Gravitational wave astronomy within ESA Science Programme

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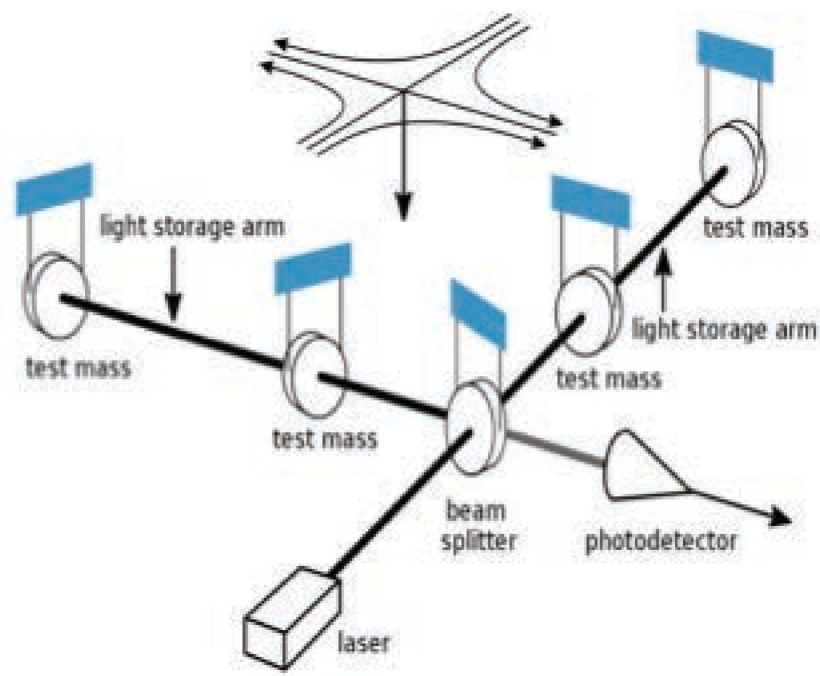
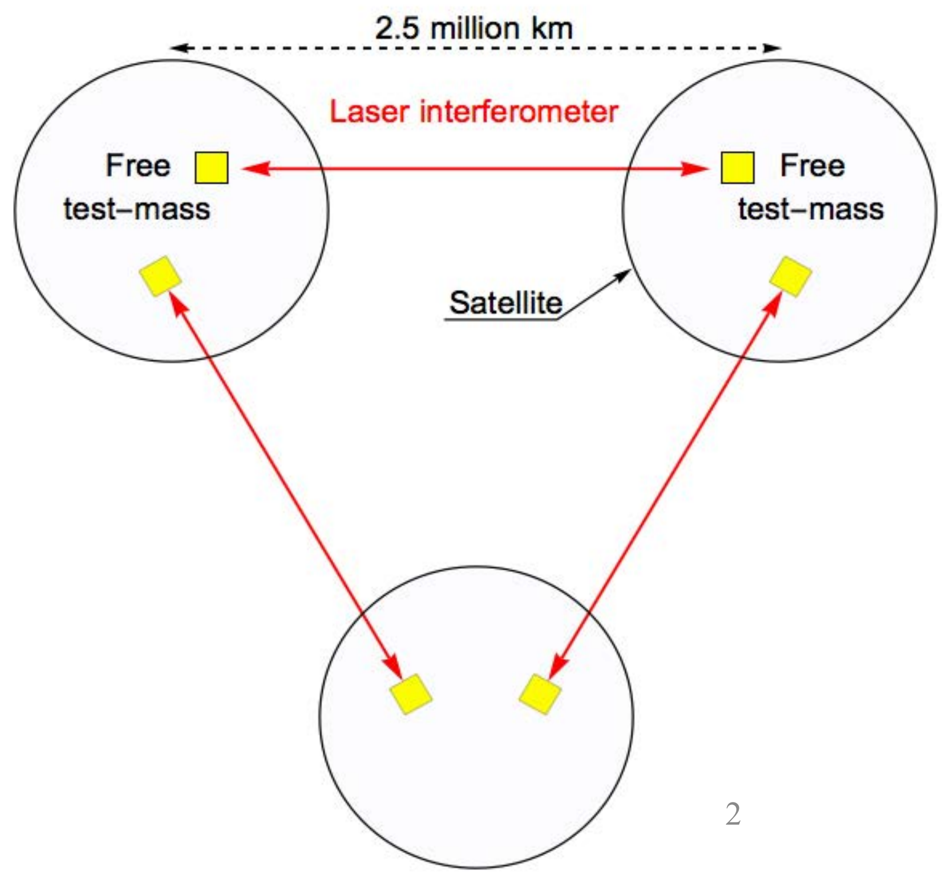
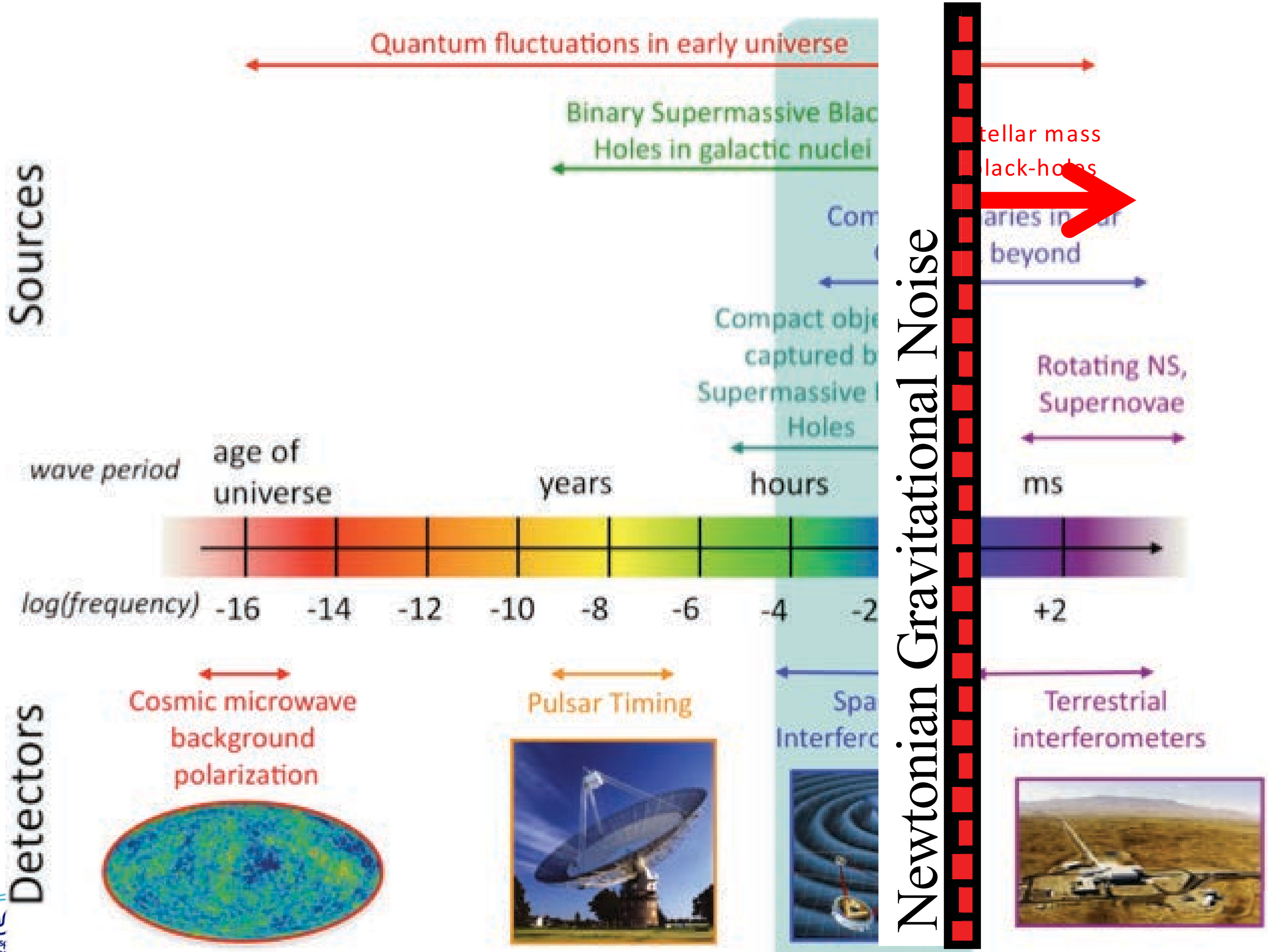
LISA: LIGO/Virgo in space

