LISA Pathfinder

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Conseil scientifique CNRS - IN2P3

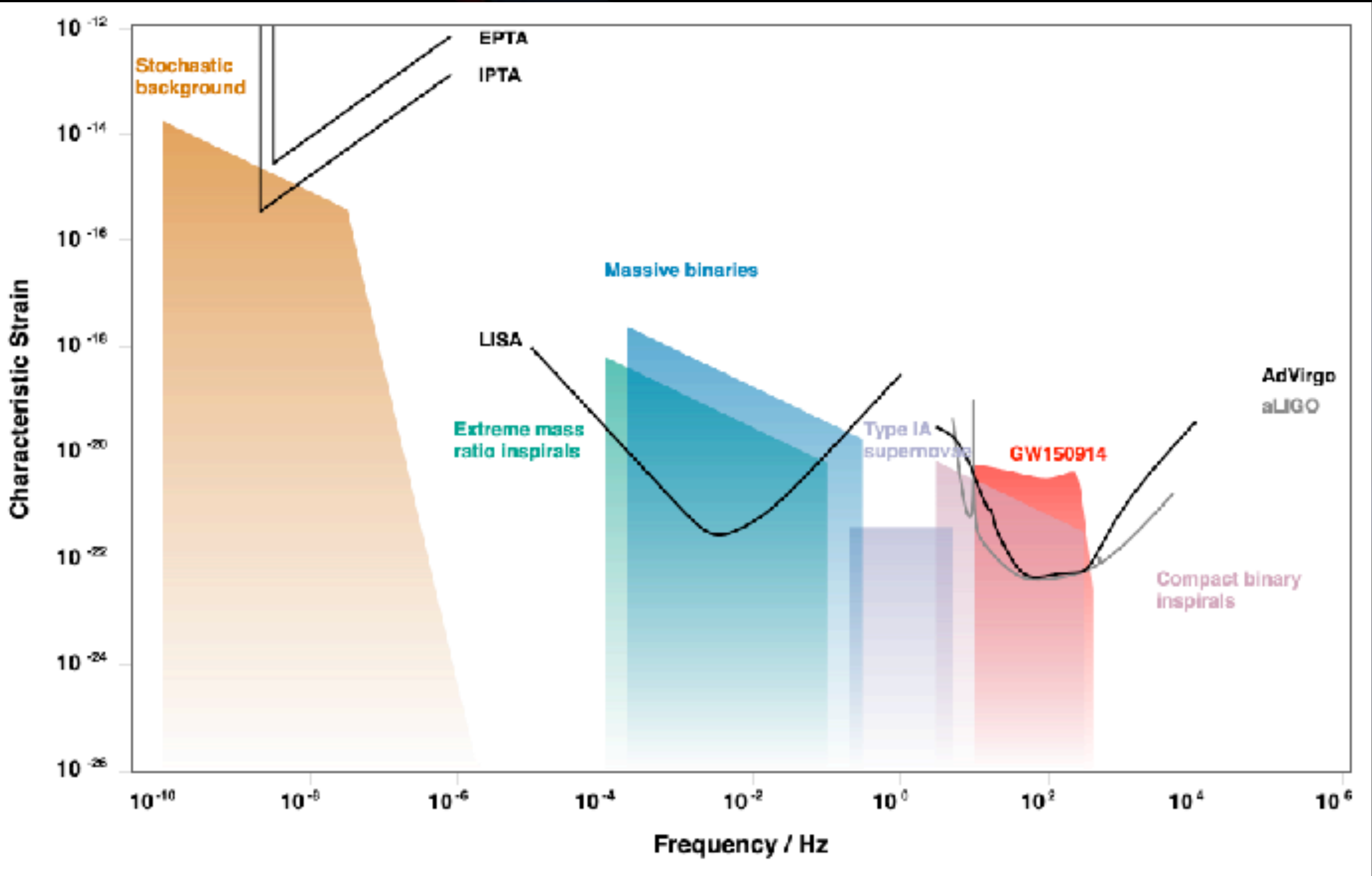
Visioconférence - 30th June 2020

Overview

- Context, objectives, history
- Mission description
  - The measurement
  - Description of instrument and spacecraft
  - French hardware contribution
- Results
  - Core results
  - In-depth investigations
  - Results and technical achievements by the French team
- Organisation and ressources
- Return of experience
- Conclusion

Context, objectives and history

- Observation of the Universe with gravitational waves: astrophysics, cosmology and fundamental physics
- Ongoing observations with ground observatories: aVirgo, aLIGO, KAGRA => high frequency
- In the milli-Hertz band, large variety and large number of sources expected



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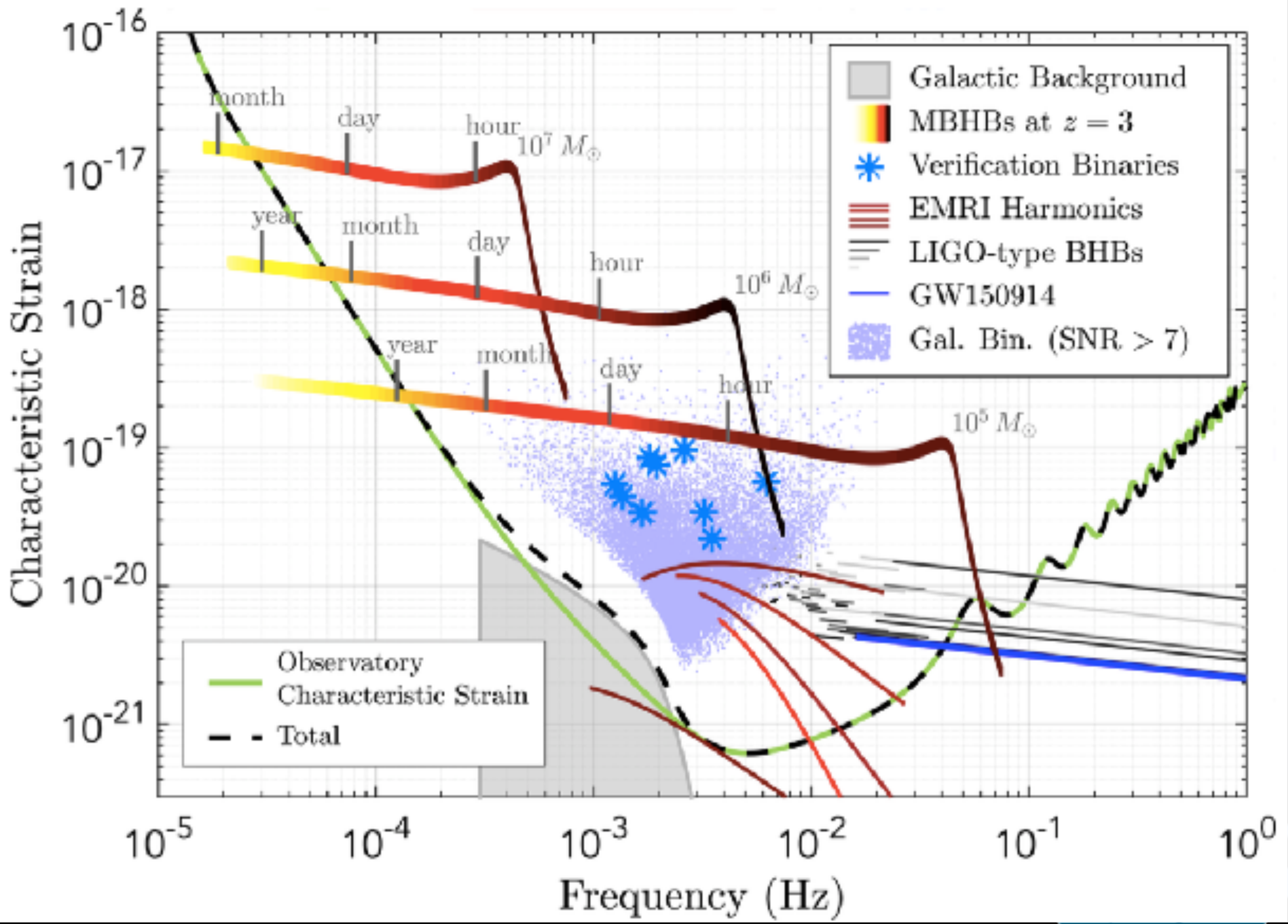


Context, objectives and history

- Milli-hertz band: on ground, problem of seismic noise and armlength limitation => need to go to space : LISA (Laser Interferometer Space Antenna)
  - End 70's: first ideas
  - 1993-2011: LISA at ESA/NASA (pre-phase A report in1998)
  - 2011- 2016: eLISA, ...
- Free fall in space with fm.s^{-2} precision identified as one of the key technology: cannot be done on ground (too noisy) => space-based technological demonstrator started, LISAPathfinder
  - 1998-2002: SMART-2 (for LISA & Darwin)
  - 2002-2014: LISAPathfinder development
  - 2015: launch
  - 2017: full results

Context, objectives and history

- 2017: success of LISA Pathfinder & GW observations on ground => main reasons behind approval of LISA at ESA

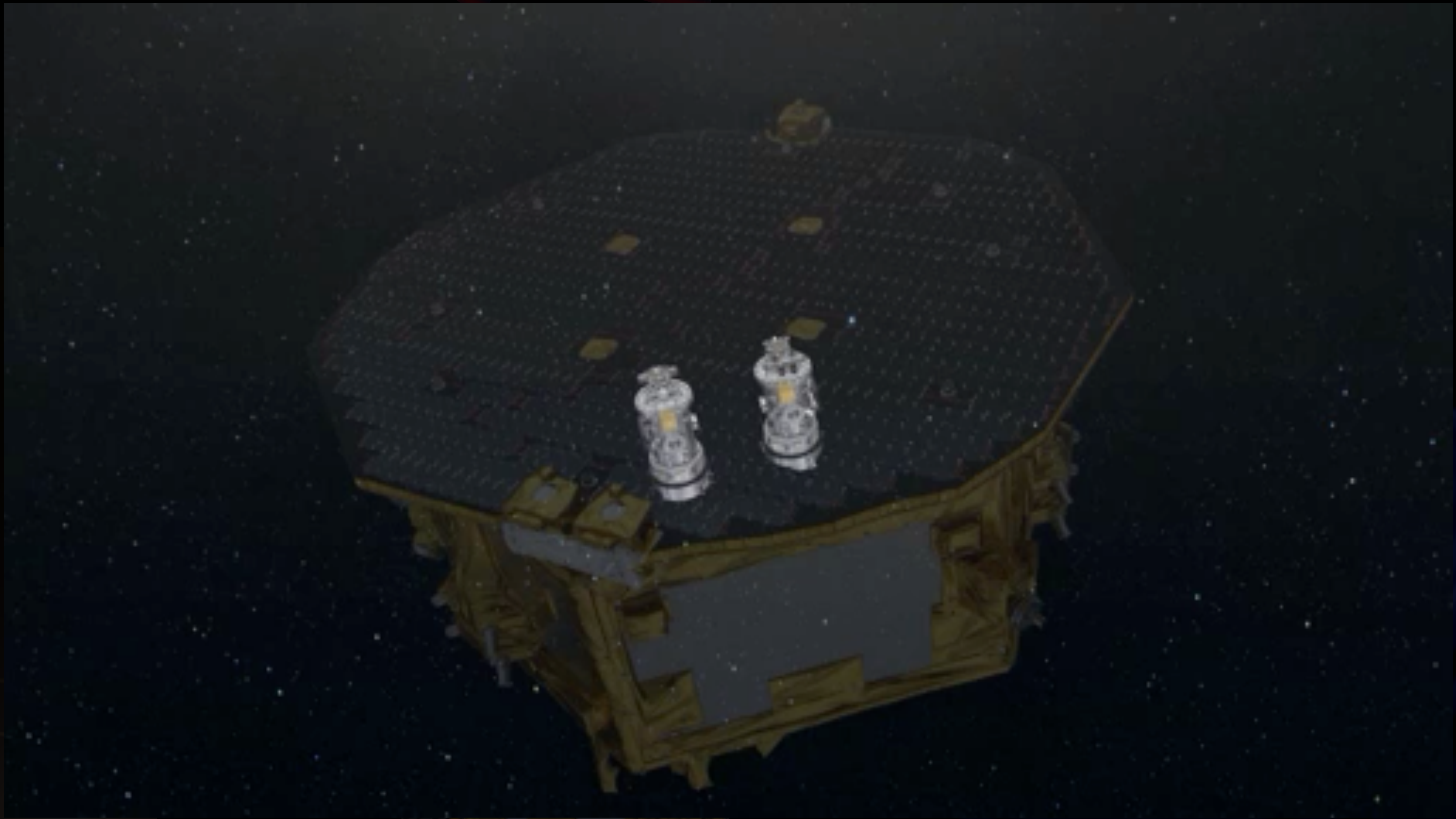
- French involvement in LISAPathfinder:
  - join the project in 2005 (initiated by P. Binétruy)
  - one lab, APC, supported by CNES and CNRS-IN2P3
  - main contribution on experiments and data analysis
  - small hardware contribution

Objectives

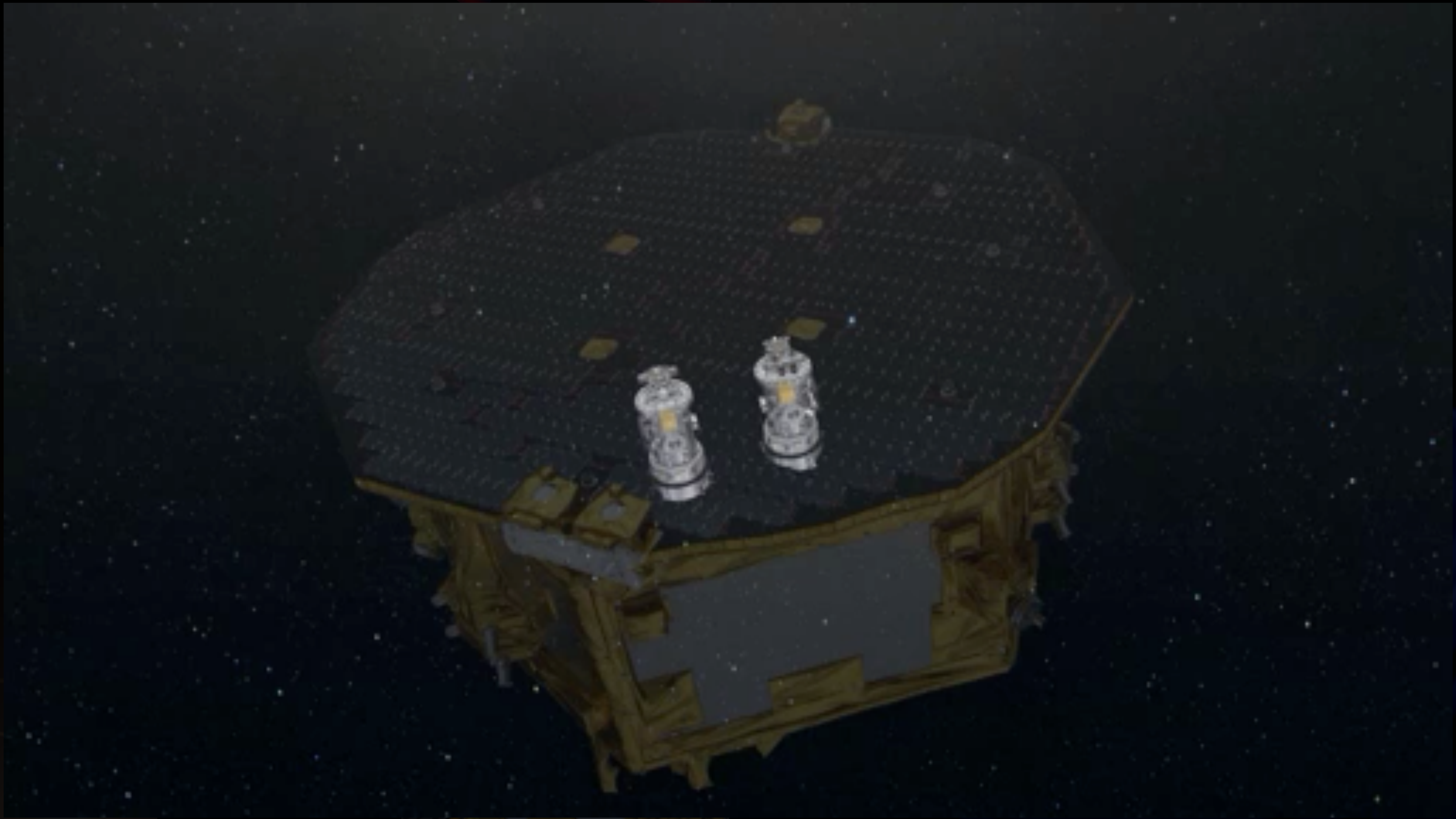
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses (TMs),
  - Micro-thrusters.

- Three main experimental objectives:
  - Measure the residual (of uncertain physical origin) acceleration noise exerted on the TMs (seen as materialized references of inertia).
  - Assess the performance achieved in space by the optical measurement system (interferometry) measuring sub-picometer displacement of the targets (TMs) on board.
  - Characterize the sub-systems performance and quantify their impact and contribution to the TM acceleration noise.

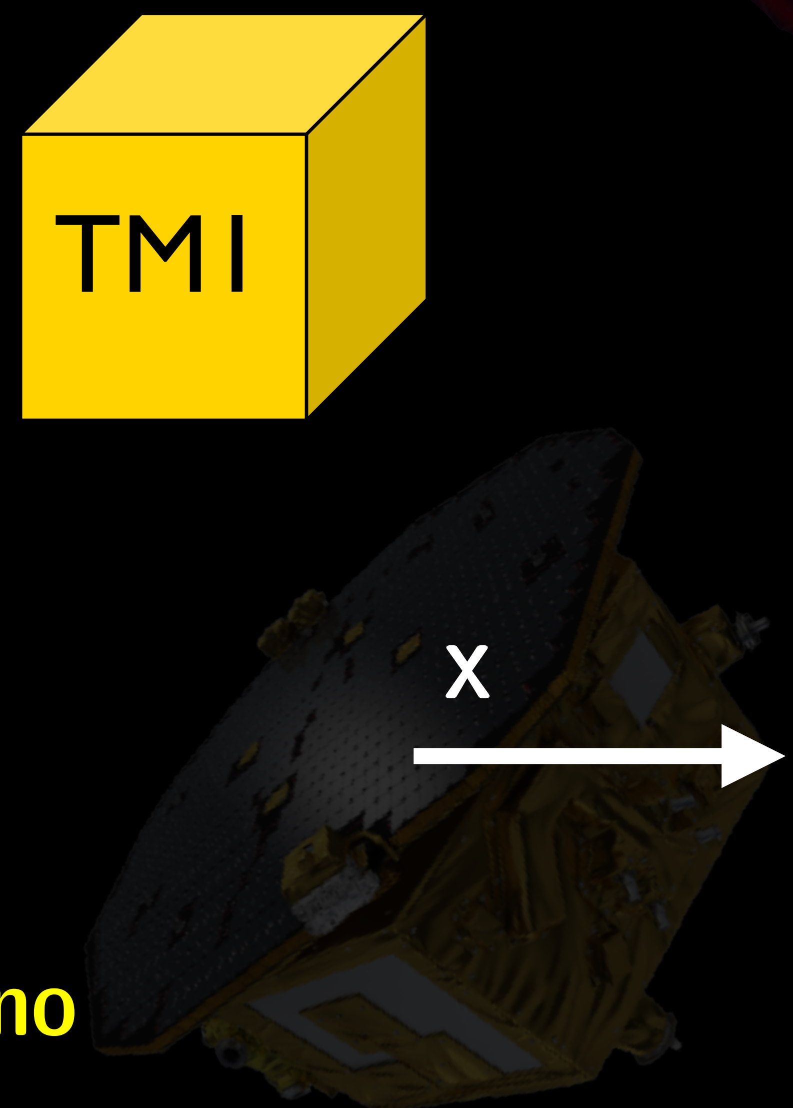
The mission



The mission

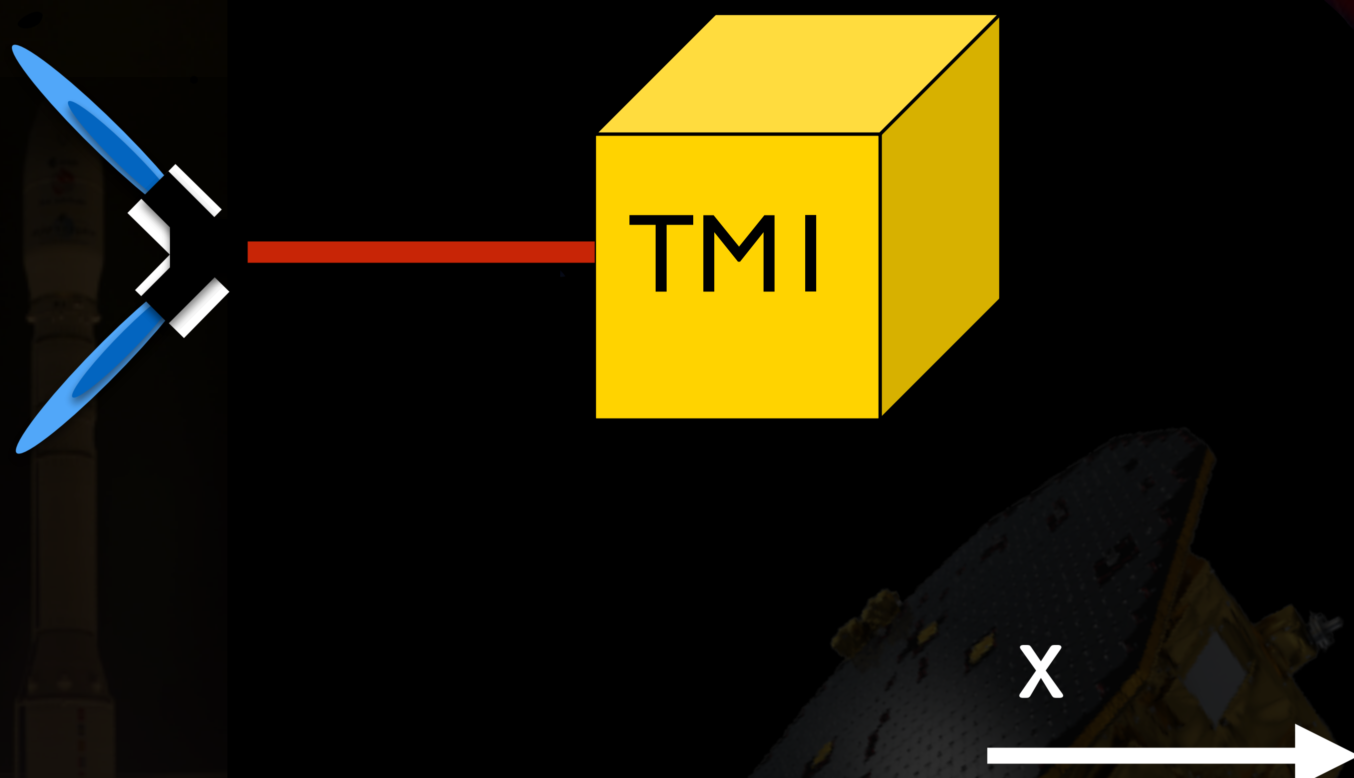


The main measurement - deltaG



by Joseph Martino

The main measurement - deltaG



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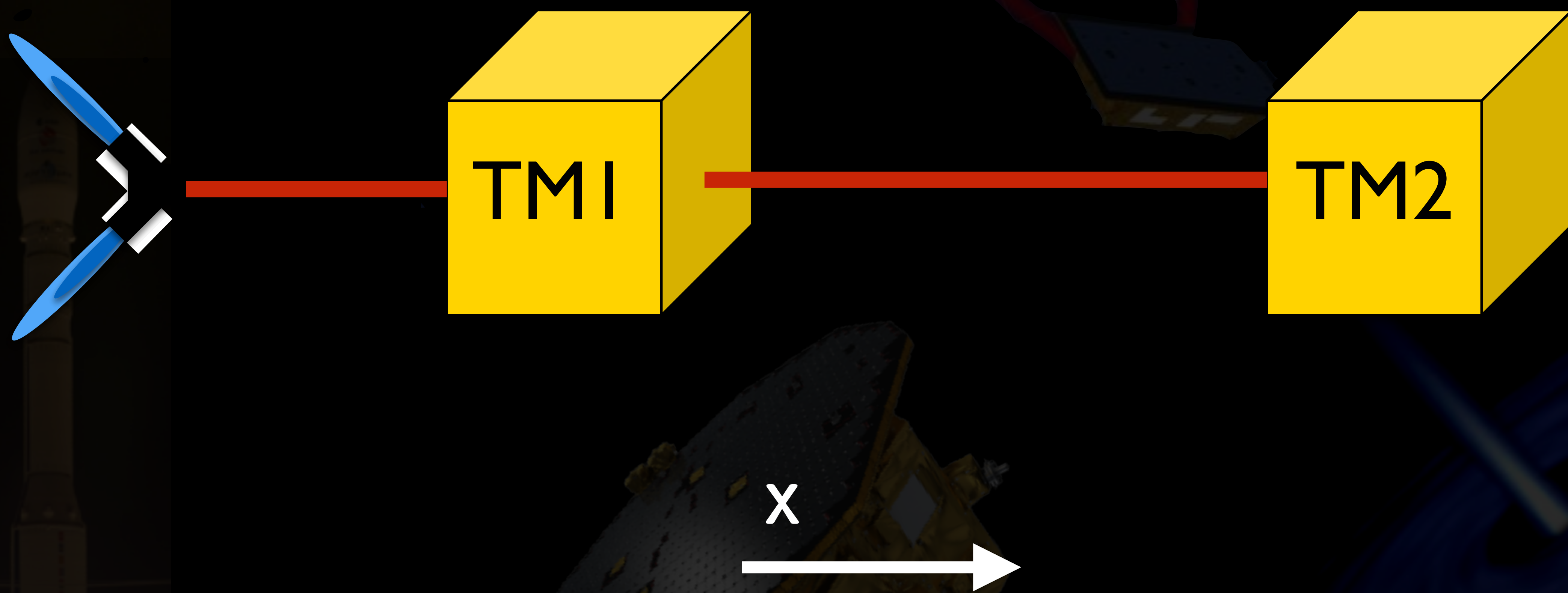

