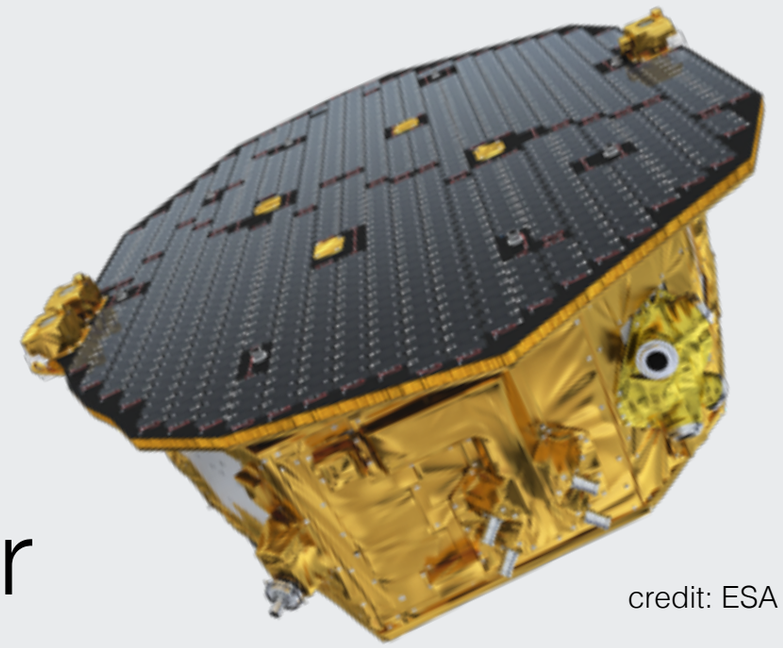
Albert Einstein Institute

DLR

Bundesministerium für Wirtschaft und Energie

lisa pathfinder

LISA Pathfinder



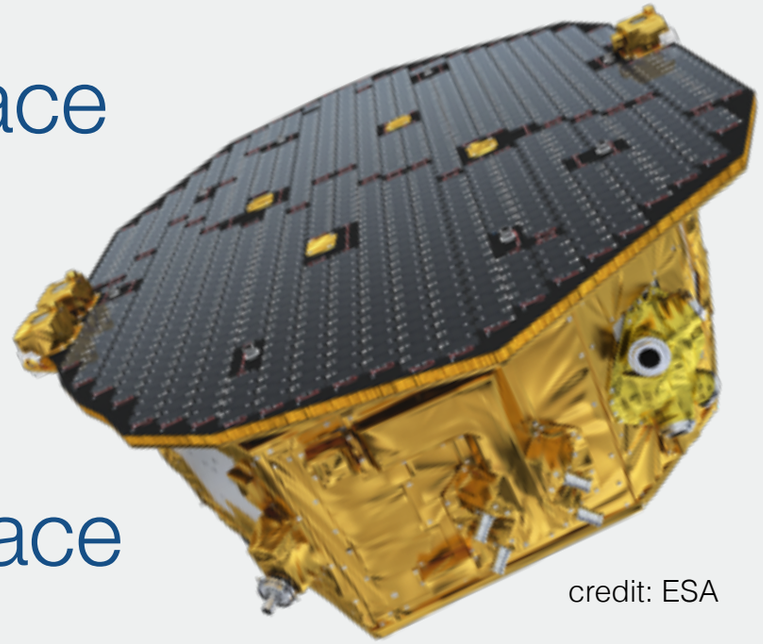
credit: ESA

Sarah Paczkowski for Gerhard Heinzel for the LPF collaboration

This work has been made possible by the LISA Pathfinder mission,
which is part of the space-science program of the European Space Agency. We gratefully acknowledge support by the European Space Agency (ESA) (22331/09/NL/HB, 16238/10/NL/HB), by Deutsches Zentrum für Luft- und Raumfahrt (DLR) with funding of the Bundesministerium für Wirtschaft und Energie with a decision of the Deutschen Bundestag
(DLR project reference numbers FKZ OQ 0501 and FKZ 50 OQ 1601) and thank the German Research Foundation for funding the Cluster of Excellence QUEST (Centre for Quantum Engineering and Space-Time Research).

Overview

- **L**ISA **P**ath**f**inder (**LPF**) project
  - why did we need LISA Pathfinder?
- LPF instrument
  - the setup of our laboratory in space
- Physics of LPF
  - measurements & results from space



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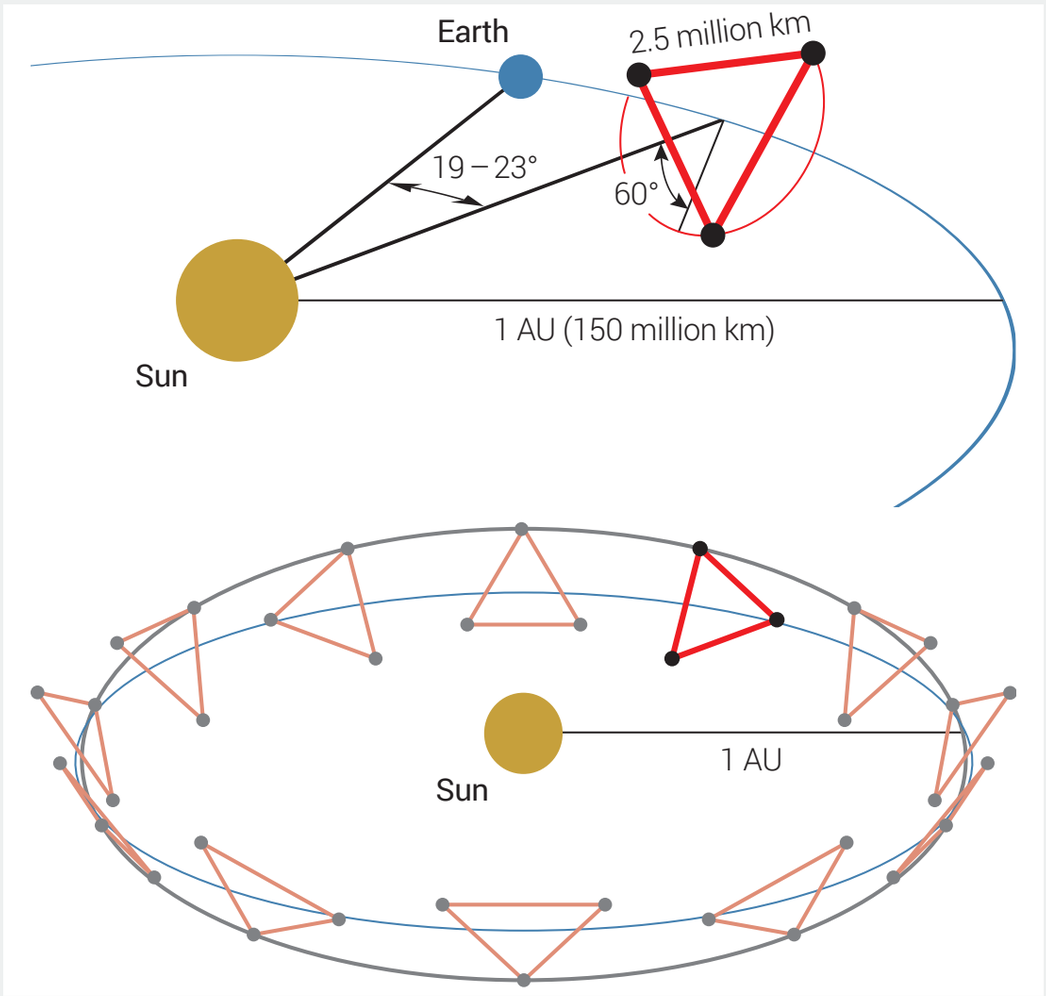
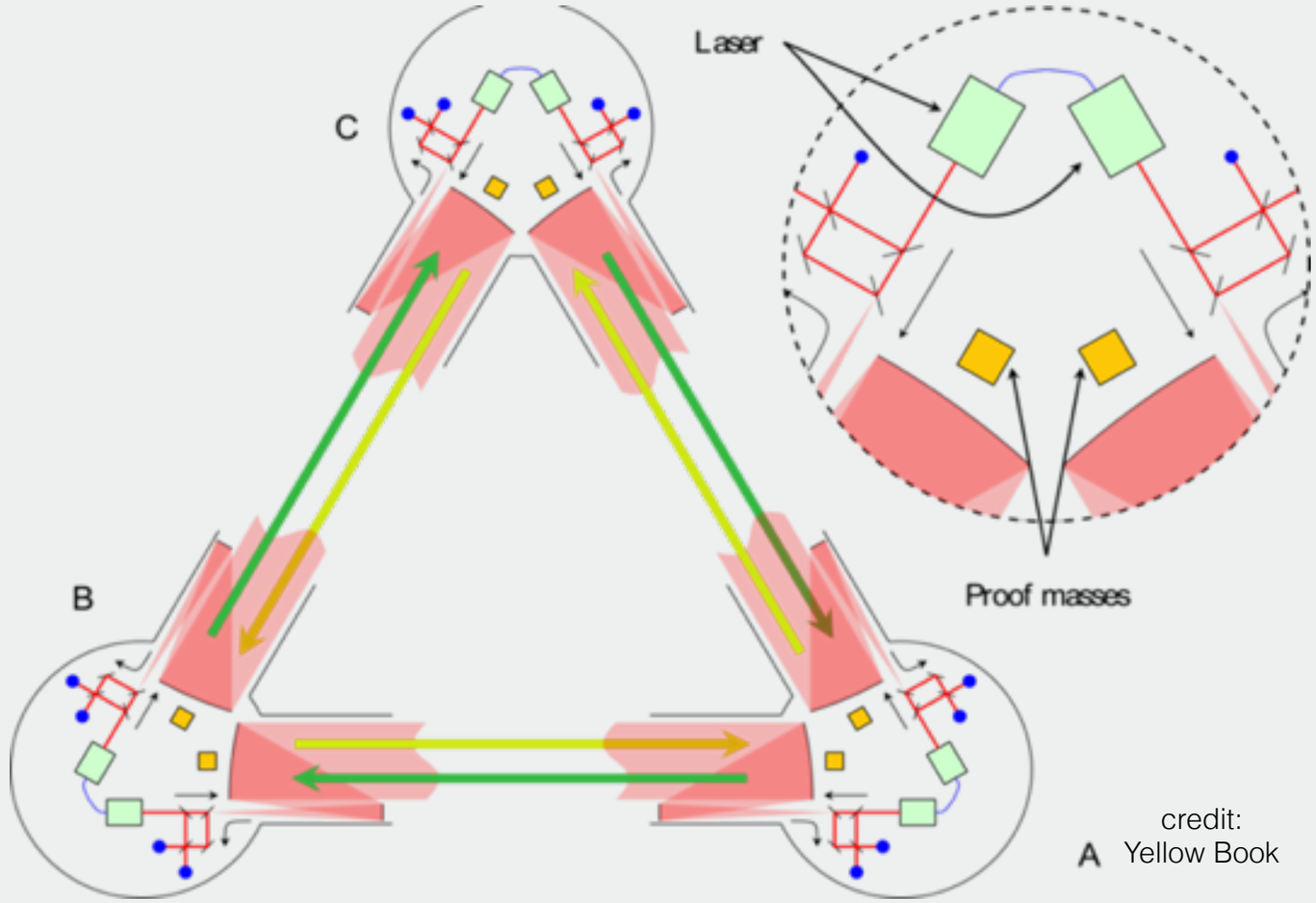
LISA requires quiet test masses!





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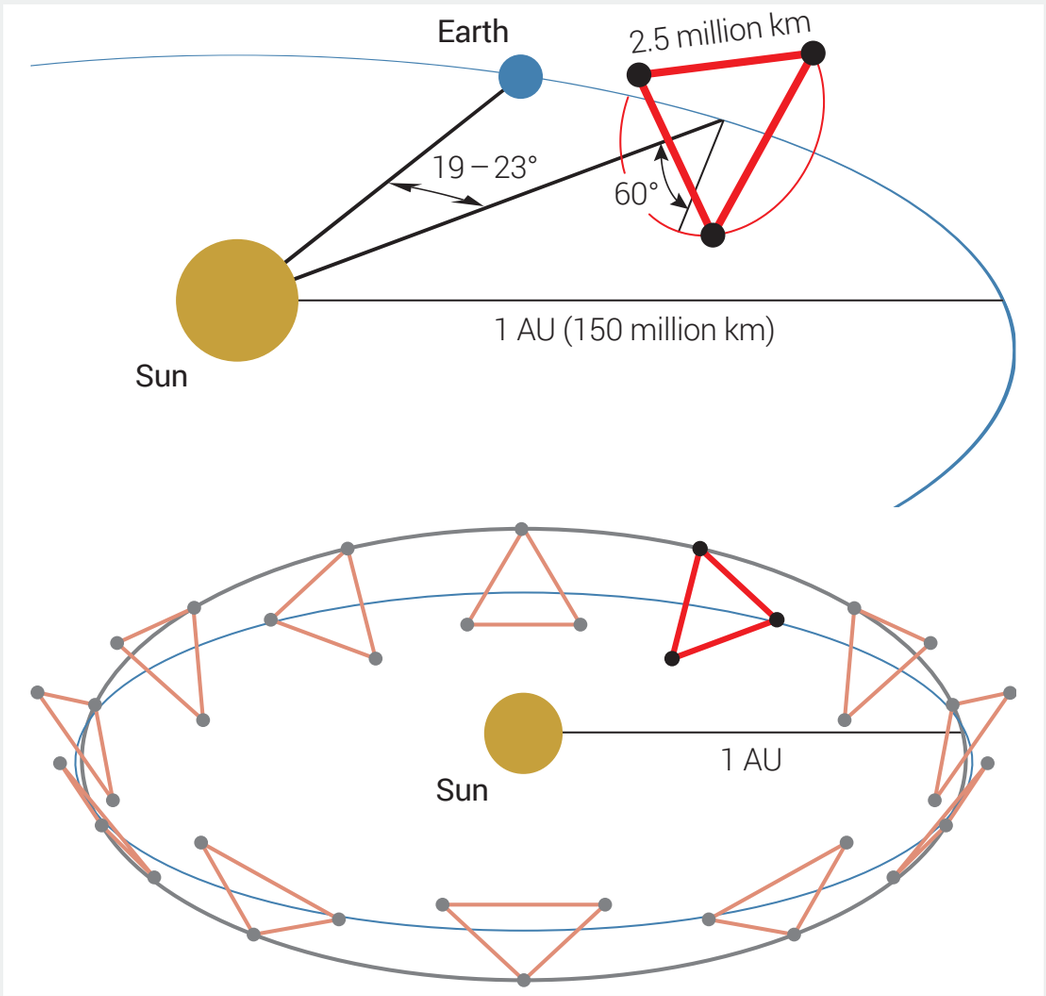
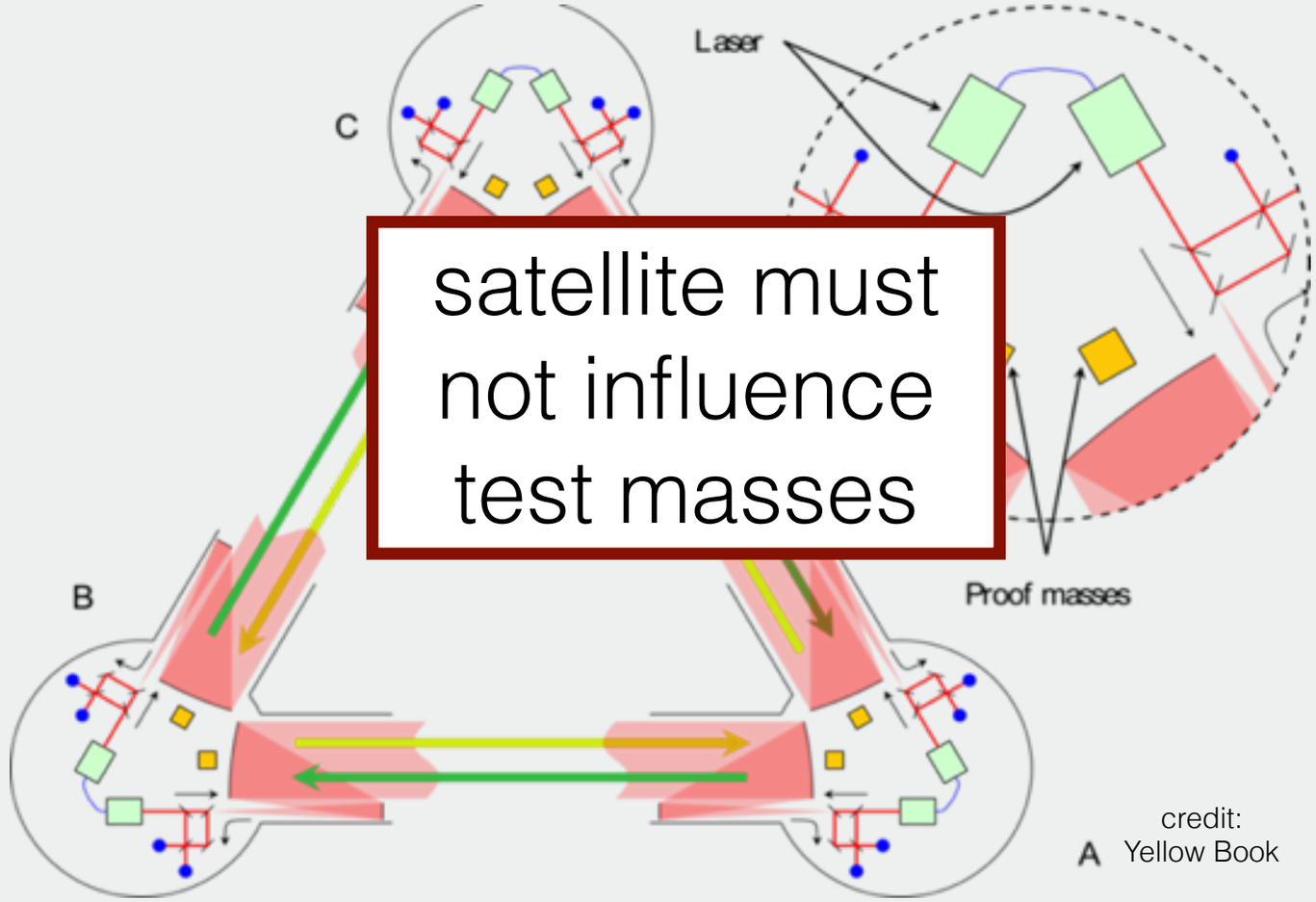
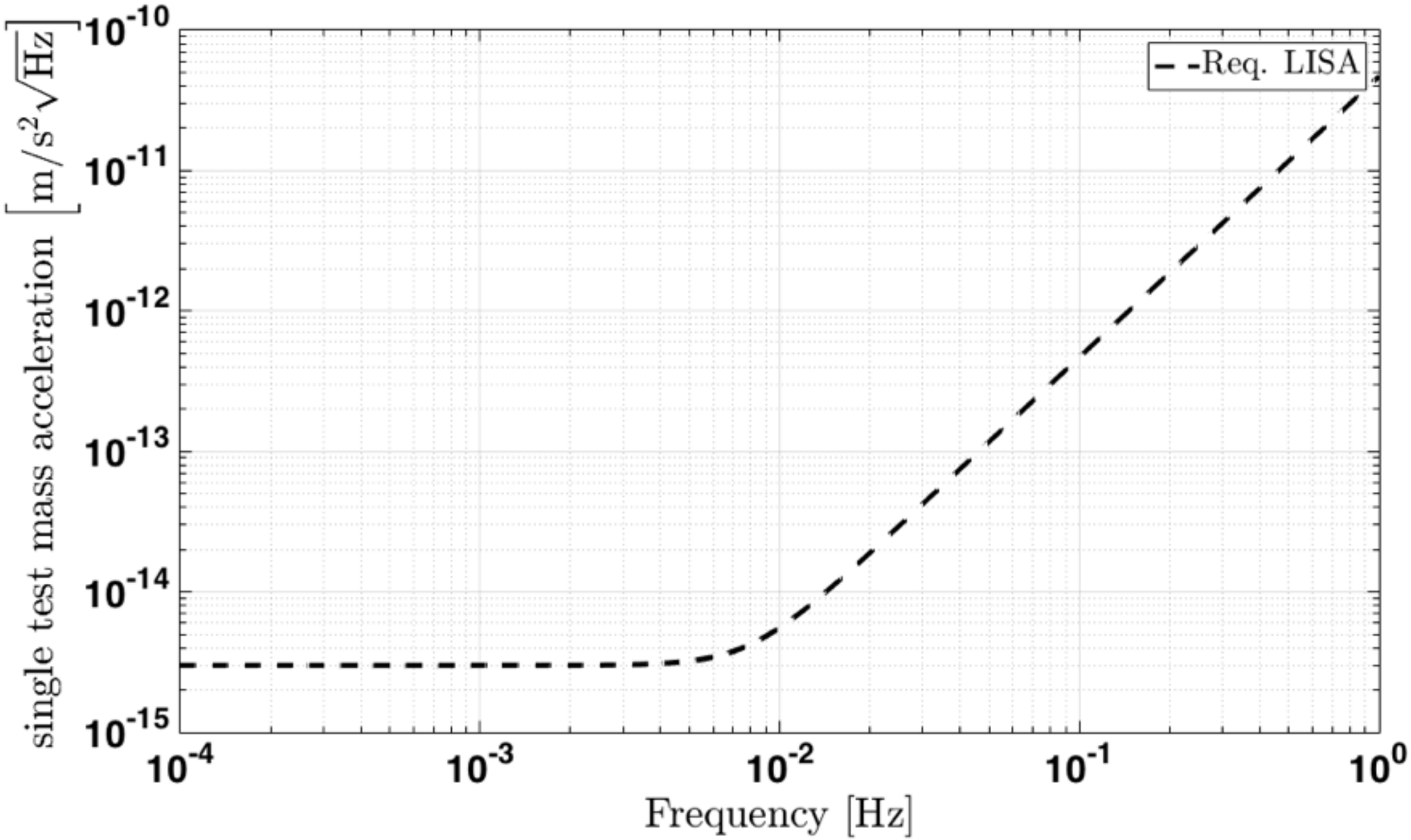




