Noise Hunting in LISA (Pathfinder)

J. Martino

Outline

LISA in 2 minutes

Free fall and LISA Pathfinder

Conclusion and back to LISA

LISA In 2 minutes

The LISA Mission



- ESA large class mission with NASA contributions
- Launch in 2035
- 4.5 Years mission duration - enough fuel for 10 years
- Gravitational Wave in the 10^-4 - 1Hz
- Instantaneous measurement of both GW polarization

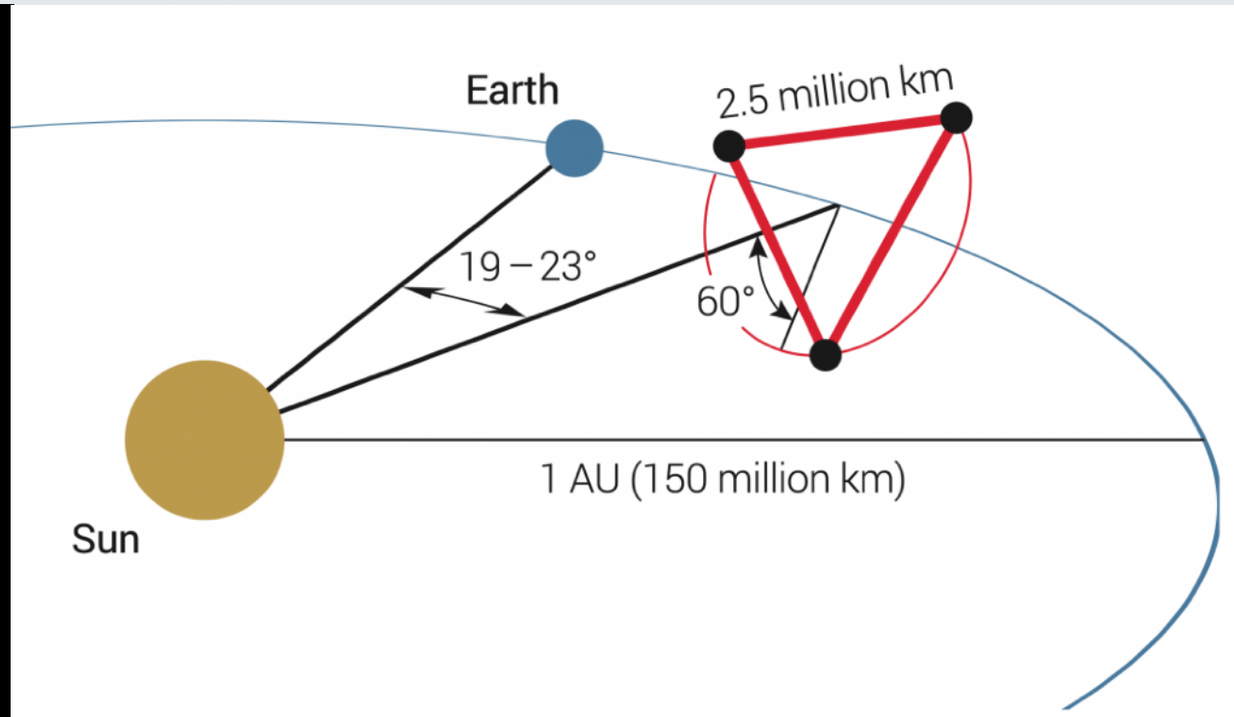
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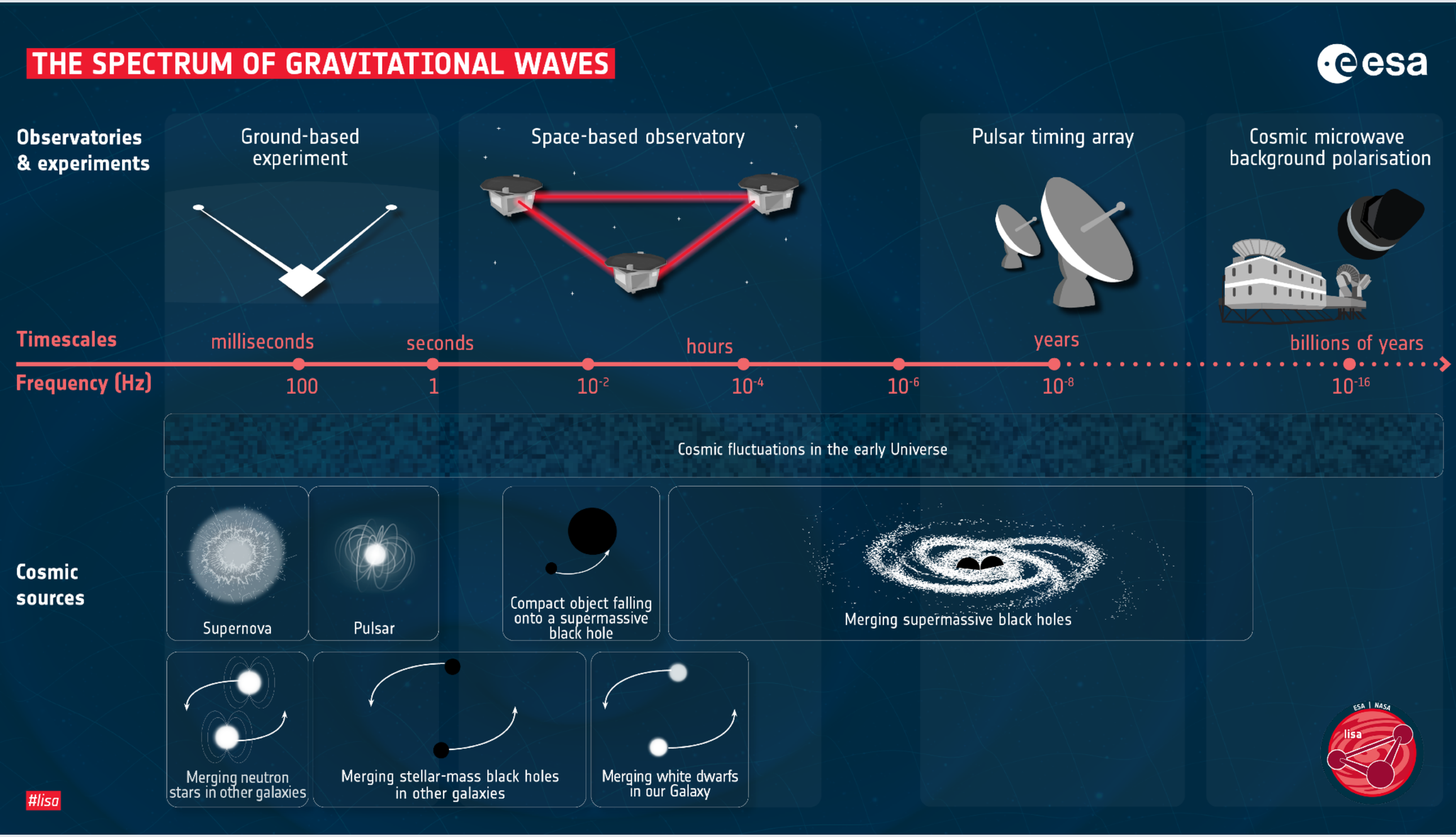
The LISA Mission



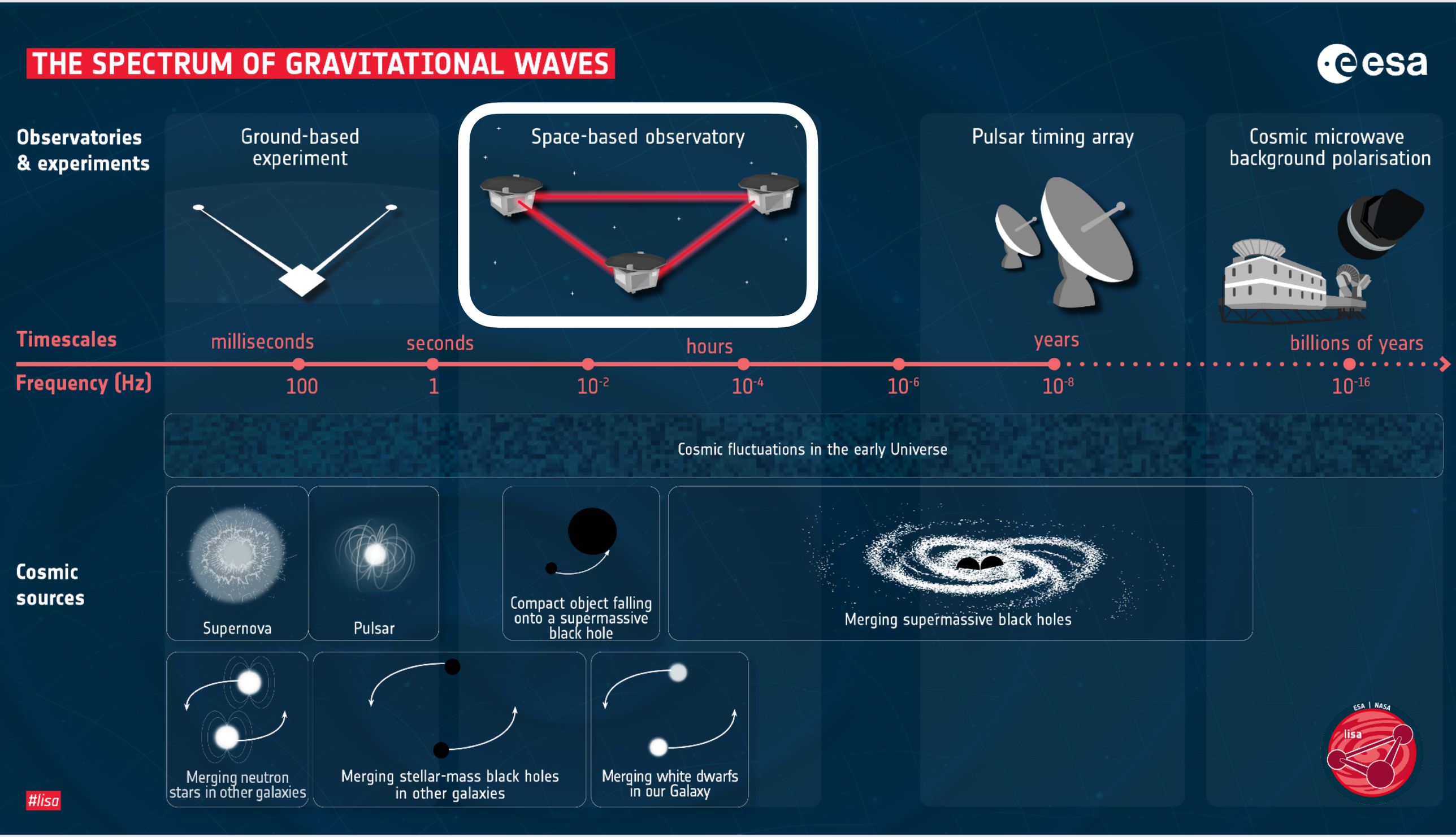


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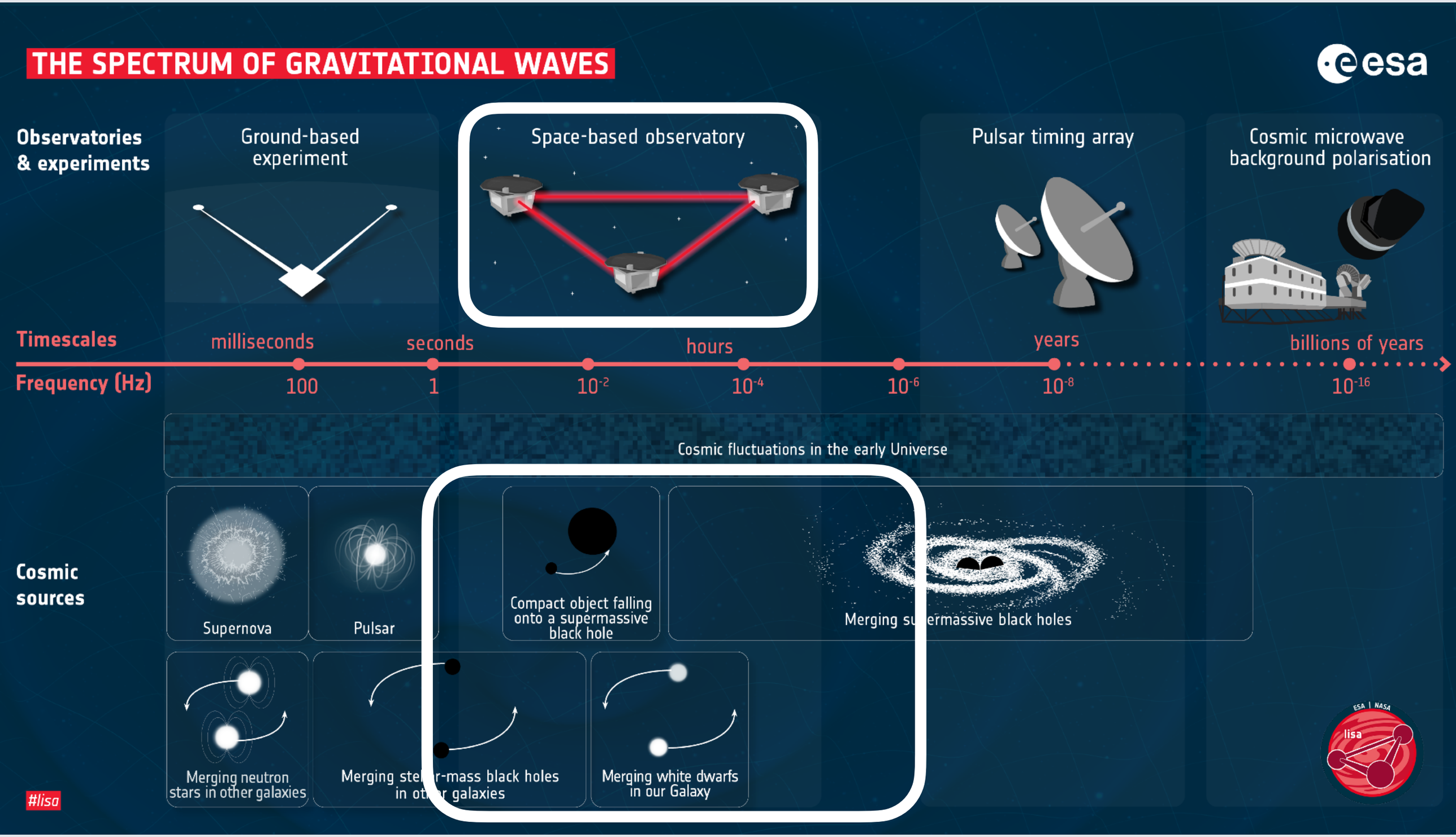
The LISA Mission



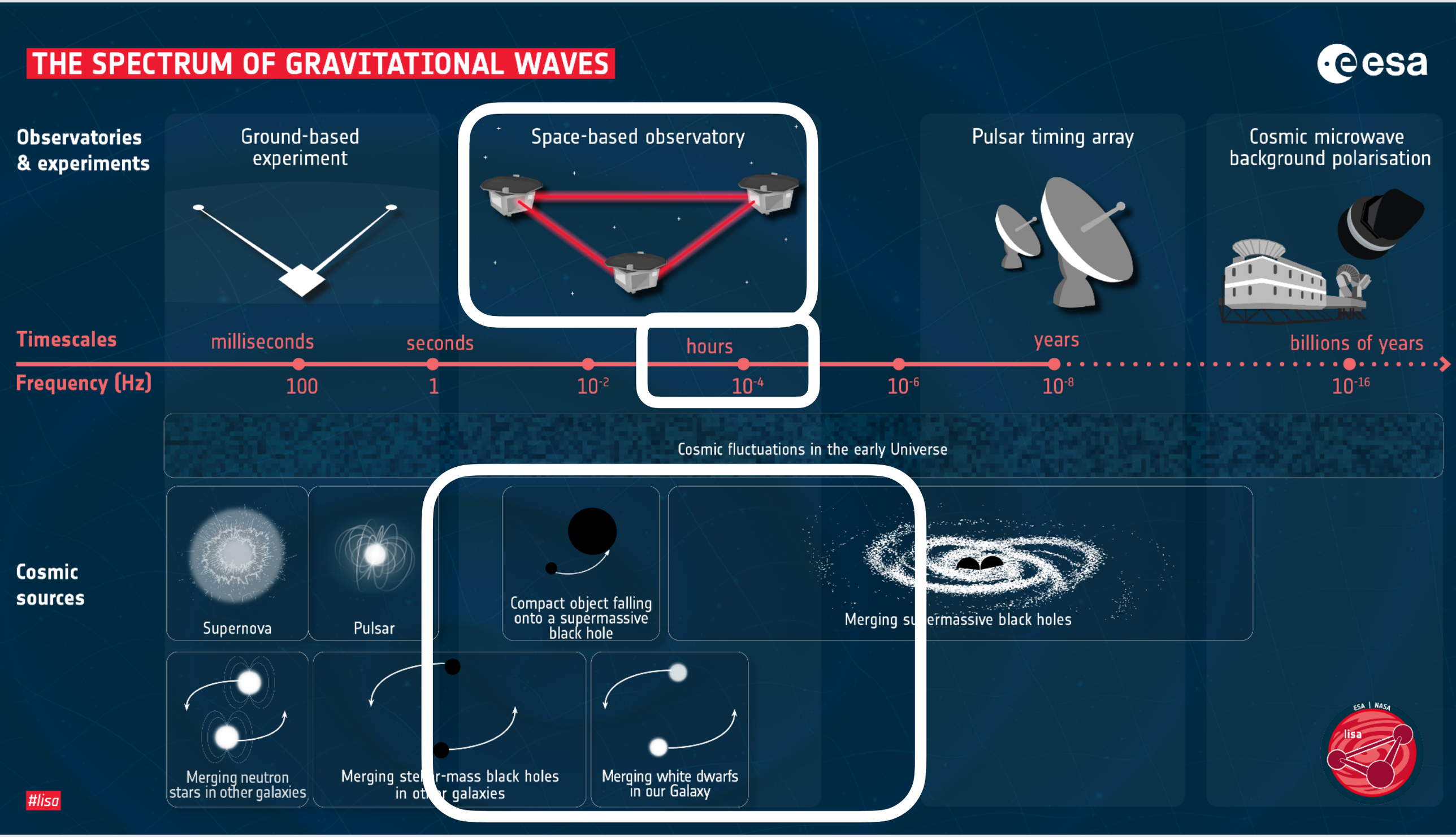
The LISA Mission



The LISA Mission



The LISA Mission



Project Schedule

Phase 0	Mission analysis and identification
Phase A	Feasibility
Phase B	Preliminary Definition
Phase C	Detailed Definition
Phase D	Qualification and Production
Phase E	Utilisation
Phase F	Disposal

Project Schedule

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2017 **Selection - L3**

2018 **2 competitive Primes Industry**

2021

Project Schedule

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2017 **Selection - L3**

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2021

2024 adoption

- Construction and operation are funded.
- Contributors identified
- Signature of MLA
- Requirements documents for each subsystem
- Preliminary Design
- Critical System at TRL 5/6

Project Schedule

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2017 Selection - L3

2018 2 competitive Primes Industry

2021

2024 adoption

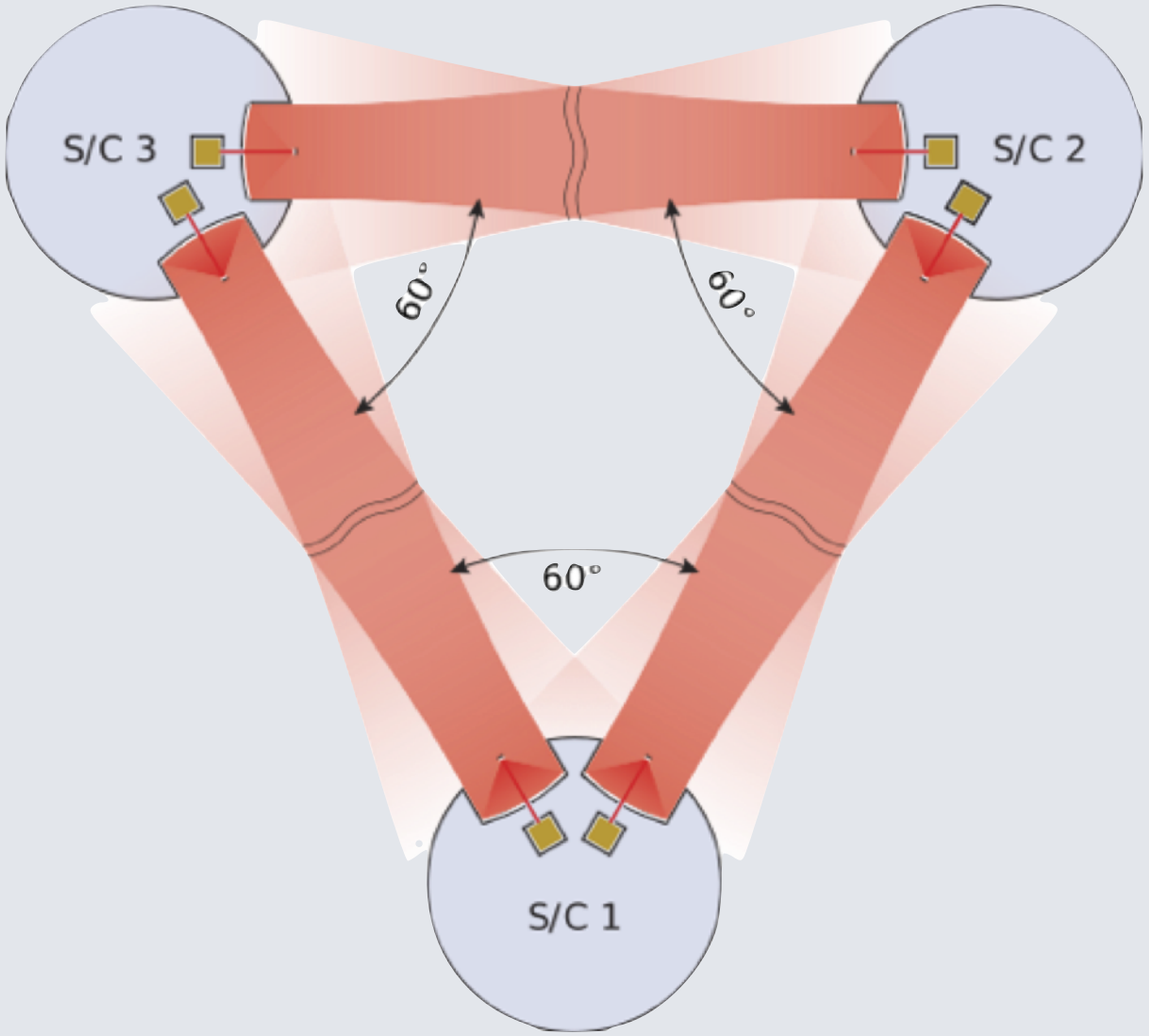
- Construction and operation are funded.
- Contributors identified
- Signature of MLA
- Requirements documents for each subsystem
- Preliminary Design
- Critical System at TRL 5/6

~ 2035 launch

~ 2037 Science Operations

~ 2045 end of the mission

The Measurement & Numbers



Gravitational Sensors

6 Test Masses - End mirrors

2kg and 4cm gold/platinum

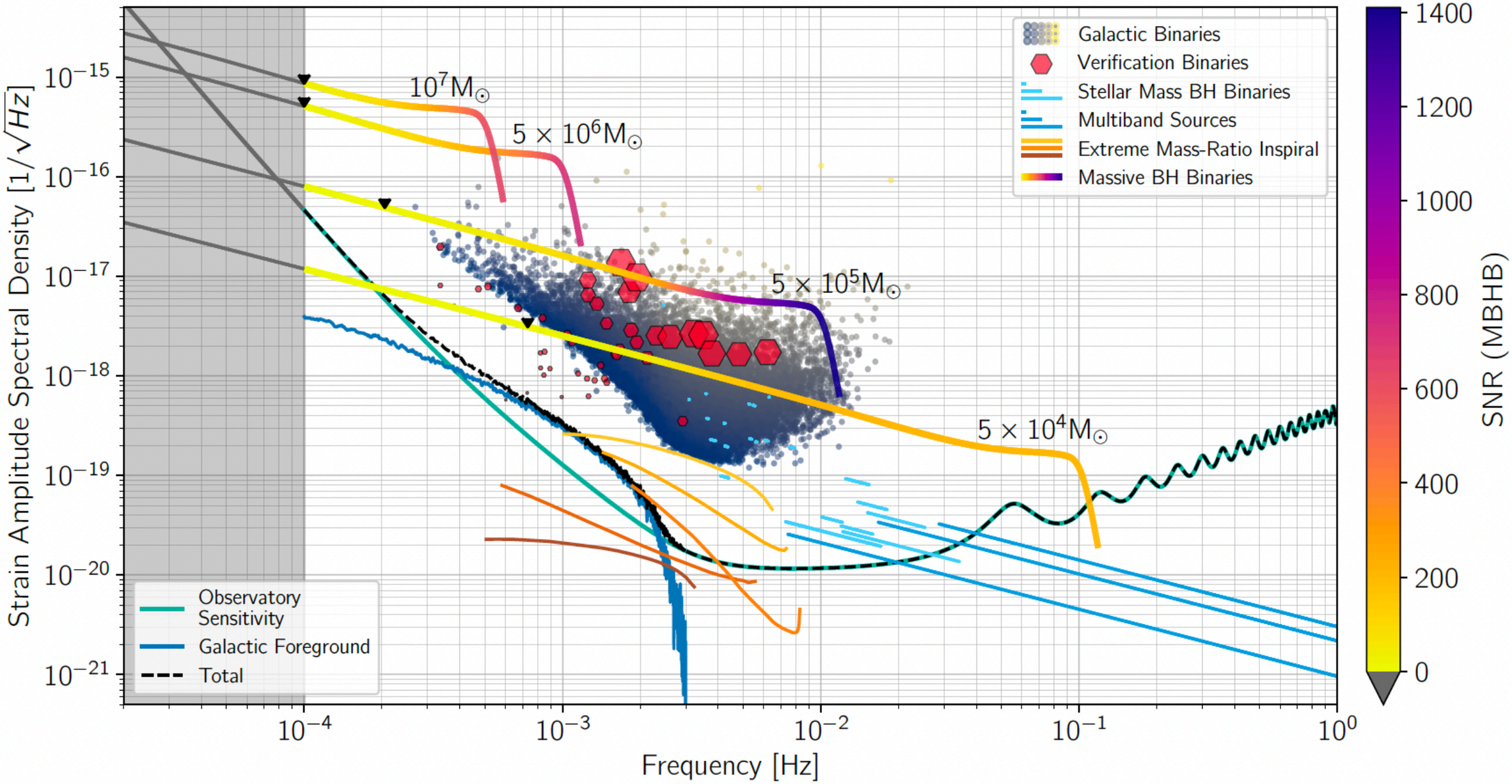


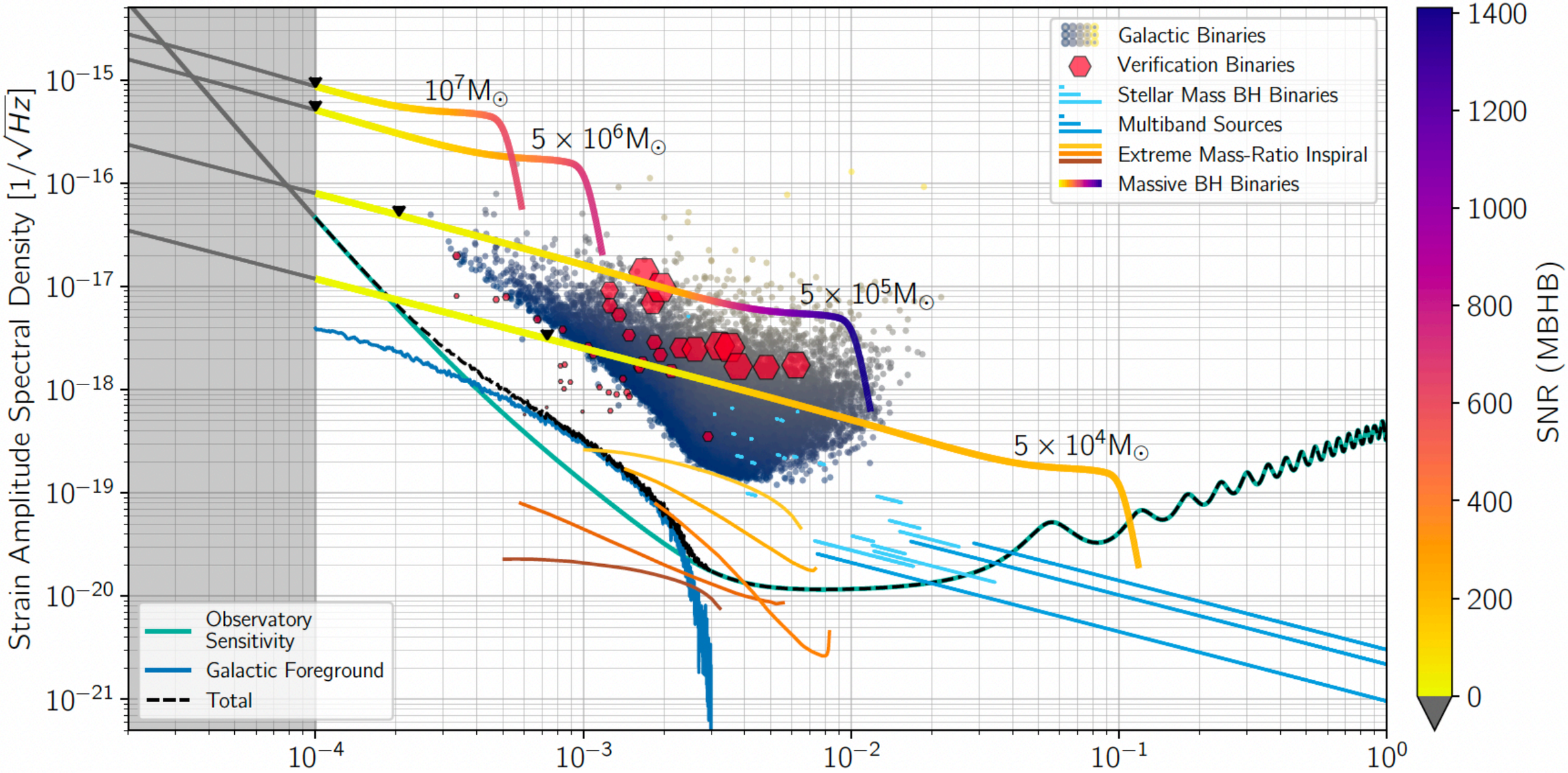
Metrology System

6 lasers of 2 watts

6 long distance Interferometric links

12 local interferometric measurements


Galactic Binaries
Verification Binaries
Stellar Mass BH Binaries
Multiband Sources
Extreme Mass-Ratio Inspiral
Massive BH Binaries
$10^7 M_\odot$
$5 \times 10^6 M_\odot$
$5 \times 10^5 M_\odot$
$5 \times 10^4 M_\odot$
Observatory Sensitivity
Galactic Foreground
Total
Strain Amplitude Spectral Density $[1/\sqrt{Hz}]$
Frequency [Hz]
SNR (MBHB)
1400
1200
1000
800
600
400
200
0



Low frequency (20μHz - 3mHz)

High frequency (3mHz - 1Hz)

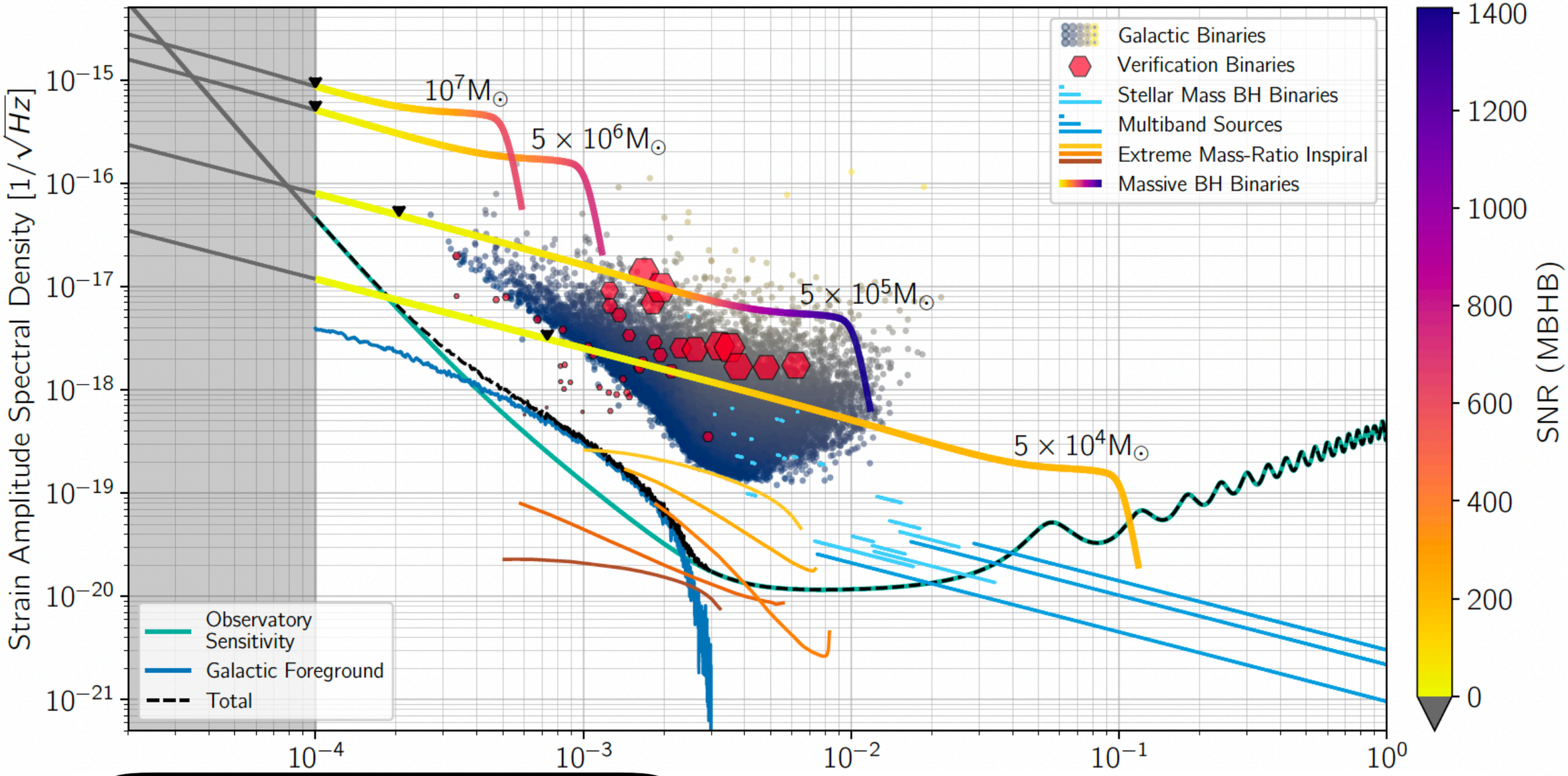
Quality of Free fall
ie: spurious forces on Test masses

