Femto Newton level testing of free-fall on-ground

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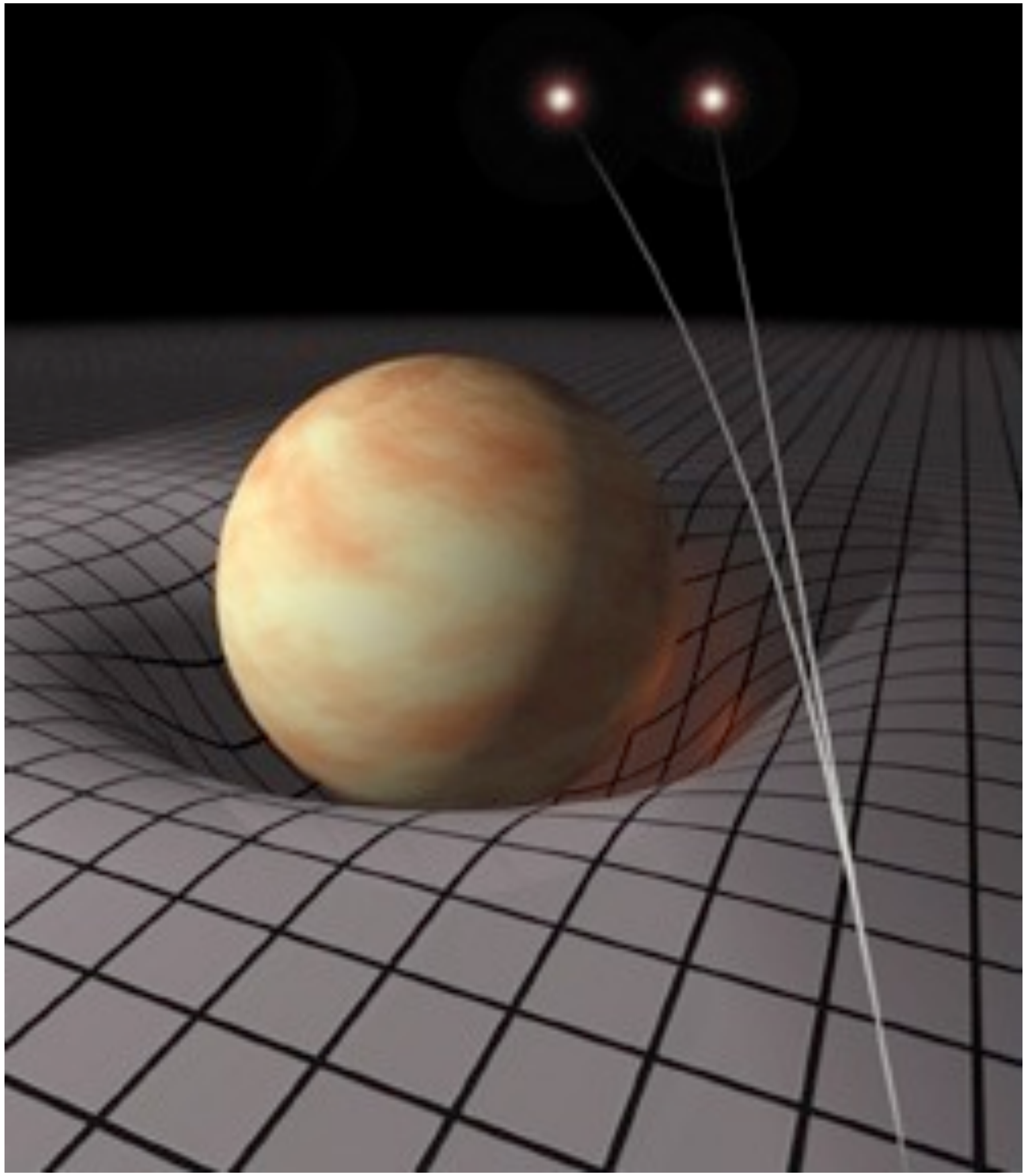
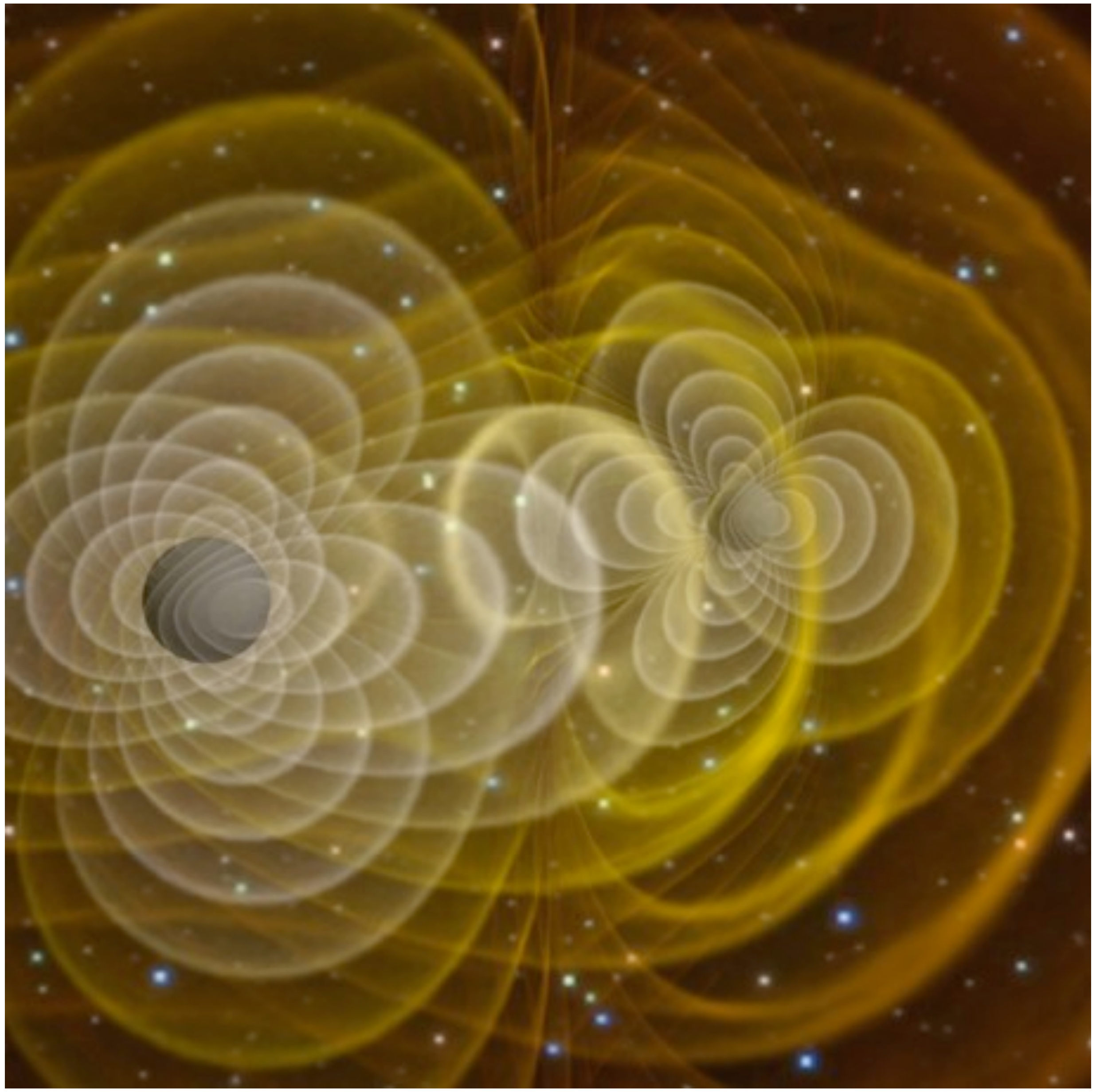
Why do we need to test free-fall?