satellite must not influence test masses

LISA requires quiet test masses!



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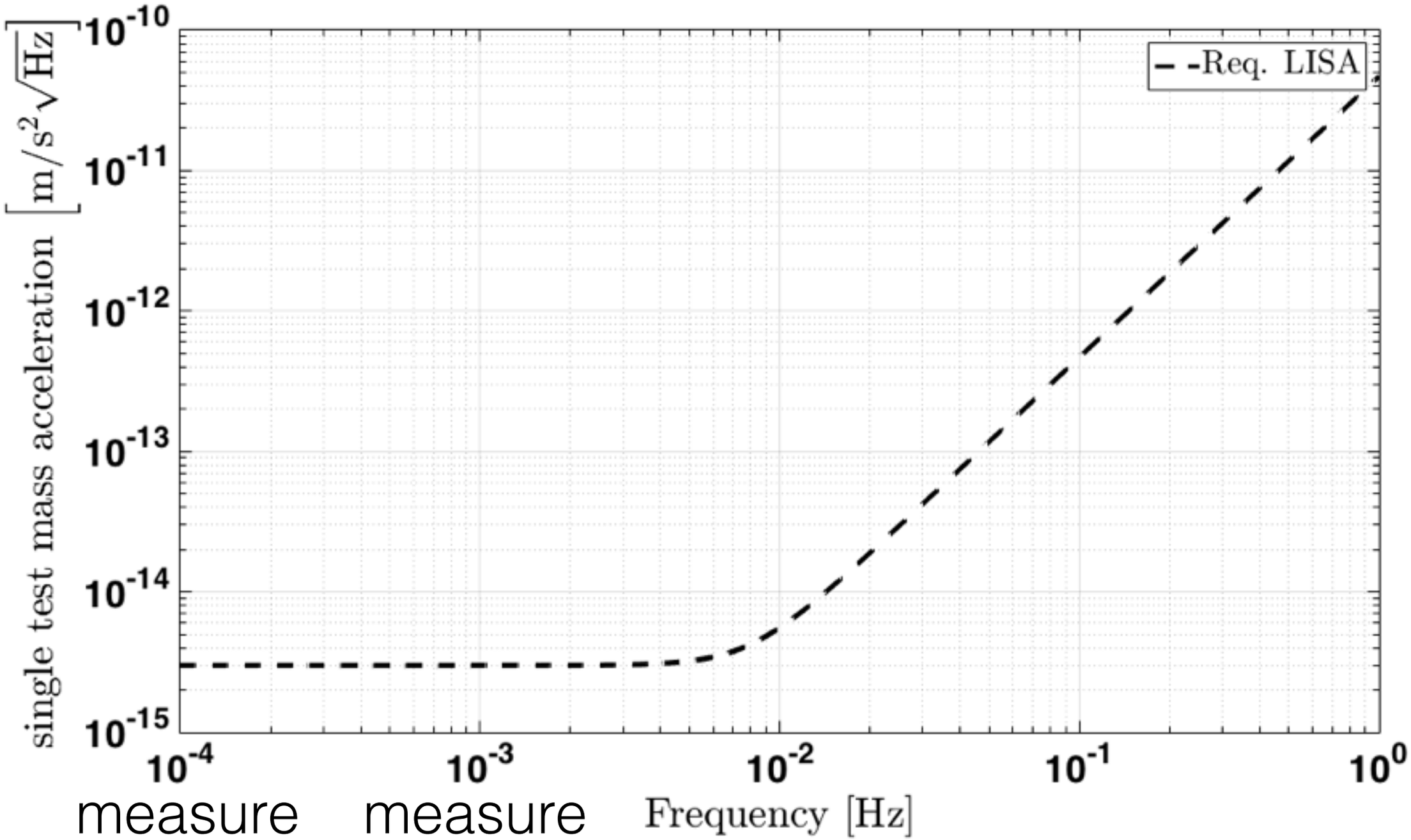
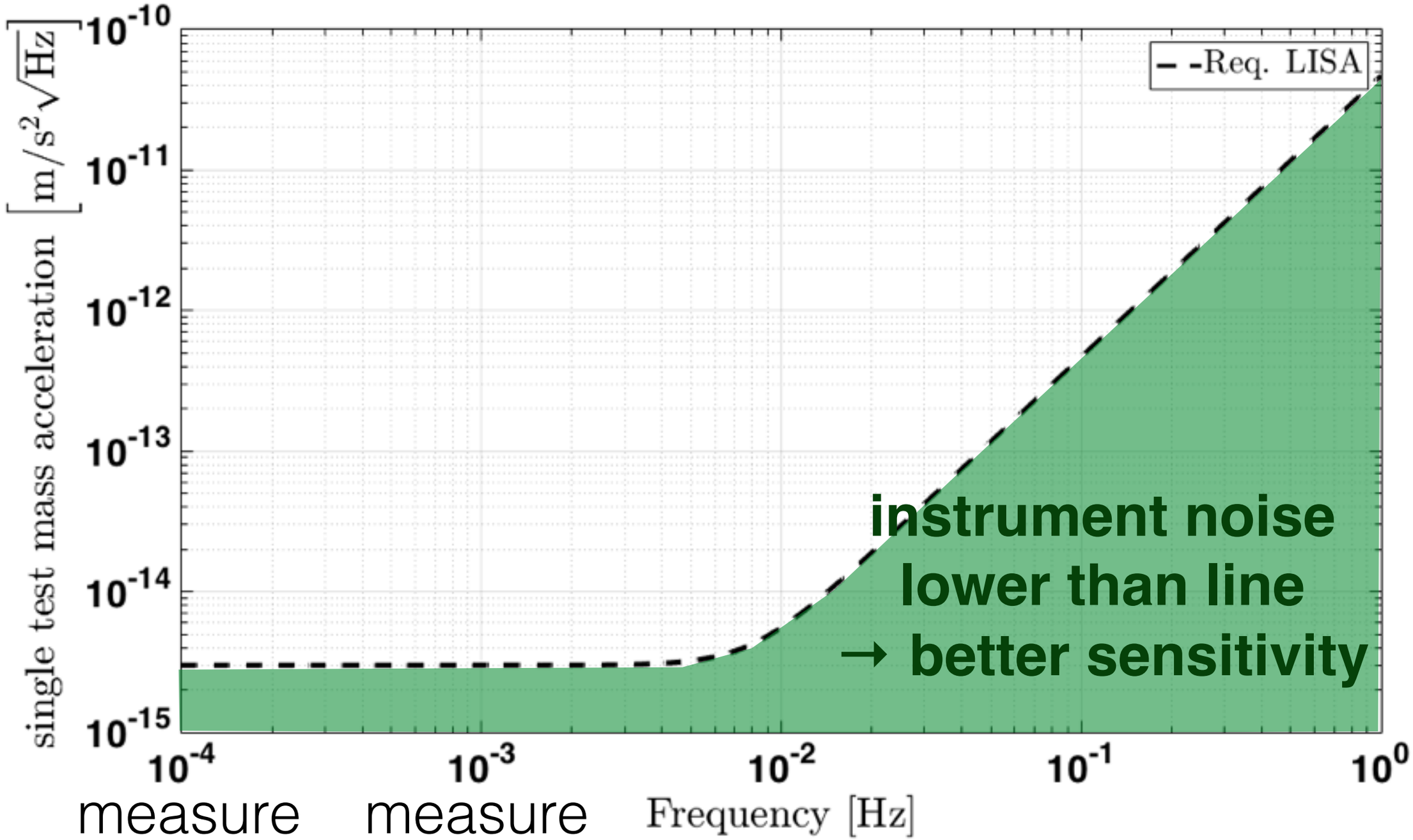


measure ~days

measure ~ hrs

LISA requires quiet test masses!



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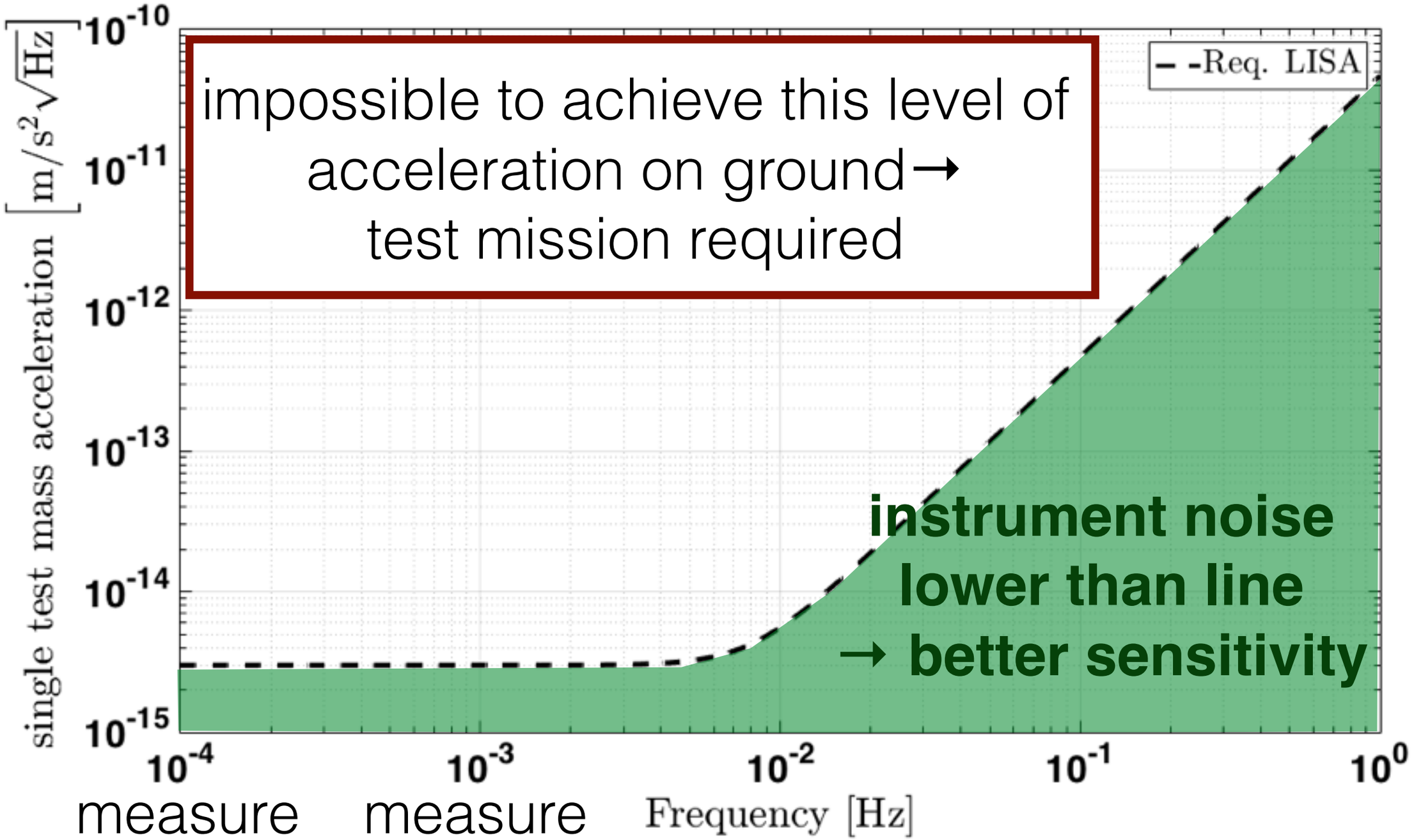


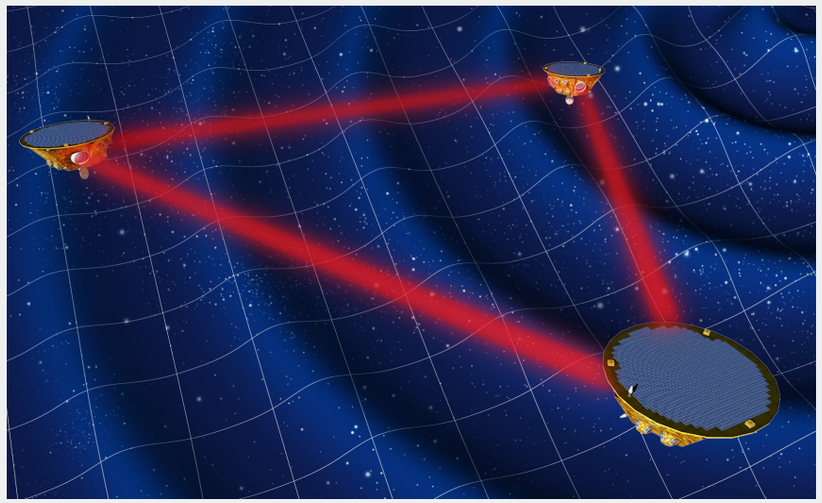
The LISA Pathfinder Project

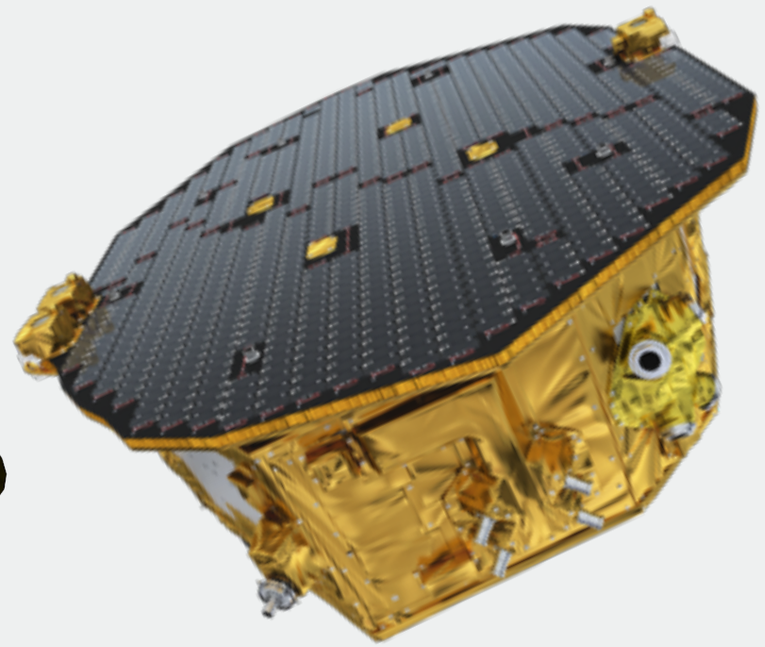
- mission goal:
  - demonstrate the technology for the future space borne gravitational wave detector LISA
    - **show nearly perfect free-fall is feasible**

- LPF **NOT** designed to measure gravitational waves

LISA Pathfinder: the test mission for LISA

select single link & shrink 2.5 million km to 38 cm!