Optical Metrology Noises

Post-Processing Noises
- Laser Frequency
- Spacecraft Jitter

3 fm/s^2/sqrt(Hz)

Metrology Noises 15pm/sqrt(Hz)



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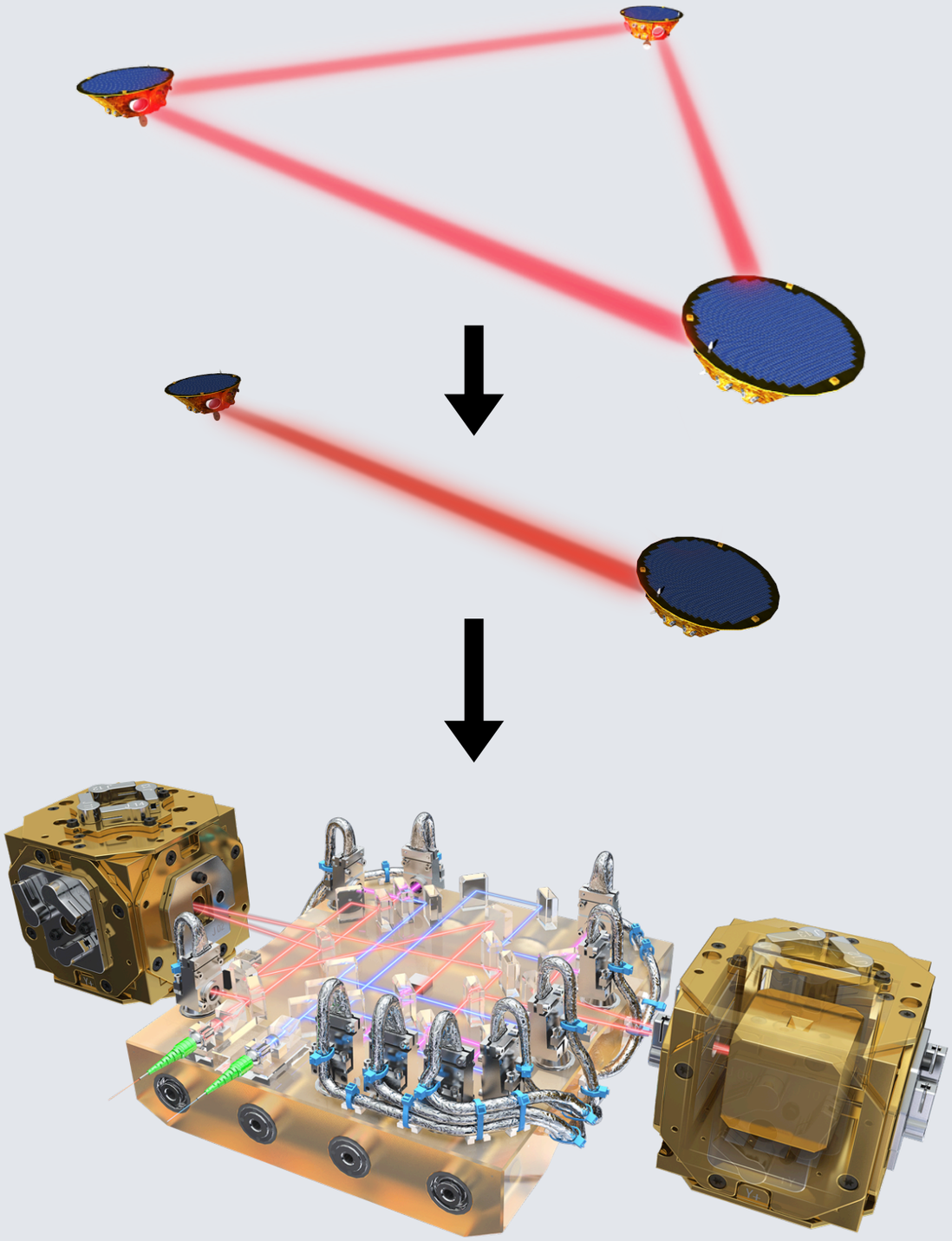
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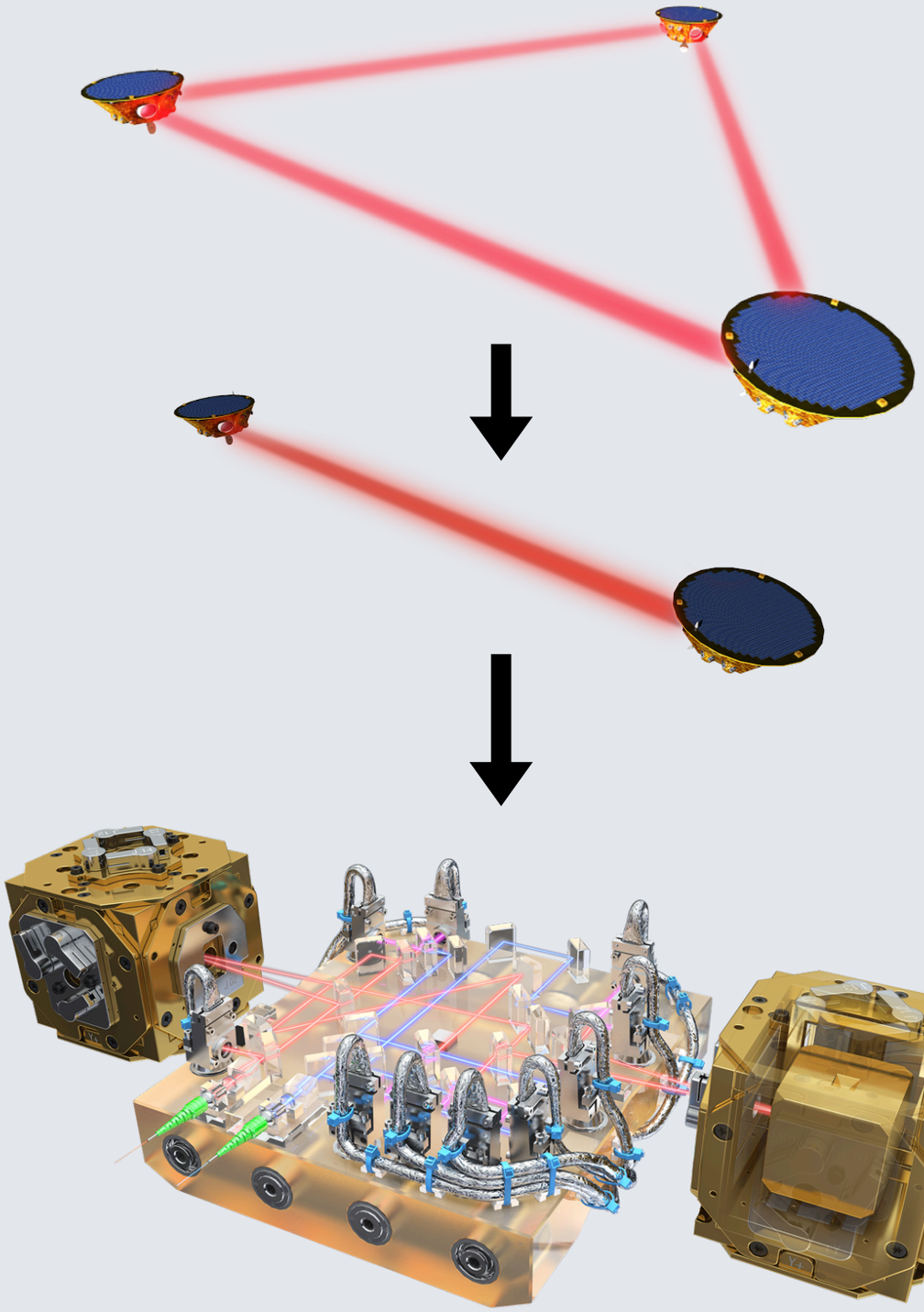


LISA Pathfinder : a noise hunting experiment

LISA Pathfinder



LISA Pathfinder



Optical Metrology System
- 37 cm
- kHz Heterodyne Interferometry
- No Telescope
- **Local** and equal arm Interferometer
- **Ultra Stable Glass Optical Bench**
- **Picometer stability below 1Hz**

GRS
-**Identical to LISA**

Spacecraft
- **Gravitational balancing**
- **Drag Free control with cold gas thrusters**

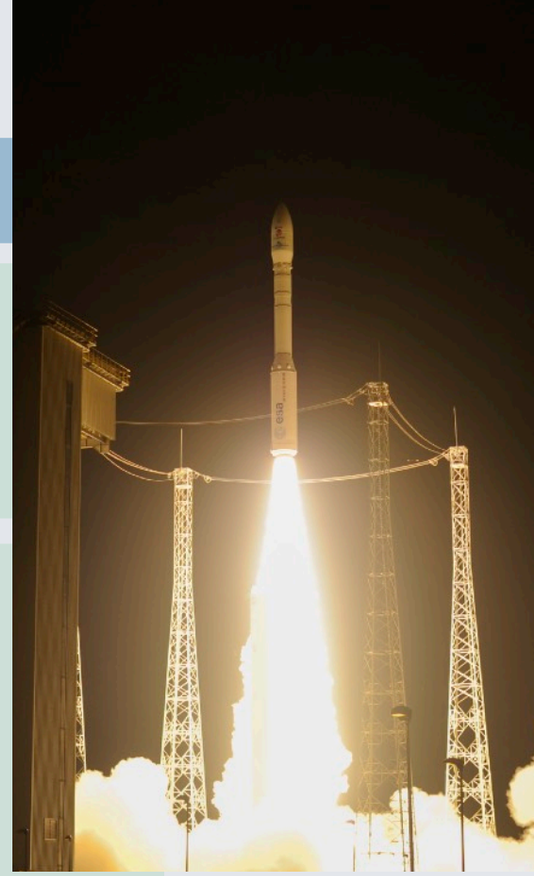
3rd Dec 2015

Launch

Commissioning

1st March 2016

Scientific Operation



1st July 2016

DRS operation

7th Dec 2016

Mission Extension

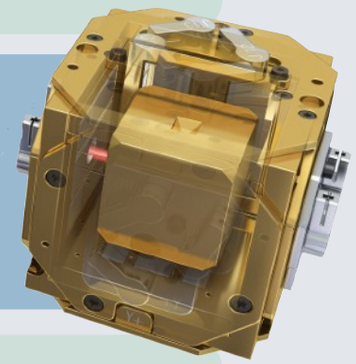
July 2017

Switch Off

3rd Dec 2015 — **Launch**

Commissioning

15/16 Feb 2016 — Test masses release



1st March 2016 — **Scientific Operation**

1st July 2016 — **DRS operation**

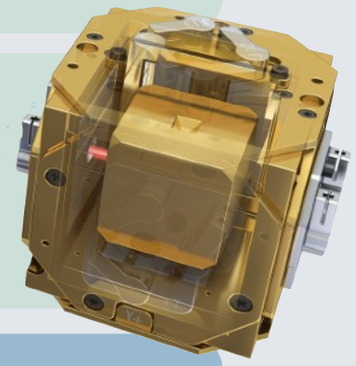
7th Dec 2016 — **Mission Extension**

July 2017 — **Switch Off**

3rd Dec 2015 — **Launch**

Commissioning

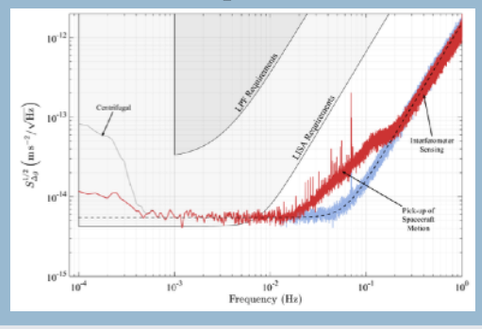
15/16 Feb 2016 — Test masses release



1st March 2016 — **Scientific Operation**

7th June 2016 — First Results





1st July 2016 — **DRS operation**

7th Dec 2016 — **Mission Extension**

July 2017 — **Switch Off**

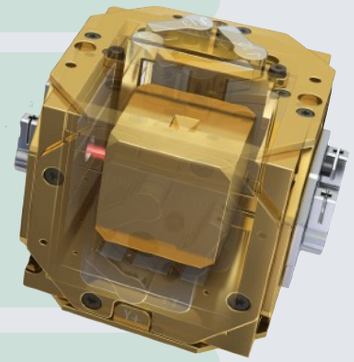
3rd Dec 2015

Launch

15/16 Feb 2016

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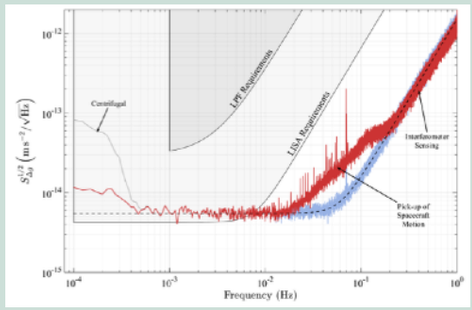
1st March 2016

Scientific Operation

7th June 2016

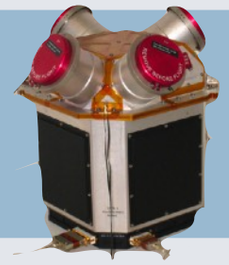
First Results





1st July 2016

DRS operation



Colloidal thrusters + Disturbance reduction system

7th Dec 2016

Mission Extension

July 2017

Switch Off

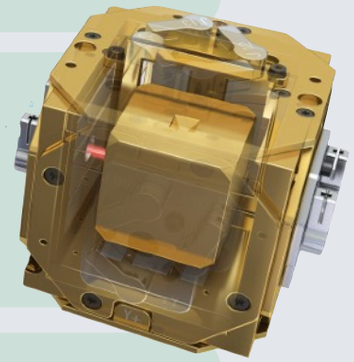
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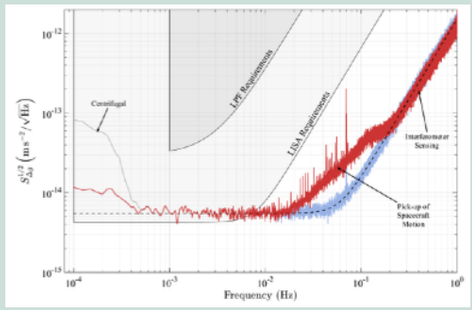
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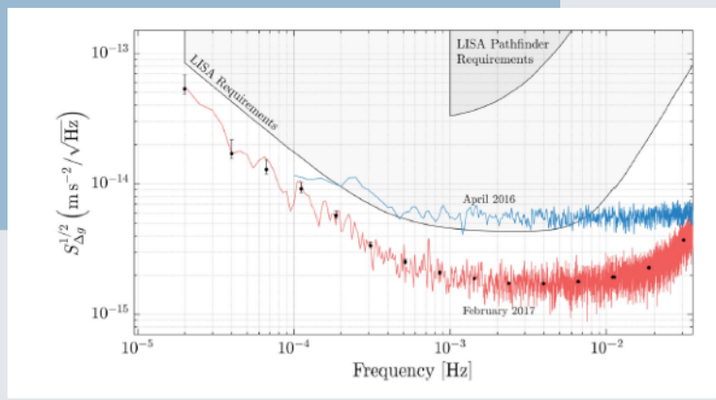
30th June 2017

End of Operation

July 2017

Switch Off

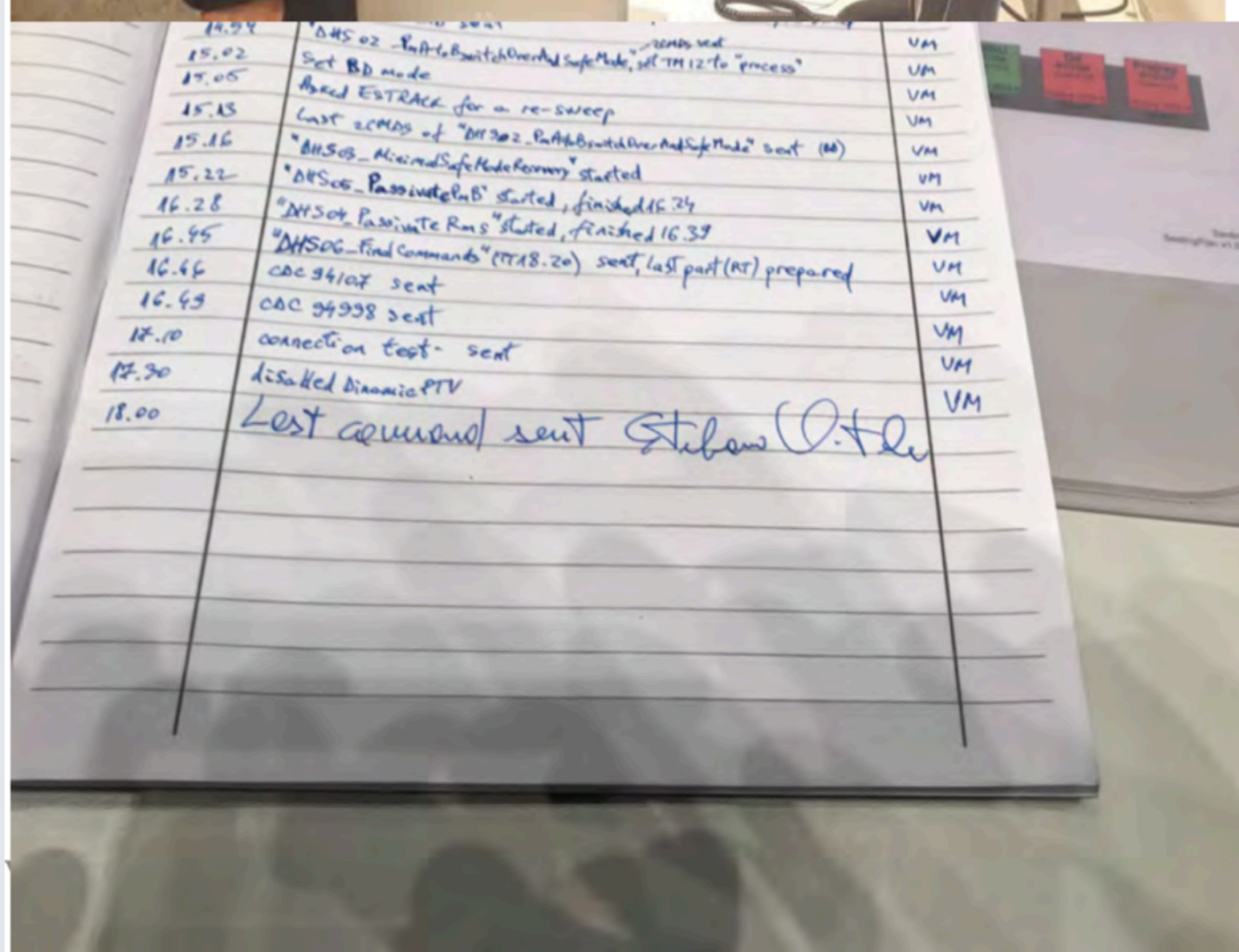
Final Results



Validation of LISA's low frequency performance (20μHz - 3mHz)

Last Command
18th July 2017

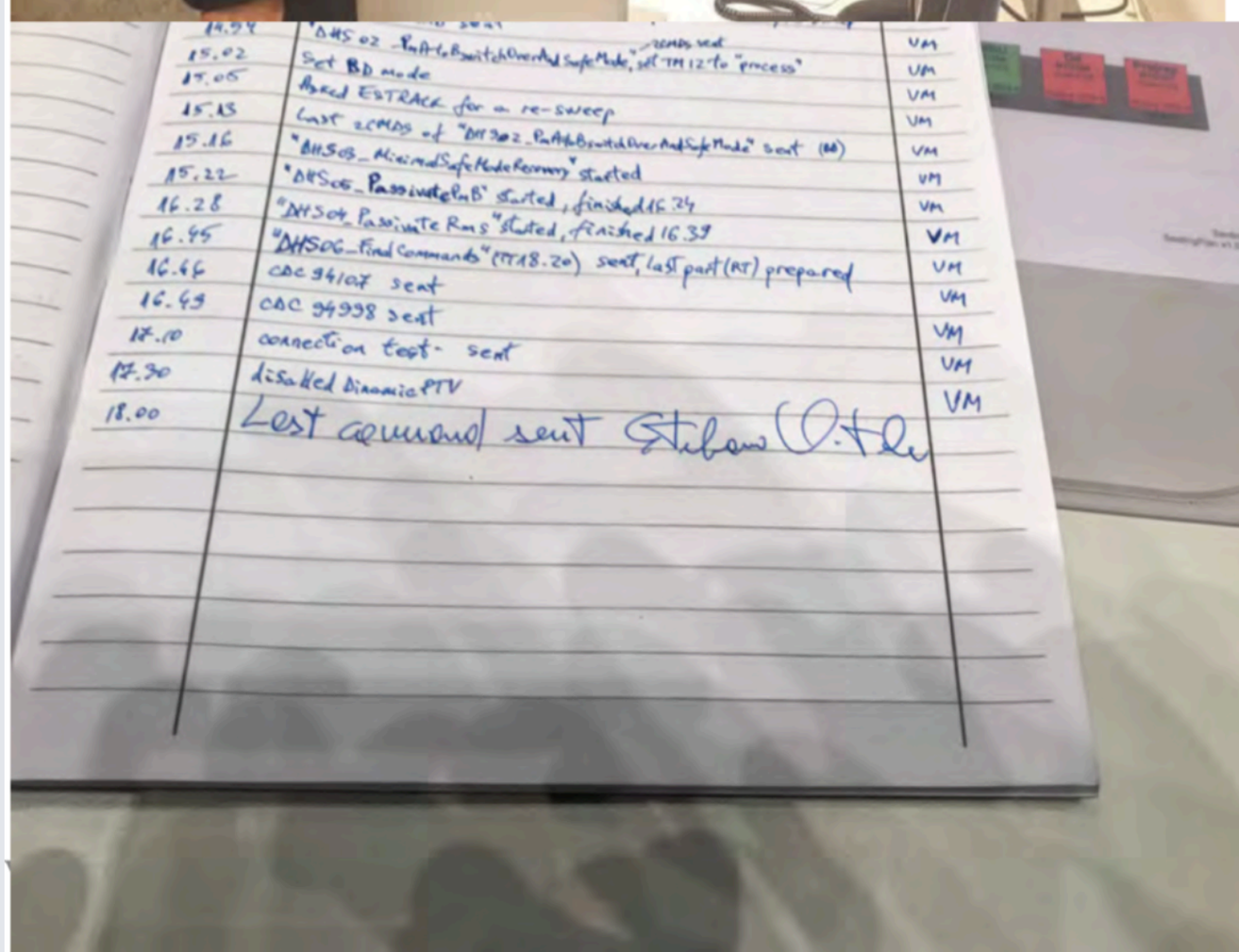




Validation of LISA's low frequency performance (20μHz - 3mHz)

Last Command
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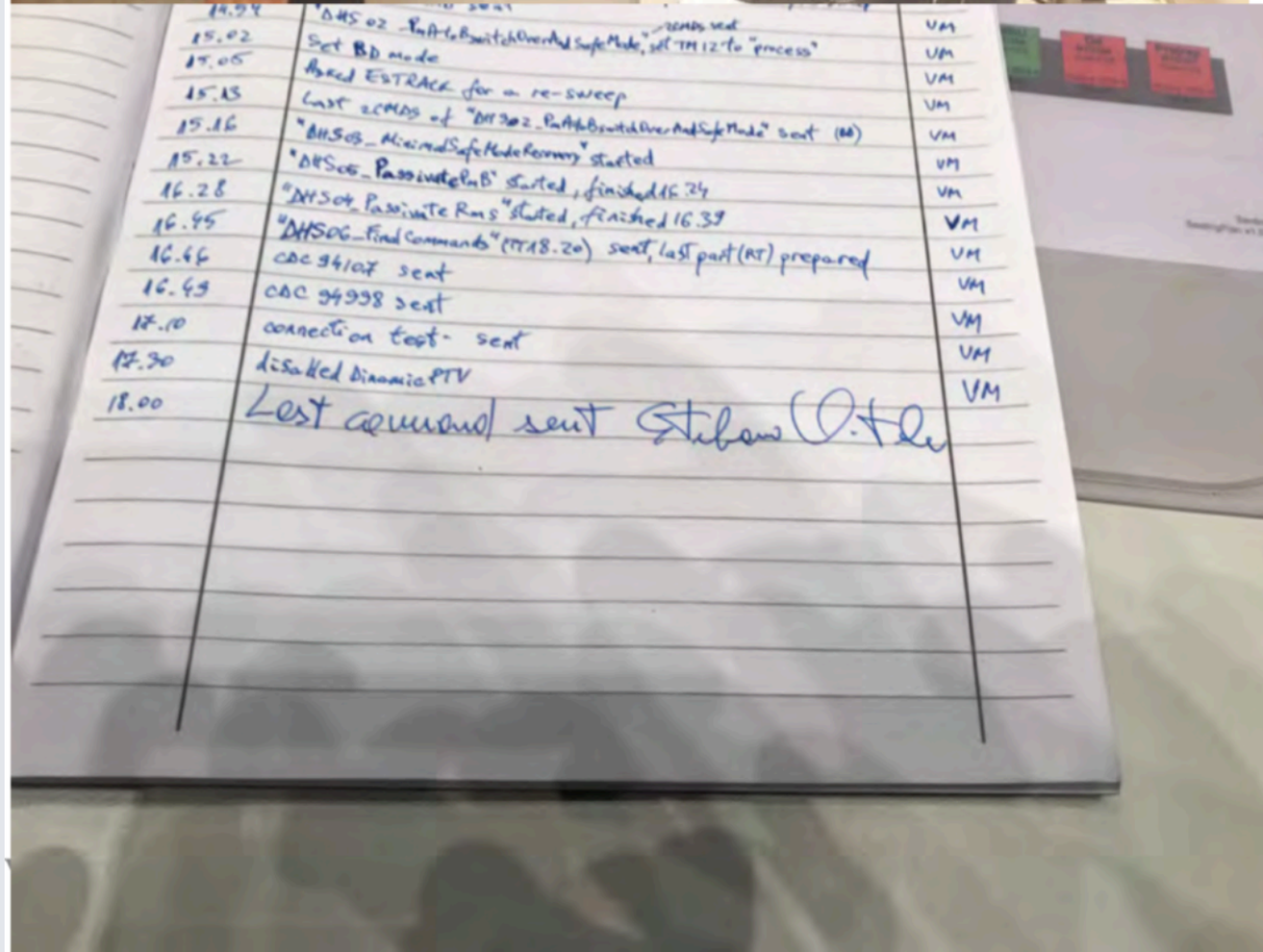


Validation of LISA's low frequency performance (20μHz - 3mHz)

Last Command
18th July 2017

593 days in space





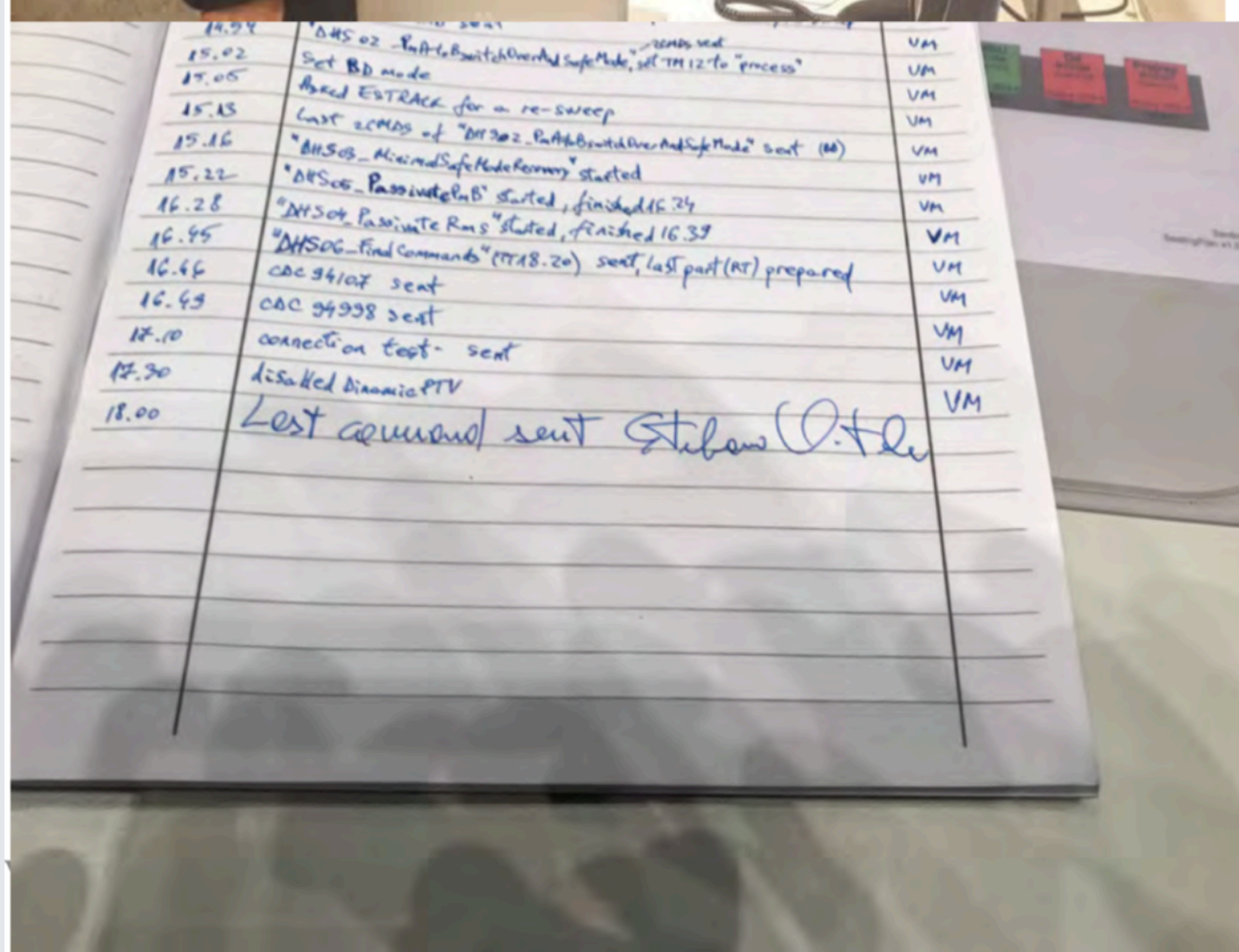
Validation of LISA's low frequency performance (20μHz - 3mHz)

Last Command
18th July 2017

593 days in space

321 days of science operation





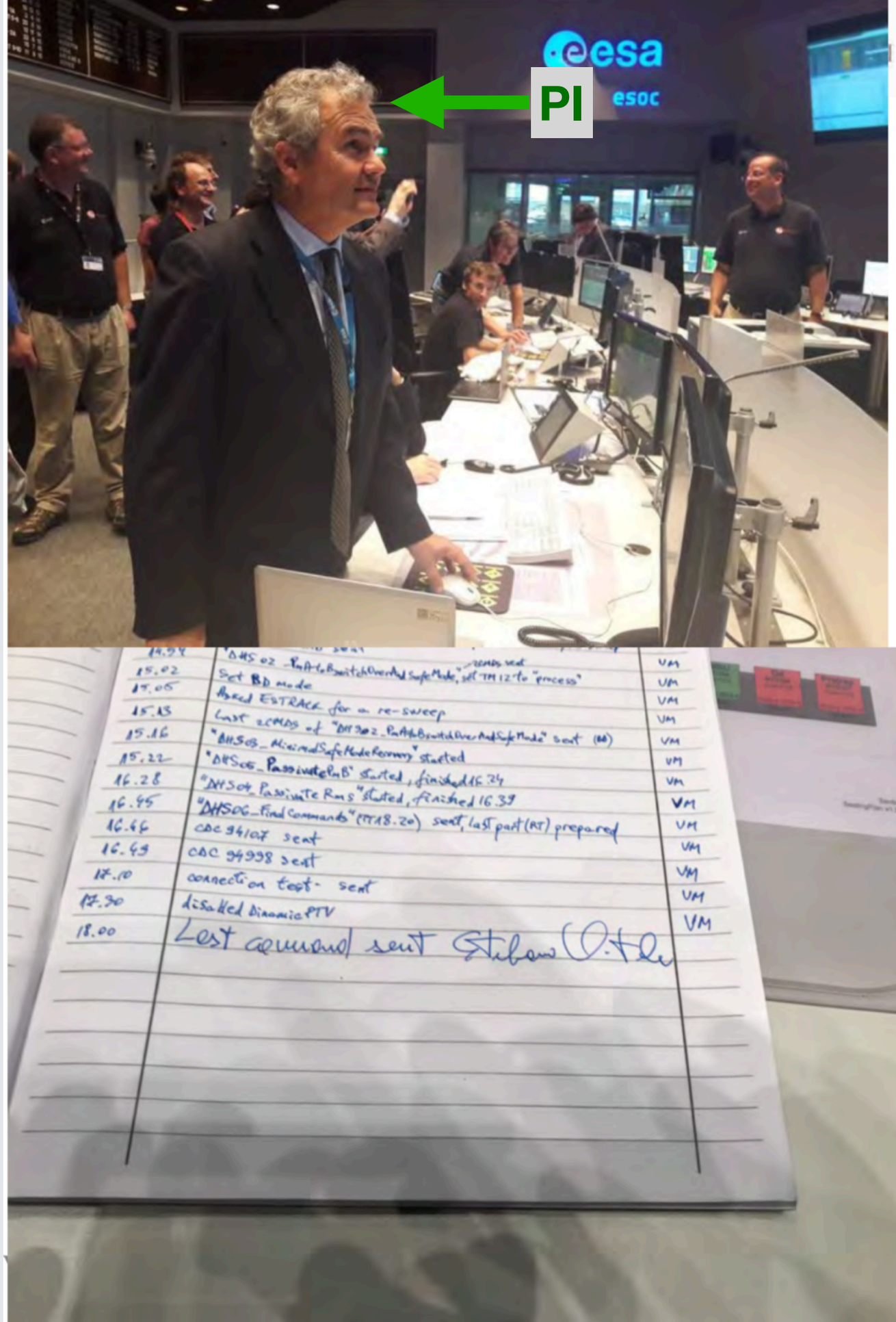
Validation of LISA's low frequency performance (20μHz - 3mHz)