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

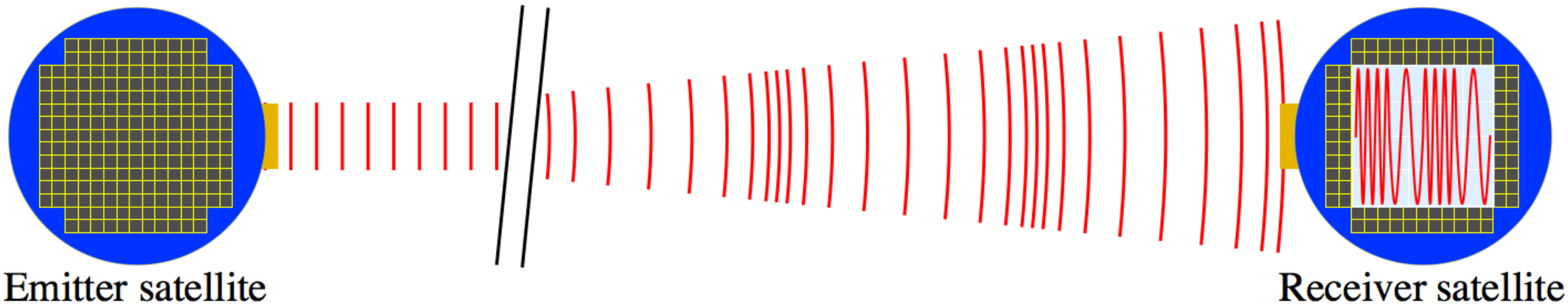




$2\times10^{-5}\div1$ Hz not accessible from ground



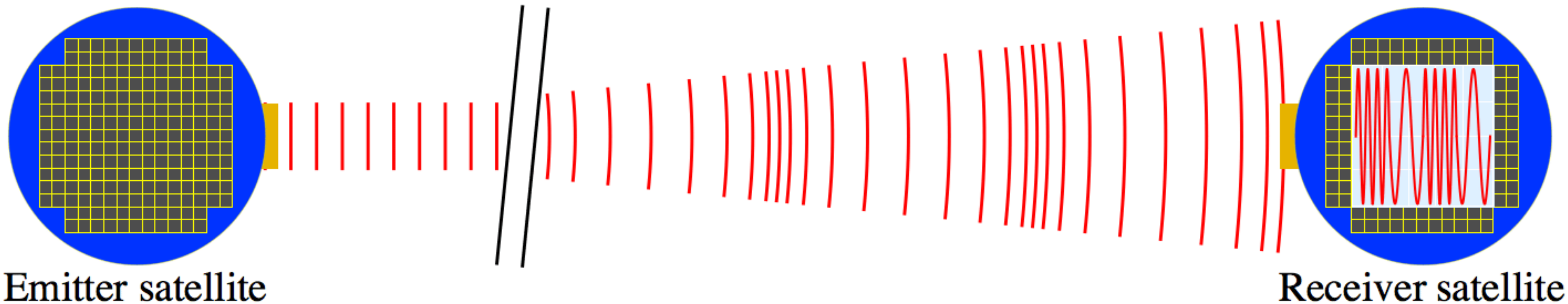
The LISA link



- GW curvature modulates the frequency of the received beam

$$\frac{d\nu_{rec.}}{dt_r}-\frac{d\nu_{em.}}{dt_e}=-\frac{c^2}{2\pi}\int_{beam}k^{\sigma}u^{\nu}R^{\rho}_{\nu\sigma 0}k_{\rho}\,d\lambda=\nu_o\left\{\dot{h}_{receiver}(t)-\dot{h}_{emitter}(t-L/c)\right\}$$