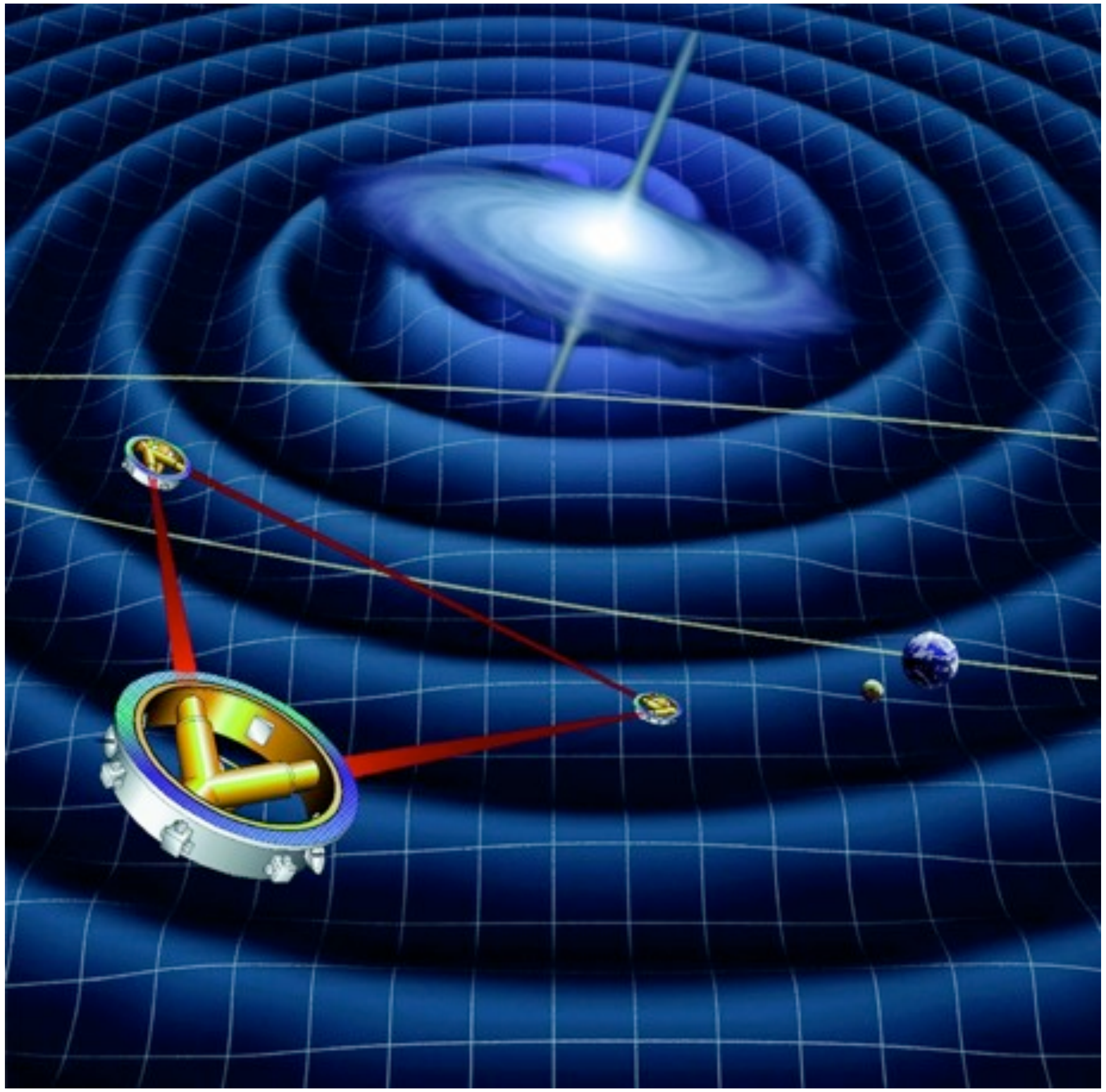
* Realisation of free-fall is the key component for defining geodesic reference frames.
* It is crucial for Gravitational Waves detection and for any other general relativity experiment.

Why do we want to detect GW?



* Confirmation of general relativity.
* Gravitational wave astronomy.
* Cosmology.

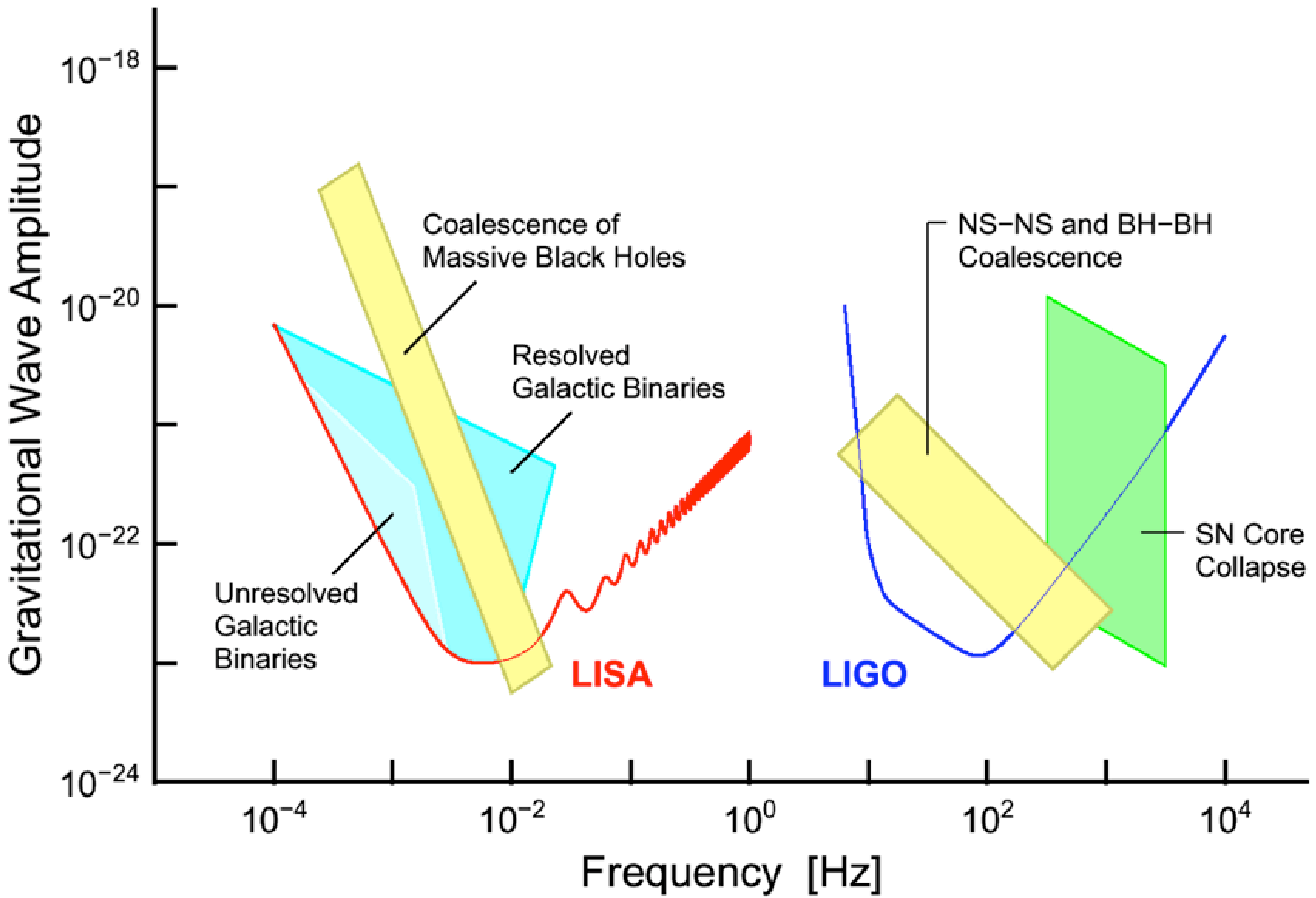
The LISA experiment



* Three spacecraft located 5 millions km away to form an equilateral triangle orbiting the Sun.
* Each spacecraft contains two test bodies nominally in free-fall.
* Distance between test bodies measured by means of interferometric ranging with pm resolution.