Last Command
18th July 2017

593 days in space

321 days of science operation

Cost estimated at
400Meuros



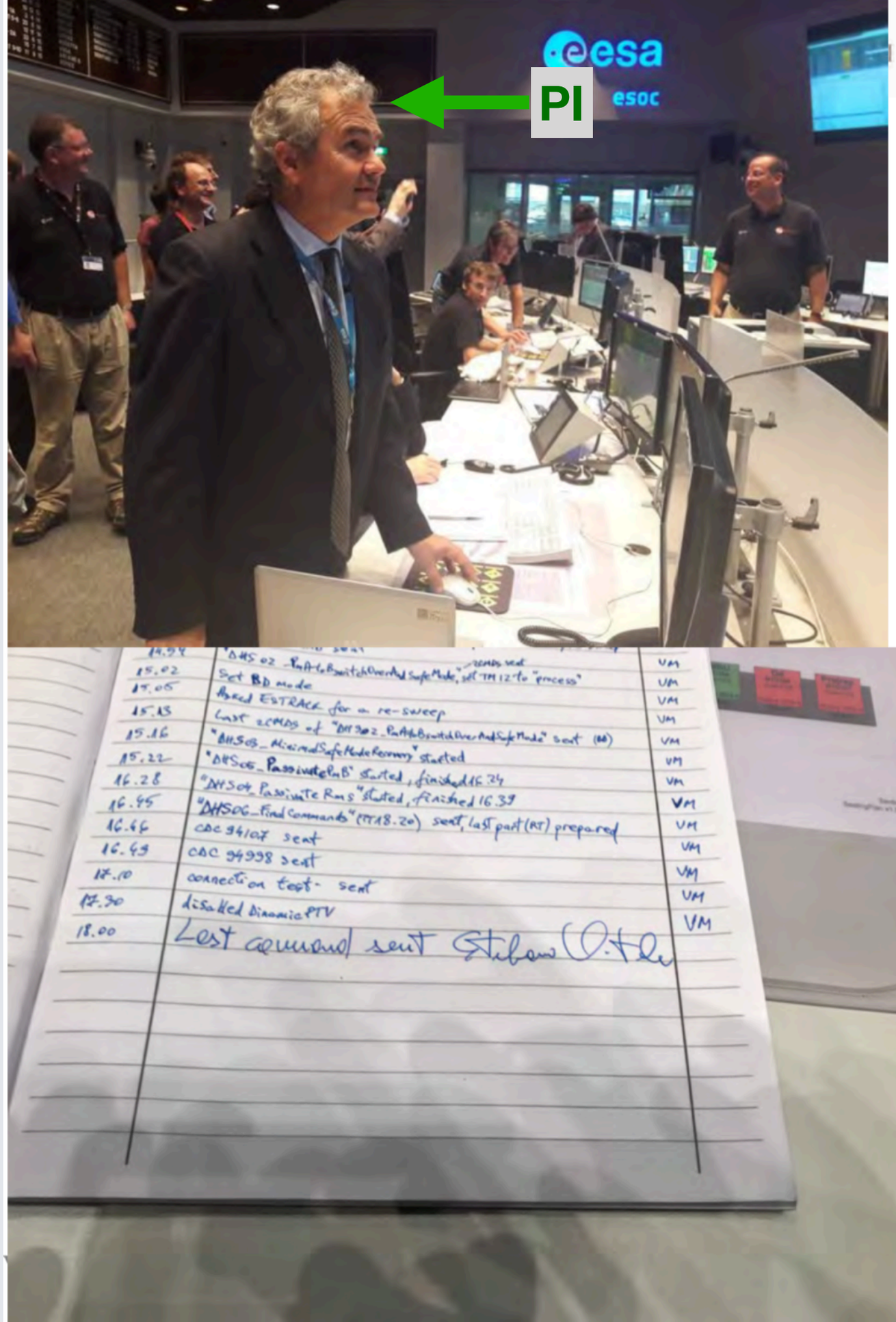
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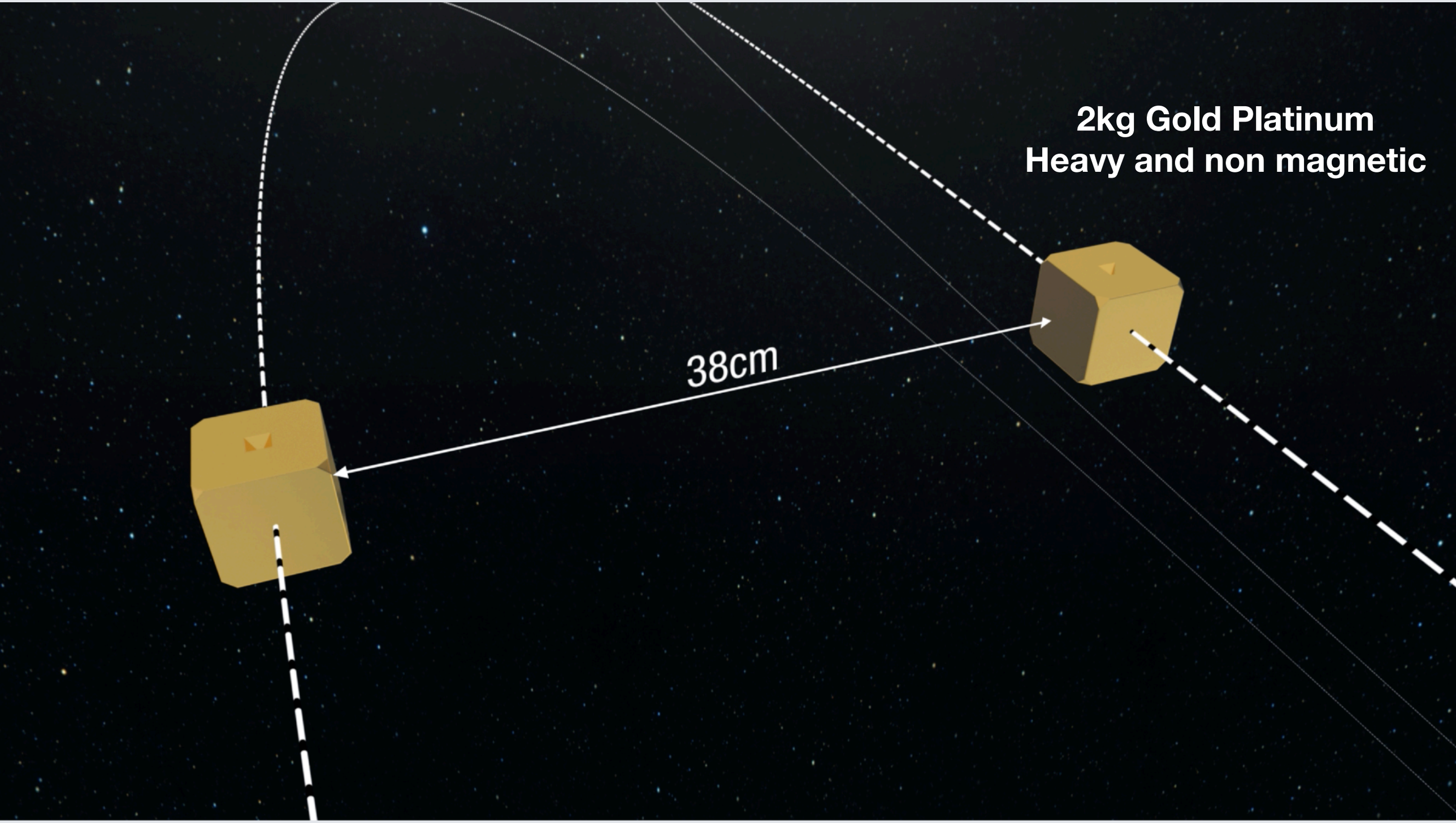
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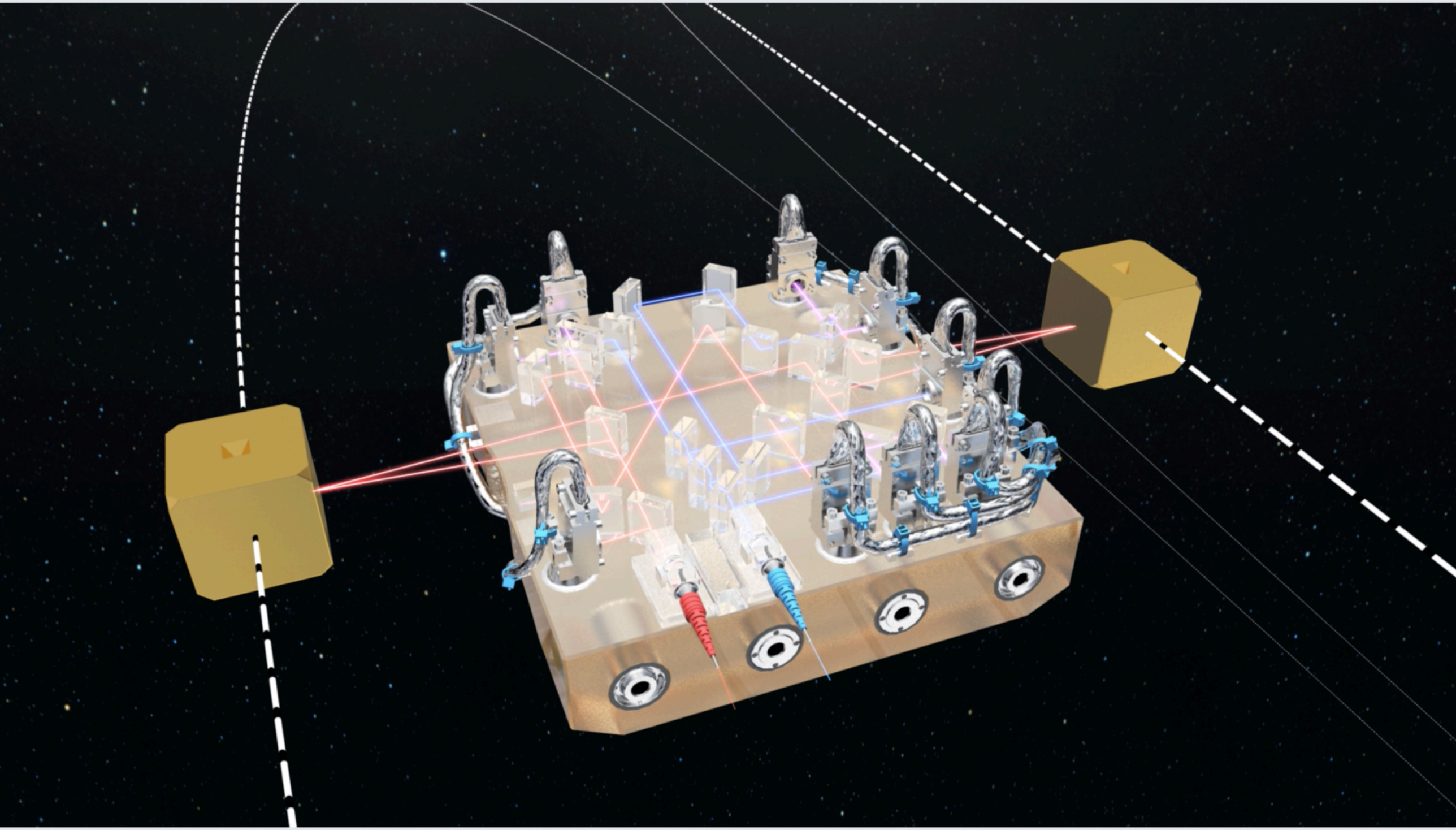
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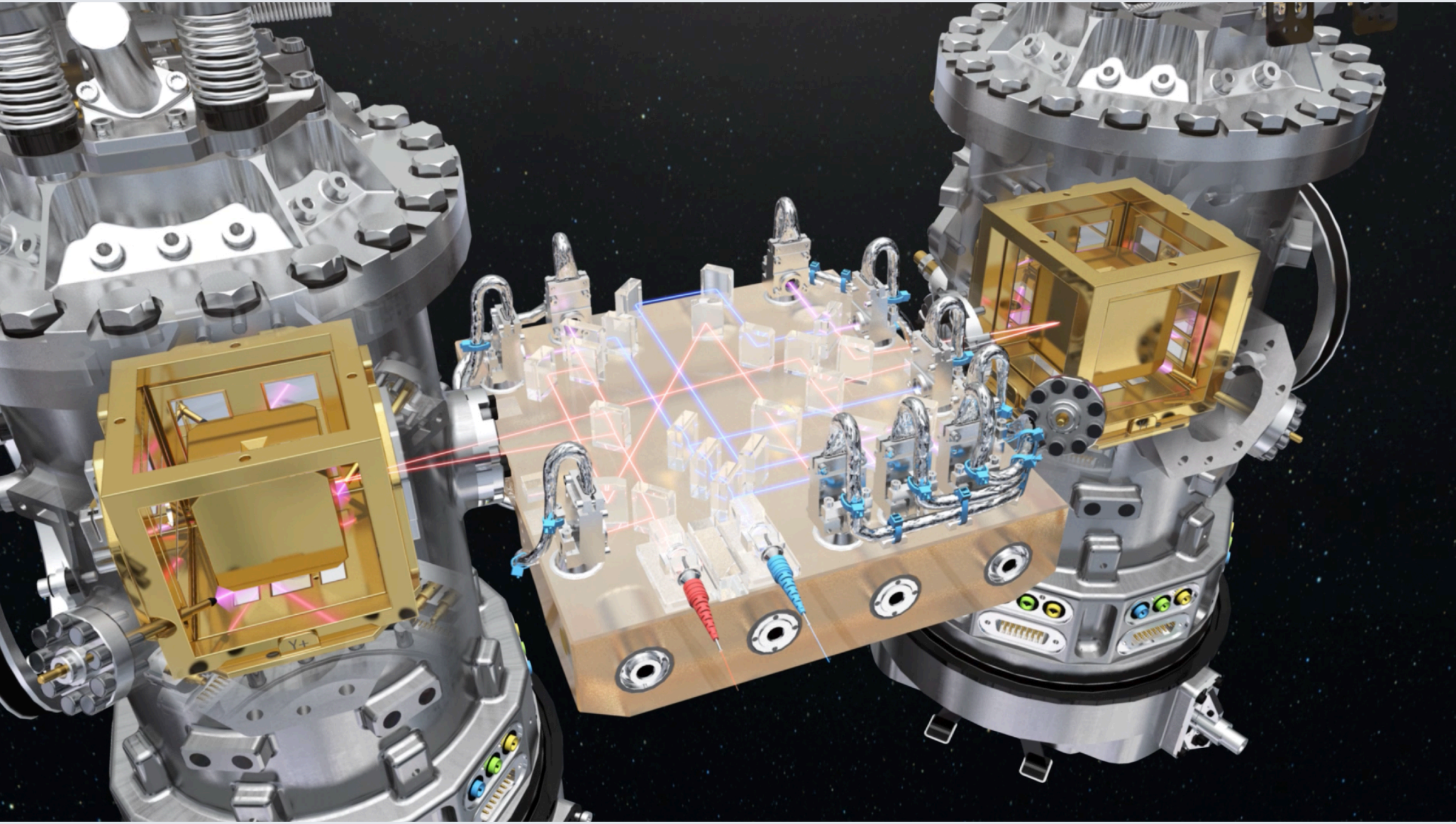
Test Masses



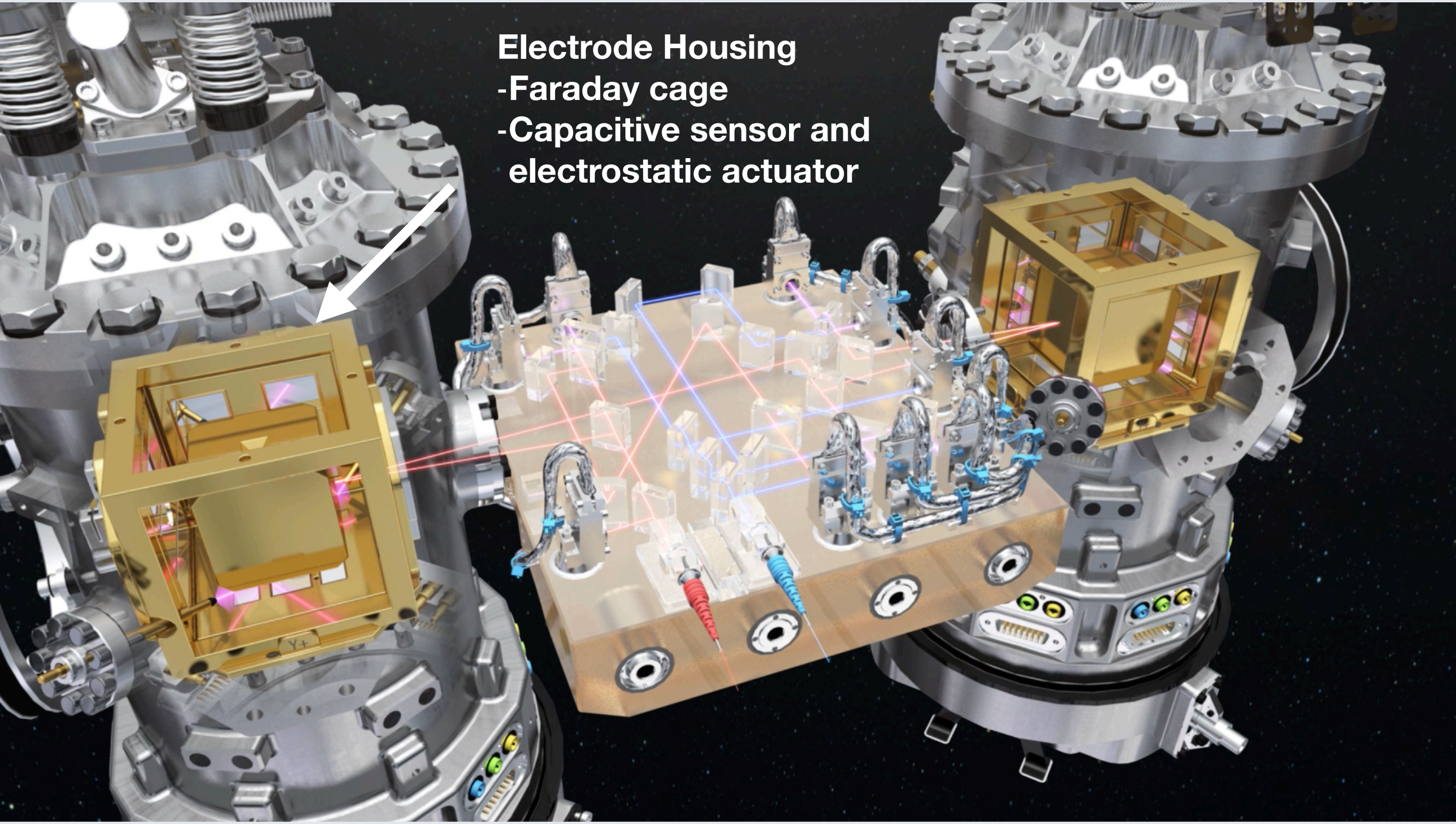
Ultra-stable Optical Bench



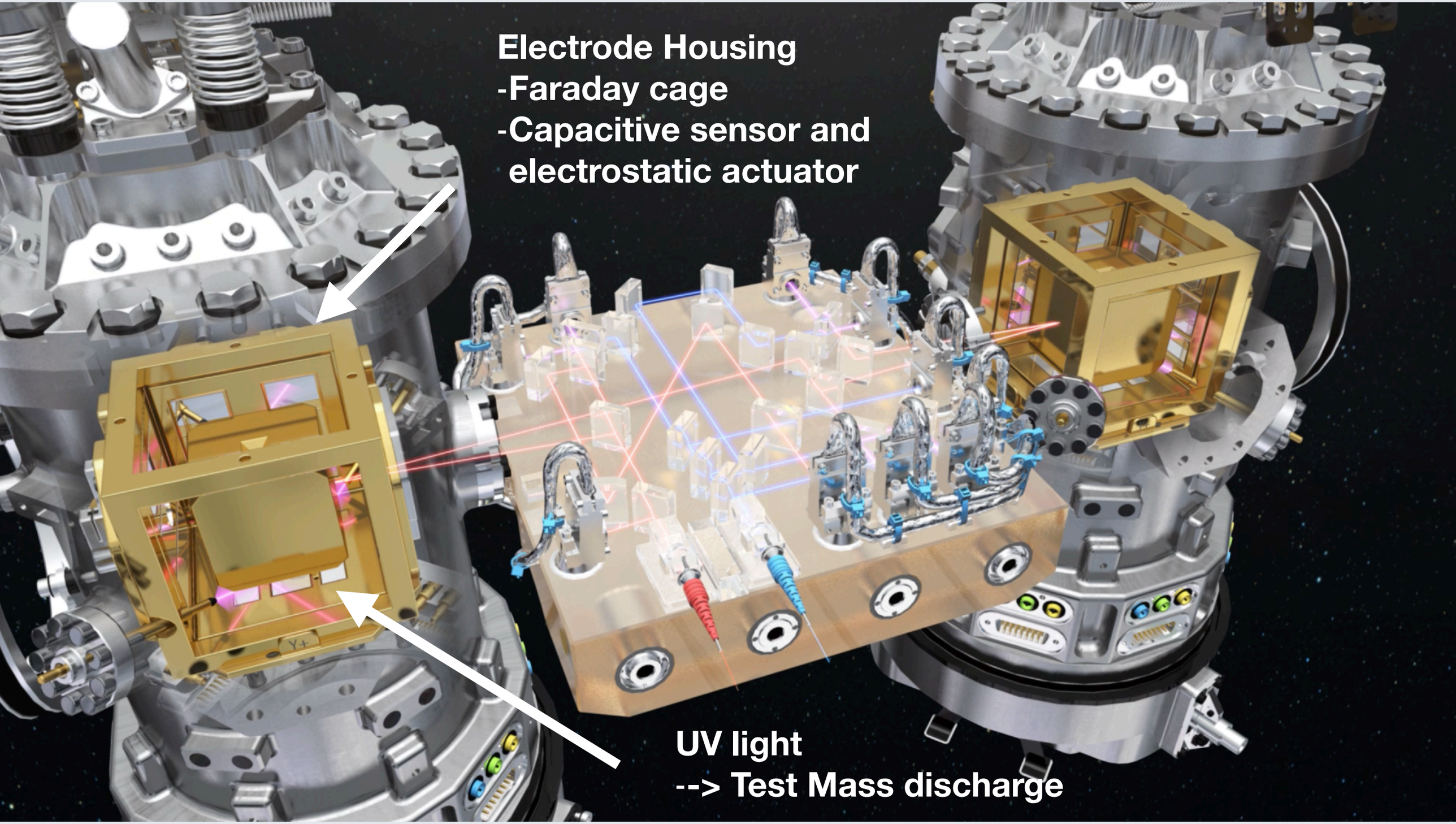
Gravitational Reference Sensor



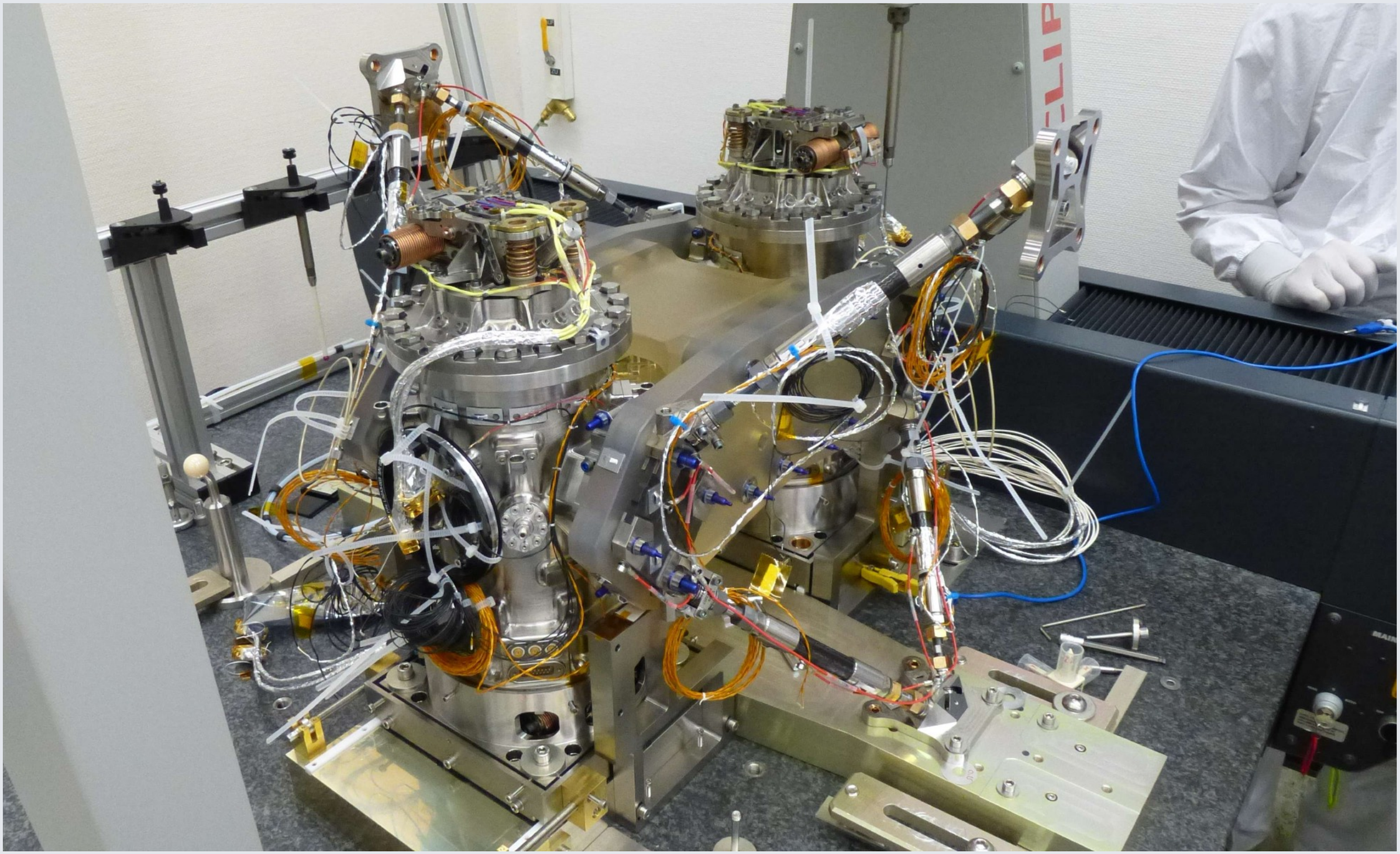
Gravitational Reference Sensor



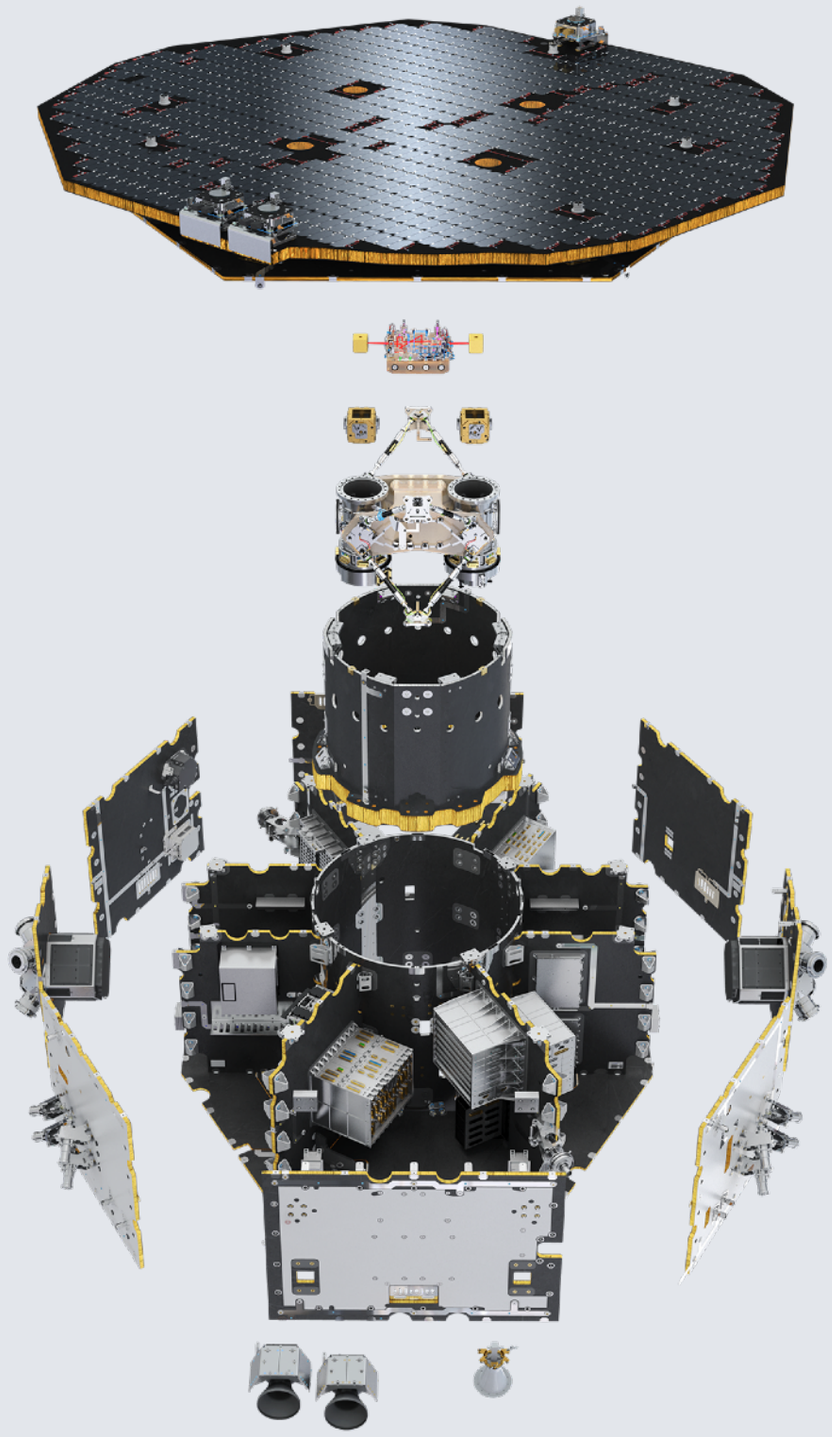
Gravitational Reference Sensor



LISA Pathfinder Payload



LISA Pathfinder Spacecraft

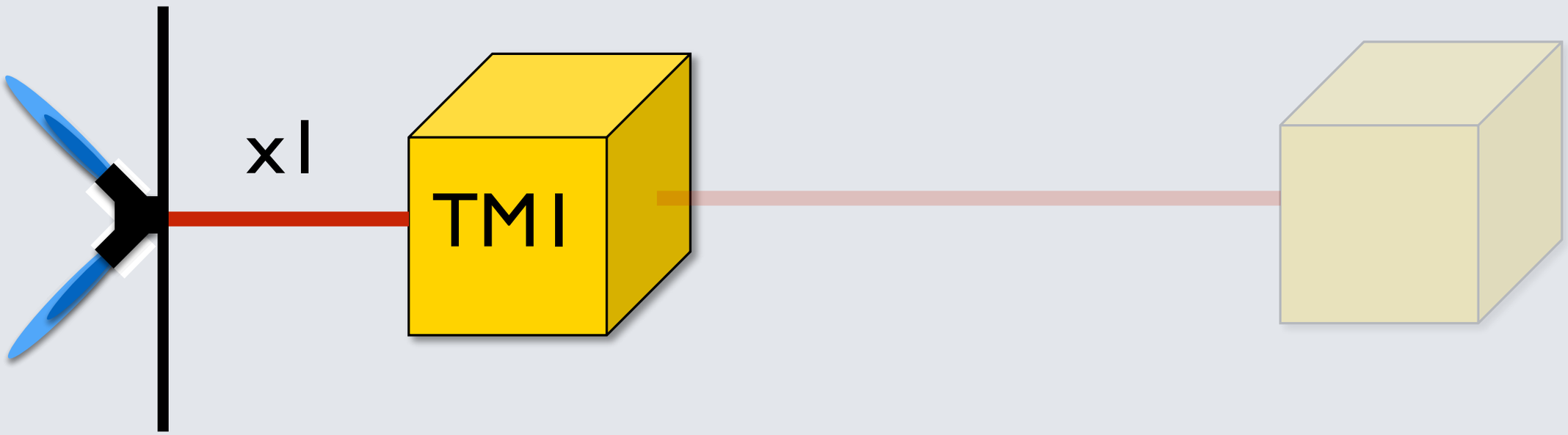




Enabling Free Fall:
Drag Free Control

External (Spacecraft) Forces

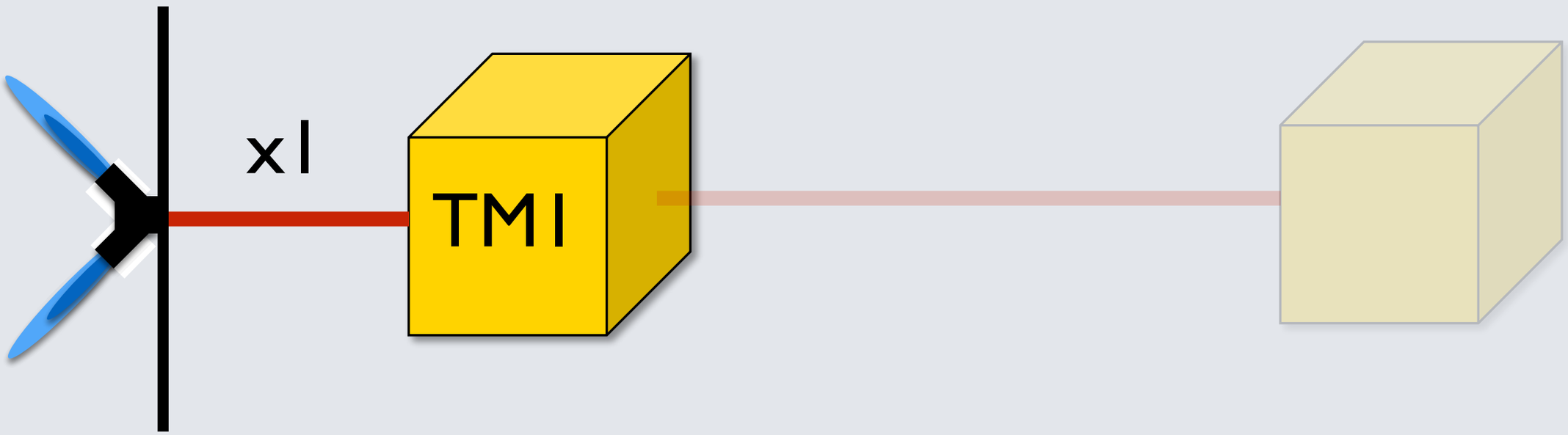
Drag Free



Null out external perturbation Satellite/TM

External (Spacecraft) Forces

Drag Free

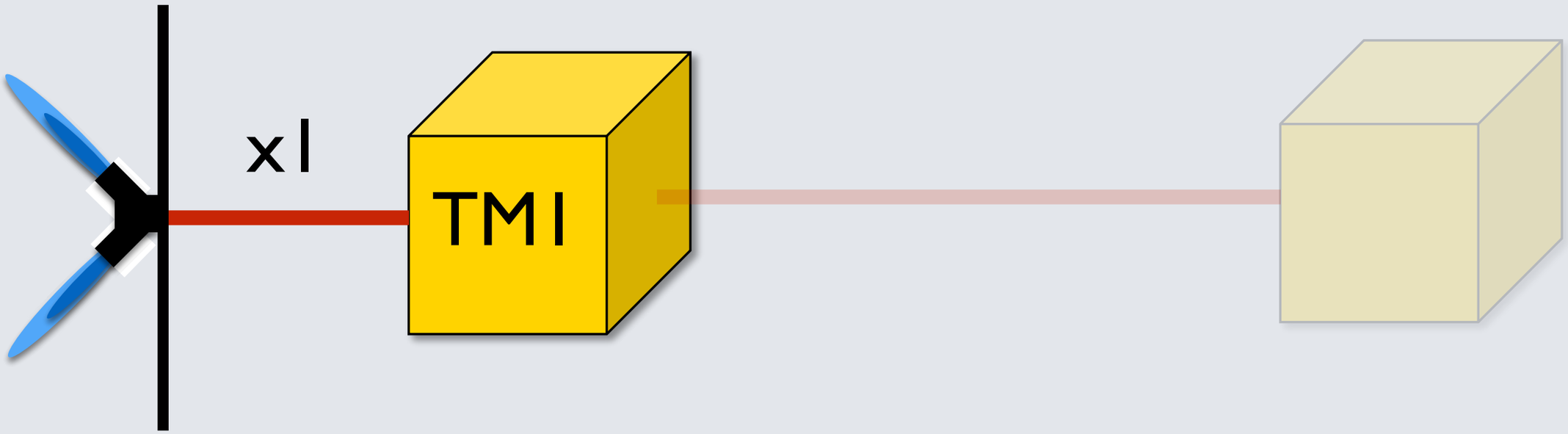


Closed Loop System
Sensor: x1 Interferometer
Spacecraft Actuator: Coldgas micro-propulsion system

