



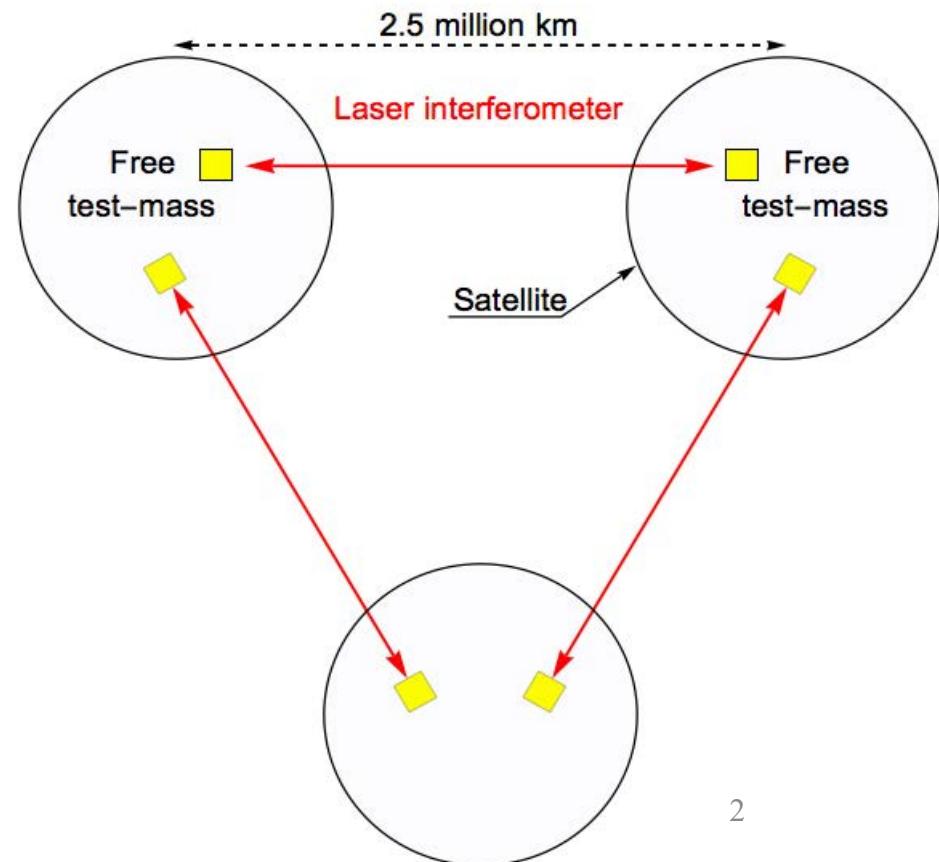
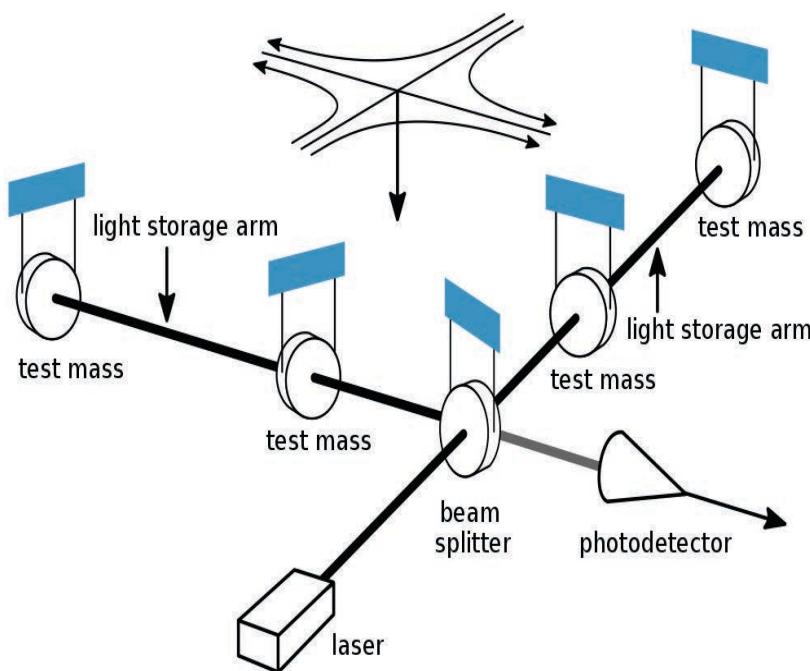
Gravitational wave astronomy within ESA Science Programme

Stefano.Vitale@unitn.it

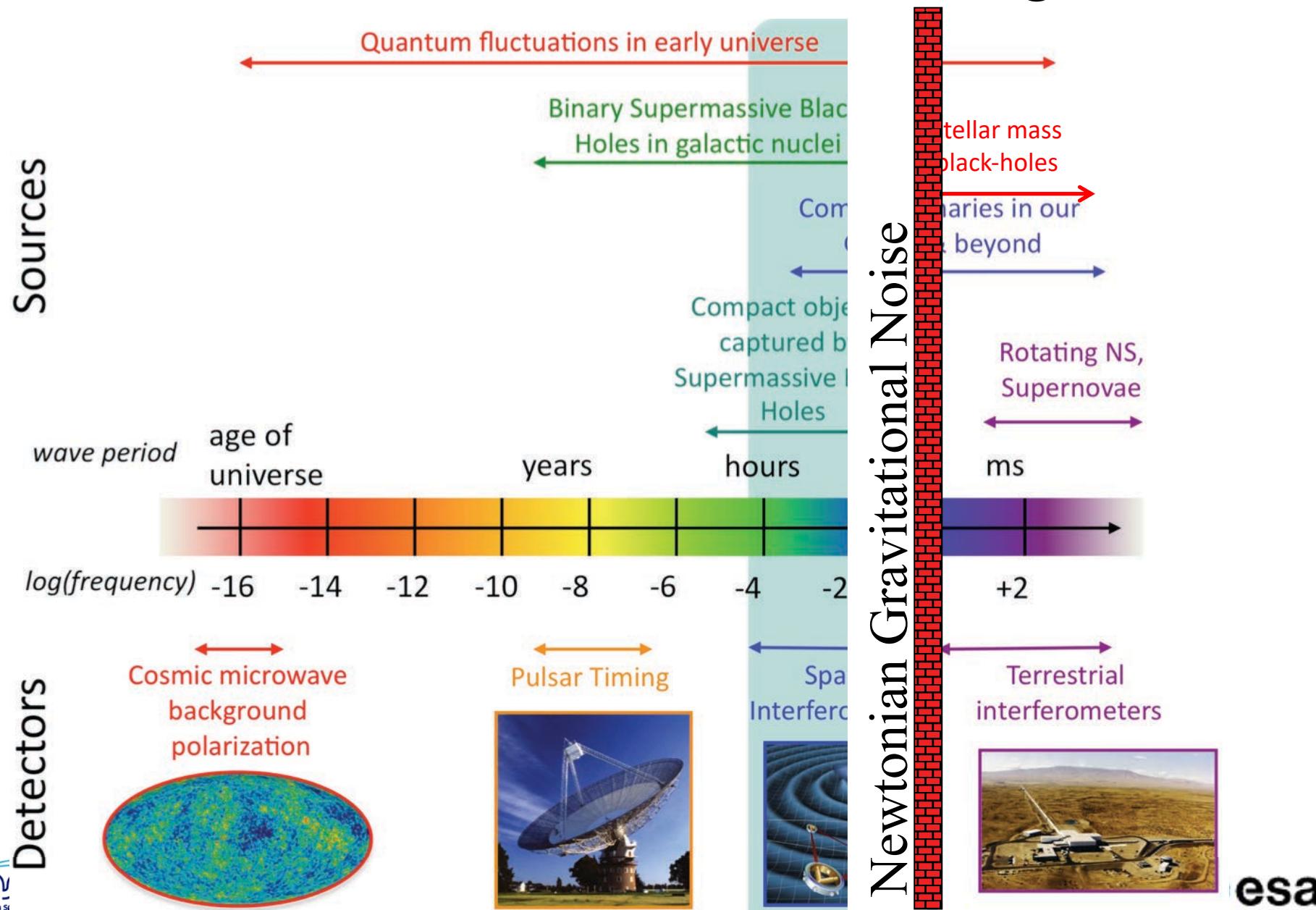
Università di Trento, Istituto Nazionale di Fisica
S. Vitale Nucleare and Agenzia Spaziale Italiana

LISA: LIGO/Virgo in space

	LIGO/Virgo	LISA
Size	4 km	2.5×10^6 km
Frequency	>10 Hz	$20 \mu\text{Hz} \div 1 \text{ Hz}$

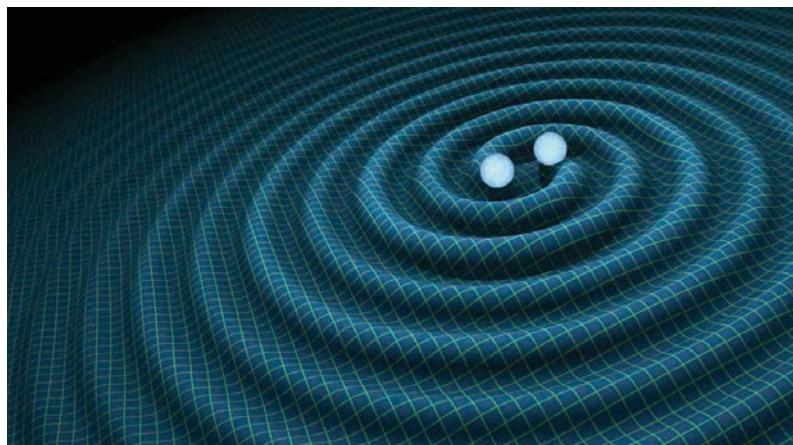


$2 \times 10^{-5} \div 1$ Hz not accessible from ground



Why low frequency?

- Frequency of GW 2 x frequency of motion



- Kepler: faraway is slow

$$f = \left(1/\pi\right) \sqrt{GM/r^3}$$

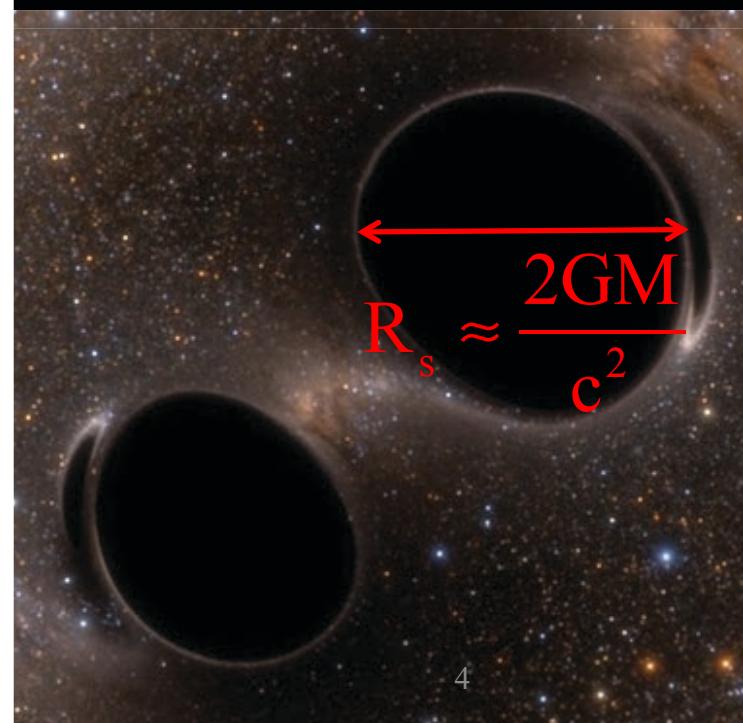
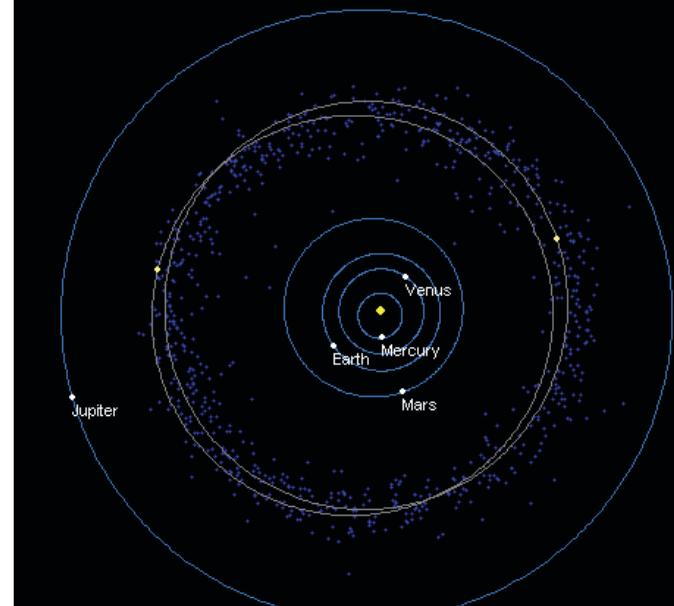
- Big black-holes: can't get closer than horizon

$$f \ll \frac{1}{\pi\sqrt{8}} \frac{c^3}{GM} : 10^6 M_{\odot} \rightarrow 0.01 \text{ Hz}$$

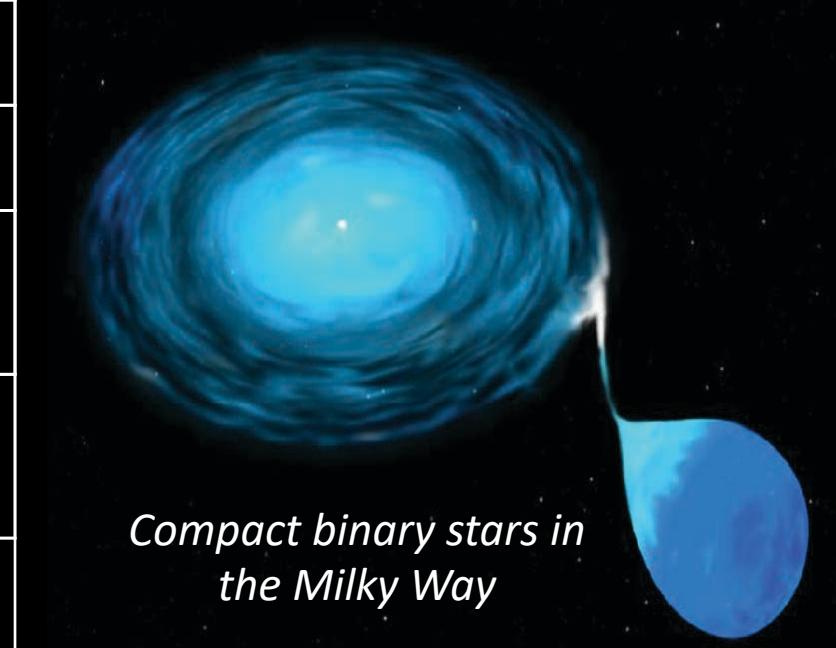
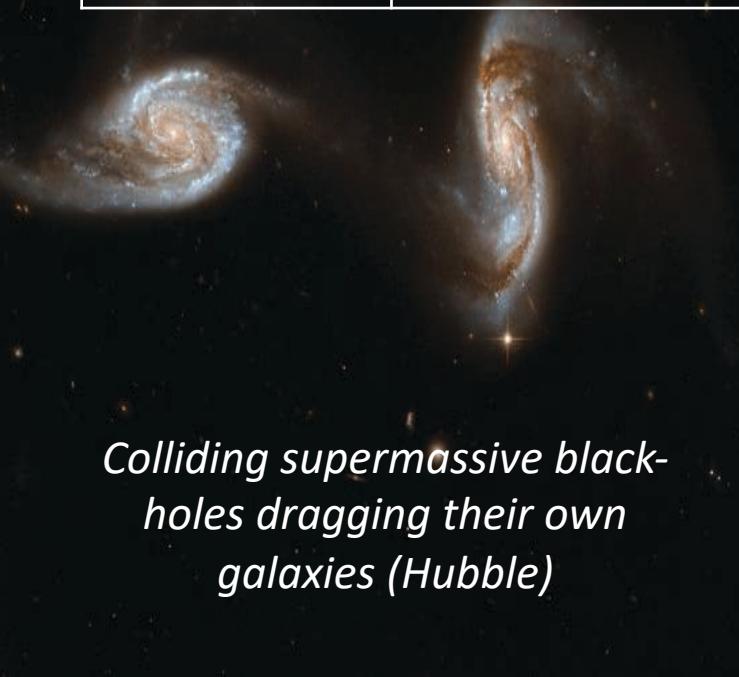
- By the way, big is powerful: $h \propto M^2$

Kitzbuhel 25/06/2019

S. Vitale



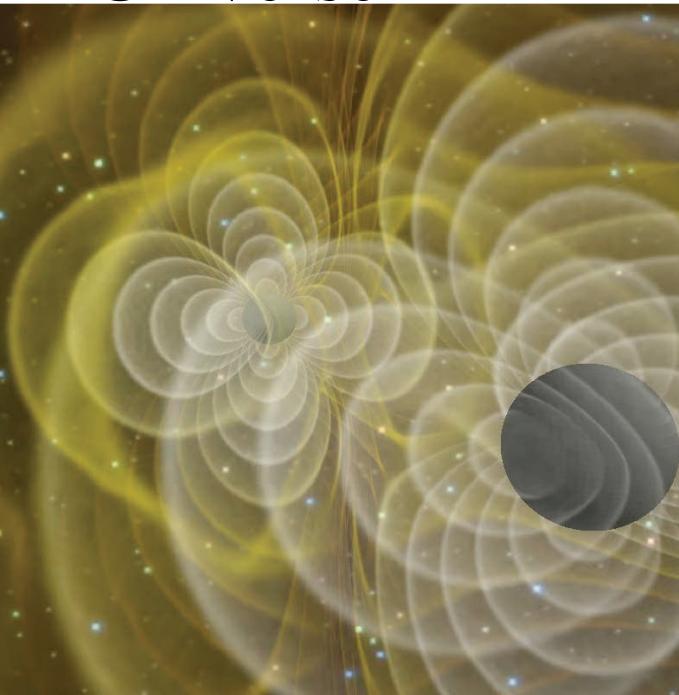
	LIGO	LISA
Size	km	Million km
Wave period	0.001-0.1 seconds	minutes to hours
Mass of sources	~ 1-10 Sun	up to 1-10 Million Sun
Size of the source	~ 100-1000 km	1-10 Million km





Million solar mass Black-Holes

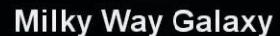
- Galaxies host > million solar mass Black-Holes
- Galaxy collide and form binary Black-Holes
- Binaries coalesce: more GW energy than all light in the Universe



Triangulum Galaxy (M33)



Milky Way Galaxy

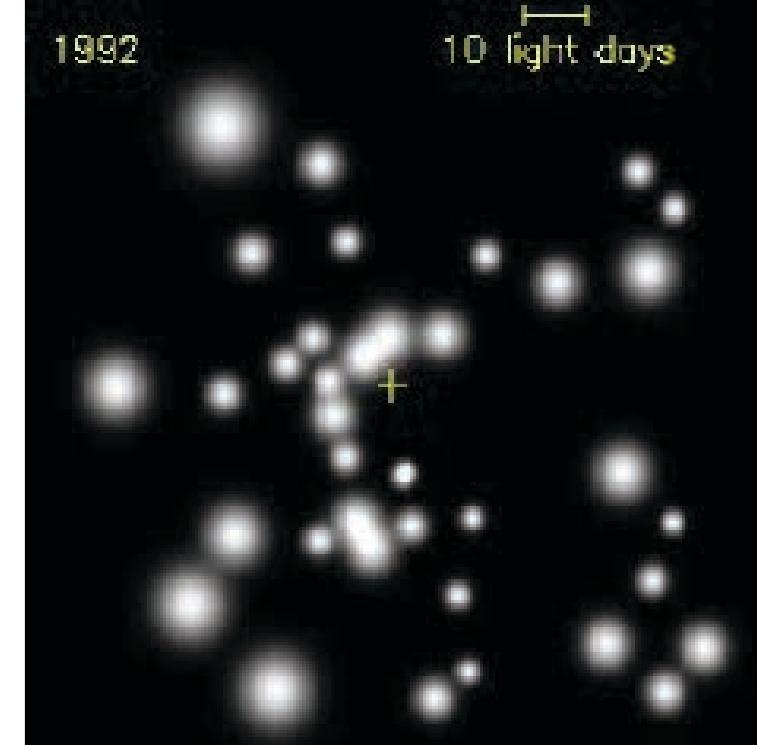


Andromeda Galaxy (M31)



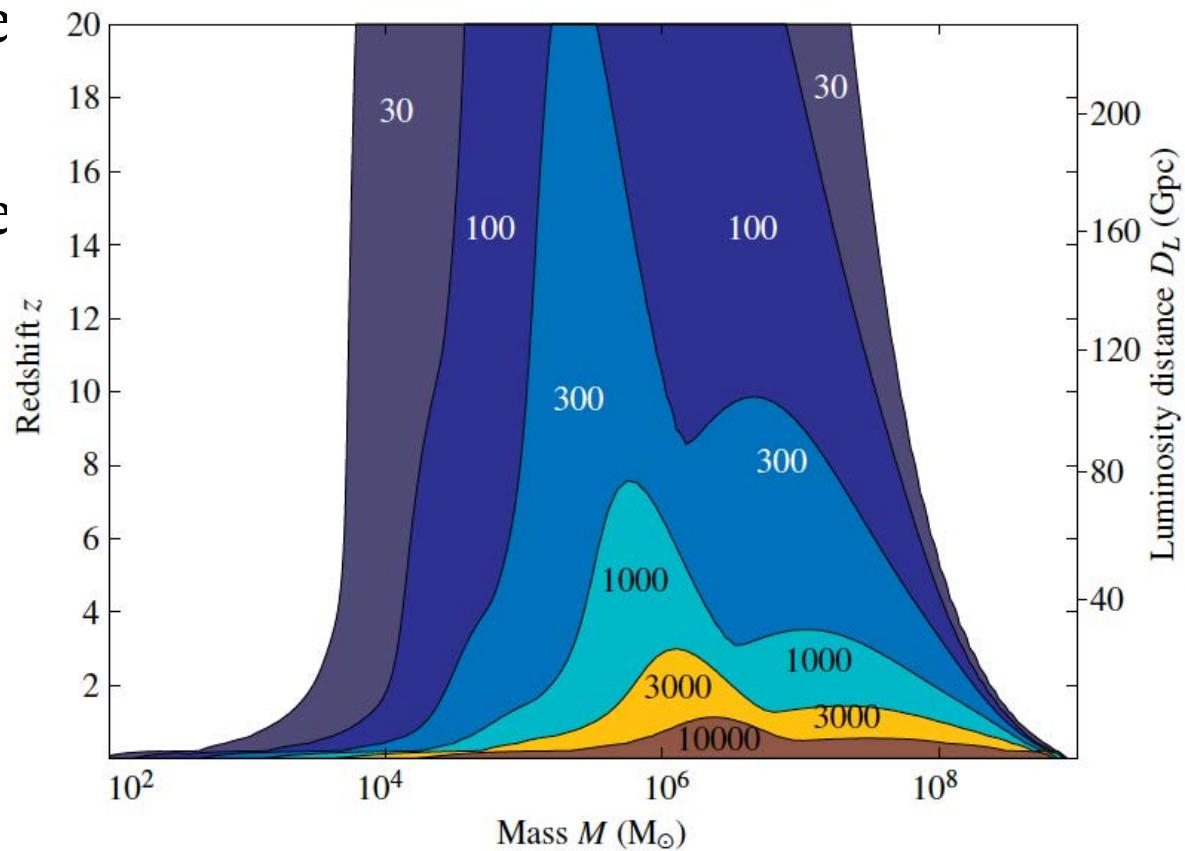
1.782 billion years

1992

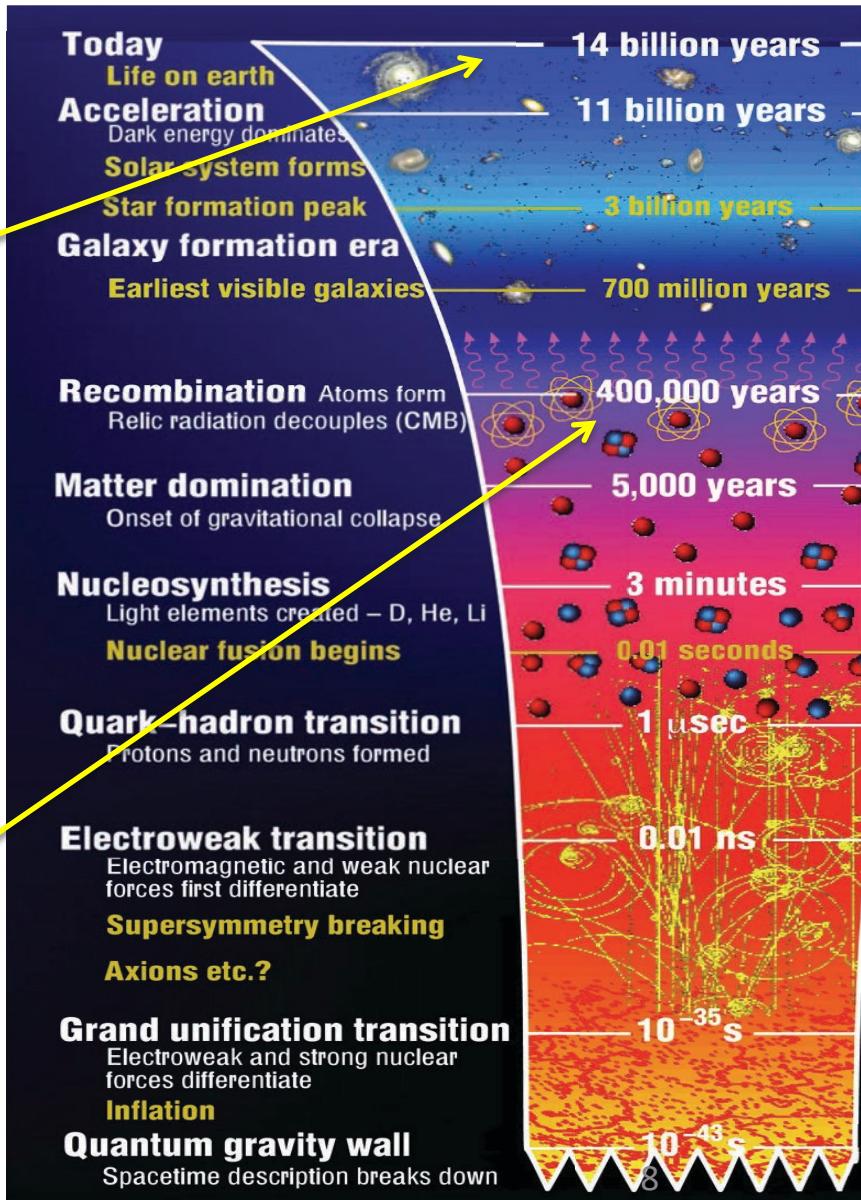
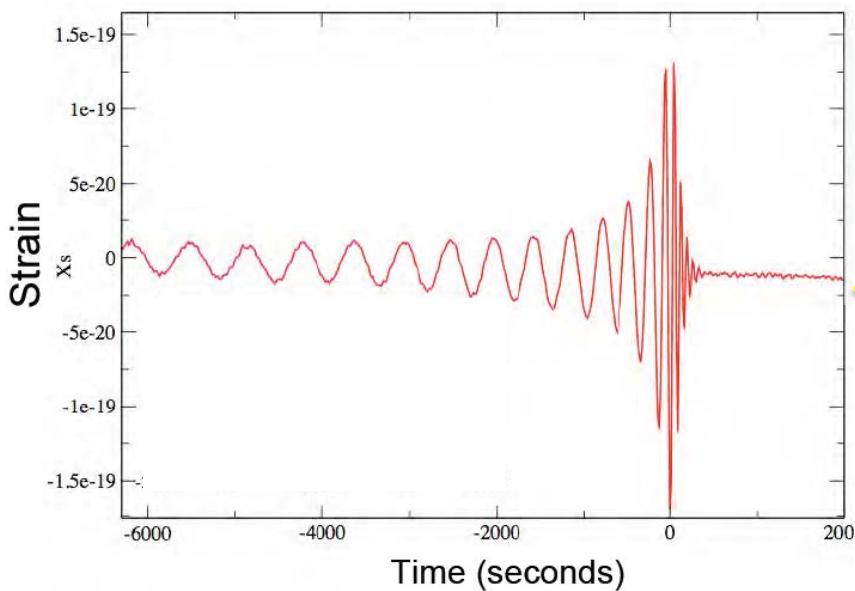
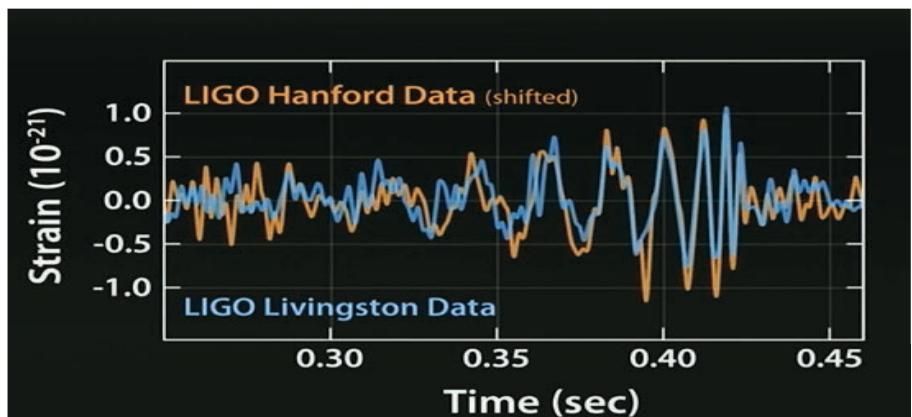