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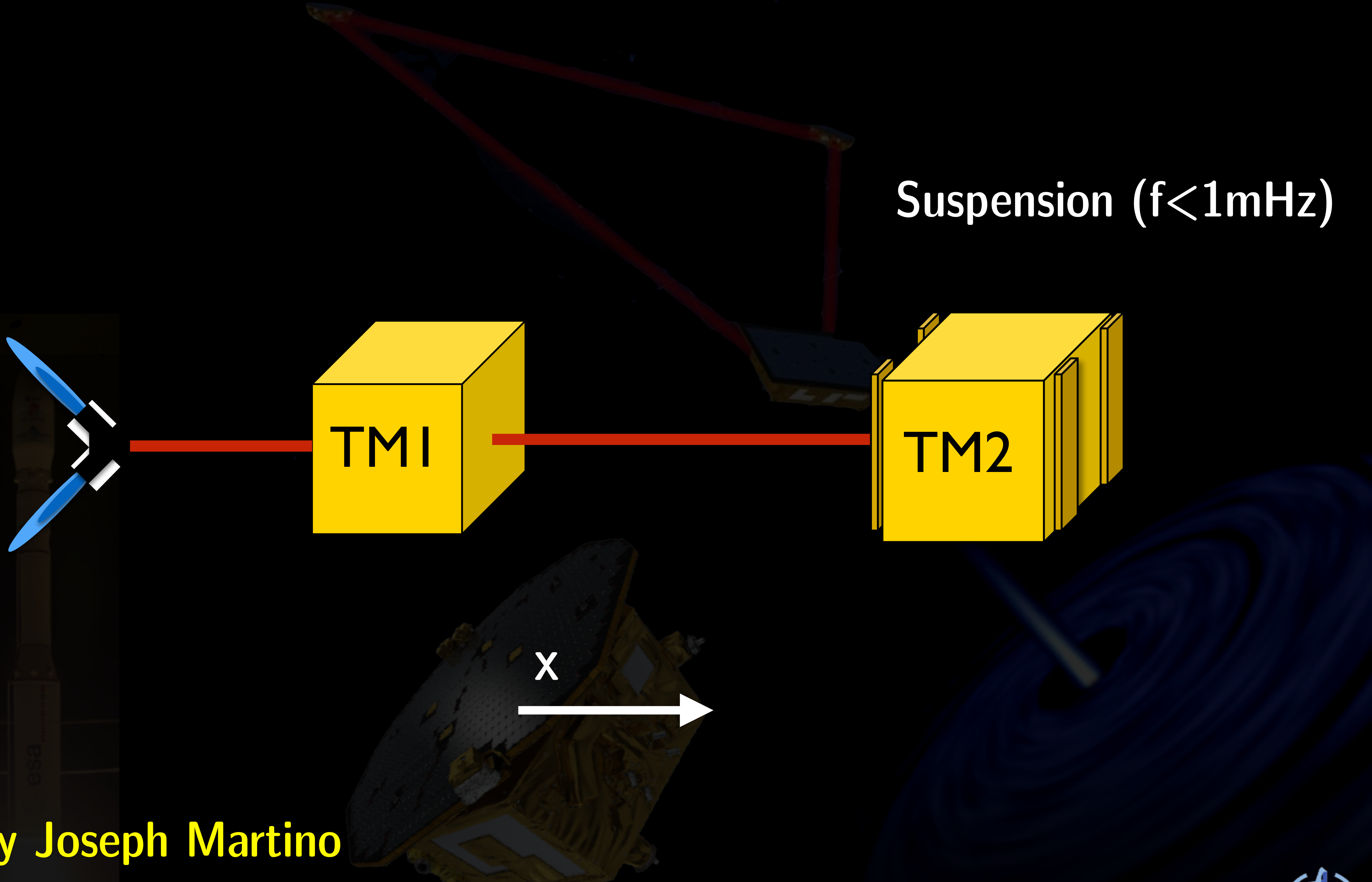


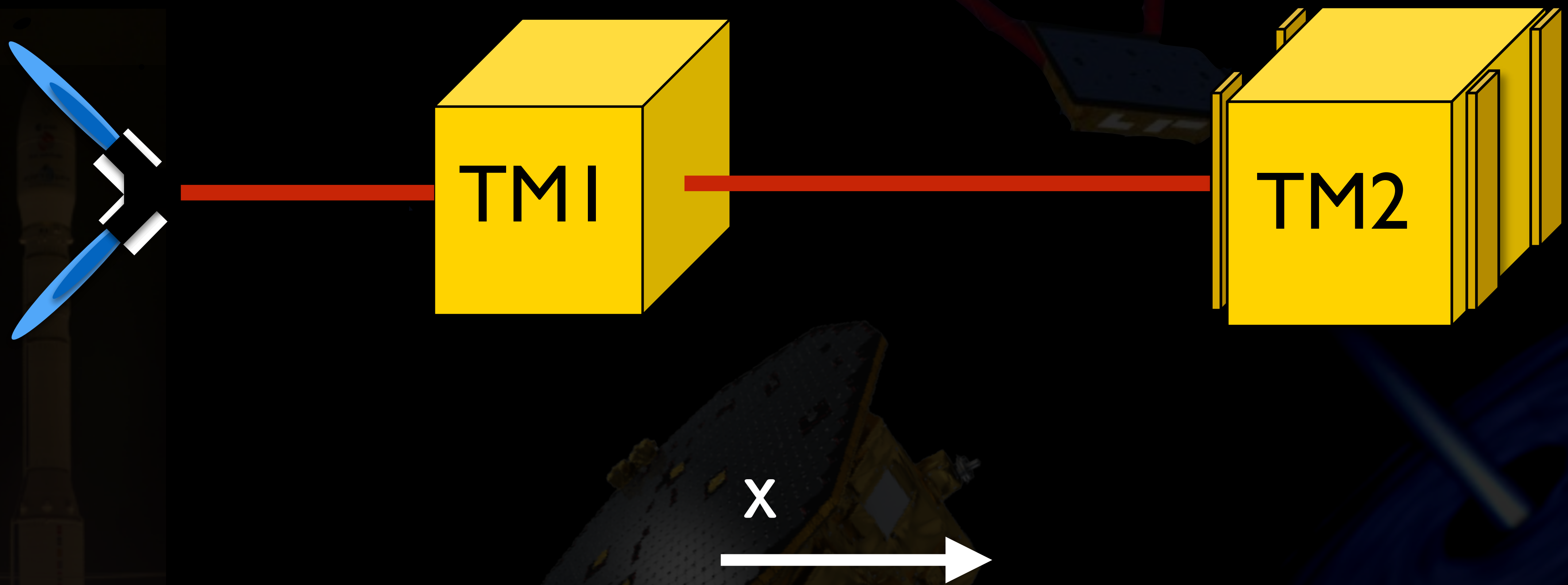
by Joseph Martino

The main measurement - deltaG

Differential acceleration:

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

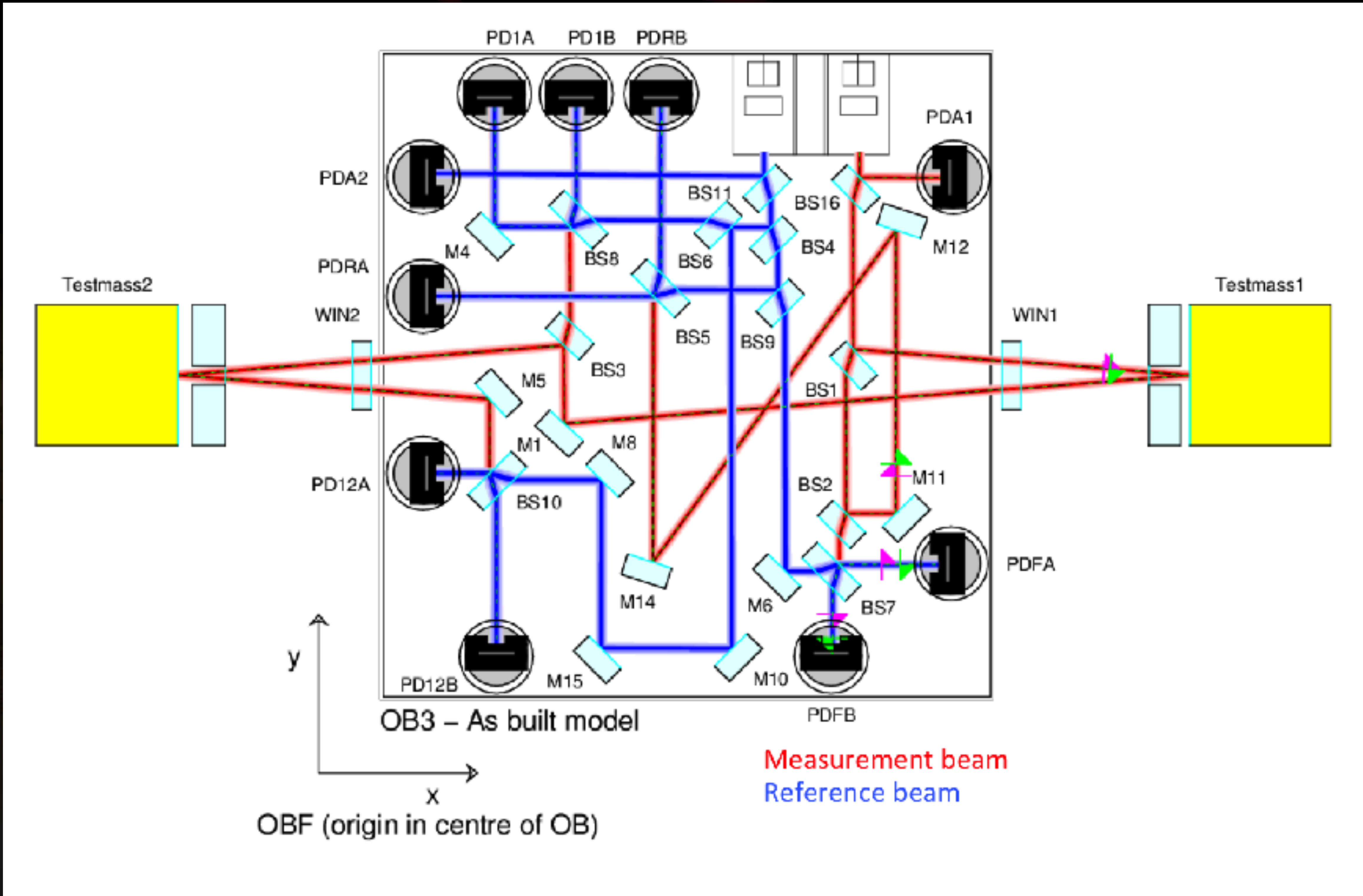
Suspension (f<1mHz)



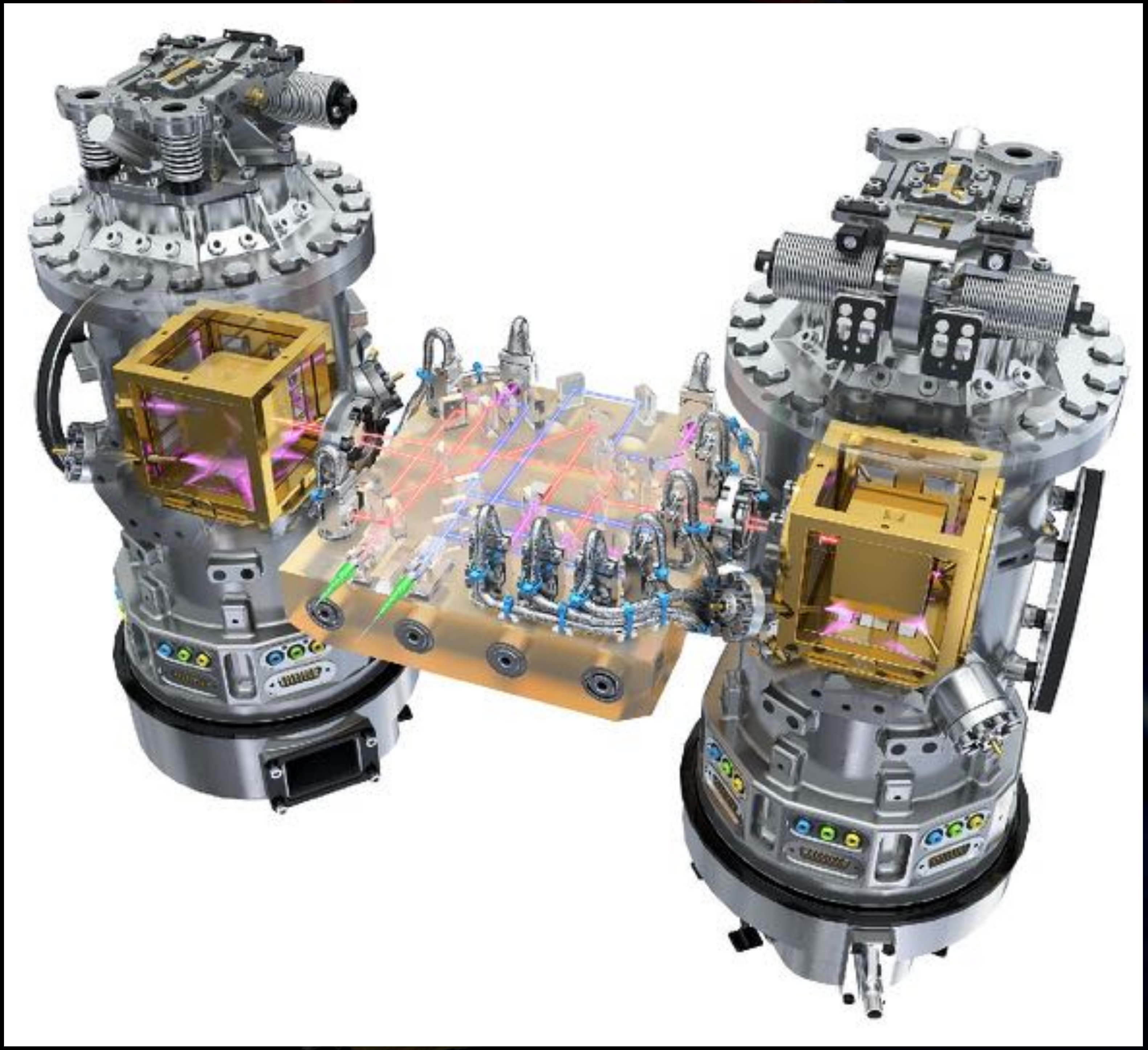
by Joseph Martino

Optical bench

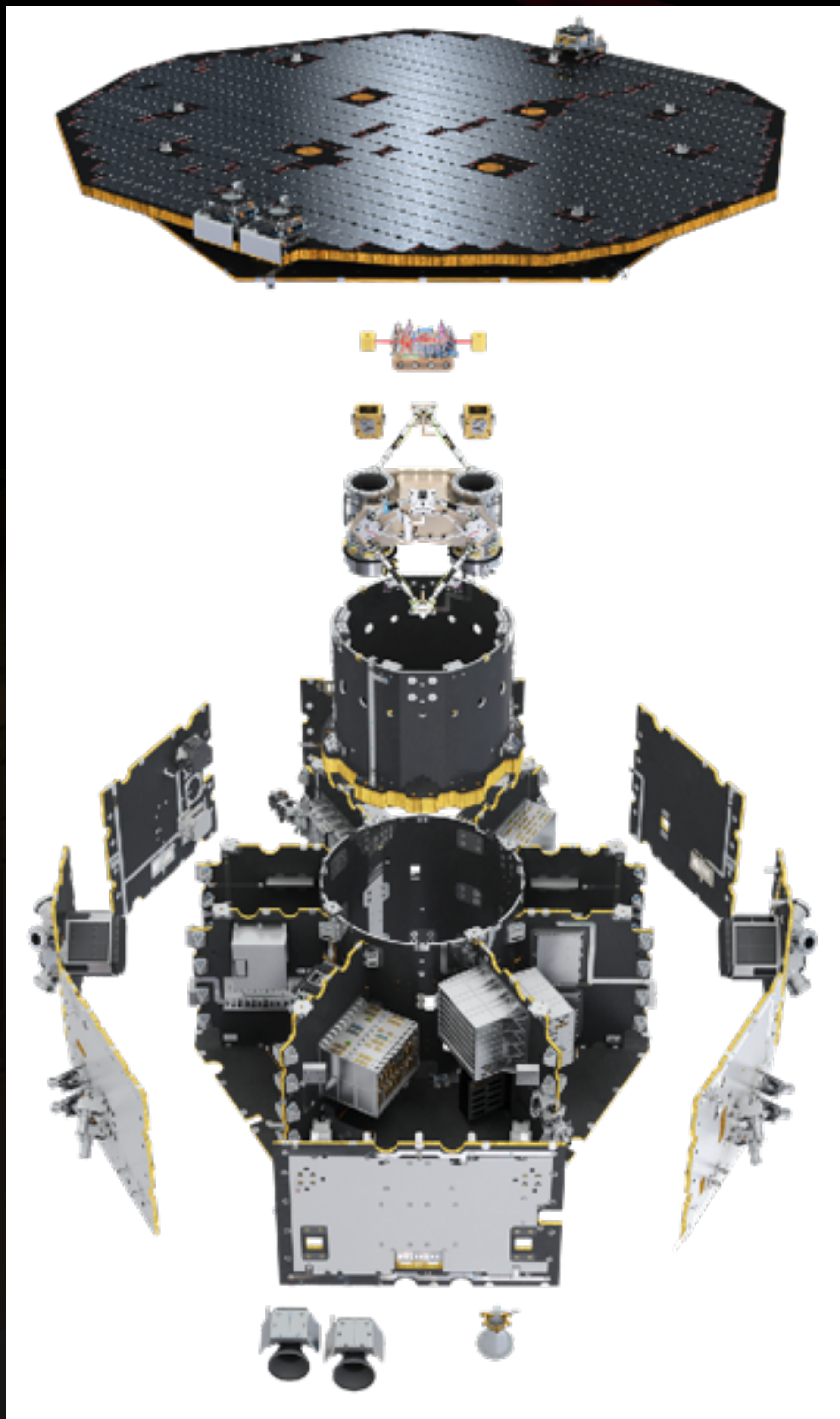
deltaG = d²(o12)/dt² - Stiff * o12 - Gain * Fx2