The LISA link



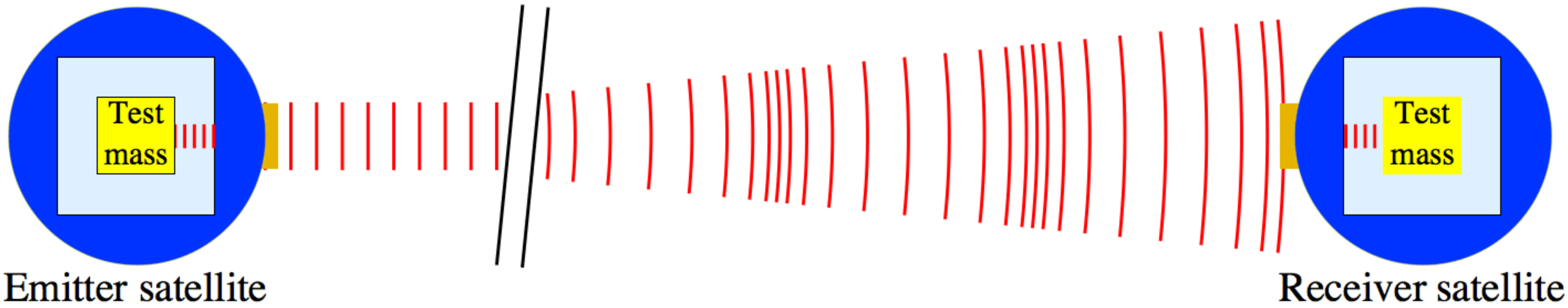
- GW curvature modulates the frequency of the received beam

$$\frac{d\nu_{\mathrm{rec.}}}{dt_r}-\frac{d\nu_{\mathrm{em.}}}{dt_e}=-\frac{c^2}{2\pi}\int_{\mathrm{beam}} k^{\sigma}u^{\nu}R^{\rho}_{\nu\sigma 0}k_{\rho}\,d\lambda=\nu_o\left\{\dot{h}_{\mathrm{receiver}}\left(t\right)-\dot{h}_{\mathrm{emitter}}\left(t-L/c\right)\right\}$$

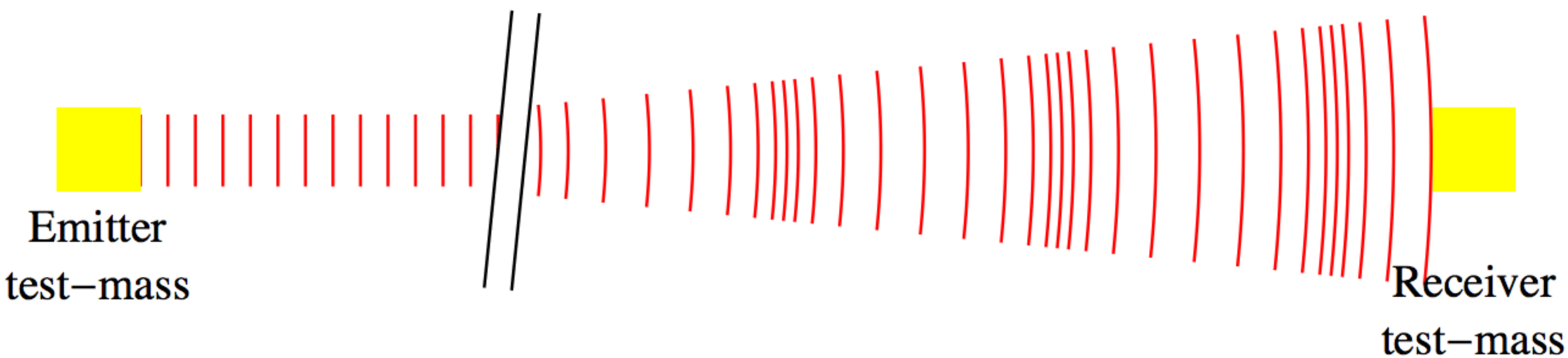
$$+f_{\mathrm{receiver}}\left(t\right)/m_{\mathrm{receiver}}-f_{\mathrm{emitter}}\left(t-L/c\right)/m_{\mathrm{emitter}}$$

- so do, via Doppler effect, accelerations of satellites *relative to their local inertial frames*

