Laser Measurement Science

in Gravitational Physics

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Chair and Department Director

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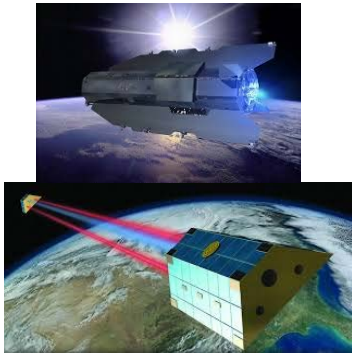
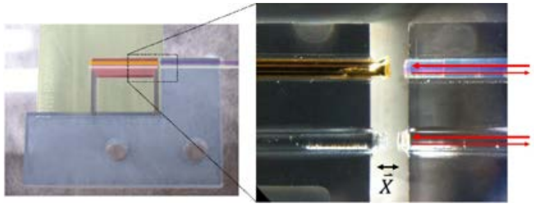
Outline

- Gravitational Wave Detectors
  - Ground-based observatories
  - Space-based observatories: LISA
  - LISA Pathfinder

- Earth Observation
  - GRACE / GRACE follow-on
  - Collaborative Research Center:
  - *geo-Q* Relativistic geodesy and gravimetry

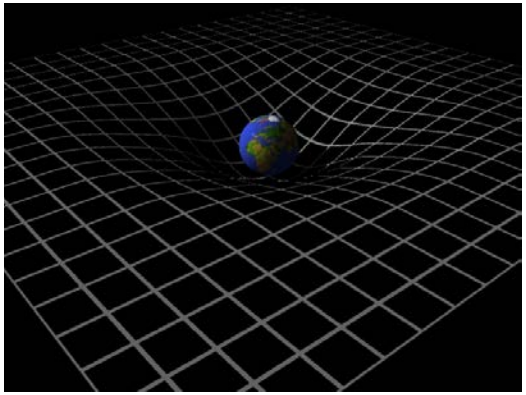


- Novel Optomechanical Technologies
  - Concept and overview of results
  - Accelerometers
  - Gravimeters and Gradiometers
  - Micro-optical motion sensors
  - Optomechanical Laser: tunable external cavity, THz source
  - Force sensors

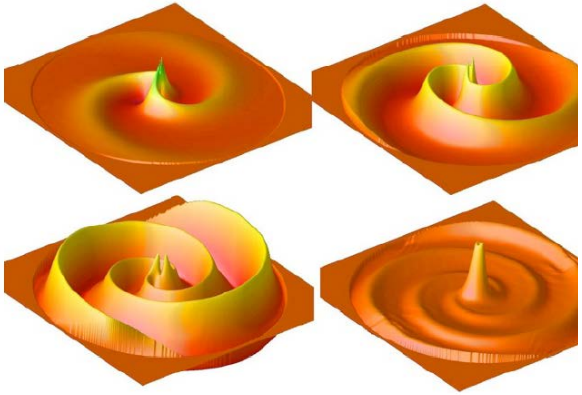


Gravitational Radiation

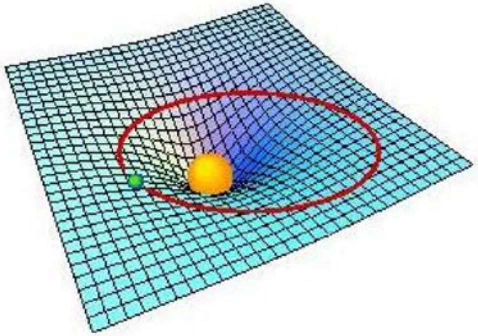
- 1916. Albert Einstein proposed a new model for Gravitation: General Theory of Relativity.
  - Mass determines spacetime curvature.
  - Curvature determines the movement of the masses.
  - Accelerated masses ➔ Gravitational Waves.



- Current astronomy is based on detection of electromagnetic radiation.
  - Multimessenger Astronomy starting now!

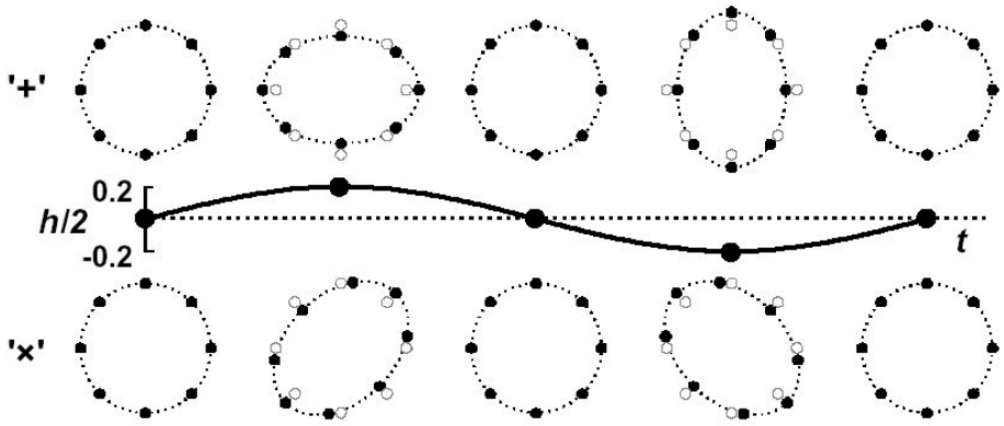


- Gravitational waves: different source of information
  - Early universe
  - Cosmological objects
  - Dark phenomena ➔ no EM radiation

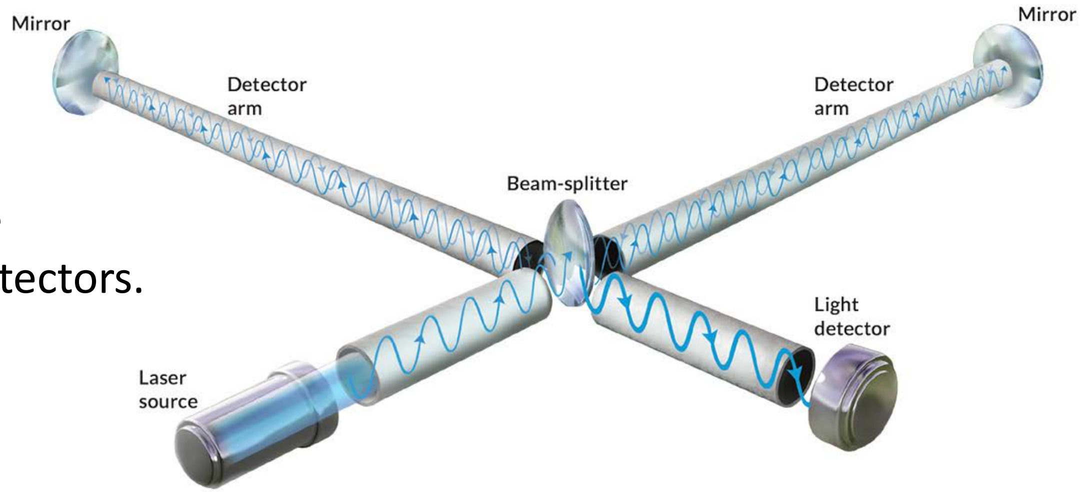


Gravitational Wave Observatories

- Gravitational waves change distances between floating test-masses as they propagate.

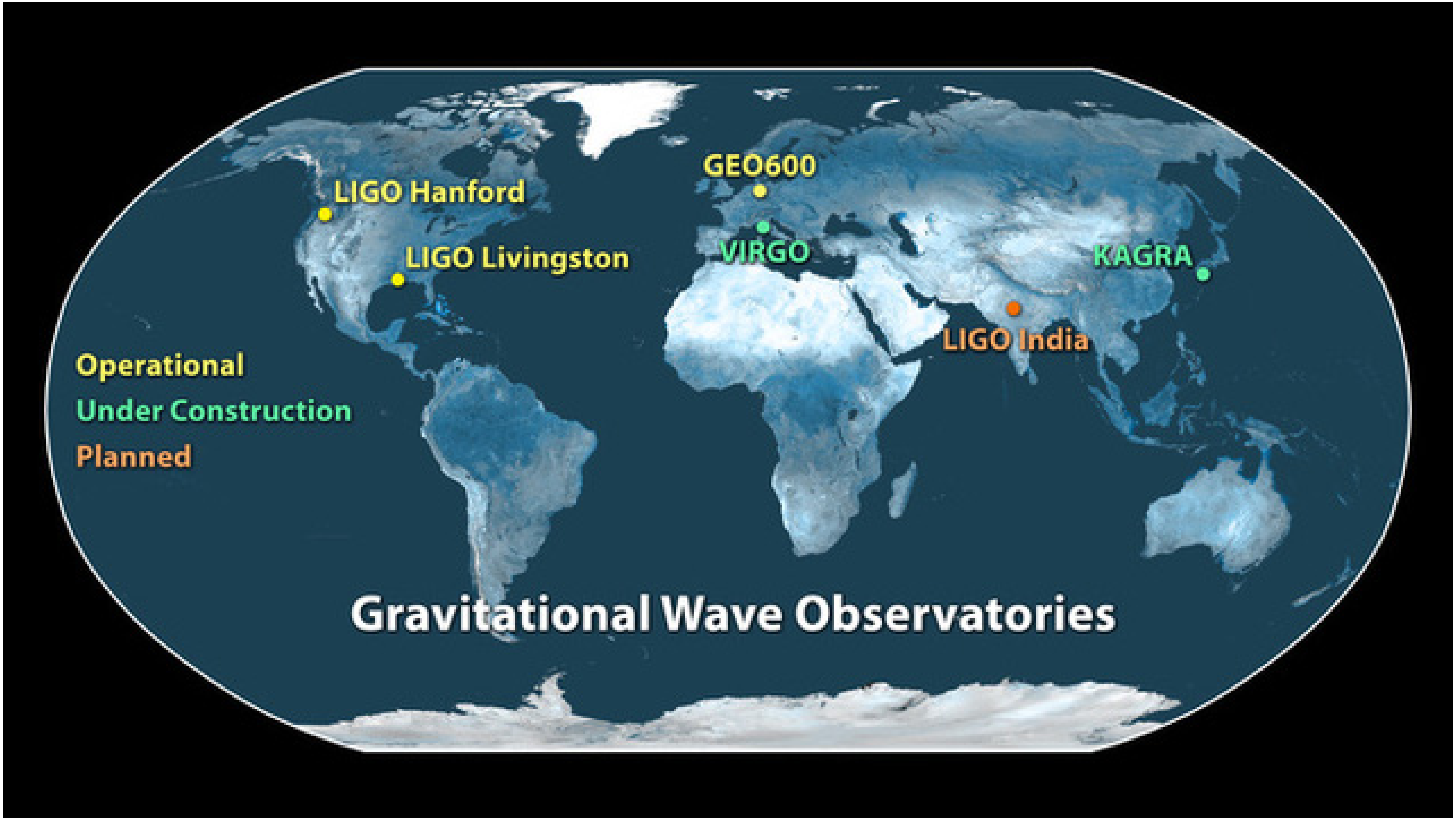


- Interferometers monitor the distance between test masses ➔ ideal GW detectors.

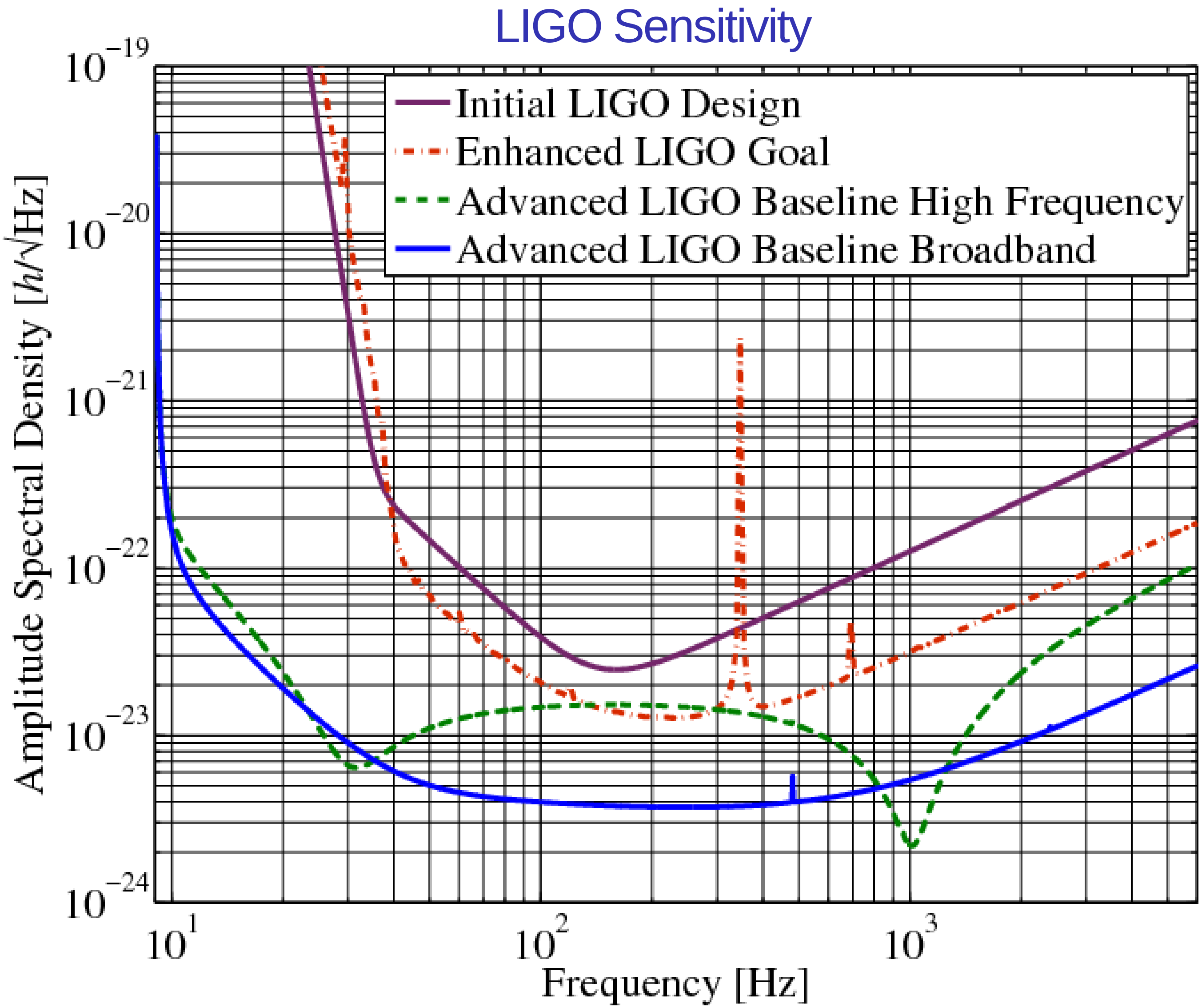


Gravitational Wave Observatories

World Wide Network



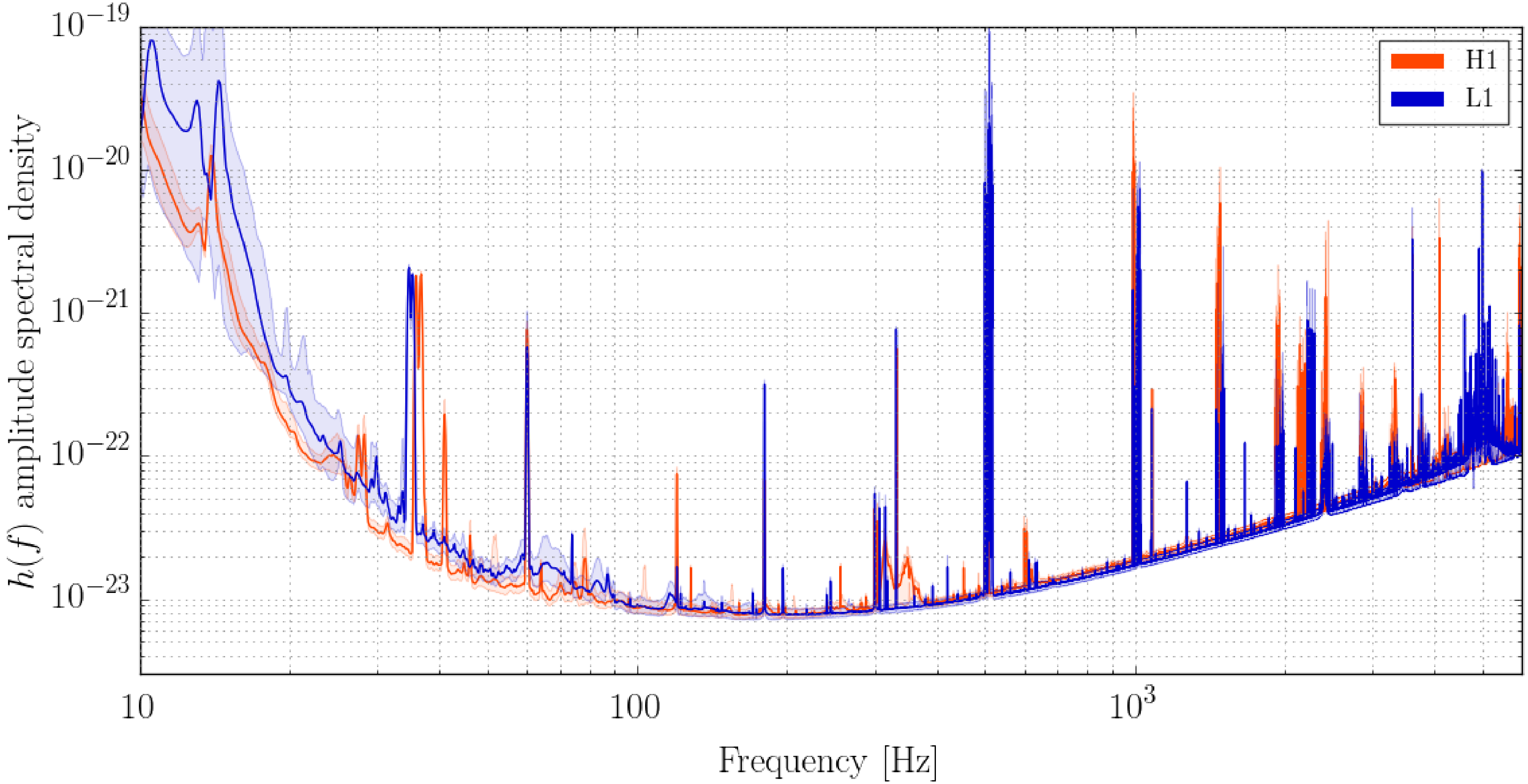
Gravitational Wave Observatories



Gravitational Wave Observatories

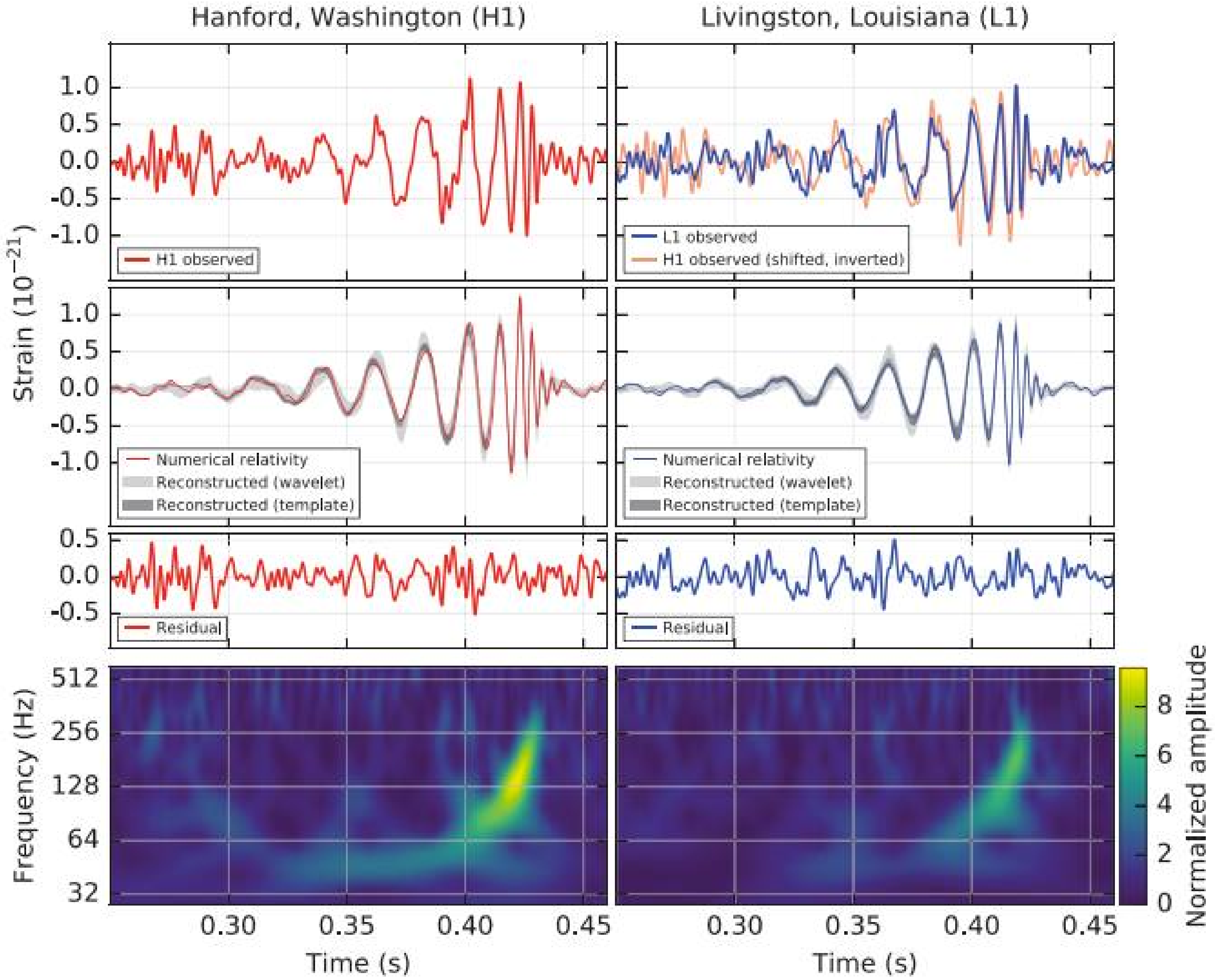
LIGO Sensitivity

$$h(f) = \frac{\delta L\,(f)}{L} \rightarrow \delta L \approx 10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$$



