LISA

A spaceborne observatory for detecting gravitational waves
Focus on time & frequency challenges

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for the LISA France collaboration

Workshop « Application des technologies du Temps-Fréquence au domaine de la défense et du spatial »

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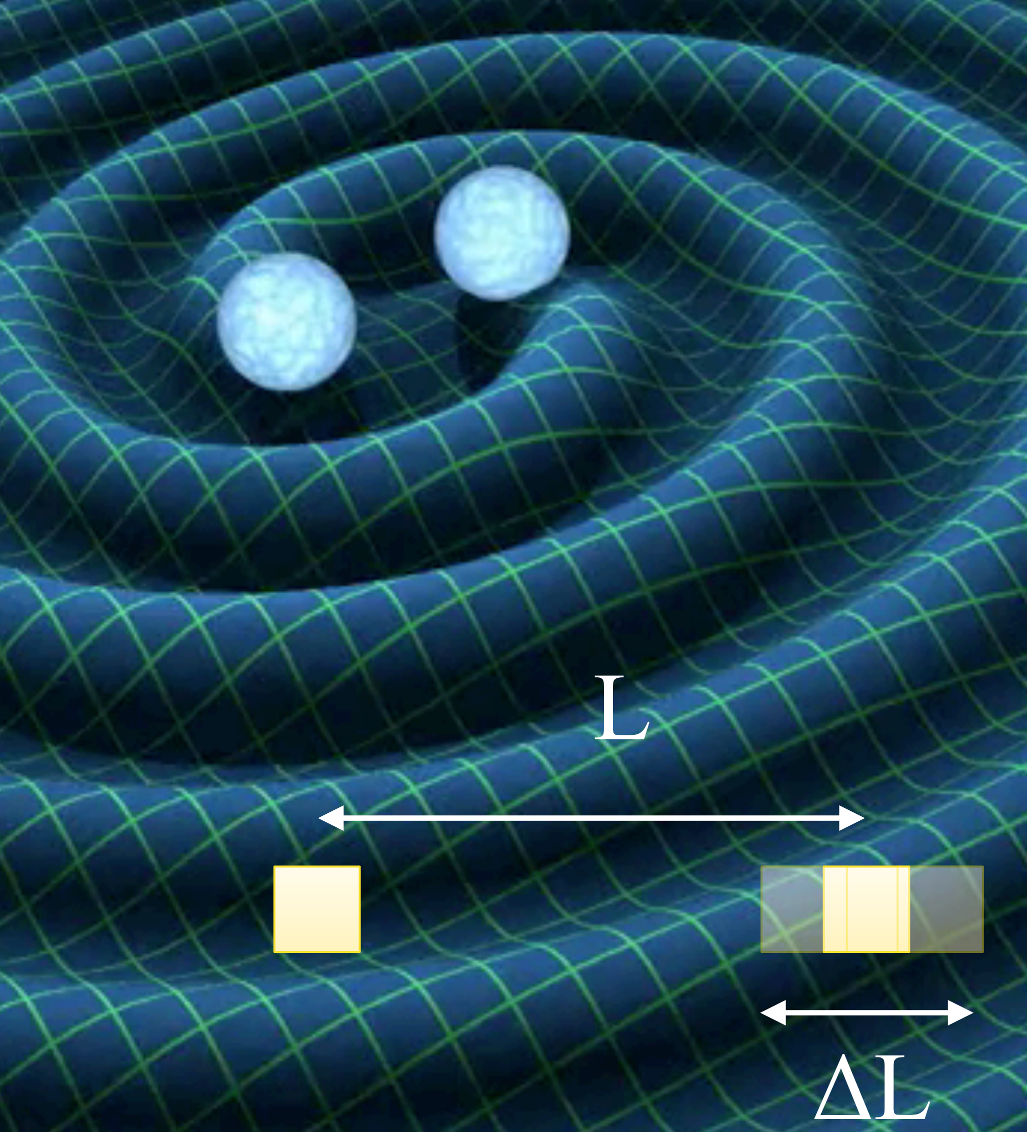
The gravitational waves in a nutshell

- What is a gravitational wave ?
  - Elastic deformation of space-time metric
  - Observable as a fluctuation of the distance between inertial masses

- A new window on the Universe
  - Observing the General Relativity in action !
  - Unique knowledge on compact objects and fondamental physics
  - Detectable at large distances