The LISA link

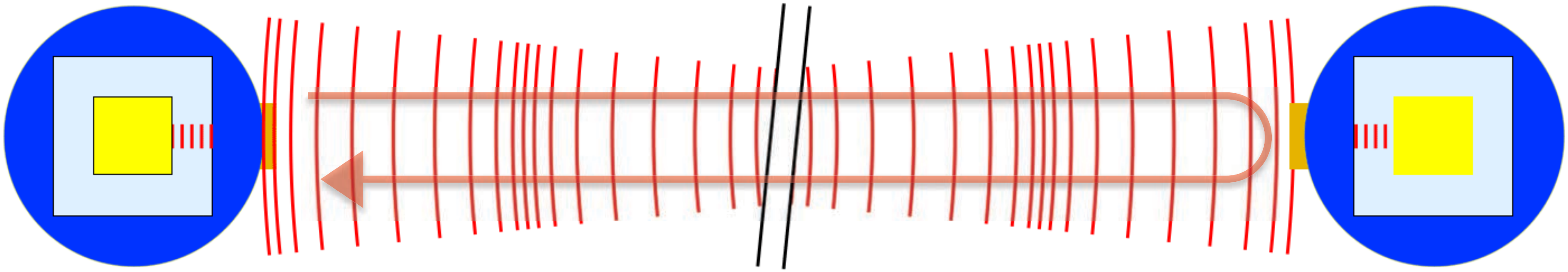


- Inertial reference test-masses are used to correct for satellite acceleration

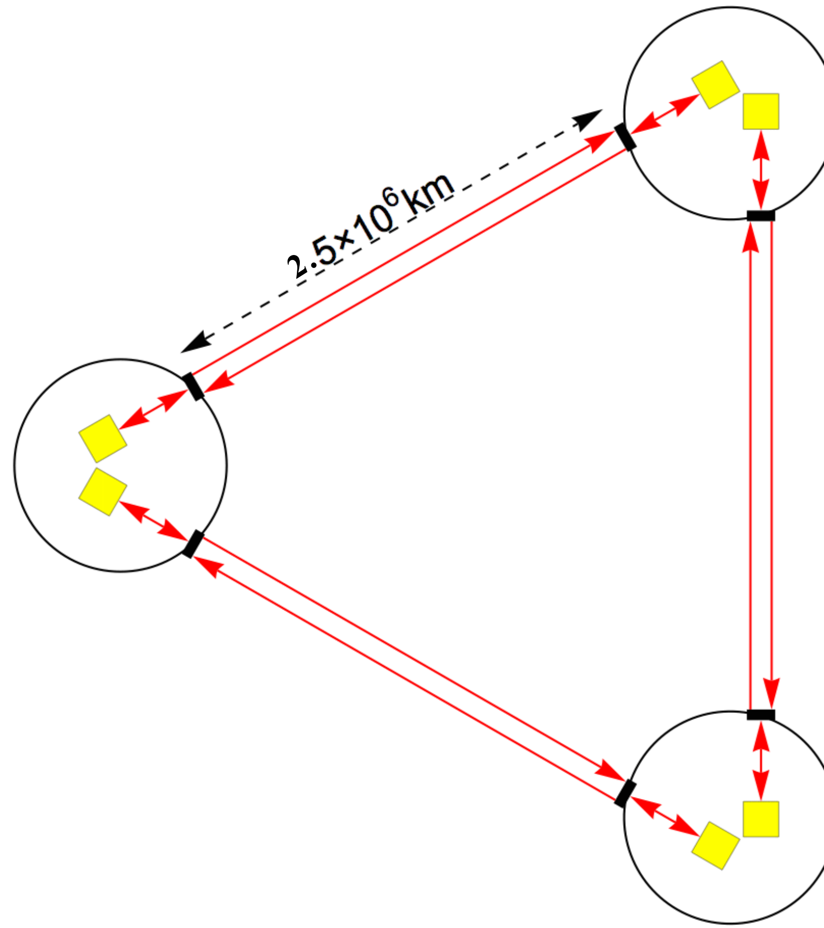


- Equivalent to directly tracking test-masses

The LISA arm

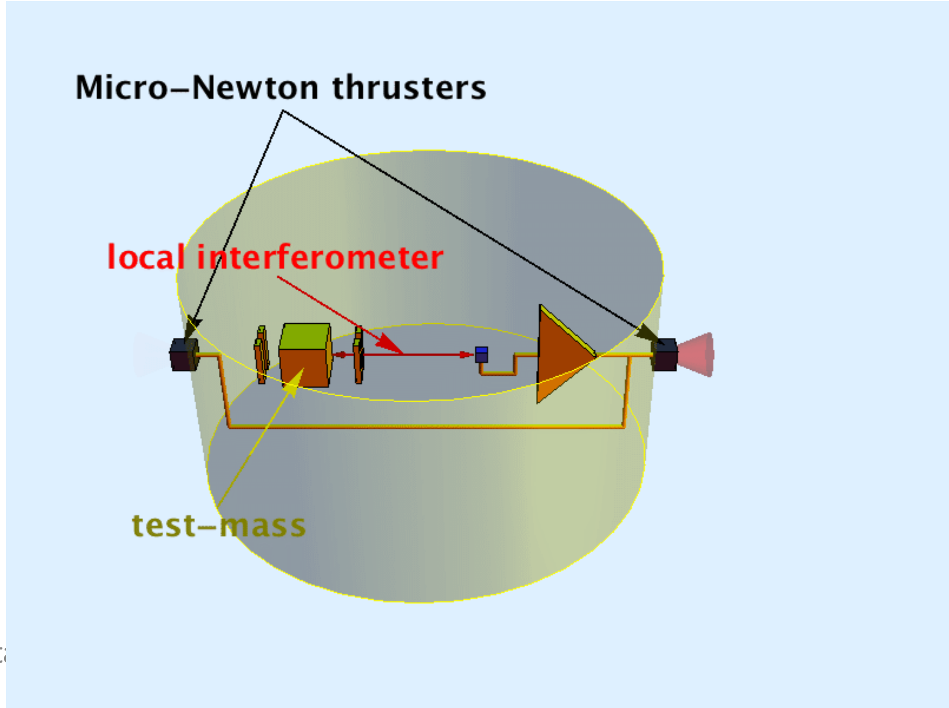


- True reflection impossible. The LISA arm: two phase-locked counter-propagating links.
- LISA: 3 arms 2.5 Mo km
- 10 pm/√Hz single-link interferometry @1 mHz



