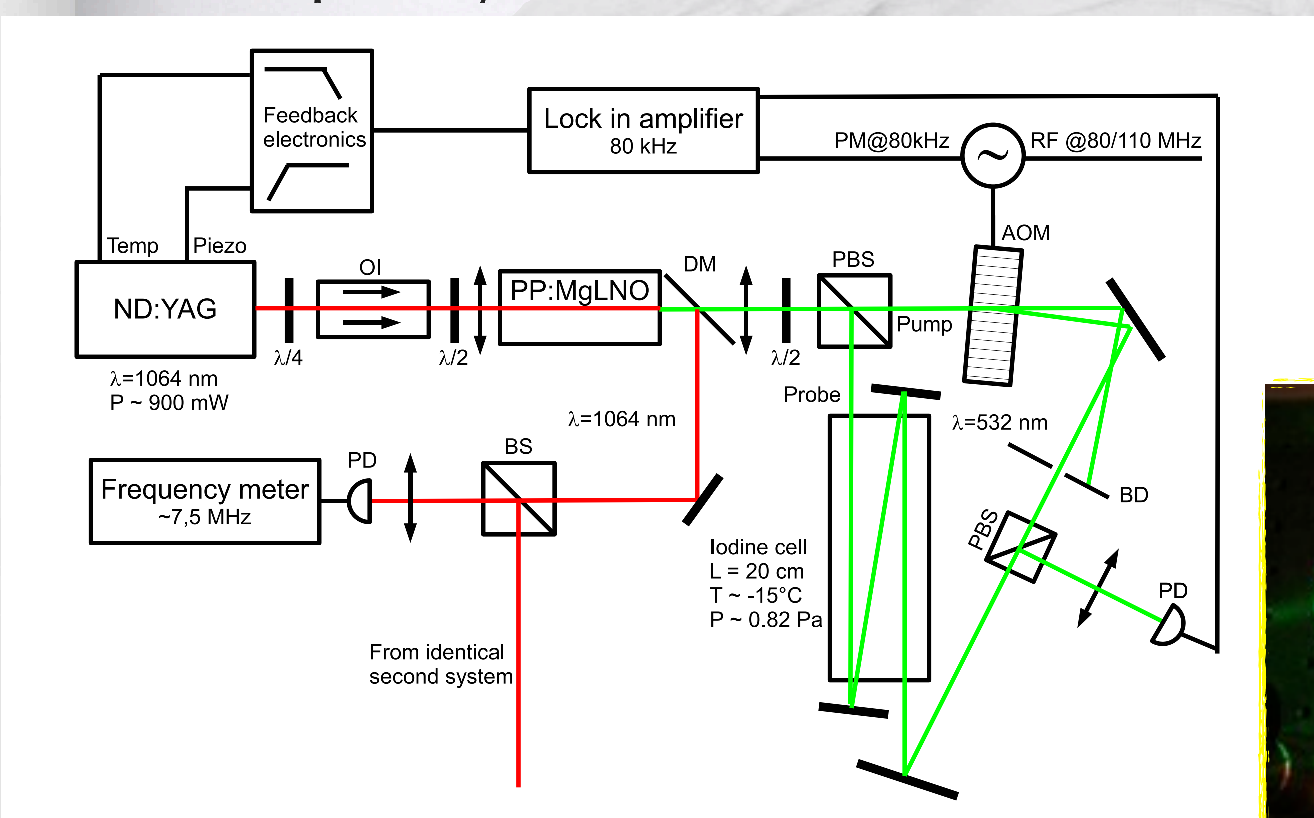


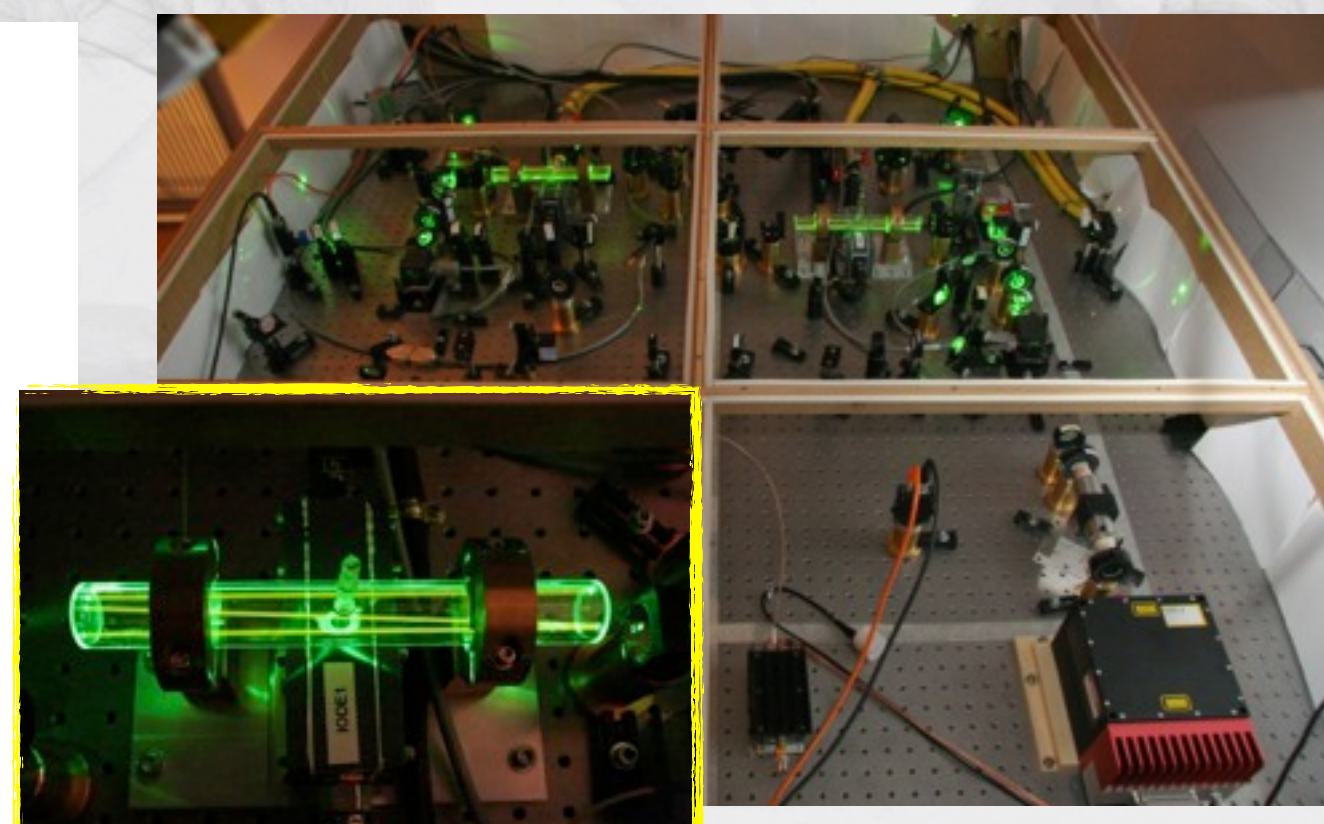
Sub-Hz activities at APC

Laser frequency stabilization

Iodine-stabilized lasers sources

- ✓ Why ? : the uncertainty on the arm length mismatch (ΔL) transfers the frequency noise of the laser source ($\delta\nu$) on the phase measurement : $\delta L = \delta\nu/\nu \, \Delta L$
- ✓ Requirements : 30 to 300 Hz/√Hz, between 1 mHz et 10 Hz (2 to 3 orders of magnitude improvement w.r.t free-running lasers).
- ✓ Goal of the experiment : demonstrating the possibility to use iodine as a frequency reference (nominal technology for eLISA : Fabry-Perot cavity)
- ✓ Experiment at the APC (following preliminary work at ARTEMIS/OCA) : laser frequency stabilization on iodine (I_2)