Null out external perturbation Satellite/TM

External (Spacecraft) Forces

Drag Free



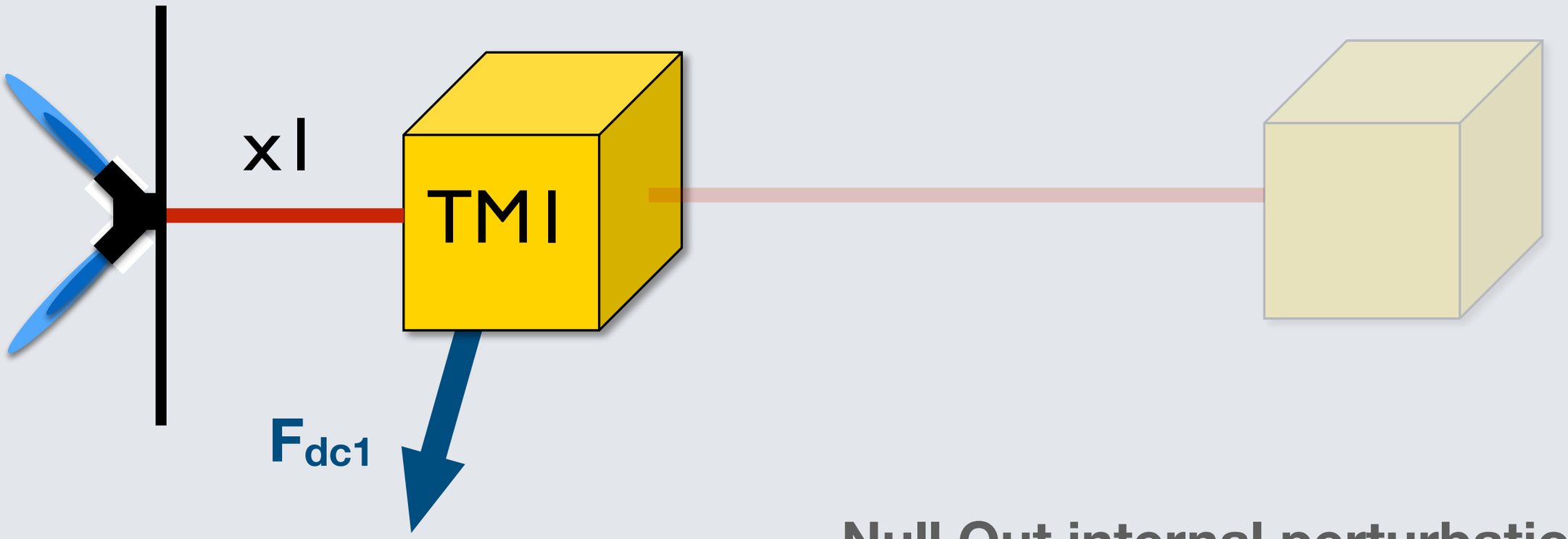
Closed Loop System
Sensor: x1 Interferometer
Spacecraft Actuator: Coldgas micro-propulsion system

Null out external perturbation Satellite/TM

- Solar Wind/Thermal Infrared (DC)
- Micro-propulsion noises (in-band)
- Micro-meteoroids (impulse)

Internal (Test Mass) Forces

Drag Free

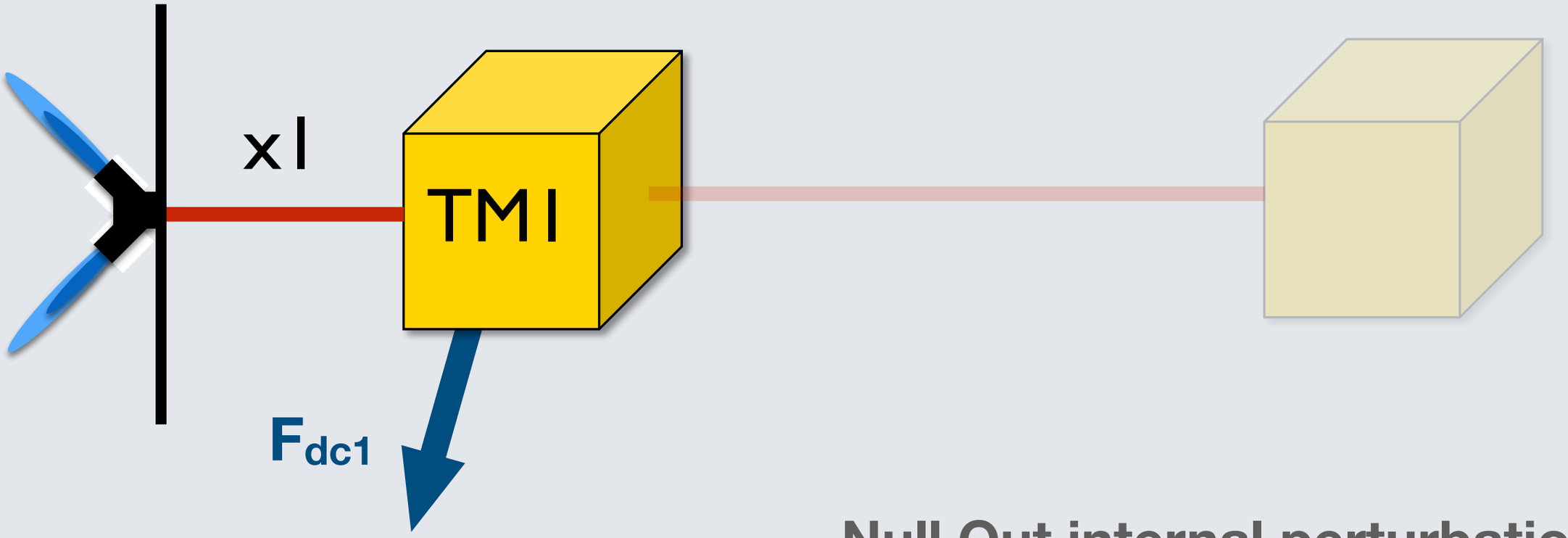


Null Out internal perturbation

Closed Loop System
Sensor: x1 Interferometer
Spacecraft Actuator: Coldgas micro-propulsion system

Internal (Test Mass) Forces

Drag Free

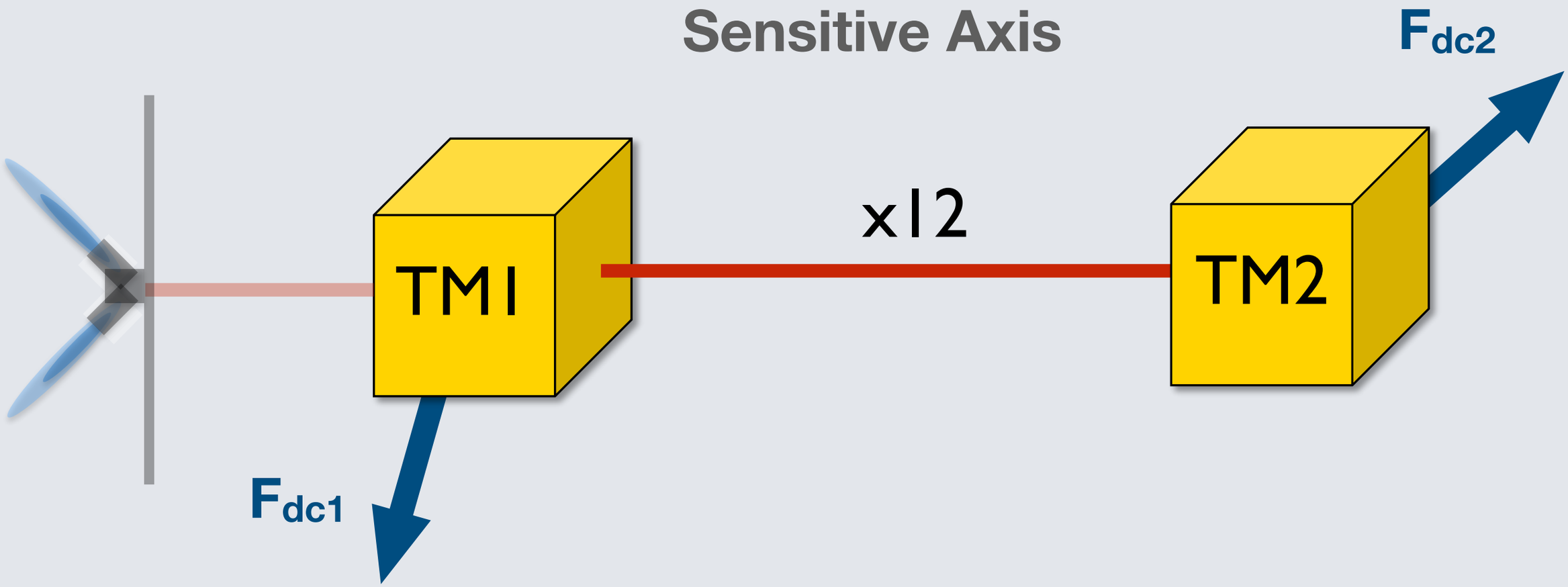


Closed Loop System
Sensor: x1 Interferometer
Spacecraft Actuator: Coldgas micro-propulsion system

Null Out internal perturbation

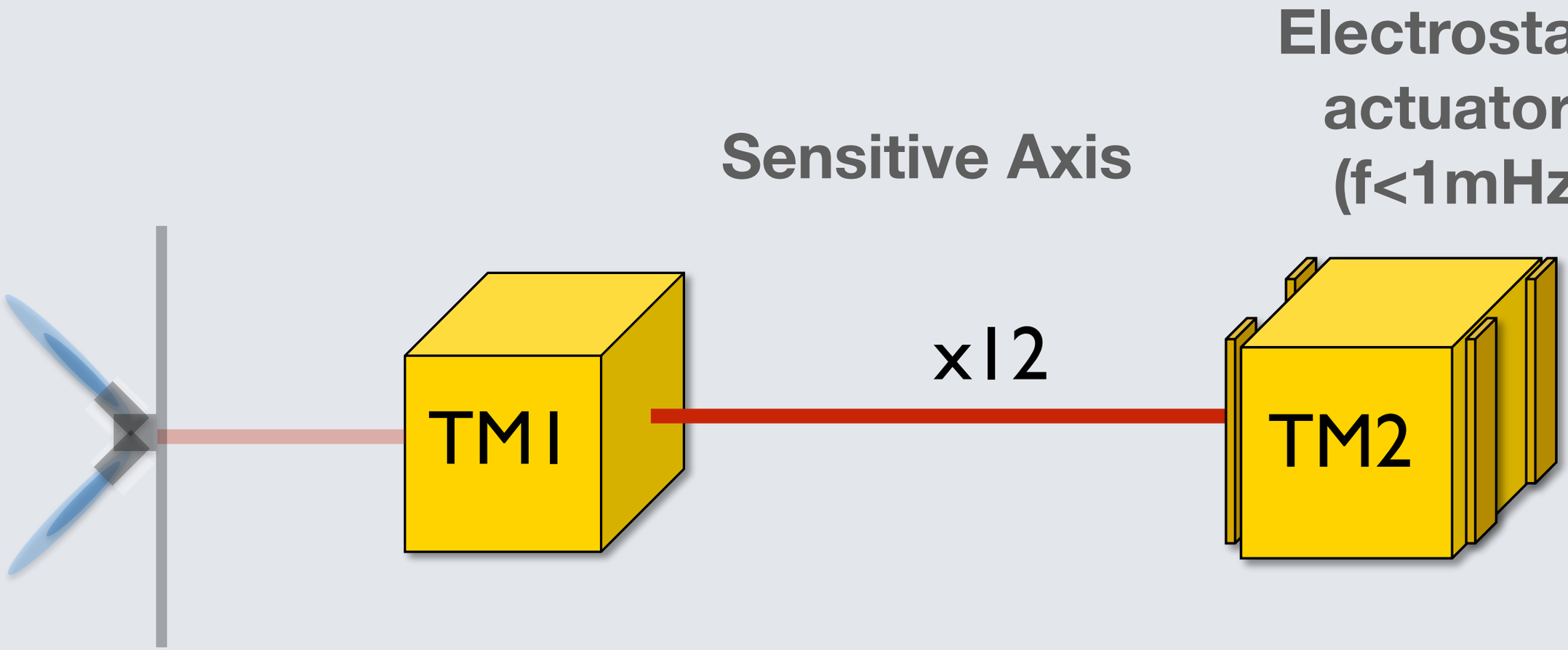
- Propellant consumption
- Gravitational balance
- Electrostatic Null
- Assymetric Outgassing

LPF case: differential DC forces



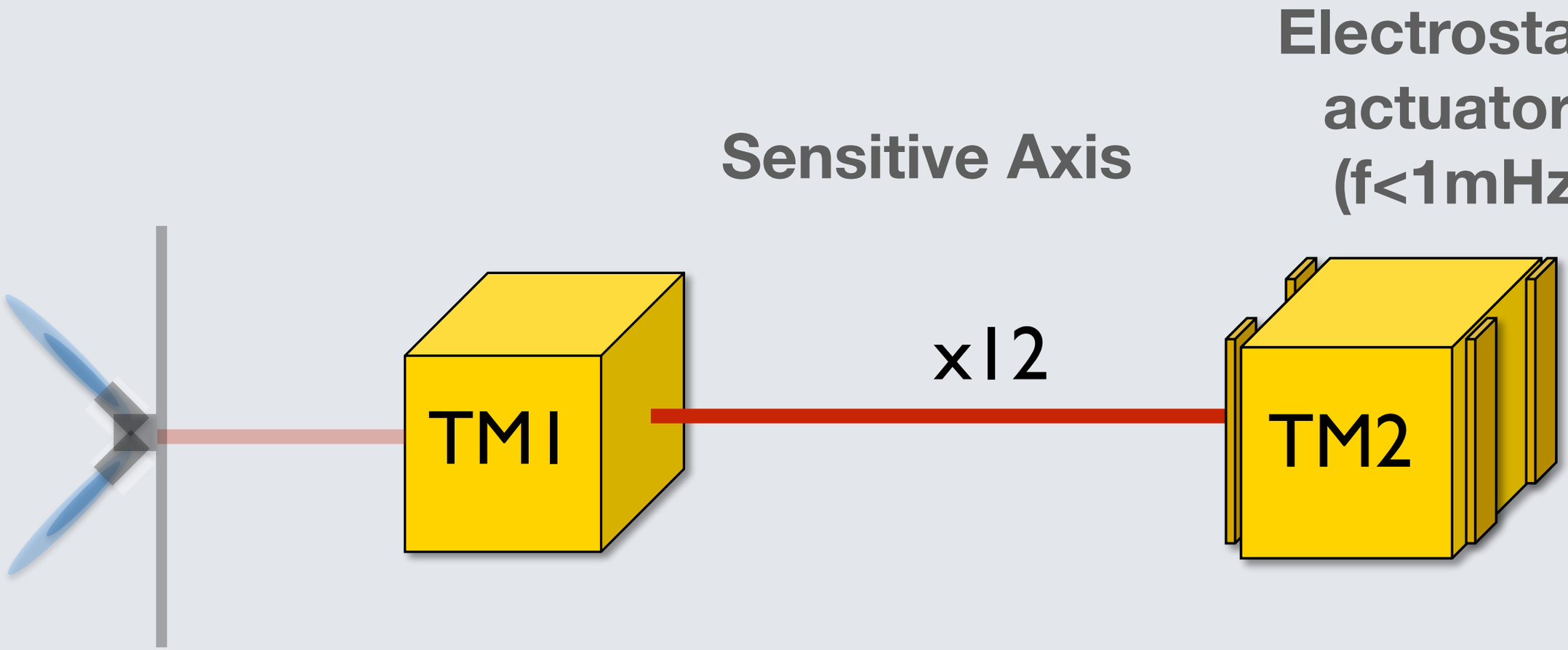
Common mode -> nulled out by Drag Free control
Differential mode: ΔFdc can't be compensated by the Spacecraft for LPF

LPF Case: differential acceleration



Electrostatic actuators in the sensitive axis is part of the measurement

LPF Case: differential acceleration



Electrostatic actuators in the sensitive axis is part of the measurement

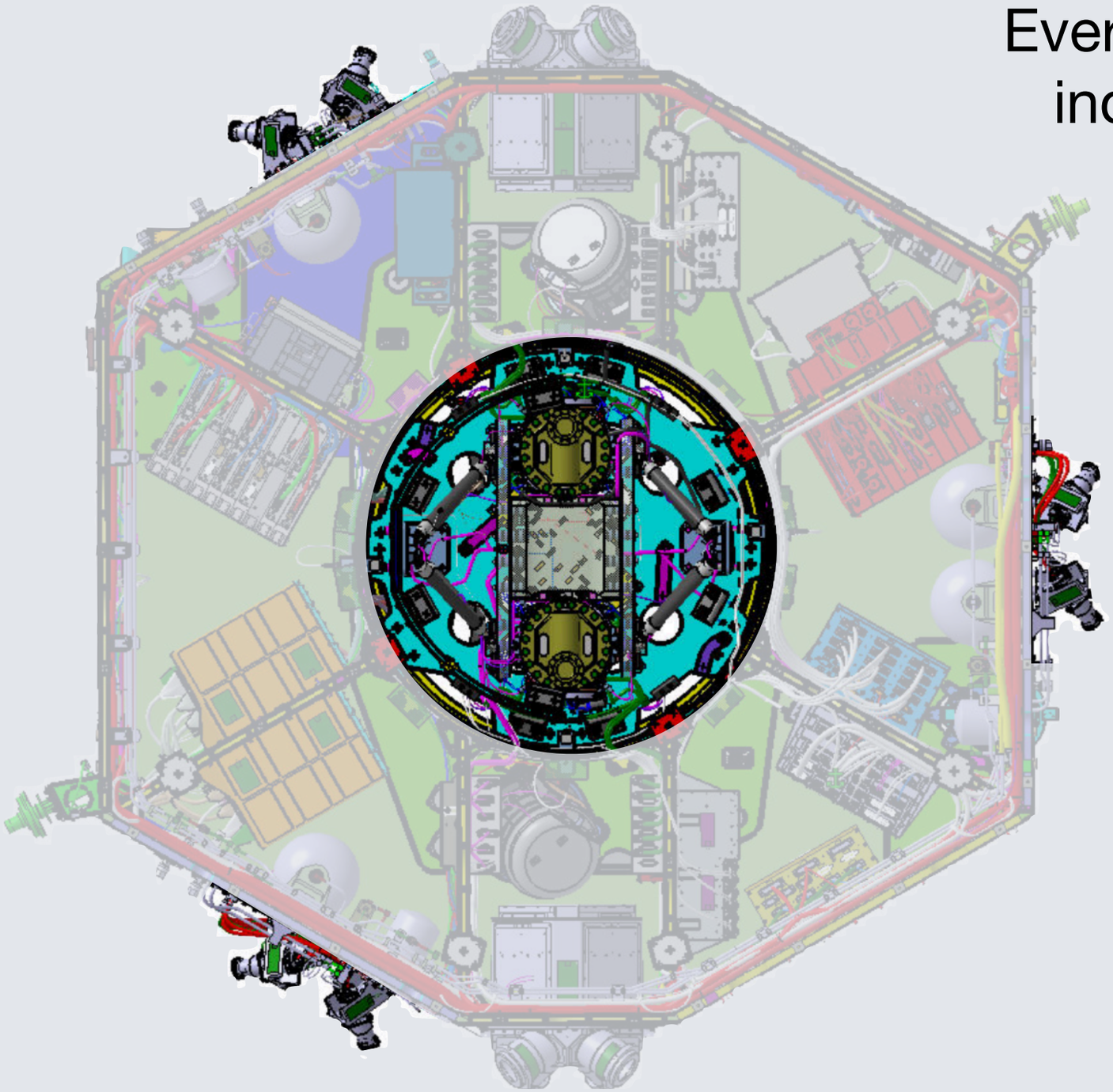
Differential Acceleration

$$\Delta \mathbf{g} = d^2(x\mathbf{12})/dt^2 - \mathbf{Fx2}/M$$

Interferometric measurement

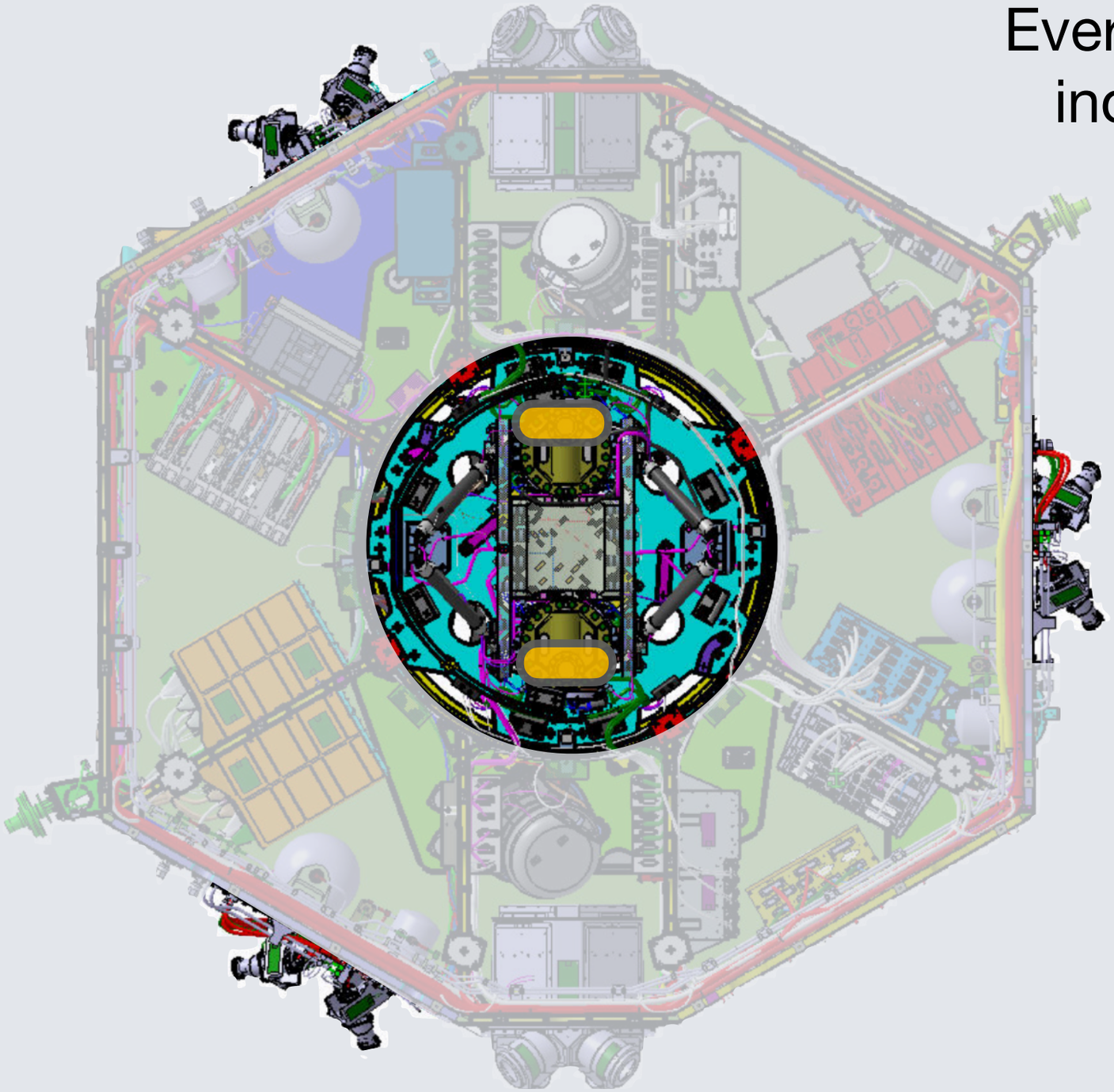
Electrostatic commanded forces

Mitigation: Gravitational Balancing



Every pieces of hardware down to individual screws (~grams) are measured and modeled

Mitigation: Gravitational Balancing

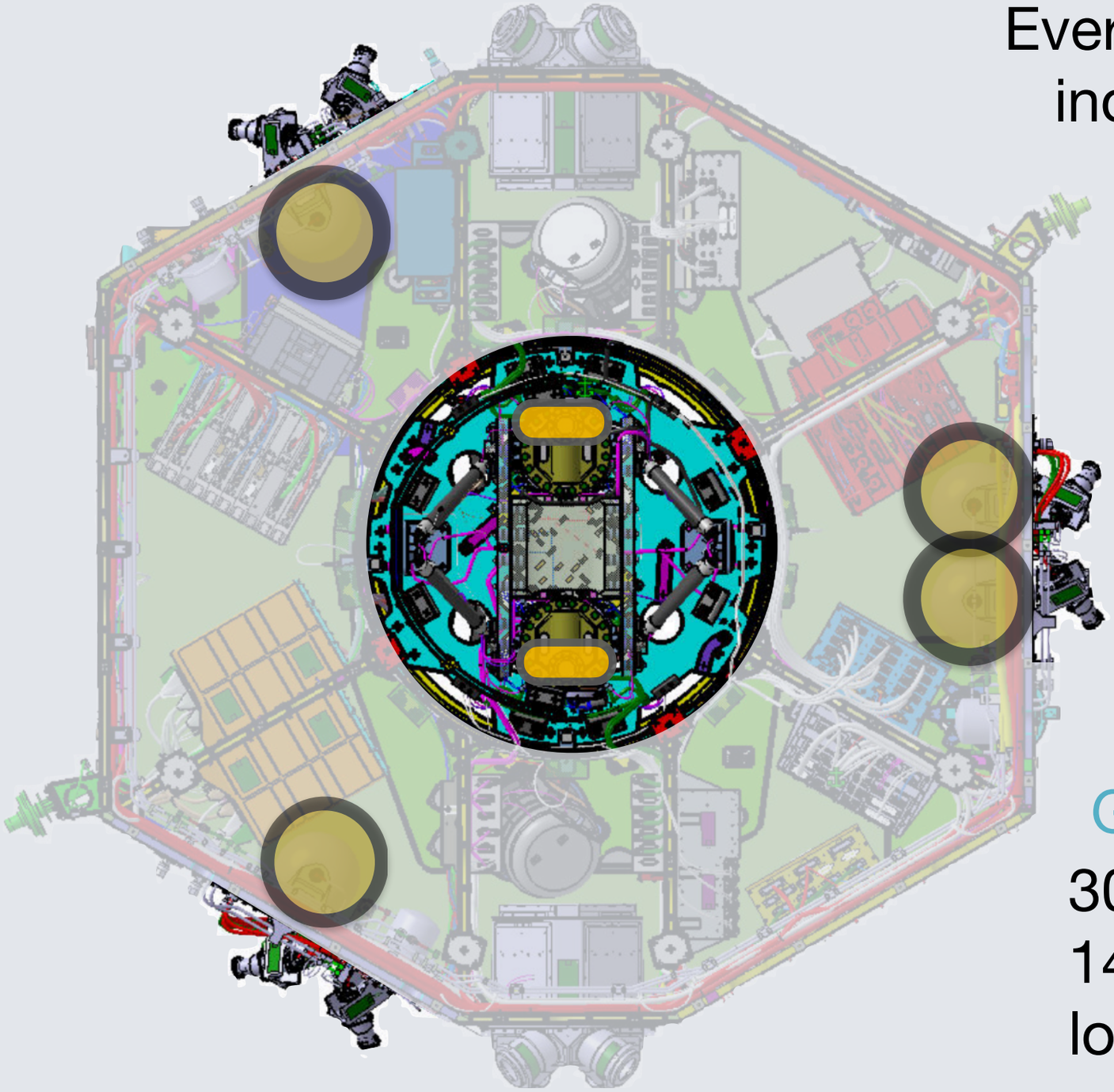


Every pieces of hardware down to individual screws (~grams) are measured and modeled

Internal Balanced Mass

Gravitational Balancing
Design: 650pm/s^2
Measured ~50pm/s^2

Mitigation: Gravitational Balancing



Every pieces of hardware down to individual screws (~grams) are measured and modeled