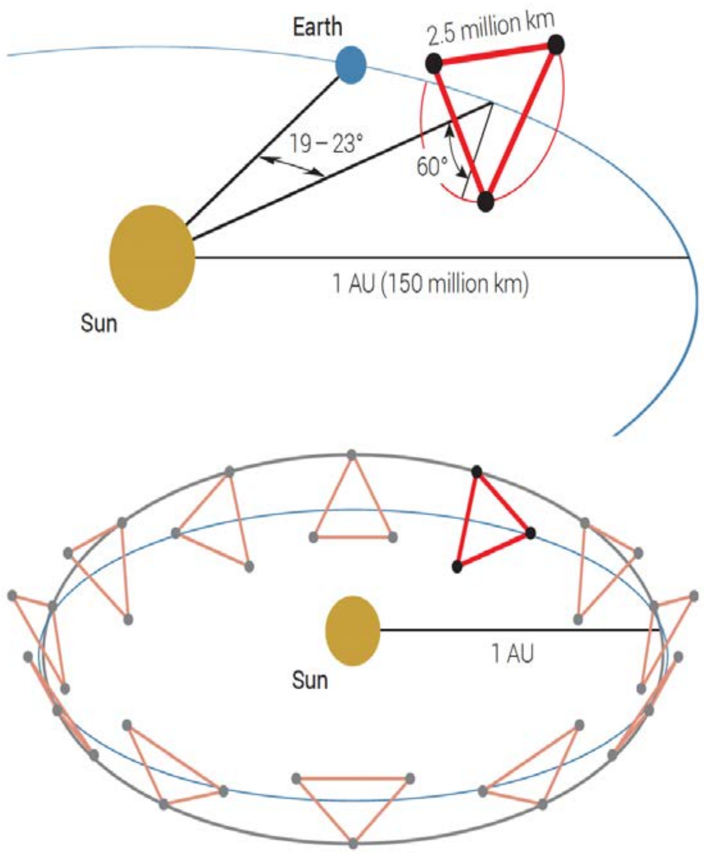
LISA fundamentals: drag-free

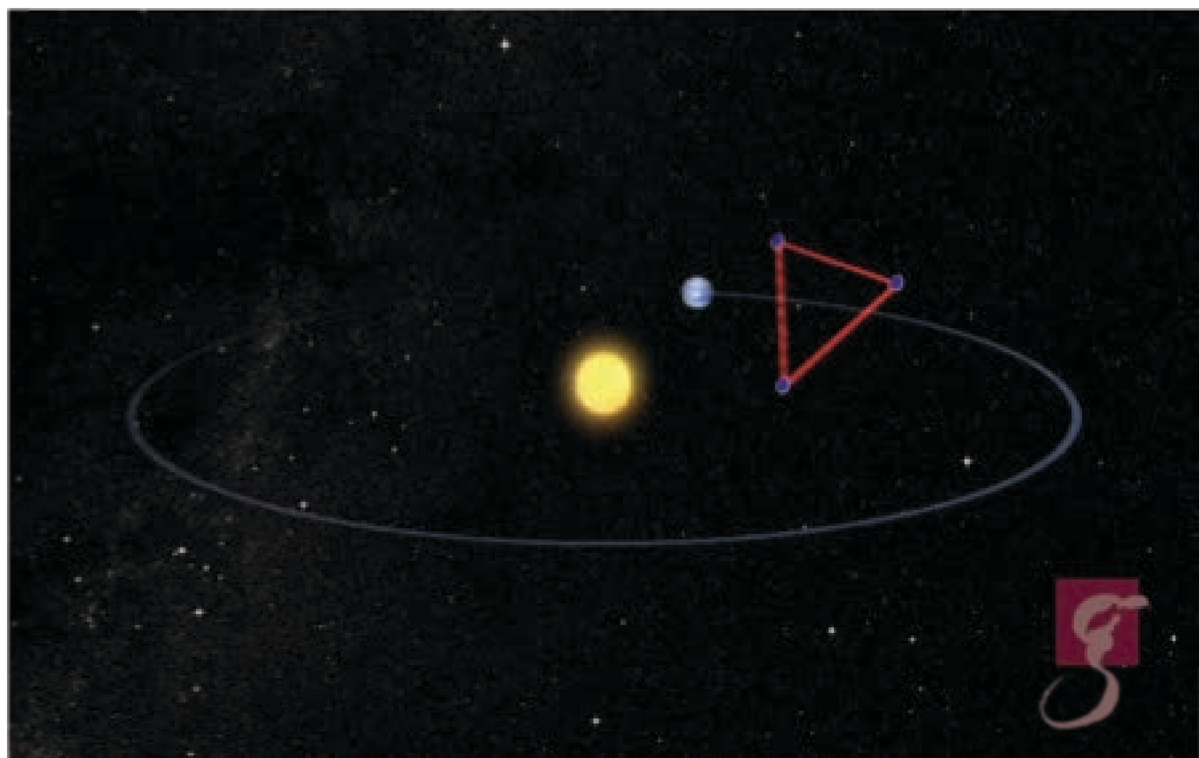
- Free-falling inside a spacecraft
  - Sooner or later test-masses will hit the walls
  - LISA: position of spacecraft relative to test-mass is measured by local interferometer
  - Spacecraft is kept centered on test-mass by acting on micro-Newton thrusters.