High-precision gravitation of deep universe

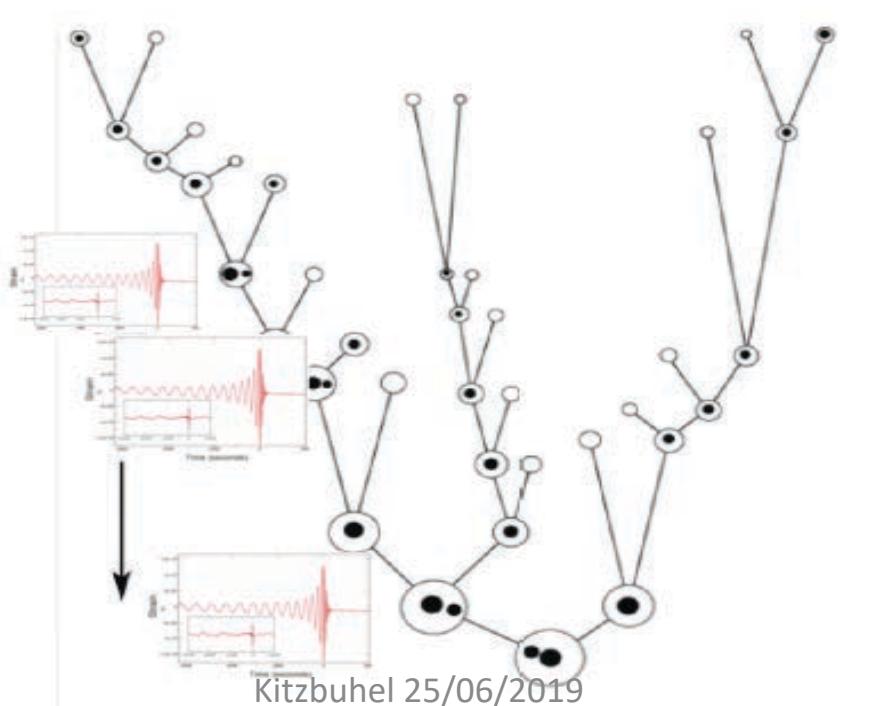
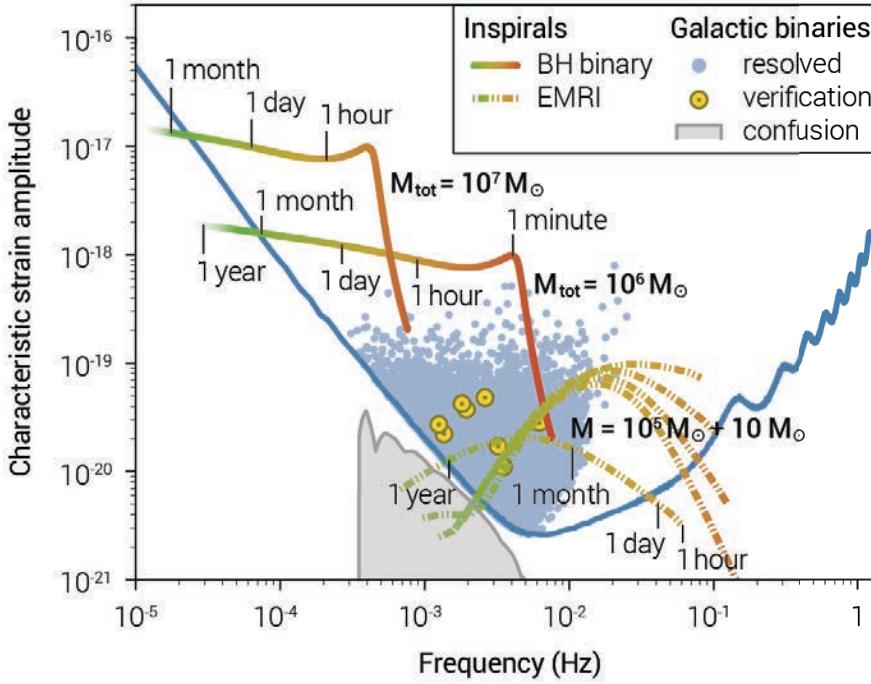
- Detect all mergers in the universe within the frequency band, even out to $z=20$, if they were happening.
- Measures: luminosity distance $1 - 5 \%$
- Sky location $0.1^\circ - 5^\circ$
- Masses to $\pm 0.1\text{-}0.5\%$
- Spin magnitudes to ± 0.01 .
- Spin *vectors* to $\pm 3\text{-}5\%$



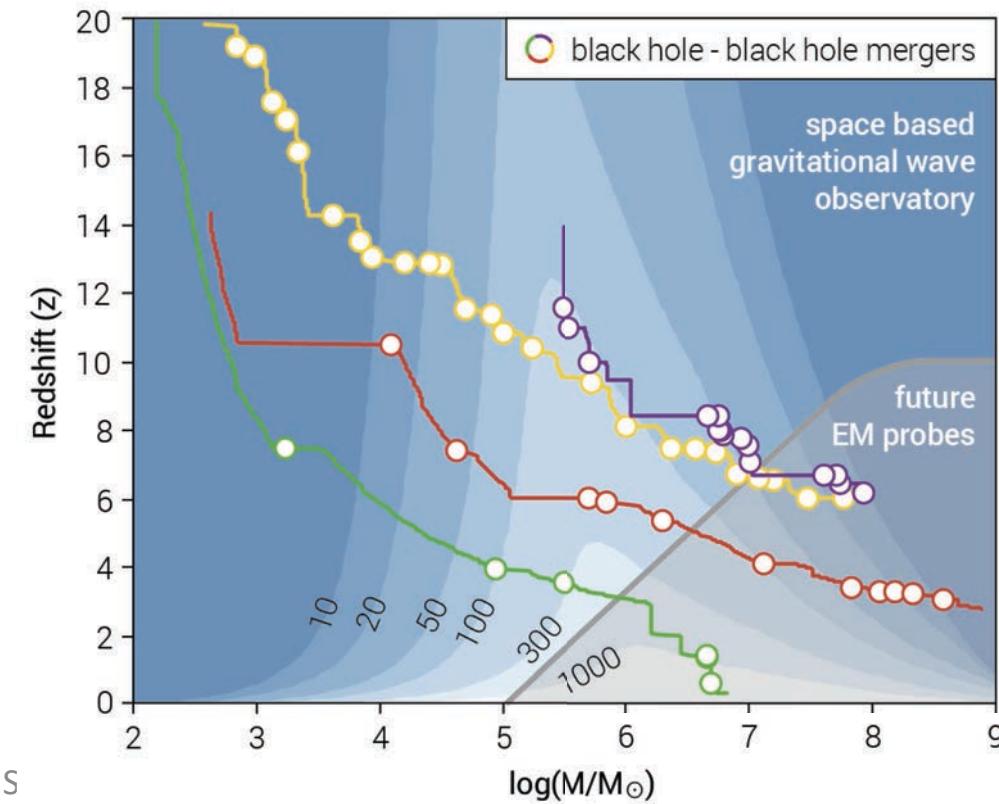
A deep universe, high resolution observatory



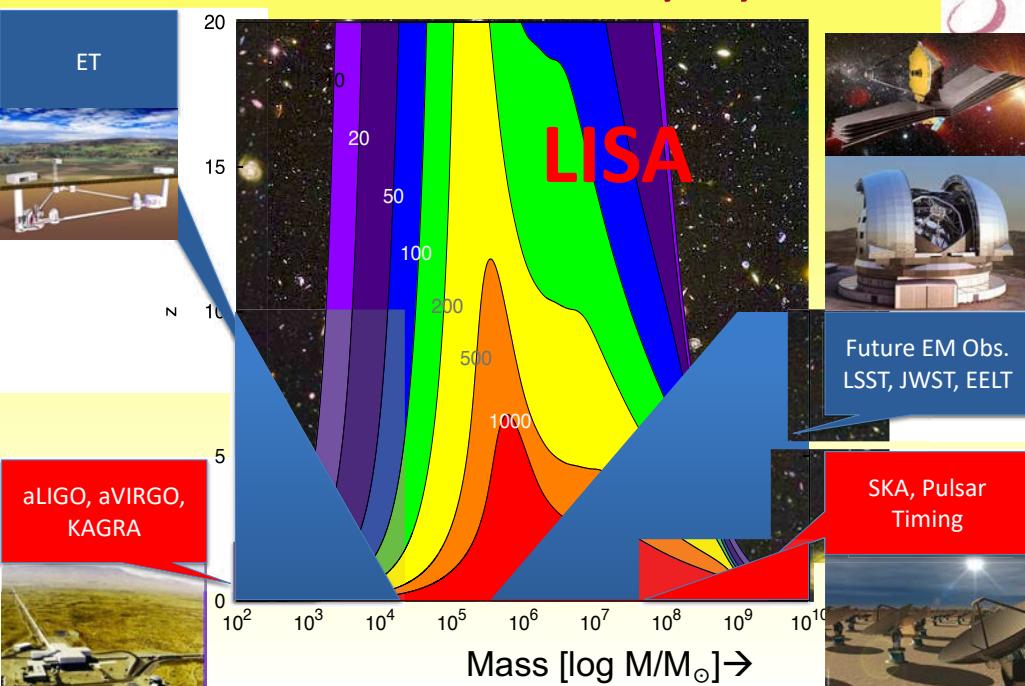
Cosmological stratigraphy



- Almost all BBH in their evolution cross LISA band (hundreds expected)
- Allows discriminating different model of galaxy formation.

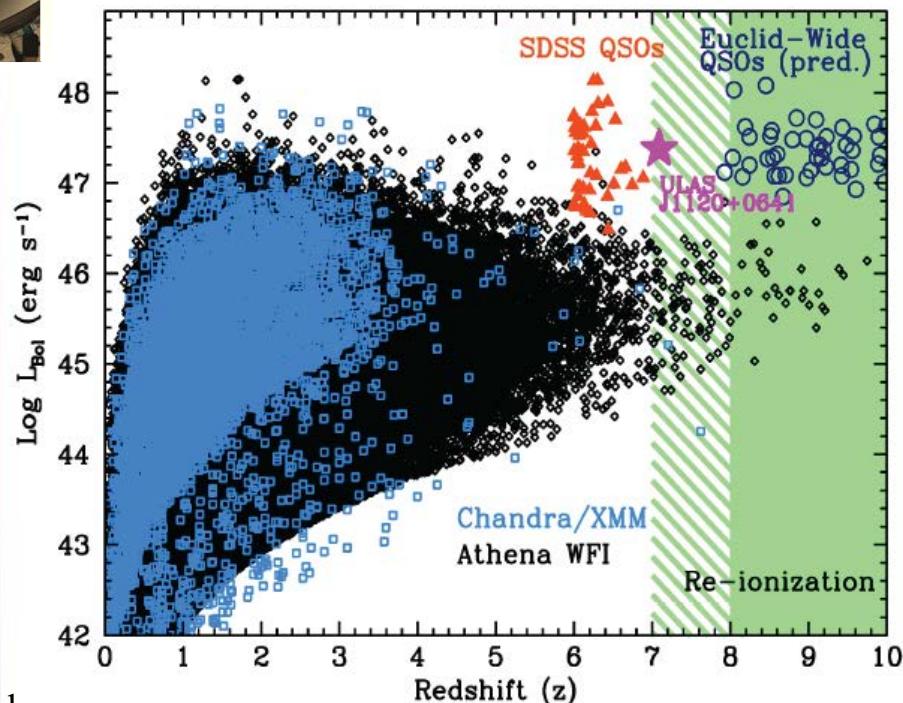


Black Hole Astronomy by 2030



Athena

ESA's MBH programme



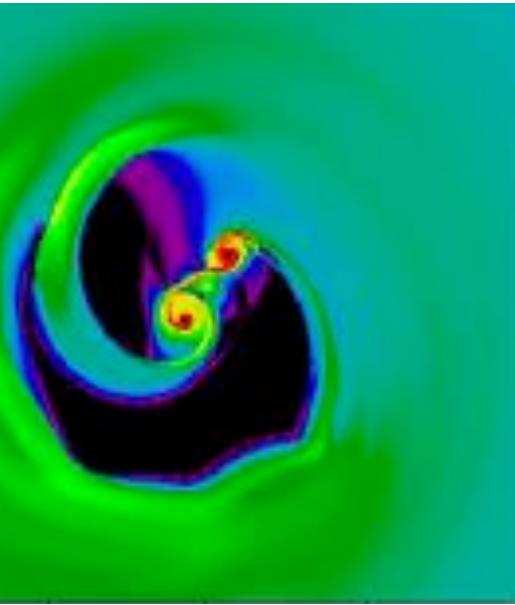
Detecting SMBH mergers with LISA and Athena

The late inspiral of supermassive black hole binaries with circumbinary gas discs in the LISA band

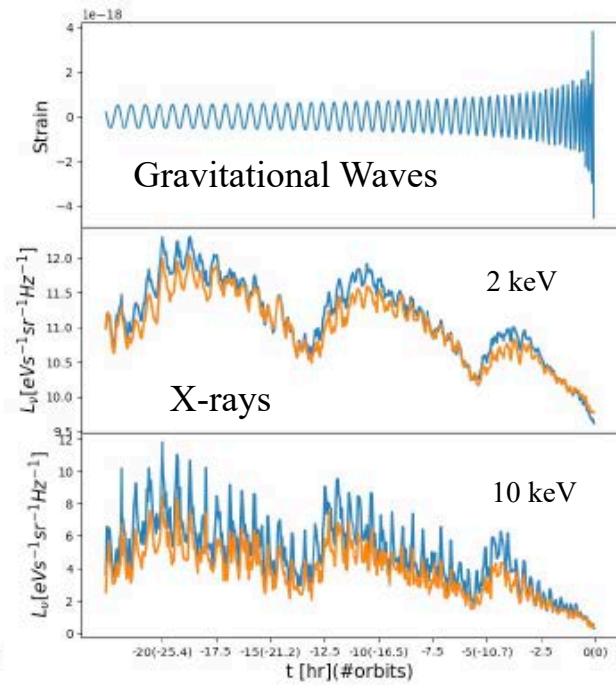
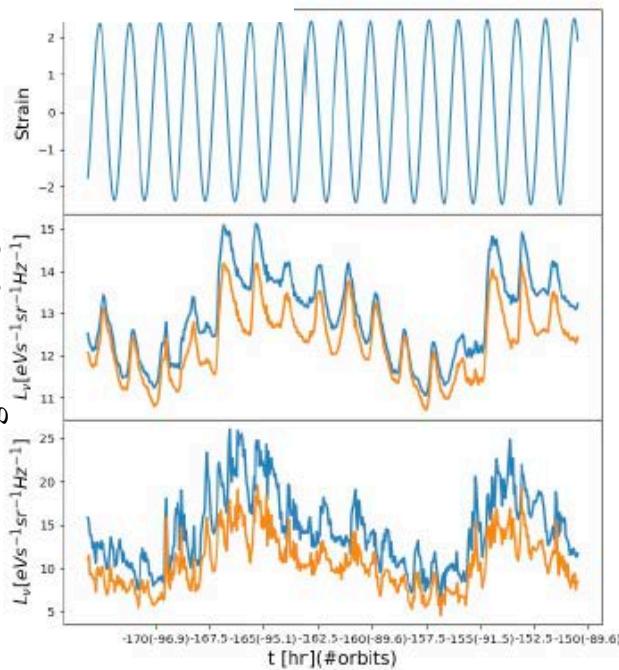
Yike Tang¹, Zoltán Haiman², Andrew MacFadyen^{1*}

¹Center for Cosmology and Particle Physics, Physics Department, New York University, New York, NY, USA, 10003

²Department of Astronomy, Columbia University, New York, NY, USA, 10027



Tang et al. 2018



Athena-LISA Synergies

Athena-LISA Synergy Working Group:

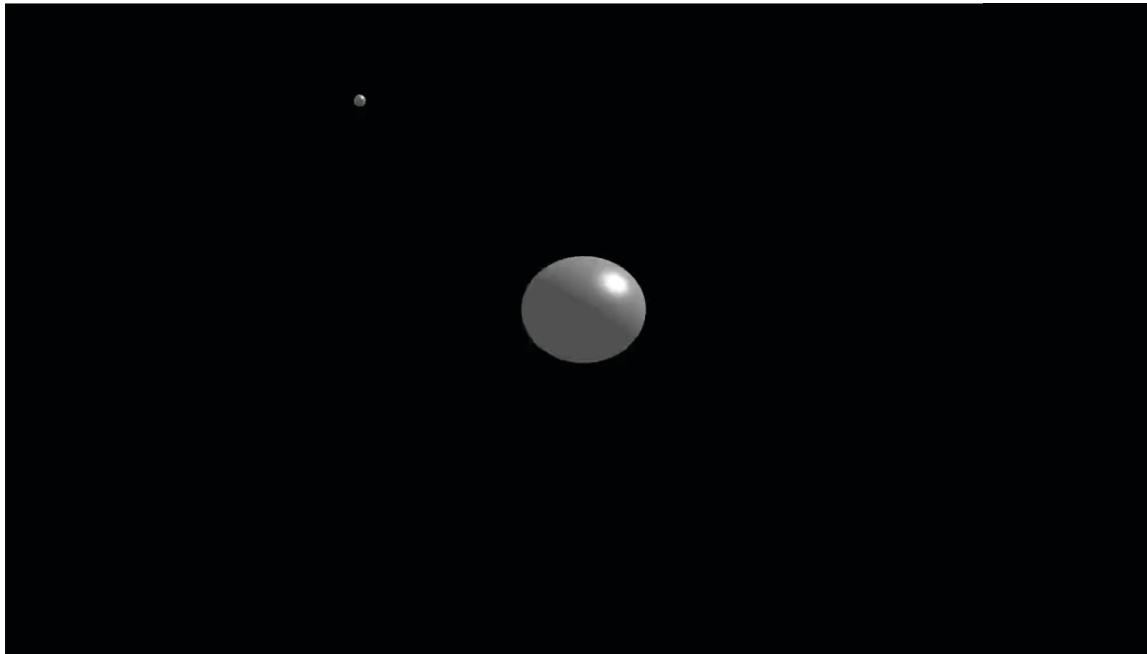
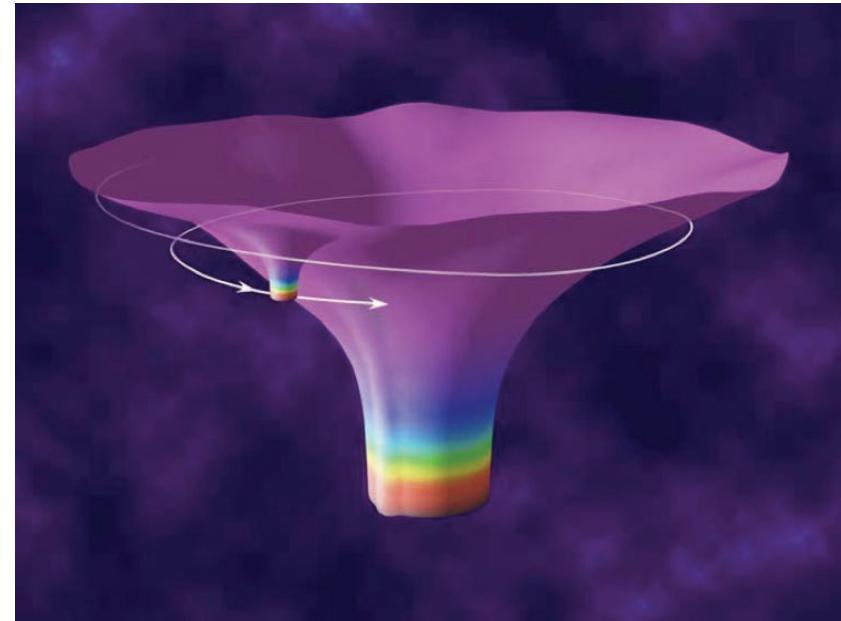
Monica Colpi, Andrew C. Fabian, Matteo Guainazzi,

Paul McNamara, Luigi Piro, Nial Tanvir

(with contributions by J.Aird, A.Klein, A.Mangiagli, E.M.Rossi, A.Sesana)

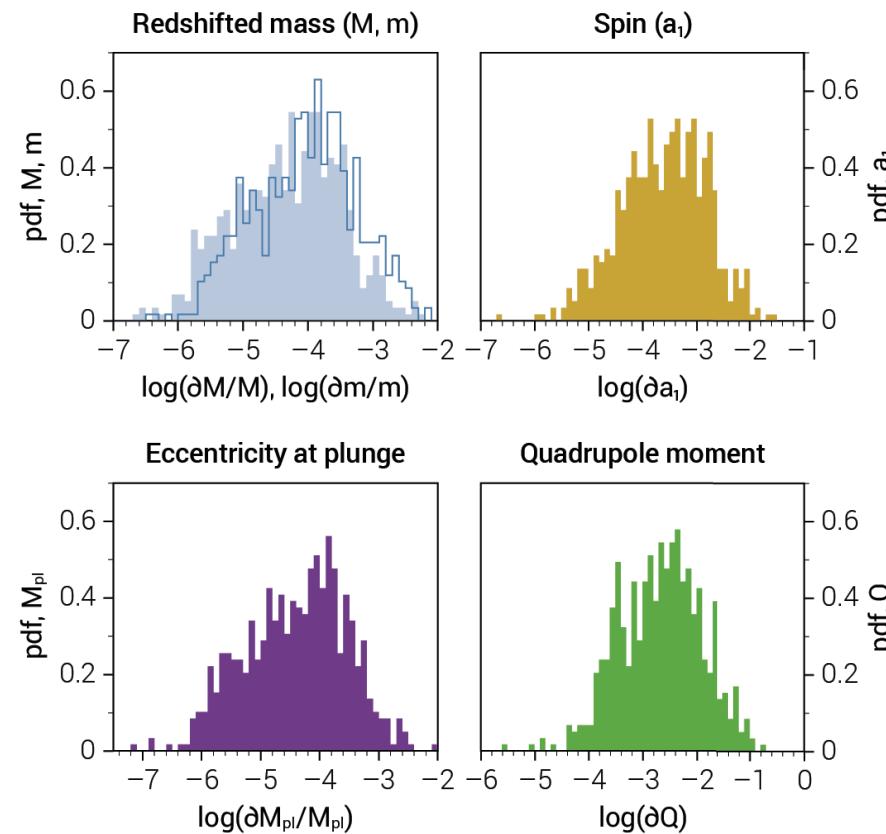
Extreme Mass-Ratio Inspirals: EMRIs

- Stellar-mass BH capture by a massive BH: dozens per year.
- 10^5 orbits very close to horizon. GRACE/GOCE for massive BHs.
 - Prove horizon exists.
 - Test the no-hair theorem to 1%.
 - Masses of holes to 0.01% -0.001%
 - Spin of central BH to 0.0001.



EMRIs as a GRG lab

- The no-hair theorem: spacetime around BH determined by mass and spin
- Quadrupole moment measured at 0.1 % - 0.01 %
- Inconsistency with Kerr multipole structure allows to discriminate:
 - Strong environmental perturbation
 - New type of exotic compact object consistent with General Relativity: boson star, horizonless objects, non-Kerr axisymmetric geometries....
 - Failure in General Relativity itself: dynamical Chern-Simons, scalar-tensor theories, braneworld models, theories with axions, constraints within parametrised models



Kepler again: well separated smaller binaries rotate at low frequency

1. LISA compact galactic binaries.
 - 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

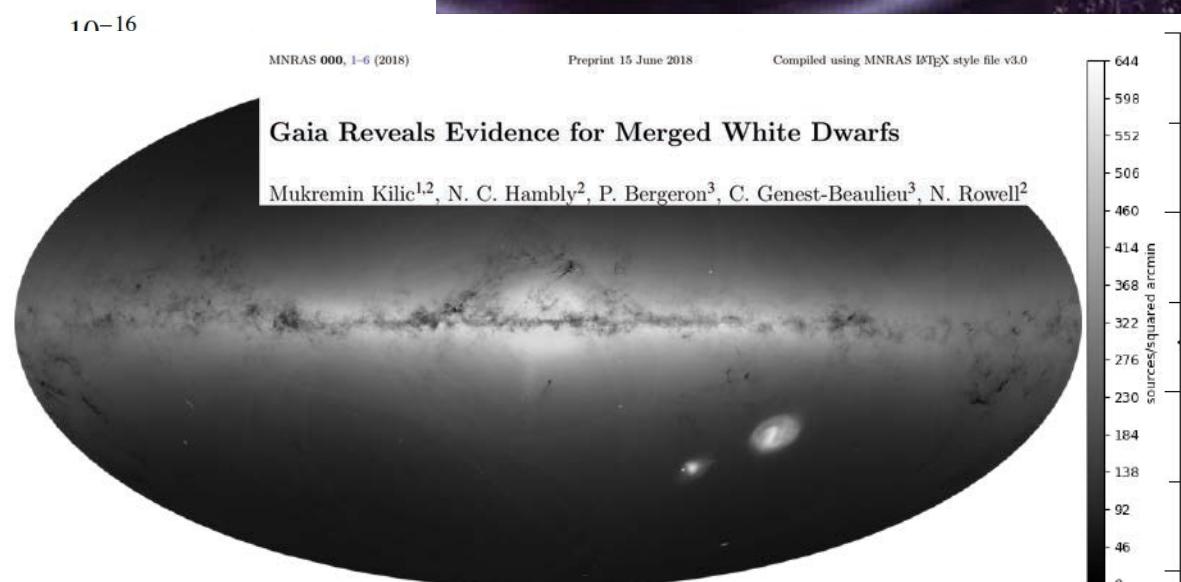
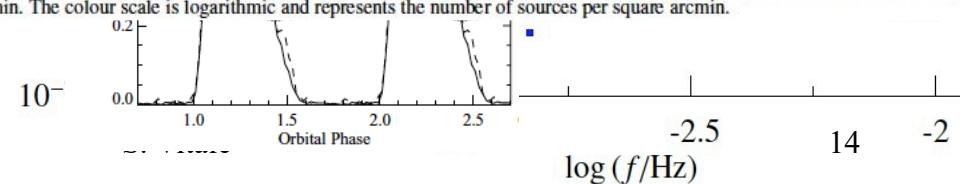


Fig. 3. Sky distribution of all *Gaia* DR2 sources in Galactic coordinates. This image and the one in Fig. 4 are Hammer projections of the full sky. This projection was chosen in order to have the same area per pixel (not strictly true because of pixel discretisation). Each pixel is ~ 5.9 square arcmin. The colour scale is logarithmic and represents the number of sources per square arcmin.