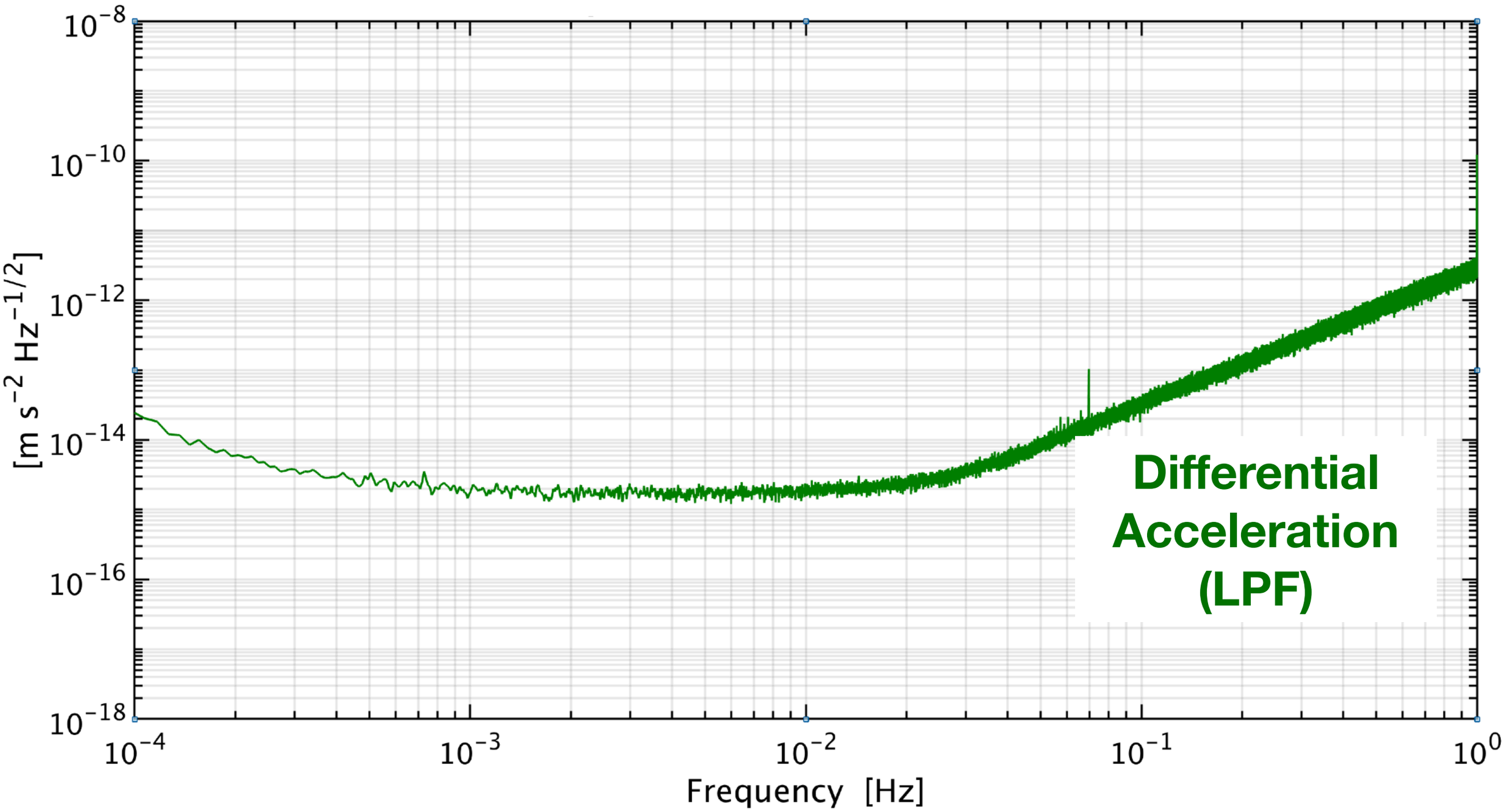
Internal Balanced Mass

Gravitational Balancing
Design: 650pm/s^2
Measured ~50pm/s^2

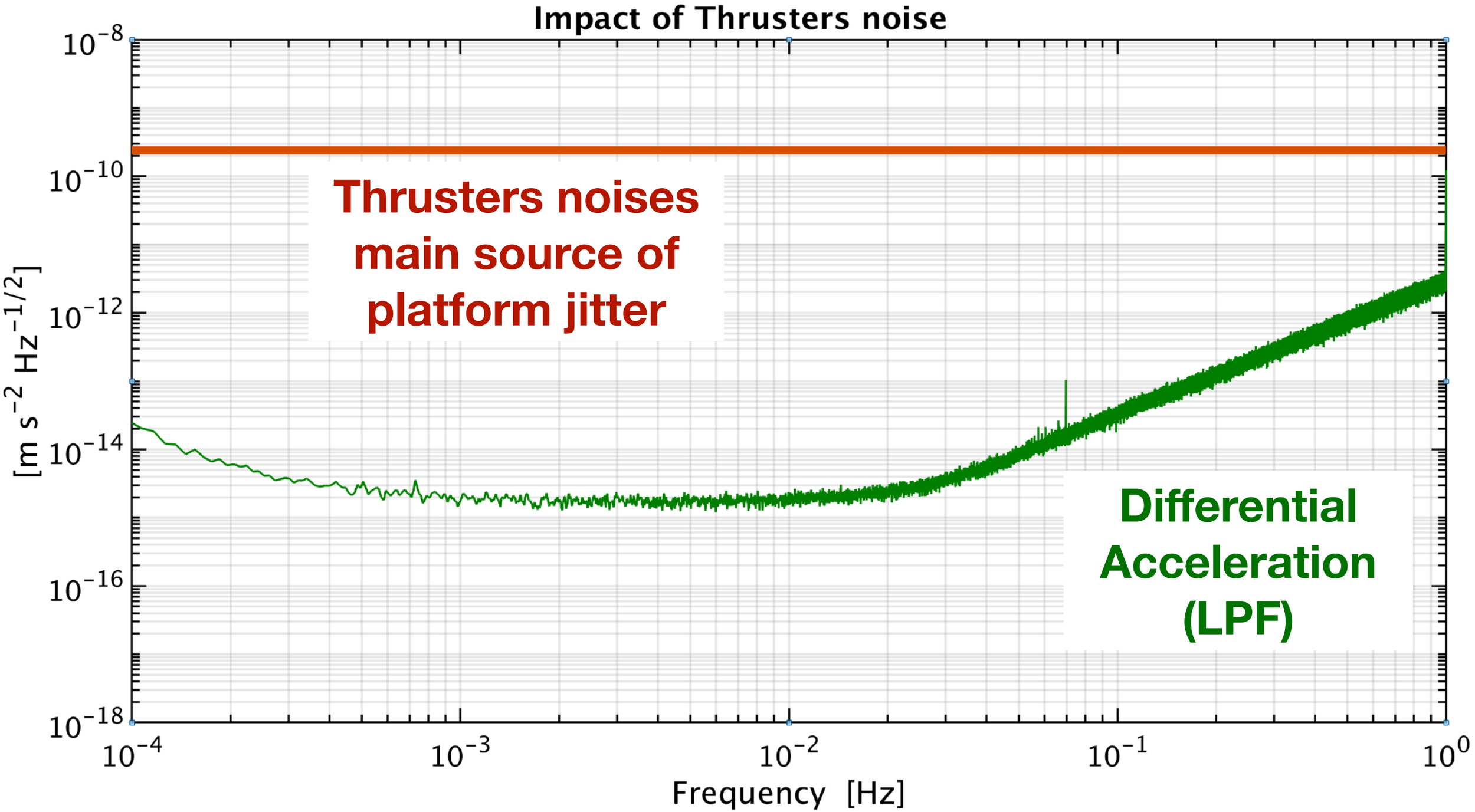
Gaz emptying strategy

300 bars Nitrogen Tanks
14g/day - dominant signal at low frequency

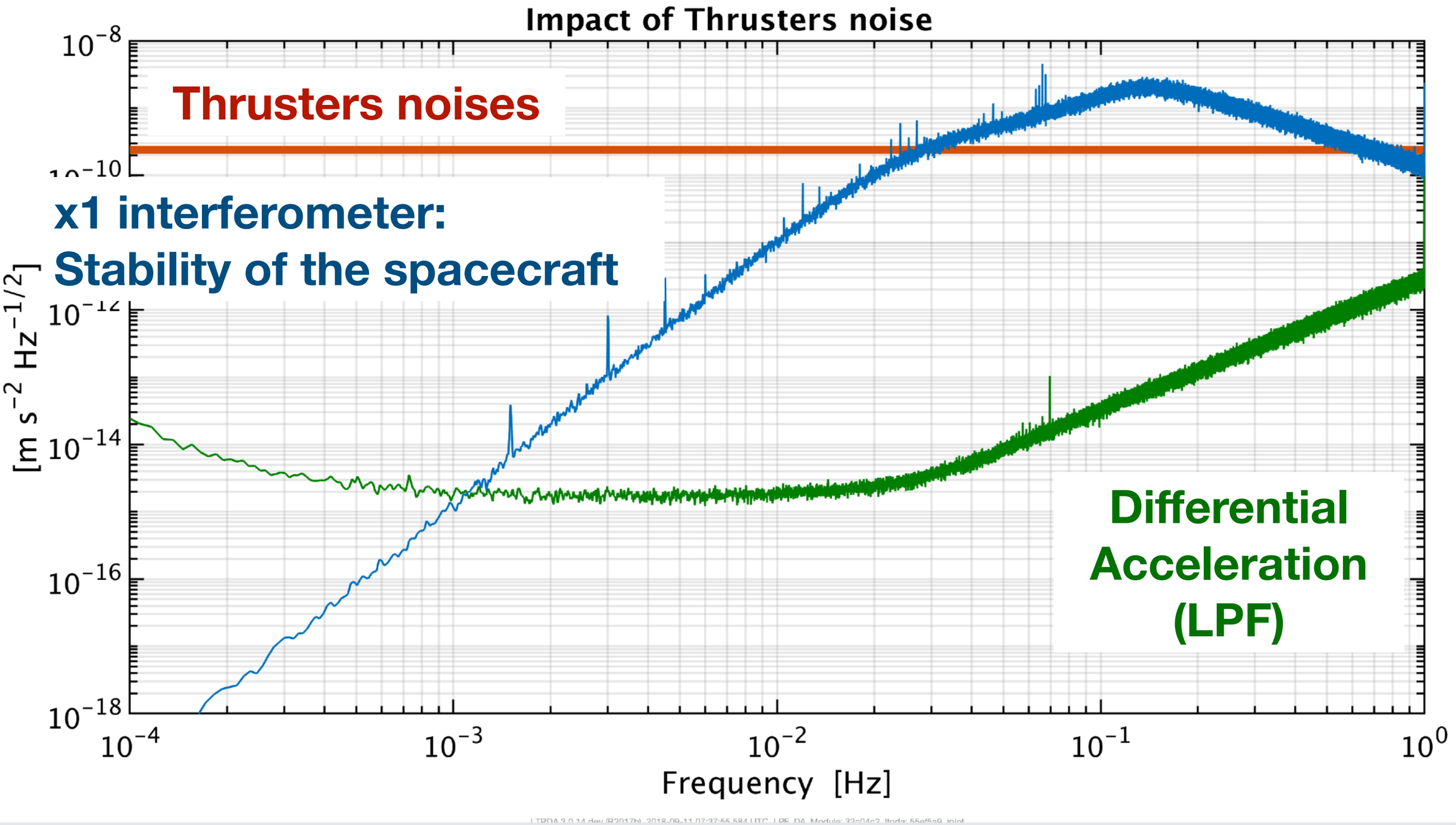
Drag Free Performance: in band



Drag Free Performance: in band



Drag Free Performance: in band



Enabling Free Fall: the environment

Coping with the environment

Test Mass Noise Budget

Magnetic

Electrostatic

Thermal

Vacuum

Radiation

Spacecraft Jitter

Coping with the environment

Test Mass Noise Budget

Magnetic Magnetic cleanliness -> choice of material

Electrostatic

Thermal

Vacuum

Radiation

Spacecraft Jitter

Coping with the environment

Test Mass Noise Budget

Magnetic — Magnetic cleanliness -> choice of material

Electrostatic — Large Gaps between Test Masse and electrodes.
No DC voltage

Thermal

Vacuum

Radiation

Spacecraft Jitter

Coping with the environment

Test Mass Noise Budget

Magnetic	Magnetic cleanliness -> choice of material
Electrostatic	Large Gaps between Test Masse and electrodes. No DC voltage
Thermal	Thermal isolators - low thermal expansion material
Vacuum	
Radiation	
Spacecraft Jitter	

Coping with the environment

Test Mass Noise Budget

Magnetic	Magnetic cleanliness -> choice of material
Electrostatic	Large Gaps between Test Masse and electrodes. No DC voltage
Thermal	Thermal isolators - low thermal expansion material
Vacuum	GRS vacuum enclosure - venting to space
Radiation	
Spacecraft Jitter	

Coping with the environment

Test Mass Noise Budget

Magnetic	Magnetic cleanliness -> choice of material
Electrostatic	Large Gaps between Test Masse and electrodes. No DC voltage
Thermal	Thermal isolators - low thermal expansion material
Vacuum	GRS vacuum enclosure - venting to space
Radiation	No contact - UV discharge system
Spacecraft Jitter	

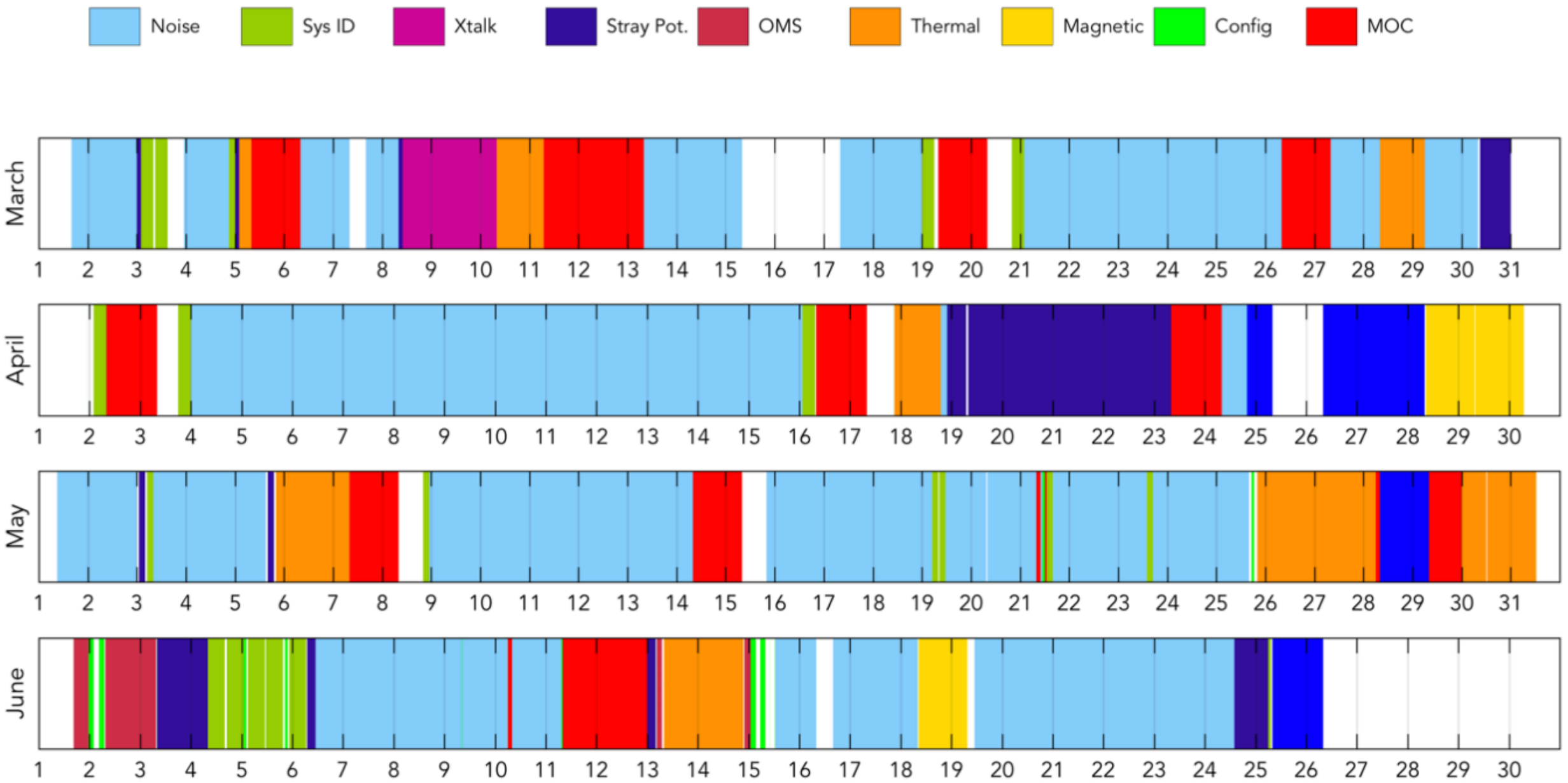
Coping with the environment

Test Mass Noise Budget

Magnetic	Magnetic cleanliness -> choice of material
Electrostatic	Large Gaps between Test Masse and electrodes. No DC voltage
Thermal	Thermal isolators - low thermal expansion material
Vacuum	GRS vacuum enclosure - venting to space
Radiation	No contact - UV discharge system
Spacecraft Jitter	Gravitational Modeling and balancing

4 months of Noise Hunting

Investigations



Operation Organisation

Multiple stakeholders

Operating LPF meant bringing together very different teams and trades

MOC

ESA · Darmstadt, Germany

Flies the spacecraft: health, safety, station keeping

STOC

ESA · near Madrid, Spain

Plans investigations, delivers data, checks data quality

Labs / PI

Trento, AEI, APC, ICL…

Design the experiments and analyse the data

Industry

Airbus

System support and simulators

During operations, everyone in one place: STOC and PI teams co-located with the MOC in Darmstadt

An investigation is a planned activity

Prepared long in advance, reviewed by the whole team

Technical note

Each investigation documented before flight

Code review

Reviewed upstream by the whole team

Committed in a shared Git

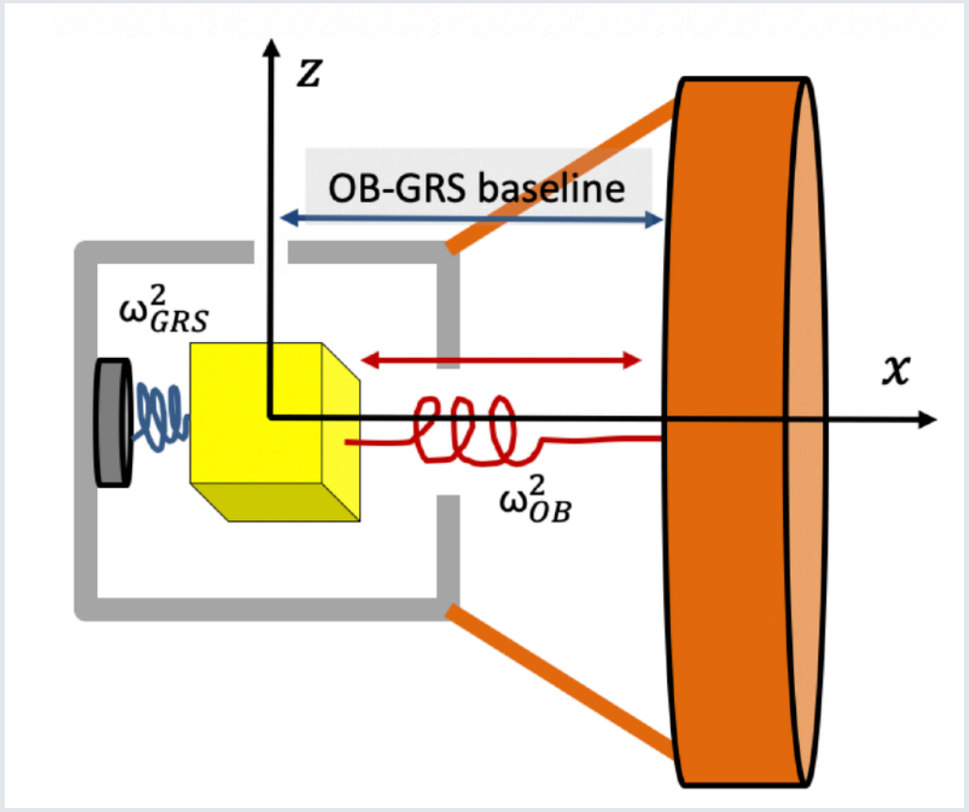
All scripts under version control and accessible to everybody

Runnable by anyone

Other members could rerun them offline

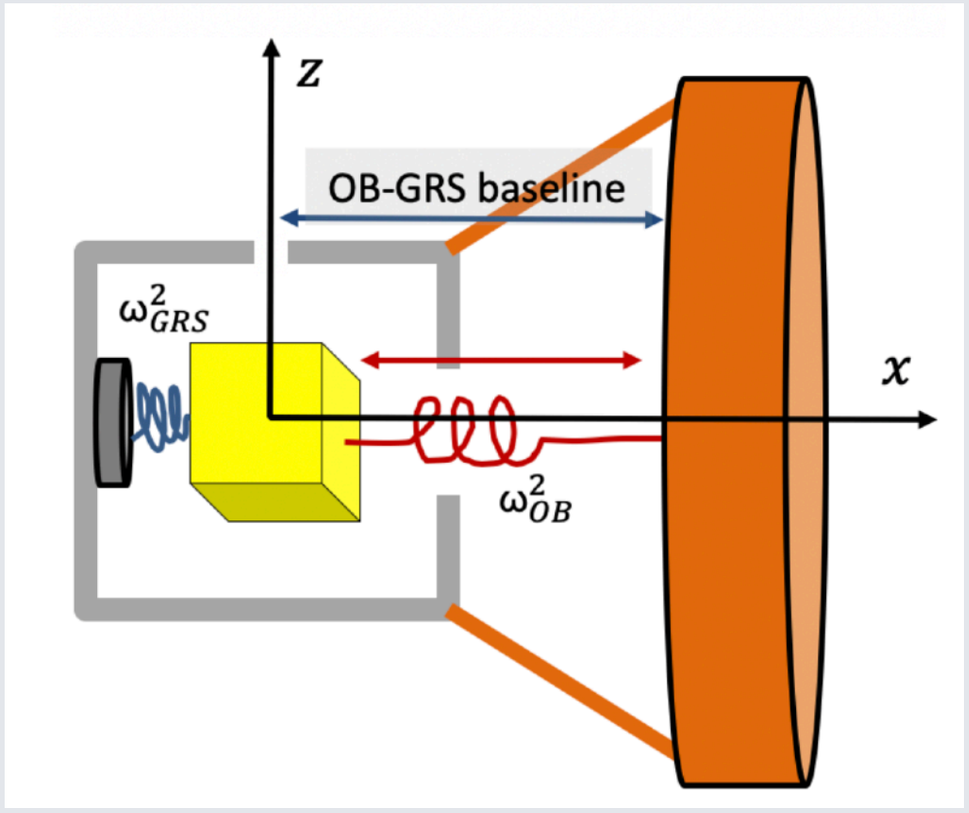
Examples in detail: System Identification

Stiffness: electric and gravitational field



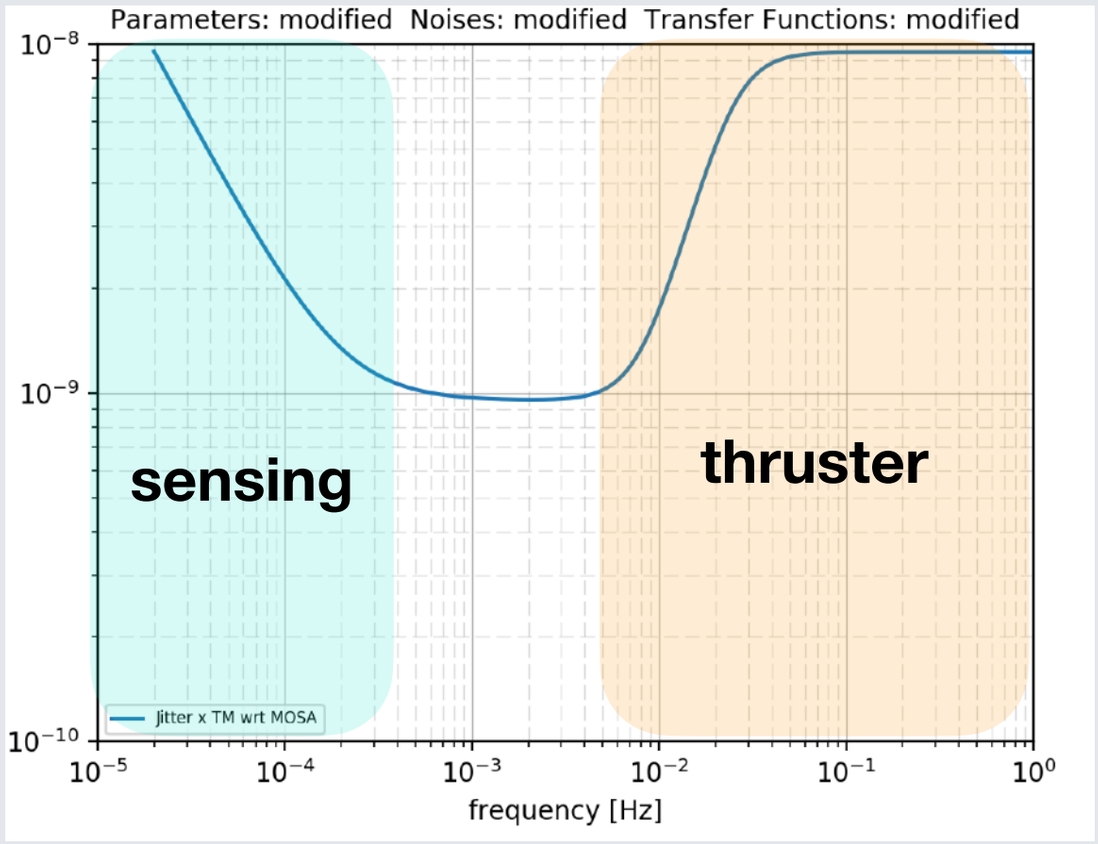
- Test Mass is in a non uniform force field: **gravitational** and electrostatic (actuation system)
- Any relative motion between the Test Mass and this gradient field will cause a stray acceleration proportional to this motion: stiffness

Stiffness: electric and gravitational field

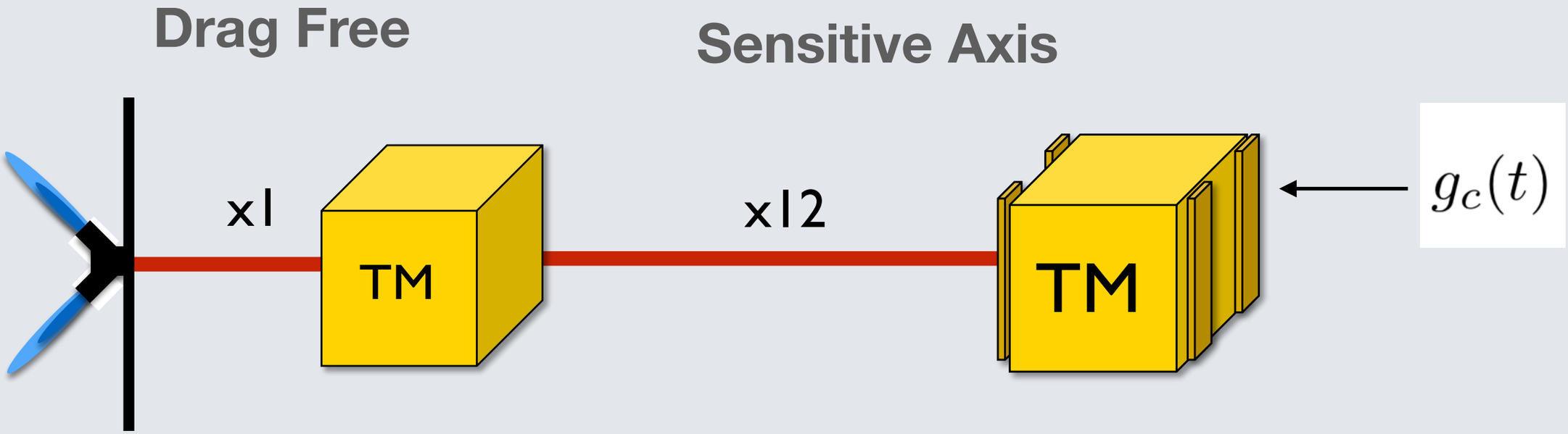


Spacecraft Jitter at nm/sqrt(Hz)

- Test Mass is in a non uniform force field: **gravitational** and electrostatic (actuation system)
- Any relative motion between the Test Mass and this gradient field will cause a stray acceleration proportional to this motion: stiffness



Stiffness Investigation

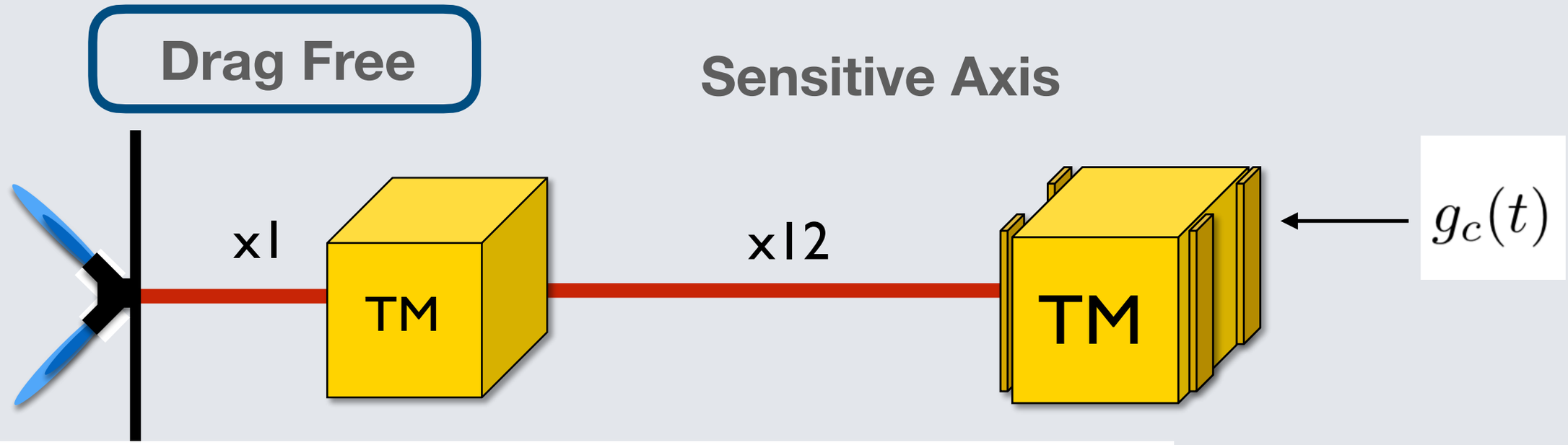


Stiffness Investigation

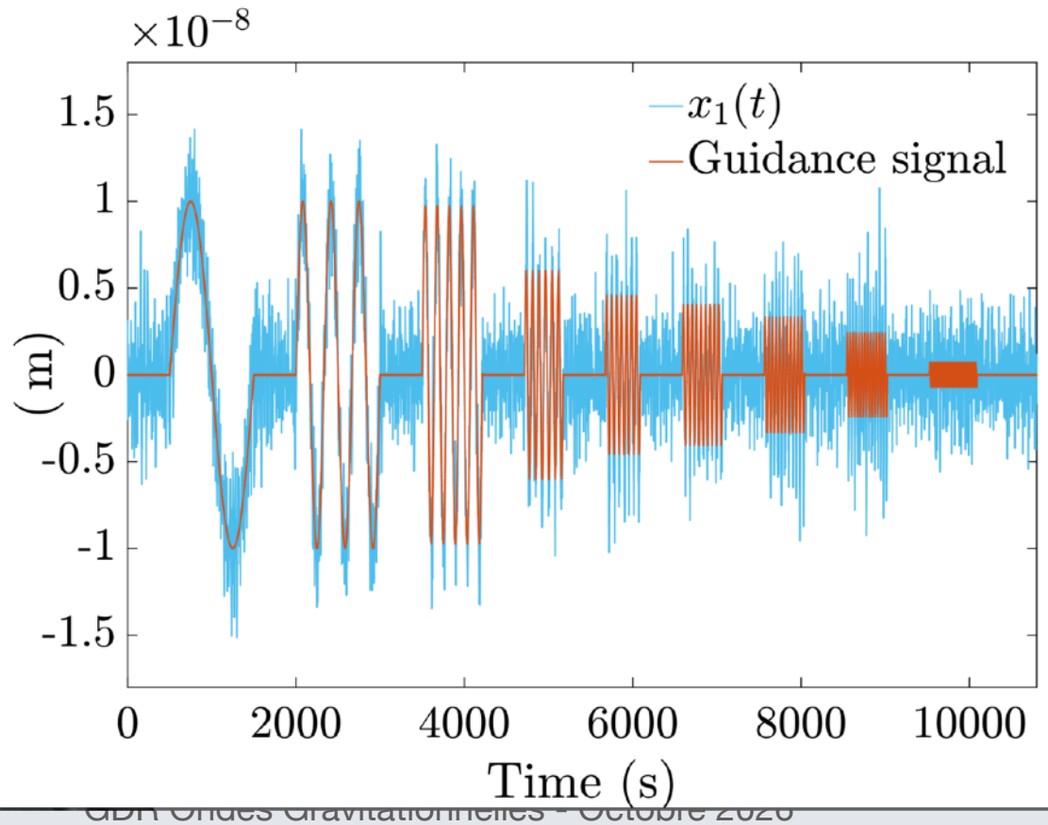


$$\Delta g(t) \equiv \Delta\ddot{x}(t) + \omega_2^2 \Delta x(t) + \Delta\omega_{12}^2 x_1 - g_c(t)$$

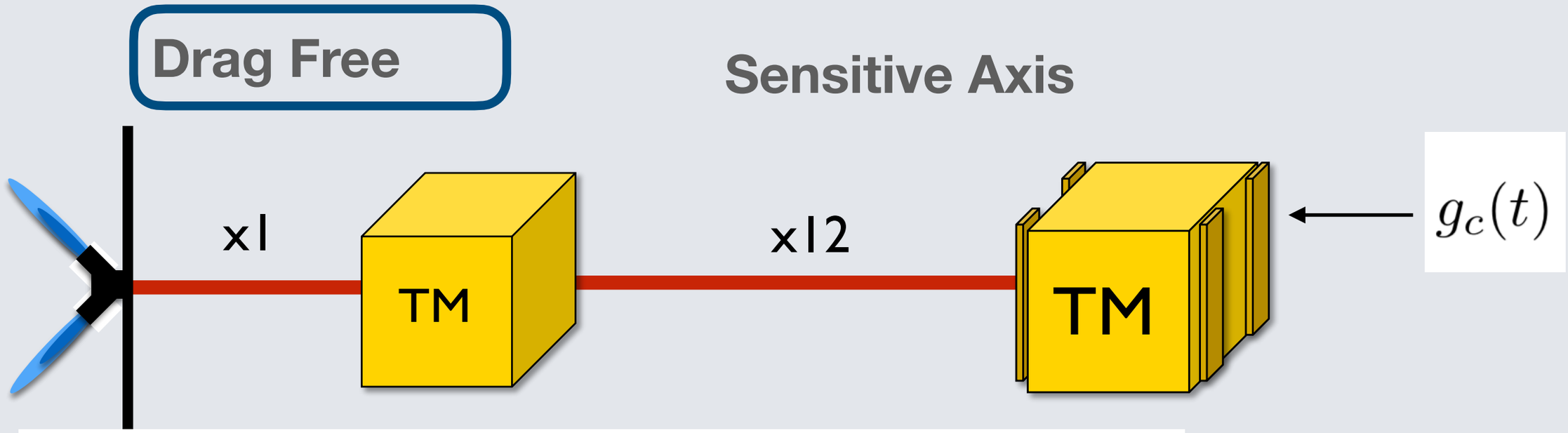
Stiffness Investigation



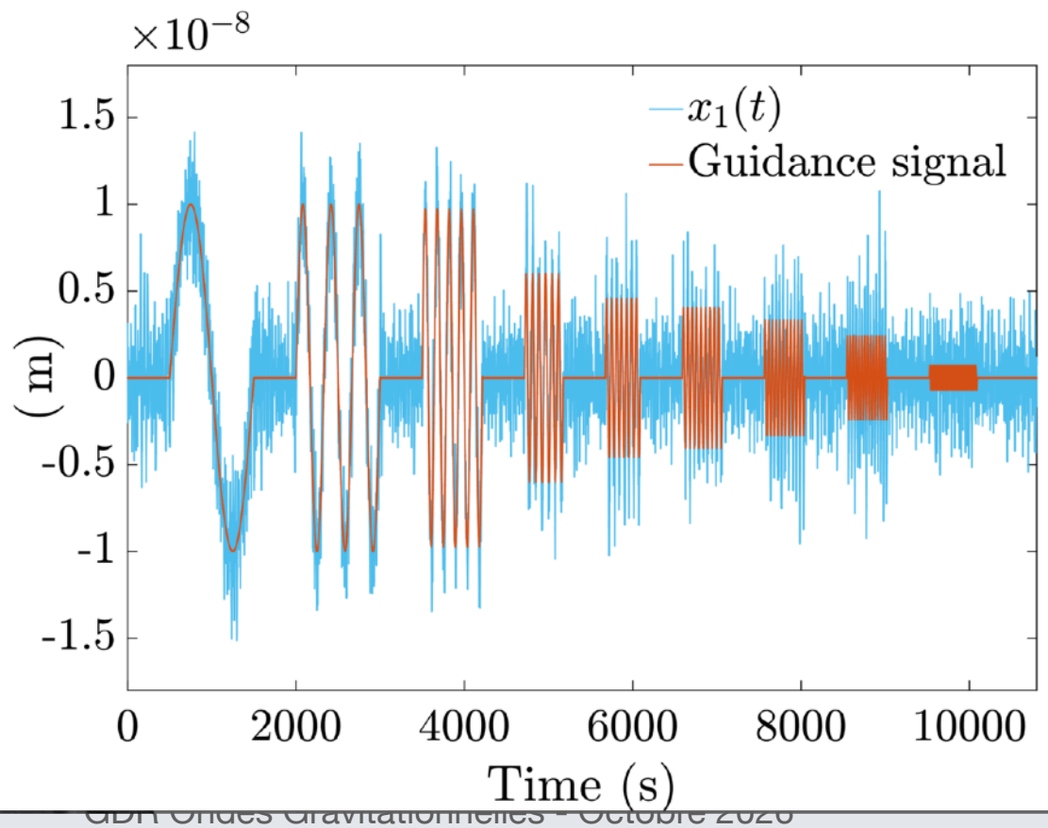
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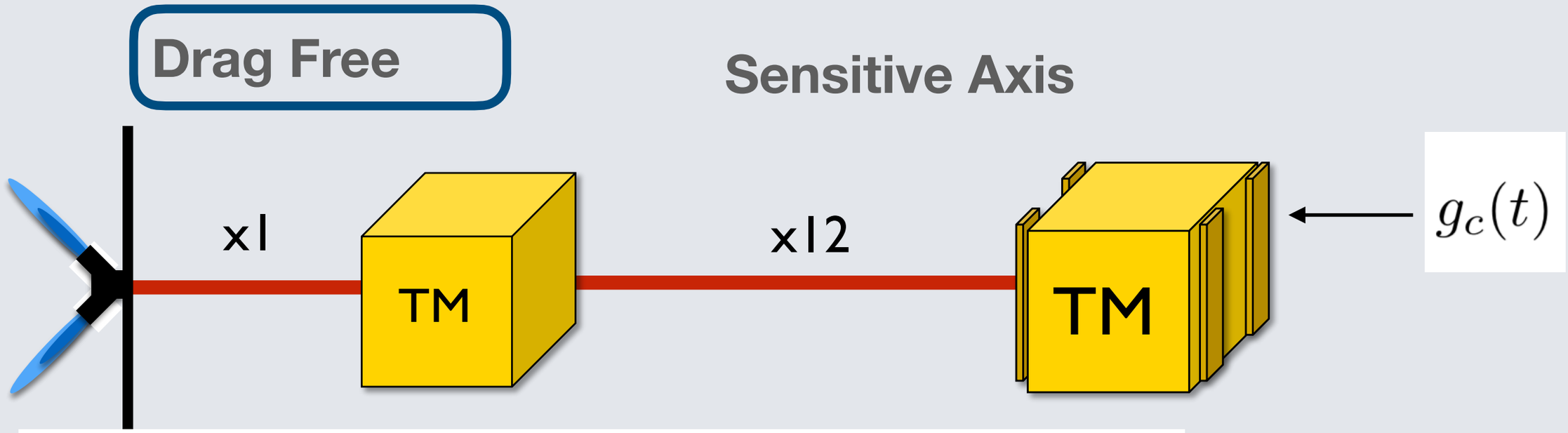
Stiffness Investigation



