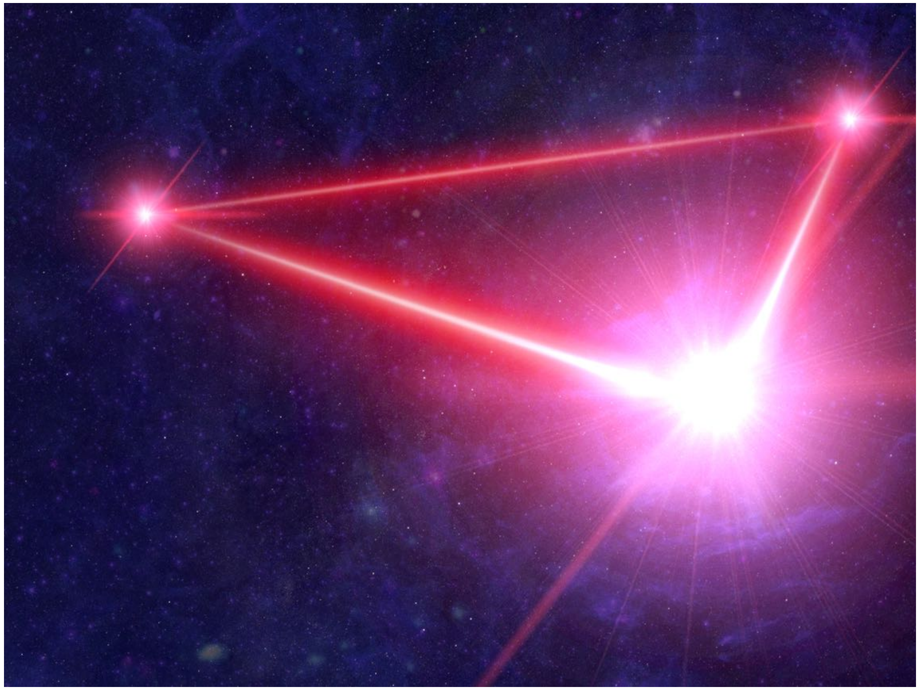
LISA Pathfinder and LISA
toward a space-based gravitational waves observatory

Rita Dolesi
University of Trento/ INFN-TIFPA
on behalf of LISA PF Team
and LISA Consortium

VULCANO Workshop 2018
Frontier Objects in Astrophysics and Particle Physics
20th- 26th, May 2018
Vulcano Island, Sicily, Italy



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TIFPA Trento Institute for Fundamental Physics and Applications

lisa pathfinder

esa

asi agenzia spaziale italiana

2016: GW exploration of the Universe has started!

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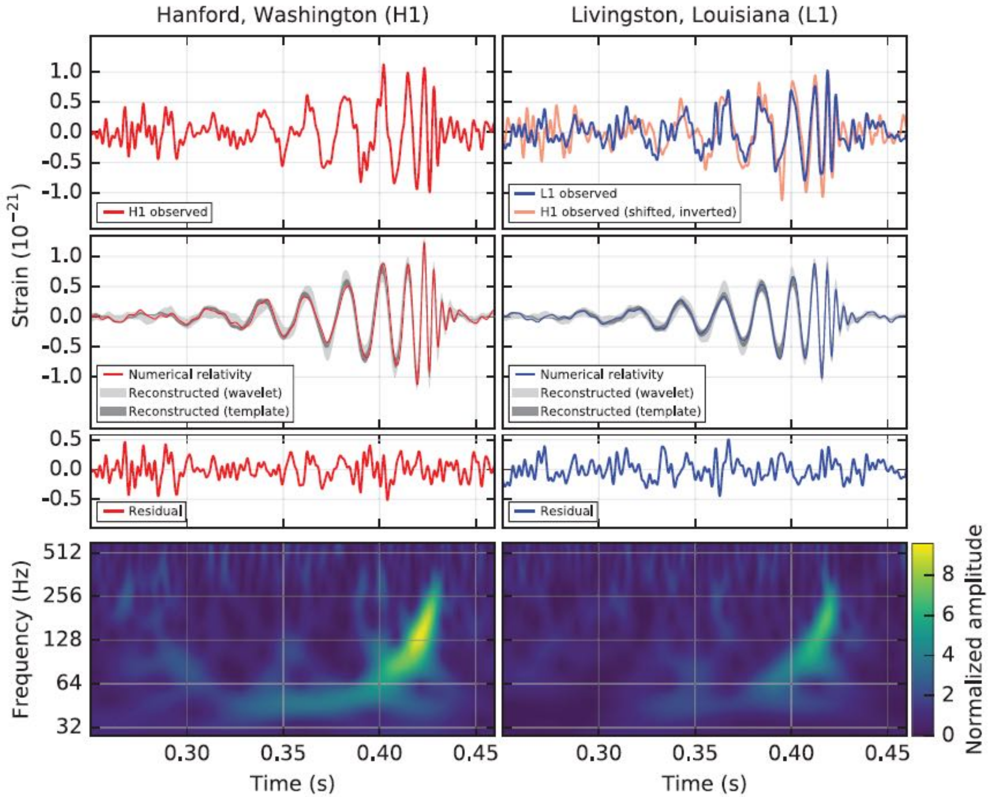
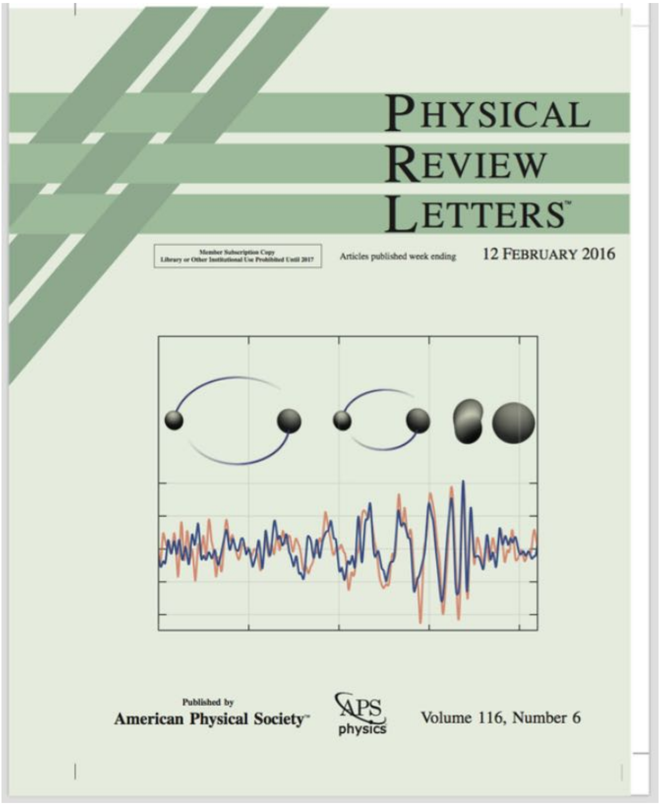
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)





2015-2017: LISA Pathfinder mission is a success

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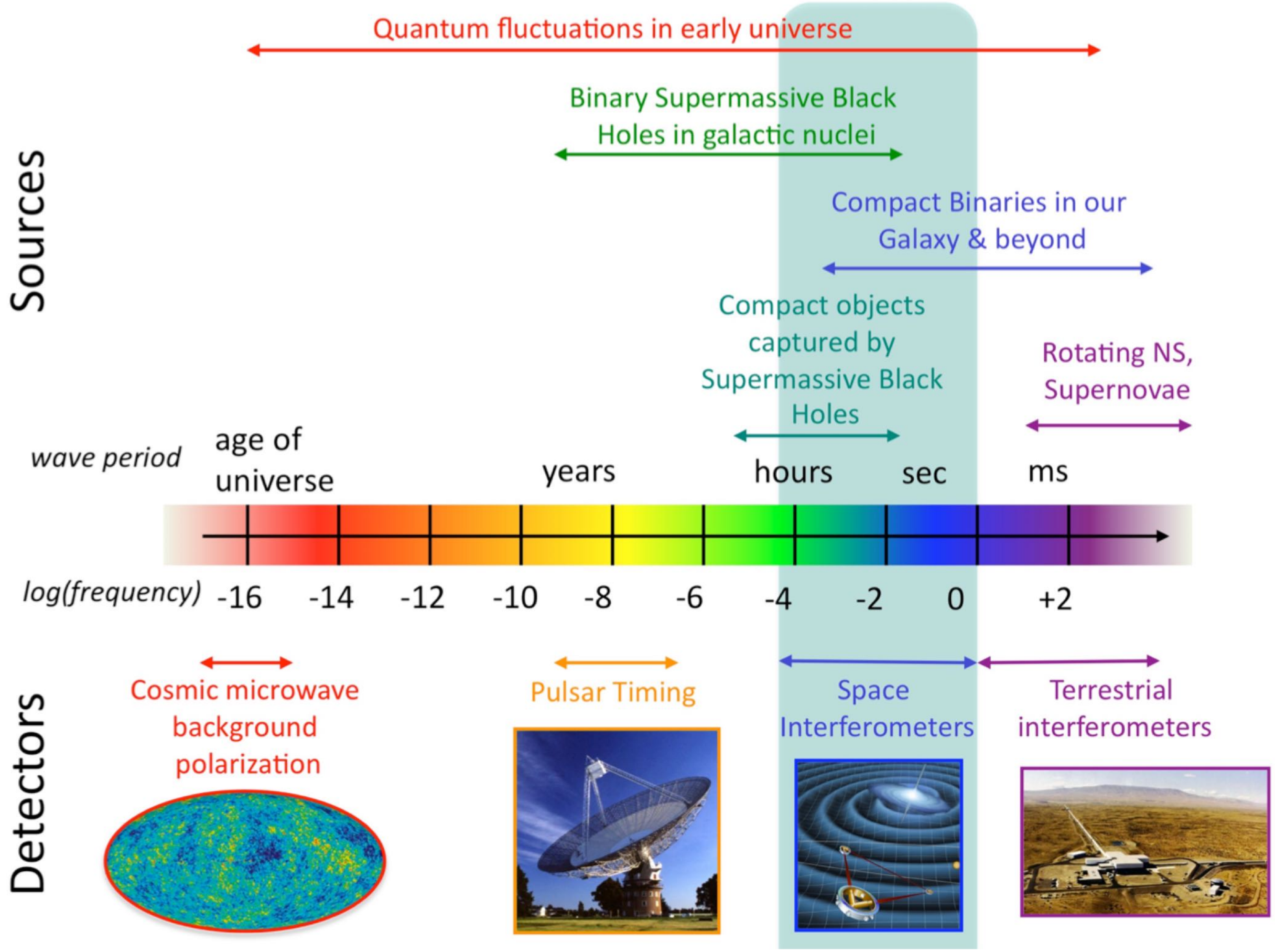
End-to end experimental demonstration of the <u>free fall of test masses</u> at the level required by future space-based GWs observatory like LISA

Performances totally in line with the mission concept in the «Gravitational Universe » selected by ESA for L3 of its Cosmic Vision Program

Gravitational Waves Spectrum



LISA science objectives→ LISA Mission Requirements→LISA payload instrument baseline

Brief LISA description

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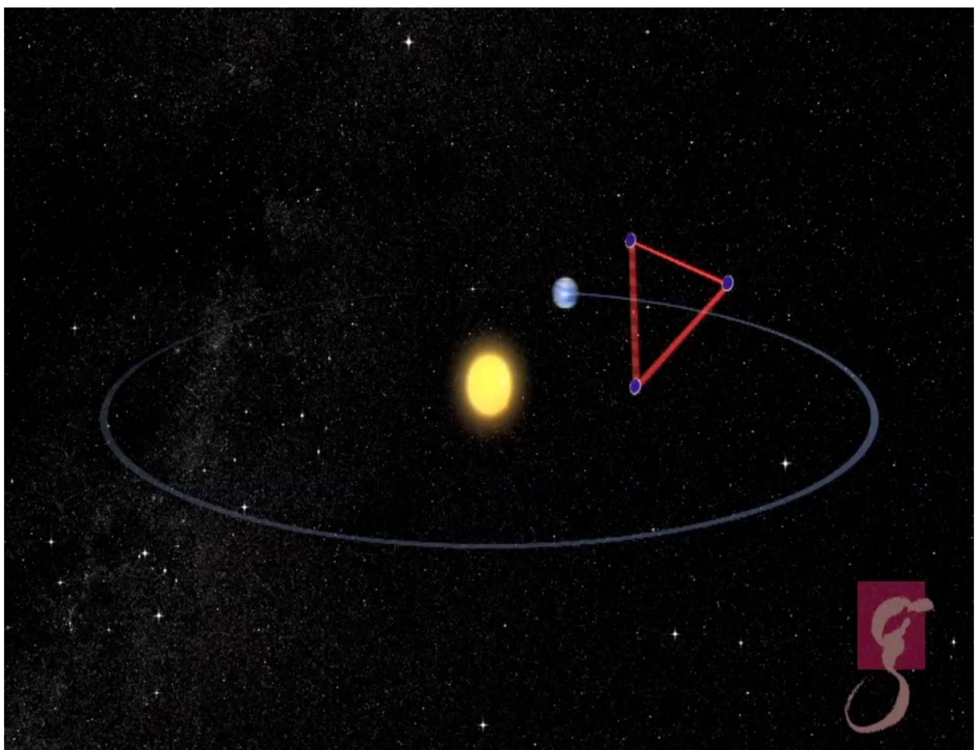
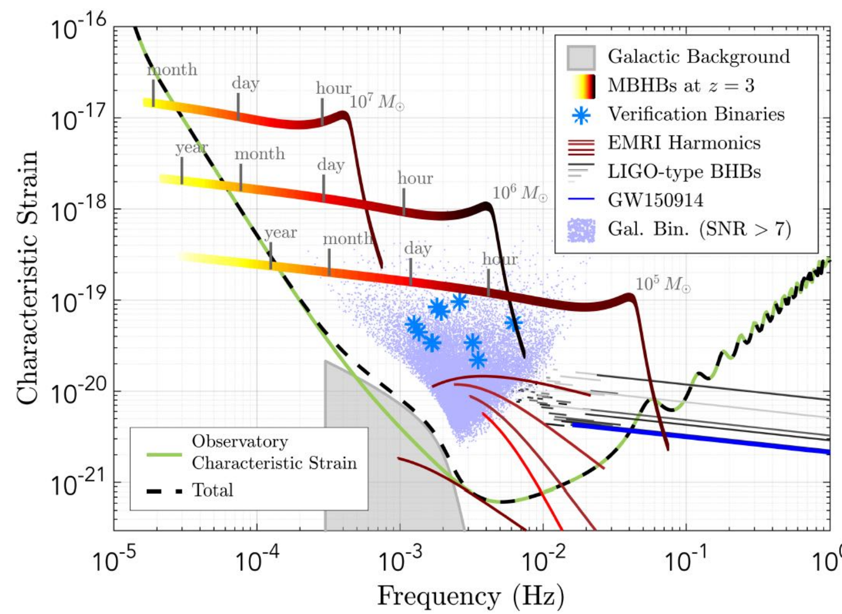
- 3 identical spacecraft
- 3 arms of 2.5 Million km
- 1 AU , 20-degree trailing Earth orbit
- Triangle rotates and changes by ±1.5°, ±20 000 km,±10 m/s



- 2 Michelson interferometers, heterodyne laser interferometry in transponder mode
- 10 pm/√Hz,
- Time Delay Interferometry
- 30 cm telescopes, 2W lasers, 100 pW at receiver, 1064 nm
- Test masses in sub-femto-g free fall (3 fm/s²/√Hz) of LISA PF



Massive black hole coalescences (MBHCs)