VIRGO/LIGO BH in their Keplerian phase

2. Detecting LIGO events before they happen

Editors' Suggestion

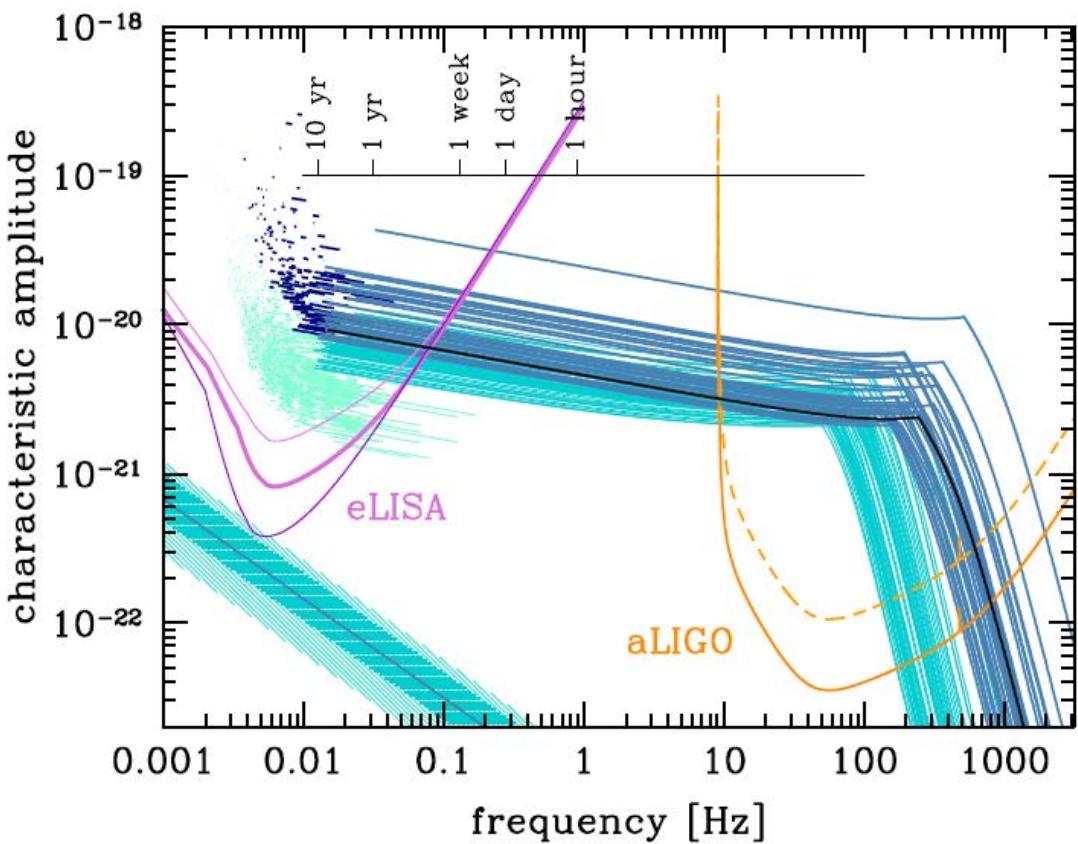
Prospects for Multiband Gravitational-Wave Astronomy after GW150914

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 facilities about locations of potential black hole mergers weeks in advance.

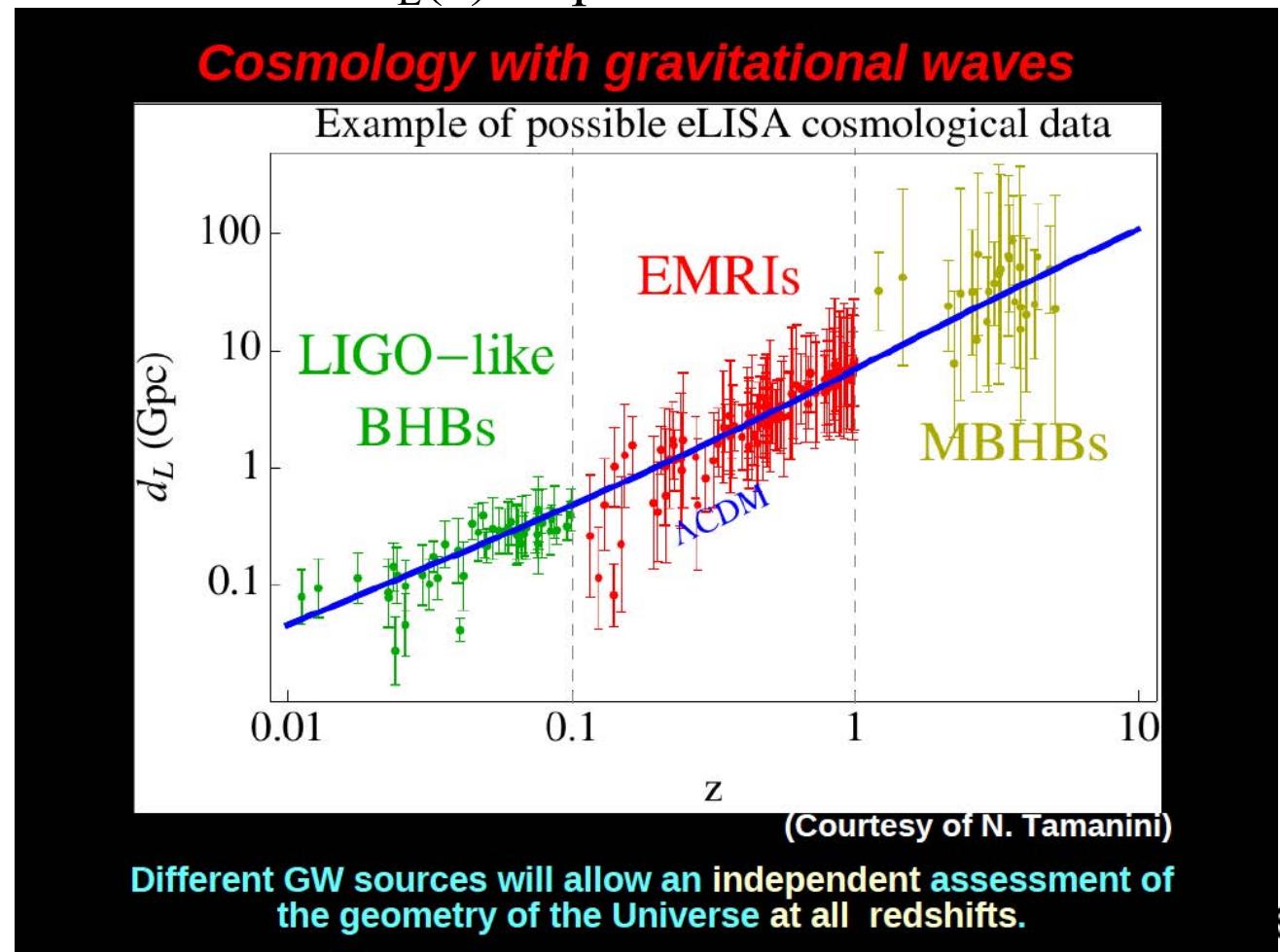


Cosmography with GW

- GW from chirping binary systems are standard sirens: *absolute* luminosity distances D_L from period P and amplitude h:

$$D_L \propto cP\dot{P}/h$$

- GW *do not measure* redshift z. $D_L(z)$ requires identification of e.m. counterpart.



Phase transitions in the early universe

- Wavelength of relic GW set by horizon scale at time of emission
- LISA band: 1 mm Horizon scale (1-1000 TeV scale)
- 3×10^{-18} - 3×10^{-10} s after Big Bang
- LISA sensitivity $\Omega_{\text{GW}} < 10^{-11} \Omega$

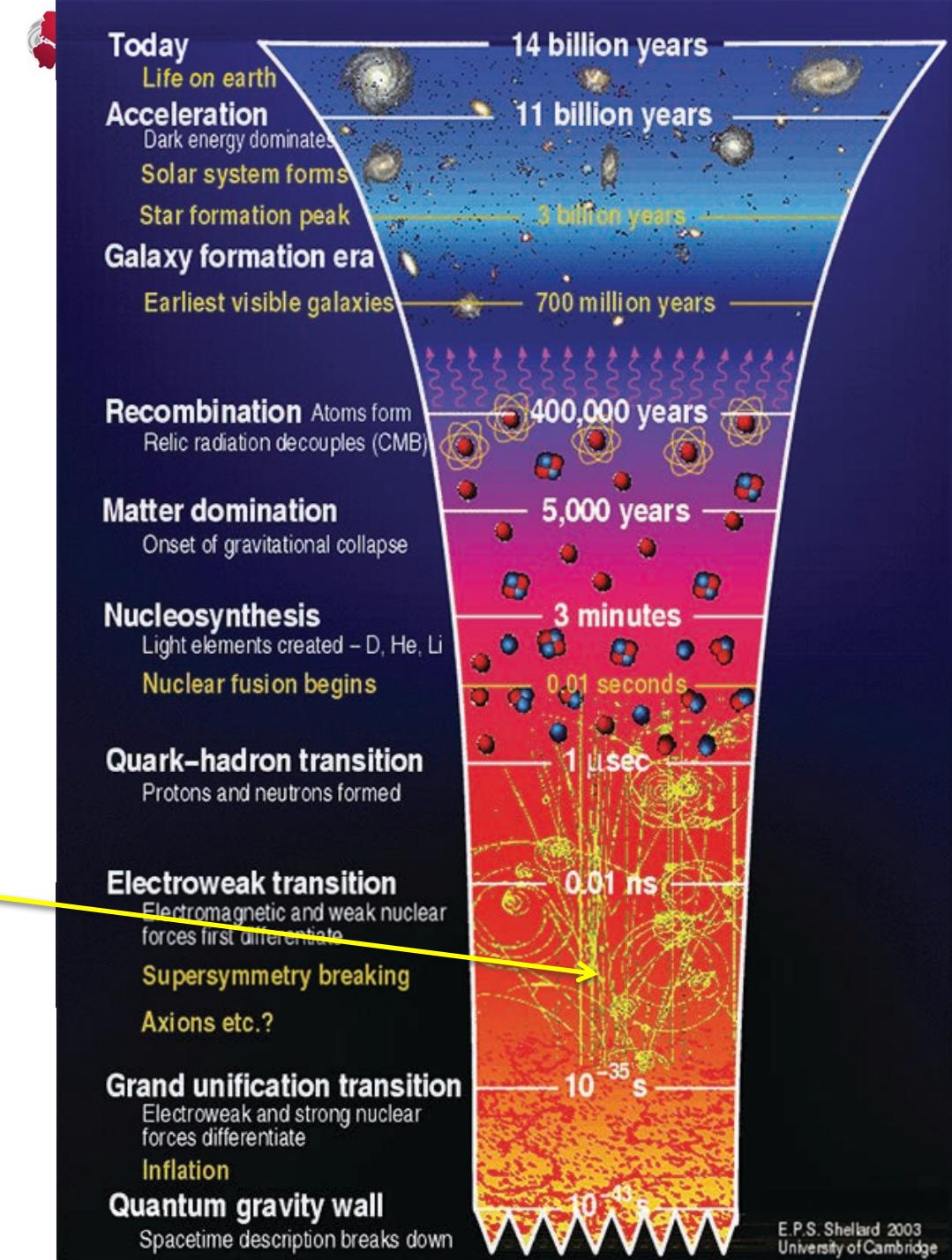


Table 1: Overview of science objectives and their respective science investigations

SO 1 Study the formation and evolution of compact binary stars in the Milky Way Galaxy

SI 1.1 Elucidate the formation and evolution of Galactic Binaries by measuring their period, spatial and mass distributions

SI 1.2 Enable joint gravitational and electromagnetic observations of galactic binaries (GBs) to study the interplay between gravitational radiation and tidal dissipation in interacting stellar systems

SO 2 Trace the origin, growth and merger history of massive black holes across cosmic ages

SI 2.1 Search for seed black holes at cosmic dawn

SI 2.2 Study the growth mechanism of MBHs from the epoch of the earliest quasars

SI 2.3 Observation of EM counterparts to unveil the astrophysical environment around merging binaries

SI 2.4 Test the existence of intermediate-mass black holes (IMBHs)

SO 3 Probe the dynamics of dense nuclear clusters using extreme mass-ratio inspirals (EMRIs)

SI 3.1 Study the immediate environment of Milky Way like massive black holes (MBHs) at low redshift

SO 4 Understand the astrophysics of stellar origin black holes

SI 4.1 Study the close environment of Stellar Origin Black Holes (SOBHs) by enabling multi-band and multi-messenger observations and multi-messenger observations at the time of coalescence

SI 4.2 Disentangle SOBHs binary formation channels

SO 5 Explore the fundamental nature of gravity and black holes

SI 5.1 Use ring-down characteristics observed in massive black hole binary (MBHB) coals whether the post-merger objects are the black holes predicted by General Theory of

SI 5.2 Use EMRIs to explore the multipolar structure of MBHs

SI 5.3 Testing for the presence of beyond-GR emission channels

SI 5.4 Test the propagation properties of gravitational waves (GWs)

SI 5.5 Test the presence of massive fields around massive black holes with masses larger than

SO 6 Probe the rate of expansion of the Universe

SI 6.1 Measure the dimensionless Hubble parameter by means of GW observations only

SI 6.2 Constrain cosmological parameters through joint GW and electro-magnetic (EM) c

SO 7 Understand stochastic GW backgrounds and their implications for the early Universe and Te

physics

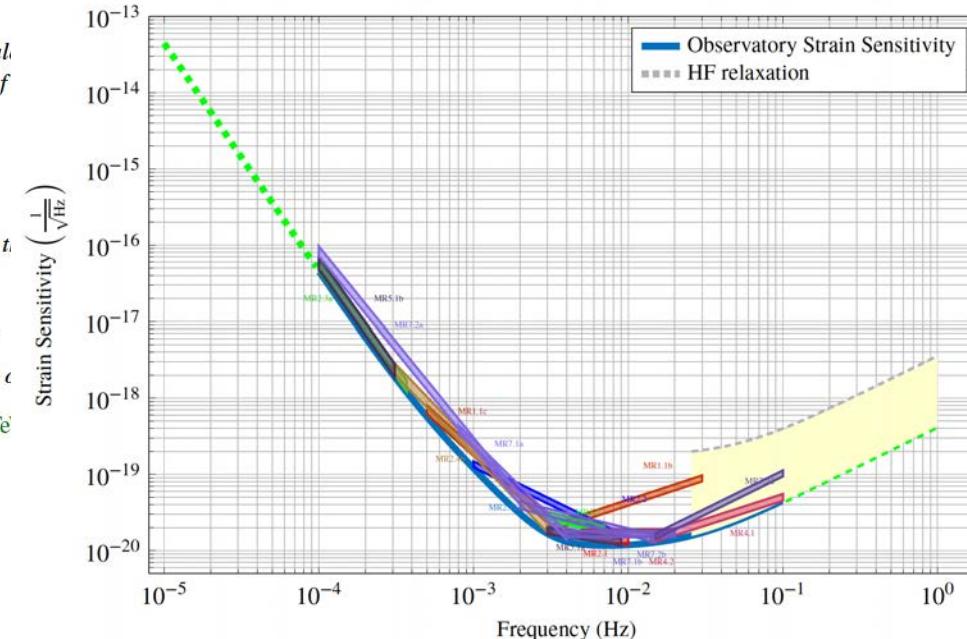
SI 7.1 Characterise the astrophysical stochastic GW background

SO 8 Search for GW bursts and unforeseen sources

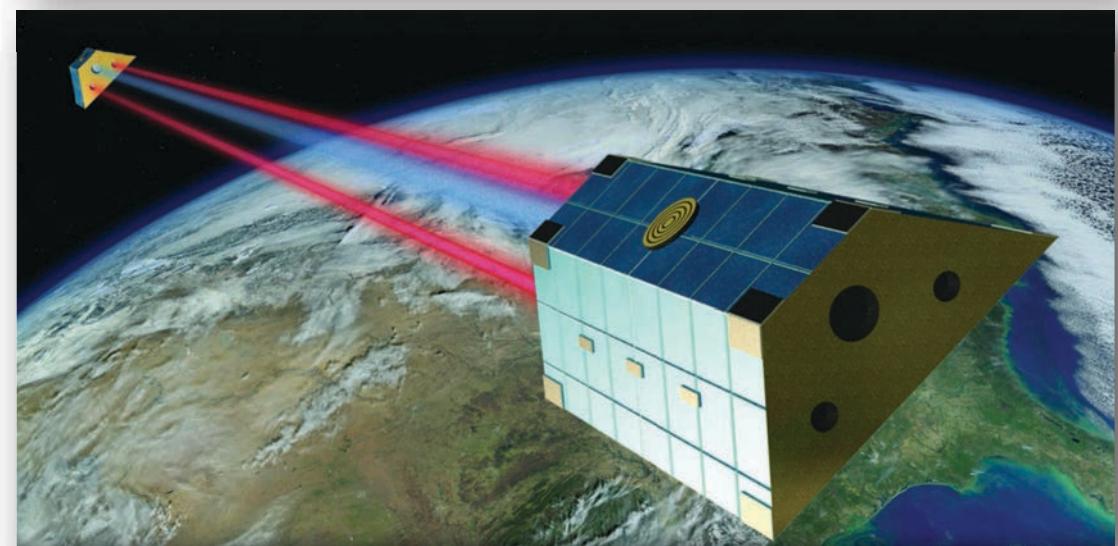
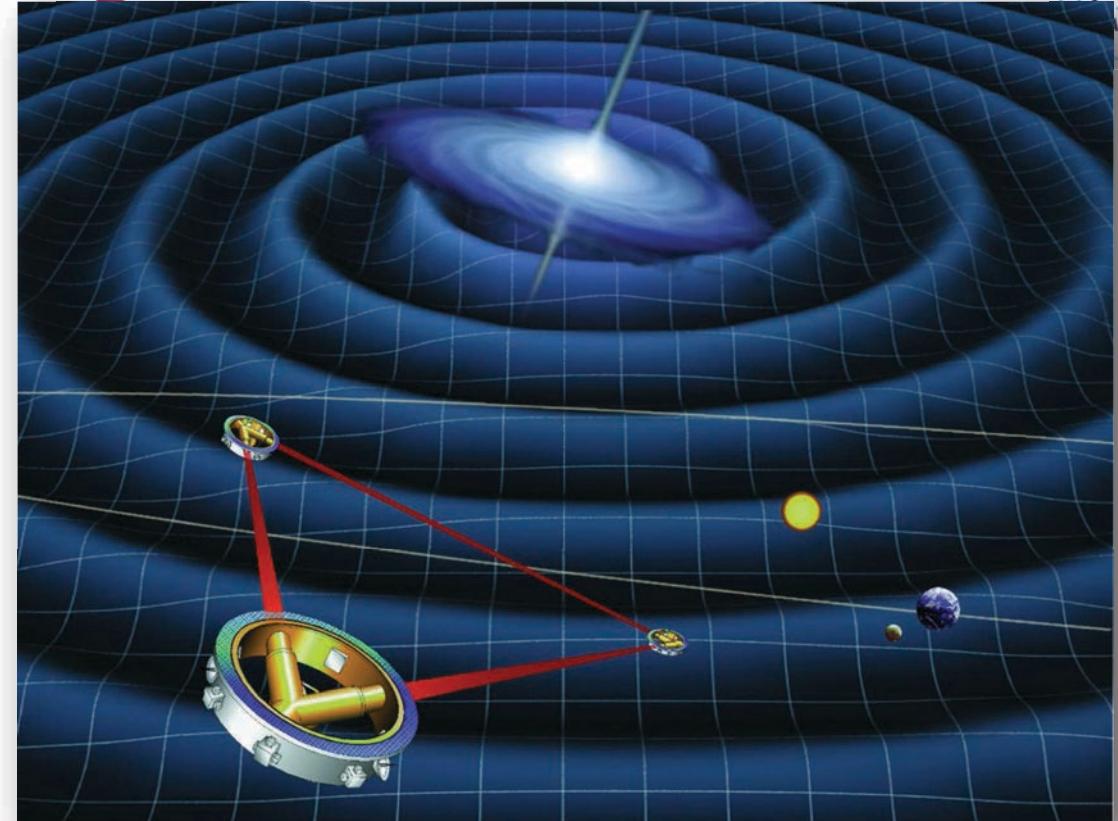
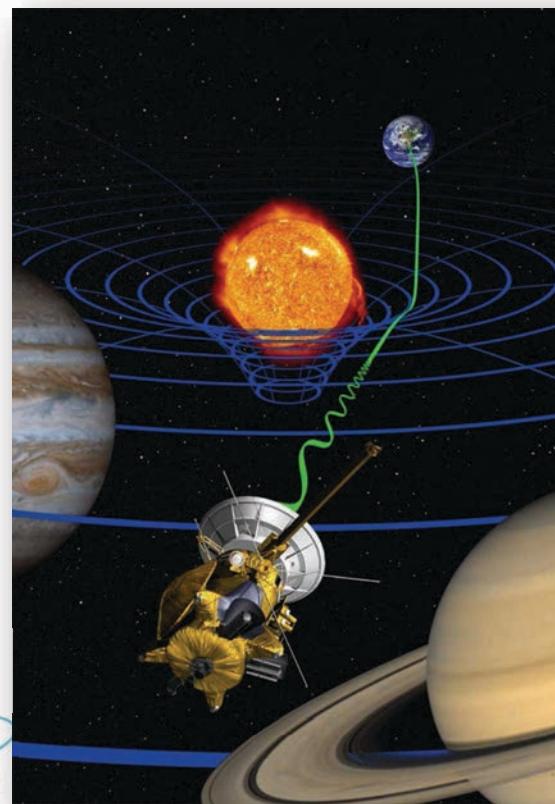
SI 8.1 Search for cusps and kinks of cosmic strings

SI 8.2 Search for unmodelled sources

And so on
 and so forth



Measuring curvature via time-varying Doppler shift between *free falling* observers



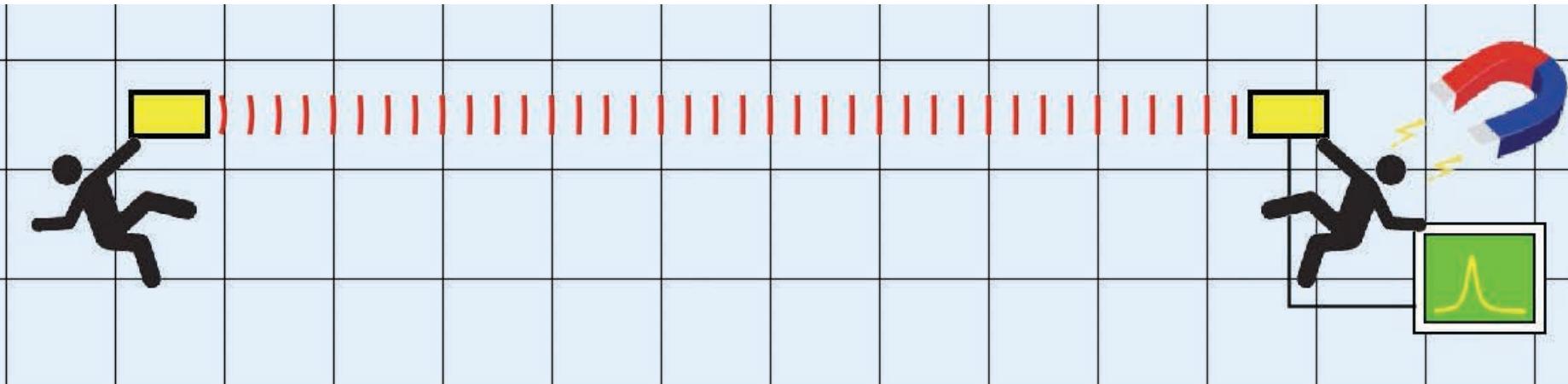
The LISA link



- Curvature of spacetime modulates frequency of beam measured by free falling observers (mutual acceleration of free falling observers)

$$\dot{\nu}_{em} - \dot{\nu}_{rec} = \nu_o (\dot{h}_{em} - \dot{h}_{rec})$$

The LISA link

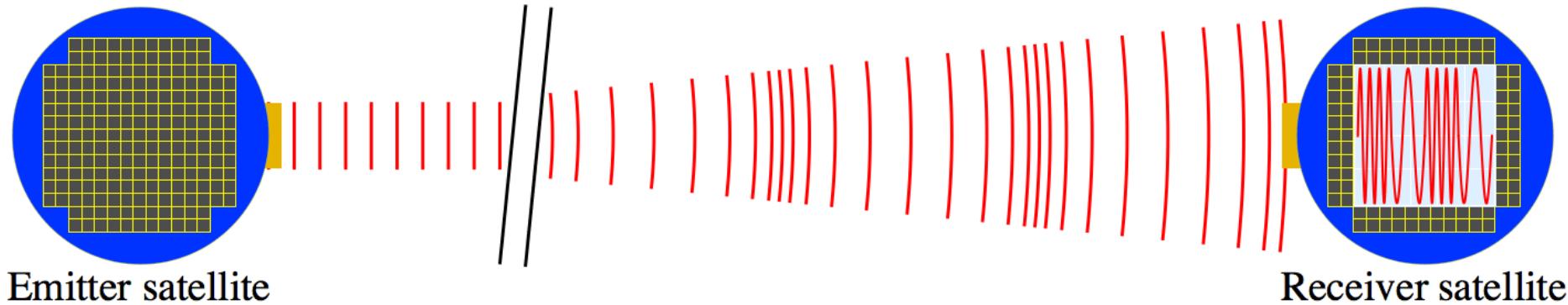


- Unfortunately frequency is also modulated by acceleration of each observer *relative to its own inertial frame*

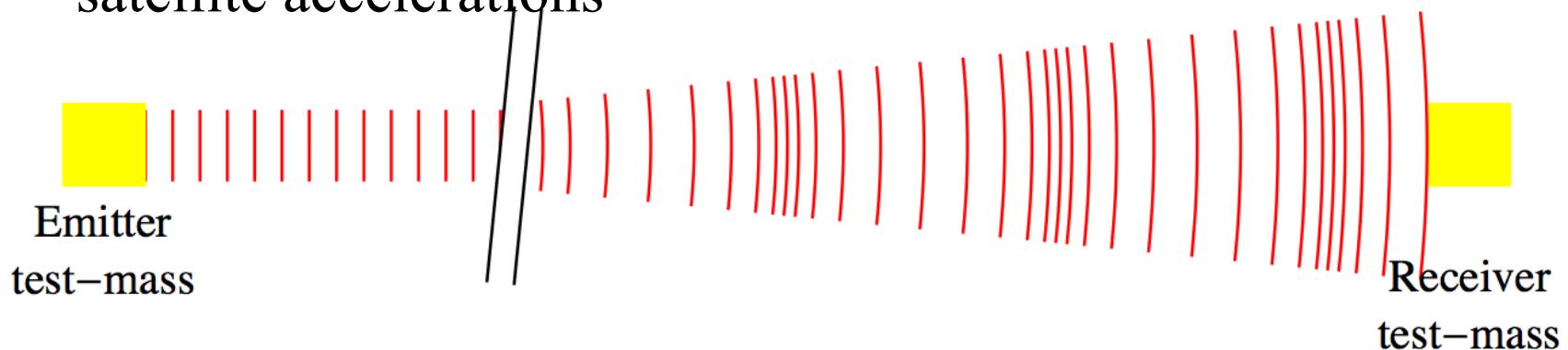
$$\dot{\nu}_{em} - \dot{\nu}_{rec} = \nu_o (\dot{h}_{em} - \dot{h}_{rec}) + \frac{f_{em}}{m} - \frac{f_{rec}}{m}$$