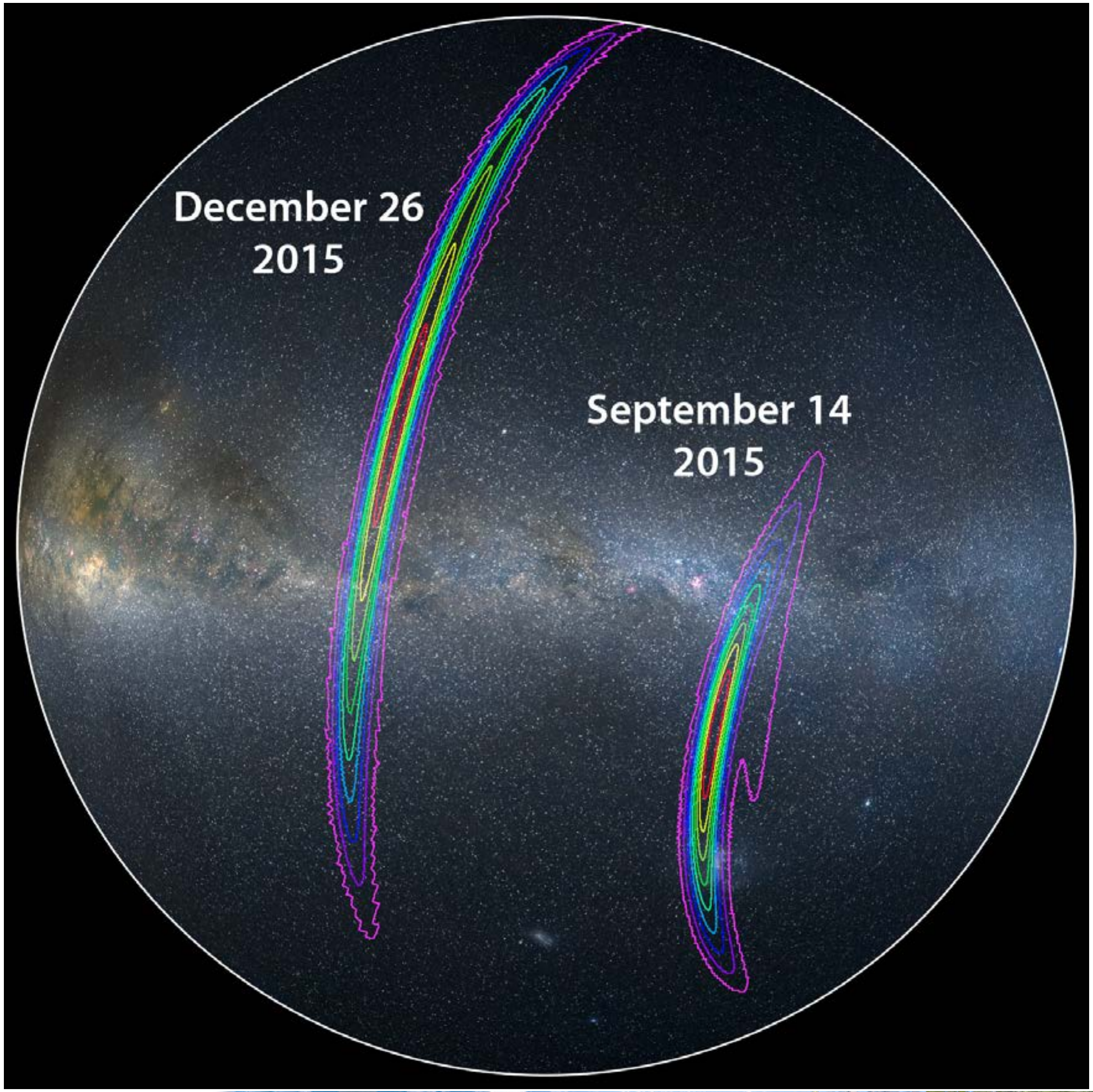
Gravitational Wave Observatories

GW 150914



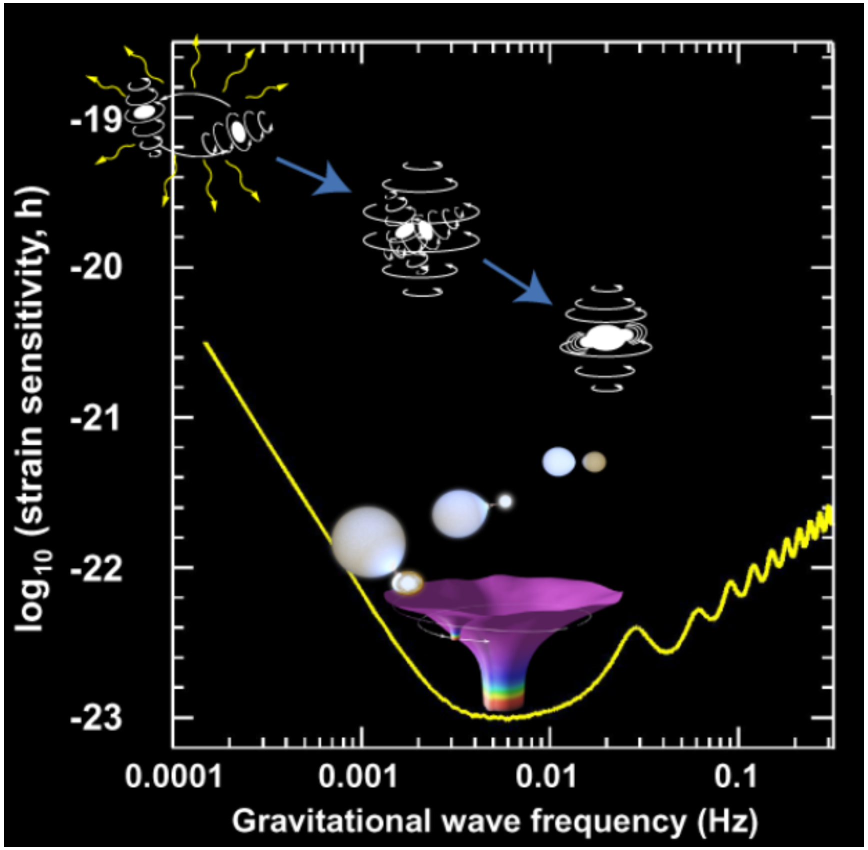
Gravitational Wave Observatories

LIGO observations



Space-based Observatories - LISA

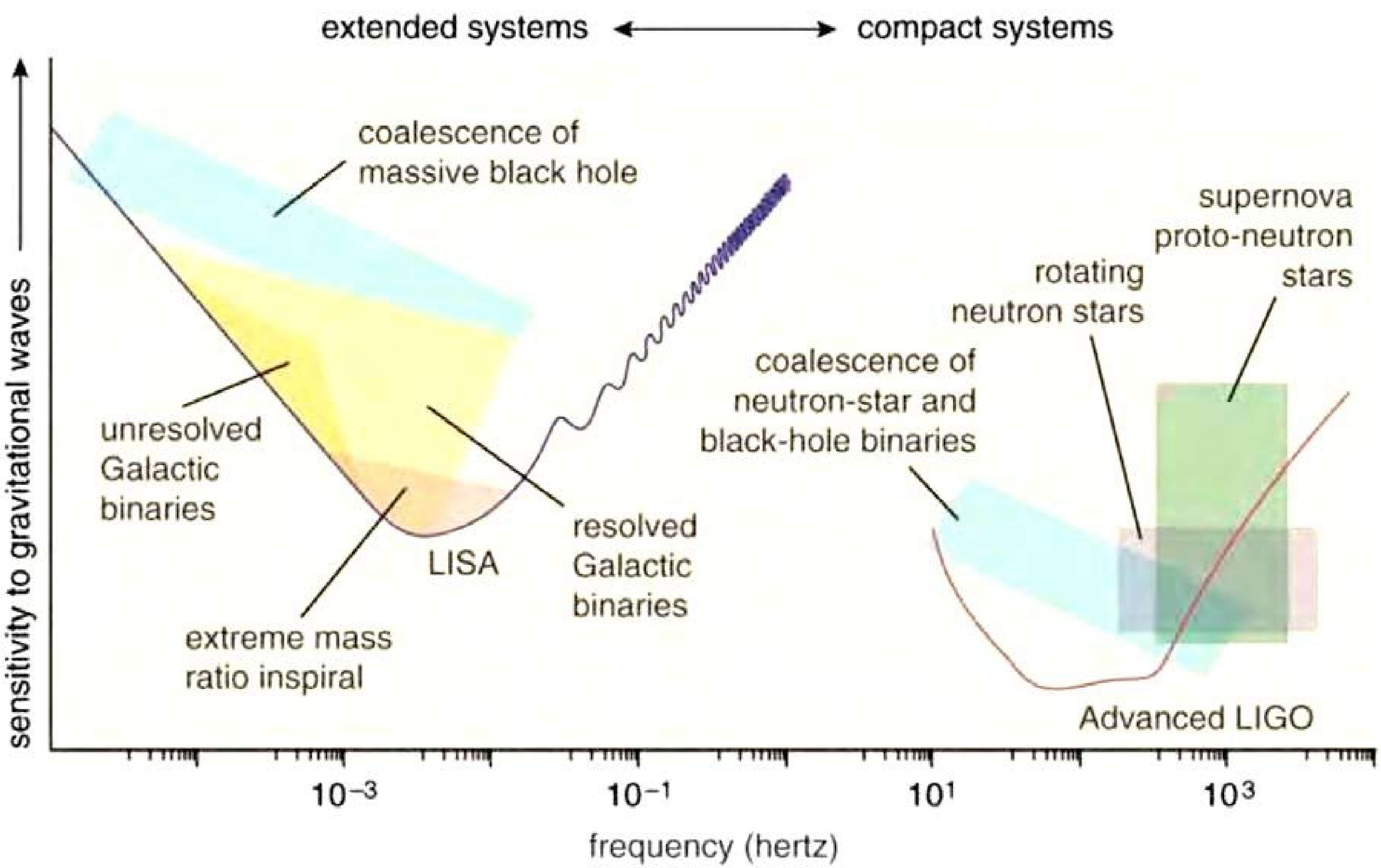
- Observations below 1 Hz
  - Observe evolution of systems
  - Sources not accessible to ground-based detectors
  - Earth's seismic noise dominates below few Hz



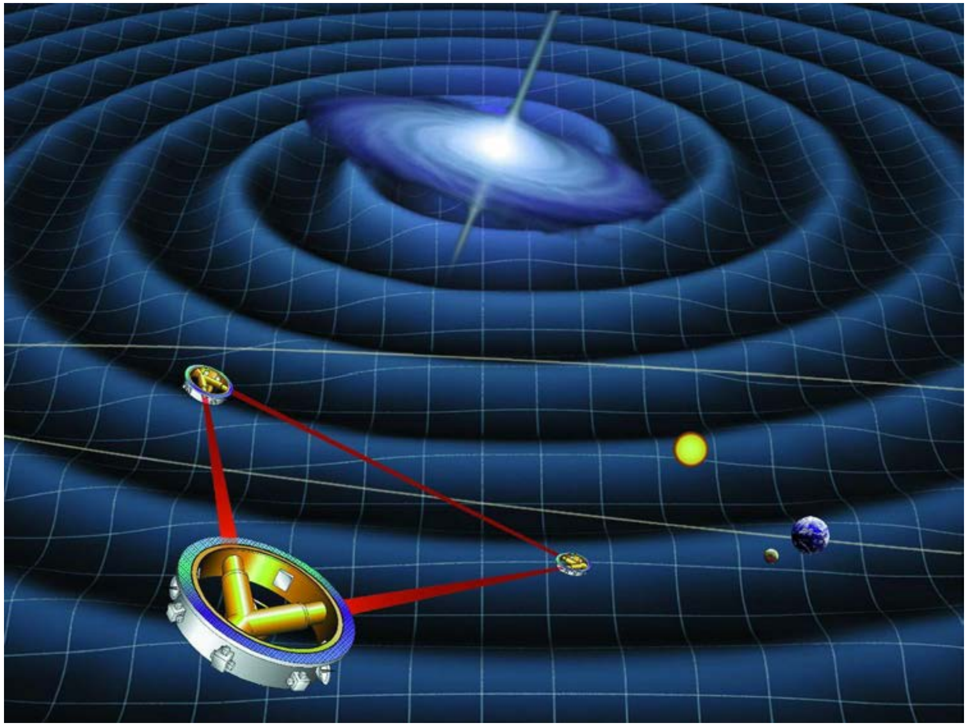
- More continuous sources at low frequencies.

- Observations a low frequencies benefit from larger detector armlengths.

Observatories – complementary observations bands



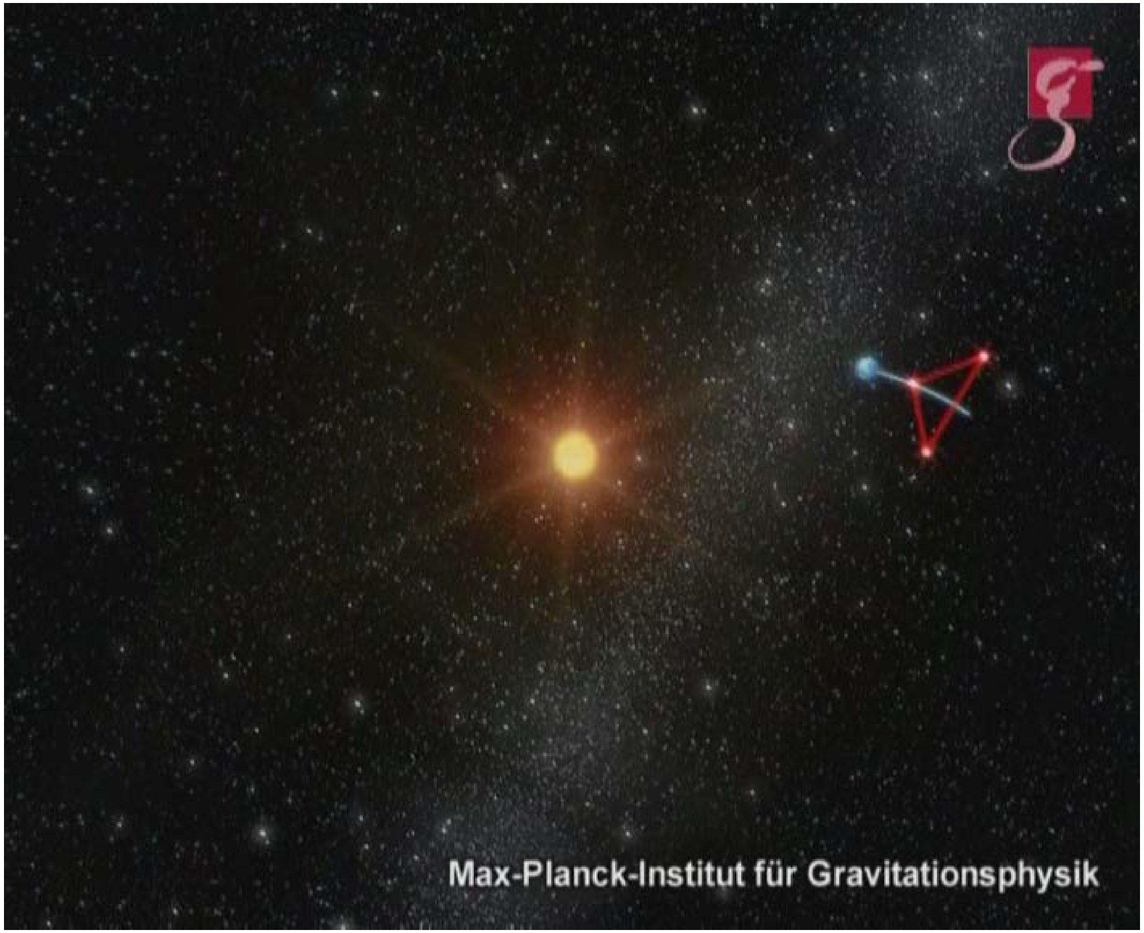
LISA: Laser Interferometer Space Antenna



- Gravitational Wave Observatory in Space.
- Observation bandwidth: 10^{-4} – 10^{-1} Hz .
- Interferometer armlength: millions of km.
- Heliocentric orbit.

