Spaceborne Gravitational Wave Detectors

Grass 2019

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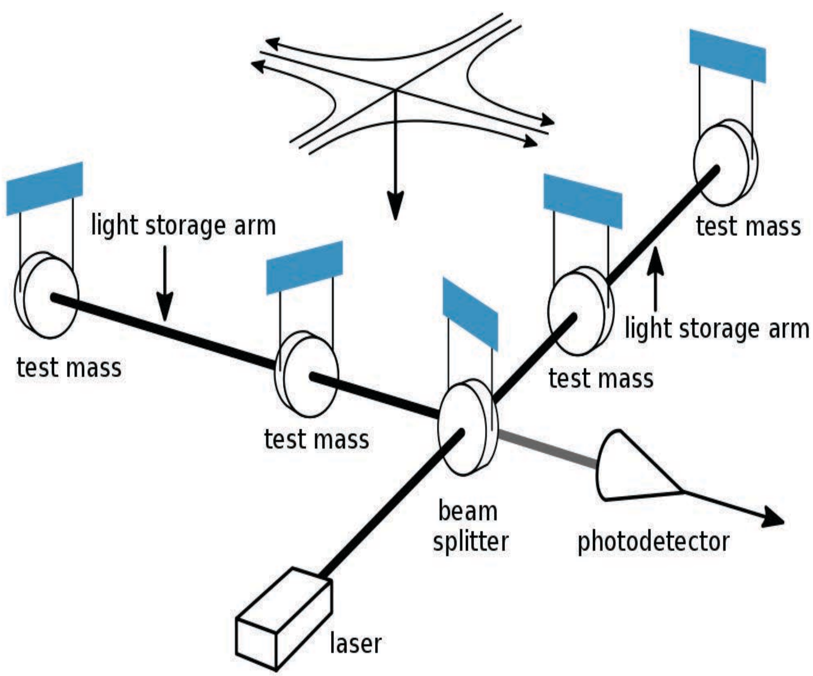
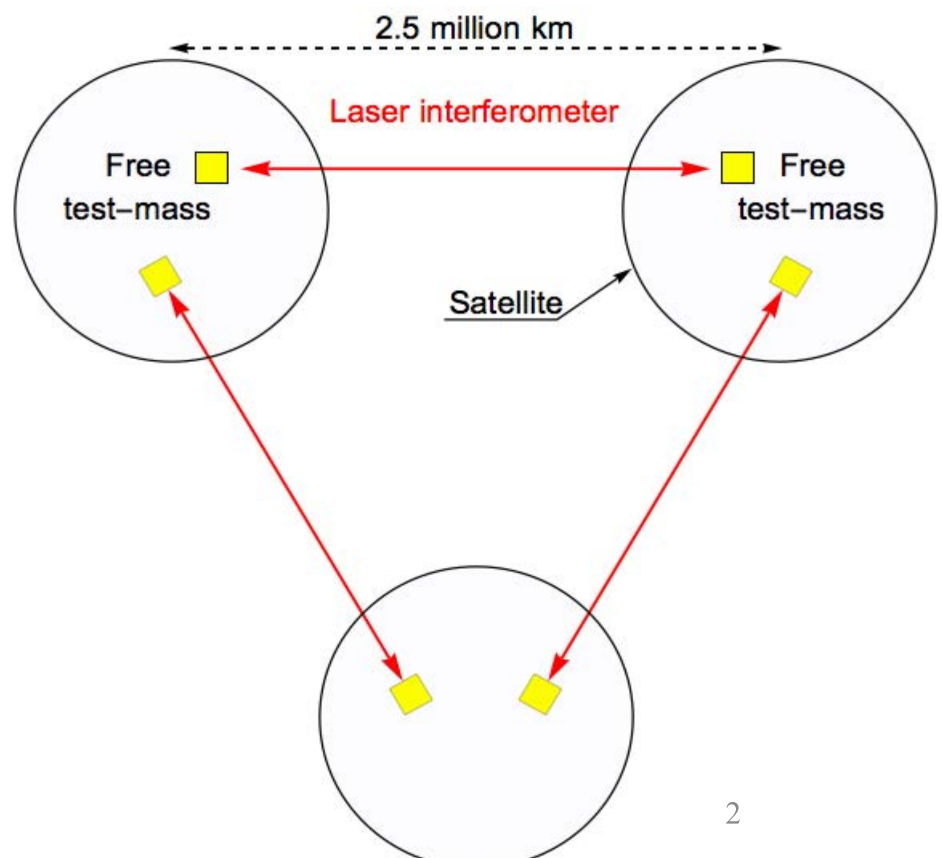
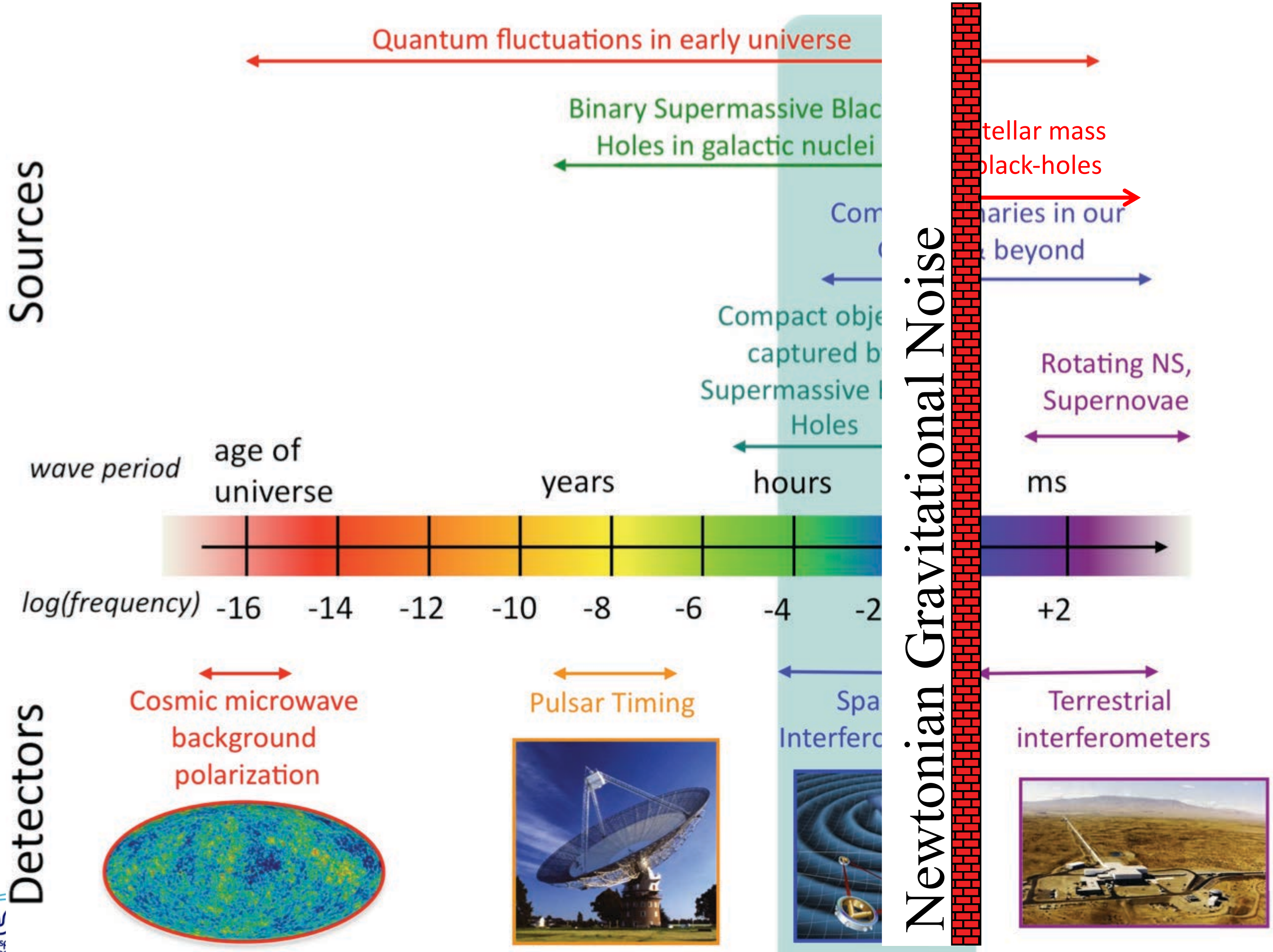
LISA: LIGO/Virgo in space

	LIGO/Virgo	LISA
Size	4 km	2.5×10^6 km
Frequency	>10 Hz	20 μHz ÷ 1 Hz



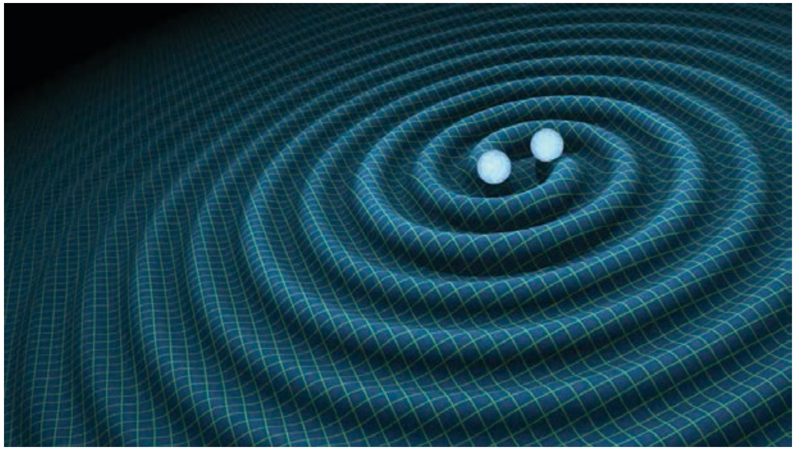


$2\times10^{-5}\div1$ Hz not accessible from ground



Why low frequency?

- Frequency of GW 2 x frequency of motion



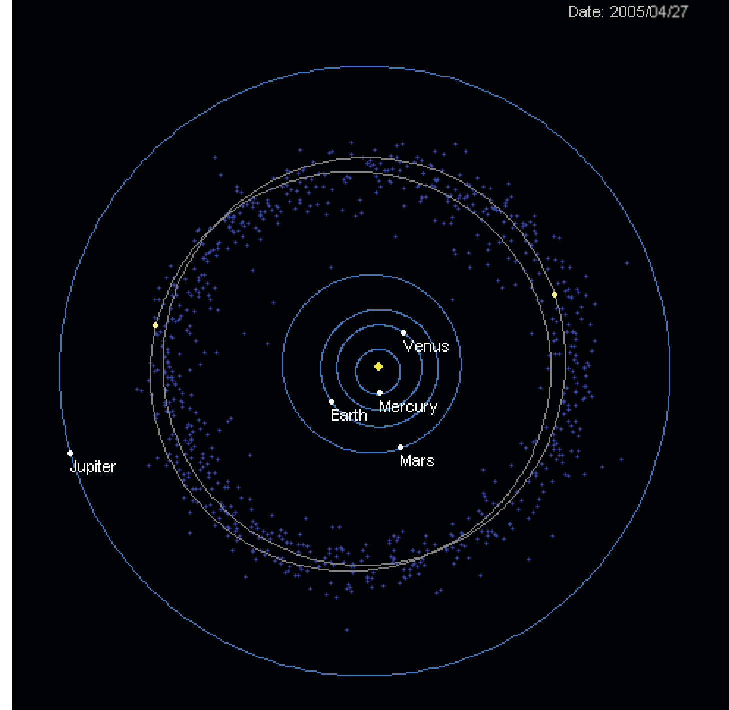
- Kepler: faraway is slow

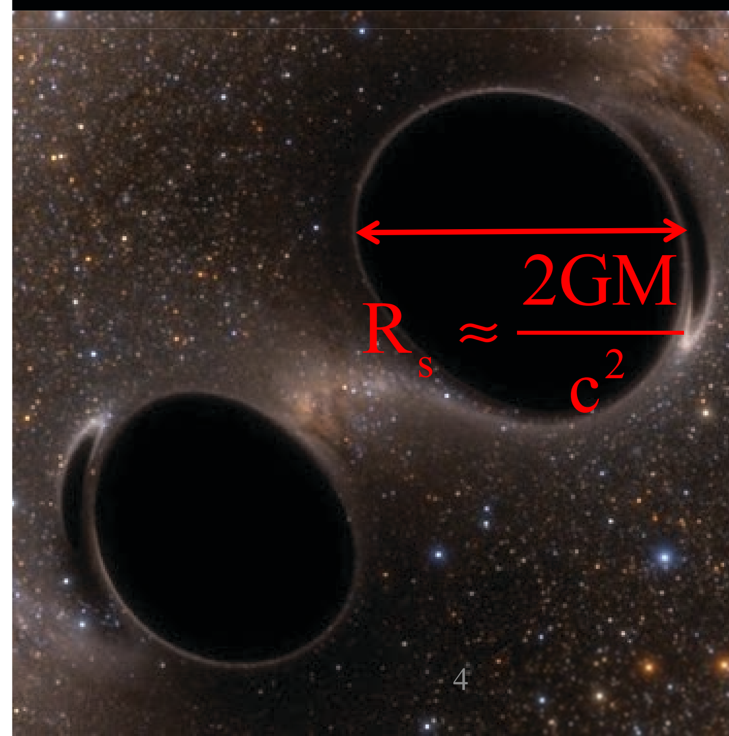
$$f = \left(1/\pi\right)\sqrt{GM/r^3}$$

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

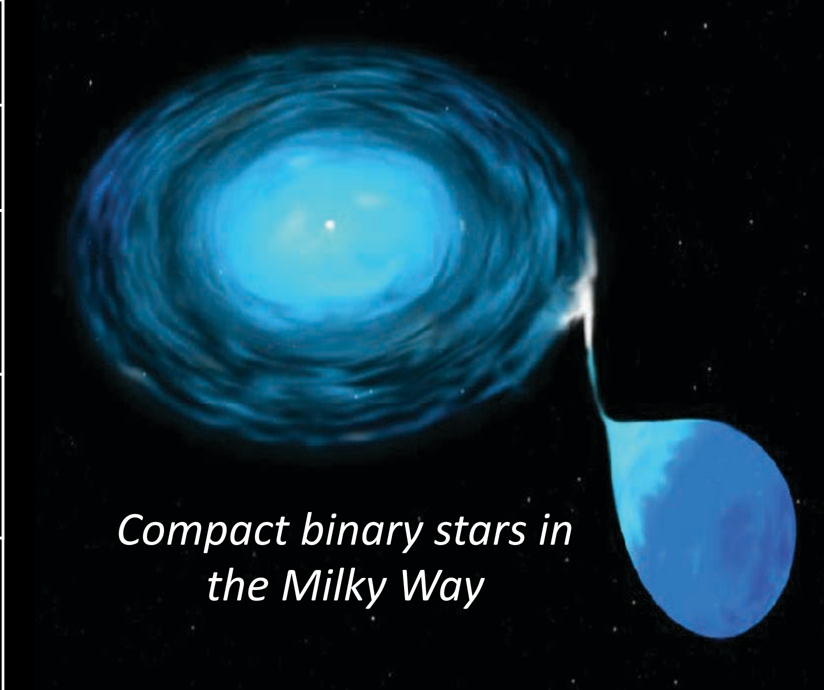
$$f \ll \frac{1}{\pi\sqrt{8}}\frac{c^3}{GM}: \quad 10^6 M_\odot \rightarrow 0.01\ \text{Hz}$$

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

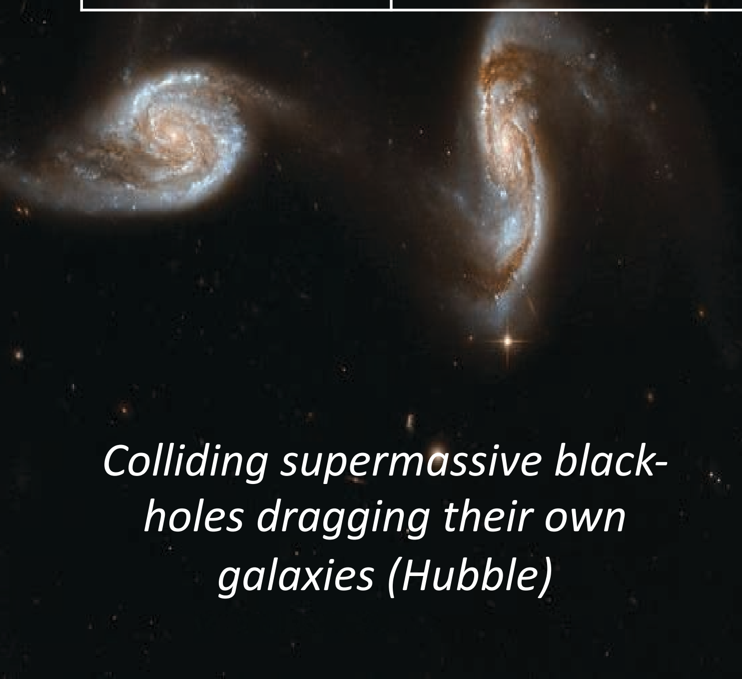




	LIGO	LISA
Size	km	Million km
Wave period	0.001-0.1 seconds	minutes to hours
Mass of sources	~ 1-10 Sun	up to 1-10 Million Sun
Size of the source	~ 100-1000 km	1-10 Million km



Compact binary stars in the Milky Way



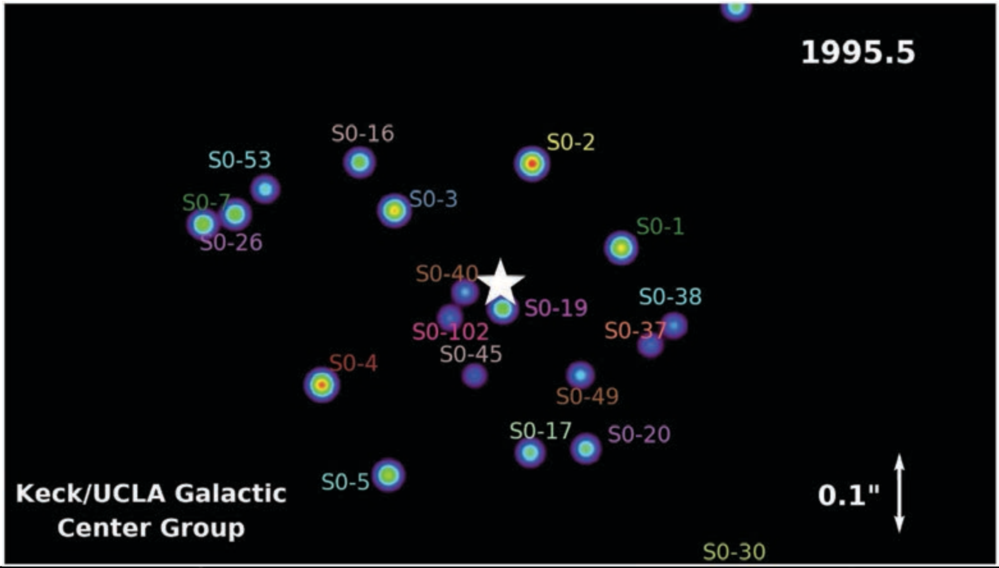
Colliding supermassive black-holes dragging their own galaxies (Hubble)

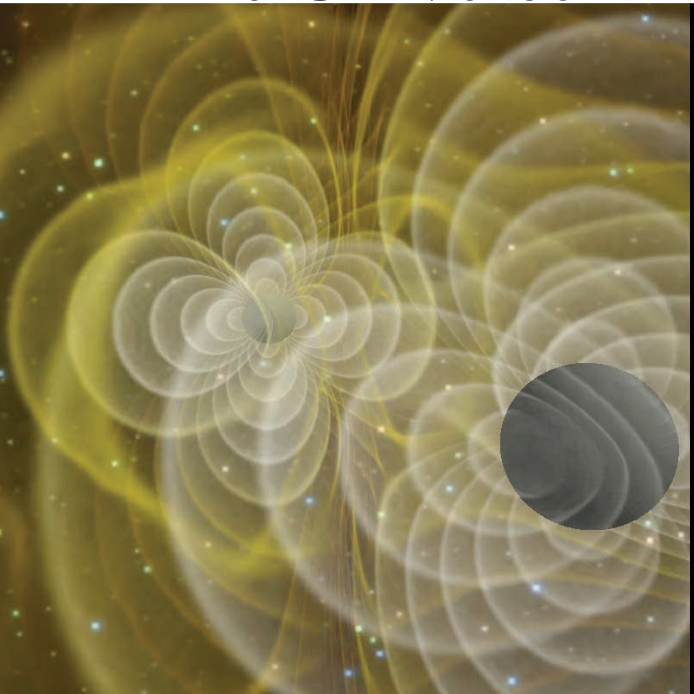
Supermassive black-hole swallowing a small one

LIGO black-hole years before final merger

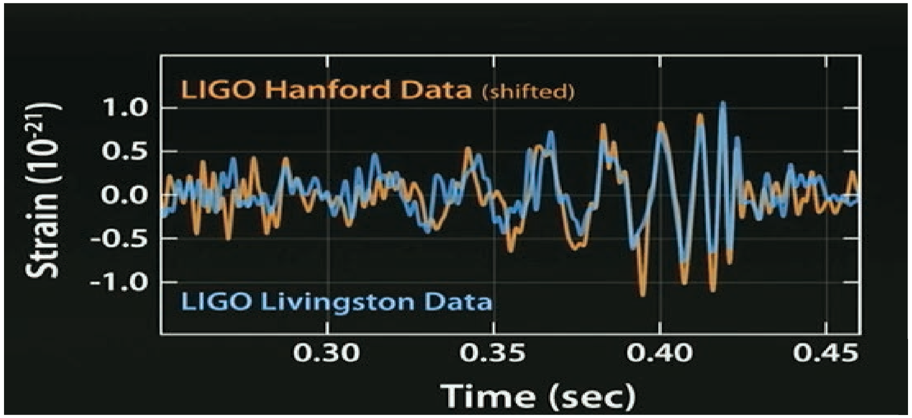
Million solar mass Black-Holes

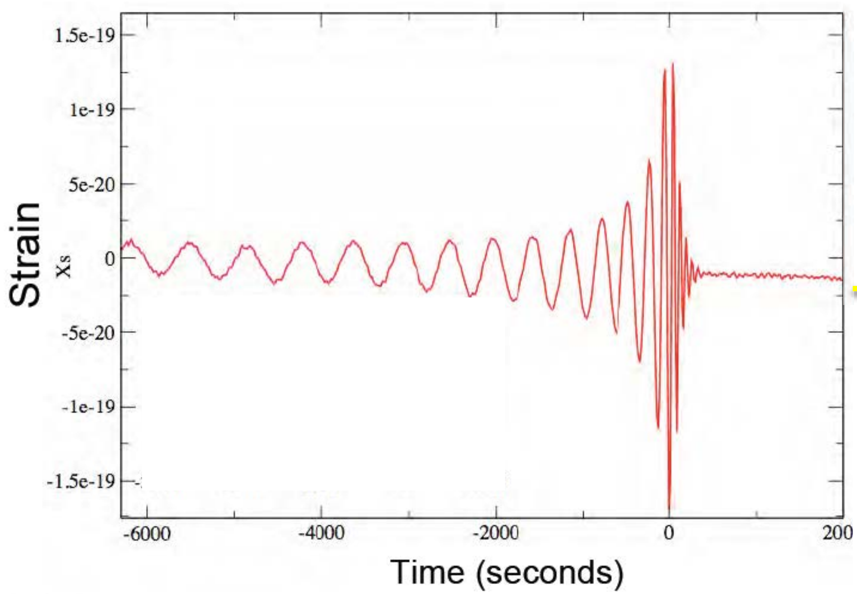
- Galaxies host > million solar mass Black-Holes
- Galaxy collide and form binary Black-Holes
- Binaries coalesce: more GW energy than all light in the Universe