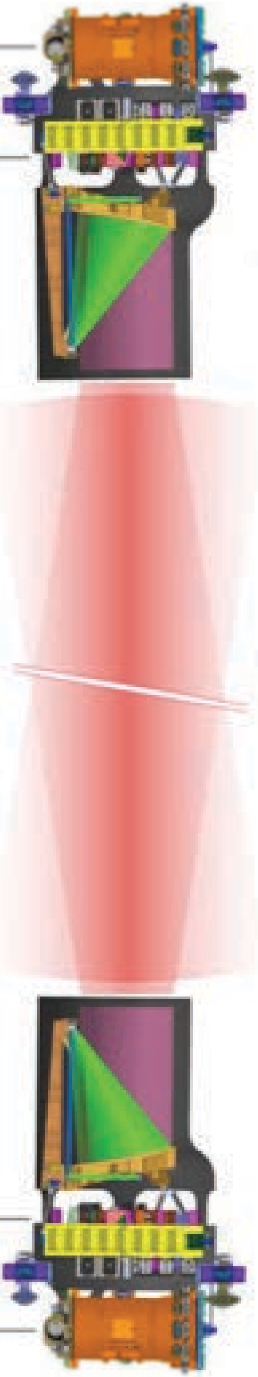


LISA fundamentals: the constellation

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

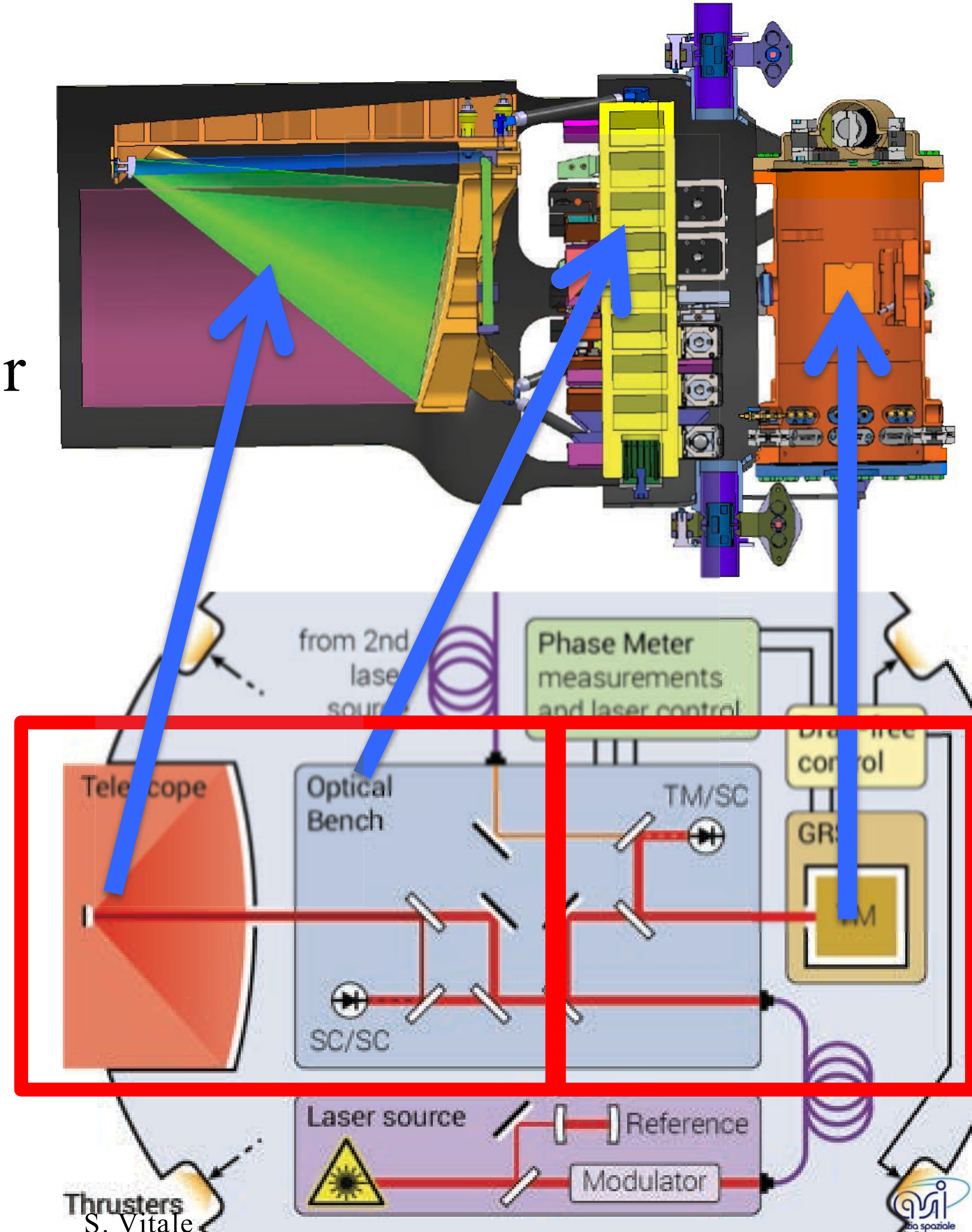






LISA Instrument

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

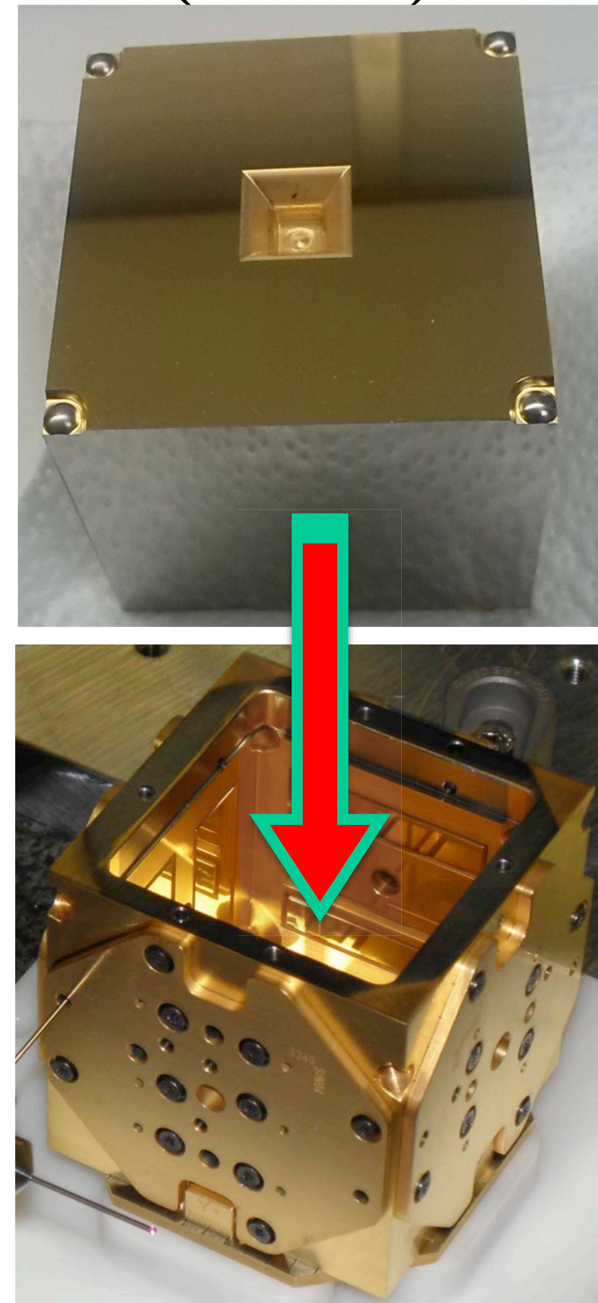


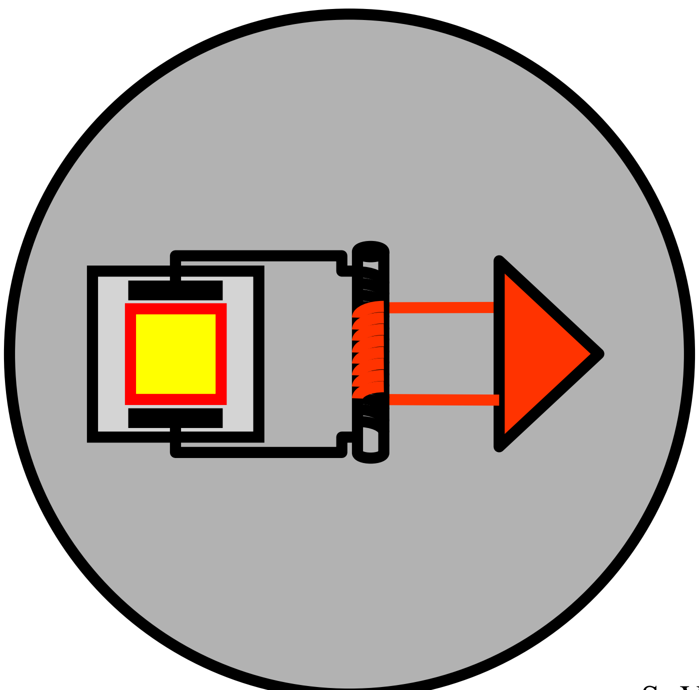
The Gravity reference Sensor (GRS)

