# HIGH PRECISION HETERODYNE INTERFEROMETRY

# MIFO/ZIFO DEMONSTRATORS

LABORATOIRE ASTROPARTICULE ET COSMOLOGIE
MAXIME VINCENT

JOURNÉES SCIENTIFIQUES PN GRAM 2023 - NICE

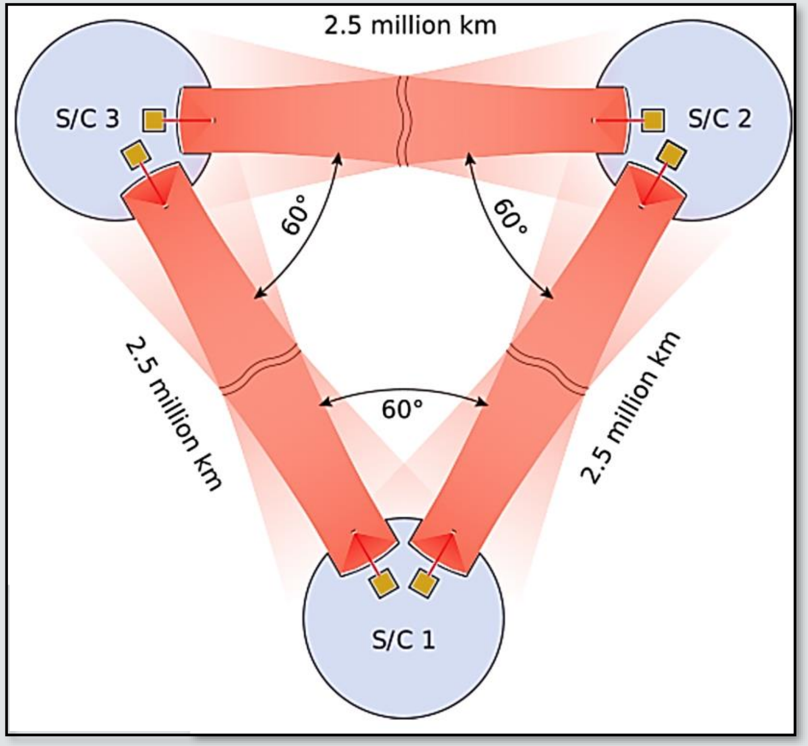
# THE LISA MISSION

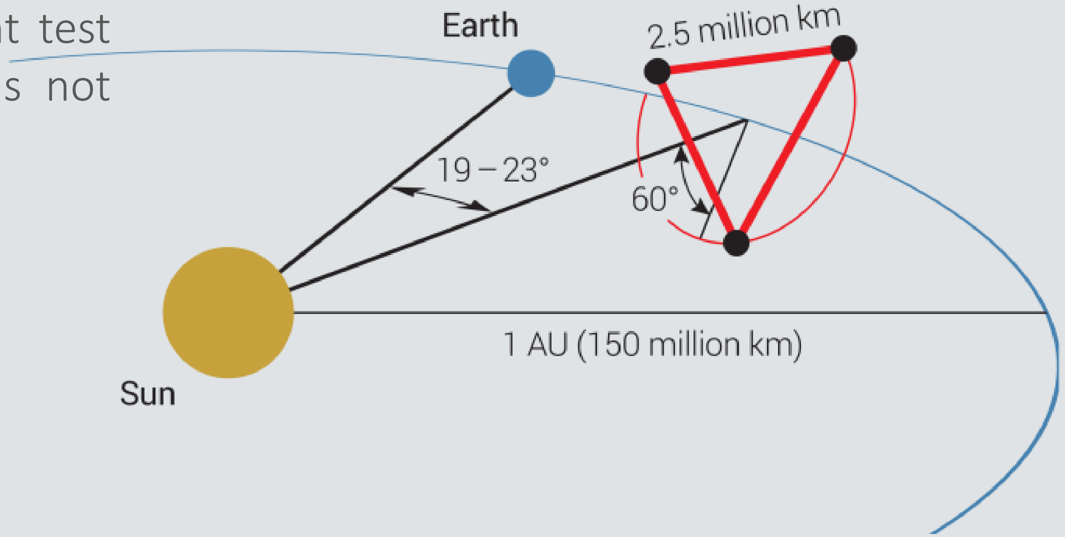
- Three satellites constellation in a triangular formation, forming 3 interferometers with 2.5 MKm arms

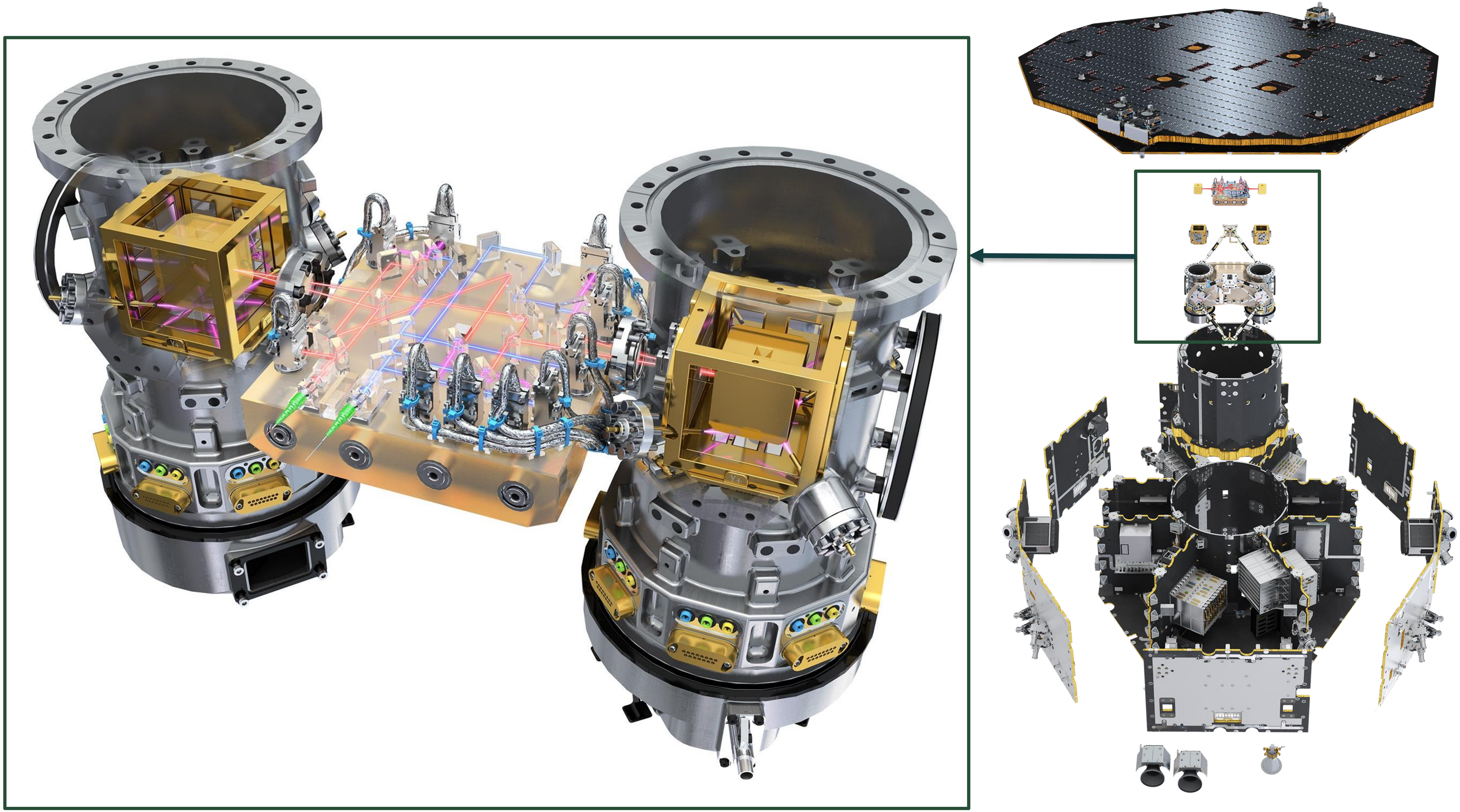
- Each spacecraft is equiped with two free flying test masses that each follow their geodesic trajectories with sub-femto g/√Hz residual acceleration providing a gravitationnal reference

- The goal is to retrieve the distance between two distant test mass to get an absolute distance measurement that is not perturbed by non gravitationnal forces

- To do so, three measurement are performed:
  - Test mass to spacecraft (TM-OB)
  - Spacecraft to spacecraft (OB-OB)
  - Spacecraft to test mass (OB-TM)



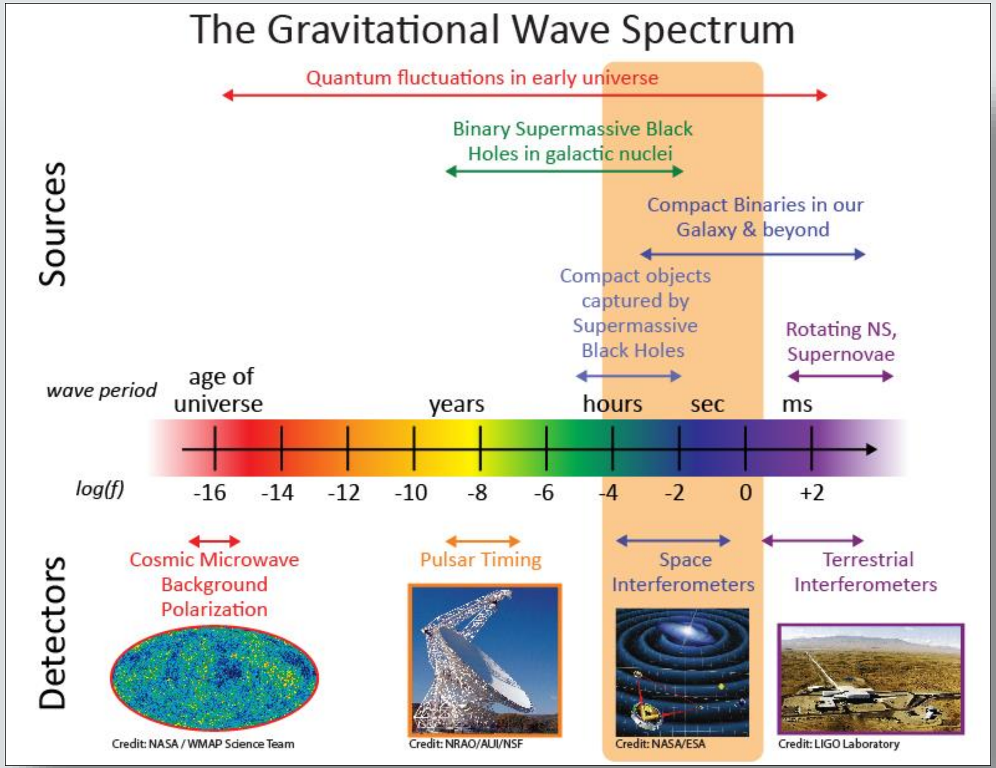





# THE LISA MISSION

- Detection in the 0,1 mHz to 1 Hz frequency band
  - Richest frequency band for GW astronomy
  - Frequency band not accessible on earth due to seismic noise at low frequency

- Utilisation of **heterodyne interferometry** : the frequency of the two interfering laser beams are slightly shifted ( ~ 15 MHz )
  - Results in a sine optical signal (**beatnote**) oscillating at the frequency of the off-set between both lasers
  - Variation of the optical pathlenght will induce a variation in the phase of the beatnote signal
  - Allows to track changes in the optical pathlenght along with the direction of displacement




$$\overrightarrow{E_i} = \overrightarrow{E_{0,i}}\cos(w_i t - \varphi_i)$$

$$I_1 = \overrightarrow{E_1}.\overrightarrow{E_1} =< E_0^2 \cos(\omega_1 t - \varphi_1)^2 >$$

$$I_2 = \overrightarrow{E_2}.\overrightarrow{E_2} =< E_0^2 \cos(\omega_2 t - \varphi_2)^2 >$$

$$I_{tot} = I_1 + I_2 = I_0 \cos(2\pi\Delta \boldsymbol{f} t - \Delta\boldsymbol{\varphi})^2$$