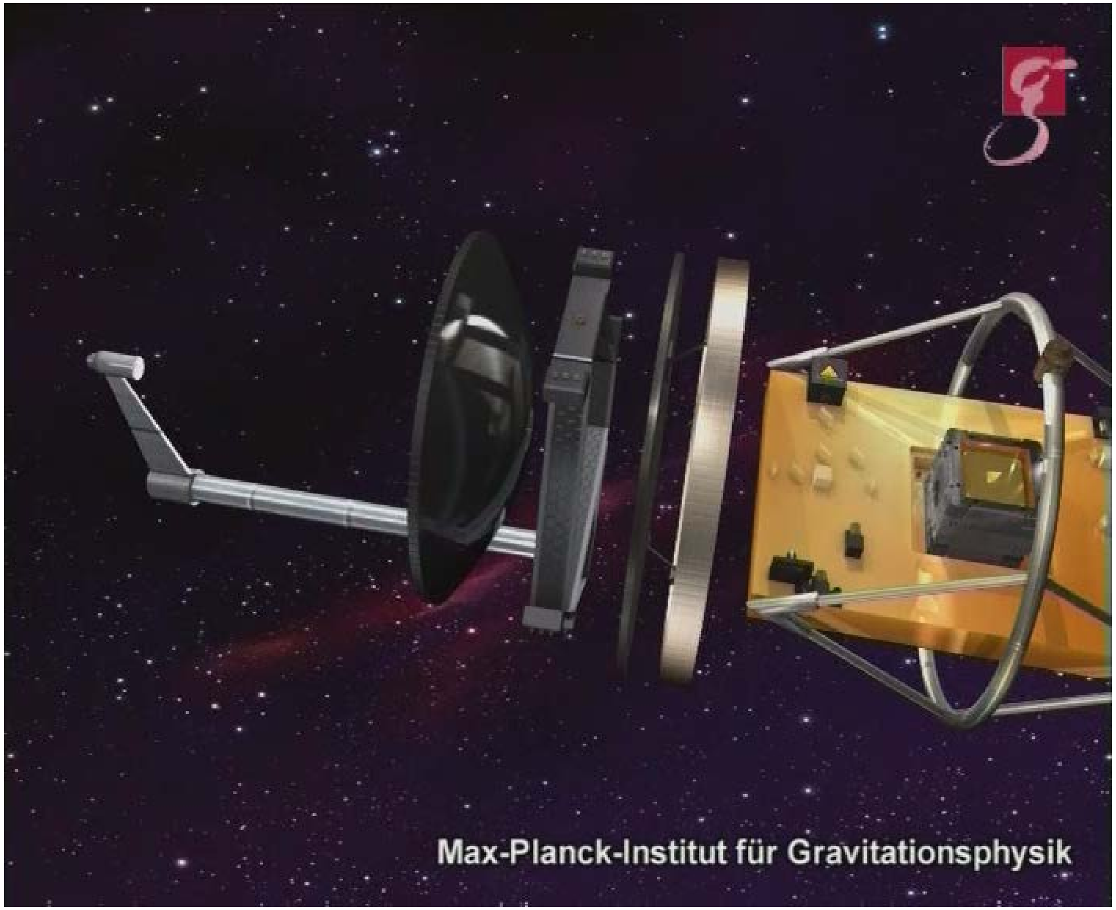
LISA Orbit

- Three spacecraft in quasi-equilateral triangle formation
- Trailing Earth around the Sun by approximately 20°
- Armlengths of few million km +/- ~ 1%



LISA optical bench and gravitational sensor

- Emitted beam:
  - ~40 cm diameter
  - 1 W optical power
- Received beam:
  - ~20 km diameter
  - 100 pW optical power



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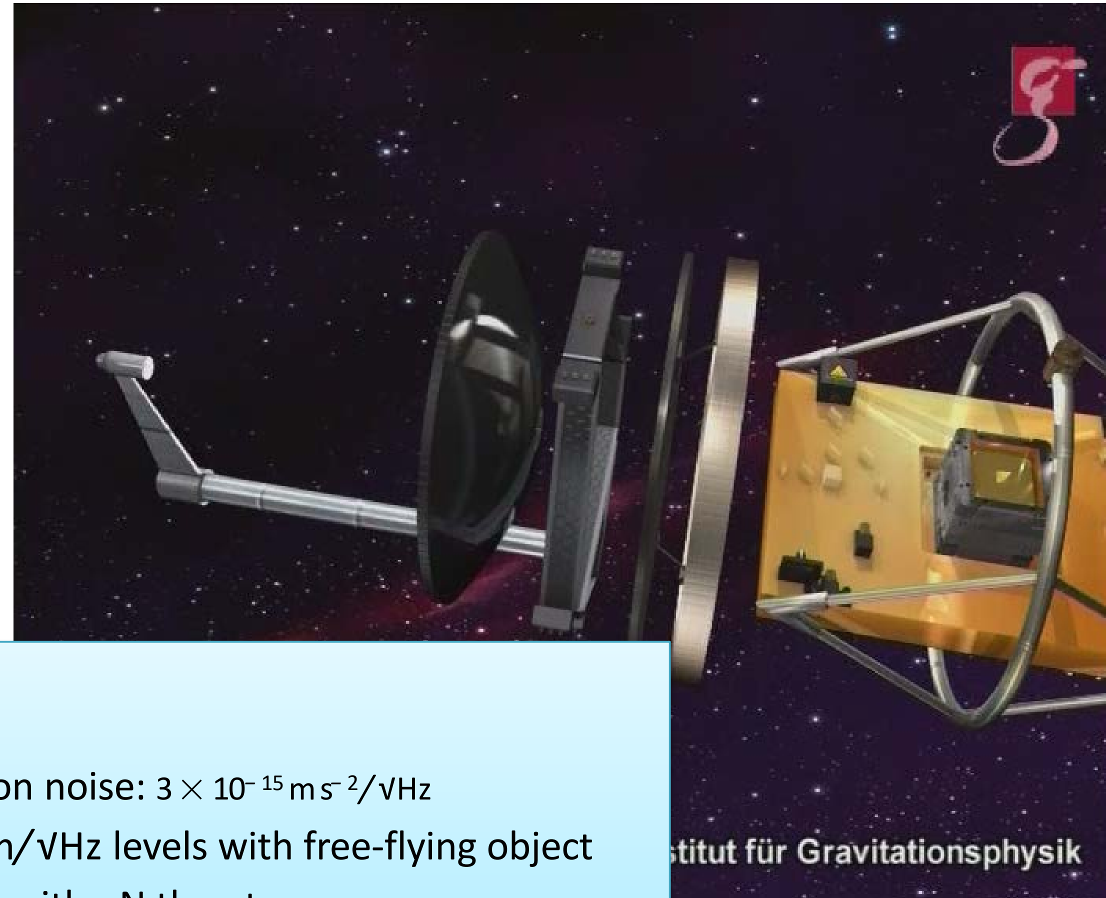

- Received bea
  - ~20 km c
  - 100 pW c

Challenges:

- Test mass acceleration noise: $3 \times 10^{-15}\,\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}$
- Interferometry at pm/√Hz levels with free-flying object
- Spacecraft actuators with µN thrust

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LISA Pathfinder

LISA Pathfinder

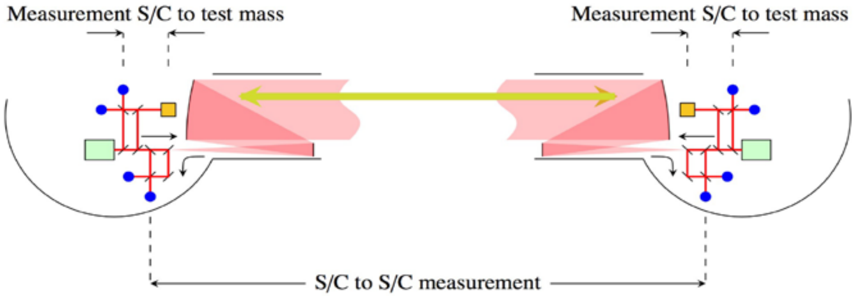
- Two LISA-like TMs inside one satellite
- ⇒ one small "LISA-arm":

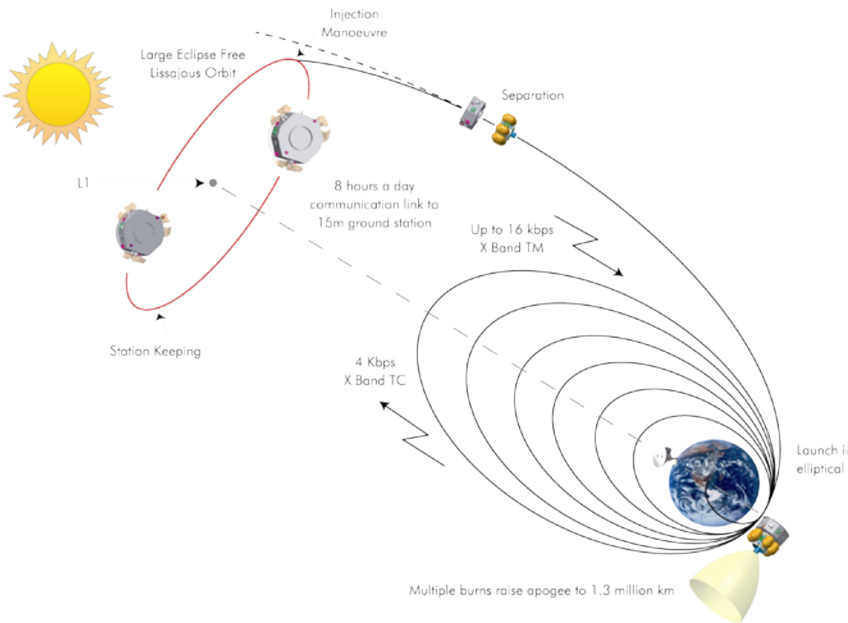
- **Interferometry** between Test-Masses with **picometer** precision.

- **Drag Free** System for Test Masses with **femtonewton** stability.

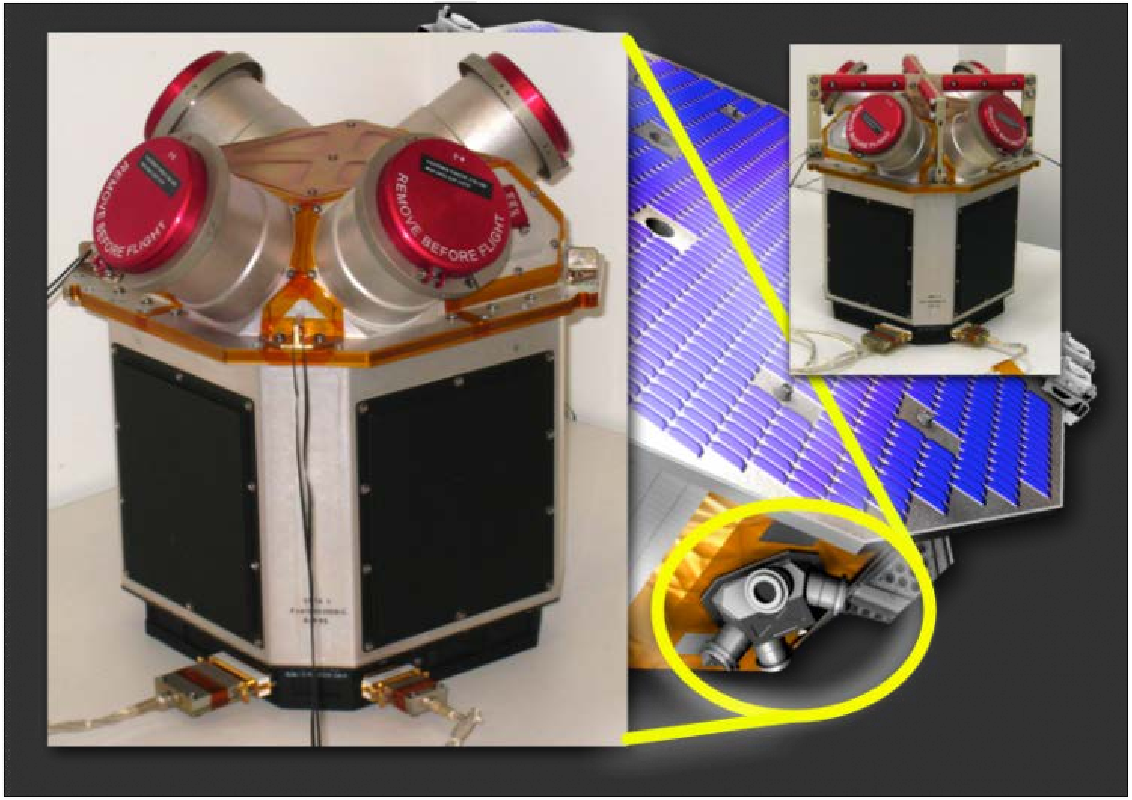
- Micronewton thrusters for drag free control of the satellite.

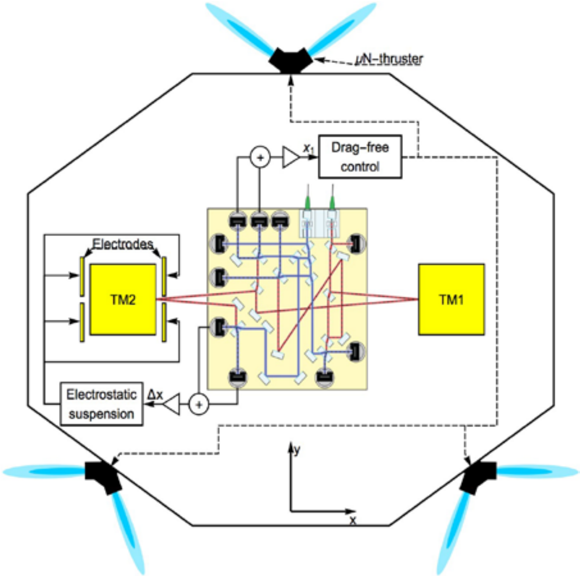
- Two experiments:
  - One European – LTP
  - One American – DRS/ST7





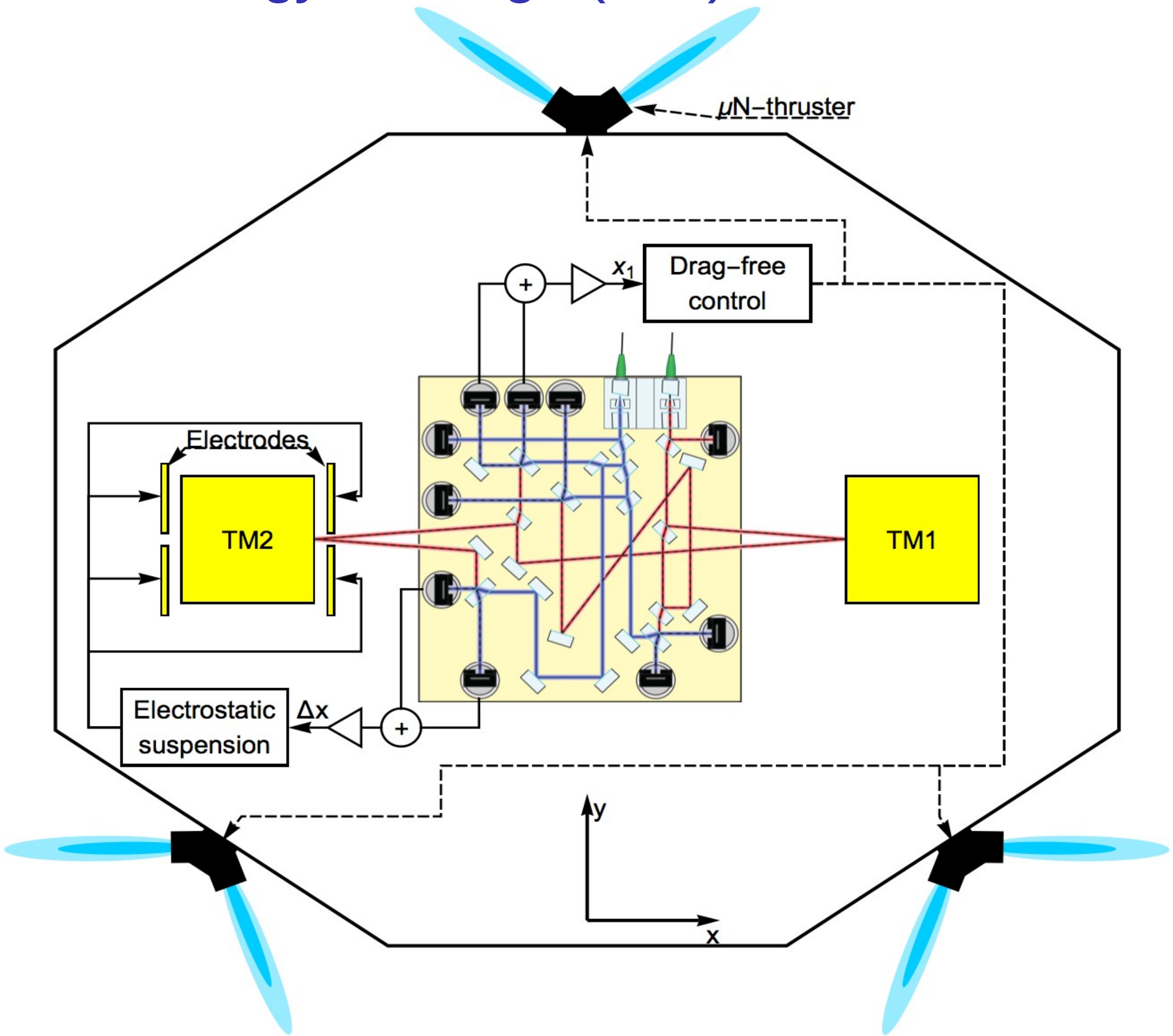
Disturbance Reduction System (DRS)





- Colloidal µN-thrusters
- Computer with control laws for drag-free

LISA Technology Package (LTP)