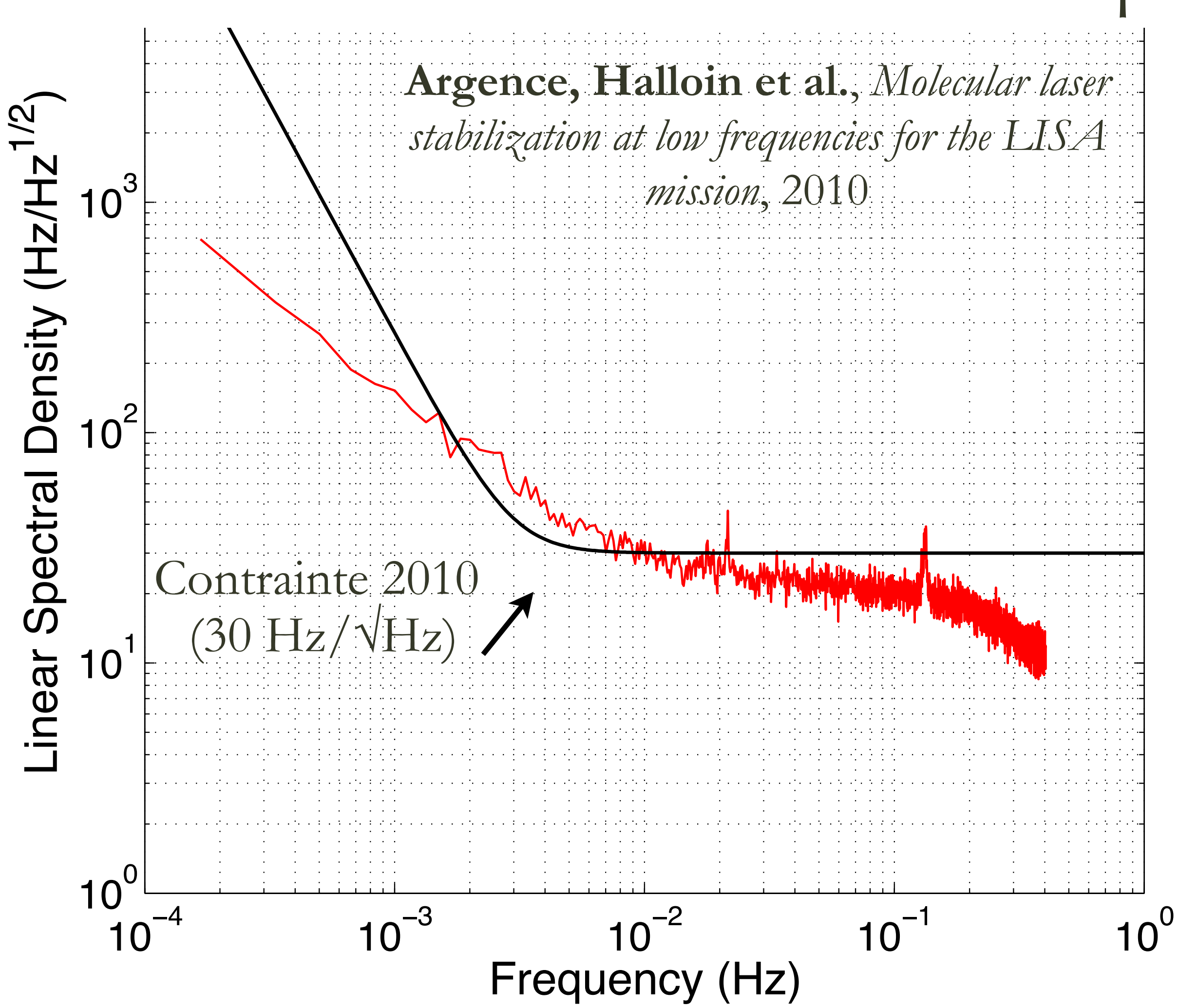


Laser frequency stabilization

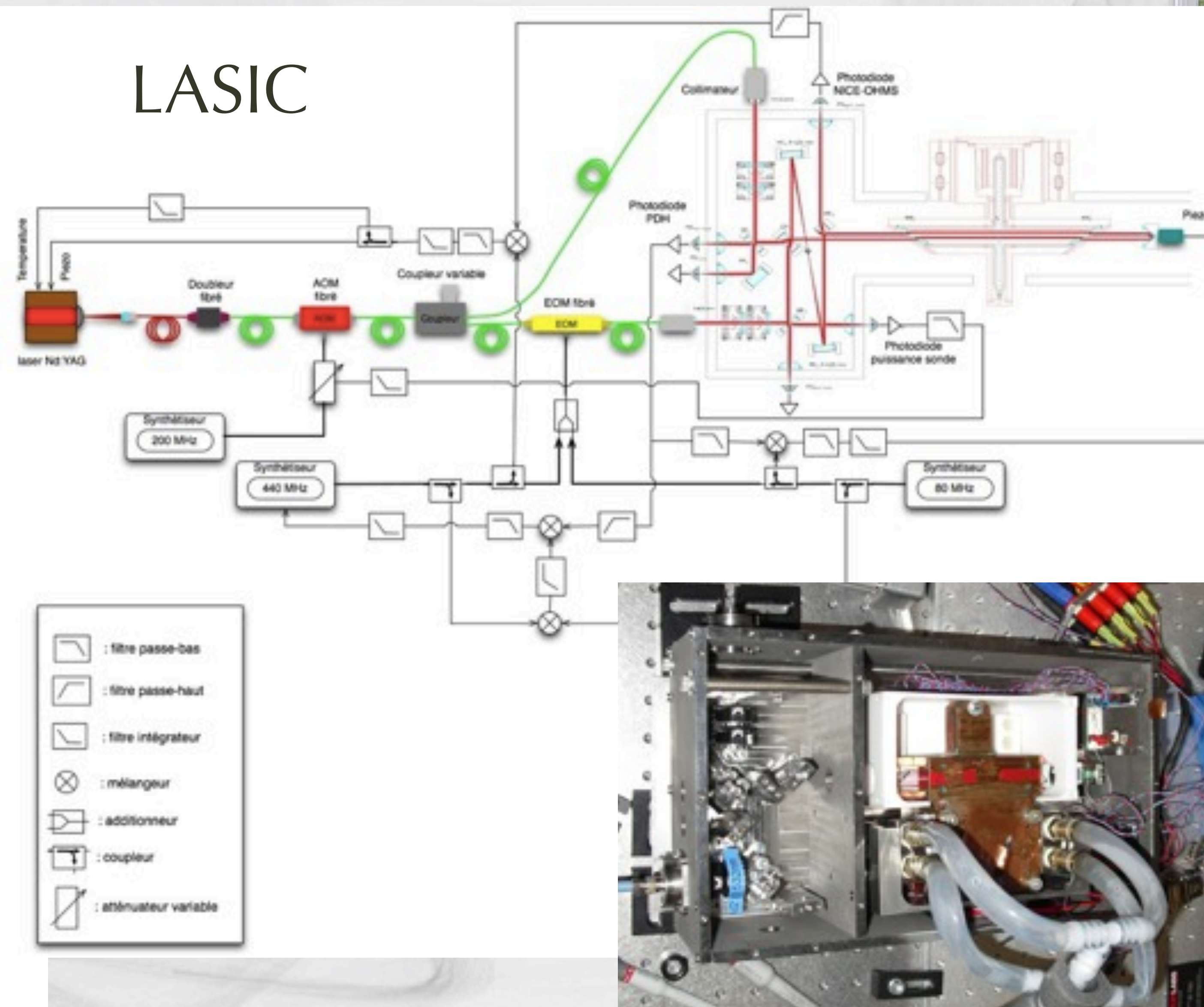
Achieved performance

- ✓ Compatible with LISA requirements (as of 2010) => alternate technology (if needed)
- ✓ Also adequate for future space-based missions (DECIGO, lidars, fundamental physics experiments, etc.)
- ✓ On-going project : LASIC (Laser Stabilized on Iodine in Cavity), increased compactness, robustness and low-frequency performance

Performance with 'standard' technique

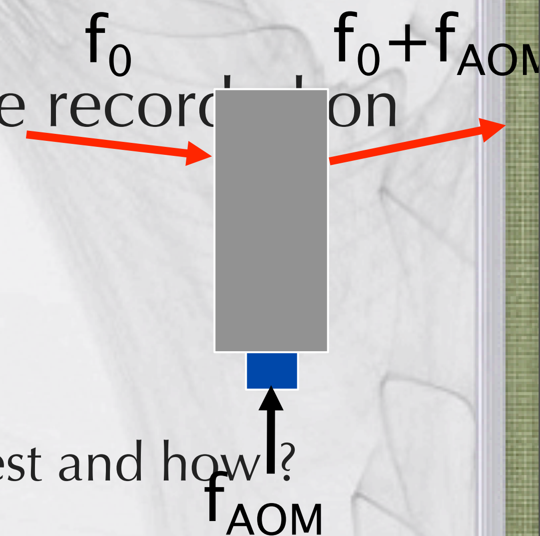


LASIC



Electro-optical demonstrator for time-delay interferometry