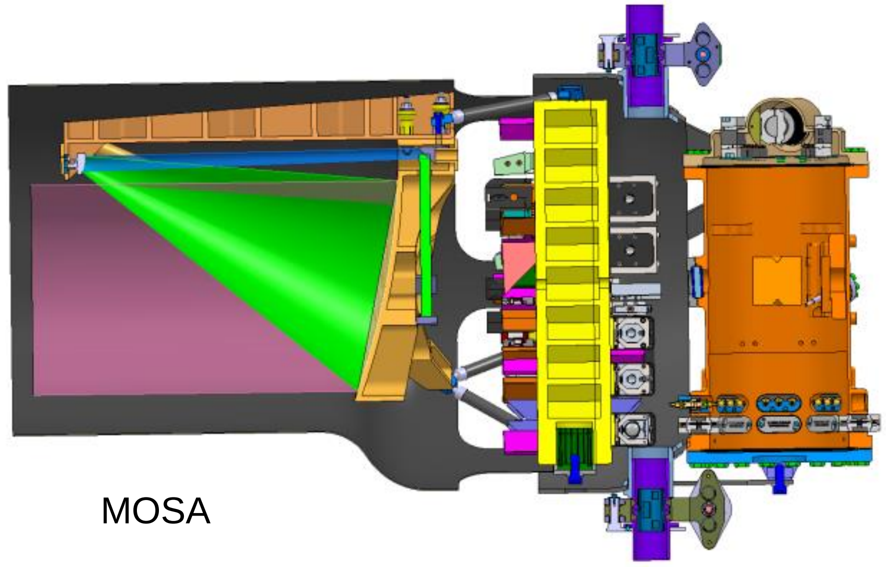
$$I_{tot} = I_1 + I_2 = I_0 \cos\left(2\pi\Delta \boldsymbol{f} t - \frac{2\pi\Delta \boldsymbol{L}}{\boldsymbol{\lambda}}\right)^2$$

# TESTING THE INSTRUMENTS

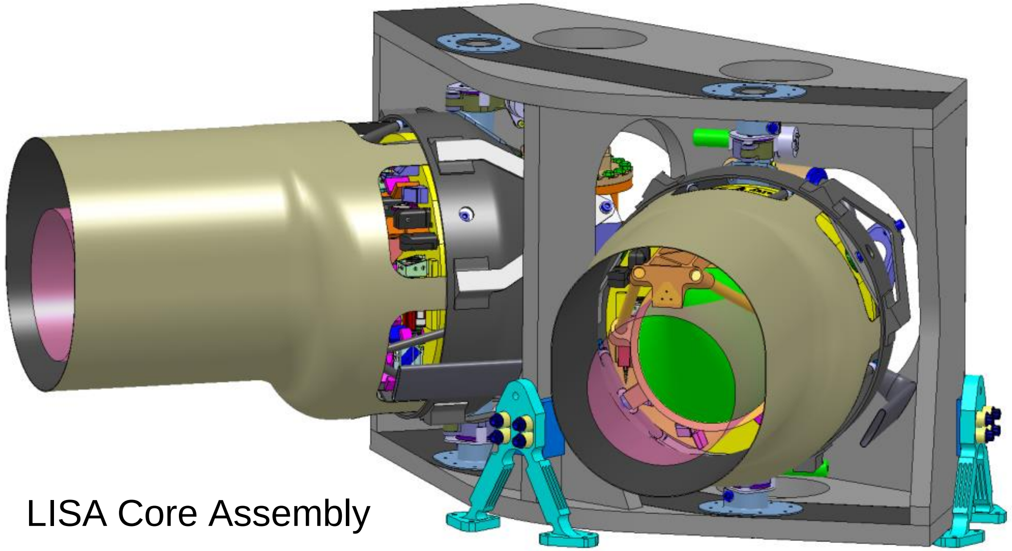
- The optical section of the LISA instrument is called the **MOSA** (Movable Optical Sub Assembly)
  - Optical bench (OB)
  - Telescope
  - Gravitationnal reference system (test mass)
  - Stable structure

- Two MOSA form the LISA Core Assembly

- The section of the instrument performing the interferometric measurement is called the **Interferometric Detection System** (IDS)
  - Optical bench (UK)
  - Phasemeter (Germany)
  - Laser (NASA)



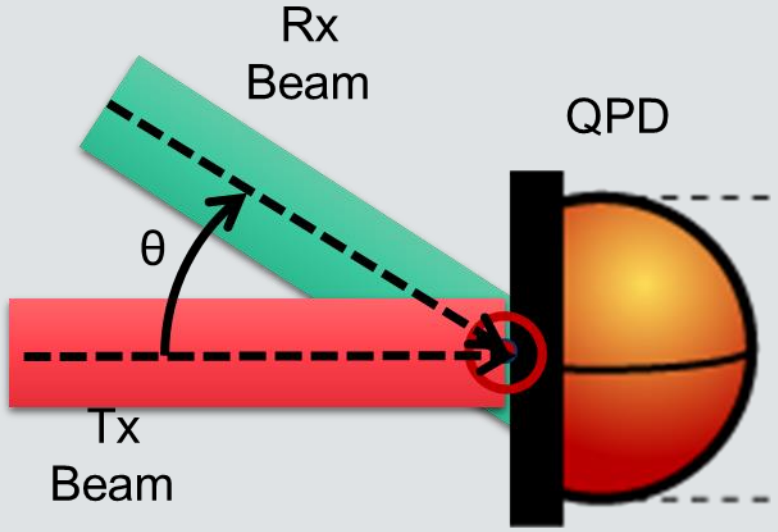
MOSA



LISA Core Assembly

# TESTING THE INSTRUMENTS

- France is tasked with the **testing** and **characterization** of the **interferometric detection system** at the heart of the MOSA
  - insure that **picometer stability** is reached on the interferometers of the LISA optical bench
  - characterize the tilt-to-lenght coupling coefficients between OPL and the beatnote phase [ dOPL(θ)/d(θ) ]



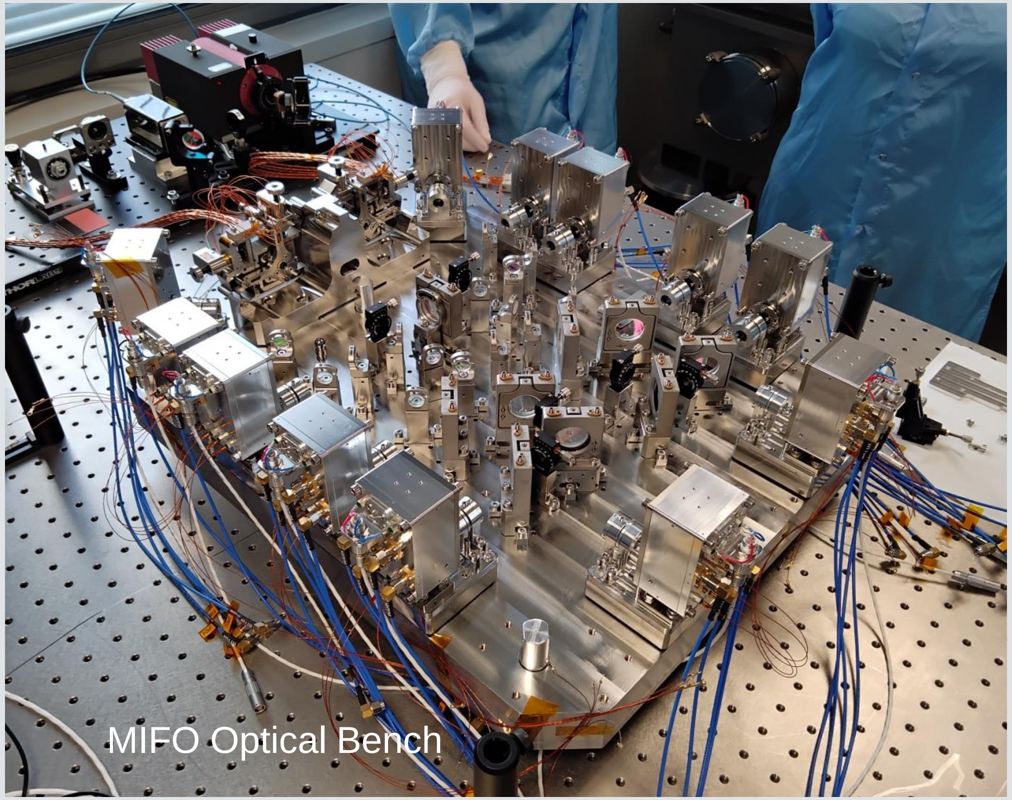

- The french laboratories are organized as a consortium called the **LISA France consortium** led by the CNES, working together for the development of  on-ground testing equipment

- IDS test campaign planned for 2026-2027

- Demonstrator campaign to develop expertise and prove our capability to fullfil our commitment to ESA

# HETERODYNE INTERFEROMETRY DEMONSTRATORS

- Two heterodyne interferometry demonstrators :
  - **MIFO** (2022) : Metallic InterFerOmeter Optical Bench
  - **ZIFO** (2023) : Zerodur InterFerOmeter Optical Bench
  - MIFO was a test run to prepare for the ZIFO test campaign



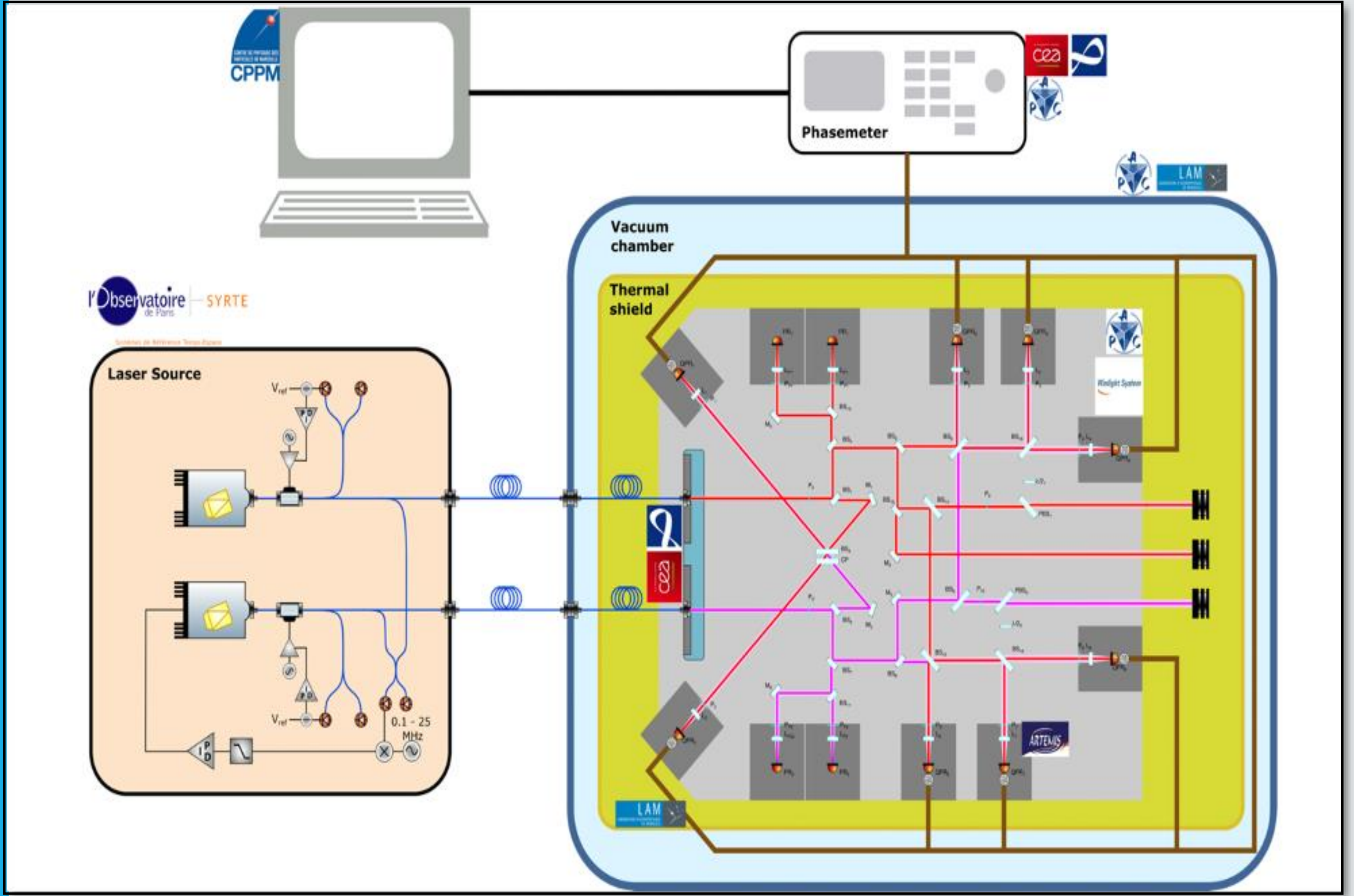
MIFO Optical Bench

ZIFO Optical Bench

# HETERODYNE INTERFEROMETRY DEMONSTRATORS

- Objectives :
  - Optical pathlenght measurement with a stability of 10 pm/√Hz in the 0,1 mHz to 1 Hz frequency band
  - Measurement of the ZIFO TTL coefficient
  - Development of an ultra stable laser source
  - Gain expertise in Zerodur optical bench development
  - Organisation of the french community to prepare for future and more complex optical benchs
  - Identification of noise sources, environmental parameters and associated performances
  - Development of data analysis procedures