$$\frac{\Delta L}{L} = \frac{h}{2}$$

Orders of magnitude

- The gravitational waves in 3 equations
  - Gravitational system compactness

$$\frac{v^2}{c^2} \approx \frac{GM}{Rc^2} = \Xi < 1$$

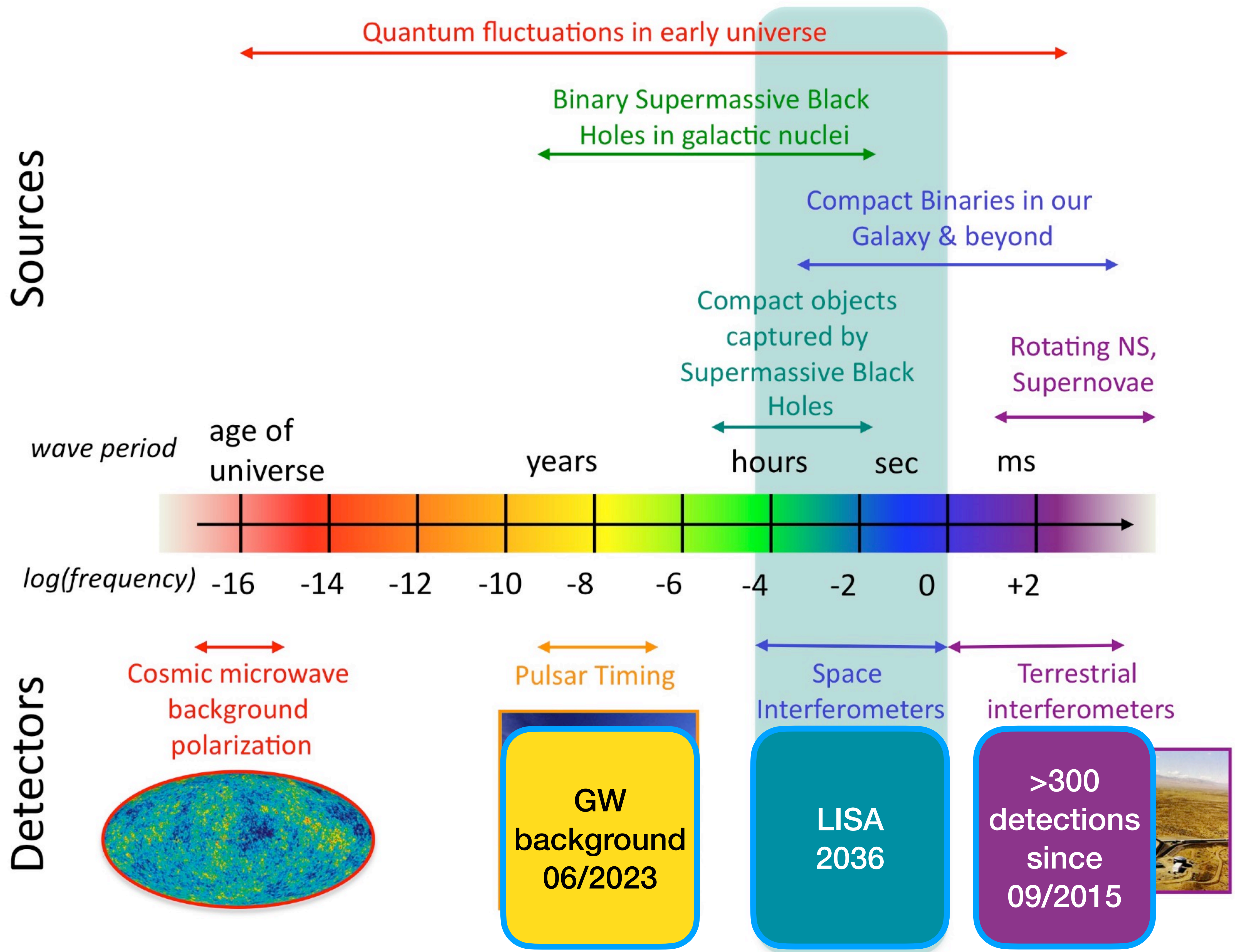
  - GW Amplitude

$$h = 2\frac{\Delta L}{L} \lesssim \frac{\Xi}{10^{-1}} \cdot \frac{M}{10^6 M_\odot} \cdot \frac{10\ \mathrm{Gpc}}{D_l} \quad \mathrm{nm/Mkm}$$

  - GW Frequency

$$f \approx 14 \times \left(\frac{\Xi}{10^{-1}}\right)^{3/2} \cdot \frac{10^6 M_\odot}{M} \quad \mathrm{mHz}$$

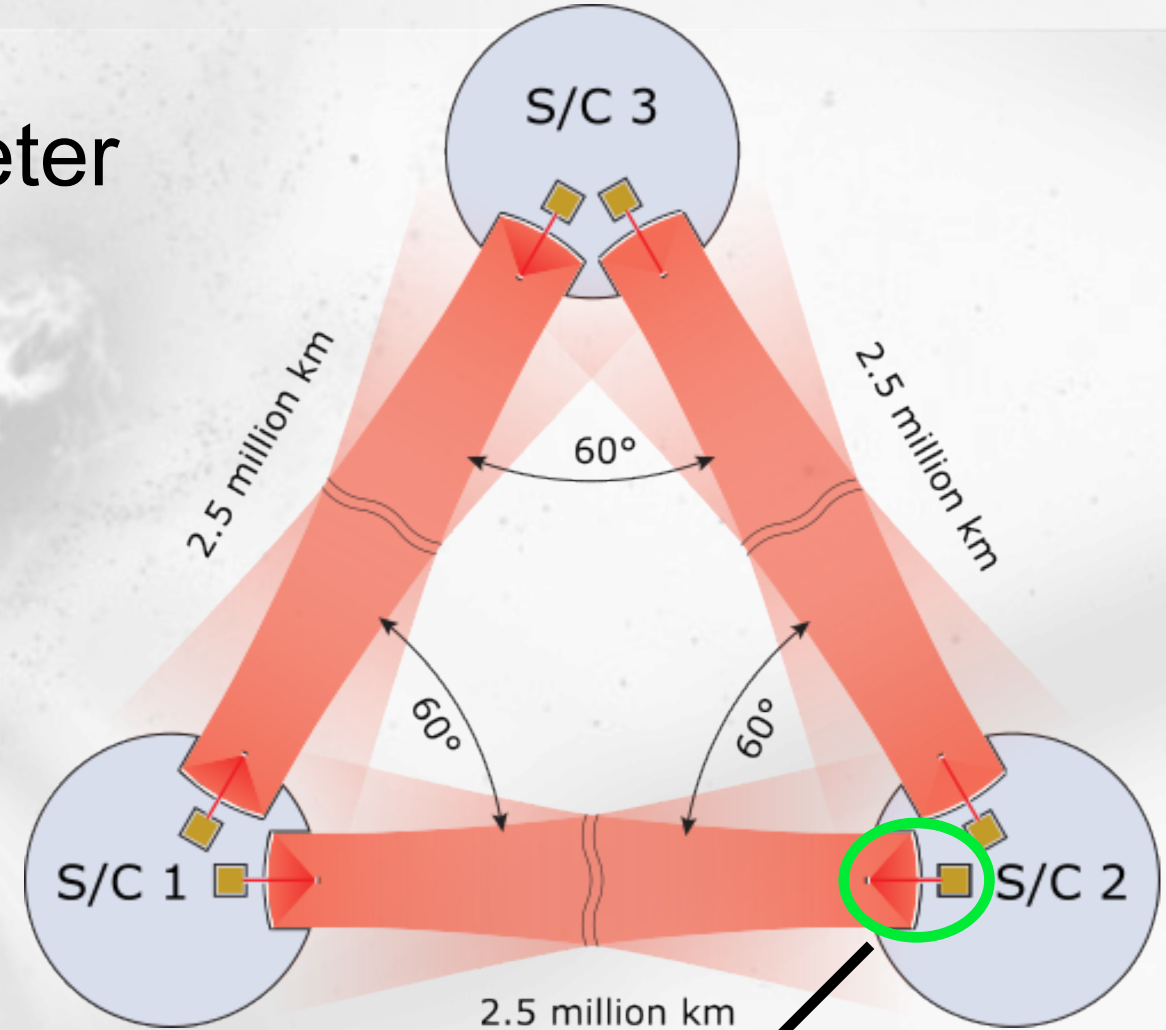
GW astronomy has started !