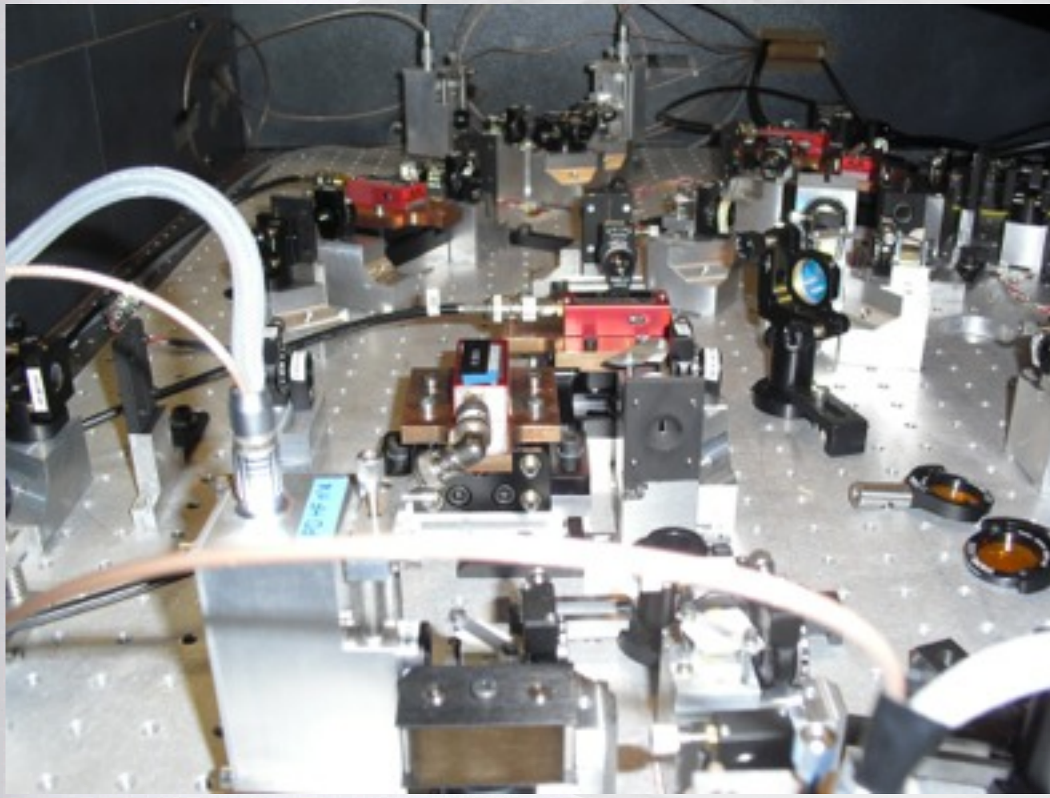
LOT : (e)LISA On Table



- ✓ Goal : generate optical and electronics beat notes, similar to those recorded on (e)LISA
  - Demonstration of noise reduction algorithms on realistic ‘hardware’ data
  - Tests of electronics prototypes (phasemeter, USO, photodiodes, etc) or new analysis methods, ...
  - Preparation for the AIVT (assembly, integration and validation tests) : what to test and how ?

How to simulate the propagation delay (a few seconds) ?

- ✓ Proposed solution : ‘imprint’ delayed noises on the arms of an heterodyne interferometer thanks to acousto-optics modulators