ZIFO Optical Bench



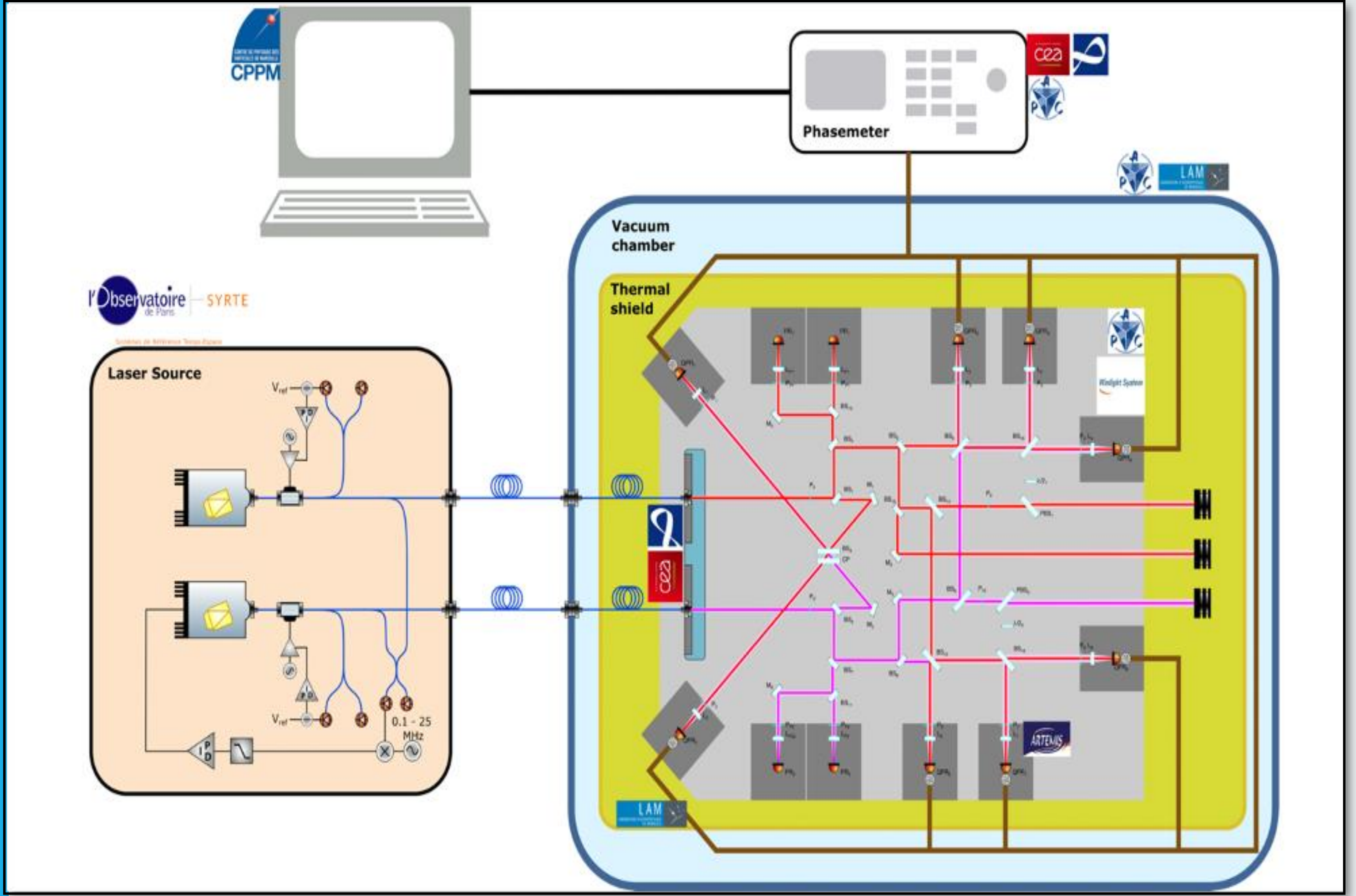

# EXPERIMENTAL SET UP

V1 Laser : two laser beam (1064 nm) are phase locked to one another and have a 1 to 25 MHz frequency offset (SYRTE)

→ limited by laser frequency noise ( ~ 20 kHz/√Hz )

V2 Laser: provides a frequency reference to stabilize the V1 laser system using a fine line of an iodine transition (SYRTE/EXAIL)

→ V1+V2 system to have a noise < 30 Hz/√Hz




# EXPERIMENTAL SET UP

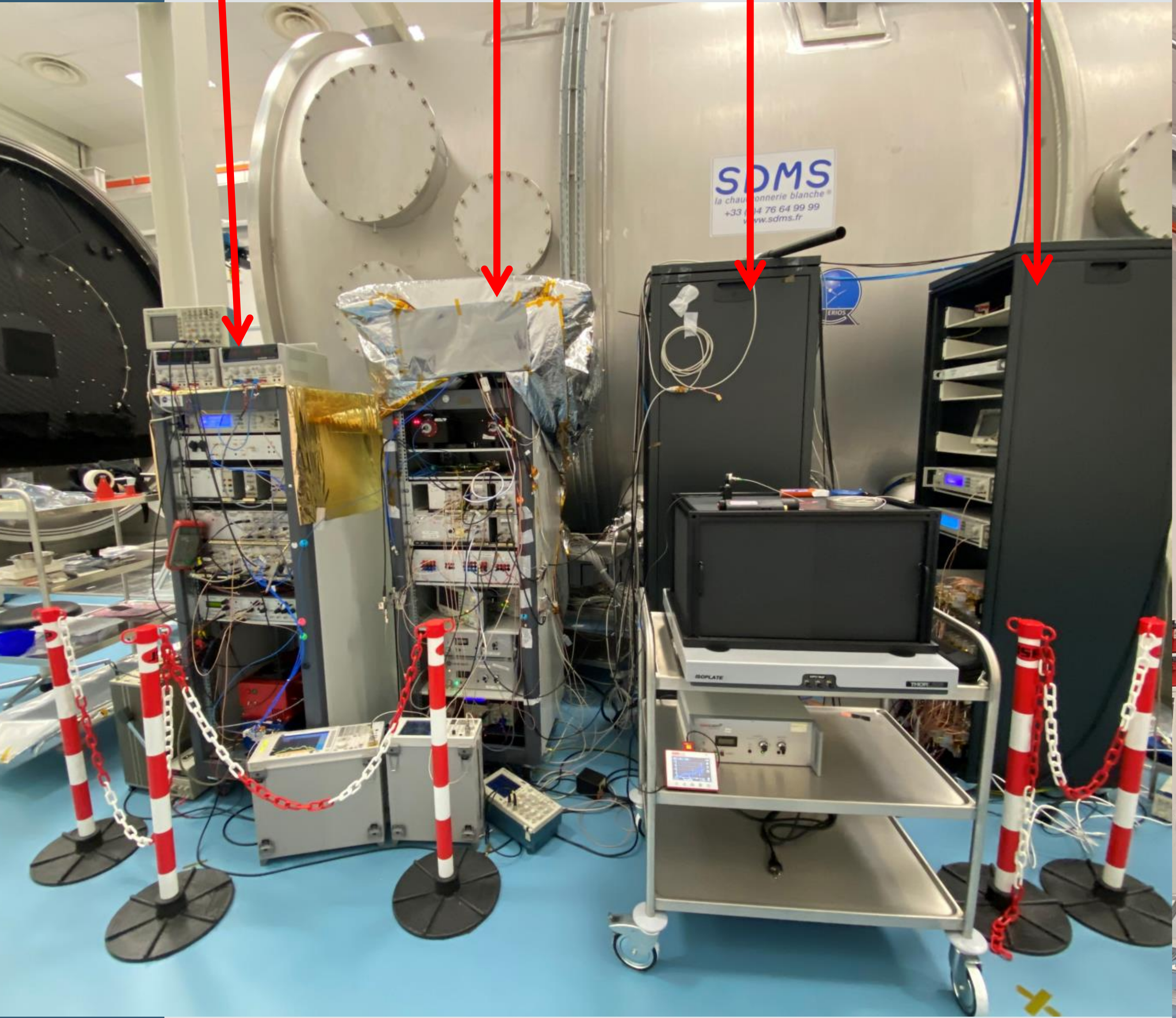
**Photoreceptors:** 8 low noise quadrant photoreceptors sensitive to the 0.1 to 25 MHz frequency band (ARTEMIS)

**Power monitoring**: 4 photodiodes are used to monitor the otpical power and estimate the relative intensity noise (ARTEMIS)

**Phasemeters**: receives the interferometric signal from the photoreceptors and measures the frequency of the signals, we retrieve phase by integrating the frequency (APC / CEA)

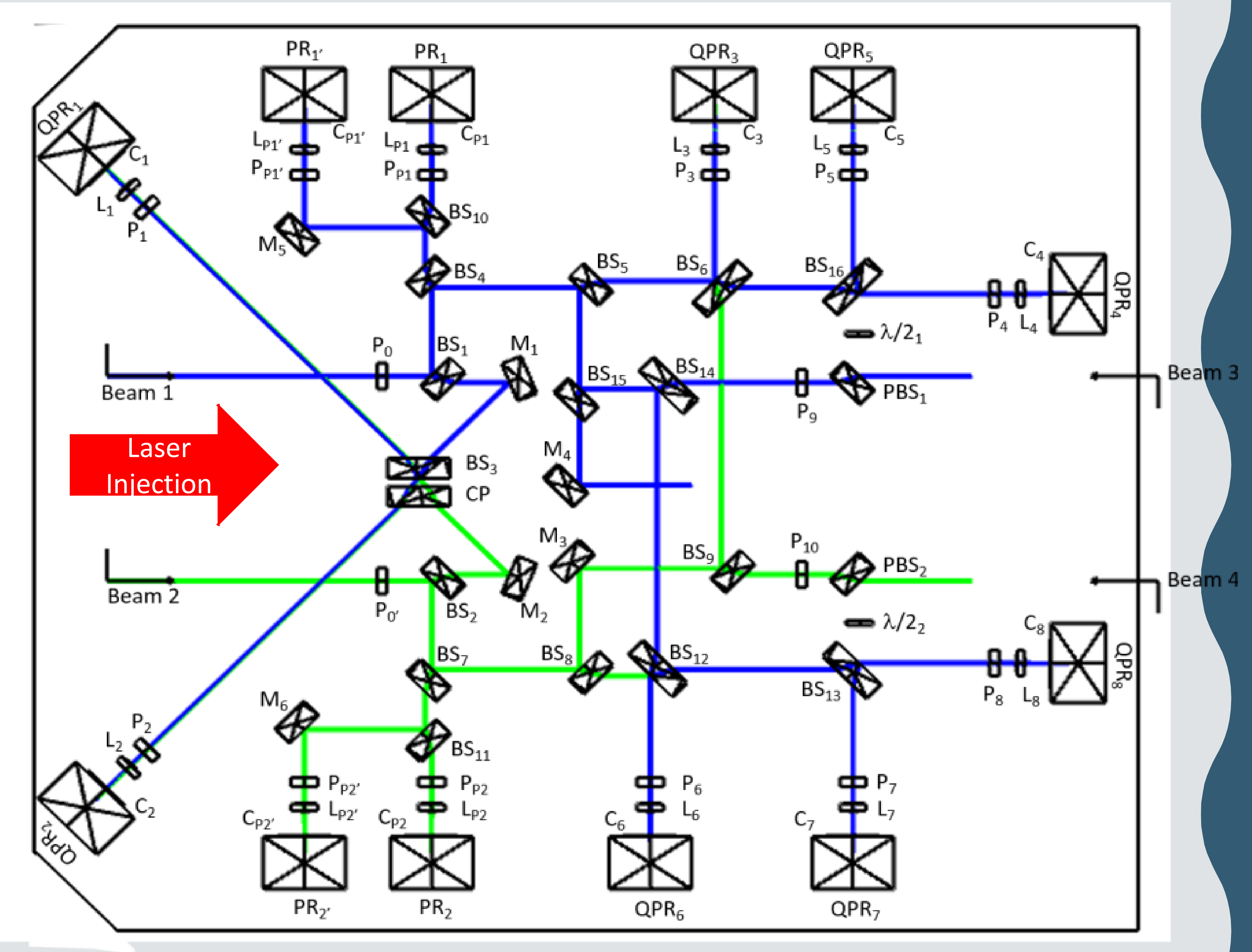
**Injectors**: steerable injection system allowing to apply a translation and a tilt on the laser beam (CEA)

