LISA

A spaceborne observatory for detecting gravitational waves

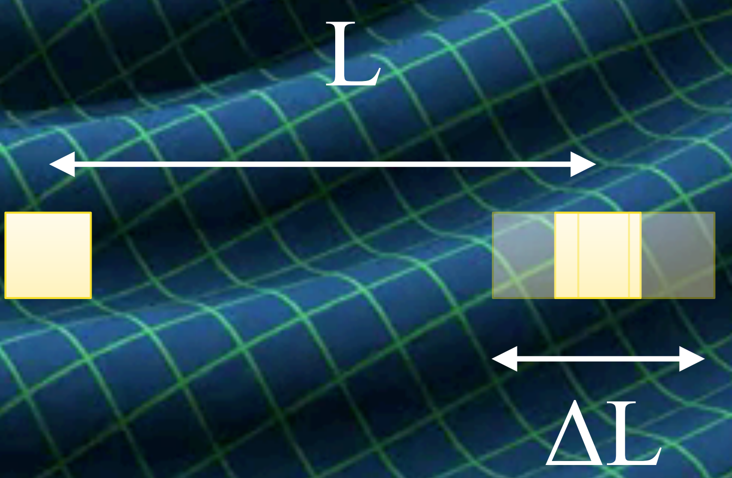
H.Halloin, APC
for the LISA France collaboration

Séminaire CPPM

Marseille, 12 mai 2025

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

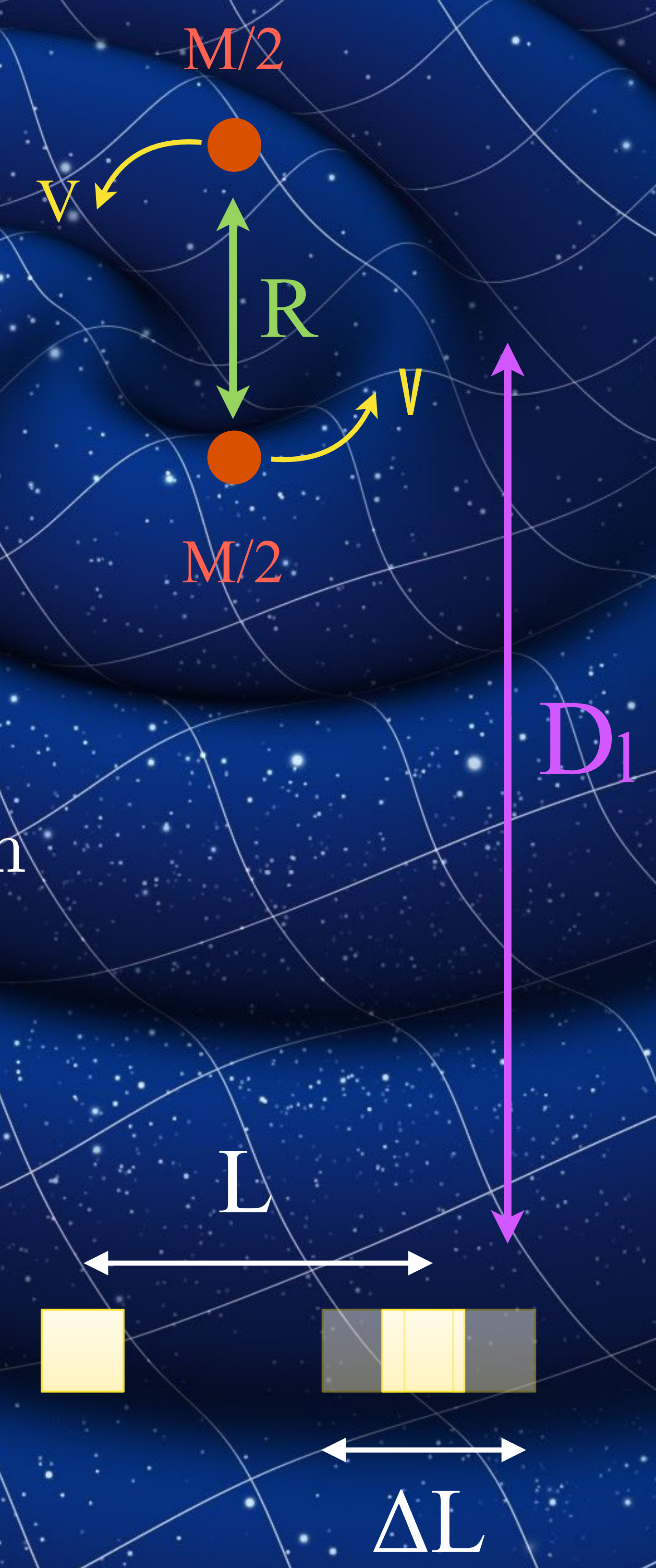
$$\frac{v^2}{c^2} \approx \frac{GM}{Rc^2} = \Xi < 1$$

  - GW Amplitude

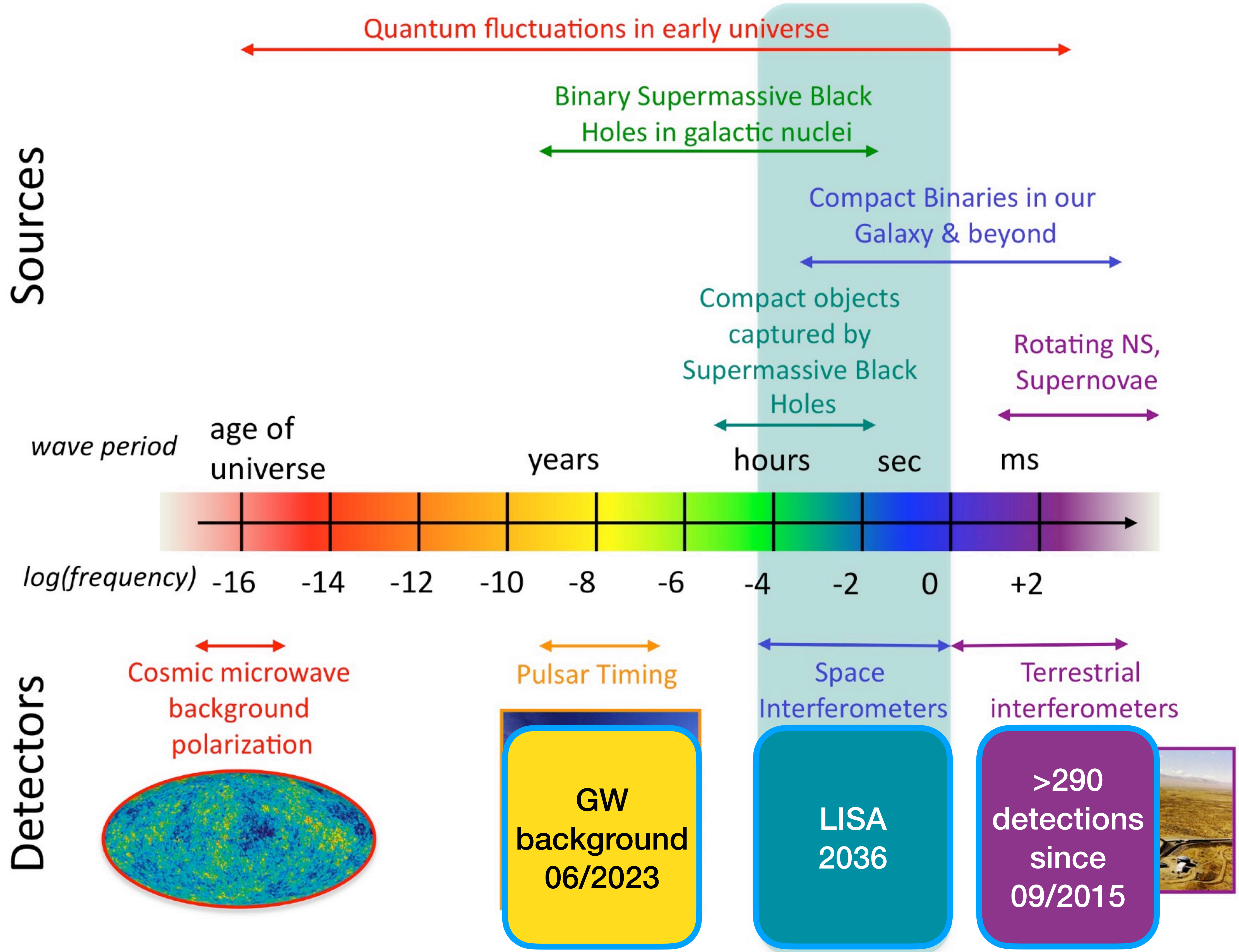
$$h = 2\frac{\Delta L}{L} \lesssim \frac{\Xi}{10^{-1}} \cdot \frac{M}{10^6 M_\odot} \cdot \frac{10\ \mathrm{Gpc}}{D_l} \quad \mathrm{nm/Mkm}$$

  - GW Frequency

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



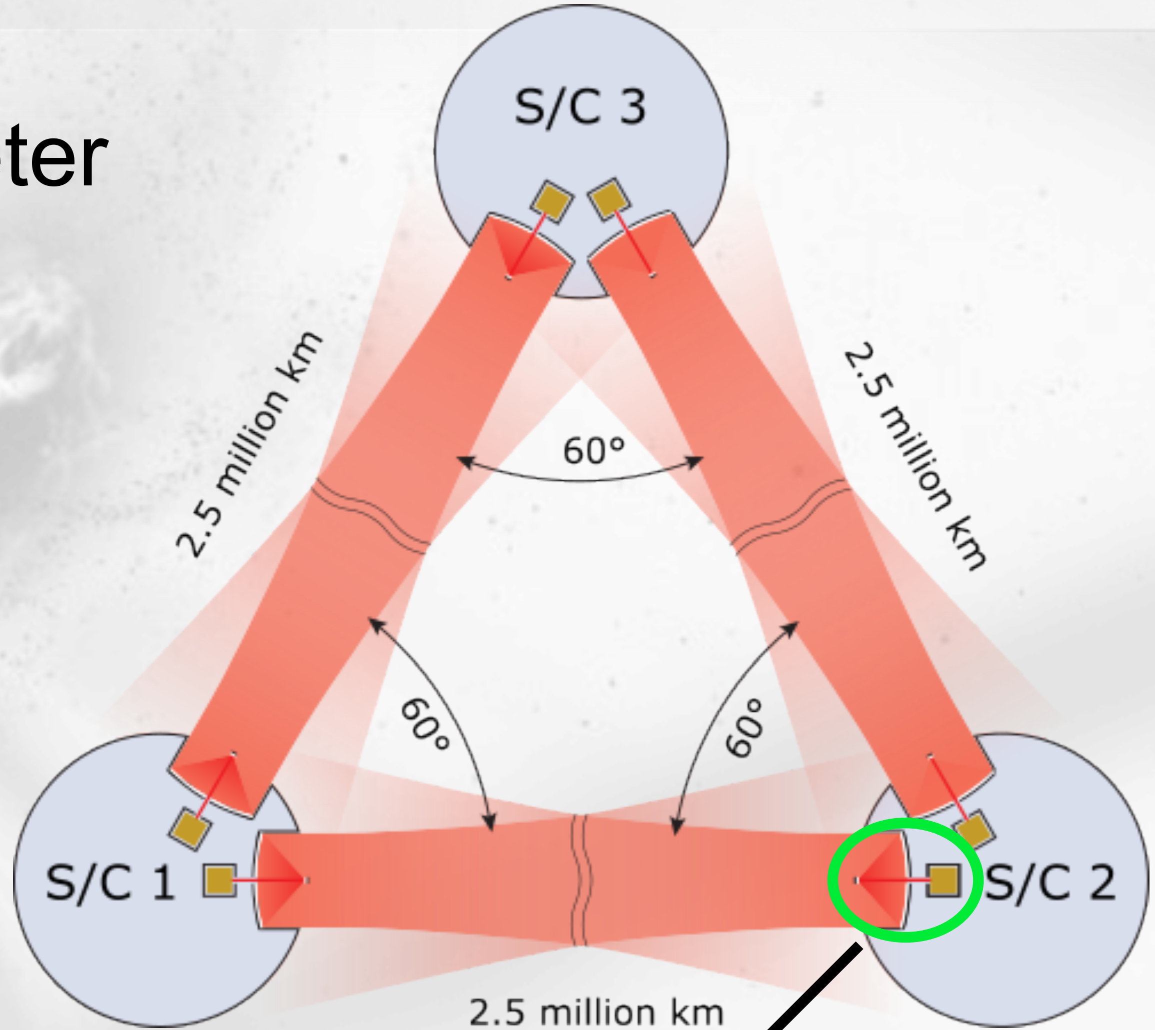
GW astronomy has started !

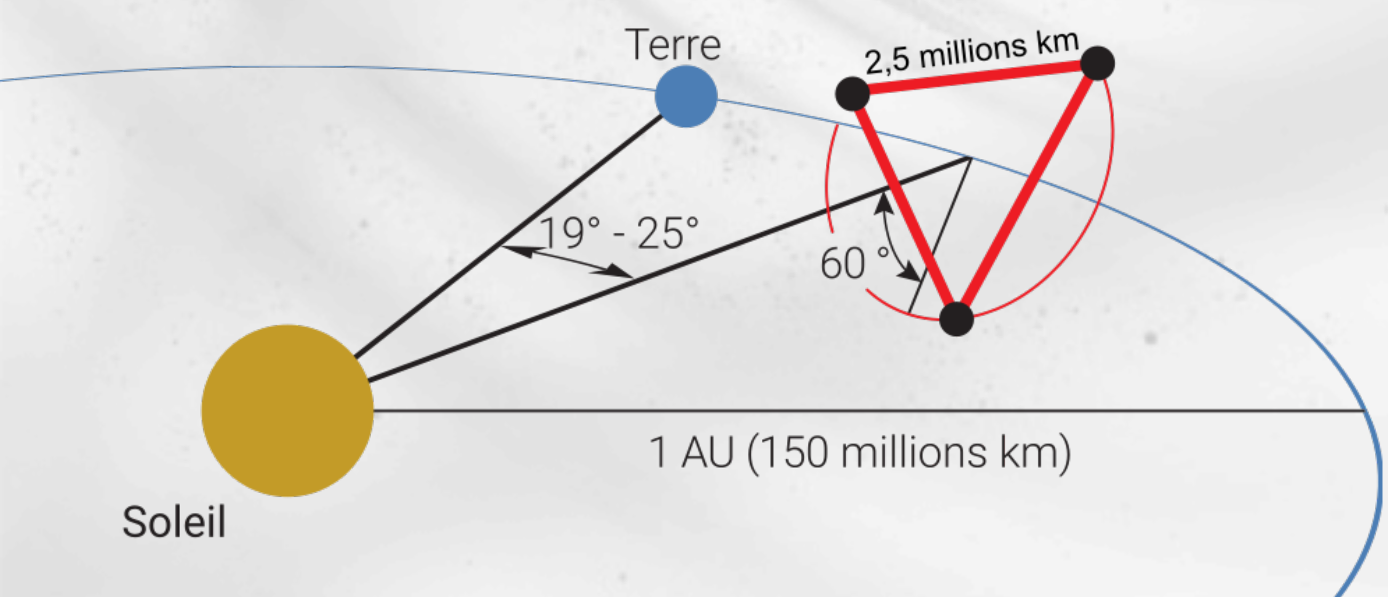


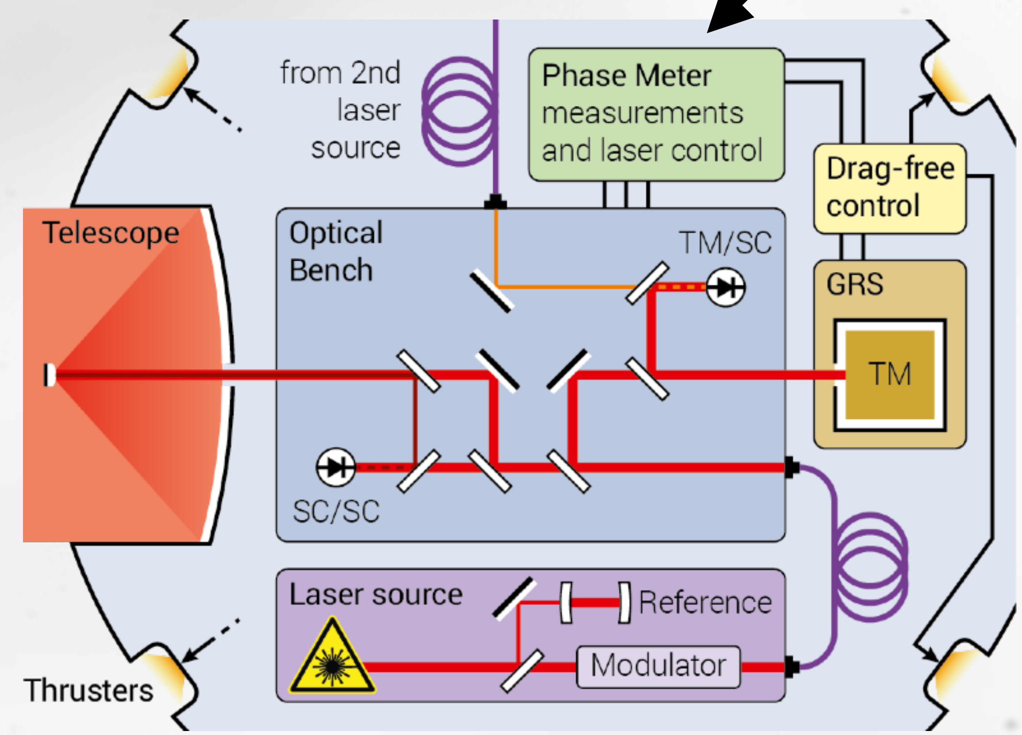
Credit: NASA Goddard Space Flight Center