- 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

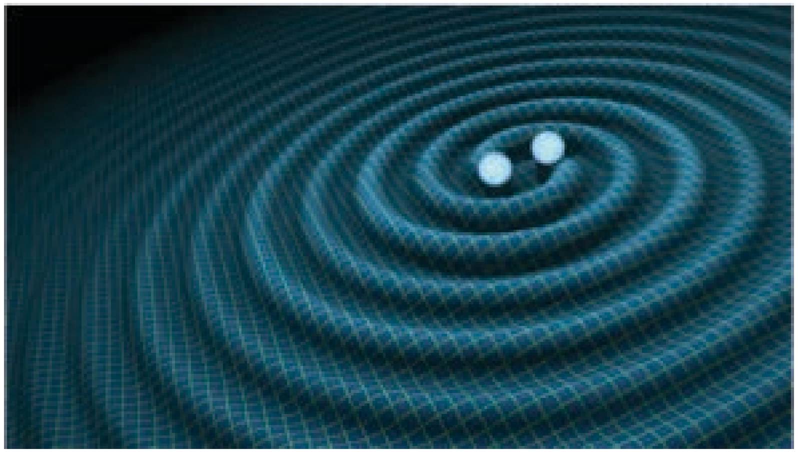
electrode housing





Why low frequency?

- Frequency of GW 2 x frequency of motion



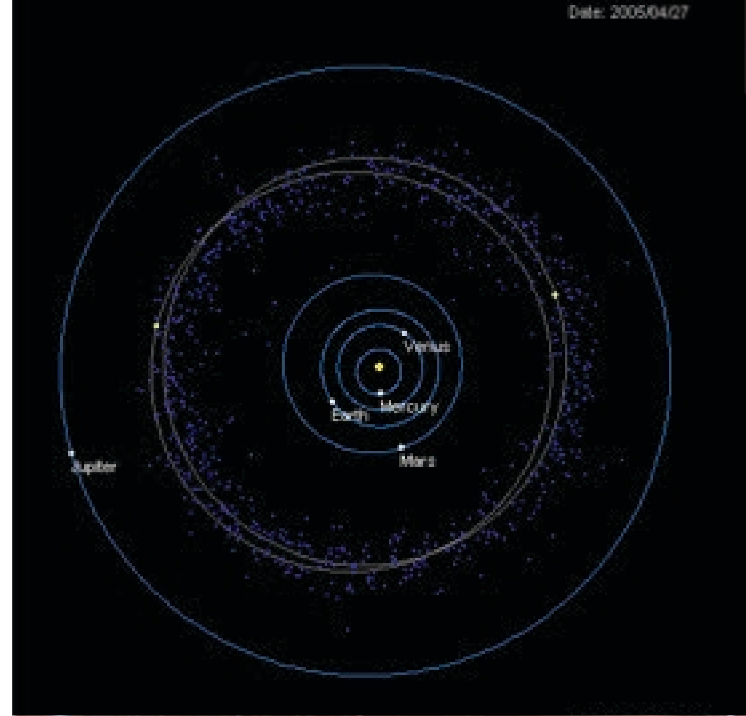
- Kepler: faraway is slow

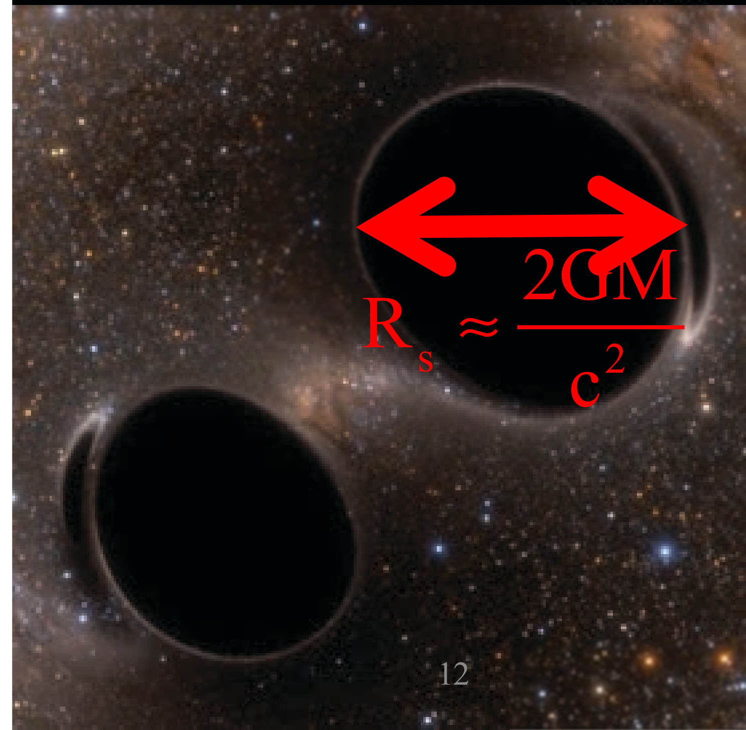
$$f = \left(1/\pi\right)\sqrt{GM/r^3}$$

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

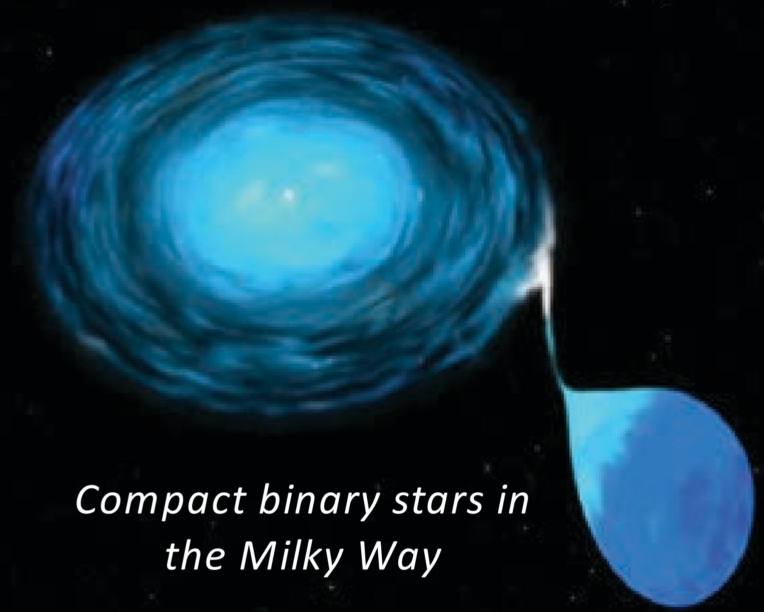
$$f \ll \frac{1}{\pi\sqrt{8}}\frac{c^3}{GM}: \quad 10^6 M_\odot \rightarrow 0.01\ \mathrm{Hz}$$