**Molecular adhesion**: increase the thermal stability of the components on the OPL





Laboratoire d'Astrophysique de Marseille




# OPTICAL LAYOUT

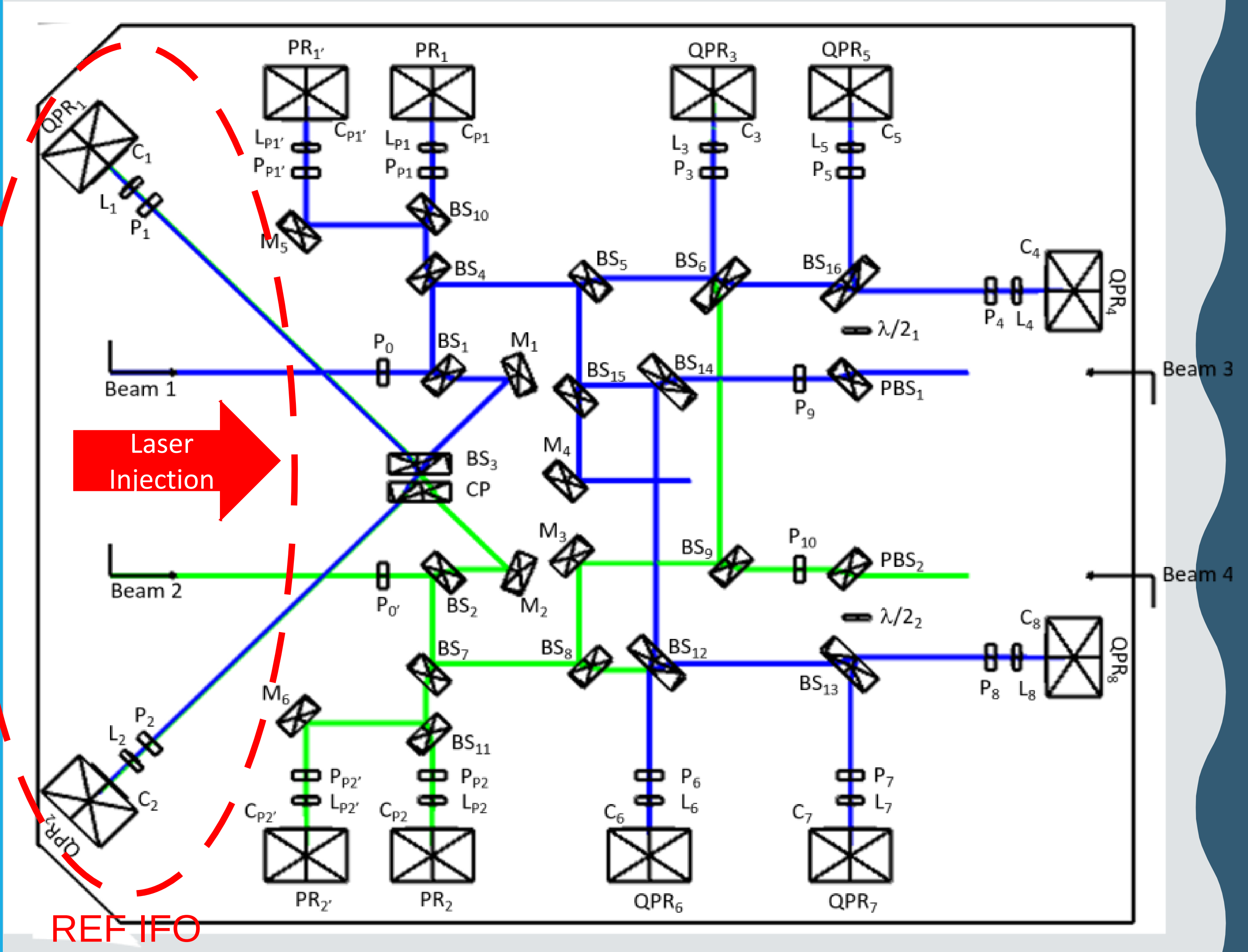
Three interferometers :

1 Reference interferometer

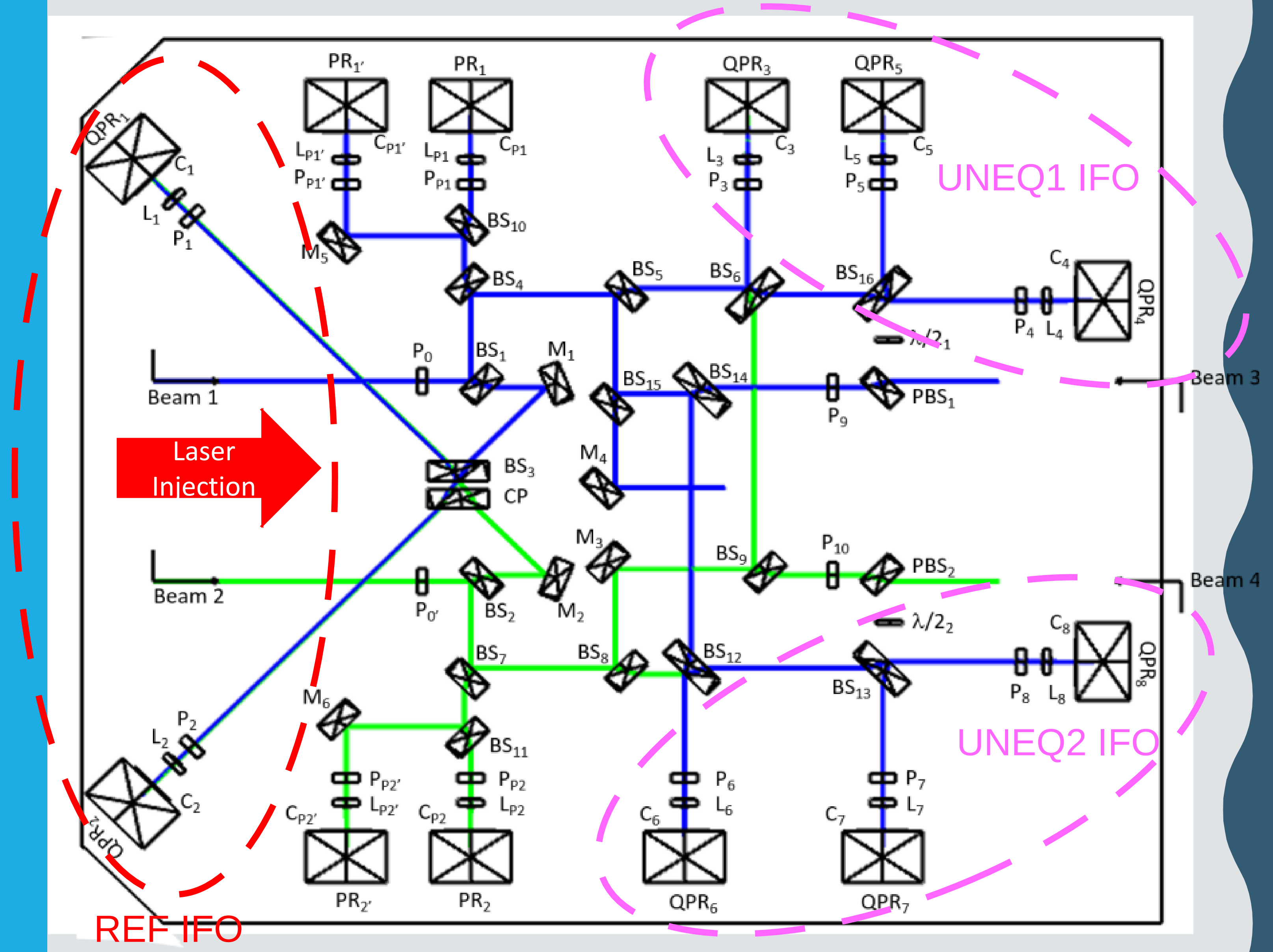
2 'Science' interferometers

The combination of the IFOs allows to retrieve the **optical path length stability**