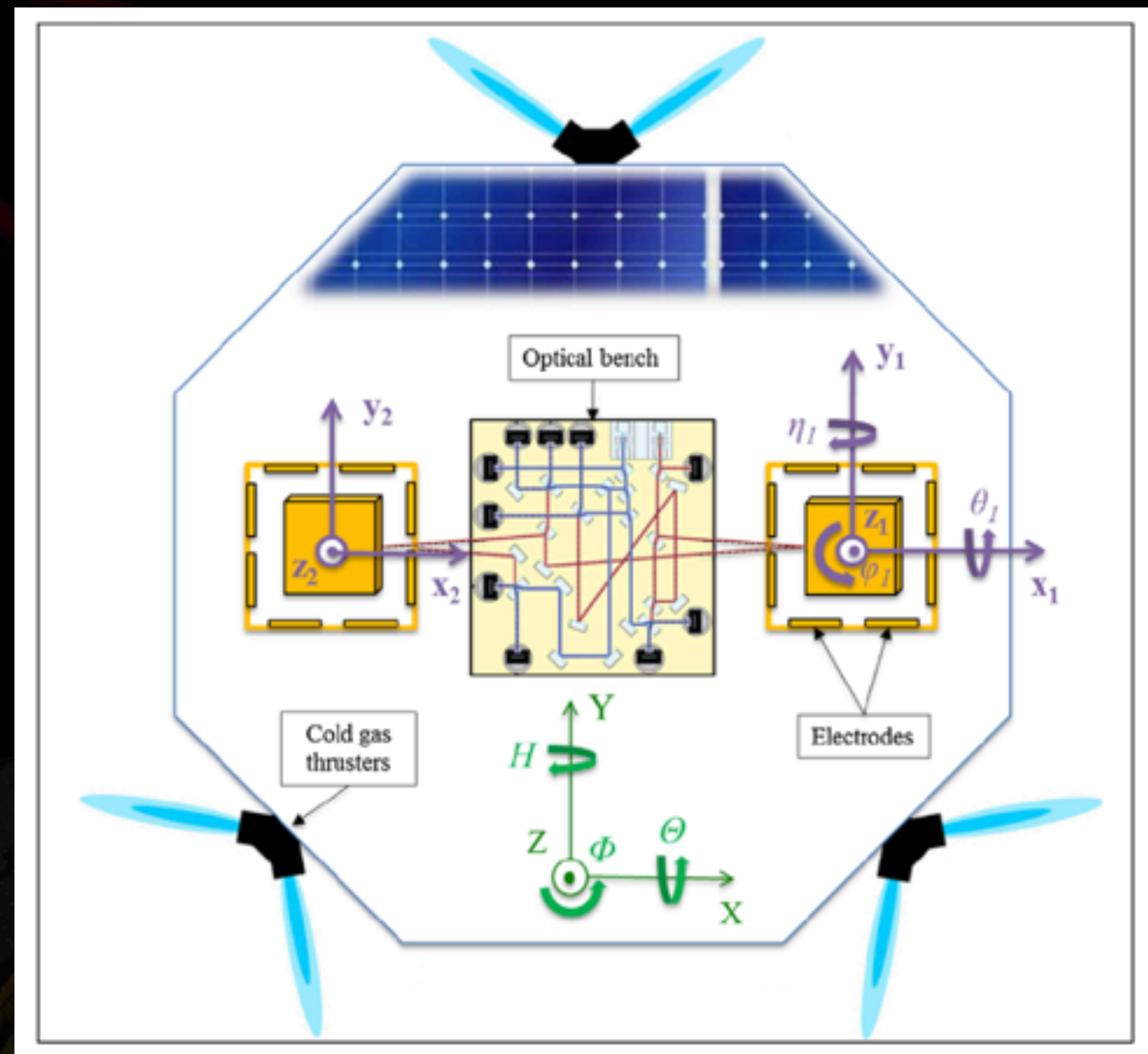


Core instrument:
LISA Technology Package



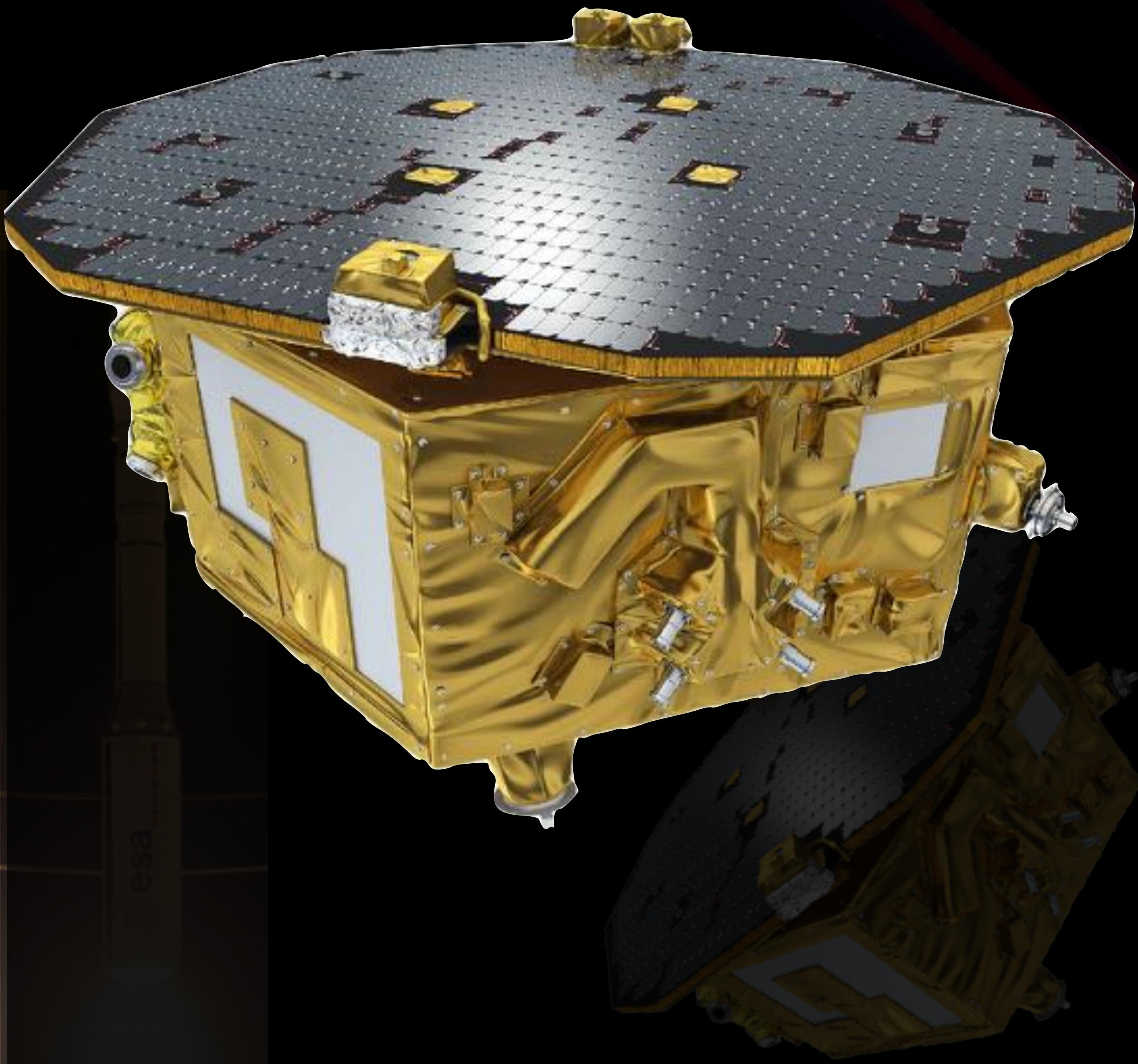
LISAPathfinder spacecraft





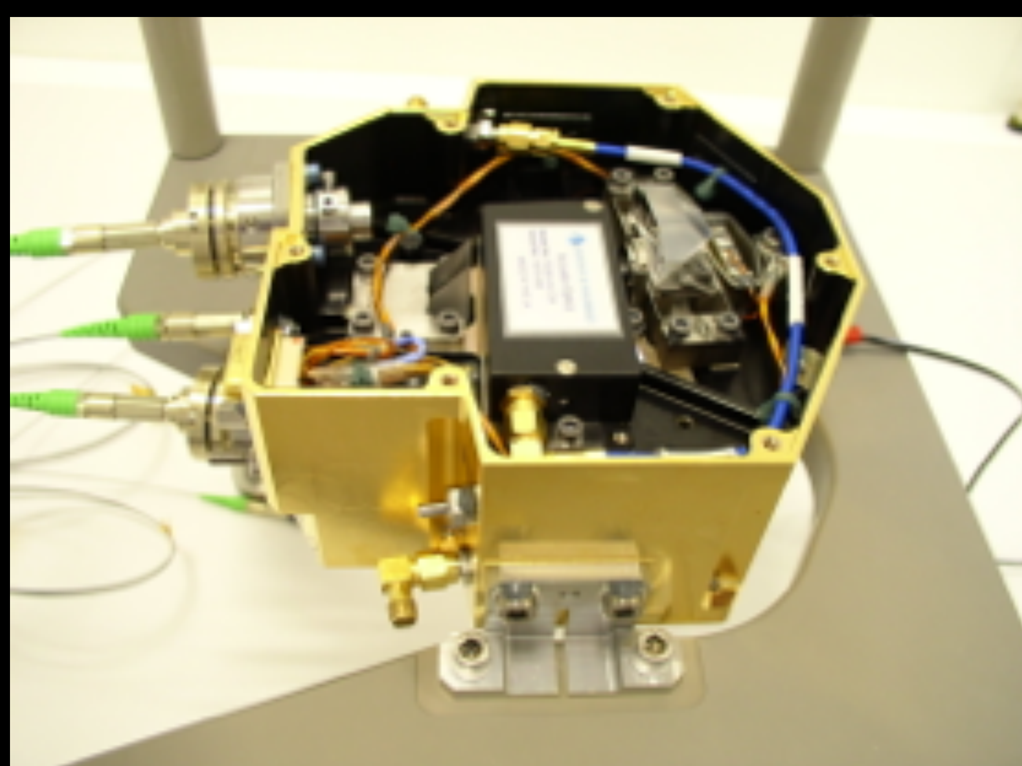
Simplified sketch of LISA Pathfinder apparatus. The system of coordinates used to describe the displacement of the test masses (purple sets of axes) and of the spacecraft (green set of axes) is made explicit.

LISAPathfinder spacecraft



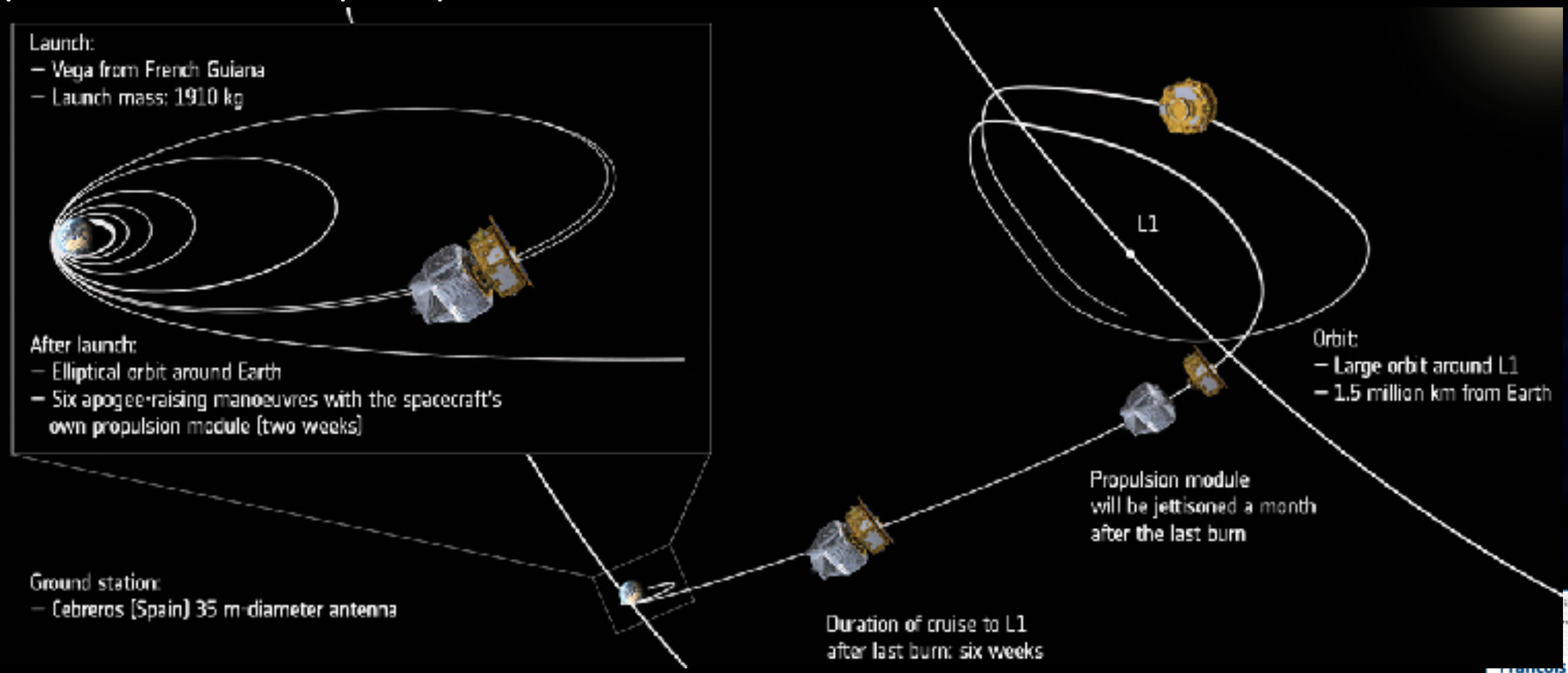
French hardware contribution

- Laser Modulator Unit (LMU) + Control System
  - Provide two laser beams to the optical bench
  - Beams frequency shifted by 1 kHz one from the other
- At APC:
  - follow industrial realisation
  - experimental demonstrations of the relevance of the characterisations



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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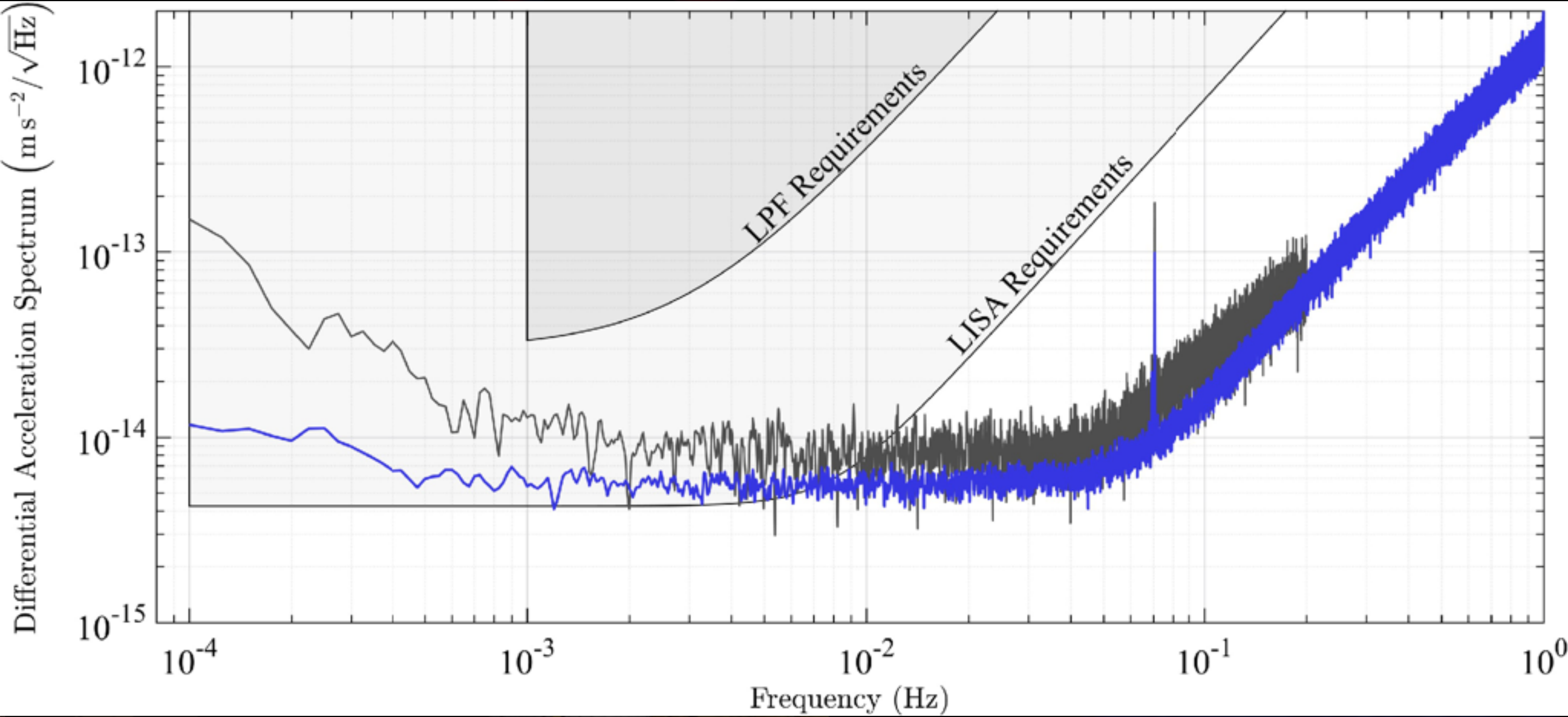
First results

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



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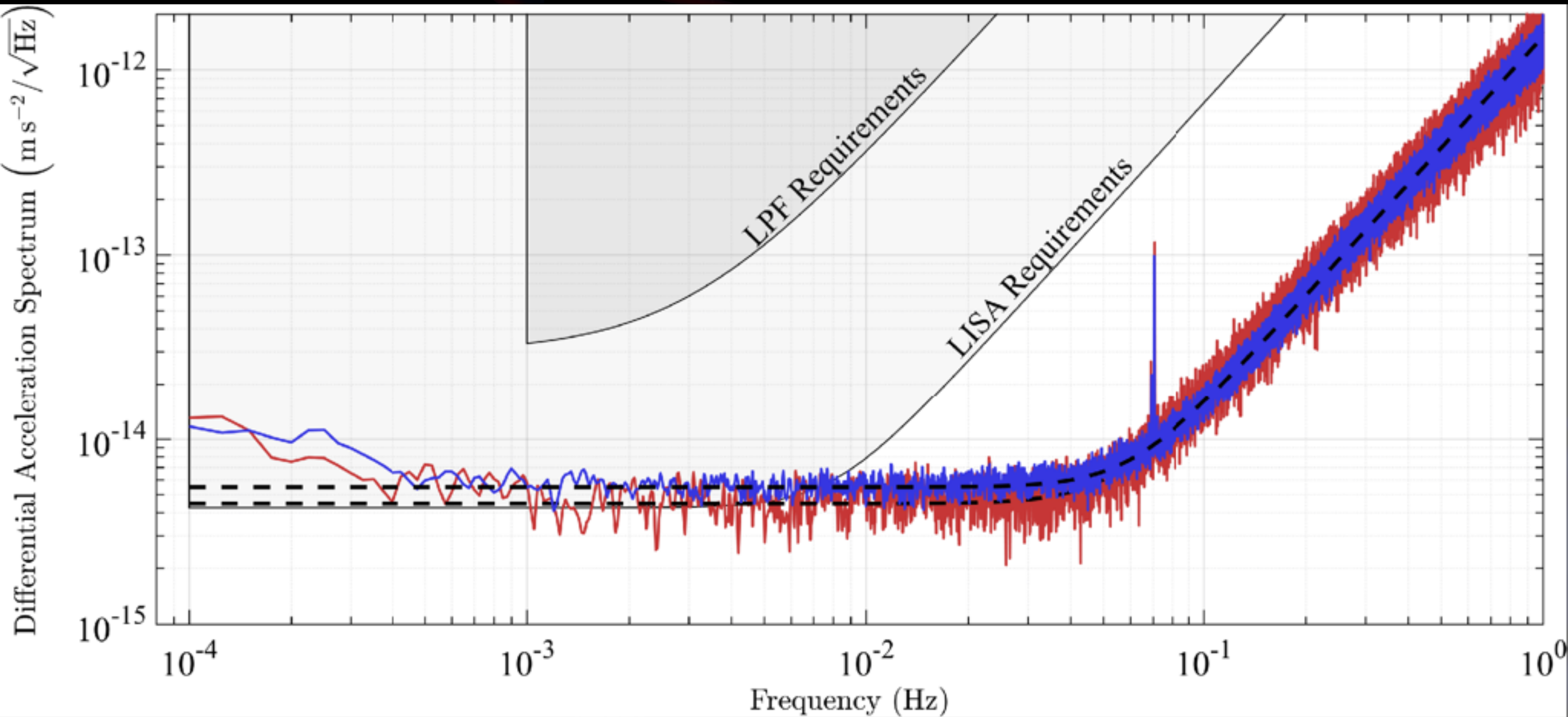

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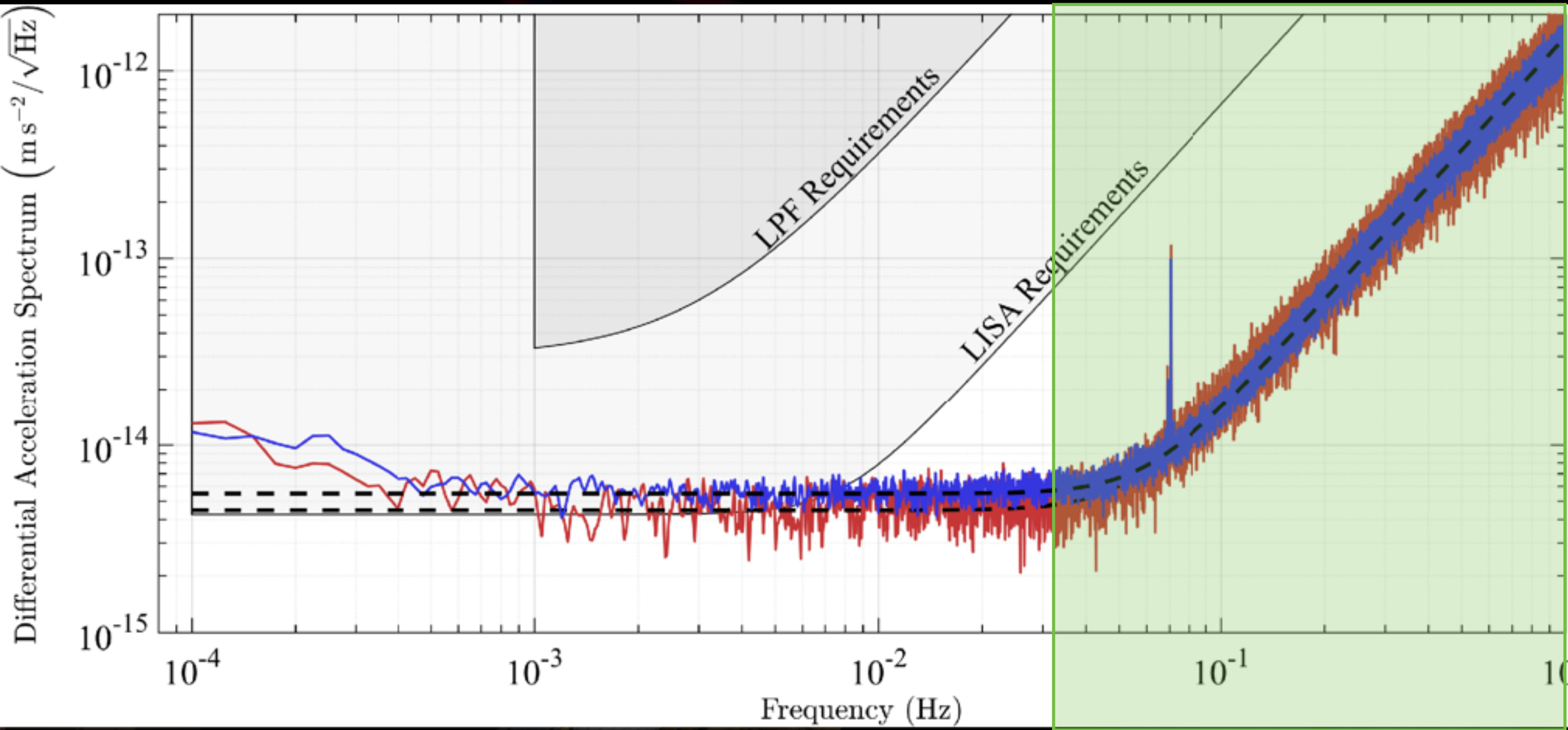

Interferometric noise: 30 fm.Hz$^{-1/2}$

Not real test-mass motion

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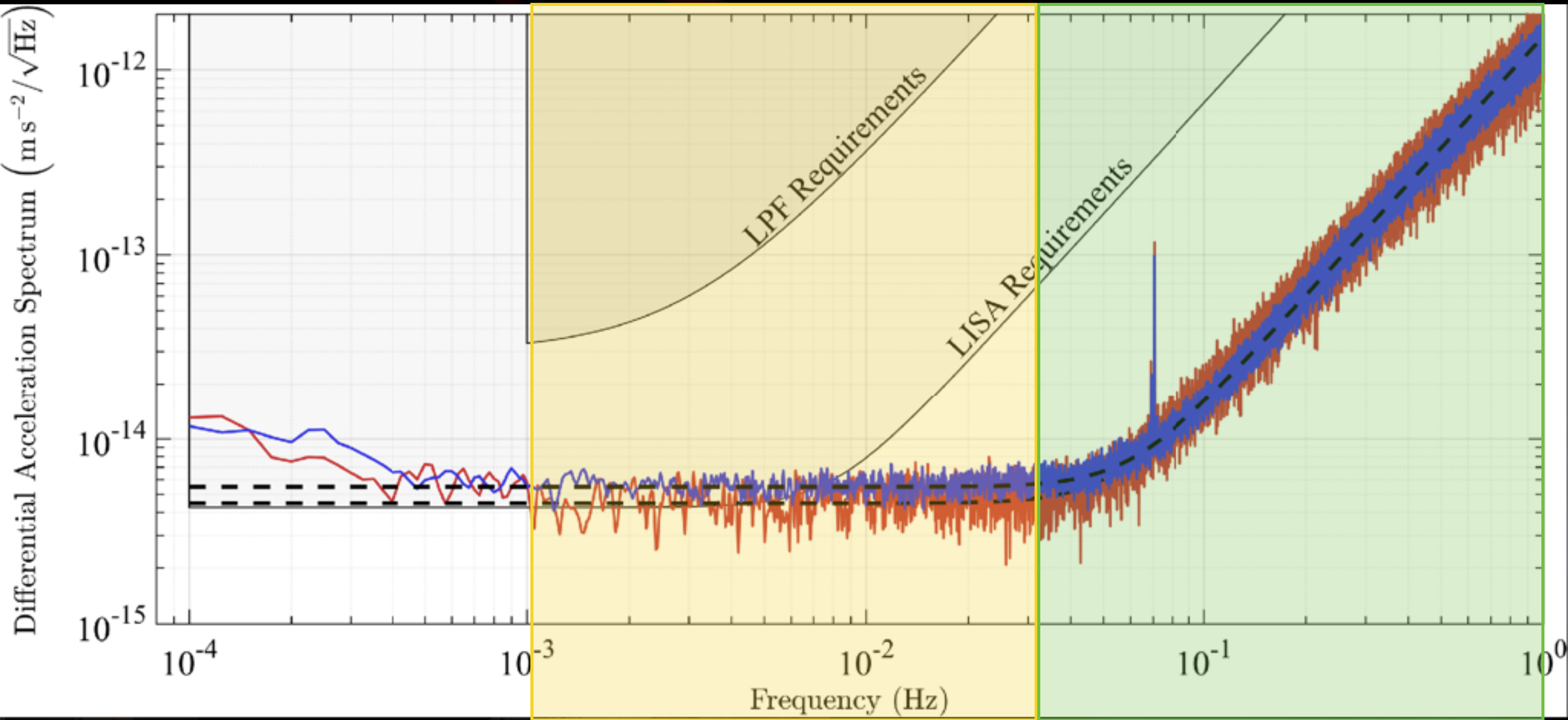

Brownian noise
Molecules within the noise
hit test-masses

First results

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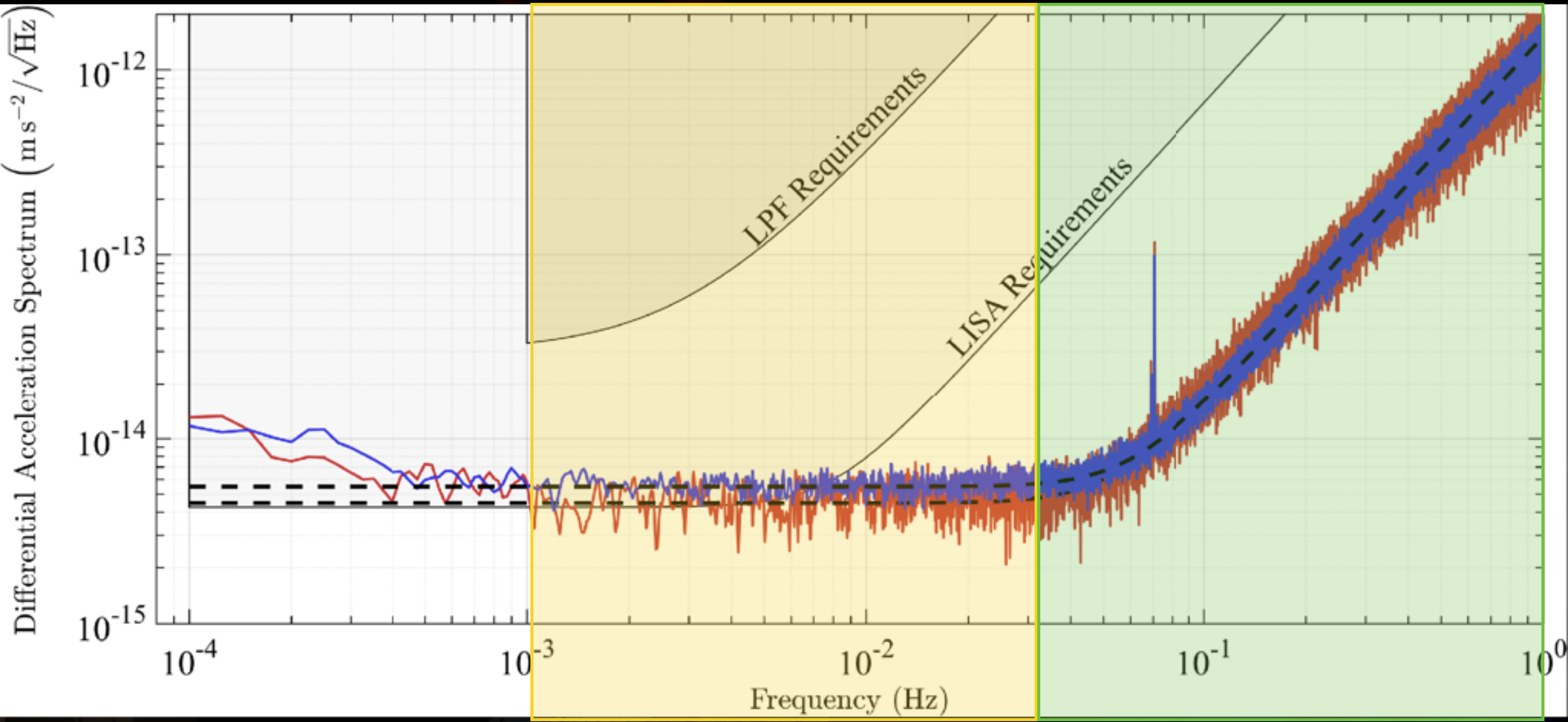