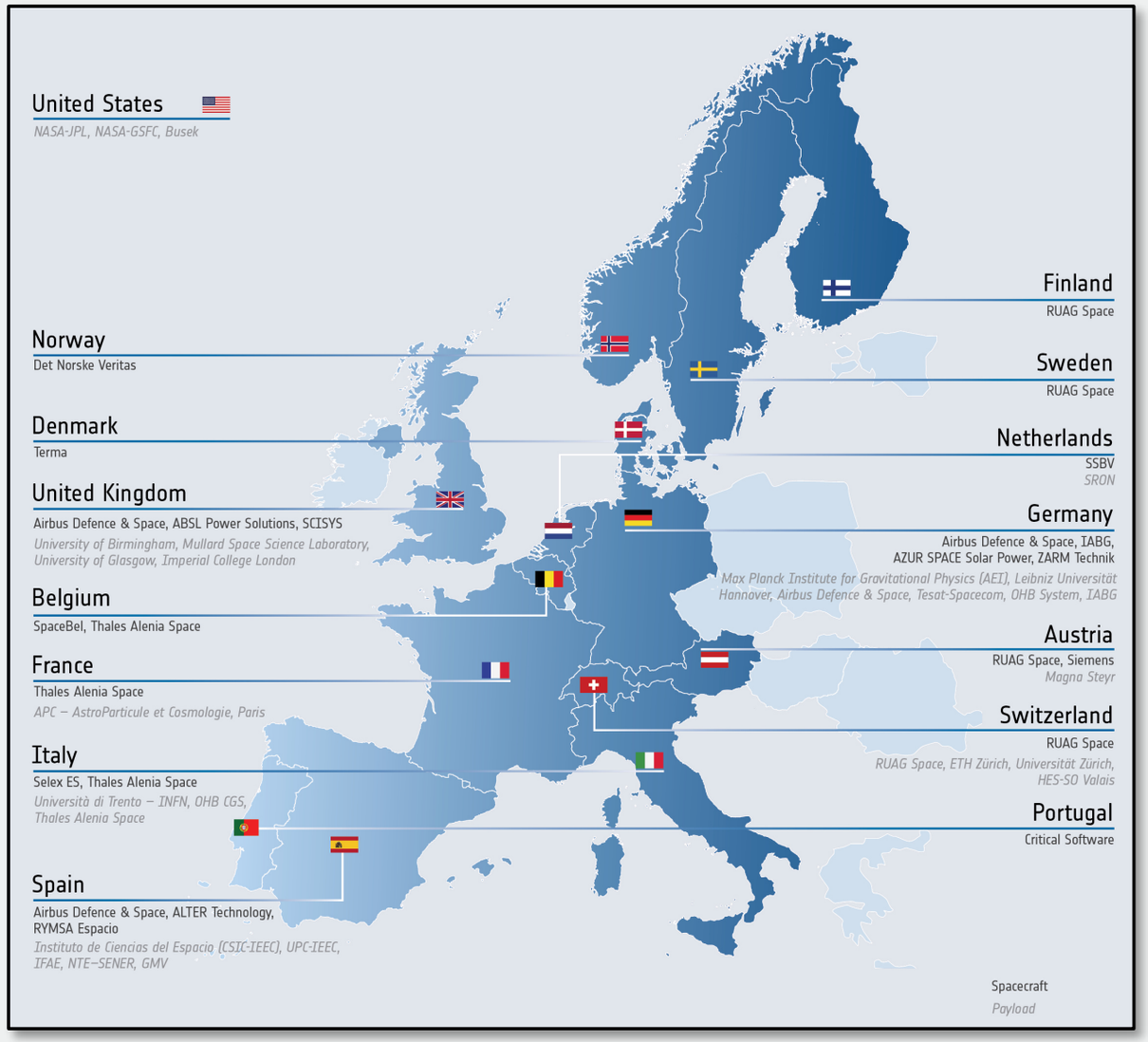
LISA Pathfinder is a European project

- more than 40 companies and (physics) institutes
- 14 European

  countries involved

- US partnership:
  - NASA **D**isturbance

    Reduction **S**ystem



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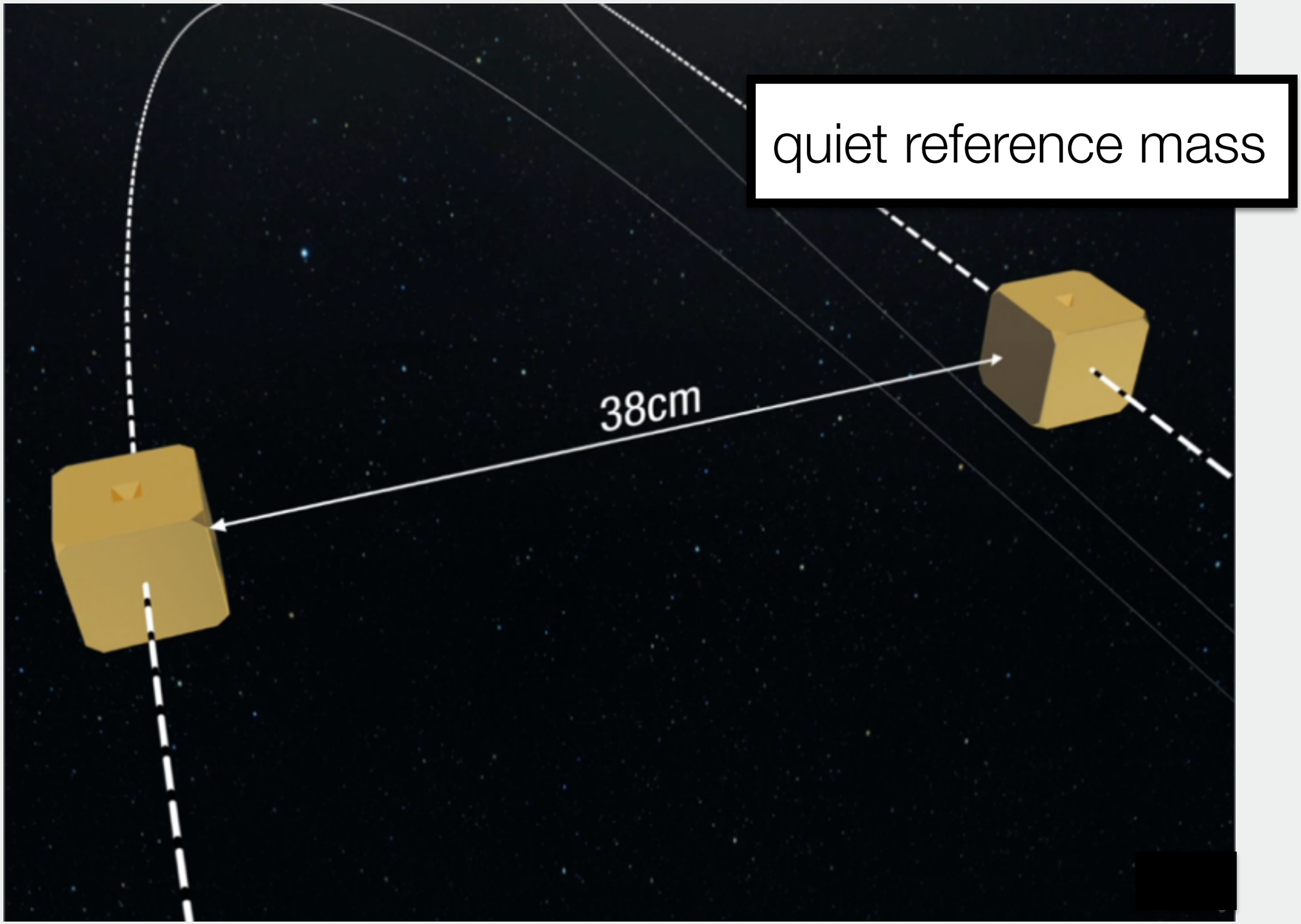
credit: ESA

Main measurement: residual acceleration



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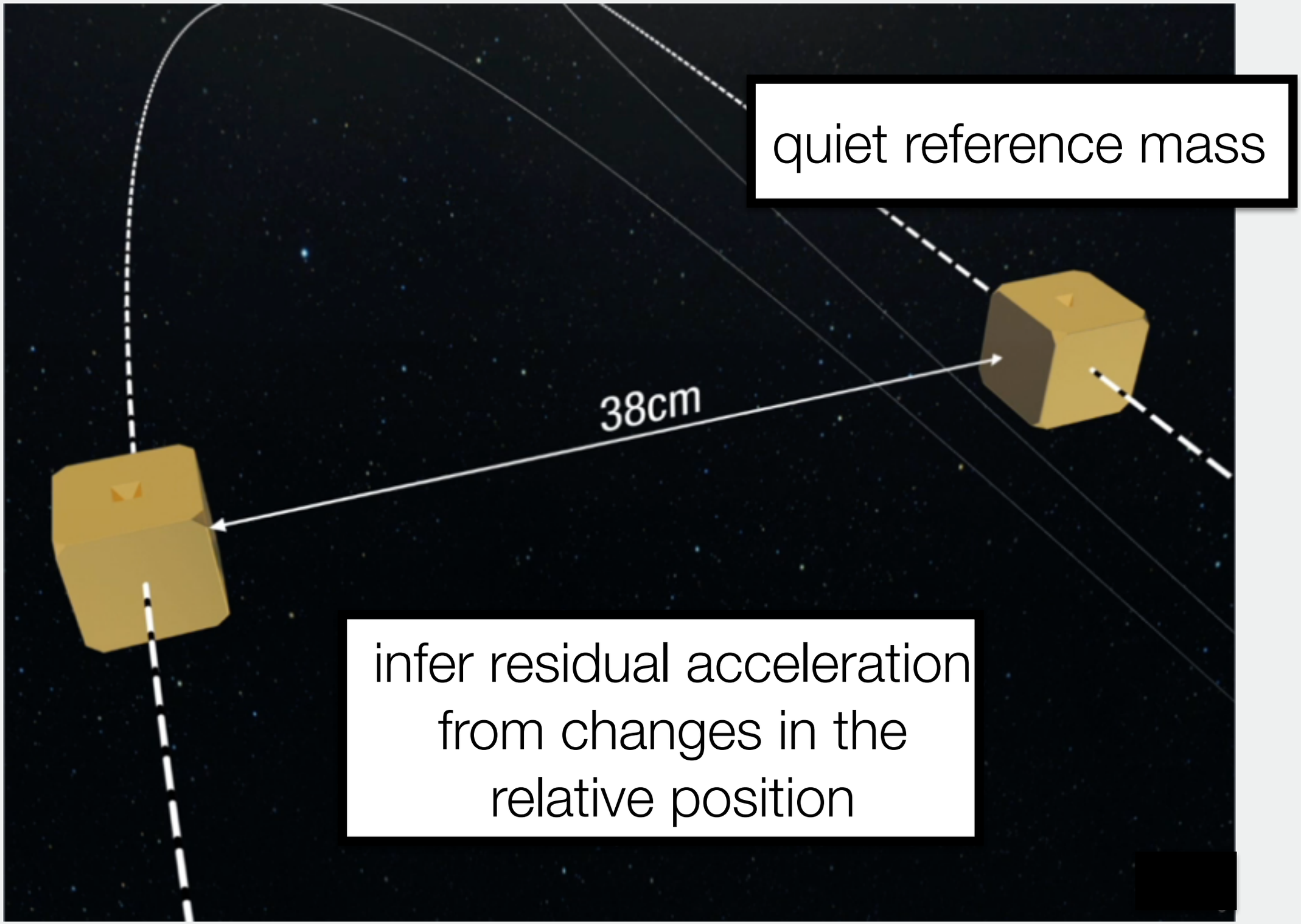
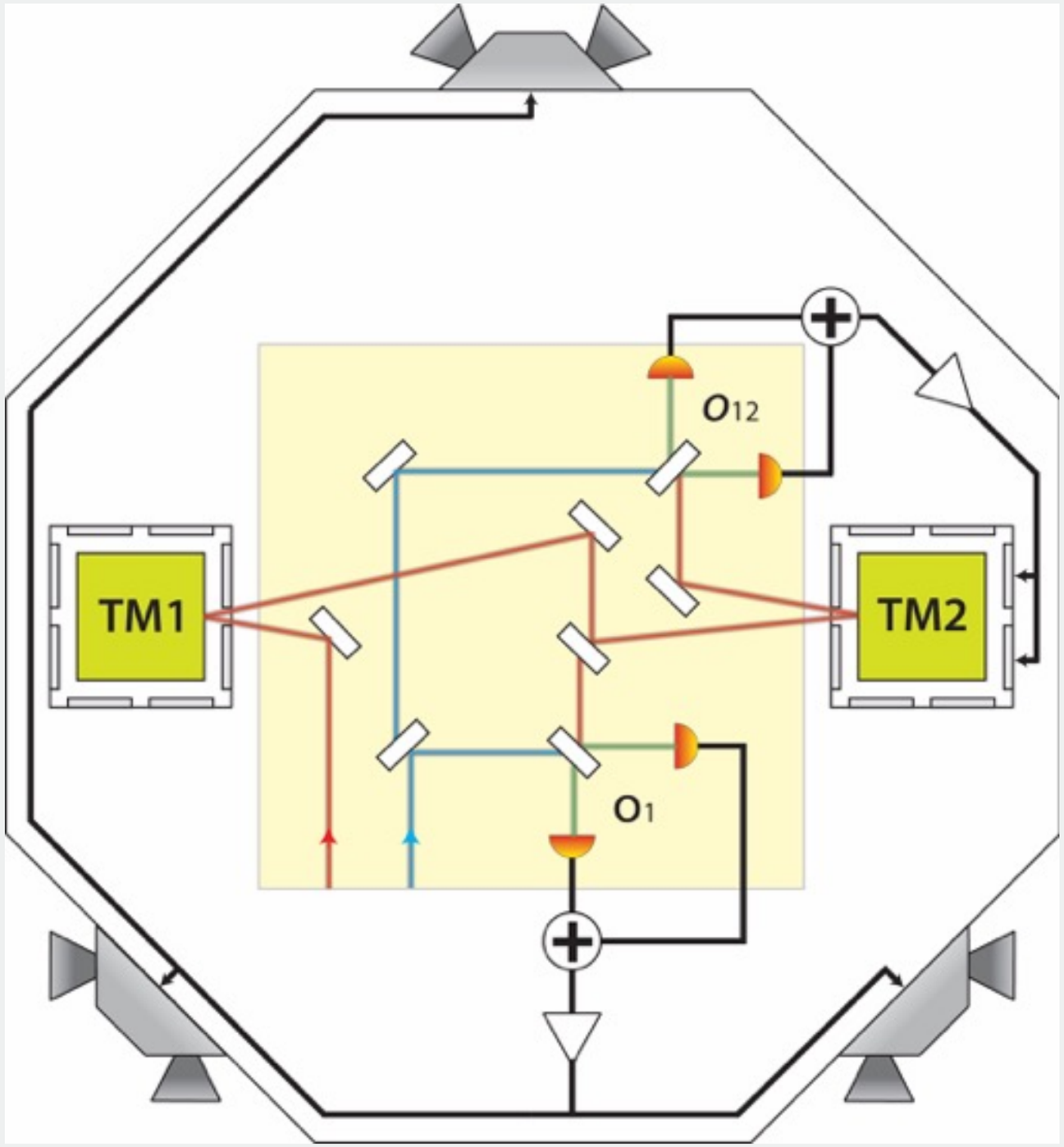