The LISA link

- Satellite accelerations too large

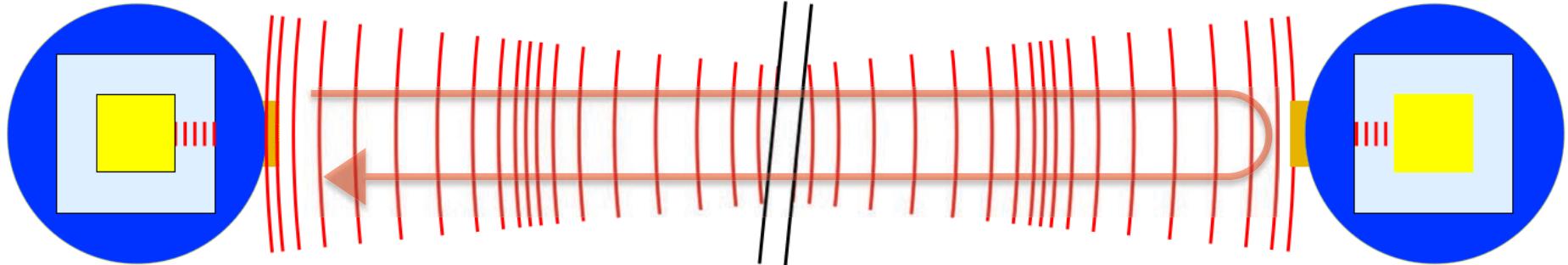


- Inertial reference test-masses are used to correct for satellite accelerations

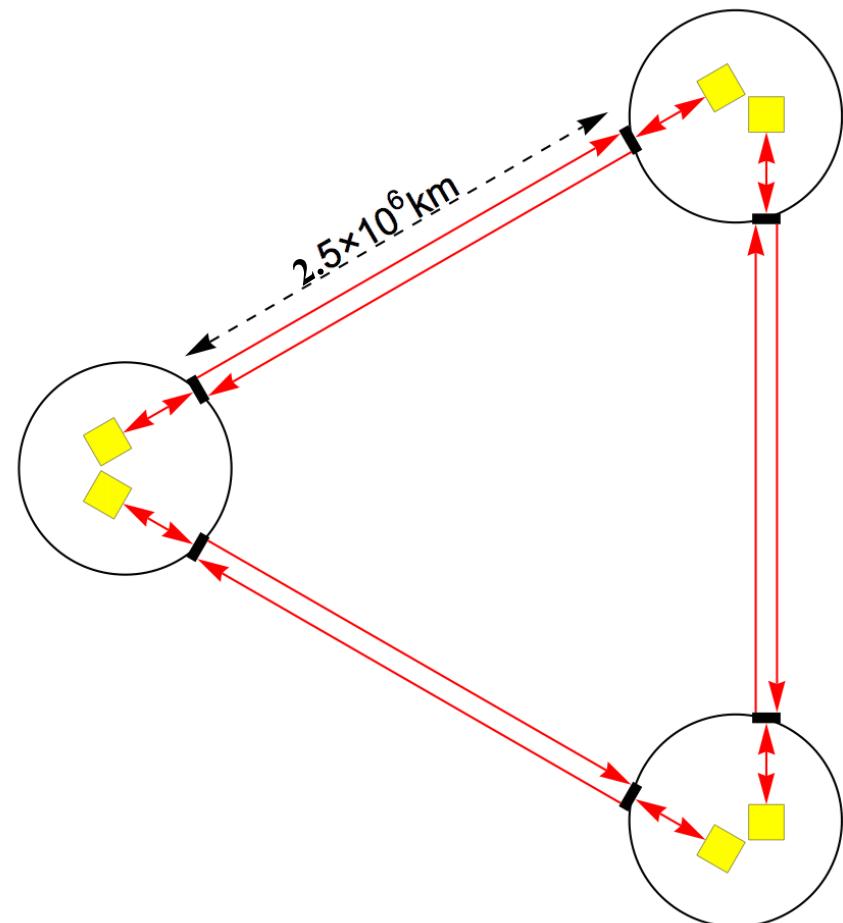


- Equivalent to directly tracking test-masses

The LISA arm

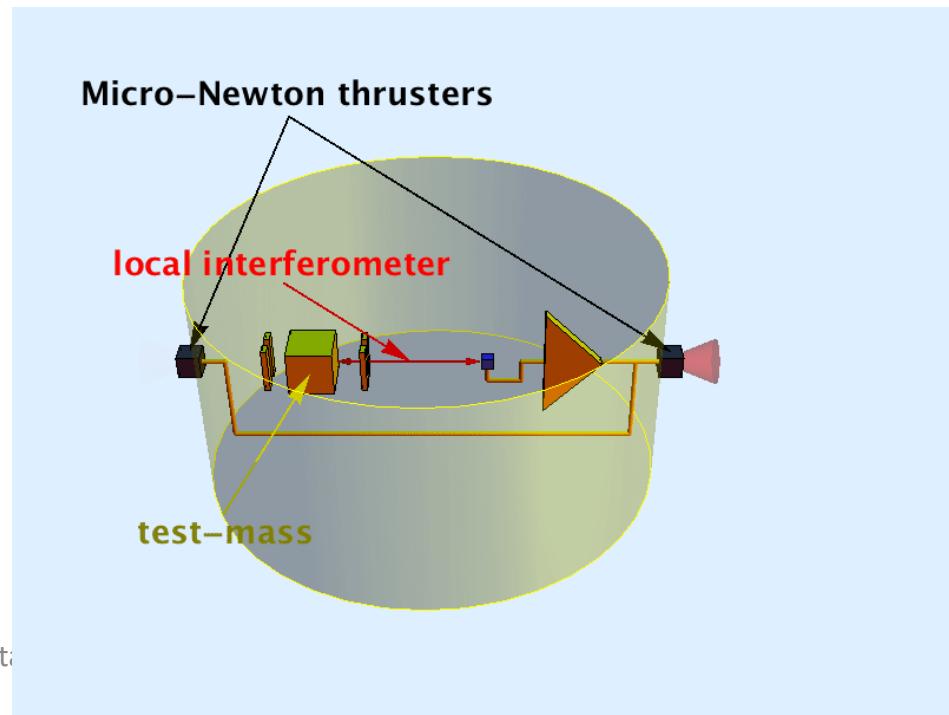


- True reflection impossible. The LISA arm: two phase-locked counter-propagating links.
- LISA: 3 arms 2.5 Mo km
- $10 \text{ pm}/\sqrt{\text{Hz}}$ single-link interferometry @ 1 mHz



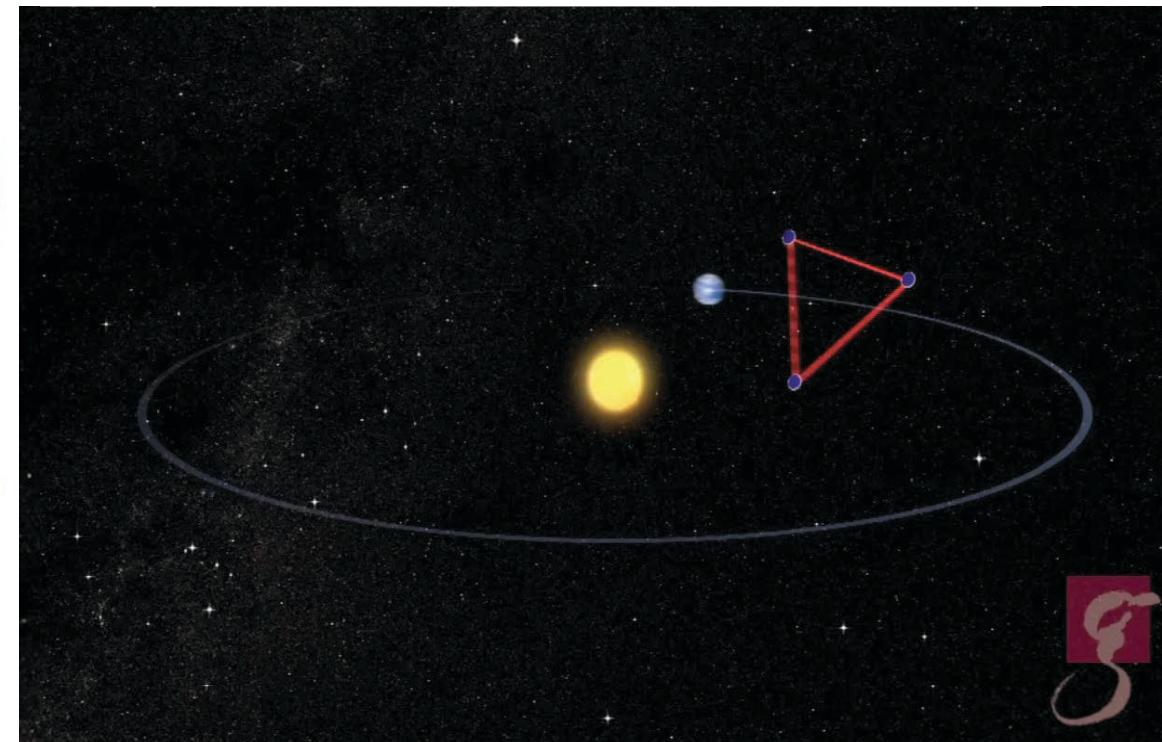
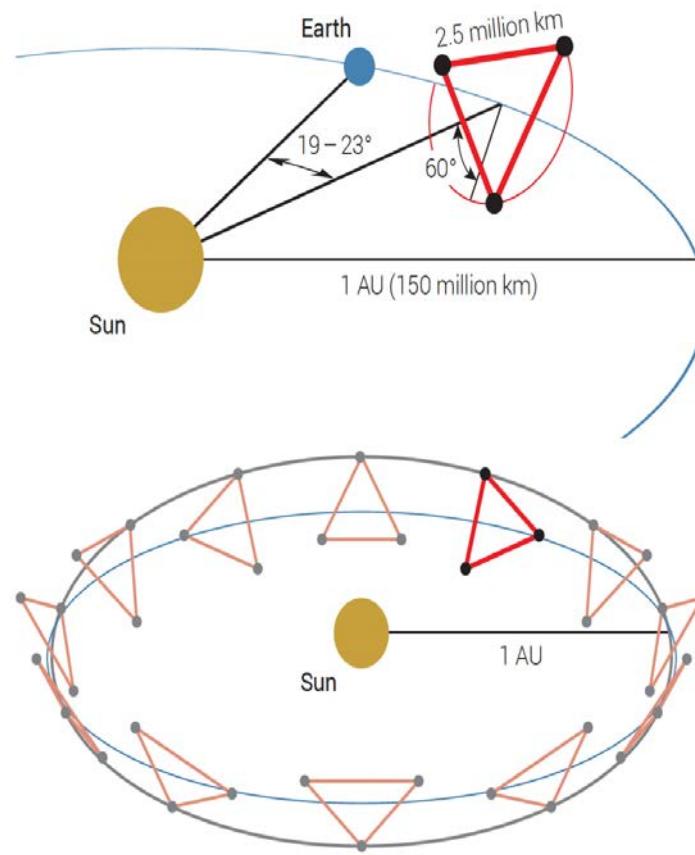
LISA fundamentals: drag-free

- Free-falling inside a spacecraft
 - Sooner or later test-masses will hit the walls
 - LISA: position of spacecraft relative to test-mass is measured by local interferometer
 - Spacecraft is kept centered on test-mass by acting on micro-Newton thrusters.



LISA fundamentals: the constellation

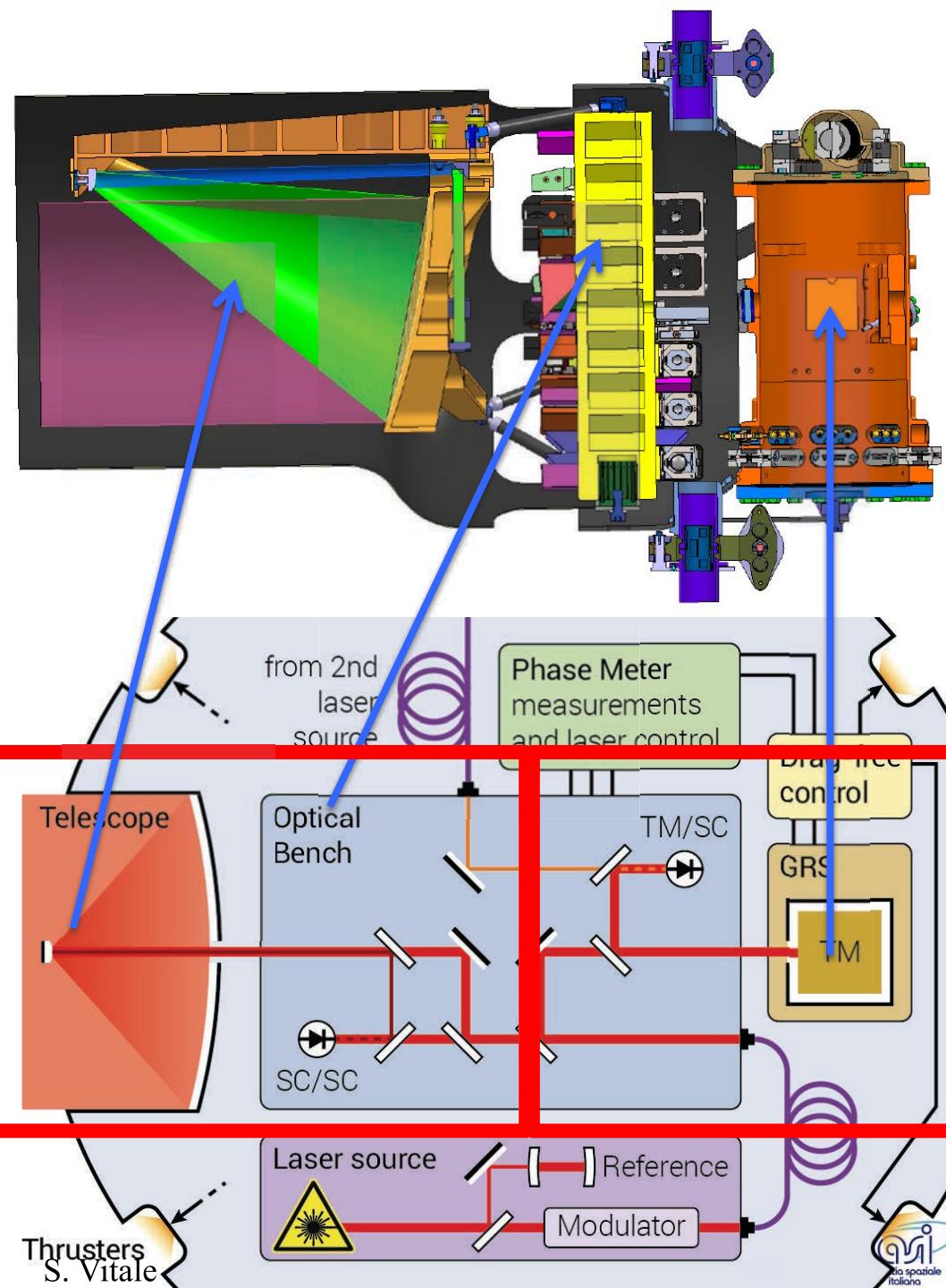
- Satellites follow independent heliocentric orbits.
No formation keeping needed
- Constellation rotates within waves and gives source location



LISA Instrument

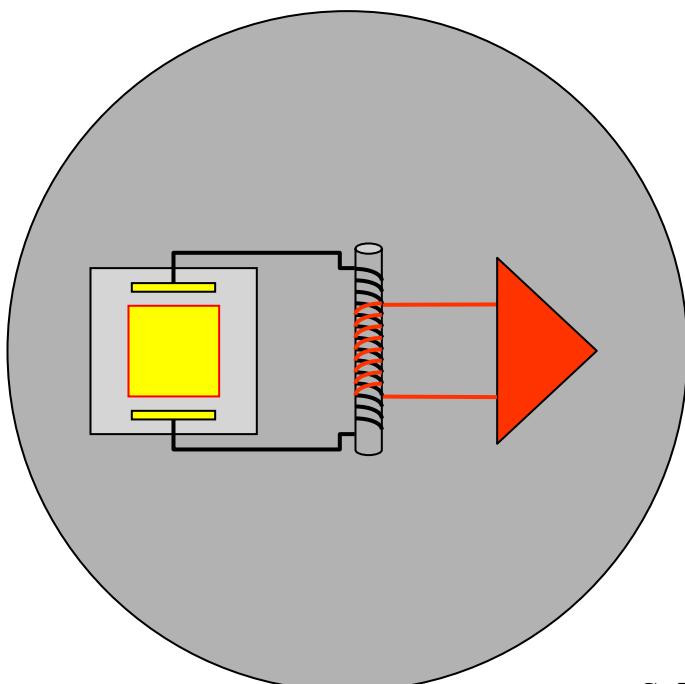
- The Gravitational Reference Sensor with the test-mass

- The Optical Bench with:
 - Local interferometer
 - Spacecraft to spacecraft interferometer, including telescope

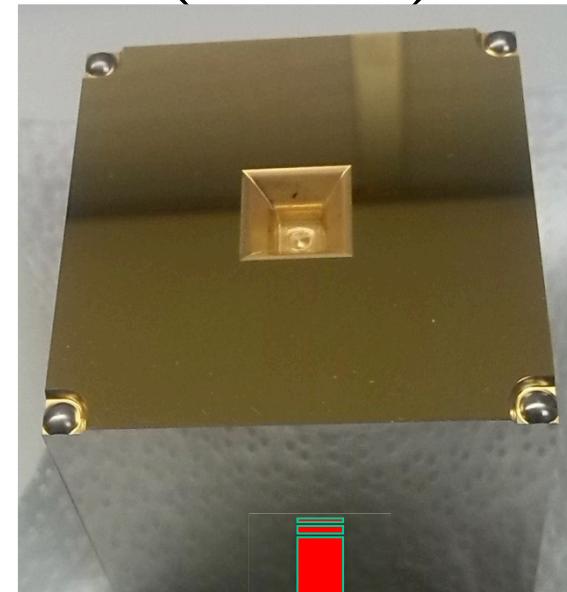


The Gravity reference Sensor (GRS)

- Drag-free along sensitive direction
- Other test-mass degrees of freedom controlled via electrostatic forces
- 3-4 mm clearance between test-mass and electrodes



test-mass

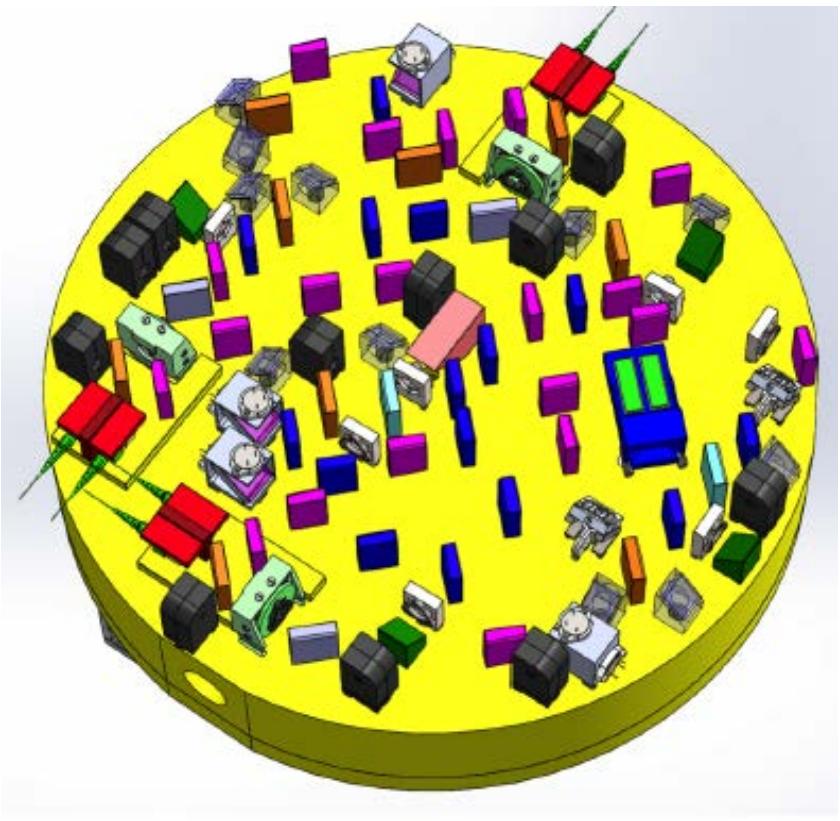
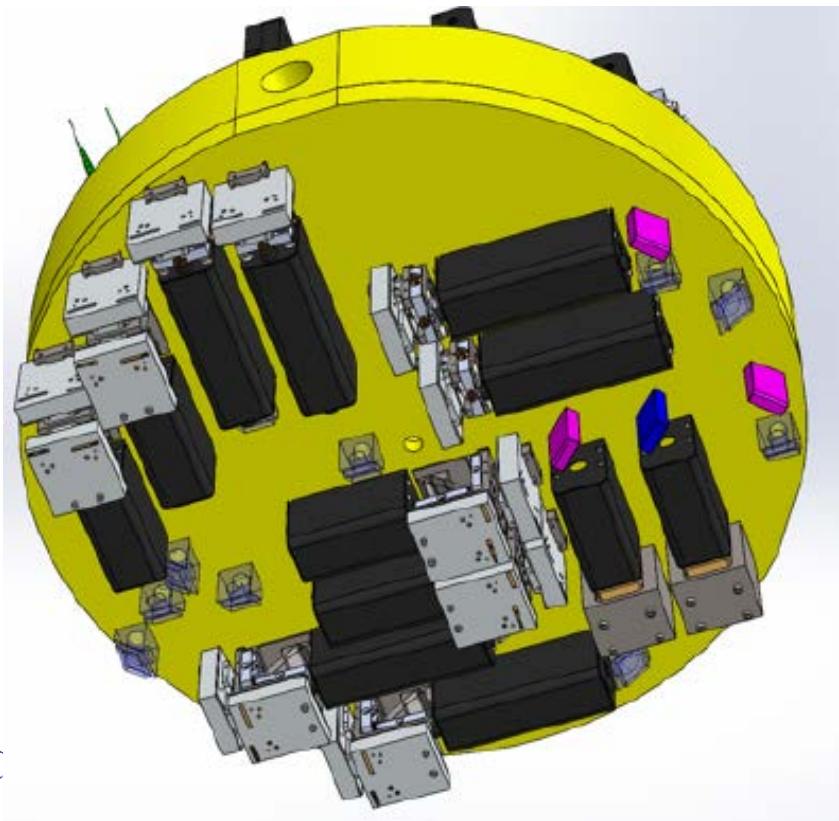


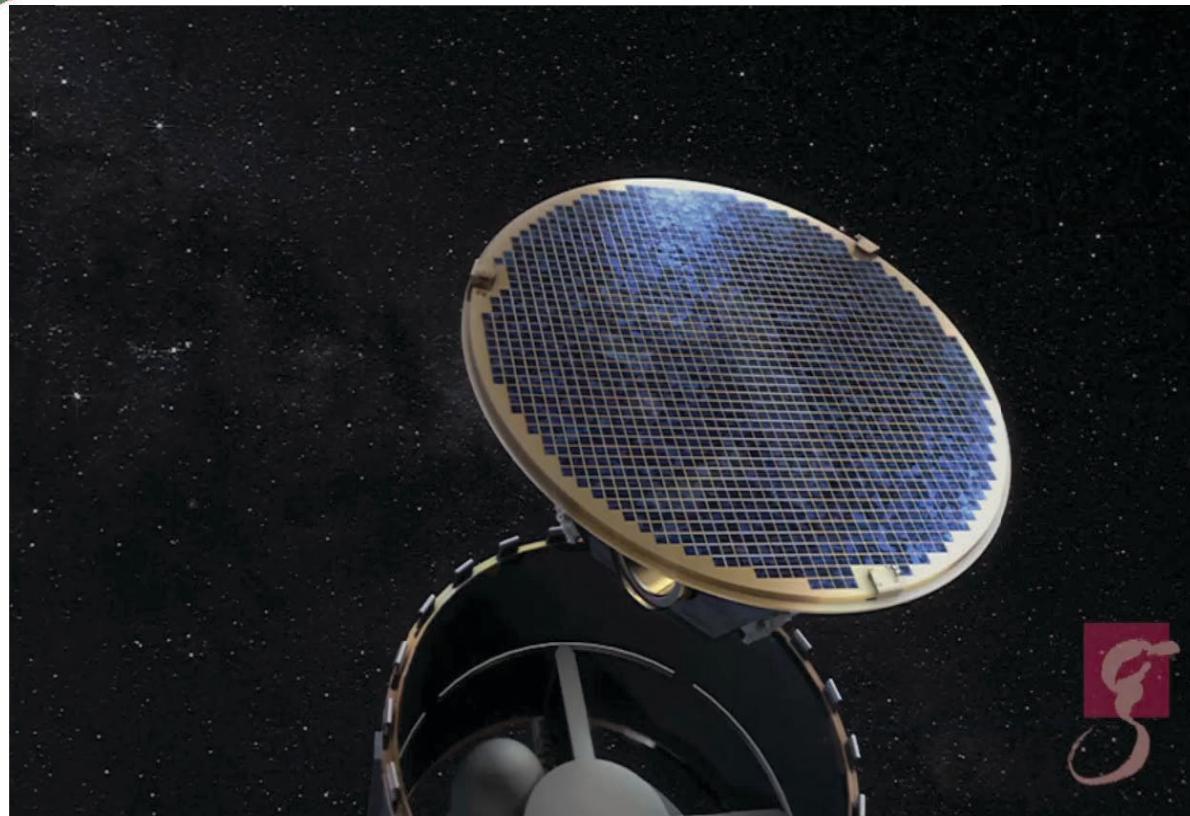
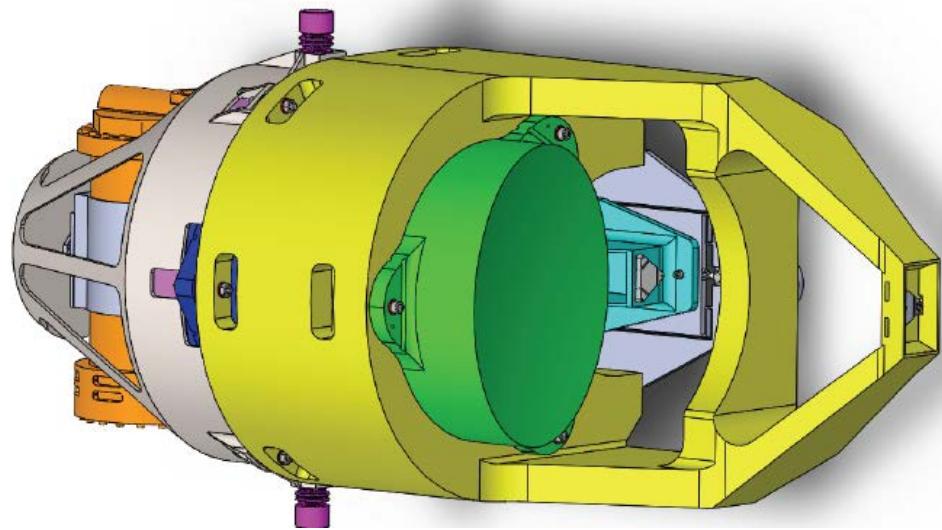
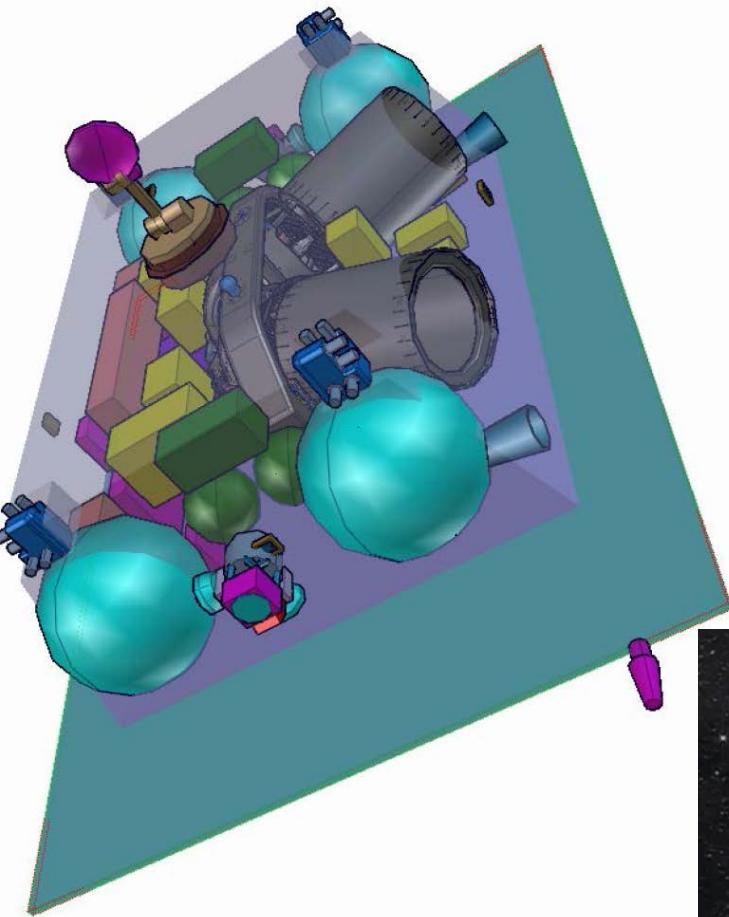
electrode housing



The optical bench

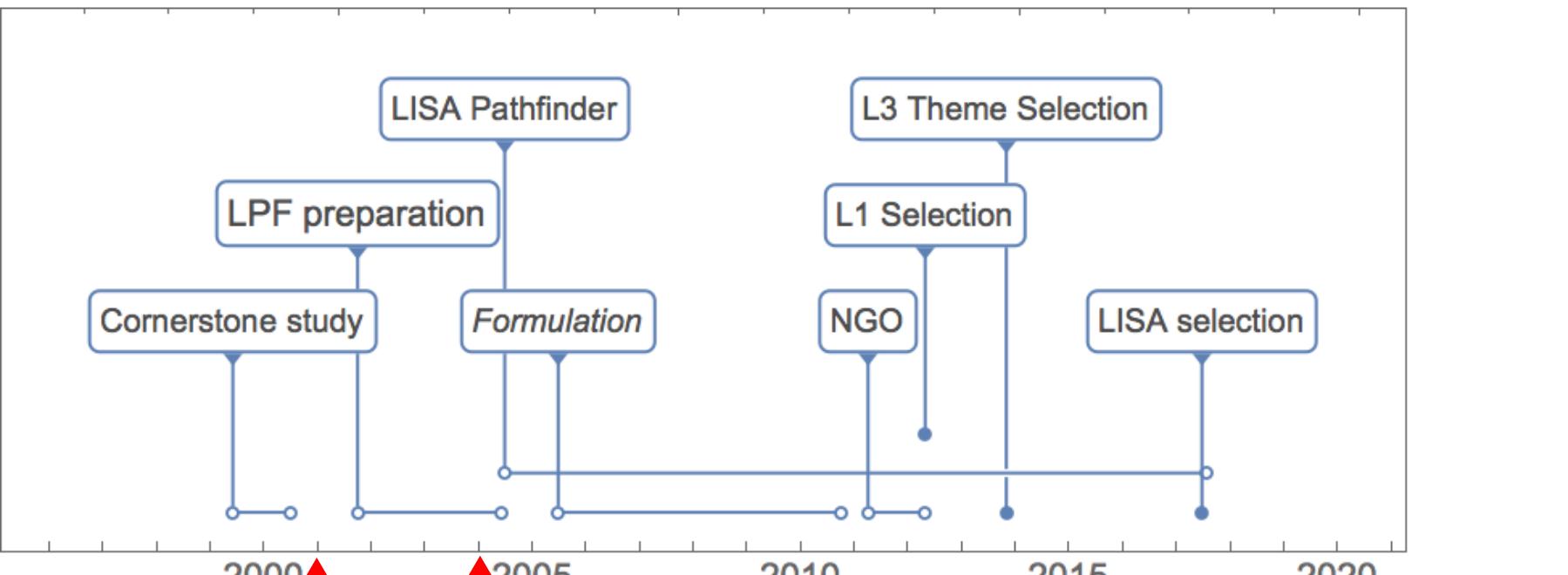
- Carries on all needed interferometry:
 - Satellite-to-satellite
 - Satellite-to- test mass
 - Satellite arm 1-arm 2





How it could
look like

LISA development and LISA Pathfinder



ESA/SSAC(2001)3
Paris, 31 January 2001

Recommendation on SMART 2

The SSAC unanimously endorses the Executive's proposal to use the SMART 2 mission, as currently scheduled, as a timely opportunity to test the technologies which are crucial to the LISA cornerstone mission, and to also test within the same mission elements of the technologies needed for the DARWIN/IRSI cornerstone.