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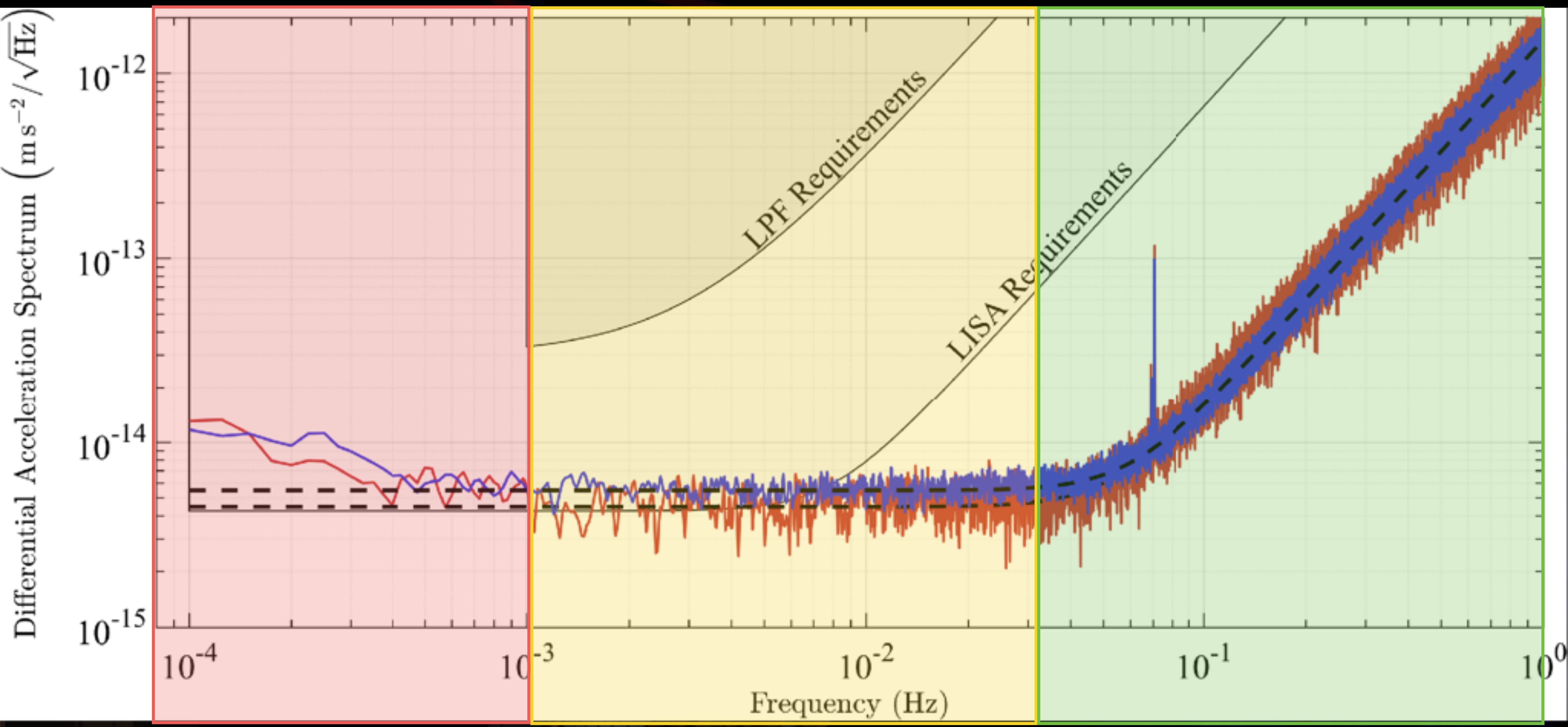
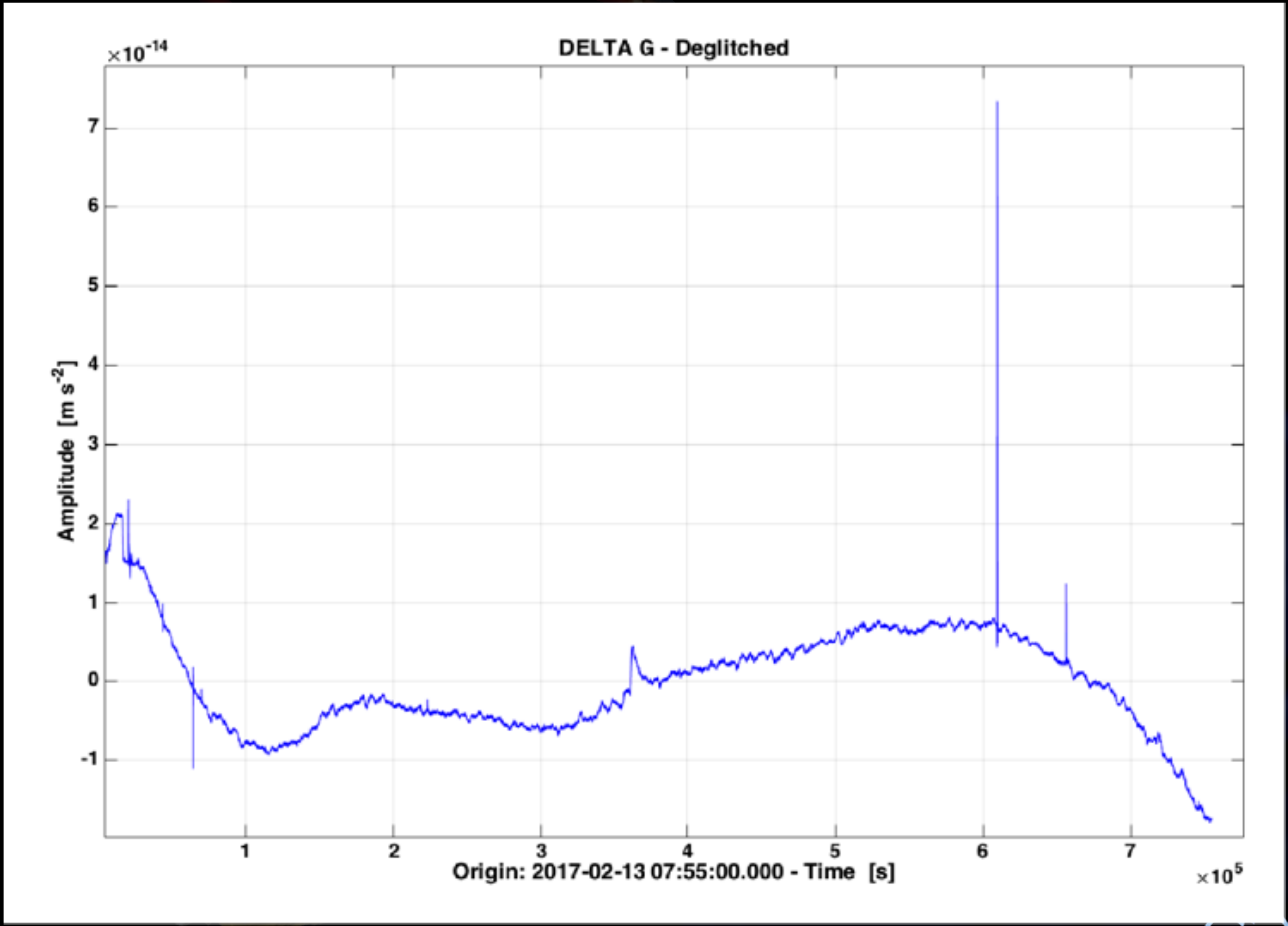


Low frequency noise
Half fully understood
...

Brownian noise
Molecules within the noise
hit test-masses

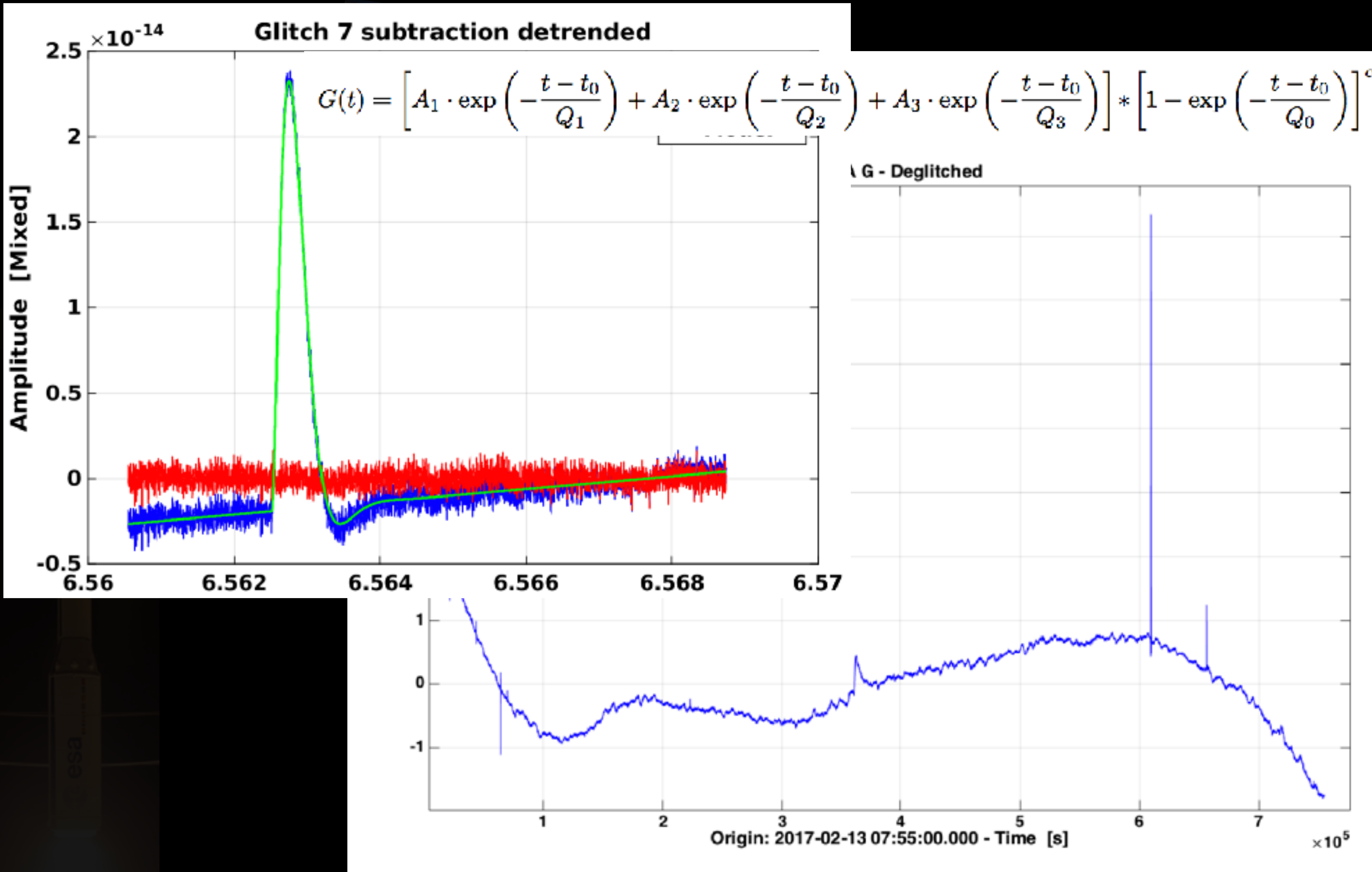
Interferometric noise
Not real test-mass motion

De-glitching



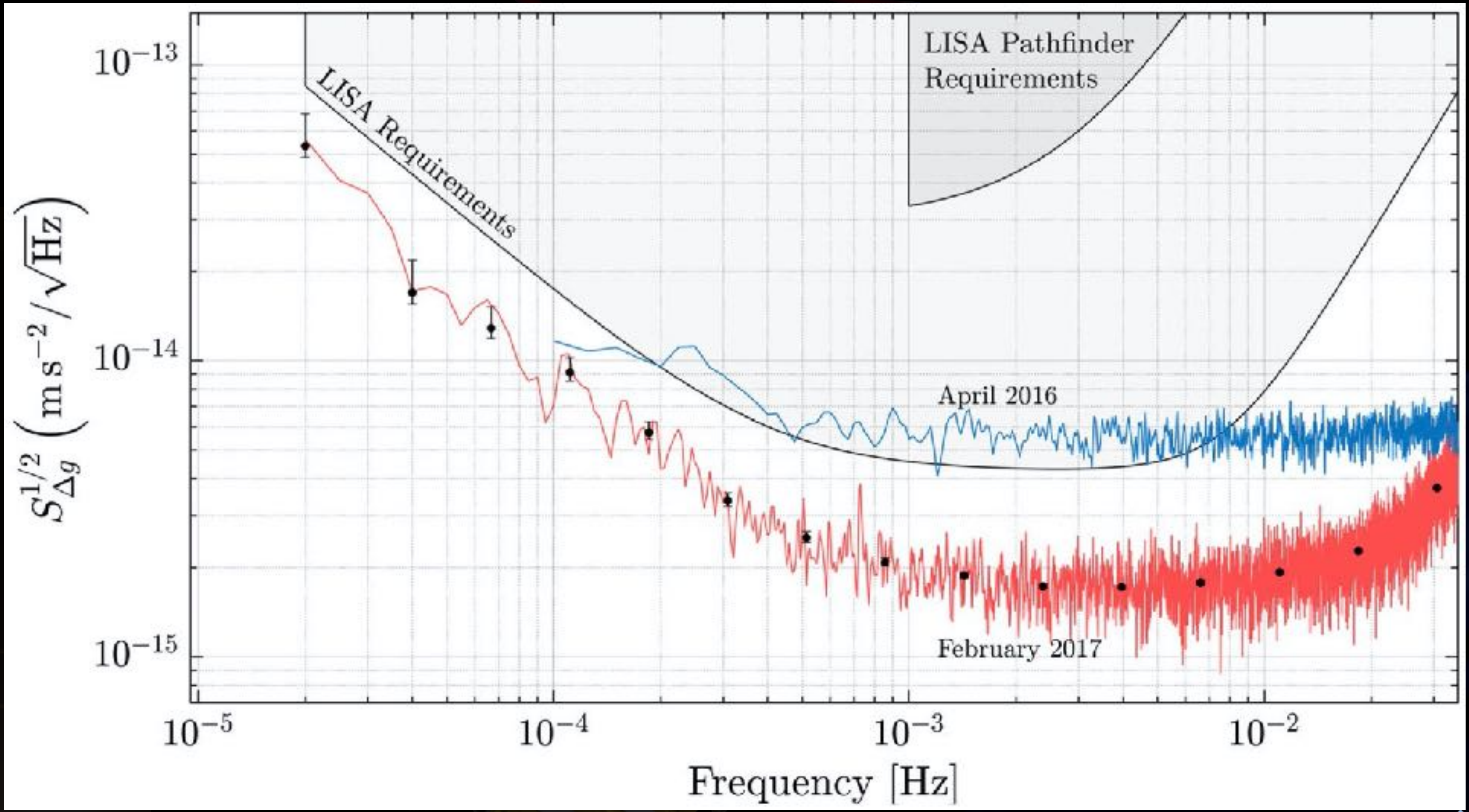
De-glitching

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



Final main results

M. Armano et al. PRL 120, 061101 (2018)



Results

- Other published studies from in-depth investigations (1/2):
  - Charge-Induced Force Noise on Free-Falling TMs (PRL.118.171101)
  - Capacitive sensing of TM motion with nm precision over mm-wide sensing gaps for space-borne gravitational reference sensors (PRD.96.062004)
  - Precision Charge Control for Isolated Free-Falling TMs (PRD.98.062001)
  - Measuring the Galactic Cosmic Ray Flux with the LISA Pathfinder Radiation Monitor (AstroPartPhys.98p28) ; Characteristics and Energy Dependence of Recurrent Galactic Cosmic-Ray Flux Depressions and of a Forbush Decrease with LISA Pathfinder (ApJ.854.2)
  - Calibrating the system dynamics of LISA Pathfinder (PRD.97.122002)
  - Experimental results from the ST7 mission on LISA Pathfinder (arxiv.1809.08969)
  - LISA Pathfinder micronewton cold gas thrusters (PRD.99.122003)
  - LISA Pathfinder platform stability and drag-free performance (PRD.99.082001)
  - LISA Pathfinder Performance Confirmed in an Open-Loop Configuration: Results from the Free-Fall Actuation Mode (PRL.123.111101)

Results

- Other published studies from in-depth investigations (2/2):
  - Temperature stability in the sub-mm band with LISA Pathfinder (MNRAS.486.3)
  - Spacecraft and interplanetary contributions to the magnetic environment on-board LISA Pathfinder (MNRAS494.2)
- Some other aspects of LPF studies are still in progress:
  - Glitch characterisations
  - Performances of the interferometric system
  - Impact of laser radiation pressure
  - Measure of laser relative intensity noise
  - Measure of photodiode performances
- Beyond noise characterisations:
  - Novel methods to measure the gravitational constant in space (PRD.100.062003)
  - Micrometeoroid Events in LISA Pathfinder (ApJ.883.1.53)

French contribution to the results

- Participation to the main results (residual acceleration), in particular the measure of key parameters (calibration)
- Thrusters: design experiments, analysis, publication
- Drag-free control: analysis and publication => platform stability and « level of inertiality » of LISAPathfinder
- Glitches: design of dedicated pipeline, analysis
- Laser Modulator Unit in-flight monitoring
- Databases (https://apclisapf.in2p3.fr/): DB, visualisation & export
- Others:
  - Understanding cross-talks experiments
  - Analysis on the gaussianity of the noise
  - Study of thermal response
  - Modelling and subtraction of the Spacecraft jitter coupling

Organisation

- ESA: lead of the mission
- Contribution from:
  - Germany (PI, main architect & laser)
  - Italy (co-PI, Test Masses & caging)
  - UK (Optical bench & TM discharge)
  - Spain (Data diagnostics & management)
  - Switzerland (Electronics)
  - France (LMU)

  + Data Analysis contribution for all
- NASA (ST7): separate small instrument: computer + thrusters

Core scientific team for operation

	Staff	CDD	PhD
AEI (Germany)	3	3	4
APC (France)	3	1	1
Barcelona (Spain)	3	0	2
ESA	2		
Glasgow (UK)	2		
Imperial College (UK)	2		1
NASA	1	1	
Trento (Italy)	3	1	4
ETH (Switzerland)	1	1	1

Development

- Development (2002-2014, longer than expected ...)
  - Extremely innovative: high stability of “free-fall” at low-frequencies
  - Many technical hurdles
  - Benefit: impressive expertise accumulated
- Lessons learned
  - Importance of integrating closely the work of the scientific teams with the industrial partners and ESA/NASA
  - Time needed, before launch, to check and optimise the data analysis software & its interface with a precise Mission/Satellite simulator
  - Thermal model of the satellite: dominant at low frequencies
  - Gas micro thrusters to be develop as ”stand alone" and not as semi-industrial components.

Operations

- Initial organisation:
  - Core operation center at ESOC (Darmstadt, ESA)
  - Complementary Data Center at FACe (Paris)
  - Institutes
- In practice: most of the activities at ESOC:
  - Mission Operation Center (ESA) + Science & Technical Operation Center (ESA) + scientific teams
- Lessons learned:
  - The colocation of the scientific teams with the mission control teams was essential
  - Importance of integrating closely the work of the scientific teams with the industrial partners and ESA/NASA

Ressources in France

- CNES (about 3.5M€):
  - hardware (LMU + tests)
  - missions
  - CDDs (8 => 11 FTE)
- Labex UnivEarthS (134 k€):
  - 1 PhD + 1 post-doc
- CNRS:
  - FACe
  - permanent (2 DR => 10 FTE, 4 engineers => 7 FTE)
- University Paris-Diderot
  - permanent (2 MCF => 5 FTE, 1 engineer => 1 FTE)

	Permanent		Non-permanent		Total
Year	Researcher	Engineer	Researcher	Engineer	
2006	1,0	2,0		0,5	3,5
2007	1,0	1,2		0,2	2,4
2008	0,8	0,5			1,3
2009	0,8	0,5			1,3
2010	0,8	0,5			1,3
2011	0,8	0,4			1,2
2012	1,6	0,3	0,9	0,9	3,7
2013	1,2	0,3	0,9	0,9	3,3
2014	1,2	0,3	0,9	0,9	3,3
2015	1,4	0,3	1	0,9	3,6
2016	1,4	1	0,3	0,9	3,6
2017	1	0,3		0,2	1,5
2018	0,8	0,2		0,5	1,5
2019	0,8	0,1		0,8	1,7
2020				0,2	0,2

Return of experiences

- Mission level:
  - Need of a smooth interaction with industries and availability of documentation
  - Importance of ground tests mastered by the (scientific) Consortium : 'Test as you fly, fly as you test'
  - Involvement of hardware providers to the integration on the instrument
  - Involvement of the Consortium to the definition of system requirements
  - Data processing tool: a single, simple to use, basic data processing and visualisation tool that is accessible to all parties
  - Flexibility in telemetry

LISA technology requirements

- Free flying test mass subject to very low parasitic forces:
  - ✓ Drag free control of spacecraft (non-contacting spacecraft)
  - ✓ Low noise microthruster to implement drag-free
  - ✓ Large gaps, heavy masses with caging mechanism
  - ✓ High stability electrical actuation on cross degrees of freedom
  - ✓ Non contacting discharging of test-masses
  - ✓ High thermo-mechanical stability of S/C
  - ✓ Gravitational field cancellation

Validated with LISAPathfinder

- Precision interferometric, local ranging of test-mass and spacecraft:
  - ✓ pm resolution ranging, sub-mrad alignments
  - ✓ High stability monolithic optical assemblies
- Precision million km spacecraft to spacecraft precision ranging:
  - ➡ High precision laser frequency stabilization + noise suppression with TDI
  - ➡ "Tilt to length" coupling (alignement control + on-ground correction)
  - ➡ Low level of stray-light
  - ➡ High stability of telescope
  - ➡ High precision phase-meter and frequency distributions

Ground-based demonstrators GRACE-FO

Return of experiences

- APC/IN2P3 level:
  - Extreme level of precision + complexity => a global understanding of the instrument and the mission is necessary
  - Hardware contribution: crucial to be part of the core team developing the instrument & an access to the relevant information
  - Importance of an 'agile' collaboration infrastructure (as FACe), in particular for in-flight preparation and operations
  - Active participation to the Operation & Data Analysis preparation effort and exercises
  - Human ressource support to capitalise on acquired experience and 'stabilise' skills (instrumentation, simulations, data analysis, etc.)
    - CNES: 'equipments' & short term contracts for technical assistance,
    - CNRS/IN2P3 to ensure a long-term support & workforce visibility

Conclusion (1/2)