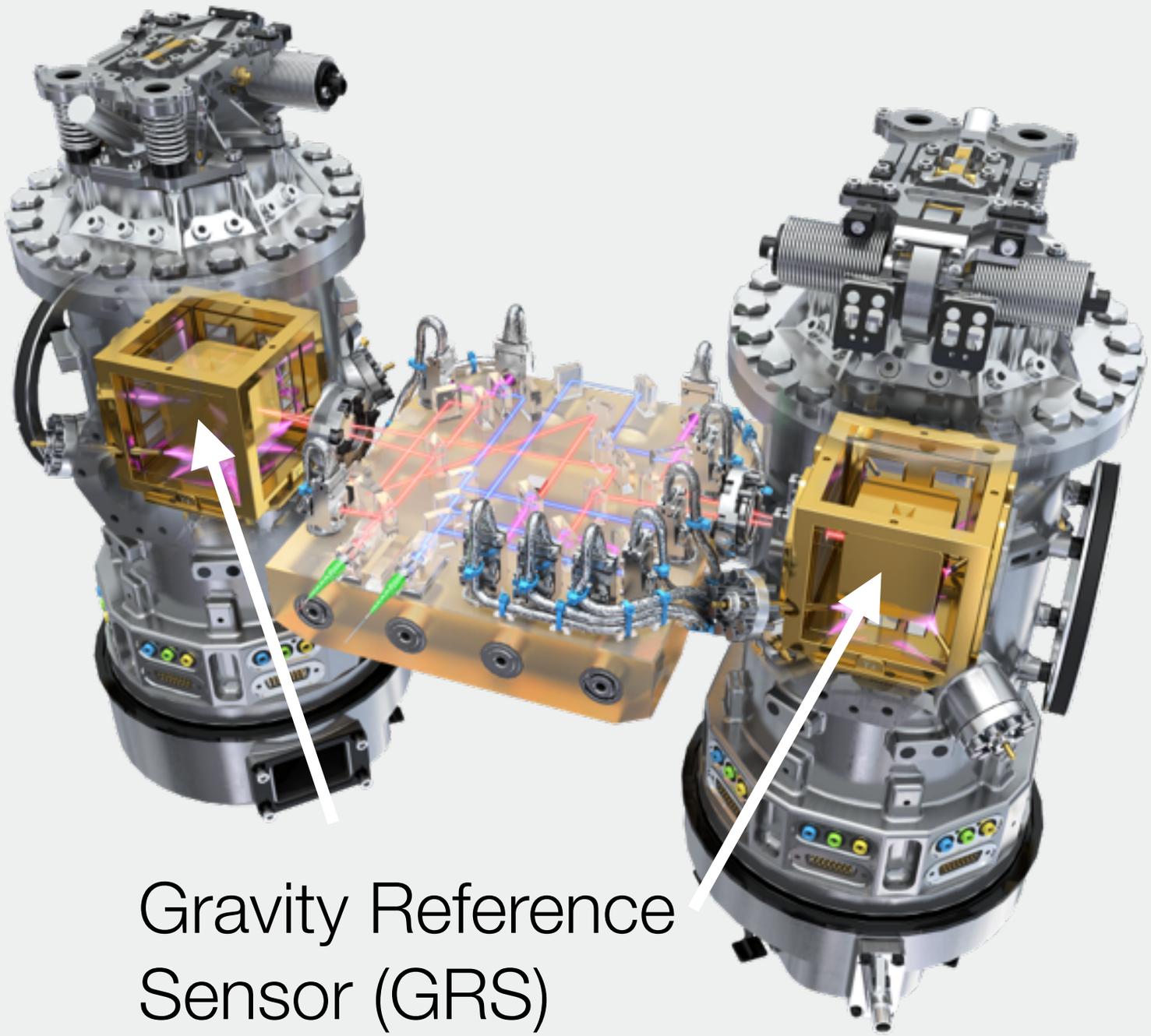
Control principle

Along sensitive axis:

- TM1 free-falling
- satellite follows TM1 using o1 sensing
- TM2 follows TM1 using o12 sensing
  - commanded force known → estimate applied force → subtracted in post-processing

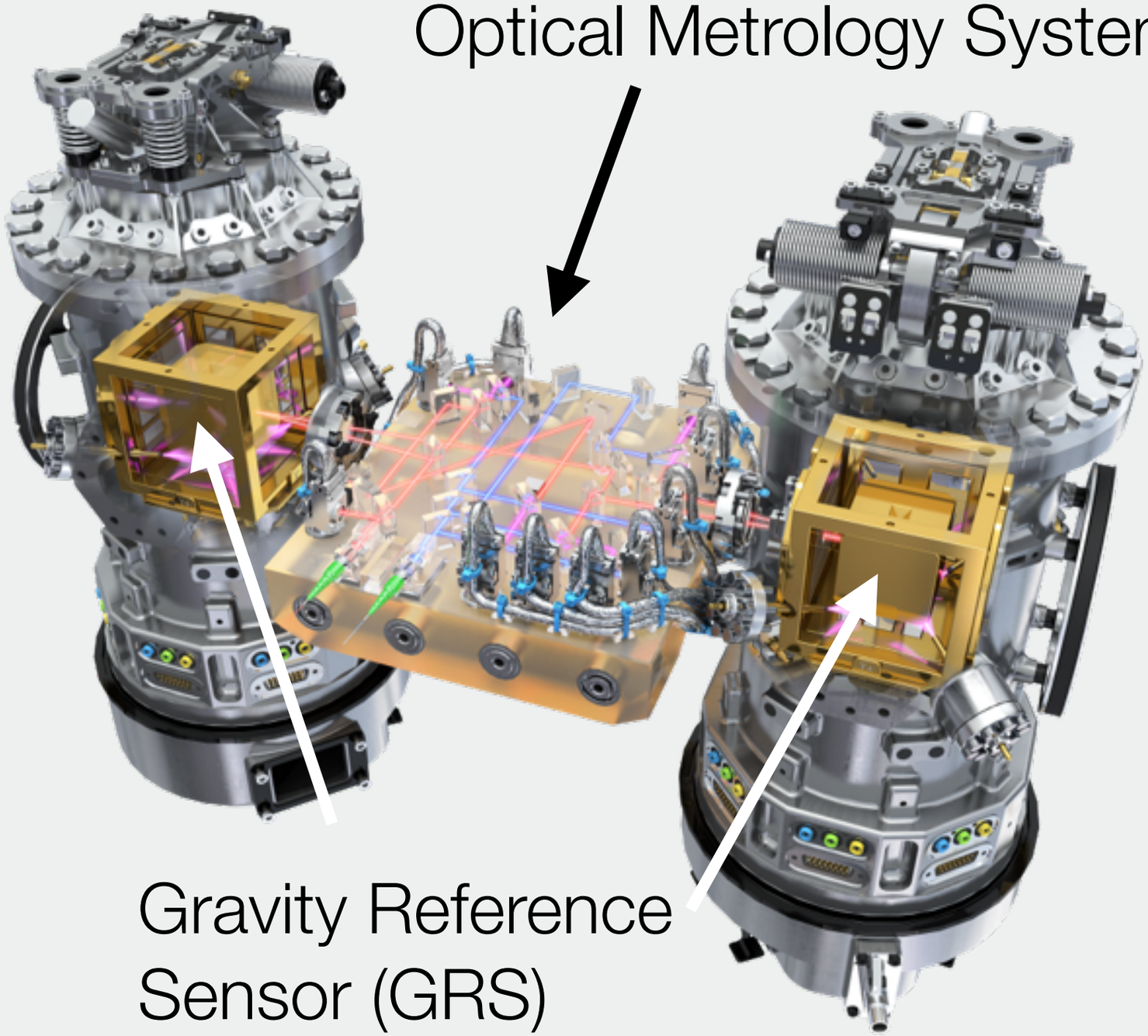


Key subsystems needed to achieve free-fall

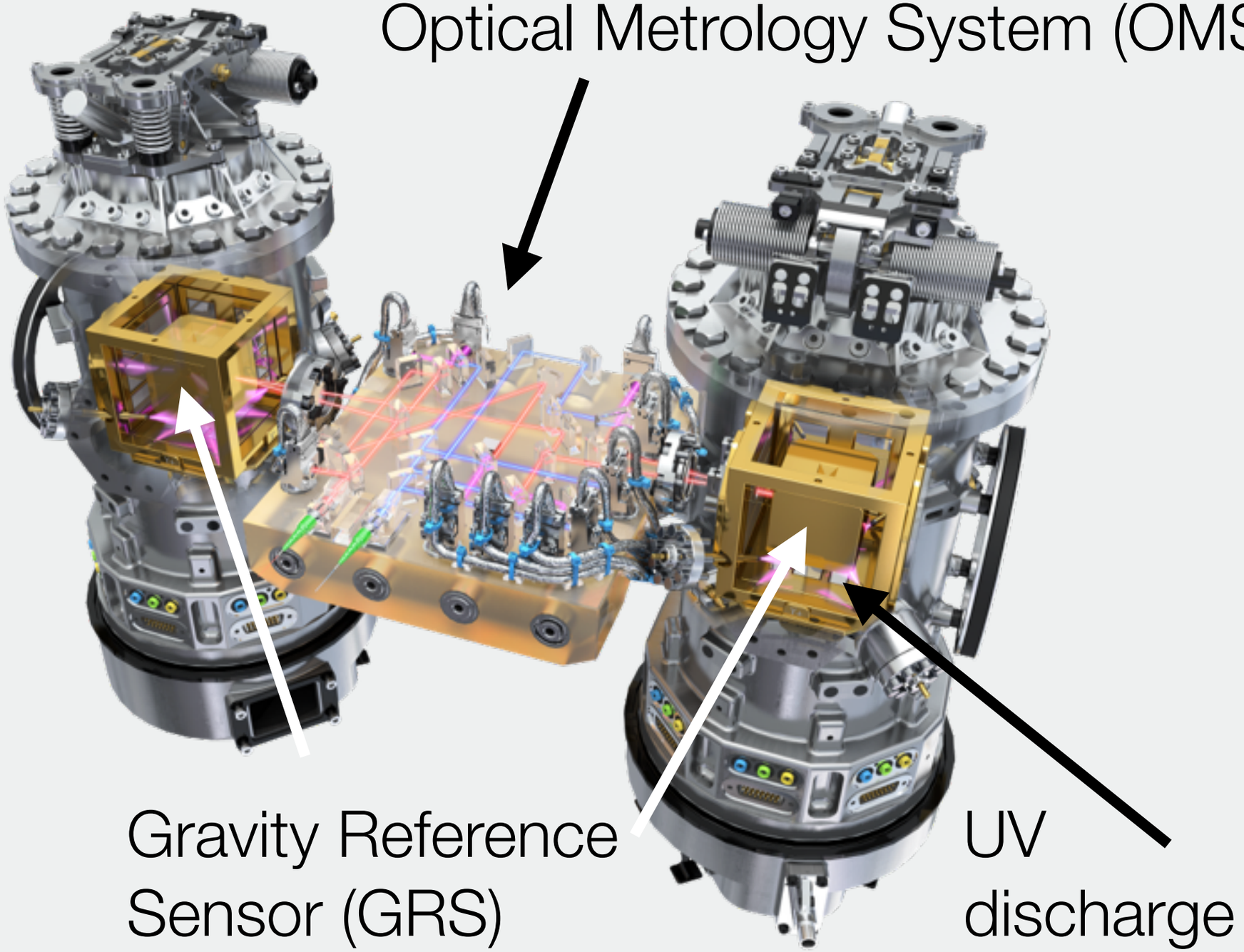


Gravity Reference Sensor (GRS)

Key subsystems needed to achieve free-fall



Key subsystems needed to achieve free-fall



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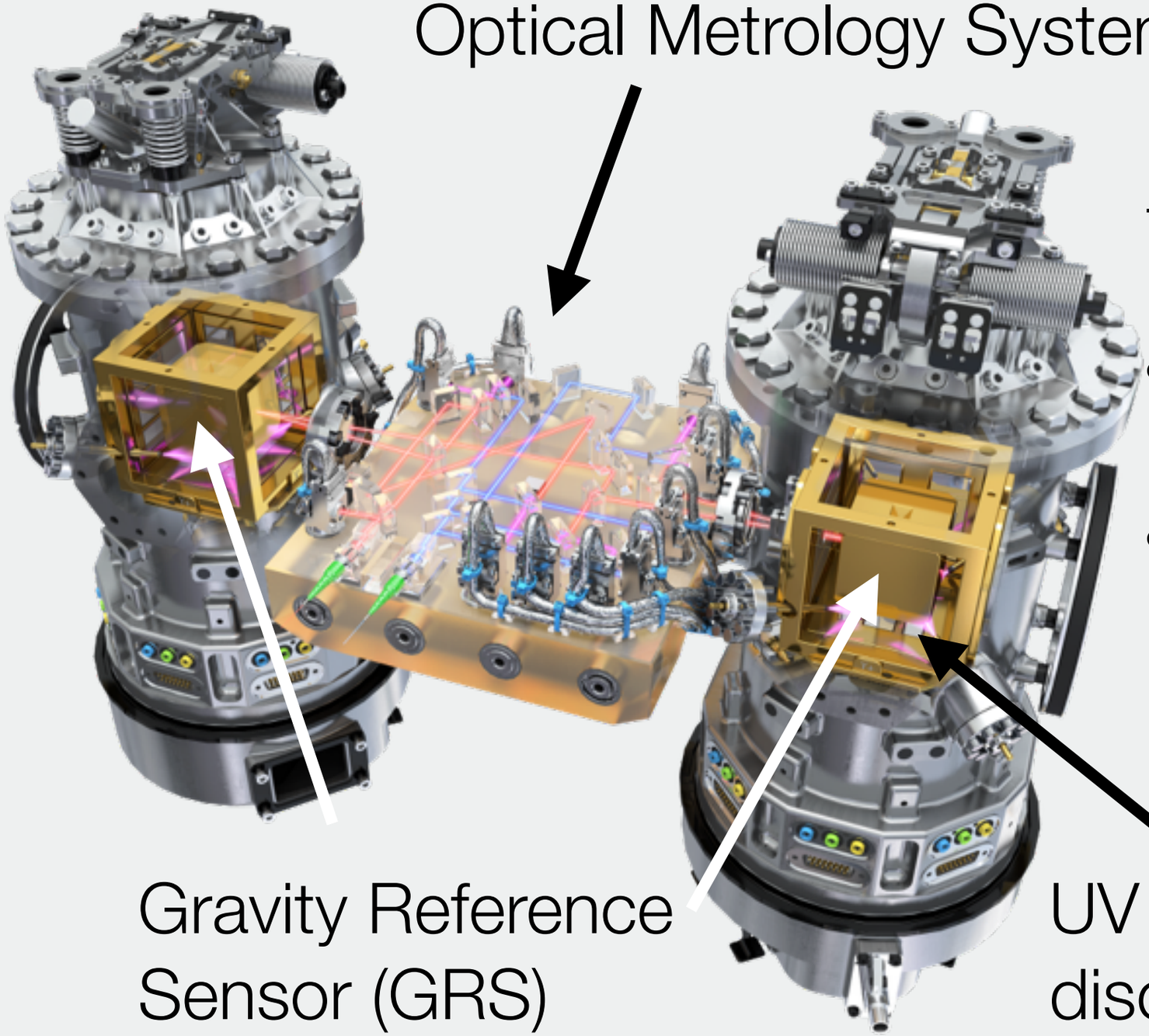
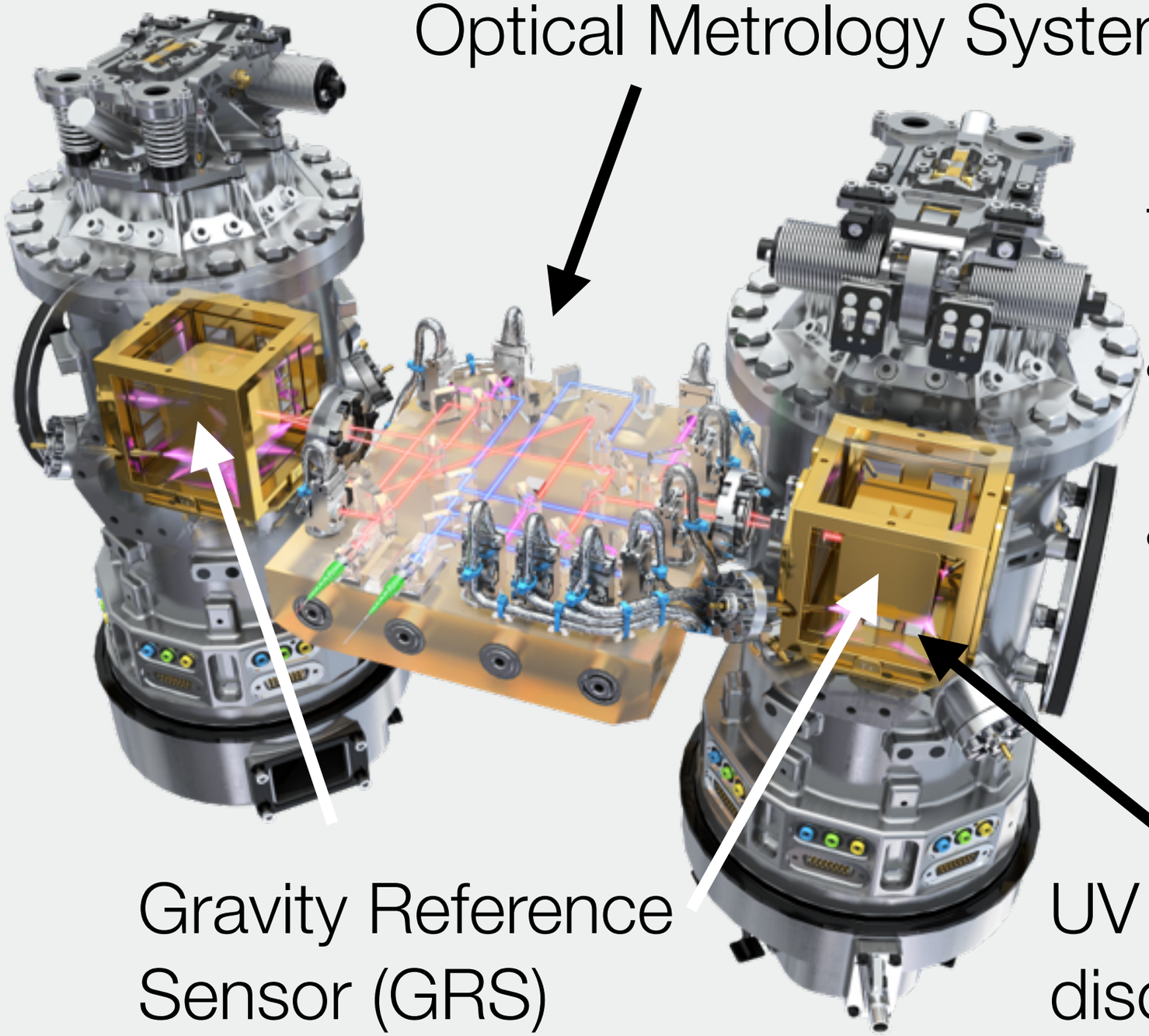