BBC NEWS

Last Updated: Thursday, 24 June, 2004, 13:07 GMT 14:07 UK

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Mission's path to new astronomy

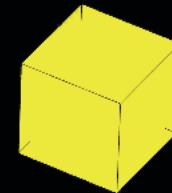
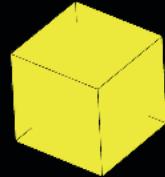
By Jonathan Amos
BBC News Online science staff

The contract has been signed that will lead to the building of one of the most ambitious space missions ever flown.

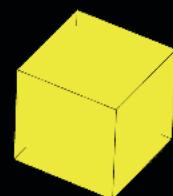
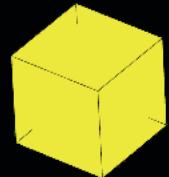
The Lisa Pathfinder will demonstrate technologies that will be necessary to detect gravitational waves in space.



free falling masses: must accelerate just because of curvature



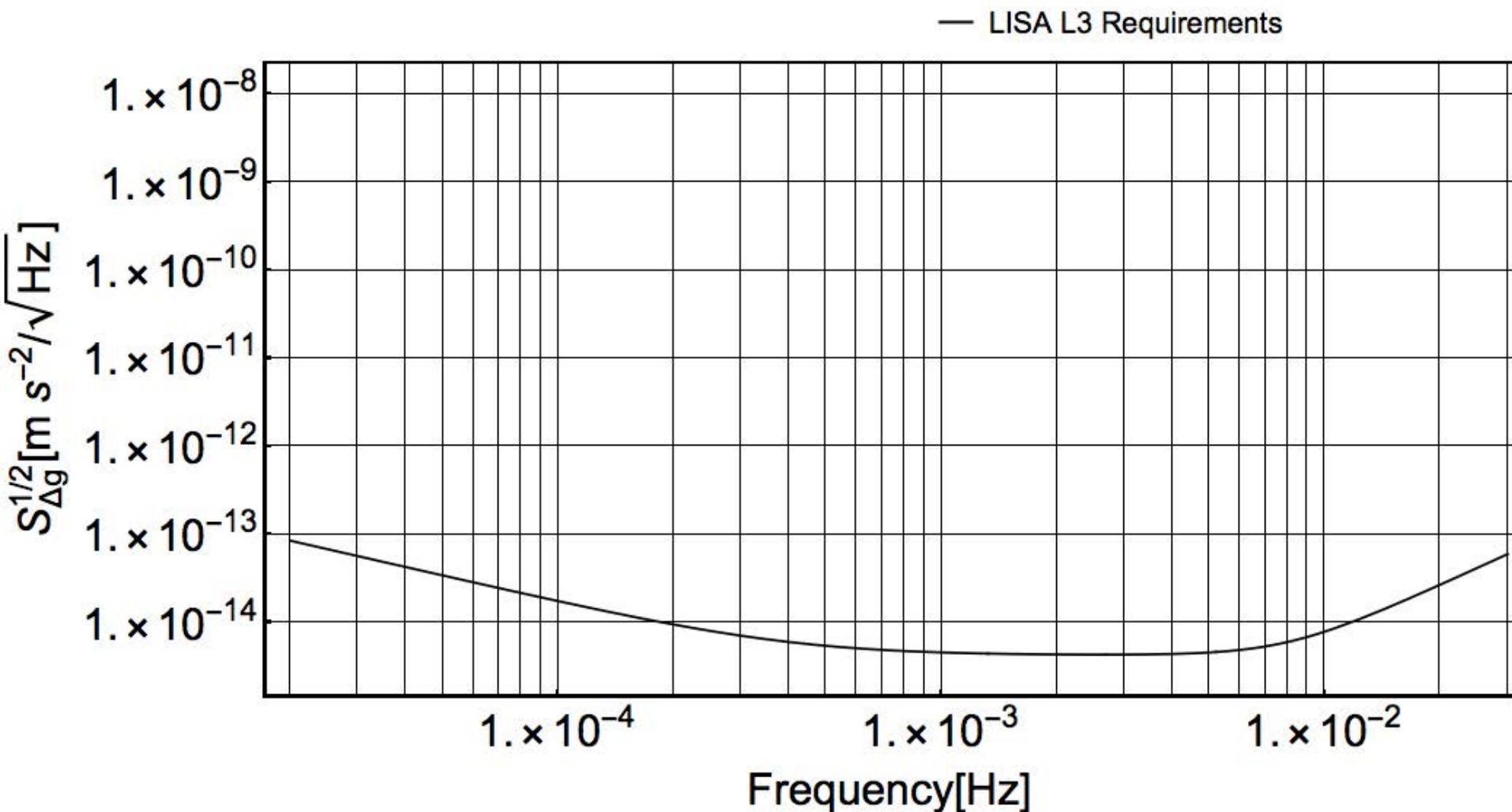
Accelerations relative to local frames must be negligible





Sub-femto-g force suppression for LISA

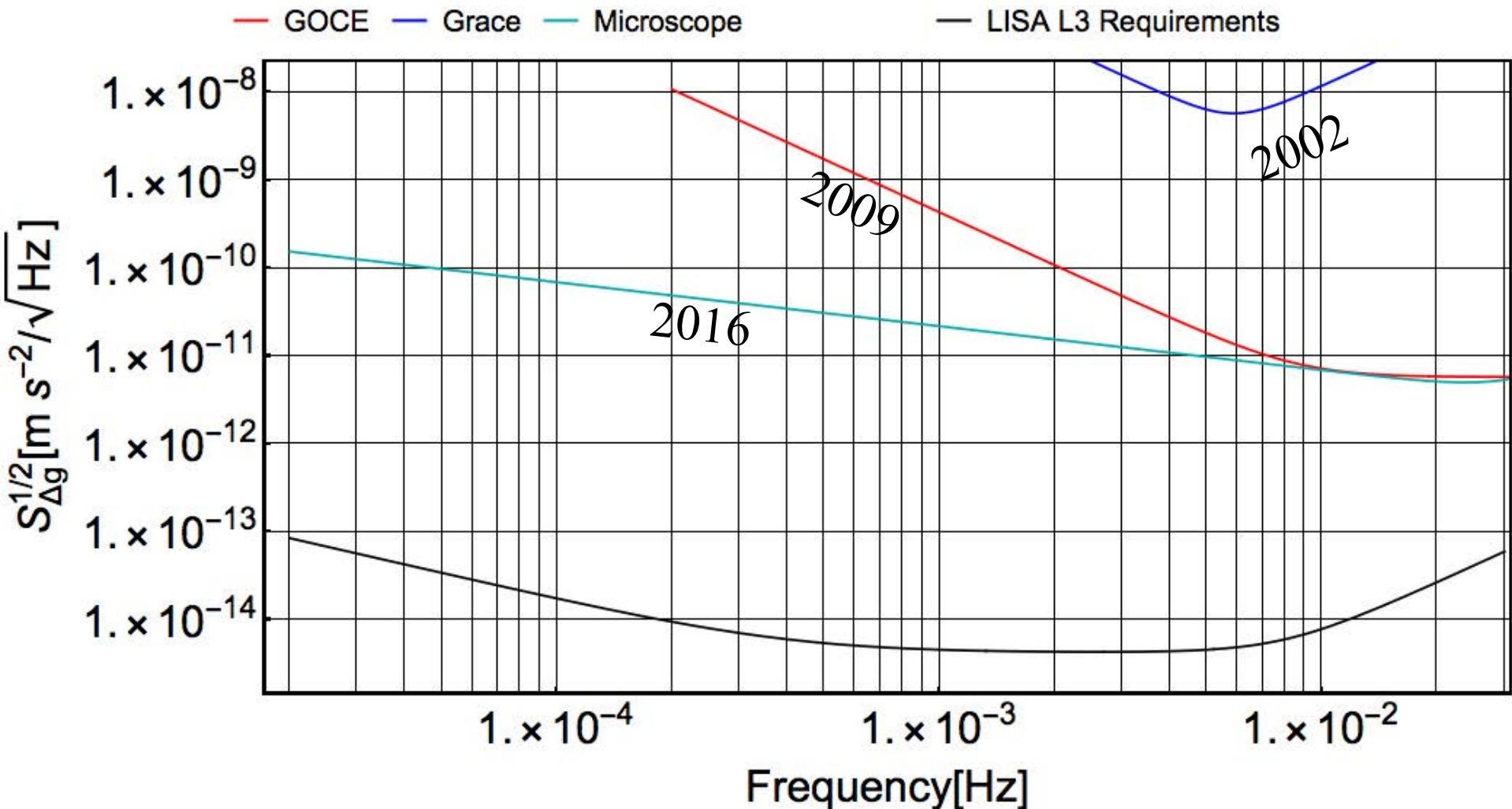
- Cannot be tested on ground $\lesssim 0.1$ Hz





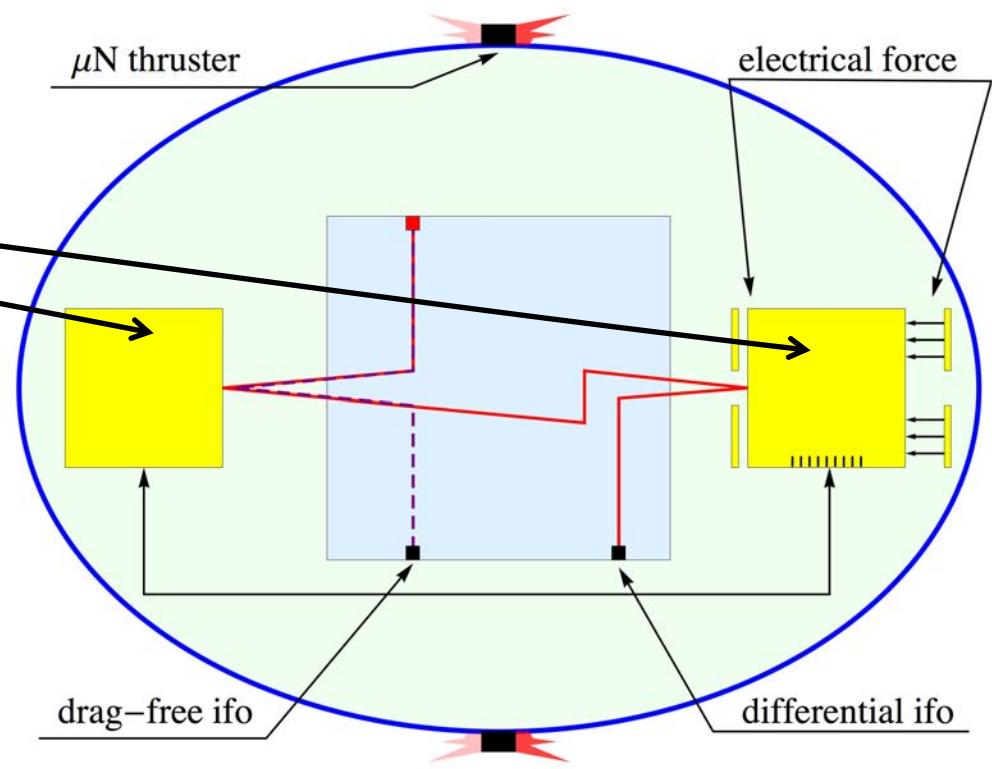
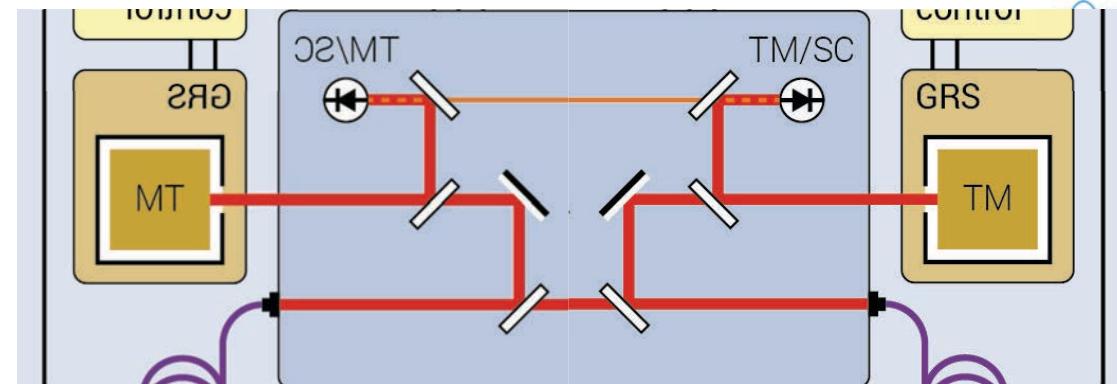
Sub-femto-g force suppression for LISA

- Cannot be tested on ground $\lesssim 0.1$ Hz
- (>3) Orders of magnitude better than any other space mission



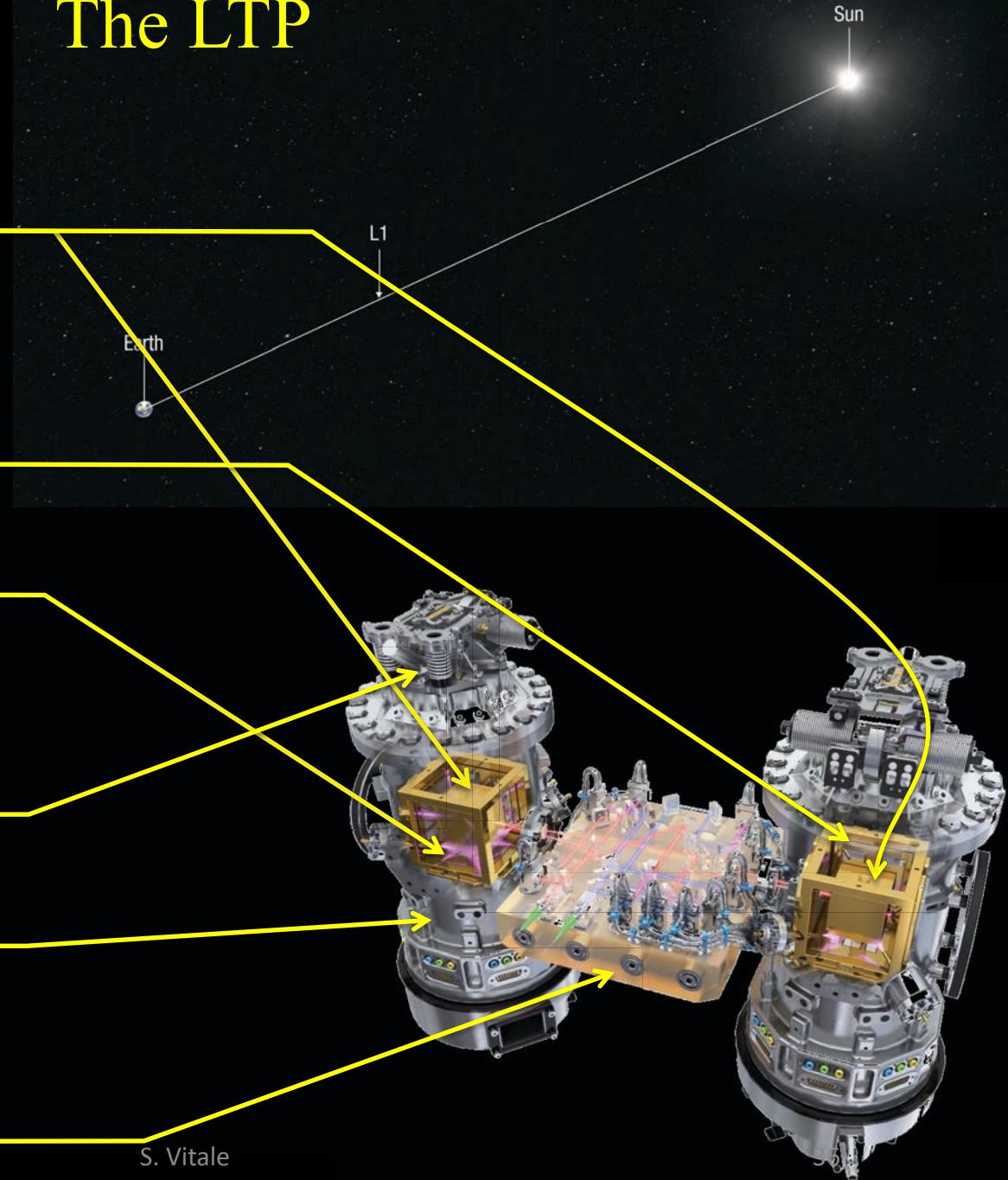
LISA Pathfinder concept

- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- ~~2 Interferometers (Ifo)~~
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



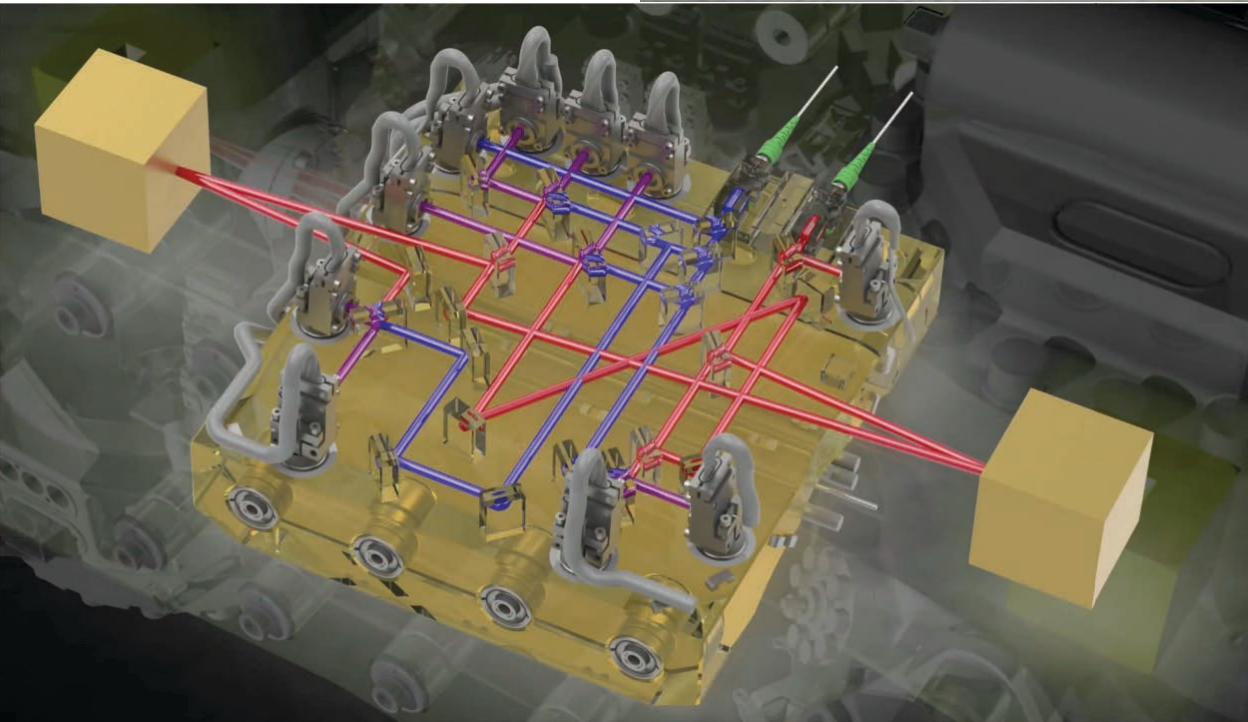
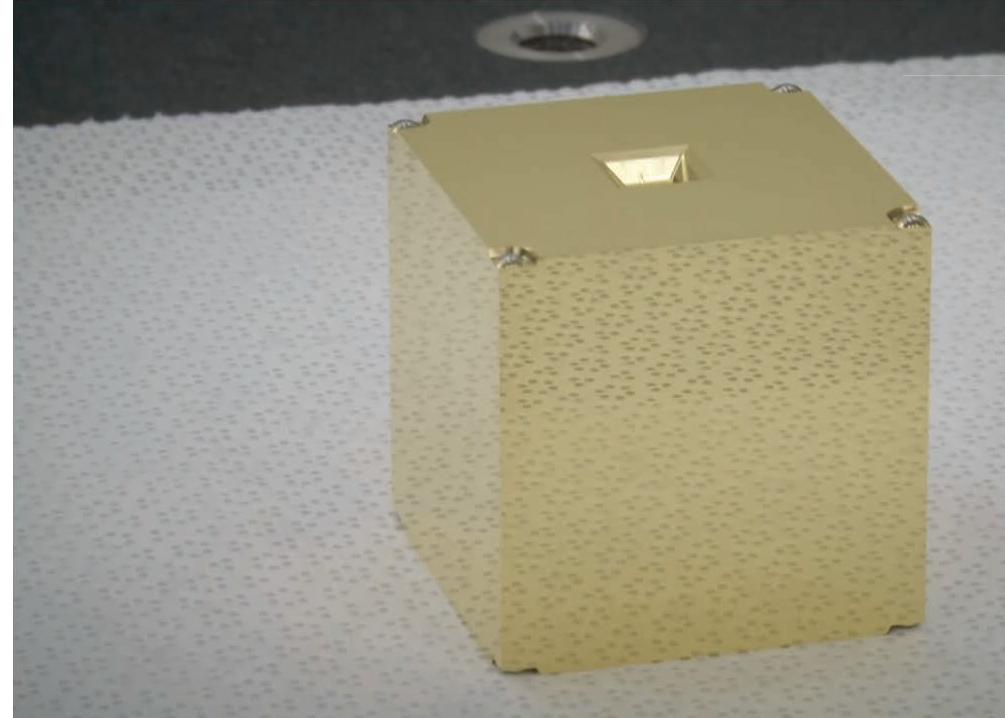
The LTP

- 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



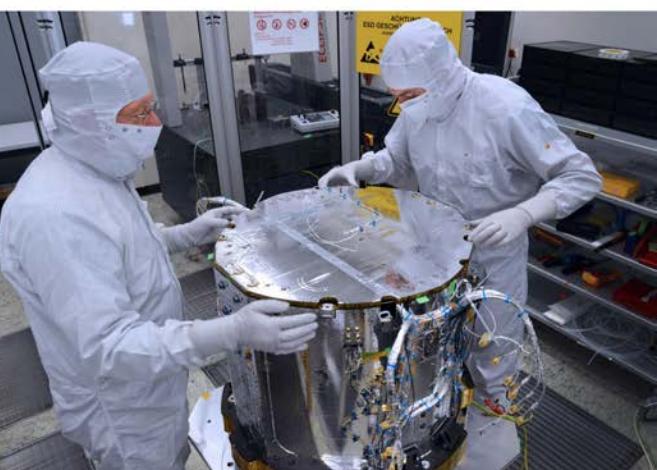
Test-mass and accessories: the gravity reference sensor

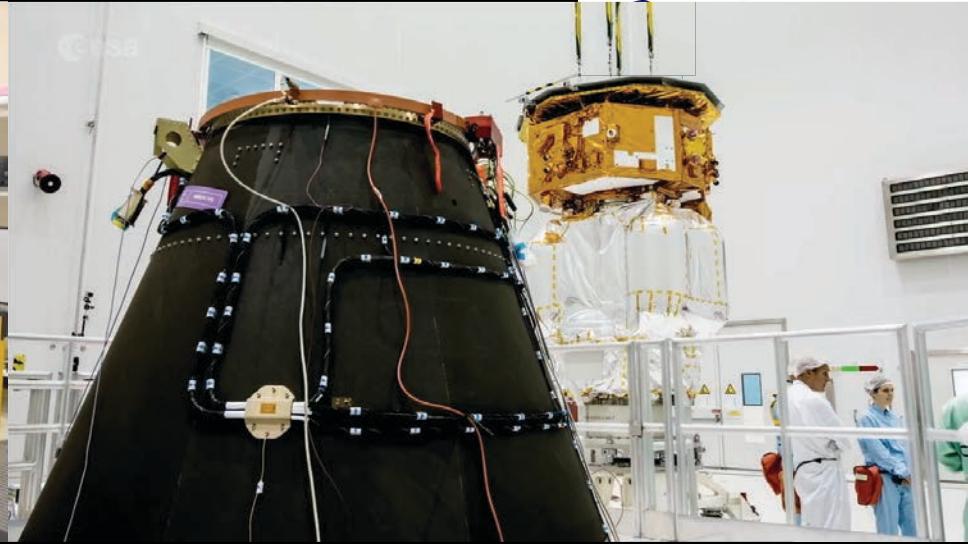
CGS-OHB, U.Trento-INFN, ETH
Zurich, Ruag, TAS-I, Imperial College,
IEEC