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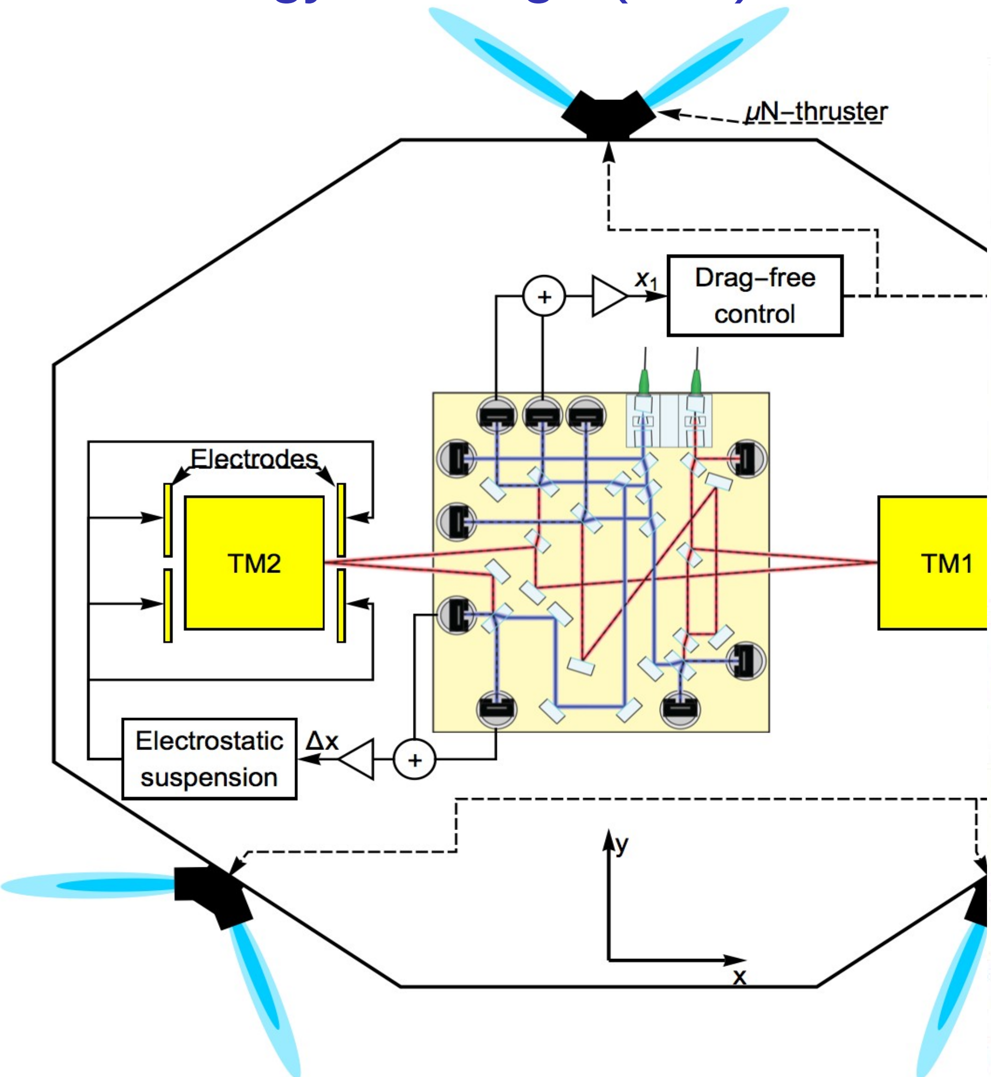
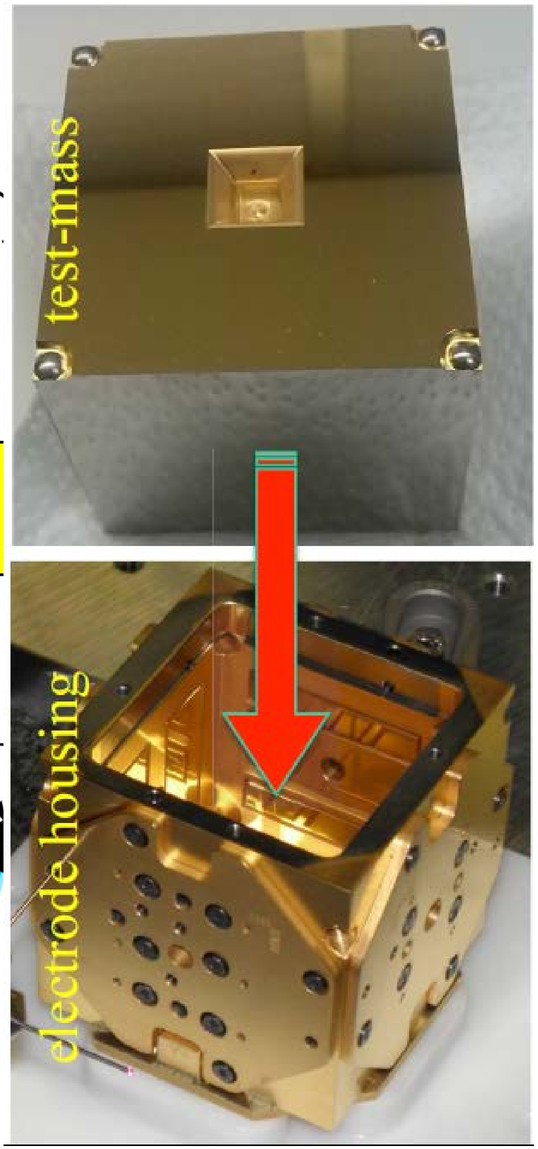
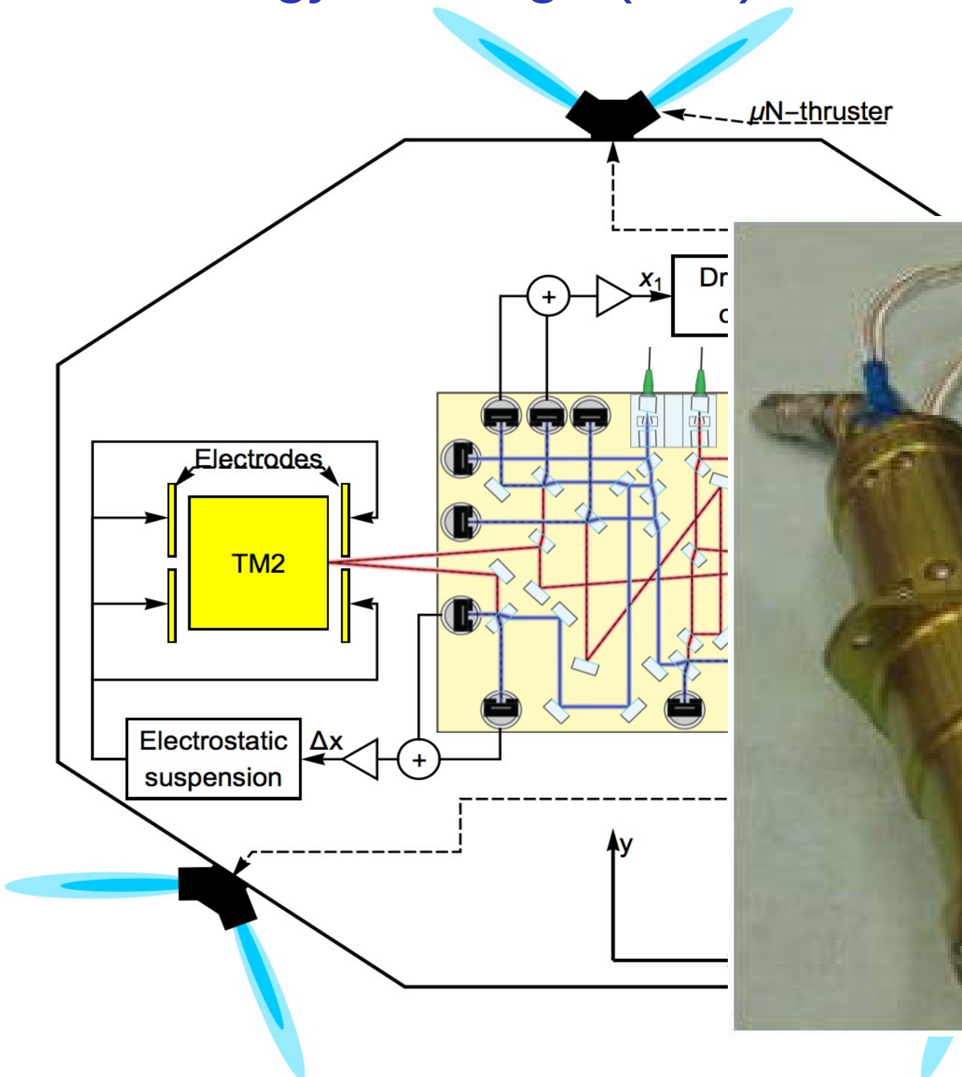




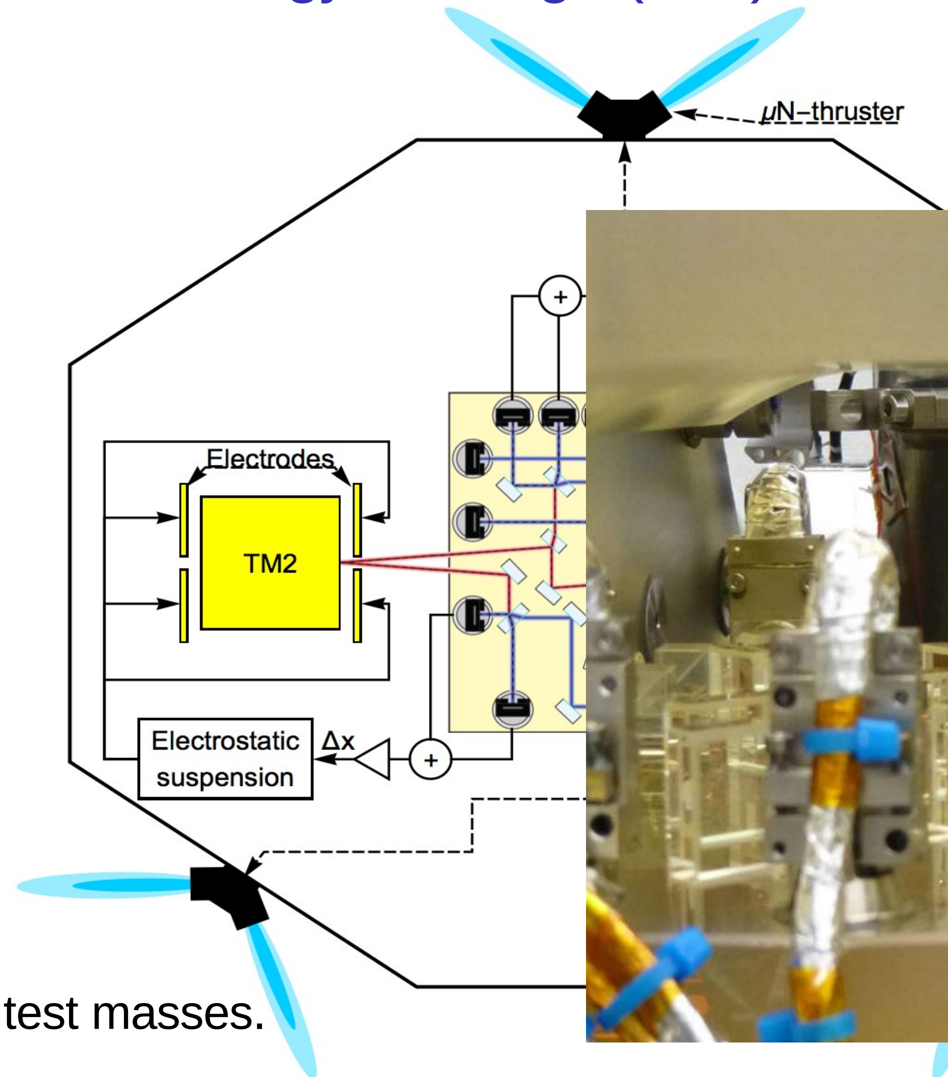
- Drag-free test masses.

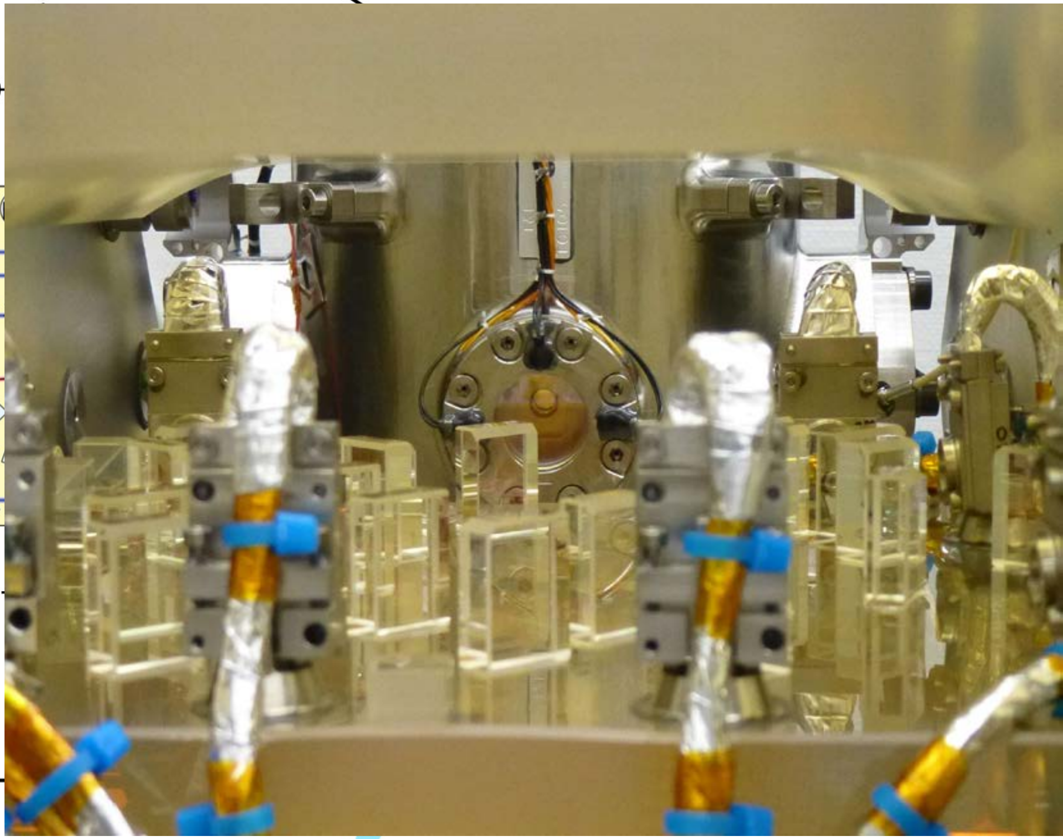
LISA Technology Package (LTP)



- Drag-free test masses.
- Cold gas (N_2) μN-thrusters.

LISA Technology Package (LTP)

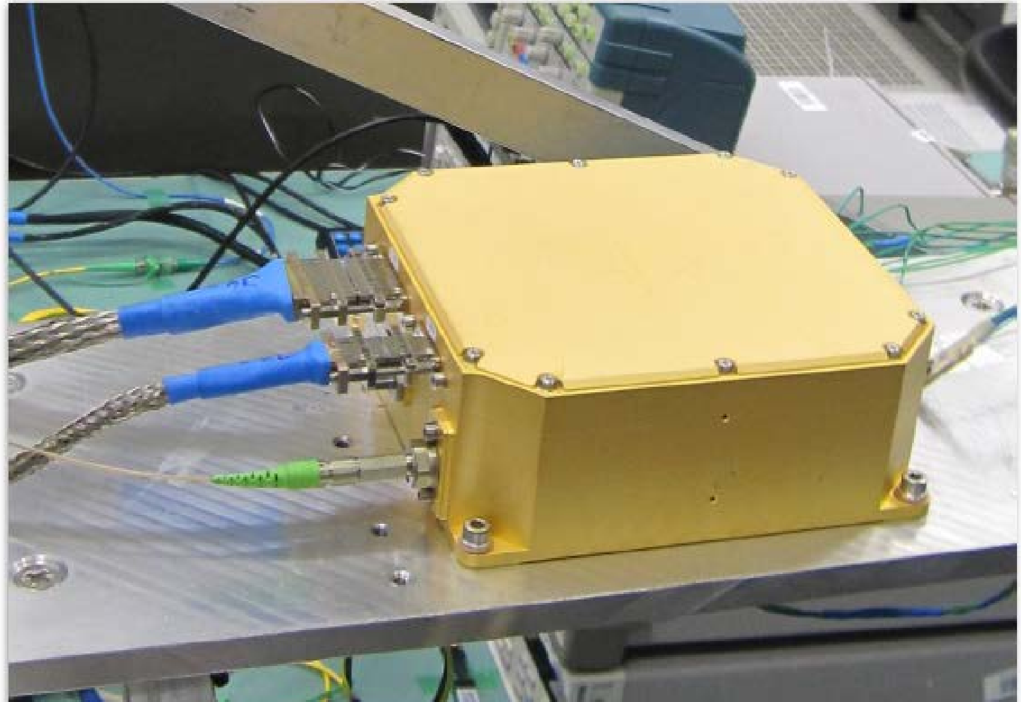




- Drag-free test masses.
- Cold gas (N_2) µN-thrusters.
- Laser interferometers between free floating test masses.

LTP Laser

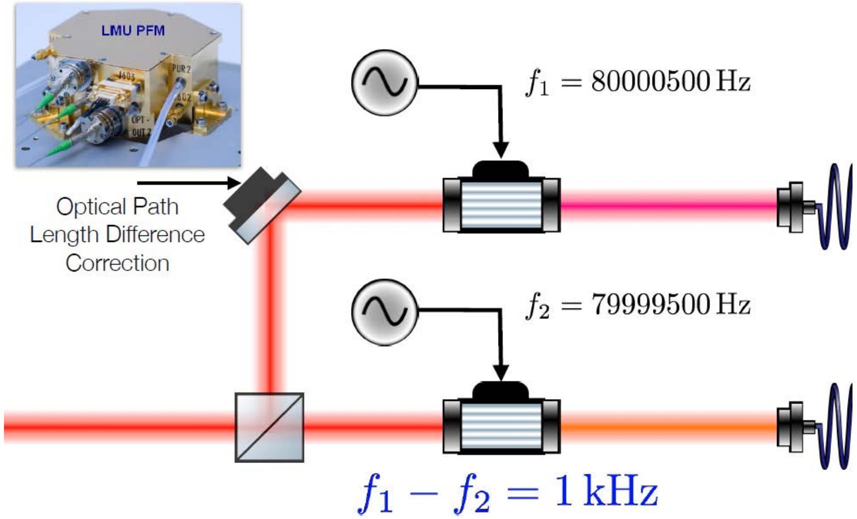
Nd:YAG laser
λ: 1064 nm
Power: 45 mW



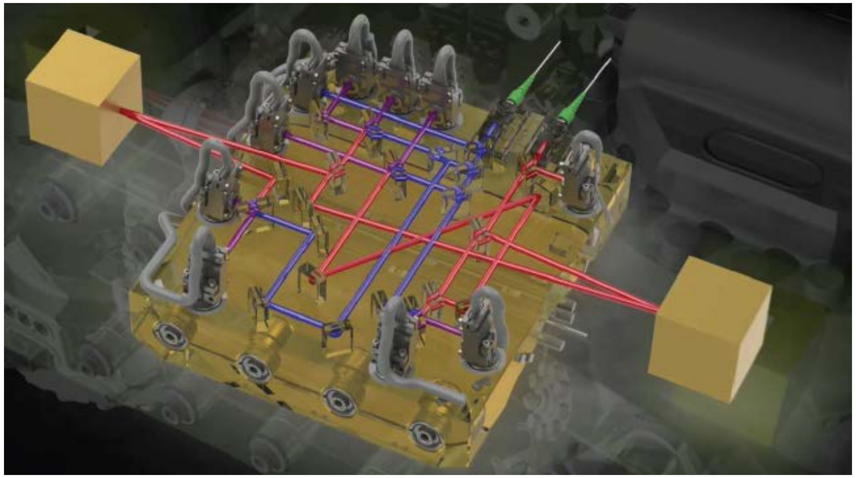
Operated at 38mW output power

LISA Pathfinder Interferometry

- Modulation Bench:
2 AOMs at nearly 80 MHz and
PZT phase actuators



- Optical bench:
Zerodur baseplate with 4 non-polarizing
Mach-Zehnder interferometers