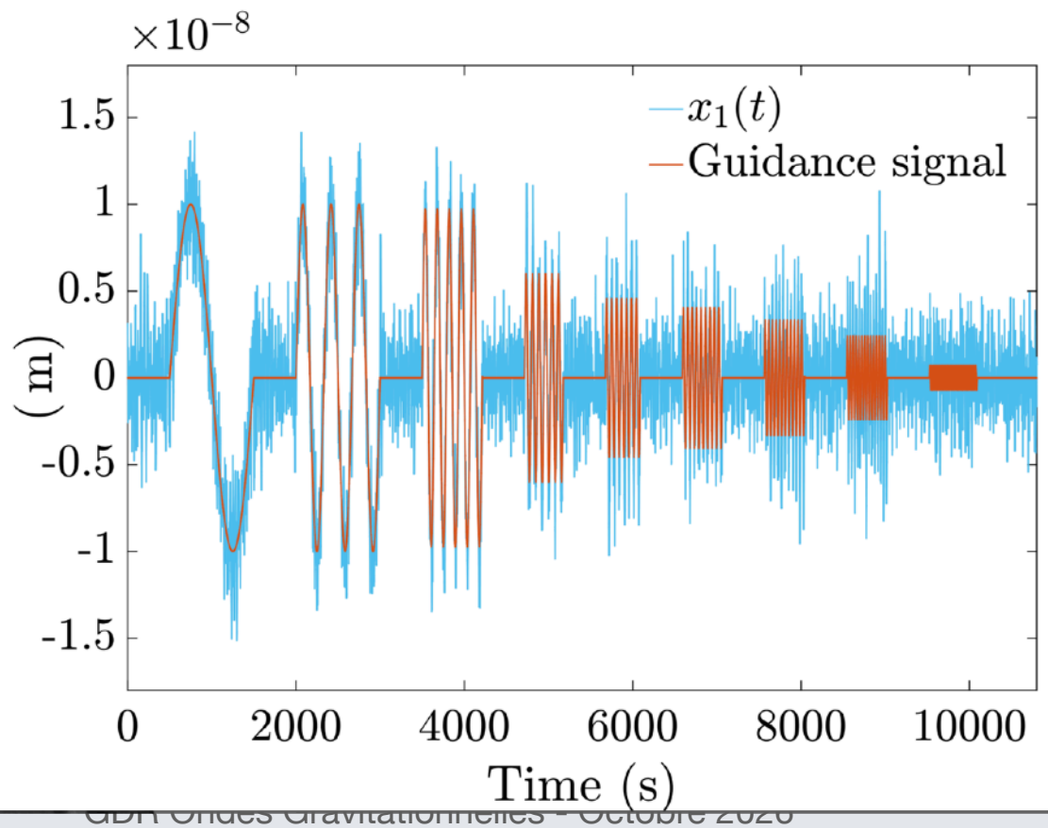
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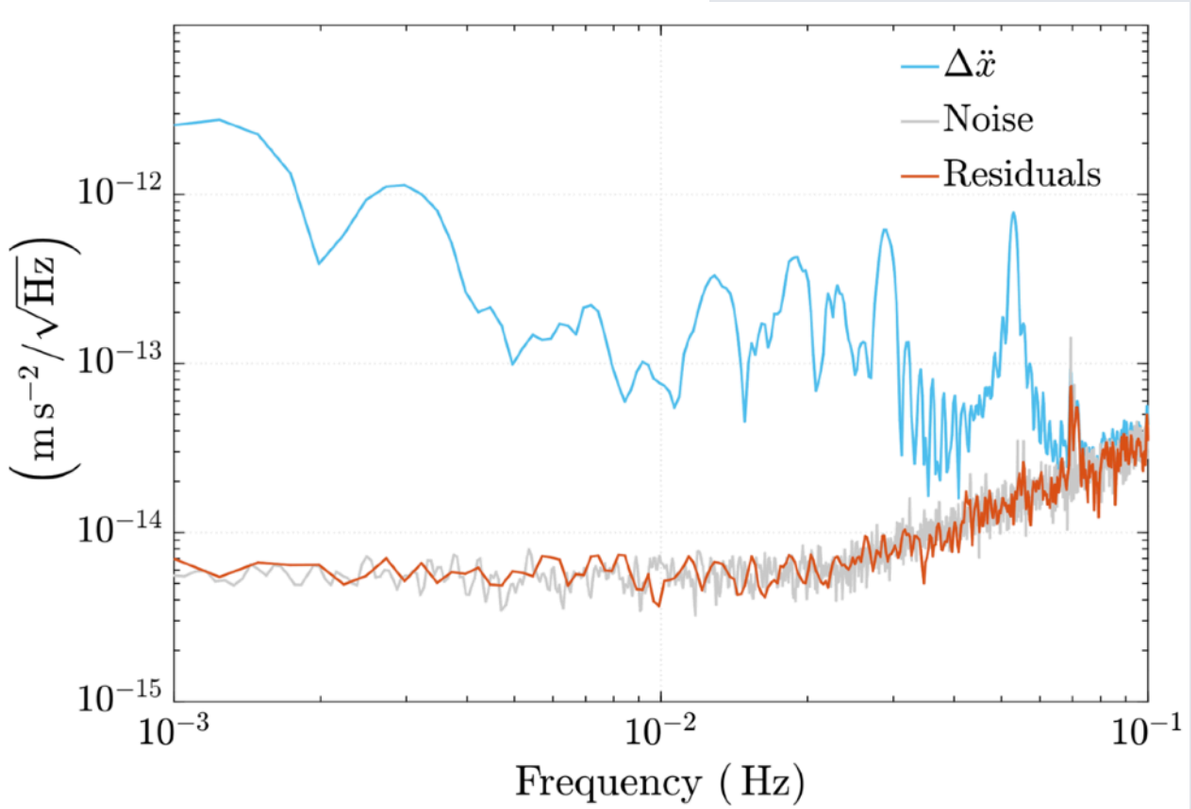


Stiffness Investigation

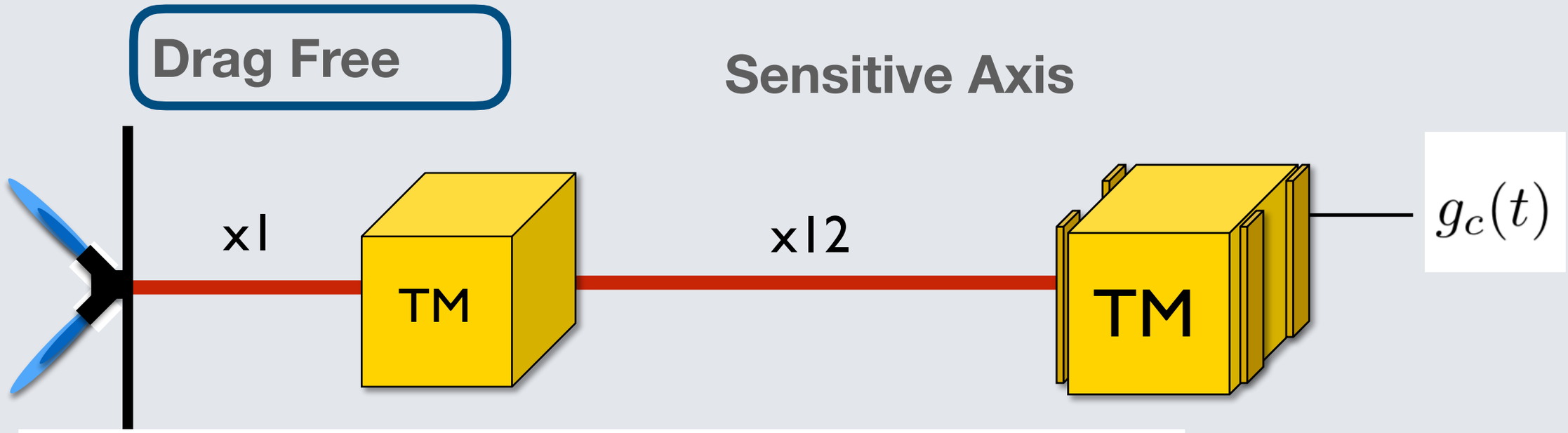


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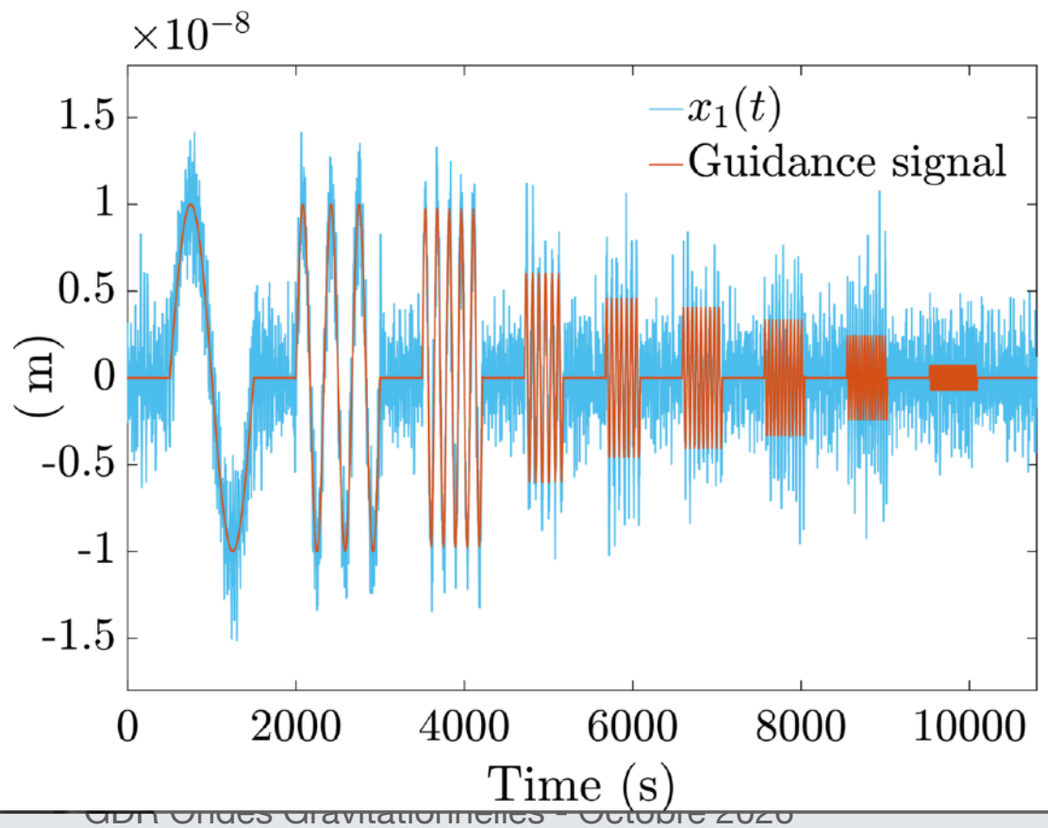


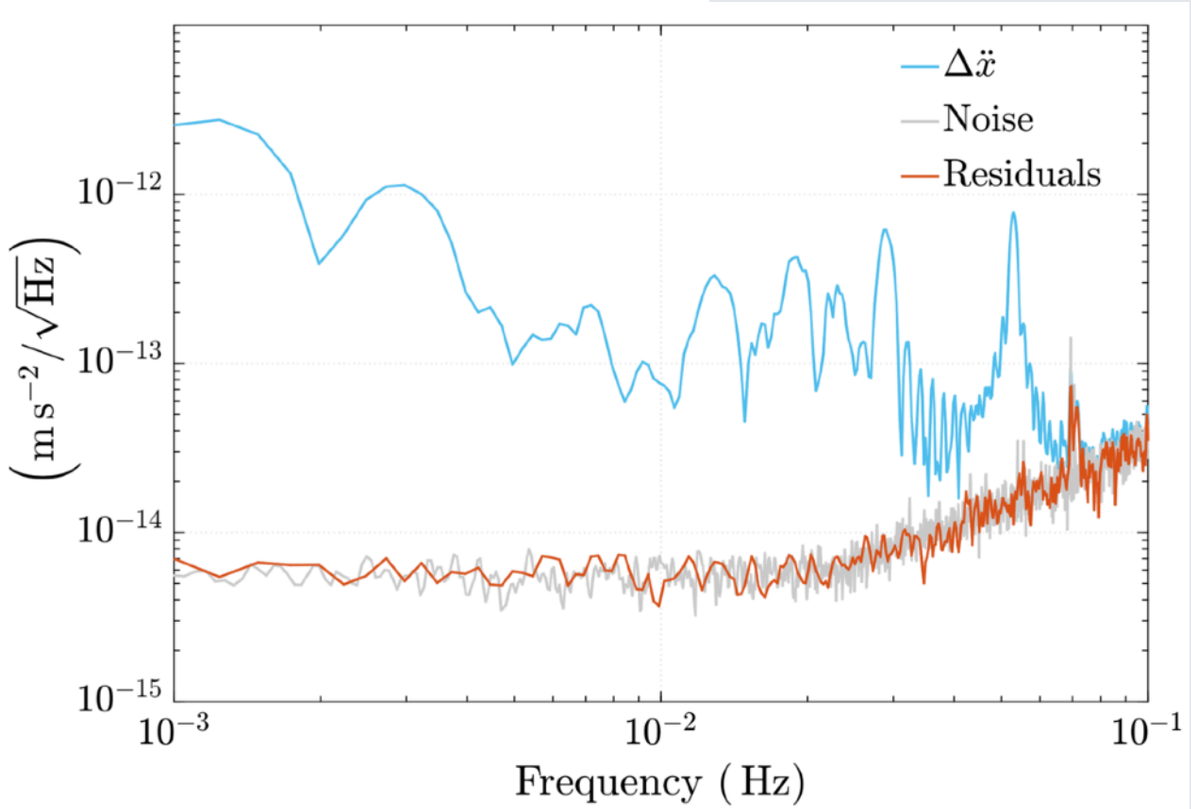


Stiffness Investigation

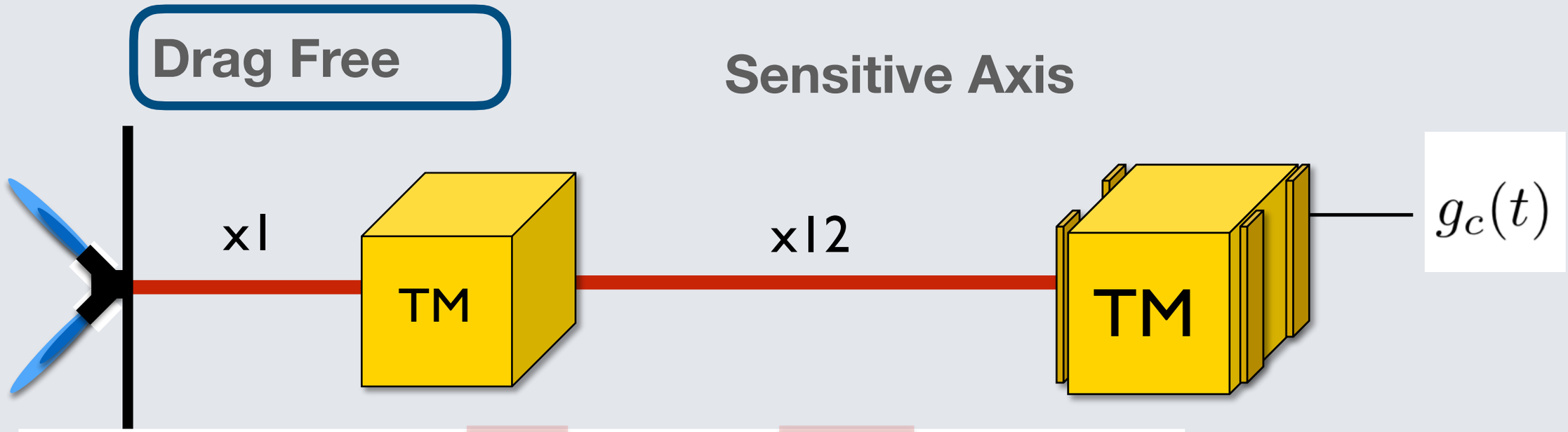


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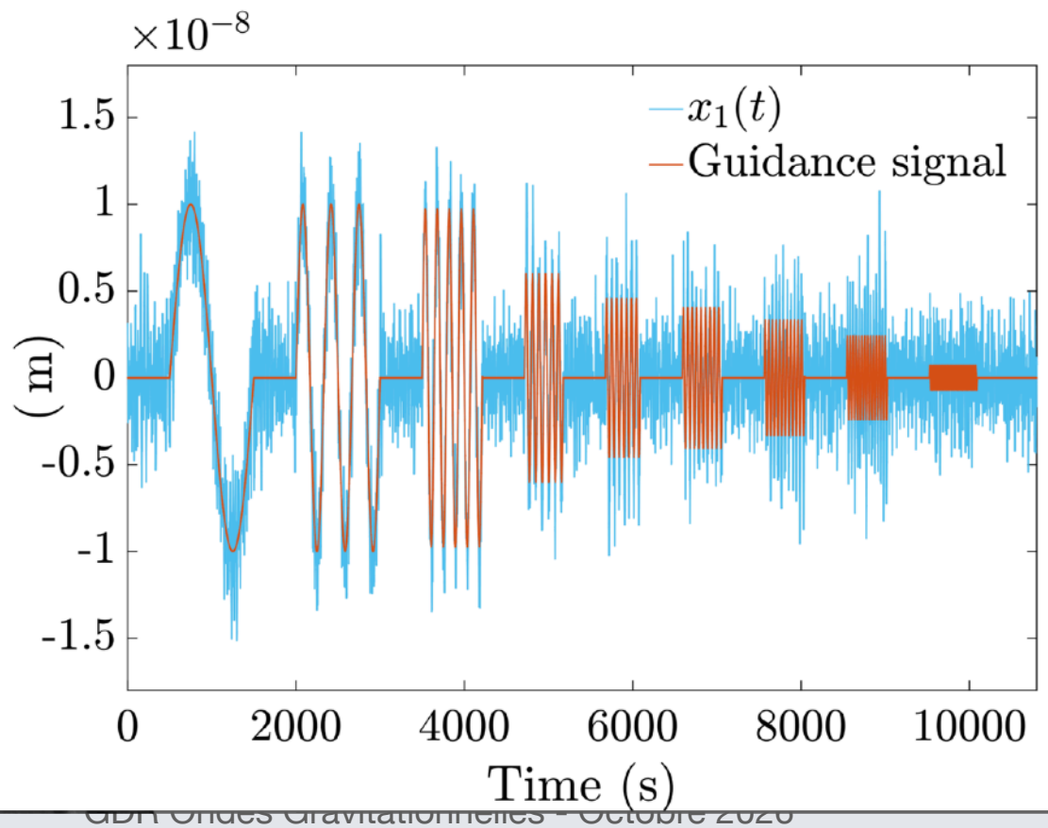


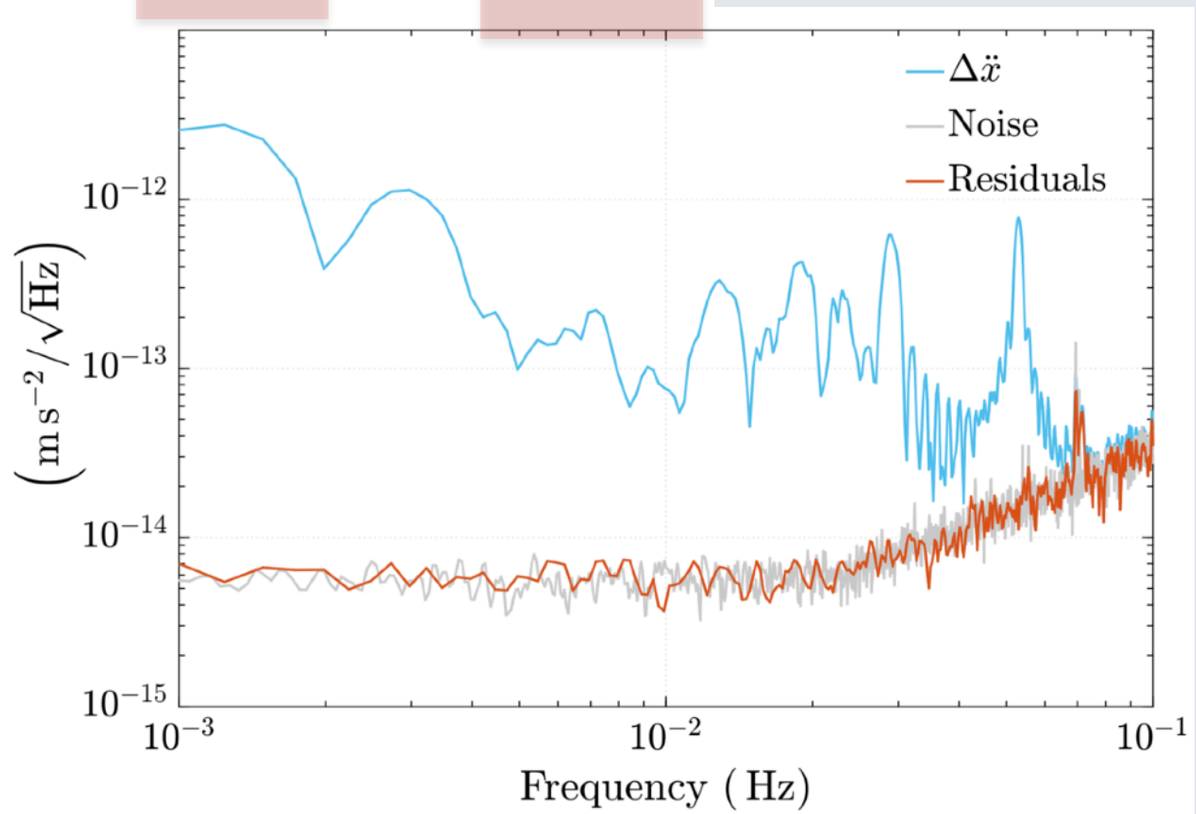


Stiffness Investigation



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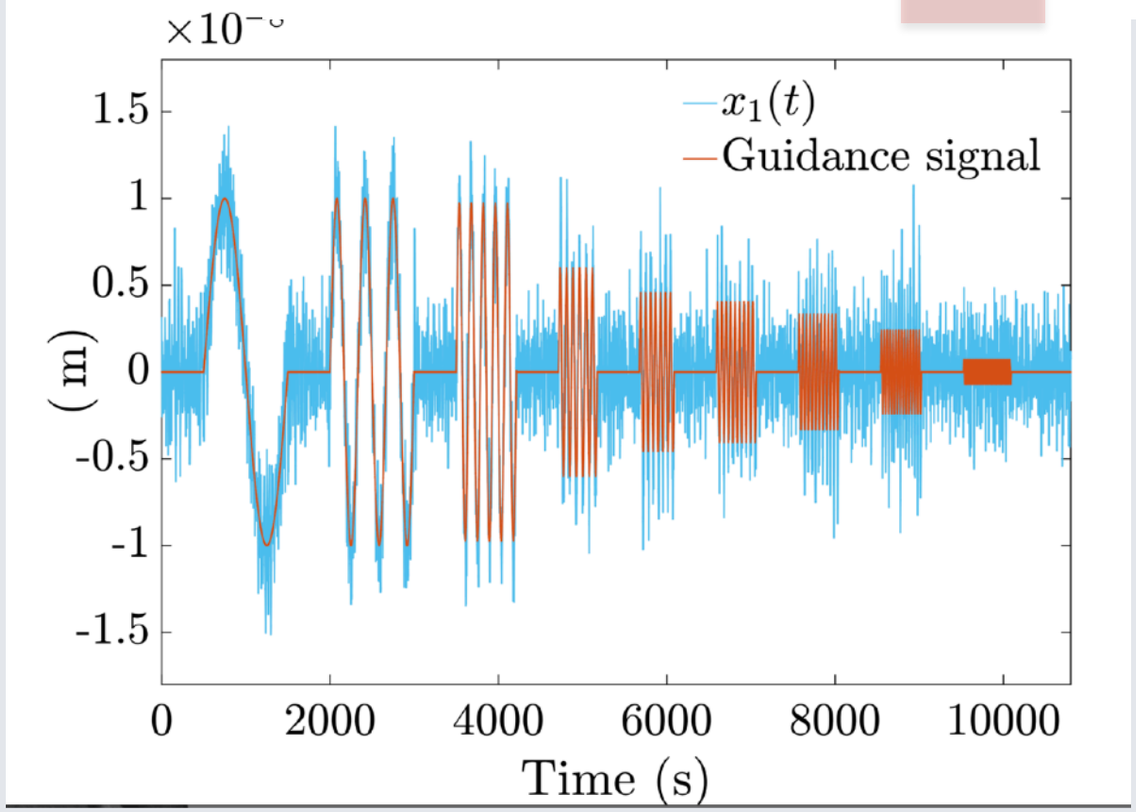




Stiffness Investigation



$$\Delta g(t) \equiv \Delta\ddot{x}(t) + \omega_2^2 \Delta x(t) + \Delta\omega_{12}^2 x_1 - g_c(t)$$



Results:

$\Delta\omega_{12}^2 \approx 0/s^2$ differential stiffness almost perfect balancing

$\omega_2^2 \approx 500 \cdot 10^{-9}/s^2$ dominated by gravitational stiffness within 10% of modelling.

Tools to validate investigations

SSM (in LTPDA)

Linear models, on my own computer

- Easy and fast
- Pipeline design and validation
- Limit: no telemetry, no full spacecraft

OSE (industrial)

Non-linear simulator, run by ESA

- Realistic, close to the real spacecraft
- Same data formats as in flight
- Limit: black box, outputs only

LTPDA: the common framework

Analysis objects with full history

Shared data repository

Same pipeline, sim and flight

Full rehearsal: the SOVT

Science Operations Verification Test: a formal end-to-end test of the science ground segment

WHAT IT DEMONSTRATED

Command planning
Plan, validate and upload payload requests

Data retrieval
Downlink, process and deliver science data

Analysis loop
Near-real-time analysis feeding the next runs

WHO TOOK PART

Industry
Real-time Testbed

MOC
Commands the spacecraft

STOC
Scheduling, data delivery

Analysis teams
Science data analysis

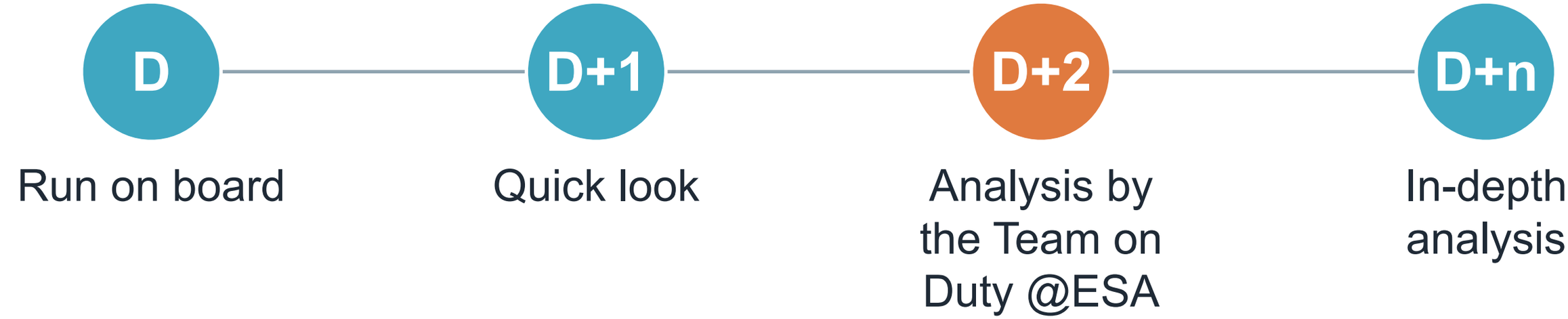
These end-to-end campaigns debugged the simulators and taught us to work as one team

The life cycle of an investigation

BEFORE FLIGHT

Design → Pipeline + validation on SSM → OSE simulation by ESA → Validation → Presentation to the PI team → Planning request to ESA

IN FLIGHT



Mixed shift teams

Team leader
Expert of the subsystem under test

Two analysts
Often from two other institutes

Report at 17:00
Results feed the next planning

Human benefit: a global view of the whole experiment

MY SHIFTS, MARCH–JUNE 2016

Dates	Investigation	With
10–11 Mar	Charge estimation, guidance	Trento
5–6 Apr	System identification, noise	APC, Trento
22–24 Apr	Long charge estimation	Imperial
26–27 Apr	Thrusters, TM2 x-scan	APC, Trento
26–29 May	Stiffness, thermal injections	Trento, ICE
2 Jun	Laser radiation pressure	APC, AEI
17–19 Jun	Noise with large x-bias	Imperial, AEI

In parallel, in the labs: in-depth analysis, next tests and test requests

Then reality kicked in

Scripts rarely used as-is

Almost none of the prepared scripts ran unchanged. Not a problem: tools and organisation were run in.

Unplanned investigations

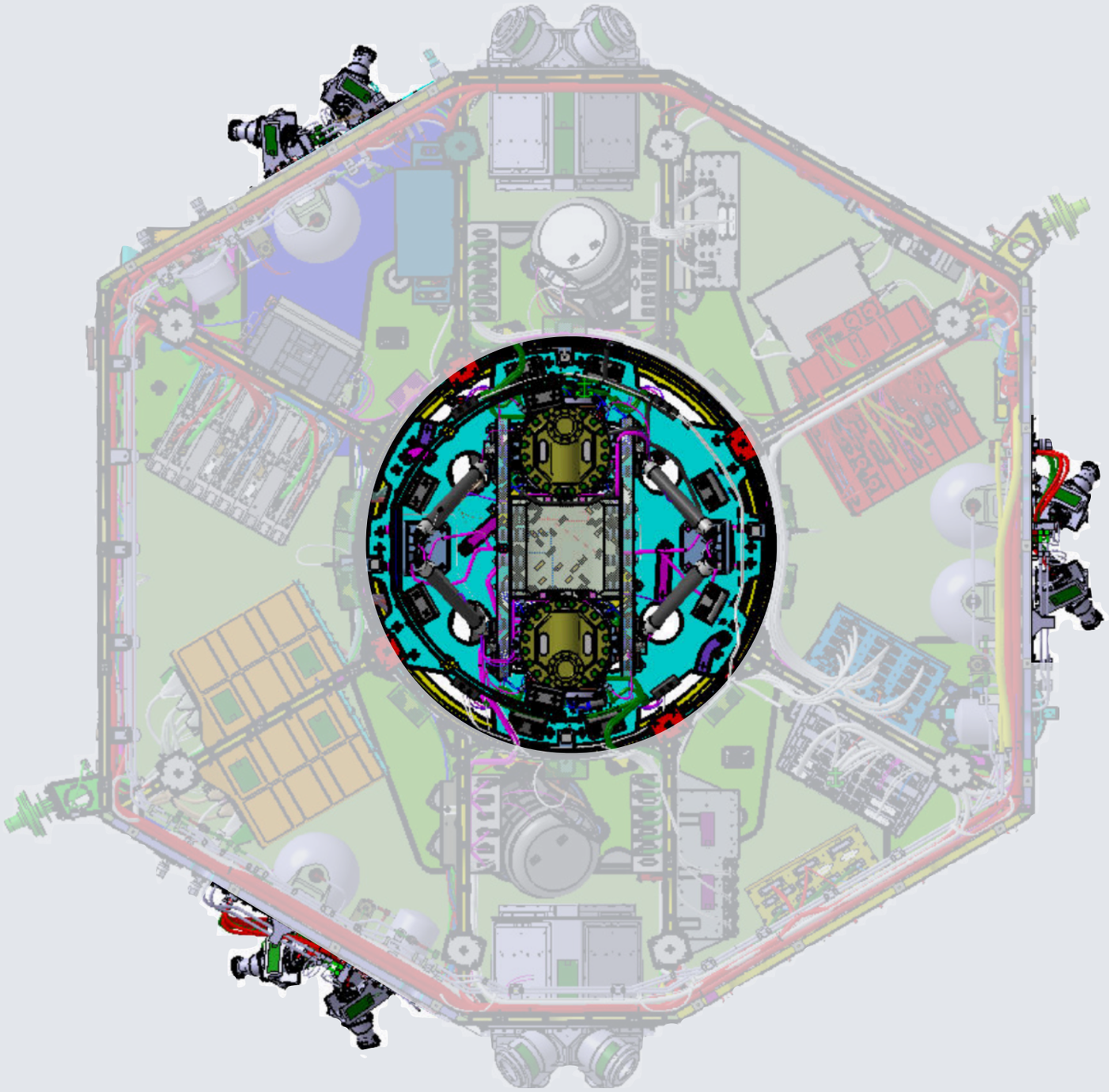
Some came up in flight. Example in detail: thruster noise and lines.