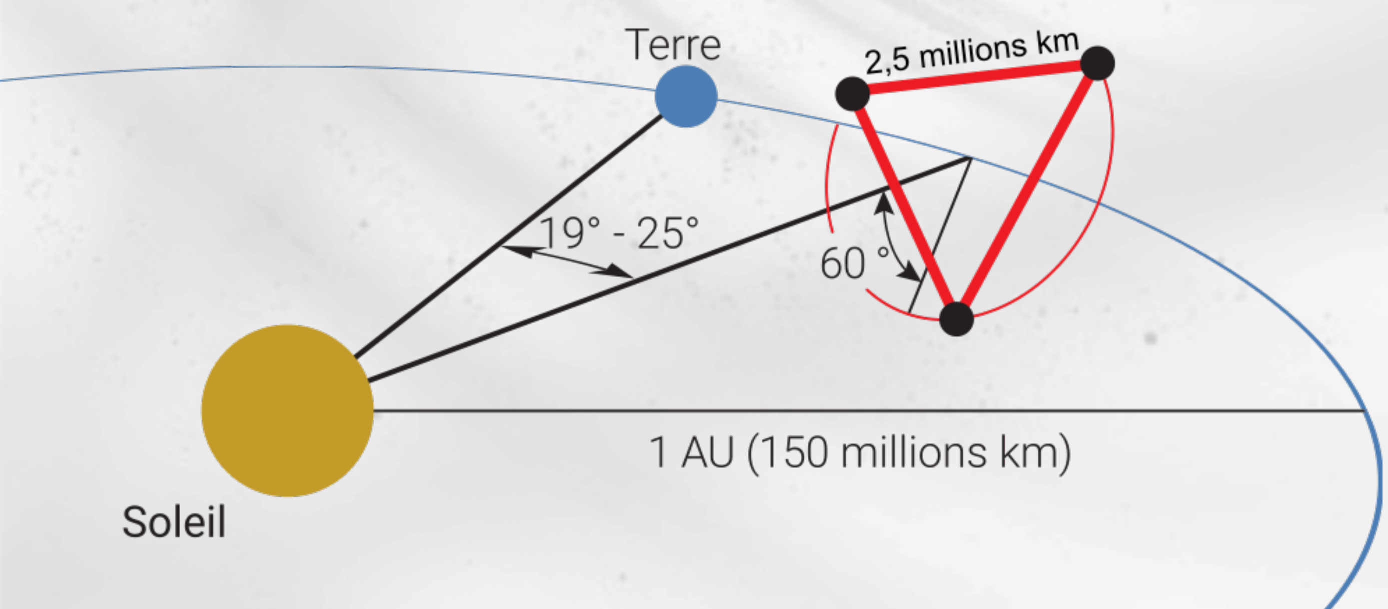


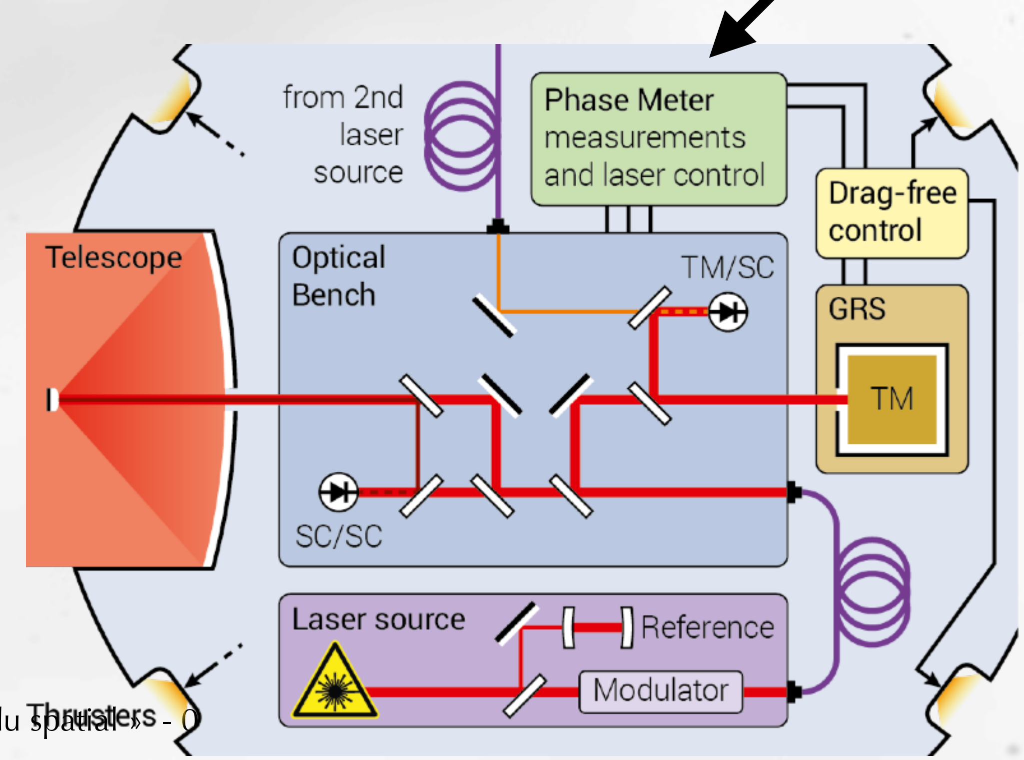
Credit: NASA Goddard Space Flight Center

LISA a new class of instrument

- LISA = giant spaceborne interferometer
  - 3 arms, 2.5 Mkm long
    - ~7 x Earth - Moon distance
  - 2 inertial masses per spacecraft
    - Drag-free system to compensate the solar pressure (and other disturbances)
  - Metrology noise **≤10 pm/√Hz à 10 mHz**
    - ⇒ Sensitivity of ~1 pm/Mkm (10^{-21})