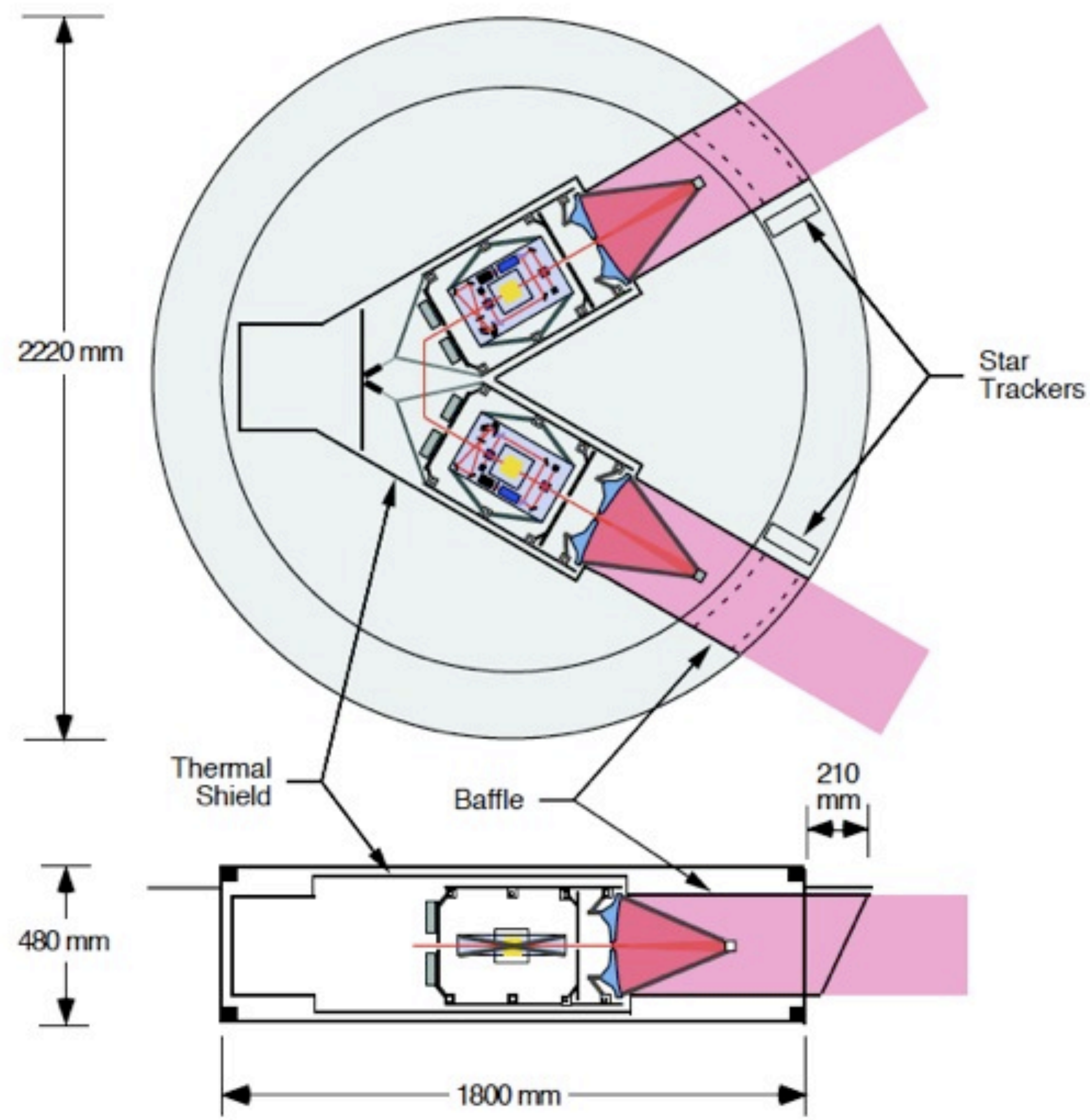
Giant Michelson interferometer in space.

Sensitivity to GW



The LISA Spacecraft in brief

* Spacecraft shields TMs from external disturbances.
* SC must be kept centred around test mass position by means of FEEP micro-thrusters.
* 2 TMs in each SC: actuation in the non scientific DOF.



The Gravitational Reference Sensor

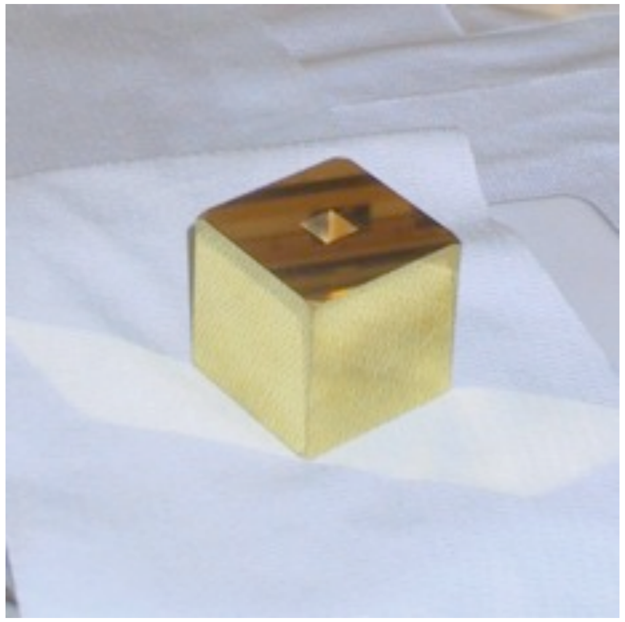
* Defines test mass environment.
* Limit forces and force gradients acting on the TM.
* Measurement of TM position in 6 DOF.
* Supply actuation authority to control test mass position.

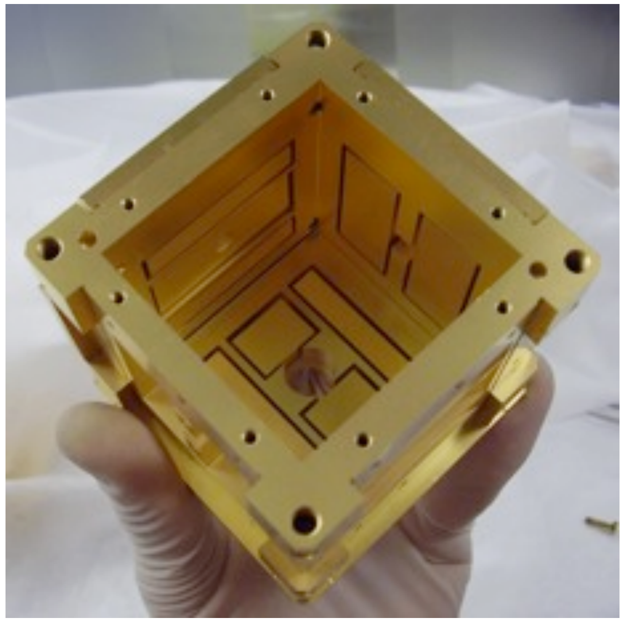
$$S_a^{1/2} < 3.0 \times 10^{-15}\ \mathrm{m\ s^{-2}\ Hz^{-1/2}}$$

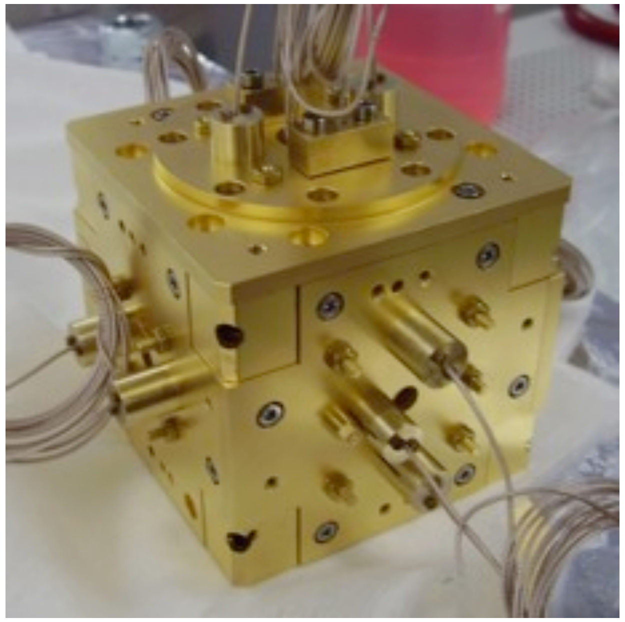
$$S_x^{1/2} < 1.8 \times 10^{-9}\ \mathrm{m\ Hz^{-1/2}}$$