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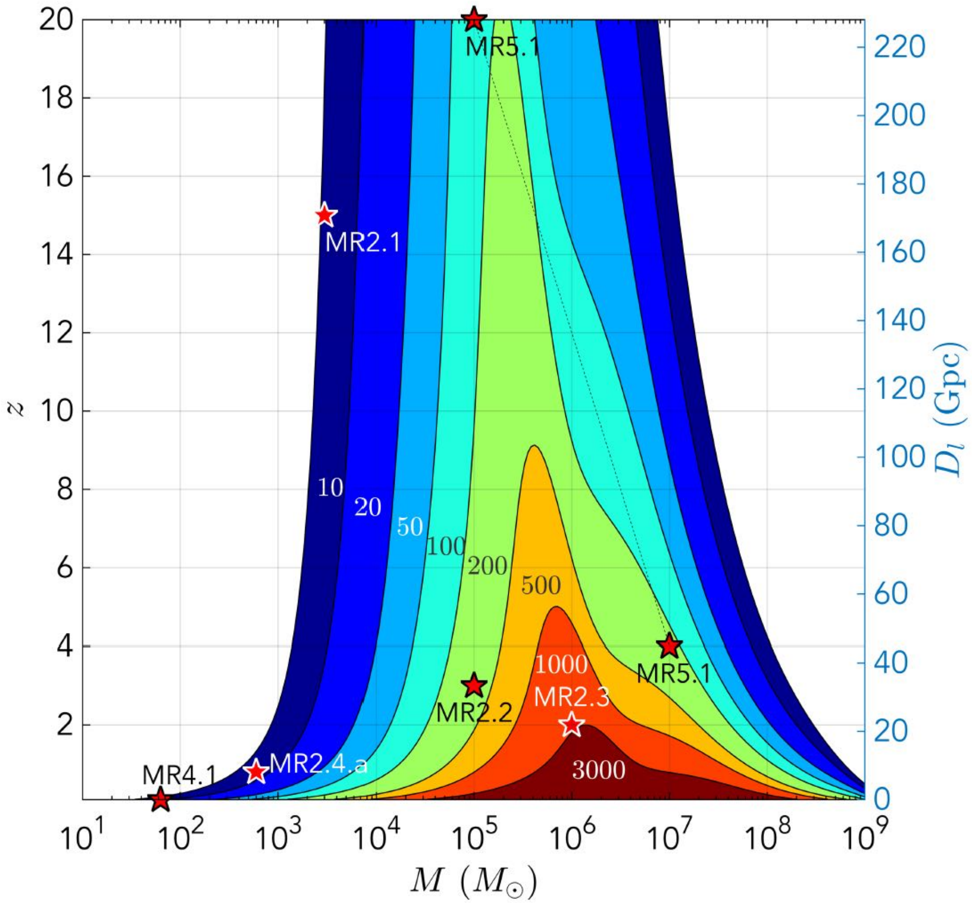
Covers almost all of the mass-redshift parameter space needed to trace black hole evolution

Galaxies host black holes bigger than million solar mass: trace galaxy mergers



Contour plot of constant SNR for the baselin observatory in the plane of total source-fram mass, M, and redshift, z

wide range of masses observable with high SNR out to high redshift.

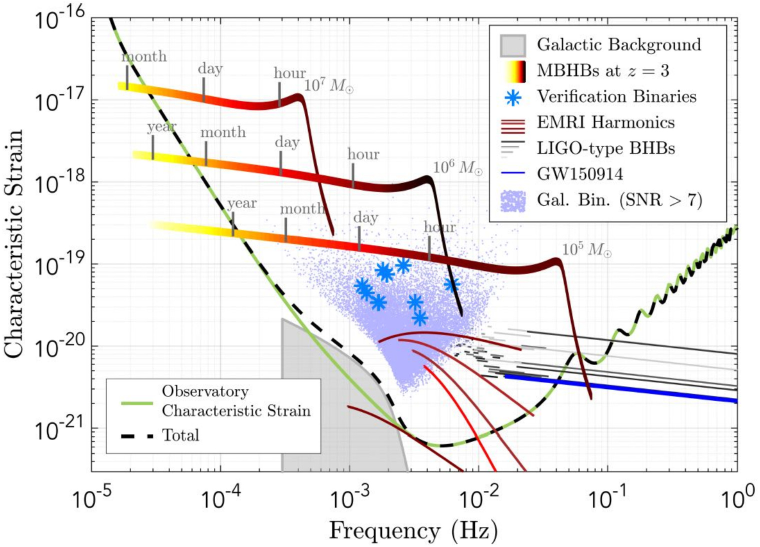
LISA is a high resolution deep Universe observatory

Extreme Mass Ratio Inspirals (EMRIs)

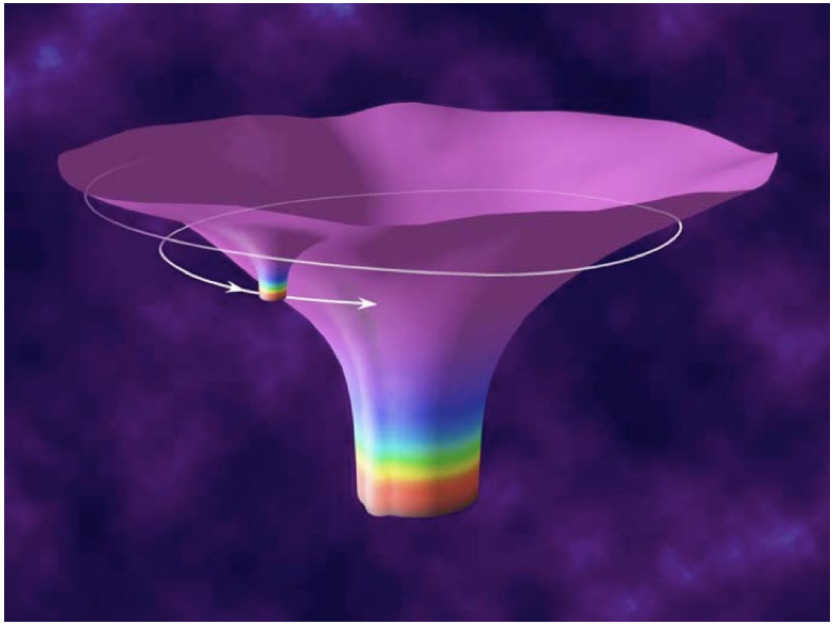
Stellar-mass BH captured by a massive BH

Probe the dynamics of dense nuclear clusters using EMRIs

Explore the fundamental nature of gravity and black holes

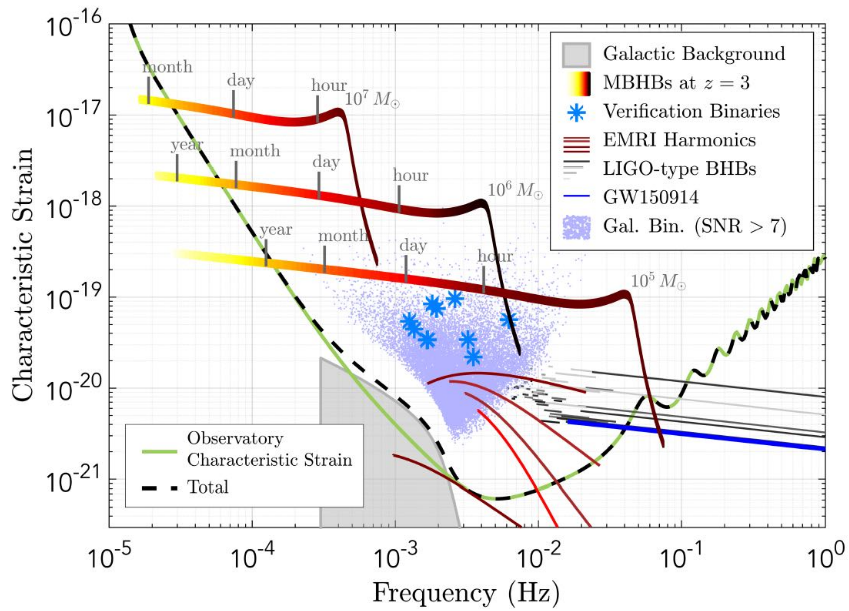


- Dozens per year.
- Prove horizon exists.
- Test the no-hair theorem to 1%.
- Masses of holes to 0.1%
- Spin of central BH to 0.001.



Compact Galactic Binaries

Study the formation and evolution of compact binary stars in the Milky Way Galaxy.



- **Guaranteed (known) sources at high SNR: verification binaries**
- **About 20000 double white dwarf binaries resolved**
- **Discovery of distant/obscured/faint binaries.**
- **The millions of ultra-compact binaries will form a detectable foreground**

Multiband GW Astronomy

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Coordinate observation with ground based interferometers and electromagnetic telescopes

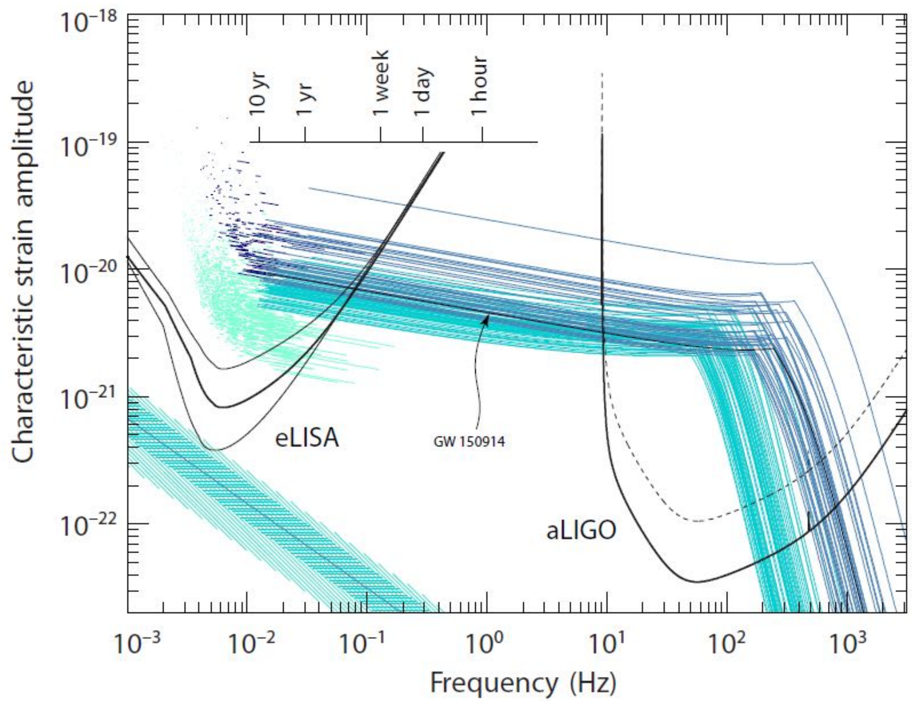
Editors' Suggestion

Prospects for Multiband Gravitational-Wave Astronomy after GW150914

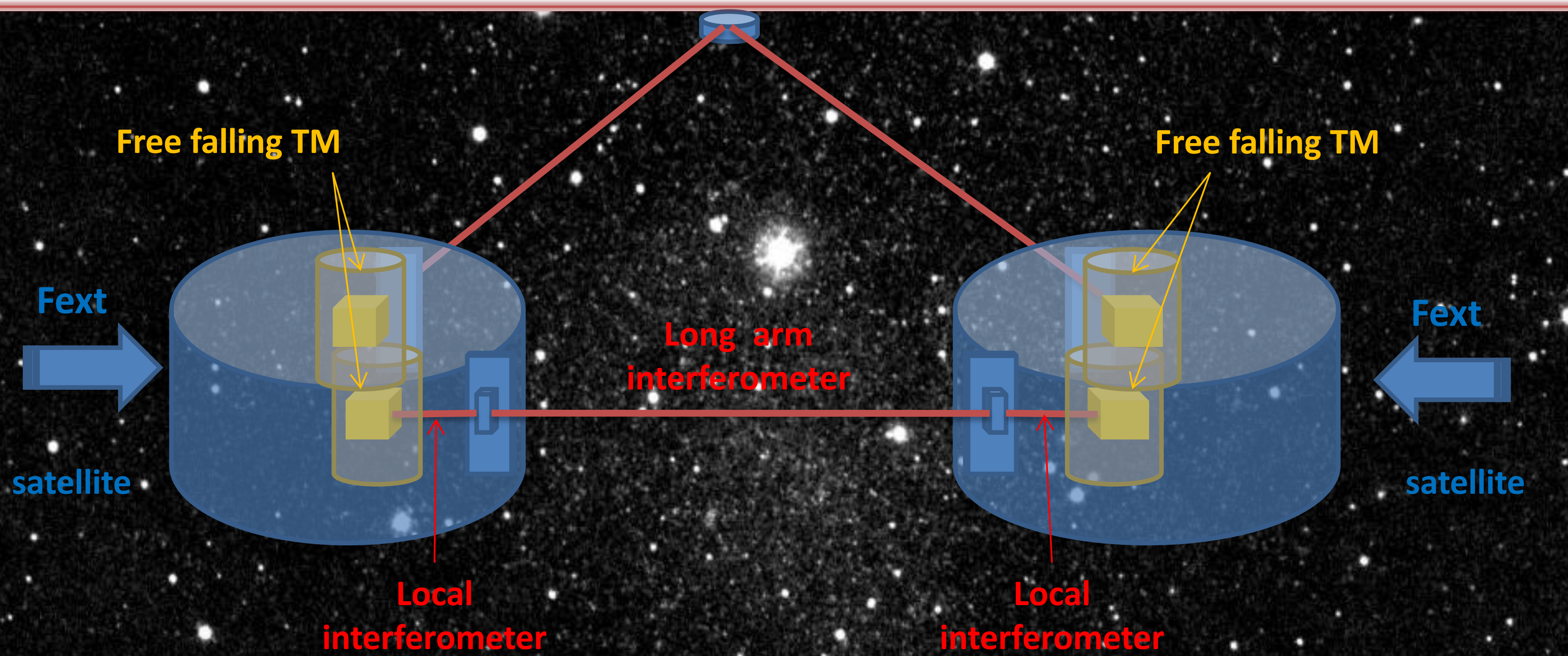
Alberto Sesana

Phys. Rev. Lett. **116**, 231102 (2016) – Published 8 June 2016

Rates of black hole merger formations inferred from the recent detection of gravitational waves suggest that a future space based facility like eLISA can efficiently inform LIGO and other facilitates about locations of potential black hole mergers



LISA basic «link» concept and performance limit



$$\frac{\dot{\nu}_{receiver} - \dot{\nu}_{emitter}}{\nu} = \frac{1}{2}\left[\dot{h}_{receiver}(t) - \dot{h}_{emitter}\left(t - \frac{L}{c}\right)\right] + \frac{1}{c}\left(a_{receiver}(t) - a_{emitter}\left(t - \frac{L}{c}\right)\right)$$

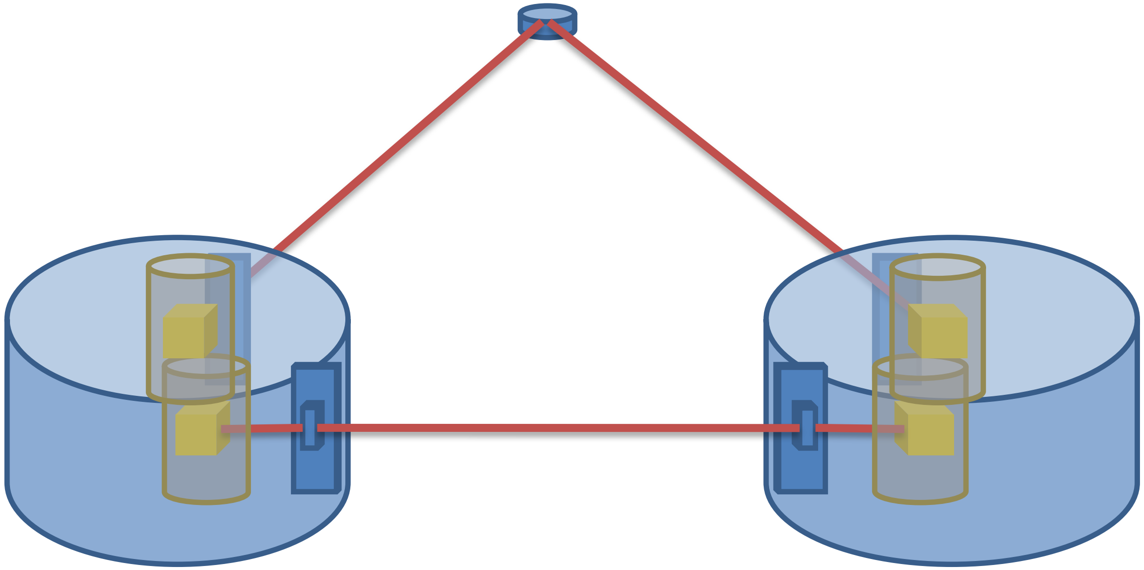
$$a_{sat} - a_{(sat-TM)} = a_{TM} + \ddot{n}_{local\ int}$$

TM residual acceleration
Relative to the local inertial frame

LISA Pathfinder Concept and Strategy

lisa pathfinder

Most of disturbances are local and can be tested within one satellite!