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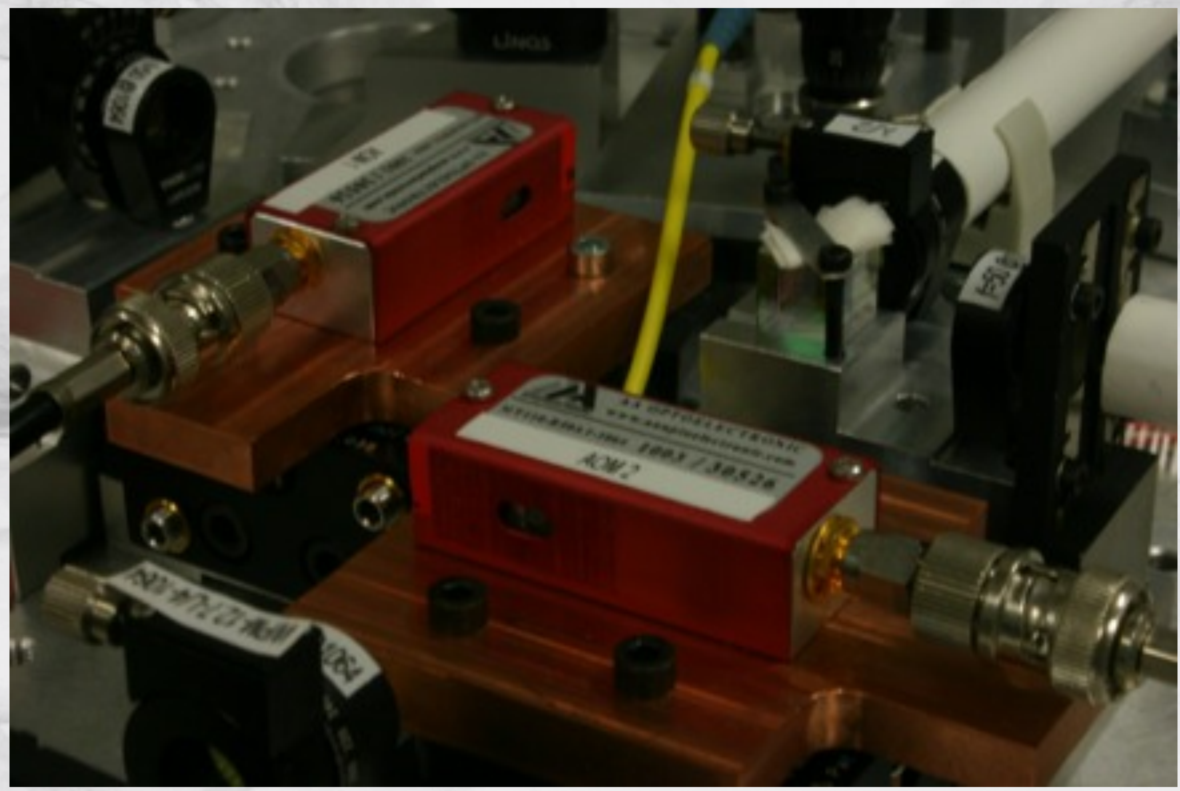
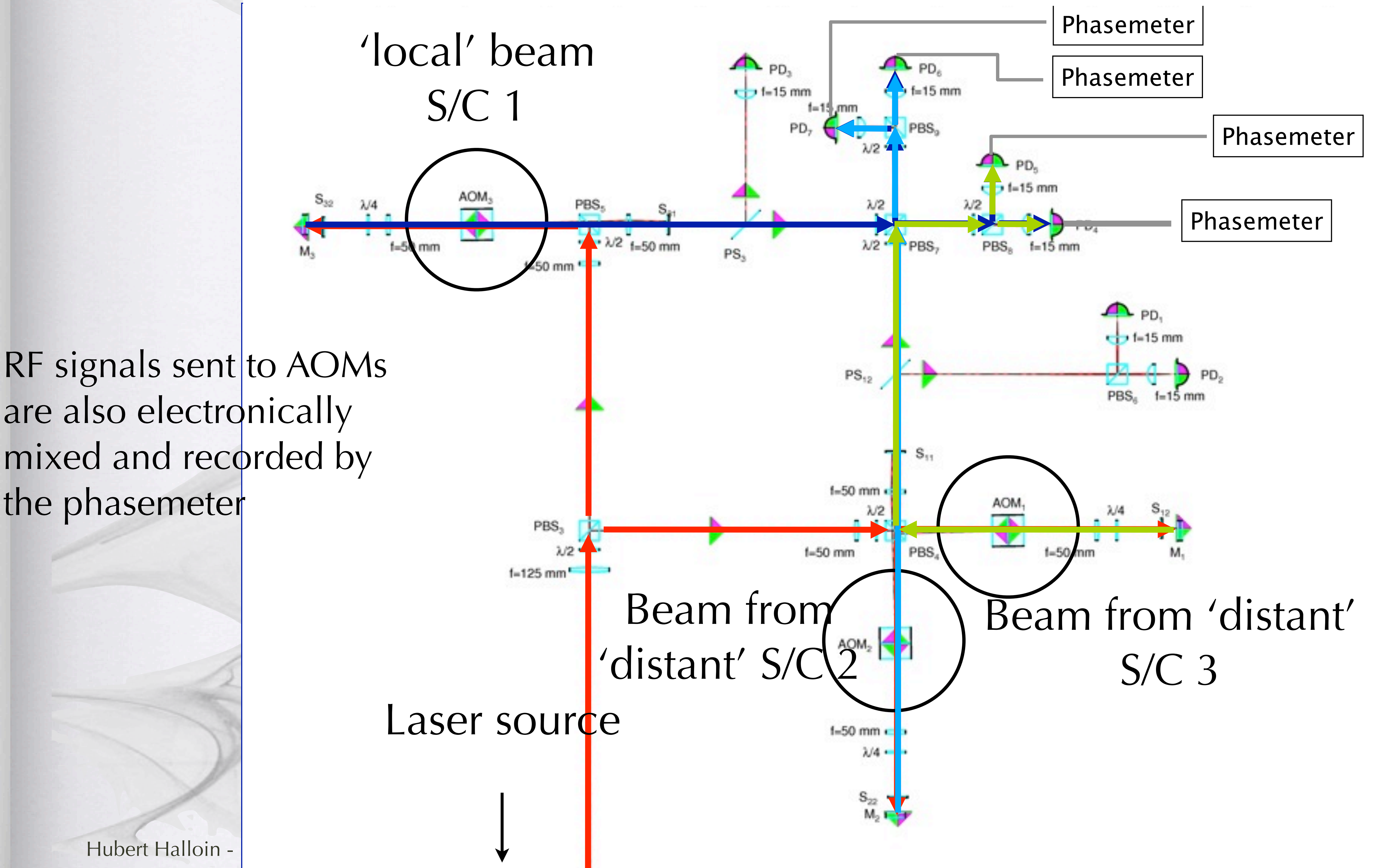