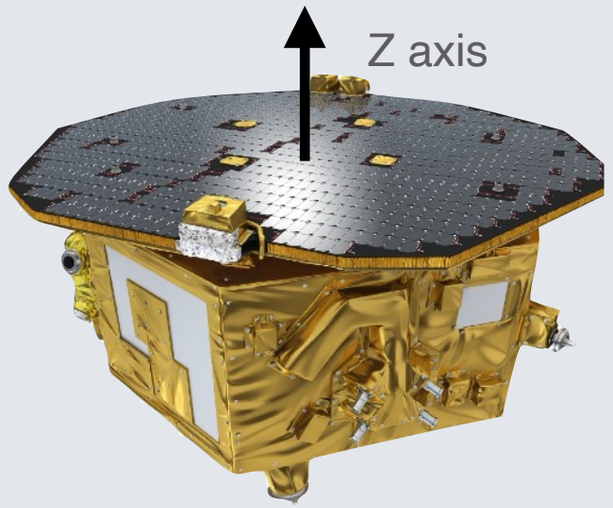
Safe modes

When problems occurred, the team around the PI gathered directly in Darmstadt.

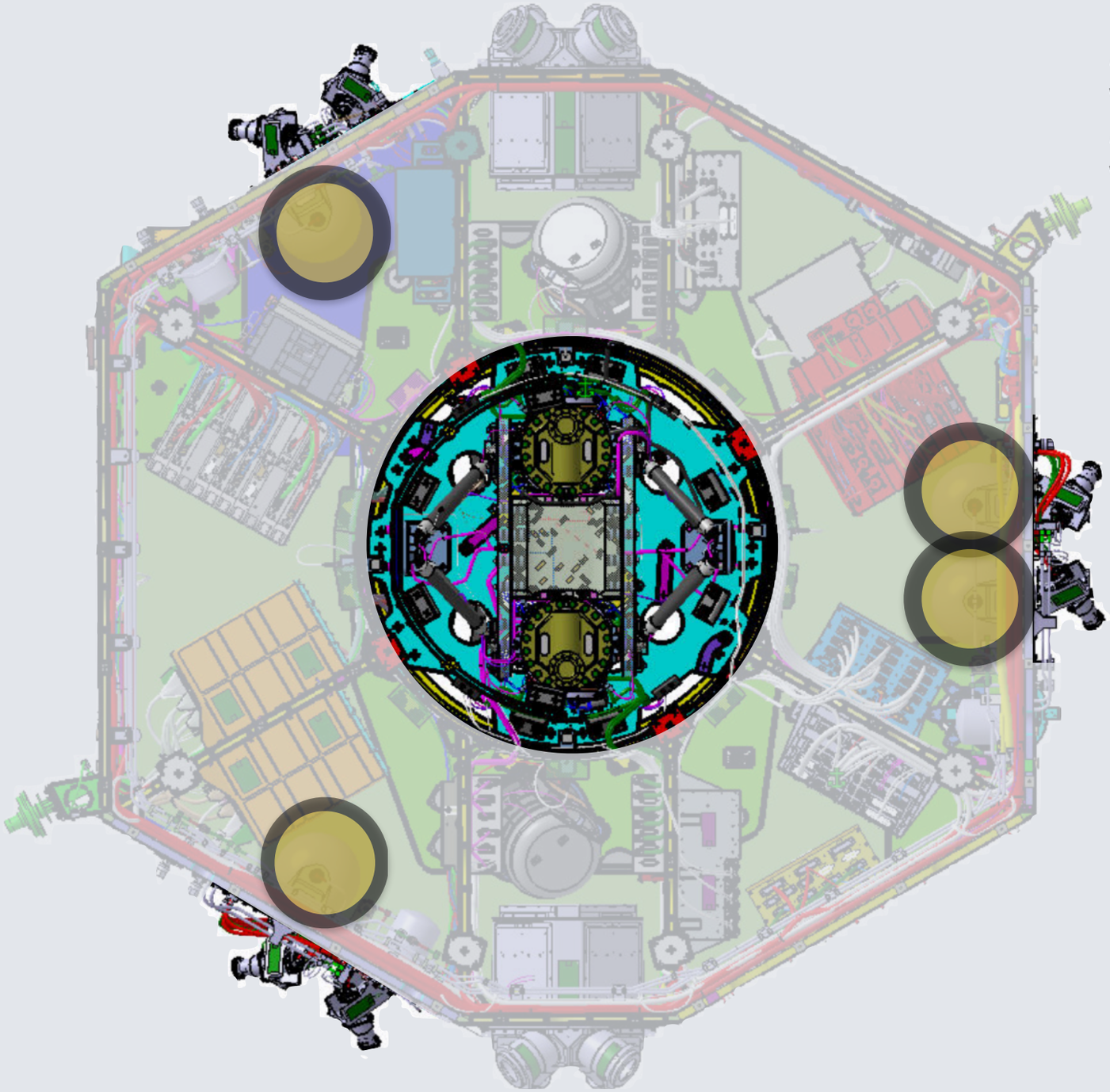
Unplanned Experiment
Thruster Lines

Thrusters in LPF

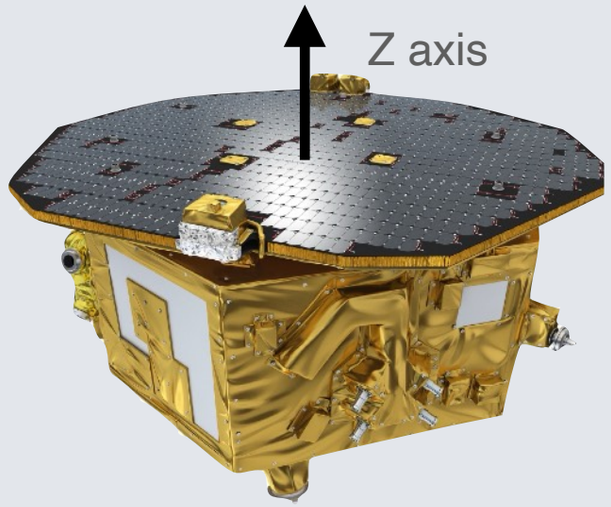




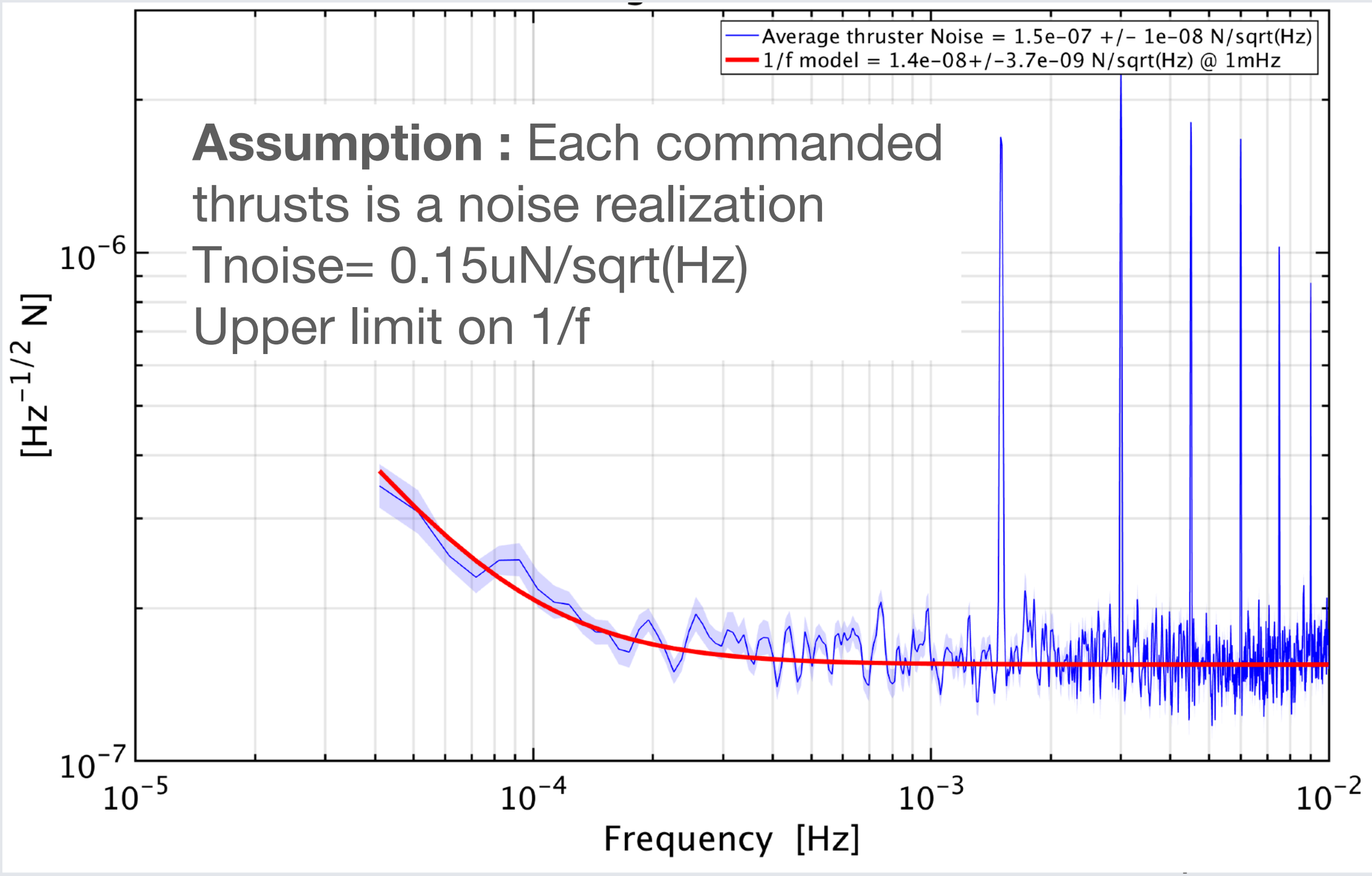
Thrusters in LPF

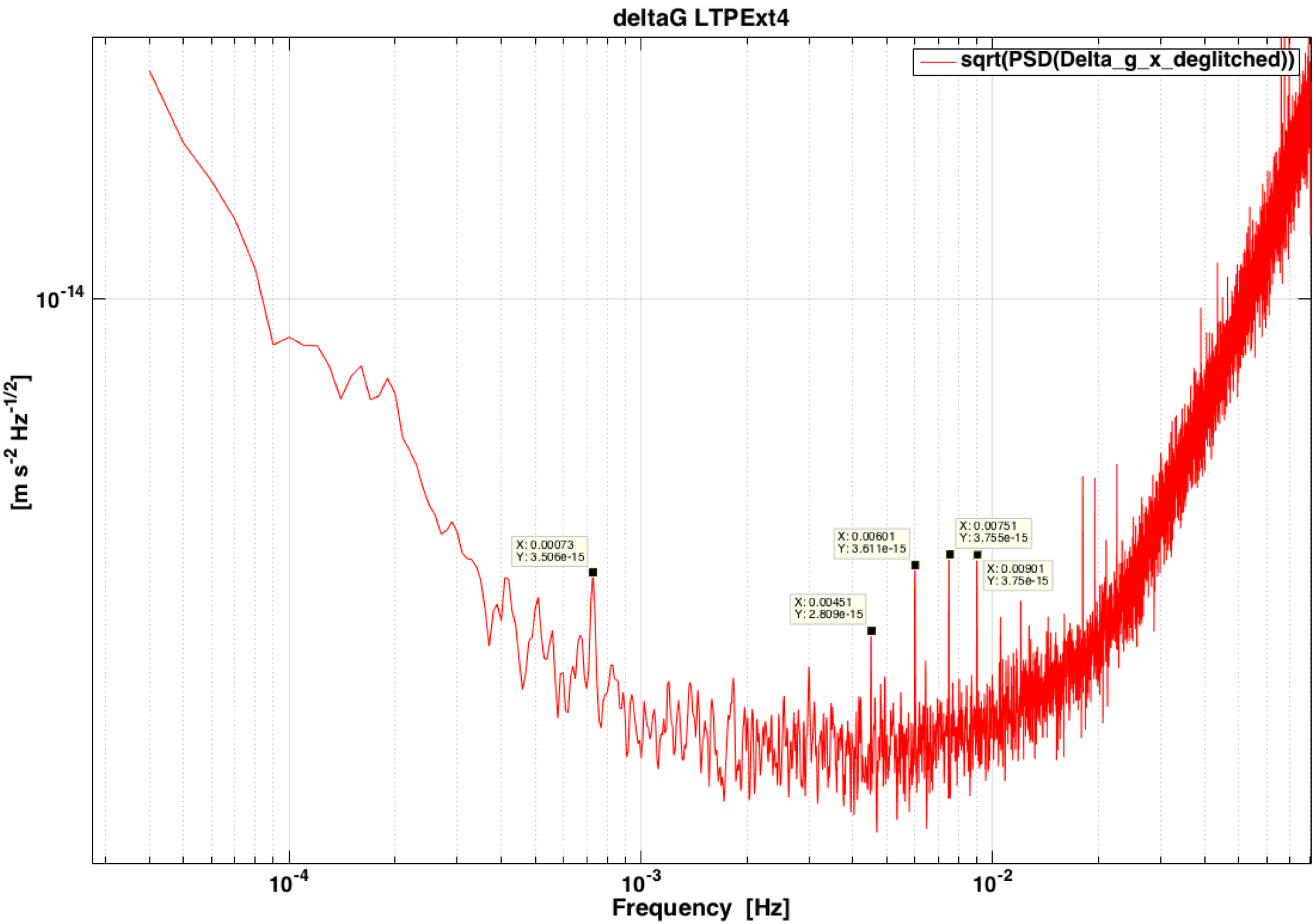


300 bars Nitrogen Tanks (8kg)
3 independent gas feedlines

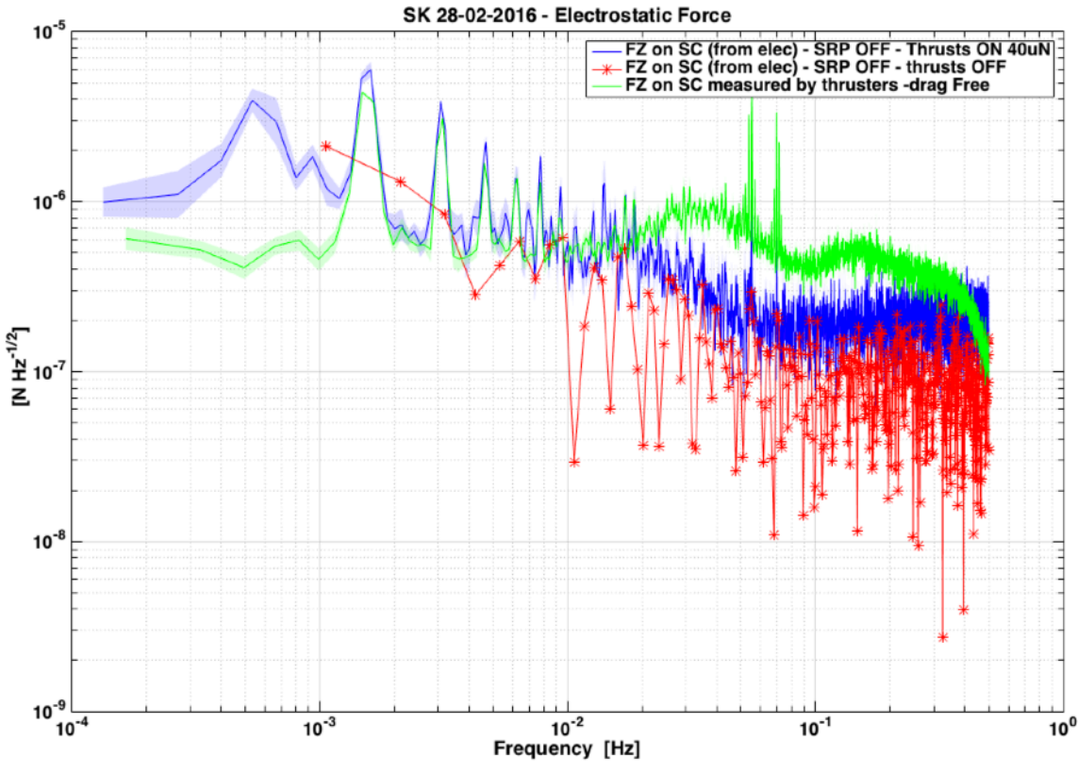


Average Thruster Noise



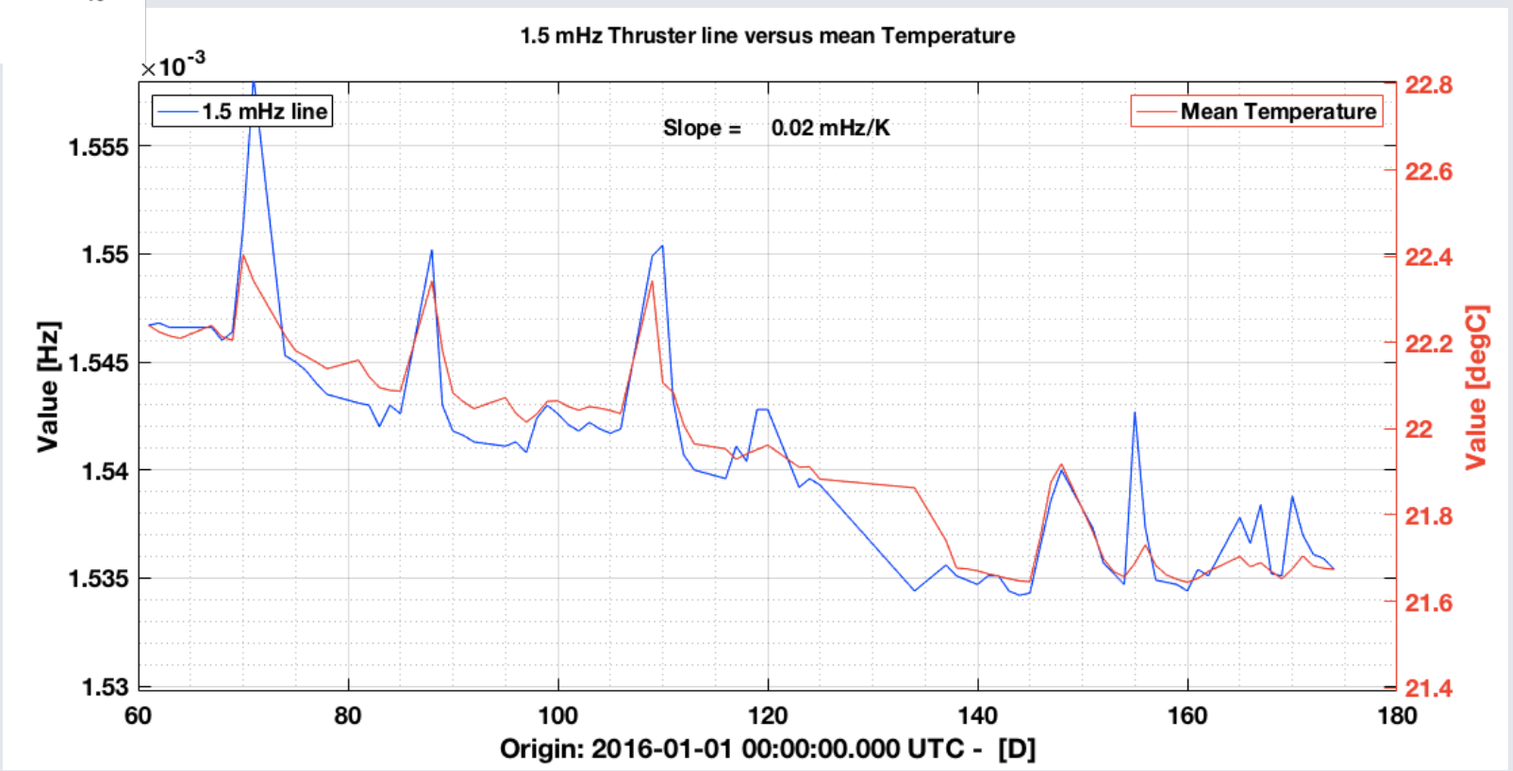

deltaG LTPExt4
sqrt(PSD(Delta_g_x_deglitched))
10^-14
[m s^-2 Hz^-1/2]
X: 0.00073
Y: 3.506e-15
X: 0.00451
Y: 2.809e-15
X: 0.00601
Y: 3.611e-15
X: 0.00751
Y: 3.755e-15
X: 0.00901
Y: 3.75e-15
10^-4
10^-3
10^-2
Frequency [Hz]

Where does the Lines come from ?