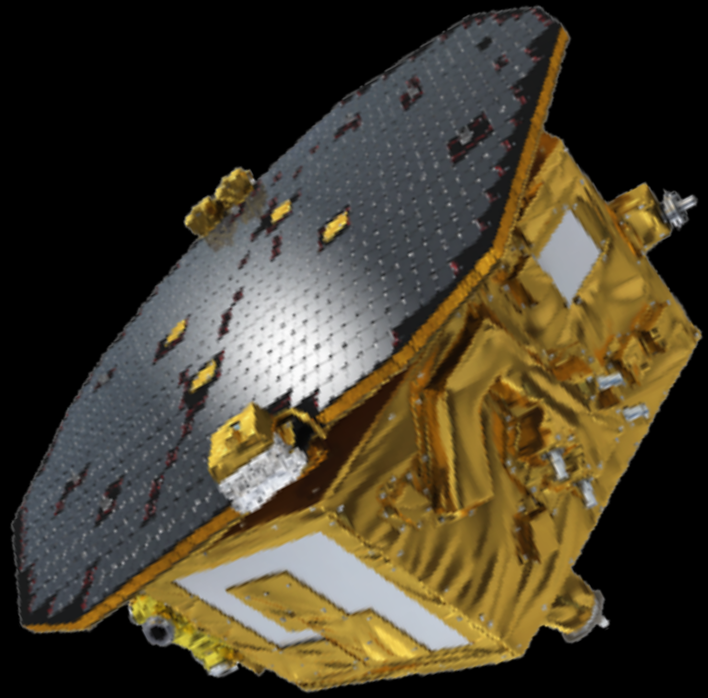
- LISAPathfinder is a technological demonstrator for LISA started in 1998, launched in 2015 and ending now
- The results are extremely good:
  - differential acceleration between free-falling test-masses: (1.74 +/- 0.01) $fm.s^{-2}$ / $Hz^{-1/2}$ above 2 mHz
  - in-depth investigations of a large number of technical aspects => large accumulated expertise
- France and IN2P3 involved with APC on:
  - operations and their preparations: data analysis, design of experiments, publications
  - hardware: Laser Modulator Unit and experimental demonstration of testing procedures

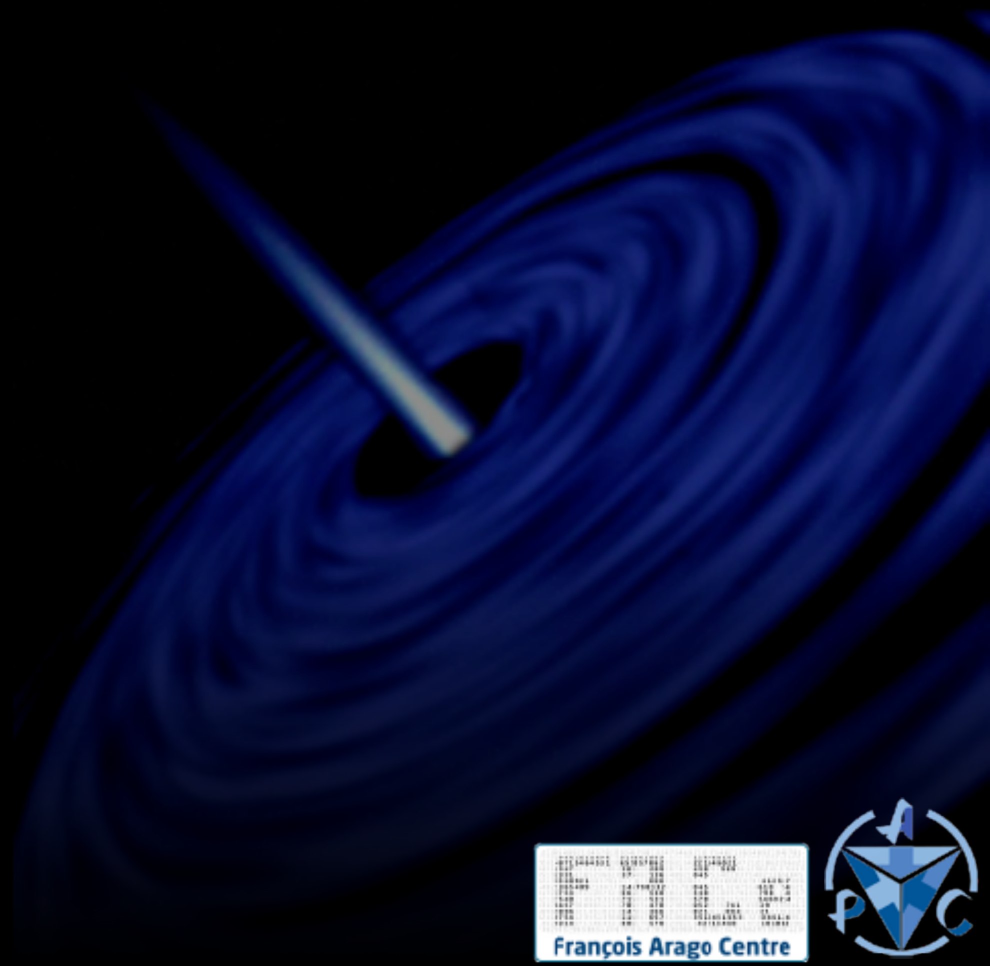
Conclusion (2/2)

- Based on LISAPathfinder's lessons learned, for LISA:
  - Long-term effort, need to get involved early
  - Frequent calendar hazards...
  - France's privileged place in LISA, in particular thanks to APC's involvement in LISAPathfinder (instrument and data analysis)
  - APC and IN2P3 currently driving, with CNES, the (consequent) collaboration LISA France => to be continued and consolidated (otherwise the leadership will go to other institutes becoming more involved)
  - Opportunity for IN2P3 to capitalize on the experience gained by LISAPathfinder and play an important role in a major scientific space mission.

lisa pathfinder

MERCI

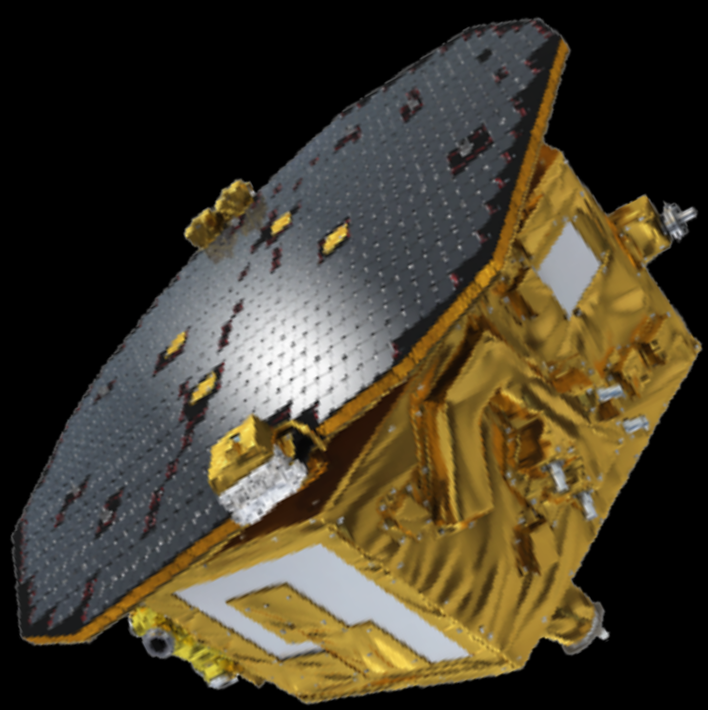


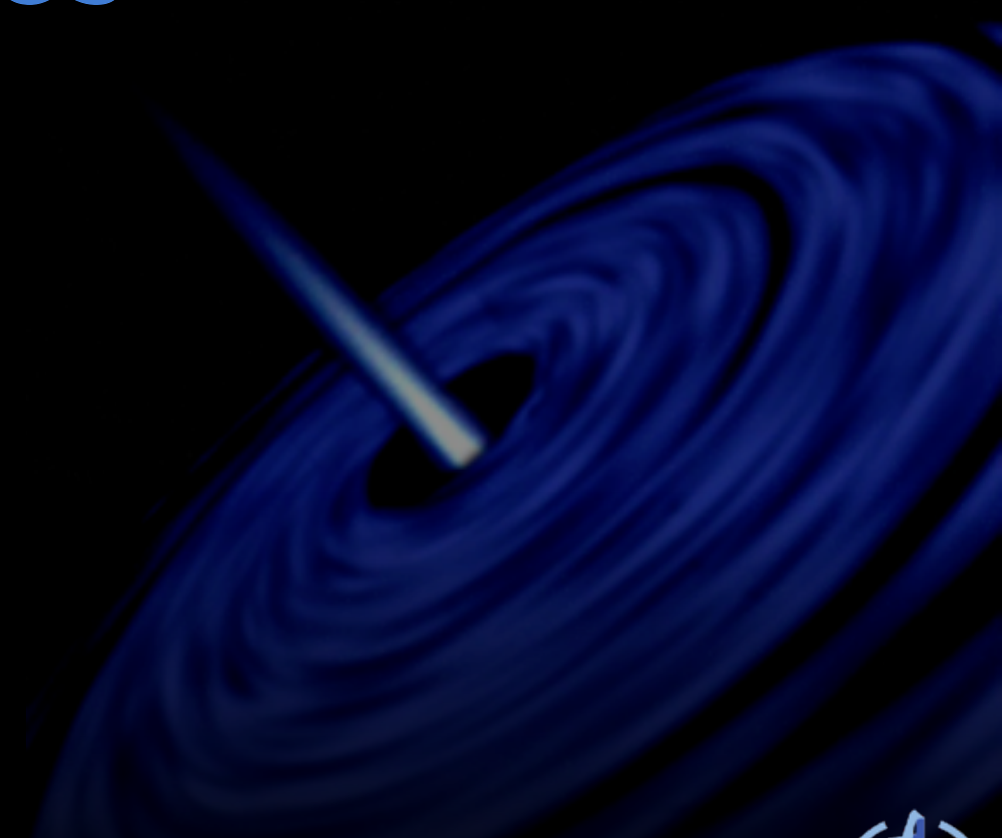


François Arago Centre

lisa pathfinder

Back-up slides





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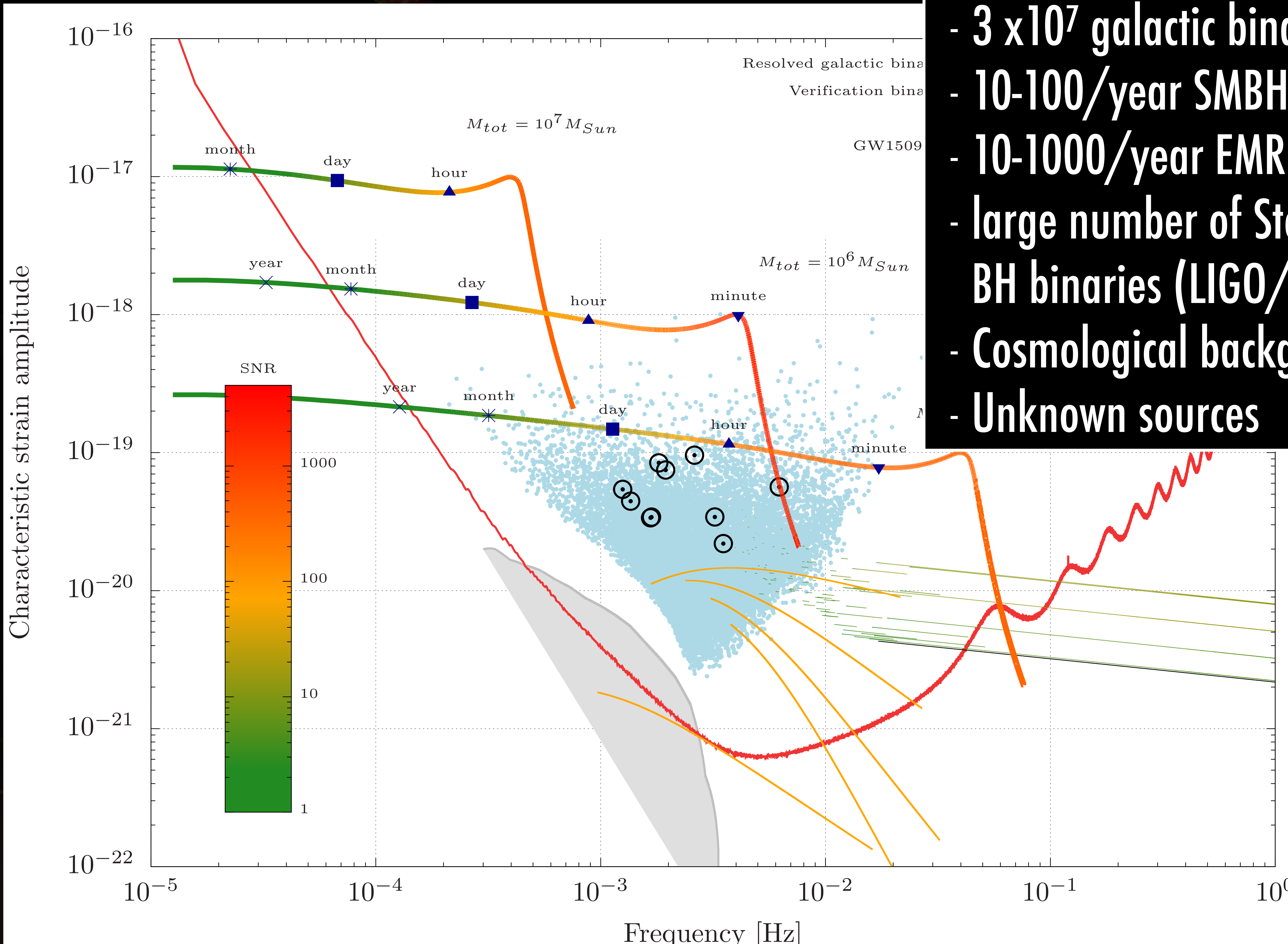
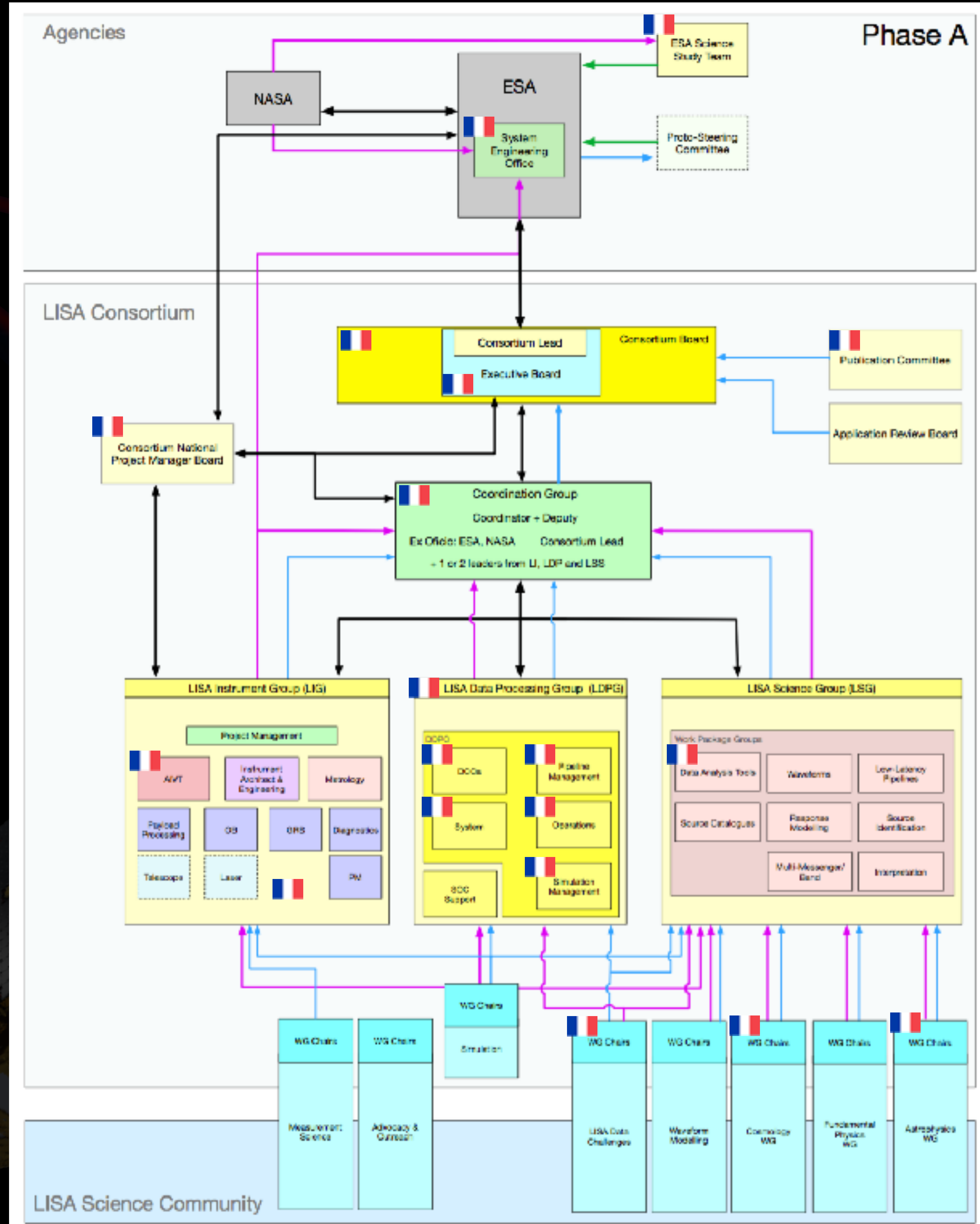
LISA GW sources

- 3×10^7 galactic binaries
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- large number of Stellar Mass BH binaries (LIGO/Virgo)
- Cosmological backgrounds
- Unknown sources

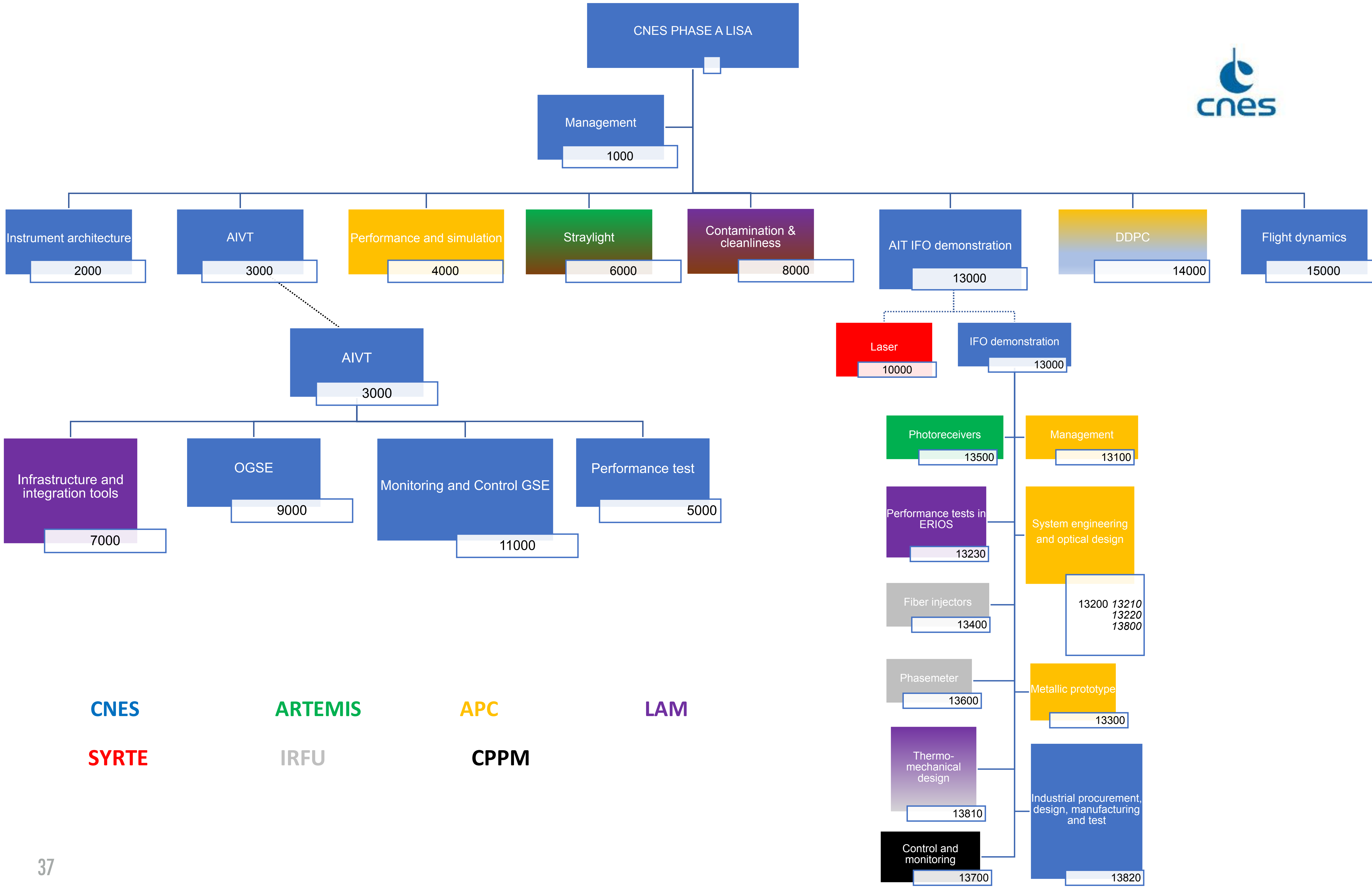


France in LISA Consortium

- At ESA level:
  - Science Study Team,
  - System Engineering Office
- At Consortium level:
  - Co-Lead, Executive Board & Board
  - Coordination Team
  - Instrument Group: AIVT (lead), Performance WG (lead)
  - Data Processing Group (lead): at least one lead in each WG
  - Science Group: Data Analysis Tools (lead)
  - LISA Data Challenge (lead)
  - AstroWG (co-chair)
  - CosmoWG (co-chair)
  - Publication & Pres. Committee (lead)



LISA project in France - phase A



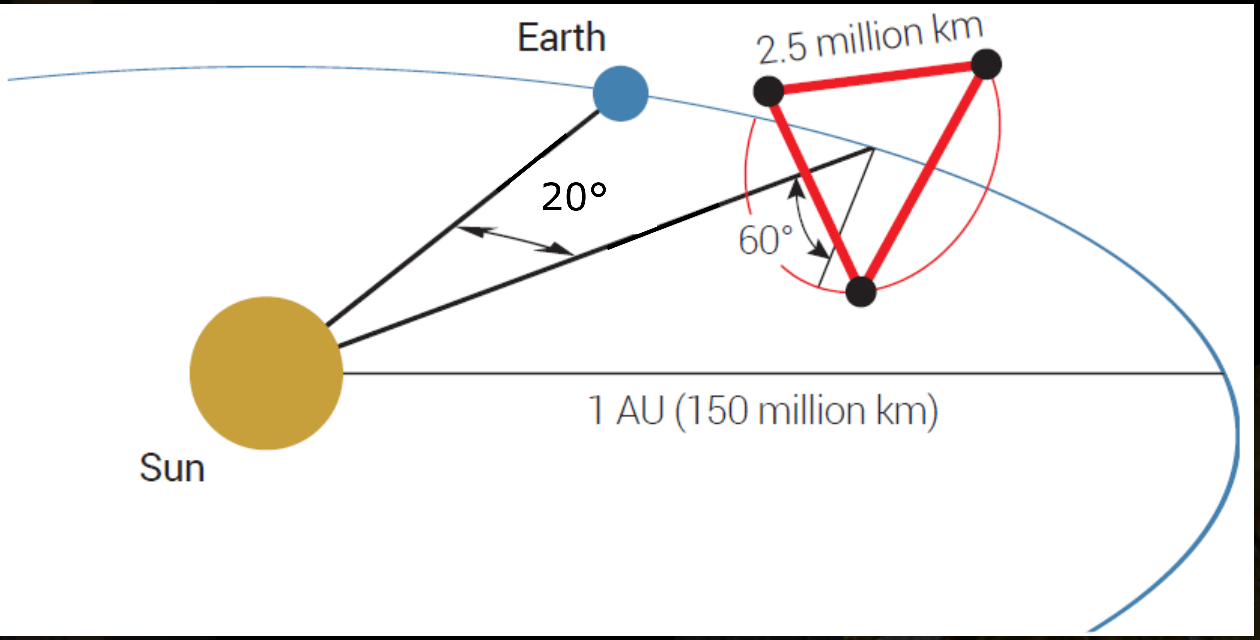
LISA timeline

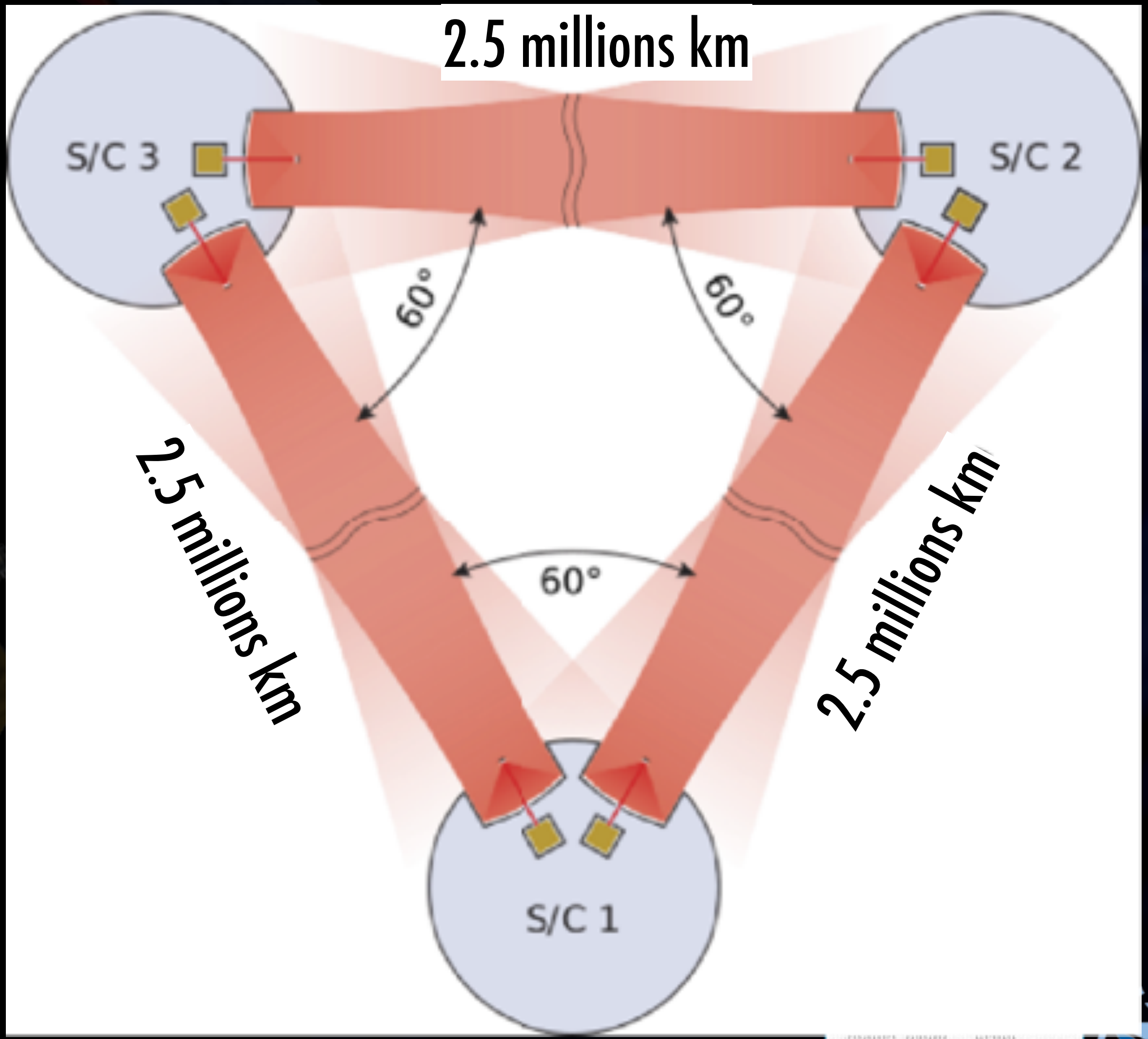
- 25/10/2016 : Call for mission
- 13/01/2017 : submission of «LISA proposal» (LISA consortium)
- 8/3/2017 : Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017 : LISA mission approved by SPC
- 8/3/2017 : Phase 0 payload (CDF June → November 2017)
- 2018→2021 : competitive phase A: 2 companies compete
- 2021→2022 : B1: start industrial implementation
- 2023 : mission adoption
- 2024→2032 : development (2025:B2→C, 2027:C→D, 2032:D→E)
- 2034 : launch Ariane 6.4
- 1.5 years for transfert
- 4-6 years of nominal mission
- Possible extension to 10 years

→ GW observations !