LISA Pathfinder Concept and Strategy

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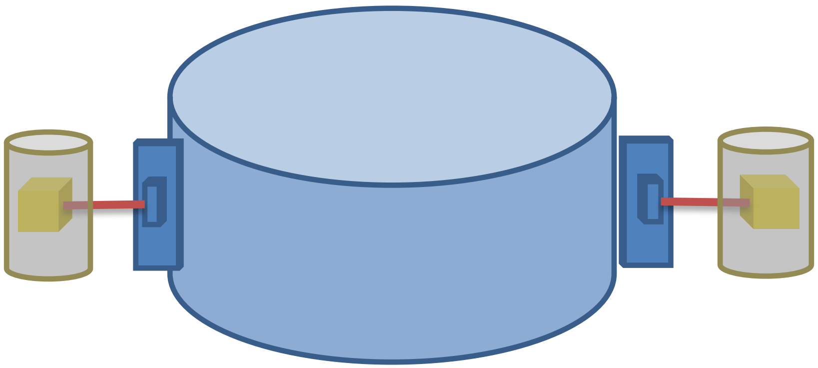
Most of disturbances are local and can be tested within one satellite!

- Measures differential acceleration noise from stray forces acting on 2 LISA TM
- Demonstrates the local interferometric measurement of TM acceleration



LISA PF requirement on max differential spurious acceleration

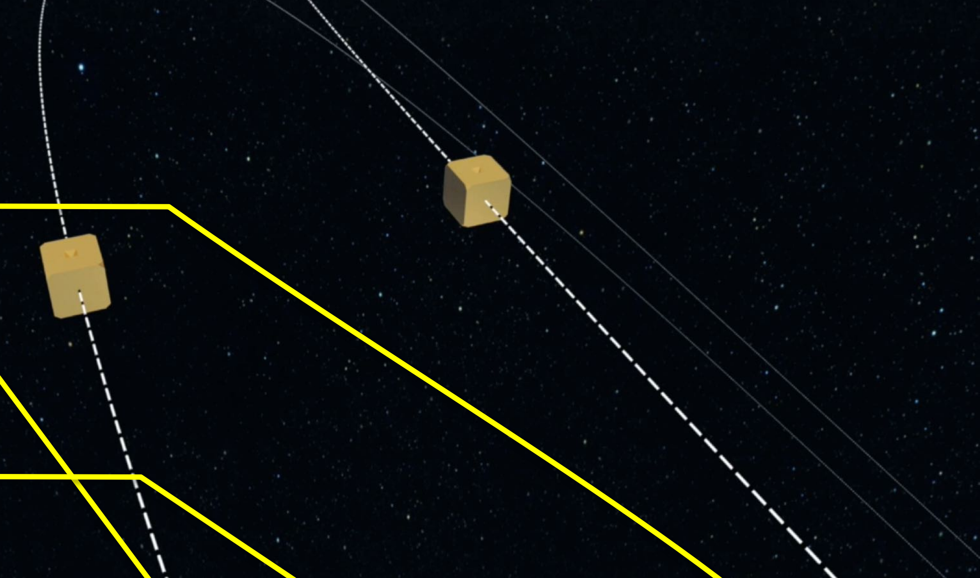
$$S_{\Delta g}^{\frac{1}{2}} \leq 30 \frac{fm}{s^2\sqrt{Hz}} \times \sqrt{1 + \left(\frac{f}{3\,mHz}\right)^4} \qquad 1\,mHz \leq f \leq 30mHz$$

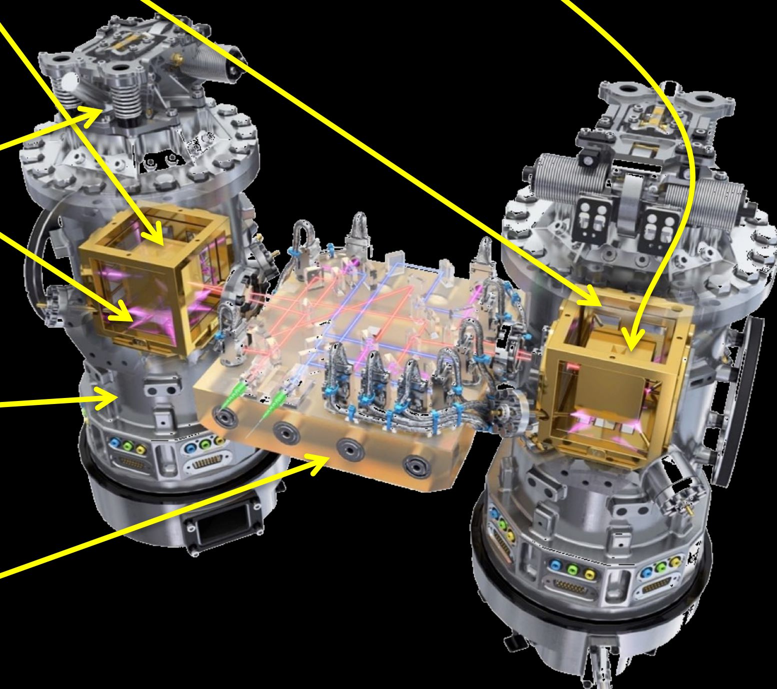
Relaxed by a factor 7 relative to LISA to allow for :

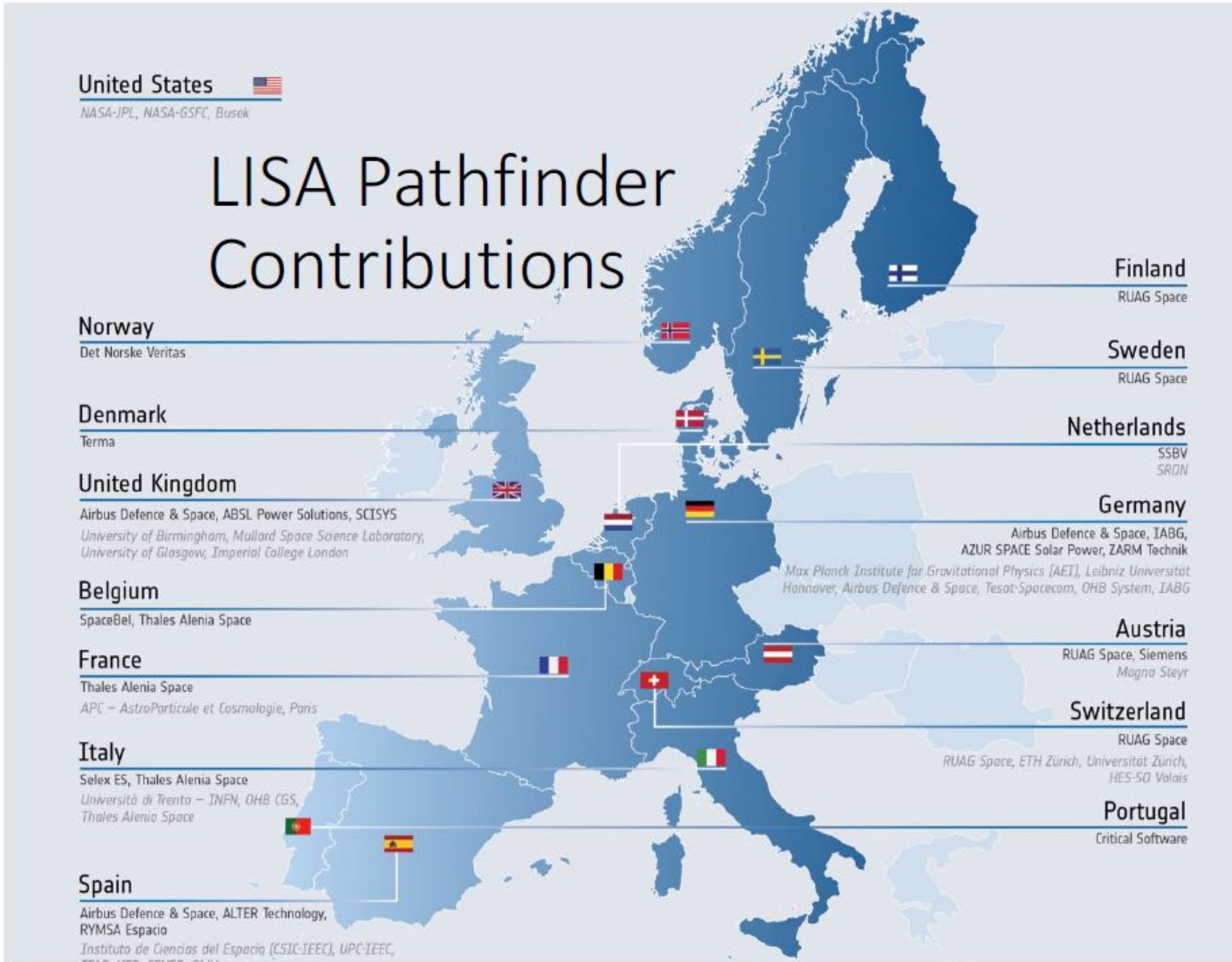
- possible more hostile spacecraft environment
- stray effects strictly due to single spacecraft configuration

The LTP

- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure to handle vacuum on ground
- Ultra high mechanical stability optical bench for the laser interferometer






United States
NASA-JPL, NASA-GSFC, Busek
LISA Pathfinder Contributions
Norway
Det Norske Veritas
Denmark
Terma
United Kingdom
Airbus Defence & Space, ABSL Power Solutions, SCISYS
University of Birmingham, Mullard Space Science Laboratory, University of Glasgow, Imperial College London
Belgium
SpaceBel, Thales Alenia Space
France
Thales Alenia Space
APC – AstroParticule et Cosmologie, Paris
Italy
Selex ES, Thales Alenia Space
Università di Trento – INFN, OHB CGS, Thales Alenia Space
Spain
Airbus Defence & Space, ALTER Technology, RYMSA Espacio
Instituto de Ciencias del Espacio (CSIC-IEEC), UPC-IEEC,
Finland
RUAG Space
Sweden
RUAG Space
Netherlands
SSBV
SRON
Germany
Airbus Defence & Space, IABG, AZUR SPACE Solar Power, ZARM Technik
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Austria
RUAG Space, Siemens
Magna Steyr
Switzerland
RUAG Space
RUAG Space, ETH Zürich, Universität Zürich, HES-SO Valais
Portugal
Critical Software

The real thing!!!

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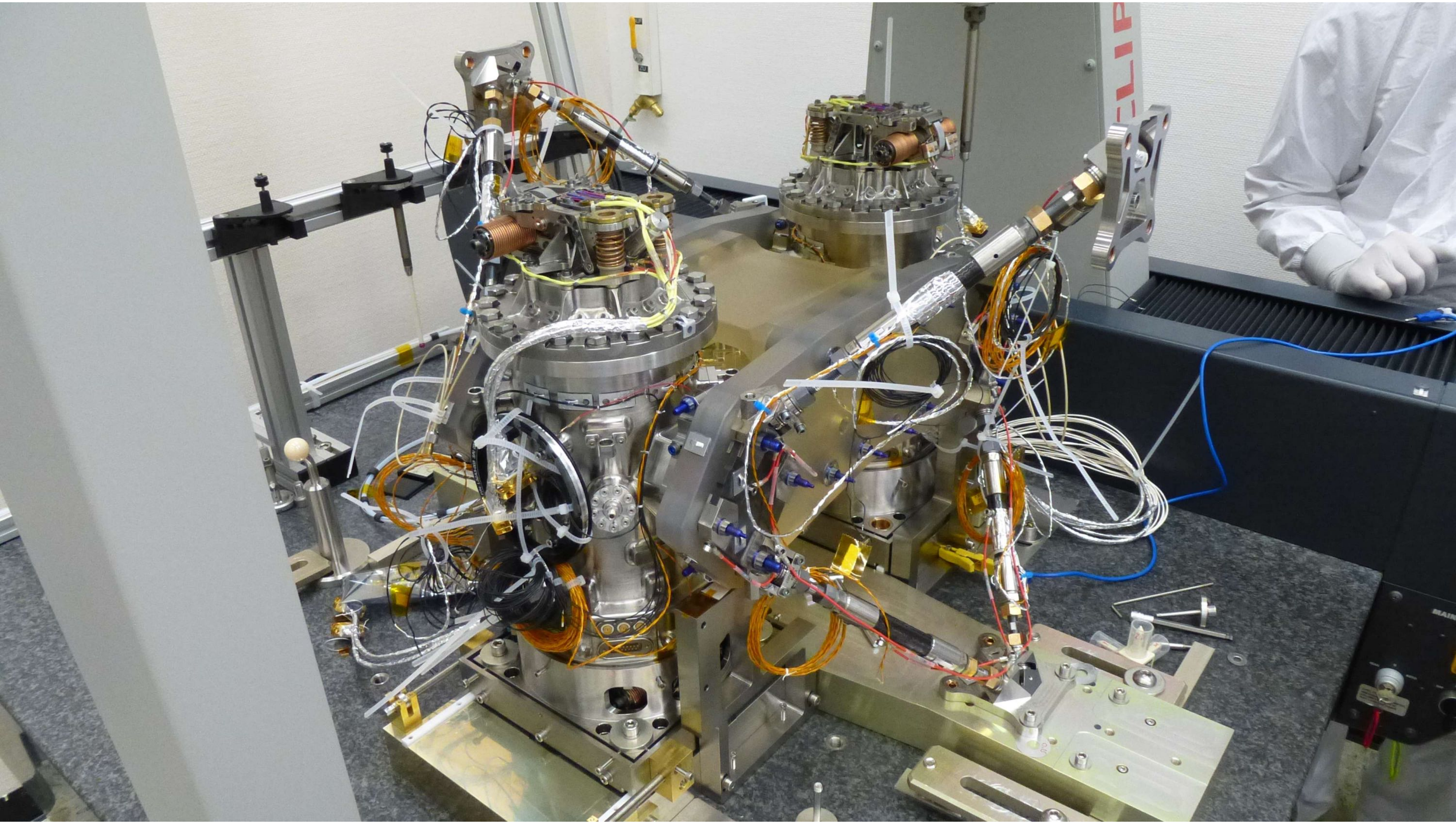
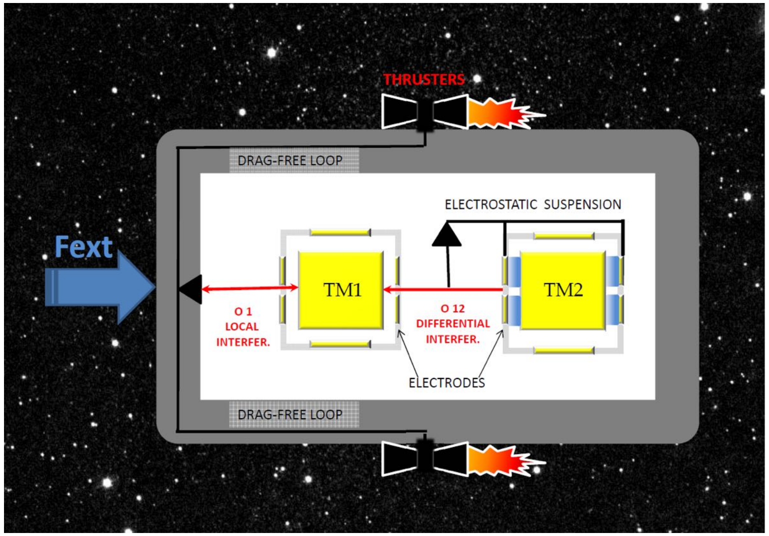