LISA GRS design

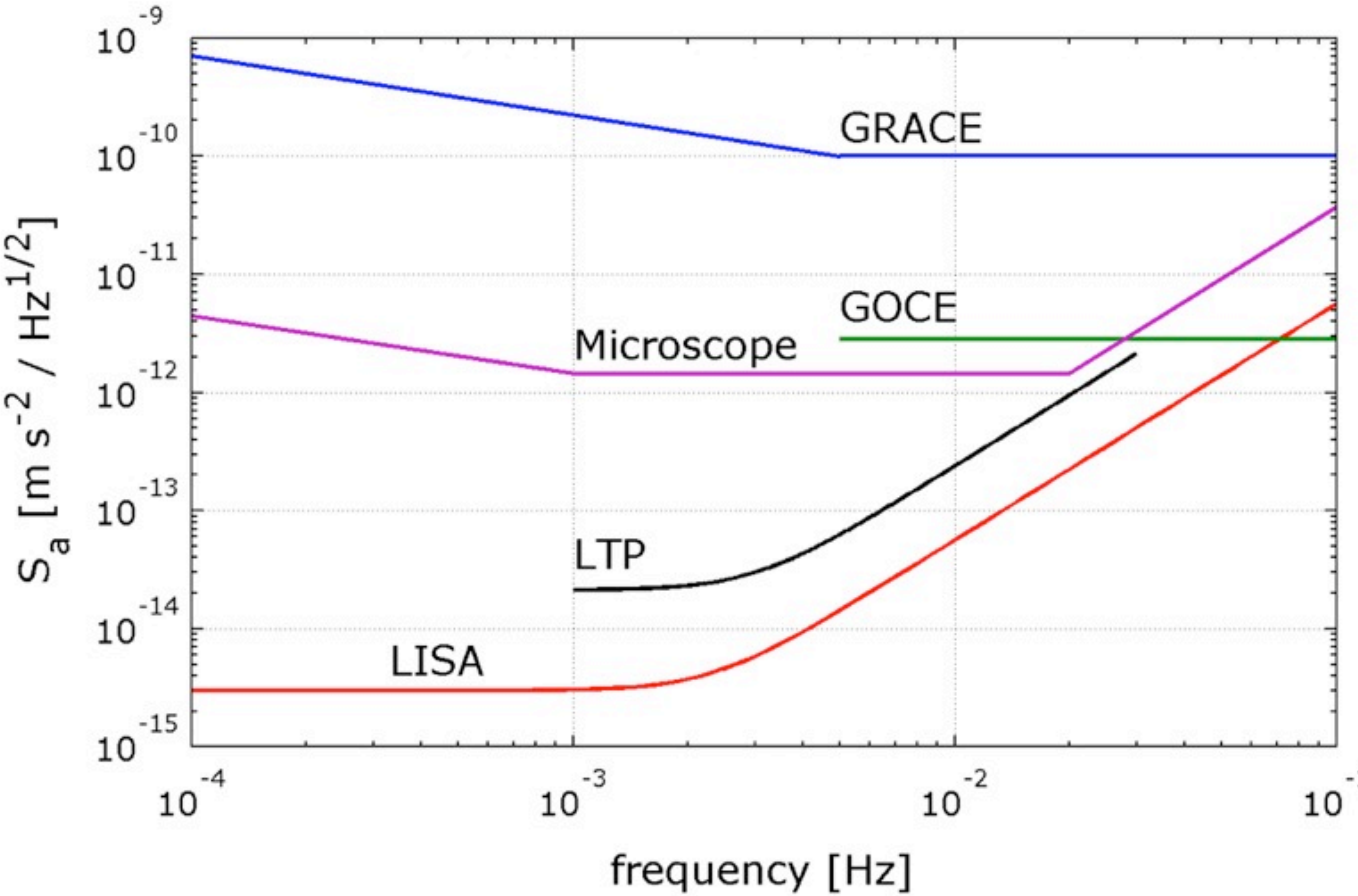
* 2 kg 46 mm cubic Au-Pt test mass
* 6 DOF capacitive sensor:
  - contact free sensing bias injection
  - resonant 100 kHz AC bridge readout.
* Audio frequency electrostatic actuation.
* Large gaps 3-4 mm.
* High thermal conductivity Mo-Sapphire construction.





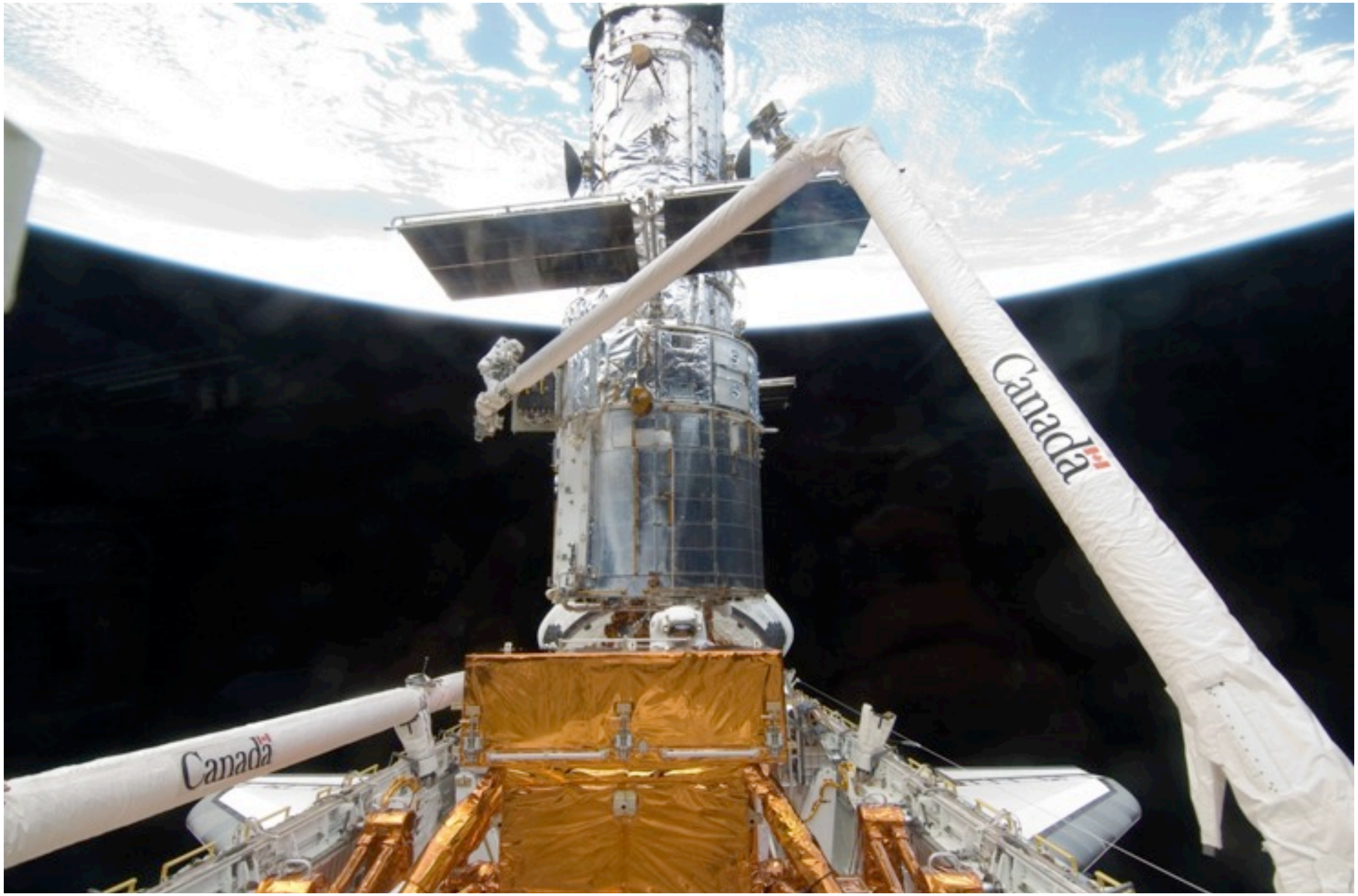


Reason for free-fall ground testing



LISA free-fall performance should be 1000x better than currently flying missions.