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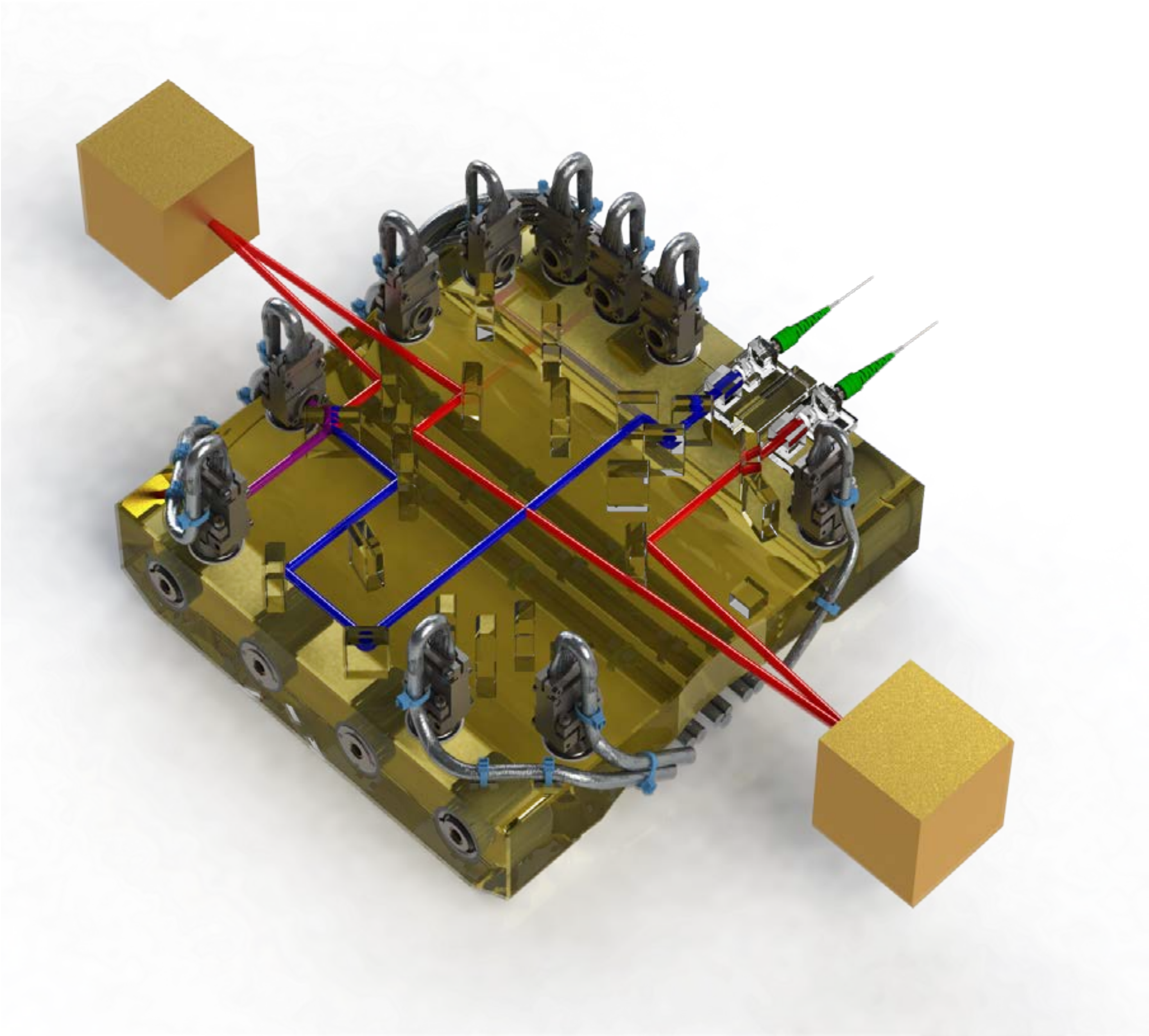
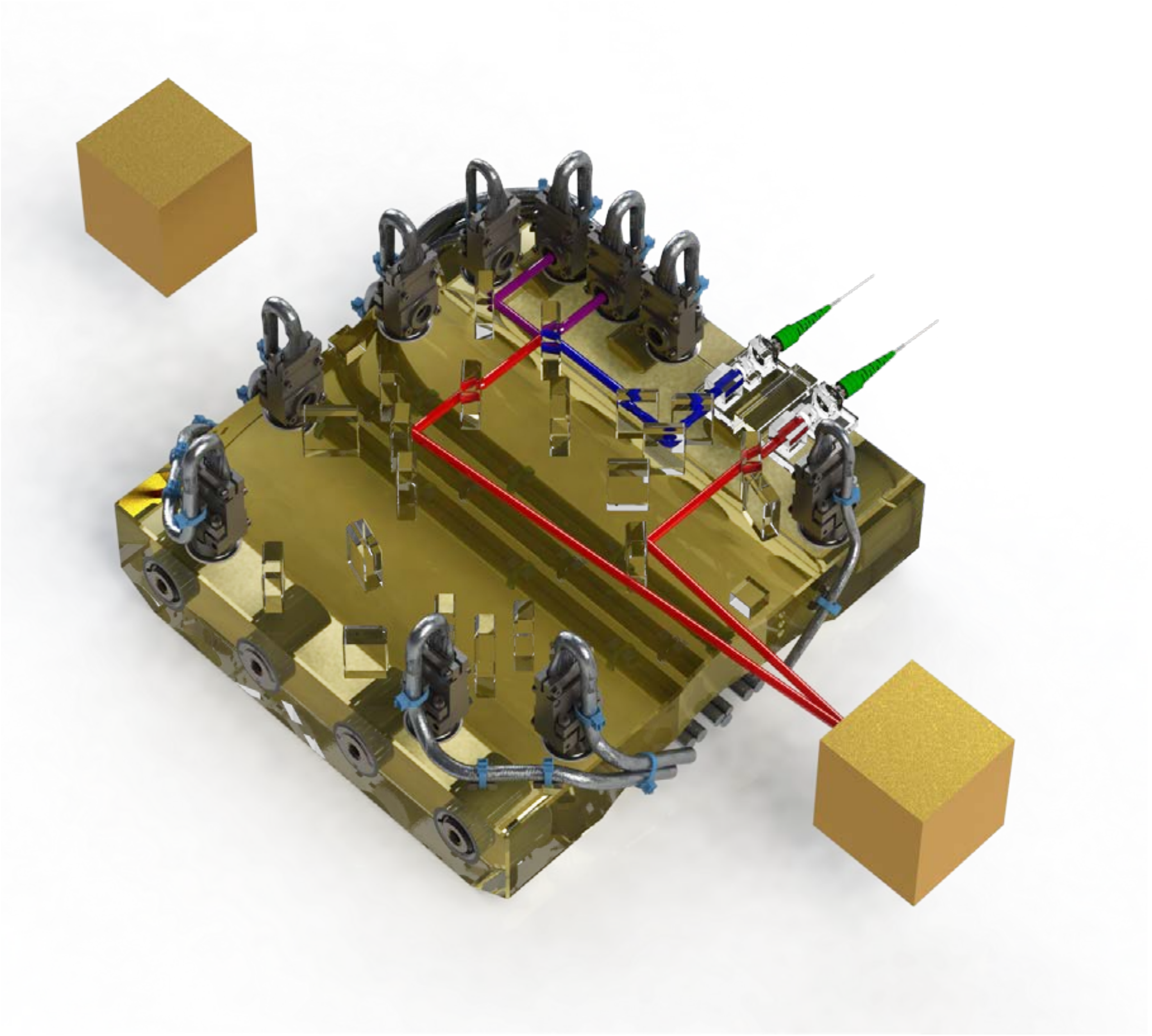


- X12 interferometer:

Measures relative separation and orientation between test masses.

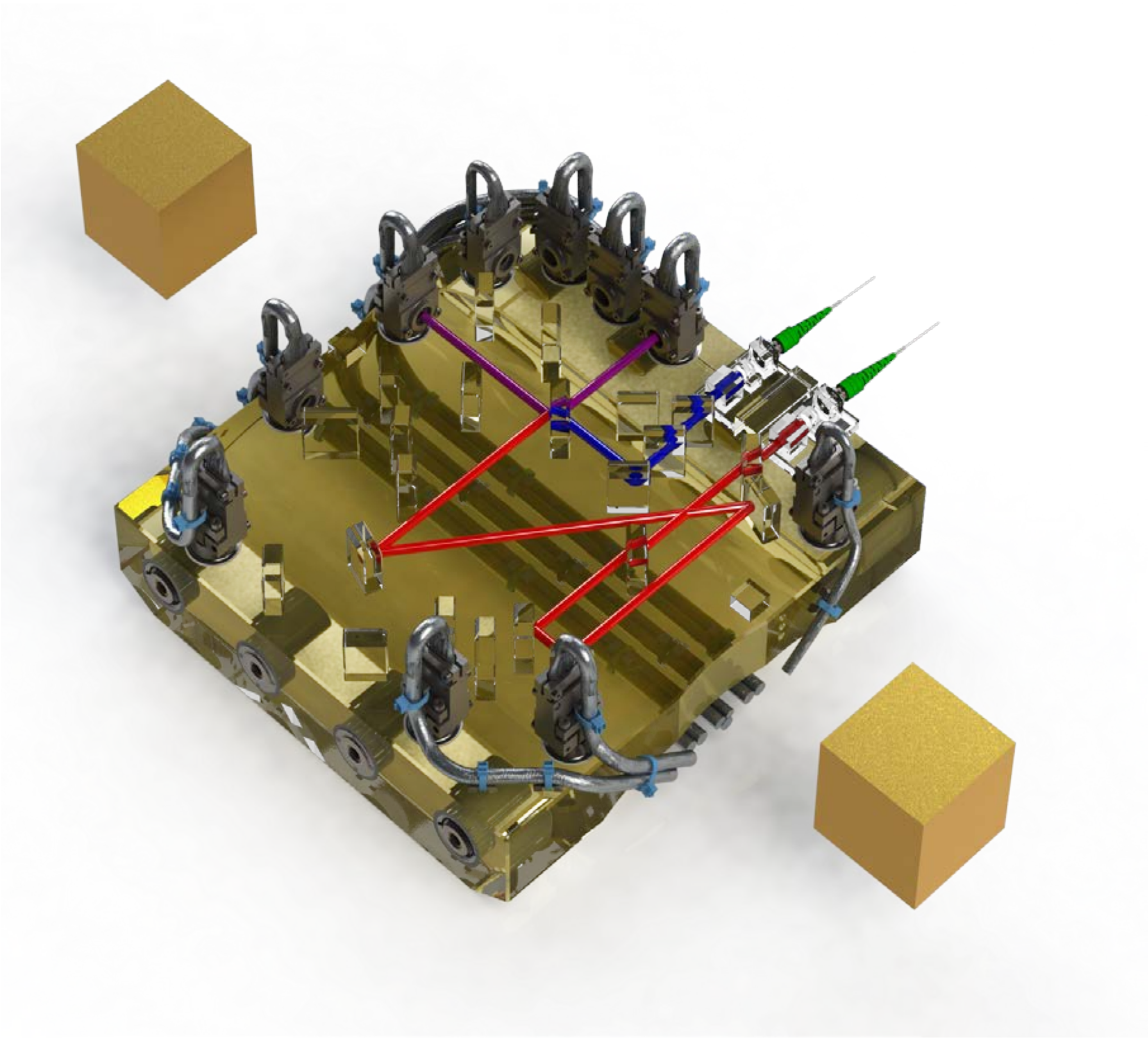
LISA Pathfinder Interferometry



- X1 interferometer:

Measures displacement and orientation of test mass 1 wrt. optical bench.

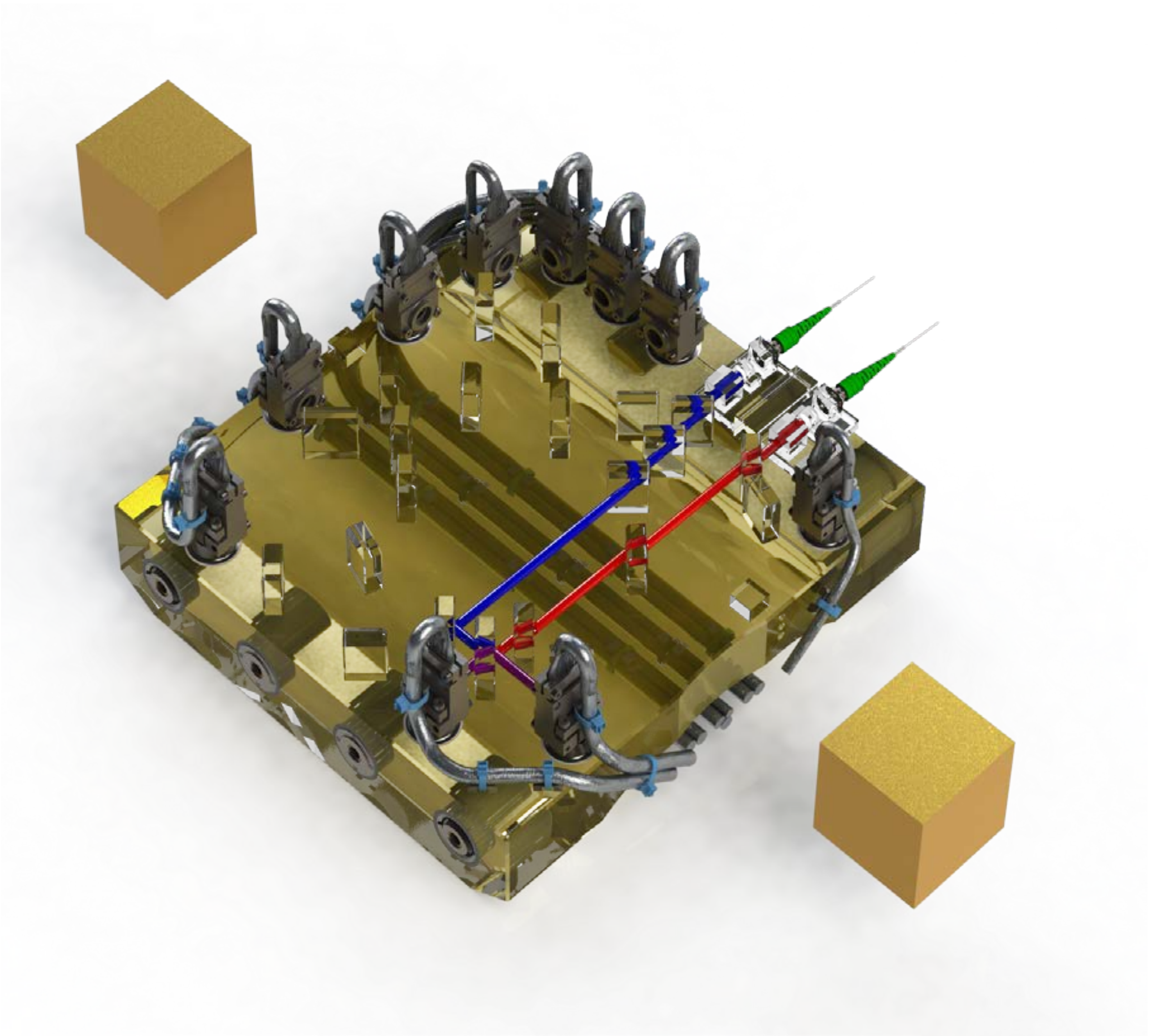
LISA Pathfinder Interferometry



- Reference interferometer:

Measures common-mode noise from modulation bench and fibers to correct other interferometers.

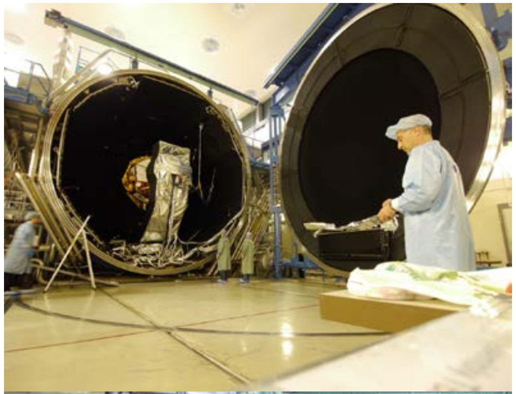
LISA Pathfinder Interferometry

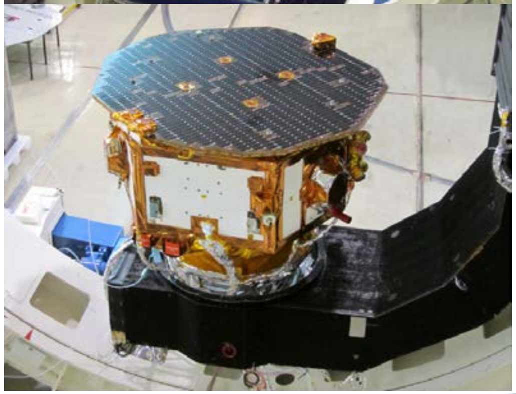


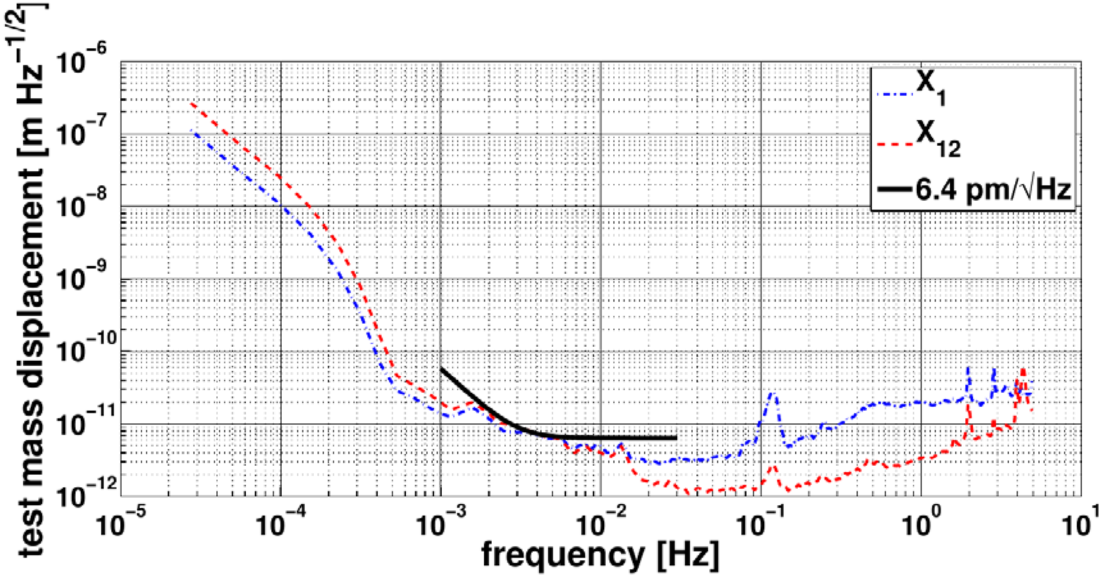
- Frequency interferometer:

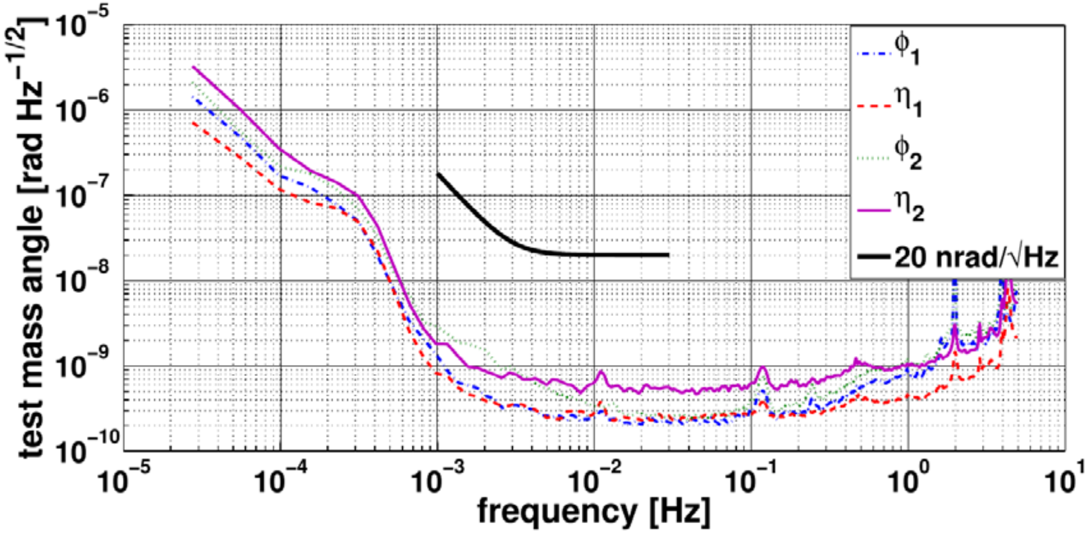
Unequal armlengths to measure the laser frequency noise and stabilize it.