Electro-optical demonstrator for time-delay interferometry

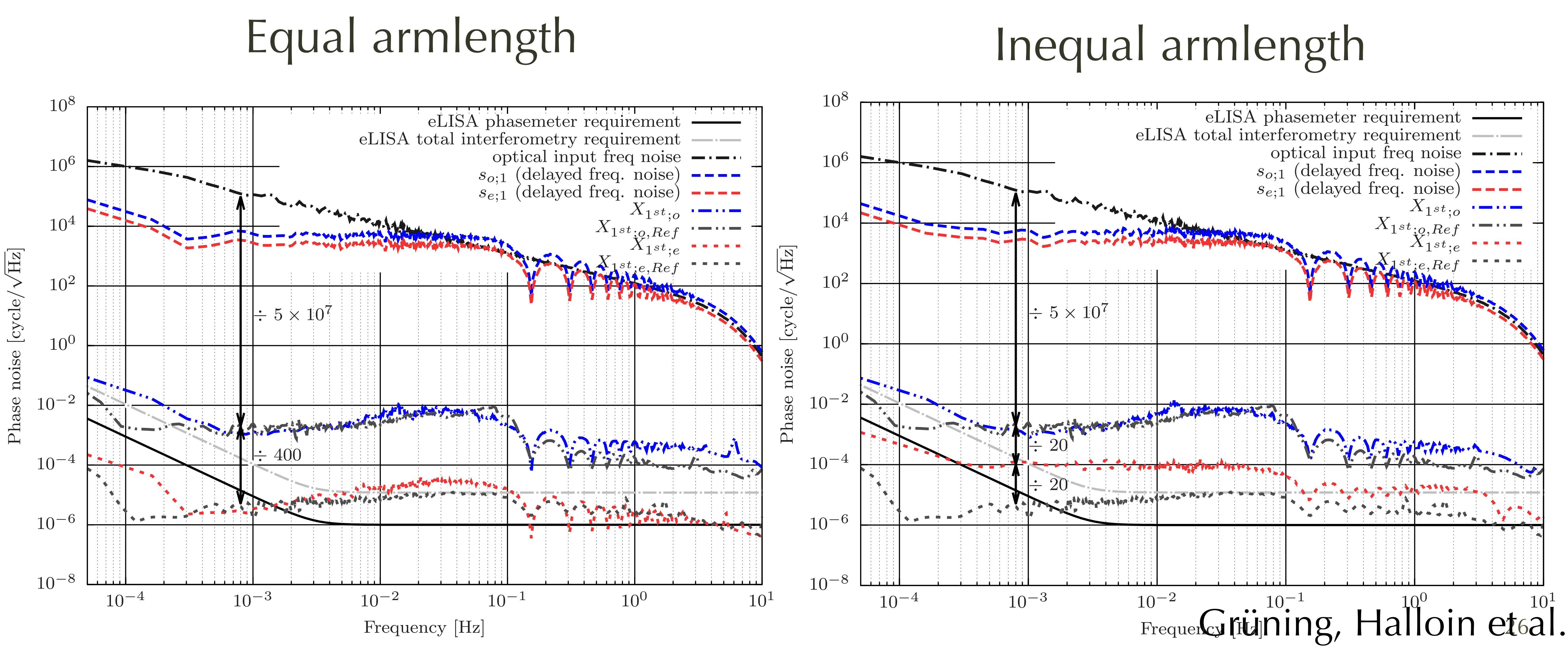
Optical layout of one module (representing one satellite)



Electro-optical demonstrator for time-delay interferometry

Results

- ✓ Validation of the experiment setup
- ✓ Validation of TDI methods on simplified configuration (fixed delays)
- ✓ Noise reduction factor : 10^9 (optical) to 10^{10} (electronics) at 1 mHz.

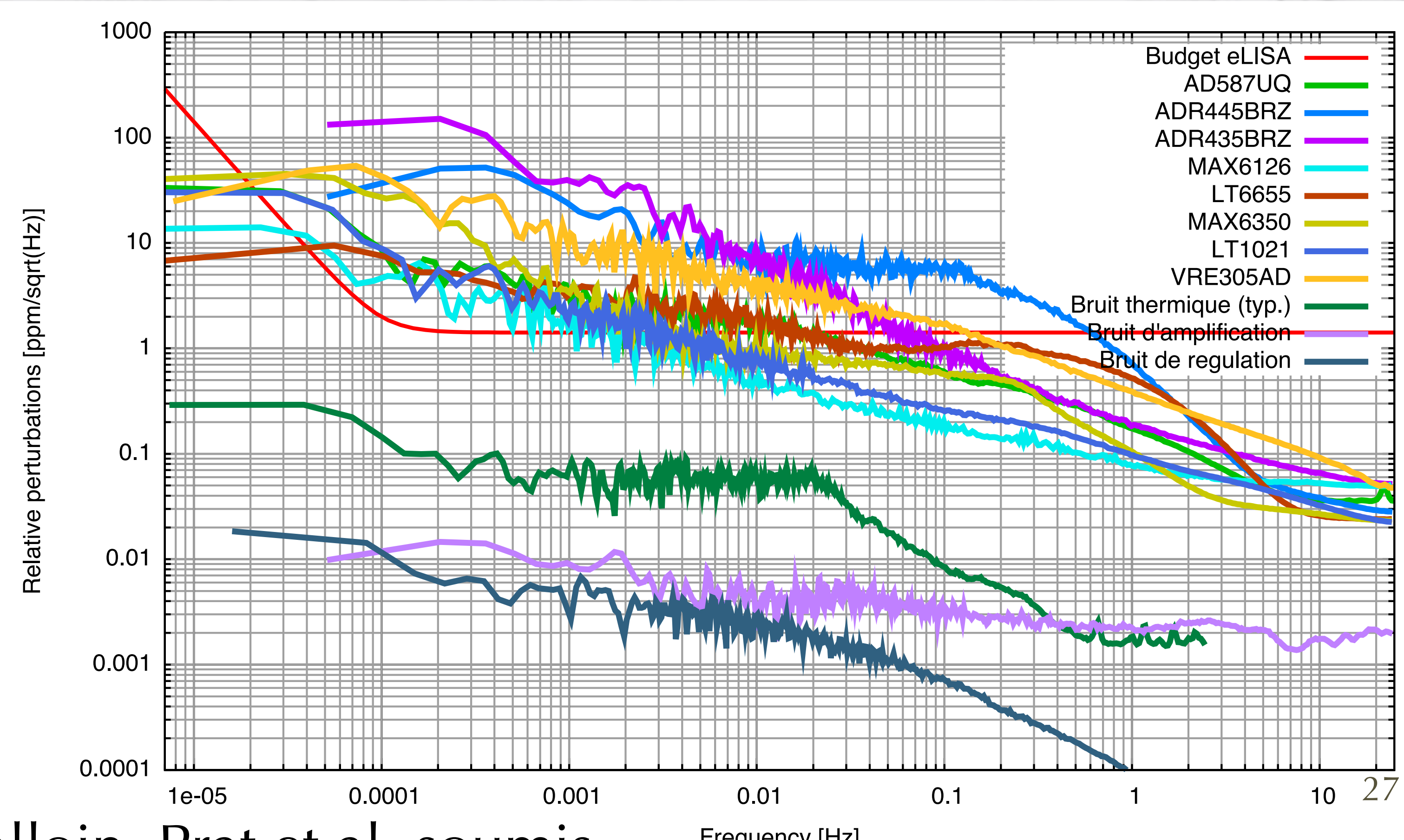


Grüning, Halloin et al., soumis

Low noise- low frequency test facility

Low noise electronics measurements at low frequencies

- ✓ First goal (based on LISA Pathfinder experience) : industrial contractors are sometimes unable to validate the performance of their realizations with the required stability aroiund 1 mHz.
- ✓ ESA suggested to develop a ‘low-noise low-frequency’ test facility at the APC
- ✓ The facility is now operational with first equipments : Faraday cage, precision multimeters, temperature stabilized oven and bath.
- ✓ First measurements : characterization of 8 ‘off-the-shelf’ voltage references and their compatibility with the eLISA requirements
- ✓ Will be coupled with an ultra-stable frequency reference (RF and optical) : ~10^{-15}@1s