# REFERENCE INTERFEROMETER

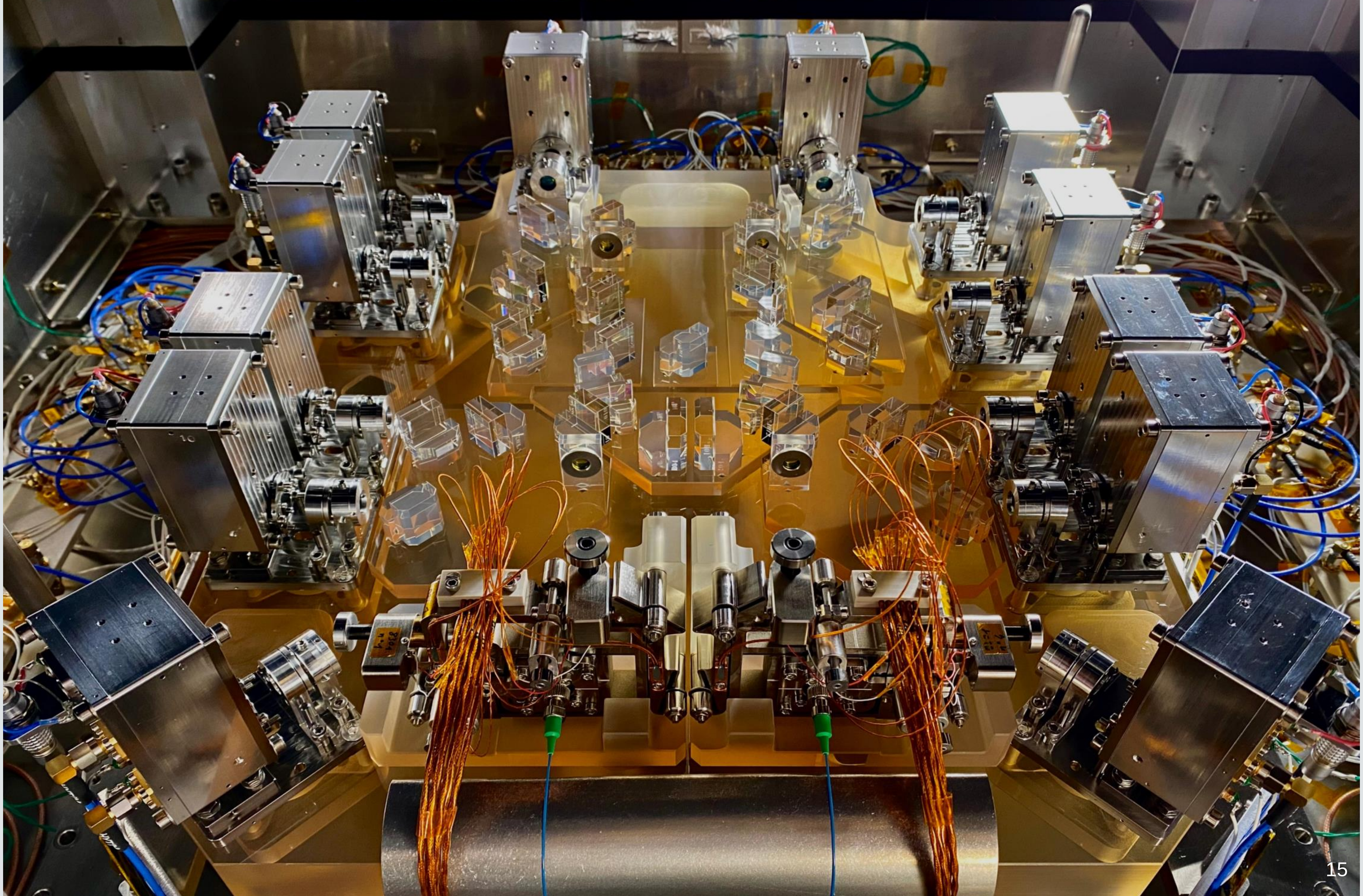


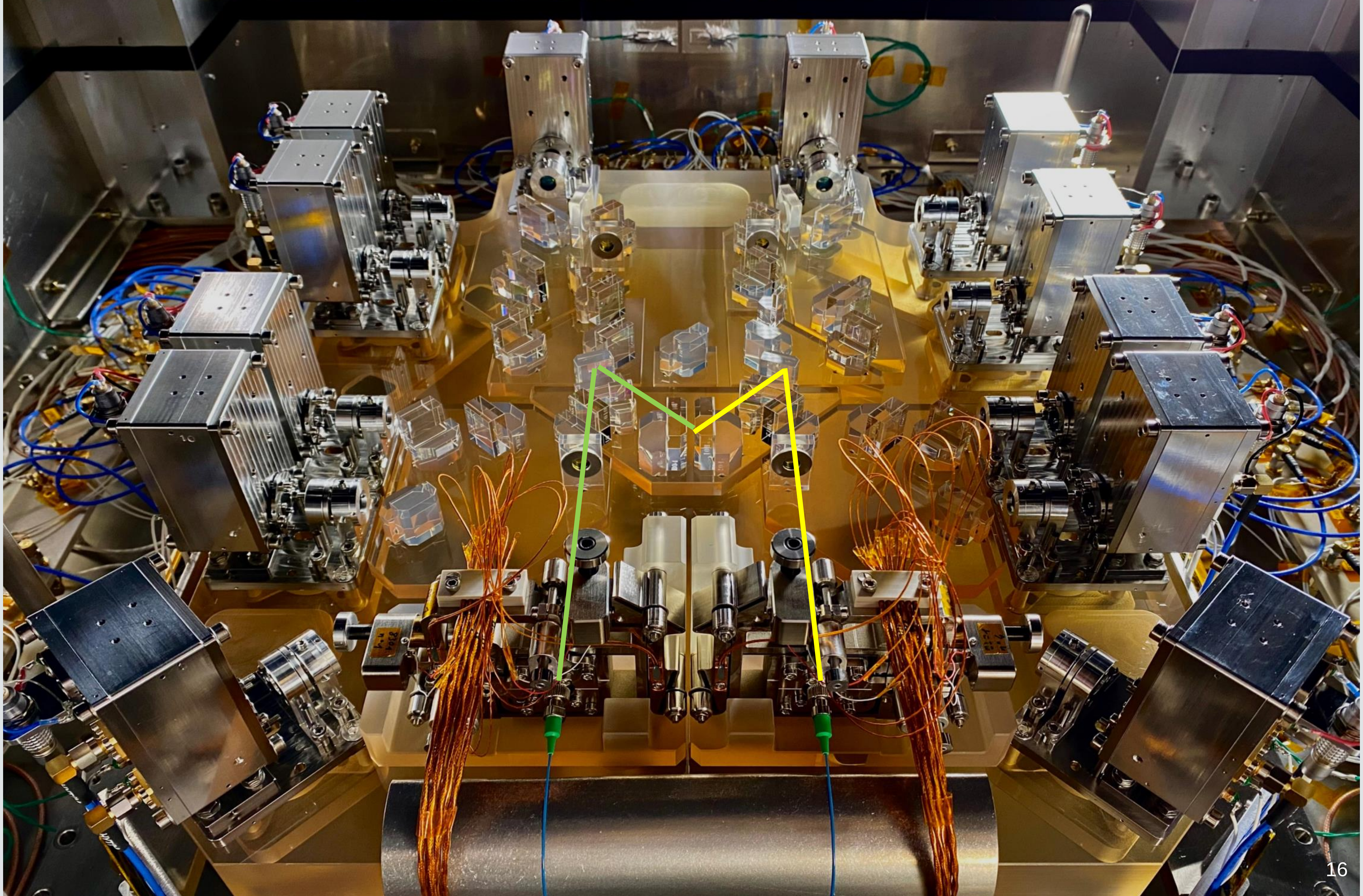

- Equal arm interferometer : same optical pathlenght for both lasers
- used as the reference IFO for phase measurements
- used to remove thermoelastic noise caused by the optical fibers and other common correlated noises