LISA Pathfinder Interferometry – Performance on ground









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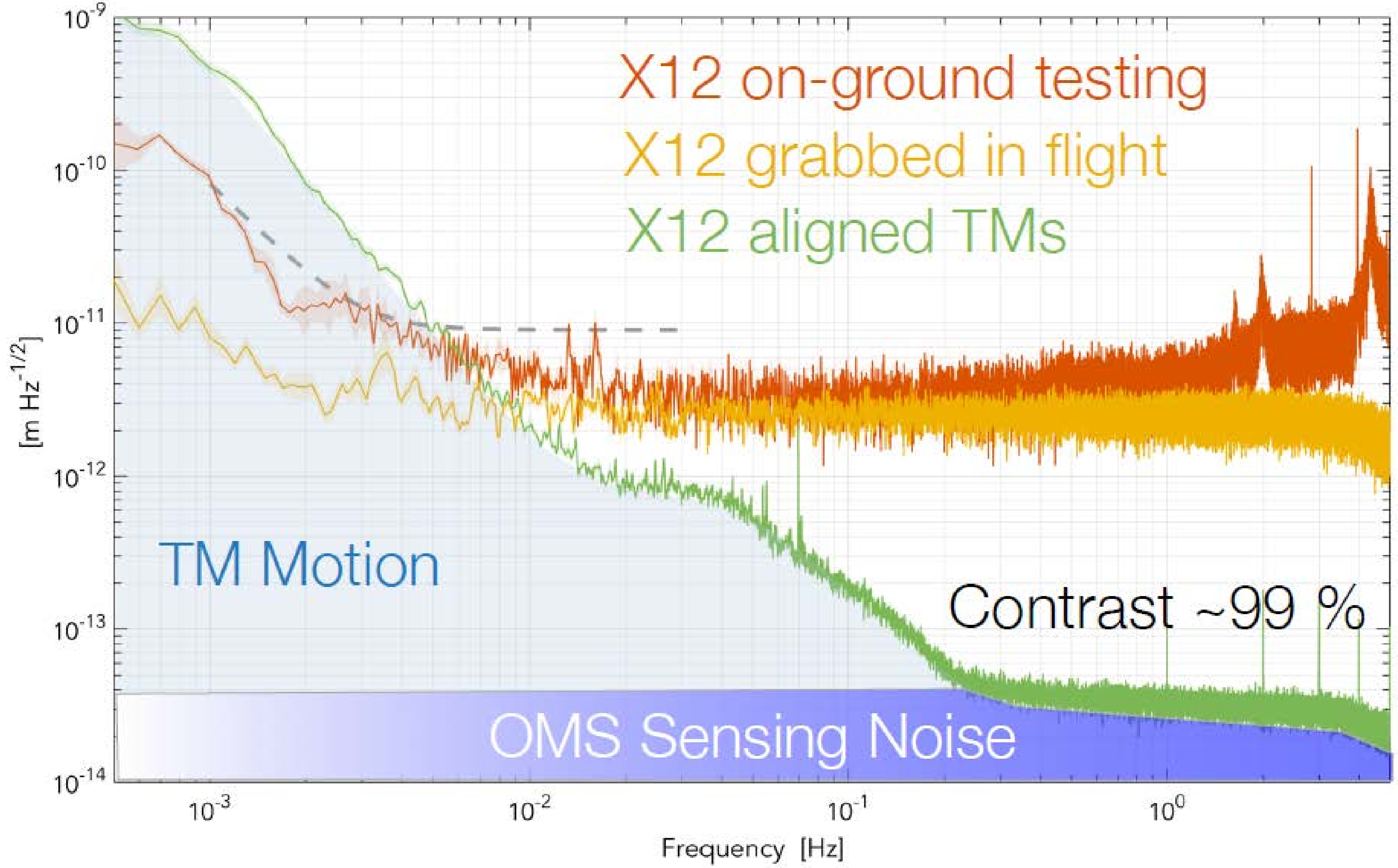
LISA Pathfinder Interferometry – Performance in orbit



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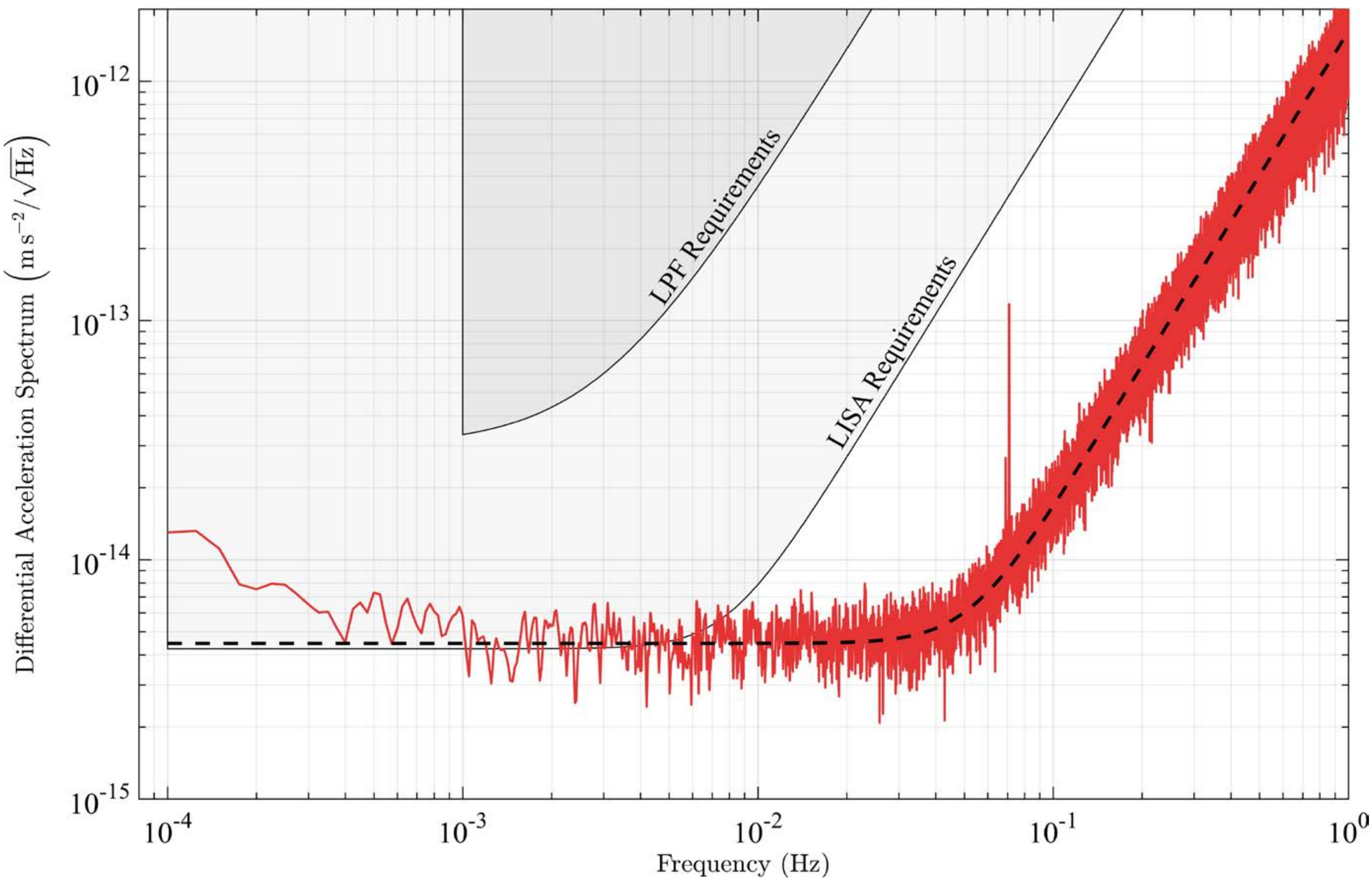

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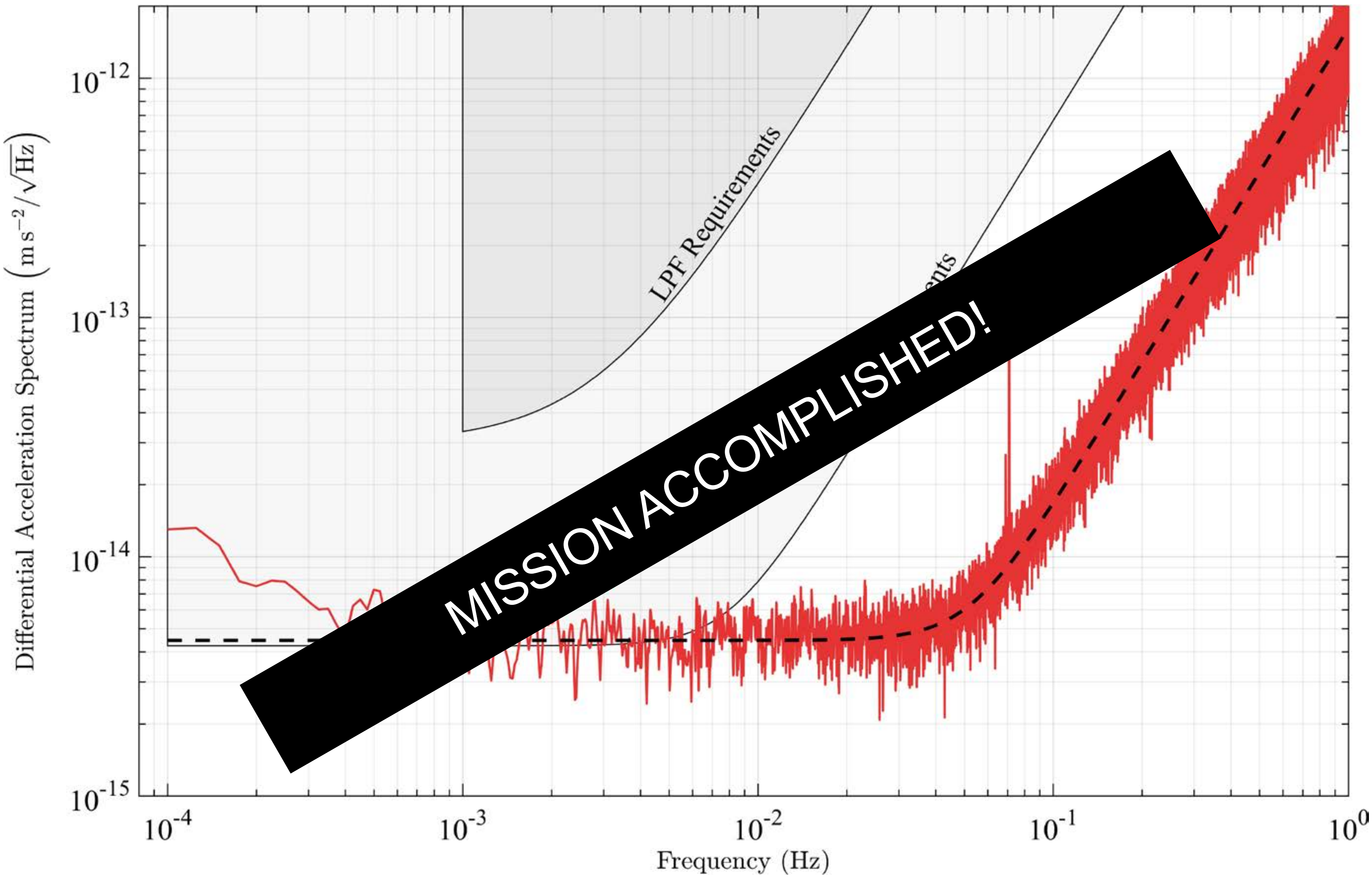

LISA Pathfinder

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- ⇒ one small ”LISA-arm”:

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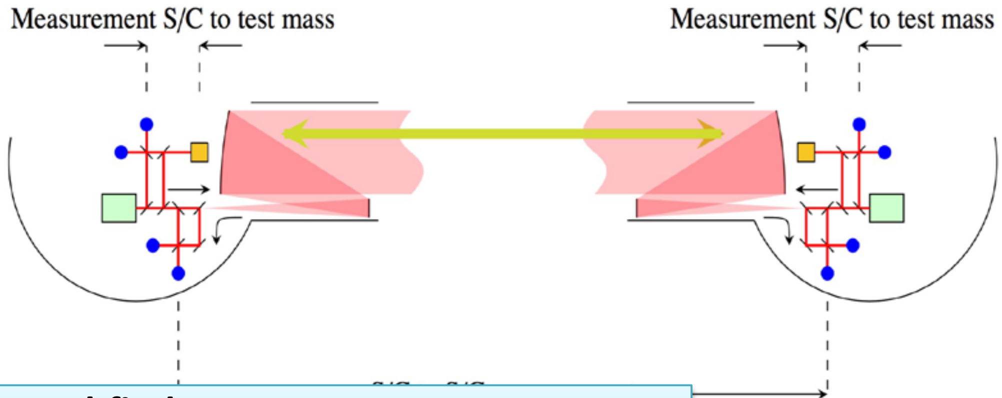

- Two
  -
  -

LISA relevant aspects not tested in LISA Pathfinder:

- Long baseline intersatellite laser interferometry with low power
- µ-Cycle phase measurement with a continuously doppler shifting beat note
- Constellation acquisition

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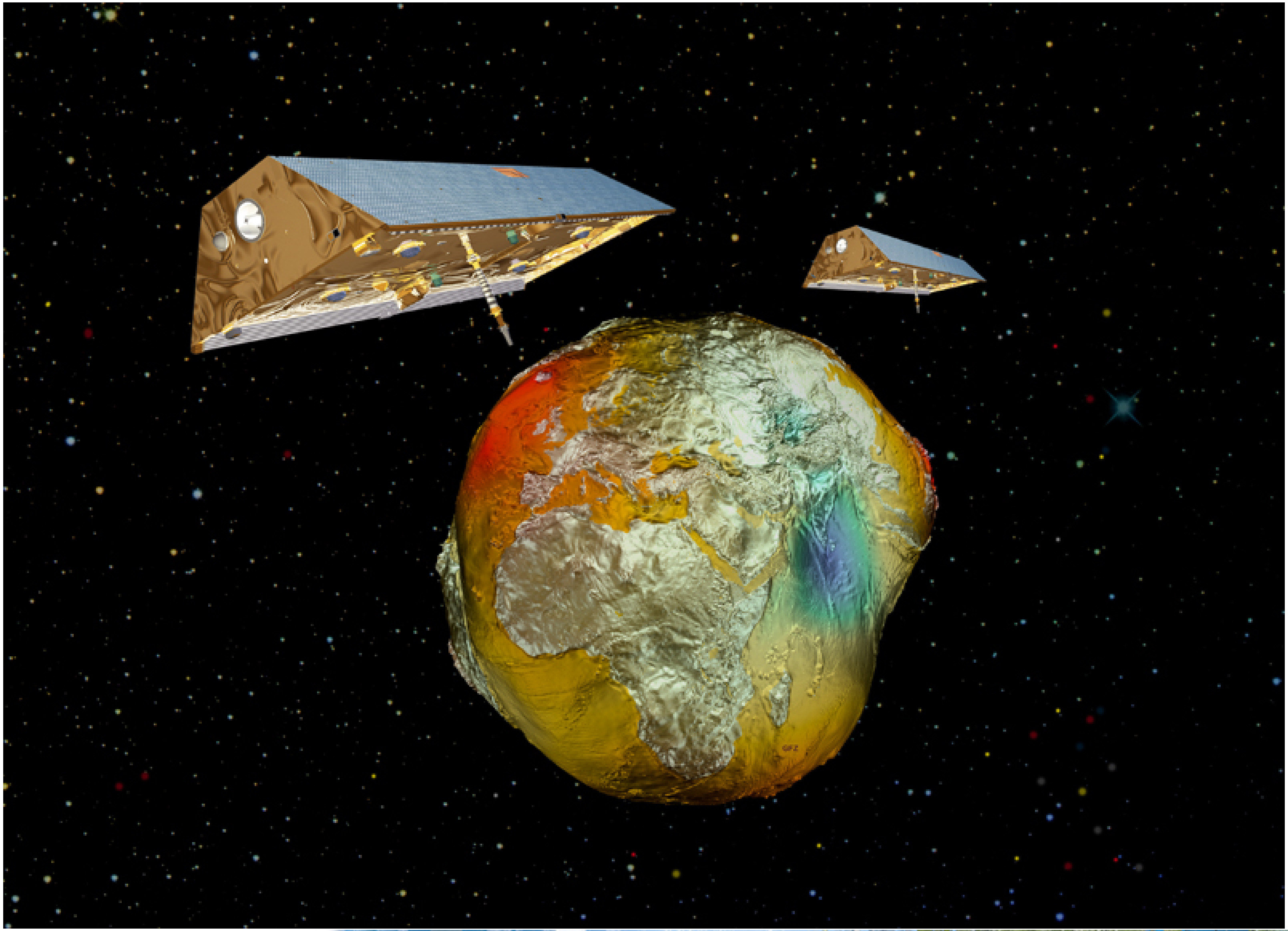
GRACE follow-on

GRACE: Gravity Recovery and Climate Experiment



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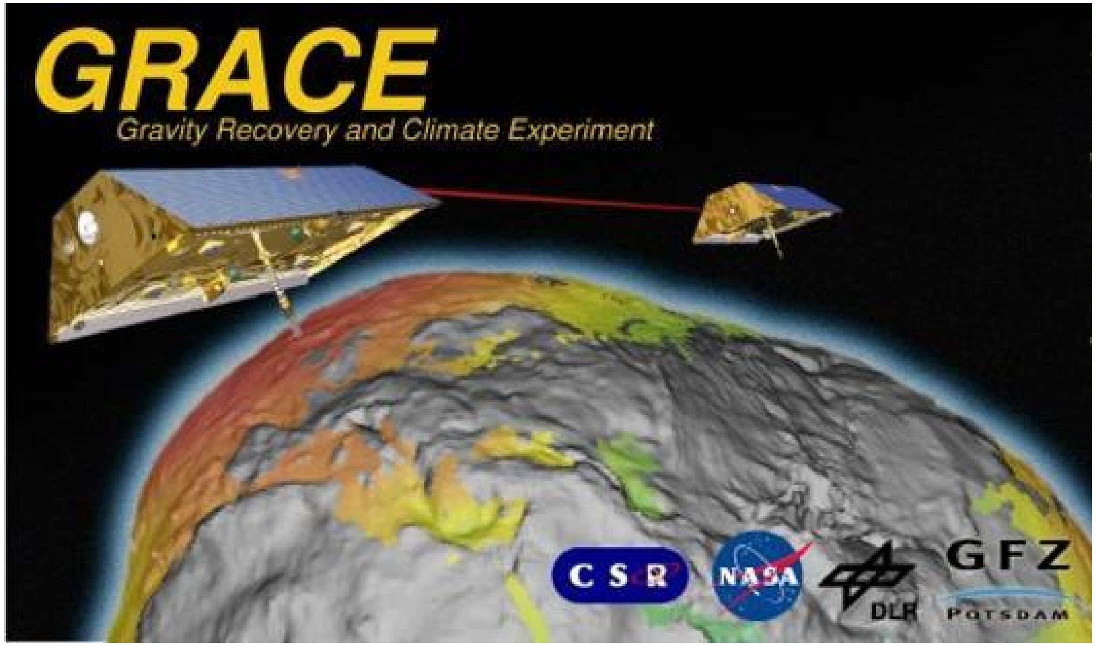

- GRACE was launched in 2002.
- Nominal orbit: 483 – 508 km, separation: 200 km
- Originally designed for 5 year nominal lifetime.
- Since 2012 in slowly decaying orbit:
  - currently at approximately 350 km

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- Since 2012 in slov
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GRACE follow-on

- Planned launch date: December 2017

- Nearly identical to GRACE
  - Main focus is to provide continuity of data to science community.
  - Minor improvements:
    - Star trackers
    - Slightly better accelerometers

- Laser ranging interferometer
  - Technology demonstration payload
  - Race-track configuration
  - Similarities to LISA:
    - Received optical power: ~100 pW
    - Doppler shifting beat note
    - Laser frequency stability (first LISA stage)

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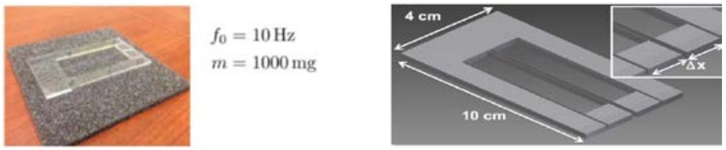
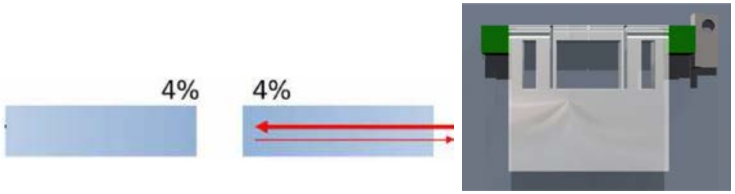
HOWEVER: required sensitivity is a few orders of magnitude less demanding than LISA.