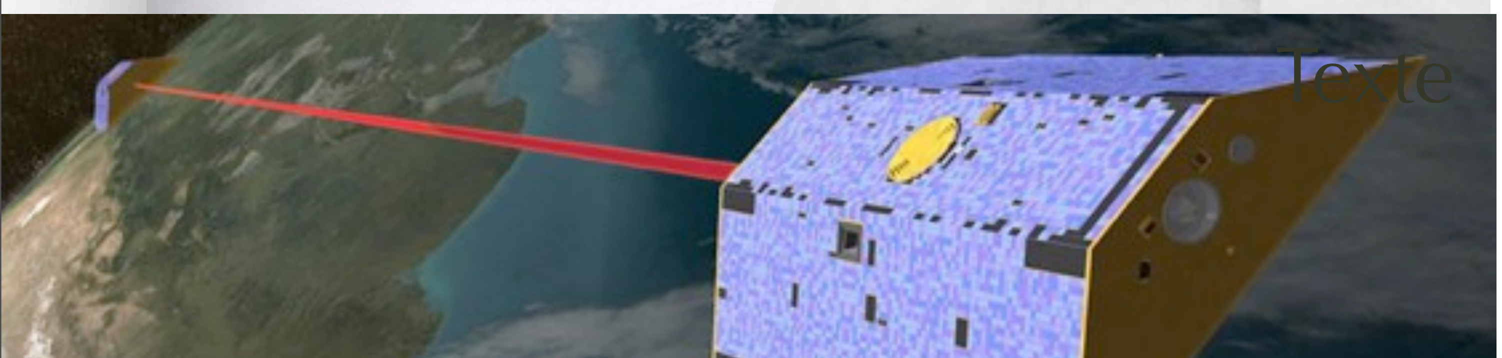


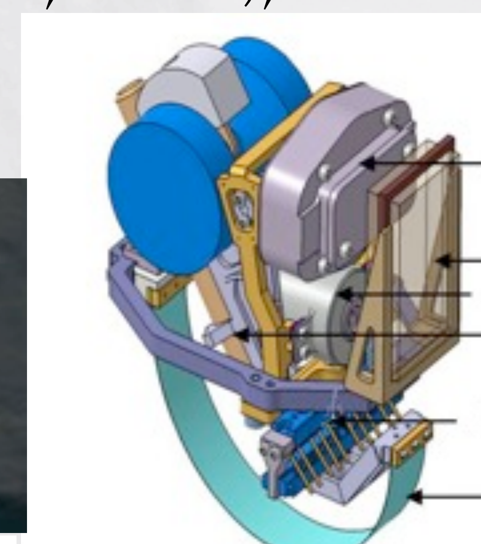
Halloin, Prat et al, soumis

Similarities with other space-based missions

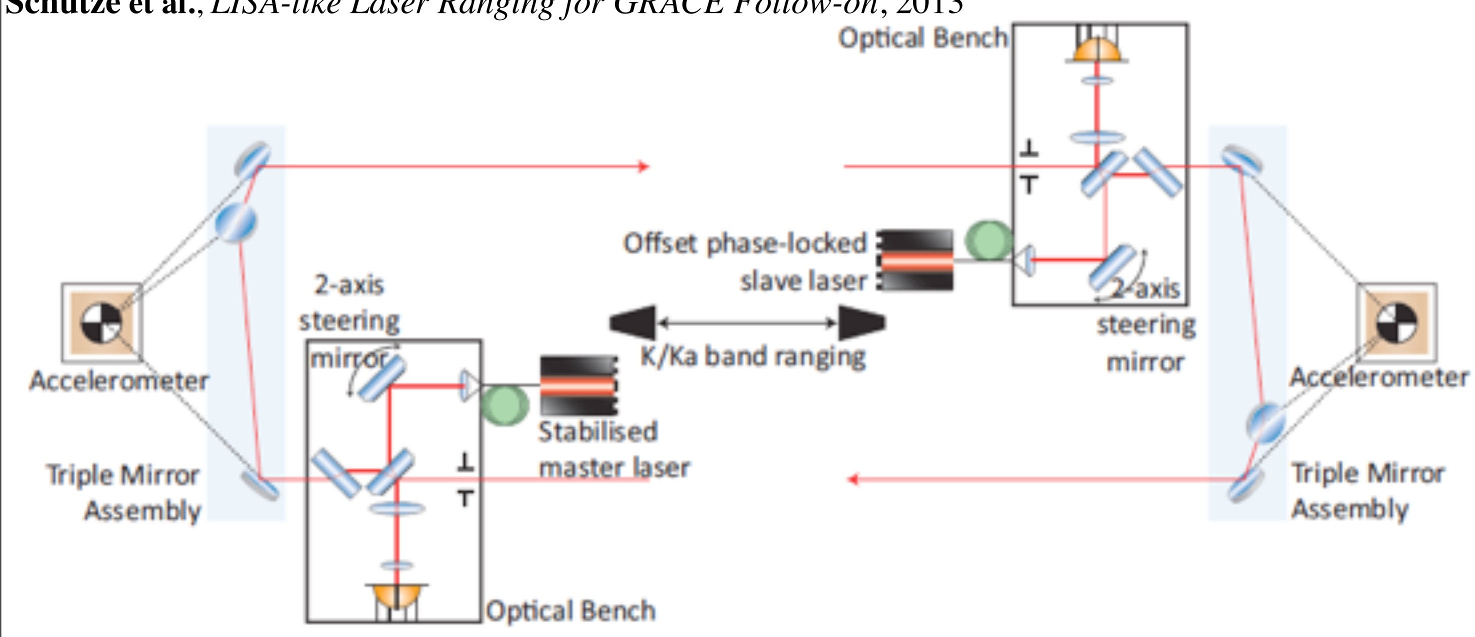
In particular : planetary missions (gradiometer, seismometer)

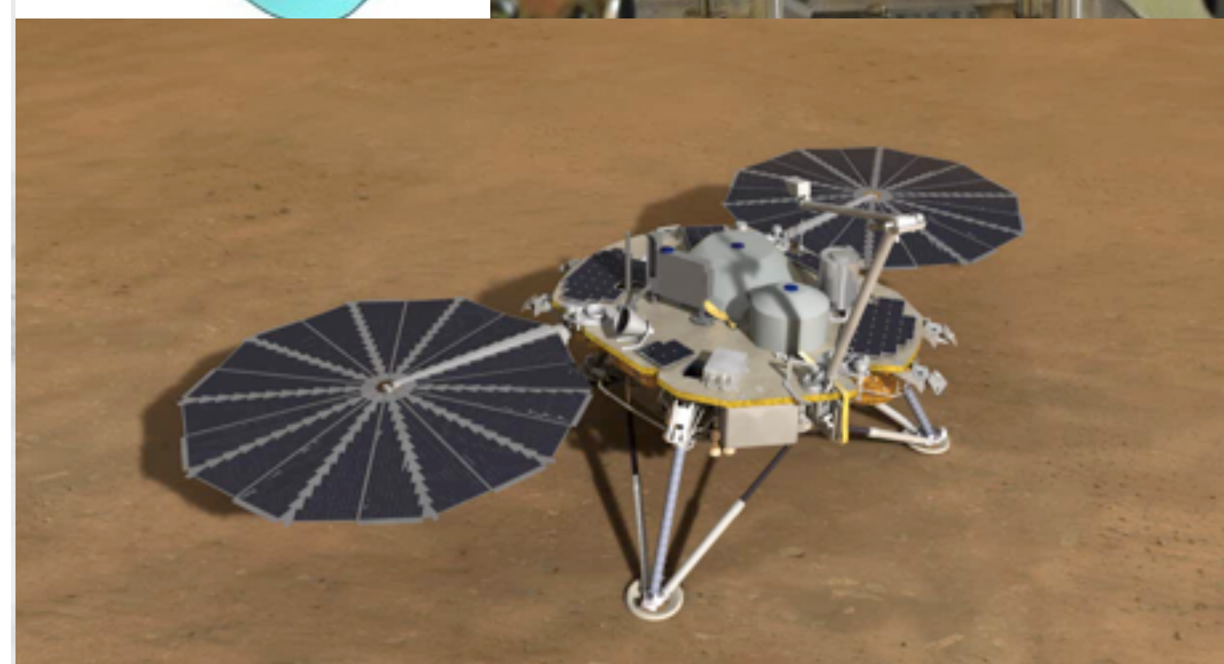
- ✓ Similar frequency bandwidth : ≲ 10Hz
- ✓ Similar environmental constraints : seismic vibrations, temperature fluctuations, 1/f electronics noises, etc.
- ✓ Examples : GRACE Follow-on (gradiometer, 2017), SEIS seismometer onboard InSight (2016)