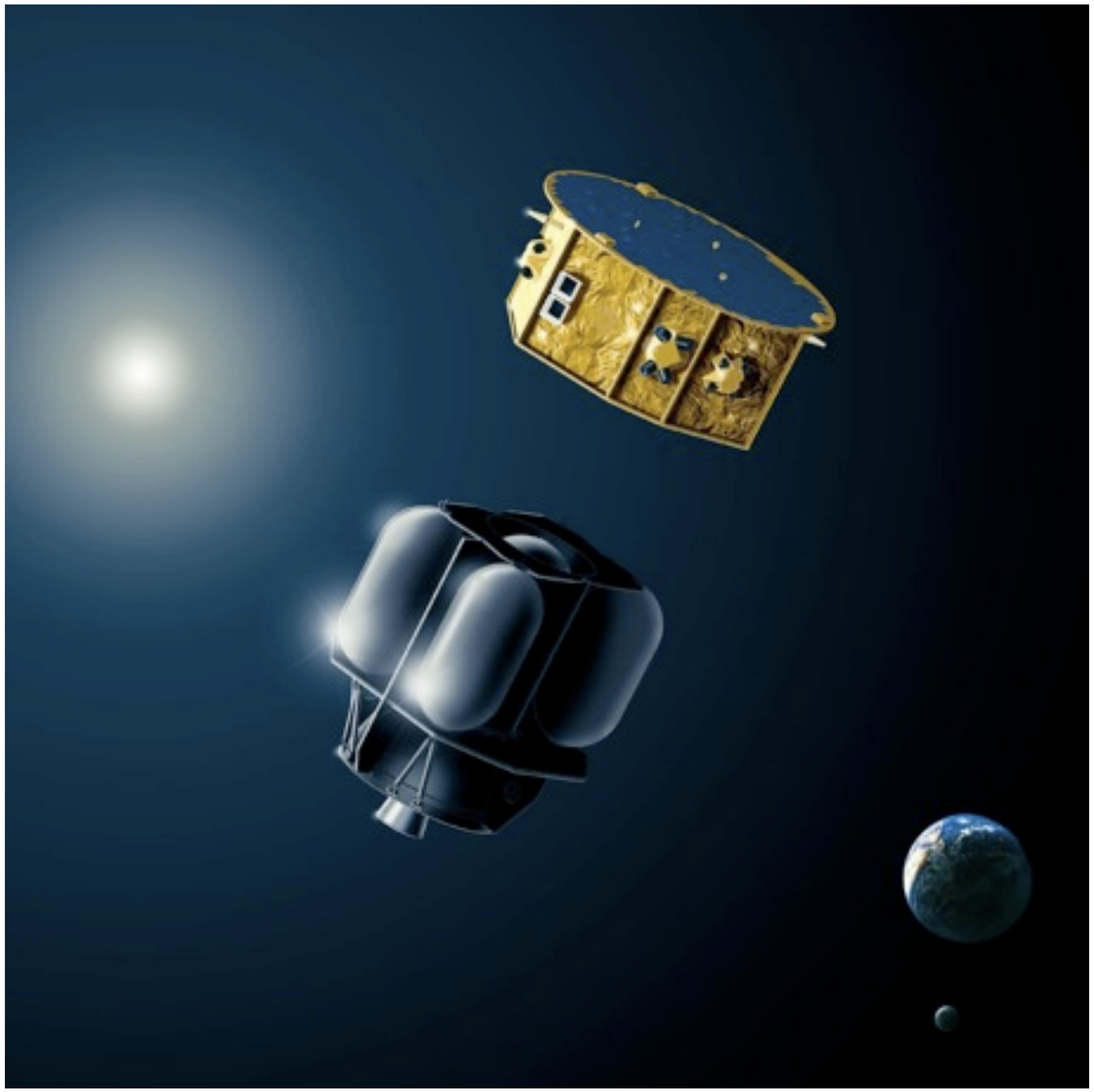
Reason for testing free-fall on-ground



STS-125 Mission servicing Hubble space telescope. NASA

No PhD students to tight bolts in space!!

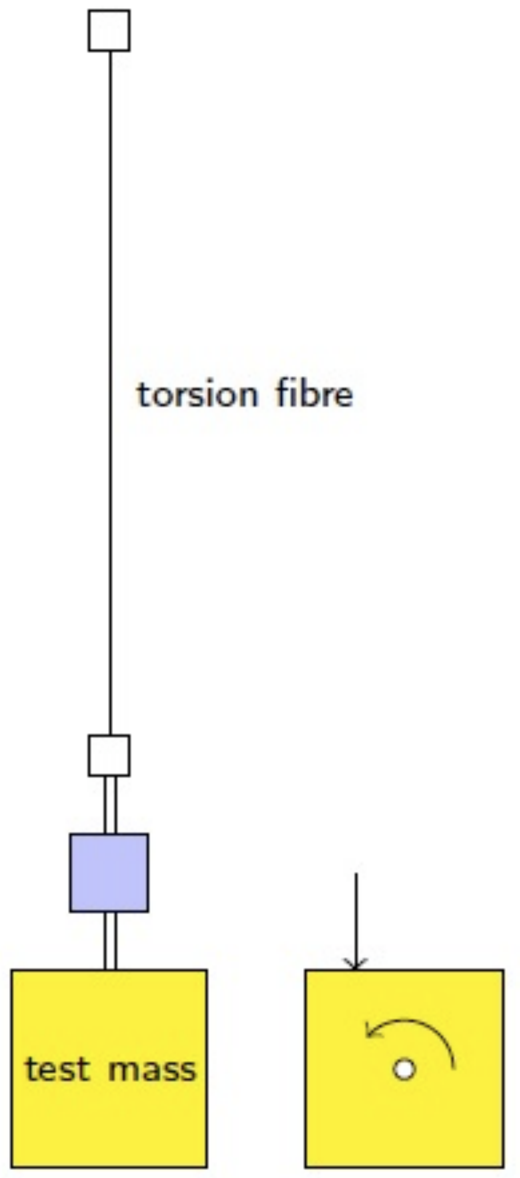
LISA Pathfinder and LTP



- Demonstration of geodesic motion.
- One particle sets the reference frame.
- One particle acts as test body.
- Measure the relative acceleration.

Shrink one LISA arm from 5 millions km to 30 cm.

On-ground free-fall testing



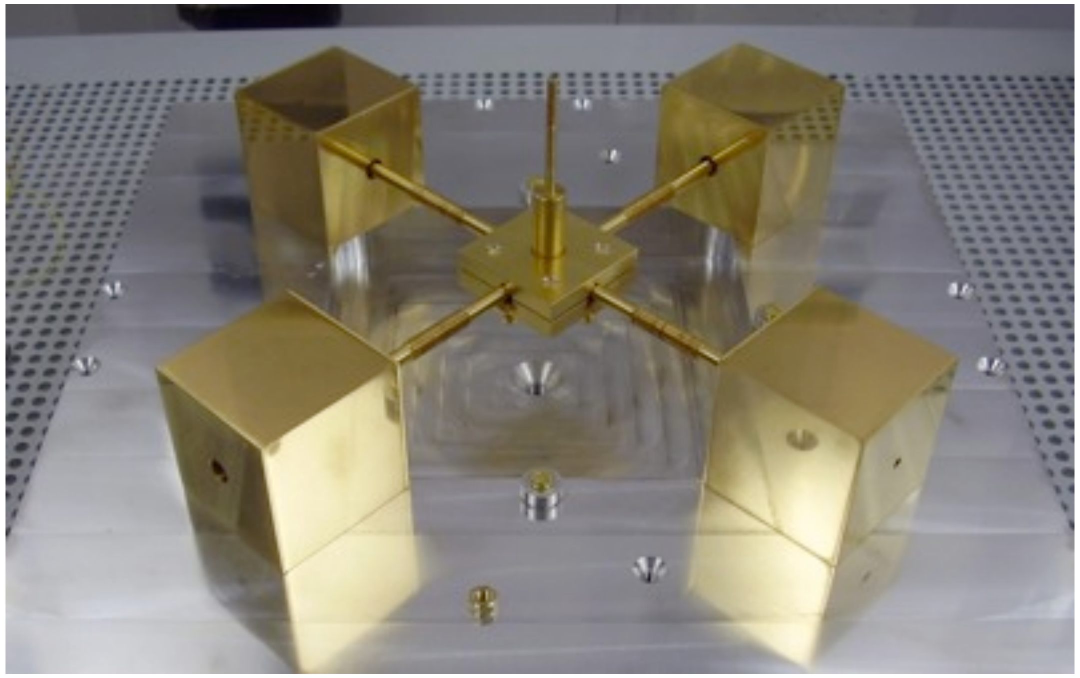
* Torsion pendulum

* Provide quasi free-fall in 1D
* Lightweight test mass
  - Hollow aluminium test mass replica
  - Test limited to surface forces
  - Bulk forces tested separately

Trento torsion pendulums facilities

* Single mass torsion pendulum: torque measurements.