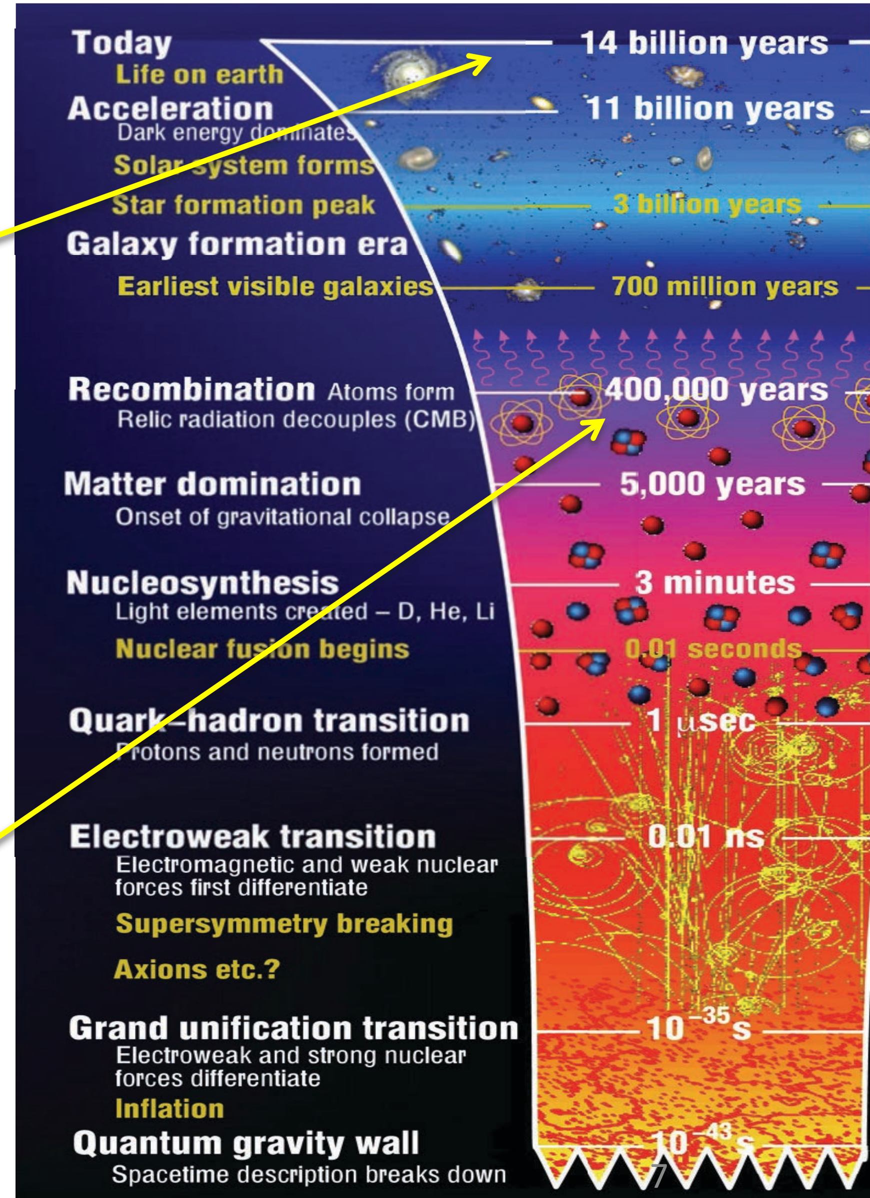




A deep universe, high resolution observatory

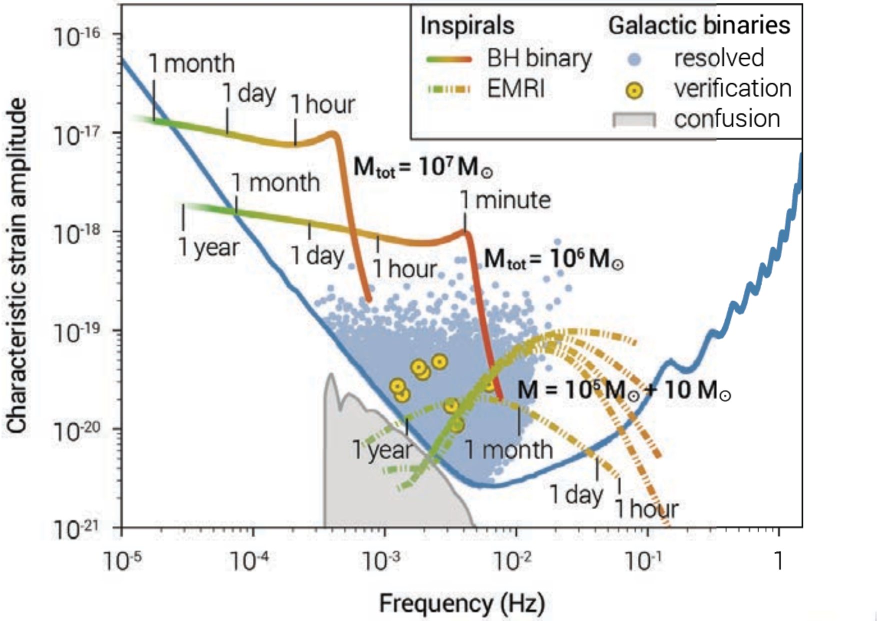


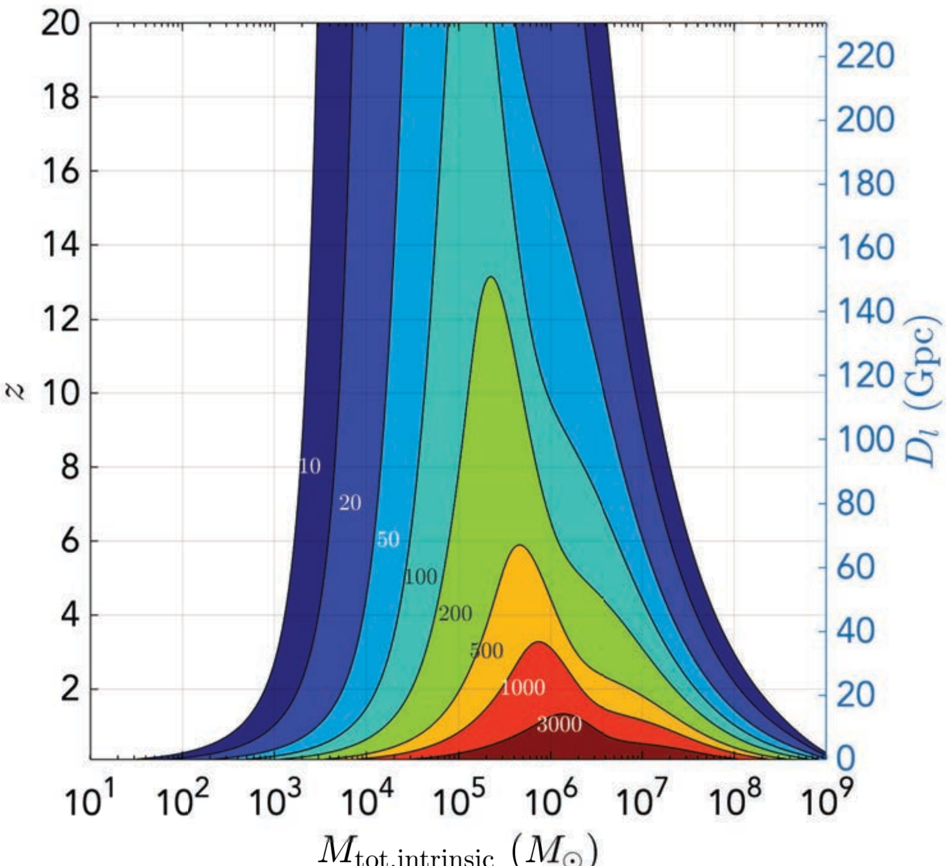


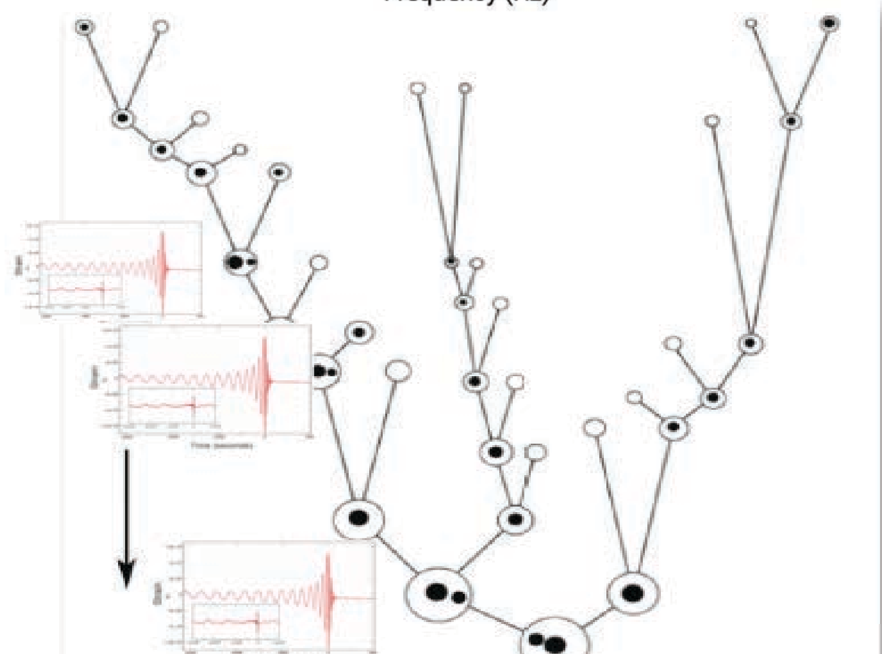


Cosmological stratigraphy

- High resolution (SNR 1000) and sky position below degree (brightest sources)
- High precision mass, luminosity distance, spin
- Almost all BBH in their evolution cross LISA band (hundreds expected)







Detecting SMBH mergers with LISA and Athena

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

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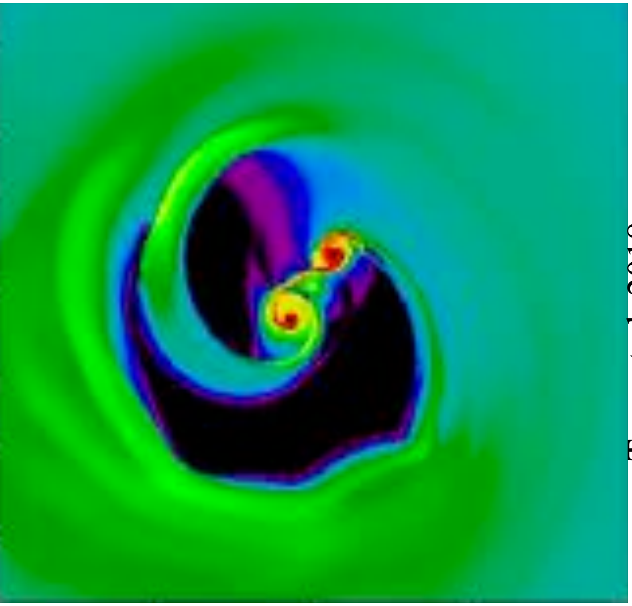
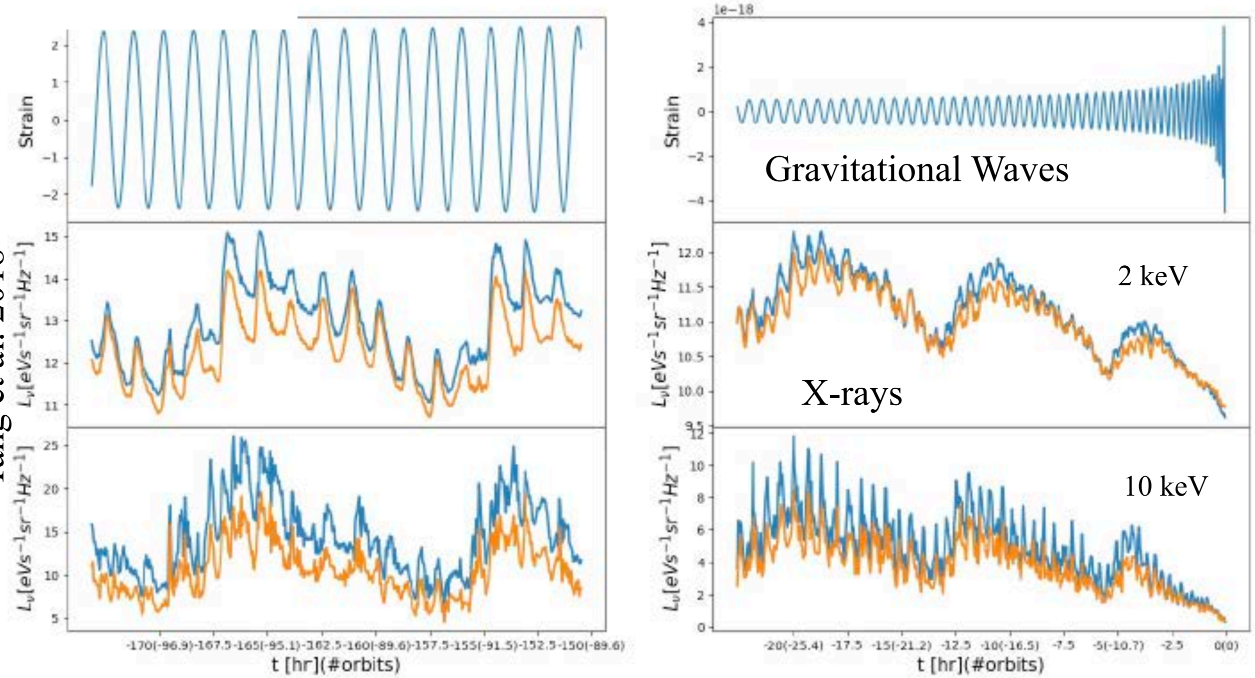
[1]Center for Cosmology and Particle Physics, Physics Department, New York University, New York, NY, USA,10003
[2]Department of Astronomy, Columbia University, New York, NY, USA,10027



Tang et al. 2018



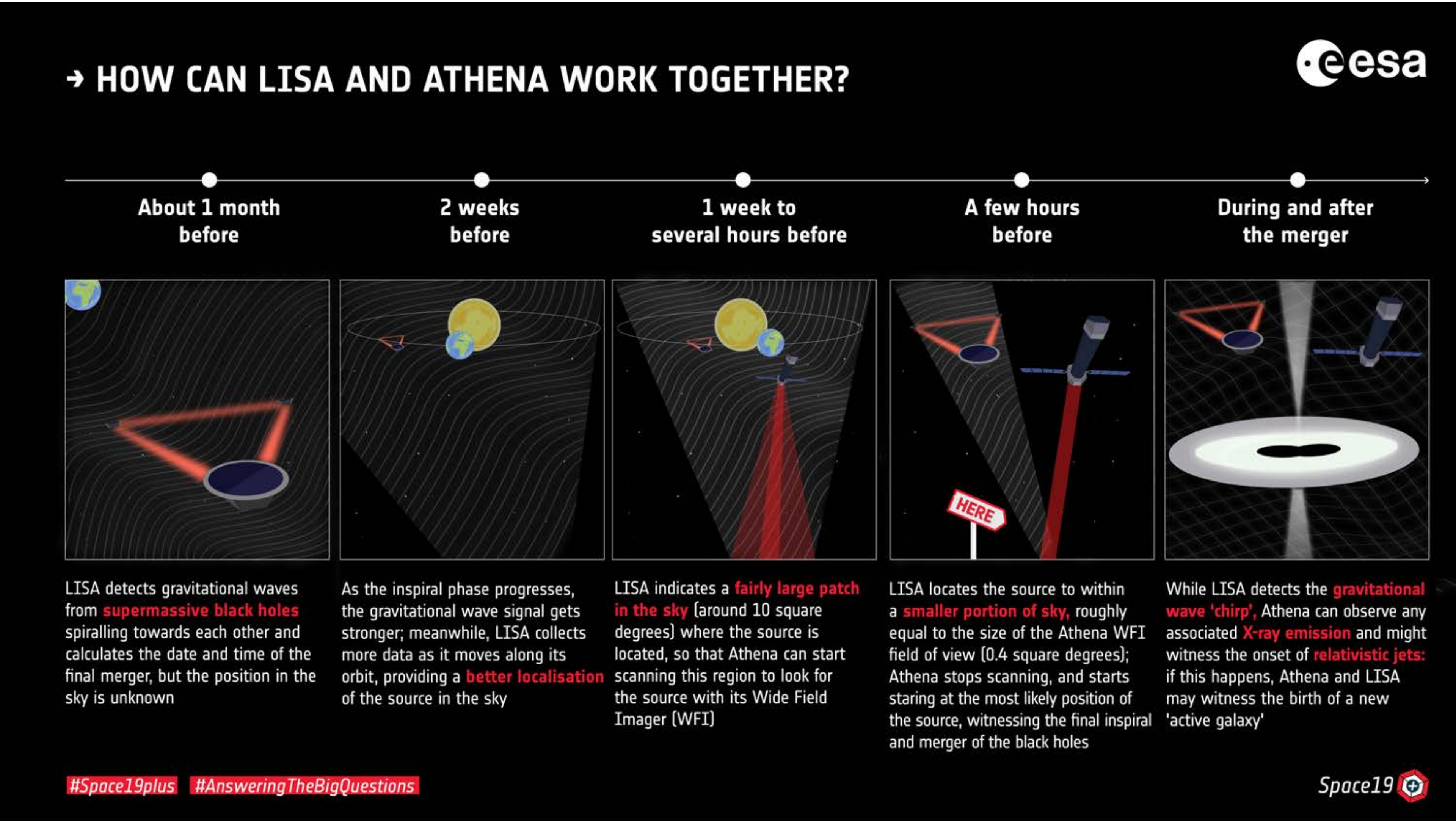
Athena-LISA Synergies

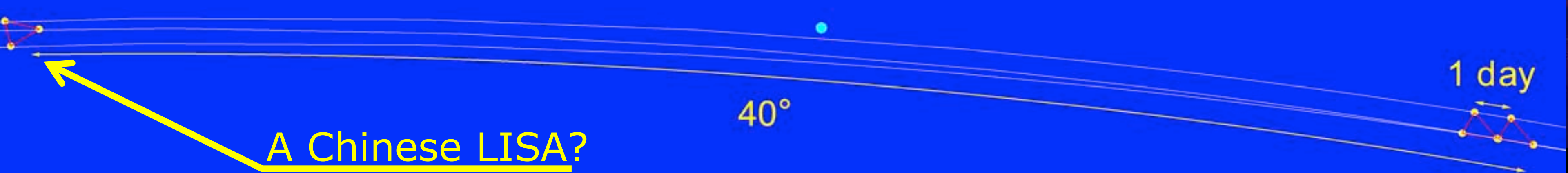
Athena-LISA Synergy Working Group:

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)

20 February 2019

An operation scenario

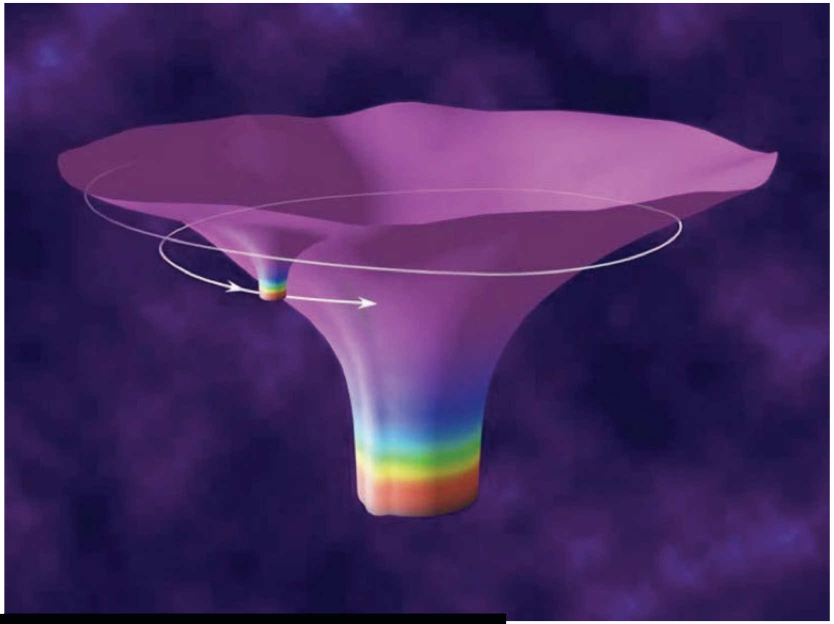


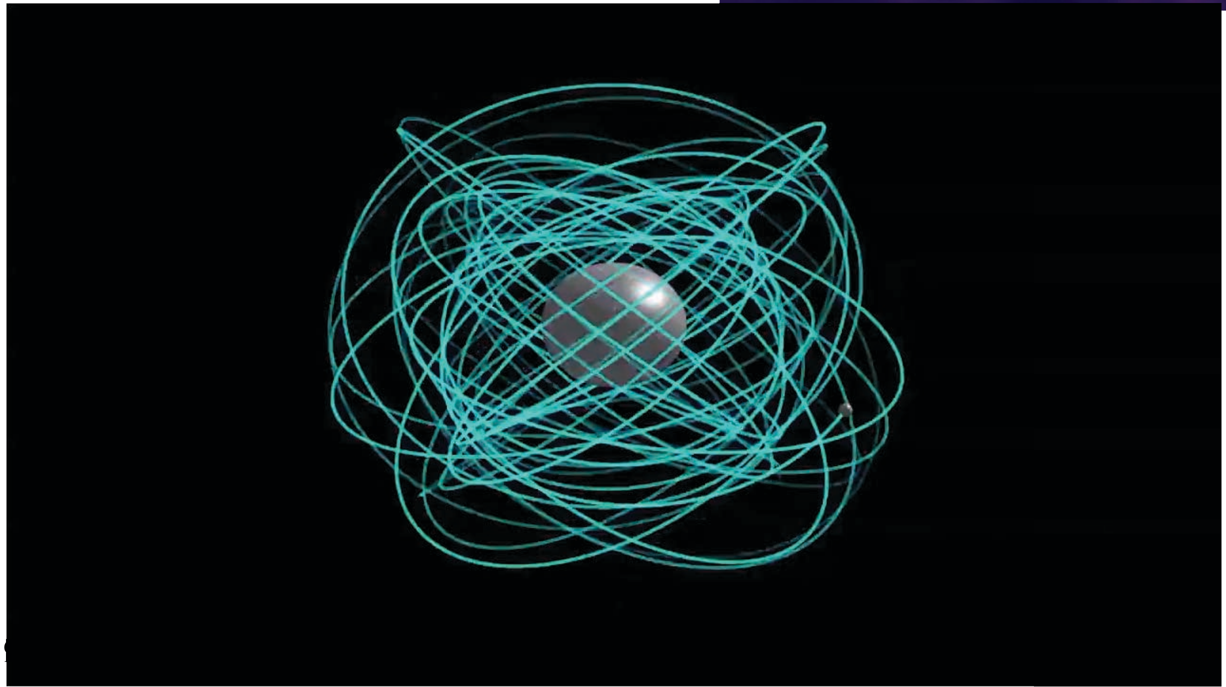


A Chinese LISA?

Extreme Mass-Ratio Inspirals: EMRIs

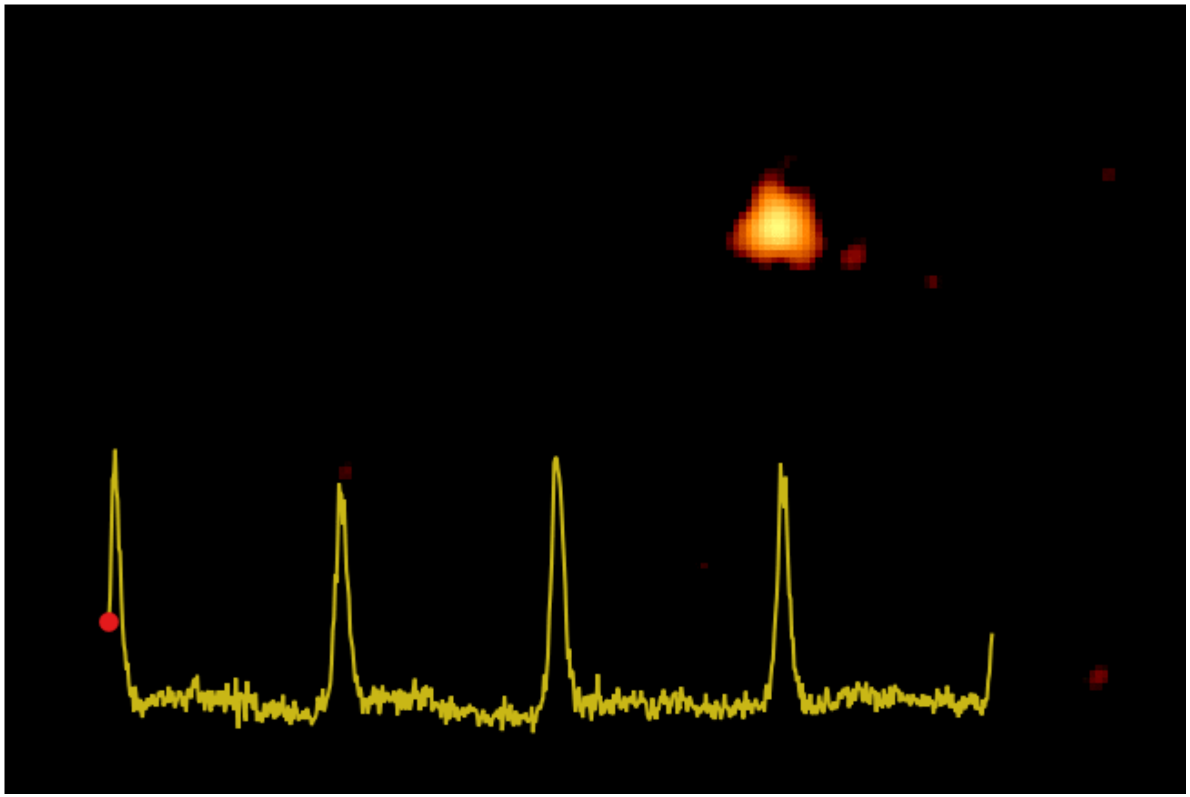
- Stellar-mass BH capture by a massive BH: dozens per year.
- 10^5 orbits very close to horizon. GRACE/GOCE for massive BHs.
  - Prove horizon exists.
  - Test the no-hair theorem to 1%.
  - Masses of holes to 0.01% -0.001%
  - Spin of central BH to 0.0001.





An EMRI in the making

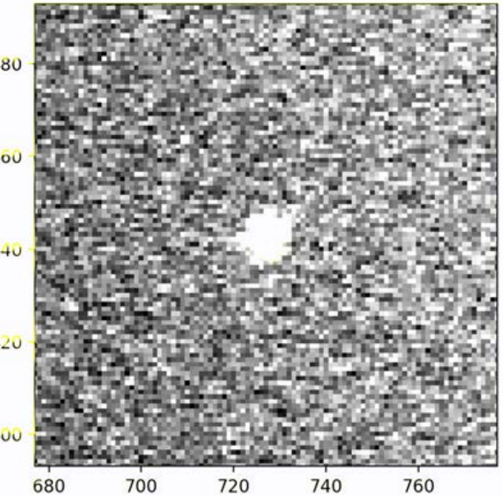
- XMM new discovery: flashes from the active black hole in GSN 069, (250 Mpsec).