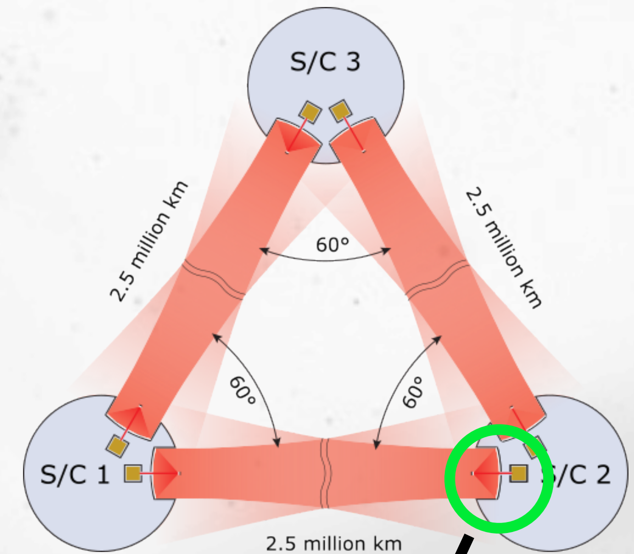




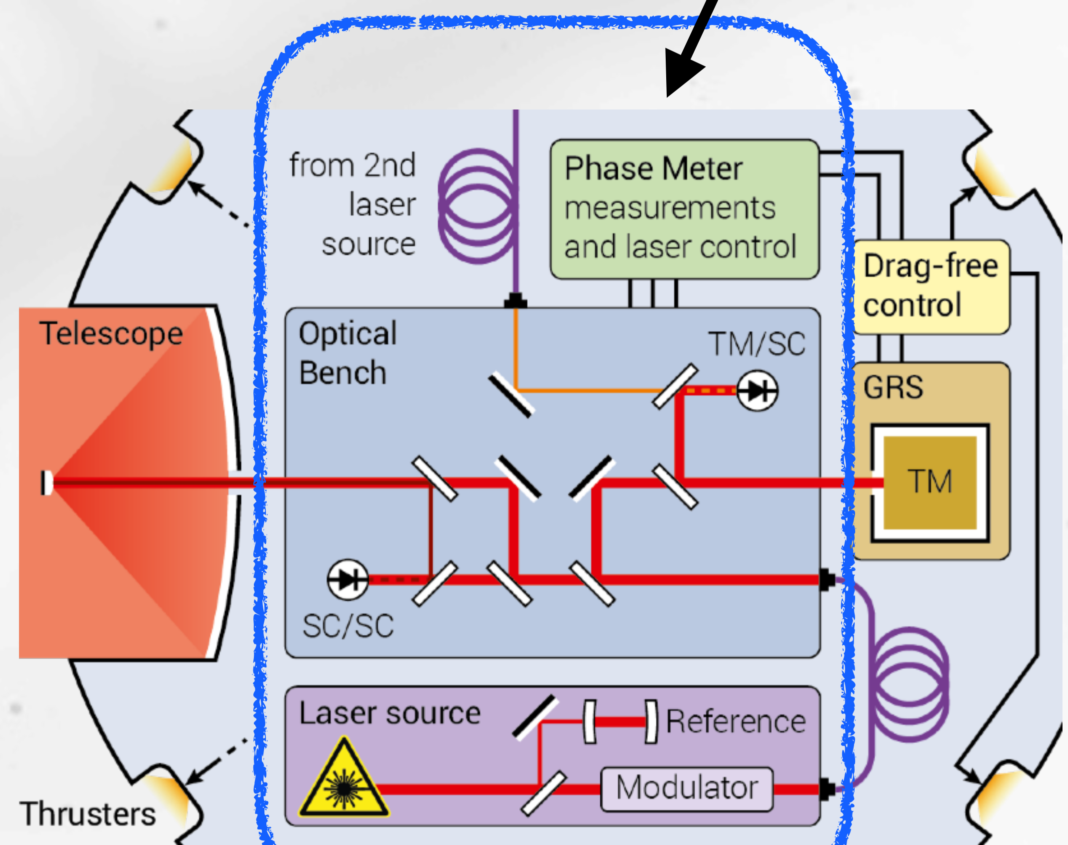


French contributions to LISA

- 3rd ESA 'Large' Mission
  - Following LISA Pathfinder 2015-2017
  - Selected in June 2017
  - **Adopted in January 2024**
  - **Presently in phase B2**
  - Expected launch in 2035
  - ~1900 Consortium Members

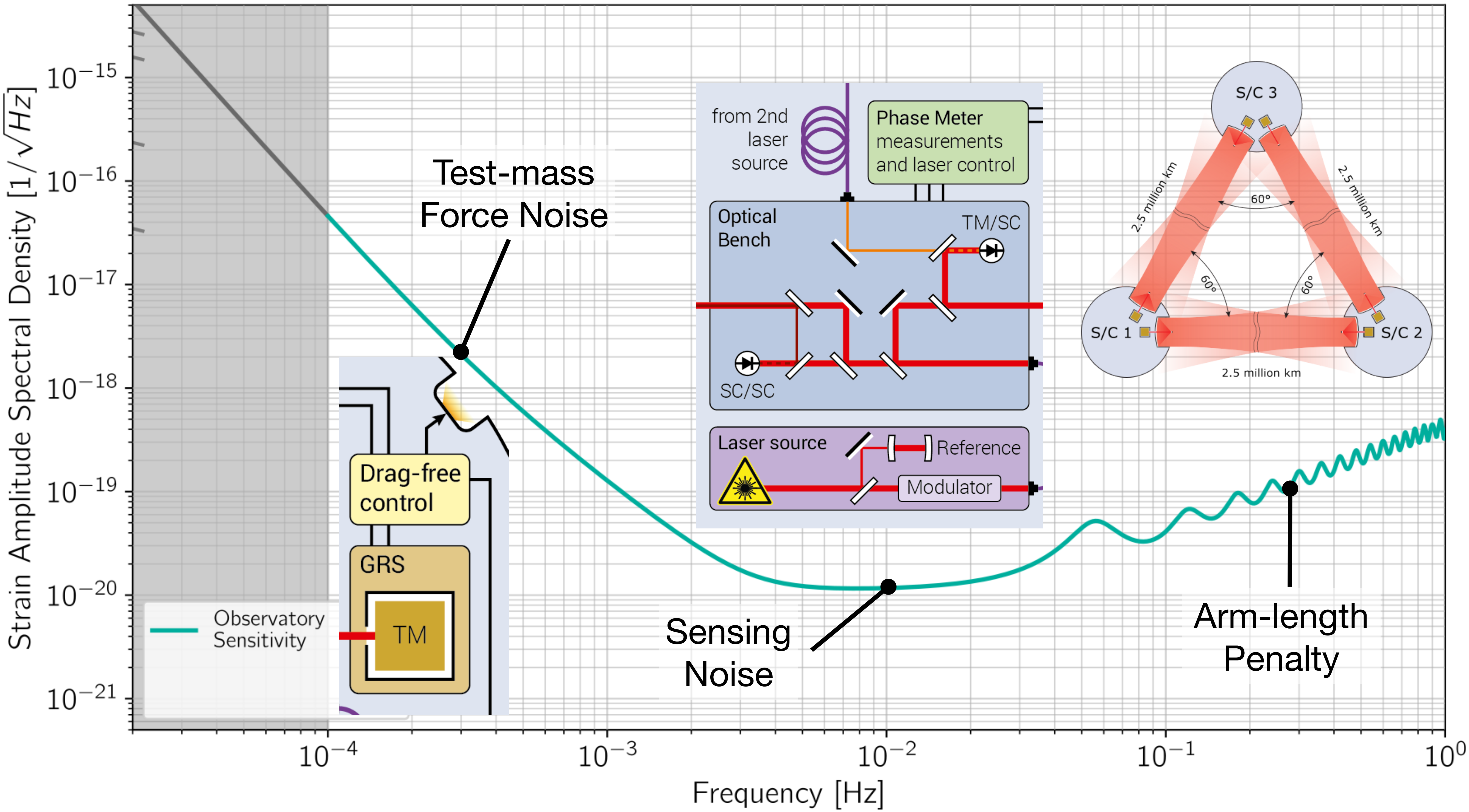


- 3 major contributions for France
  - Distributed Data Processing Center
  - Ground test and validation of the LISA metrology 'Core'
  - 'Performance & Operations'