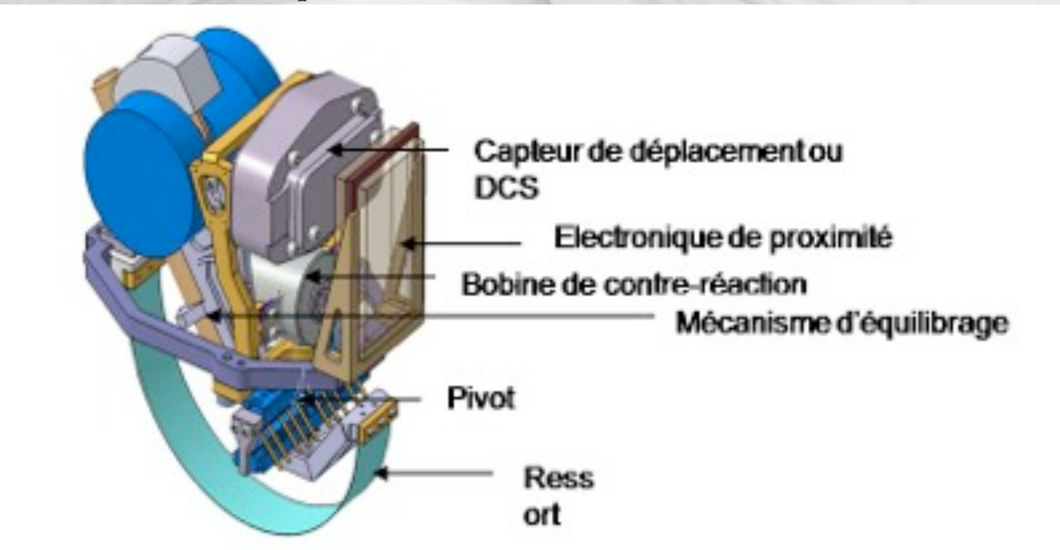


Schütze et al., *LISA-like Laser Ranging for GRACE Follow-on*, 2013



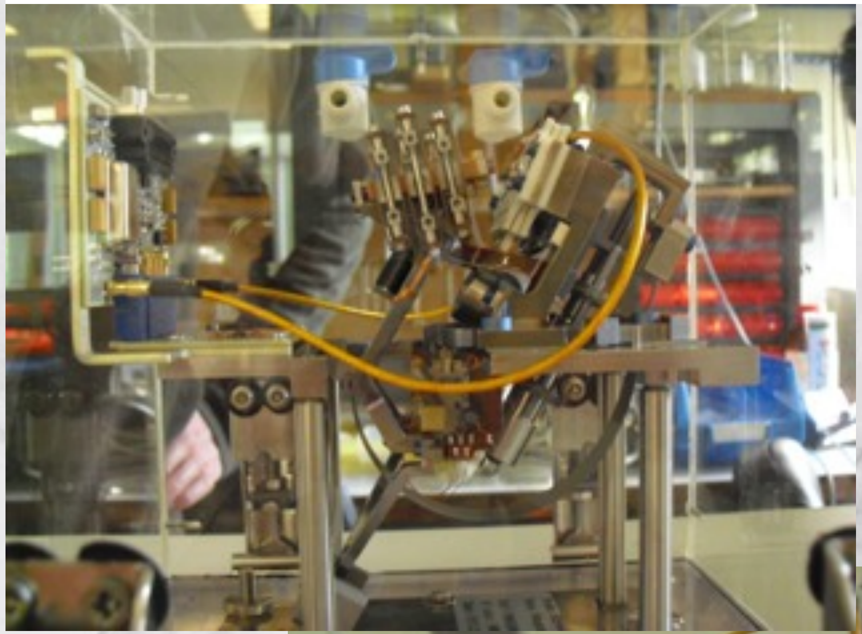


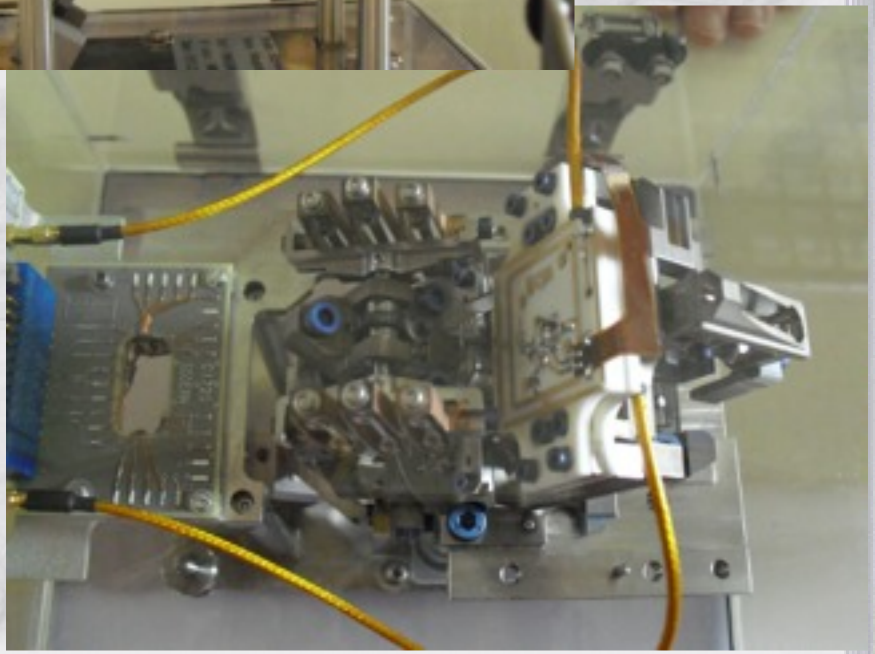
Optical readout for planetary seismometers



On-going collaboration with IPGP

- ✓ Present planetary seismometers use capacitive readout for measuring the position of the lever, which limits the performance at ~100 pm/√Hz.
- ✓ The required front-end electronics induces perturbations and a complex design
- ✓ Goal of the experiment : use of an optical readout to increase the performance and reduce the proximity electronics