LISA a new class of instrument

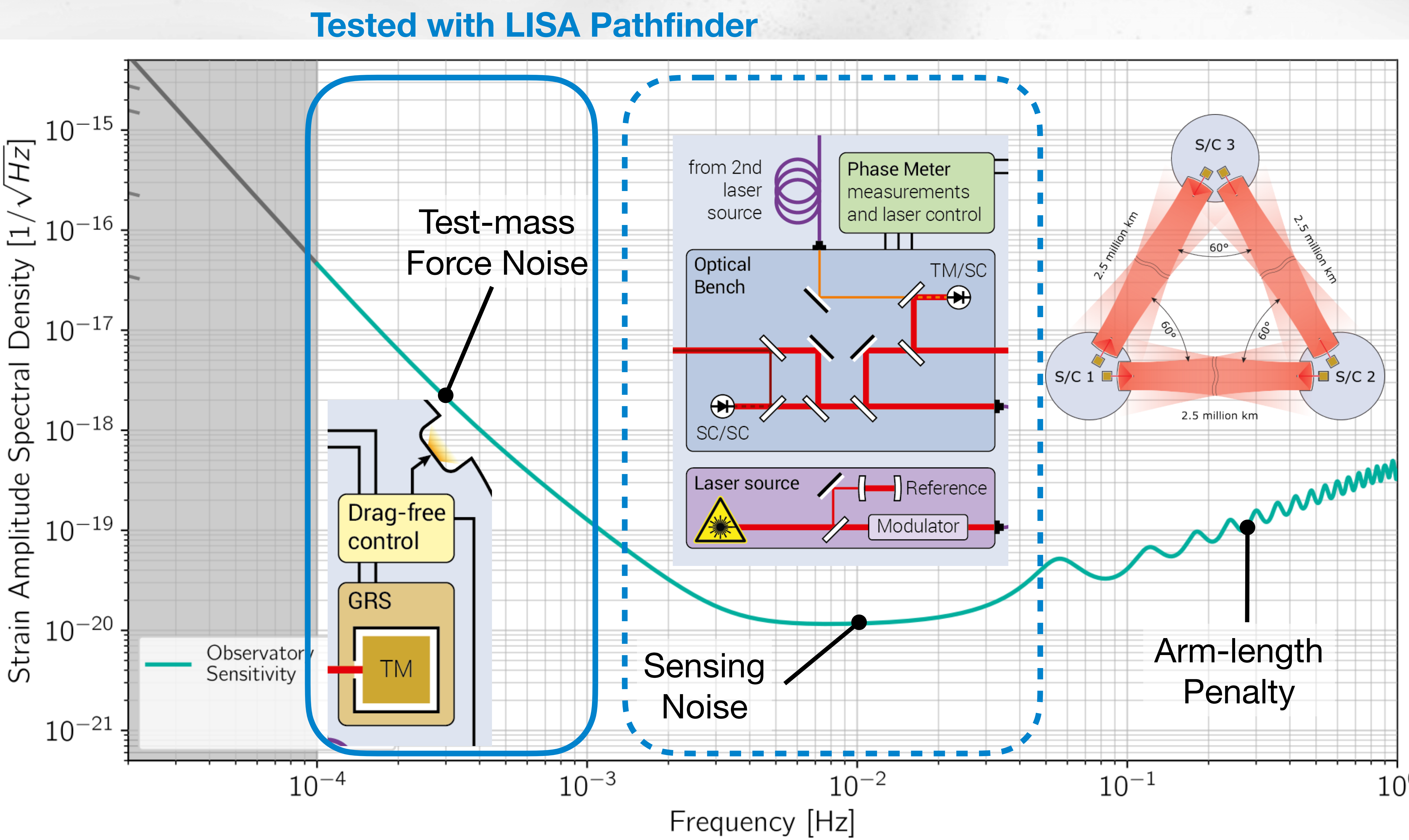
- LISA = giant spaceborne interferometer
  - 3 arms, 2.5 Mkm long
    - ~7 x Earth - Moon distance
  - 2 inertial masses per spacecraft
    - Drag-free system to compensate the solar pressure (and other disturbances)
  - Metrology noise **≤10 pm/√Hz à 10 mHz**
    - ⇒ Sensitivity of ~1 pm/Mkm (10^{-21})





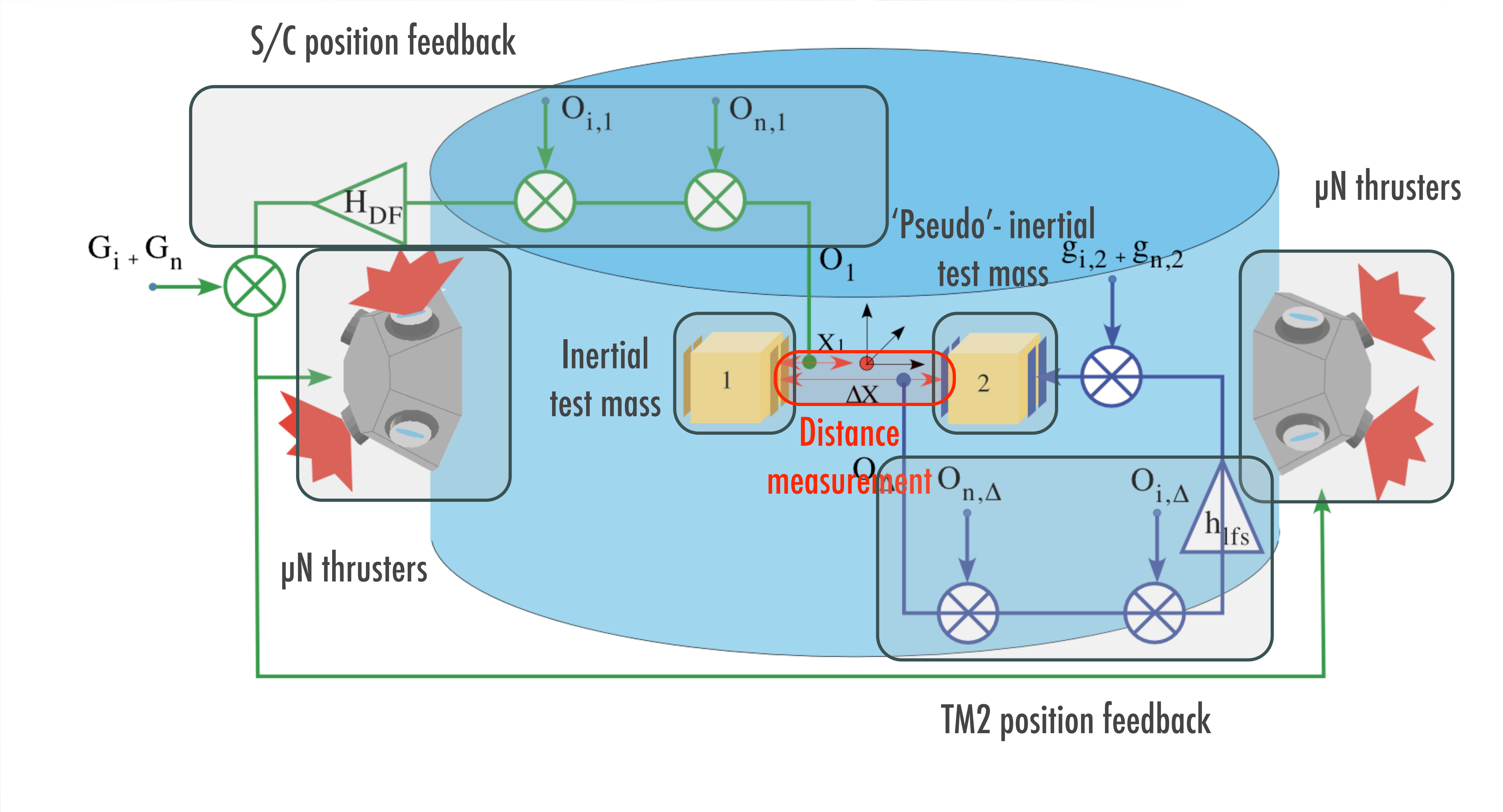


LISA Sensitivity

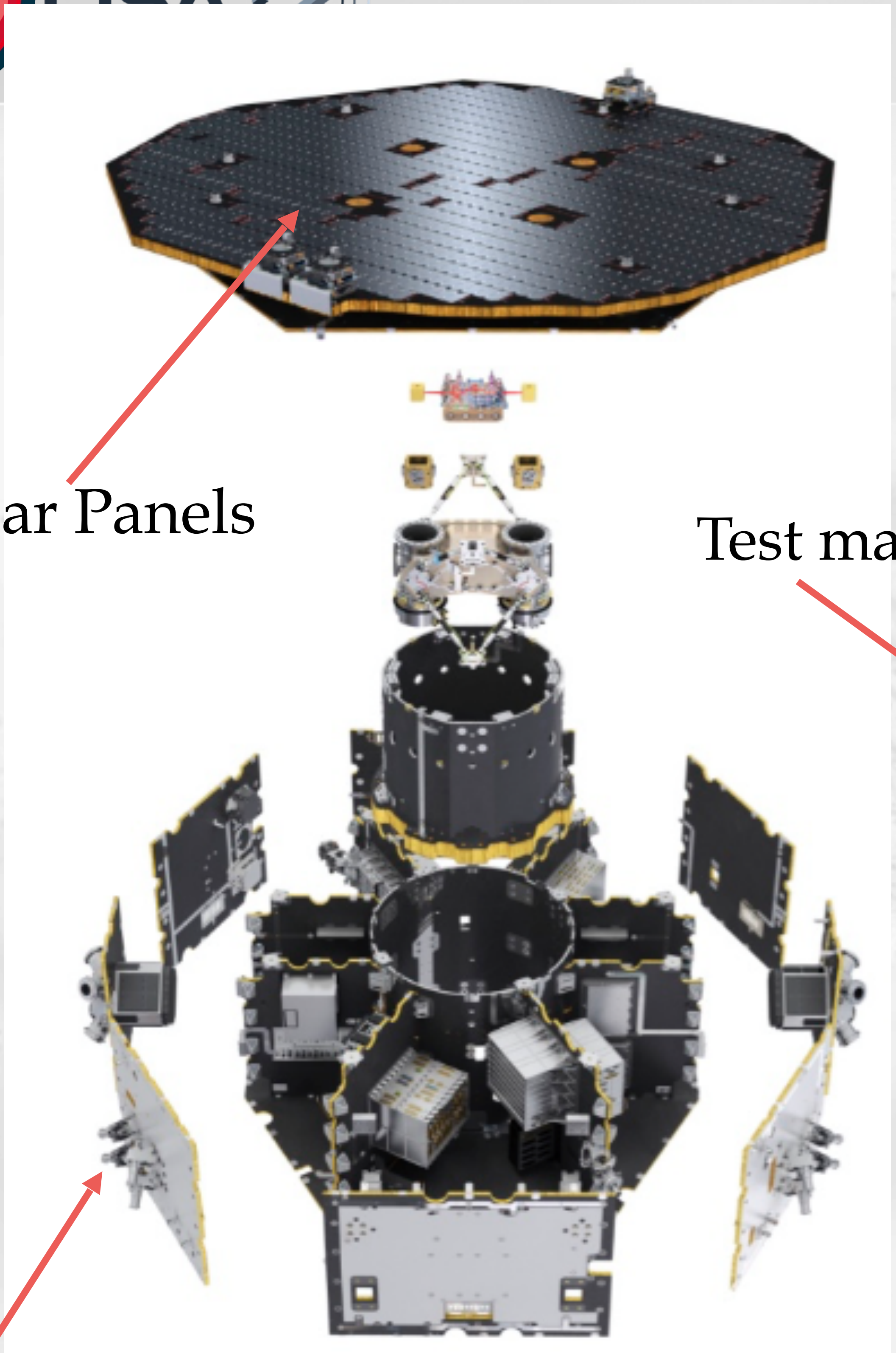


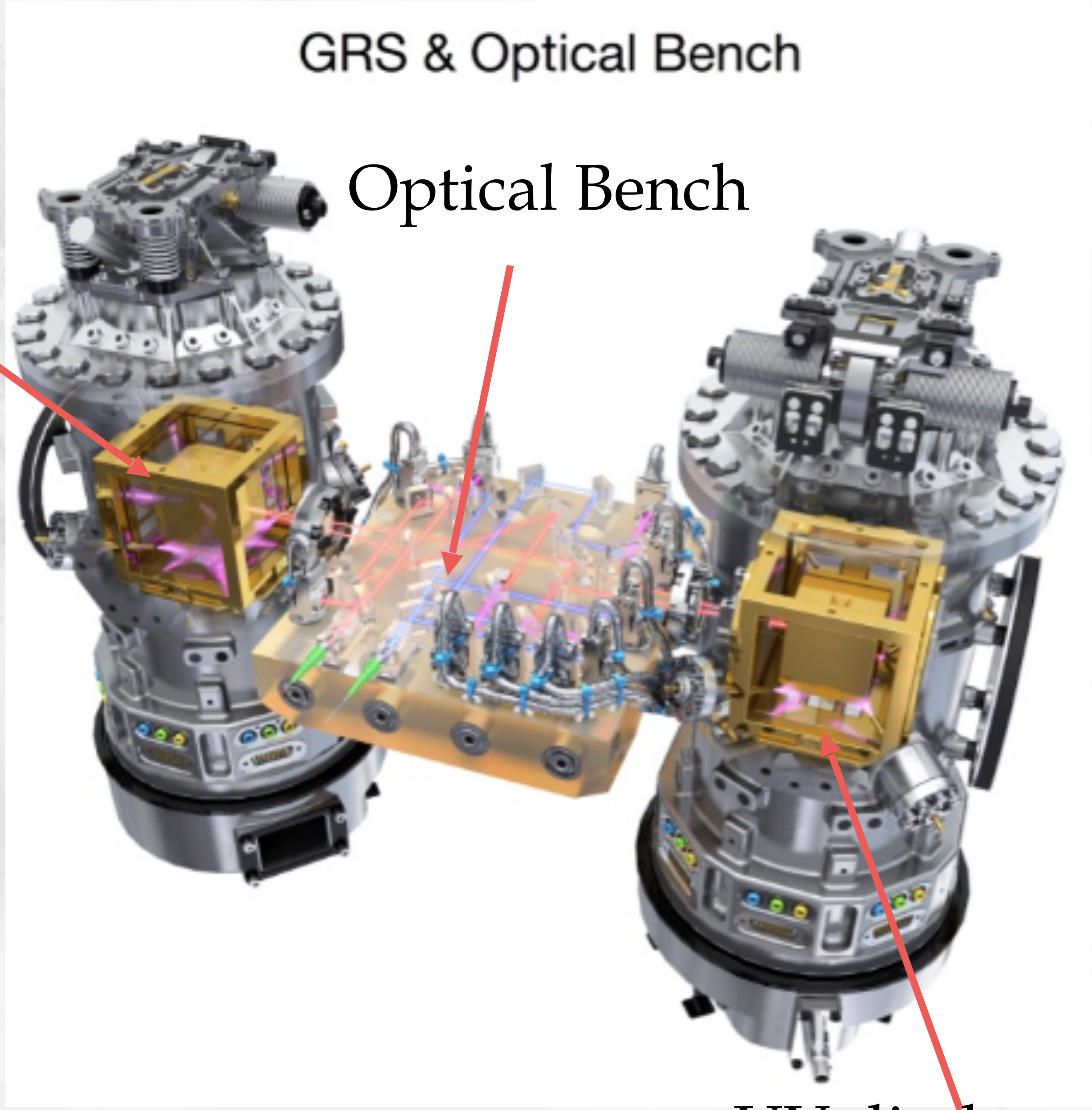
Testing drag-free flying: LISA Pathfinder