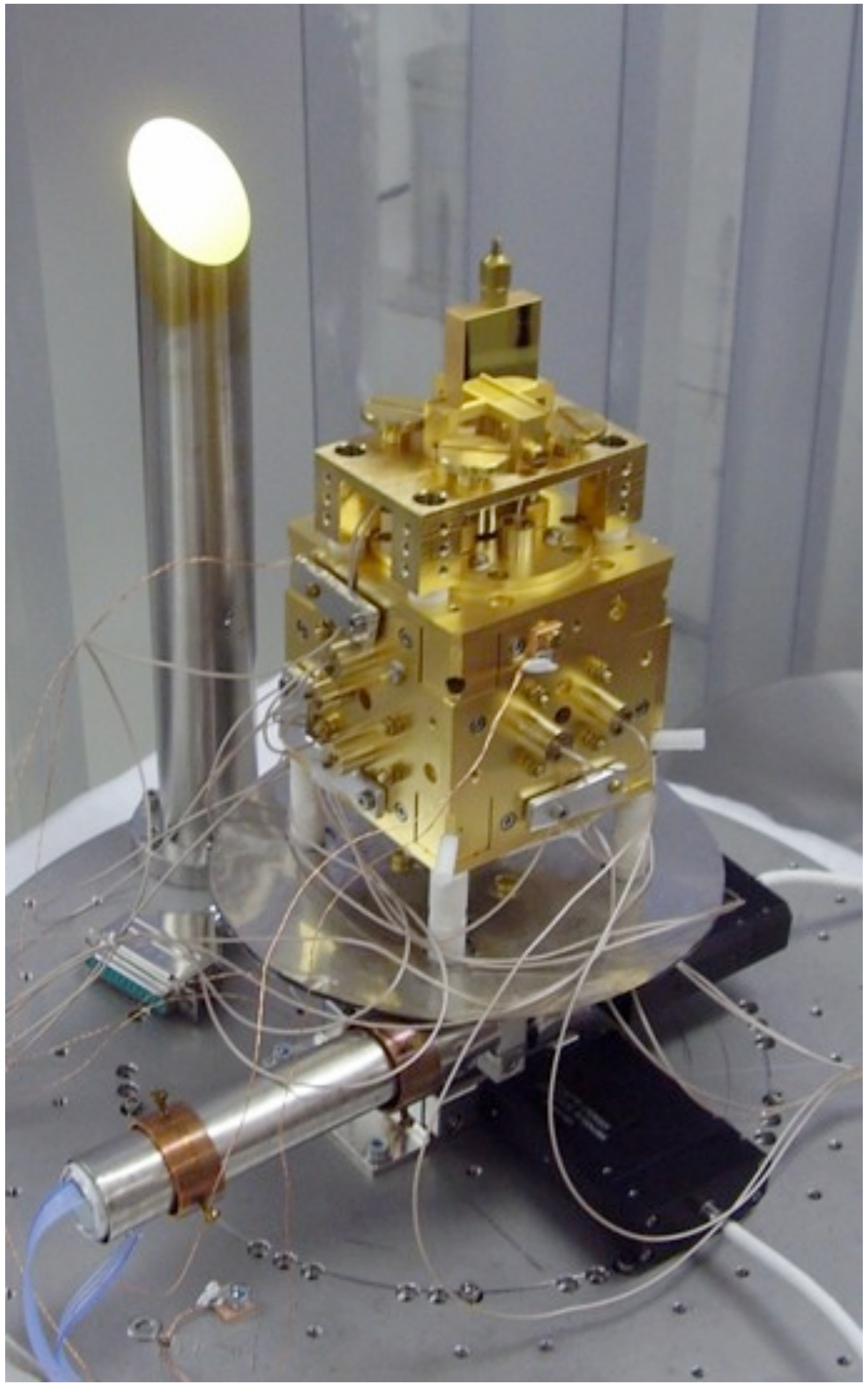
* Four masses torsion pendulum: direct force sensitivity.



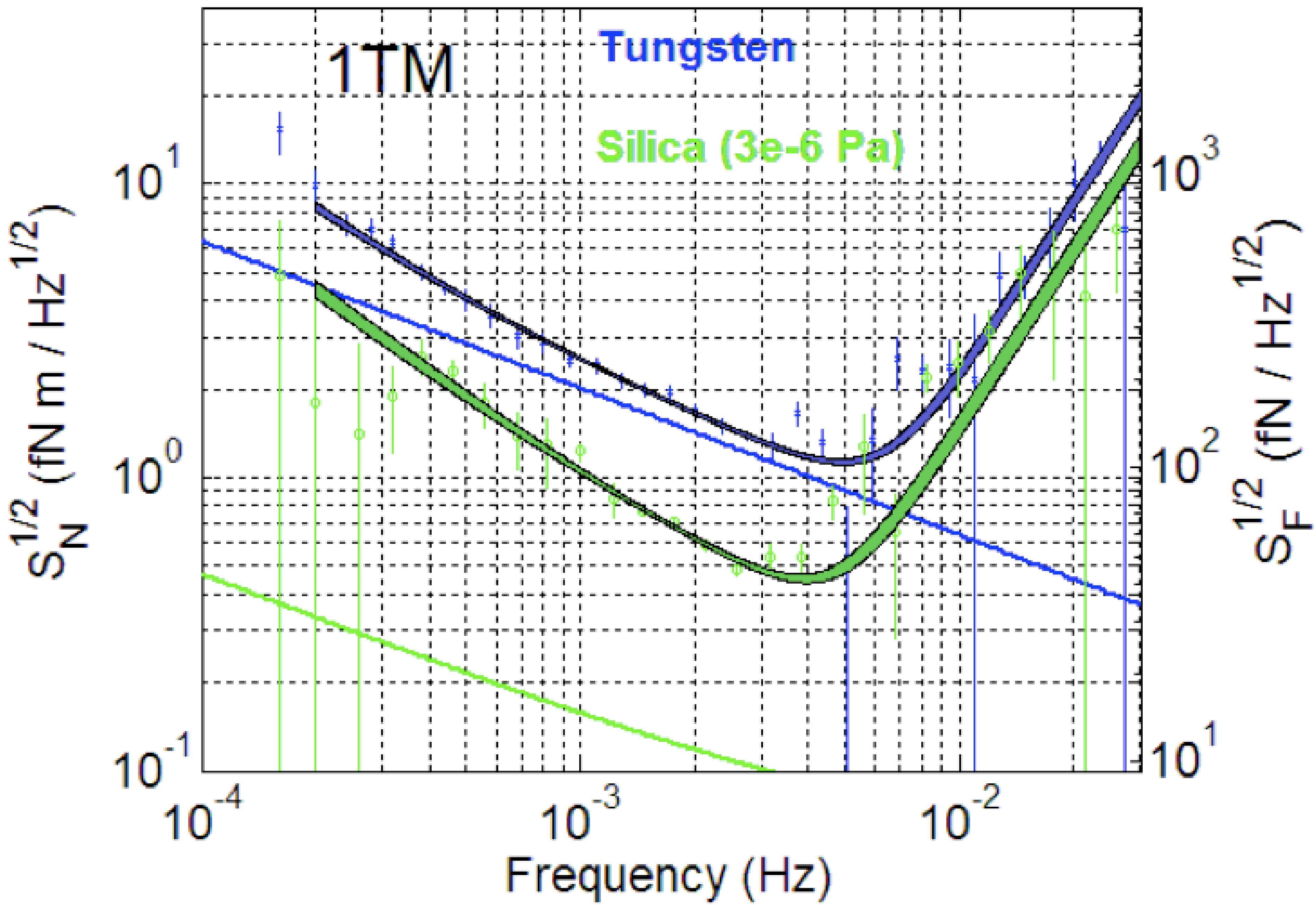
* Sensitivity limited by thermal noise and angular read-out noise.