+ (not visible here)

- micro Newton thruster
- Drag-Free Attitude Control System (DFACS)

Key subsystems needed to achieve free-fall



+ (not visible here)

- micro Newton thruster
- Drag-Free Attitude Control System (DFACS)

+ thermally & magnetically quiet environment

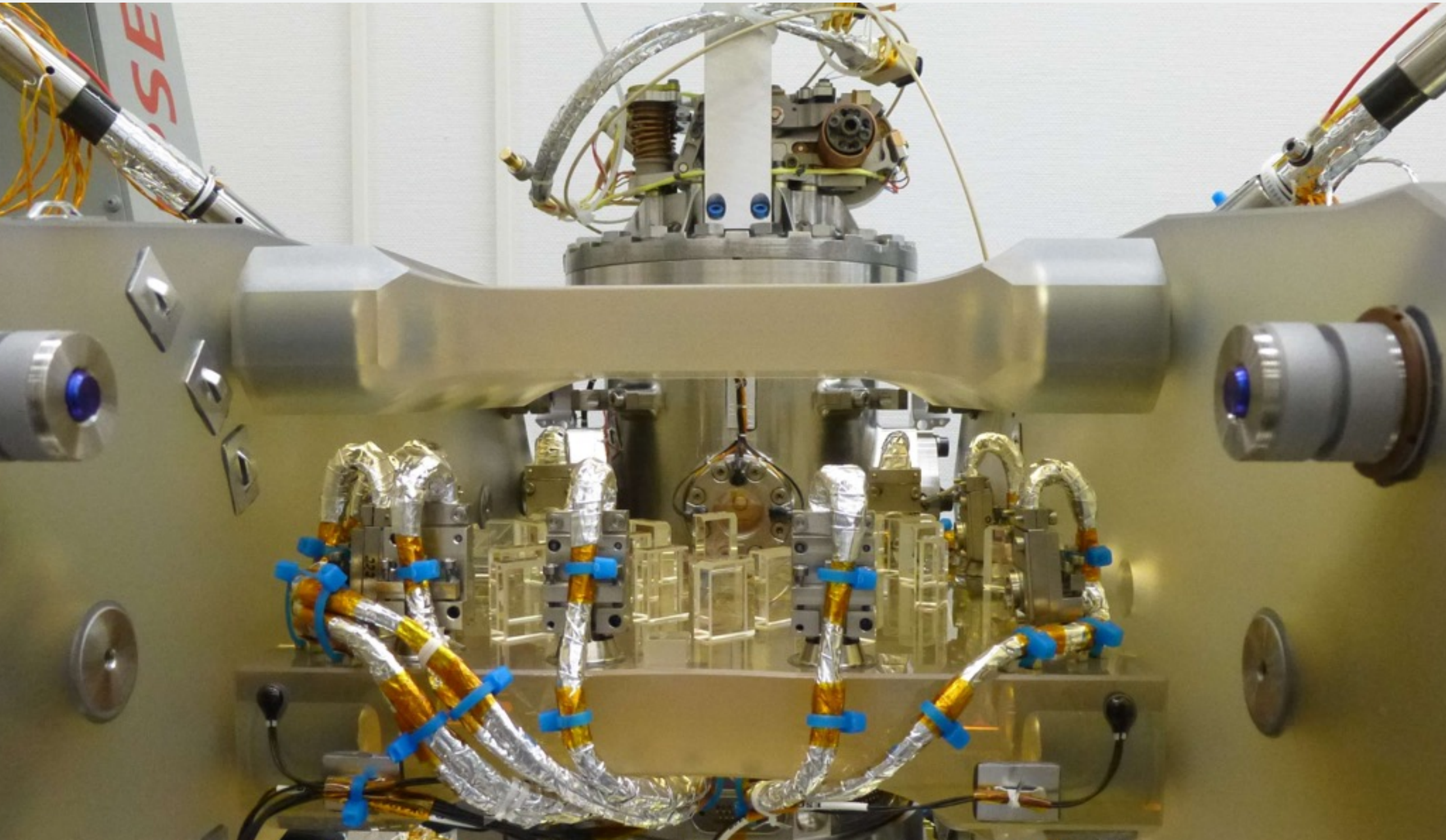
The **O**ptical **M**etrology **S**ystem (OMS)

OMS: measure distance with respect to quiet reference mass with required accuracy of

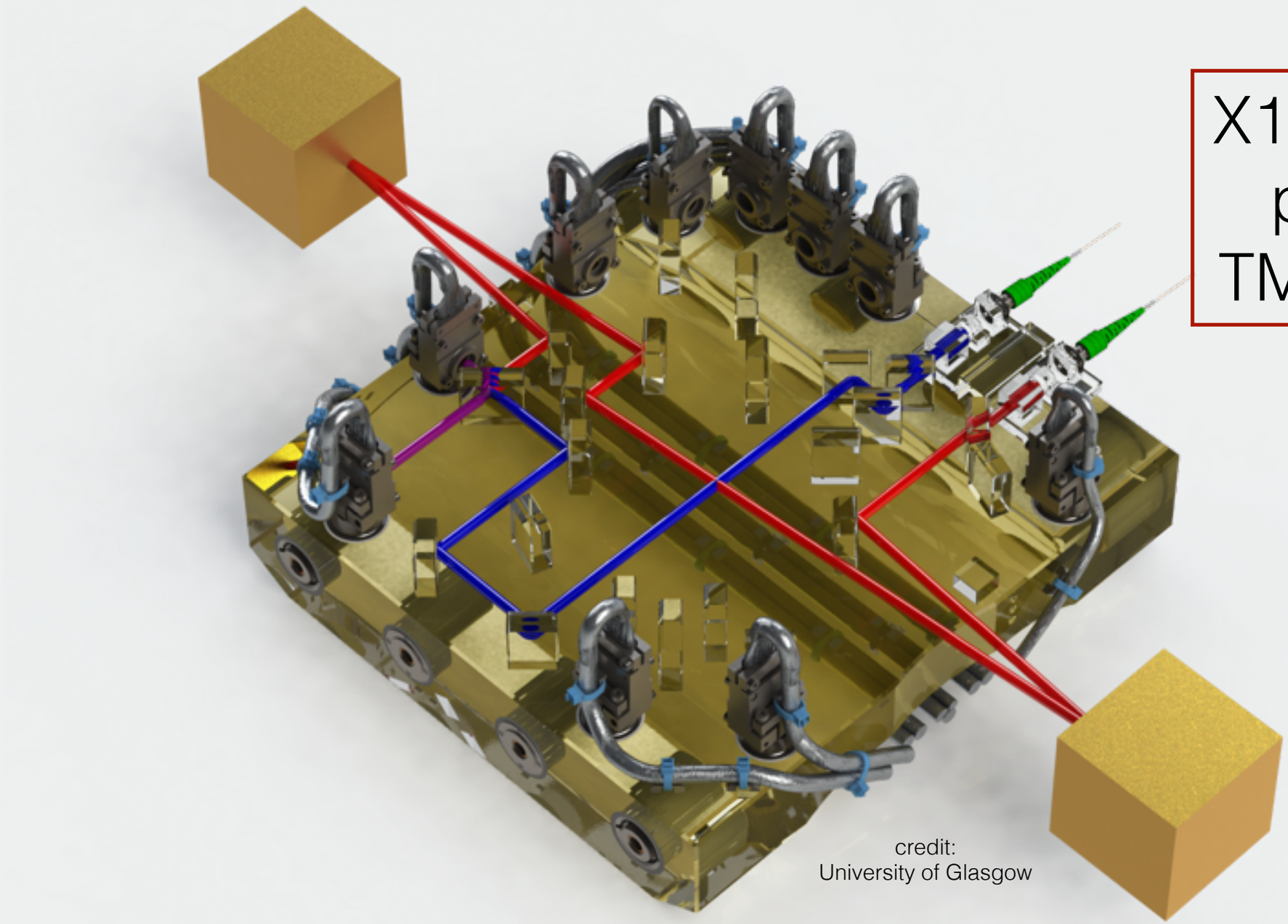
$$S_{\delta x} \leq 9 \frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}} \left(1 + \left(\frac{3\,\mathrm{mHz}}{f}\right)^2\right)$$

heterodyne interferometry

The **O**ptical **M**etrology **S**ystem (OMS)