- Principle scheme



LISA Pathfinder





Solar Panels

Test mass

Optical Bench

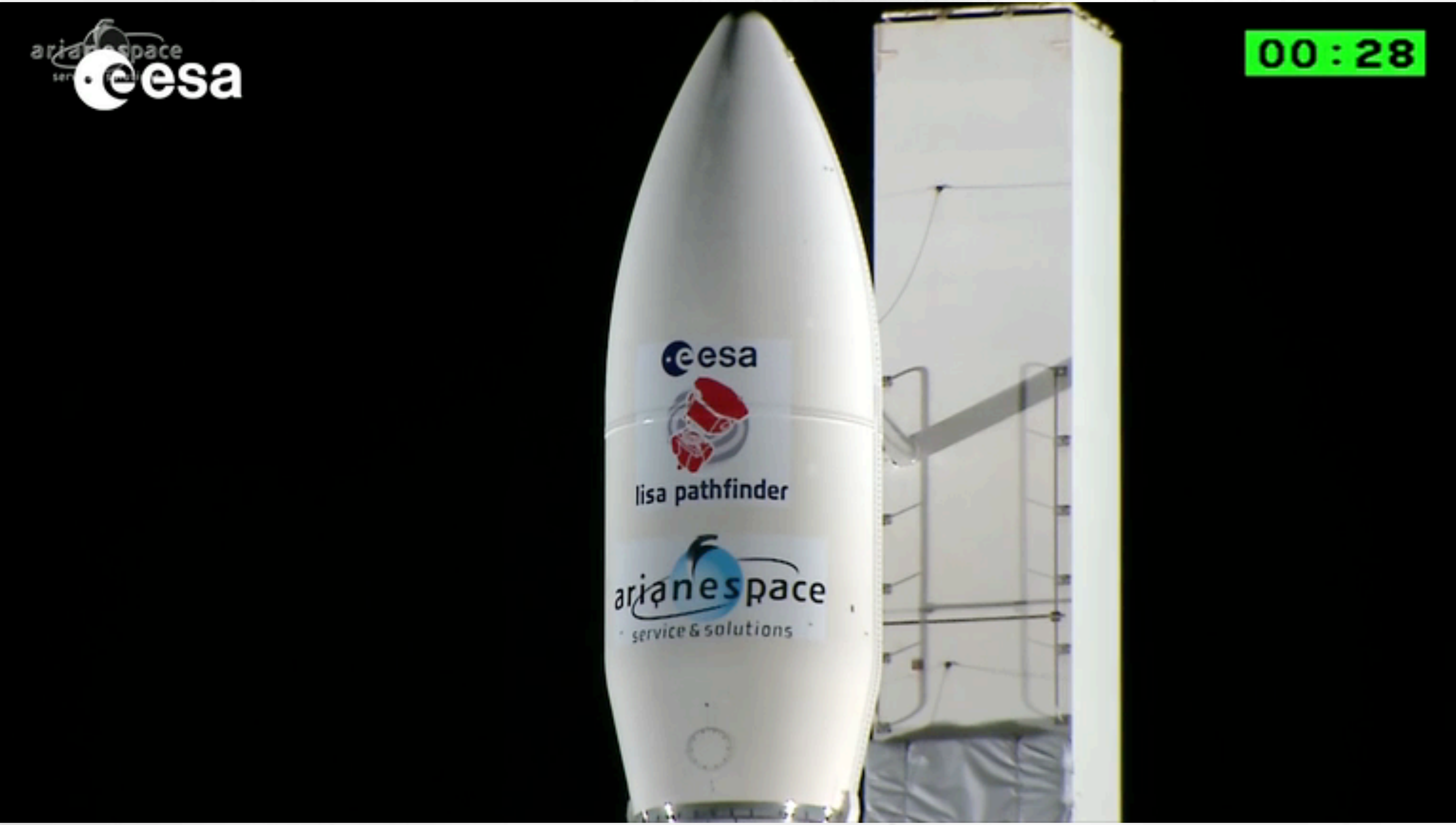
µN cold gas thrusters

UV discharge lamp


iABG

LISA Pathfinder - 03/12/15

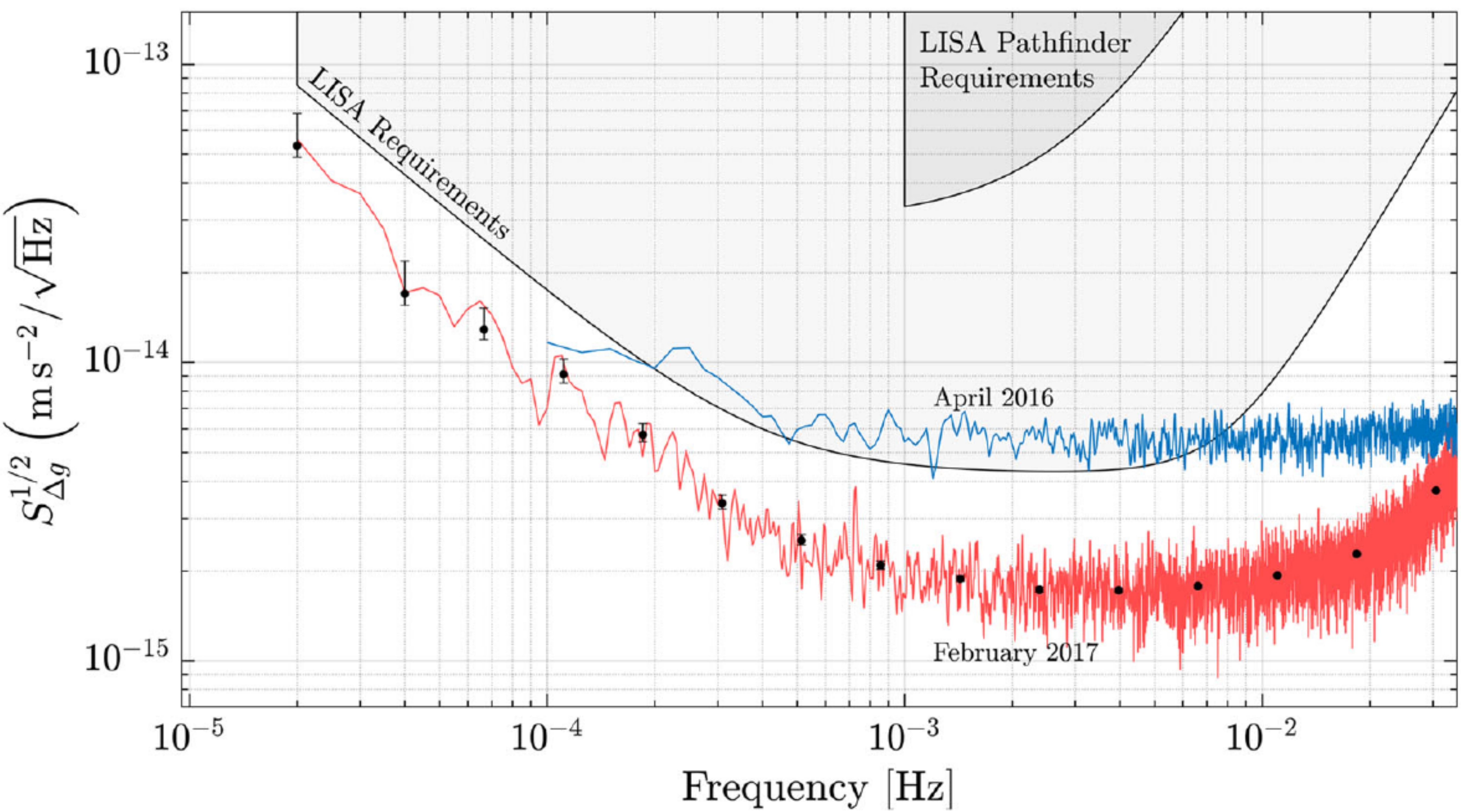
http://www.esa.int/spaceinvideos/Videos/2015/12/LISA_Pathfinder_liftoff



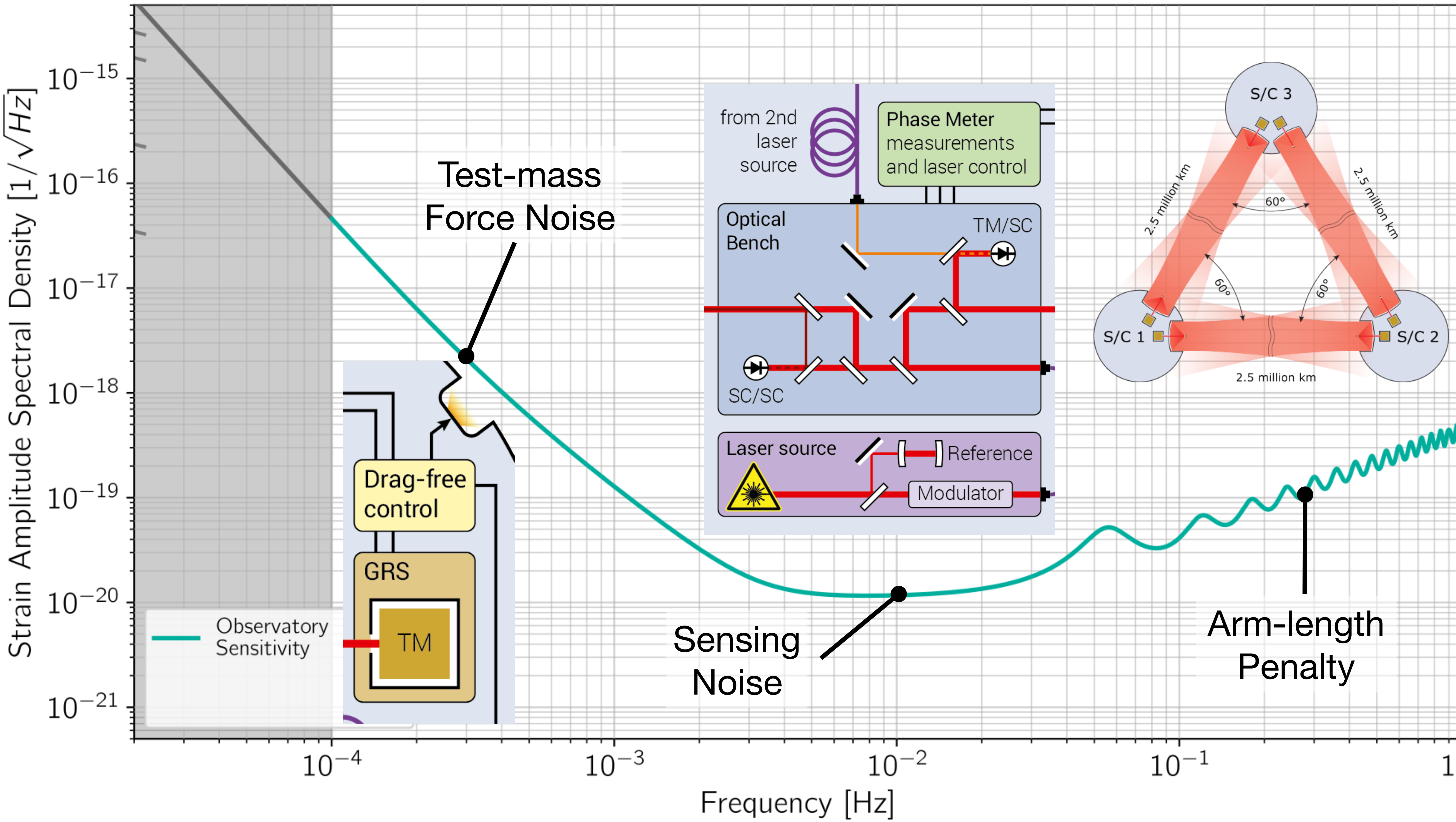
PHYSICAL REVIEW LETTERS **120**, 061101 (2018)

Editors' Suggestion | Featured in Physics

Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz

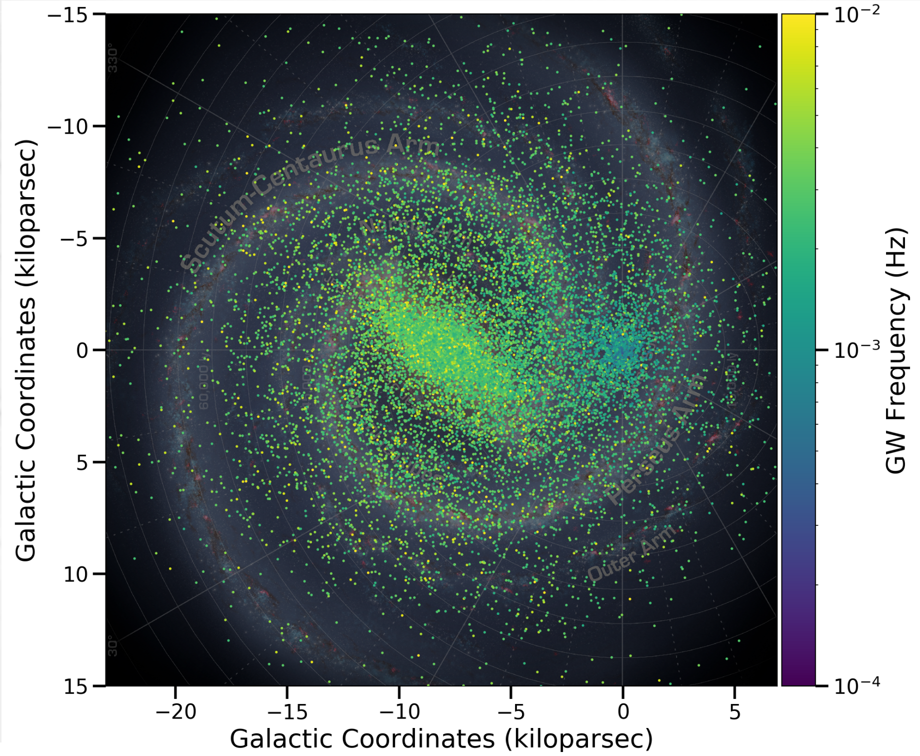


LISA Sensitivity



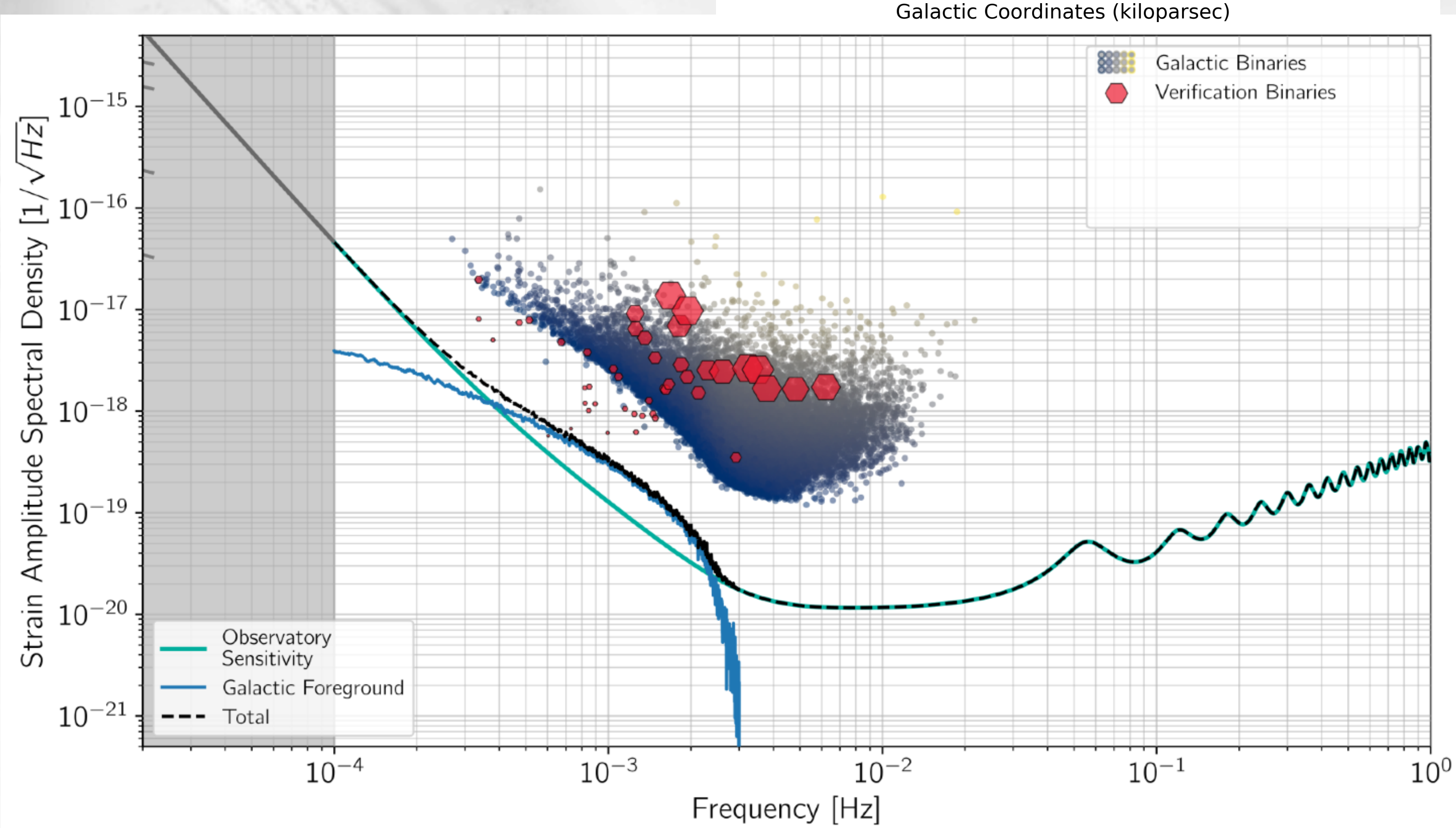
Formation and evolution of compact binaries in our Galaxy

- White dwarfs, Neutron stars and stellar black holes
- Estimated population : ~10^7
  - Galactic foreground
  - ~10^4 individually detectable
  - A few 10s verification binaries



➡ Formation and evolution of compact binaries

➡ Mass distribution within the Galaxy



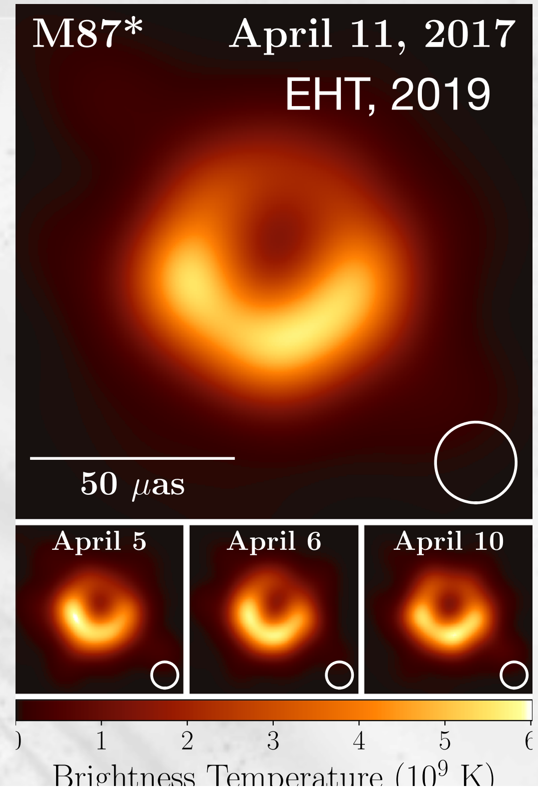
Origins, growth and fate of massive Black Holes