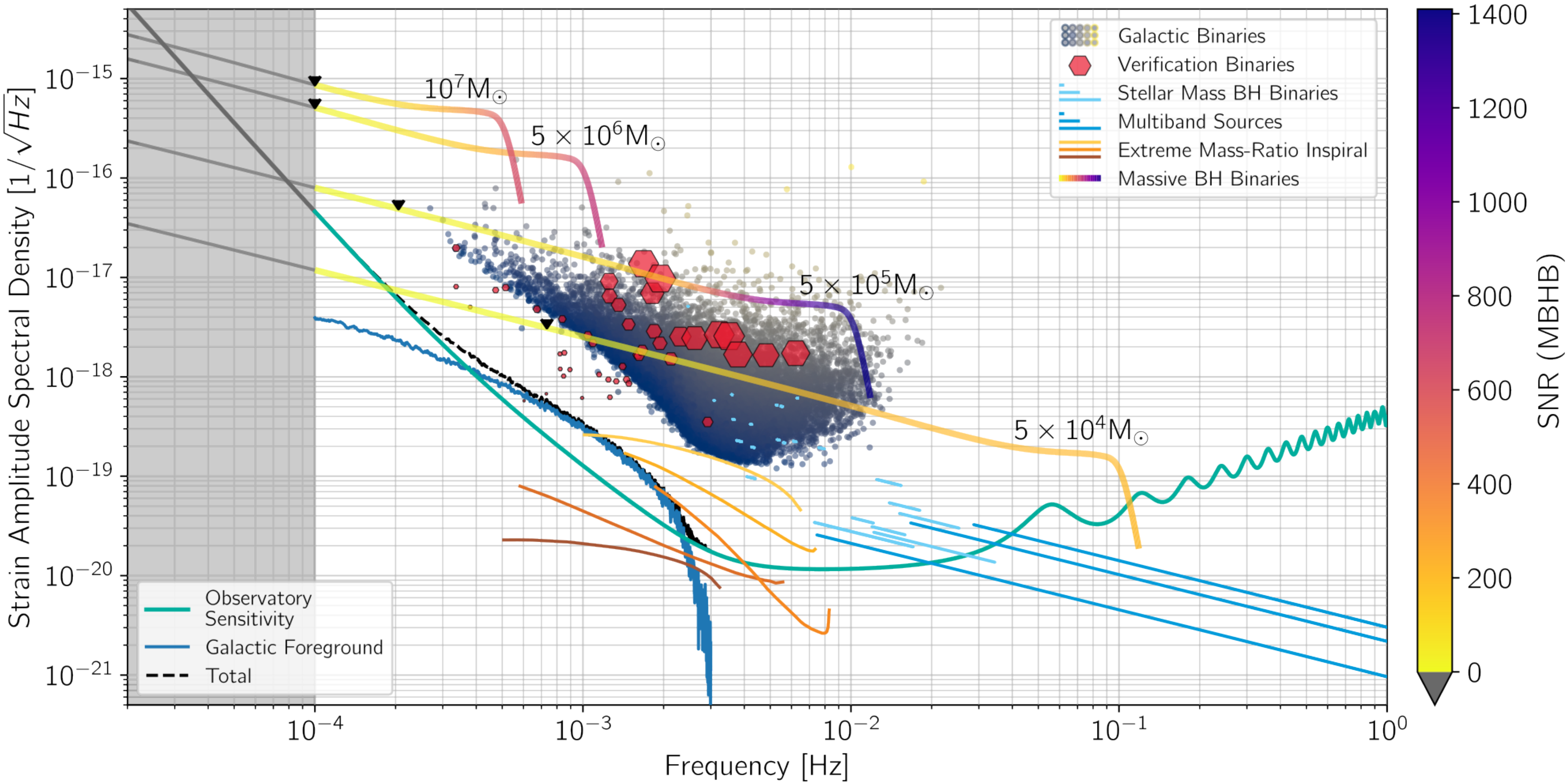
- 17 French research institutes on LISA
  - APC, ARTEMIS/OCA, CNES, CPPM, Fresnel, IAP, IP2I, IPhT, IRAP, IRFU, L2IT, LAM, LPCC, LPC2E, LUTH, LTE/Obs. Paris, ONERA

LISA Sensitivity



Main LISA sources

- More infos ?
  Read the LISA 'Red Book' : https://www.cosmos.esa.int/web/lisa/lisa-redbook



Laser frequency noise

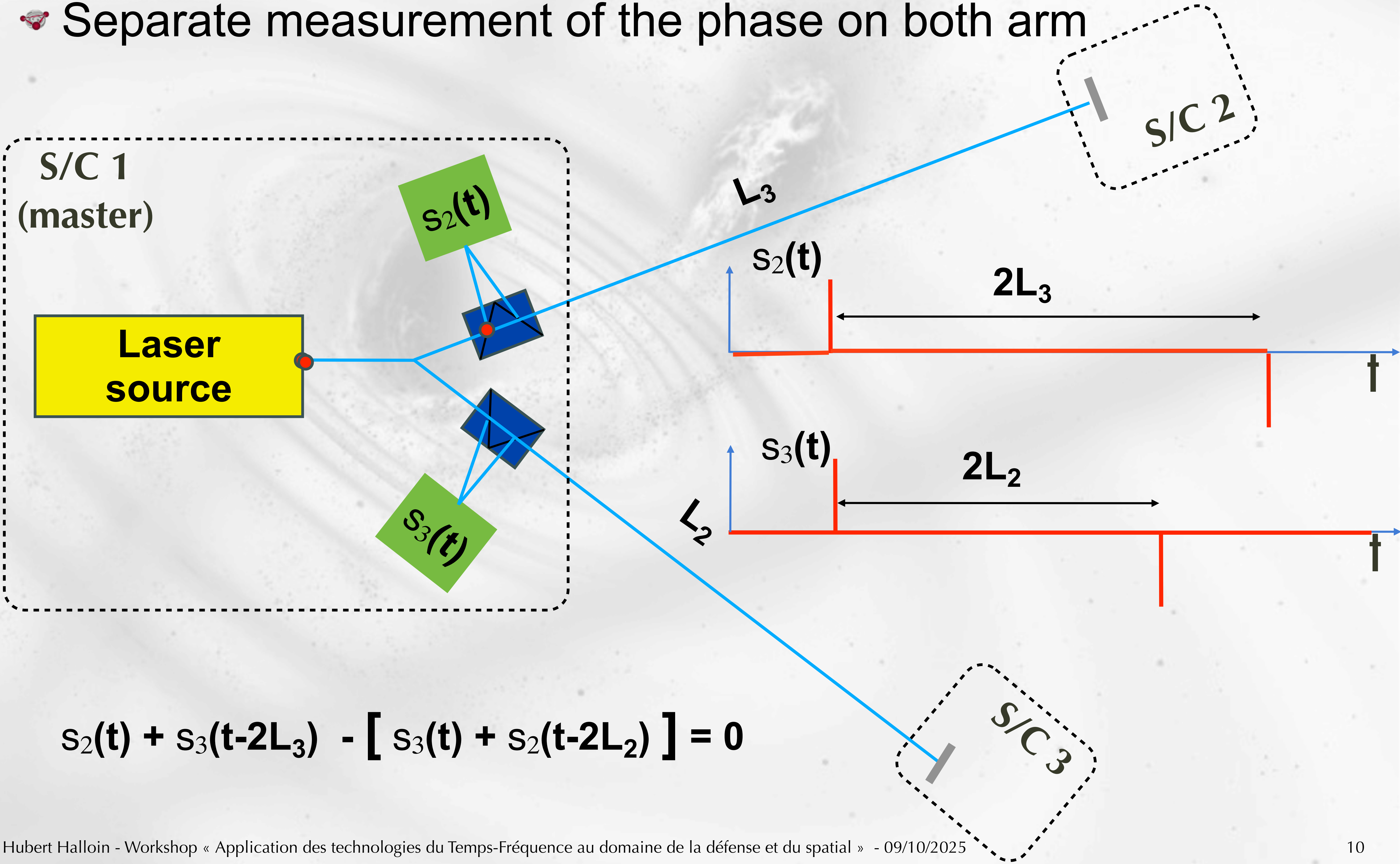
- Frequency instability of a laser beam couples to phase noise for unequal arm length

$$\delta\Phi = \Phi(t - 2L/c) - \Phi(t - 2(L - \Delta L)/c)$$
$$\approx \frac{2\Delta L}{c}\frac{\partial\Phi}{\partial t}(t - 2L/c) = \frac{2\Delta L}{c}2\pi\delta\nu$$
$$\Rightarrow \delta x = \lambda\frac{\delta\Phi}{2\pi} = 2\Delta L\frac{\delta\nu}{\nu}$$