Laser interferometer

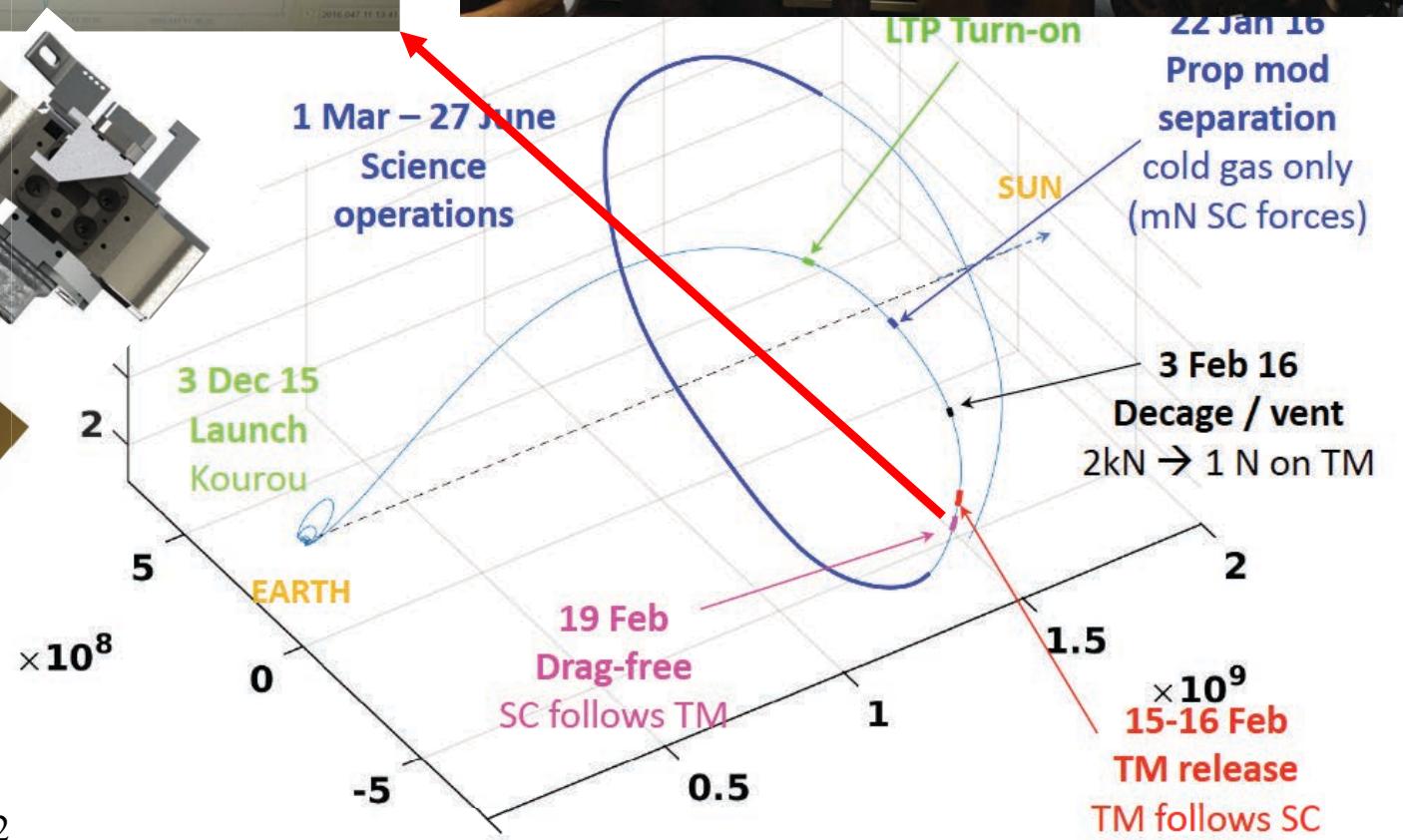
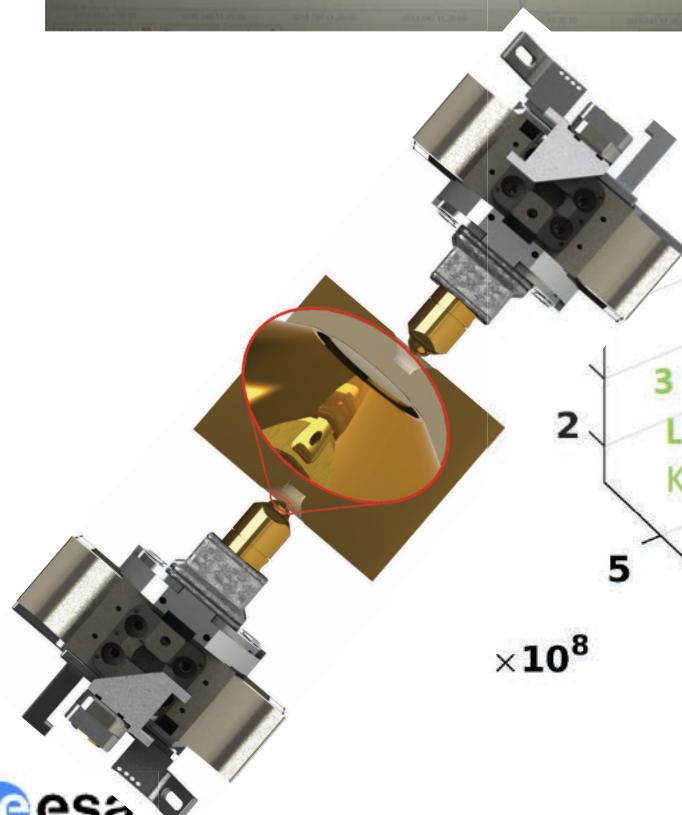
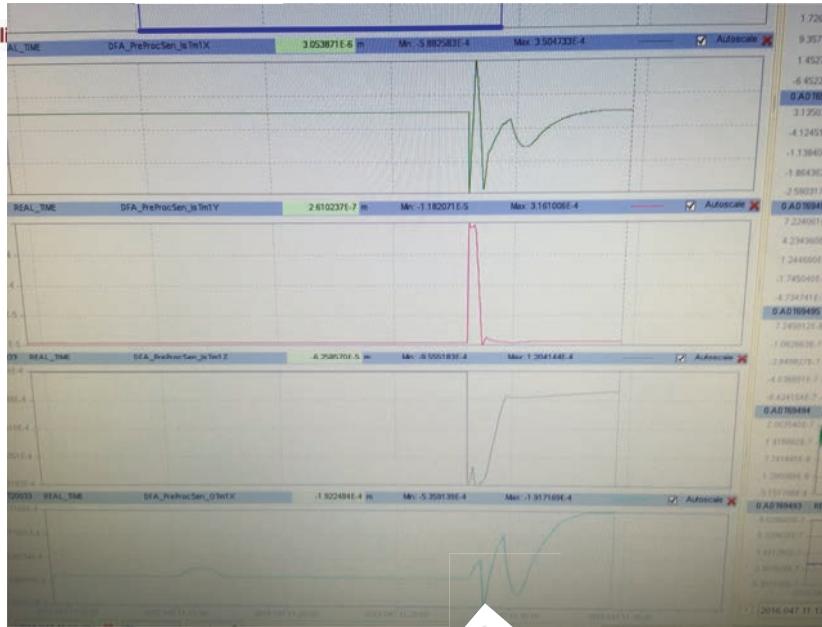
U. Glasgow, AEI-Max Planck, U.
Birmingham, AIRBUS DS, APC-
CNRS, IEEC,





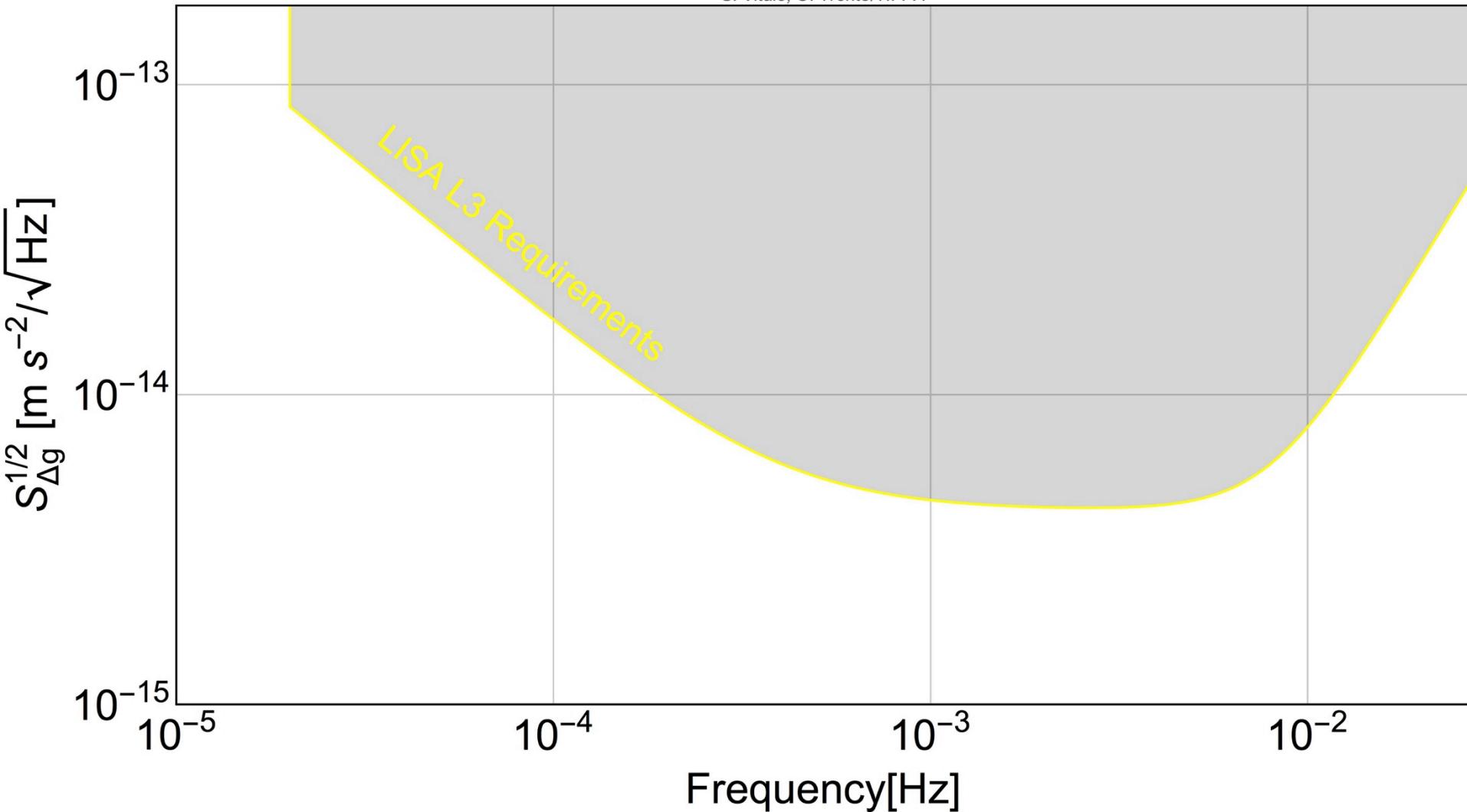
From instrument integration to
beginning of operations 2014-2016





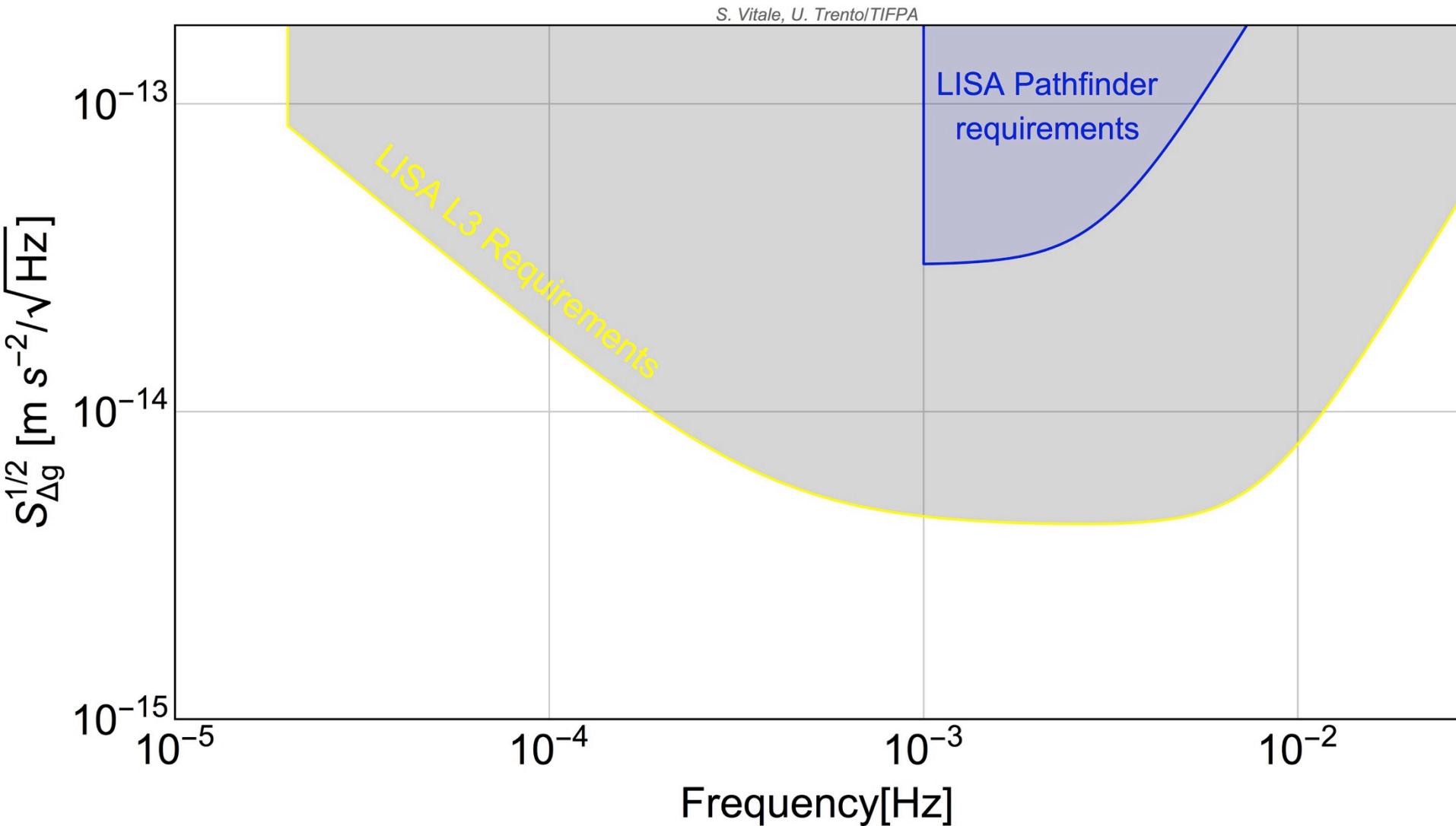
LISA (L3) disturbance acceleration requirements

S. Vitale, U. Trento/TIFPA



LISA Pathfinder requirements

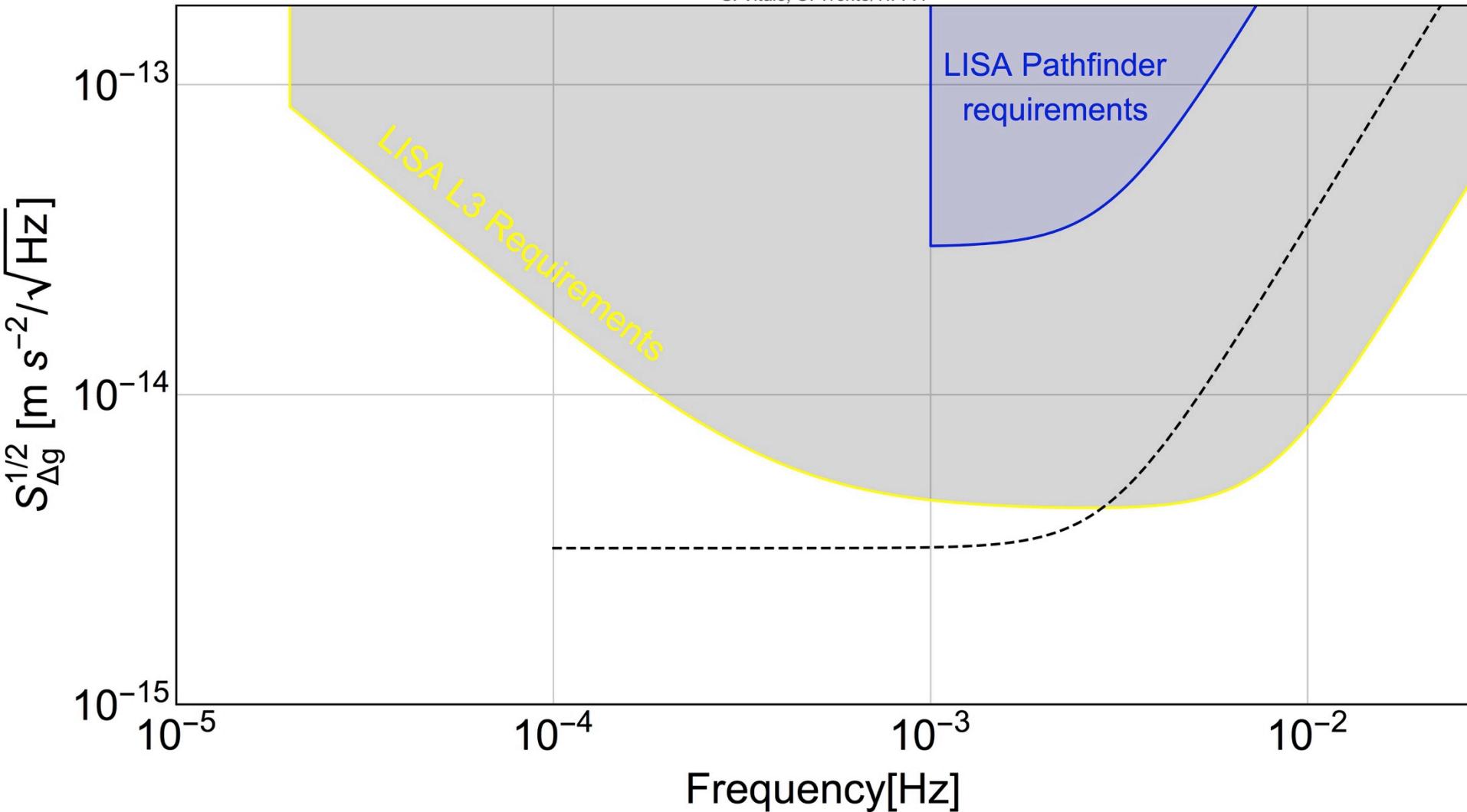
- Amplitude requirement relaxed because single spacecraft experiment more noisy
- Frequency requirement relaxed to cut down ground testing time



LISA Pathfinder requirements

- Amplitude requirement relaxed because single spacecraft experiment more noisy
- Frequency requirement relaxed to cut down ground testing time
- Interferometer requirements maintained at $9 \text{ pm}/\sqrt{\text{Hz}} \sim$ as in LISA

S. Vitale, U. Trento/TIFPA



What were we expecting?

Class. Quantum Grav. **28** (2011) 094002F Antonucci *et al*

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

Source	PSD ($\text{fm s}^{-2} \text{Hz}^{-1/2}$)	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 $\overleftrightarrow{\delta D}$ and $\overleftrightarrow{\delta C}$
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 2. Leading sources of differential force-per-unit-mass disturbances and their PSD values at 1 mHz.

Source	PSD ($\text{fm s}^{-2} \text{Hz}^{-1/2}$)	Estimated from
Actuation, x -axis	10.1	Measurement of flight-model electronics stability
Brownian	7.2	Measurement with torsion pendulum

- Two dominating sources:
 - Actuation noise:
 - Electrostatic force is noisy, as voltage fluctuates.
 - Noise scales with setting of maximum force g_{\max} you are prepared to counteract: the larger you set g_{\max} the larger the noise
 - Brownian noise:
 - Random collisions with gas molecules
 - Noise scales with pressure: more pressure more noise

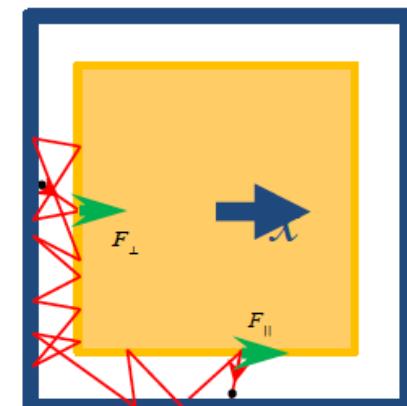
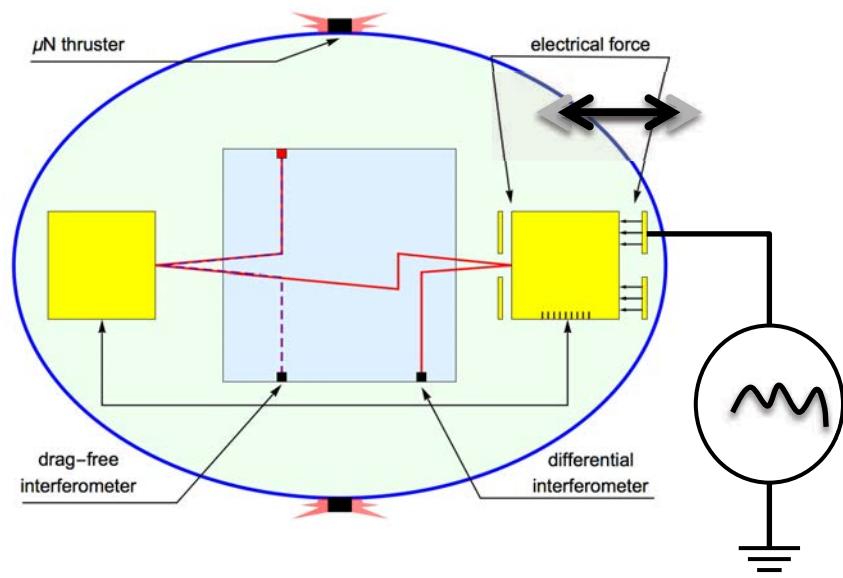


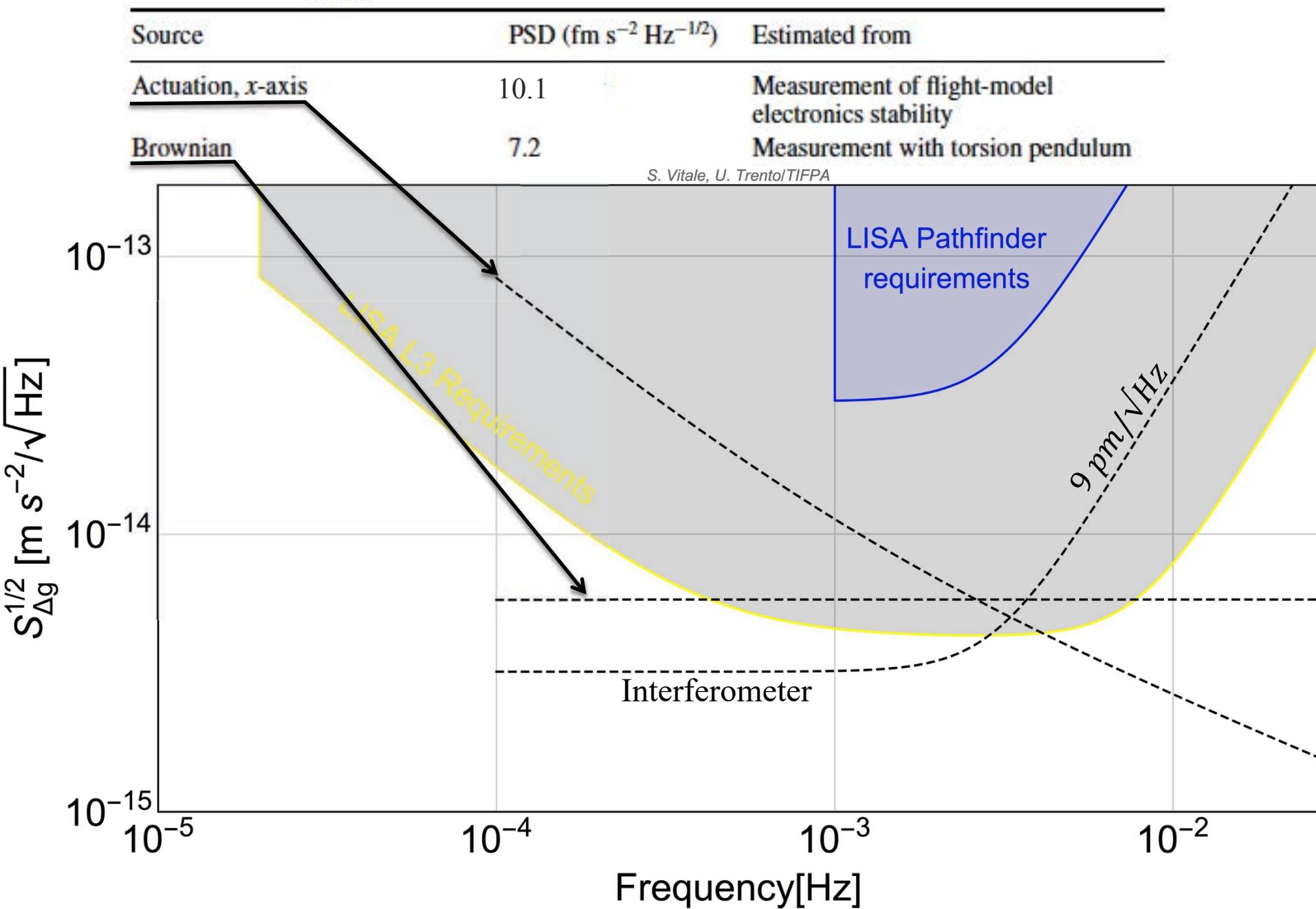
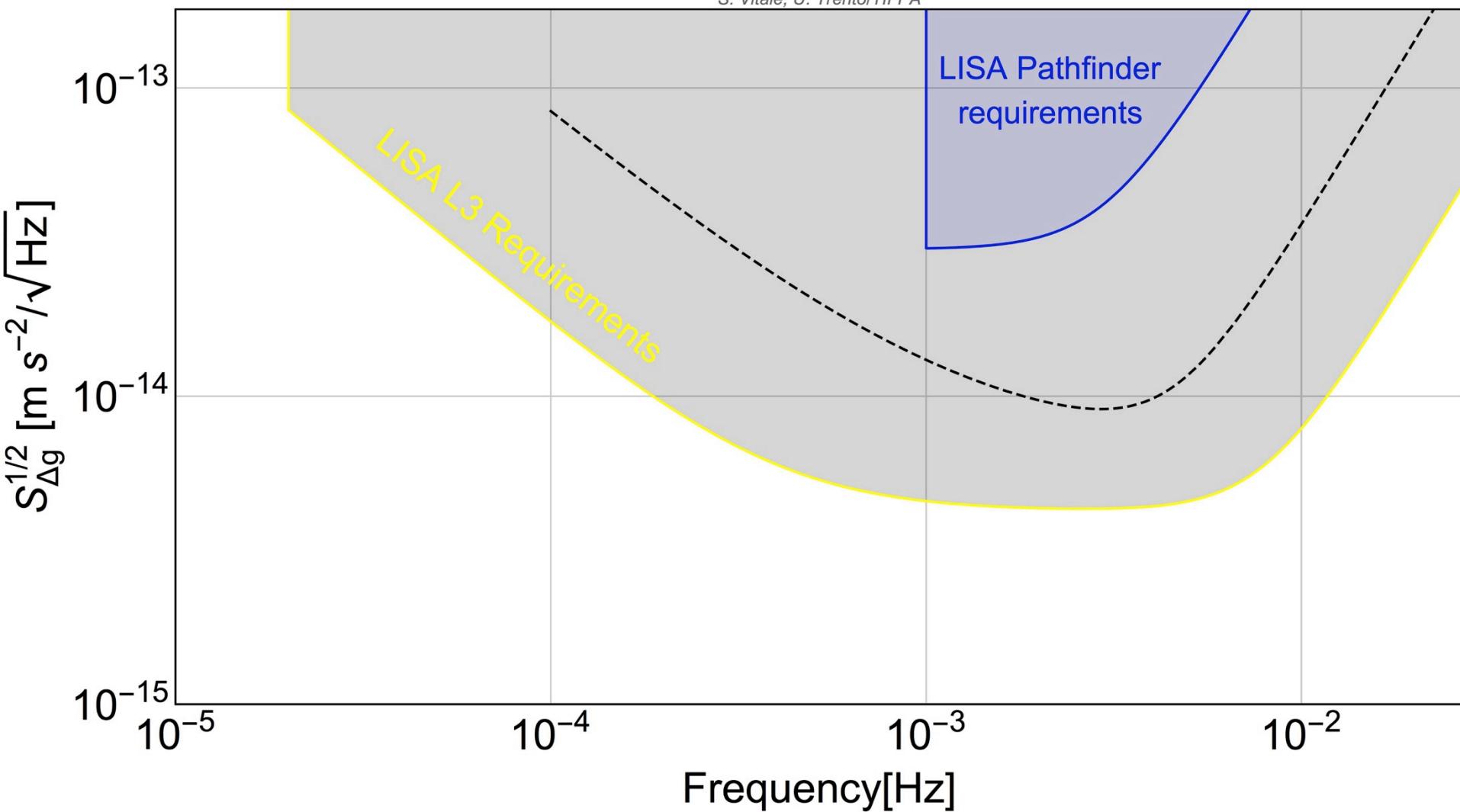
Table 2. Leading sources of differential force-per-unit-mass disturbances and their PSD values at 1 mHz.