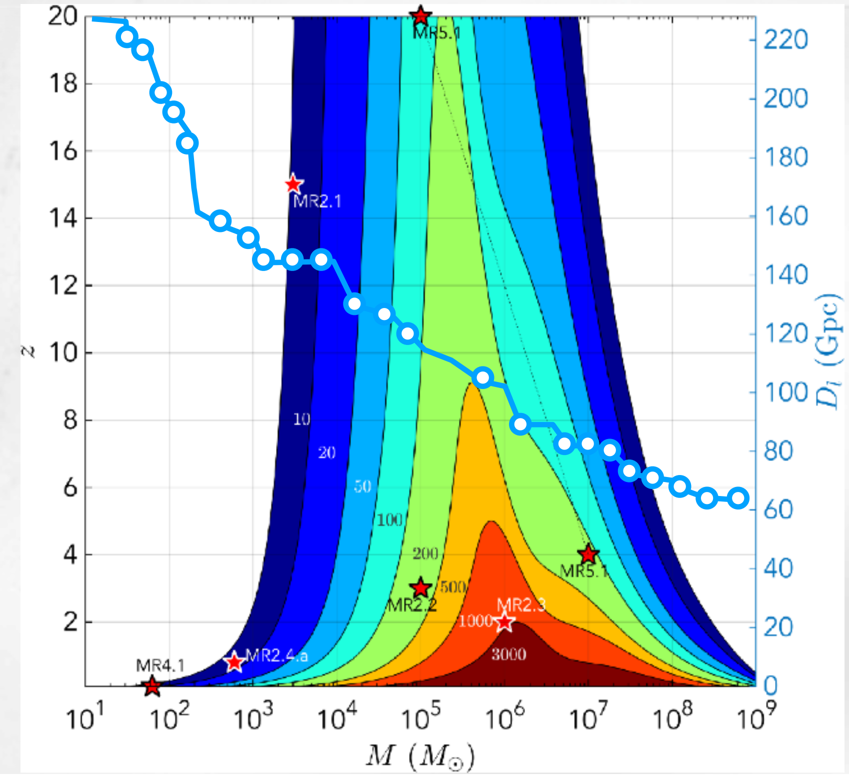
- Super massive black holes at the center of Galaxies
  - 10^4 to 10^7 $M_\odot$
  - Detectable up to z~12
  - Potential EM counterparts up to z~3

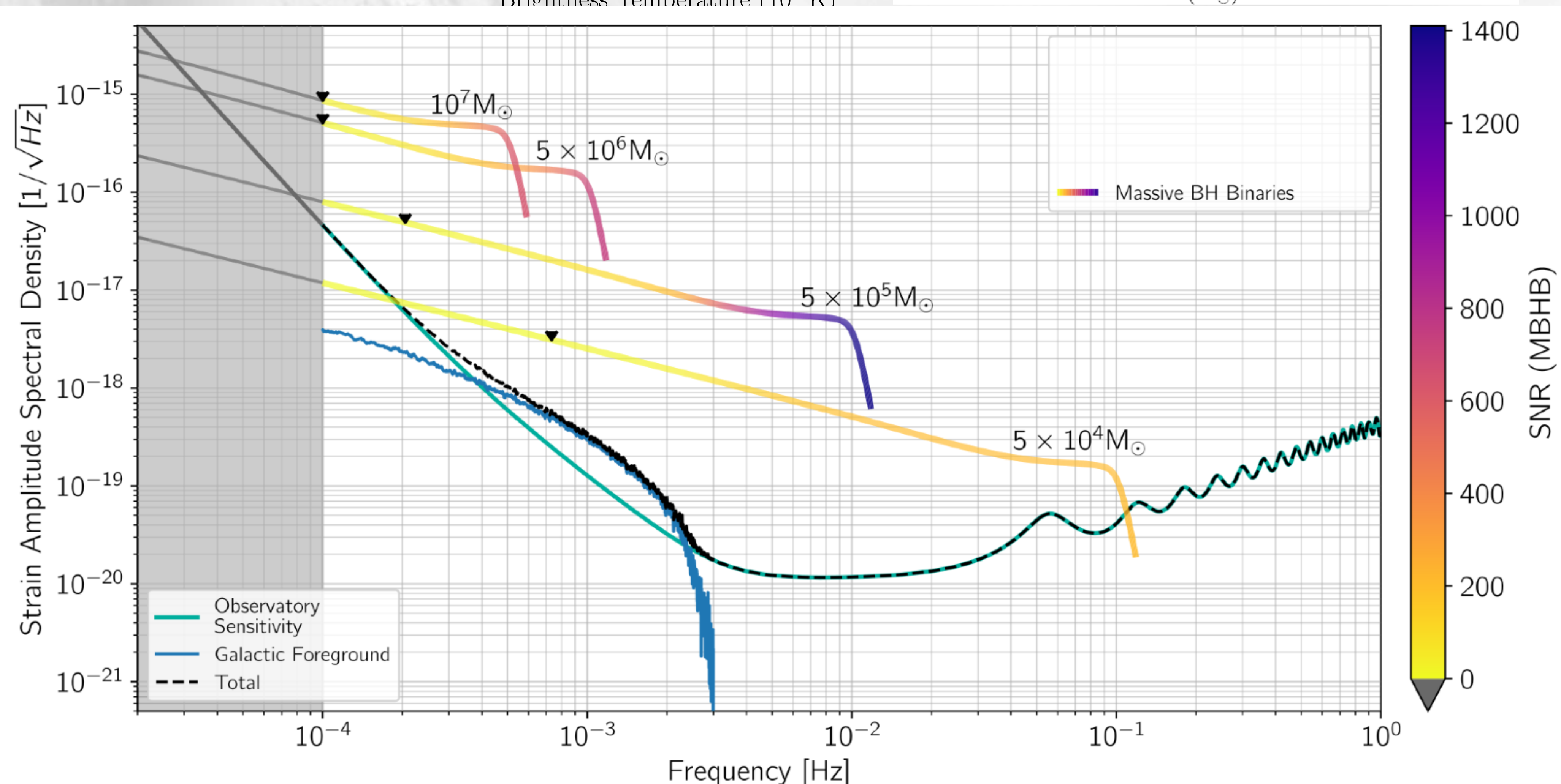
➡ Nature and origin of seed BH at cosmic reionisation

➡ Growth mechanisms and merger history of massive BH

➡ Accretion description during and after coalescence

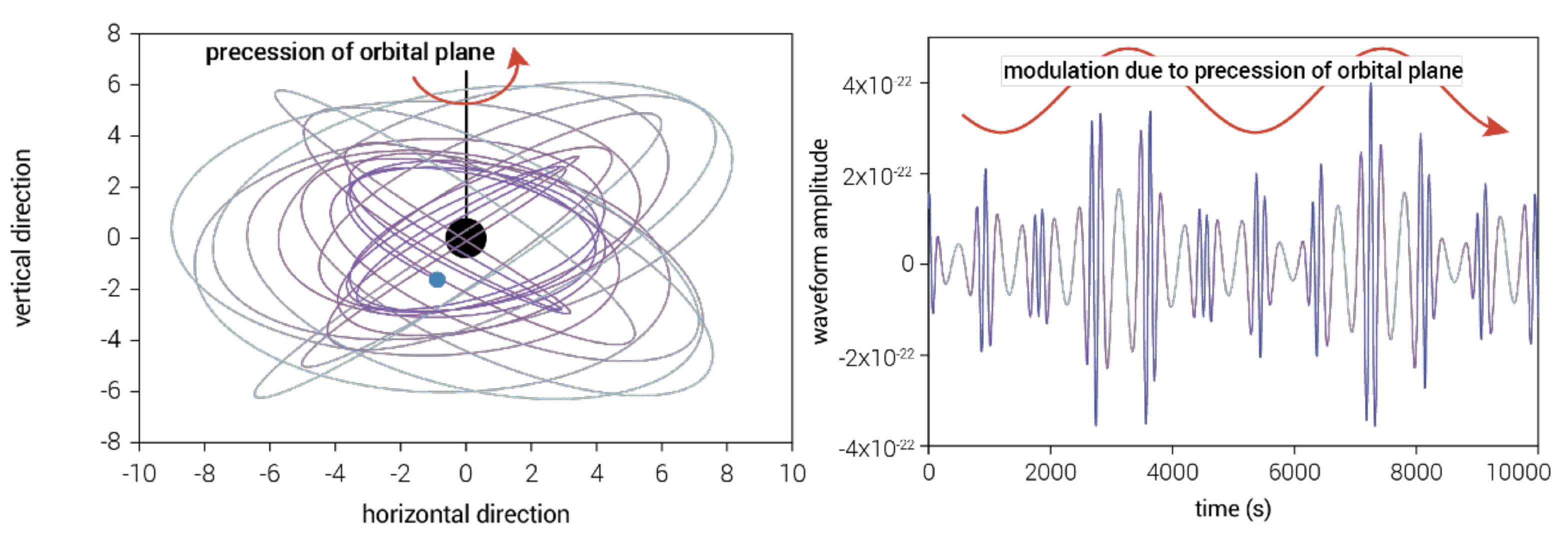






Properties and environments of Black Holes

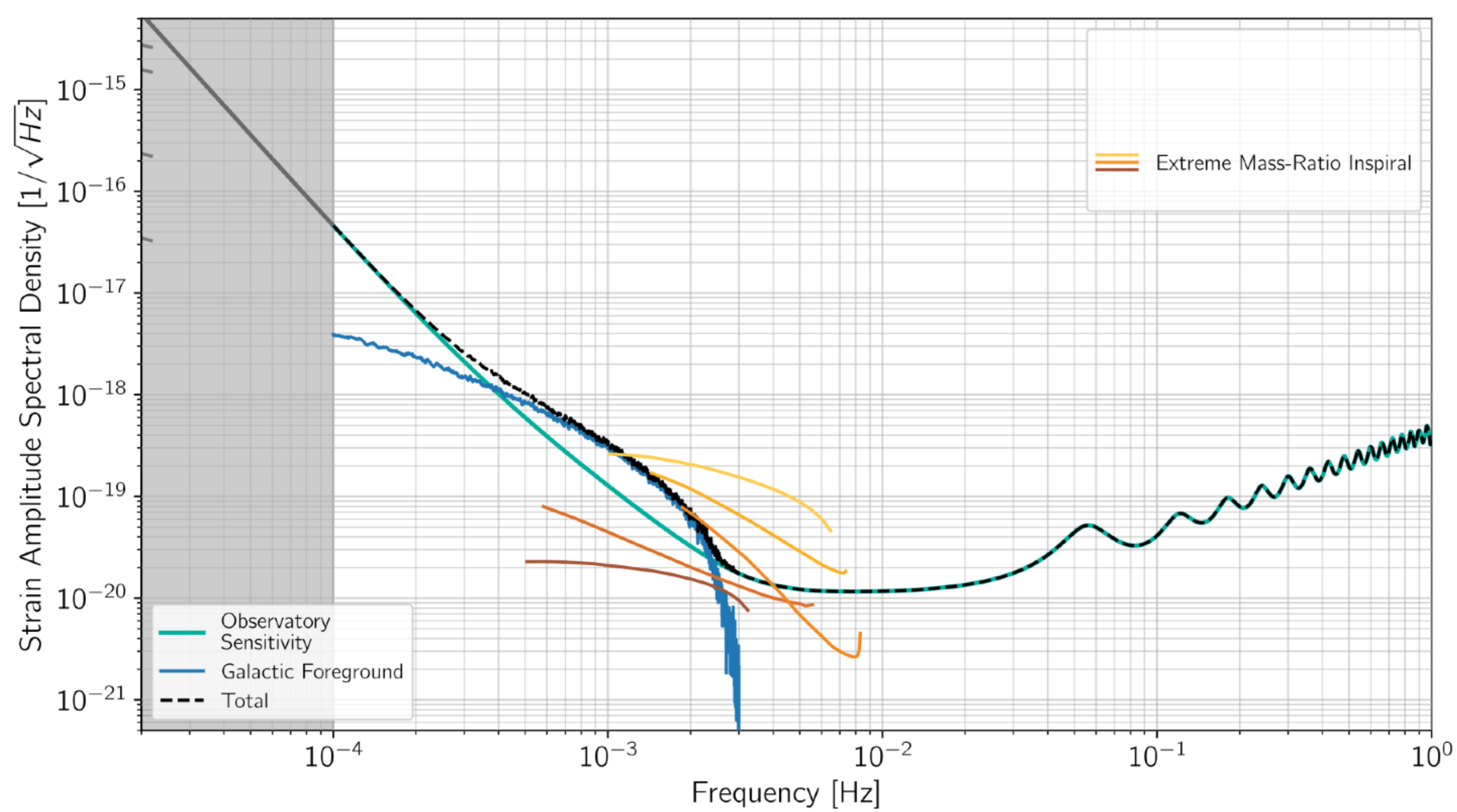
- 'Small' Black Hole (10^2 - 10^5 $M_\odot$) orbiting a super-massive one (>10^6 $M_\odot$)
- Highly relativistic trajectory and GW signal
- Probe of the properties of quiescent massive Black Holes



➡ Properties of massive BH (spin, mass)

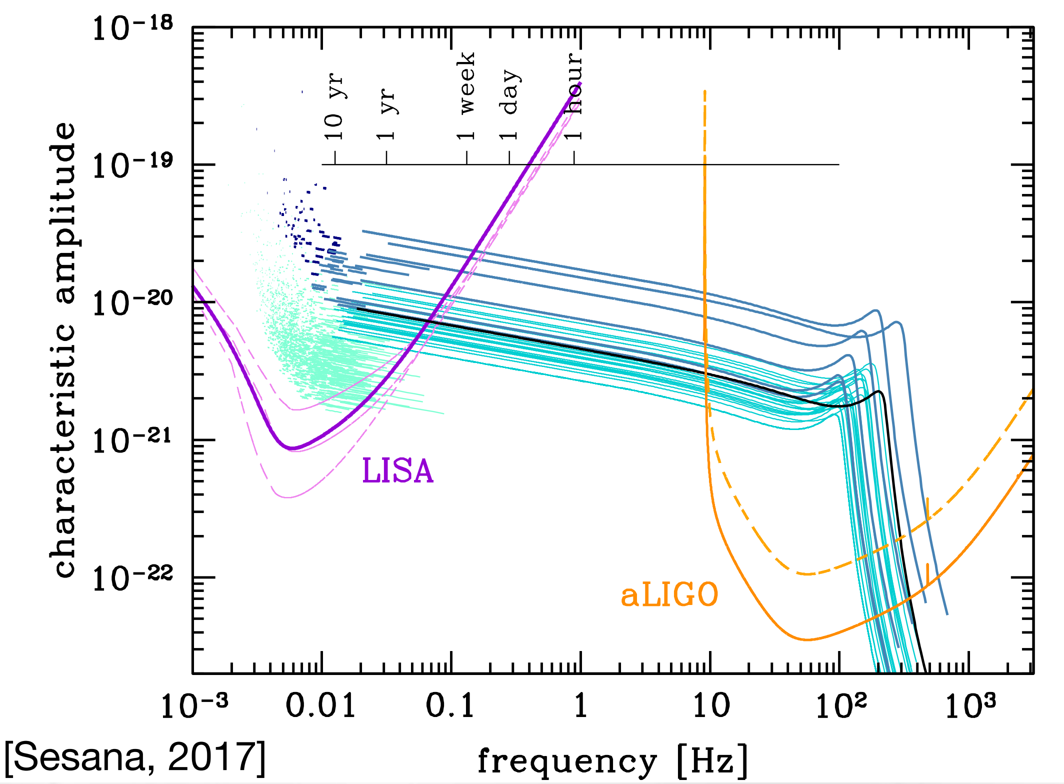
➡ Immediate environments of massive BH (gas, stars, etc.)