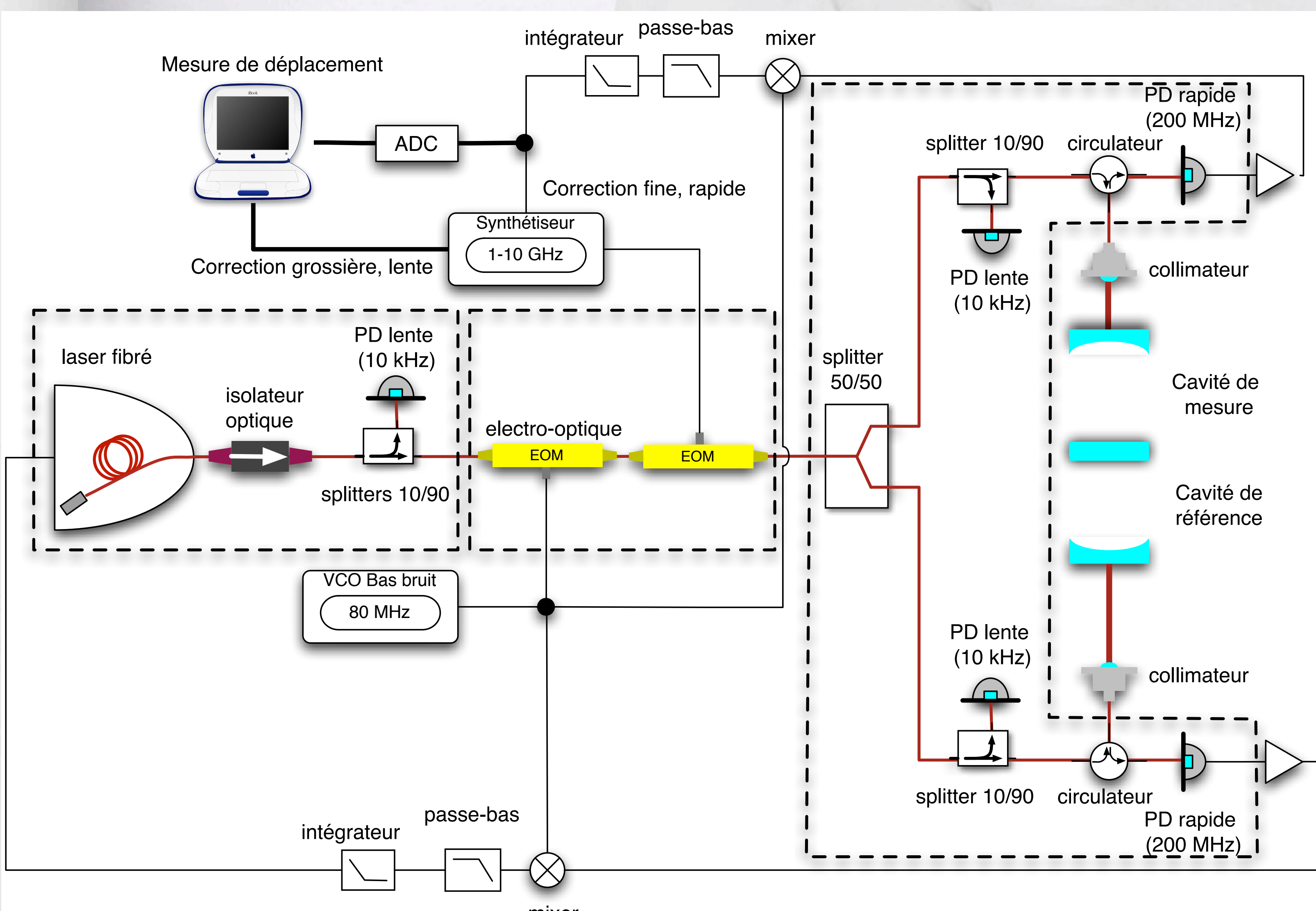


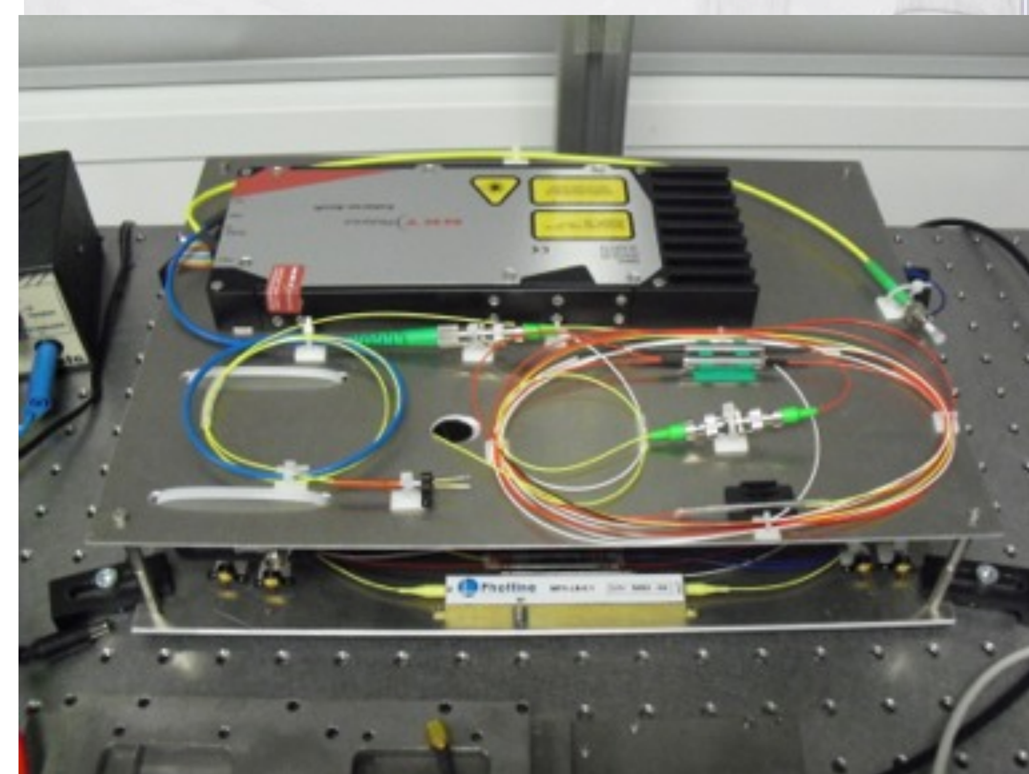


Optical readout for planetary seismometers

Proposed design :

- ✓ Simultaneous frequency locking on 2 back-to-back Fabry-Perot (small) cavities
- ✓ Use of EOMs for side bands frequency locking
- ✓ The displacement is deduced from the difference of the resonant frequencies
  - Common mode noise rejection





Optical readout for planetary seismometers

Theoretical noise levels

- ✓ In-depth study of the thermal noise sources for the cavity
  - The dominant noises are from spacer and mirrors (incl. coating) brownian noise.
  - Thermal noise level is theoretically compatible with 10^{-15} m/√Hz at 10 mHz
- ✓ Influence of the tilt misalignment (seismometer arm movement) on the coupling into the fiber
  - Simulated … and found to be negligible …
- ✓ Vibration insensitive cavity design
- ✓ Cavity manufacturing expected soon …