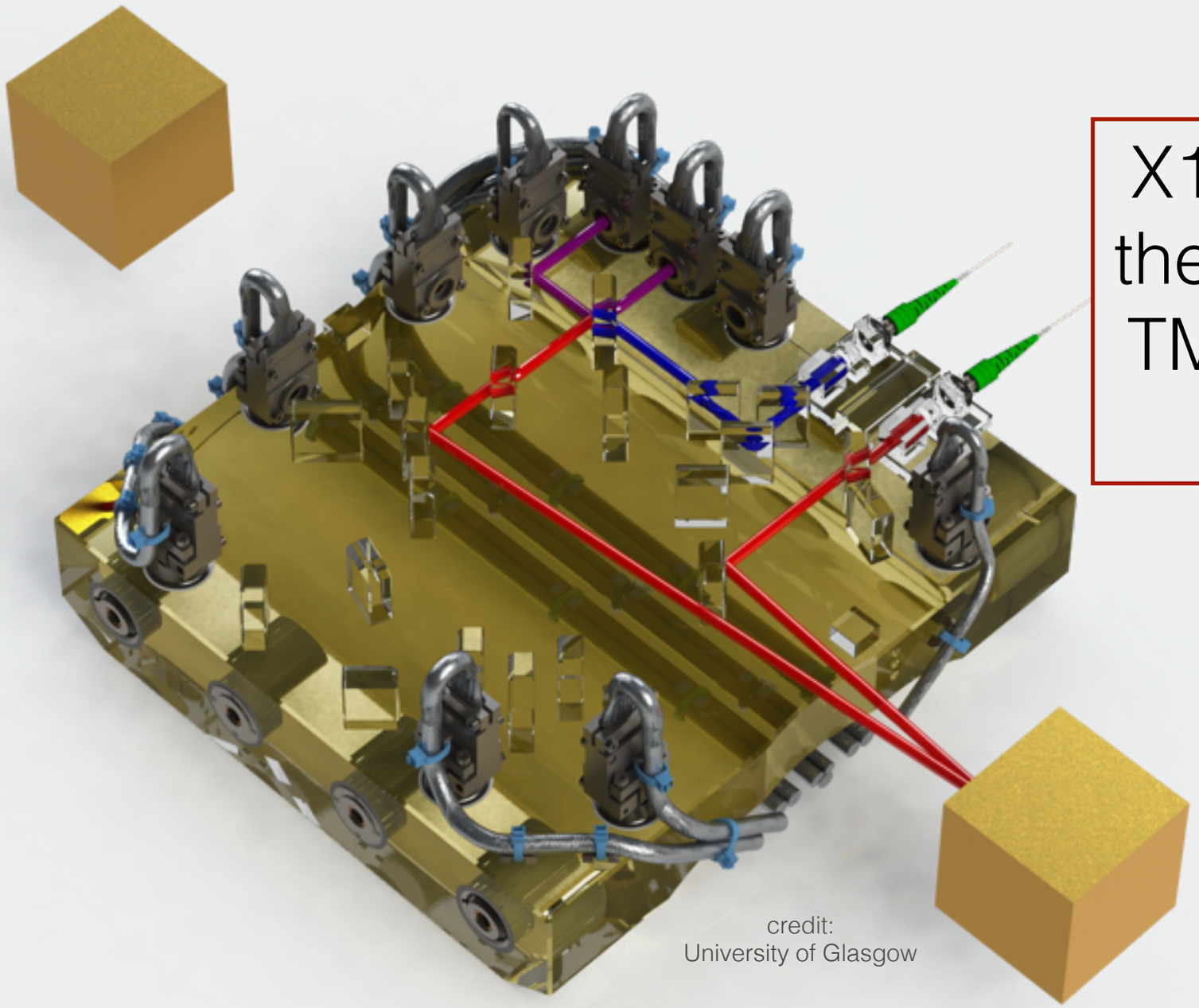
LPF optical bench: X12 interferometer



credit:
University of Glasgow

X12 measures position of TM2 w.r.t TM1

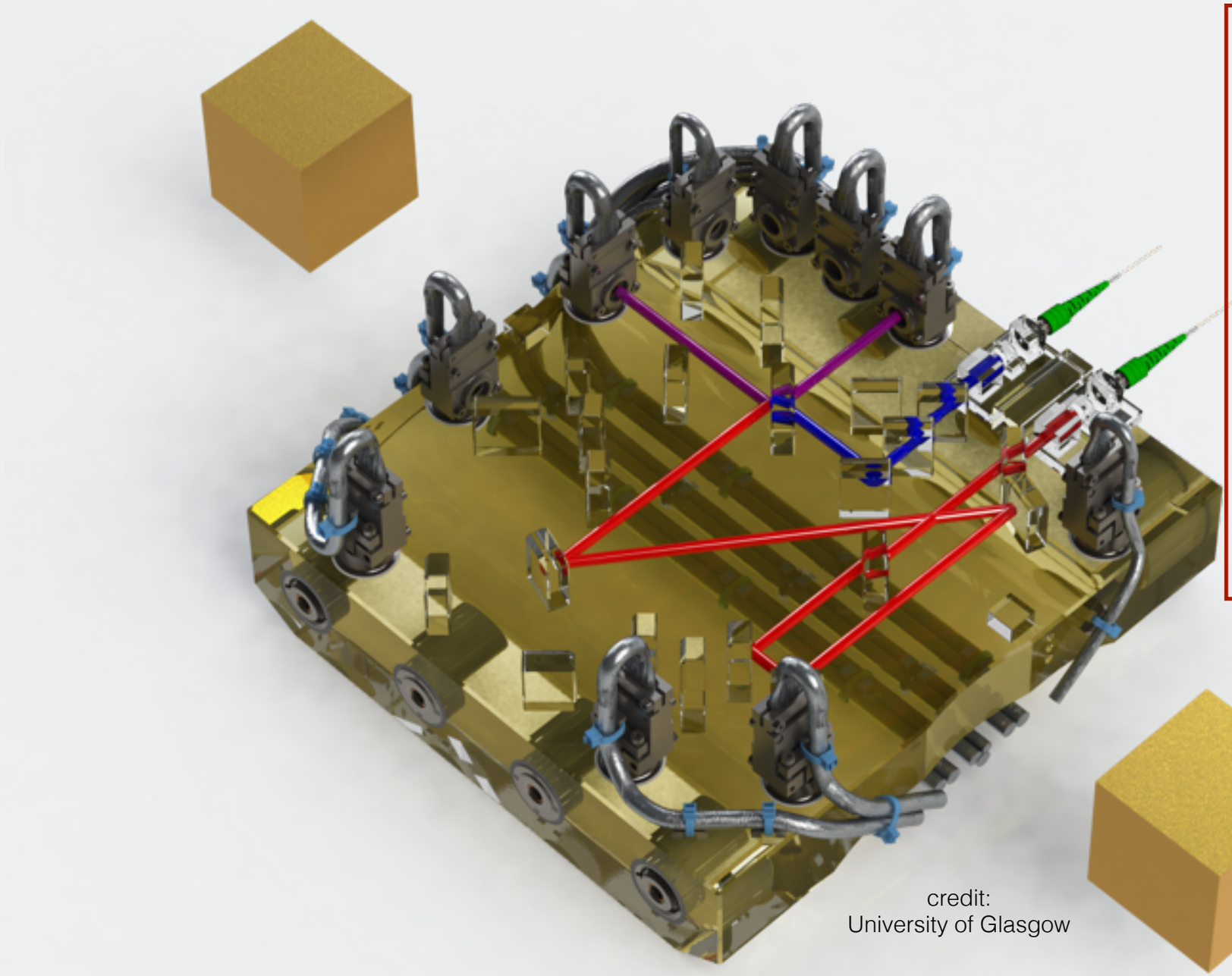
LPF optical bench: X1 interferometer



credit:
University of Glasgow

X1 measures the position of TM1 w.r.t. the satellite

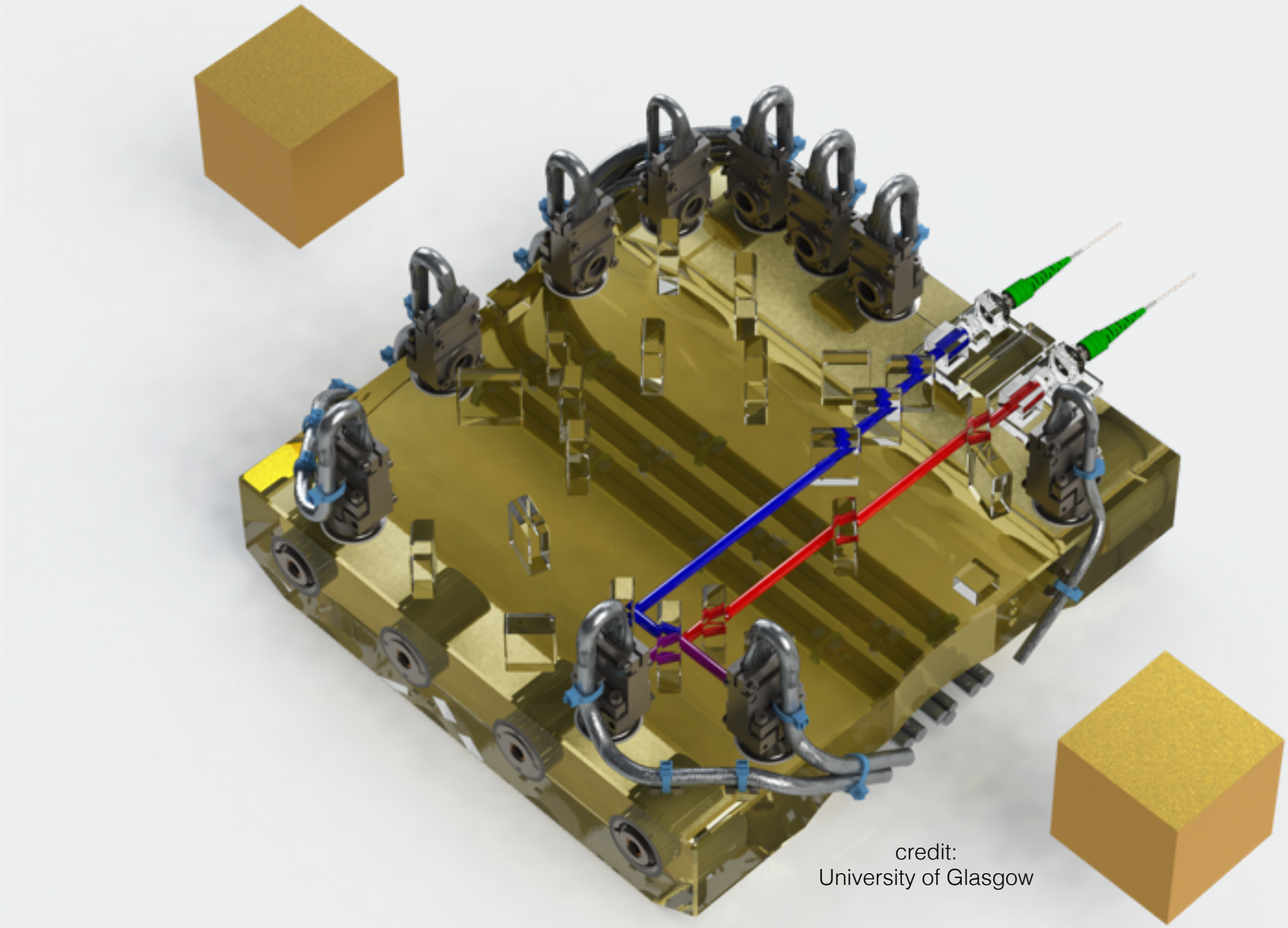
LPF optical bench: reference interferometer



credit:
University of Glasgow

reference interferometer measures the common-mode path length fluctuations

LPF optical bench: frequency interferometer



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measures the laser frequency fluctuations

The LISA Pathfinder project history

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The LISA Pathfinder project history

travel to L1 orbit	in-orbit commission-ing	nominal LTP operations	nominal DRS operations	mission extension

launch 3-12-15

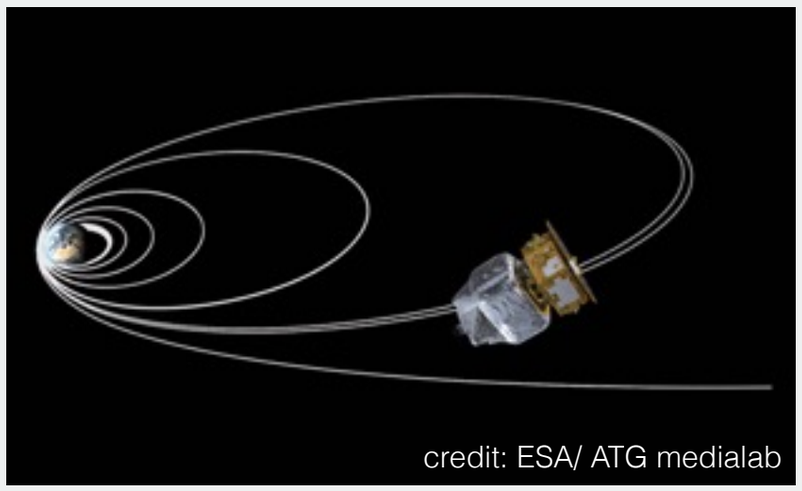
11-01-16

01-03-16

26-06-16

07-12-16

good bye July,18 17



LISA Pathfinder: our laboratory in space

Here is how we organise our measurements

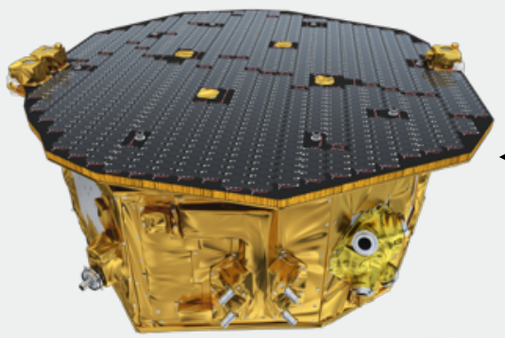
human-readable schedule

STOC

investigations

MOC

telecommands



credit: ESA

transfer data to repositories

LTPDA = **L**ISA **T**echnology **P**ackage **D**ata **A**nalysis

elisascience.org/ltpda/

scientists

analyse data → determine next experiments

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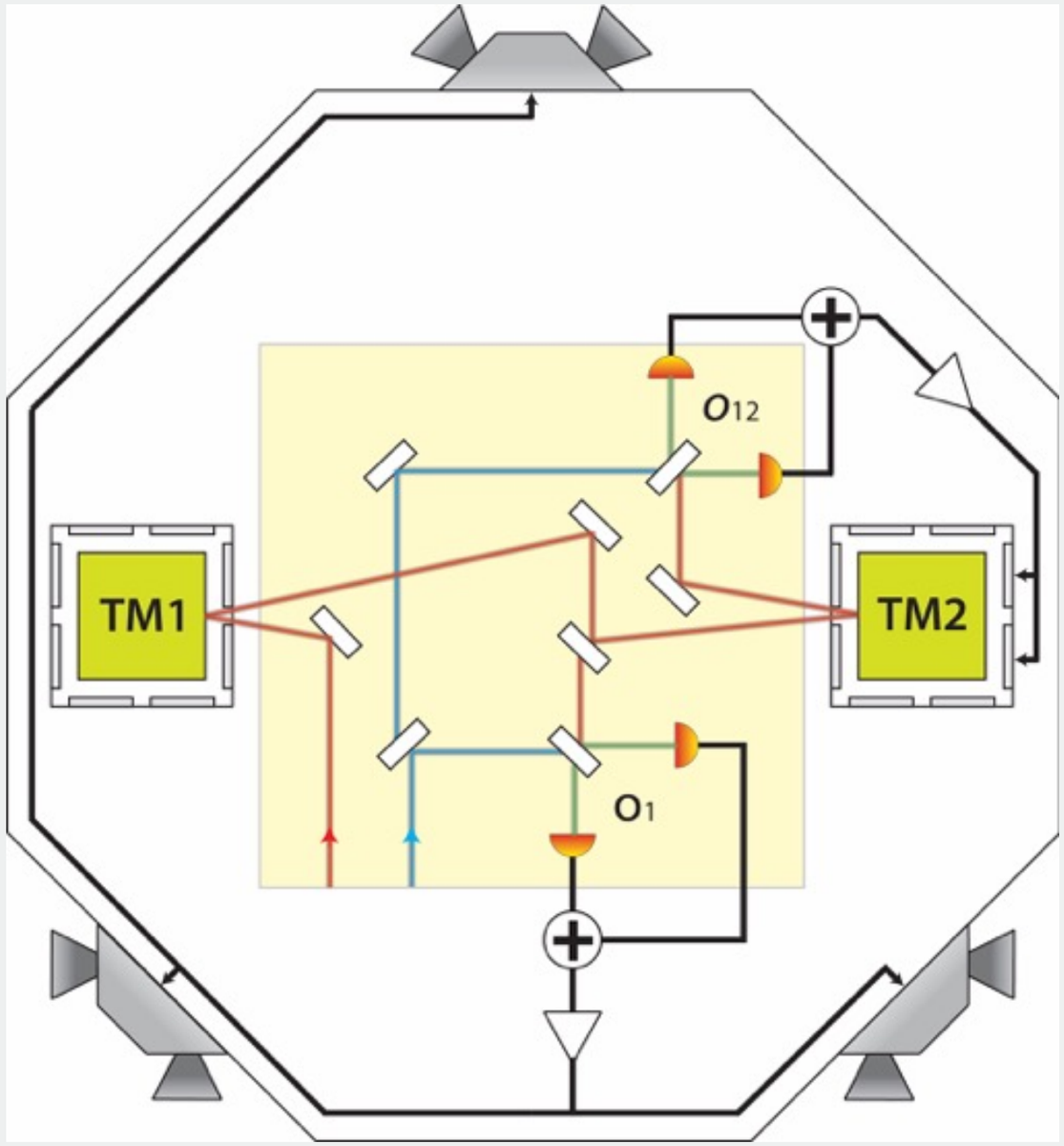
- **Physics of LPF**
  - **measurements & results from space**
- Future of LPF
  - space borne gravitational wave observatory LISA

The residual acceleration measurement summarised

$$\Delta g = \ddot{x}_{12} \qquad - g_c(t)$$

applied forces on reference TM



The residual acceleration measurement summarised

include corrections for known effects!

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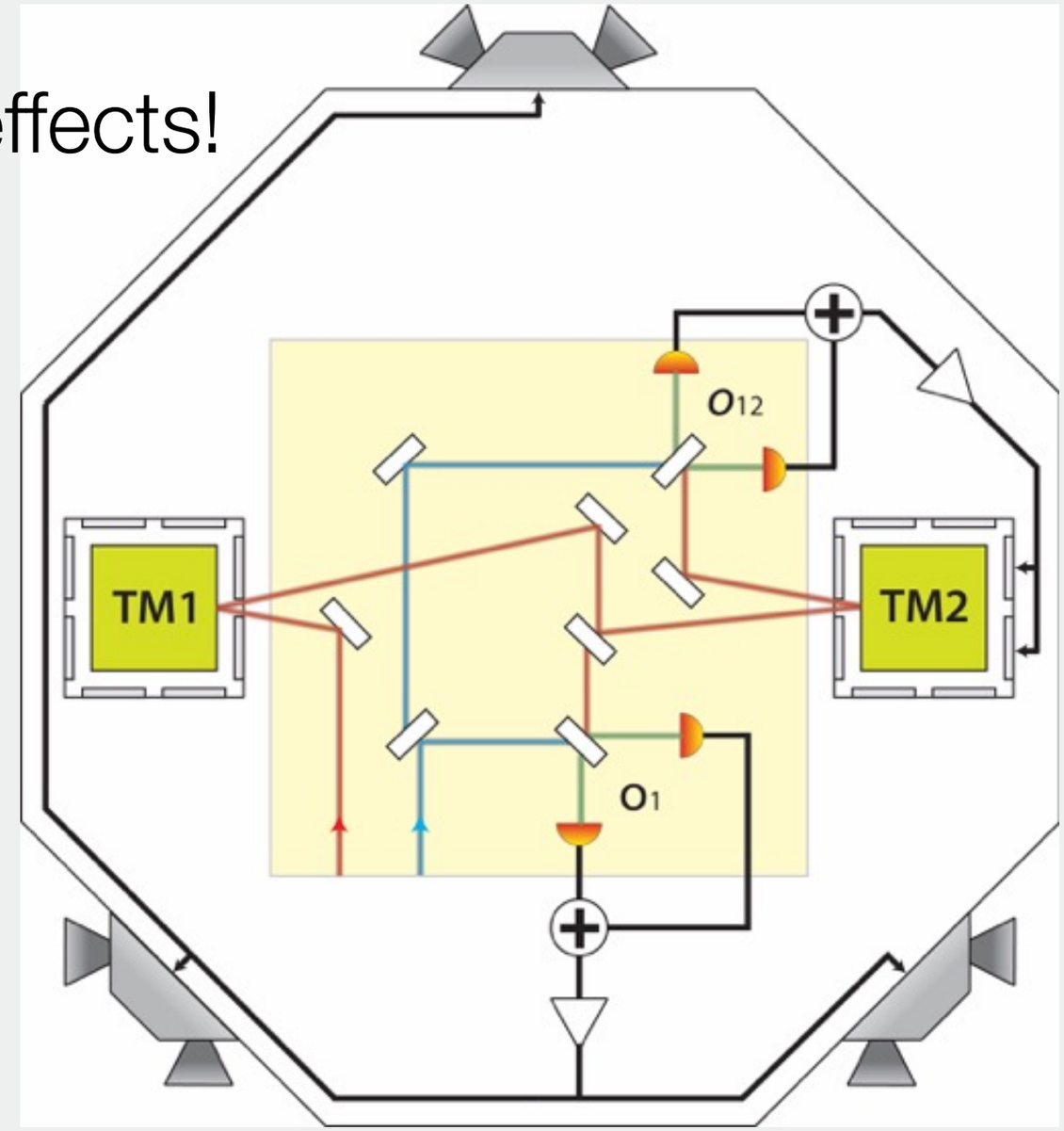


The residual acceleration measurement summarised

include corrections for known effects!

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

stiffness term

applied forces on reference TM

stiffness term

The residual acceleration measurement summarised

include corrections for known effects!