LISA Pathfinder as differential accelerometer



The satellite and TM2 are following TM1

$$o_1 = x_1 - x_{SC} + n_1$$

Nulled by the drag free loop

$$o_{12} = x_2 - x_1 + n_{12}$$

Nulled by the electrostatic suspension (below 1 mHz)

$$a_{TM_2} - a_{TM_1} = \frac{f_{TM_2}}{m} - \frac{f_{TM_1}}{m} + \left(\omega_2^2 - \omega_1^2\right)\left(x_1 - x_{SC}\right) + \omega_2^2\left(x_2 - x_1\right) - \frac{F_{ES}}{m}$$

$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_2^2 - \omega_1^2\right) o_1 + \omega_2^2 o_{12}$$
$$= \Delta g + \ddot{n}_{12} + \left(\omega_2^2 - \omega_1^2\right) n_1 + \omega_2^2 n_{12} + n_{F_{ES}}$$

Last published «best estimate» of LPF noise (pre-flight)

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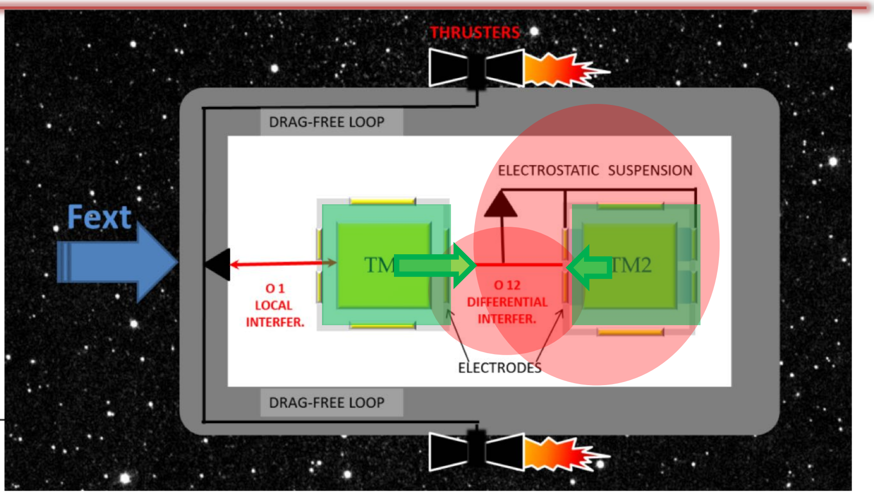
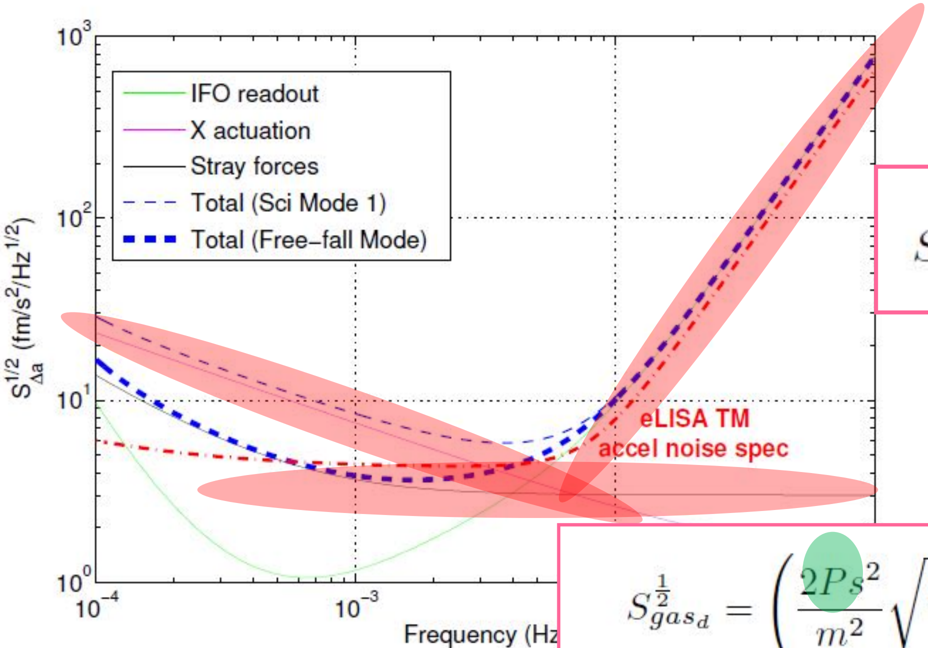
$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_2^2 - \omega_1^2\right) o_1 + \omega_2^2 o_{12}$$
$$= \Delta g + \ddot{n}_{12} + \left(\omega_2^2 - \omega_1^2\right) n_1 + \omega_2^2 n_{12} + n_{F_{ES}}$$

10th International LISA Symposium (LISAX)
Journal of Physics: Conference Series **610** (2015) 012005



$$S_{\frac{F_{ES}}{m}}^{\frac{1}{2}} \simeq \Delta g_{st}\, 2\, S_{\frac{\delta V}{V}}^{\frac{1}{2}}$$



$$S_{int}^{\frac{1}{2}} \simeq \omega^2 S_{o12}^{\frac{1}{2}}$$

$$S_{gas_d}^{\frac{1}{2}} = \left(\frac{2Ps^2}{m^2}\sqrt{\frac{512\, m_0 k_B T}{\pi}}\left(1 + \frac{\pi}{8}\right)\right)^{\frac{1}{2}}$$

Launch, Cruise, Commissioning and …Science Operations start

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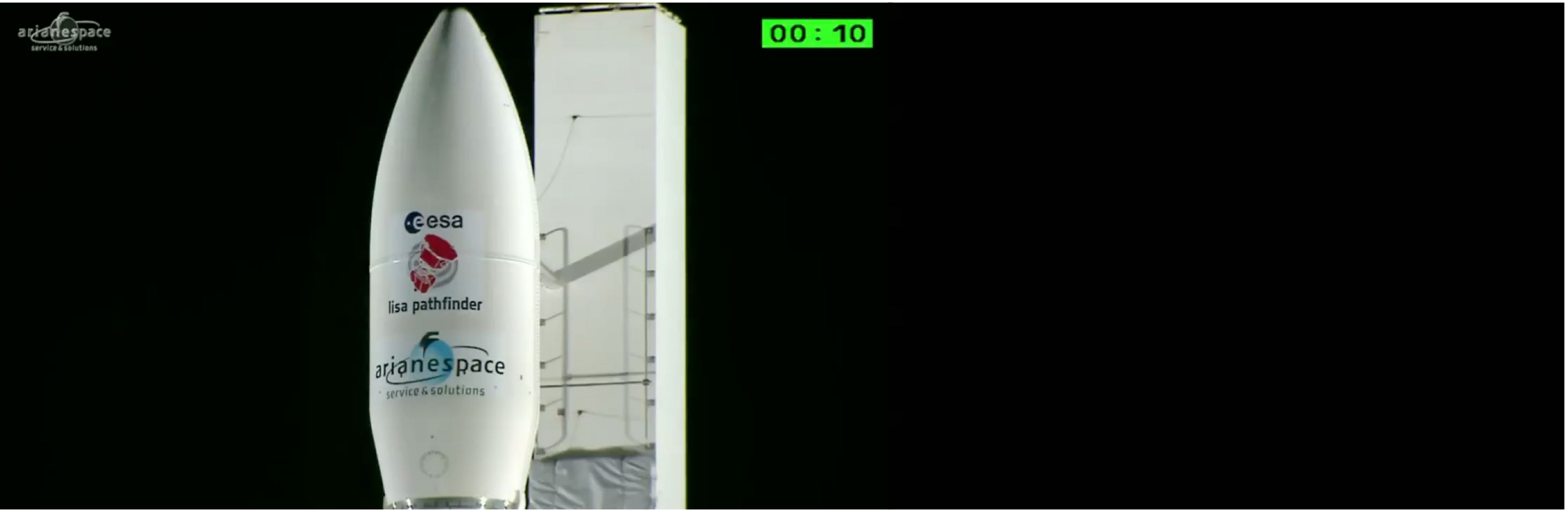


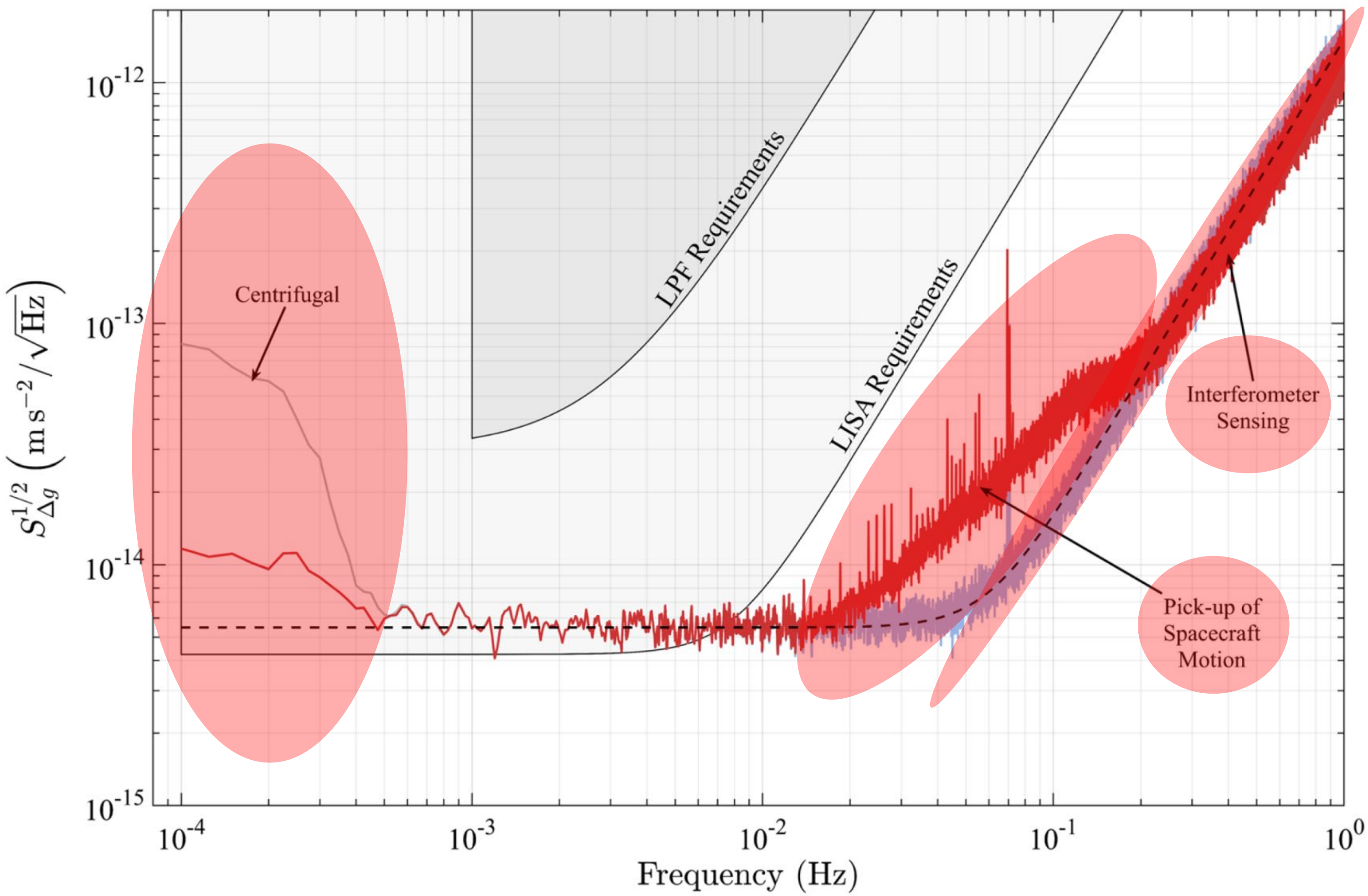
- LISA Pathfinder was launched on 3 December 2015 at 04:04UTC
- Transfer to Lagrange Point 1 (L1) took ~50 days
- 11 January Switch-on of LISA Technology Package
- 15 & 16 February Test Mass release → free floating test masses
- 1 March Start of Science Operations
- NASA DRS joint operations July-December 2016
- • 7 December 2016 mission extension began
- • Switched off in July 2017

First results from LISA Pathfinder

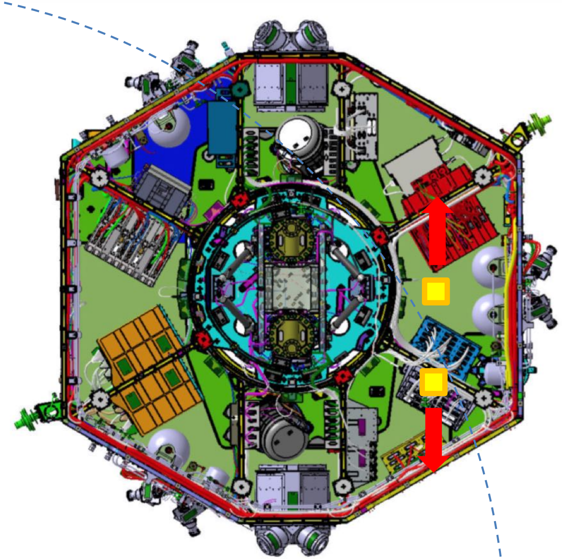
PRL 116, 231101 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

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

$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_2^2 - \omega_1^2\right) o_1 + \omega_2^2 o_{12} - g_\Omega$$
$$= \Delta g + \ddot{n}_{12} + \left(\omega_2^2 - \omega_1^2\right) n_1 + \omega_2^2 n_{12} + n_{F_{ES}} + n_{g\Omega}$$



Centrifugal force correction below 0.5 mHz



All measurements are performed wrt SC reference frame
that is a rotating frame

$$\vec{\Omega}_{SC} = \vec{\Omega}_{qs} + \vec{\Omega}_{n}$$

few degrees per day, needed to keep the communication antenna pointed toward the Earth

angular velocity jitter arises from the noisy star trackers that drive the SC attitude controlle

noisy centrifugal force appears

$$g_{\Omega} = \left(\vec{\Omega}_{SC} \times (\vec{\Omega}_{SC} \times \vec{r}_{TMs})\right) \cdot \vec{e}_{x}$$

$$\propto \Omega_{qs}\,\Omega_{n}$$

$\vec{\Omega}_{qs}$ estimate from Star Trackers

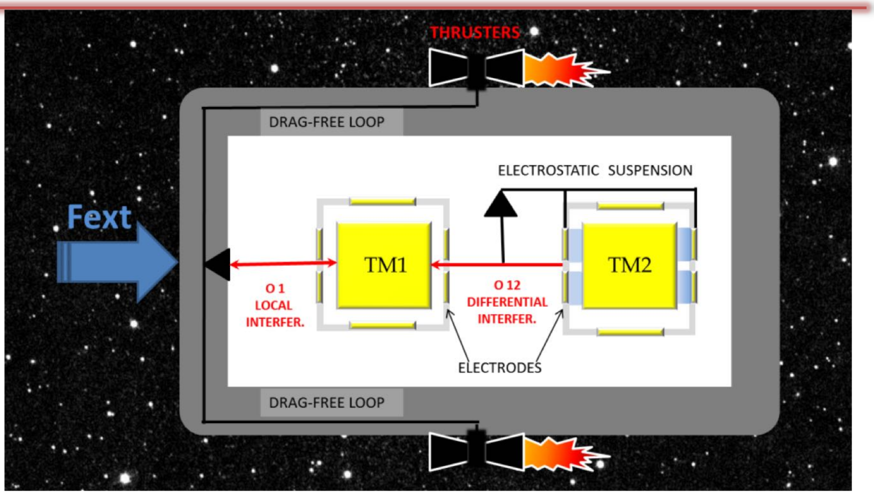
$\vec{\Omega}_{n}$ estimate by integrating the torque applied to TMs to hold them with fixed orientation wrt SC

➡ we generate the time series of the centrifugal force.