➡ Constraints on formation channels for such binary systems



Study of the stellar-mass Black Holes

- Ground detectors observed BH up to ~140 $M_\odot$
  - ~10 000 detections, up to z~1, expected at LISA observation time
- Detectable years before coalescence in LISA
- Some will be observed while drifting into the ground detector bandwidth

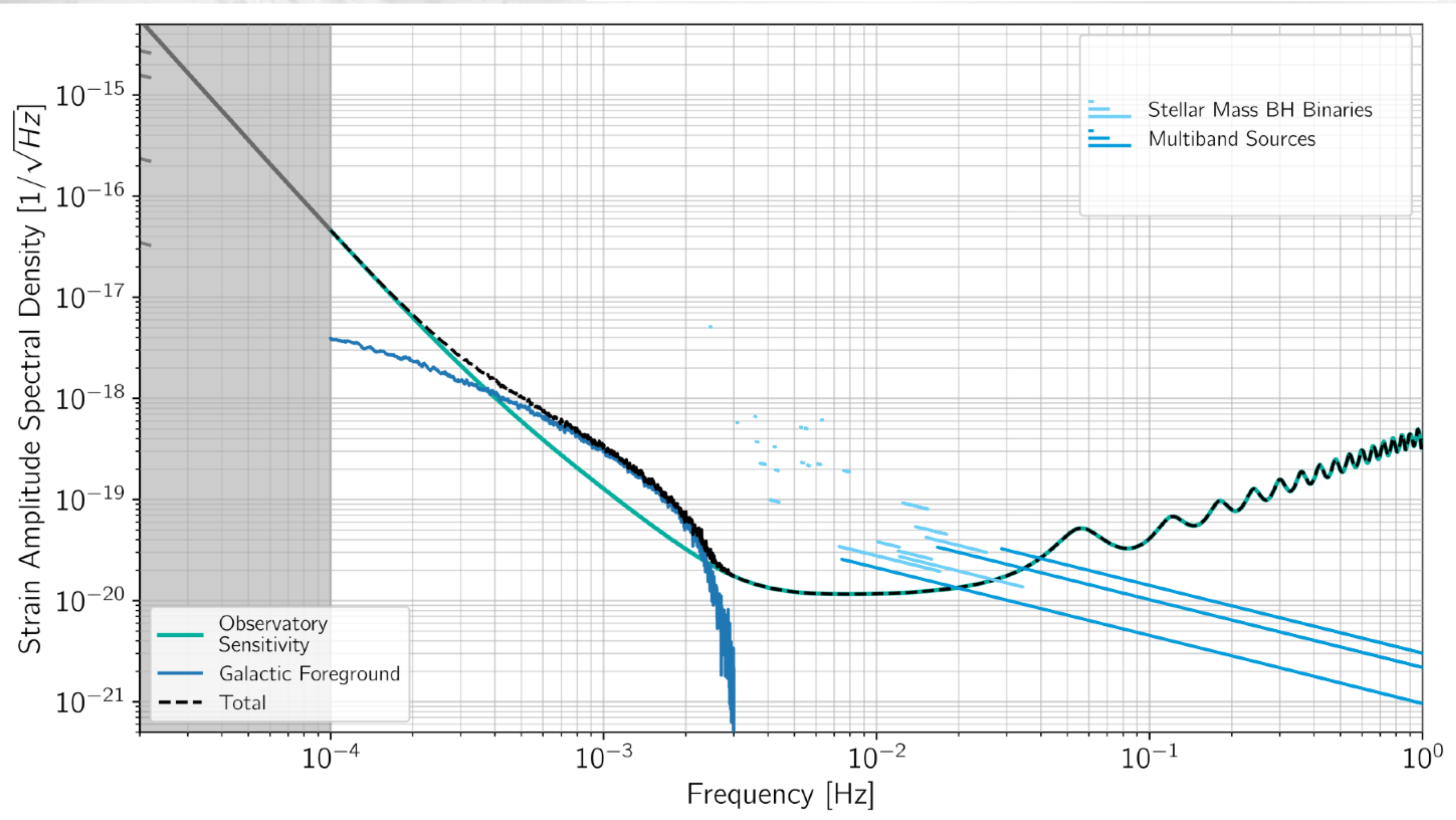


[Sesana, 2017]

➡ Stellar-mass BH formation channels

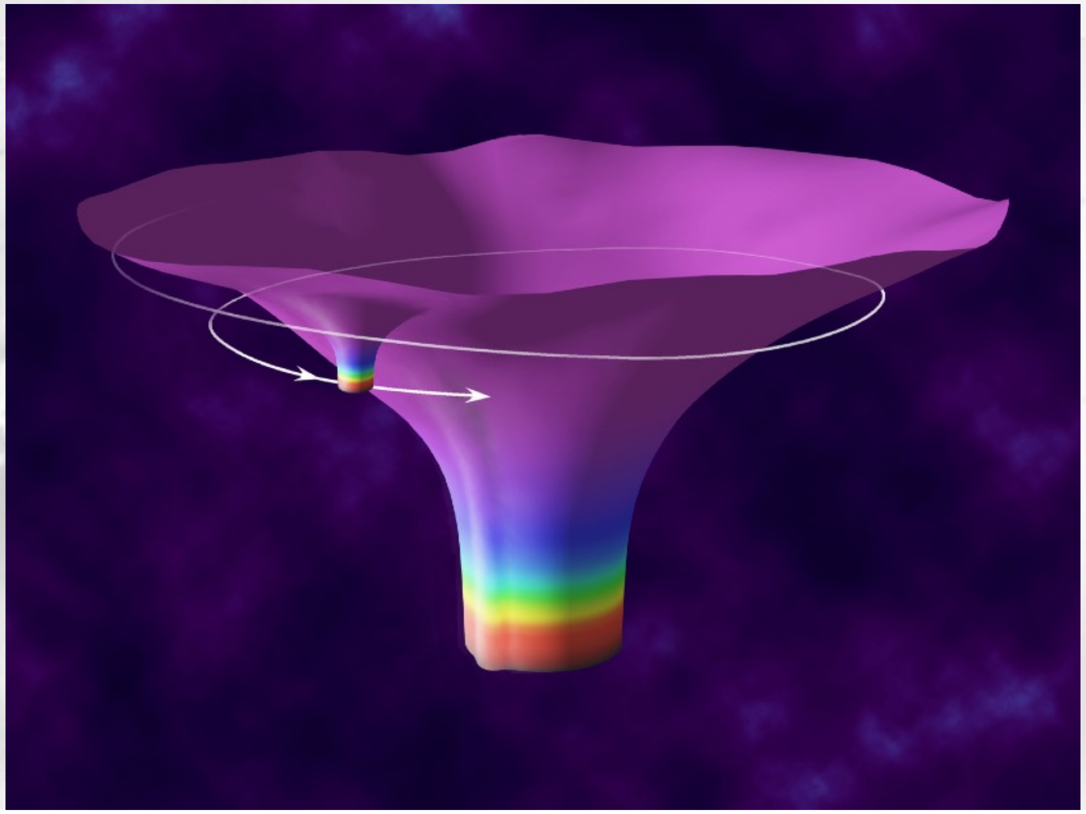
➡ Properties of the environment of these BH

➡ Alerts for ground based detectors and multi-messenger observations



Fundamental nature of gravity and Black Holes

- Observation of intertidal trajectories in strong gravitational fields (e.g. EMRIs)
- Coalescence and ringdown of massive Black Holes
- Mapping of the spacetime metric close to the Black Hole

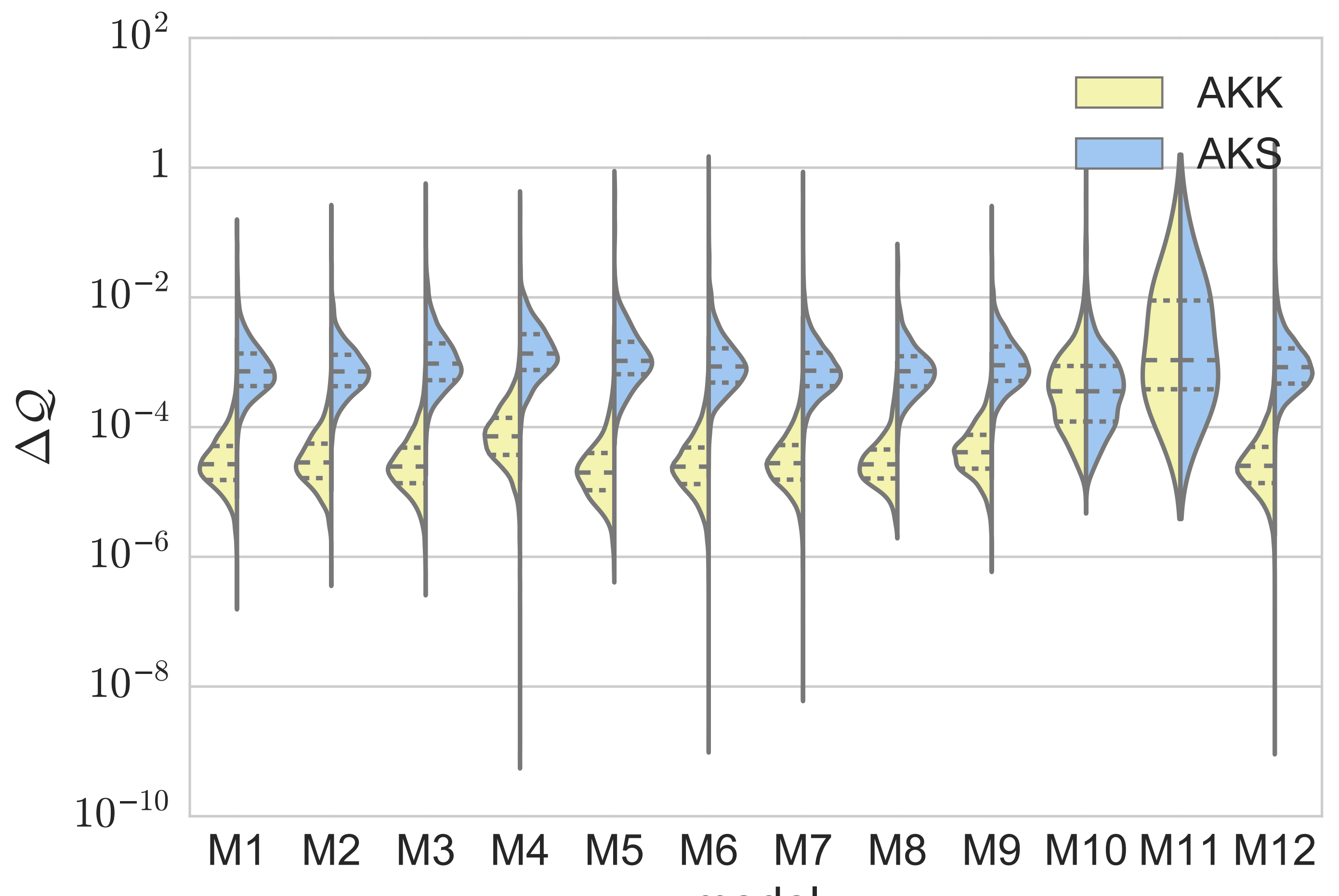


➡ Are massive BH correctly described by the Kerr solution ?

➡ Existence of horizonless compact sources ?

➡ New light fields and « no hair » theorem

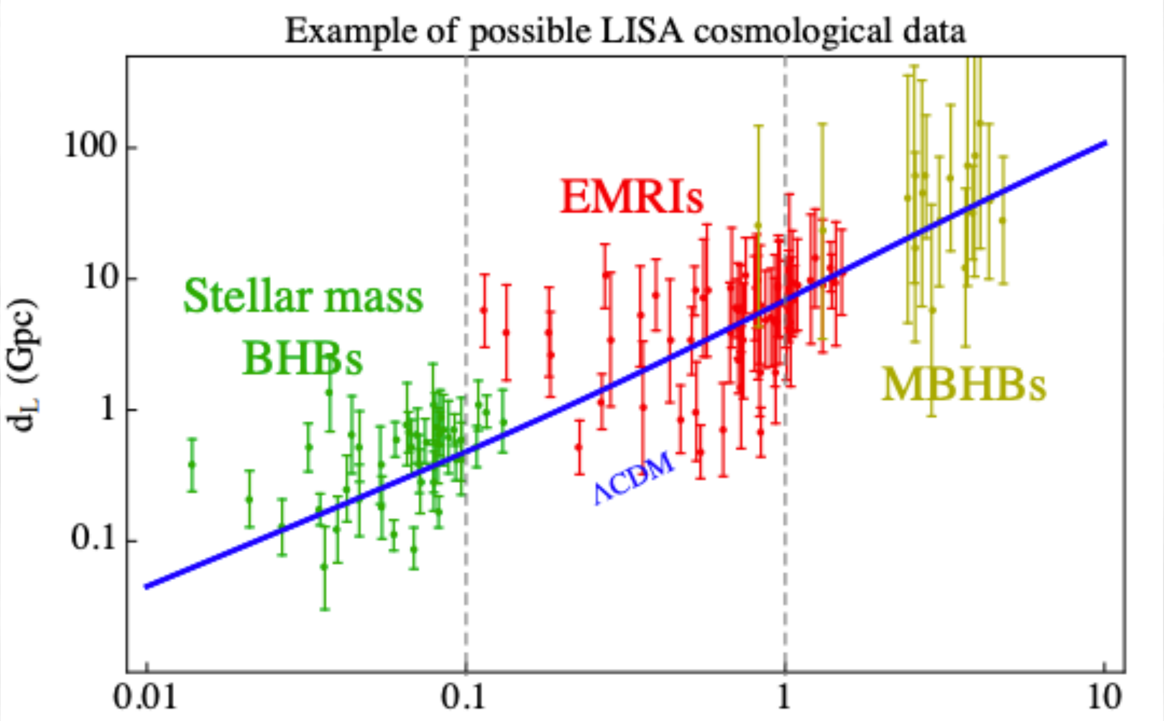
➡ GW beyond the standard model and GR ?



[Babak+, 2017]

Cosmology and stochastic backgrounds

- Black Holes binaries as standard 'sirens'
  - In conjunction with EM observations or statistical inference
- Astrophysical backgrounds, galactic and extra-galactic
- Cosmological background from the early Universe