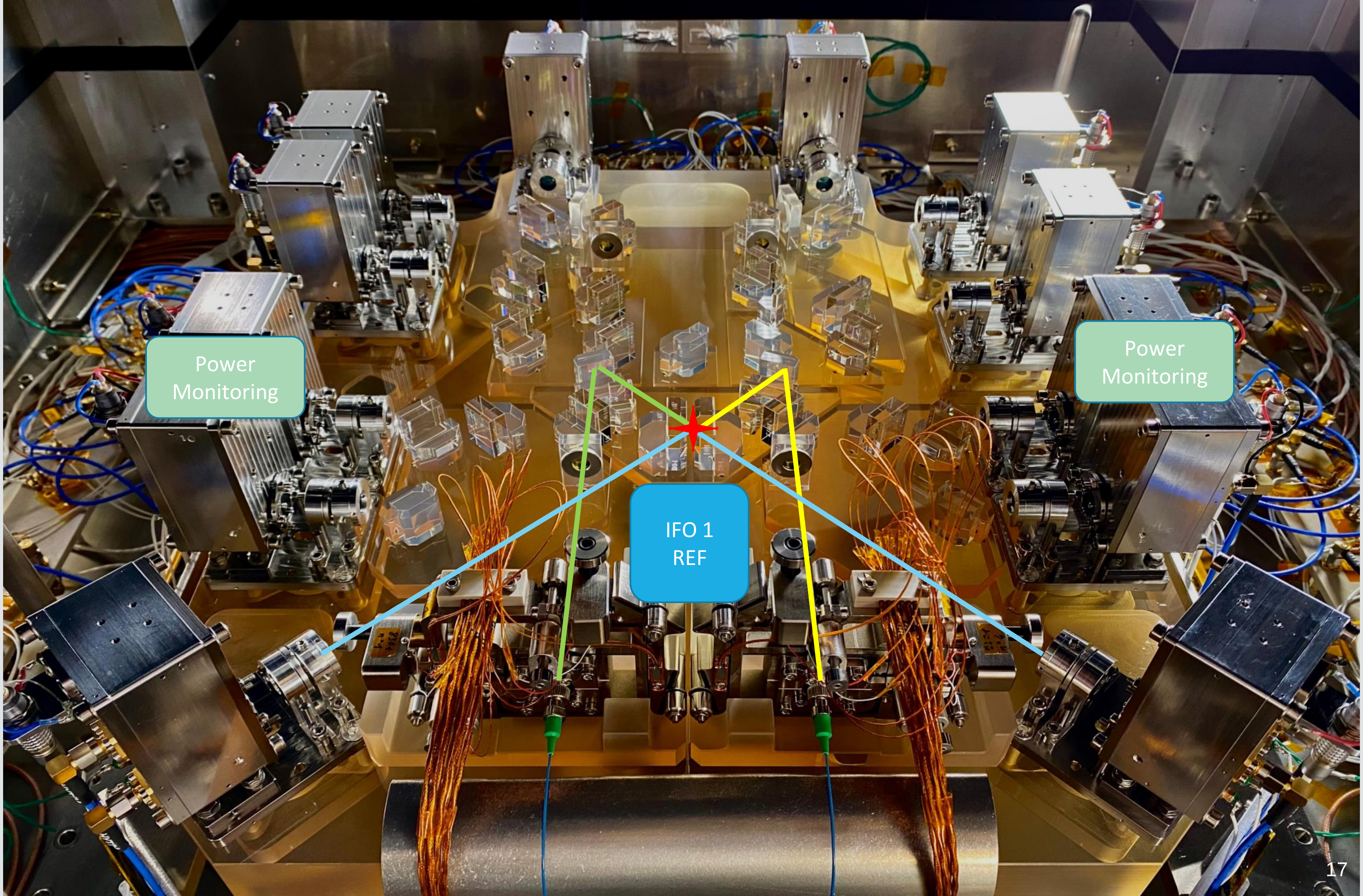


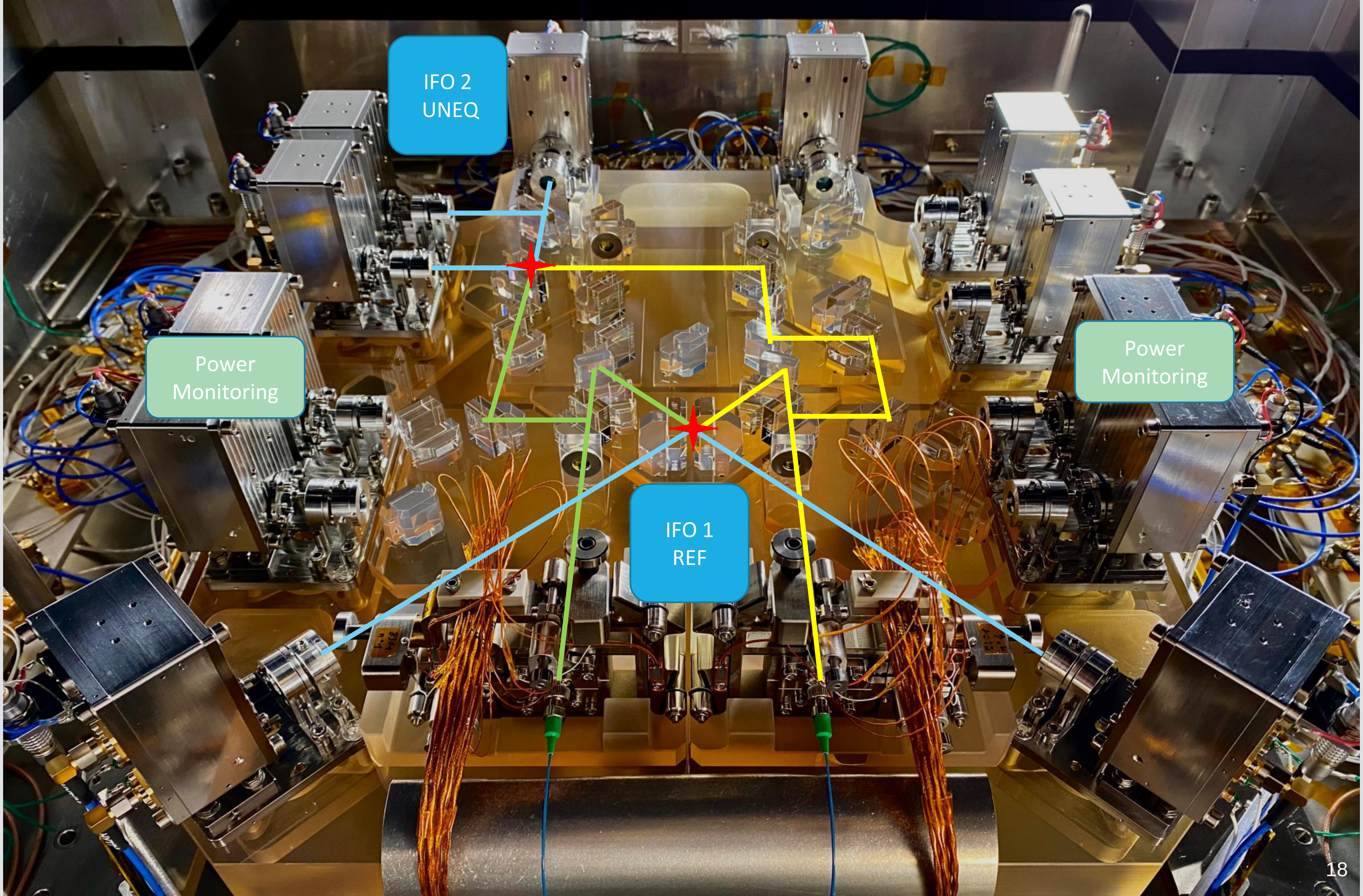

# UNEQUAL ARM INTERFEROMETERS

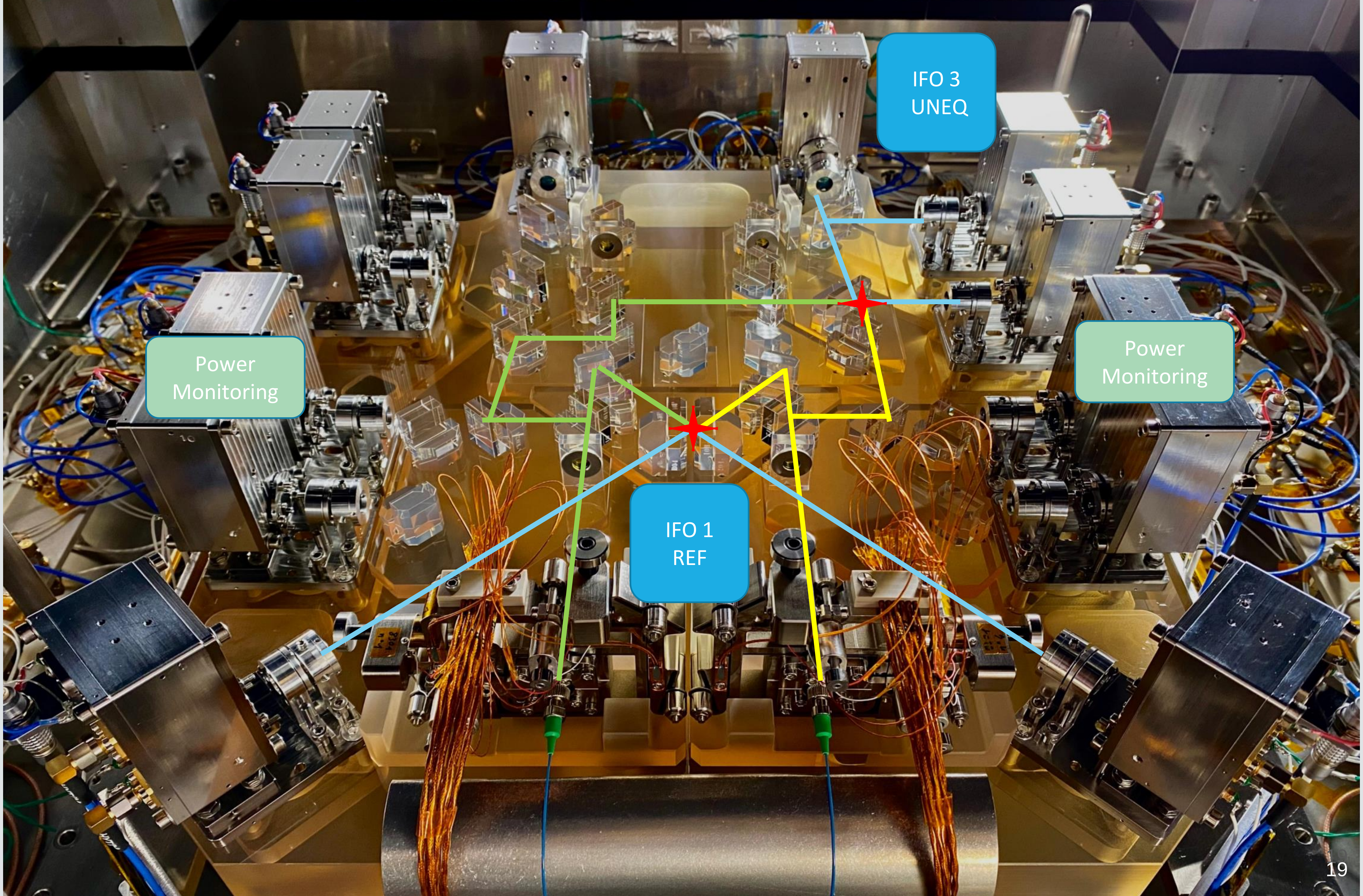
- Unequal arm IFO : optical path lenght difference of 20 cm between laser 1 and 2
- UNEQ 1 and 2 are used to estimate the measurement noises, like thermal noises and laser frequency noise
- Thermal instabilities cause changes in the index of optics and changes the optical pathlength due to the expansion of materials