Not relevant for LISA

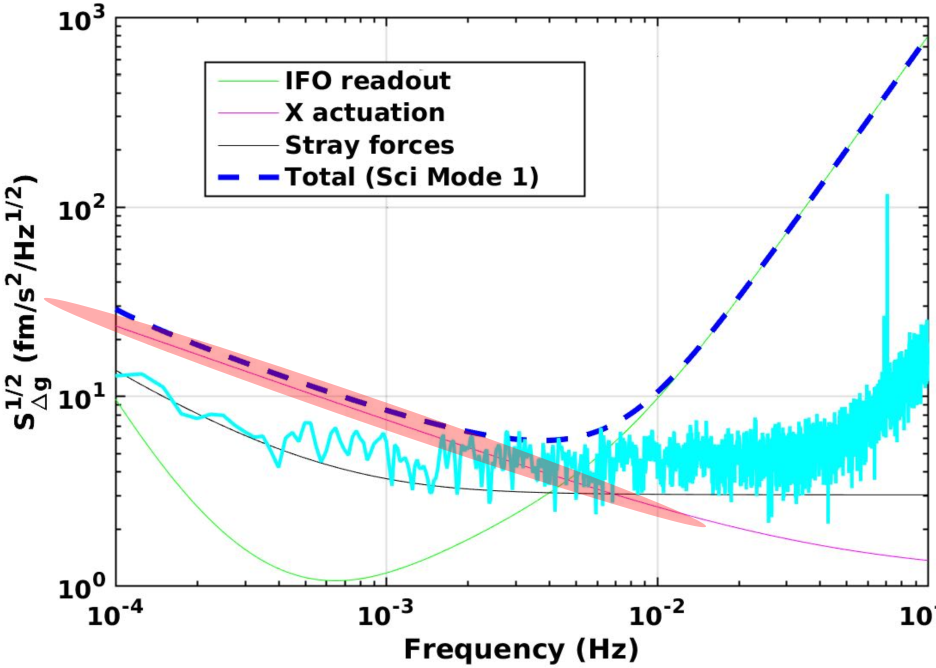
Compare with the pre-flight noise bydget

$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_2^2 - \omega_1^2\right) o_1 + \omega_2^2 o_{12} - g_\Omega$$
$$= \Delta g + \ddot{n}_{12} + \left(\omega_2^2 - \omega_1^2\right) n_1 + \omega_2^2 n_{12} + n_{F_{ES}} + n_{g\Omega}$$



$$S^{\frac{1}{2}}_{\frac{F_{ES}}{m}} \simeq \Delta g_{st}\, 2\, S^{\frac{1}{2}}_{\frac{\delta V}{V}}$$

Δg_{st} < 20 nm/s^2
On-flight



lower force authority
→lower actuation noise
And at 1mHz is now neglibile

Reducing Δg_{st} by gravitational balance

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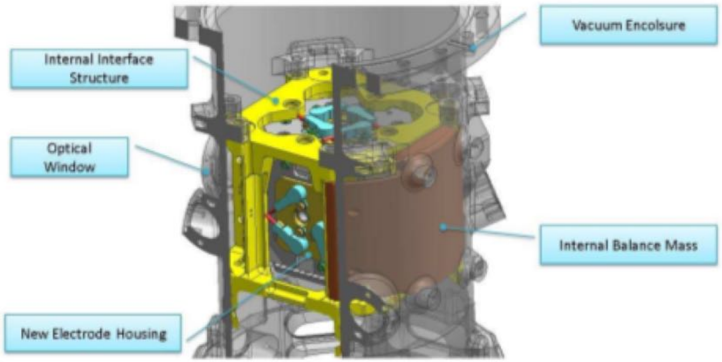
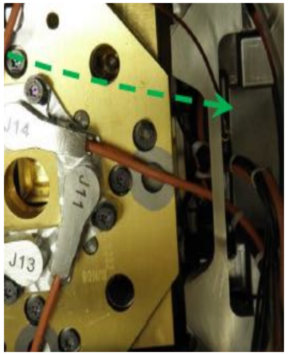
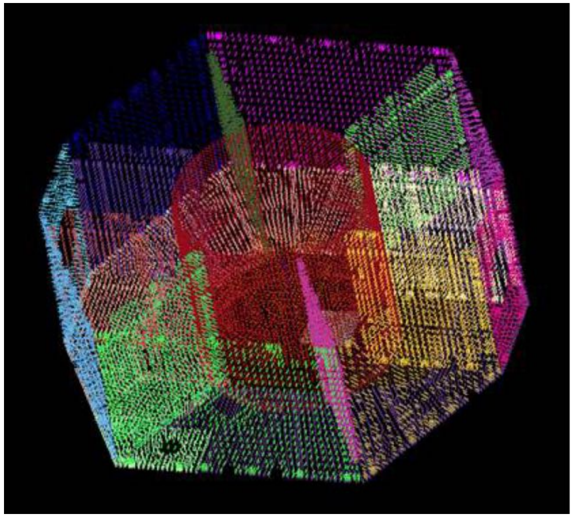
By means of a protocol based on:

- **measurements of the "as-built" position and the mass of all parts (>10000)**
- **finite element calculation tool**

Updated at different stages of hardware construction
...and correct with balance masses



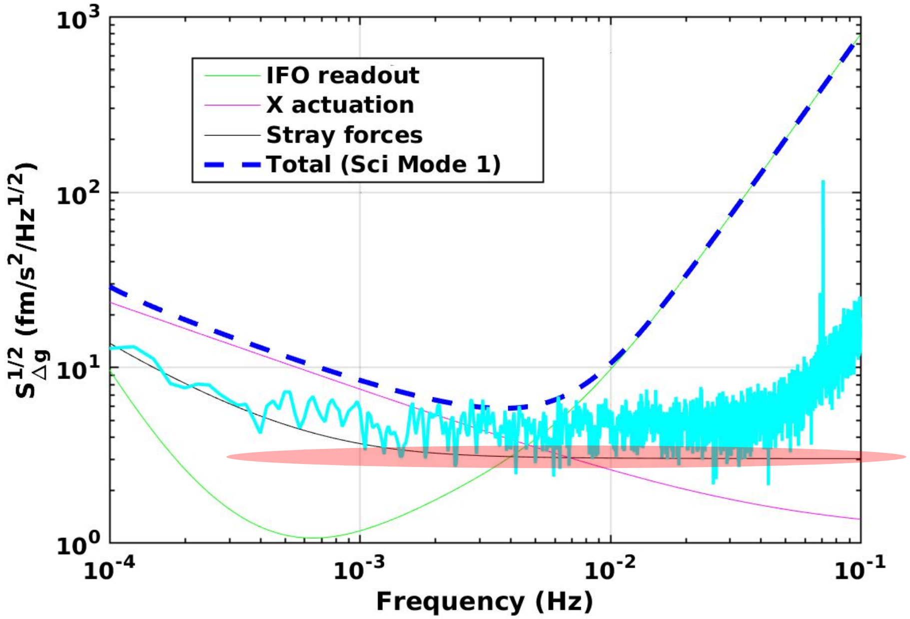


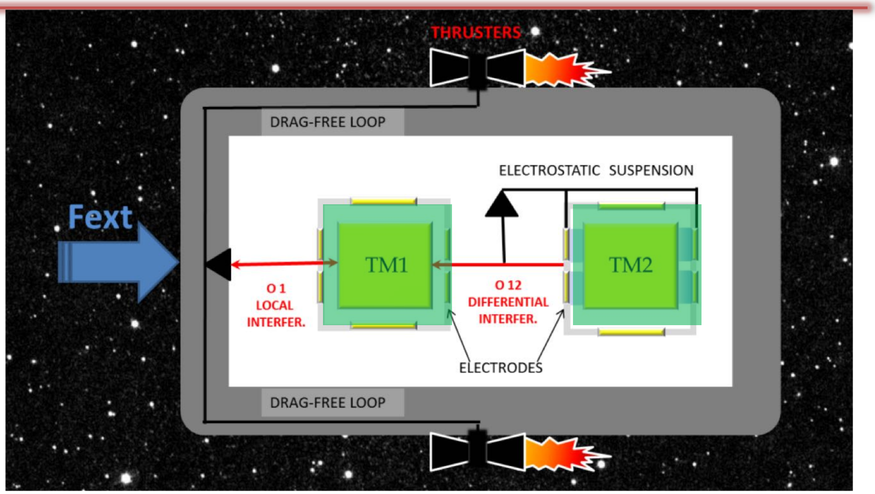


Spacecraft finite element model

Compare with the pre-flight noise budget

$$\Delta\hat{g} \equiv \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_2^2 - \omega_1^2\right) o_1 + \omega_2^2 o_{12}$$
$$= \Delta g + \ddot{n}_{12} + \left(\omega_2^2 - \omega_1^2\right) n_1 + \omega_2^2 n_{12} + n_{F_{ES}}$$





Pre-flight estimation: 2 μPa

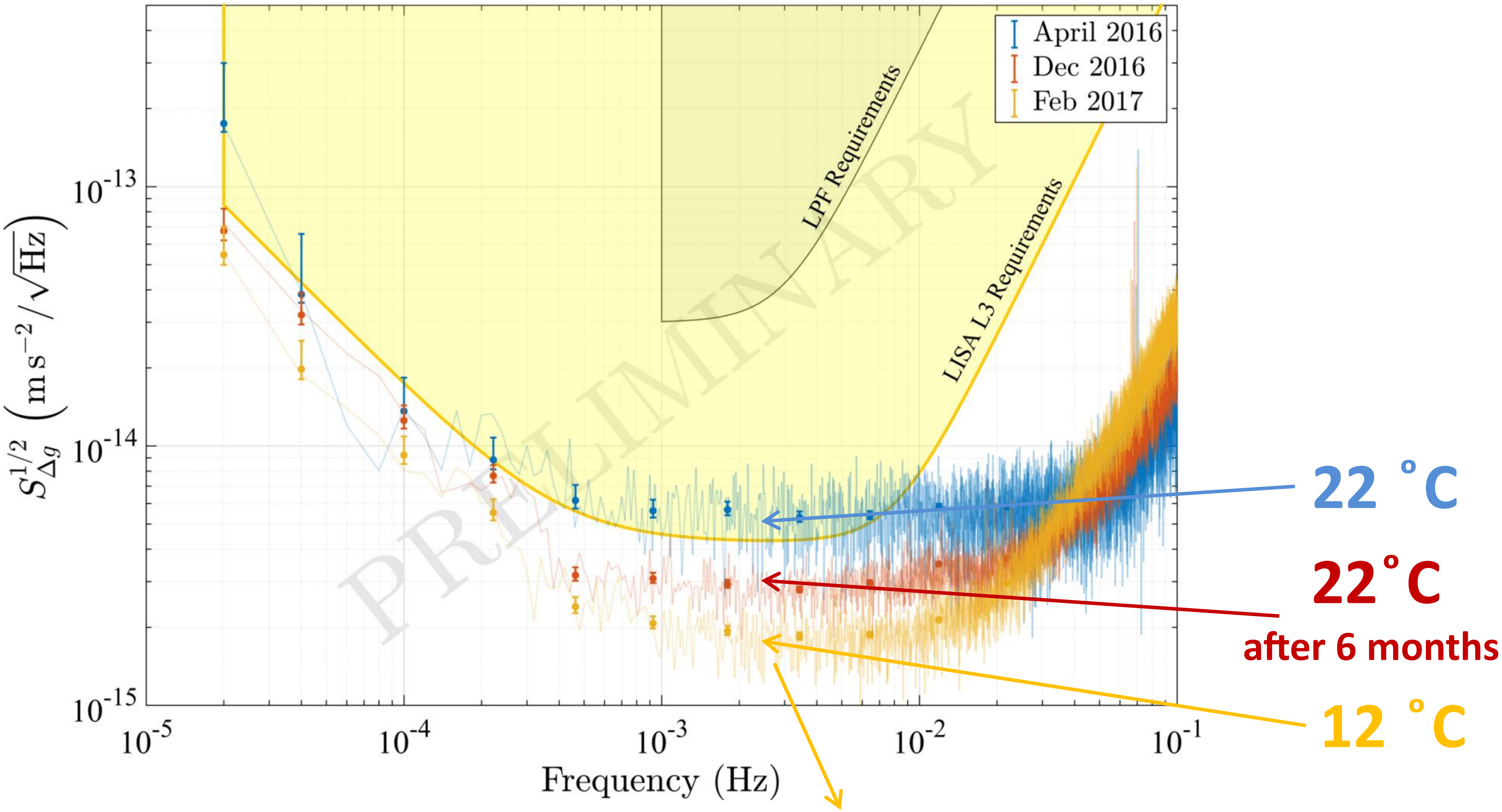
The noise floor In flight could be explained by ~10 μPa of H_2O decreasing in time

Brownian noise due to residual gas pressure

$$S_{gas_d}^{\frac{1}{2}} = \left(\frac{2Ps^2}{m^2}\sqrt{\frac{512\, m_0 k_B T}{\pi}}\left(1+\frac{\pi}{8}\right)\right)^{\frac{1}{2}}$$

LISA PF Noise curve progression

- Brownian noise reduces in time and by decreasing the temperature → decrease the outgassing rates → decrease in pressure around the test masses



Brownian noise of about 1 μPa residual gas of H_2O

Final published results: February 2018

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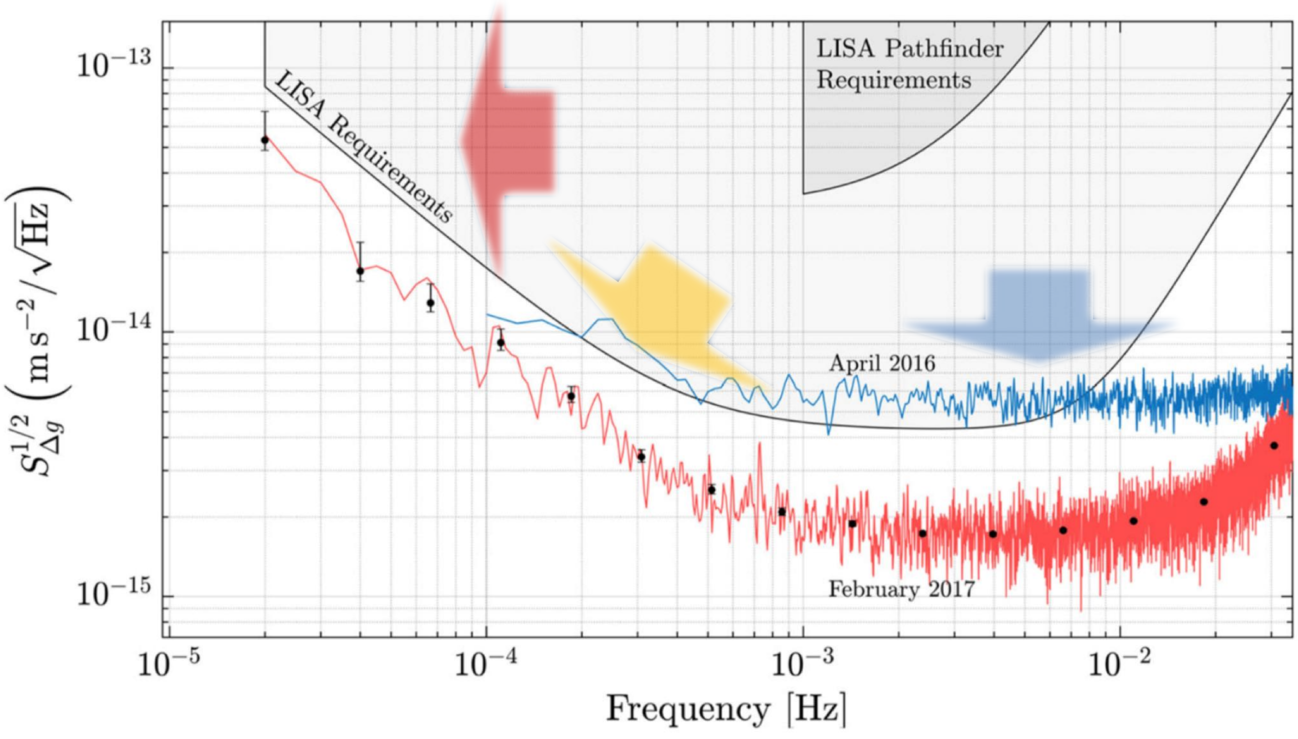
- Residual gas Brownian noise
- Improved correction of non-inertial effects (centrifugal+Euler force)
- Lower actuation + Better calibration of the electrostatic force actuation
- (digitization error correction)
- long noise measurement runs allowed the measurement of noise down to 20 µHz
- (glitch events were detected and fitted away)