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

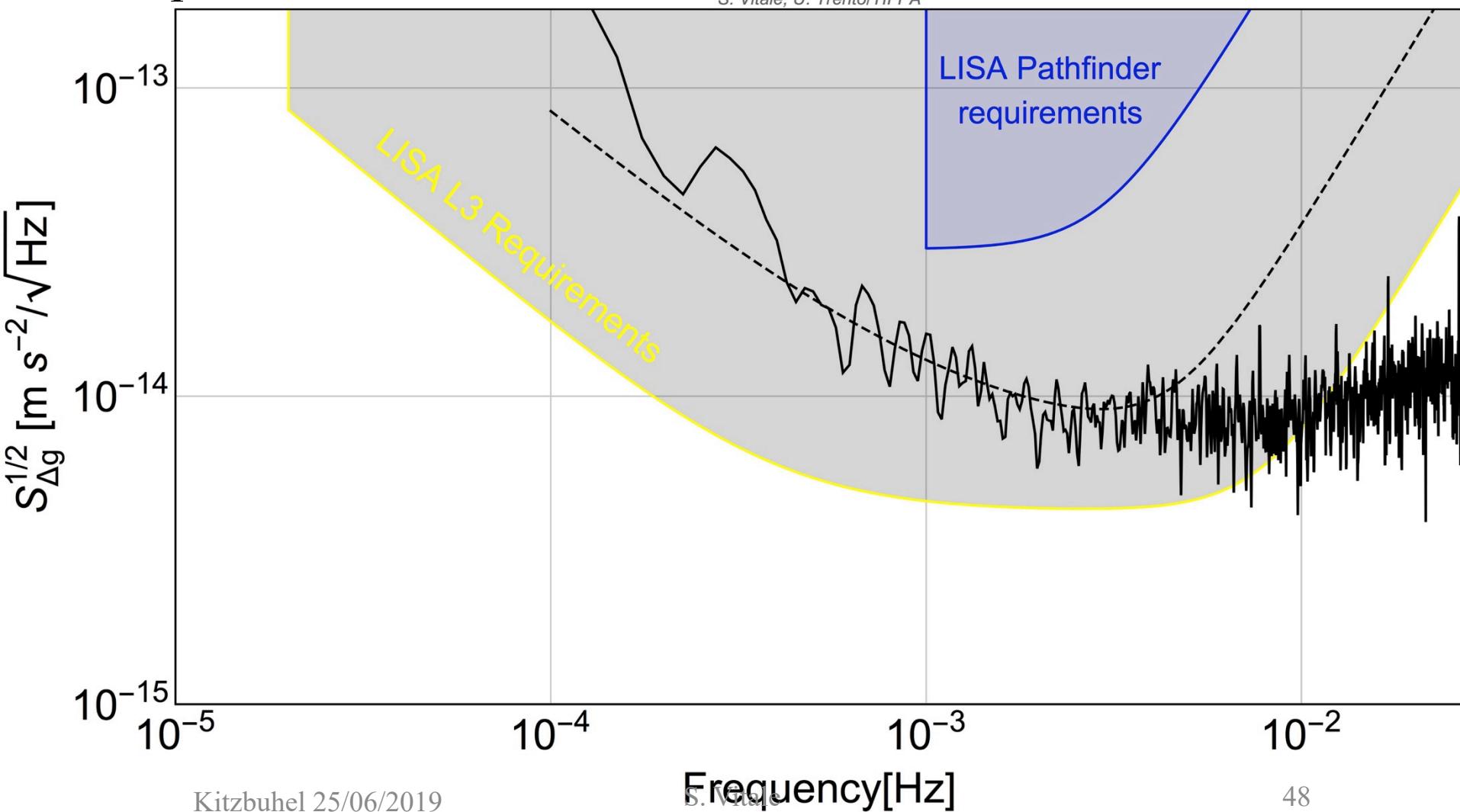
Source	PSD ($\text{fm s}^{-2} \text{Hz}^{-1/2}$)	Estimated from
Actuation, x -axis	10.1	Measurement of flight-model electronics stability
Brownian	7.2	Measurement with torsion pendulum

S. Vitale, U. Trento/TIFPA



- Better than requirement.
- Close to prediction
- Except interferometer noise at 35 fm/ $\sqrt{\text{Hz}}$!

S. Vitale, U. Trento/TIFPA



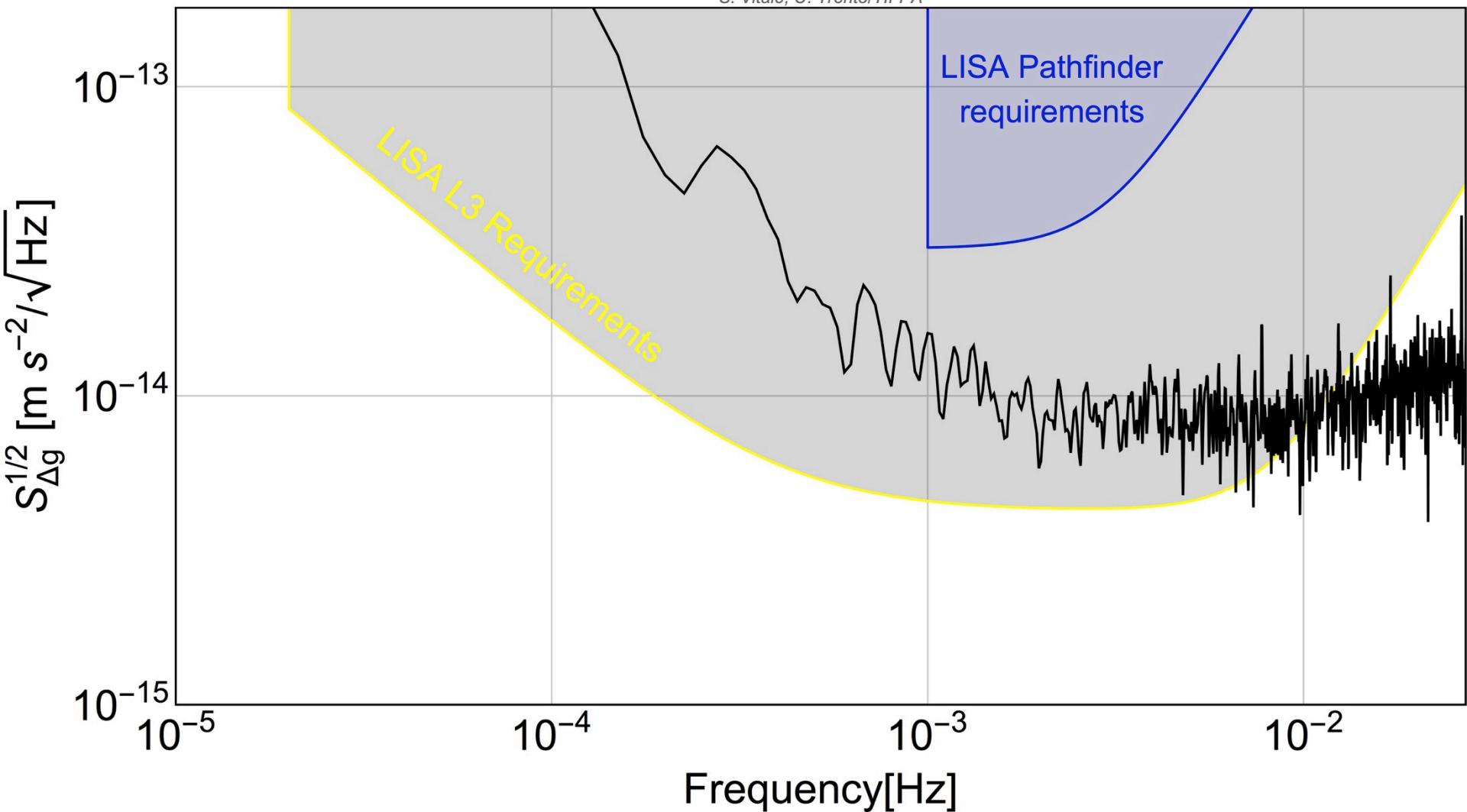
Gravitational control and actuation

- Electrostatic force mostly compensates gravitational force
 - Gravitational force canceled in dead reckoning with ~ 1.8 kg balance mass
 - Specification $g_{\max} < 650 \text{ pm s}^{-2}$ ($3 \sigma +$ margin)



Authority: 650 pm s^{-2}

S. Vitale, U. Trento/TIFPA



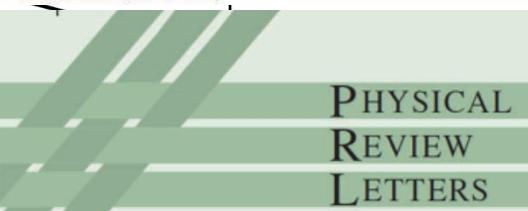
Gravity probe exceeds performance goals

By Jonathan Amos
BBC Science Correspondent, Boston

© 18 February 2017 Science & Environment

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The long-planned LISA space mission to detect gravitational waves looks as though it will be green lit shortly.



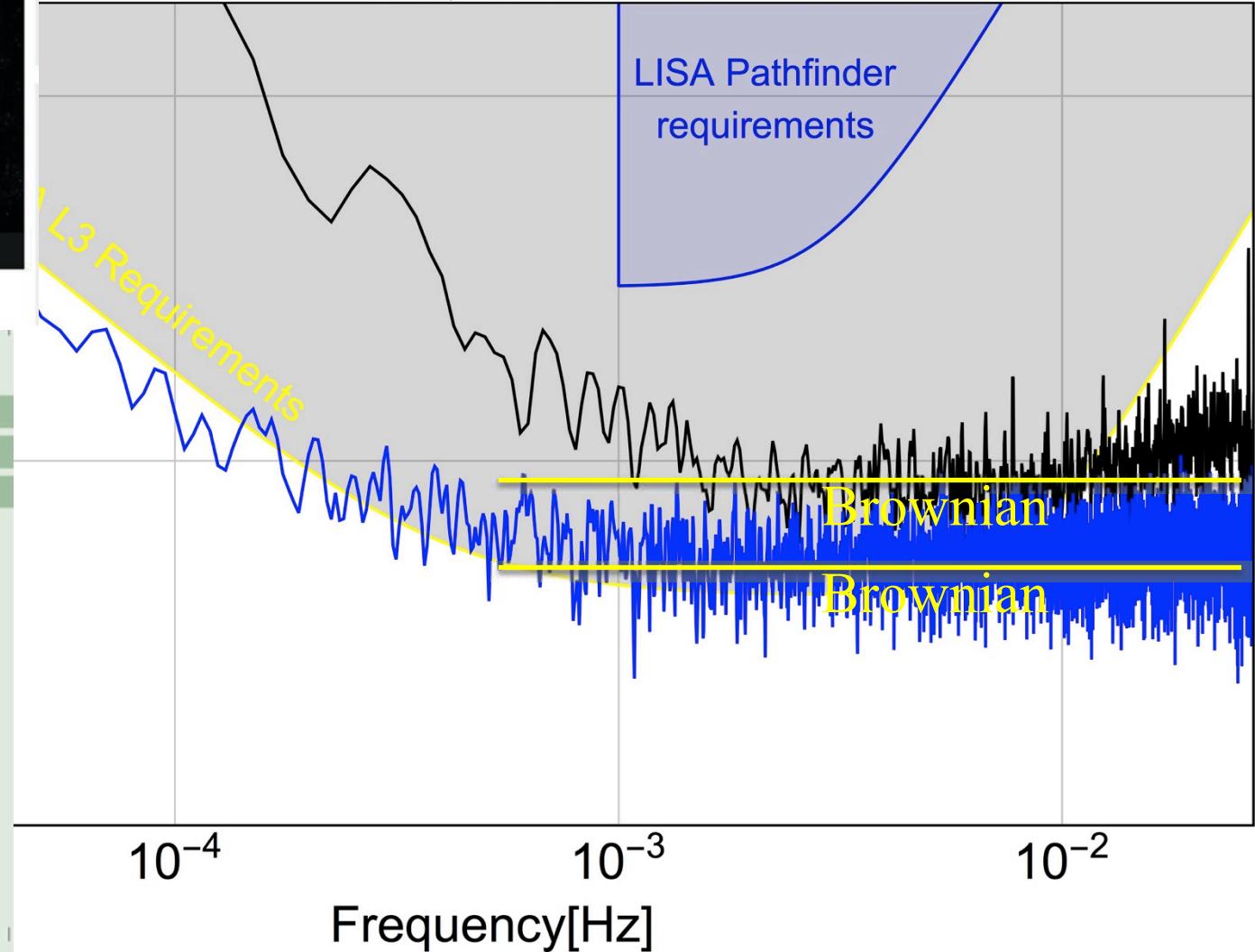
April 2016

iced to 50 pm s^{-2}

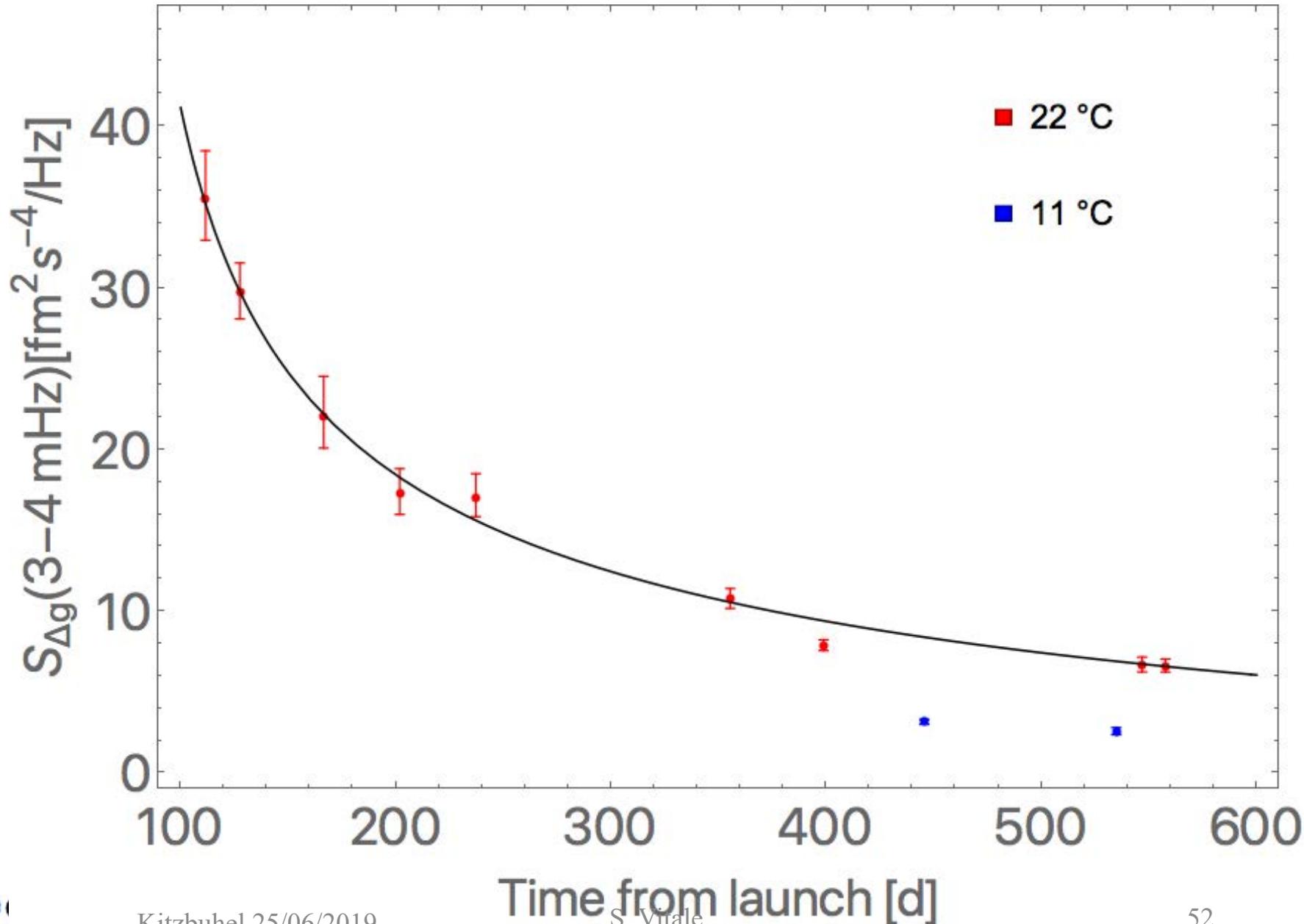
June 2016

Brownian decaying thanks to venting to space

S. Vitale, U. Trento/TIFPA



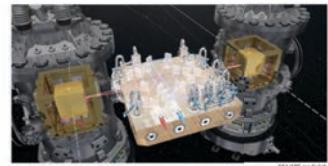
Pressure and Brownian decay



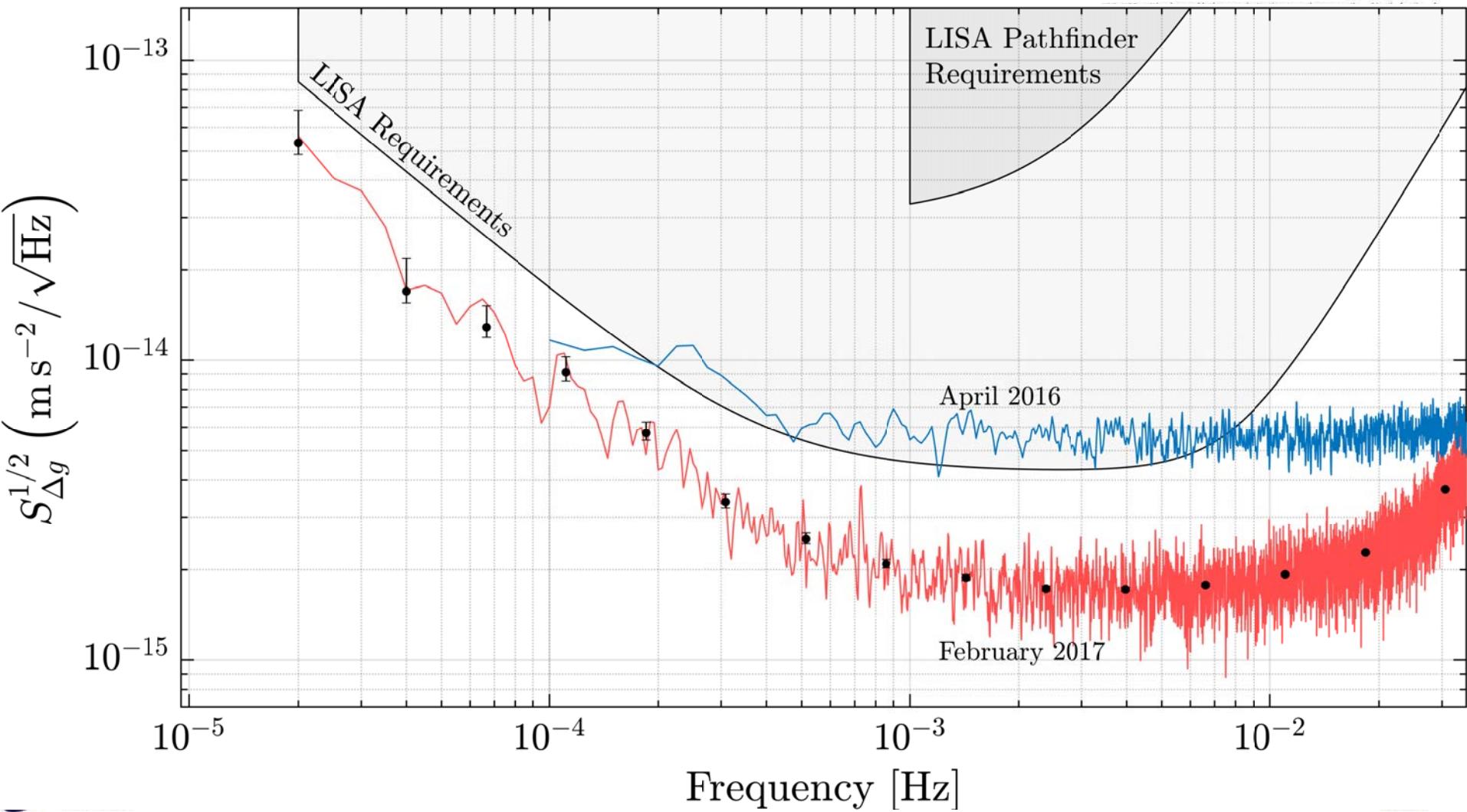


February 5, 2018

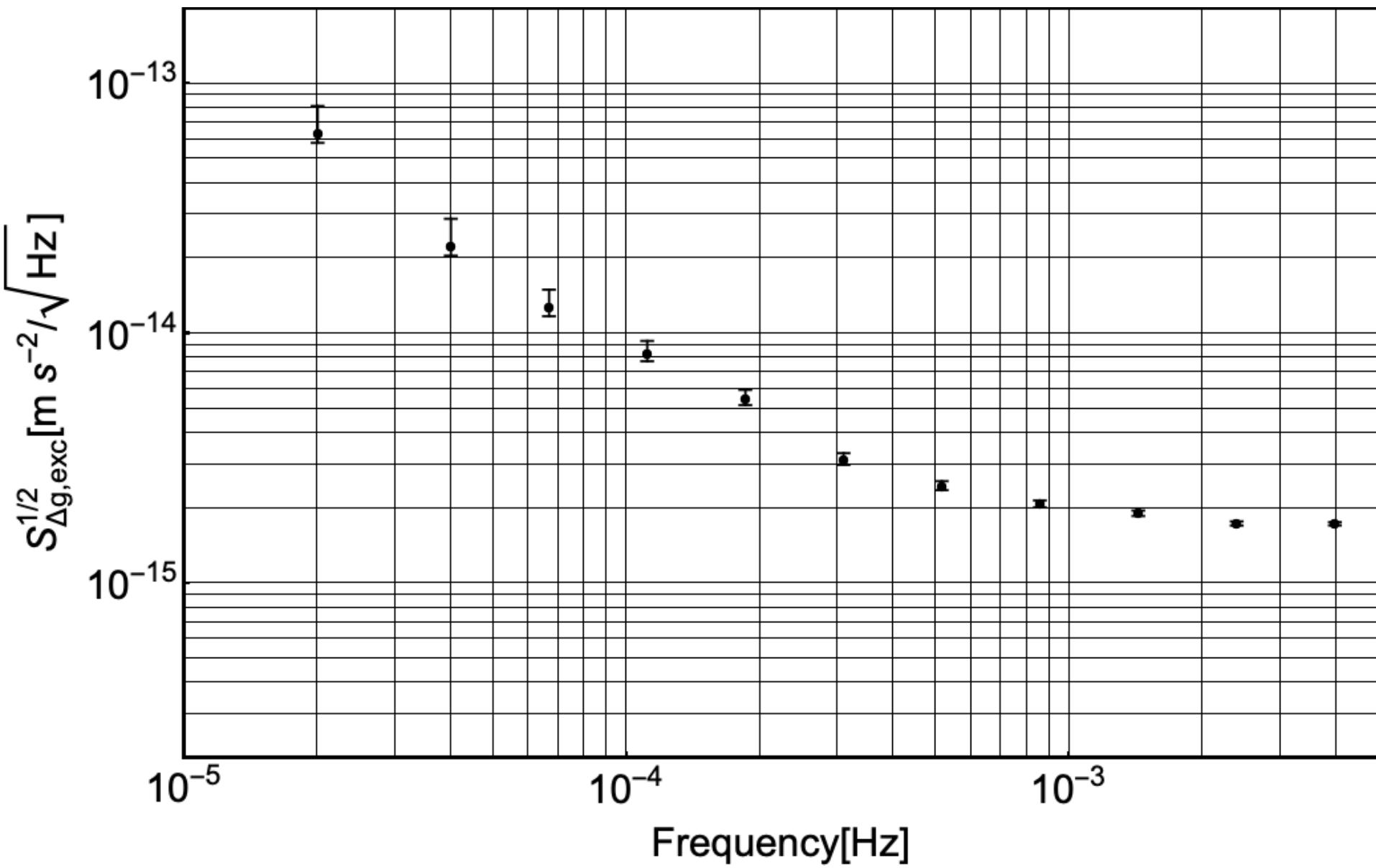
The final results from LISA Pathfinder show that the satellite's technology meets the requirements for space-based gravitational-wave detection.