$$\Delta g = \ddot{x}_{12} + \omega_2^2 x_{12}(t) - g_c(t) - g_\Omega(t) - g_{\mathrm{decorr}}(t) - g_{\mathrm{bump}}(t) + \Delta\omega_{12}^2 x_1(t)$$

stiffness term

centrifugal forces

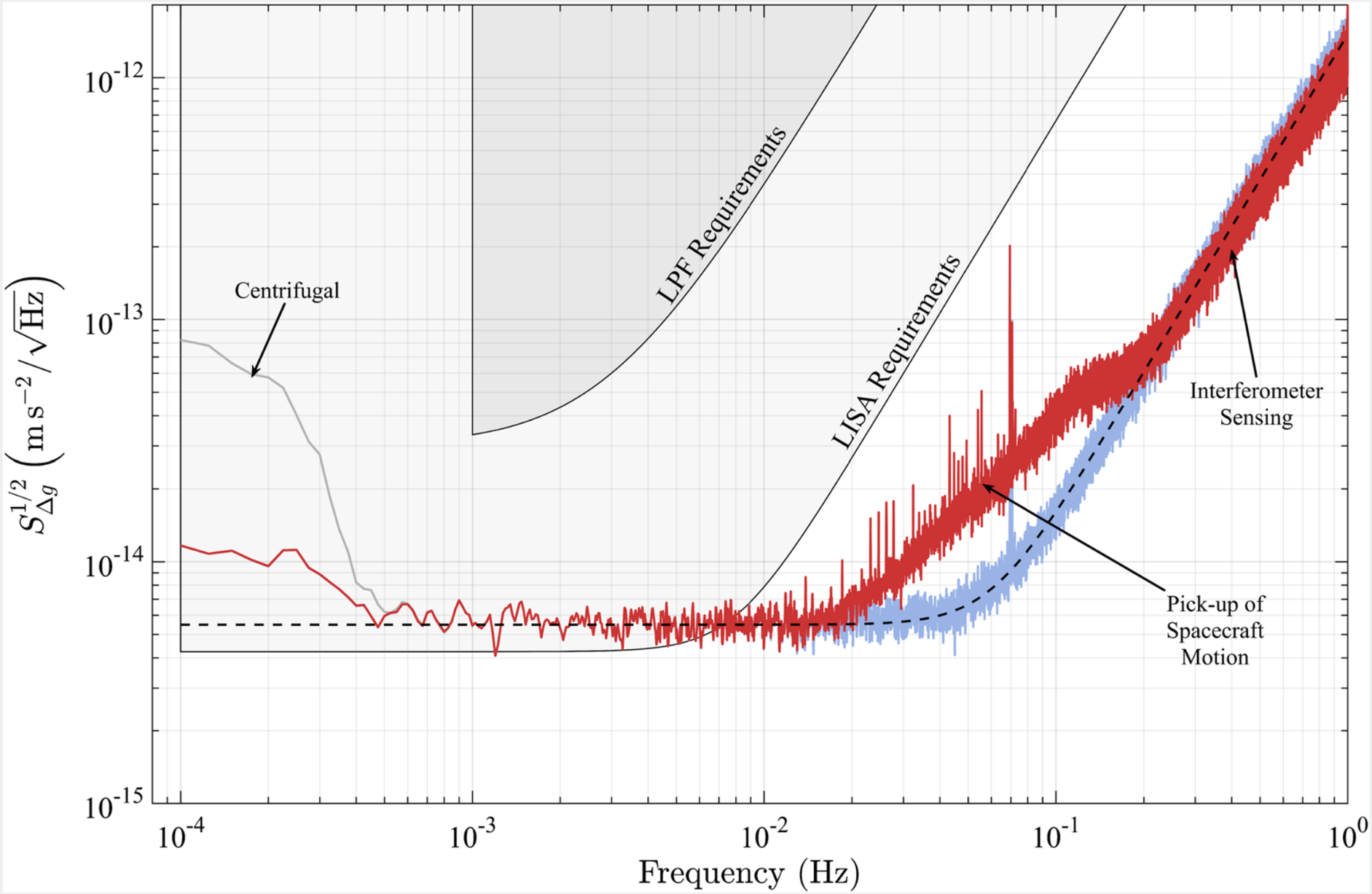
tilt-to-length coupling

stiffness term

applied forces on reference TM

spacecraft angular acceleration effects

The first LISA Pathfinder results



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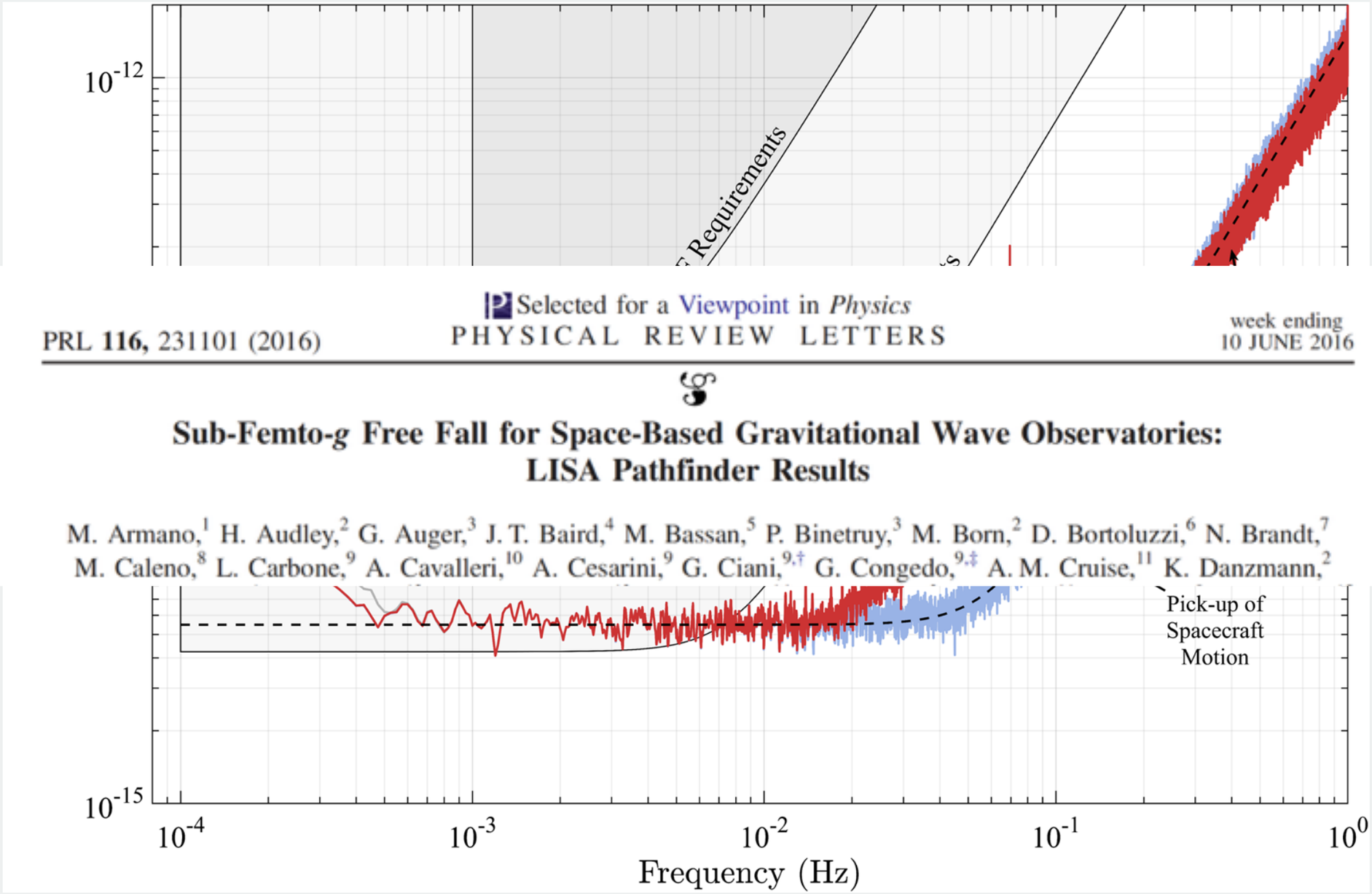

Selected for a Viewpoint in *Physics*

PRL **116,** 231101 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

M. Armano,[1] H. Audley,[2] G. Auger,[3] J. T. Baird,[4] M. Bassan,[5] P. Binetruy,[3] M. Born,[2] D. Bortoluzzi,[6] N. Brandt,[7] M. Caleno,[8] L. Carbone,[9] A. Cavalleri,[10] A. Cesarini,[9] G. Ciani,[9,†] G. Congedo,[9,‡] A. M. Cruise,[11] K. Danzmann,[2]

Improvement during mission!

We do more than measuring noise!

main goal:

show nearly perfect free-fall is feasible

We do more than measuring noise!

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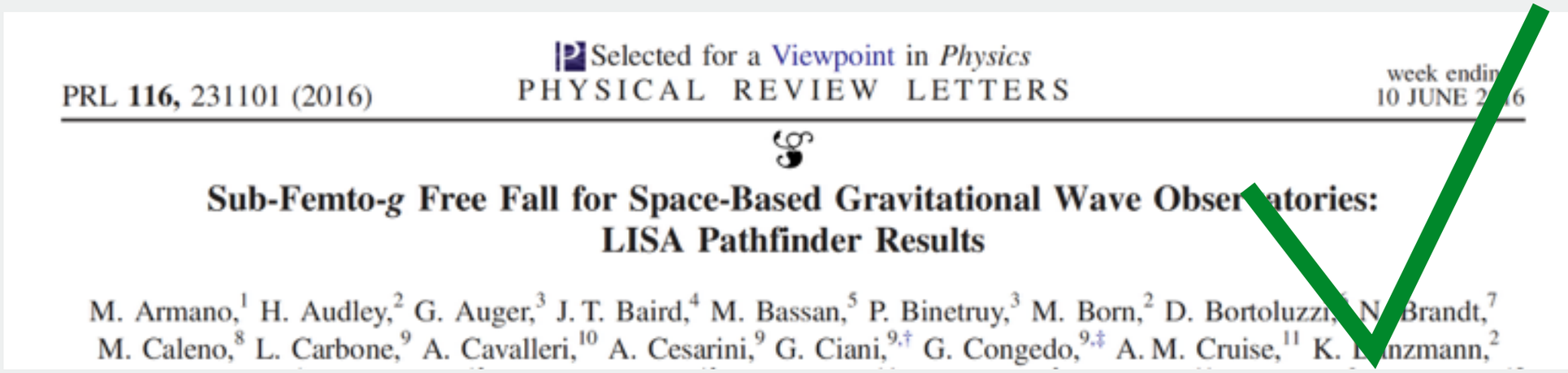
show nearly perfect free-fall is feasible



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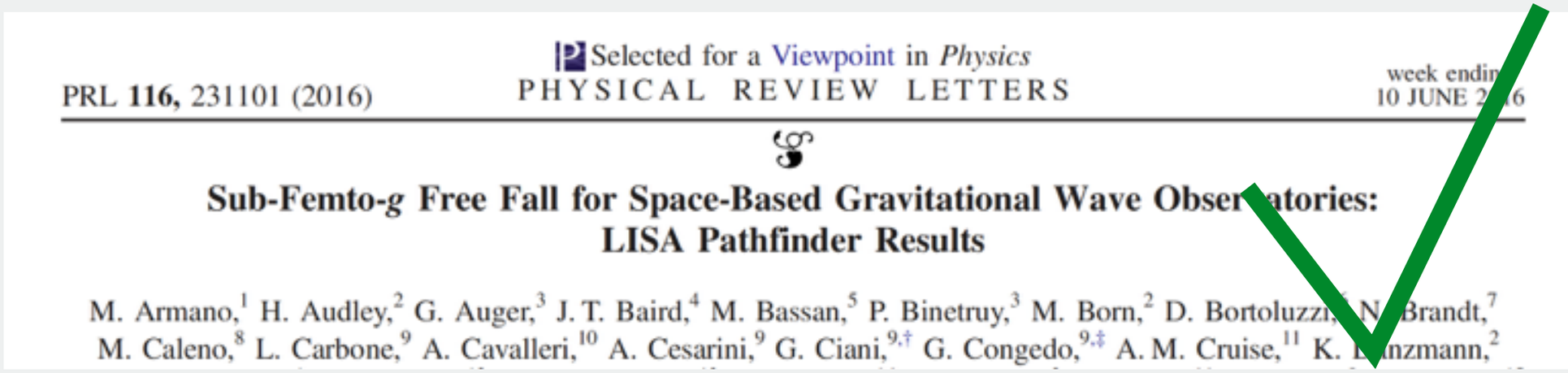

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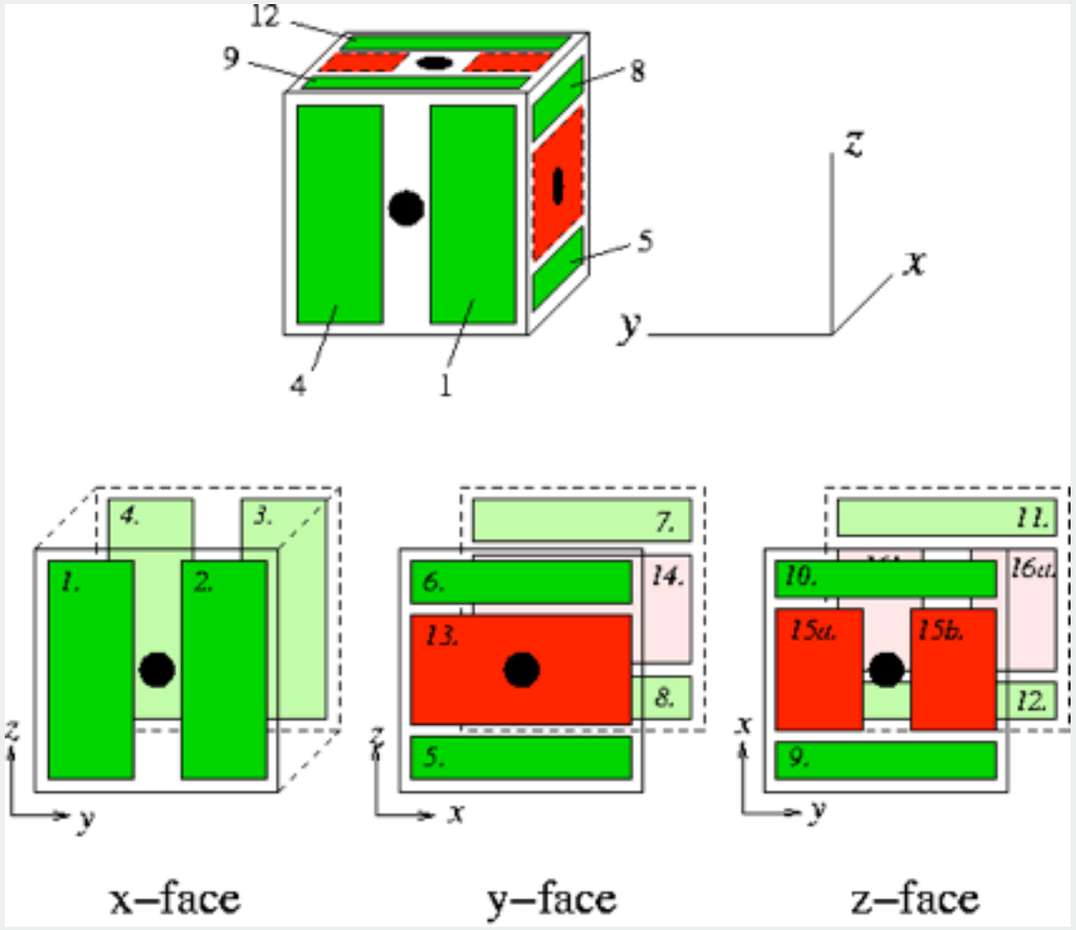
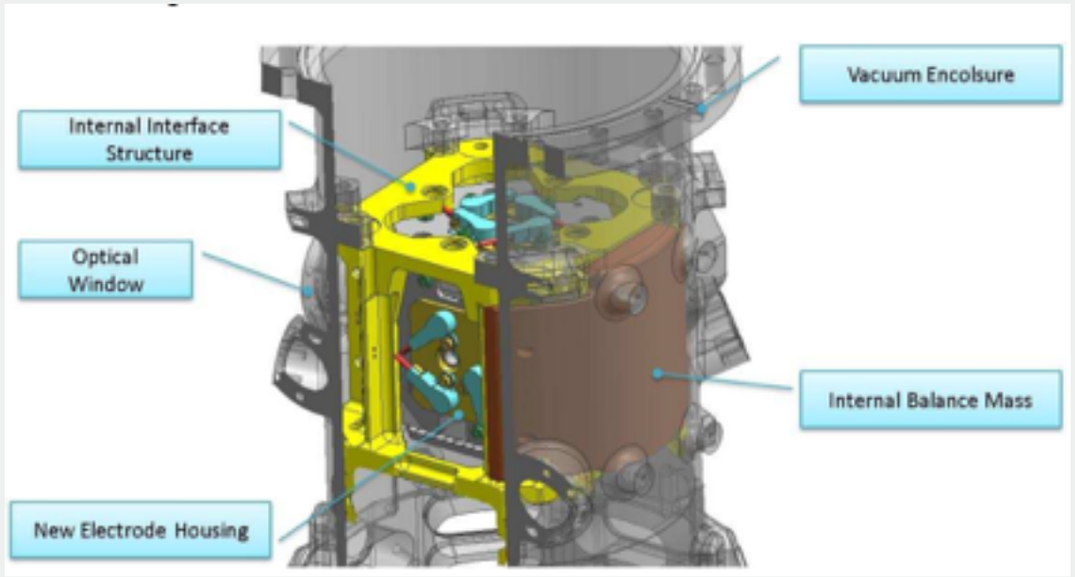
characterise each subsystem to learn as much as we can for LISA

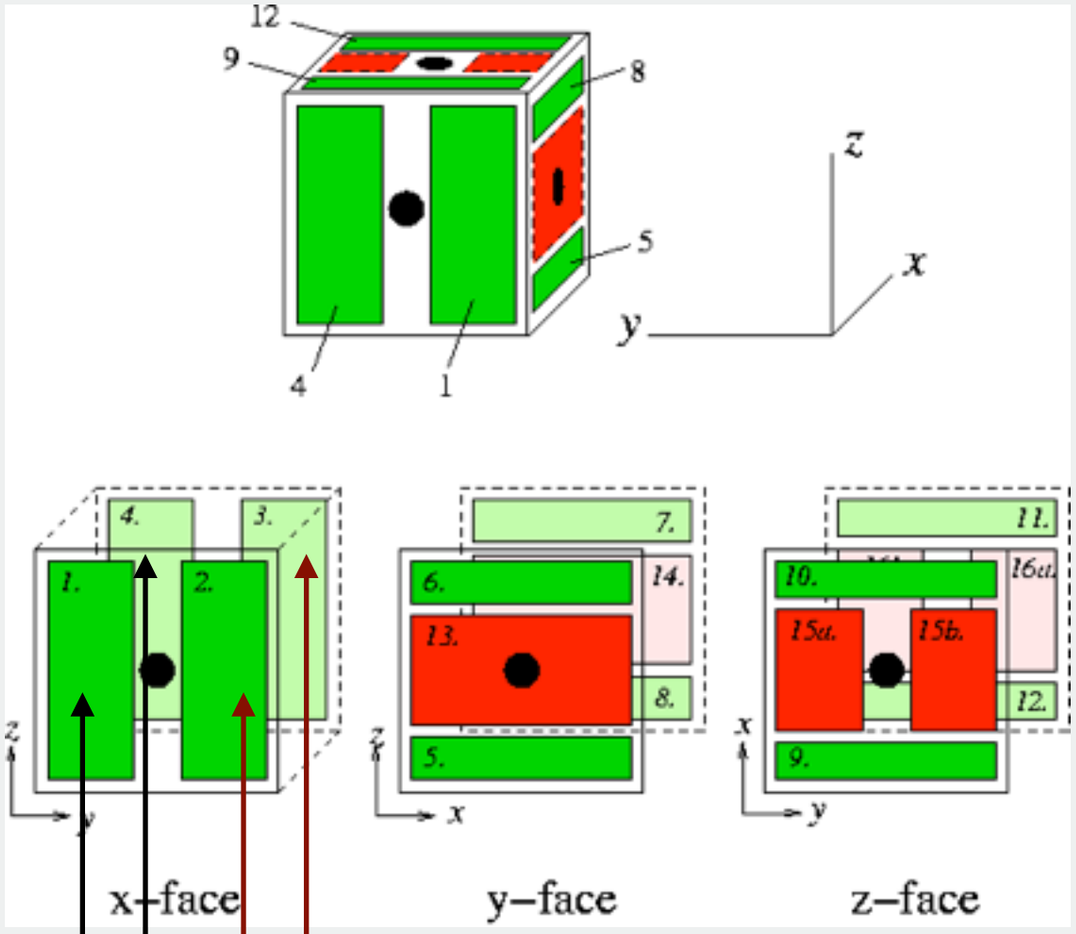
One example for detailed studies: actuation noise





- electrostatic actuation and sensing
- gravitational balancing on the satellite determines forces needed
- design: $\Delta g_{\mathrm{DC}} = 650\ \frac{\mathrm{pm}}{\mathrm{s}^2}$
- in flight: $\Delta g_{\mathrm{DC}} < 50\ \frac{\mathrm{pm}}{\mathrm{s}^2}$
- reduce actuation authority → reduce the voltages → reduce the voltage noise → reduce the force noise
- other effects independent of actuation authority?