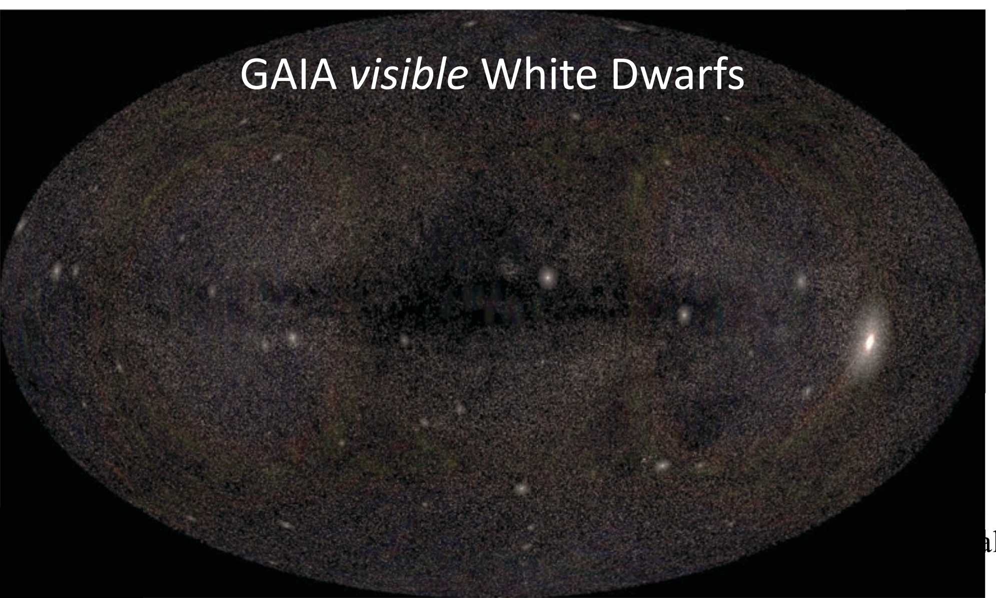


- A compact object crossing the accretion disk

Galactic binaries

1. LISA compact galactic binaries.
   - List of 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





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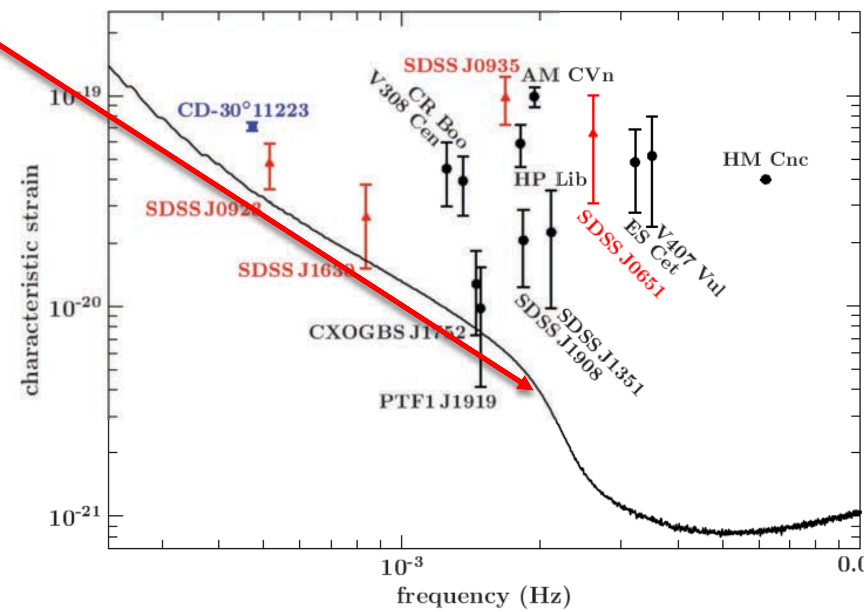
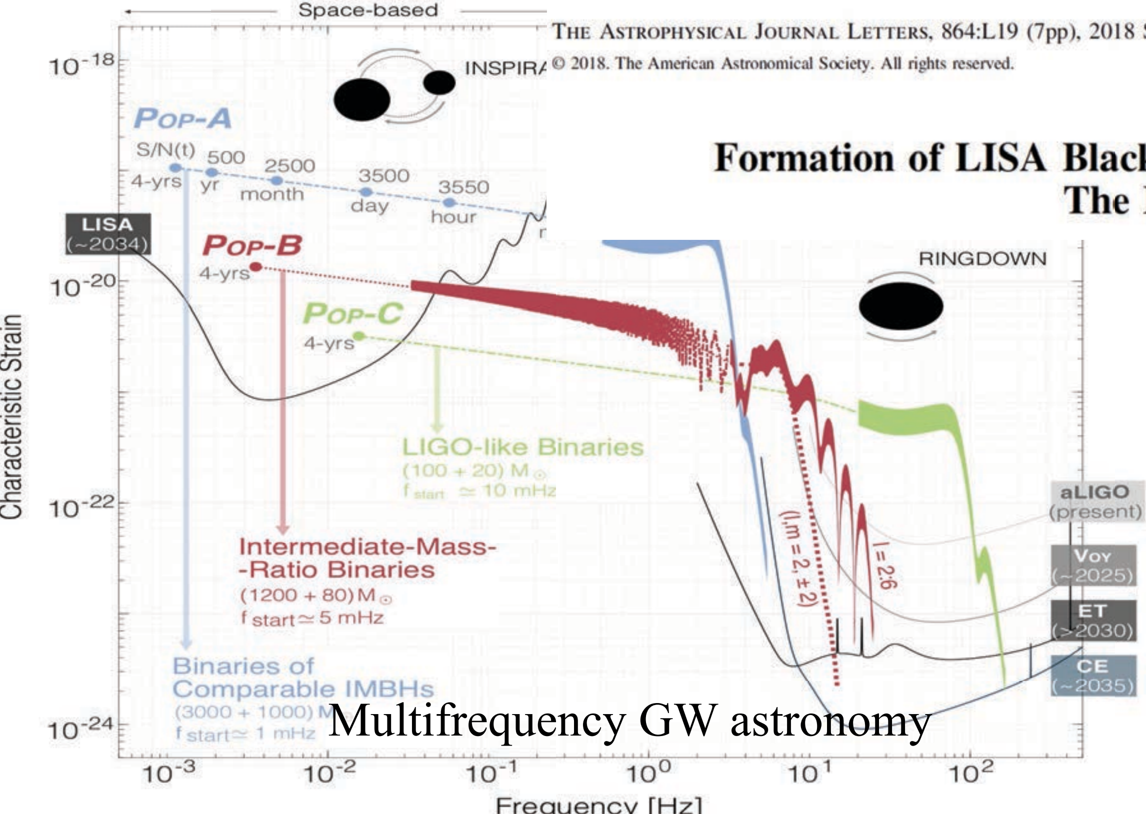


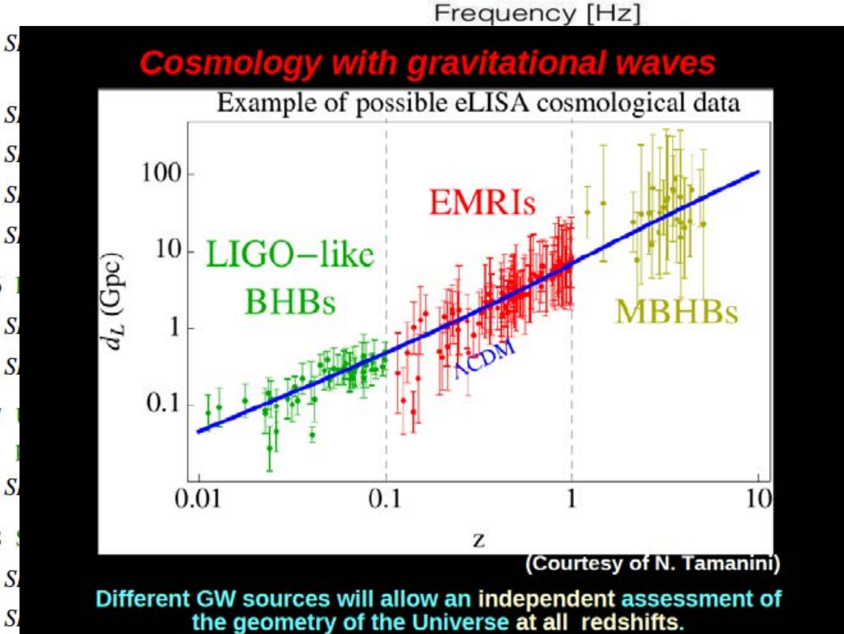
The Astrophysical Journal Letters, 864:L19 (7pp), 2018 September 1 https://doi.org/10.3847/20

Formation of LISA Black Hole Binaries in Merging Dwarf Galaxies: The Imprint of Dark Matter



Multifrequency GW astronomy

And growing…..



SO 6

SO 7

SO 8

oalescences to test

of Relativity (GR)

er than 10^3 $M_\odot$

ly

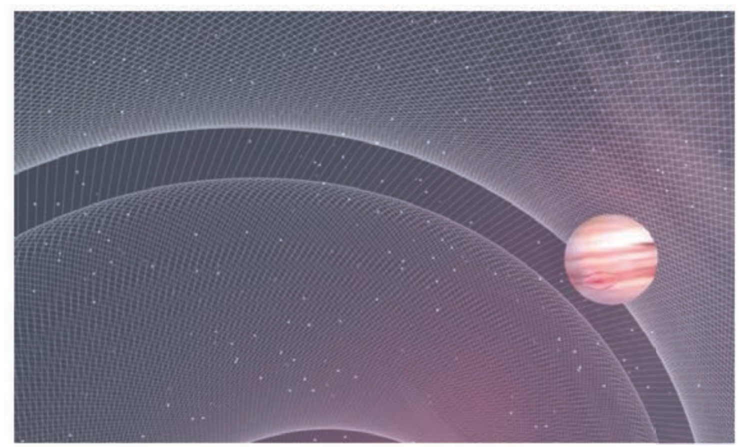
M) observations

TeV-scale particle

JULY 9, 2019

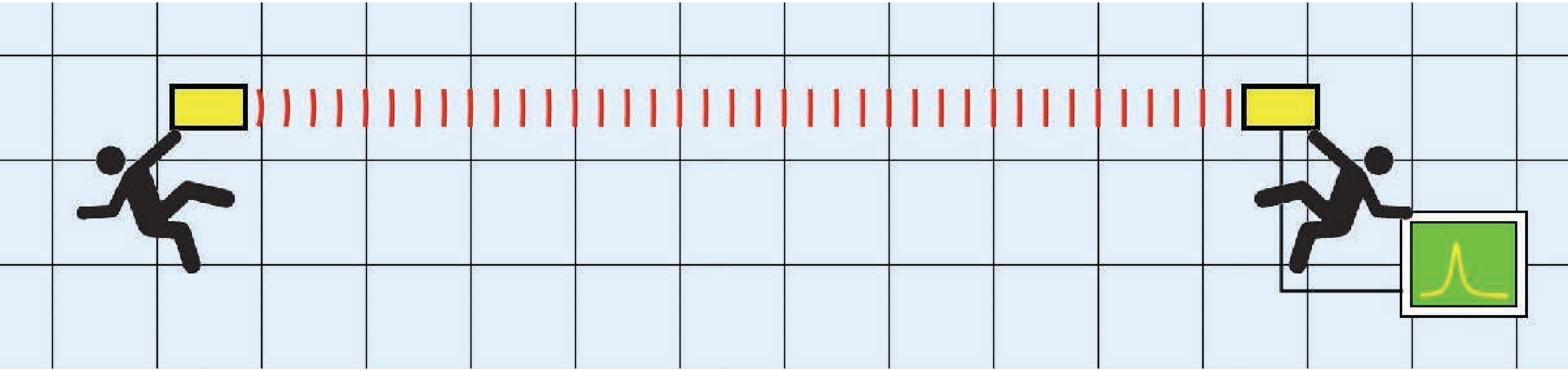
Discovering exoplanets with gravitational waves

by Max Planck Society



Artistic representation of gravitational waves produced by a compact binary wh…

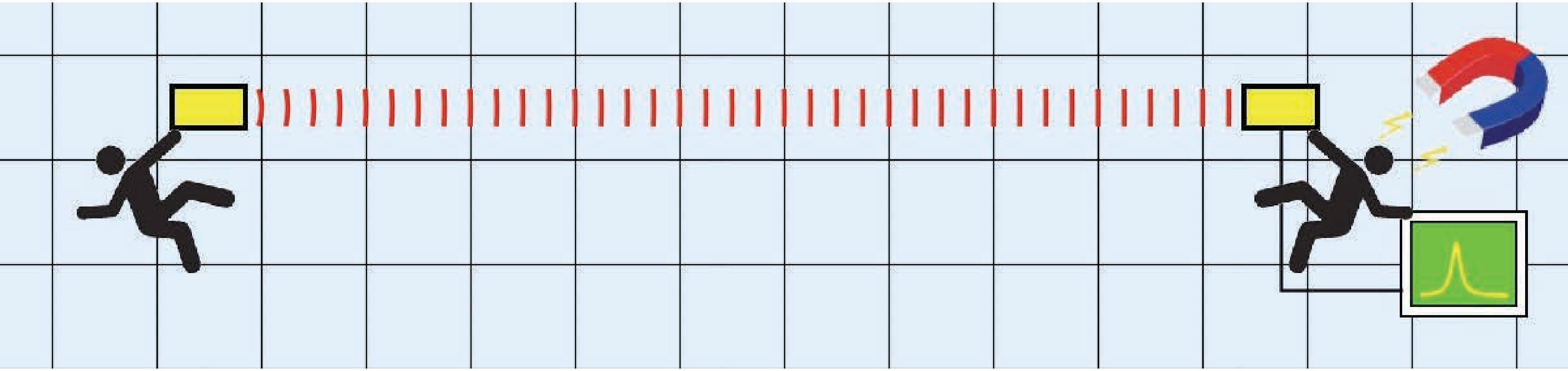
The LISA link



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

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

The LISA link

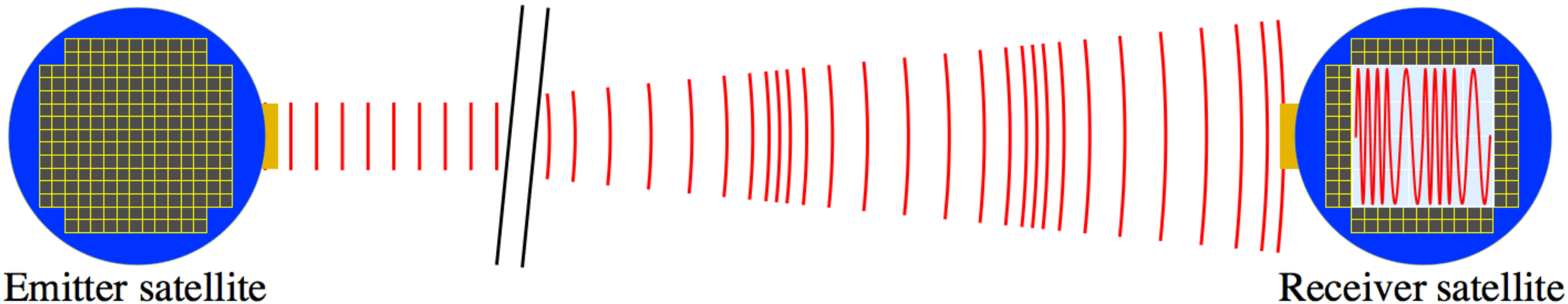


- Unfortunately frequency is also modulated by acceleration of each observer *relative to its own inertial frame*

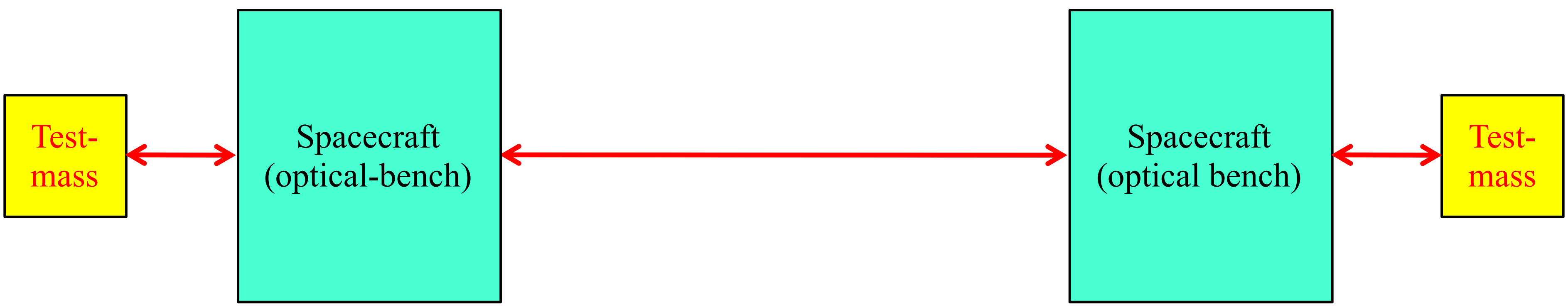
$$\dot{\nu}_{em} - \dot{\nu}_{rec} = \nu_o\left(\dot{h}_{em} - \dot{h}_{rec}\right) + \frac{f_{em}}{m} - \frac{f_{rec}}{m}$$

LISA fundamentals: the link

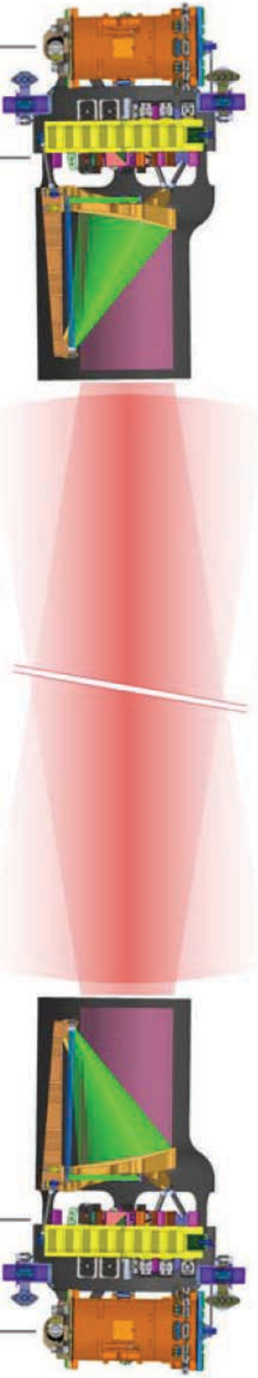
- Satellite accelerations too large



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

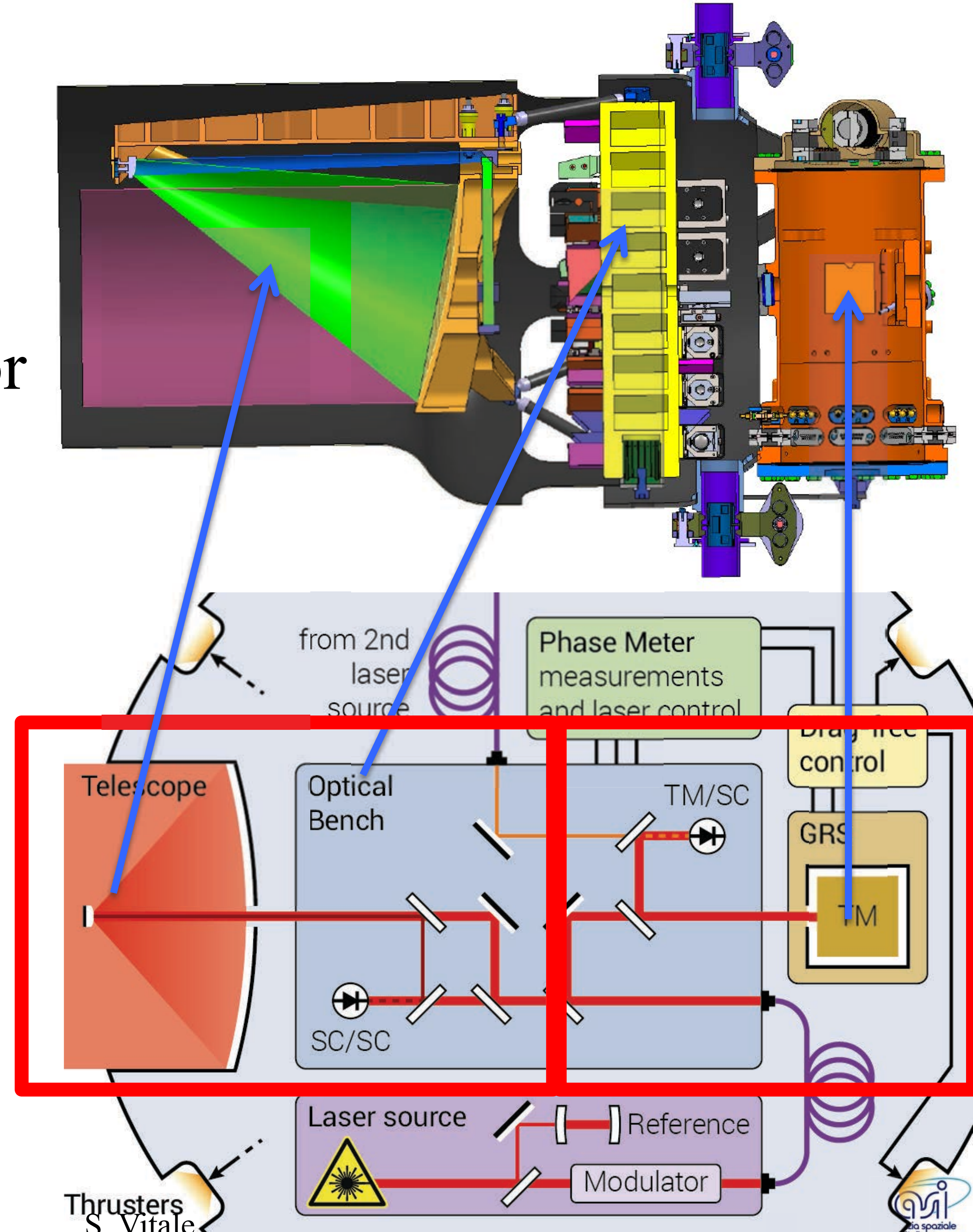


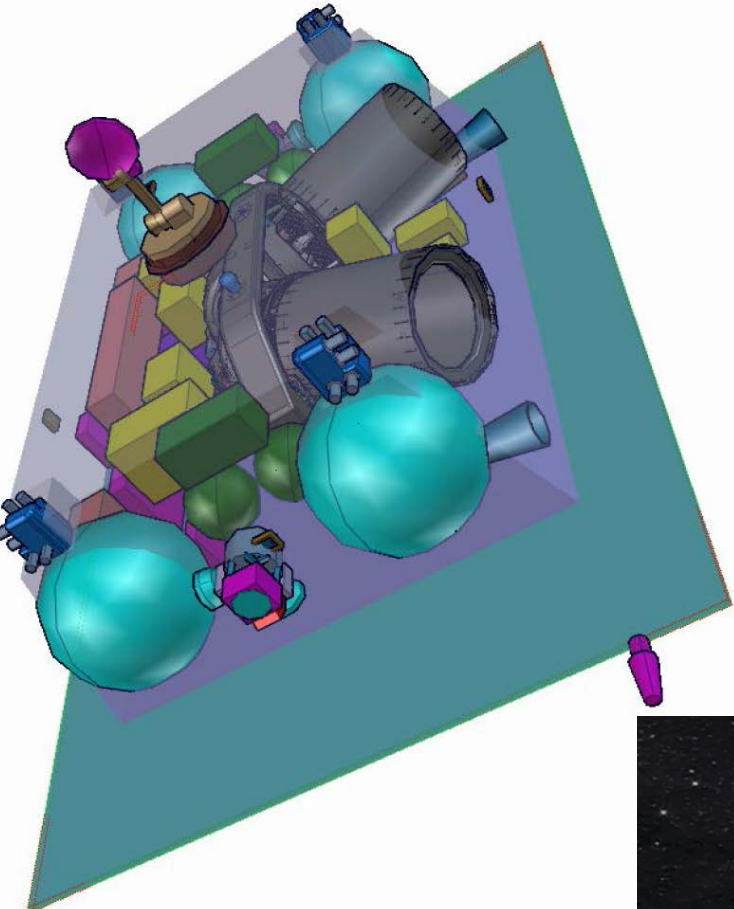
- Equivalent to directly tracking test-masses, but requires composite measurements

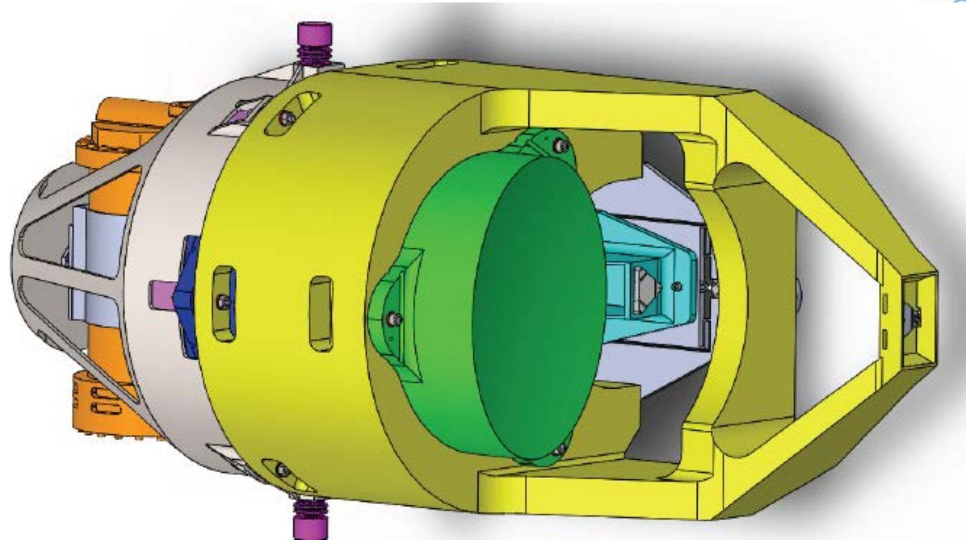


LISA Instrument

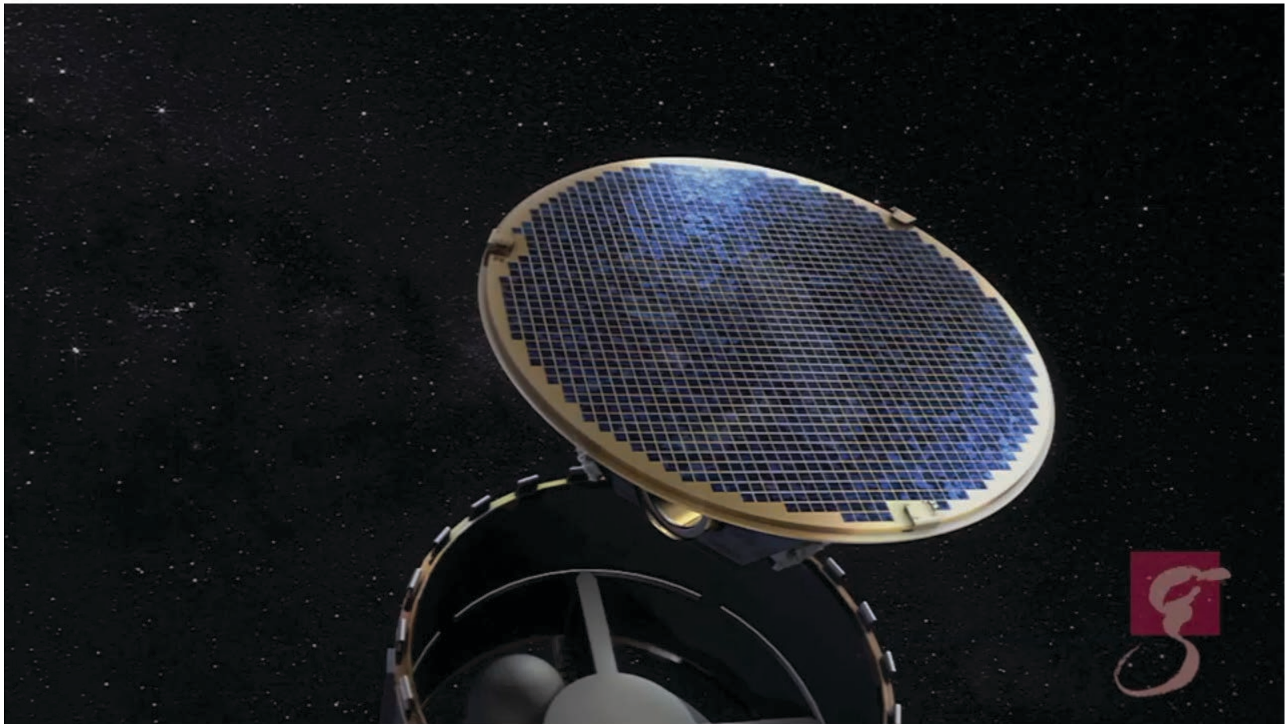
- The Gravitational Reference Sensor with the test-mass
- The Optical Bench with:
  - Local interferometer
  - Spacecraft to spacecraft interferometer, including telescope