Torsion pendulum upper limits on GRS force noise

* Quietest possible conditions.
* Angular deflection measurement with two readouts: GRS capacitive sensing and optical readout.
* Cross correlation to distinguish true torque noise floor from background readout noise.
* Average over many runs each one lasting one WE.

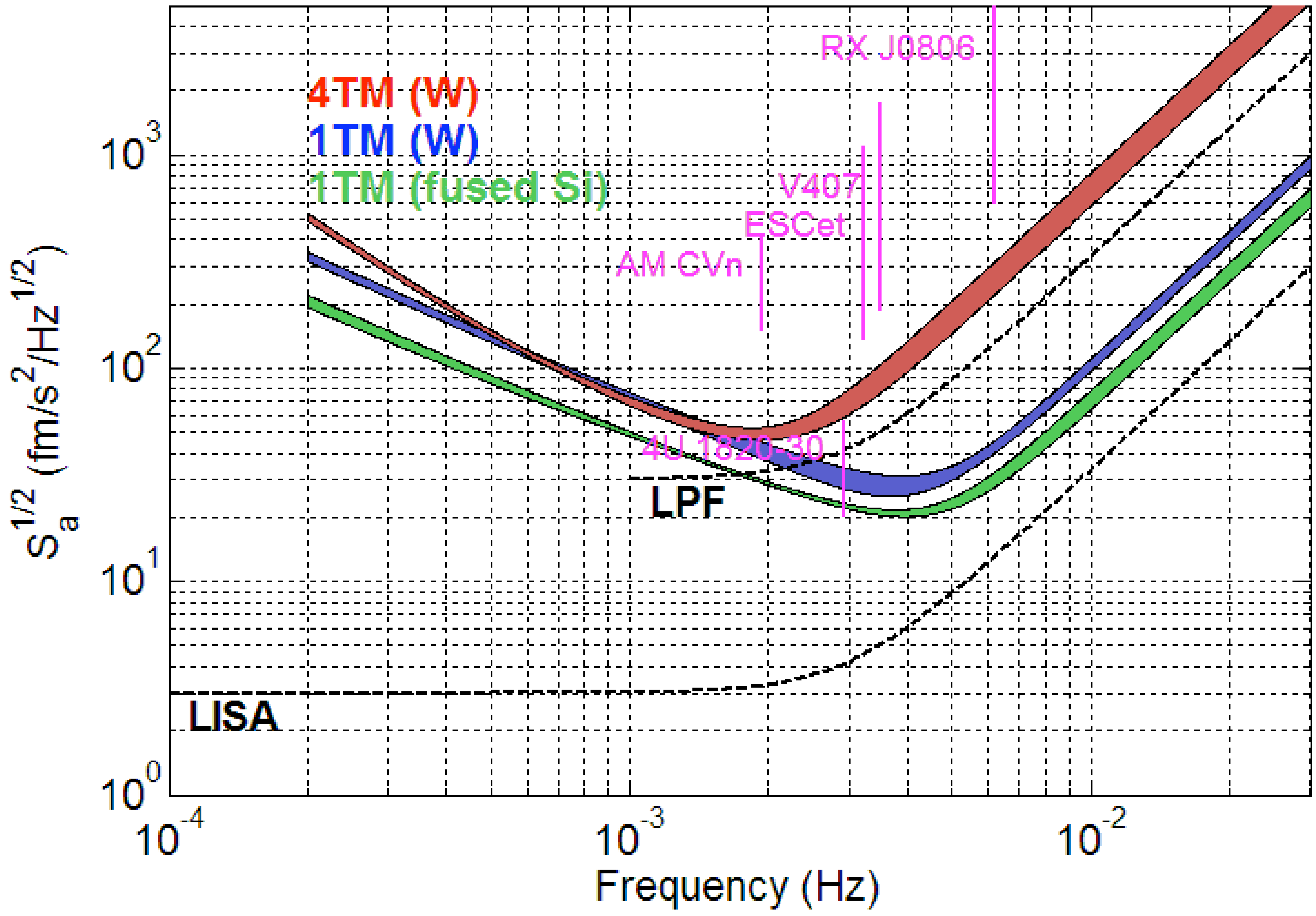


Torsion pendulum upper limits on GRS force noise



Fibre upgrade from Tunghsten with Q = 3000
to Fused Silica with Q = 740000

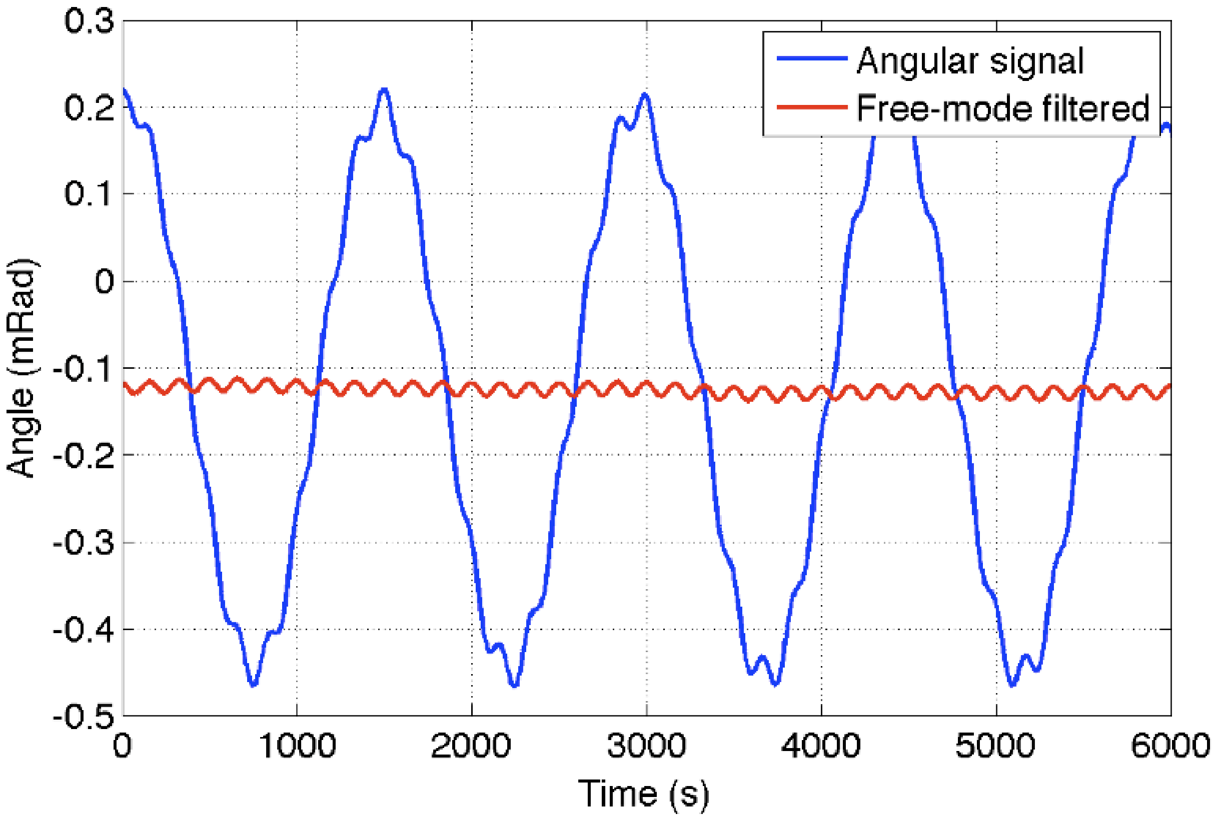
Conversion to test mass acceleration noise



$$50 \times 10^{-15}\ \mathrm{m\ s^{-2}\ Hz^{-1/2}}\ @\ 1\ \mathrm{mHz}$$

Known noise sources investigation

- Coherent detection:
  - modulate force disturbance source
  - measure coherent pendulum motion



- Examples:
  - Thermal gradients induced forces
  - Electrostatic forces

Ongoing effort

* Understand detected torque noise excess:
  - known disturbances transfer function measurements.
  - detailed noise budget.
* Interferometric angular readout development:
  - few nrad Hz^-1/2 sensitivity in 0.1 mHz -1 Hz
  - based on LTP design: heterodyne wave-front sensing
  - in collaboration with AEI Hannover
* Thinner fused silica torsion fibre:
  - improve production technique
  - reduce read-out noise impact
  - in collaboration with Glasgow University