LISA

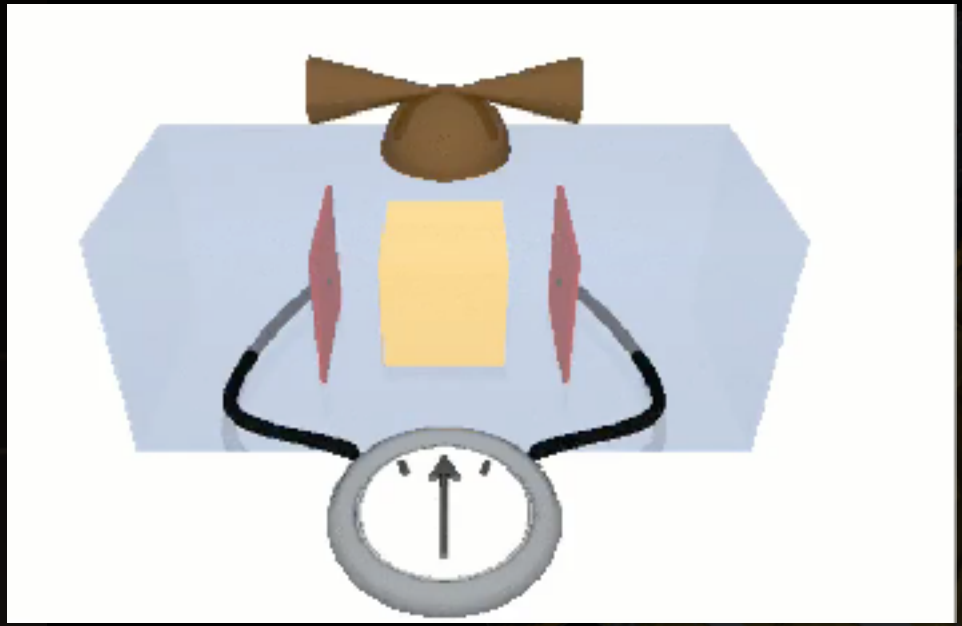
- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers

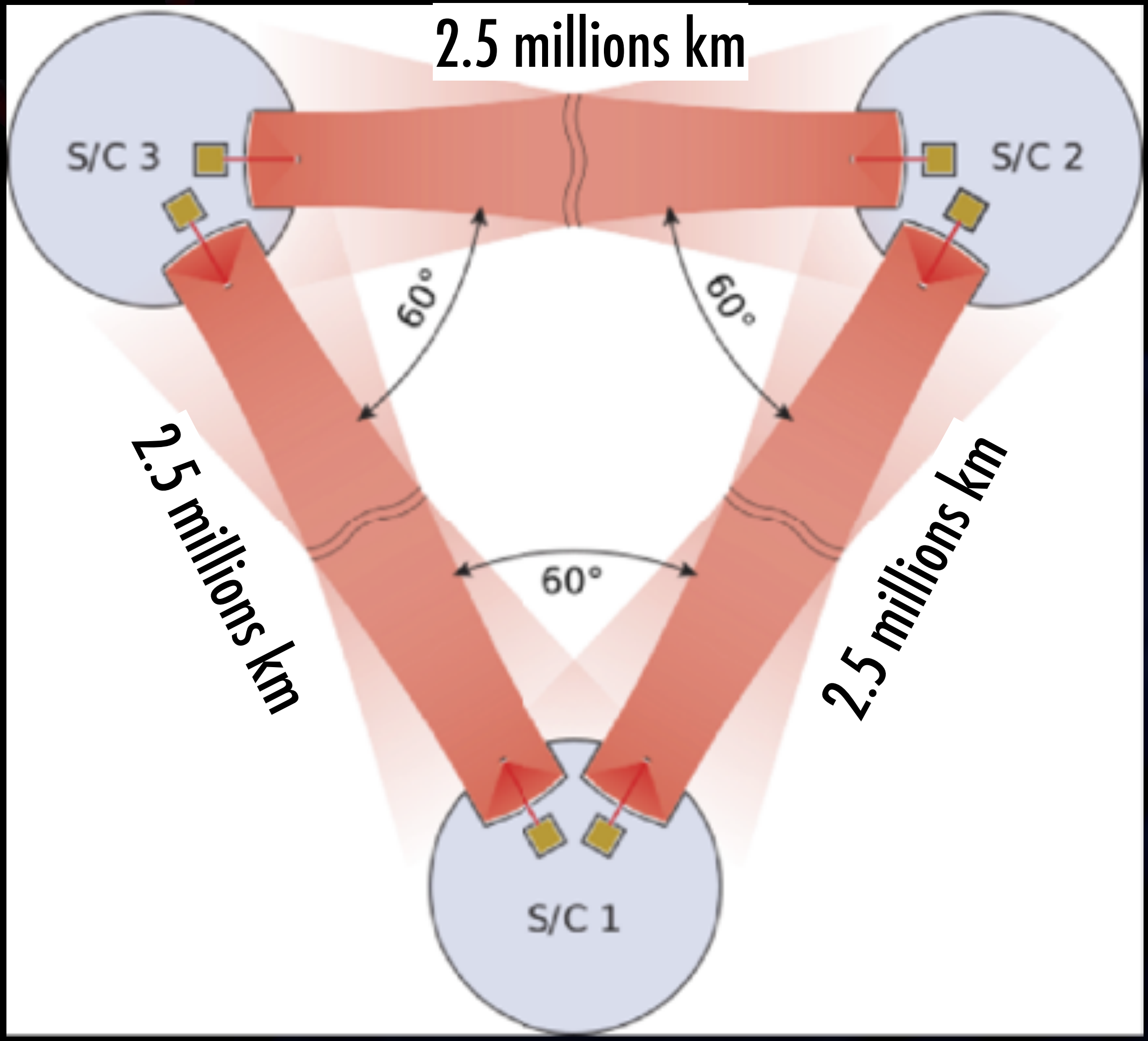




LISA

- 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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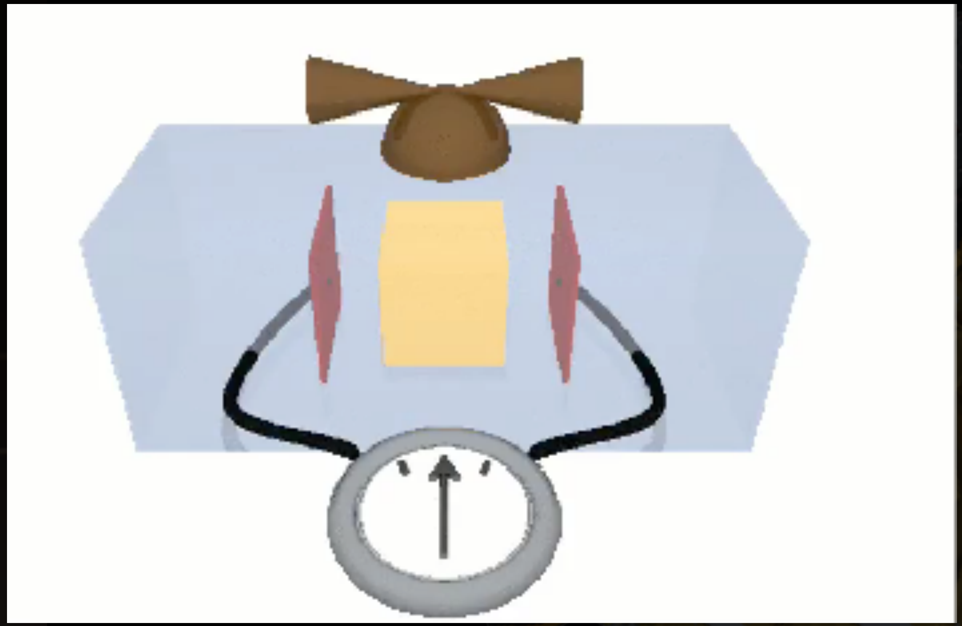
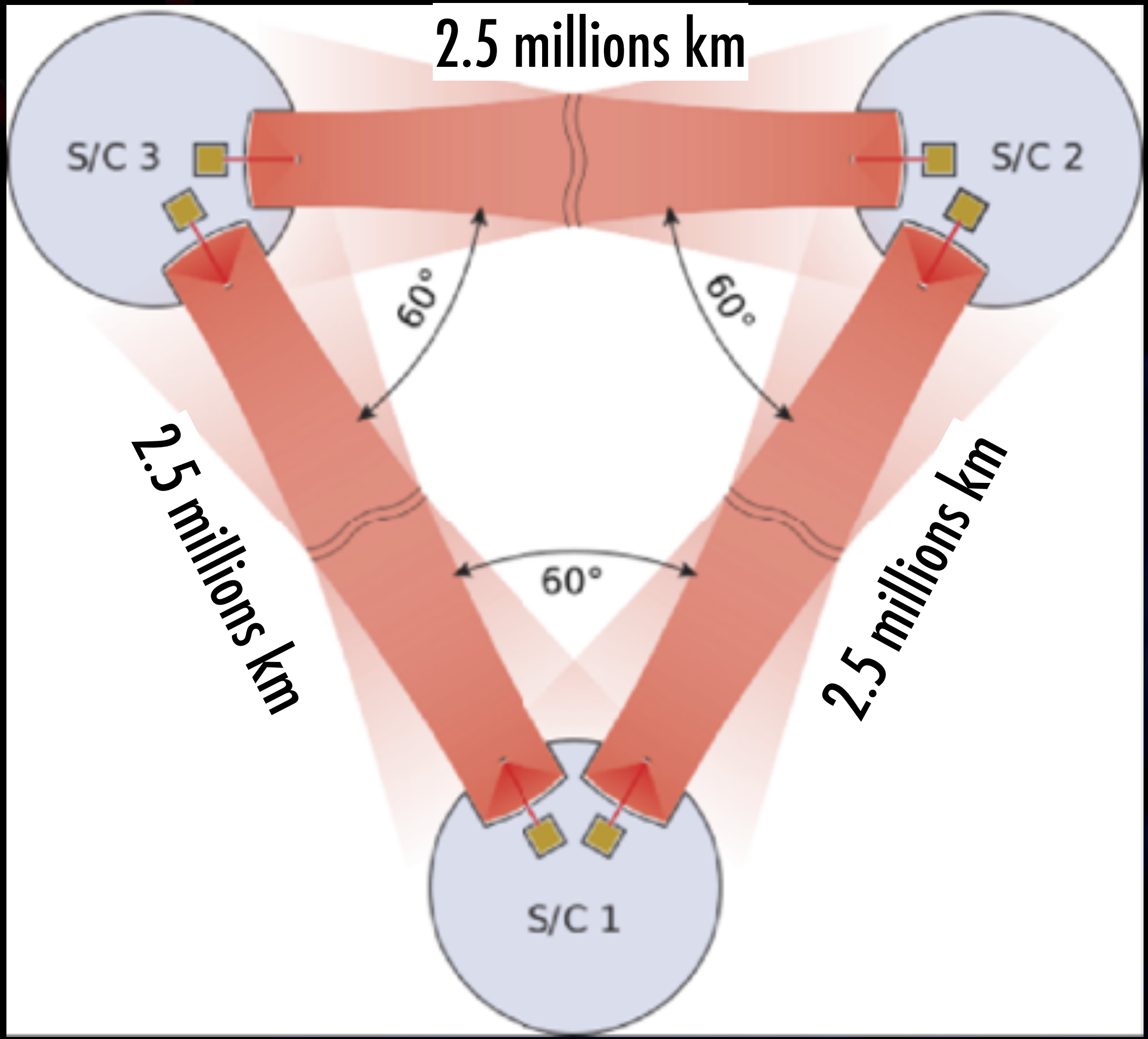
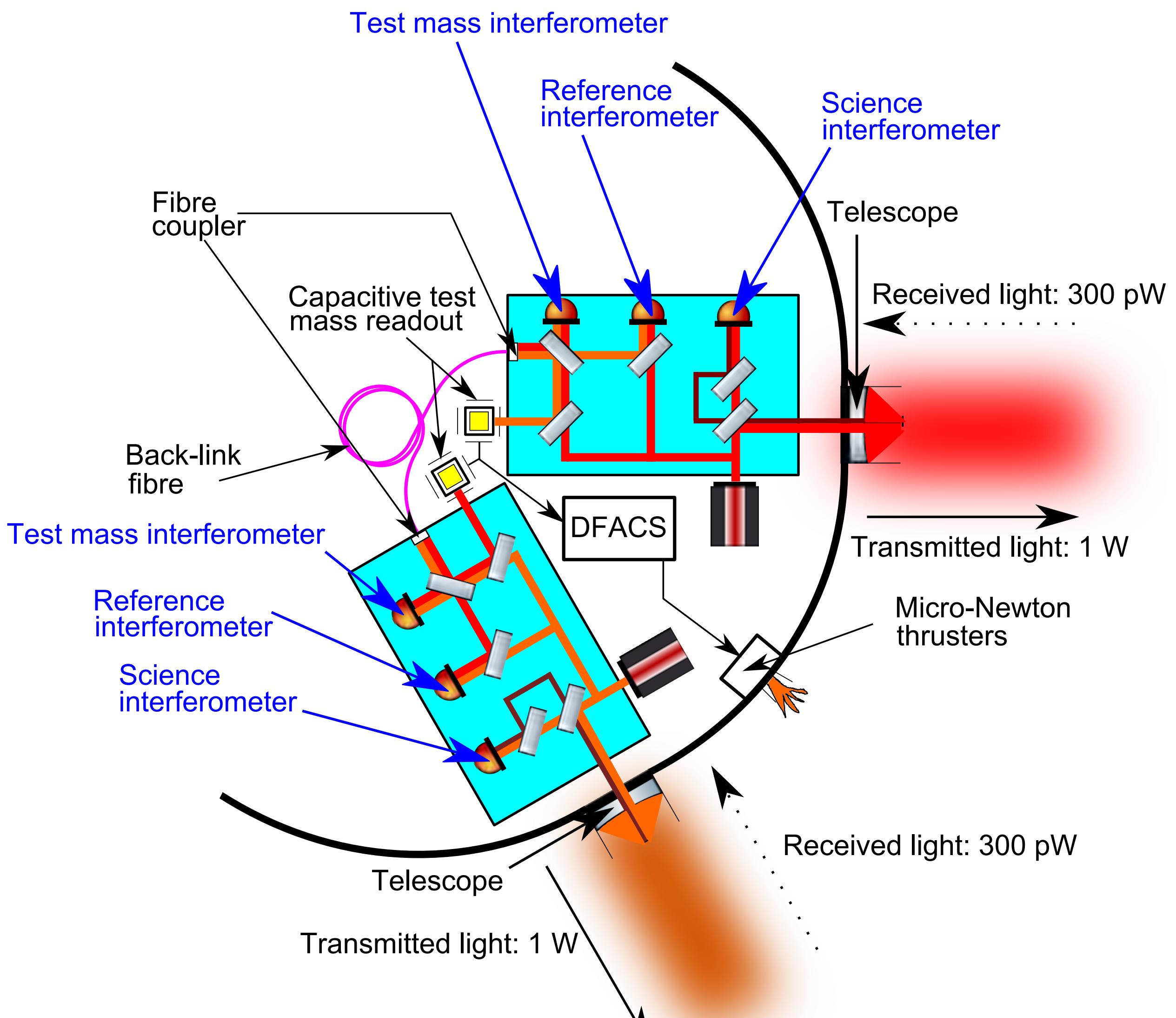




LISA

- 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

LISA

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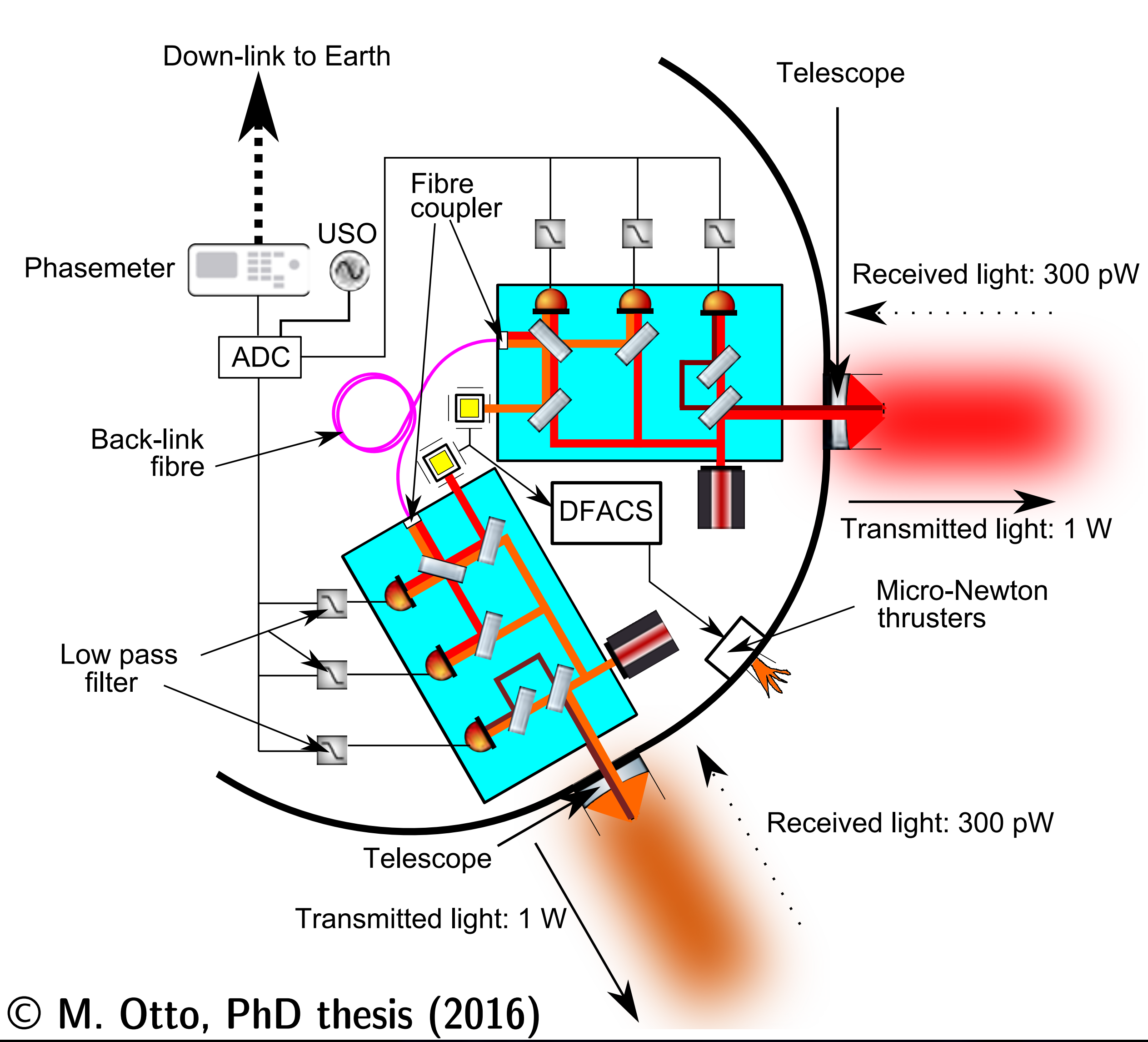

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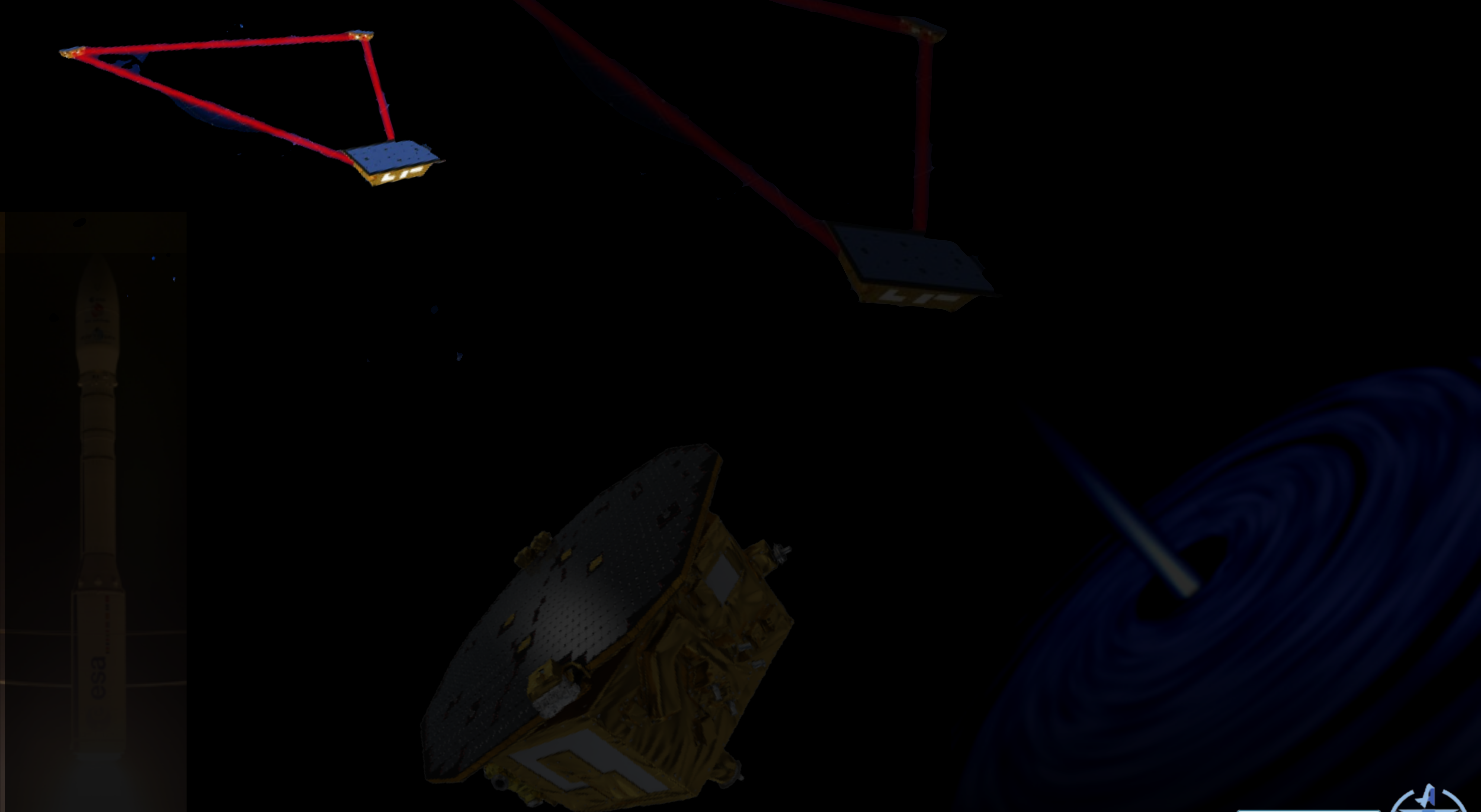
LISA