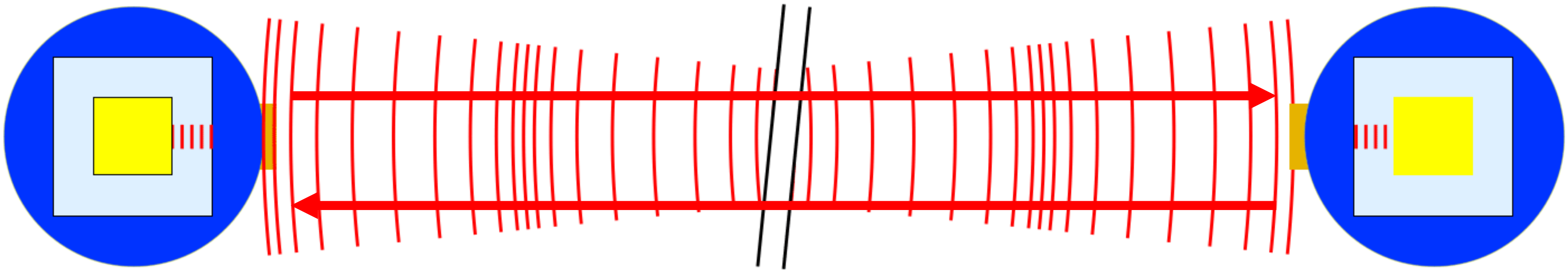




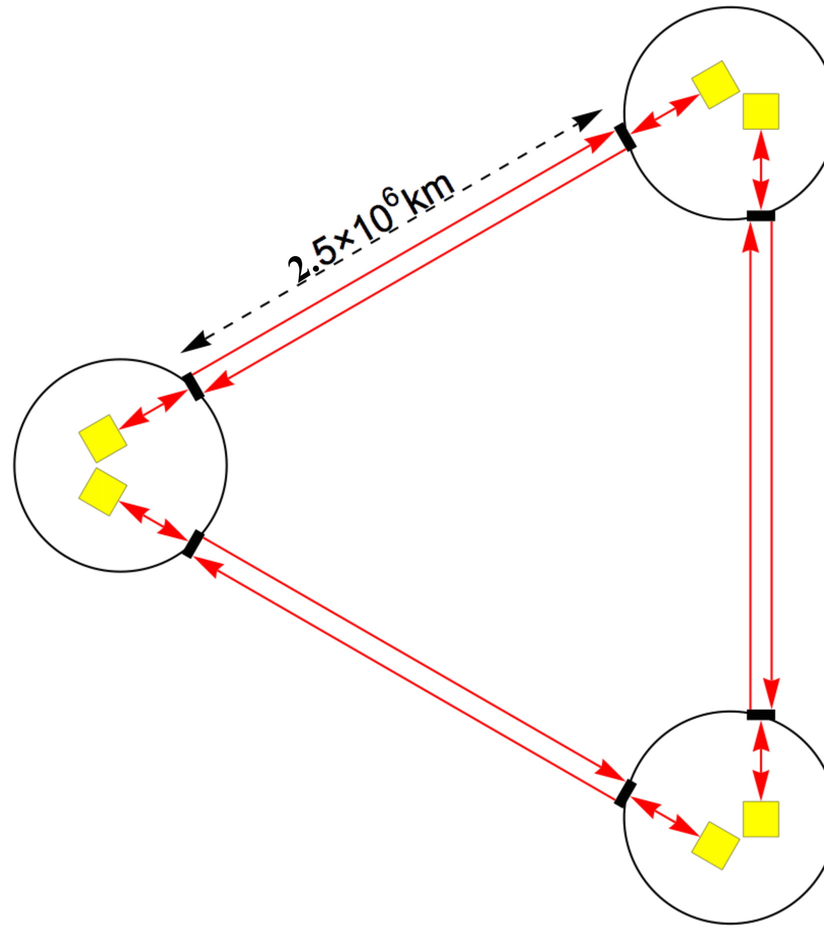
How it could look like



LISA fundamentals: the arm



- True reflection impossible. The LISA arm: two counter-propagating links.
- LISA: 3 arms 2.5 Mo km
- 10 pm/√Hz single-link interferometry @1 mHz



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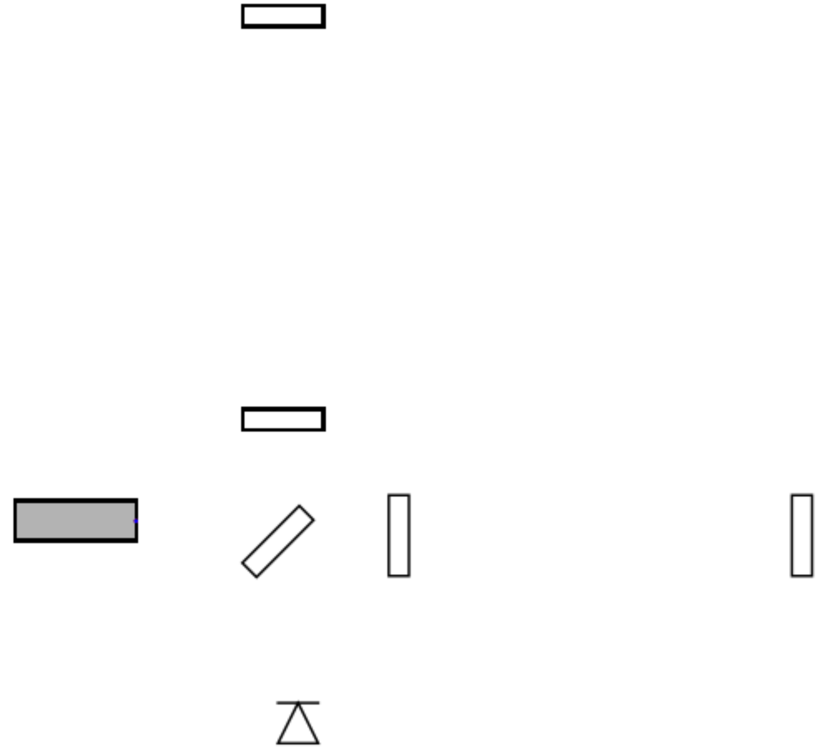
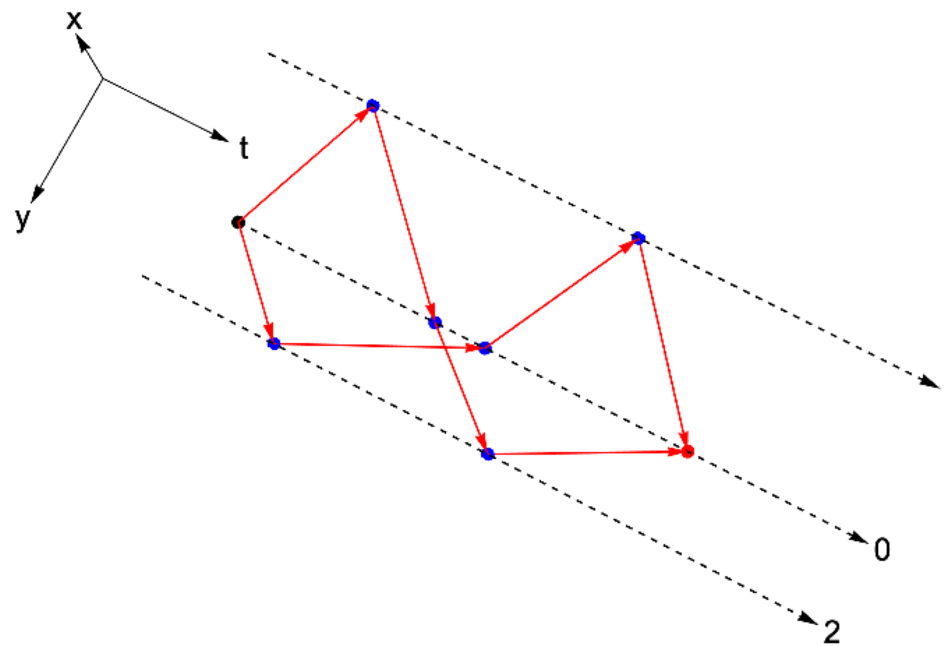
Time delay interferometry

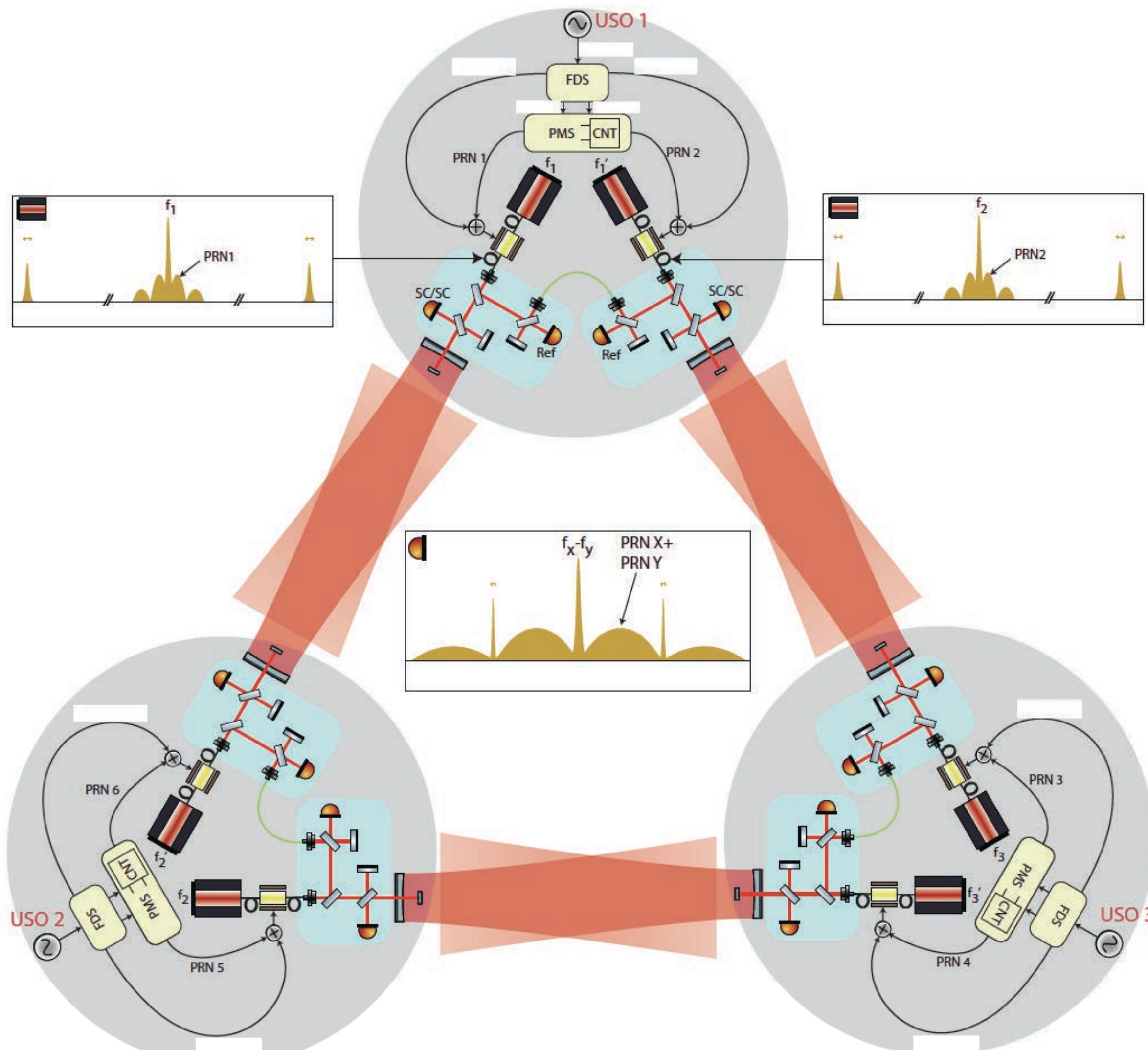
- Best stabilizes laser frequency noise off scale.
- Ground based interferometers beat noise comparing beams emitted at same time (equal arms)
- LISA: arms are unequal (100000 km) and time varying
- Combine single-link signals to mimic light beams that have traveled equal lengths



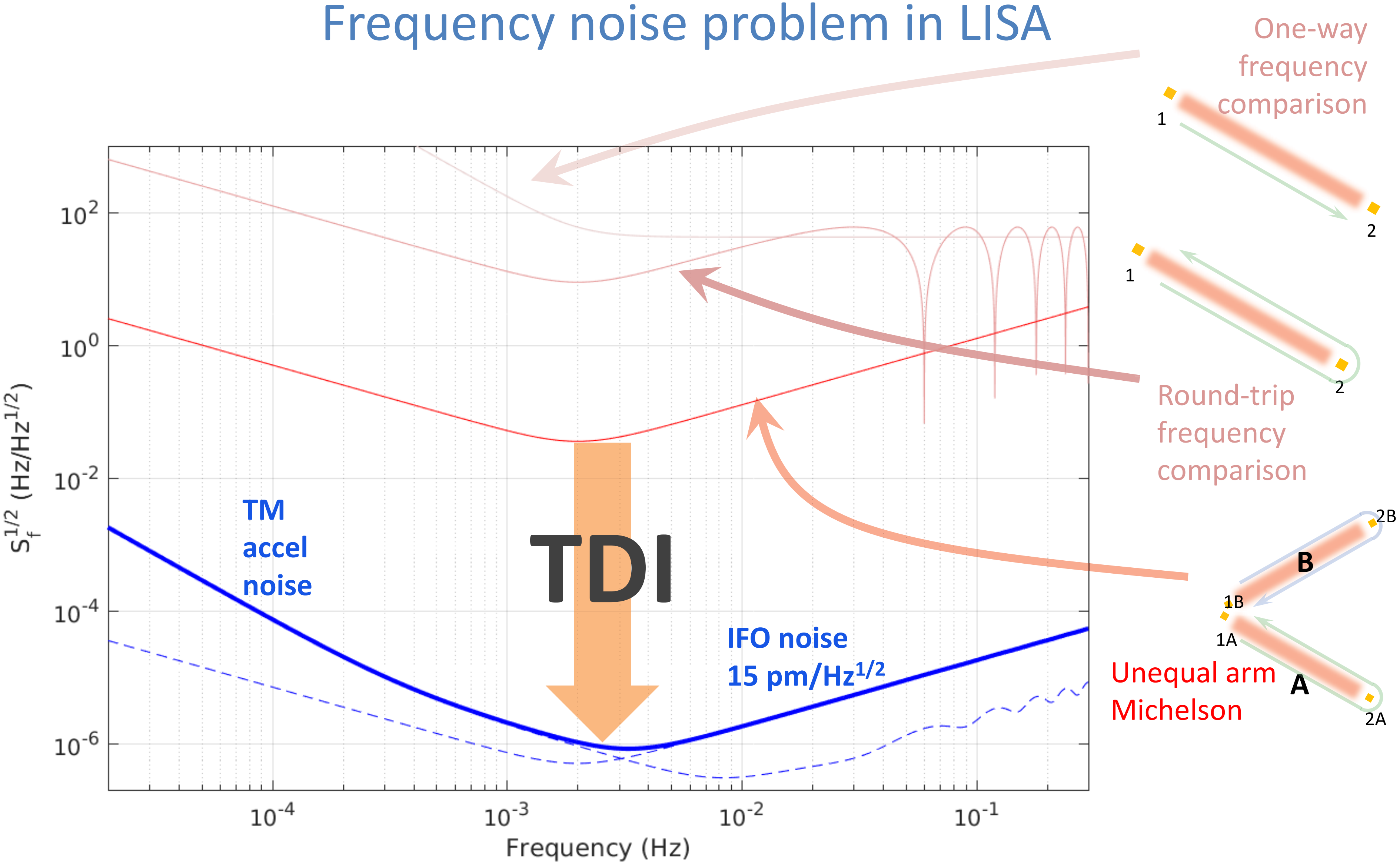


Ranging at 10 cm, clocks and all that

- Ranging with GPS-like pseudocode (~10 cm)
- Clocks for interferometry distributed and compared in post-processing
- Data exchanged on side bands

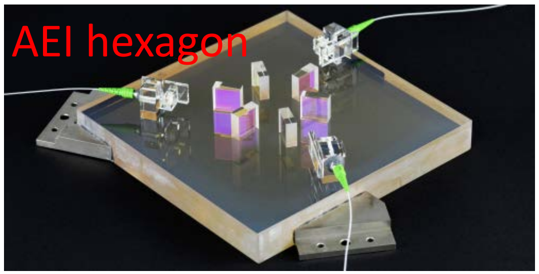


Frequency noise problem in LISA

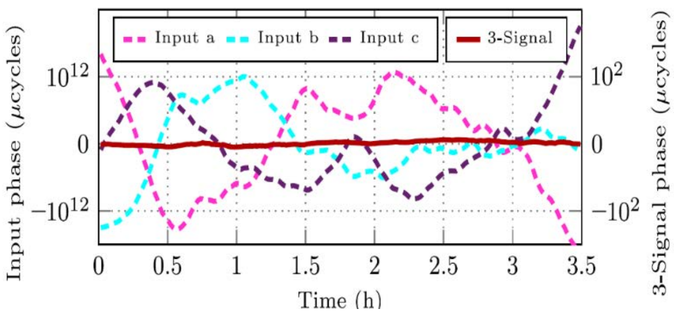


Experimental steps towards LISA interferometry

LISA GW resolution (5 mHz):	0.3 μHz/Hz$^{1/2}$
Laser noise:	30 Hz/Hz$^{1/2}$
Orbital Doppler shifts:	10 MHz