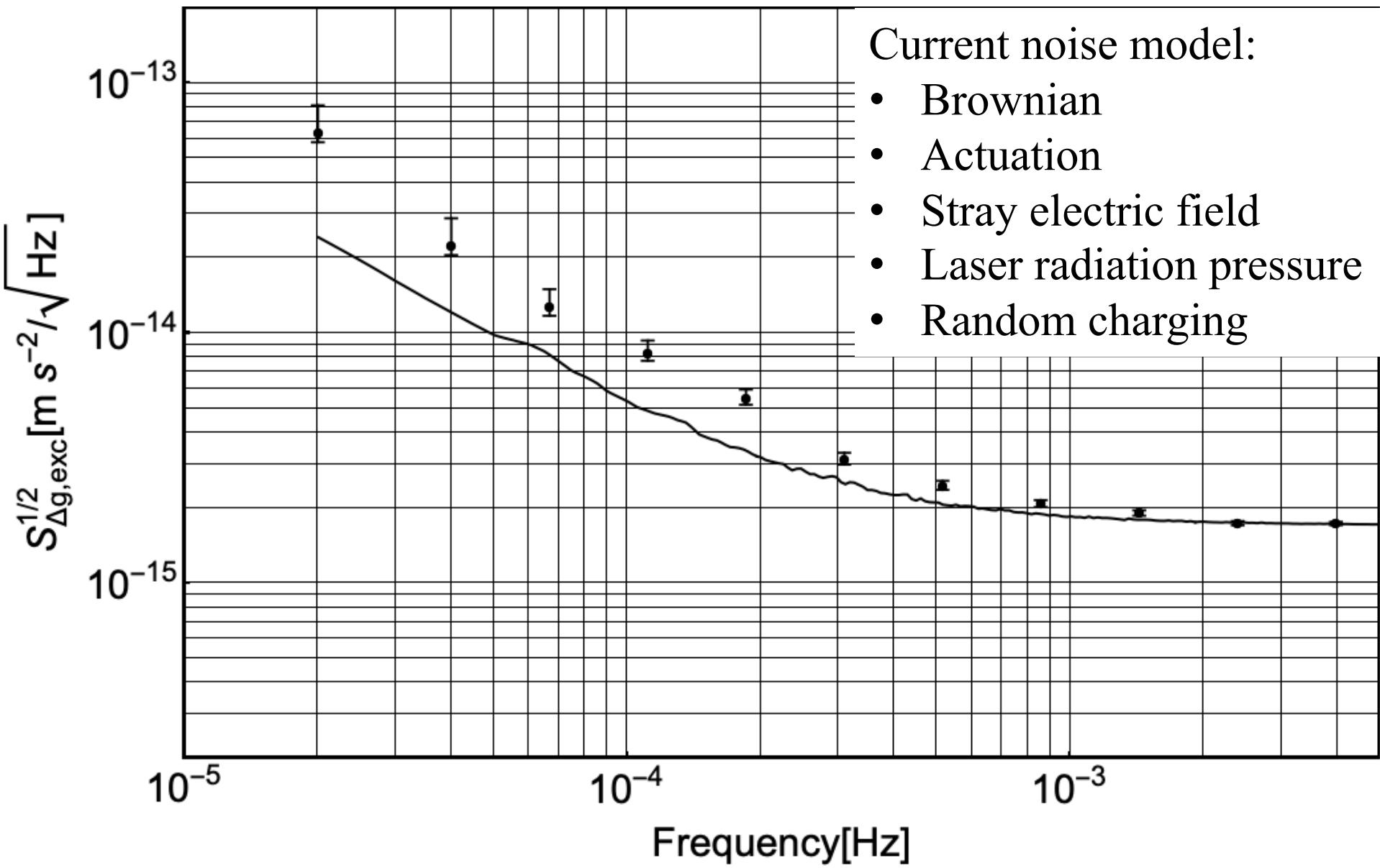
The ultimate performance



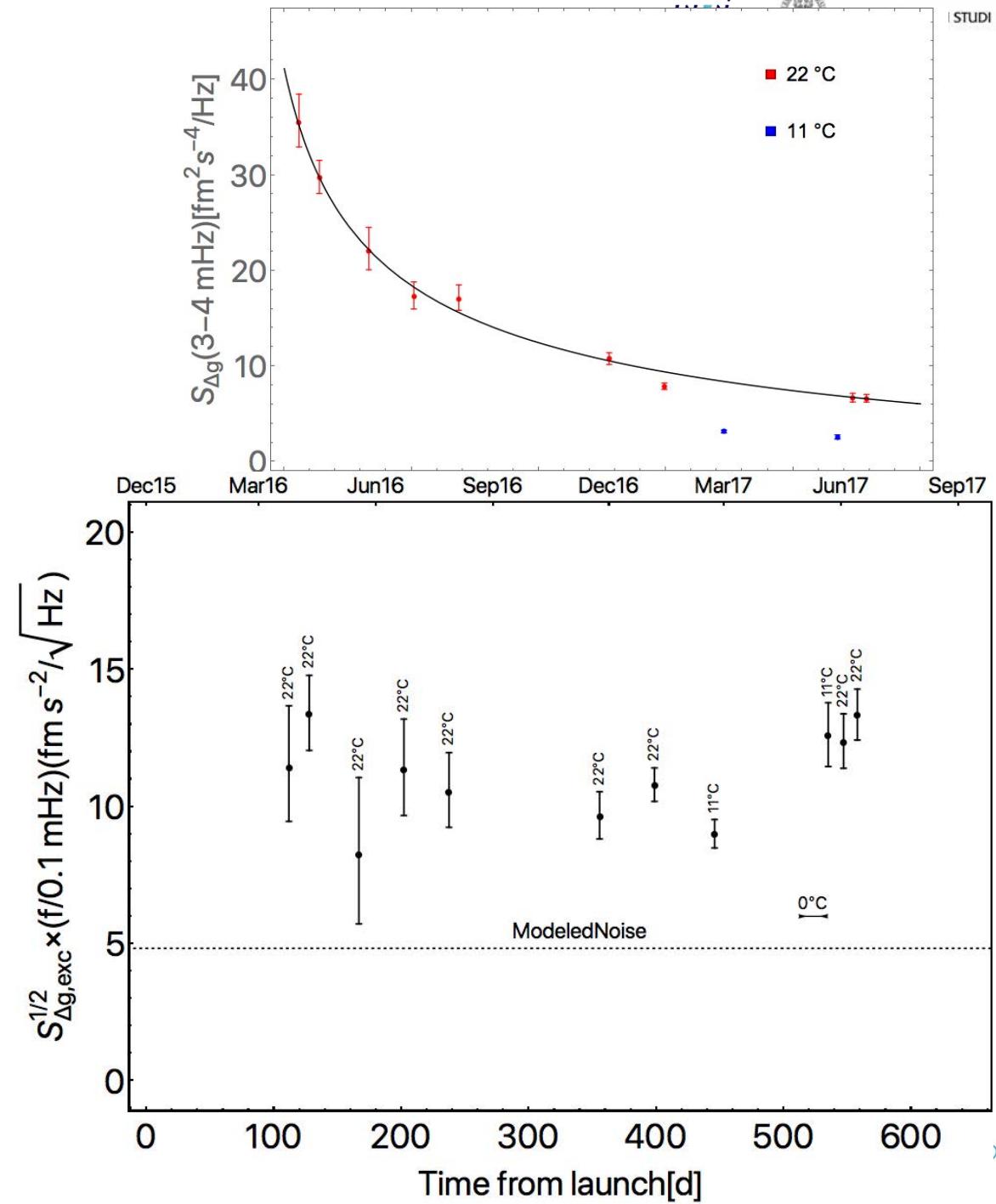
The low frequency tail



Noise excess under investigation

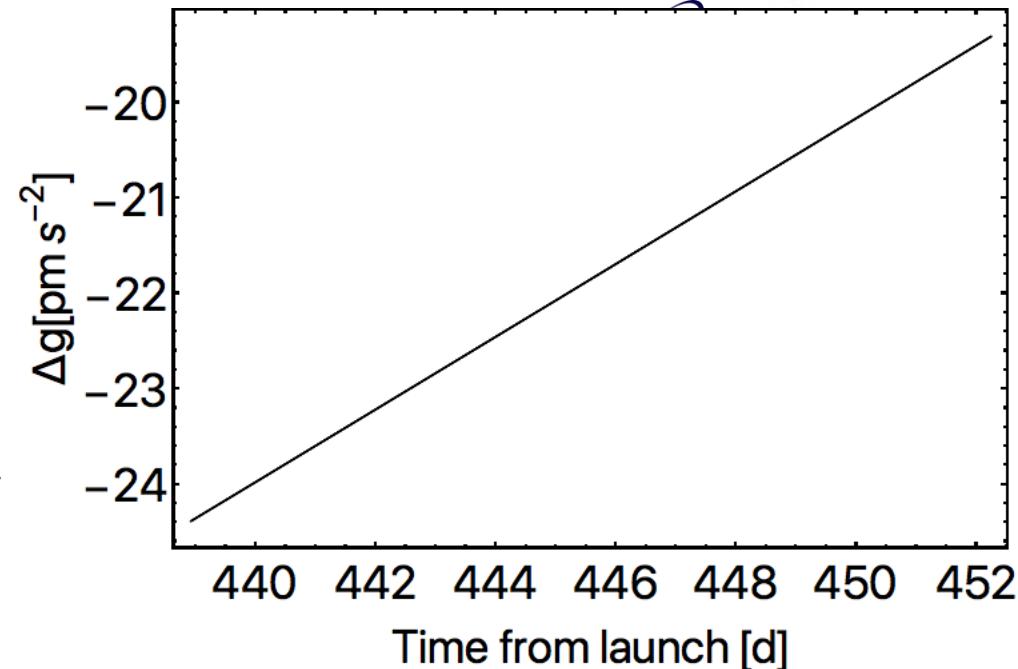
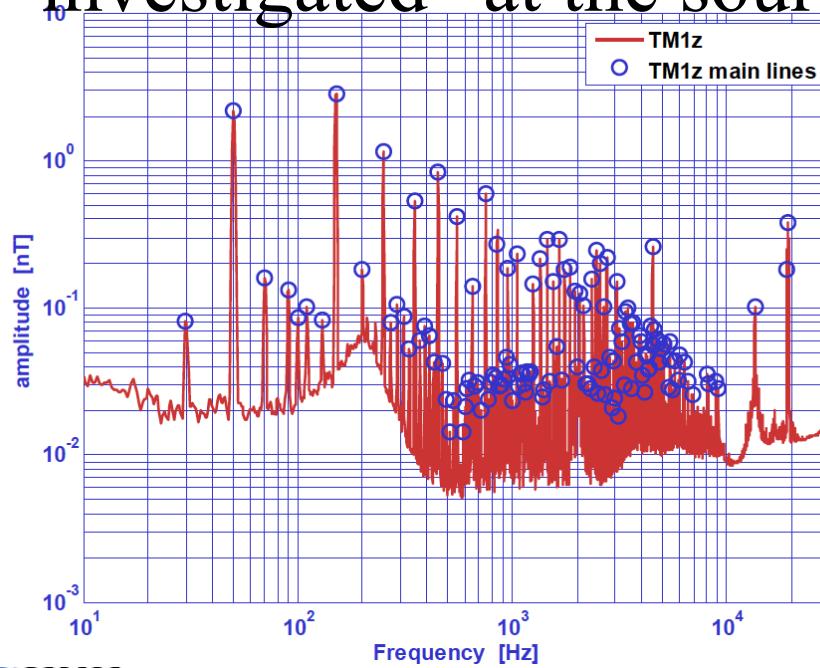


Remarkably stable



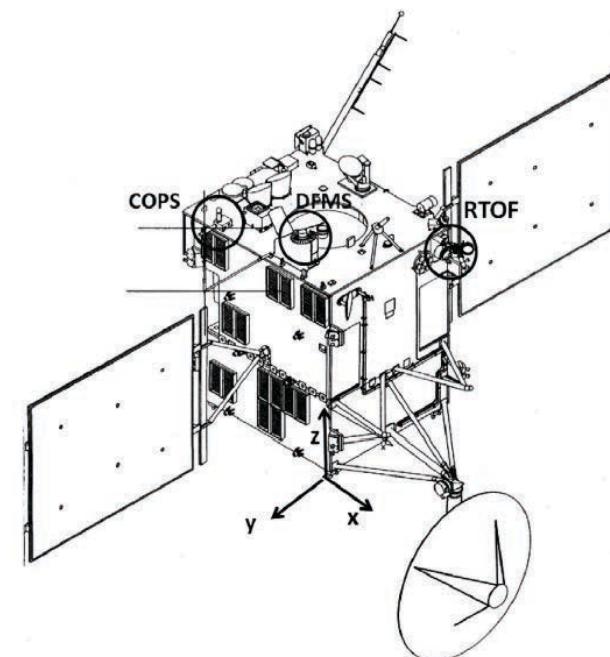
Possible sources

- Gravitational noise
 - Tank depletion
 - Spacecraft outgassing
- High frequency magnetic field noise
- Disturbances can be investigated “at the source”

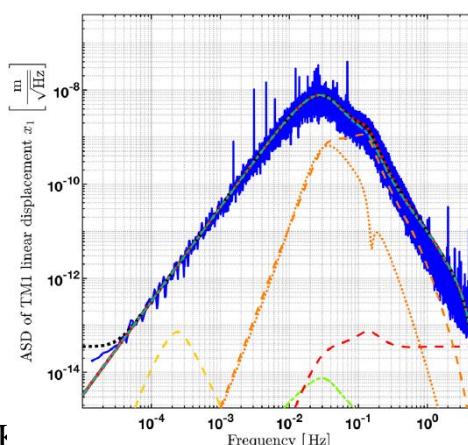
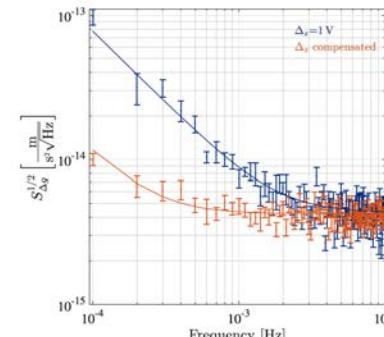
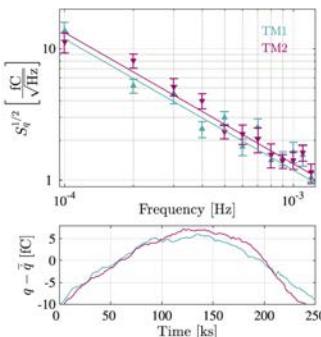
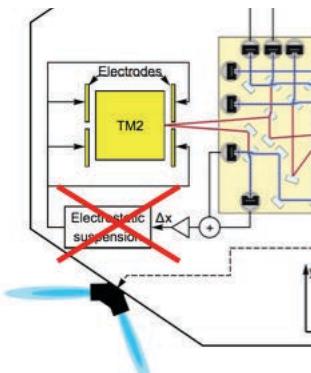


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SCHLÄPPI ET AL.: SPACECRAFT OUTGASSING



A full menu of experiments



- [1] M. Armano, et al. Sub-femto- g free fall for space-based gravitational wave observatories: Lisa pathfinder results. *Phys. Rev. Lett.*, 116:231101, Jun 2016.
- [2] D. Vetrugno et al. Lisa pathfinder first results. *International Journal of Modern Physics D*, 26(05):1741023, 2017.
- [3] M. Armano, et al. Charge-induced force noise on free-falling test masses: Results from lisa pathfinder. *Phys. Rev. Lett.*, 118:171101, Apr 2017.
- [4] M. Armano, et al. Capacitive sensing of test mass motion with nanometer precision over millimeter-wide sensing gaps for space-borne gravitational reference sensors. *Phys. Rev. D*, 96:062004, Sep 2017.
- [5] M. Armano, et al. Characteristics and energy dependence of recurrent galactic cosmic-ray flux depressions and of a forbush decrease with LISA pathfinder. *The Astrophysical Journal*, 854(2):113, Feb 2018.
- [6] M. Armano, et al. Beyond the required lisa free-fall performance: New lisa pathfinder results down to 20 μ Hz. *Phys. Rev. Lett.*, 120:061101, Feb 2018.
- [7] M. Armano, et al. Calibrating the system dynamics of lisa pathfinder. *Phys. Rev. D*, 97:122002, Jun 2018.
- [8] M. Armano, et al. Precision charge control for isolated free-falling test masses: Lisa pathfinder results. *Phys. Rev. D*, 98:062001, Sep 2018.
- [9] G. Anderson, et al. Experimental results from the st7 mission on lisa pathfinder. *Phys. Rev. D*, 98:102005, Nov 2018.
- [10] M. Armano, et al. Forbush decreases and <2 day GCR flux non-recurrent variations studied with LISA pathfinder. *The Astrophysical Journal*, 874(2):167, apr 2019.
- [11] M. Armano, et al. Lisa pathfinder platform stability and drag-free performance. *Phys. Rev. D*, 99:082001, Apr 2019.
- [12] M Armano, et al. Temperature stability in the sub-milliHertz band with LISA Pathfinder. *Monthly Notices of the Royal Astronomical Society*, 486(3):3368–3379, 04 2019.
- [13] M. Armano et al. Lisa pathfinder micronewton cold gas thrusters: In-flight characterization. *Phys. Rev. D*, Accepted June 2019.

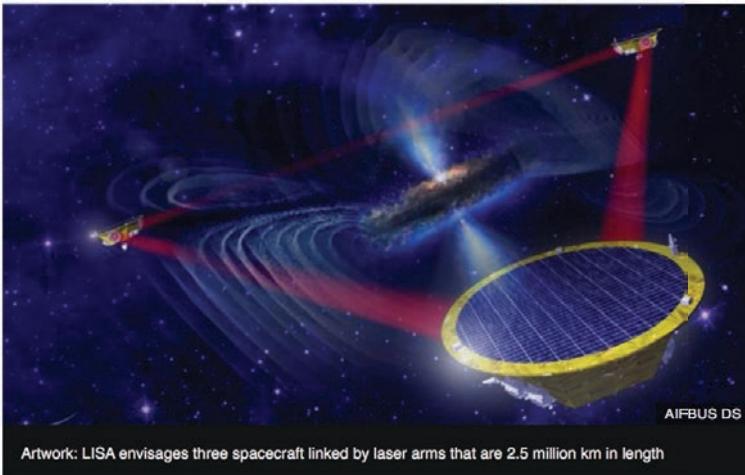
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Science & Environment**Europe selects grand gravity mission**

By Jonathan Amos
BBC Science Correspondent, Paris

© 20 June 2017

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Artwork: LISA envisages three spacecraft linked by laser arms that are 2.5 million km in length

Green Light for LISA

ESA Unclassified – For official use

ESA/SPC/MIN/154, rev.1 (Final)
Att.: Annex
ESA/SPC/OJ/154, rev.1 (Final)
Paris, 29 March 2018
(Original: English)

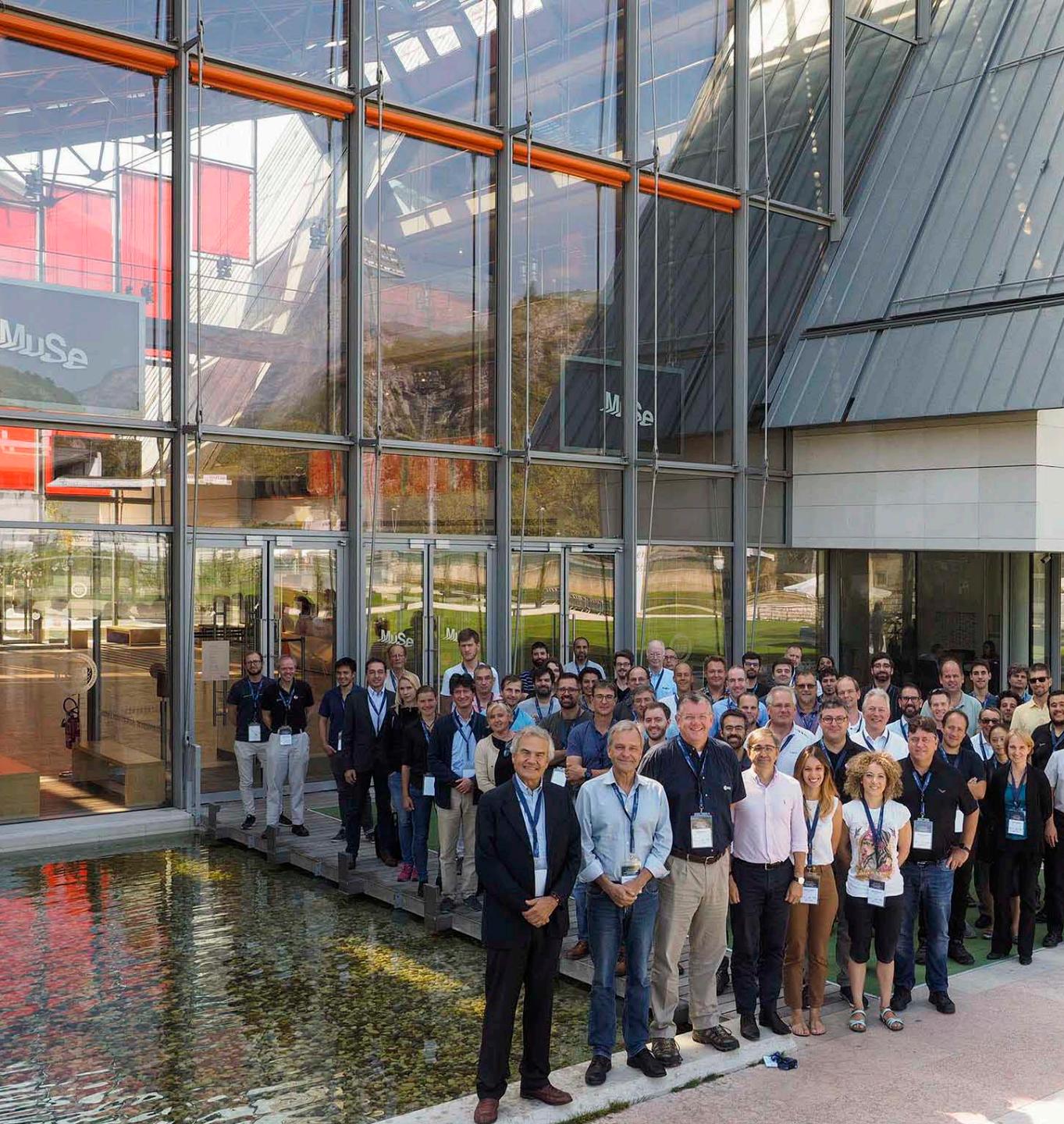
EUROPEAN SPACE AGENCY**SCIENCE PROGRAMME COMMITTEE**

One hundred and fifty-fourth meeting,
held at ESAC, in Villanueva de la Cañada on 20 and 21 June 2017

Minutes, as approved during the 155th meeting held on 21 and 22 November 2017

Chair: Mr J. Christensen-Dalsgaard (Denmark)
(Participants: see Annex)

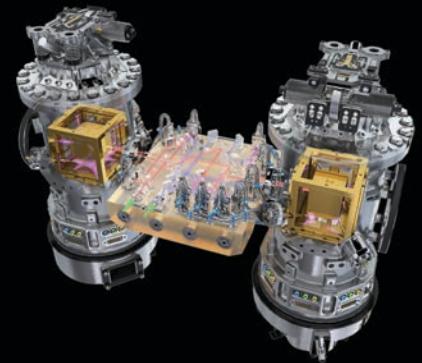
The Committee unanimously selected (with Greece in writing) the LISA mission for the L3 flight opportunity, with a planned launch date in 2034, and with an estimated CaC of €1.05b (at 2017 e.c.).



LISA Pathfinder Mission Accomplished

Opening the Path to the Gravitational Universe

Scientific Gathering
MUSE, Trento, 11-13 September 2018



AEI, Hannover
DLR
Imperial College
OHB Italia
University of Glasgow

Contract: karine.frischegli@unitn.it

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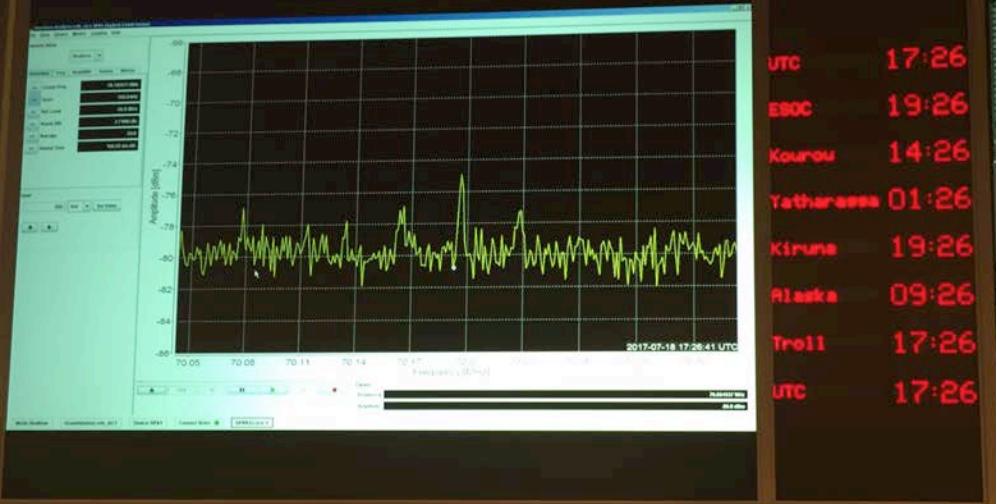
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LISA Pathfinder: Time called on Europe's gravity probe

By Jonathan Amos
BBC Science Correspondent

© 18 July 2017 [Share](#)

ESA

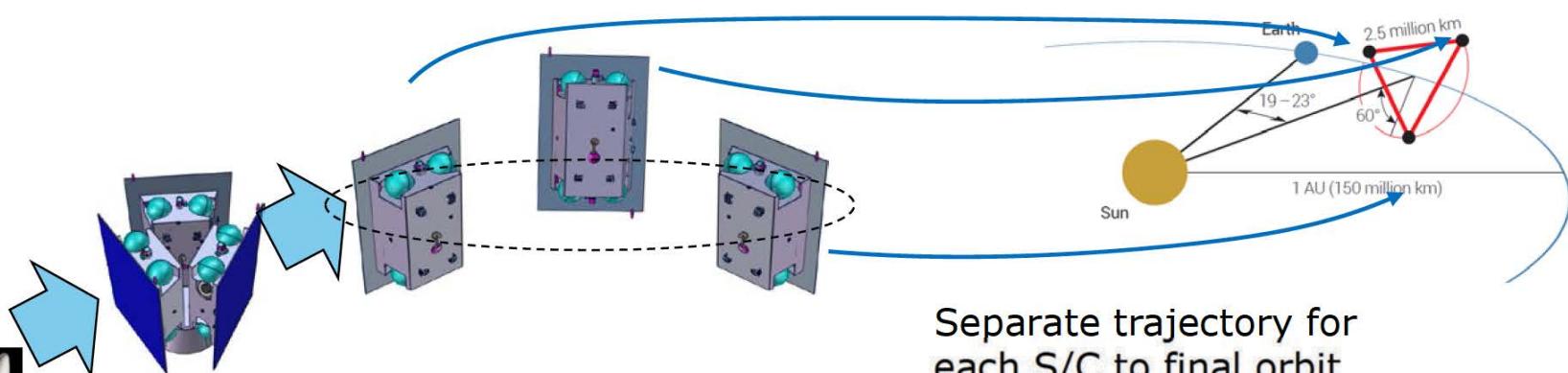
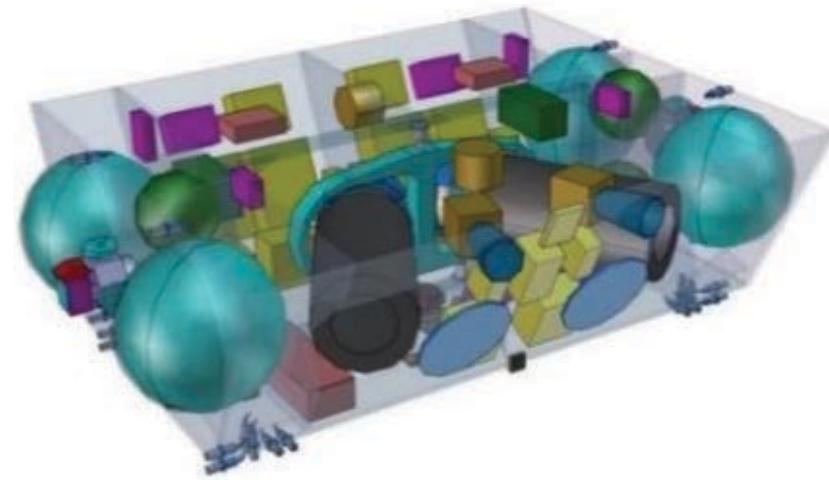
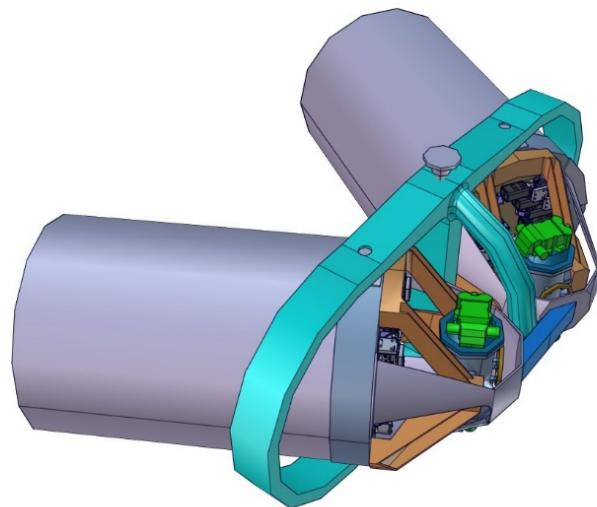
The European Space Agency (Esa) has turned off one of its most successful ever missions.

Location	Time (UTC)
UTC	17:59
ESOC	19:59
Kourou	14:59
Yatharassee	01:59
Kiruna	19:59
Alaska	09:59
Troll	17:59
UTC	17:59

european space operations



LISA charging ahead



Launch in stacked configuration
Direct injection into escape trajectory

Separation of the stack right after launch



Separate trajectory for each S/C to final orbit

“Bringing sound to the cosmic movies”

Athena

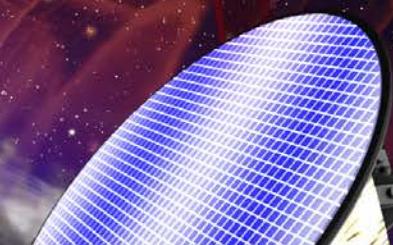
hot gas structures

supermassive black holes



LISA

gravitational wave observation



A Chinese LISA?

40°

1 day

GW astronomy from space