ZARM DLR

Novel optomechanical technologies for gravitational physics and inertial sensing

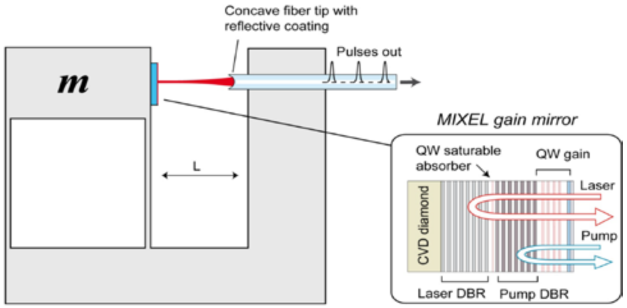
Gravimeters & Gradiometers



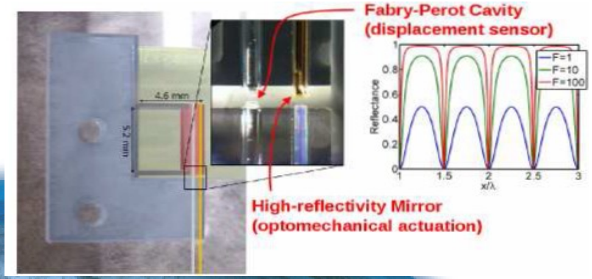


Micro-optical motion sensors

An Optomechanical Laser



Self-referenced force sensors



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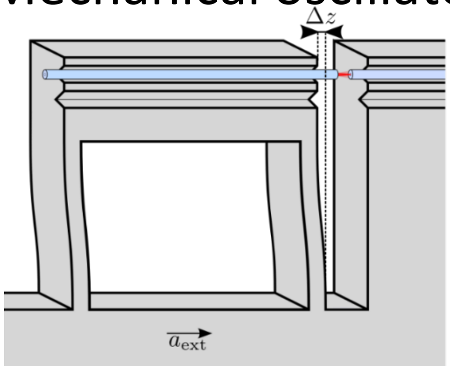
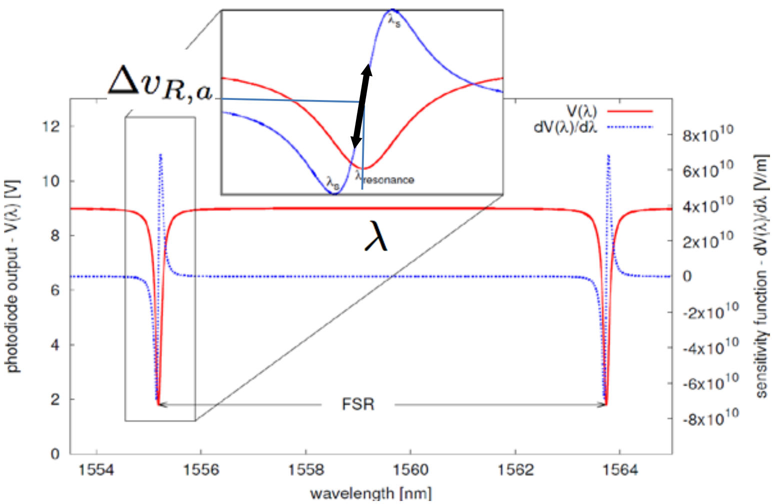
Optomechanical accelerometer concept

Mechanical oscillator



- Acceleration ➔ test mass displacement Δz_m
- Linear uniaxial motion $\frac{\Delta z(\omega)}{a_{\mathrm{ext}}(\omega)} = -\frac{1}{\omega_0^2 - \omega^2 + i\frac{\omega_o}{Q}\omega}$
  - Two parameters:
    - natural frequency w_0
    - mechanical quality factor Q
  - SI frequency standard traceability
- Optical length changes ➔ reflected power changes

Fabry-Pérot cavity



- Absolute optical length measurement:
  Free Spectral Range (*FSR*): distance between resonances

$$\boldsymbol{L = \frac{c}{2\,FSR}}$$

- Linearization: $\Delta v_{R,a} = \frac{\lambda_0}{\bar{z}_m}\left(\frac{\mathrm{d}v}{\mathrm{d}\lambda}\right)\Delta z_m$
  - Three parameters:
    - cavity length $\bar{z}_m$
    - laser wavelength λ_0
    - derivative of reflectivity wrt. wavelength $\frac{\mathrm{d}R}{\mathrm{d}\lambda}$
  - SI wavelength standard traceability

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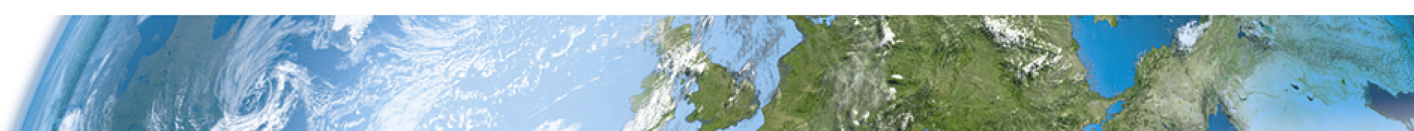


Optomechanical accelerometer prototype

Mechanical oscillator – *Q* measured: 4×10^6

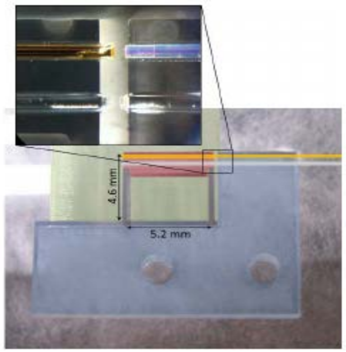
- Monolithic fused-silica flexure

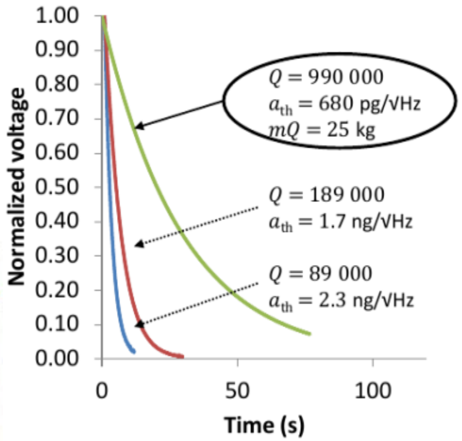
$\omega_0 = 2\pi \times 10.7$ kHz

$m = 25$ mg

$Q \approx 10^6$

$a_{th} = 680$ pg/√Hz

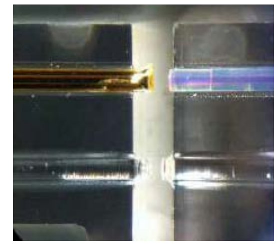




Optical sensor

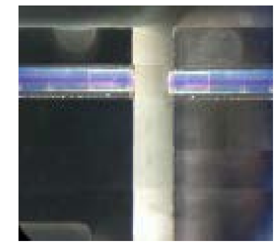
- Fabry-Pérot fiber micro-cavities of low and high finesse
- Cavity lengths of 40-200 µm | FSR at THz frequencies

low finesse: 2-100



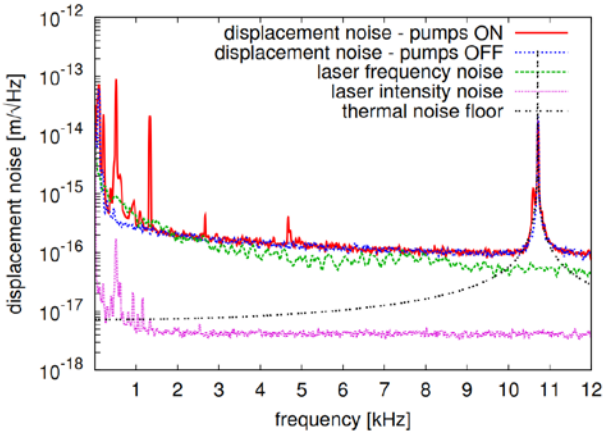
- plano-plano uncoated flatly cleaved fibers
- plano-concave dielectric and metalized fiber mirrors

high finesse: > 1500

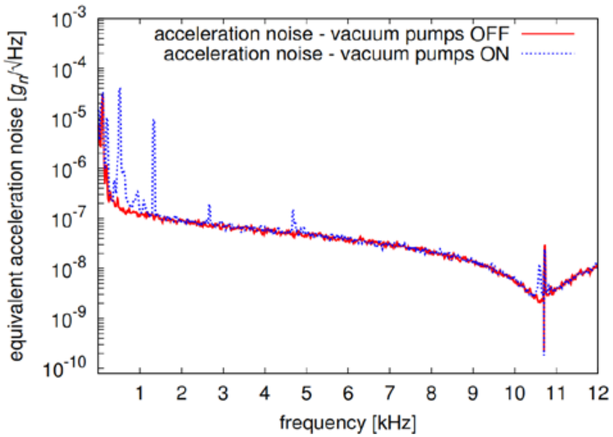


- plano and laser-ablated concave fiber mirrors with HR dielectric coatings

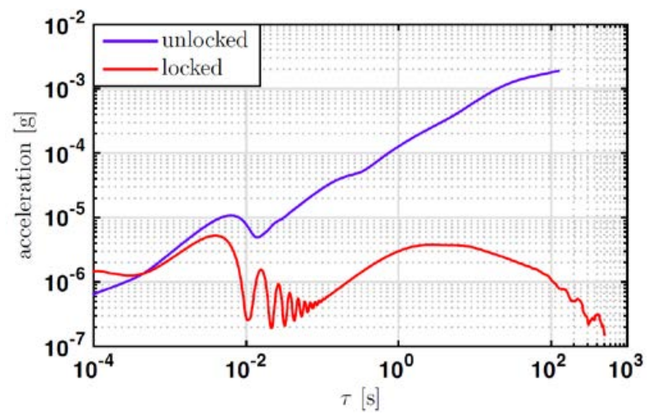
displacement resolution: 10^{-16}m/√Hz



acceleration resolution: < 100 n*g*/√Hz



Allan variance - $10^{-5}g$ over 100s



* Felipe Guzmán Cervantes, *et al*, High sensitivity optomechanical reference accelerometer over 10 kHz, Applied Physics Letters 104 (22), 221111 (2014).
Felipe Guzmán Cervantes, *et al*, Optomechanical motion sensors. American Society of Precision Engineering, Conference on Precision Interferometry, 2015.
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Yiliang Bao, Felipe Guzmán, *et al*. An optomechanical accelerometer with a high-finesse hemispherical optical cavity. IEEE Symposium on Inertial Sensors and Systems, 2016.

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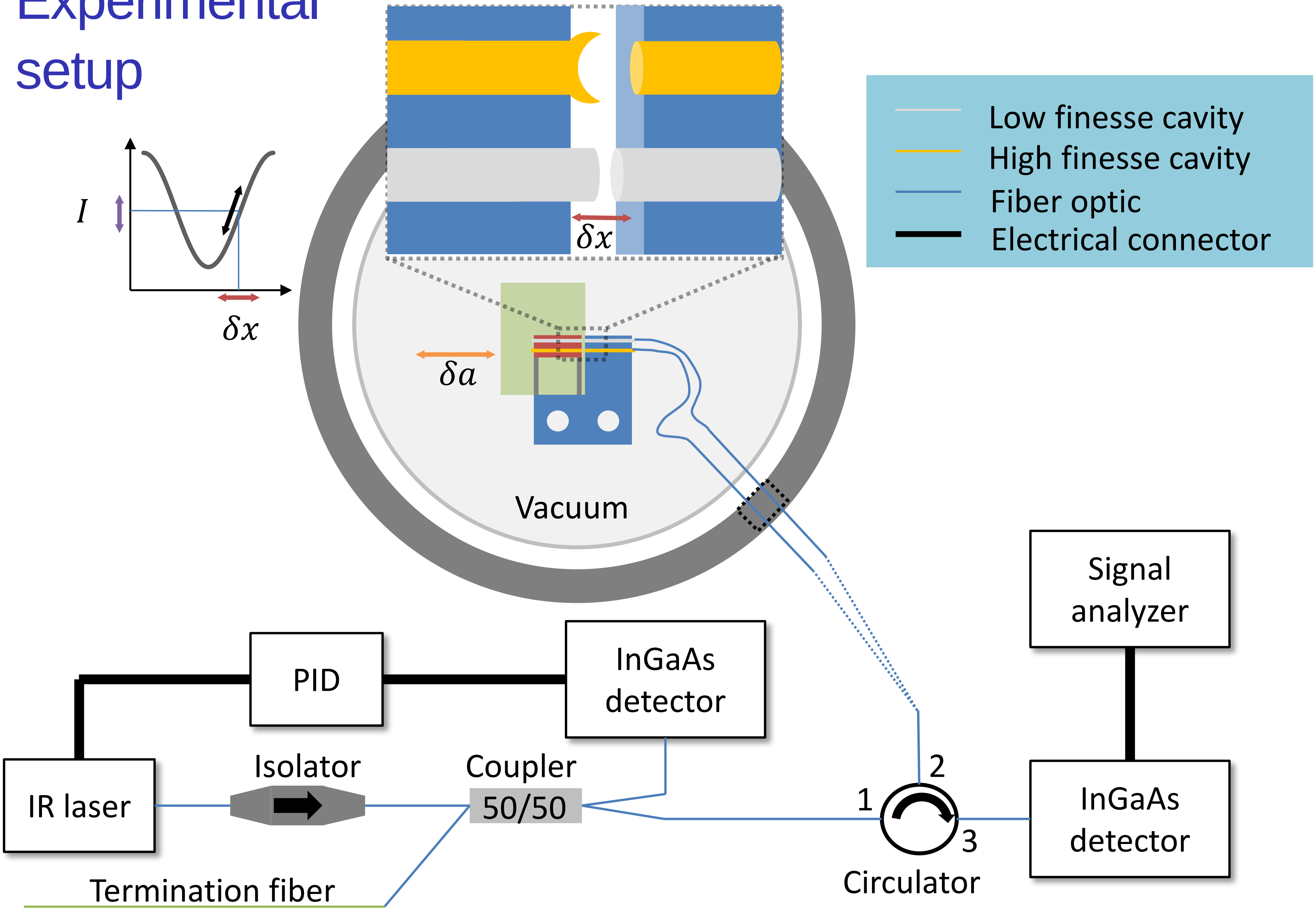
Experimental setup



Displacement detection

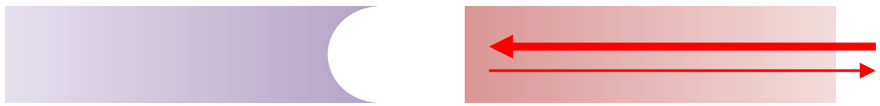
$\mathcal{F} \approx 1500$

$Q_{opt} \approx 430\,000$

Visibility $\approx 97\%$

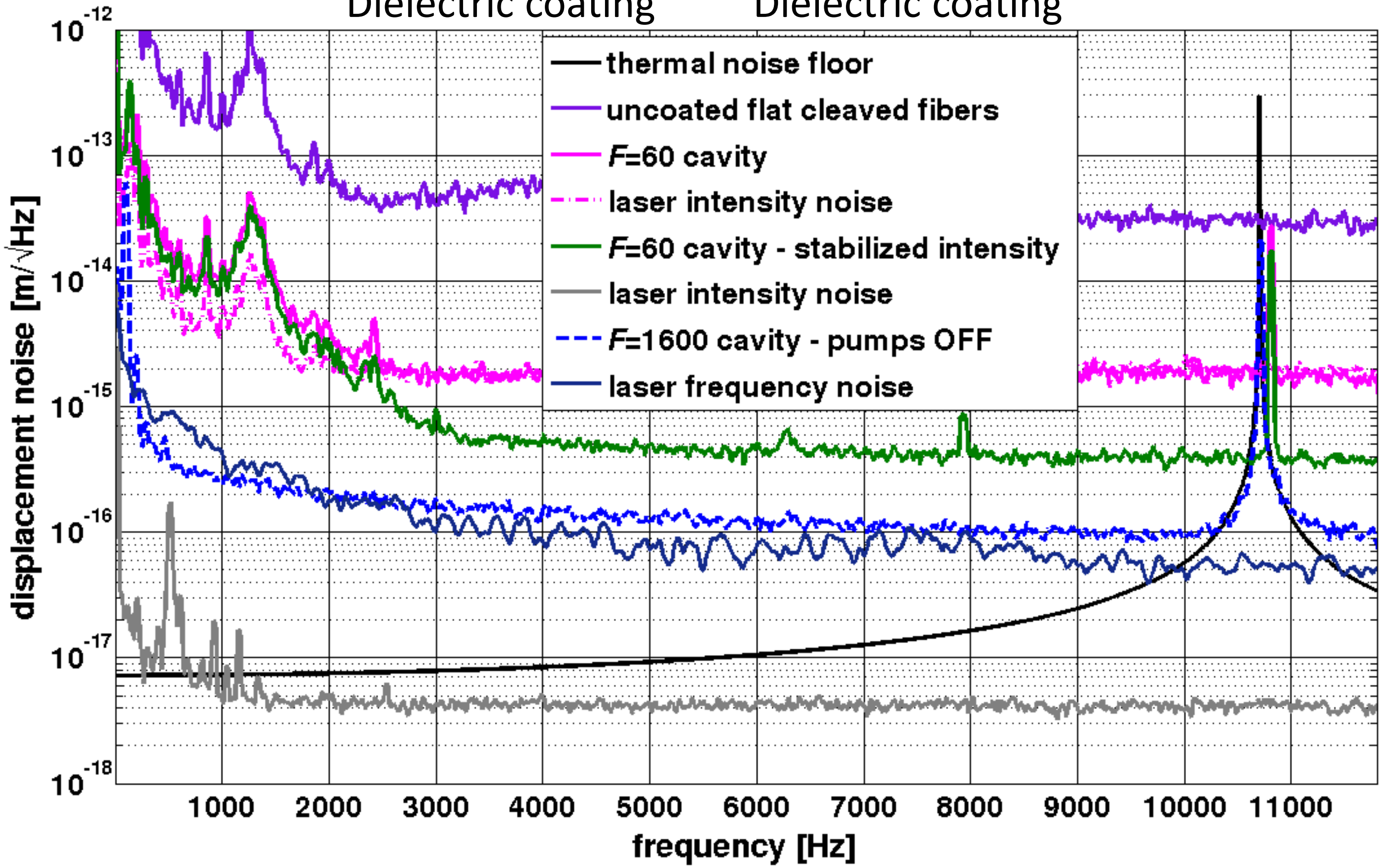
Low noise laser

99.9992%   99.7%



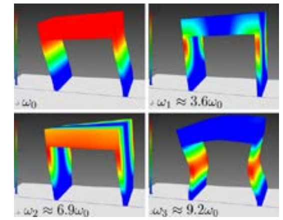
Laser ablated Dielectric coating

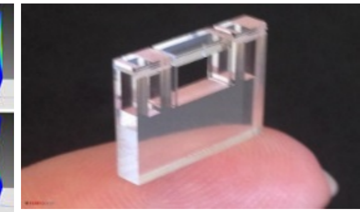
Flat cleaved Dielectric coating

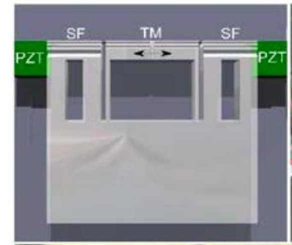


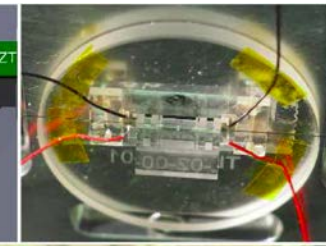
Optomechanical accelerometer - setup

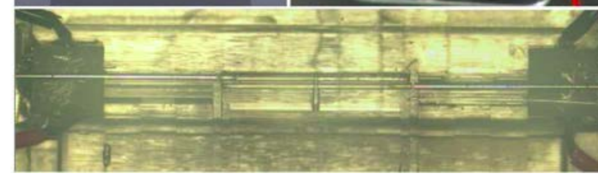
- PZT tunes side-flexure cavities over a full fringe:
  - Cavities approximately 70µm +/- 0.5 µm
  - FSR: 2 THz, finesse: 1000, linewidth: 2 GHz
  - Range approx. 1.7 µm (more than one fringe)
- Dual cavity readout – common-mode laser noise cancellation
  - Single cavity reaching 70 am/√Hz at high frequencies. 10 fm/√Hz @ 1 Hz.
- Laser, fiber-optic light distribution & modulators:
  - Laboratory grade equipment utilized so far.
  - Highly compact equivalent COTS components available.
  - Performance with COTS to be tested.
- Vibration isolation platform required for gravity and inertial sensing.