PHYSICAL REVIEW LETTERS **120,** 061101 (2018)

Editors' Suggestion Featured in Physics

Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz



Current noise budget

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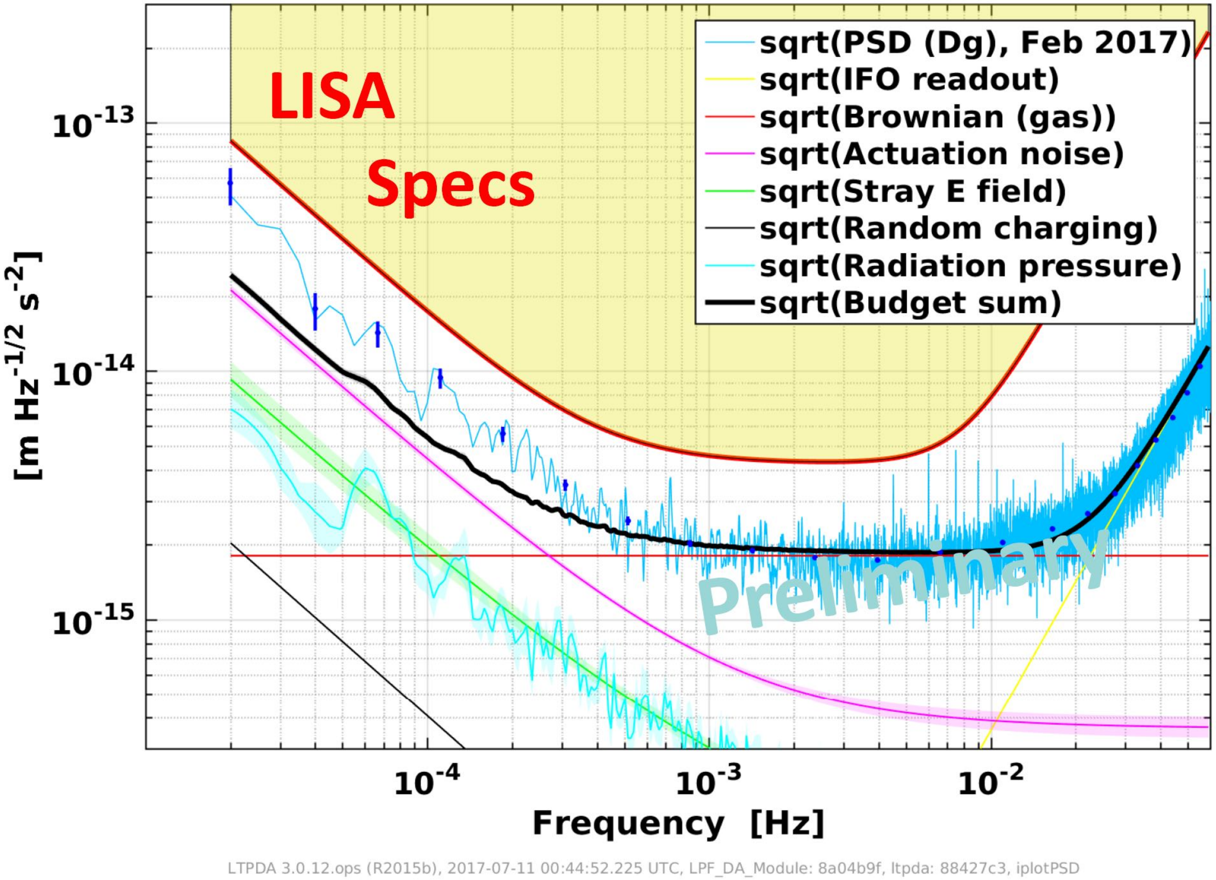
LPF acceleration noise below LISA requirement at all frequencies



BUT noise budget (conservative) explains less than half noise (power) at low frequencies

Further stray forces investigations for LISA

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Possible noise sources at very low frequency:

- Low frequency magnetic fluctuations.
- Fluctuations of GRS-TM relative position with T.
- Spontaneous outgassing.
- Small-scale surface potential fluctuations.
- Pressure fluctuations in the tanks.
- Outgassing of the spacecraft.

Possible sources of glitches:

- No torque, environmental, diagnostic coincidences. No change Δg DC.
- Thermo-mechanical liberated gas outburst requires 10 nPa on top of μPa.
- Possibly testable on ground with torsion pendulum.

Free fall performance consolidation

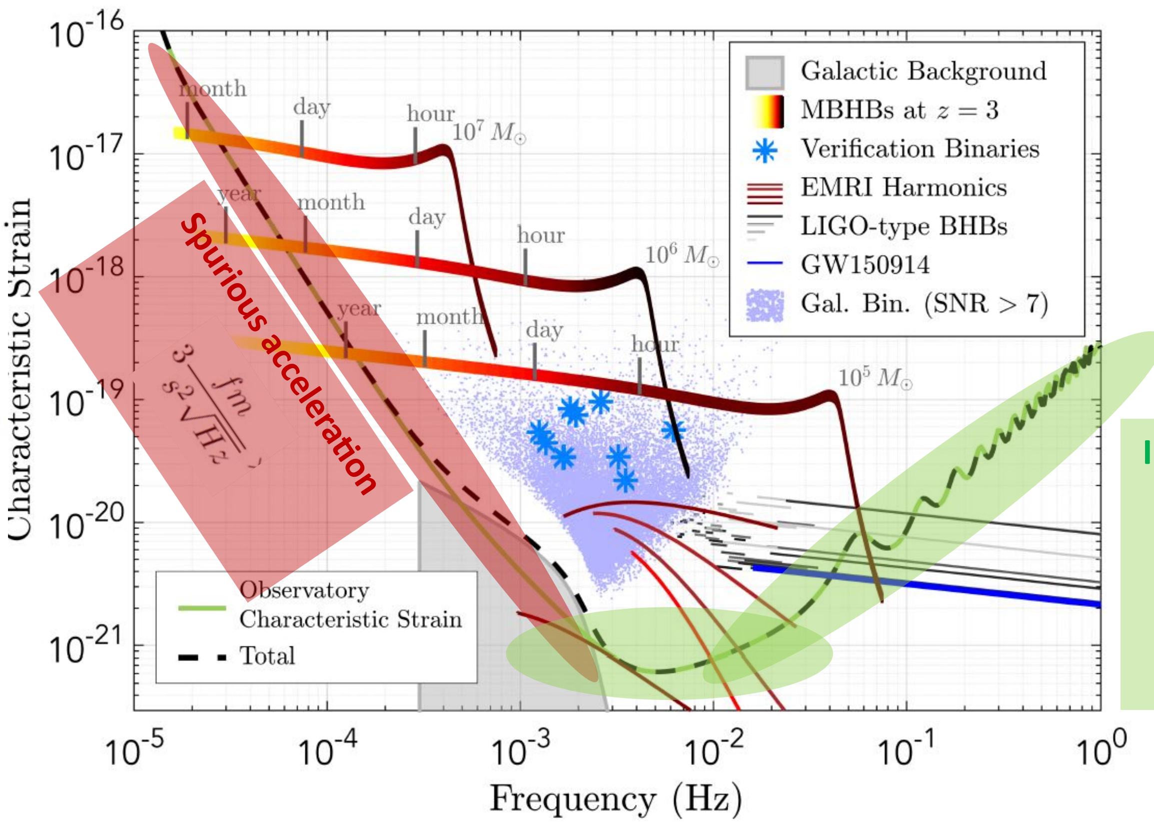
- Gravitational Reference Sensor physical properties and their on-ground verification strategy need to be consolidated in order to guarantee the same level of performance also on the final observatory.

- Measurement, calibration, and mitigation of some known force sources will be required also in LISA → transfer of LISA Pathfinder stray accelerations measurement and suppression strategies to the LISA mission design .

LISA performances assessment

Free-fall

Credit: ESA/ATG medialab

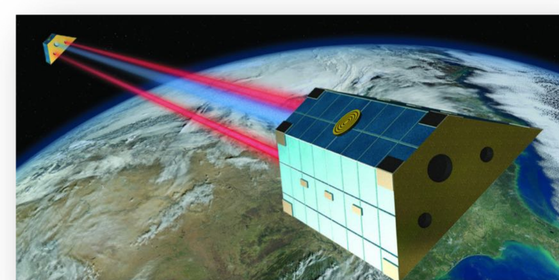


Interferometer +shot noise 10 pm/sqrt(Hz)

armlength response 2.5 mio km

Laser interferometry

- for the **drag-free control** has been developed and tested **in LISA PF**
- **Ground based demonstrator**
- **Inter-spacecraft laser interferometry**: **Laser Ranging Interferometer** will be demonstrated on **GRACE Follow-On mission** using elements inherited from LISA technology development efforts.
- GRACE Follow-On is a US-German joint project
- **Targeted to launch May 22, 2018 !!!!**



LISA Instrument

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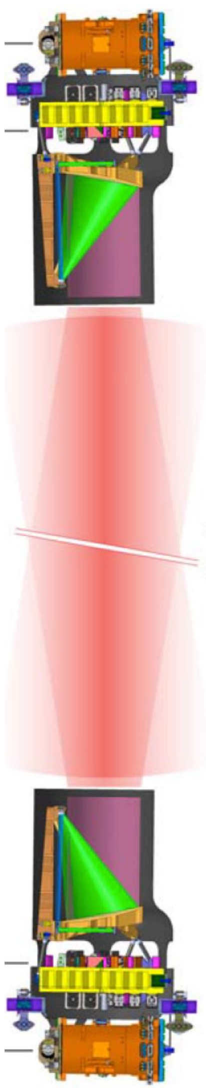
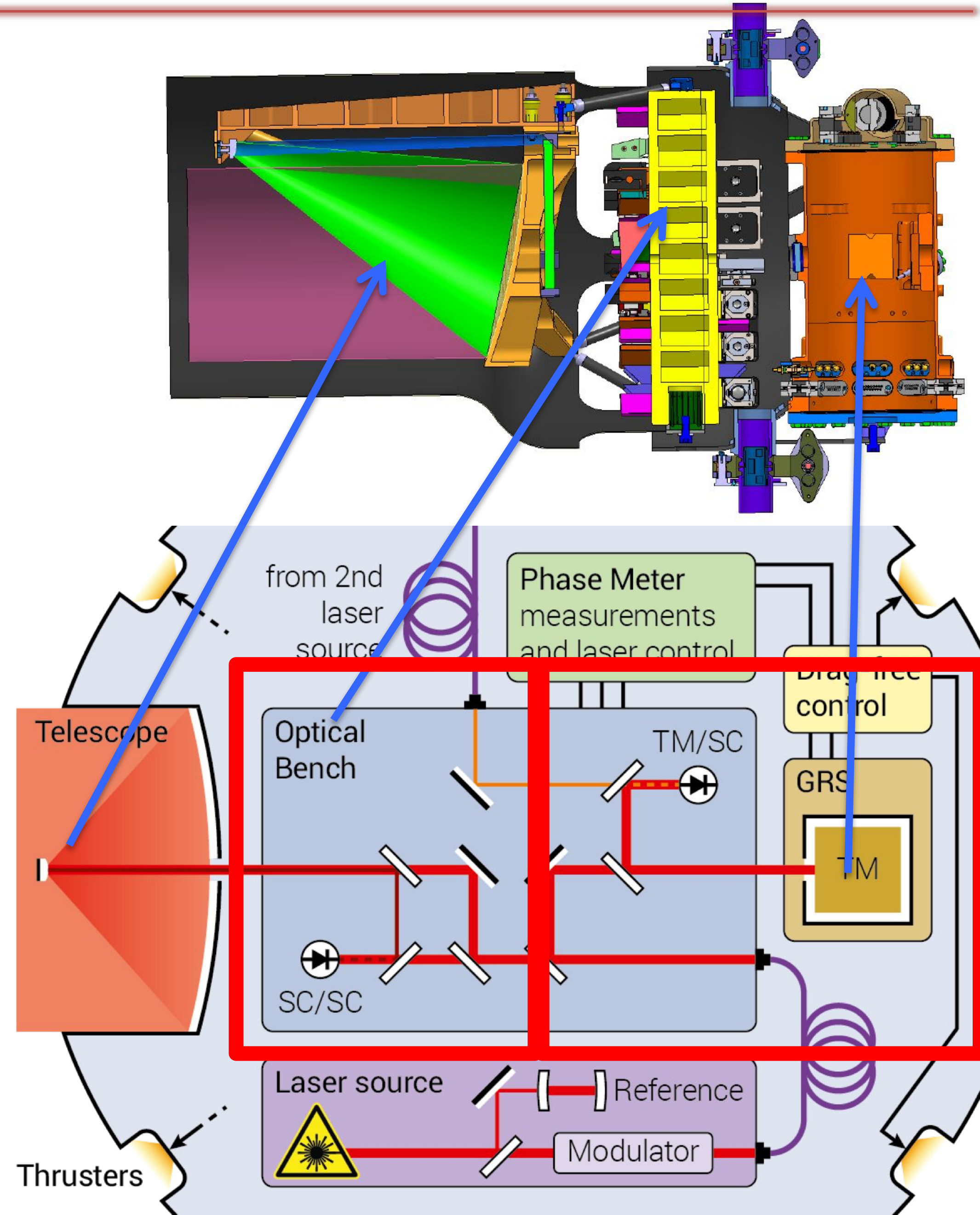


- The Gravitational Reference Sensor with the test-mass
- The Optical Bench with:
  - Local interferometer
  - Spacecraft to spacecraft interferometer
- Telescope for the spacecraft to spacecraft interferometer



LISA long arm interferometry challenges

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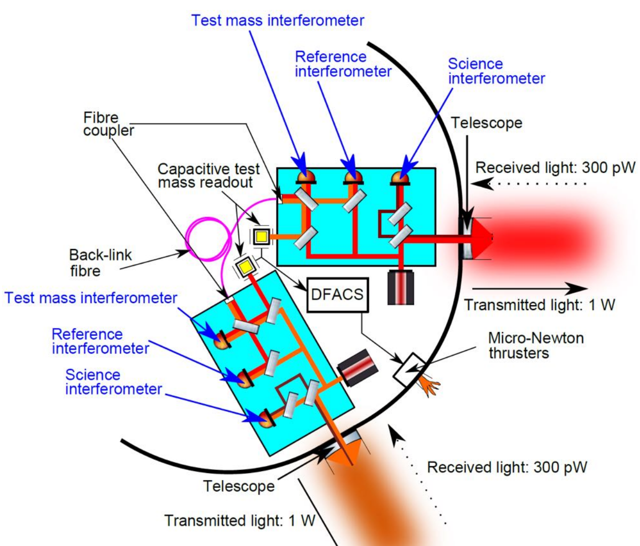
Precision million km spacecraft to spacecraft precision ranging