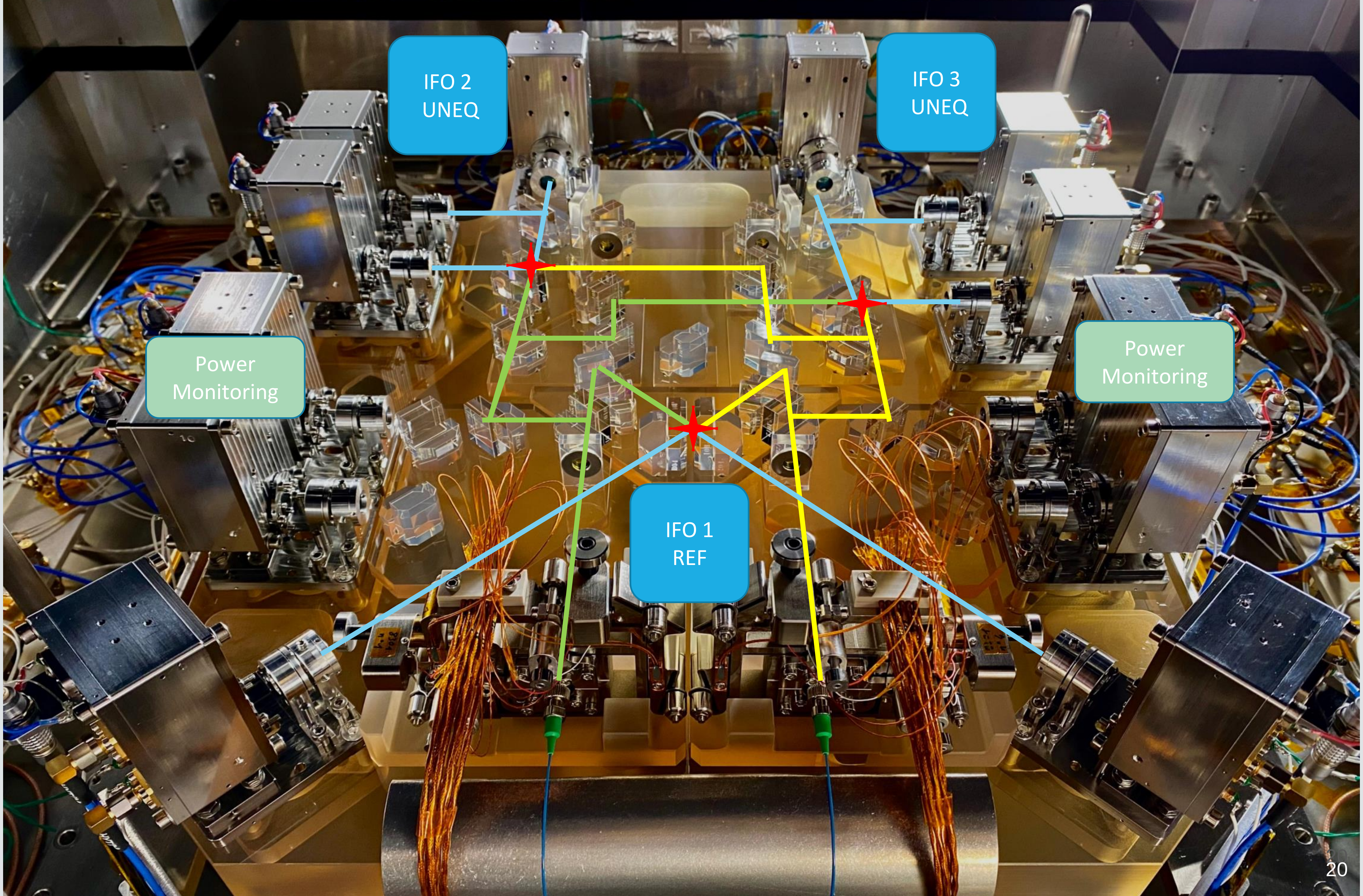




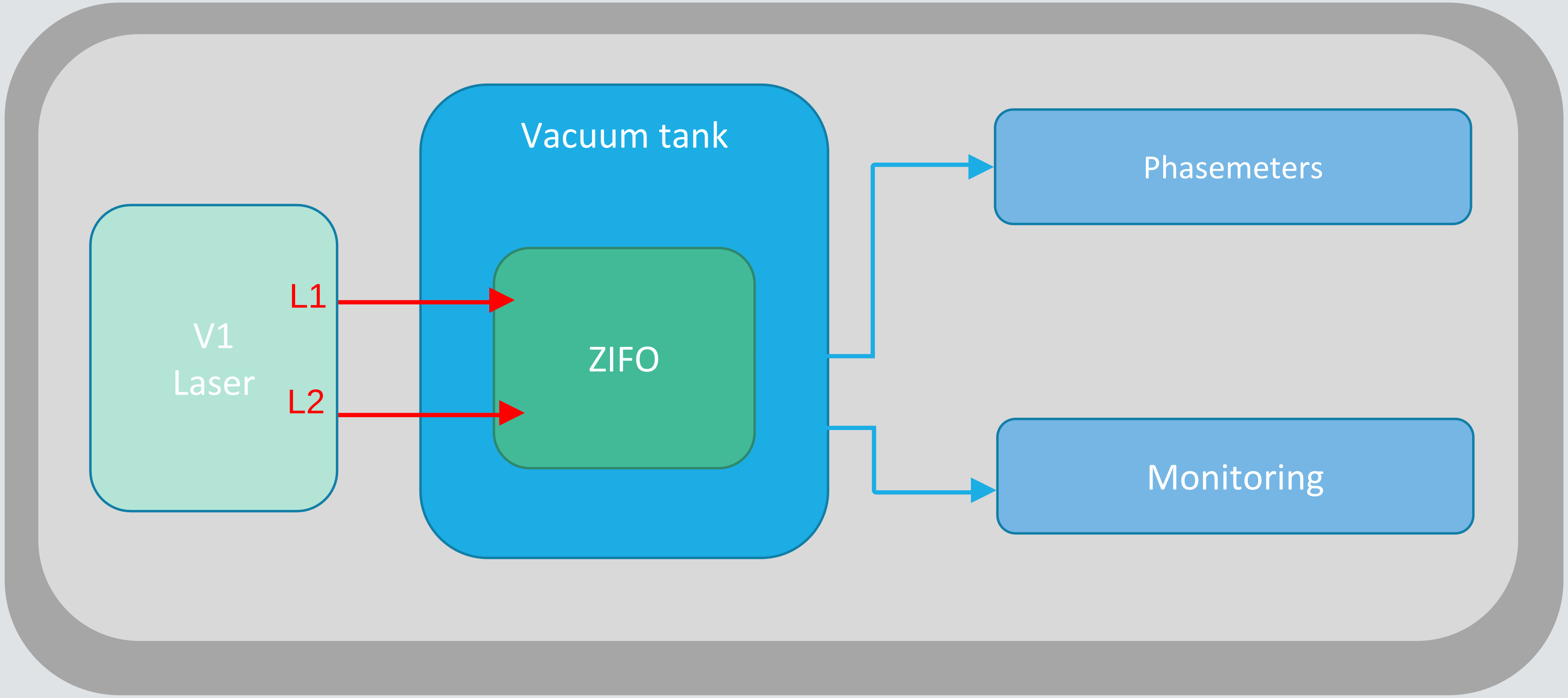

Power Monitoring
Power Monitoring
IFO 1 REF


IFO 2
UNEQ
Power
Monitoring
Power
Monitoring
IFO 1
REF


IFO 3
UNEQ
Power
Monitoring
Power
Monitoring
IFO 1
REF


IFO 2
UNEQ
IFO 3
UNEQ
Power
Monitoring
Power
Monitoring
IFO 1
REF

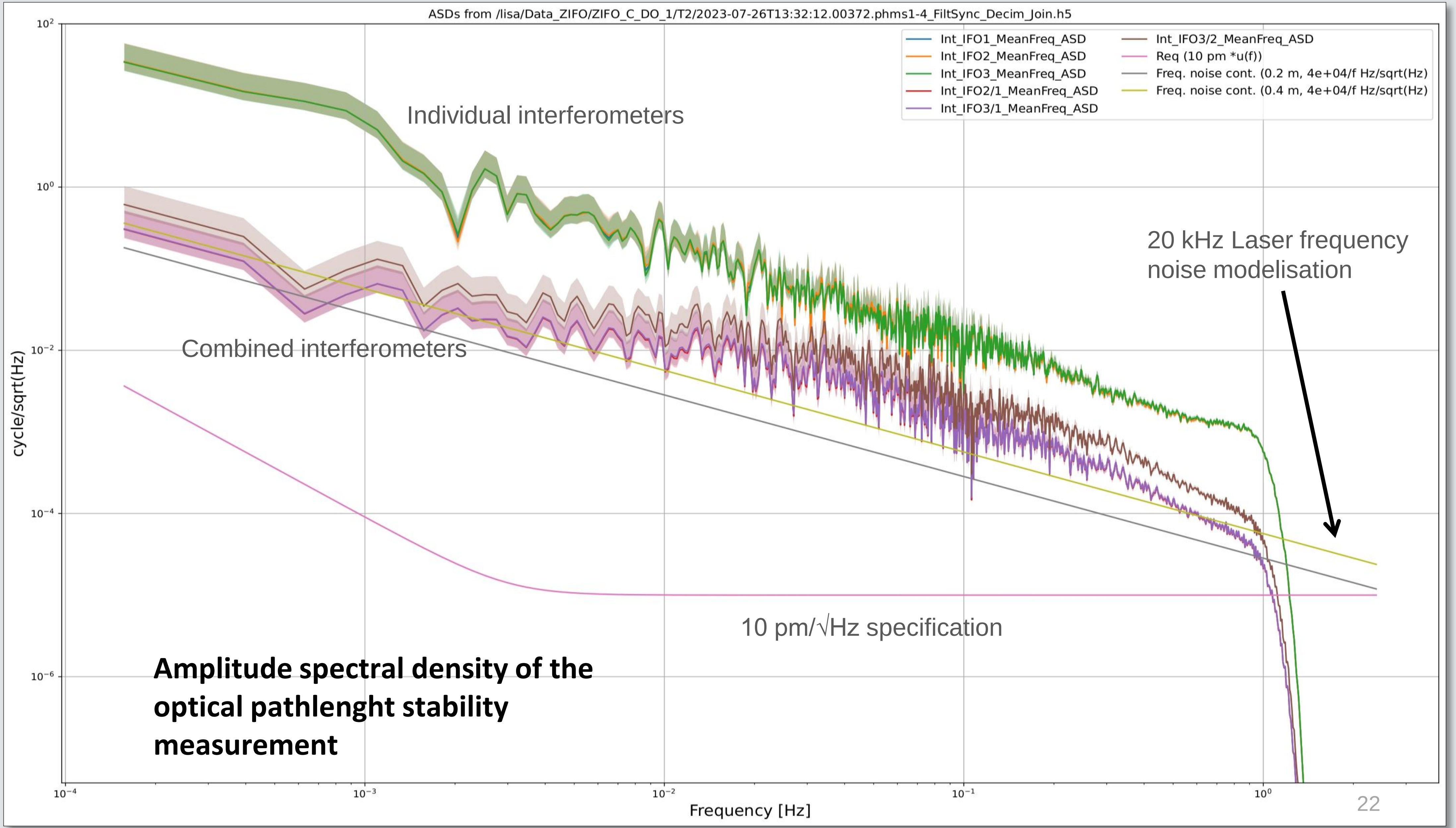
# ZIFO TEST RESULTS : OPTICAL PATHLENGHT STABILITY WITH V1 LASER ONLY



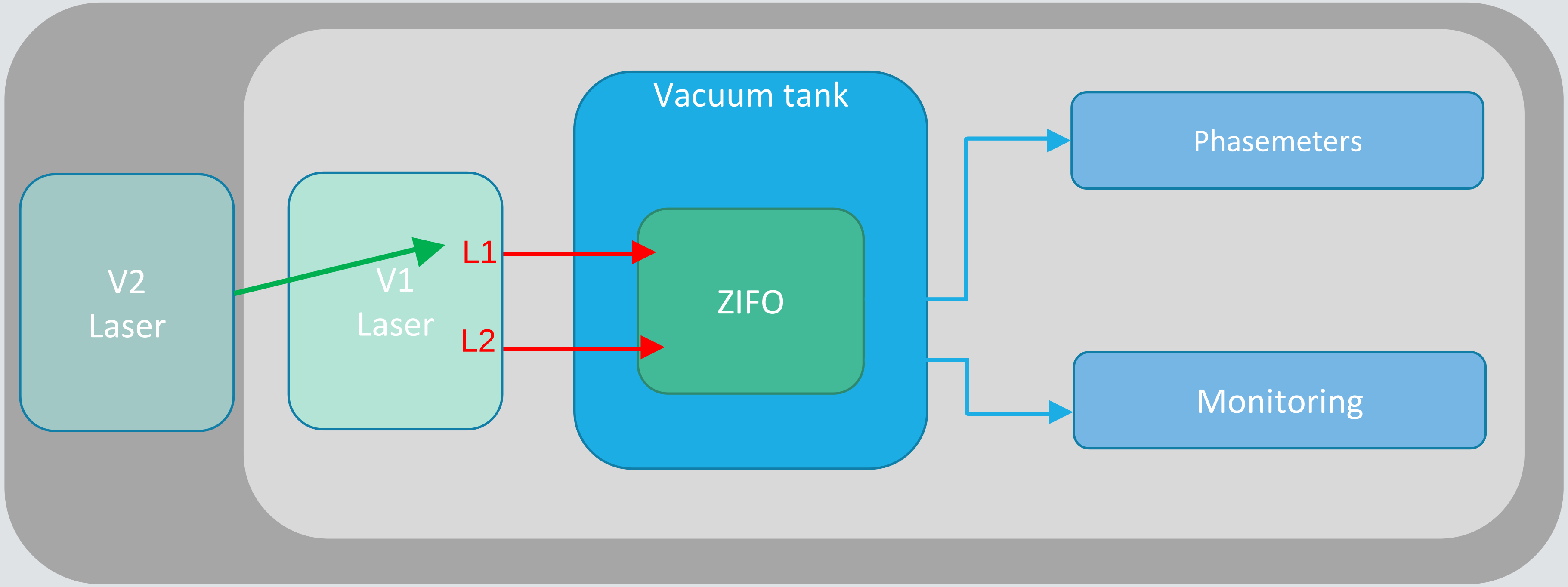

Configuration 1 :

- **V1 Laser : Laser frequency noise limited**
- 15 hour acquisition in air with a heterodyne frequency of 16 MHz
- In the ERIOS vacuum tank at Laboratoire d’Astrophysique de Marseille

# ZIFO TEST RESULTS : OPTICAL PATHLENGHT STABILITY WITH V1 LASER ONLY



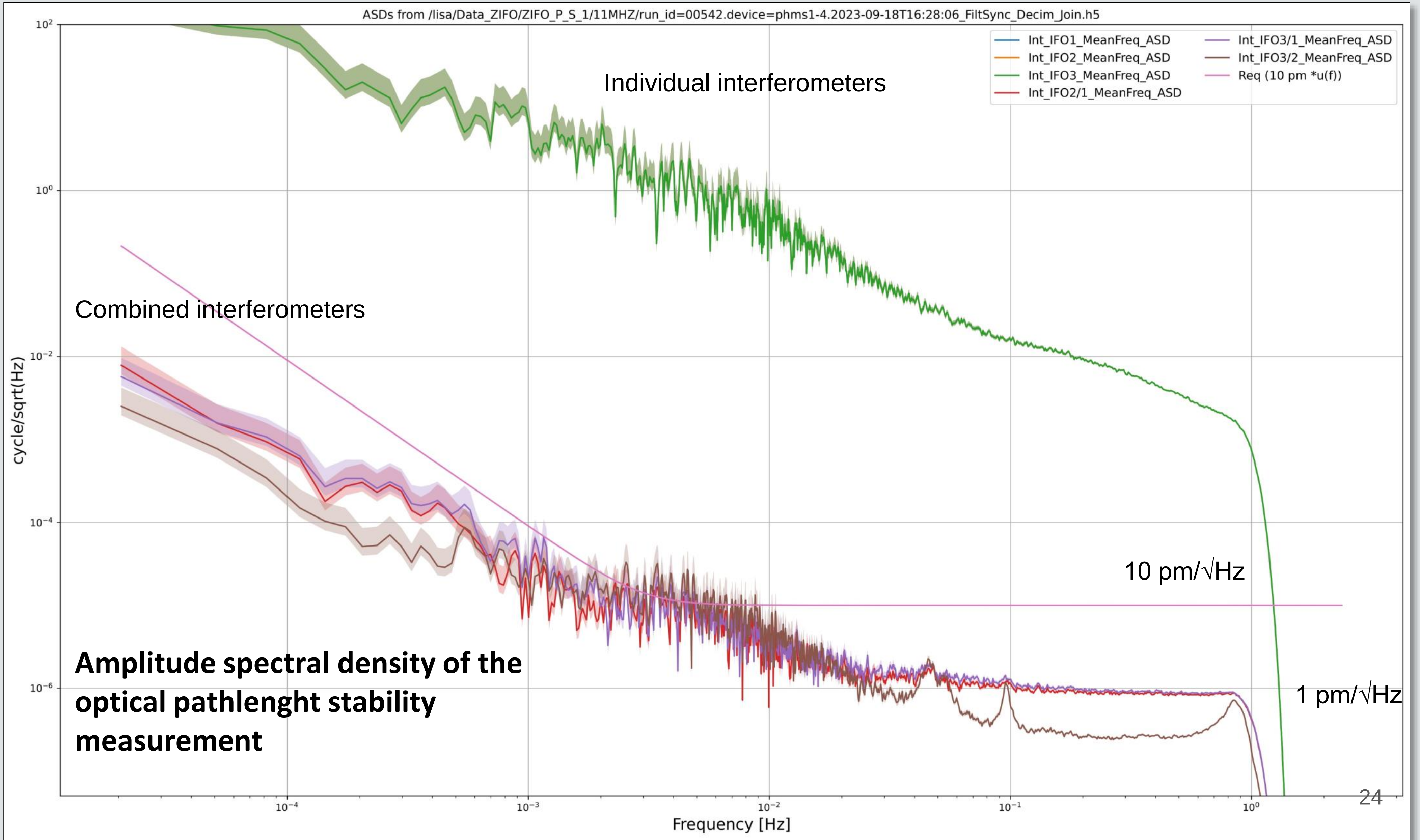
# ZIFO TEST RESULTS : OPTICAL PATHLENGHT STABILITY WITH V1 AND V2 LASER




Configuration 2 :

- In secondary vacuum ($10^{-6}$ mbar) in the ERIOS tank at Laboratoire d'astrophysique de Marseille
- **Additional stable frequency reference for the laser system : V1 + V2 <30 Hz/√Hz added noise**
- >15 hours of acquisition at a heterodyne frequency of 11 MHz

# ZIFO TEST RESULTS : OPTICAL PATHLENGHT STABILITY WITH V1 AND V2 LASER




**Amplitude spectral density of the optical pathlenght stability measurement**

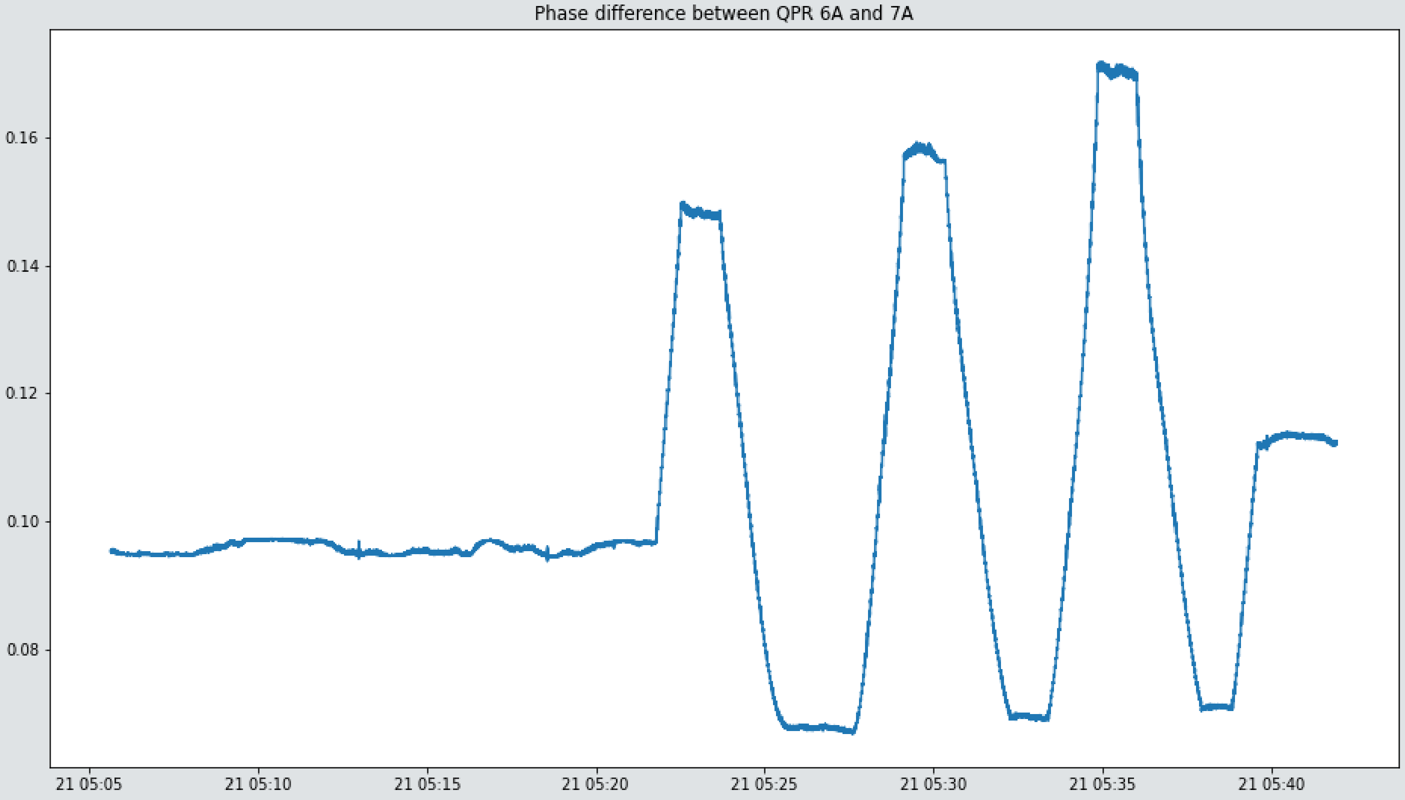
# ZIFO TEST RESULTS : TTL COUPLING BETWEEN OPL AND PHASE OF THE BEATNOTE

- Movement of one degree of freedom on one of the two injectors resulting in one laser beam rotating or translating relative to the other beam