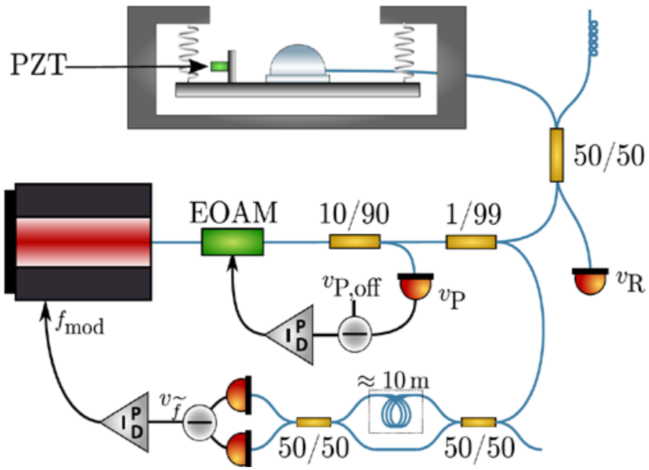


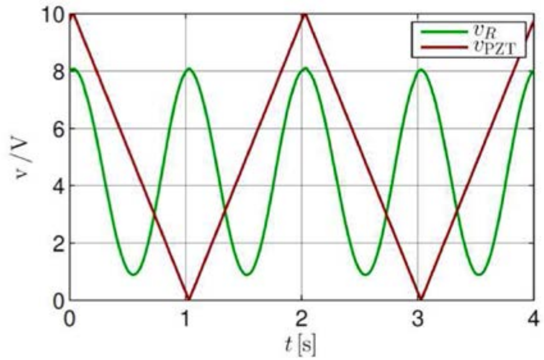


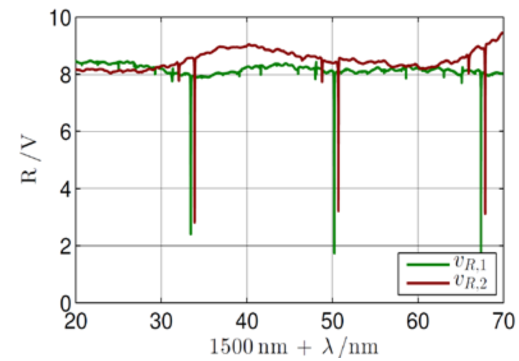












Felipe Guzmán Cervantes, *et al*, High sensitivity optomechanical reference accelerometer over 10 kHz, Applied Physics Letters 104 (22), 221111 (2014).
Felipe Guzmán Cervantes, *et al*, Optomechanical motion sensors. American Society of Precision Engineering, Conference on Precision Interferometry, 2015.
Felipe Guzmán Cervantes, *et al*, MEMS optomechanical accelerometry standards. American Society of Precision Engineering, Conference on Precision Interferometry, 2015.
Yiliang Bao, Felipe Guzmán, *et al*. An optomechanical accelerometer with a high-finesse hemispherical optical cavity. IEEE Symposium on Inertial Sensors and Systems, 2016.

Optomechanical Gravimeters

- Ideal for space applications
  - Compatible materials and simple robust geometry
  - Cost-effective, small and light weight
  - Redundancy: dual test mass approach
  - Tunable performance space through smart and simple geometry

- Applications
  - Geodesy, Gravimetry, seismometry, structural analysis and control, quantum & fundamental physics, Inertial Navigation

- Performance limit $$\underbrace{\delta a}_{SHO} = \sqrt{\frac{4 k_B T \omega_o}{m_{eff}\, Q}}$$

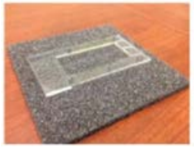
- Lower resonance frequency $$\delta a = \omega_o^2 \underbrace{\delta x}_{\substack{\text{displacement} \\ \text{noise density}}}$$

- Low stiffness flexures
  - Readout with large dynamic range (> λ)
  - Active test mass control / force rebalancing

- Test mass: 10^{-3} kg, Q: 2000, f_o=10 Hz
- Dual test mass approach - redundancy
- Total sensor mass: < 30 g

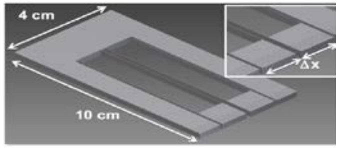
- **Current acceleration sensitivity limit:**

$7 \times 10^{-10}\ \mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}$



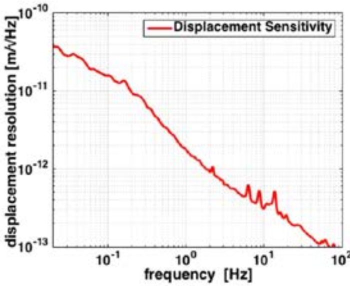
$f_0 = 10\,\mathrm{Hz}$

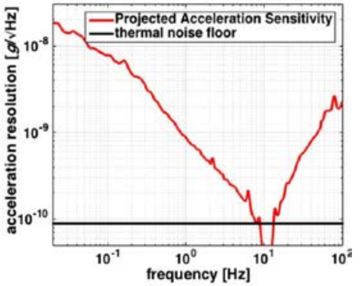
$m = 1000\,\mathrm{mg}$



$$\frac{x(\omega)}{a(\omega)} = -\frac{1}{\omega_o^2 - \omega^2 + \frac{i\omega_o}{Q}\omega}$$

free-running Fabry-Pérot low-finesse fiber interfometer



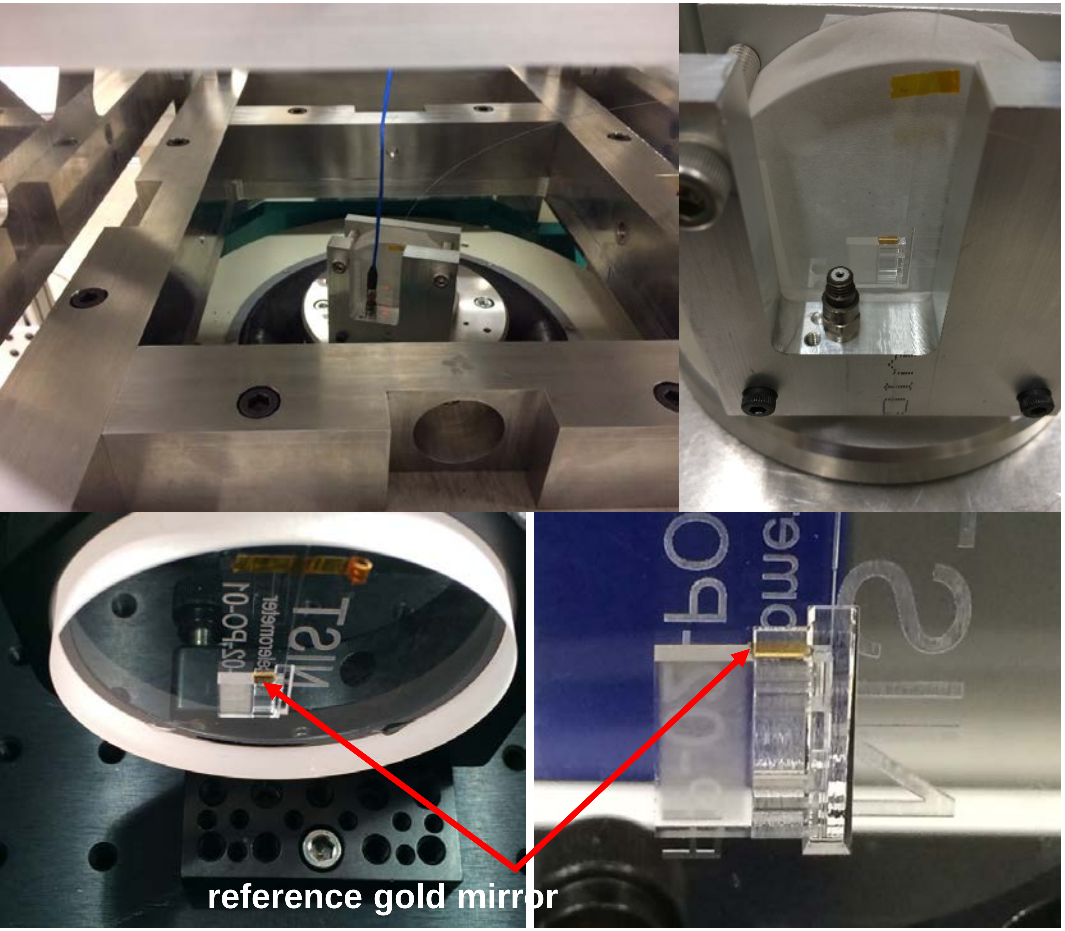


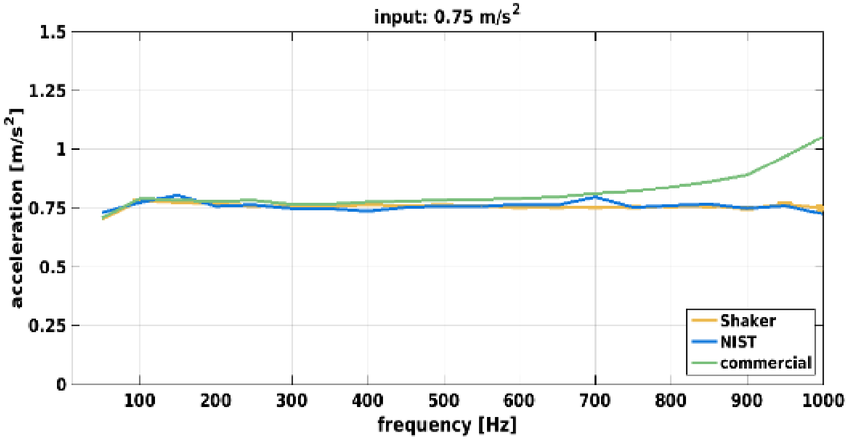
Provisional Patent US 62/355,208: F. Guzmán, L. Kumanchik, J. R. Pratt, J. M. Taylor, PS-2016-095, 2016

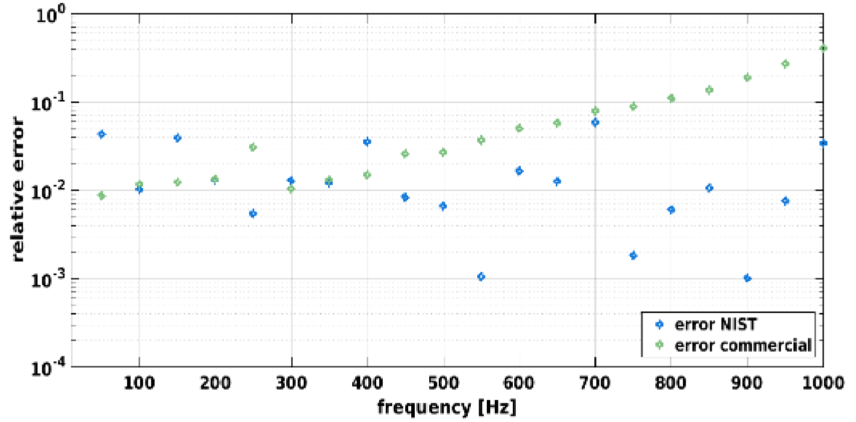
Provisional Patent US 62/355,210: F. Guzmán, PS-2016-096, 2016

Optomechanical accelerometer – primary standard

- National Metrology Institutes (NMI) state-of-the-art acceleration metrology
  - Comparison measurements against primary standards demonstrate NMI grade accuracies at levels of 10^{-3}—10^{-2}.



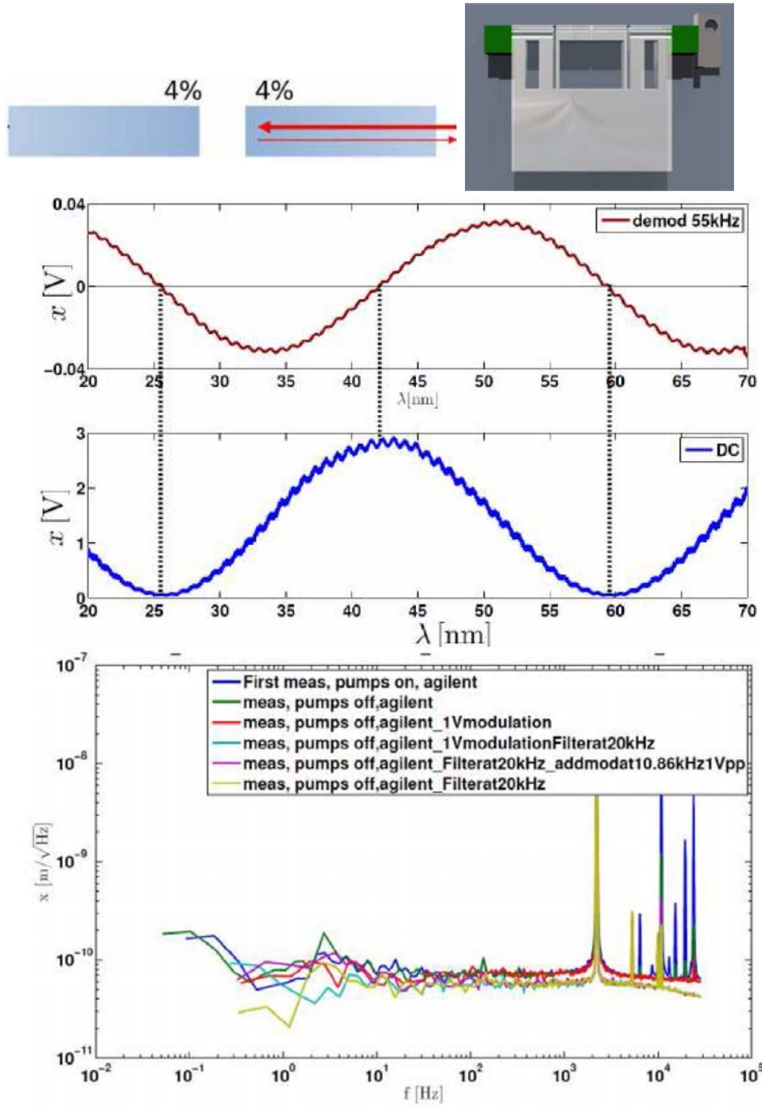




Micro-optical motion sensors

- Low-finesse limit: bare glass 4% reflectivity
- Nearly sinusoidal response
- Extremely large *FSR*s ~ THz
- Enable absolute distance and displacement measurements
- DC read out sensitive to a few fm/√Hz
- Mechanical modulation:
  - AC read out and servo technique
  - Provides error signal for cavity and laser control
  - Signal in quadrature from demodulation
  - Signals in quadrature for tracking over several fringes
- Preliminary tests show sensitivities of:

40-80 pm/√Hz @ 10s mHz – 10s kHz



Felipe Guzmán Cervantes , *et al*, Optomechanical motion sensors. American Society of Precision Engineering, Conference on Precision Interferometry, 2015.

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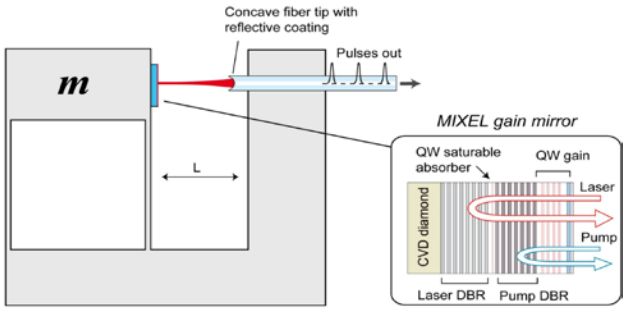
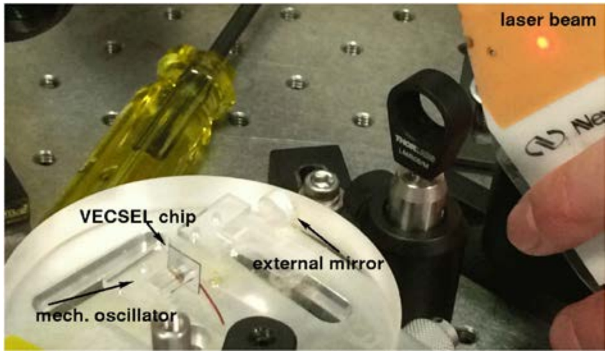
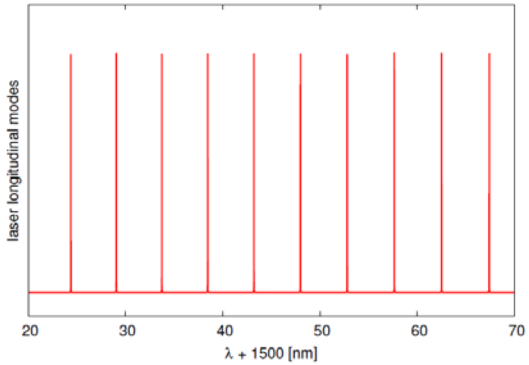
An Optomechanical Laser
Displacement to Frequency conversion

- VECSEL - Vertical-External-Cavity Surface-Emitting Laser:
    - Consists of surface-emitting chip (“half of a VCSEL”)
    - External mirror to complete laser cavity
    - Single-mode and Mode-locked operations possible
    - Optical pumping possible for high lasing power: > 10 W
    - Electrical pumping possible as well, lower optical output power





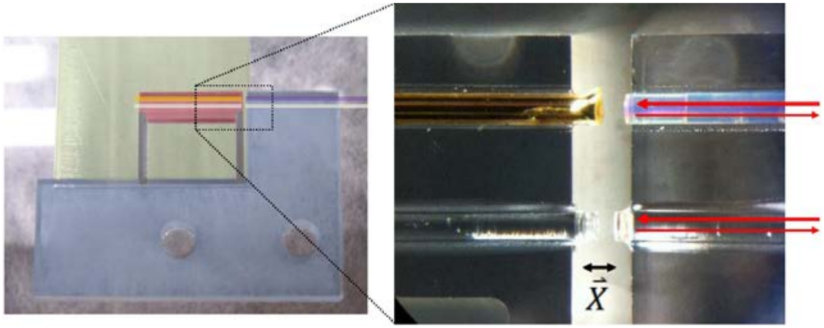
- Dynamics to Frequency transduction:
    - Dynamics: displacement, acceleration, force,
      inertial field and gravitational potential.
    - Test mass displacement ➔ lasing cavity length changes
    - Test mass motion changes lasing frequency/wavelength
    - Mode-locked FSR / mode-beating ➔ absolute measurement of cavity length
    - Absolute displacement measurements by using
      true frequency standards and their accuracies



- Frequency combs ➔ THz down conversion:
    - Short cavities yield a *coherent photonic THz source*
    - Reference laser frequency combs
    - Compact and portable fiber combs

Provisional Patent US 62/355,215: F. Guzmán, J. R. Pratt, J. M. Taylor, PS-2016-097, 2016

Thank you



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DLR

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- G. A. Shaw, P. Williams, J. Stirling, F. Guzmán Cervantes and J. Lehman, "Using small mass and force metrology for laser power measurement," *2016 Conference on Precision Electromagnetic Measurements (CPEM 2016)*, Ottawa, ON, 2016, pp. 1-2.
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- F. Guzmán. American Geophysical Union (AGU) Meeting, Poster Contribution, San Francisco, CA, USA, December 2015.
- F. Guzmán. American Society of Precision Engineering, Conference on Precision Interferometry, Oral Contributions, Golden, Colorado, USA, July 2015.
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- Patent Applications

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Optomechanical Gravity Gradiometer – Patent PS-2016-096, University of Maryland, , US 62/355,210.
Optomechanical Laser – Patent PS-2016-097, University of Maryland, , US 62/355,215.