- For LISA :
  - ΔL~10 000 km (inertial orbits), λ=1064 nm ⇒ δν~10^{-6} Hz/√Hz in the range [0.1 mHz : 10 Hz]
- Best 'transportable' stable laser at ~10 Hz/√Hz …
  - In LISA : ultra-stable Fabry-Perot cavity
- How to reduce the frequency noise by 7 orders of magnitude ?
  - Time Delay Interferometry
  - Post processing for digital reconstruction of virtual equal arm length interferometers

Time Delay Interferometry

- Separate measurement of the phase on both arm



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

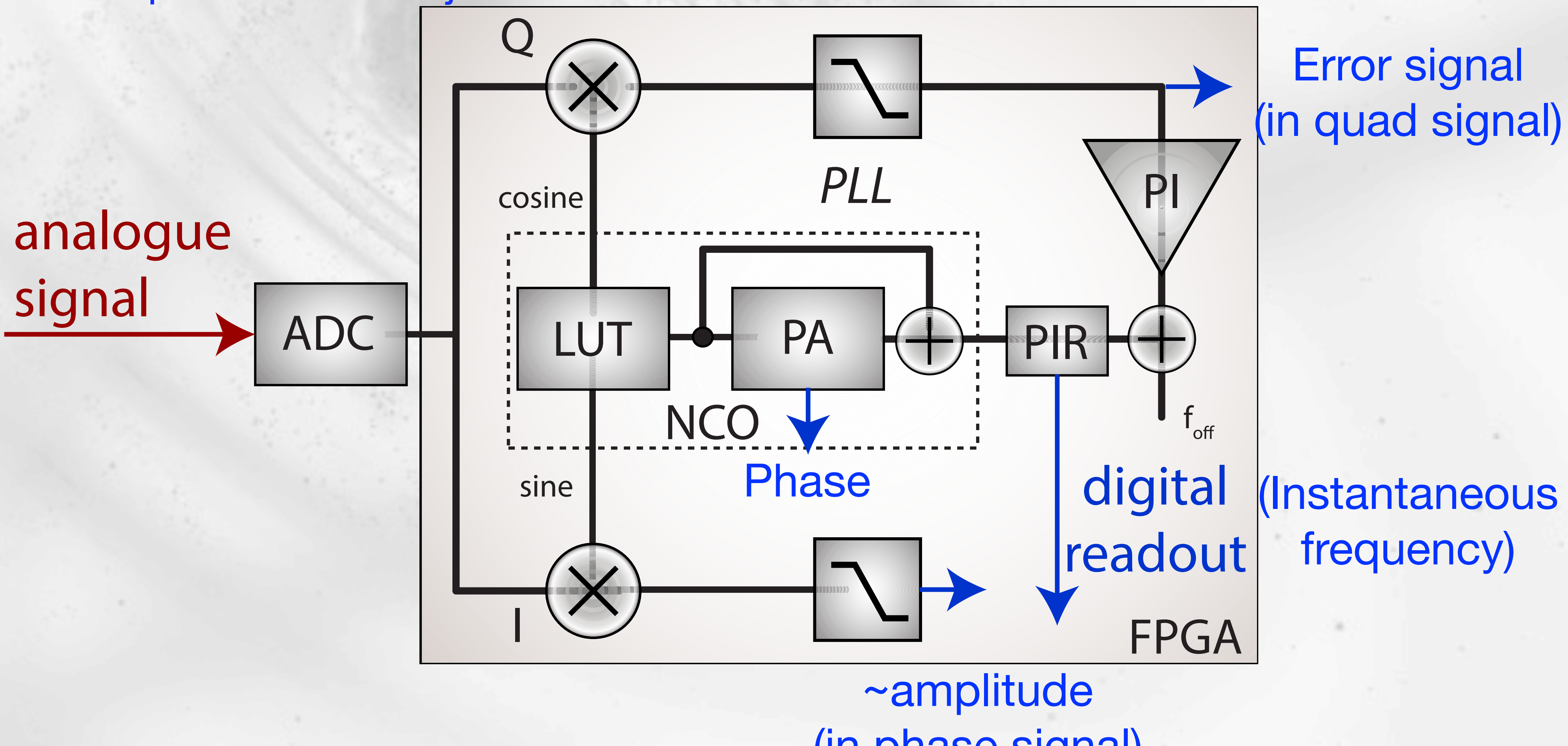
Time Delay Interferometry

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

- The arm length difference is replaced by the uncertainty on the *knowledge* of the armlength
- Cancellation of propagated noises (mostly laser phase noise)
- Transfer function shaping (no signal at f multiple of 1/(2L) ~60 mHz)
- ⇒ Requires the knowledge of :
  - S/C distances with a few meters accuracy
  - Relative clock drifts at a few ns