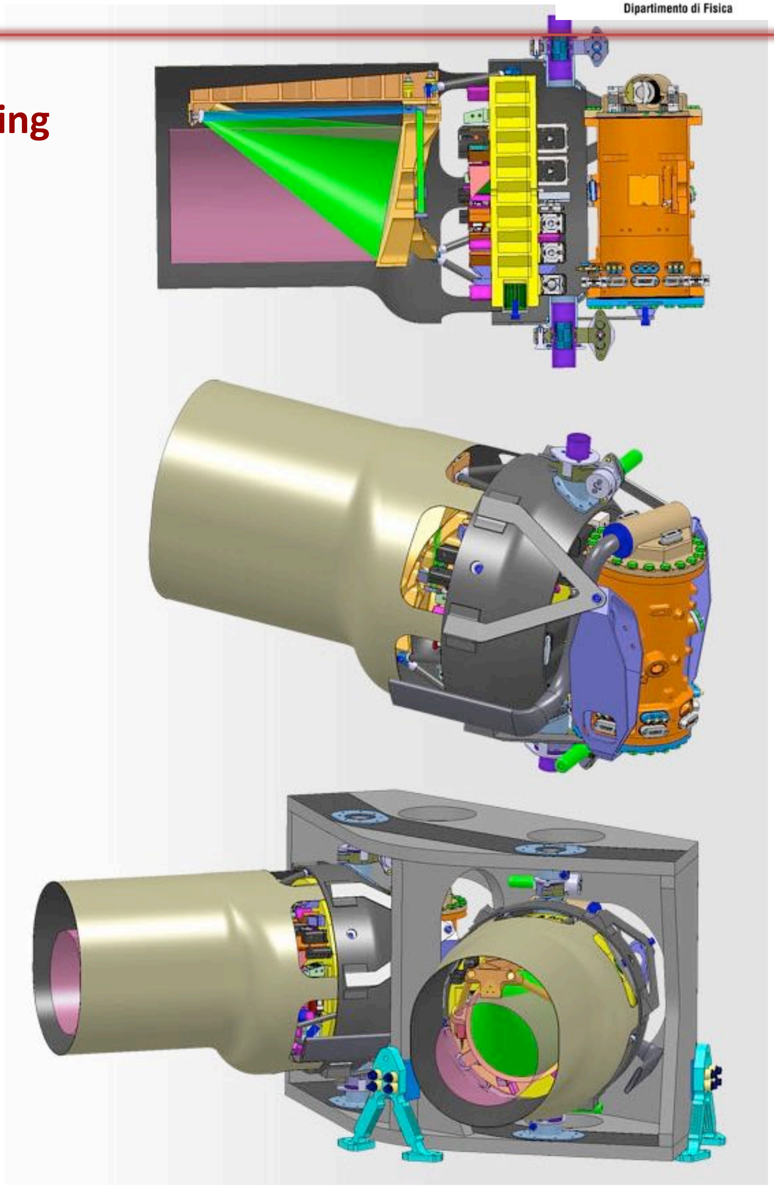
High stability telescopes
High accuracy phase-meter and frequency distribution
High accuracy frequency stabilization (incl. TDI)

Telescope   Pointing

LISA moving optical subassemblies (MOSAs): telescope+ optical bench + GRS



© M. Otto, PhD thesis (2016)



courtesy of Airbus D&S

LISA Mission Schedule

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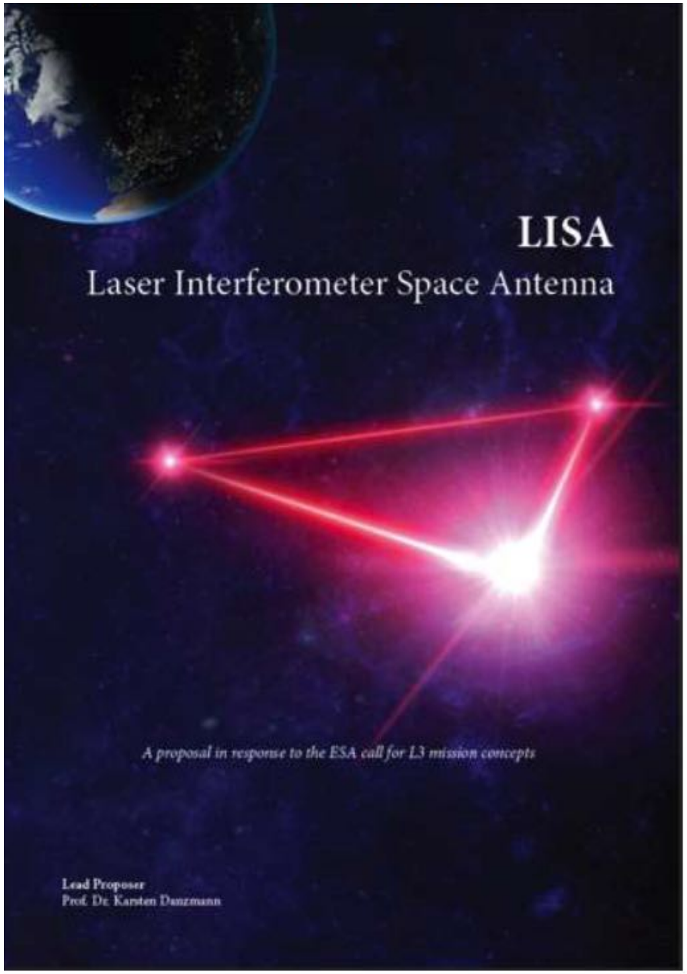
- At the end of 2016: Call for mission project addressing the science of the “Gravitational Universe” was issued by ESA
- An international collaboration of scientists called “ LISA Consortium” submitted a proposal in January 2017
- Beginning 2017 ESA started CDF study
- Mission selection in June 2017
- Mission Definition Review in Nov 2017
- Phase A , industrial implementation studies 2018-2020
- Mission adoption 2020-2022
- Launch 2030-2034

Parallel competitive industrial studies for mission design just startet !

THALES-ALENIA (Torino)

ASTRIUM



The LISA Consortium:
12 EU Member States +US

www.lisamission.org/proposal/LISA.pdf

LISA Consortium

Led by K.Danzmann

In parallel with the mission study, the Consortium will:

support the definition of the payload, the requirements and the performances.

support ESA System Engineering Office

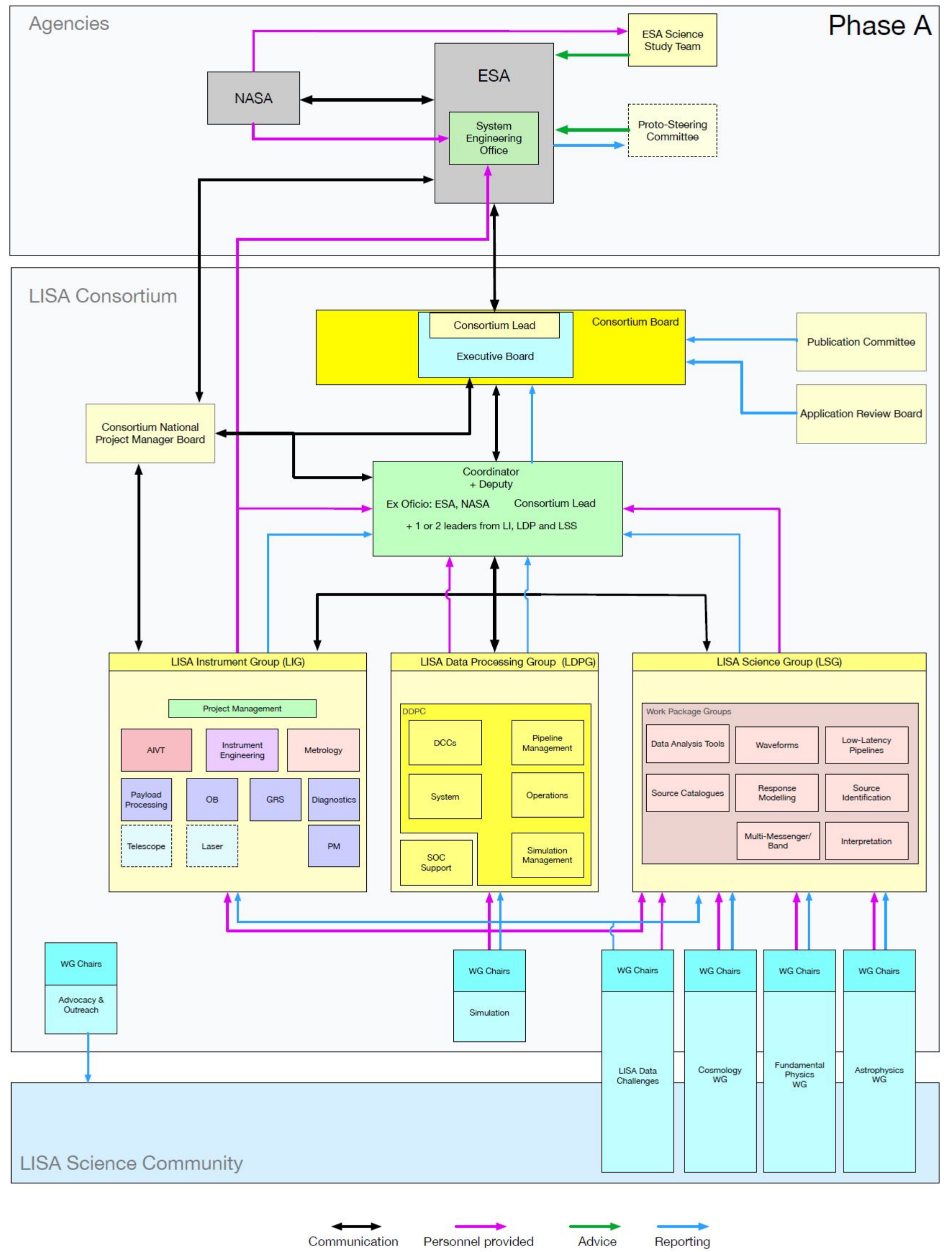
deliver the integrated and tested science instrument at the heart of the payload, lasers and telescopes, will be procured by ESA or provided by NASA

Active Science Working Groups

- Astrophysics;
- Cosmology;
- Fundamental Physics;
- LISA Data Challenges;
- Simulation;
- Advocacy and Outreach

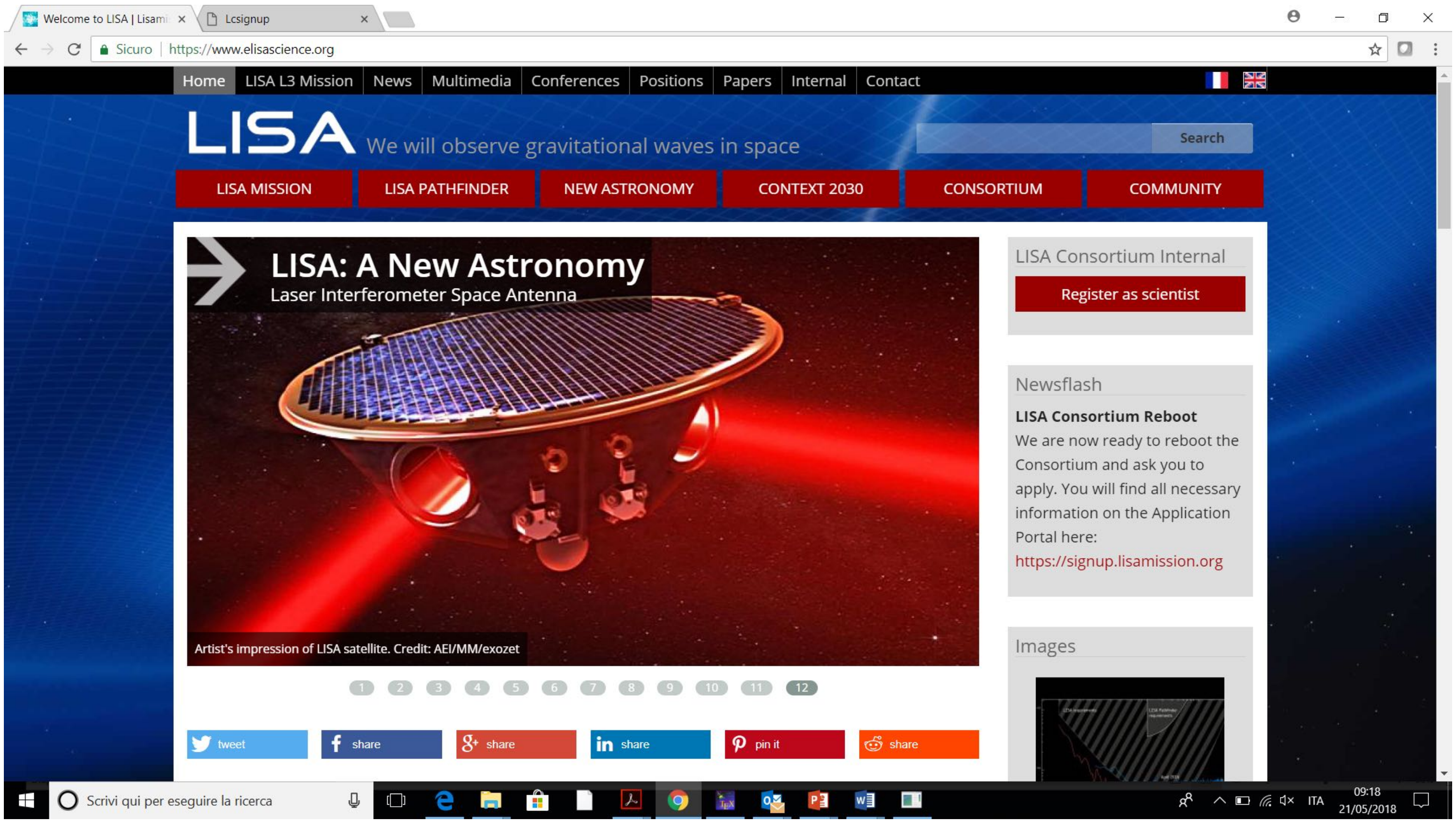
interface with the science community interested in LISA

LISA Organigram in PHASE A



Thank you !!!

https://www.elisascience.org/

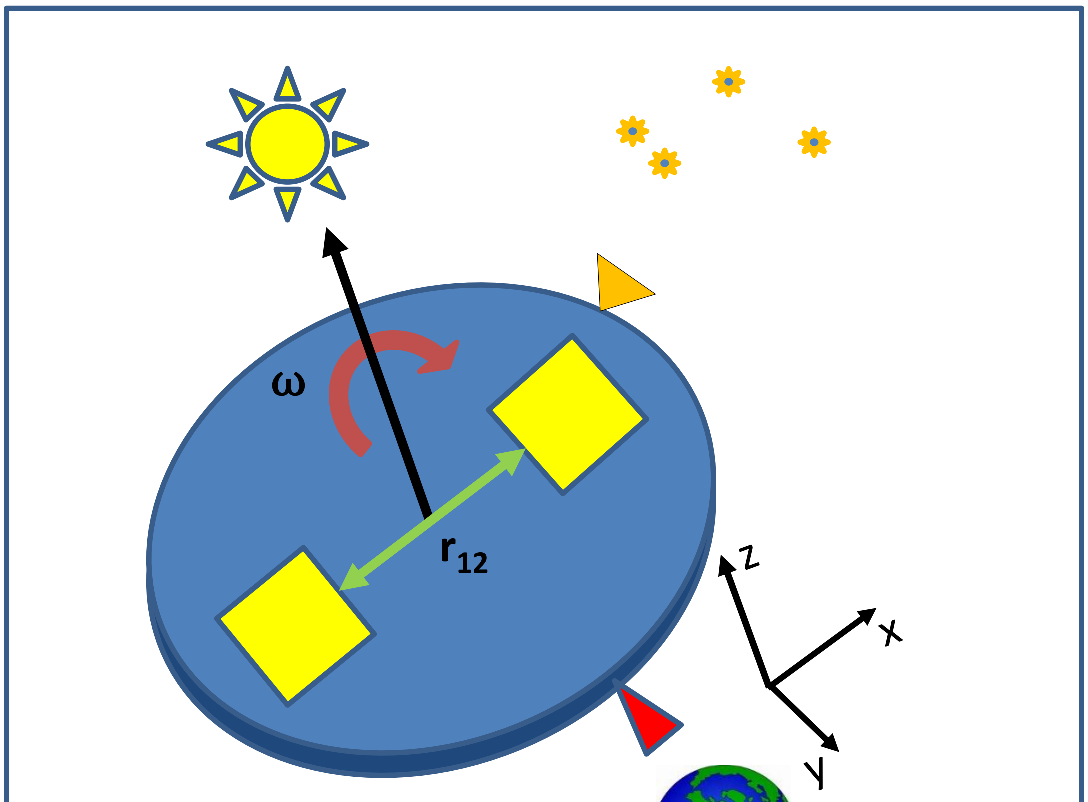


EXTRA SLIDES

At very low frequencies the spacecraft is a rotating reference frame – Part I

$$\Delta g(t) = a_{12} - \lambda f_{2,cmd} + \omega_2^2 o_{12} + \Delta\omega^2 o_1 - \vec{\omega}\times(\vec{\omega}\times\vec{r_{12}})\cdot\hat{\imath} - (\vec{\omega}\times\vec{v_{12}})\cdot\hat{\imath}$$