Another example for detailed studies: capacitive sensing



sensing channel 2x

sensing channel 1x

- applied to all 6 DoF of both TMs
- displacement = average of two channels, rotation = difference of two channels
- above 1mHz: test mass displacement noise of

$$2.4\,\mathrm{nm}/\sqrt{(\mathrm{Hz})}$$

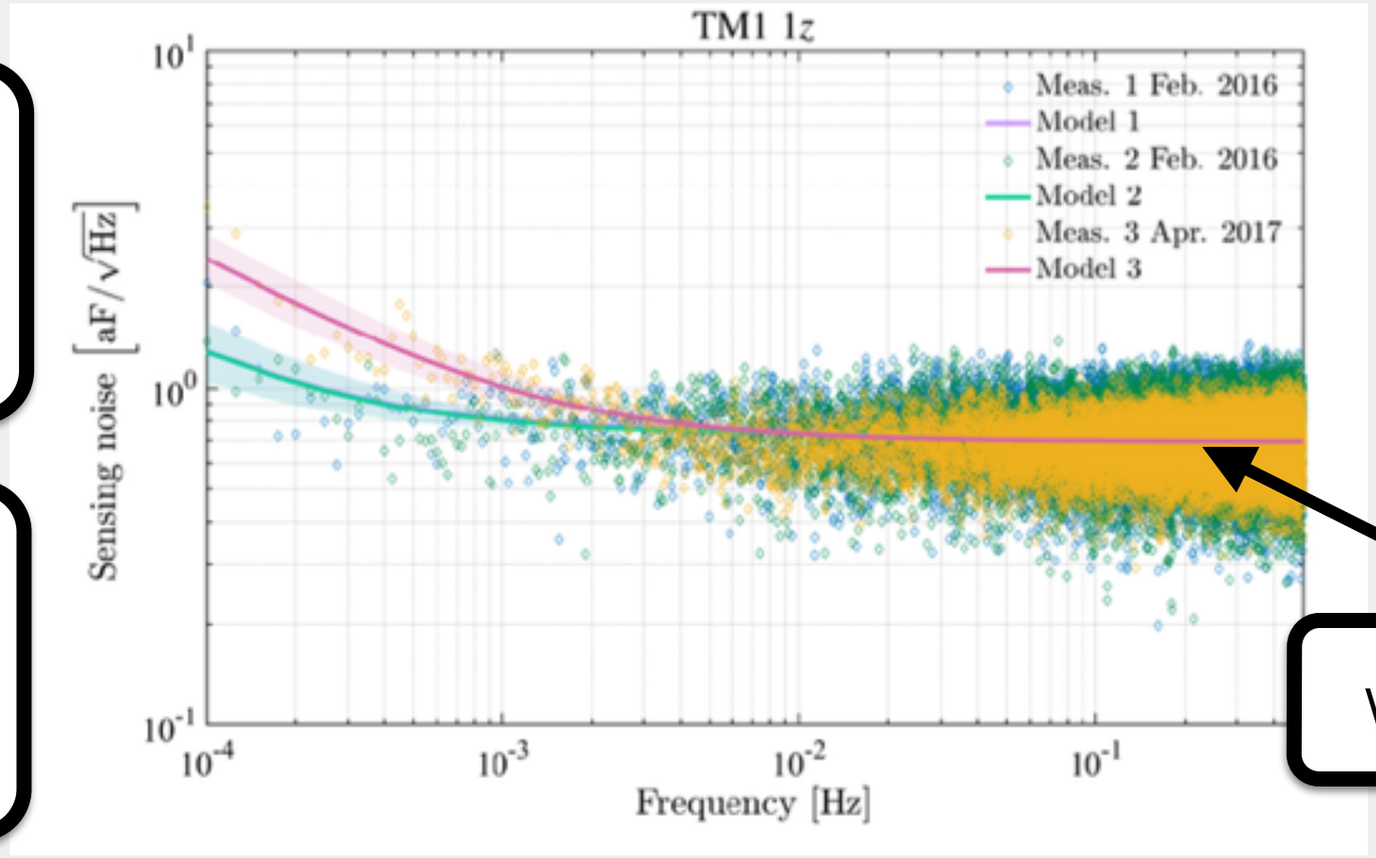
- but: channels 1... less noisy and reach thermal limit

Another example for detailed studies: capacitive sensing

At low frequencies:

position dependent 1/f noise (common)

1/f noise for individual channels



PHYSICAL REVIEW D **96,** 062004 (2017)

Capacitive sensing of test mass motion with nanometer precision over millimeter-wide sensing gaps for space-borne gravitational reference sensors

Another example for detailed studies: Charge

- issue: noisy force on free-falling TMs arises from

1. mixing of **noisy charge** with stray potentials

   - caused by high-energy cosmic rays and solar energetic particles

   - remedy: compensate potentials

2. mixing of static TM charge with **noisy stray voltage**

   - caused by surface patch potentials and GRS electronics noise

   - discharge TM with UV light

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2. mixing of static TM charge with **noisy stray voltage**

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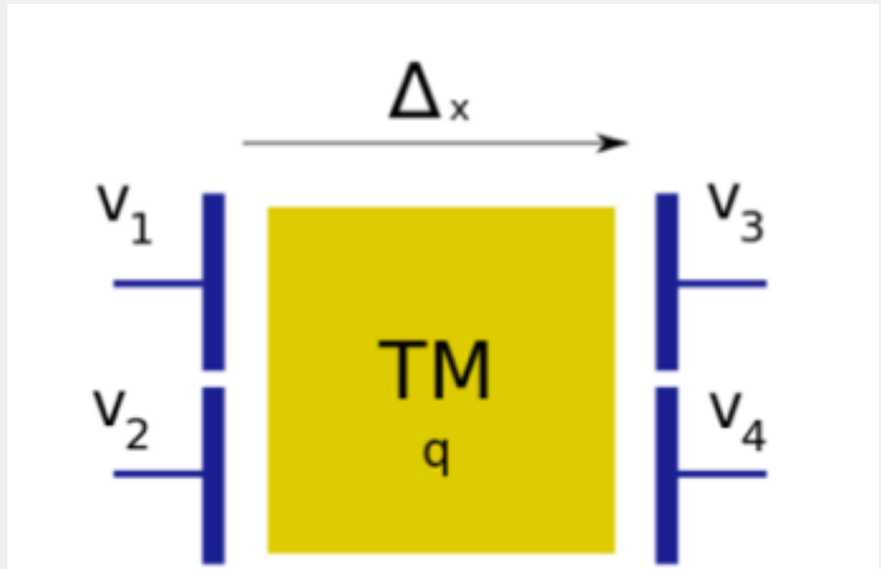
   - discharge TM with UV light

effect also minimised by gap size

Another example for detailed studies: Charge

- characterise by 2 experiments
  - charge estimate by modulating voltages
  - stray potential estimate by the resulting force from a change in charge
- by far not limiting LPF performance



credit: F.Gibert

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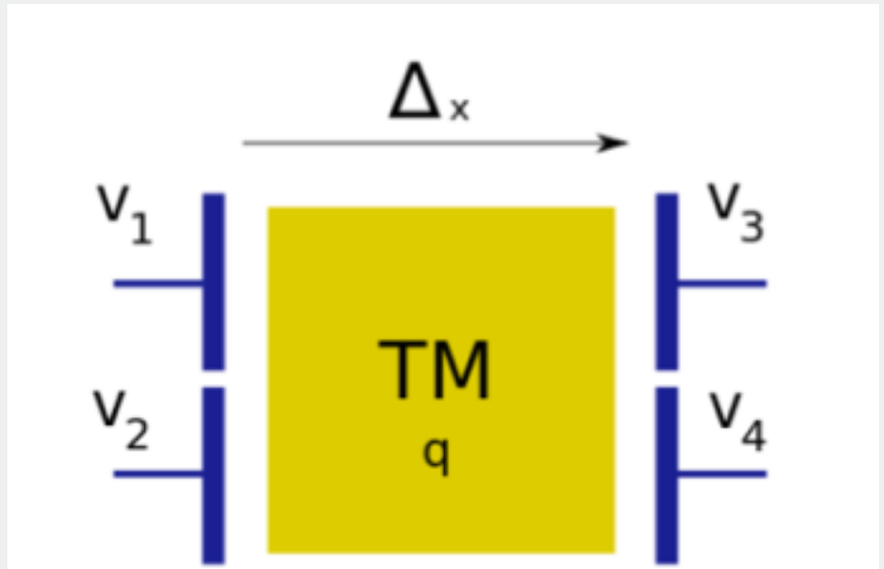

credit: F.Gibert

- by far not limiting LPF performance

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Charge-Induced Force Noise on Free-Falling Test Masses: Results from LISA Pathfinder

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Another example for detailed studies: OMS

... low noise & stable!

selected OMS noise sources investigated

- laser frequency noise
- common mode **P**ath **L**ength (PL) noise
- **R**elative **I**ntensity **N**oise (RIN)

OMS noise sources: **L**aser **F**requency (**LF**) noise

phase noise
in X12, X1 or R

$$\delta\phi = 2\pi \frac{\Delta s}{c} \delta f$$

path length
difference
or arm length
mismatch

frequency
fluctuations

OMS noise sources: **L**aser **F**requency (**LF**) noise

OMS noise sources: **L**aser **F**requency (**LF**) noise

functioning of loop
also verified by dedicated
characterisation experiments

OMS noise sources: common mode PL noise

in addition:
optical
path length
difference
(**OPD**)
control loop

- actuators adjust PL of fibres in modulation unit

OMS noise source: **R**elative **I**ntensity **N**oise (**RIN**)

heterodyne interferometry:

$$\mathrm{P}(t) = \mathrm{P}_{\mathrm{Laser}}(t)\,(1 \pm c\cos(\omega_{\mathrm{het}} t - \varphi))$$

power impinging on photodiode

insert fluctuations

contrast

heterodyne frequency

OMS noise source: **R**elative **I**ntensity **N**oise (**RIN**)

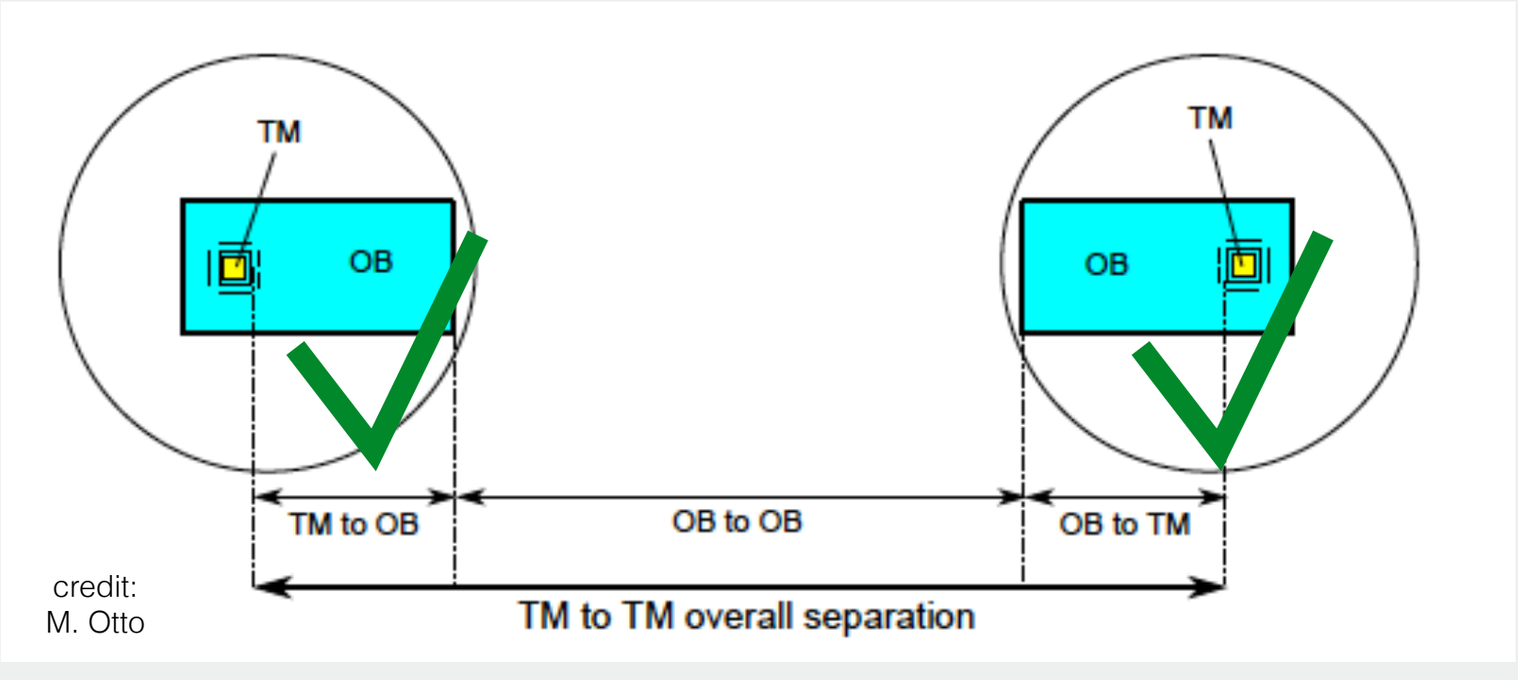
phasemeter: only terms at ω_{het}

RIN @

DC	radiation pressure noise
ω_{het}	cancels with balanced detection
2 ω_{het}	depends on TM position

OMS noise budget

Outlook: LISA and the split-interferometry concept



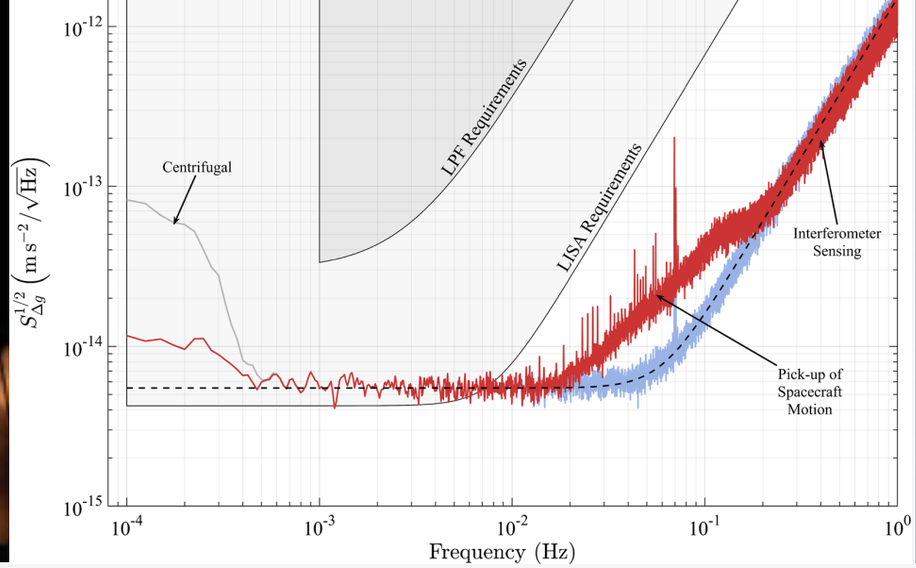
credit:
M. Otto

- high precision local interferometry at the core of LISA
  - **successfully tested by LISA Pathfinder OMS**
- long-arm interferometry: (some) insight from Grace Follow-On Laser Ranging Instrument expected

Summary: LISA Pathfinder

- ... is the technology demonstrator mission for the future space borne gravitational wave observatory LISA
- ... free-fall performance is excellent: Good enough for LISA!
- ... optical metrology system more than 100 times better than on ground: similar to local interferometer on LISA
- ... all subsystems have been characterised in detail

LISA mission concept has been selected and work is well underway



Thank you for your attention on behalf on the whole team!