- A measurements in several steps



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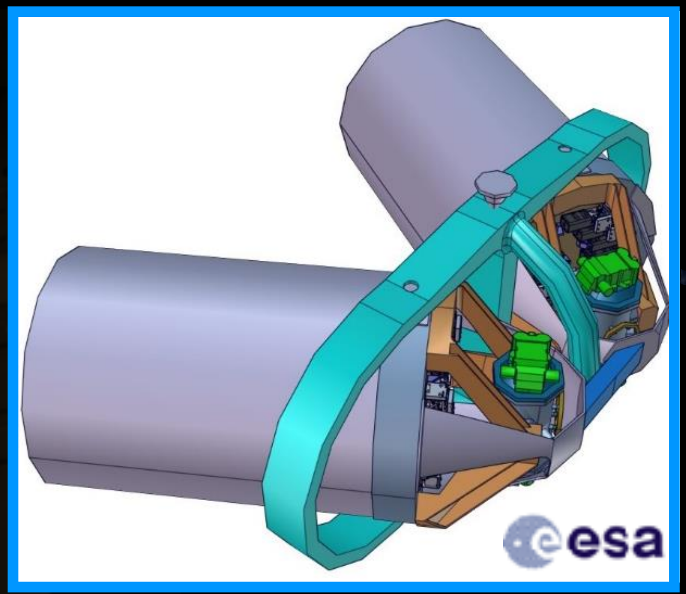

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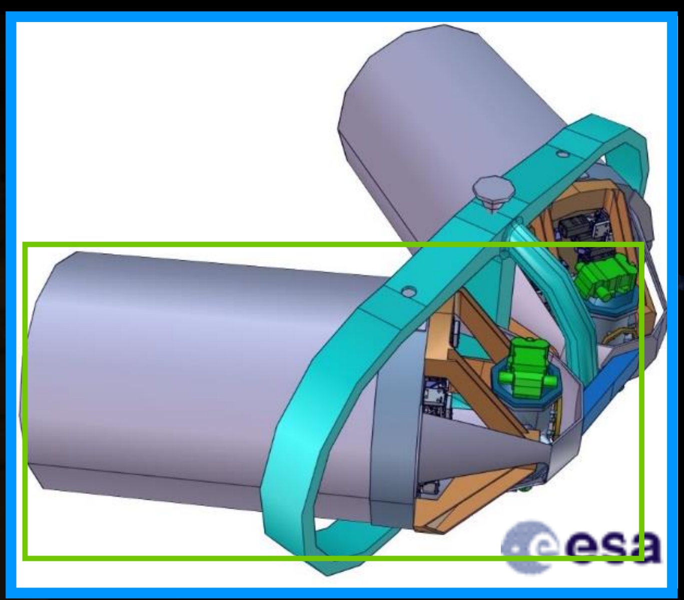

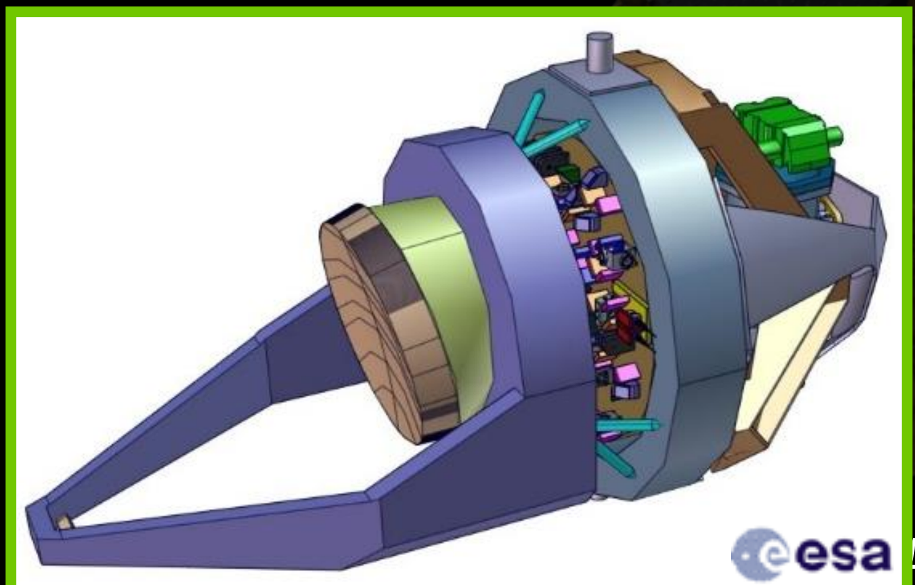

LISA

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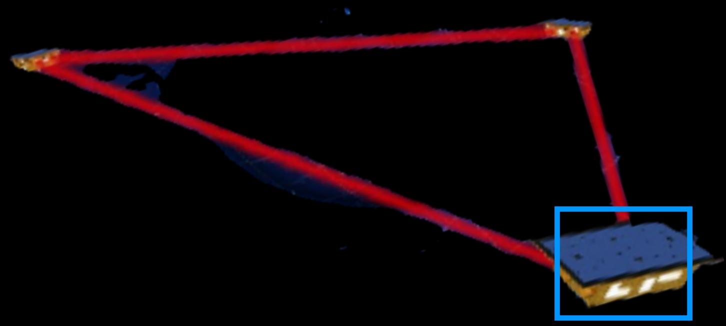

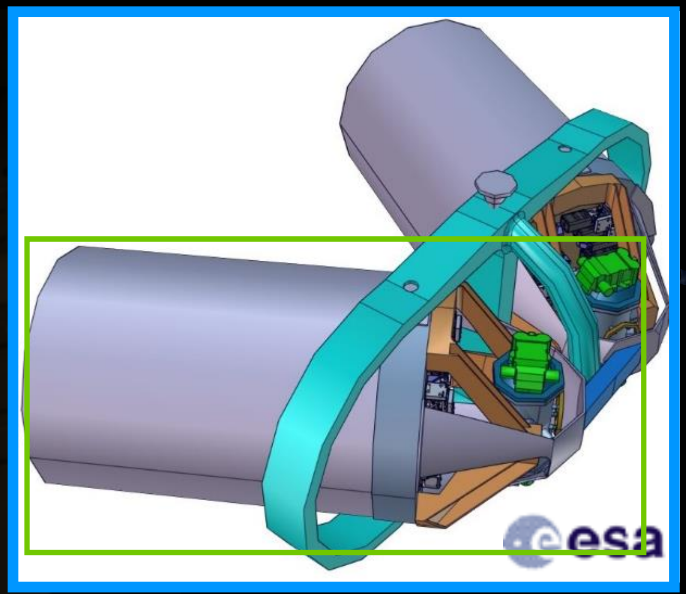

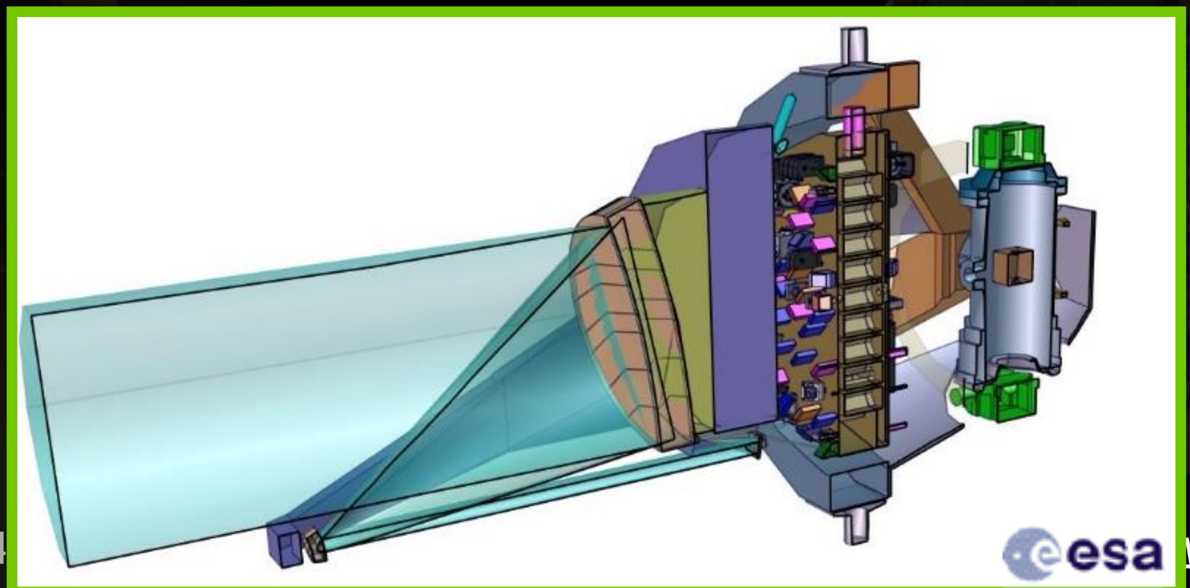

LISA

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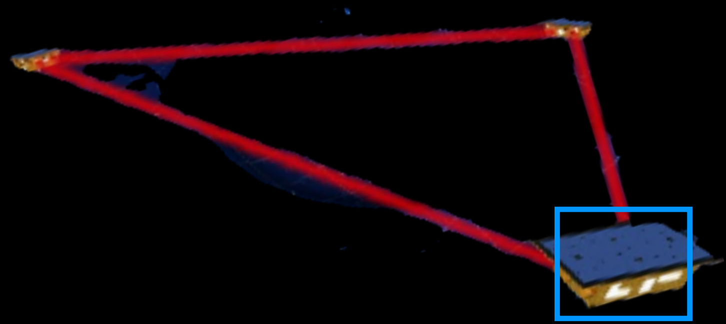
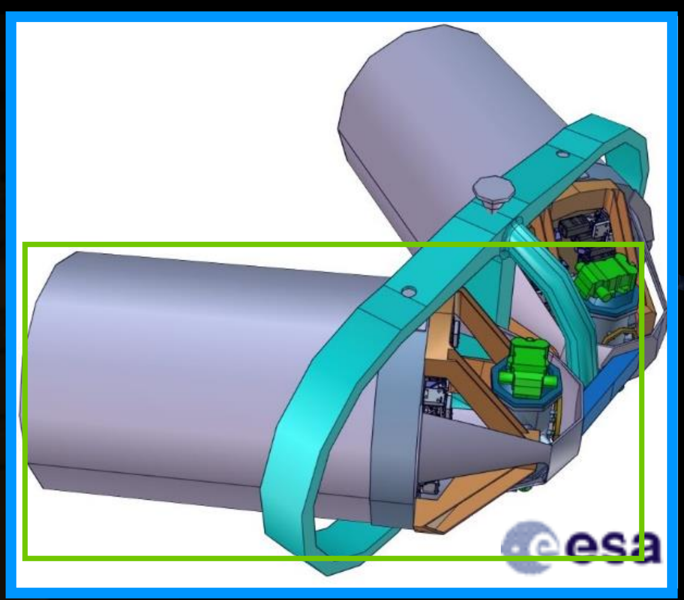
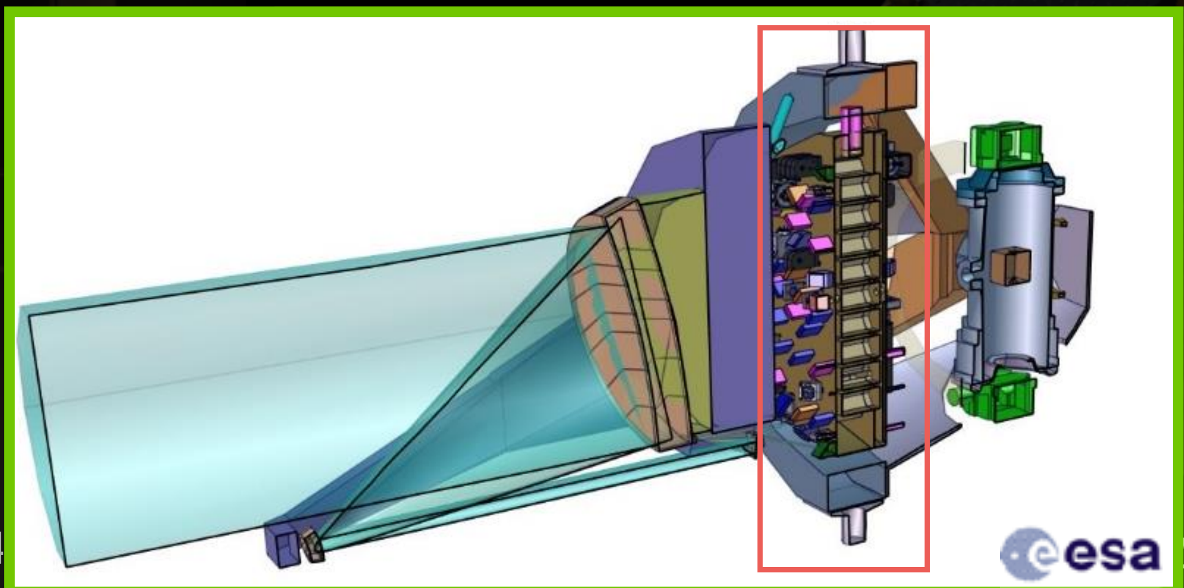


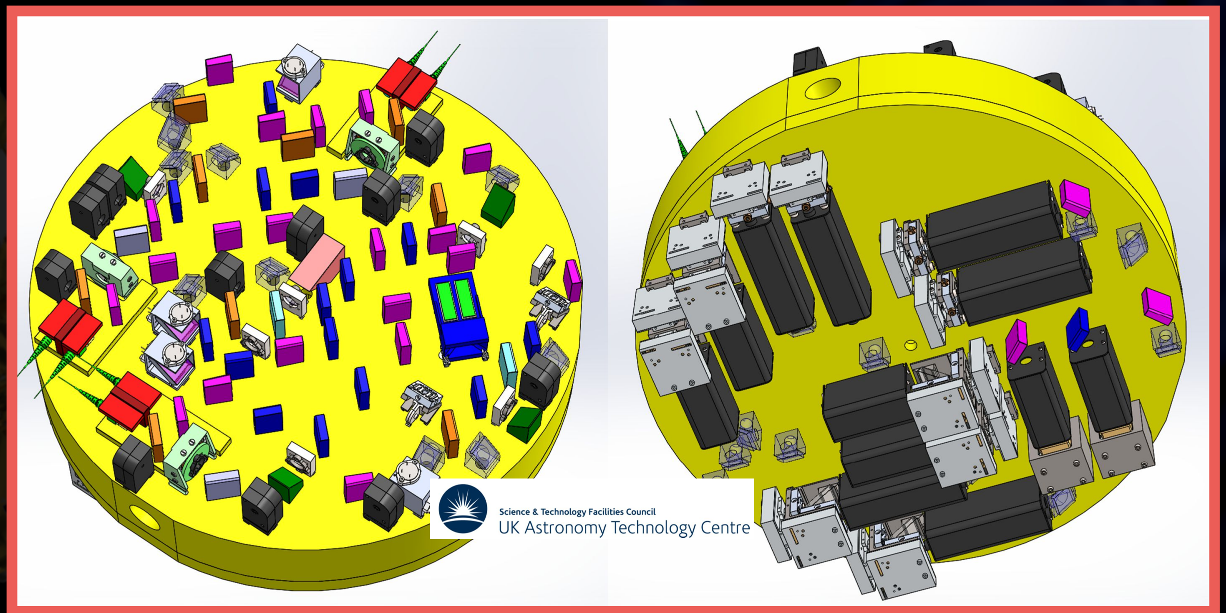


LISA:

Local measurement of 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

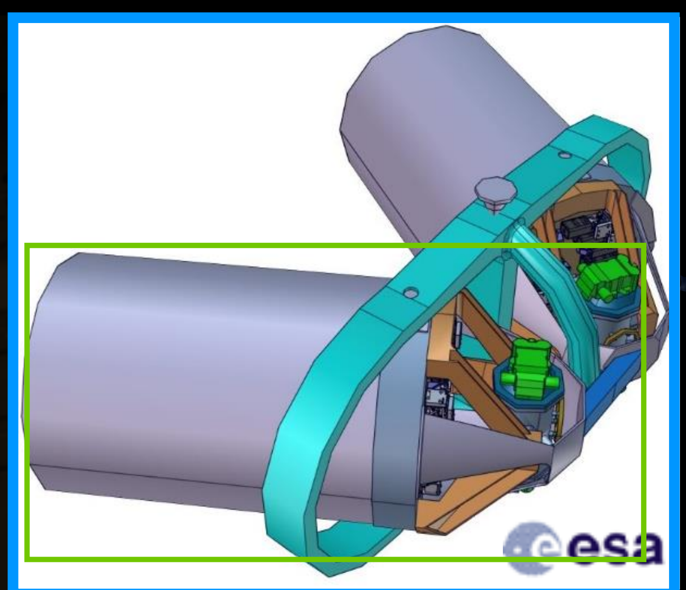


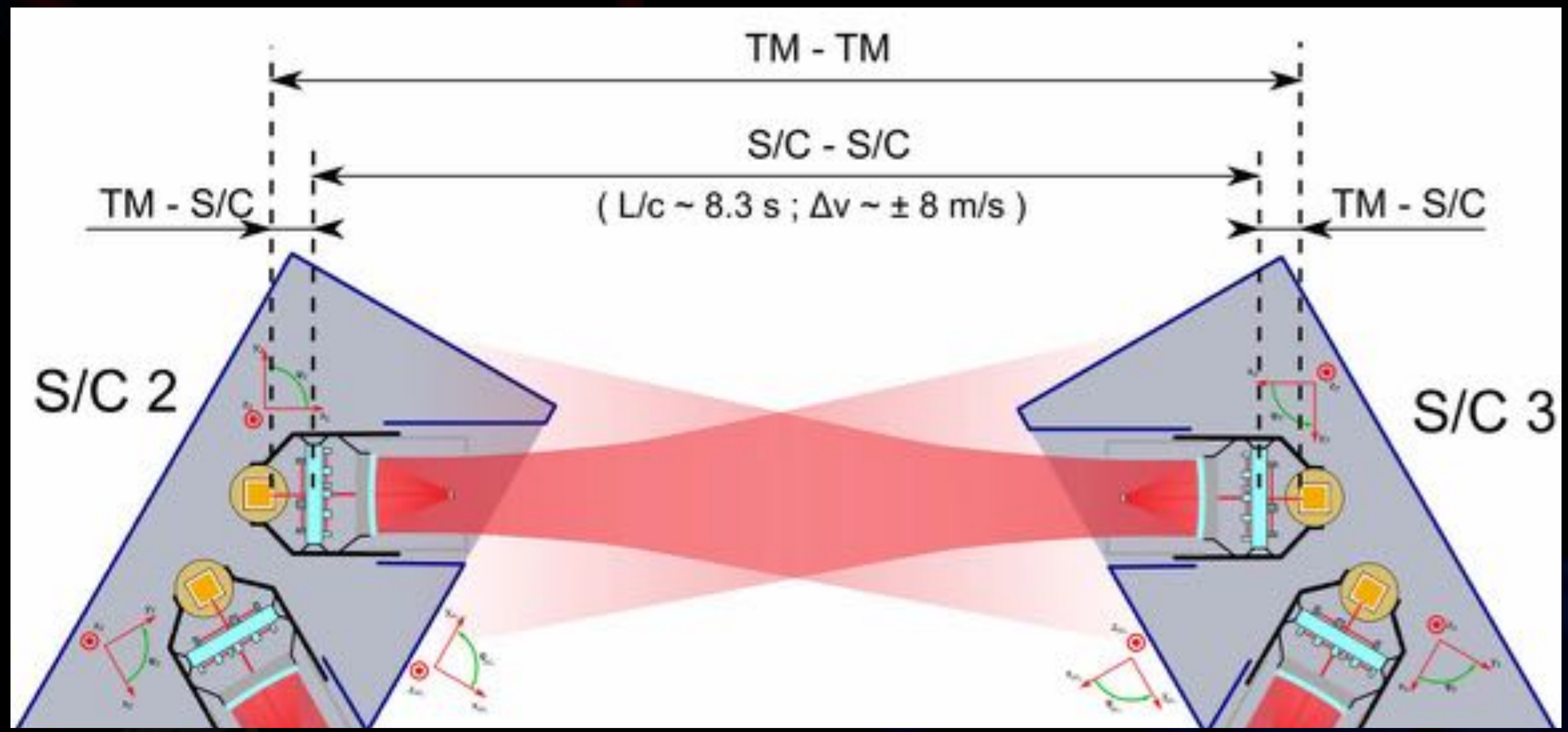


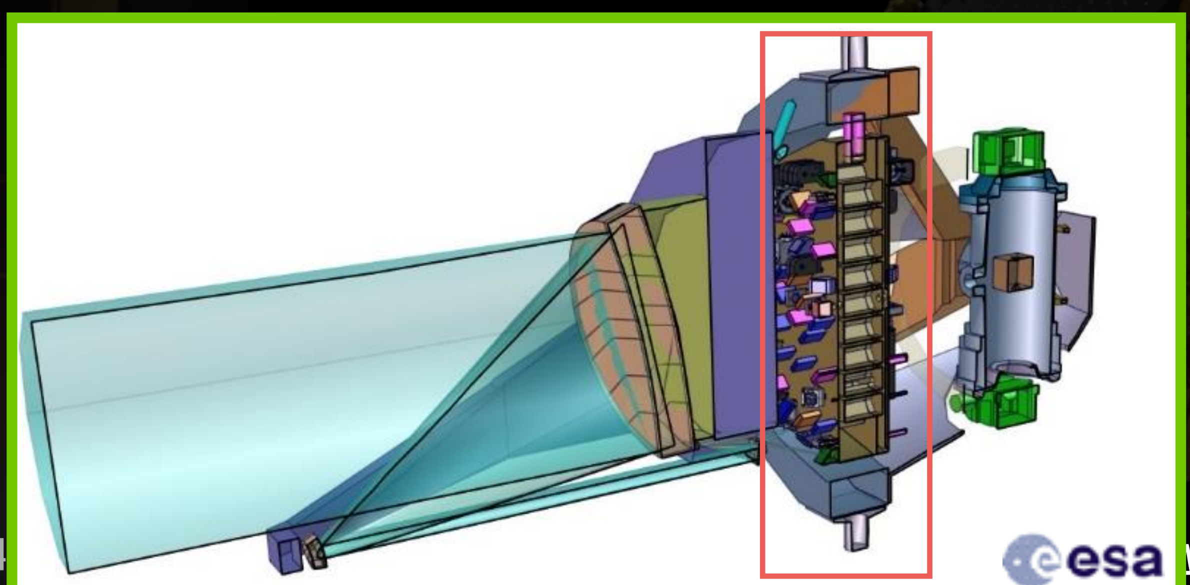
LISA

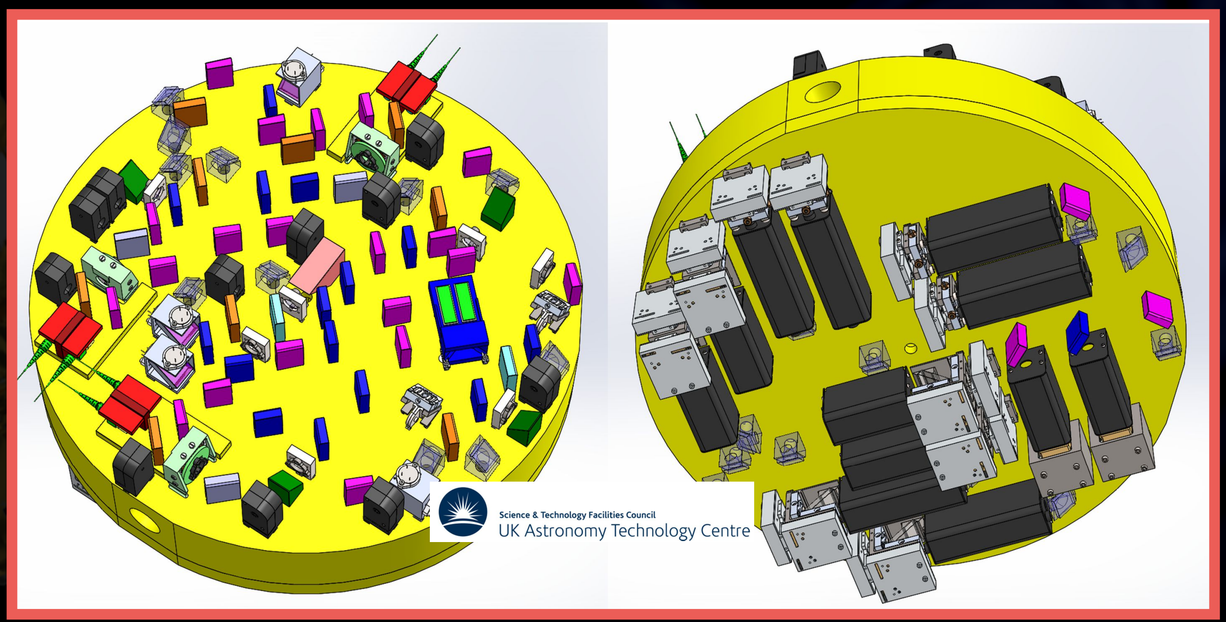
- A measurements in several steps

(TM2→SC2) + (SC2→SC3) + (SC3→TM3)