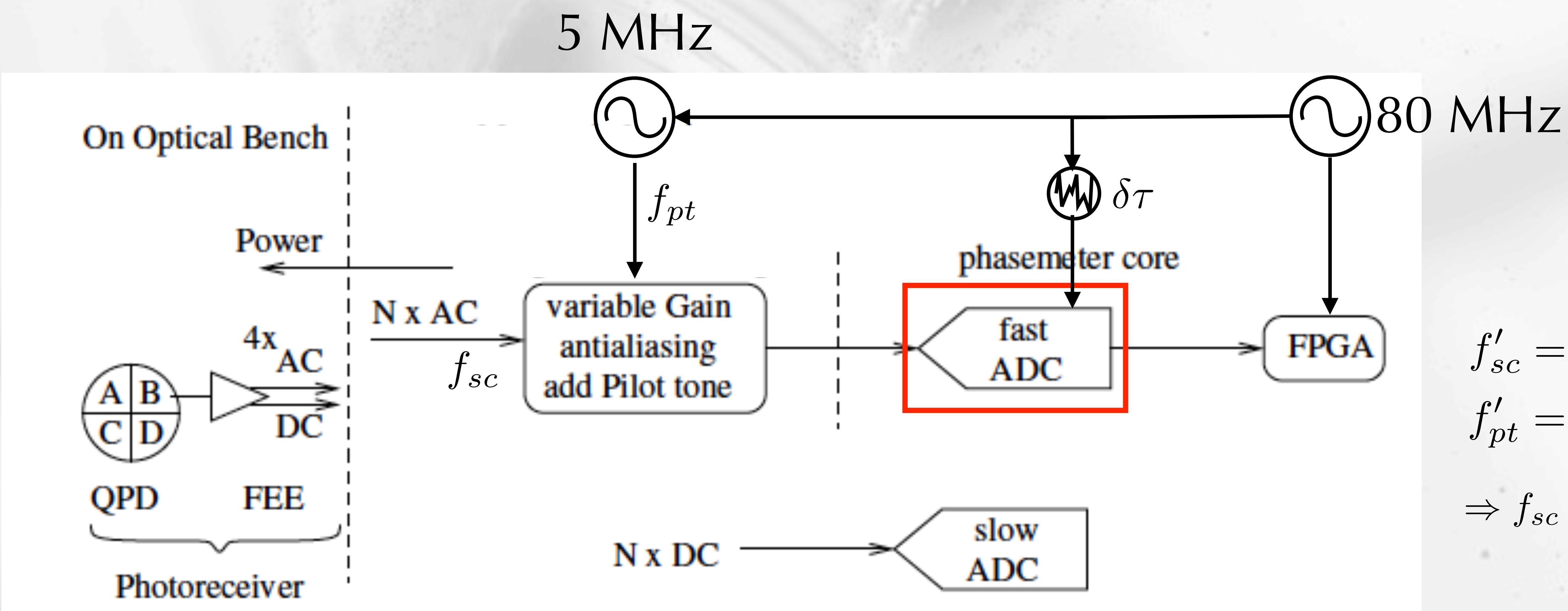
Phase measurement stability

- S/C to S/C Doppler shifts require heterodyne interferometry
  - ~ +/-8 MHz frequency shifts on months timescale
  - GW signature as tiny phase fluctuations in 0.1 mHz to 1 Hz
  - → beatnote frequency between 5 and 25 MHz
  - → expected noise floor at ~1 µcycle/√Hz w.r.t RF clock (i.e. 40 fs/√Hz at 25 MHz)
- In LISA : direct numérisation and digital PLL
  - Pros : preserve the signal amplitude, flexible, reproducible noises and easier synchronization
  - Cons : quantization and jitter noises



Phase measurement stability

- ADC jitter noise
  - The ADC sampling jitter noise induces an unacceptable phase noise
  - Corrected by adding an RF signal of known frequency on the same ADC



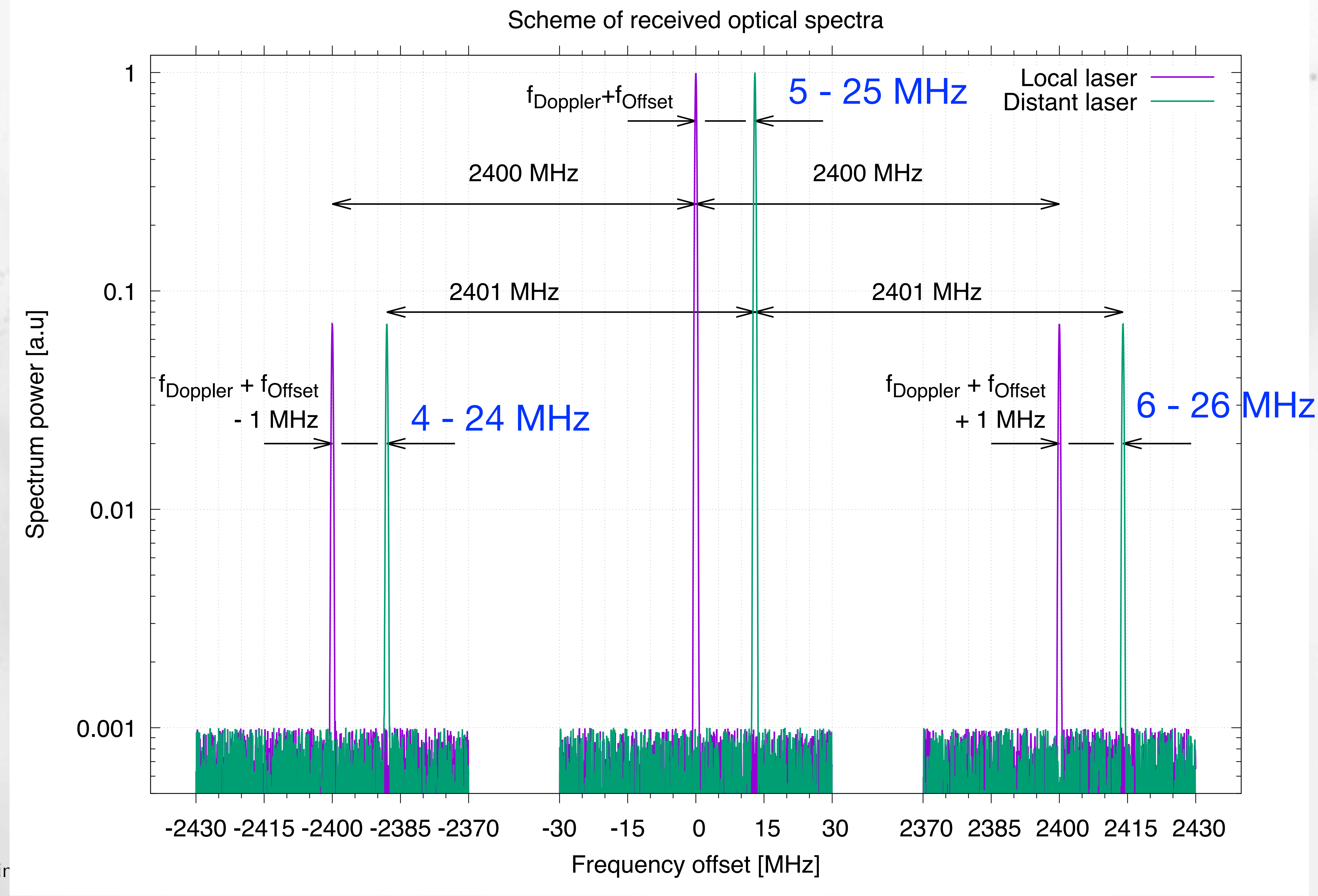
$$f'_{sc} = f_{sc}(1 + \dot{\delta\tau})$$