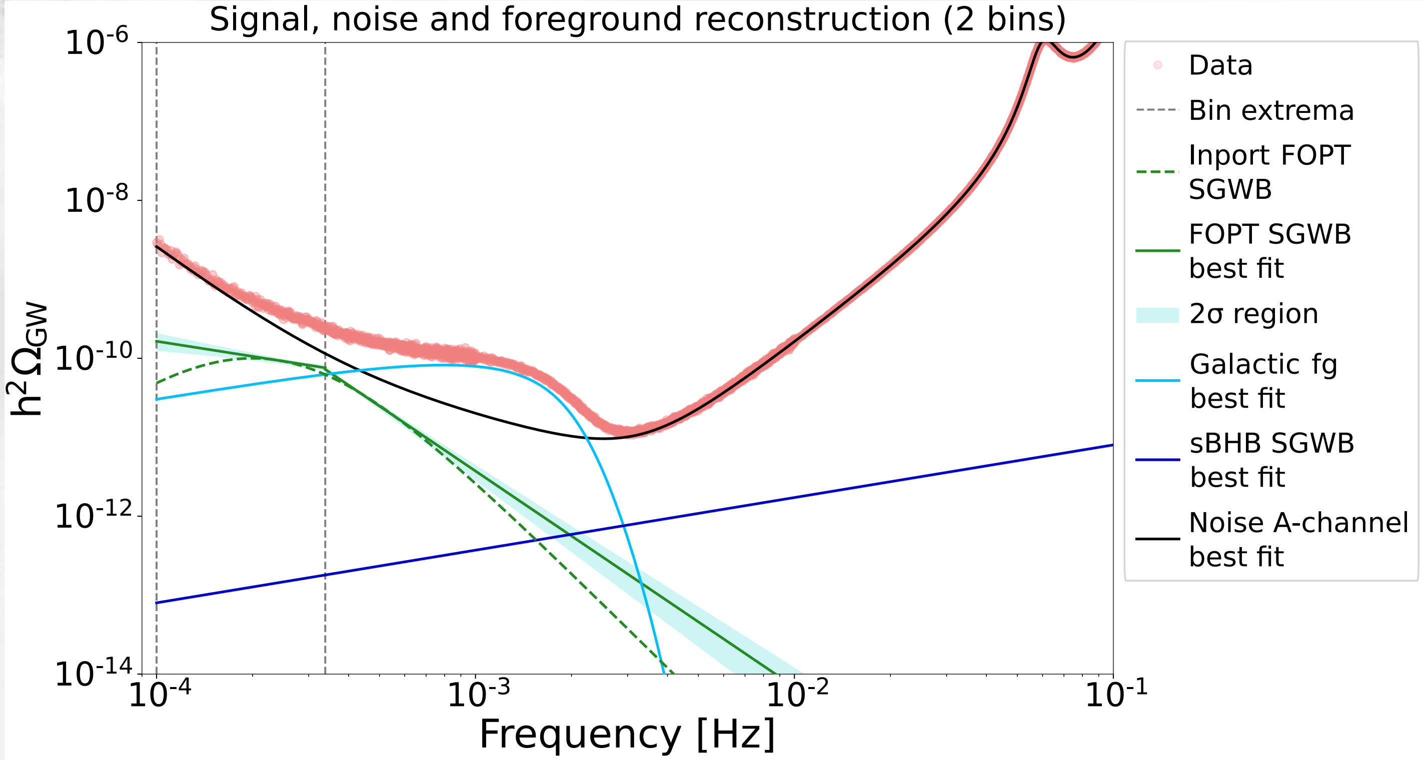
N. Tamanini J. Phys. CF 2016

➡ Expansion rate of the universe at high redshift

➡ The Early Universe beyond standard model

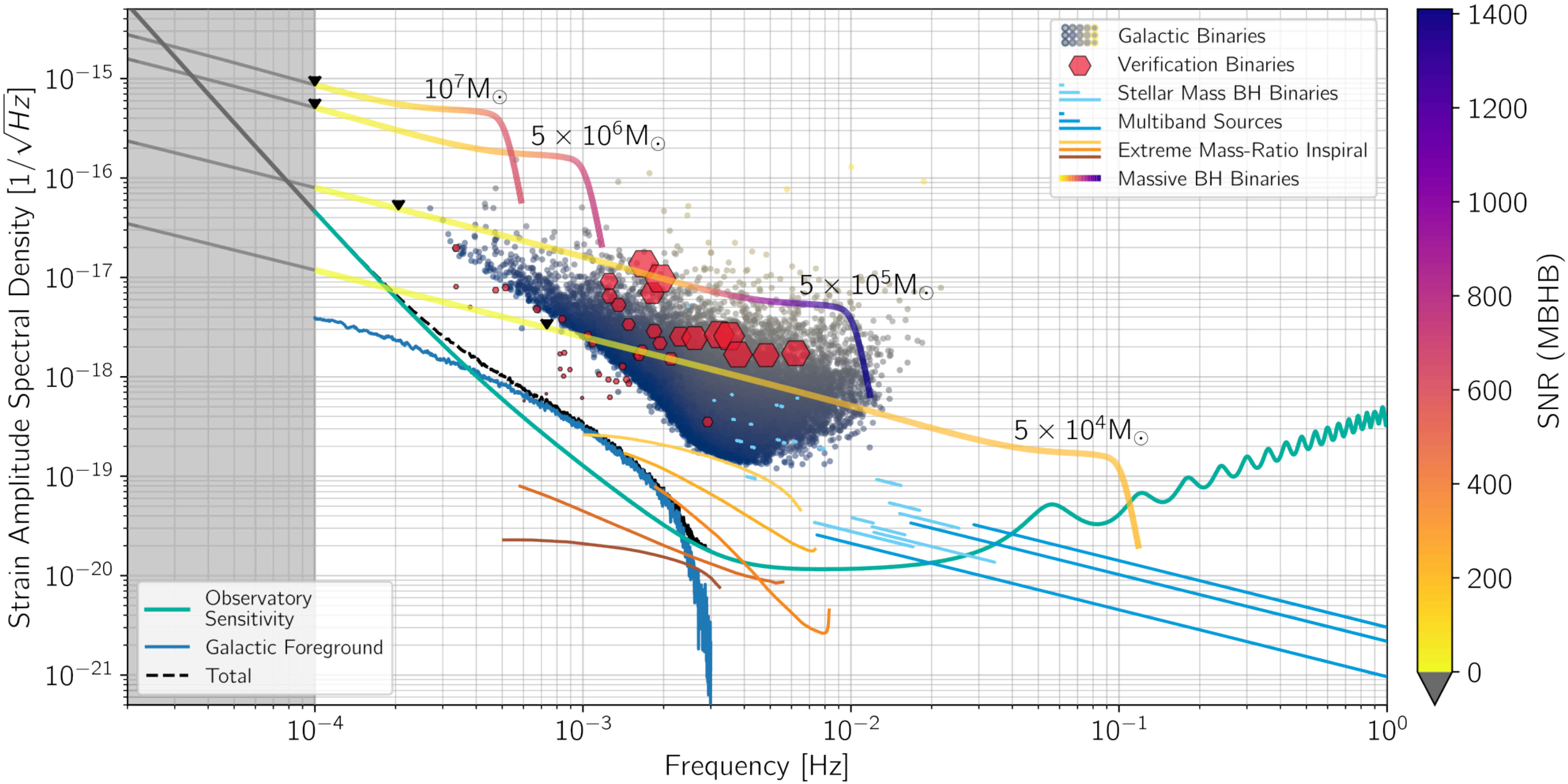
➡ Measurement / constraints on the background amplitudes

➡ Large scale anisotropies of GW backgrounds



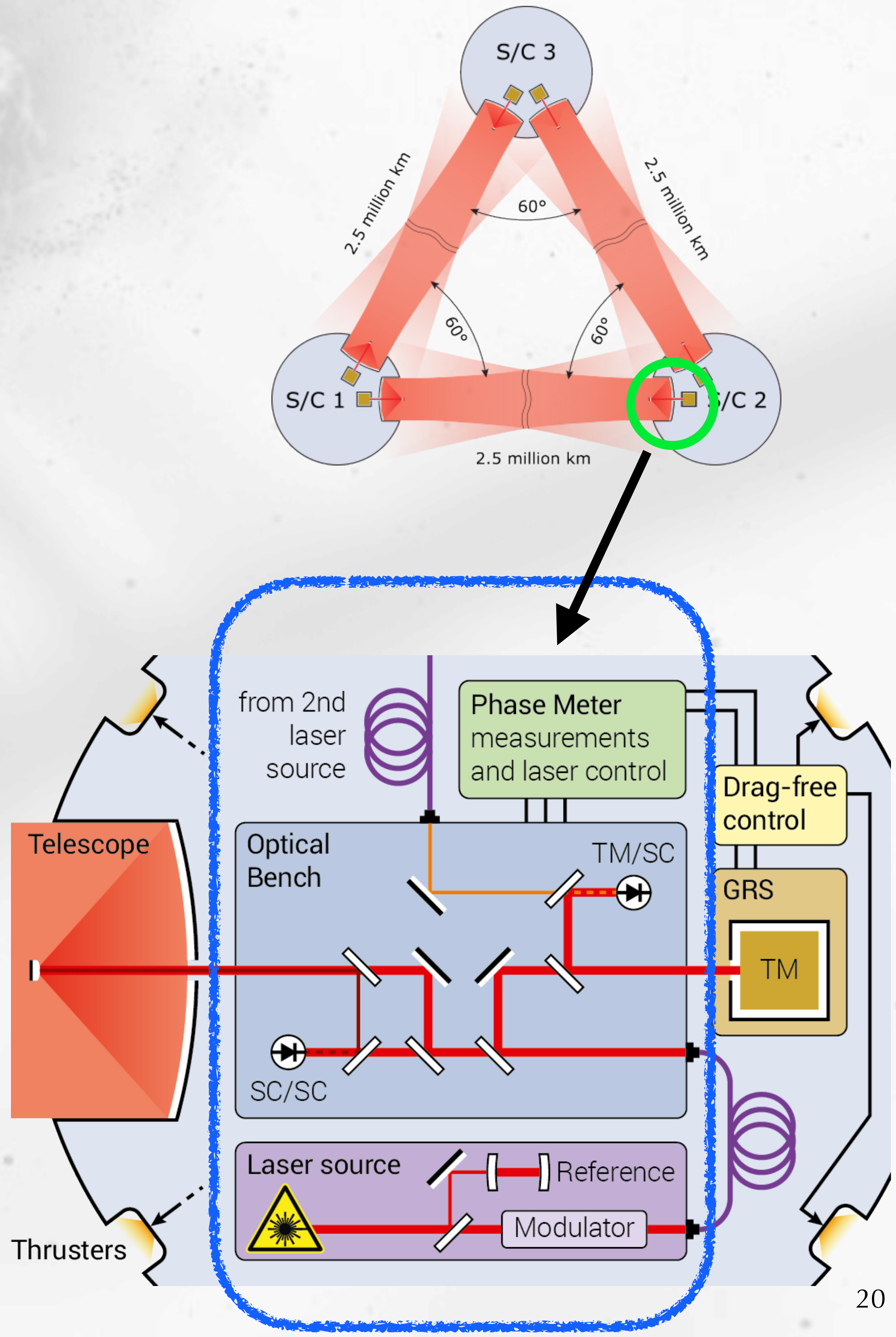
Main LISA sources

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



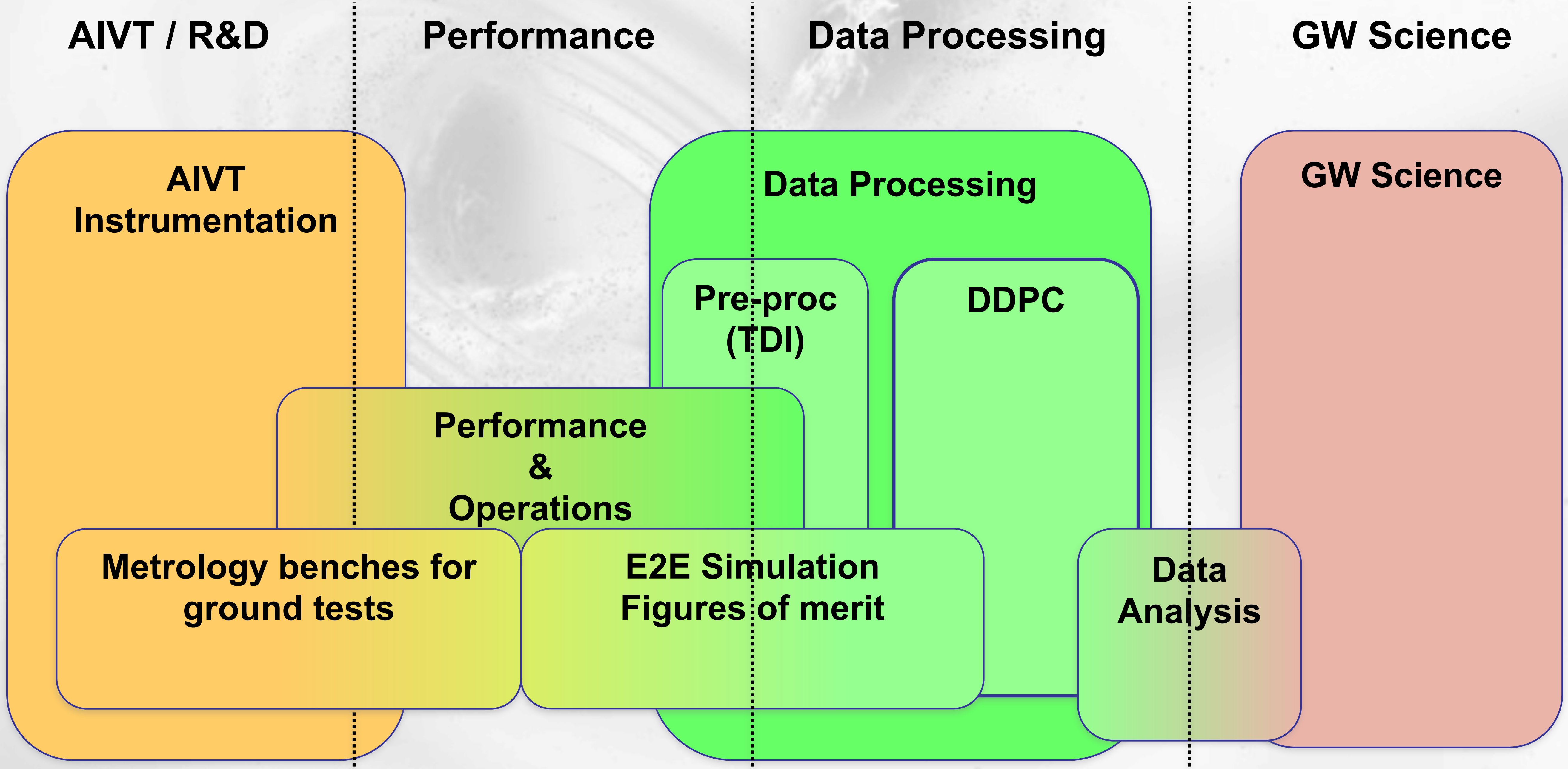
French contributions to LISA

- 3rd ESA 'Large' Mission
  - Following LISA Pathfinder 2015-2017
  - Selected in June 2017
  - **Adopted in January 2024**
  - 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, ONERA, SYRTE/OBSPM



Overview of the French contributions

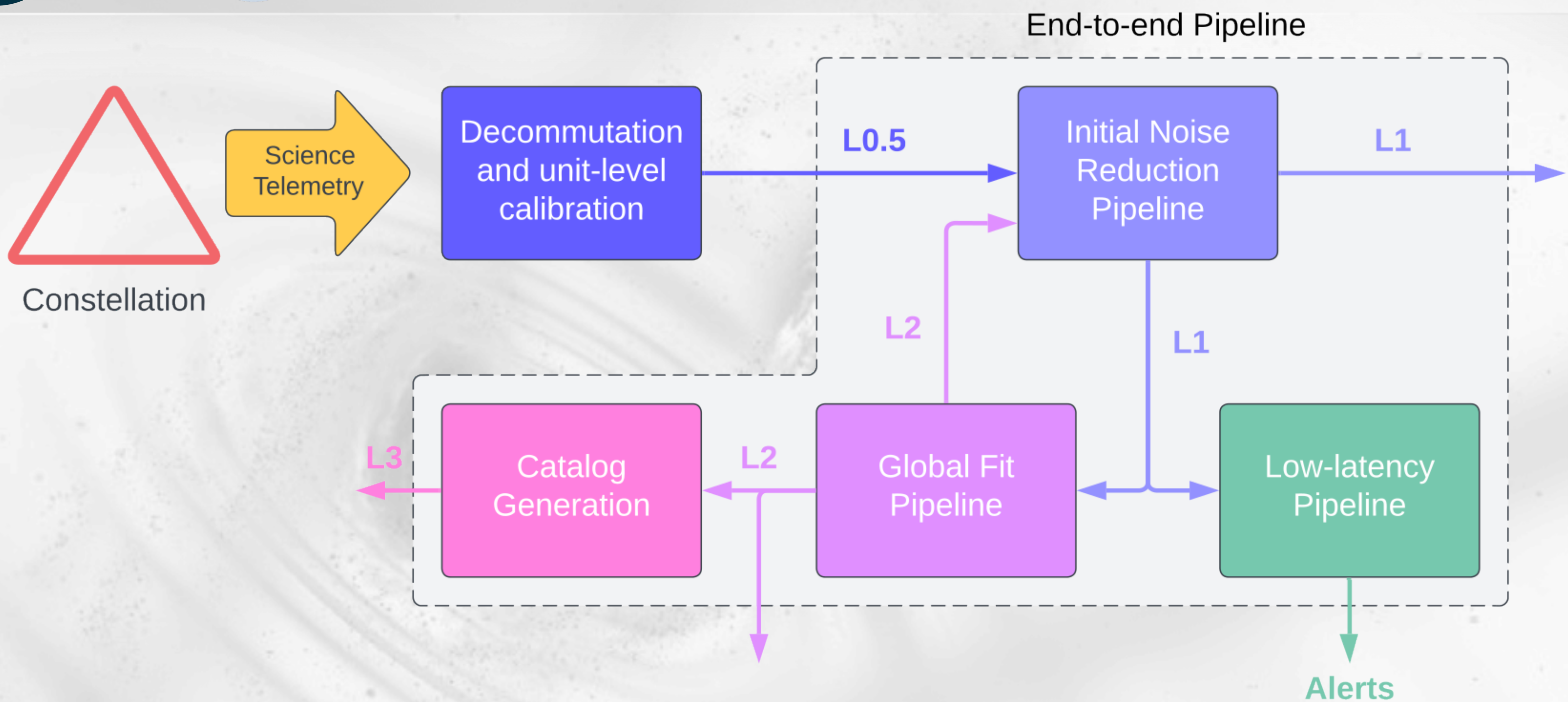
- Broad and continuous coverage from instrument development to GW science



Main LISA development milestones

Event	From	To	Comment
Phase 0 (Concept study)	Jul 2017	Nov 2017	Completed
Mission Definition review (MDR)	27 Nov 2017		Successful
Phase A (Feasibility study)	June 2018	Oct 2020	Completed
Mission Consolidation review (MCR)	22 Oct. 2019		Successful
Extended Phase A	Oct 2020	Dec 2021	Completed
Mission Formulation review (MFR)	End 2021		Successful
Phase B1 (Preliminary Definition with concurrent Prime Contractors)	Jan 2022	Dec 2023	Completed
Mission adoption review (MAR)	Nov. 2023		Successful
Mission adoption (by ESA SPC)	**Jan. 2024**		**Successful**
Phase B2 (Preliminary Definition with a single Prime Contractor)	*Q1 2024*	*April 2027*	*On-going*
Mission Preliminary Design review	April 2027		
Phase C (Detailed Definition)	Q3 2027	Q4 2030	
Mission Critical Design review (CDR)	Jan. 2031		
Phase D (production and Verification)	Q1 2031	2034/2035	
Flight Acceptance Review (FAR) and Launch	**2034/2035**		
Transfer & commissioning	1.5/0.5 years		
Operations	4.5 years		7.5 years of science mission
Extended mission	Up to 3 more years		