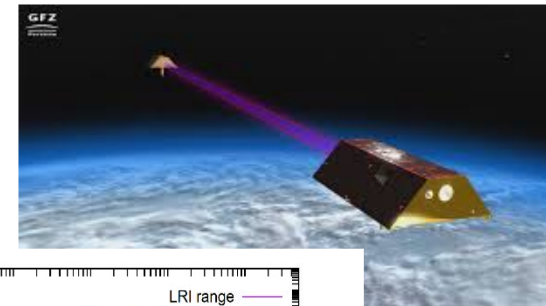


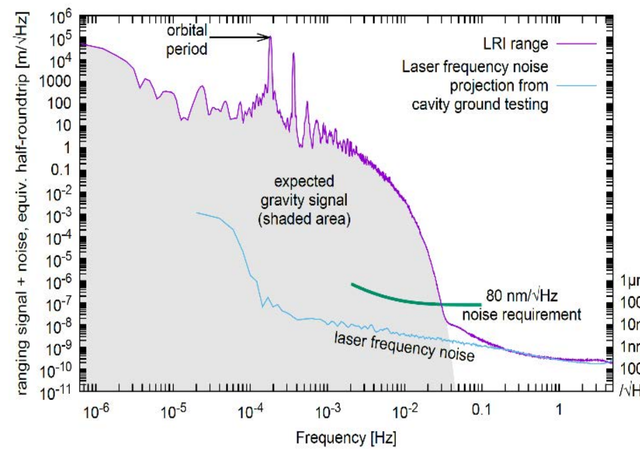
Schwarze+
PRL 2019



Demonstrated needed 10^{11} dynamic range phasemeter

GRACE geodesy:
Laser Ranging Interferometer

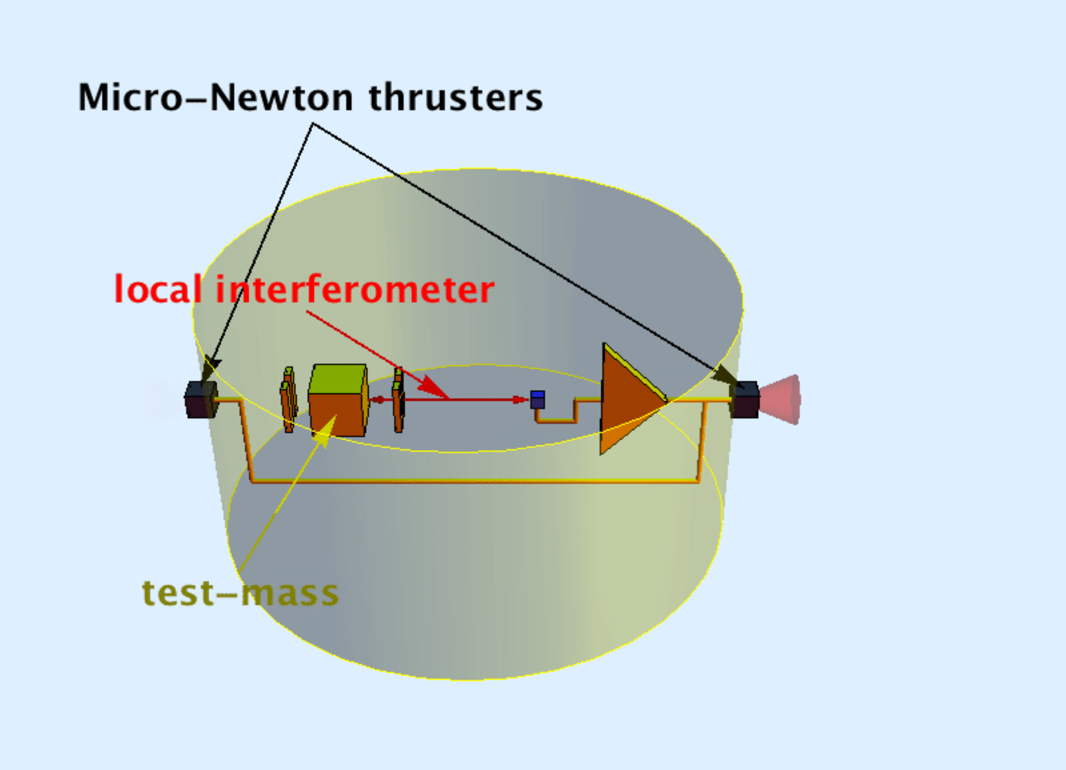


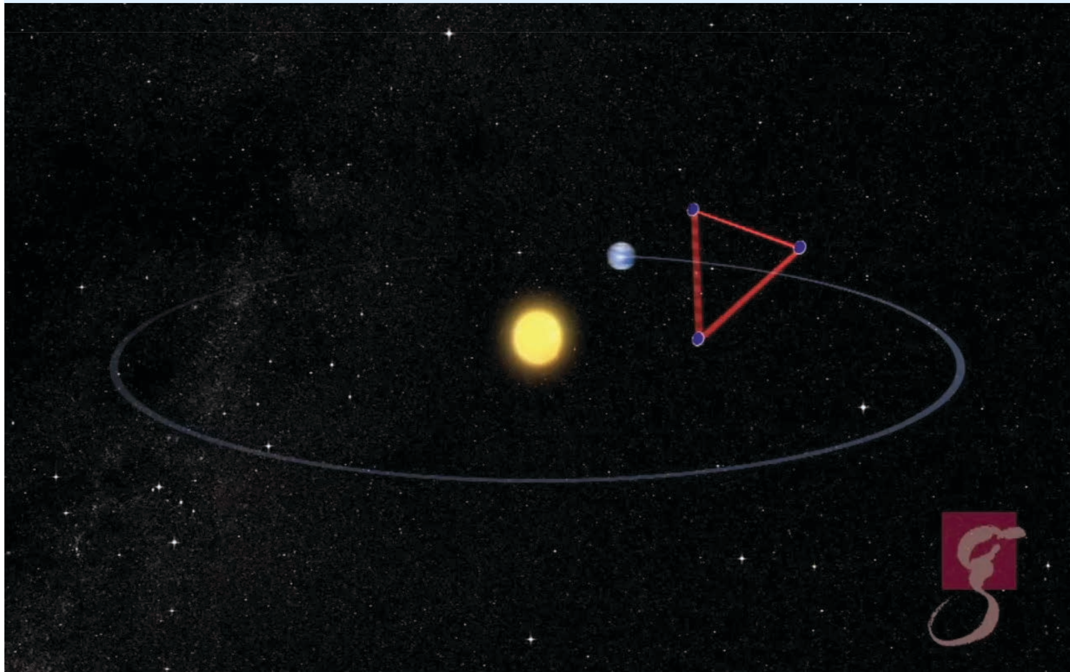


Inter-spacecraft laser interferometry at 200 pm/Hz$^{1/2}$ level

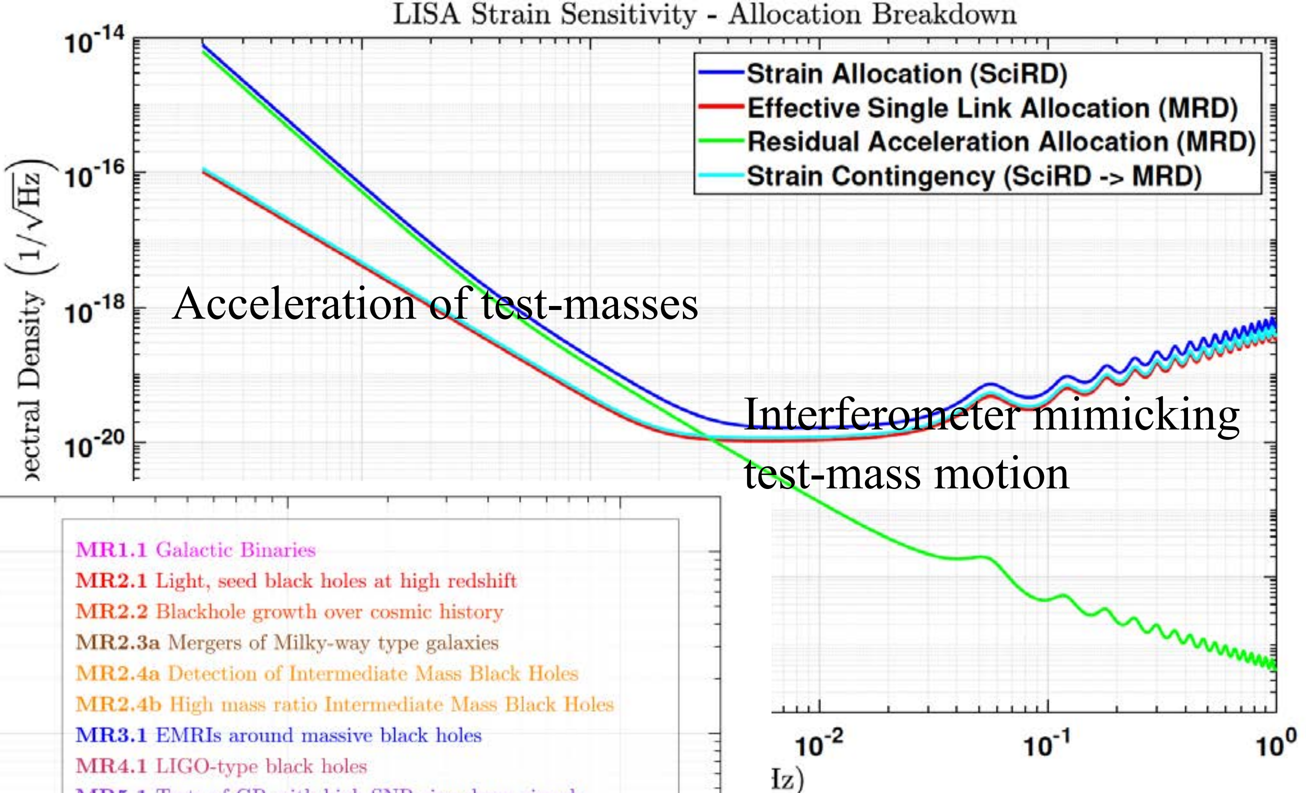
LISA fundamentals

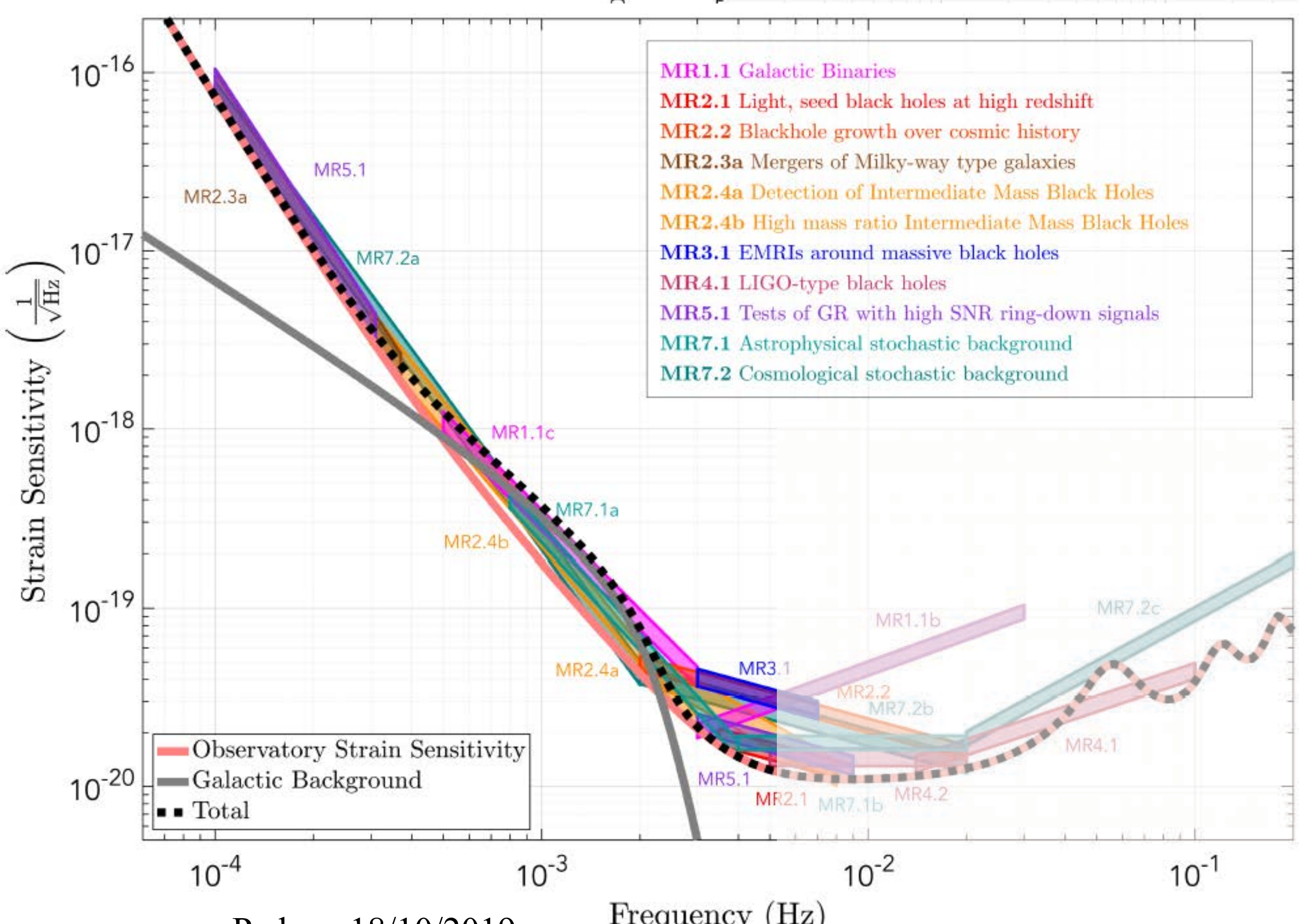
- Free-falling inside a spacecraft
  - position of spacecraft relative to test-mass measured by interferometer and kept fixed by micro-Newton thrusters.
- Satellites follow independent heliocentric orbits.
  - Constellation rotates within waves and gives source location





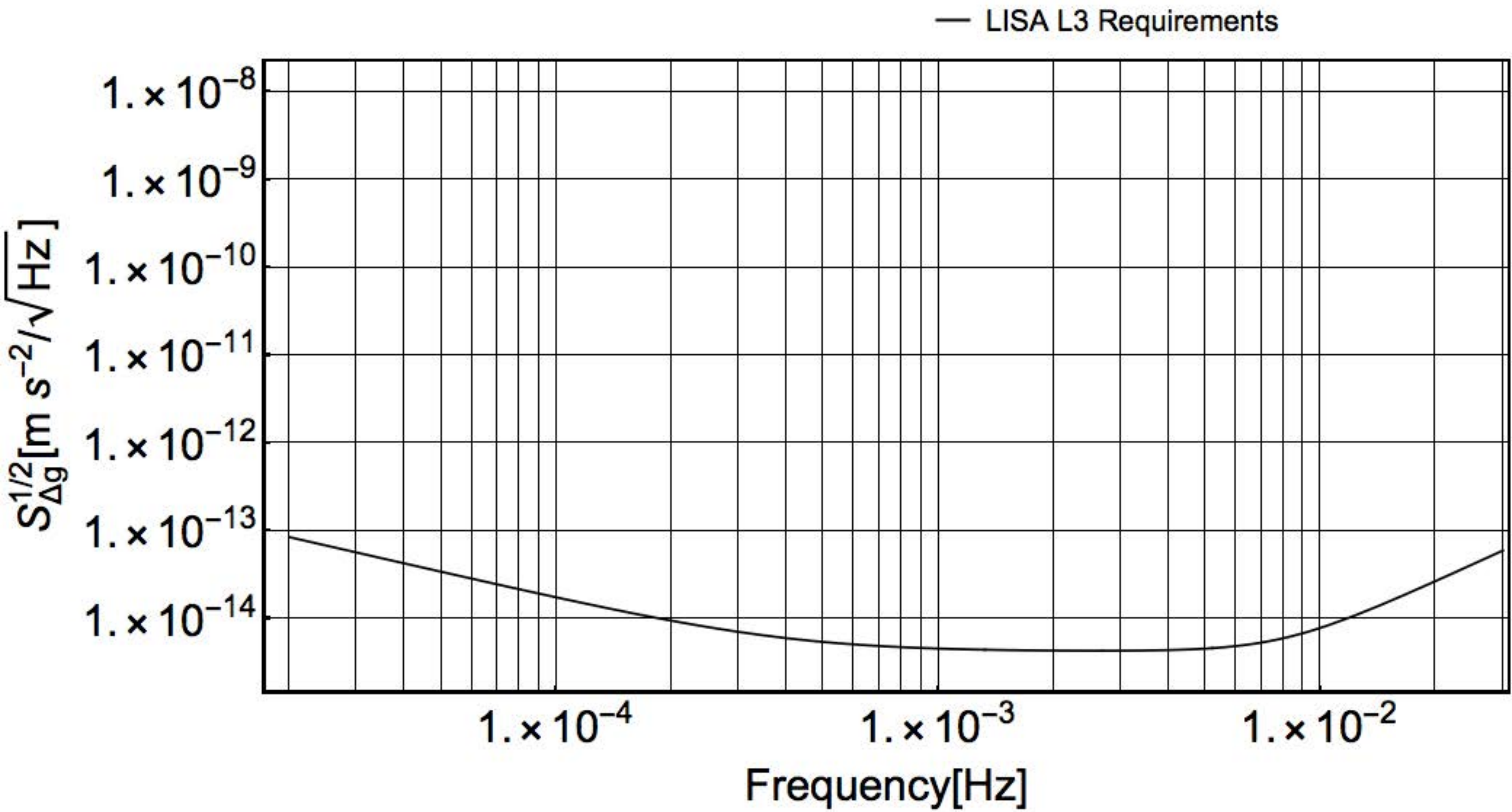
LISA sensitivity and LISA science





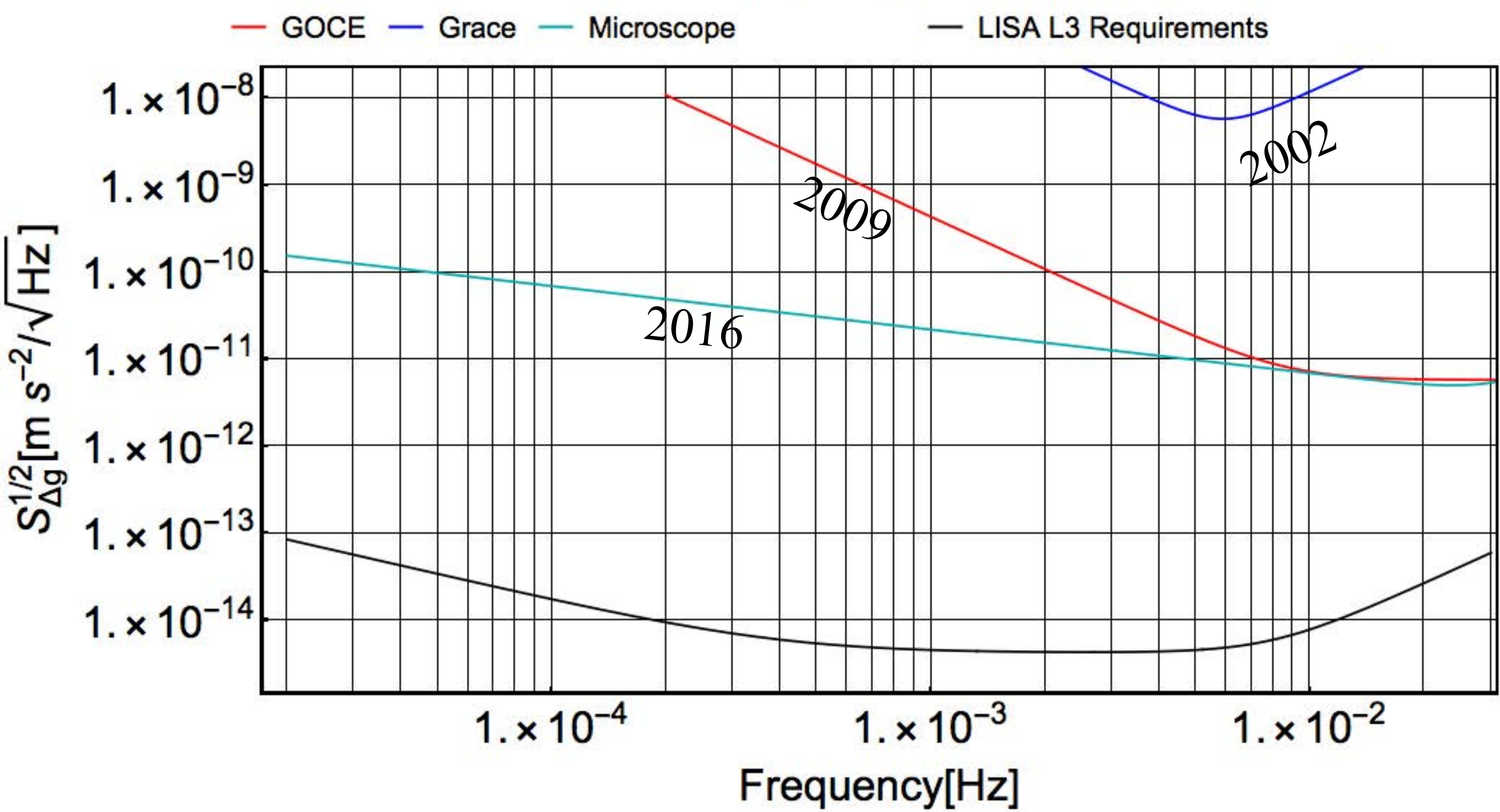
Sub-femto-g force suppression for LISA

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

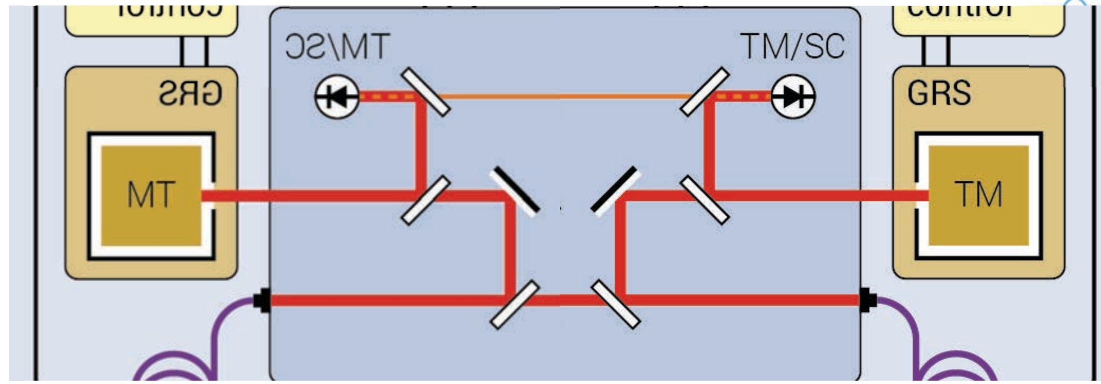


Sub-femto-g force suppression for LISA

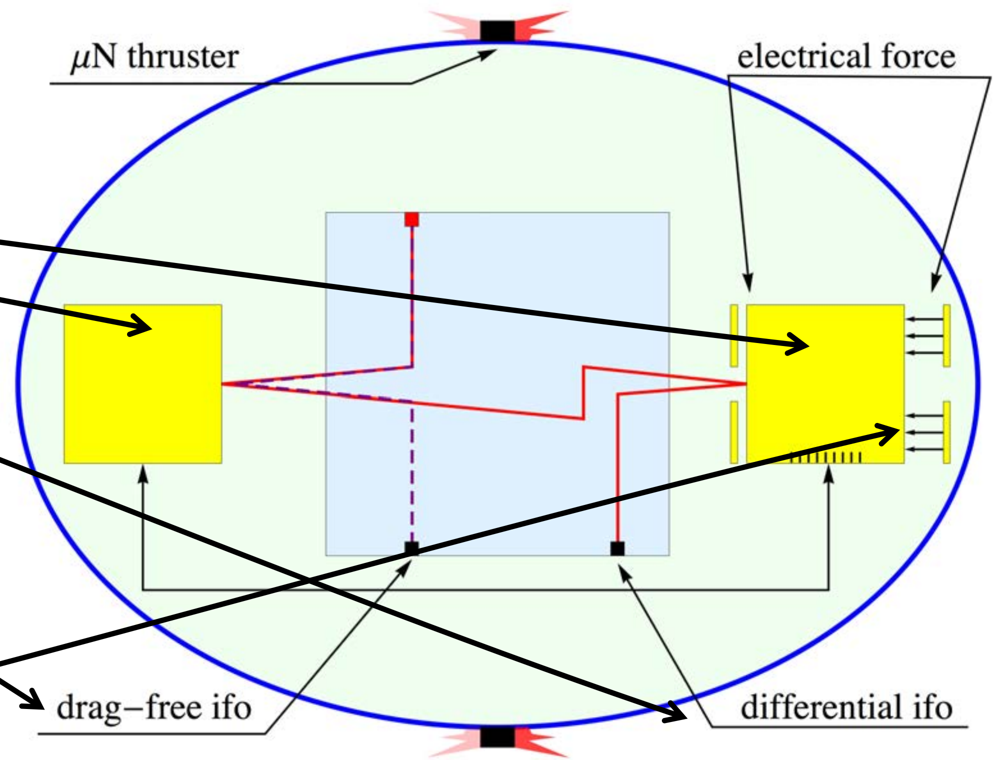
- Cannot be tested on ground $\lesssim 0.1$ Hz
- (>3) Orders of magnitude better than any other space mission



LISA Pathfinder concept

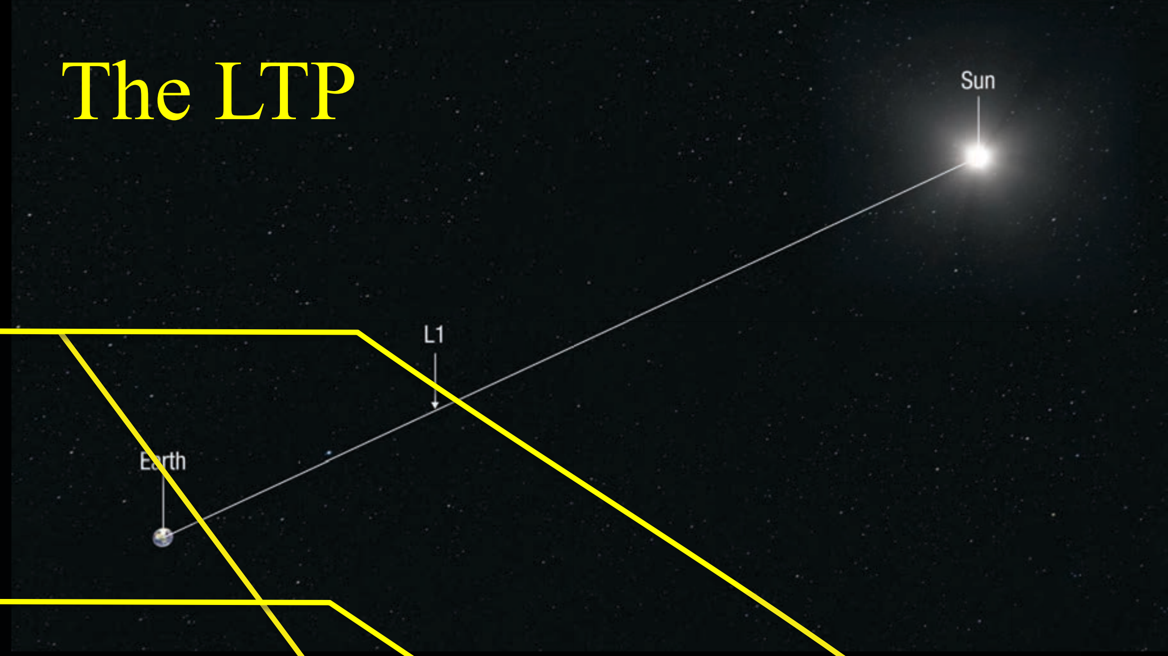


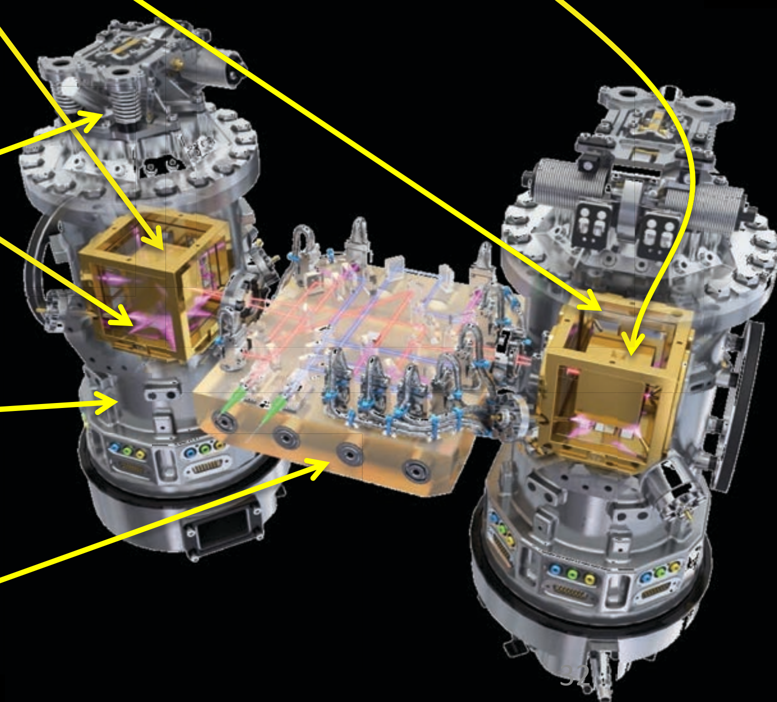
- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- 2 Interferometers (Ifo)
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



The LTP

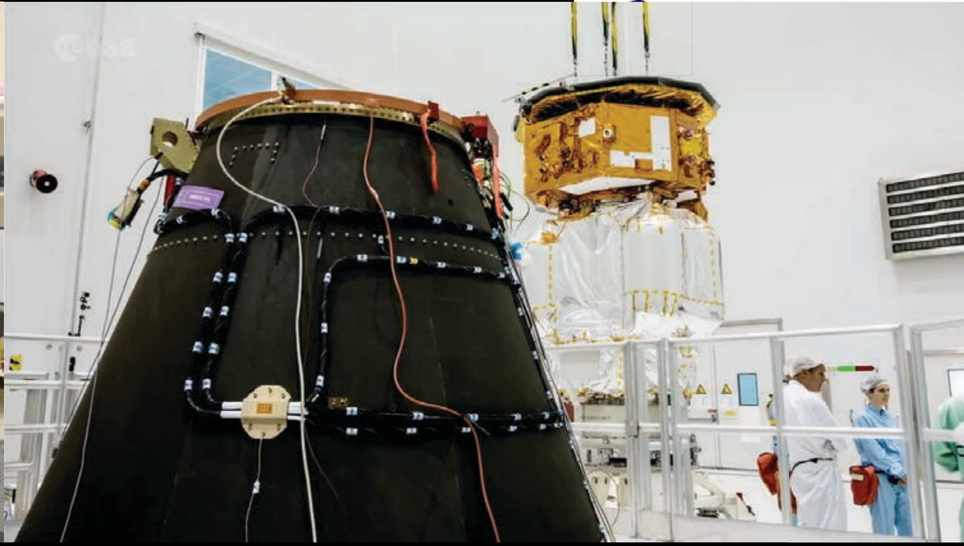
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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






+Y

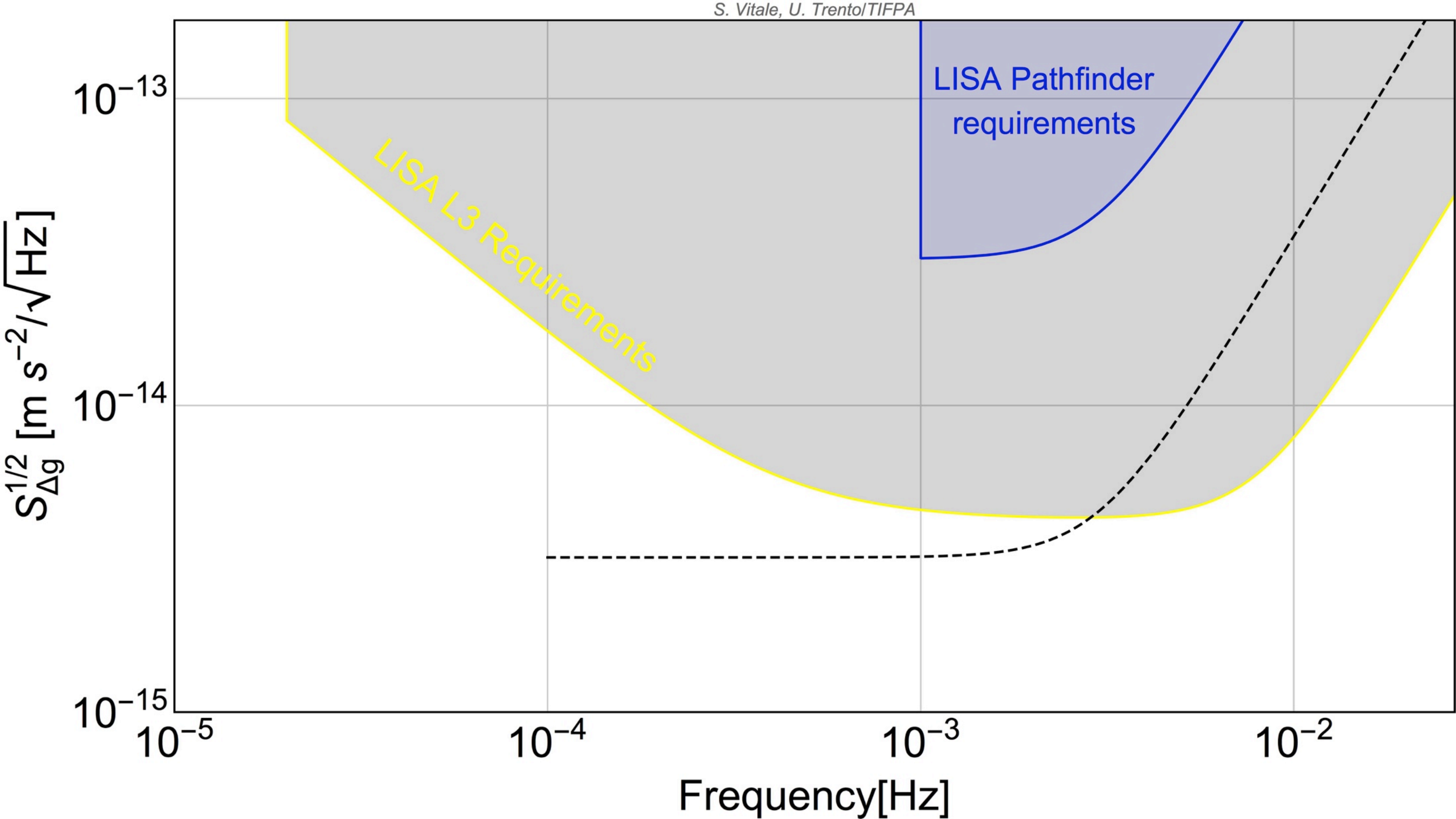

ECLIPSE



From instrument integration to beginning of operations 2014-2016

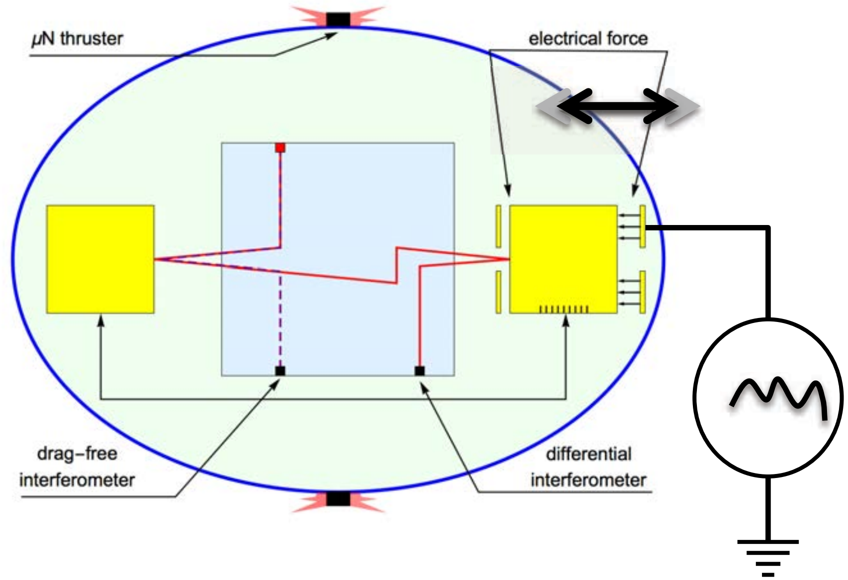
LISA Pathfinder requirements

- Amplitude requirement relaxed because single spacecraft experiment more noisy
- Frequency requirement relaxed to cut down ground testing time
- Interferometer requirements maintained at 9 pm/√Hz ~ as in LISA