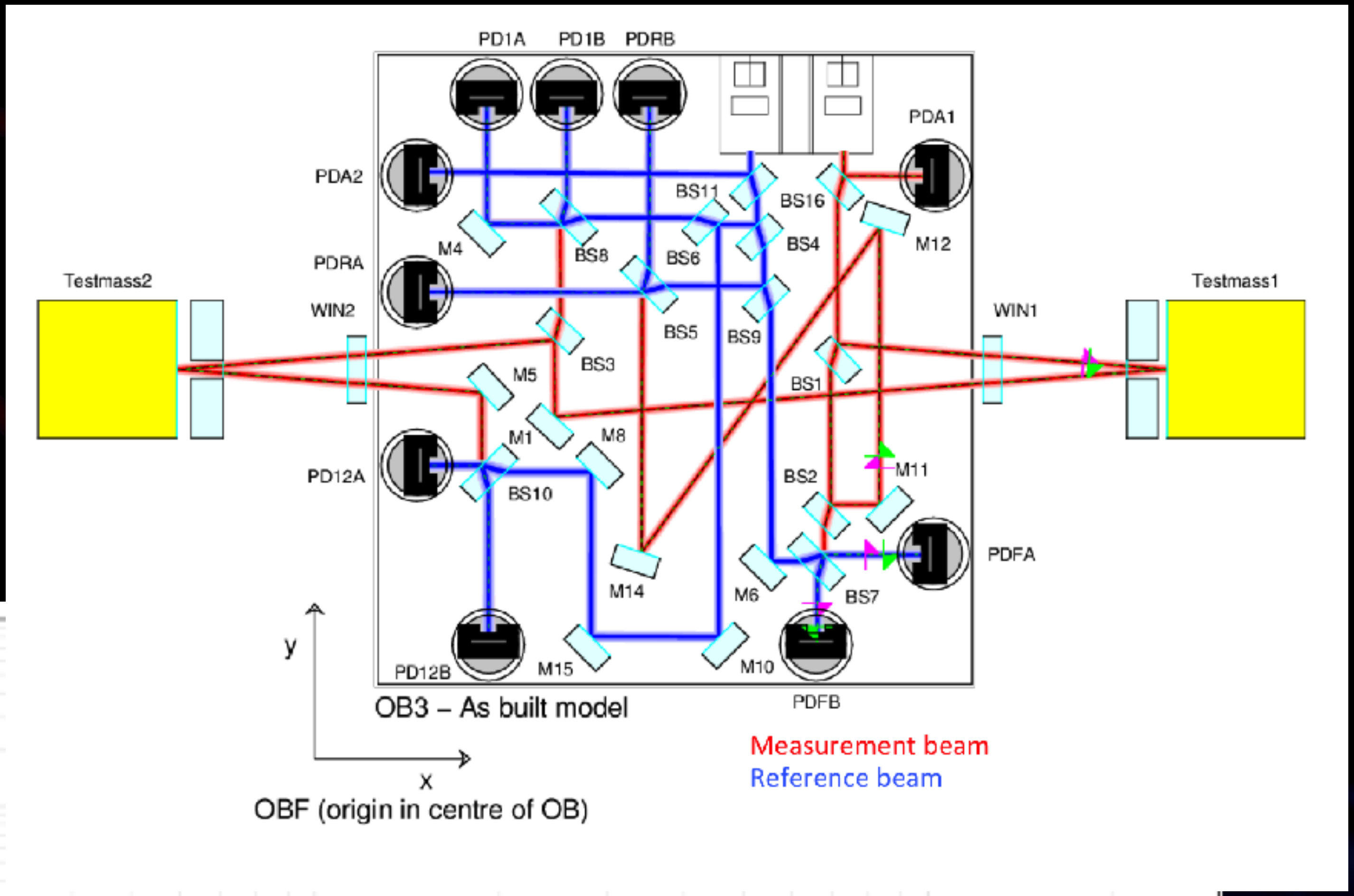


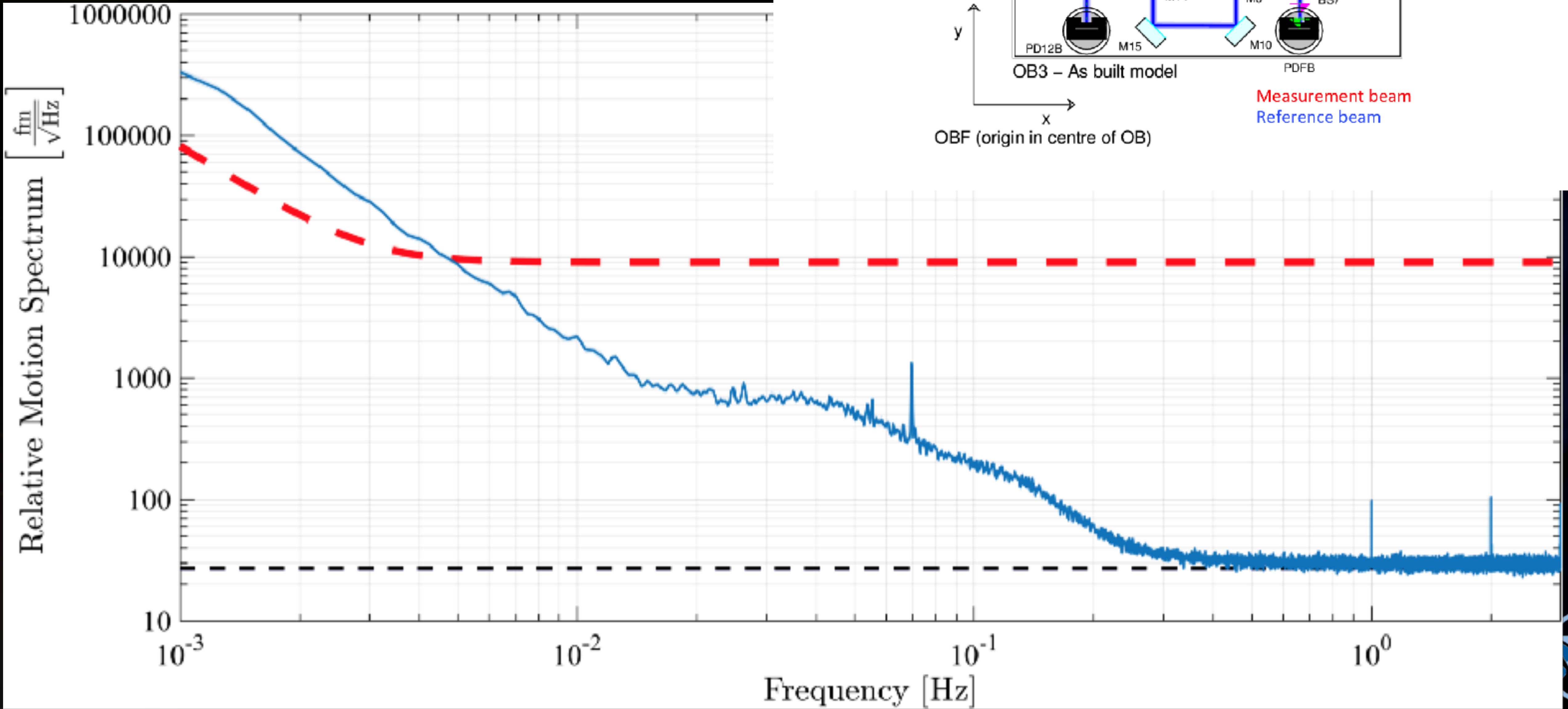




High frequency limit

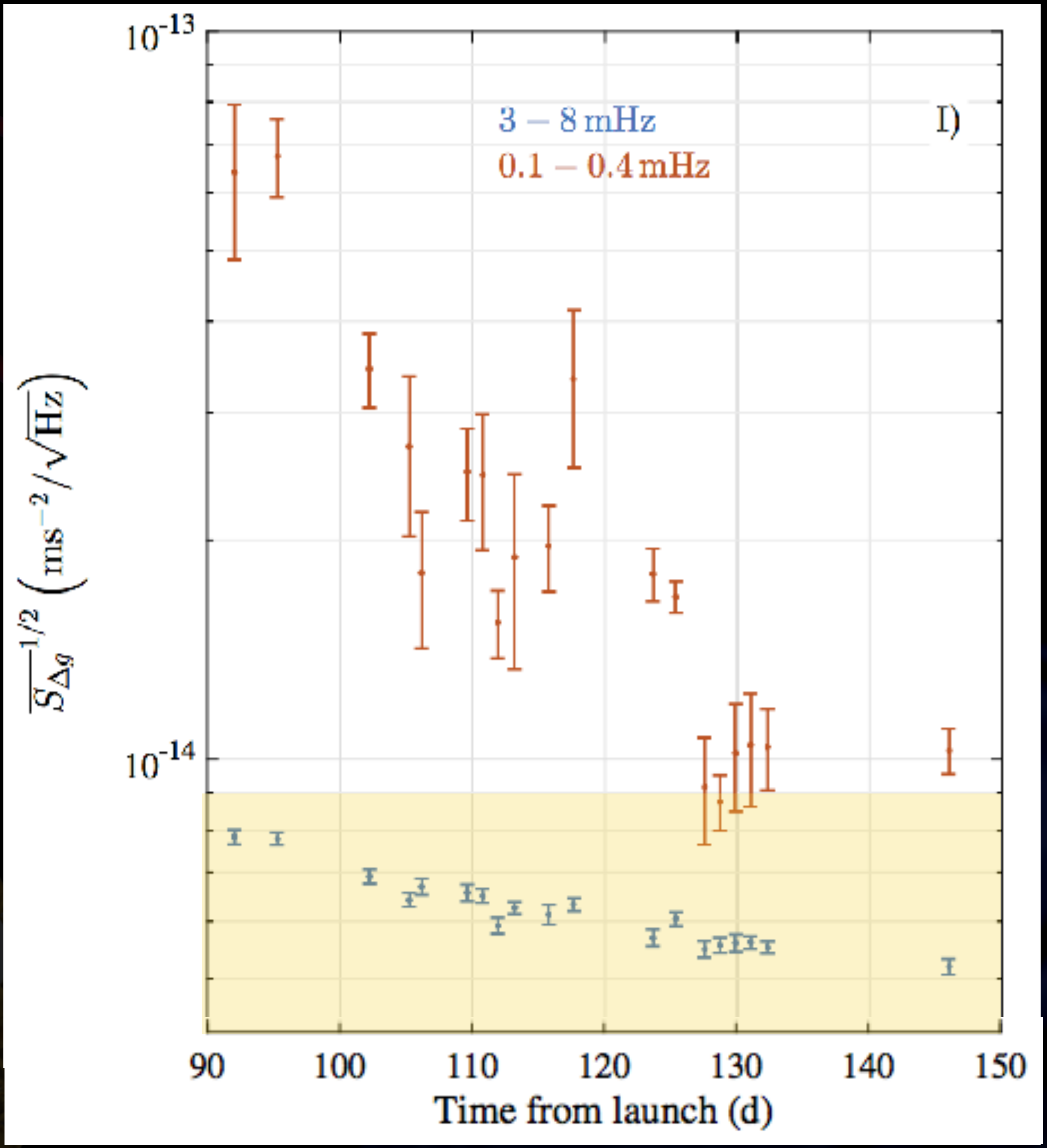
- Optical measurement system:
  - Interferometric precision: 30 fm.Hz$^{-1/2}$
  - Orientation of test-masses





Mid-frequency limit

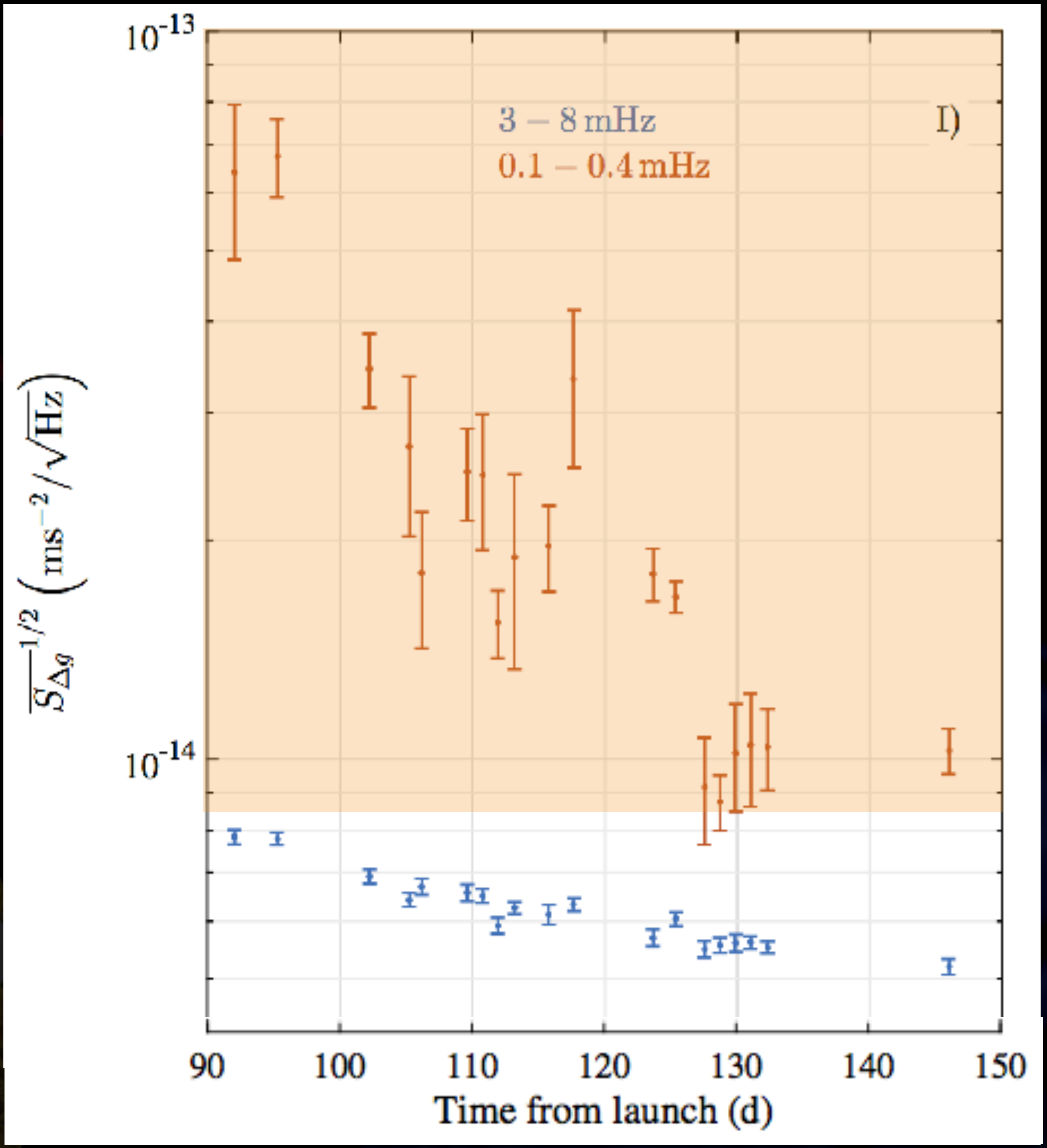
- Noise in 1–10 mHz: brownian noise due to residual pressure:
  - Molecules within the housing hitting the test-masses
  - Possible residual outgassing
- Evolution:
  - Pressure decreases with time => constant improvement



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

Low-frequency limit

- Noise in 0.1 – 1 mHz:
- 50% understood: actuation noises
- Still 50% not completely explained:
  - 1/f slope
  - Temperature ? Small glitches ?



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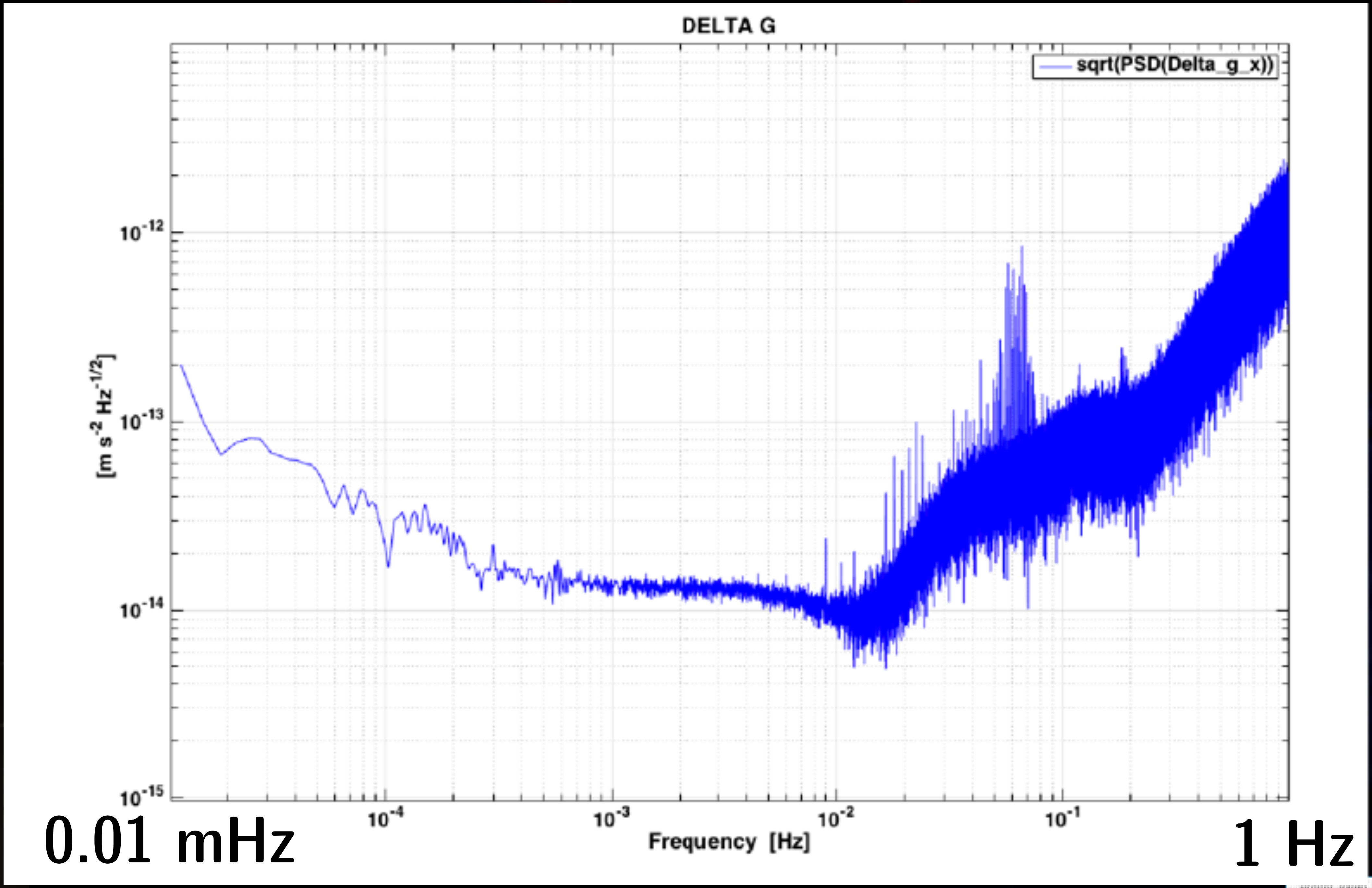
Results

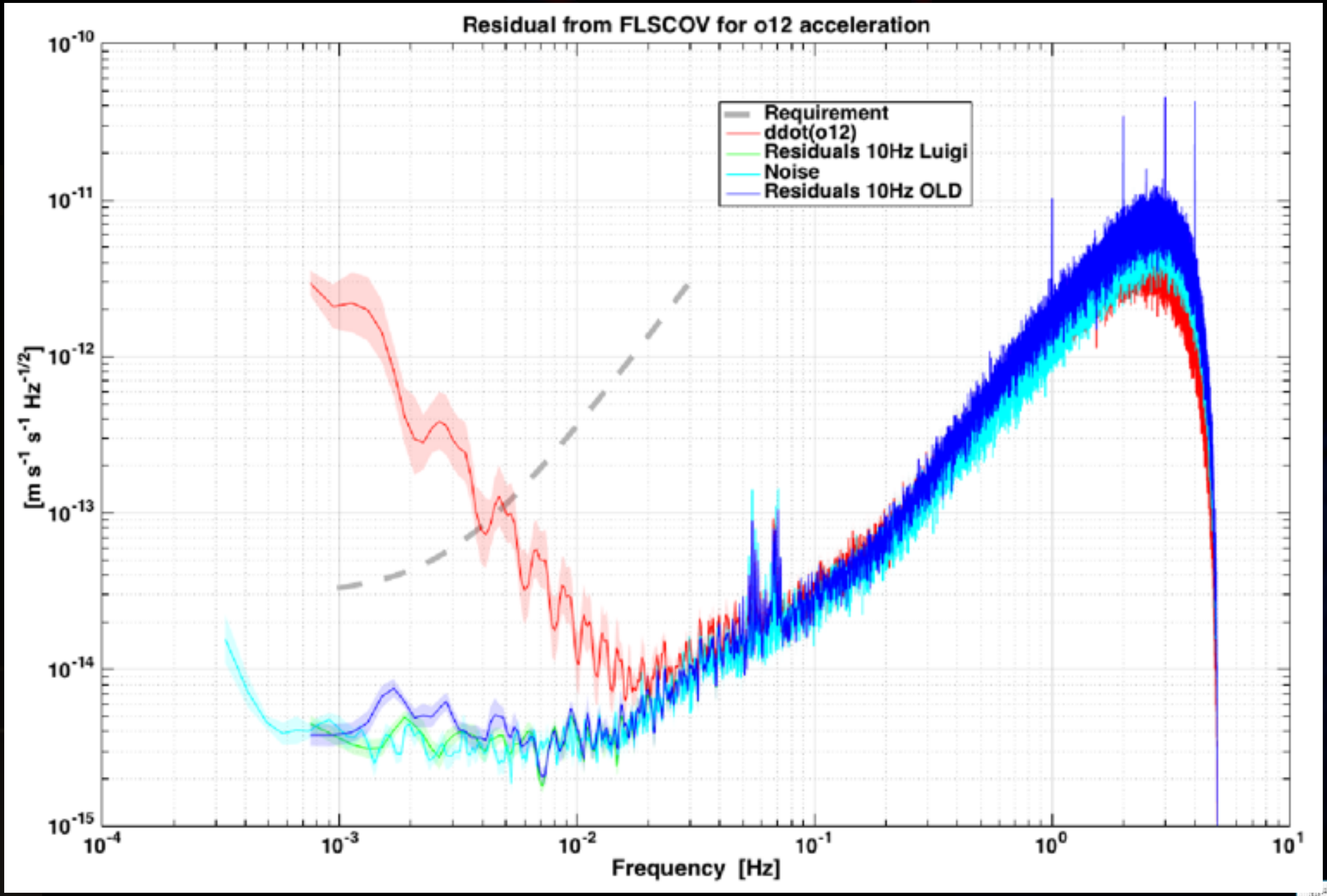
- Differential acceleration Test Mass1 - Test Mass2
- $\Delta g = d^2(o12)/dt^2$ - Stiff * o12 - Gain * Fx2



by Joseph Martino

System-Identification

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



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