LISA ground segment

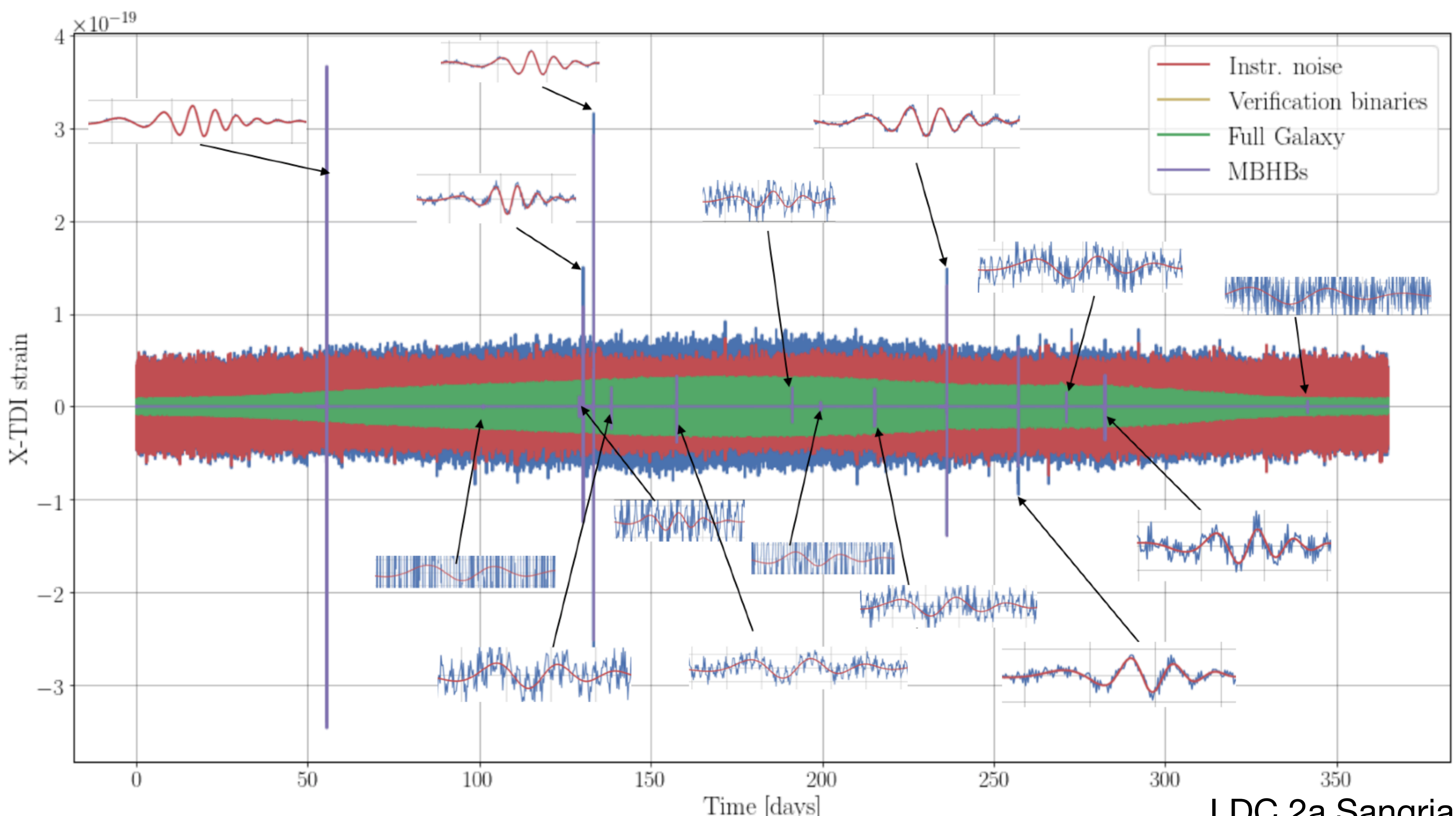


- SC → L0
  - Packets extraction, removal of corrupted data, time-ordering …
  - Processed by ESA
- L0 → L0.5
  - Calibrated, de-biased, synchronized data
  - Processed by ESA with support of instruments teams
- L0.5 → L1
  - Calibrated and noise-corrected TDI streams
  - Processed by ESA with TDI algorithms from the scientific community
- L1 → L2
  - 'Global fit' : Sources parameters extraction
  - Processed by the scientific Data Processing Center
- L2 → L3
  - Catalogs of consolidated data + L1 residuals
  - Processed by the scientific Data Processing Center
  - Released by ESA

From LISA Data Challenges to DDPC deliverables

- LISA Data Challenges :
  - Foster R&D on this challenging signal dominated analysis
  - Support ESA reviews on that topic
  - Get cost estimate and DDPC design drivers

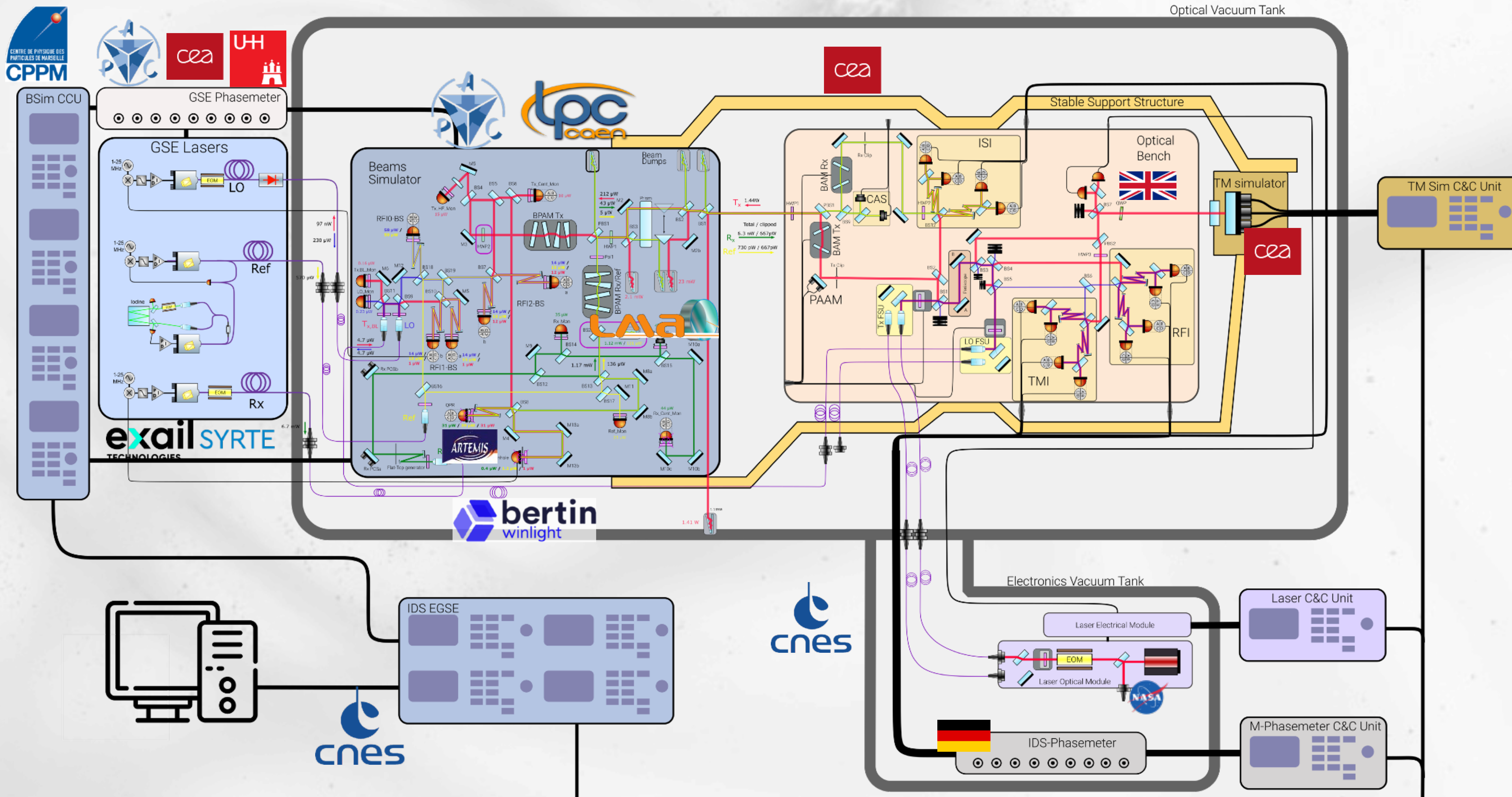
- Challenges
  - LDC 1a Radler / 1b Yorsh
    - Beginner's data set with individual sources
  - LDC 2a Sangria
    - 2/3 global-fit prototypes for first enchilada (GB+MBHB) challenge
  - LDC 2b Spritz
    - Dealing with gaps and glitches



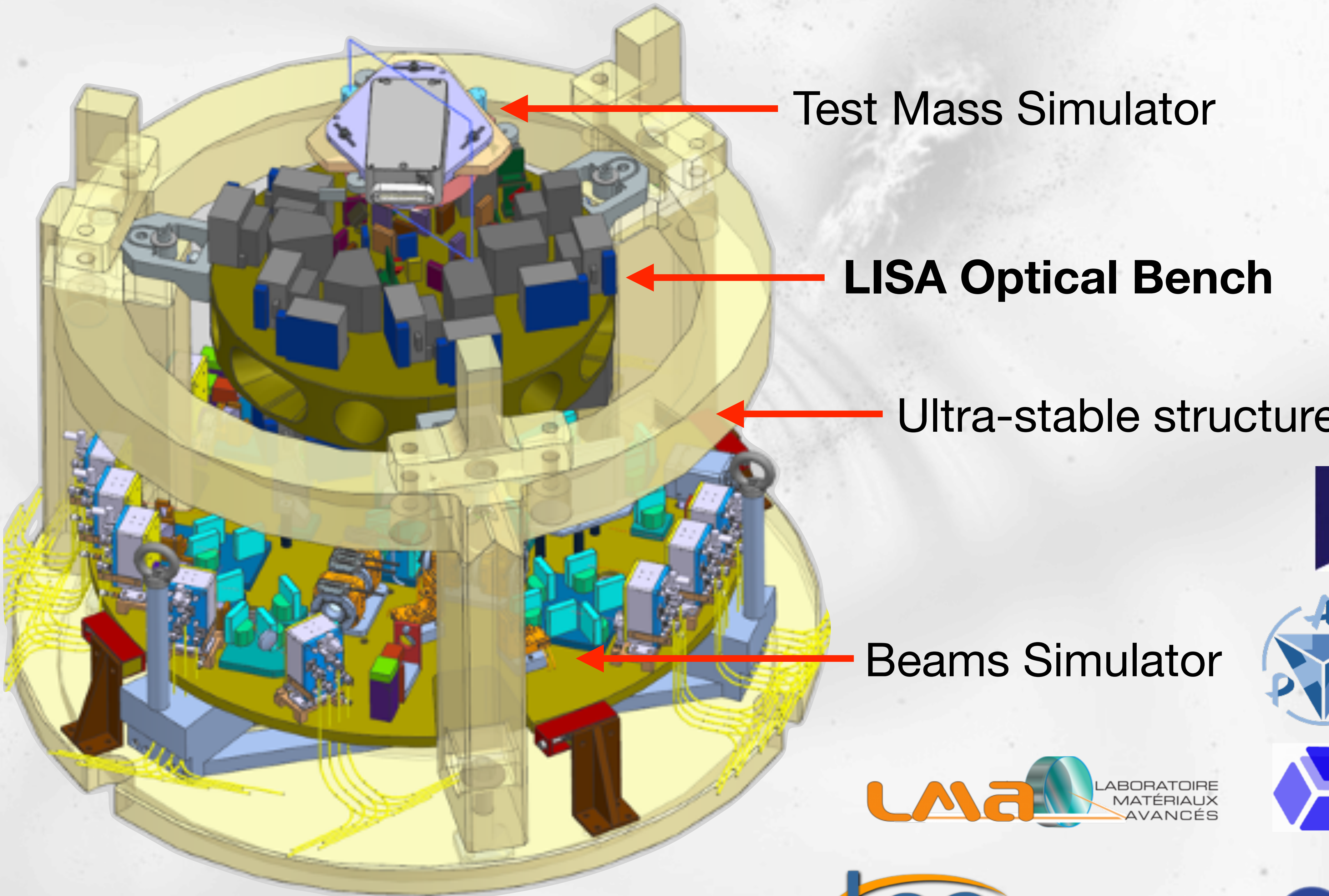
LDC 2a Sangria

Testing LISA on ground

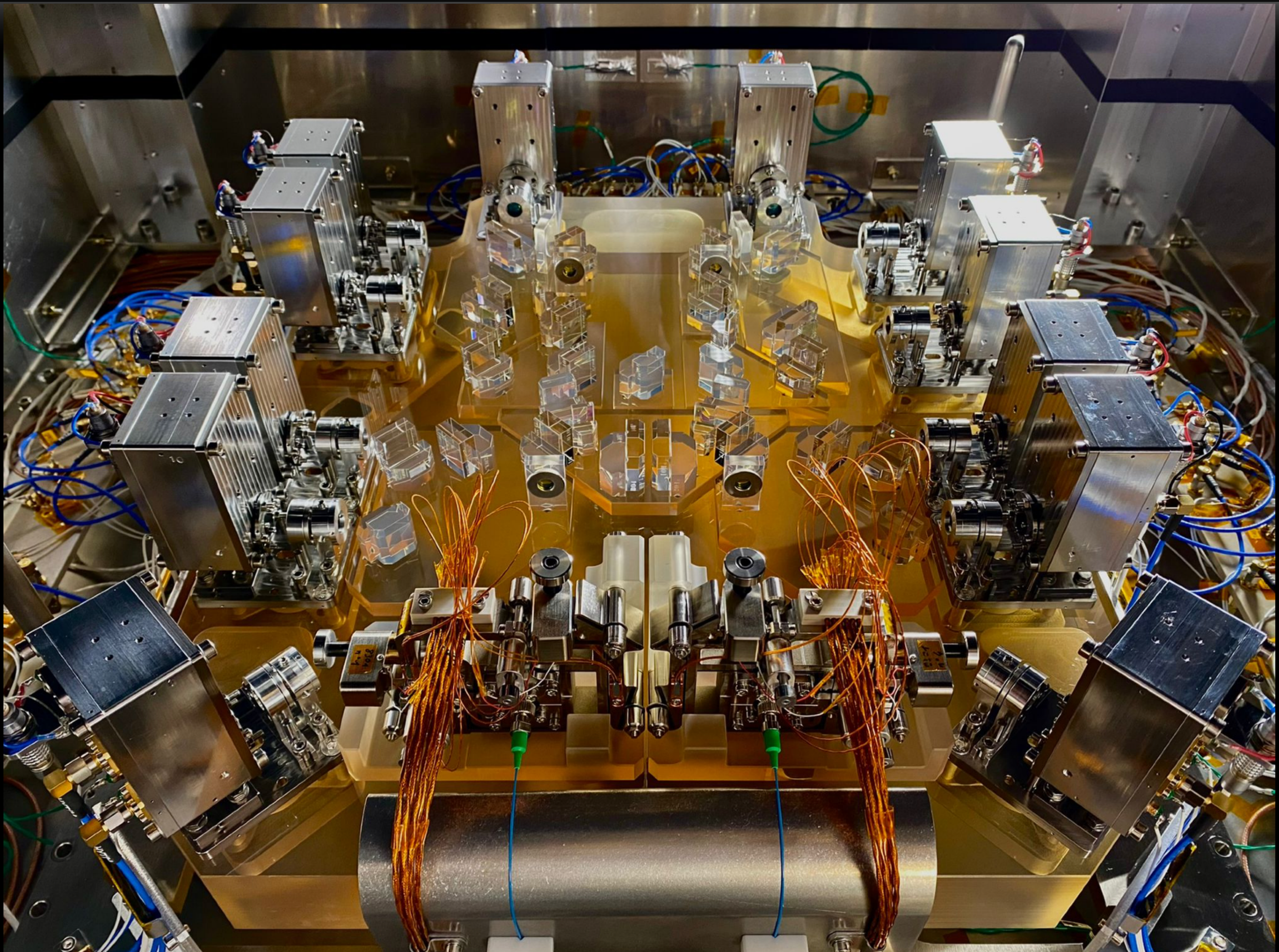
- Main objective : validate the metrological concept of LISA
  - Critical functionalities
  - Optical path length stability
  - Wavefront errors and alignment accuracies