Expected performance

- 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



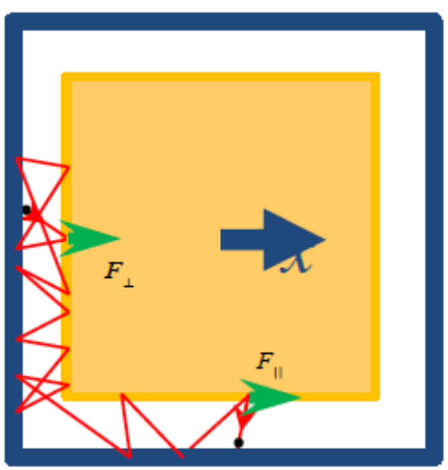
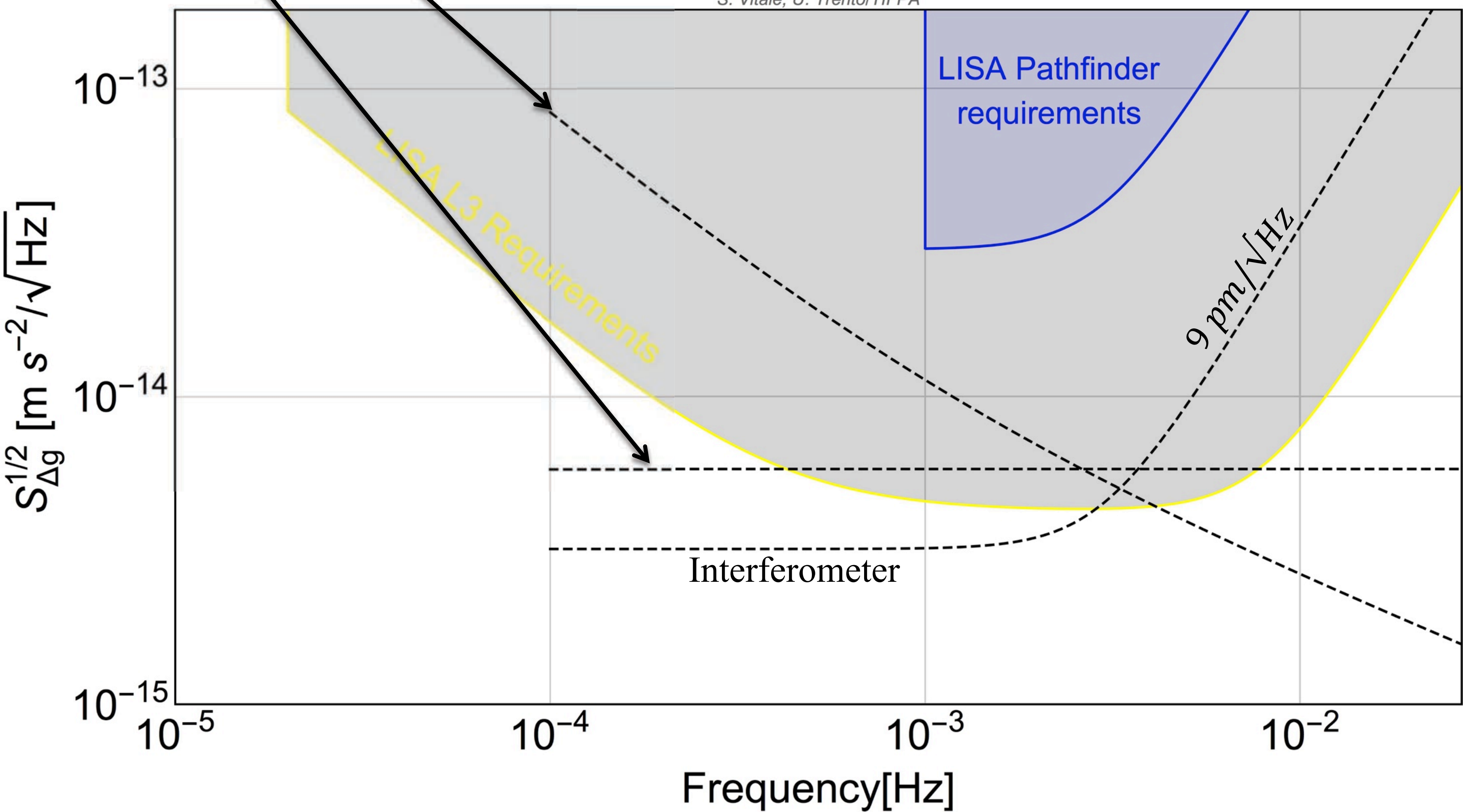


Table 2. Leading sources of differential force-per-unit-mass disturbances and their PSD values at 1 mHz.

Source	PSD (fm s^{-2} $Hz^{-1/2}$)	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



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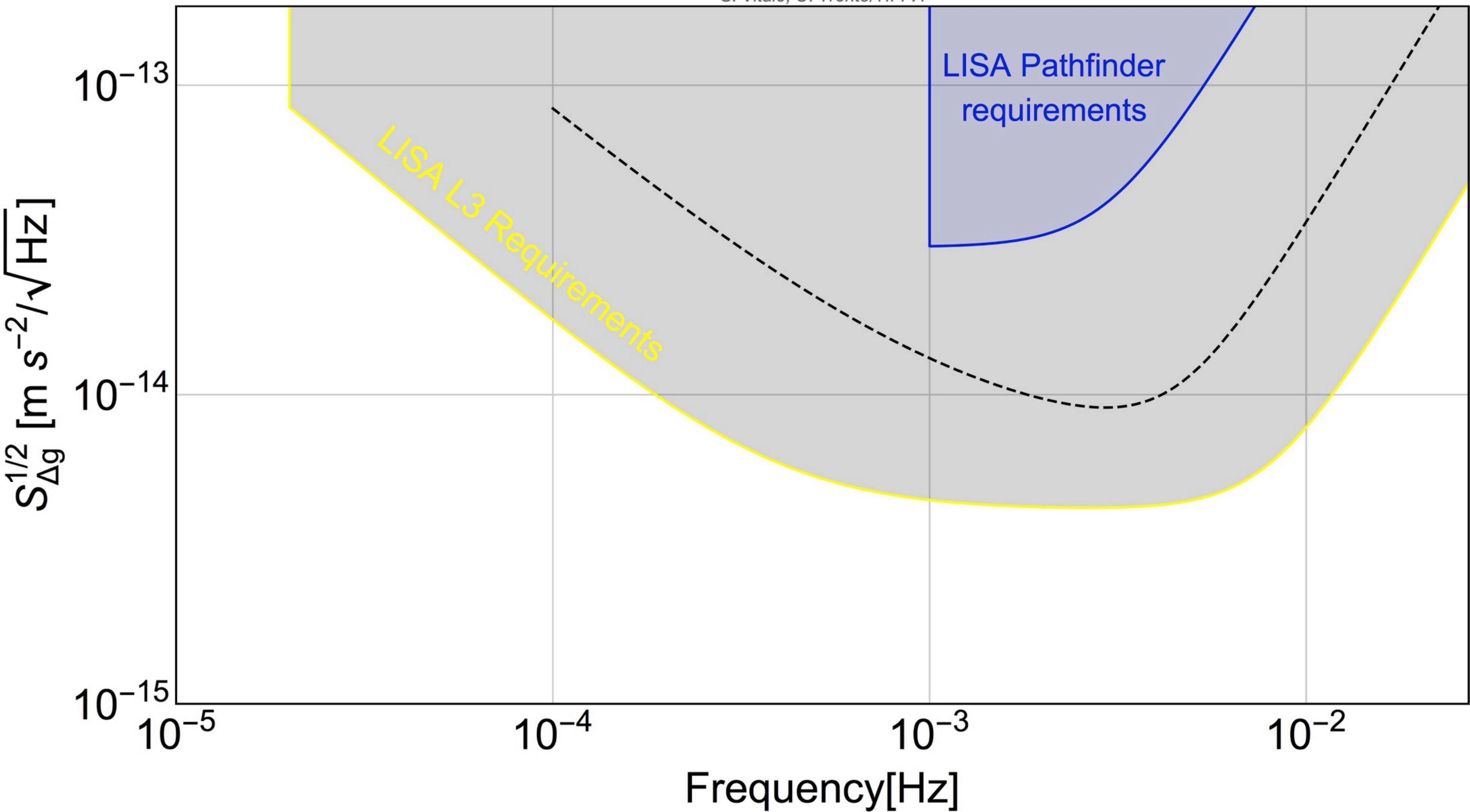
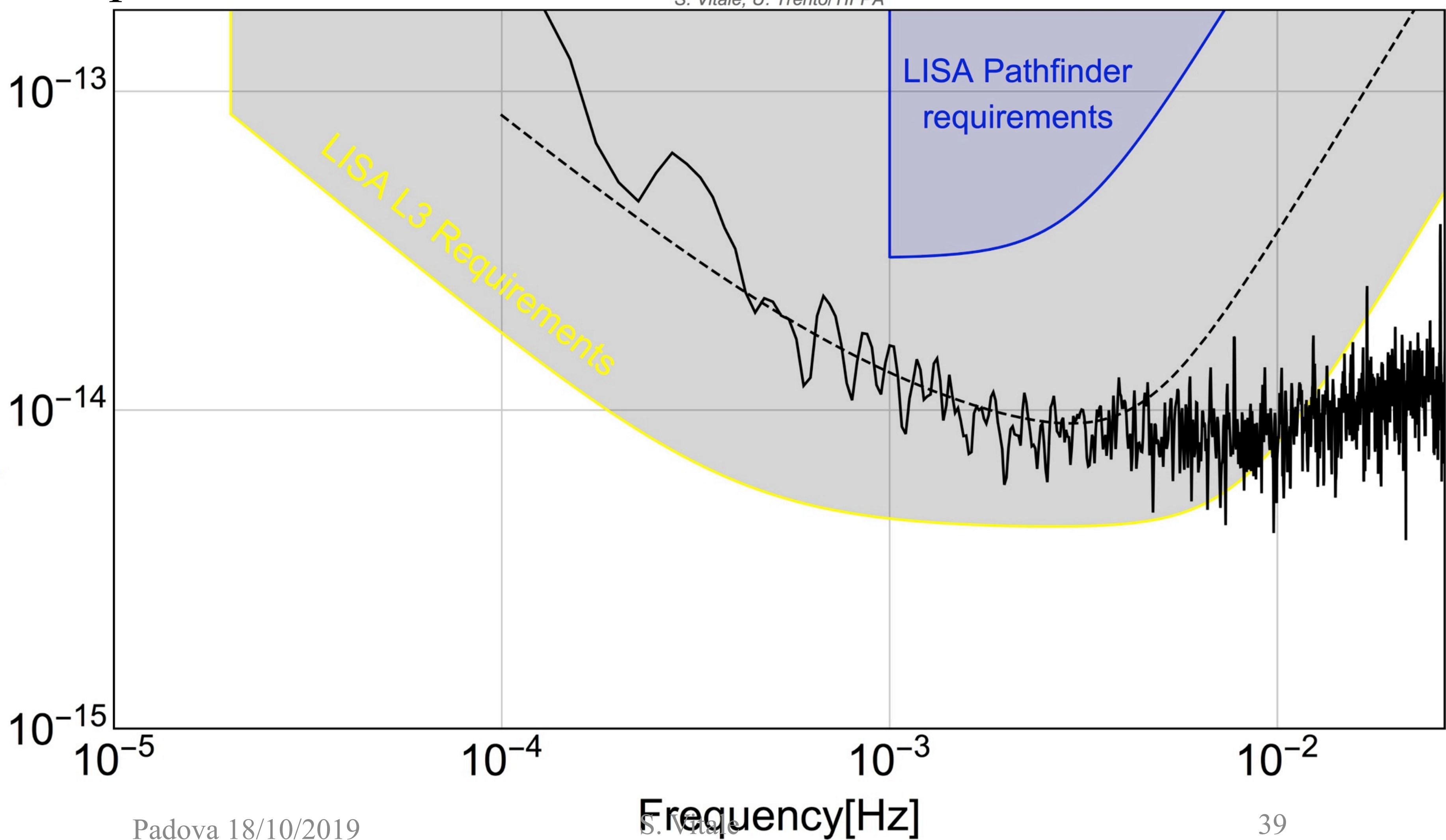


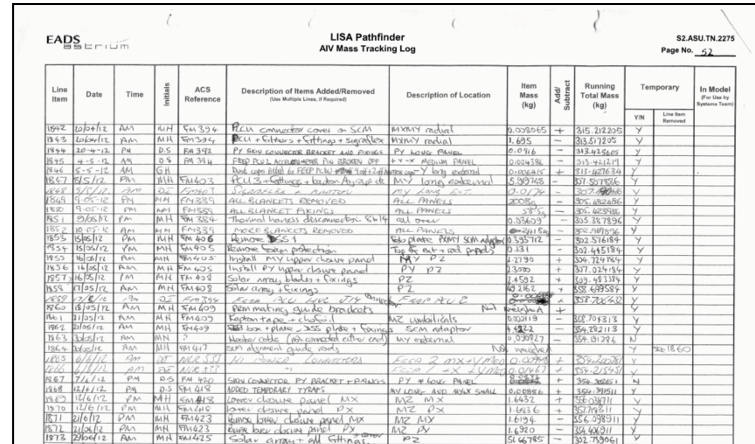
First day of operations, March 1st 2016

- Better than requirement.
- Close to prediction
- Except interferometer noise at 35 fm/√Hz!



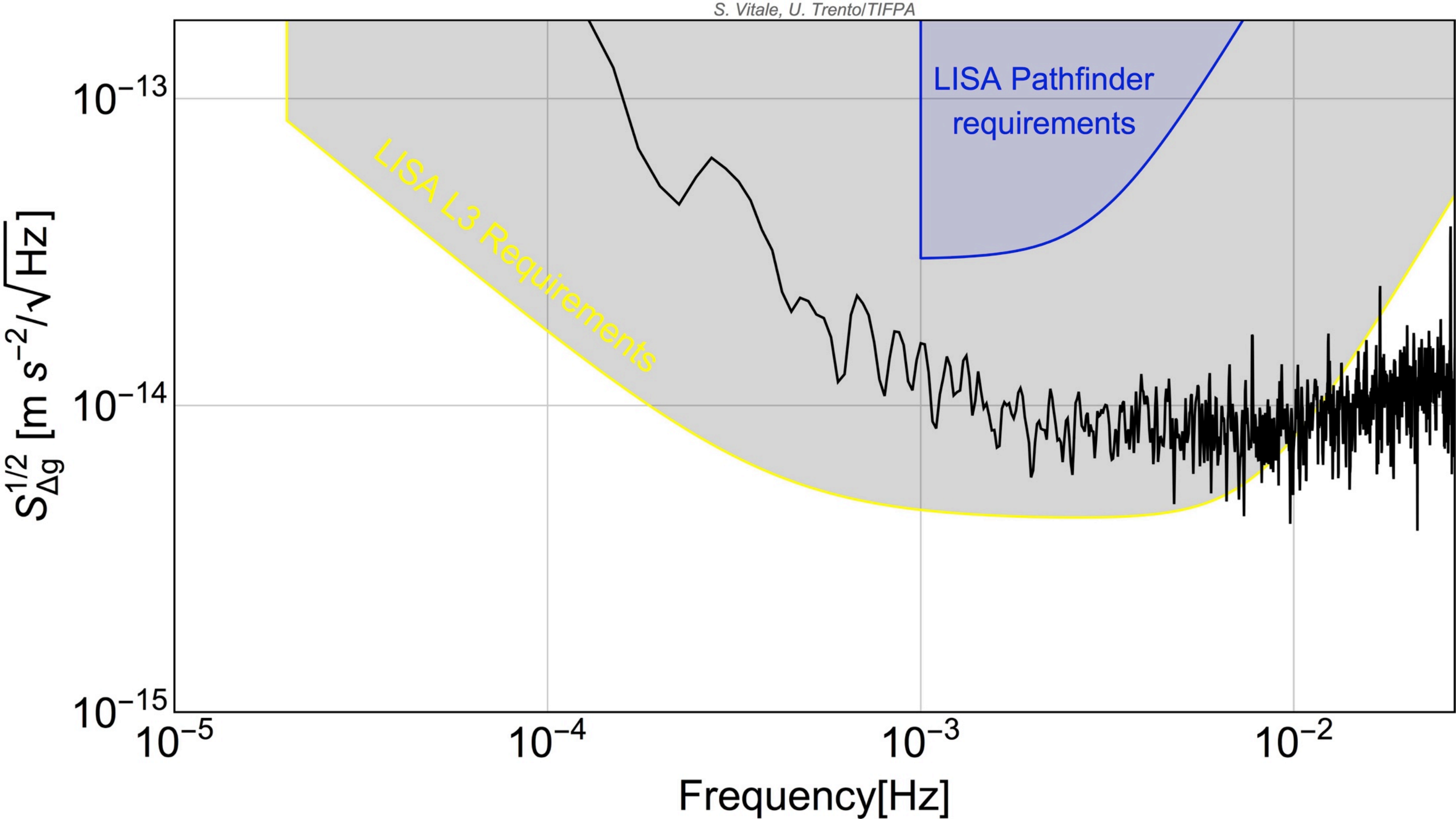
Gravitational control and actuation

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



LEVEL	NAME	REMARKS	Min X [m]	Max X [m]	Min Y [m]	Max Y [m]	Min Z [m]	Max Z [m]	Min m [kg]	Max m [kg]	X cog [mm]	Y cog [mm]	Z [
	New Electrode Housing										0.054419202	-6E-05	-0.
	M3 HEXALOBULAR SOCKET SCREW M3x6.4 (D)	Guard ring z- screws (all)	-0.026201	0.026185	-0.026197	0.026182	-0.037475	-0.029135	1.22E-10	2.42E-08	-0.000151604	-0.0003	-3
	M3 HEXALOBULAR SOCKET SCREW M3x6.4 (D)	Guard ring z- screws (all)	-0.026201	0.026185	-0.026182	0.026197	0.029135	0.037475	1.22E-10	2.42E-08	-0.000151604	0.00033	3
	M3 HEXALOBULAR SOCKET SCREW M3x6.4 (D)	Z- cover screws (all)	-0.022529	0.022523	-0.020769	0.020756	-0.043075	-0.034735	1.23E-10	2.35E-08	-7.04325E-05	-0.0003	-3
	M3 HEXALOBULAR SOCKET SCREW M3x6.4 (D)	Z+ cover screws (all)	-0.022529	0.022523	-0.020756	0.020769	0.034735	0.043075	1.23E-10	2.35E-08	-7.04325E-05	0.00027	3
	M3 HEXALOBULAR SOCKET SCREW 3X6.4 (A)	X- face screws	0.029662	0.037972	-0.030199	0.030198	-0.029194	0.029191	9.41E-11	3.64E-08	34.36440315	-0.0001	6
	M3 HEXALOBULAR SOCKET SCREW 3X6.4 (A)	X+ face screws	-0.037972	-0.029662	-0.030198	0.030199	-0.029194	0.029191	9.41E-11	3.64E-08	-34.36440315	0.0001	6
	M3 HEXALOBULAR SOCKET SCREW 3X6.4 (A)	Y- face screws	-0.032203	0.032203	0.028562	0.036872	-0.030198	0.030197	9.41E-11	3.64E-08	-9.38224E-05	33.2644	0.
	M3 HEXALOBULAR SOCKET SCREW 3X6.4 (A)	Y+ face screws	-0.032203	0.032203	-0.036872	-0.028562	-0.030198	0.030197	9.41E-11	3.64E-08	9.38224E-05	-33.264	0.
	M3 HEXALOBULAR SOCKET SCREW 3X6.4 (A)	Z- face screws	-0.032993	0.032993	-0.032991	0.032991	-0.037472	-0.029162	9.41E-11	3.64E-08	-0.000201659	-1E-05	-3
	M3 HEXALOBULAR SOCKET SCREW 3X6.4 (A)	Z+ face screws	-0.032993	0.032993	-0.032991	0.032991	0.029162	0.037472	9.41E-11	3.64E-08	-0.000201659	1.1E-05	3
	M3 HEXALOBULAR SOCKET SCREW 3X6.9 (B)	y+ dir	0.034734	0.043568	-0.019636	-0.015239	-0.006856	-0.002459	1.18E-10	2.39E-08	39.75527429	-17.436	-4.
	M3 HEXALOBULAR SOCKET SCREW 3X6.9 (B)		0.034734	0.043568	0.015239	0.019636	-0.006856	-0.002459	1.18E-10	2.39E-08	39.75527429	17.4358	-4.
	M3 HEXALOBULAR SOCKET SCREW 3X6.9 (B)		-0.043568	-0.034734	0.015239	0.019636	-0.006856	-0.002459	1.18E-10	2.39E-08	-39.75527429	17.4358	-4.
	M3 HEXALOBULAR SOCKET SCREW 3X6.9 (B)		-0.043568	-0.034734	-0.019636	-0.015239	-0.006856	-0.002459	1.18E-10	2.39E-08	-39.75527429	-17.436	-4.
	M3 HEXALOBULAR SOCKET SCREW 3X6.9 (B)	all y- cover screws	-0.011346	0.001784	0.033634	0.042468	-0.010393	0.010171	1.18E-10	2.45E-08	-3.854340843	38.6552	-
	M3 HEXALOBULAR SOCKET SCREW 3X6.9 (B)	all y+ cover screws	-0.001784	0.011346	-0.042468	-0.033634	-0.010393	0.010171	1.18E-10	2.45E-08	3.854340843	-38.655	-
	EH Frame		-0.035911	0.03592	-0.035923	0.03592	-0.034455	0.034464	1.58E-10	5.32E-07	0.168660707	-0.0001	0.
	Z+ Face Assy												

Authority: 650 pm s^{-2}

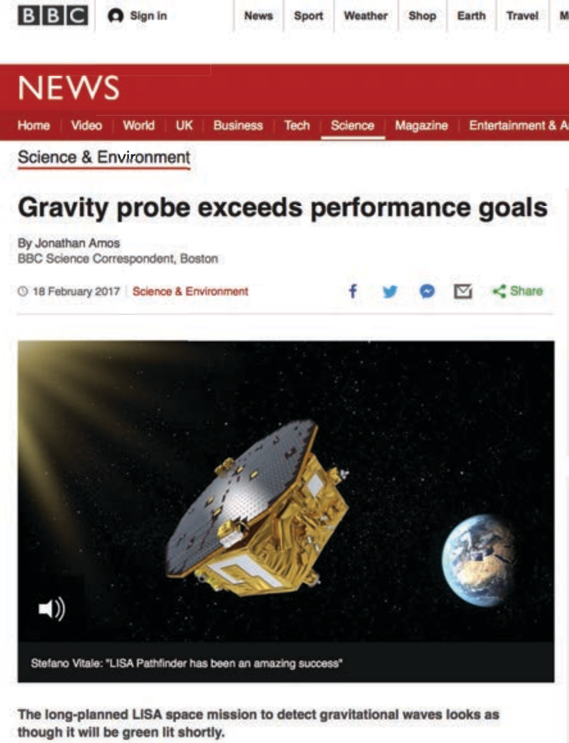


April 2016

…ced to 50 pm s^{-2}

…une 2016

…rownian decaying thanks to venting to space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Gravity probe exceeds performance goals

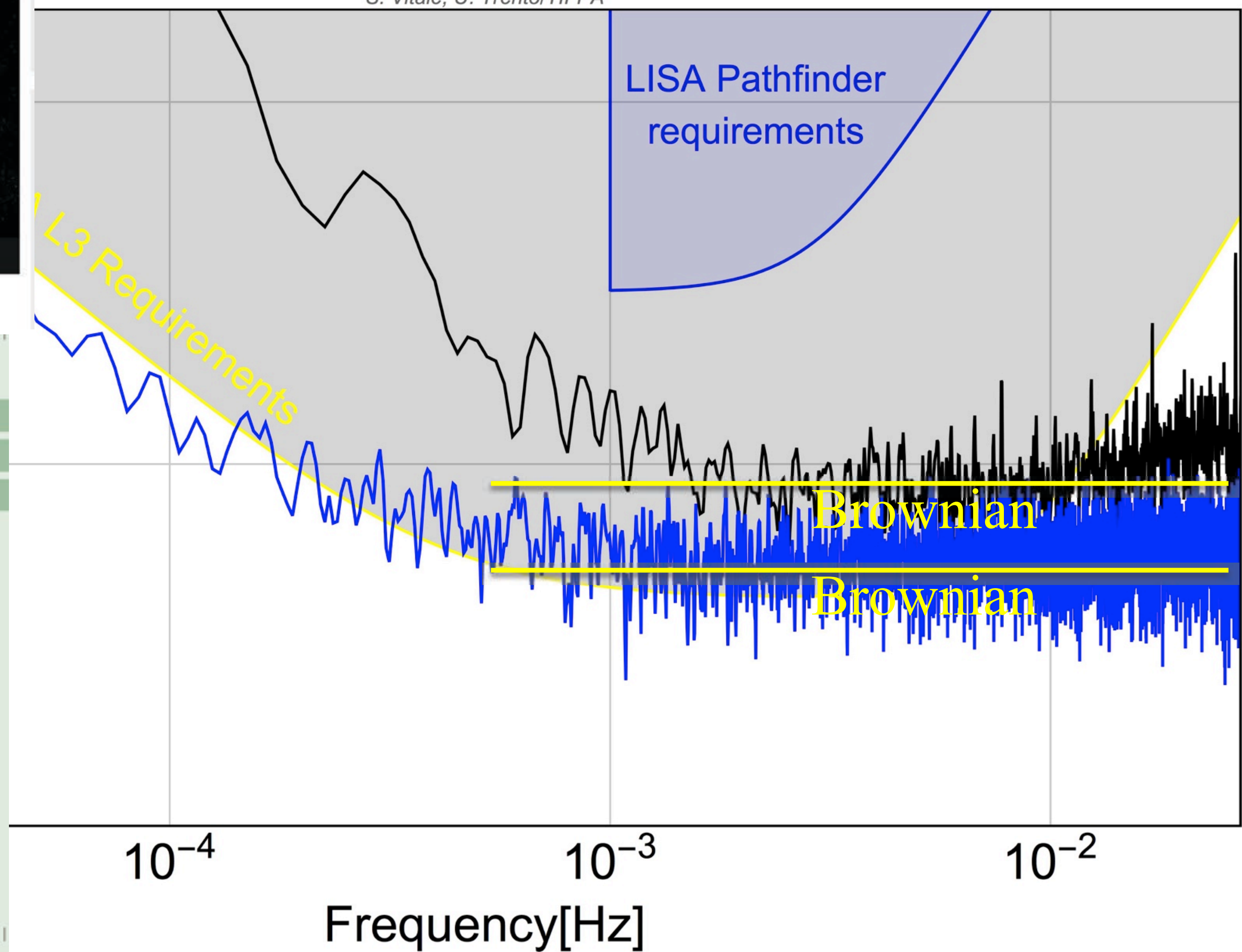
By Jonathan Amos
BBC Science Correspondent, Boston