Centrifugal Coriolis



- Autonomous Star Trackers (AST) keep the attitude of the spacecfraft w/r fixed stars and Sun
- $\Omega \sim 10^{-7}$ rad s^{-1}/sqrt(Hz) @0.1 mHz
- $r_{12} \sim 38$ cm

Courtesy of D. Vetrugno

At very low frequencies the spacecraft is a rotating reference frame – Part II

$$\Delta g(t) = a_{12} - \lambda f_{2,cmd} + \omega_2^2 o_{12} + \Delta\omega^2 o_1 \; +$$

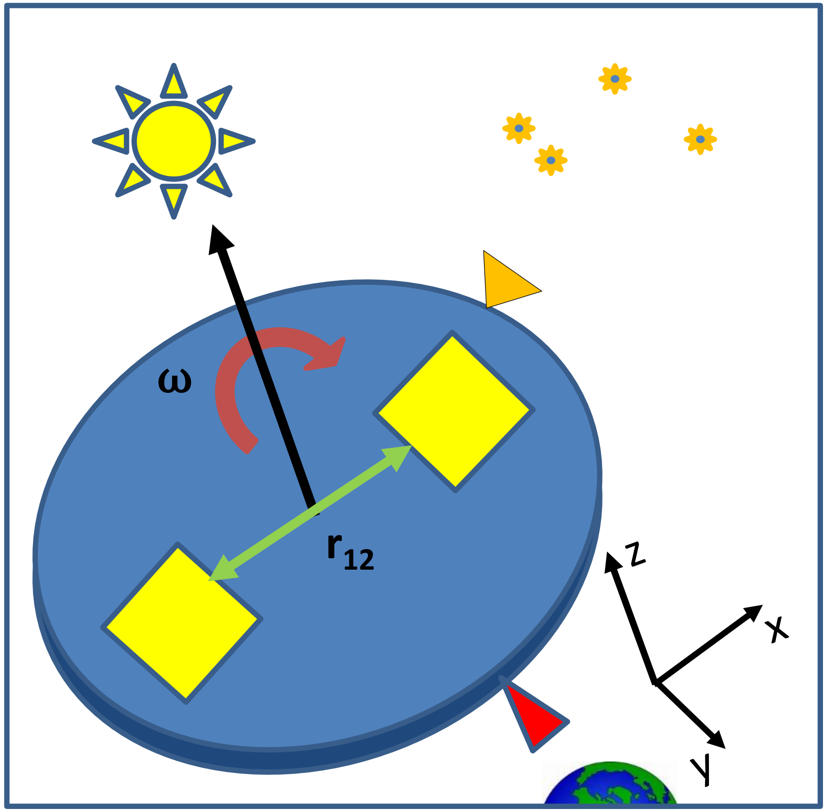
$-\vec{\omega}\times(\vec{\omega}\times\overrightarrow{r_{12}})\cdot\hat{\imath}$ Centrifugal

~~$-(\vec{\omega}\times\overrightarrow{v_{12}})\cdot\hat{\imath}$ Coriolis~~

$-(\dot{\vec{\omega}}\times\overrightarrow{r_{12}})\cdot\hat{\imath}$ Euler

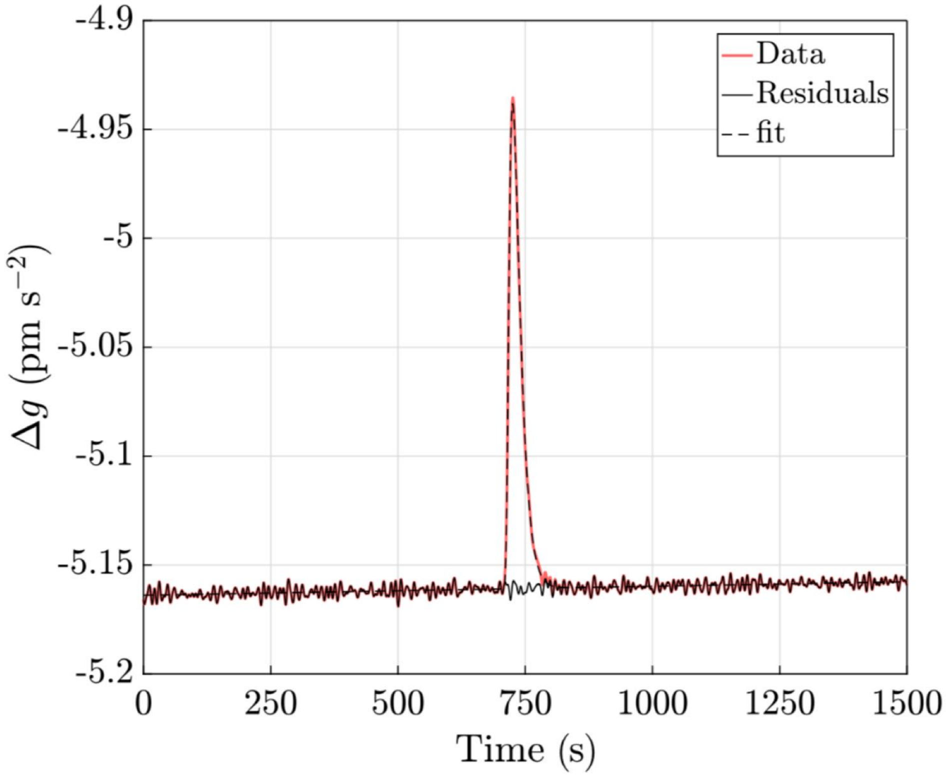
$\dot{\Omega}\sim 10^{-10}$ - 10^{-11} rad s^{-2}/sqrt(Hz) @ 0.1 mHz

Parameter	Estimated ±σ before 19 June 2016	from 19 to 25 June 2016	after 25 June 2016
$\delta\phi$ (mrad)	-0.47 ± 0.03	-0.40 ± 0.03	-0.39 ± 0.02
$\delta\eta$ (mrad)	-0.066 ± 0.007	-0.032 ± 0.003	-0.137 ± 0.003



Courtesy of D. Vetrugno

Glitches in the data were detected



Statistics and characteristics

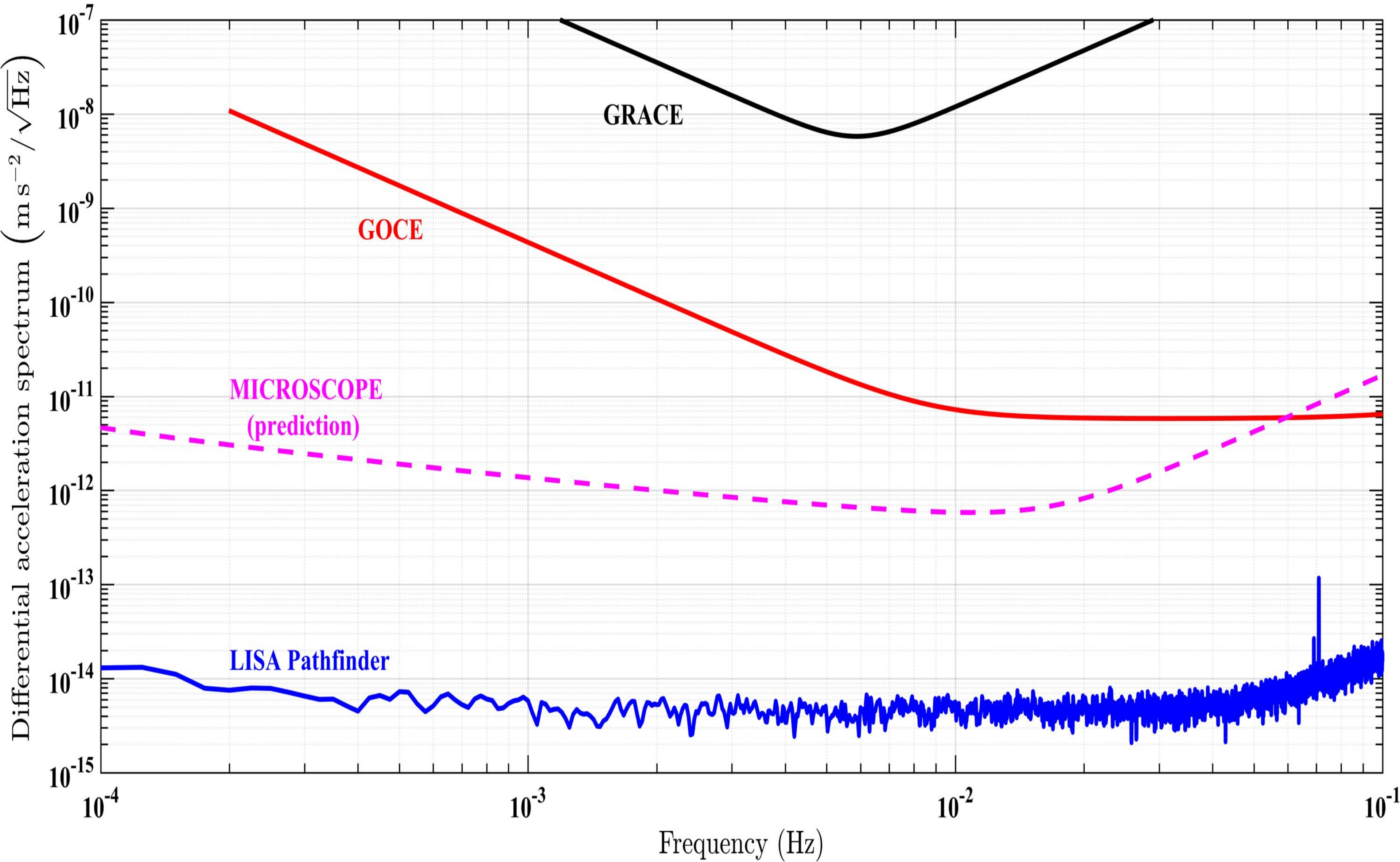
- Observationally indistinguishable from quasi impulse on TMs.
- Duration: few seconds – hours (rare).
- Arrival: 0.8/day (Poissonian).
- Impulse: about 10 pm/s.
- Model: double exponential, single amplitude.

Da Gerhard

New features compared to LPF

- Armlength 2..3 Mio km
  → use of telescopes, ≈100 pW received power
- Velocity ±10 m/s → Doppler ± 10 MHz
  → heterodyne inteferometry at 5...25 MHz
- Armlength variation ±1% = 20000...30000 km,
  → Time Delay Interferometry to cancel frequency noise
- Need for very stable sampling clocks, passively synchronized betwen 3 spacecraft
  → clock noise transfer with GHz sidebands on laser beams
- Angle variations ±1.5°
  → Pointing mechanism, two options
- Point-Ahead Angle ±6 μrad
  → Point Ahead Angle Actuator Mechanism (PAAM)
- Absolute ranging of armlengths and data transfer between the arms
  → additional weak spread spectrum code modulation on laser beams

Sub-femto-g differential accelerometry: orders of magnitude improvement in the field of experimental gravitation



LISA Science Objectives

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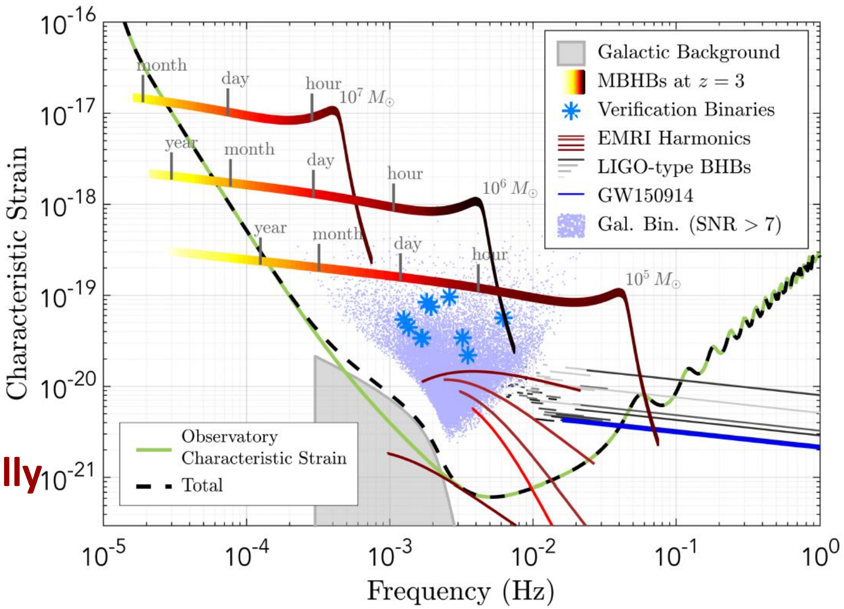
- SO 1 Study the formation and evolution of compact binary stars in the Milky Way Galaxy
- SO 2 Trace the origin, growth and merger history of massive black holes across cosmic ages
- SO 3 Probe the dynamics of dense nuclear clusters using extreme mass-ratio inspirals (EMRIs)
- SO 4 Understand the astrophysics of stellar origin black holes
- SO 5 Explore the fundamental nature of gravity and black holes
- SO 6 Probe the rate of expansion of the Universe
- SO 7 Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
- SO 8 Search for GW bursts and unforeseen sources

LISA: a high resolution, deep Universe observatory

Exploring redshifts larger than z 20
systems of blackholes with masses ranging from a few M⨀ to 108M⨀.
Test the General-Relativistic nature of black holes through detailed study of the amplitude and phase of the waveforms
The LISA mission will scan the entire sky as it follows behind the Earth in its orbit, obtaining polarisations of the Gravitational Waves ,
and will measure source parameters with astrophysically relevant sensitivity in a band from below 10−4 Hz to above 10−1 Hz.



LISA Pathfinder pre-flight performance budget

lisa pathfinder

From laboratory experiments to LISA Pathfinder:

a(

Table 2. Leading sources of differential force-per-unit-mass disturbances and their PSD values at 1 mHz.

Source	PSD (fm s^{-2} $Hz^{-1/2}$)	Estimated from
Actuation, *x*-axis	7.5 (0.8)[a]	Measurement of flight-model electronics stability
Brownian	7.2	Measurement with torsion pendulum
Magnetics	2.8	Measurement of magnetic field stability
Stray voltages	1.1	Upper limit from the torsion pendulum test campaign
Laser radiation pressure	0.7	Measurement of laser power stability
Force from dynamics of other DoF	0.4	From simulated dynamics of DoF other than x, and estimated worst-case values of $\overleftrightarrow{\delta \mathcal{D}}$ and $\overleftrightarrow{\delta \mathcal{C}}$
Thermal gradient effects	0.4	Upper limit from the torsion pendulum test campaign
Self-gravity noise	0.3	Upper limit from thermo-elastic stability simulations
Noisy charge	0.1	Upper limit from the charge simulation and measured voltage balance
Coupling to SC motion via force gradients	0.1	From the estimation of stiffness and simulated SC jitter
Total	10.9 (7.9)[a]	Root square sum

[a] The values within parentheses refer to the free-flight mode. See the text for explanation.

Table 3. Leading sources of optical metrology disturbances, and their PSD values at 30 mHz.

Source	PSD (pm $Hz^{-1/2}$)	Remarks
Phase noise	4	End-to end measurement on the ground, including transmission through optical windows
Pick-up of motion along degrees of freedom different from x	1.6	Analysis based on the simulation of imperfections and the measurement of alignments of the optical bench
Total	4.3	Root square sum