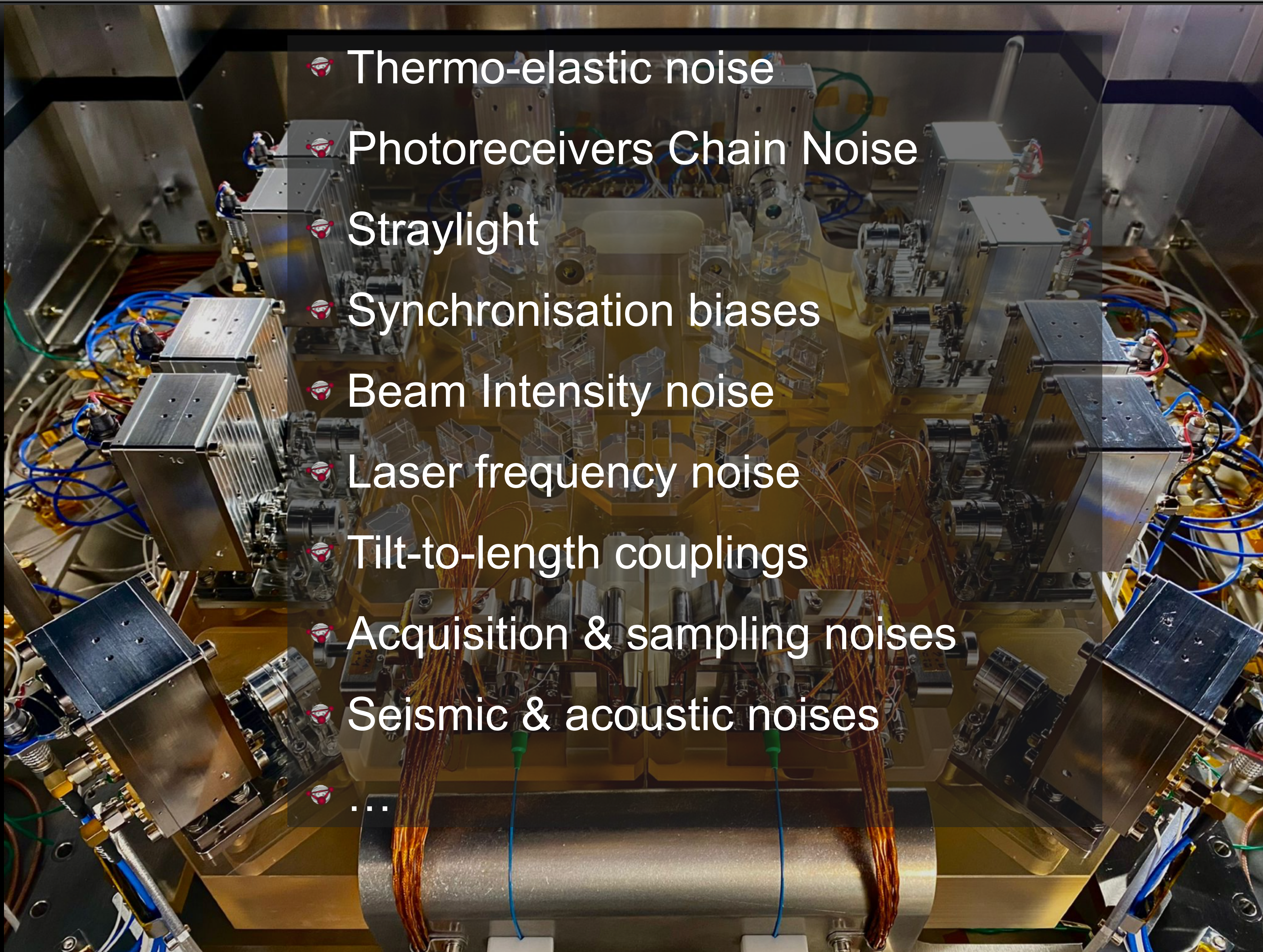
Testing LISA on ground



Zerodur Demonstration Bench

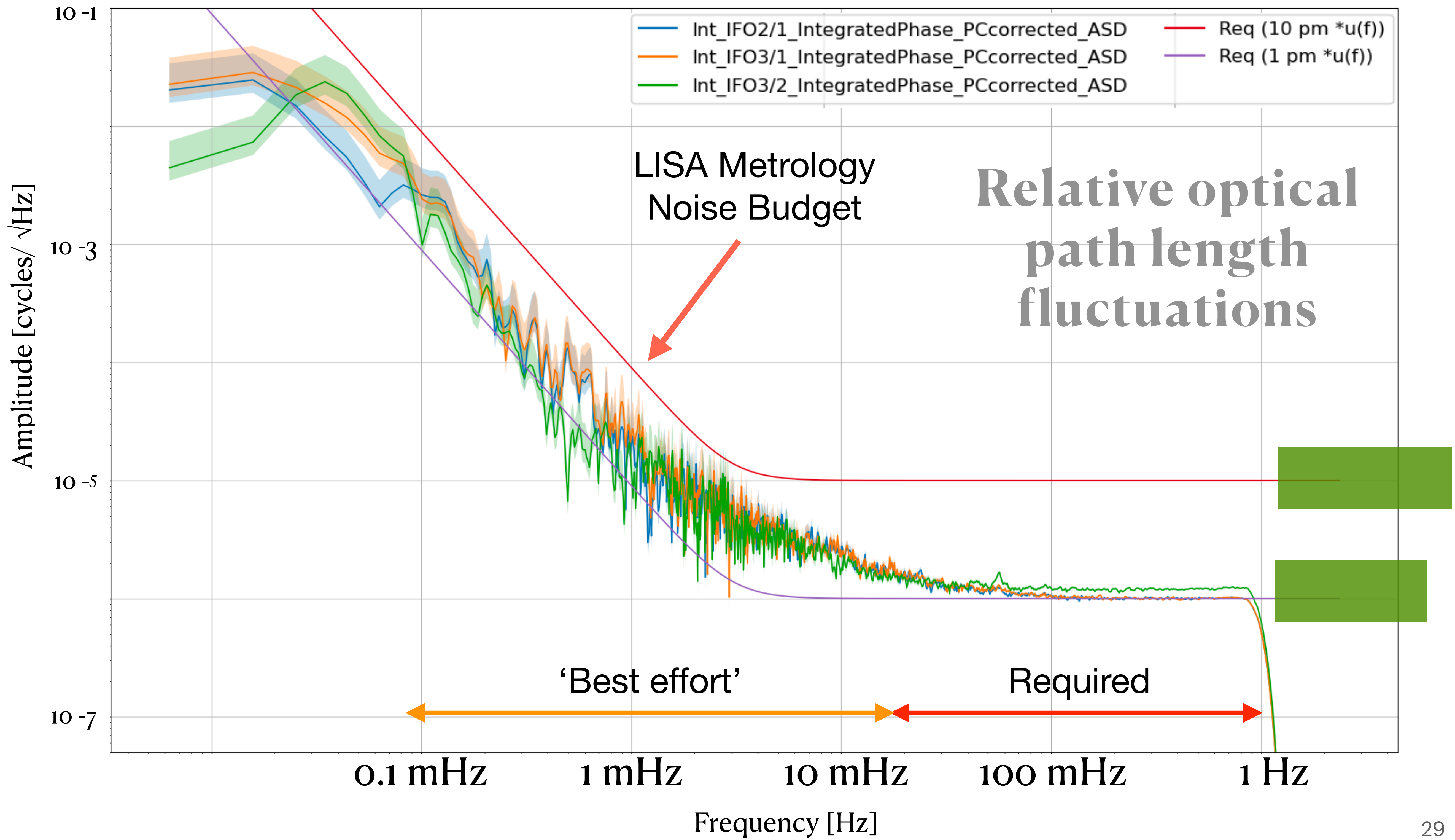


Zerodur Demonstration Bench



- Thermo-elastic noise
- Photoreceivers Chain Noise
- Straylight
- Synchronisation biases
- Beam Intensity noise
- Laser frequency noise
- Tilt-to-length couplings
- Acquisition & sampling noises
- Seismic & acoustic noises
- …

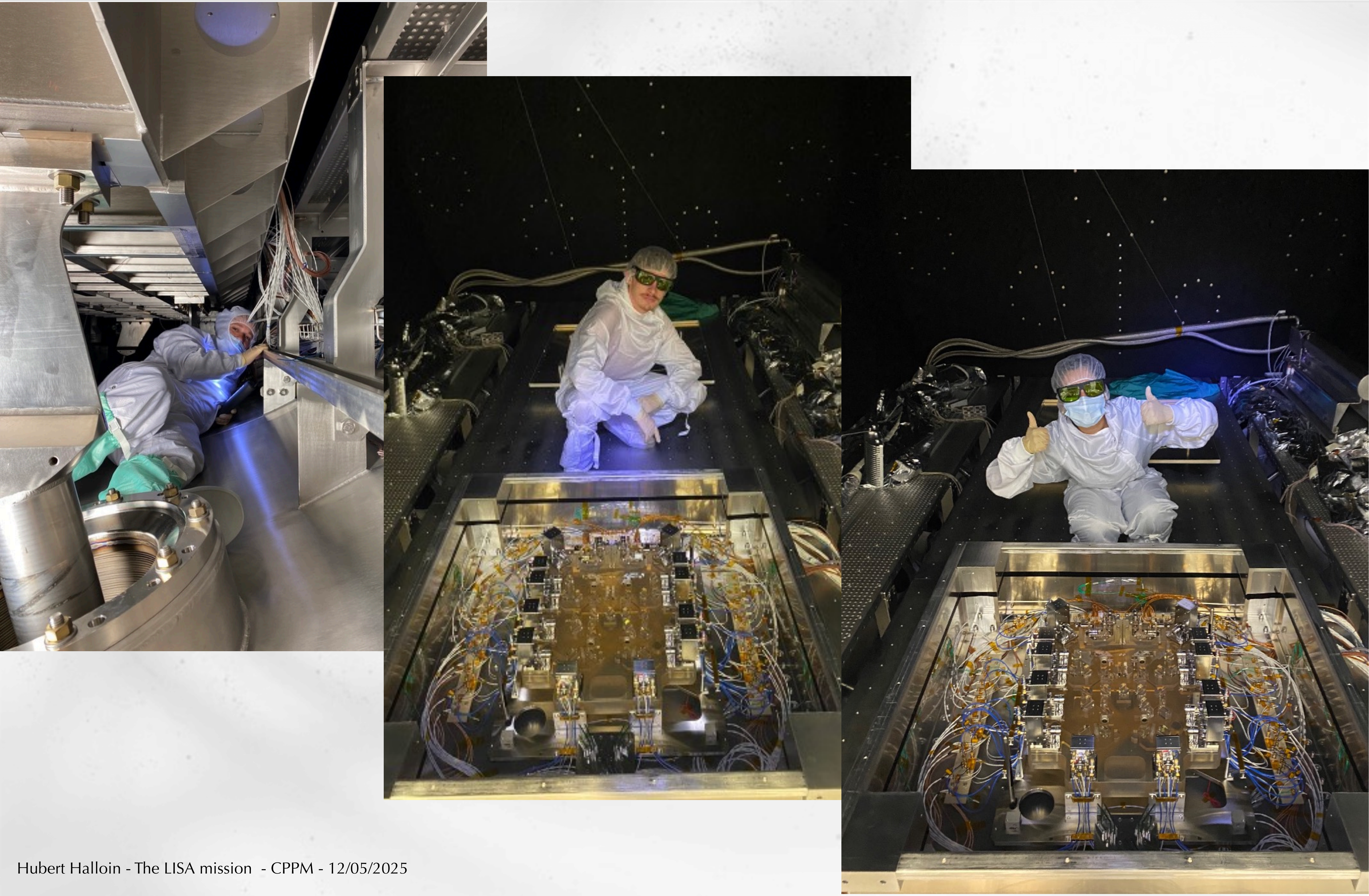
Performances obtenues

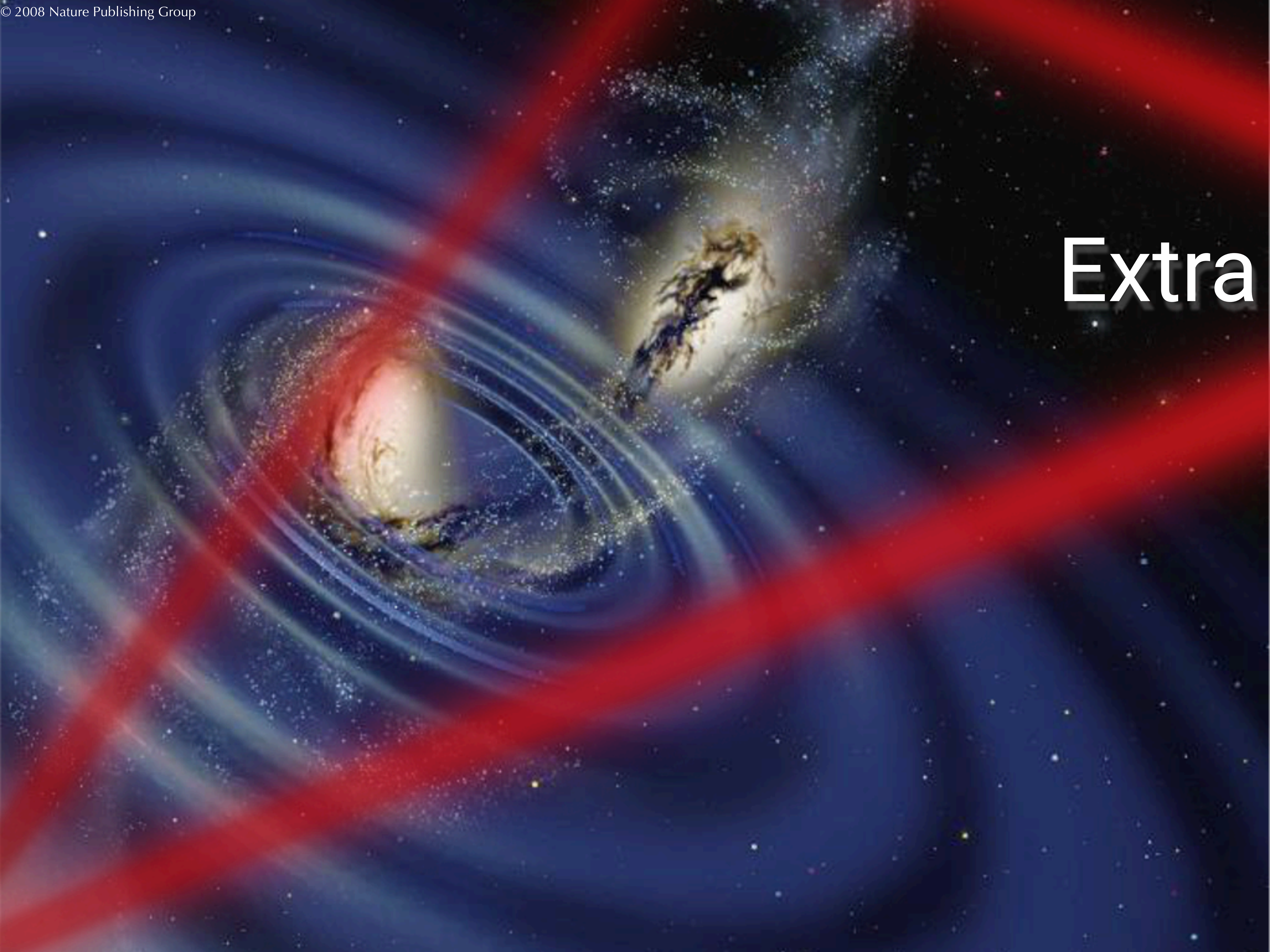


Conclusion

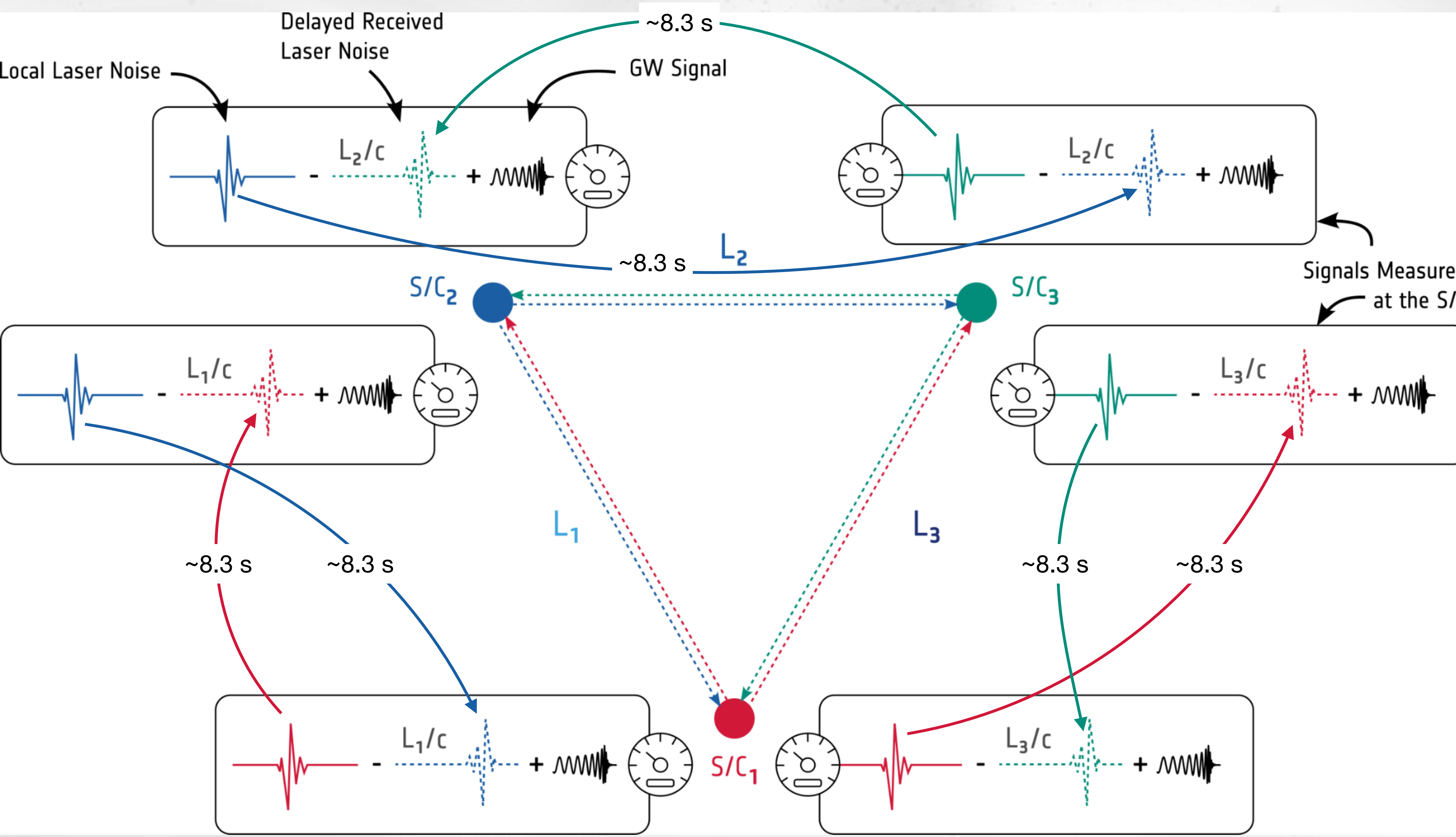
- LISA is an ambitious and technically challenging mission for detecting GW from space
  - Selected for flight in 20234/2035, now in phase B2
- Many of the key technologies have been demonstrated with LISA Pathfinder
- 17 French institutes contribute (today) to the mission development
  - Instrument EM and QM performance tests on ground
  - Development of the Distributed Data Processing center
  - Preparation to in-flight operations and scientific exploitation
- The development of the DDPC and ground support equipments has started

Some LISA enthusiasts…




Extra

Time Delay Interferometry



Time Delay Interferometry

- Combination of delayed recorded data streams to cancel out propagated laser noises
  - Requires accurate knowledge of the S/C to S/C distance
  - Noise reduction factor ~7 orders of magnitude
  - Numerically and experimentally demonstrated