18 February 2017 Science & Environment Share

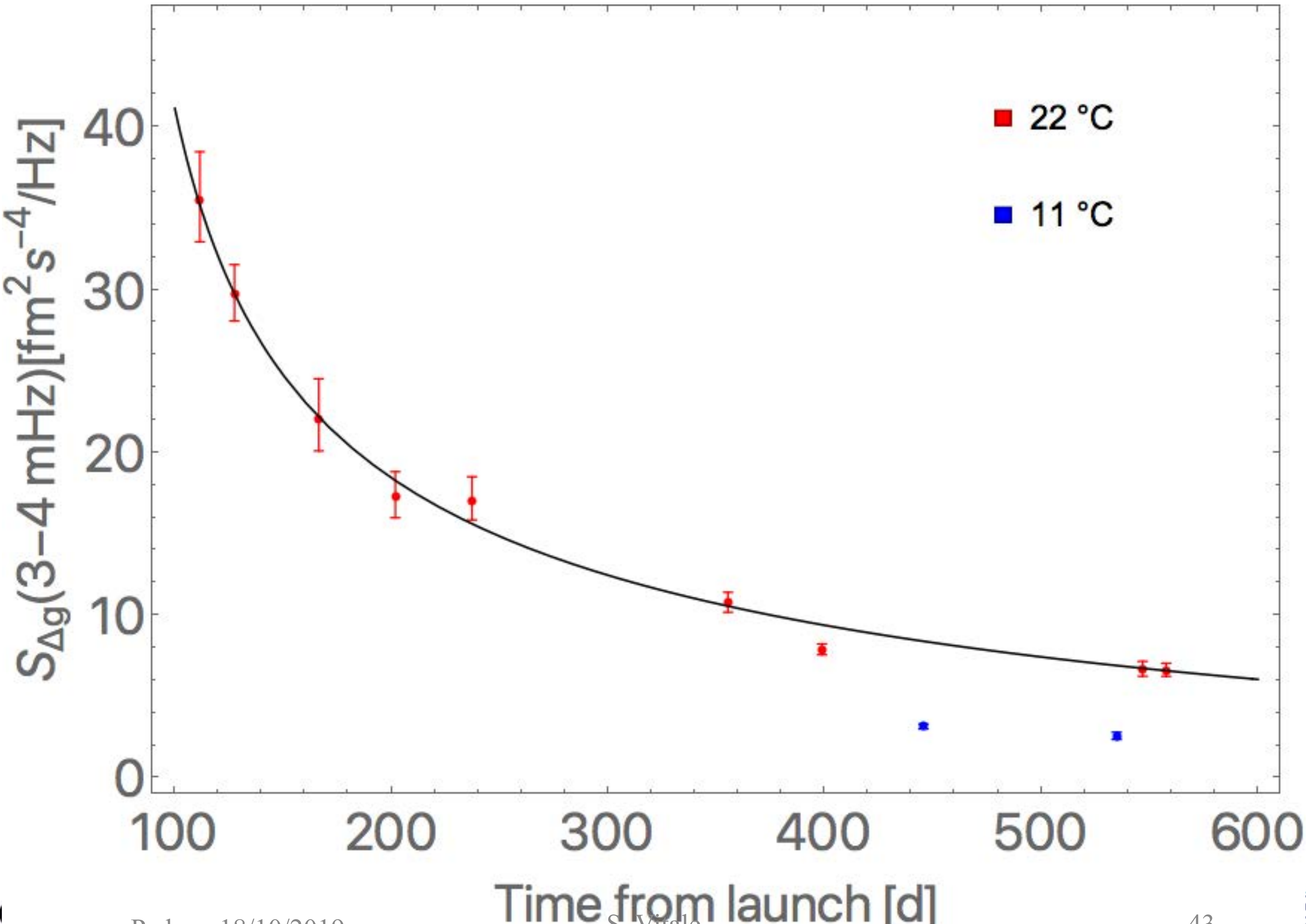
Stefano Vitale: "LISA Pathfinder has been an amazing success"

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

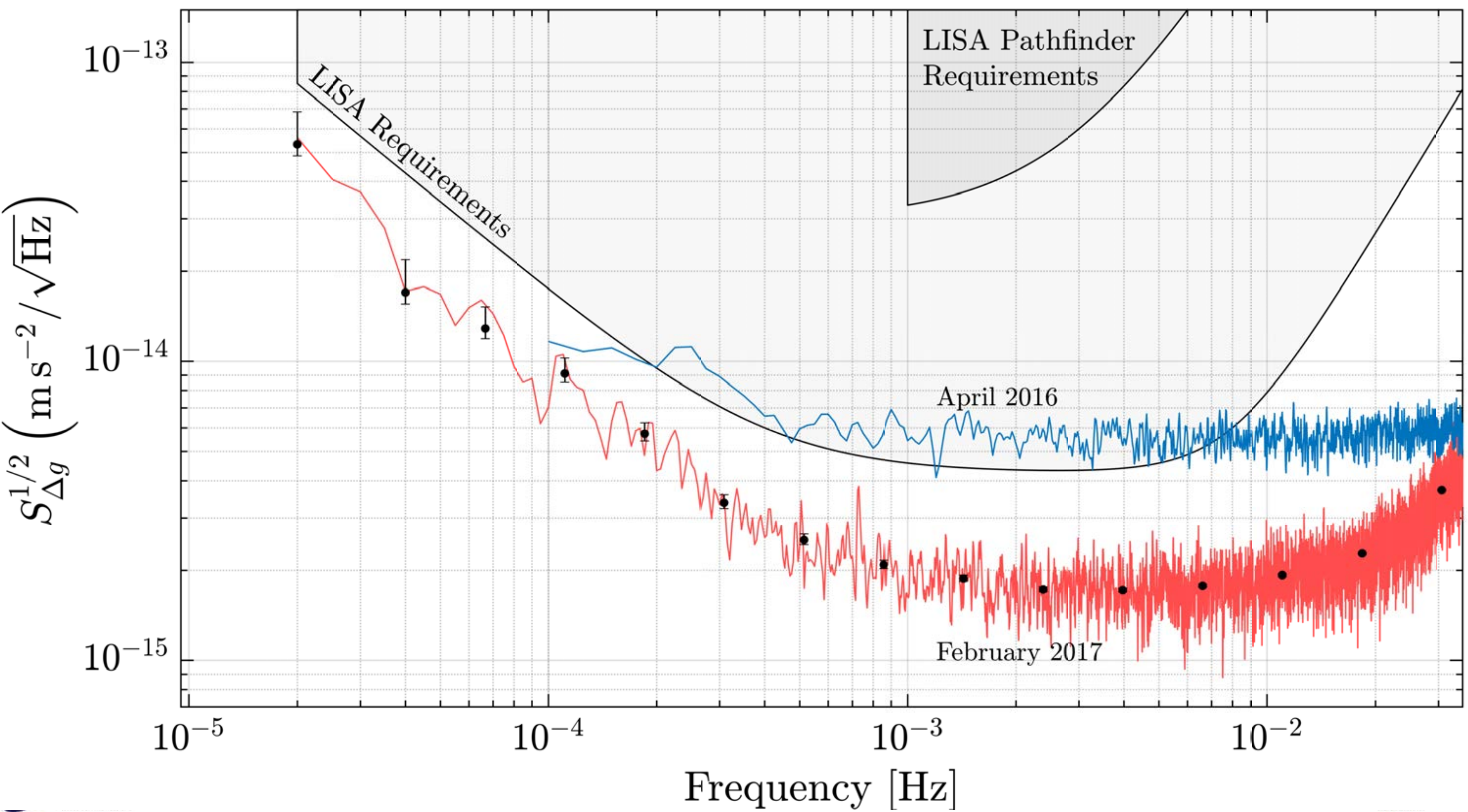
S. Vitale, U. Trento/TIFPA



Pressure and Brownian decay

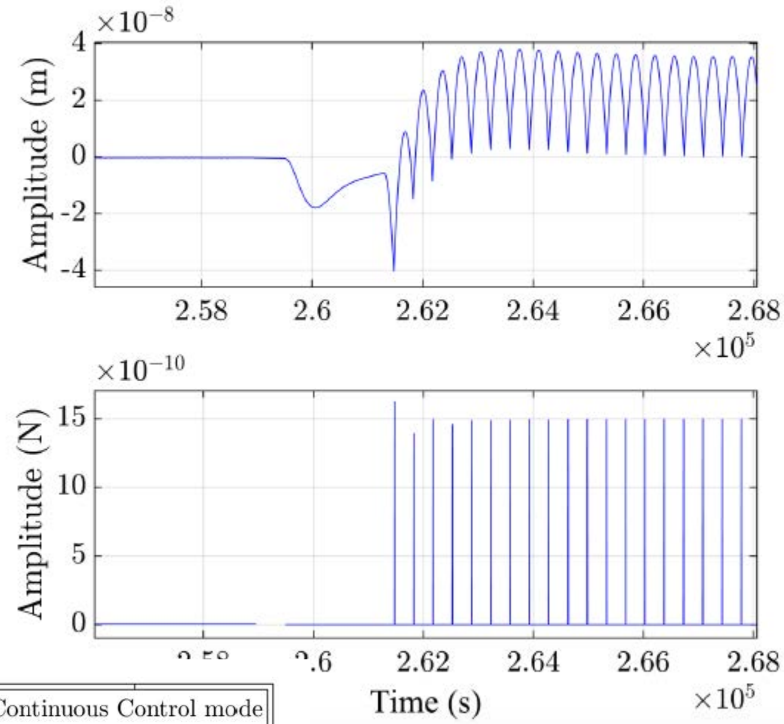


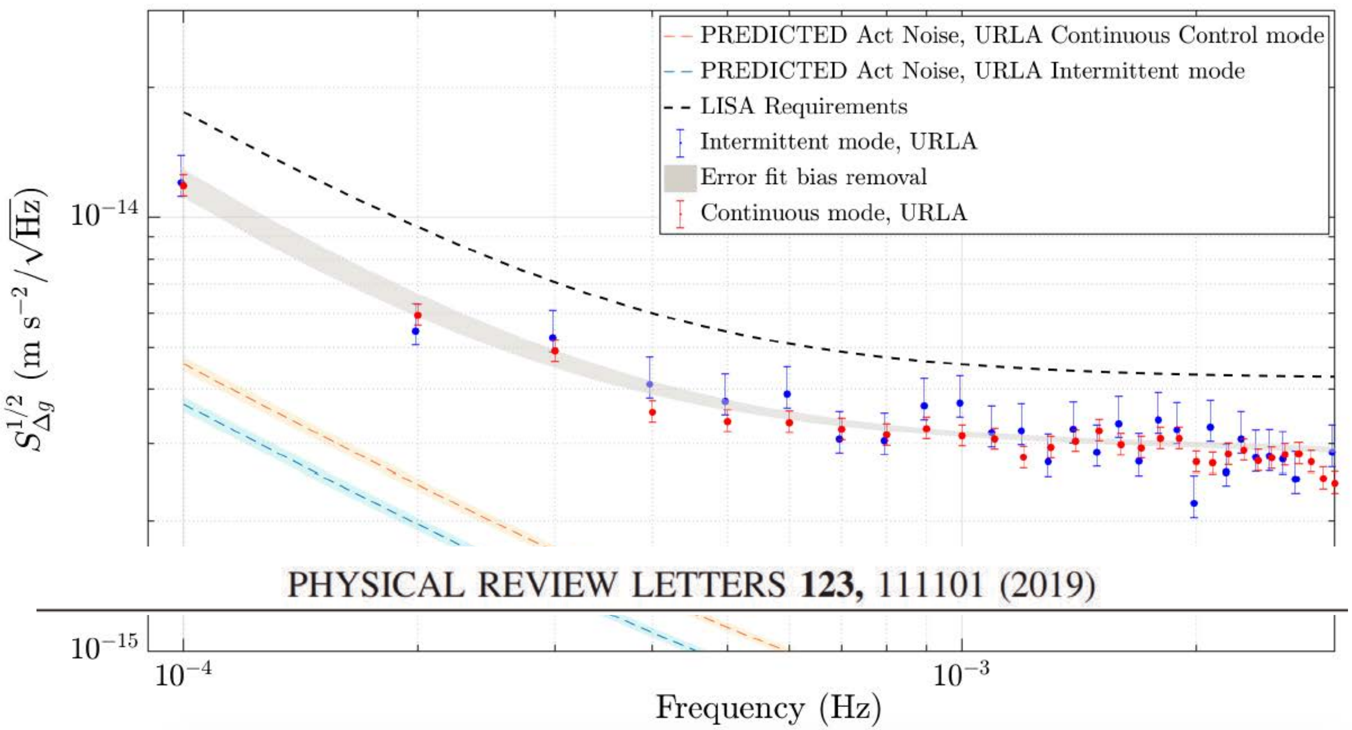
The ultimate performance



An independent check: gravimeter vs accelerometer

- Control with intermittent force pulses and unperturbed 300 s flights in between
- Noise on time scale > 300 s accurately interpolated





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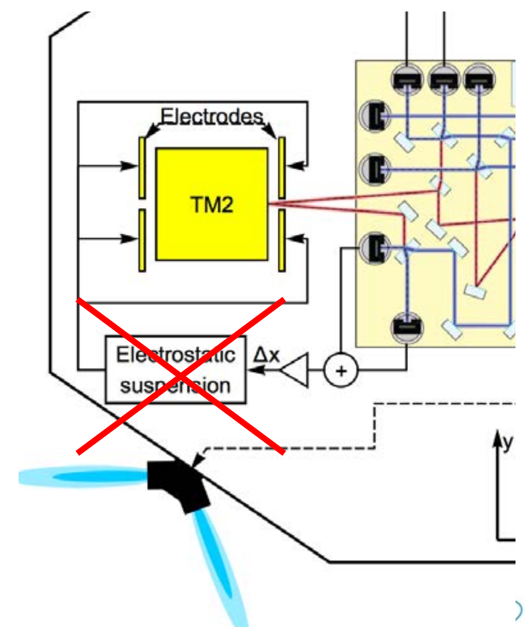
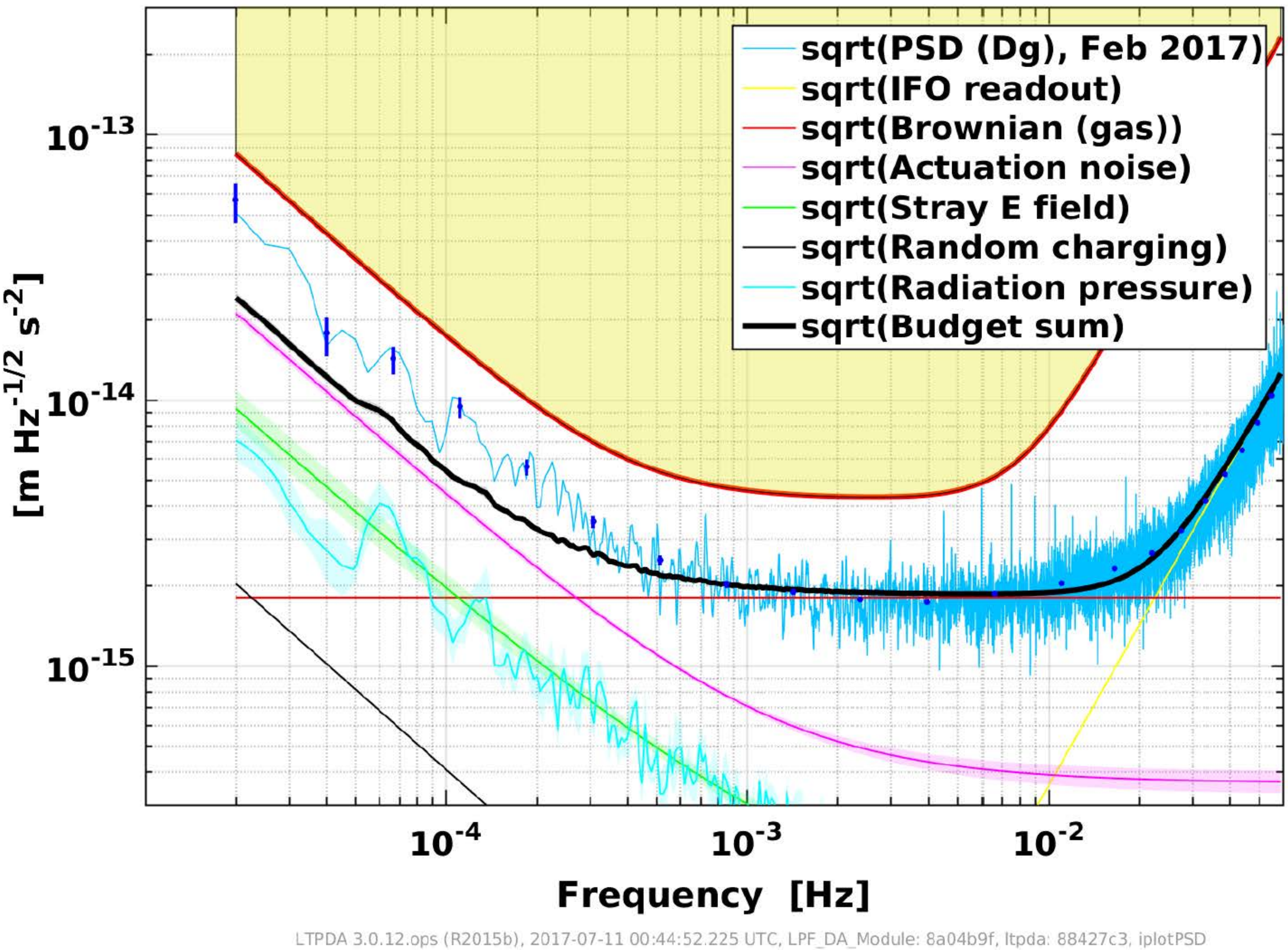
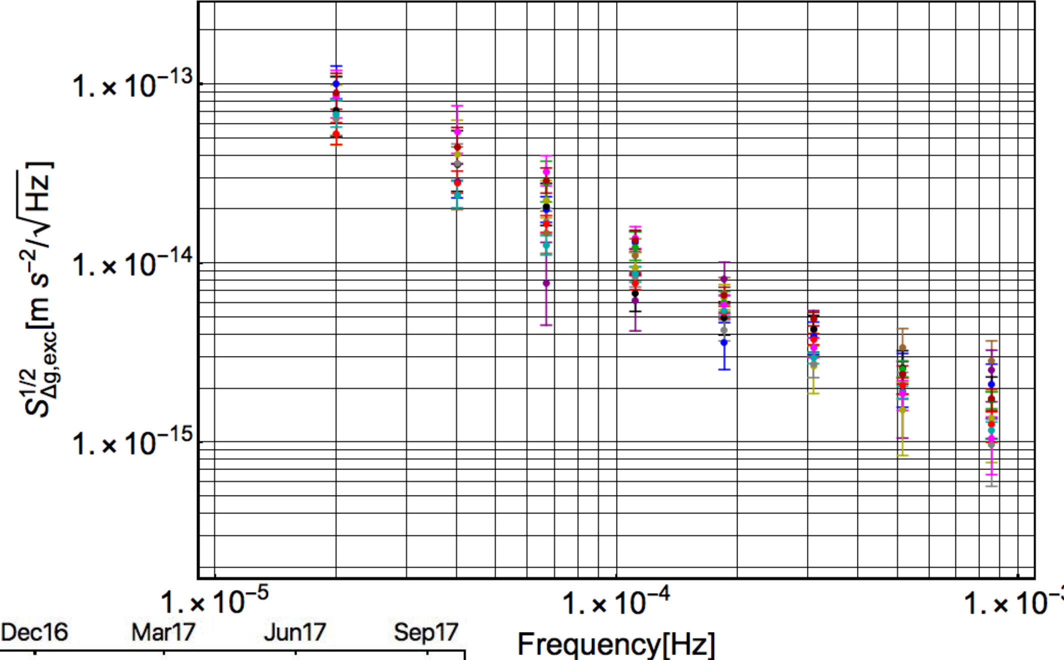
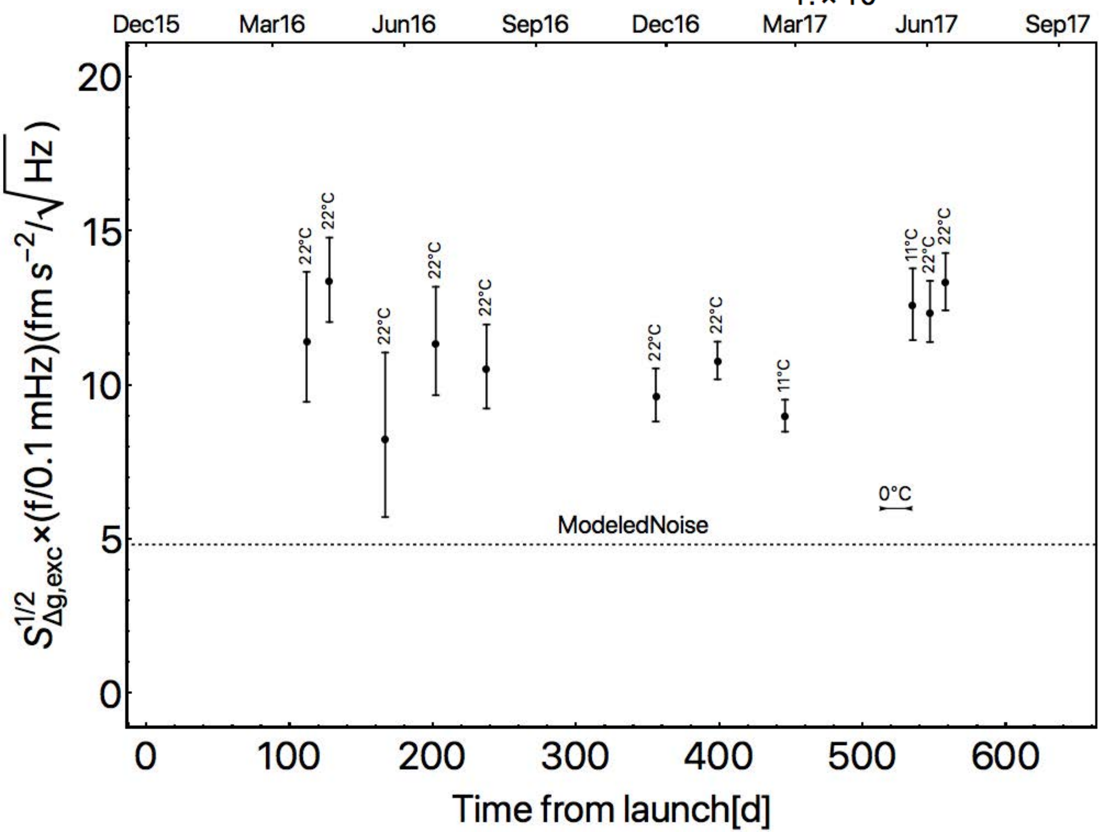


Excess noise at low frequency



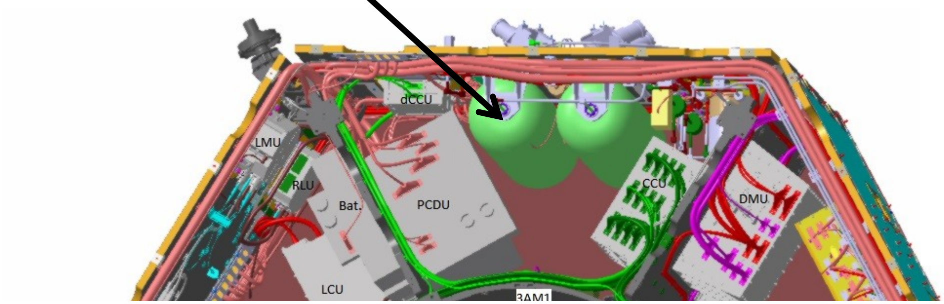


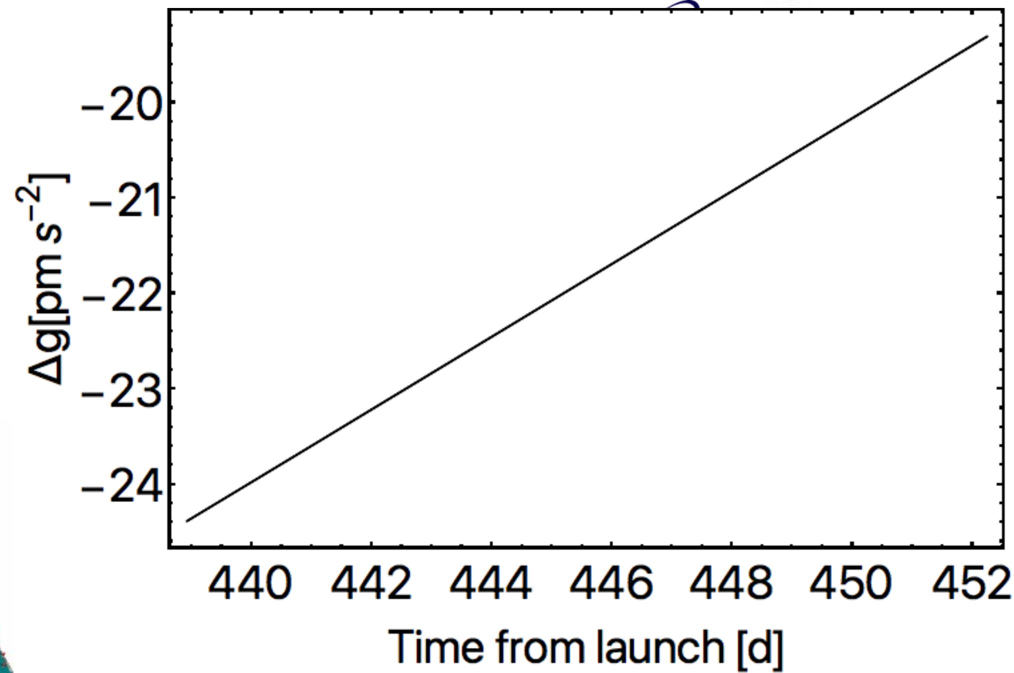


Remarkably stable

Possible sources

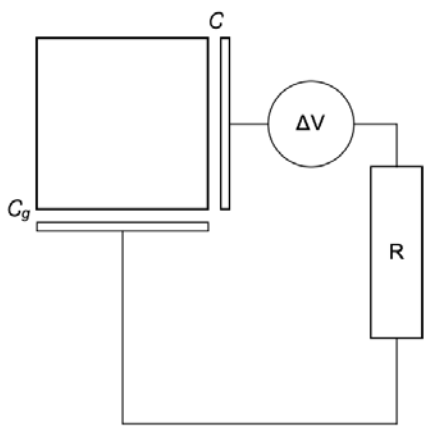
- Gravitational noise
  - Tank depletion