Thanks

The Trento LISA Team:

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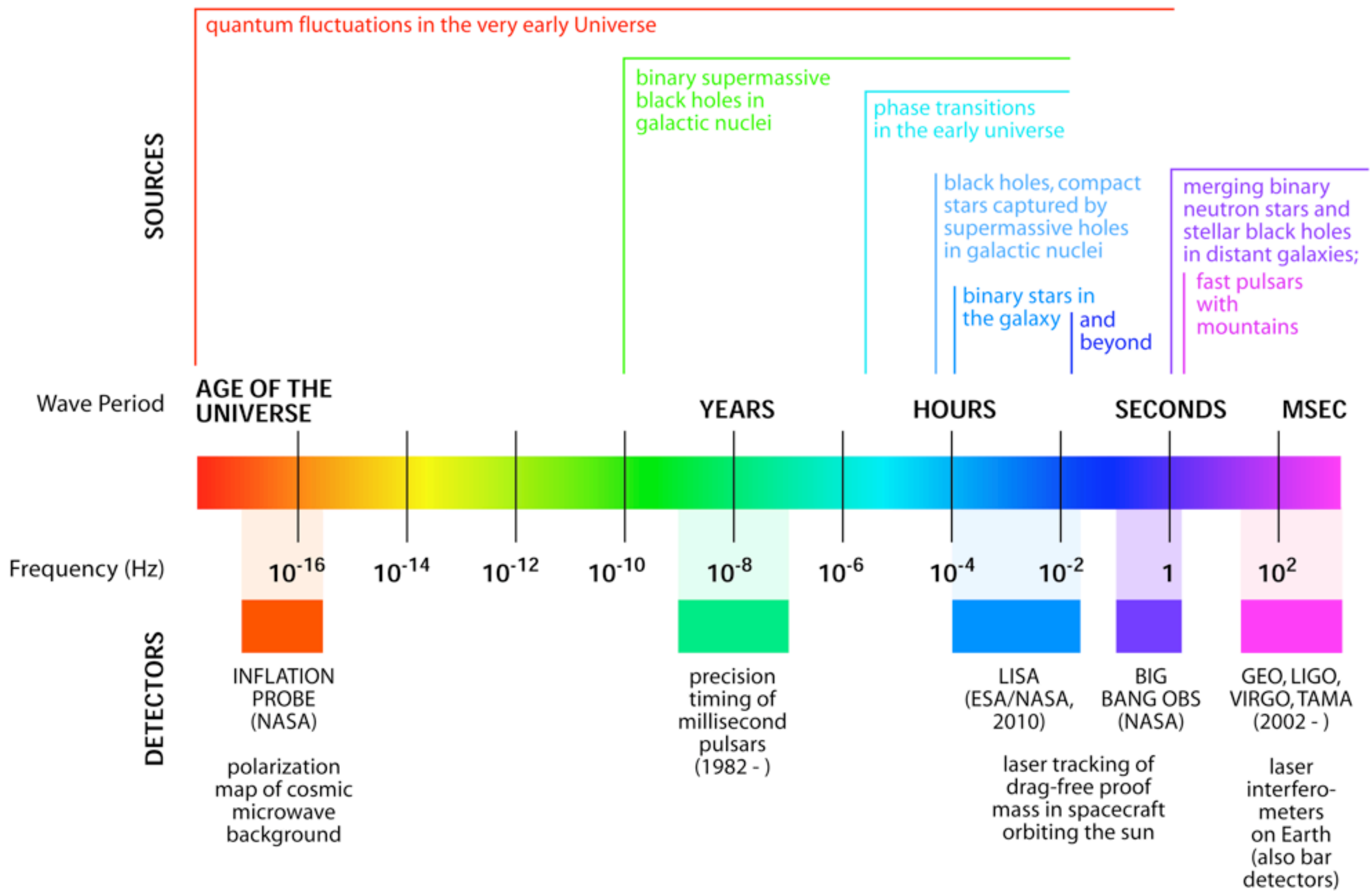
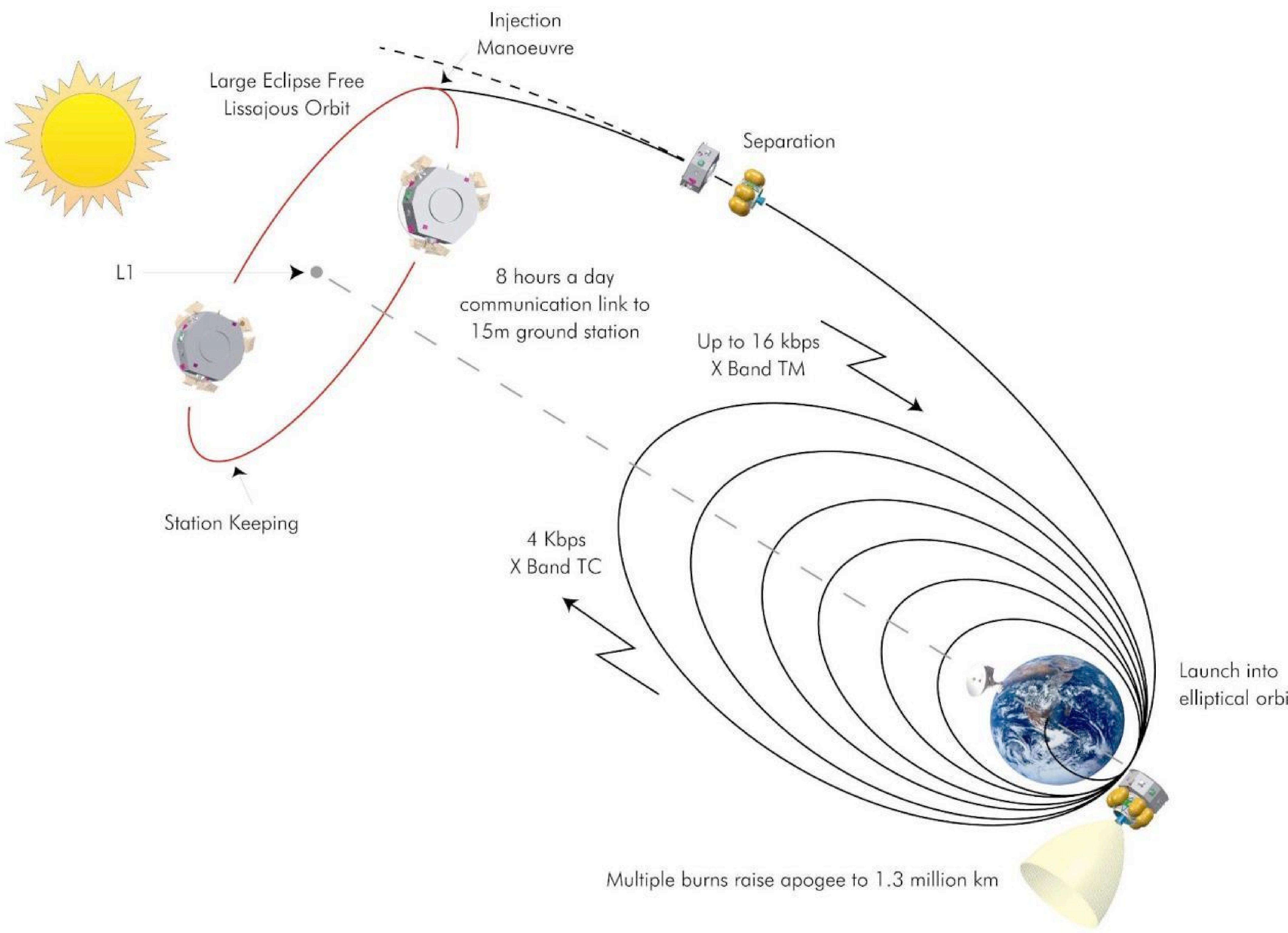
R. Dolesi - L. Ferraioli - M. Hueller - D. Nicolodi
D. Tombolato - S. Vitale - P. J. Wass - W. J. Weber

THE GRAVITATIONAL WAVE SPECTRUM



LISA Pathfinder mission



Interferometric read-out scheme