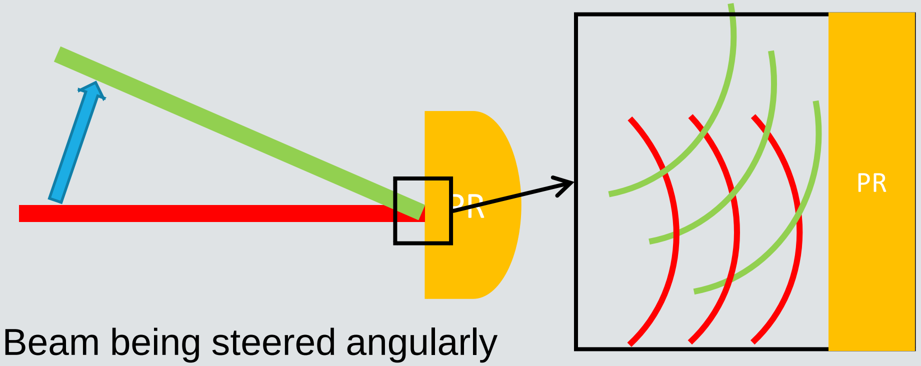
- Measurement of the instantaneous phase of the heterodyne beatnote on each photoreceptor

- Allows to retrieve the TTL coefficients of each interferometer on the bench

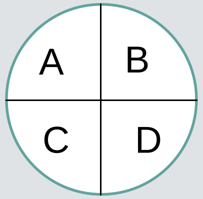
- Data yet to be analyzed



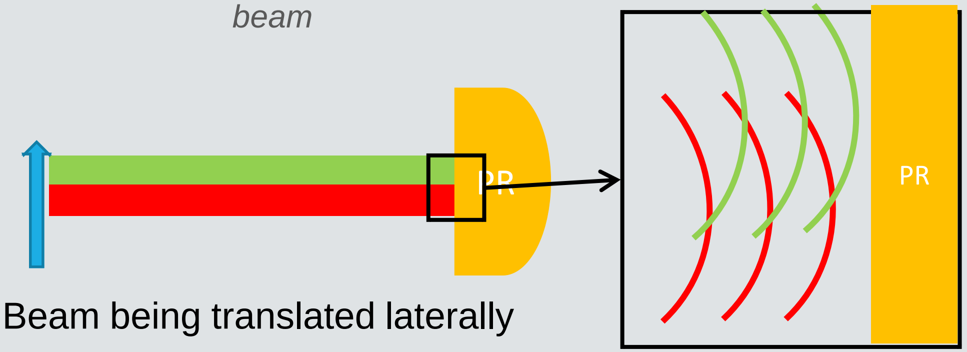

*Phase difference (rad) between two photoreceptor of the bench while one laser beam is rotating arround the other beam*




Beam being steered angularly



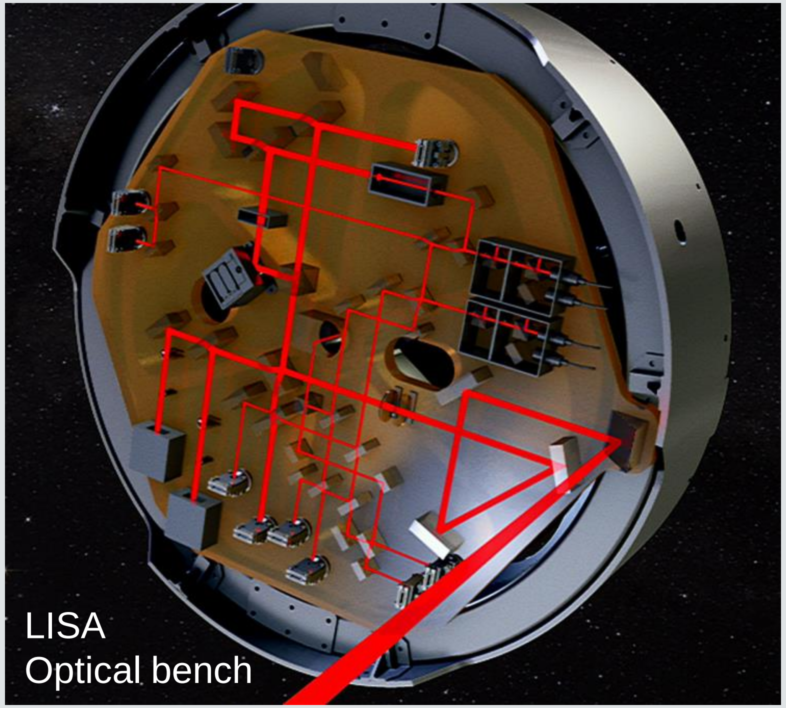

Quadrant Photoreceptor

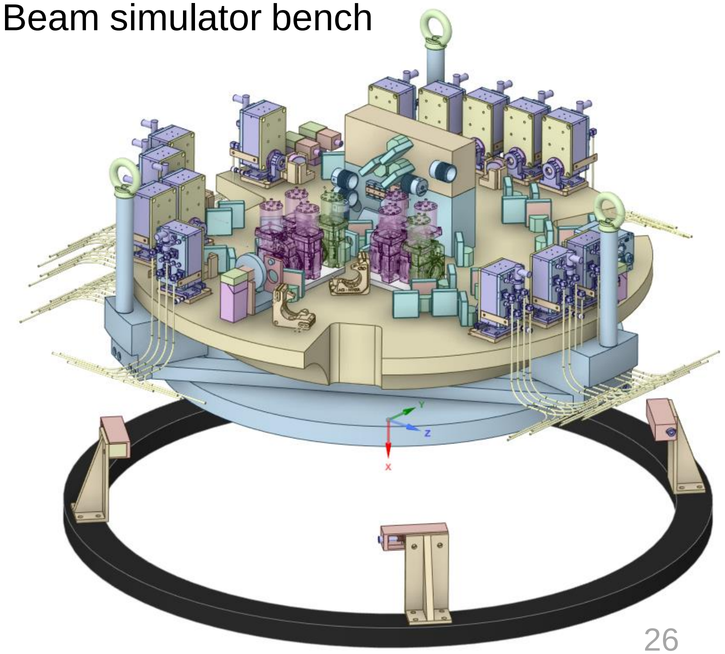



Beam being translated laterally

# PAVING THE WAY FOR THE IDS TEST CAMPAIGN

- A lot of expertise has been gained in low frequency ultrastabe interferometry amongst the french collaboration
- The technical specification for the 2026 IDS test campaign has already been reached for the ZIFO test campaign
- Long awaited result that consolidates the french contribution pointing towards mission adoption
- Development of the Beam Simulator optical test bench and IDS test set up are ungoing in the LISA France consortium for the futur picometric stability and TTL characterisations of the LISA OB


LISA
Optical bench

Beam simulator bench


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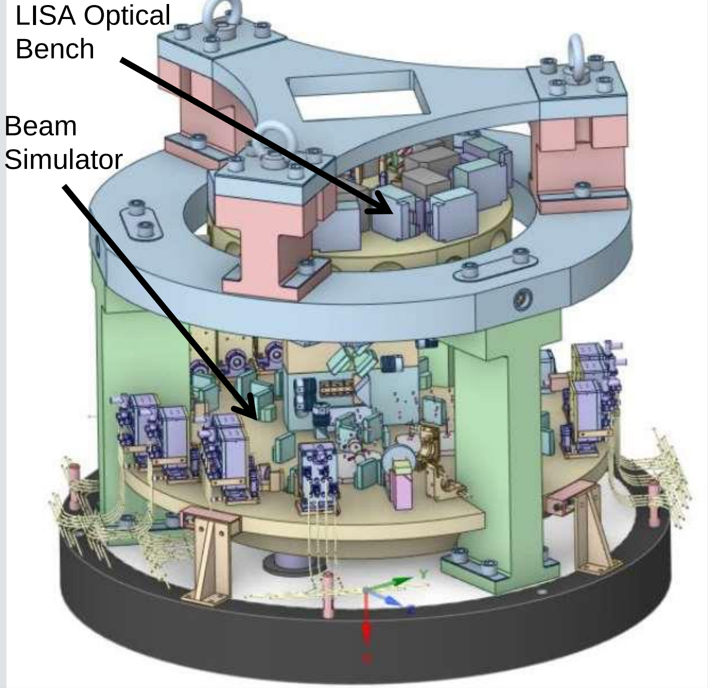
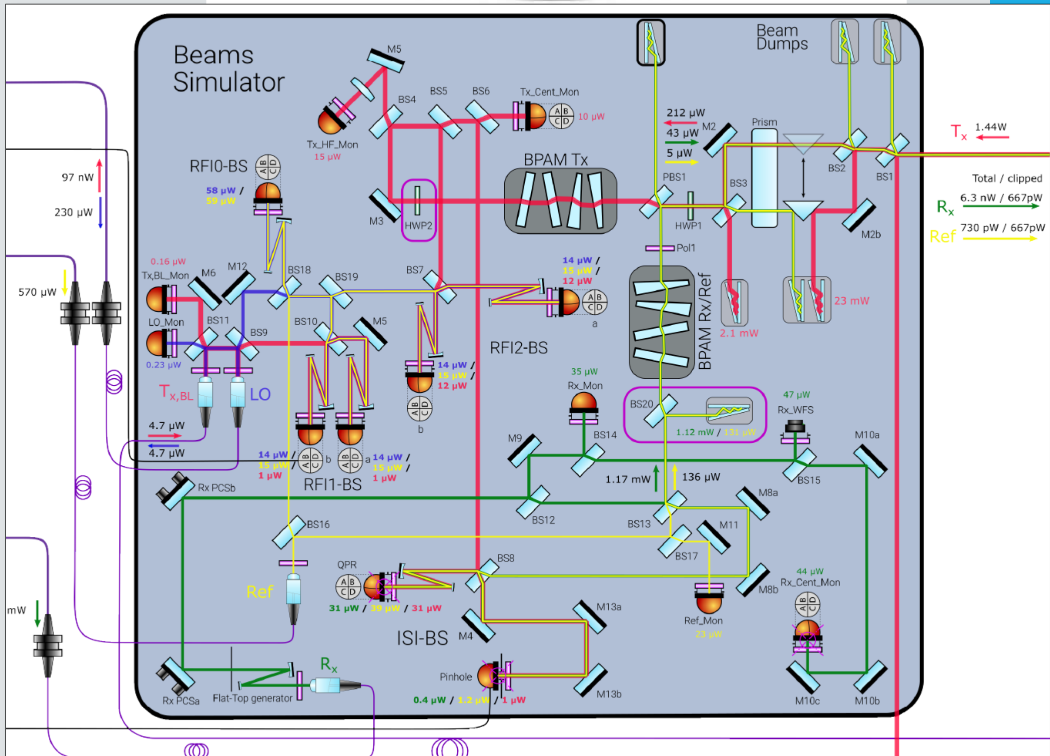



- The beam simulator is made to simulate the optical interface with the distant spacecraft and the adjacent MOSA on the same spacecraft
- Creation of a flat top beam (flat wavefront), adequat dumping of the powerfull laser beams to have a flight representative config
- Characterization of the picometric stability
- Characterization of the tilt-to-lenght coefficient of the optical bench




Thank you for your attention !