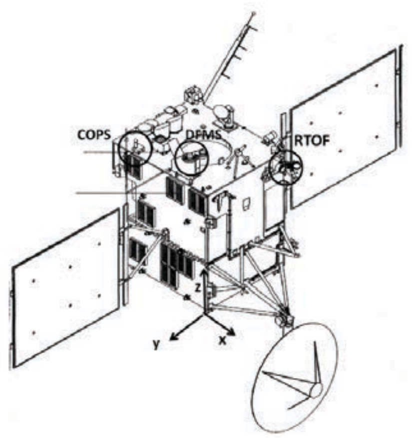




  - Satellite outgassing

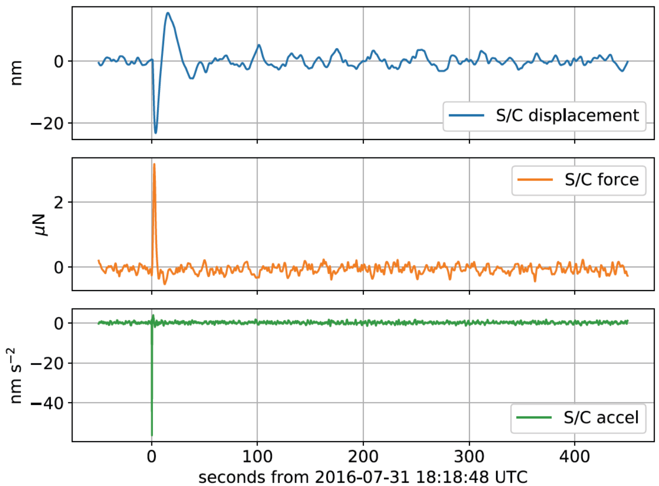
A12313 SCHLÄPPI ET AL.: SPACECRAFT OUTGASSING

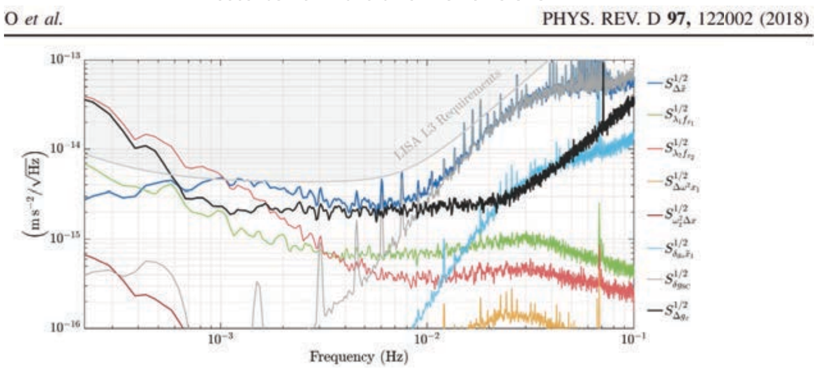


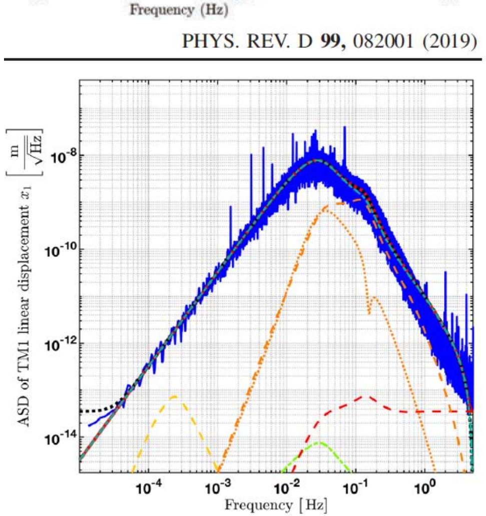


- Brownian noise from extra dissipation
- Sources are being investigated with dedicated experiments

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 μHz. *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*, 99:122003, Jun 2019.

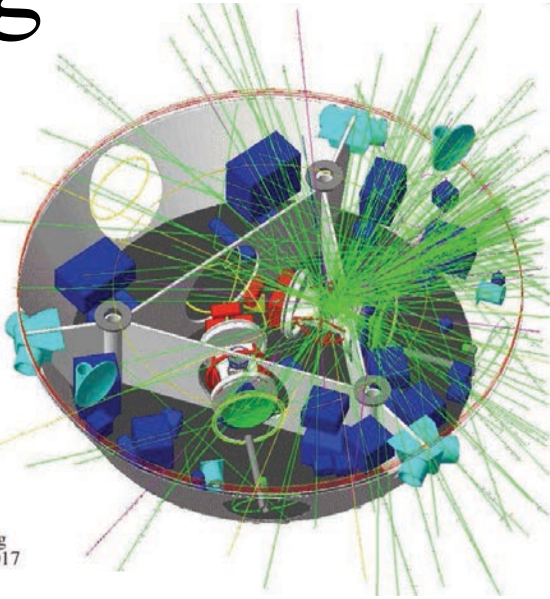
[14] M. Armano, et al. Lisa pathfinder performance confirmed in an open-loop configuration: Results from the free-fall actuation mode. *Phys. Rev. Lett.*, 123:111101, Sep 2019.

[15] J. I. Thorpe, et al. Micrometeoroid events in LISA pathfinder. *The Astrophysical Journal*, 883(1):53, sep 2019.

[16] M. Armano, et al. Novel methods to measure the gravitational constant in space. *Phys. Rev. D*, 100:062003, Sep 2019.

S.

Test mass charging



- Cosmic rays keep charging up the test-mass
- Random charge δQ produces force noise $\delta F_Q = \frac{\delta Q \Delta V}{d}$

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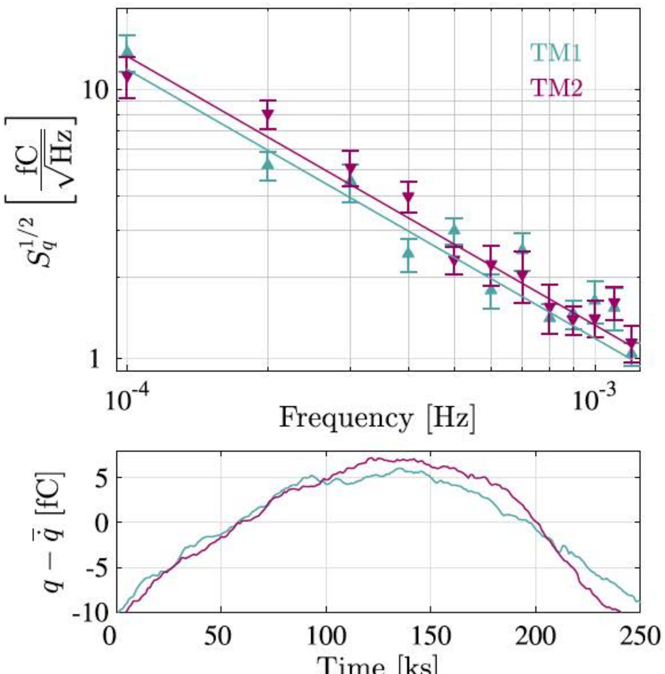
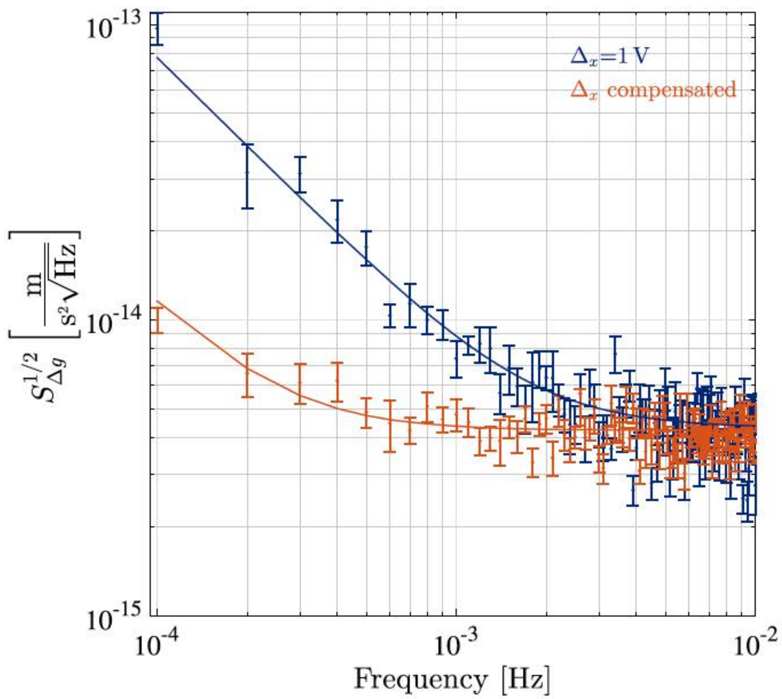
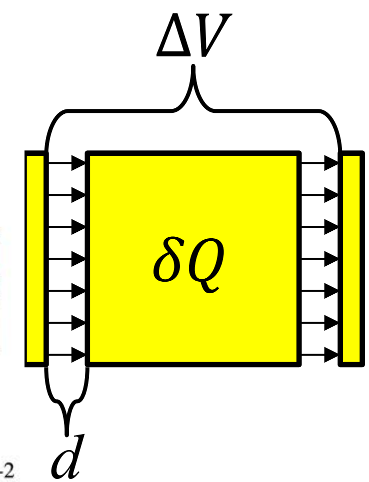


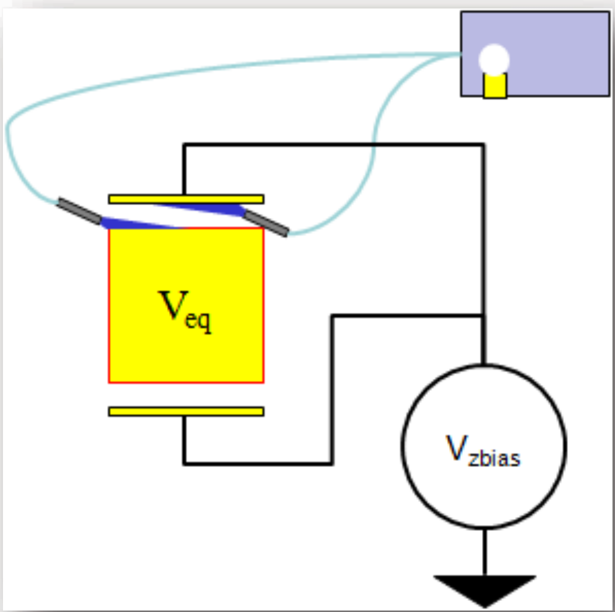


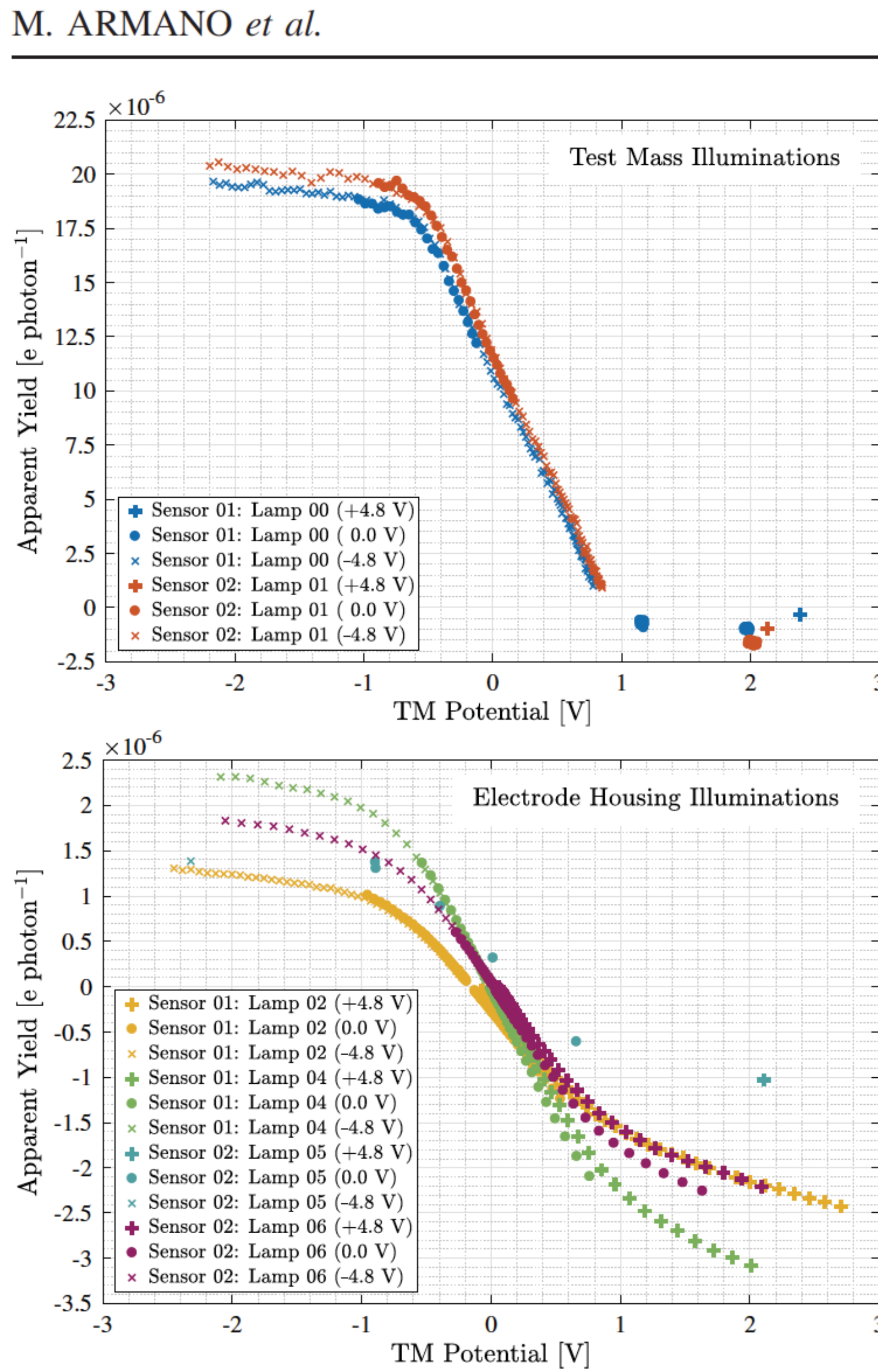


lisa pathfinder

Test mass discharging

- Charge biases TM and needs to be removed
- Discharging performed with UV light (non contacting)
- Electron can both be extracted from TM or deposited onto it
- Full bipolar discharging achieved





PHYSICAL REVIEW D **98,** 062001 (2018)

lisa pathfinder

LISA charging ahead

UNIVERSITÀ DEGLI STUDI DI TRENTO

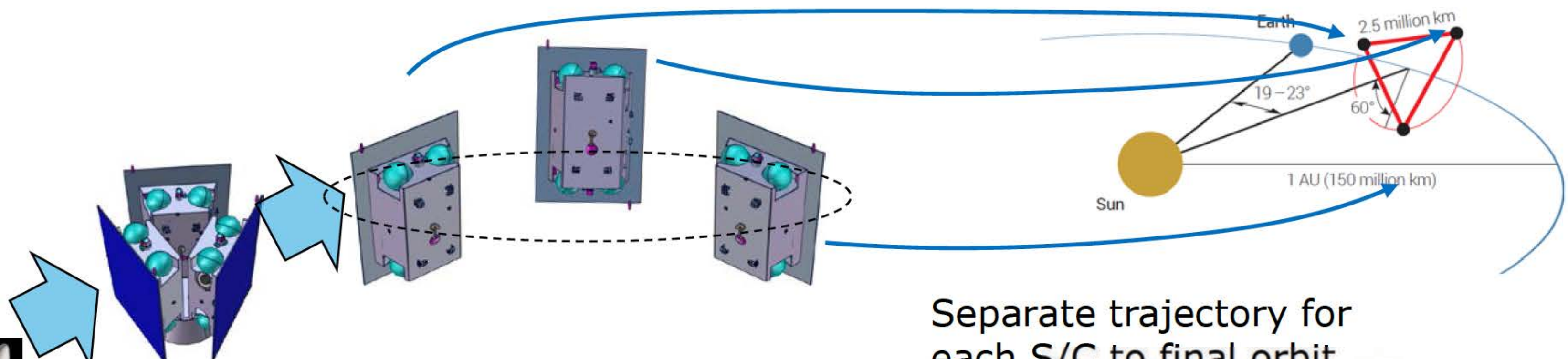
EUROPEAN SPACE AGENCY

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

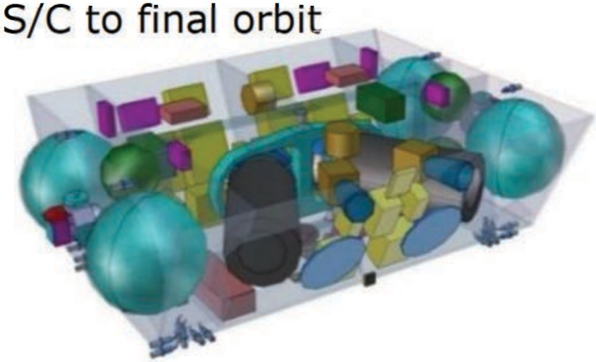
The Committee unanimously selected (with Greece in writing) the LISA mission for the L3 flight opportunity, with a planned launch date in 2034, and with an estimated CaC of €1.05b (at 2017 e.c.).



Separate trajectory for each S/C to final orbit

Separation of the stack right after launch

Launch in stacked configuration
Direct injection into escape trajectory

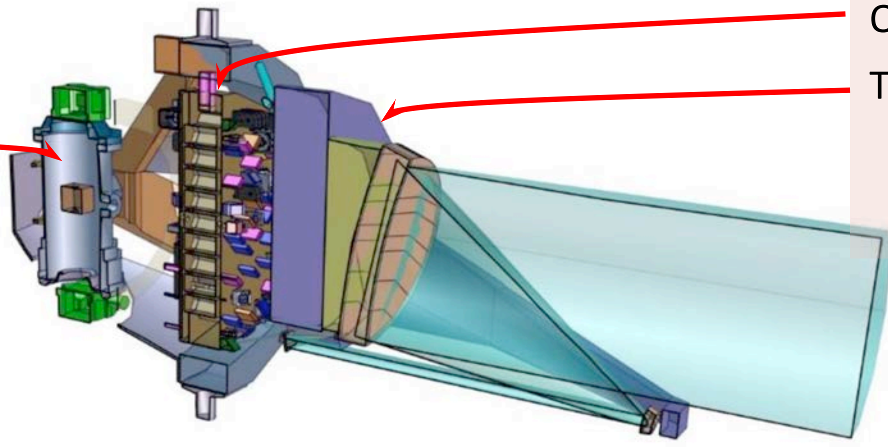


LISA Consortium: probable instrument contributions

MOSA: moving optical sub-assembly

Gravitational reference system

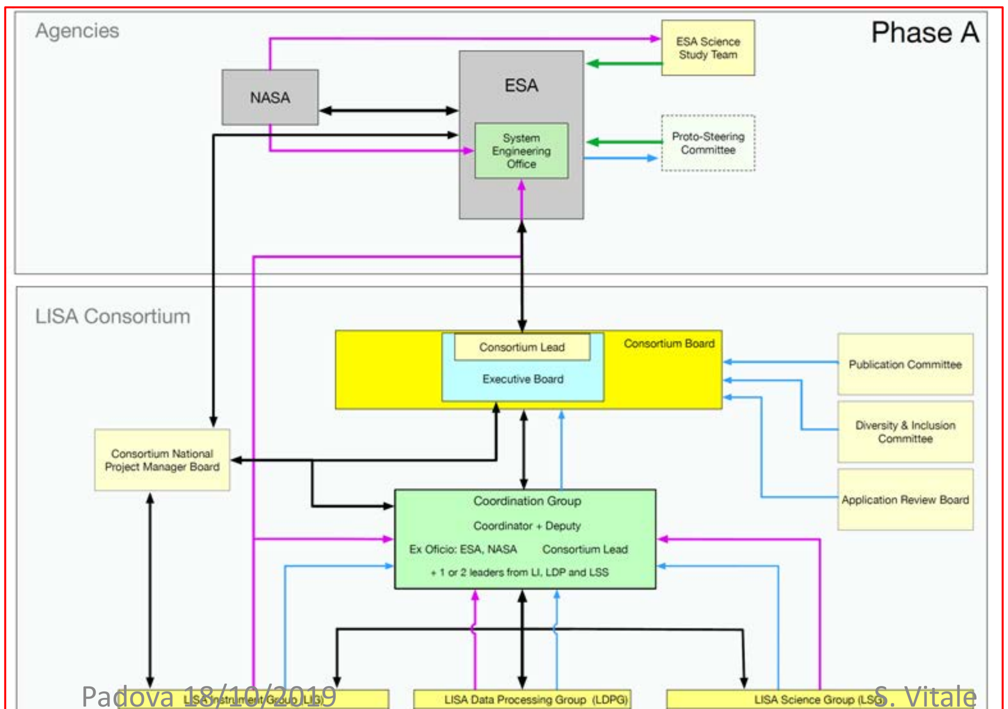
- GRS head
- + electronics
- + UV light source



Optical metrology system

- Optical bench
- Telescope
- + phasemeter
- + laser

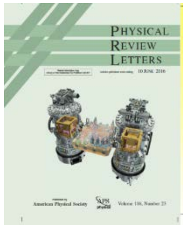
- + consortium lead
- + integration
- + diagnostics/data
- +



«instrument and science» consortium

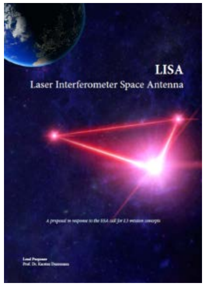
- ESA member states + international partners
- provide MOSA (x6) instrument
- working with ESA to deliver LISA science

LISA: when will it launch and where are we now?



2015-2016:

- LIGO observes GW
- LPF launches (and works!)



Jan-June 2017

- LISA proposed,
- selected by ESA for L3

Fall 2017 – Spring 2018 **ESA internal study**

May 2018 – mid 2020 **LISA mission «phase A»**

- Competitive (x2) industrial study of baseline mission
- Consortium formation and study of instrument (MOSA)
- Technology development activities (telescope, optical bench ...)

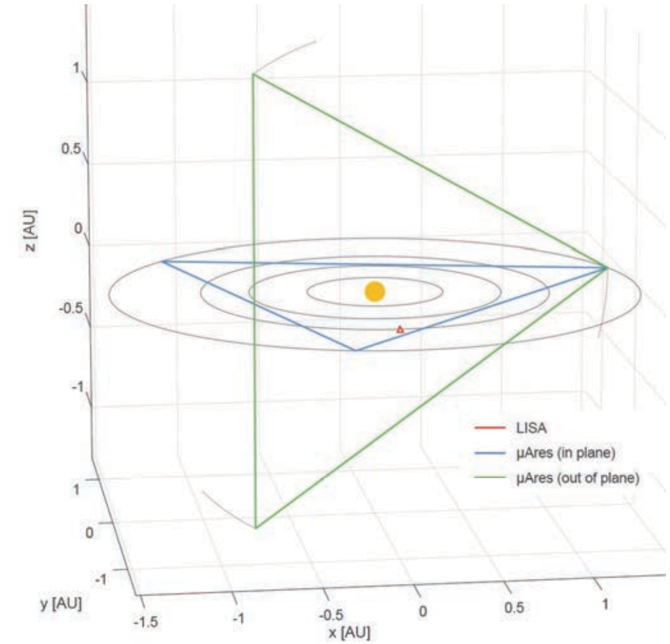
Right now! **Mission Consolidation Review**

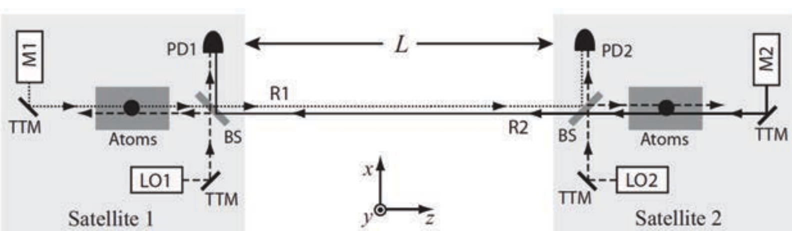
- do we have a baseline mission?

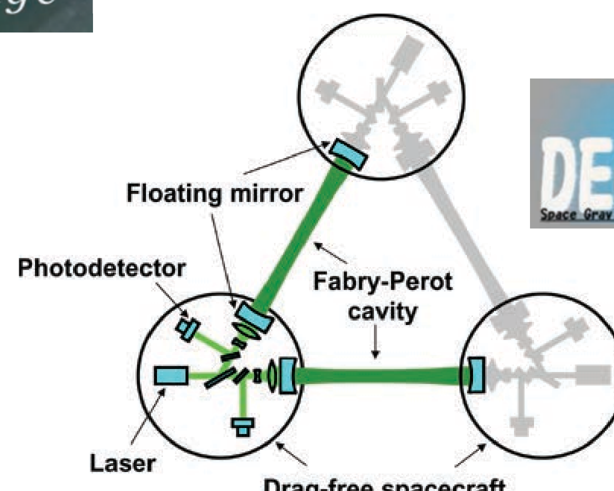
2034 **Current ESA L3 launch date**

- **ESA exploring science program funding increase**
- **→ ensure early 2030's launch and simultaneous LISA / Athena observation**

Beyond LISA







DECIGO
Space Gravitational Wave Antenna


LISA Pathfinder Mission Accomplished
Opening the Path to the Gravitational Universe
Scientific Gathering
MUSE, Trento, 11-13 September 2018
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Thank you!