Solar Sailing

$$\frac{\Delta f}{\Delta T} = 0.02 Hz/K$$



MicroThrusters Assembly

N2

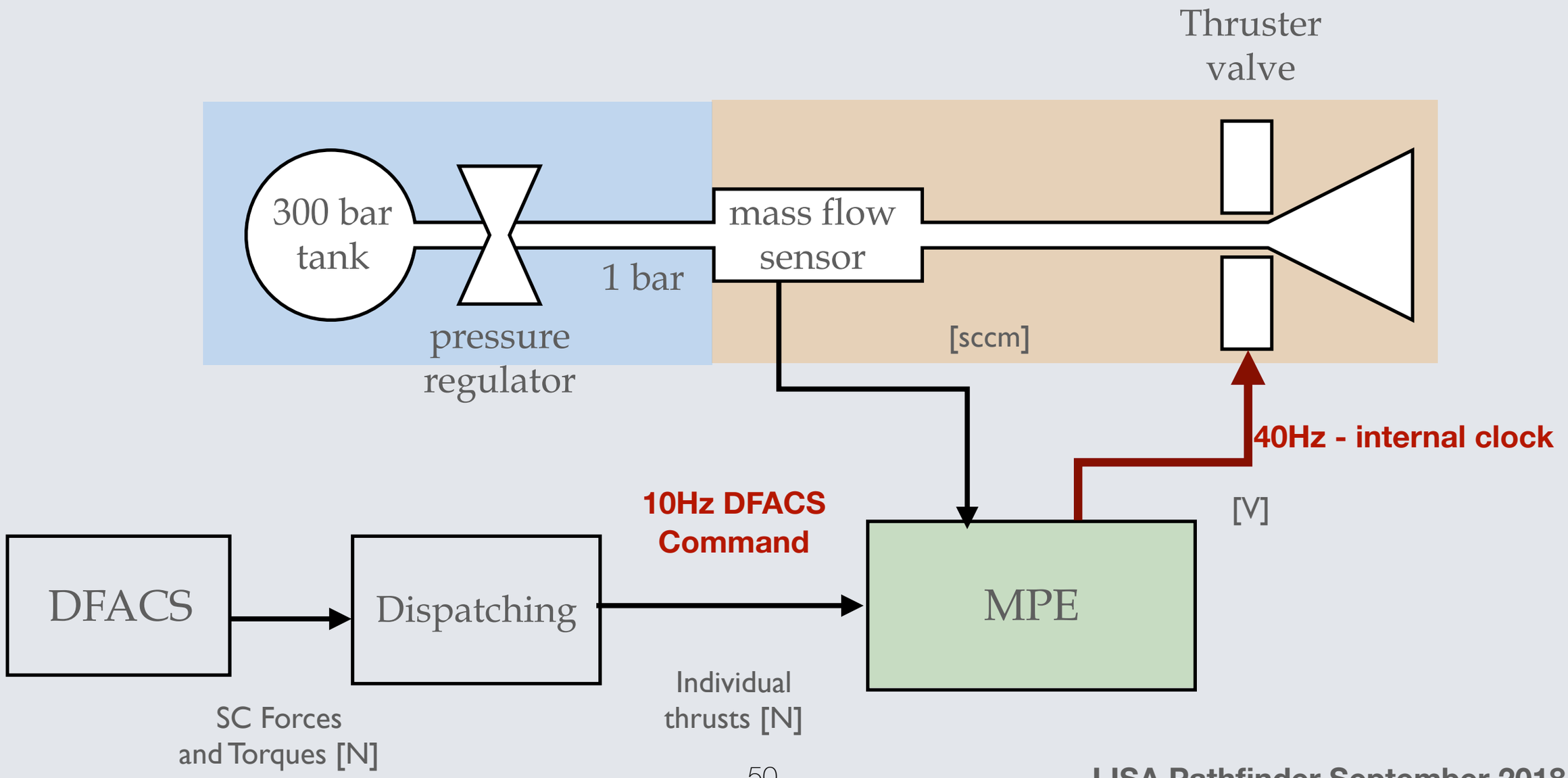
- Nitrogen storage and feed system

MTA

- Mass Flow Sensor
- Thruster Valve (TV)
- Gas filter

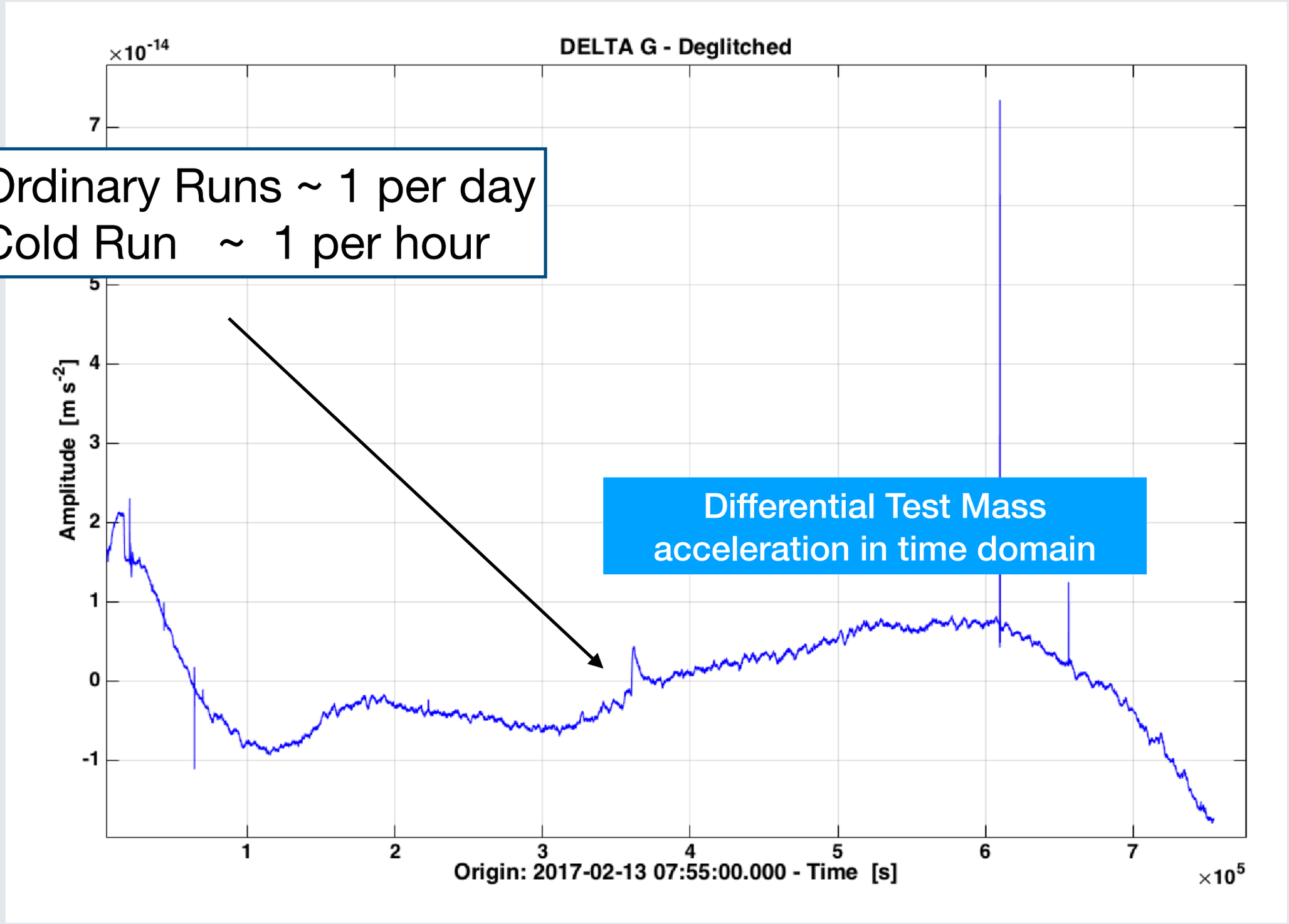
MPE

- Micro Propulsion Electronic

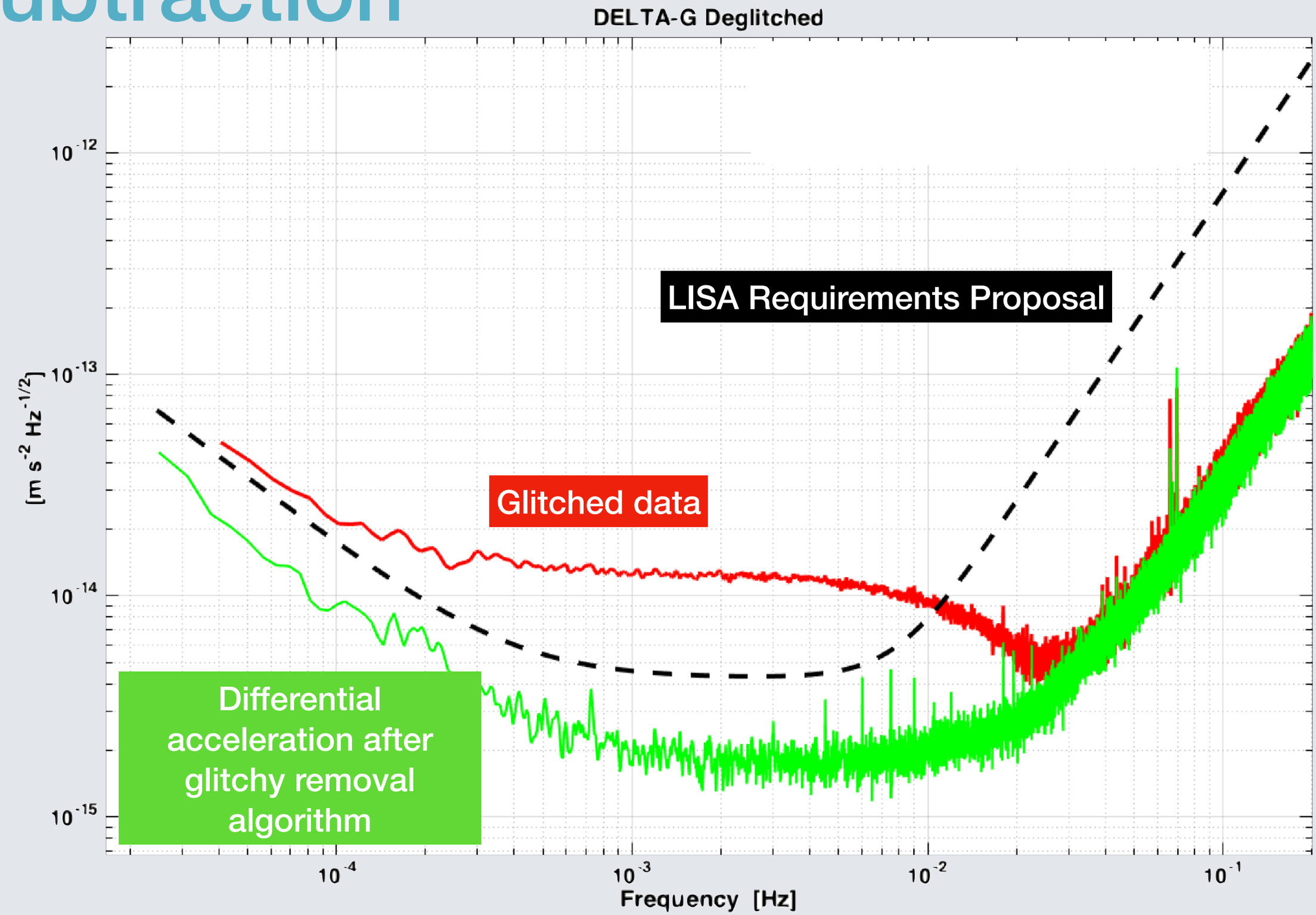


In-depth analysis
Glitches

Transients from minutes to hours

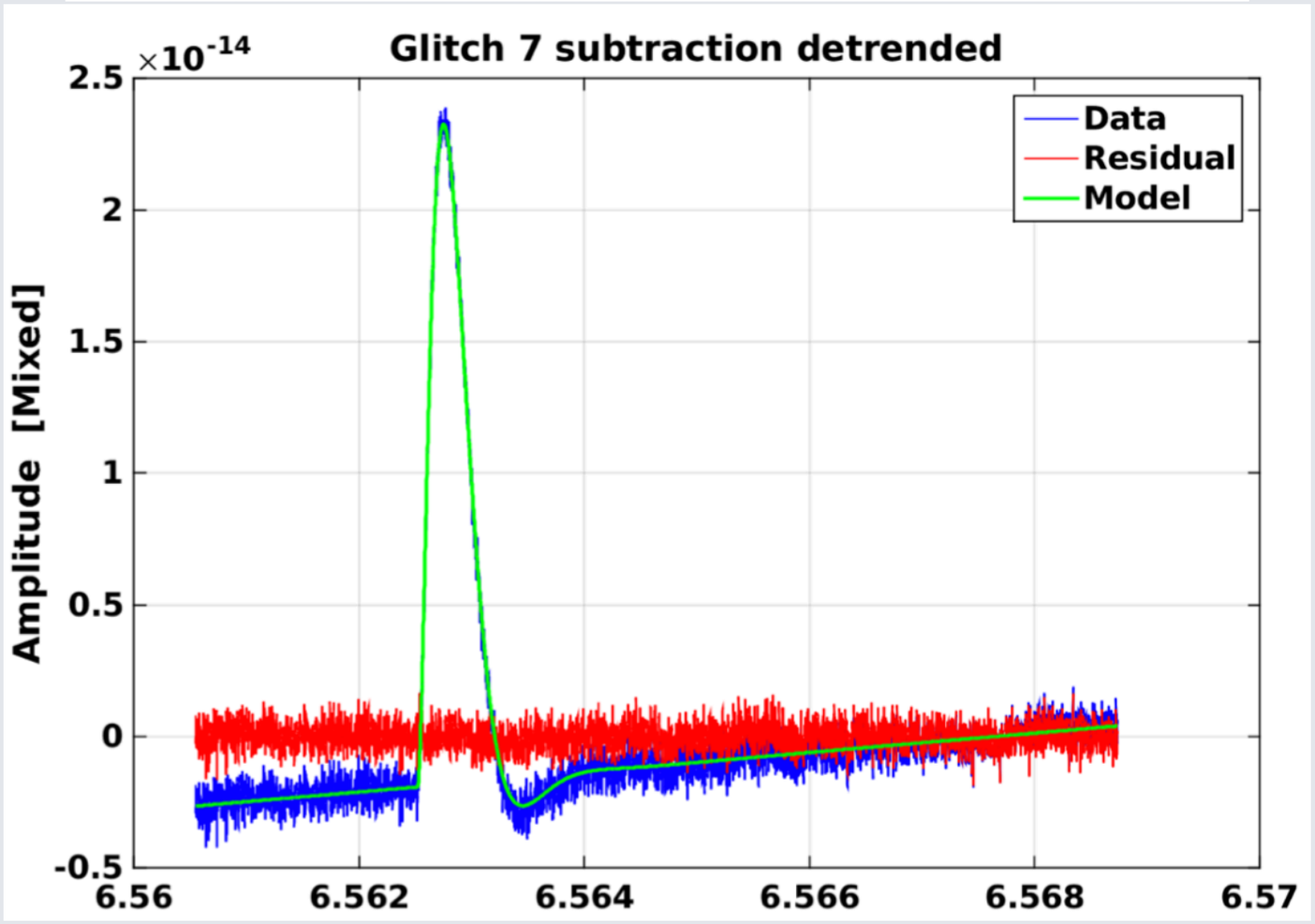


Signal dominated: requires subtraction



Transients

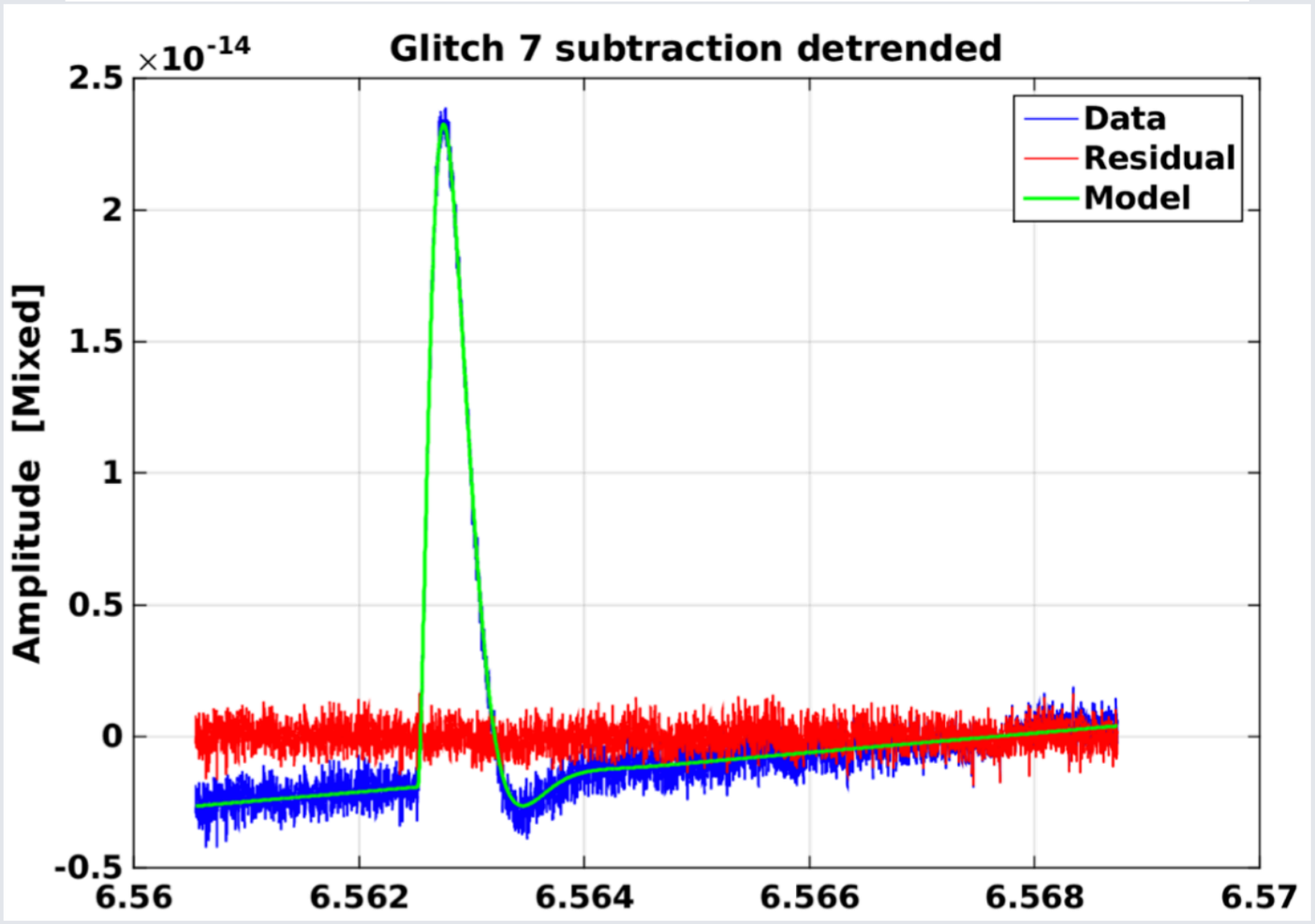
$$h_2(t) = \frac{\Delta v}{\tau_1 - \tau_2}\left(e^{-t'/\tau_1} - e^{-t'/\tau_2}\right)\Theta(t'), \quad t' = t - t_0,$$



- Simple analytical model with exponential decay
- Interpreted as real forces on the Test Mass: outgassing events
- Thermo-mechanical stress during cold run increase the rate

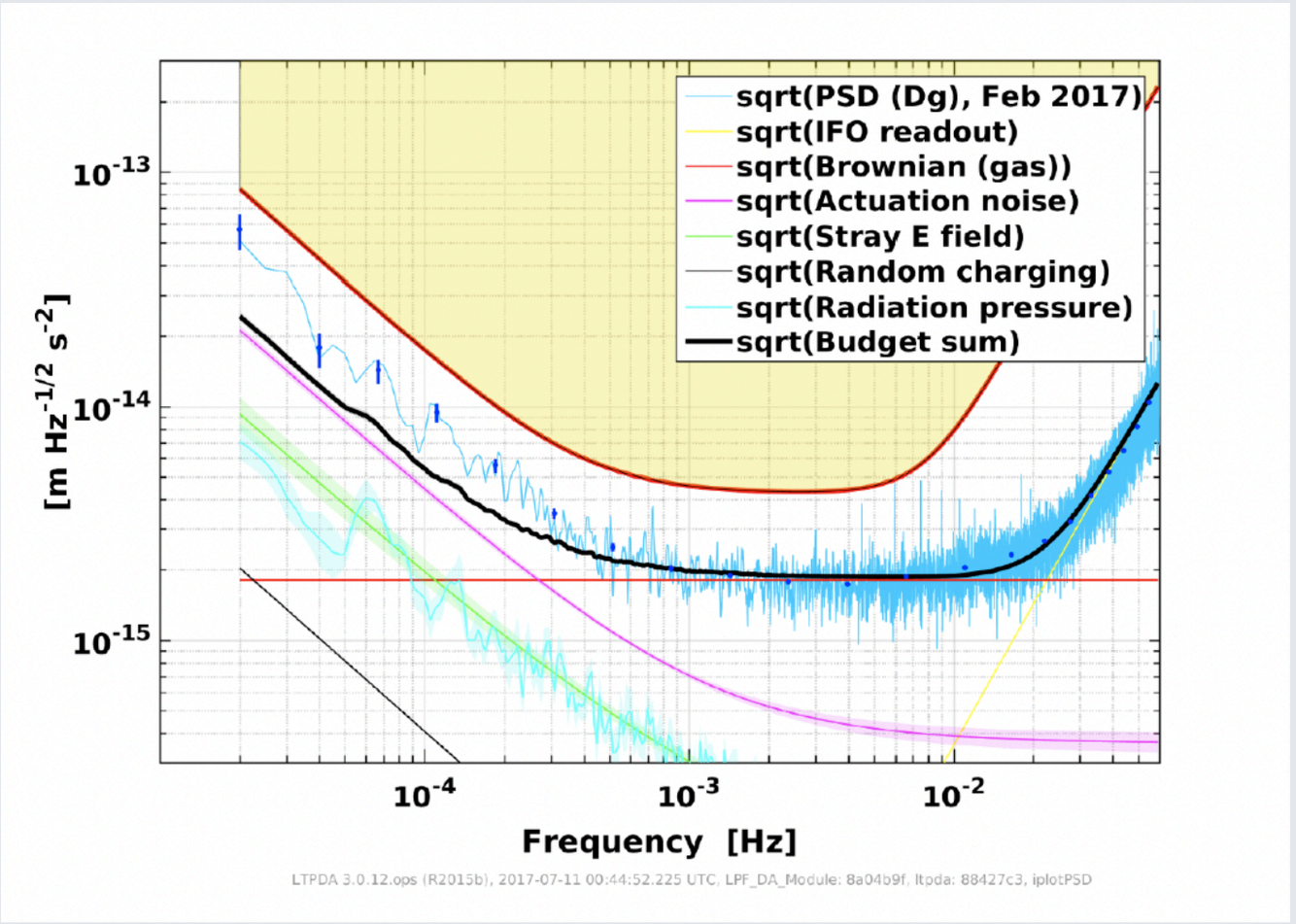
Transients

$$h_2(t) = \frac{\Delta v}{\tau_1 - \tau_2}\left(e^{-t'/\tau_1} - e^{-t'/\tau_2}\right)\Theta(t'), \quad t' = t - t_0,$$



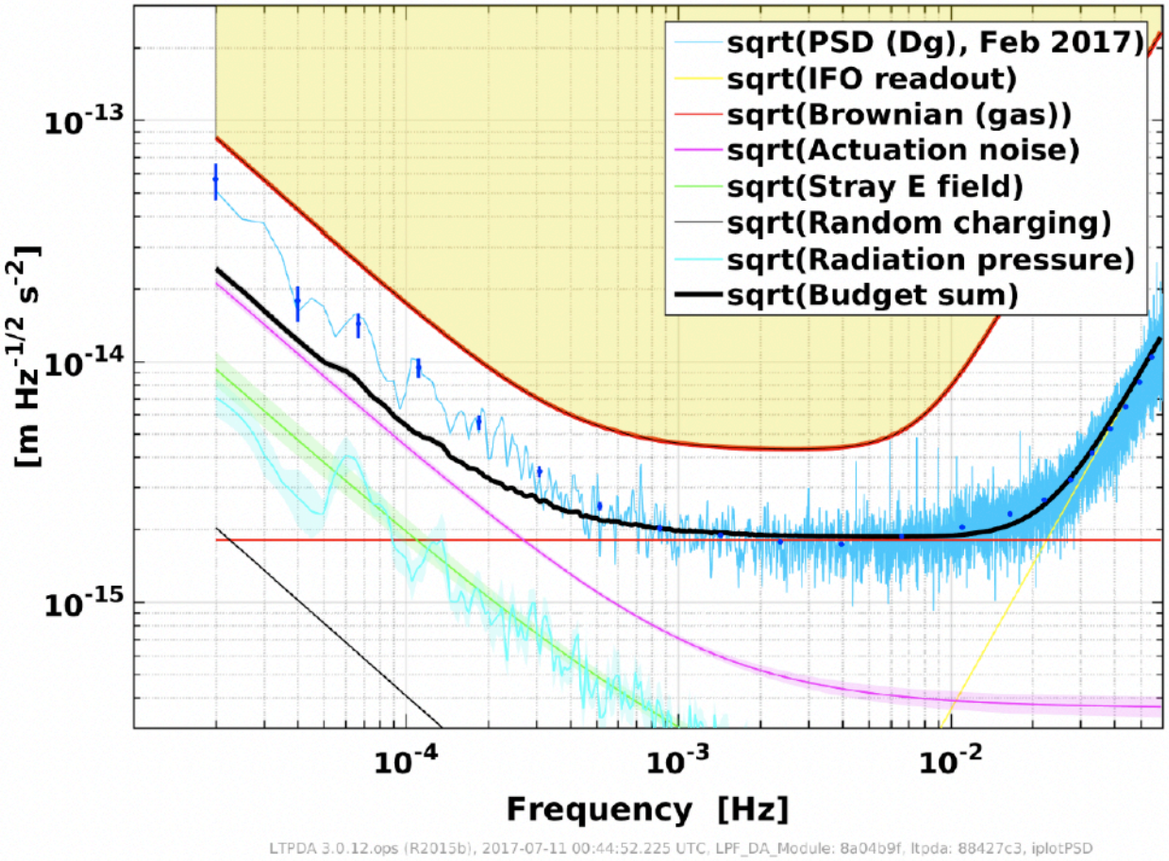
- Simple analytical model with exponential decay
- Interpreted as real forces on the Test Mass: outgassing events
- Thermo-mechanical stress during cold run increase the rate
- Challenge for LISA:
  - -> 6 Test Masses
  - -> All measured at the same time
  - -> Signal
  - -> Confirm the scenario

Projection for LISA



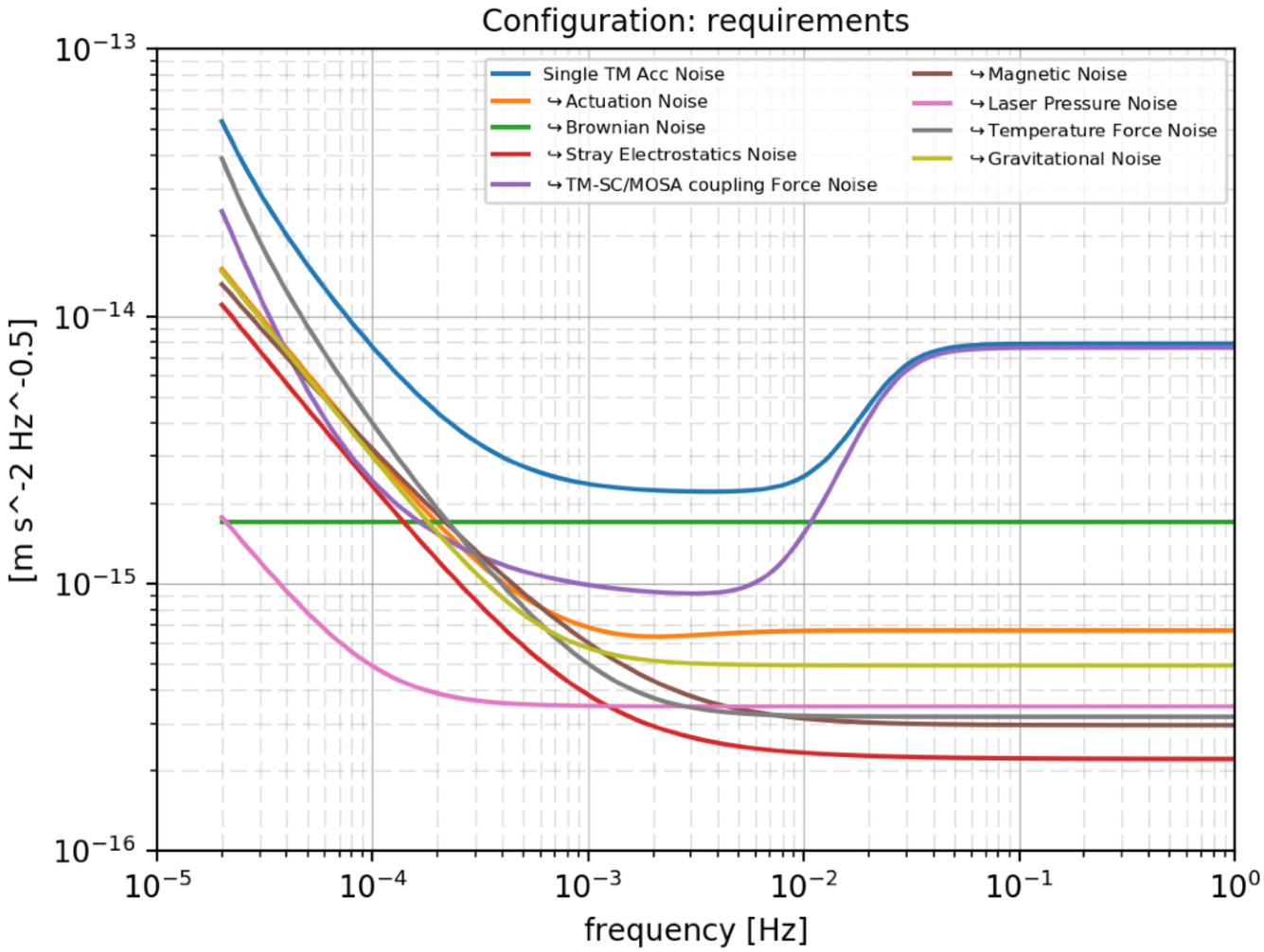
Build a budget with models and measured parameters via dedicated investigations

Projection for LISA

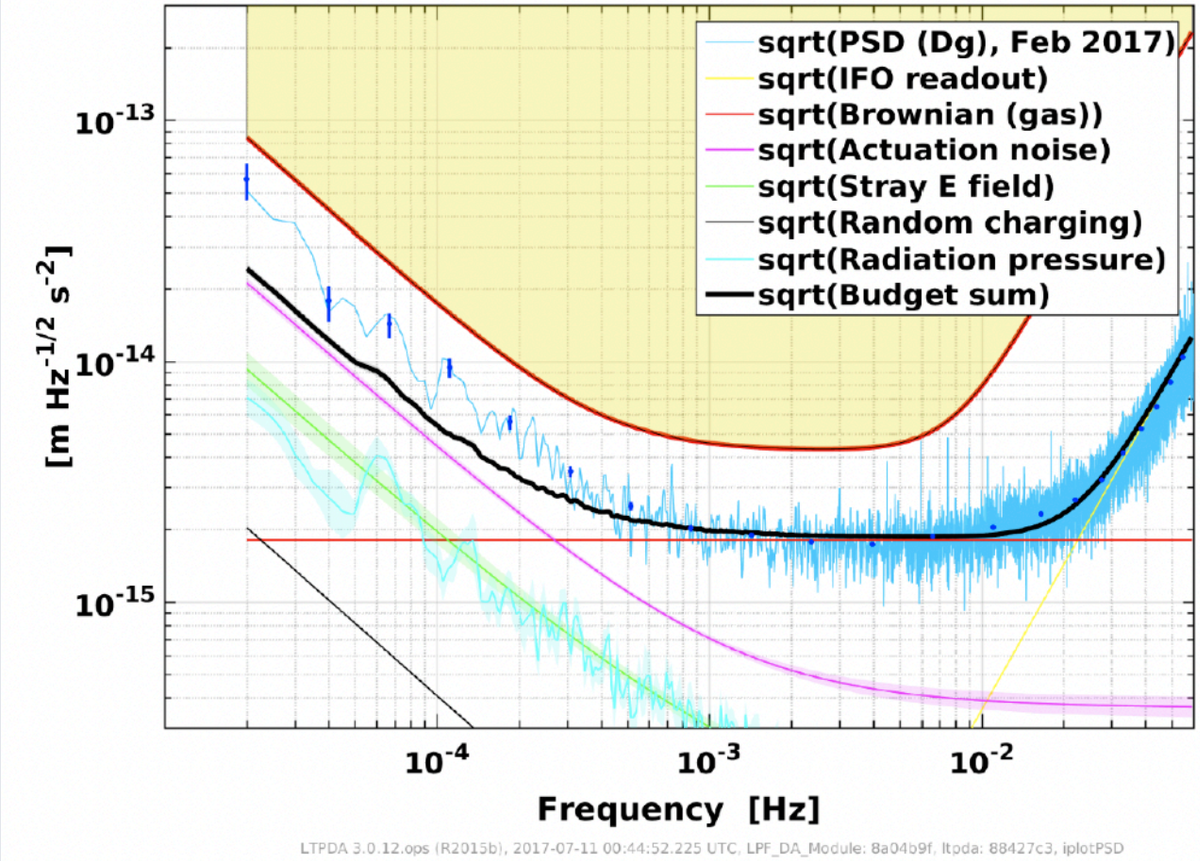


Build a budget with models and measured parameters via dedicated investigations

Same models and parameters are scaled to LISA to build the noise budget.

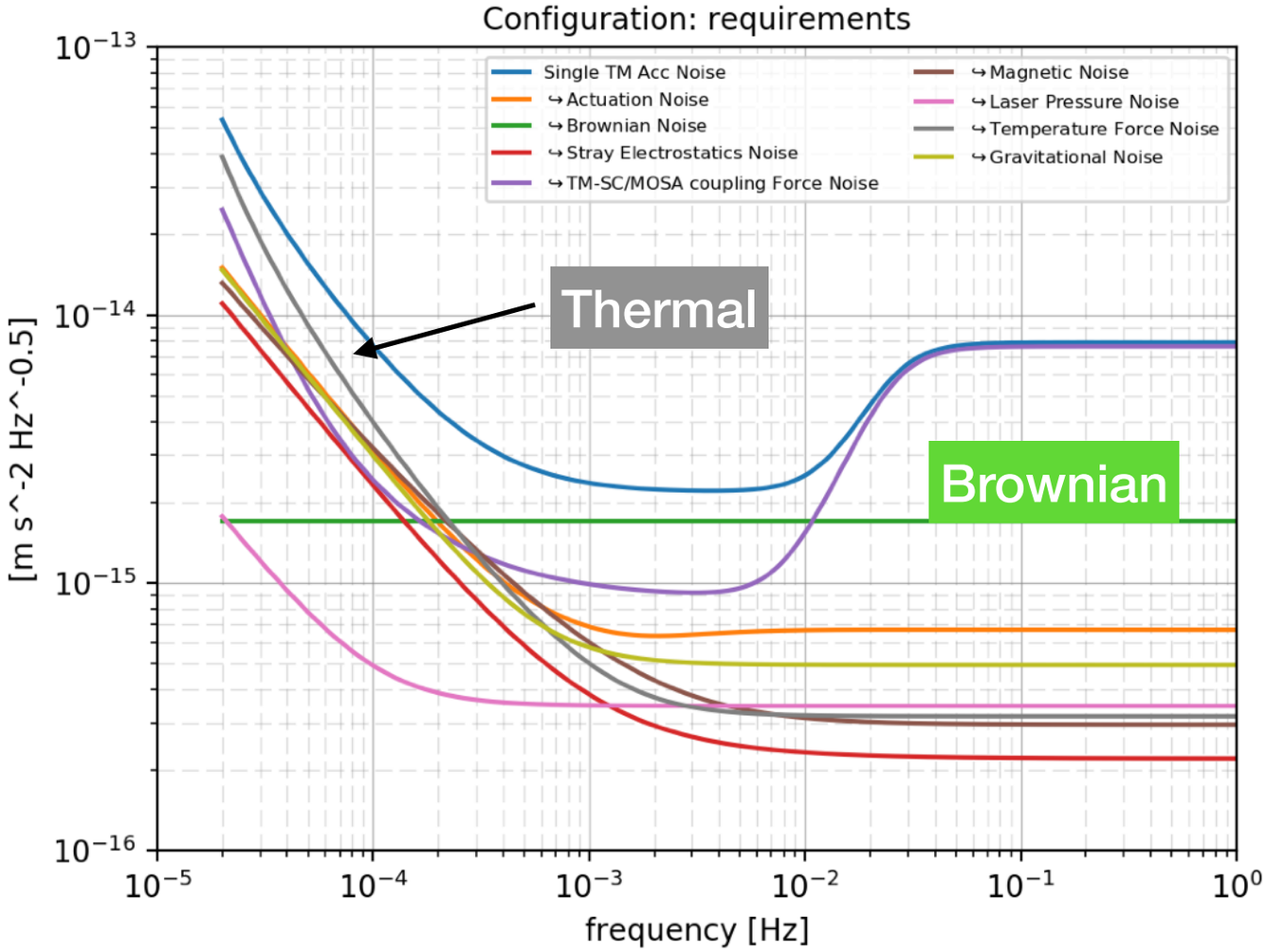


Projection for LISA

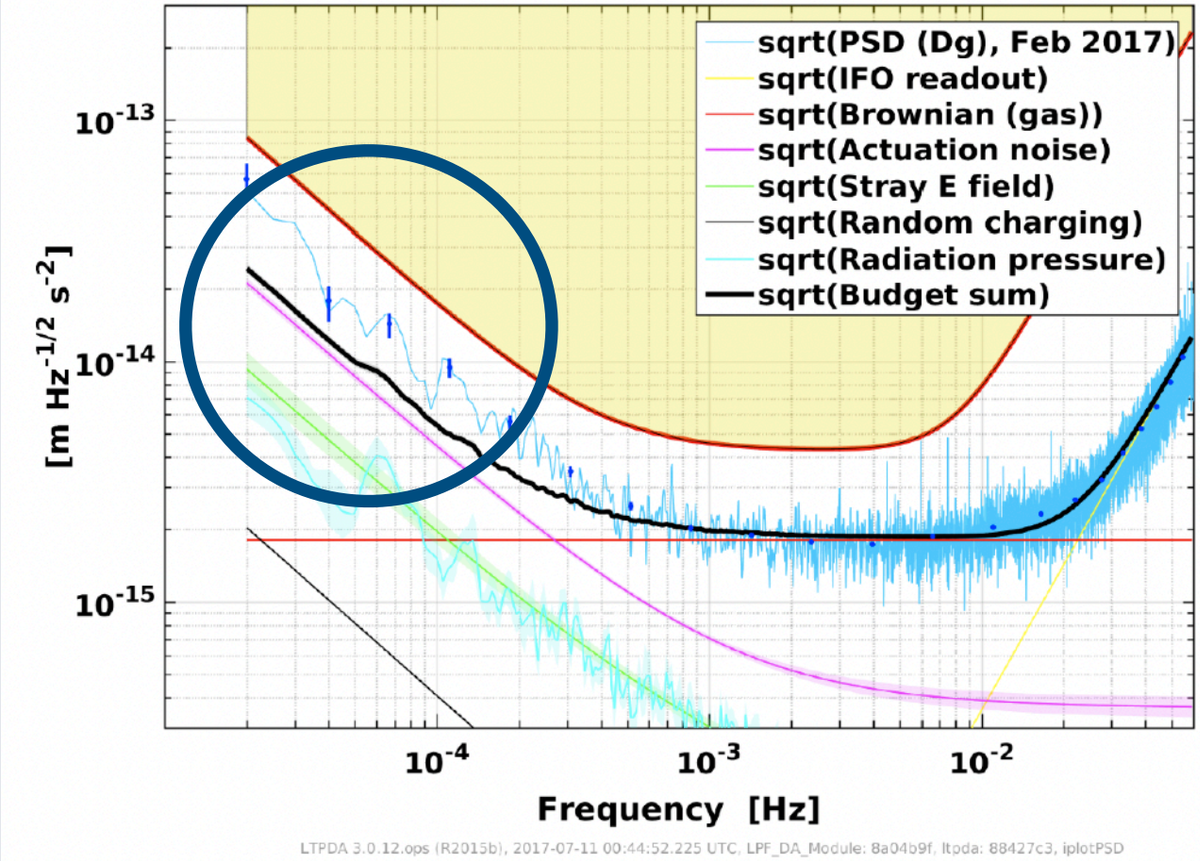


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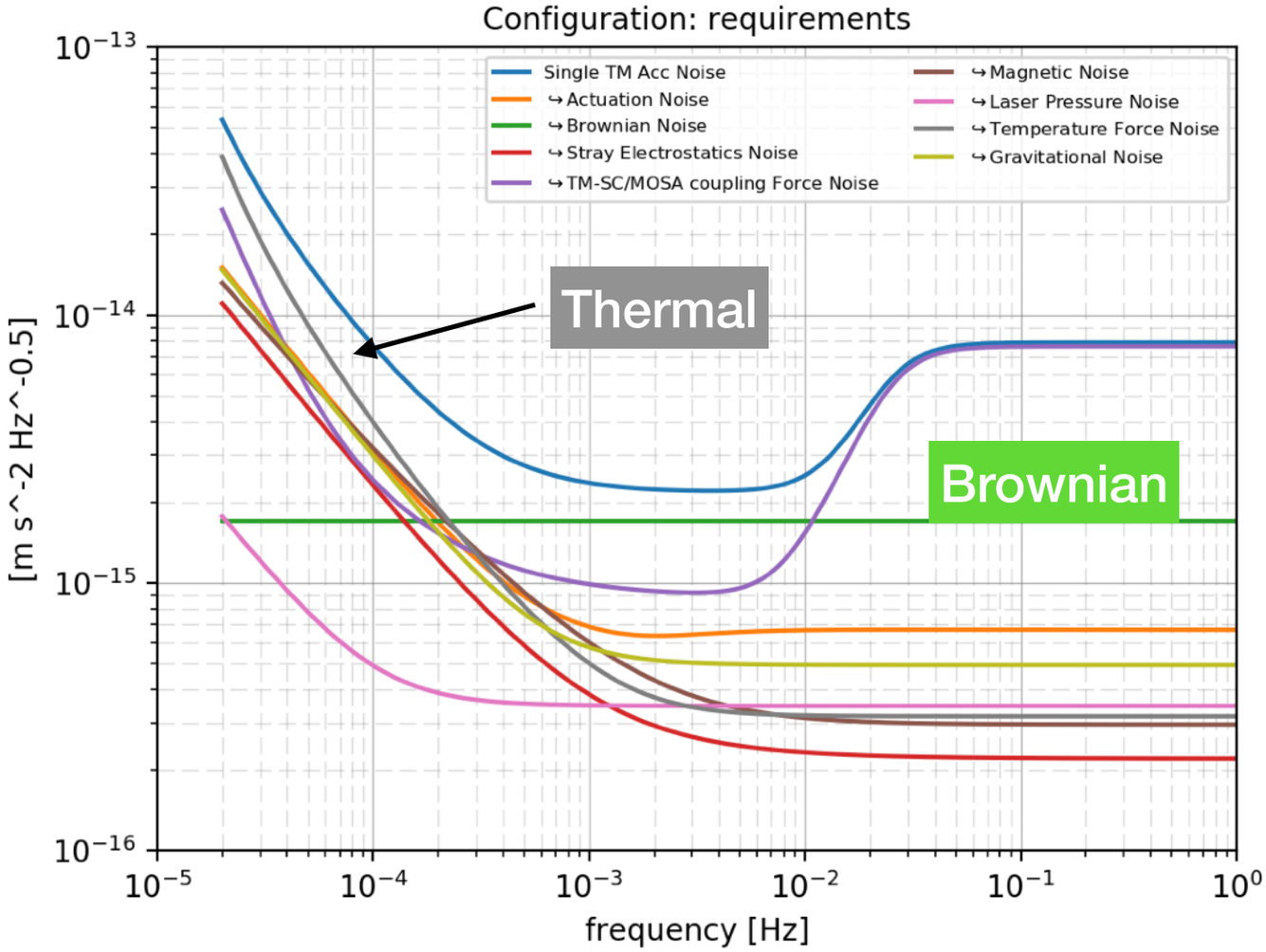


Projection for LISA



Build a budget with models and measured parameters via dedicated investigations

Same models and parameters are scaled to LISA to build the noise budget.



Not everything was solved

In-depth analysis of LPF performance (LPF Collaboration, 2024)

~50 %

of the sub-mHz excess noise explained by modelled sources

STILL UNEXPLAINED: POSSIBLE SOURCES

- Patch potential fluctuations
- Actuation electronics non-linearity
- Unmodelled gravitational noise
- Pressure fluctuations
- High-frequency magnetic fields
- Undetected glitches?

LPF beat its requirements, yet we did not model everything: stay humble

Back to Organisation

What really worked

A common environment

LTPDA: same tool, shared data repository, full history of each analysis

Pipelines readable by all

In Git, reviewed, rerunnable offline by anyone

Co-location

Fast decisions, problems solved within the day

Mixed teams

We analysed everyone's experiments: cross-checks, fast learning

End-to-end rehearsals

On day one, tools and interfaces worked

Short time, real means

Short commissioning, but a generous budget to prepare

LISA today: activities in parallel

Performance & Operations

Performance model with the full LISA noise budget, in the frequency domain

DDPC

Time-domain instrument simulation, and simulated data processing from L0 to L1

LISA France ground tests

BSIM: long-arm interferometer · Test Mass SIM: test-mass interferometer · SLOGSE: stray light. See Christelle Buy's talk

Data Challenge

End To End simulation for Data Challenge Aim at building analysis pipeline with simplified instrument modelling

The challenge for the coming years: making all these activities converge

Towards LISA

Uncertain

Tools, algorithms, and the problems we will face

Certain

The human side: none of us would work differently. An integrated team was among the first things back on the agenda.

BUT MUCH MORE COMPLEX

1 → 6

science interferometers

From one science interferometer on LPF to six on LISA

Source-dominated

gravitational waves

Signal likely dominant: no signal-free noise baseline as in LPF noise runs

TDI in between

post-processing

Laser-noise reduction sits between instrument experts and source-parameter extraction

What I would keep, whatever the hardware

1 Co-location

We need to be fast and close the loop.
It sets the stage for later remote work.

2 All expertise on board

Instrument experts, data analysts, noise hunters: we need all of them.

3 Mixed teams

One interconnected instrument: working in silos makes no sense at that stage.

4 Full rehearsal

If you can afford a SOVT, it is gold for building an organisation that works.

A global view of the instrument does not come overnight: train and recruit.
LPF was also a school: many of us were young then… a little less today.