$$f'_{pt} = f_{pt}(1 + \dot{\delta\tau})$$

$$\Rightarrow f_{sc} = f'_{sc} \times \frac{f_{pt}}{f'_{pt}}$$

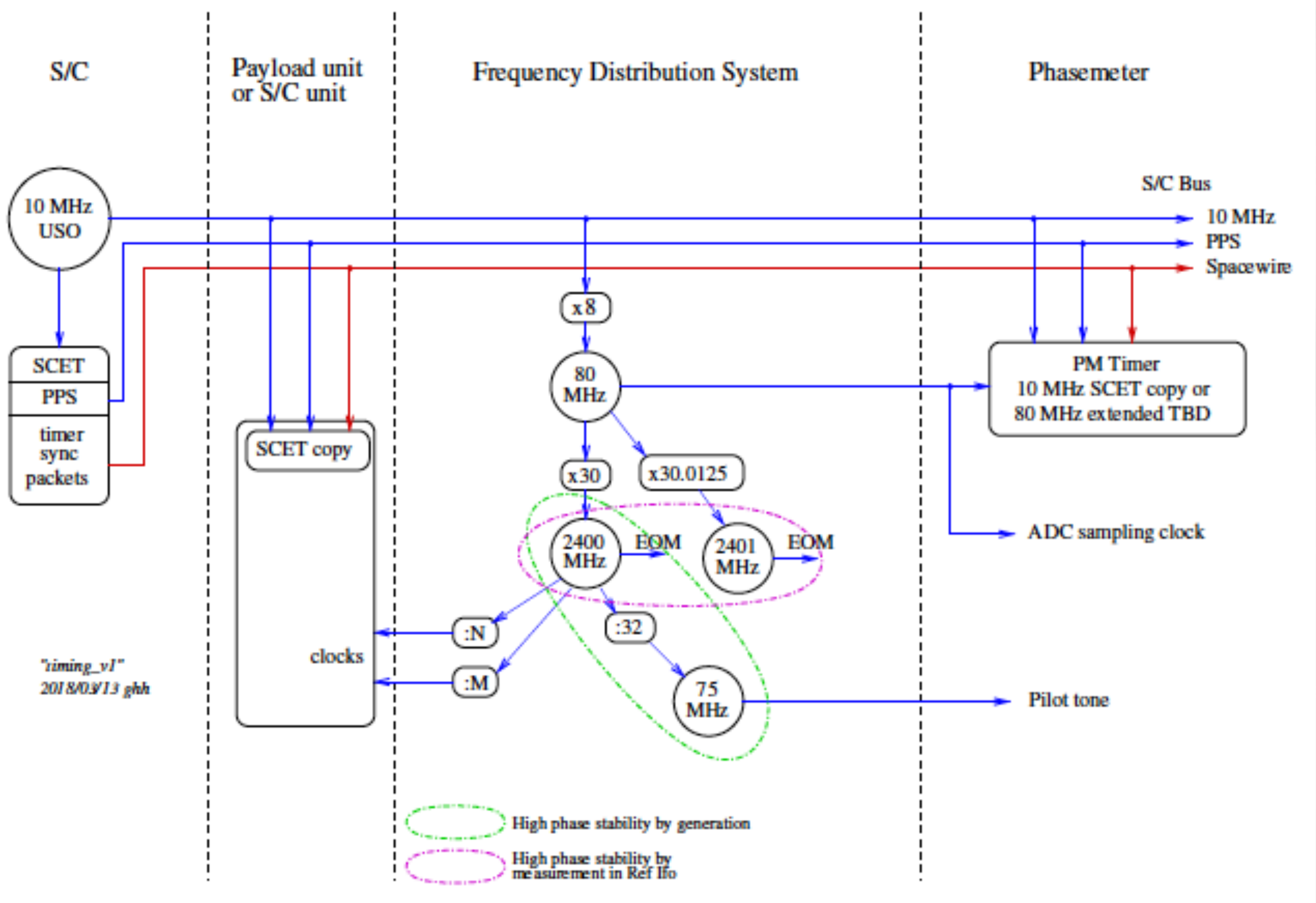
Phase measurement stability

- Clock jitter noise
  - The phase measurement are performed on different S/C and then combined
  - → The relative clock jitter must be measured and subtracted
  - → Side band modulation at ~2.4 GHz
  - The SB/SB phase noise is ~100 to 500 times the contribution to the scientific beatnote



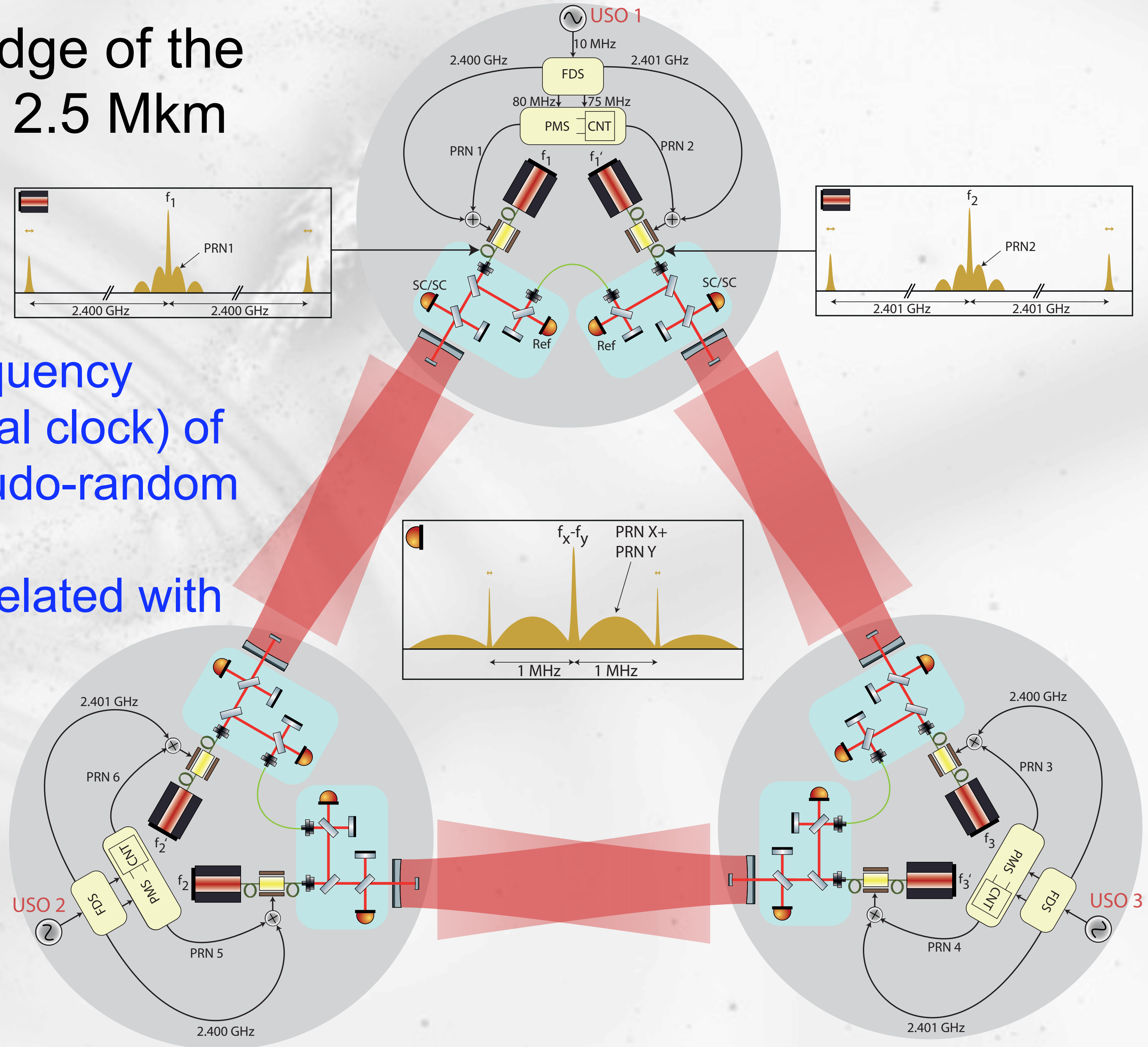
Frequency distribution topology

TAI
TDB



Ranging

- TDI requires the knowledge of the arm length at ~1 m over 2.5 Mkm
  - Achieved using a low frequency modulation (sync with local clock) of the laser carrier with pseudo-random noise (PRN)
  - The received PRN is correlated with a local, delayed, copy



Conclusion

- LISA is an ambitious and technically challenging mission for detecting GW from space
  - Selected for flight in 2035, now in phase B2

- Many of the key technologies have been demonstrated with LISA Pathfinder or in previous ground experiments

- Ultra-stable frequency distribution and time-stamping is a challenge, achieved with different techniques
  - Pilot tone for ADC jitter correction
  - Clock exchange over the laser link for clock jitter correction
  - PRN codes for ranging
  - Time synchronisation with ground clocks using standard space exchange protocols