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

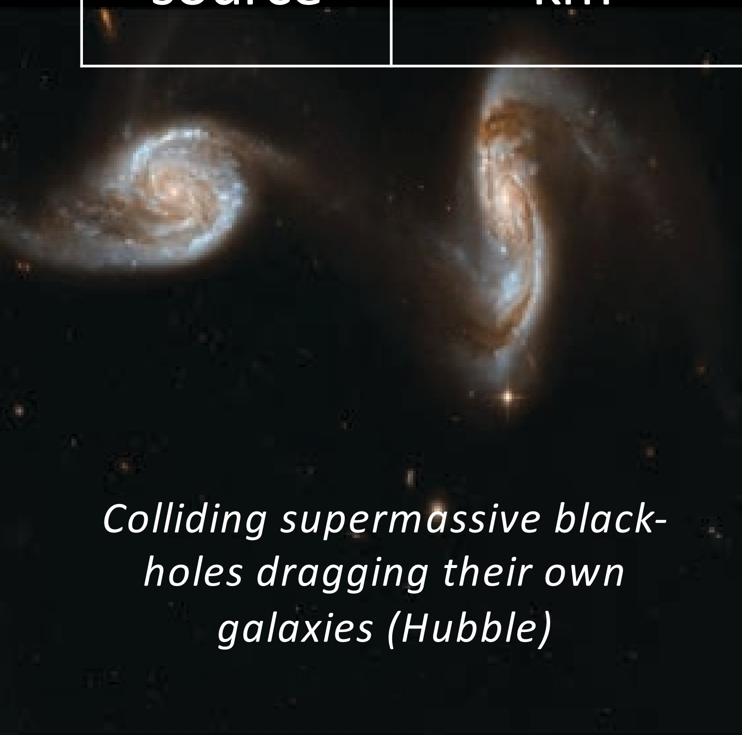




	LIGO	LISA
Size	km	Million km
Wave period	0.001-0.1 seconds	minutes to hours
Mass of sources	~ 1-10 Sun	up to 1-10 Million Sun
Size of the source	~ 100-1000 km	1-10 Million km



Compact binary stars in the Milky Way



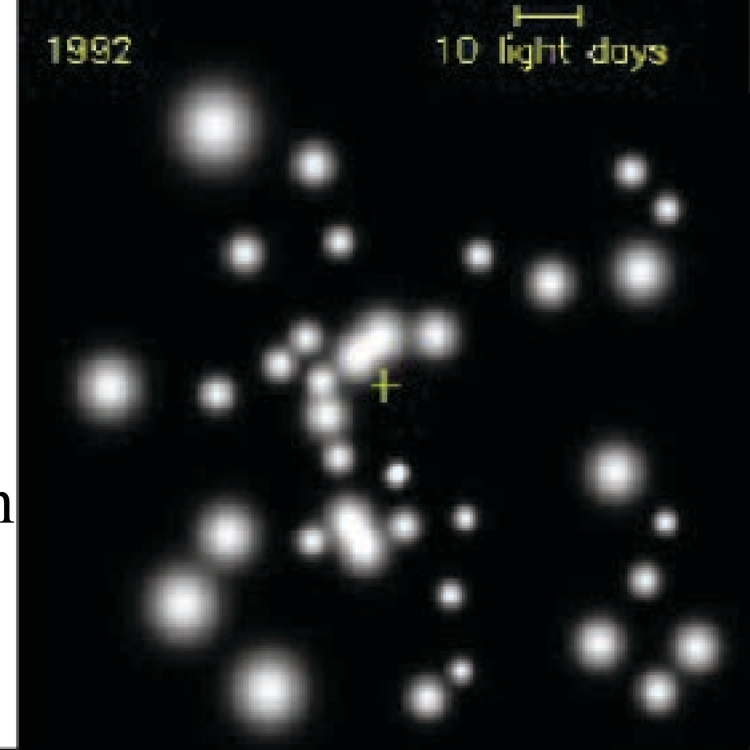
Colliding supermassive black-holes dragging their own galaxies (Hubble)

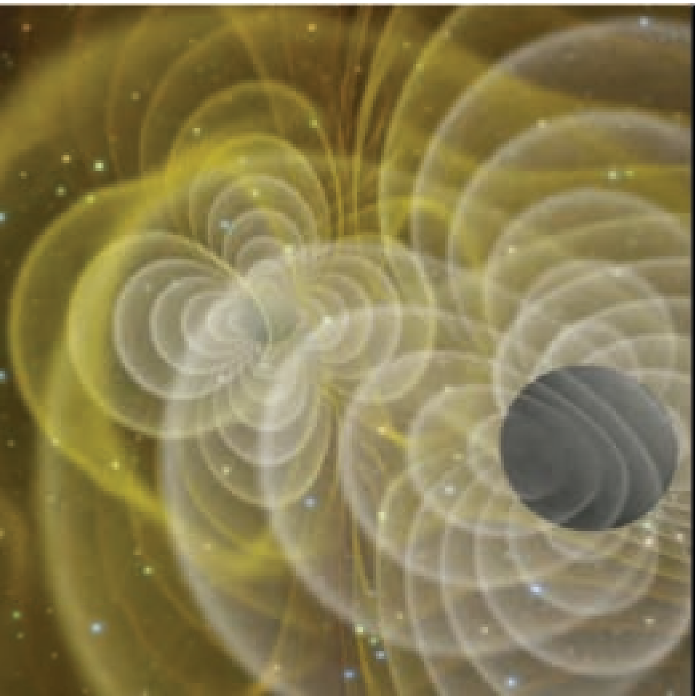
Supermassive black-hole swallowing a small one

LIGO black-hole years before final merger

Million solar mass Black-Holes

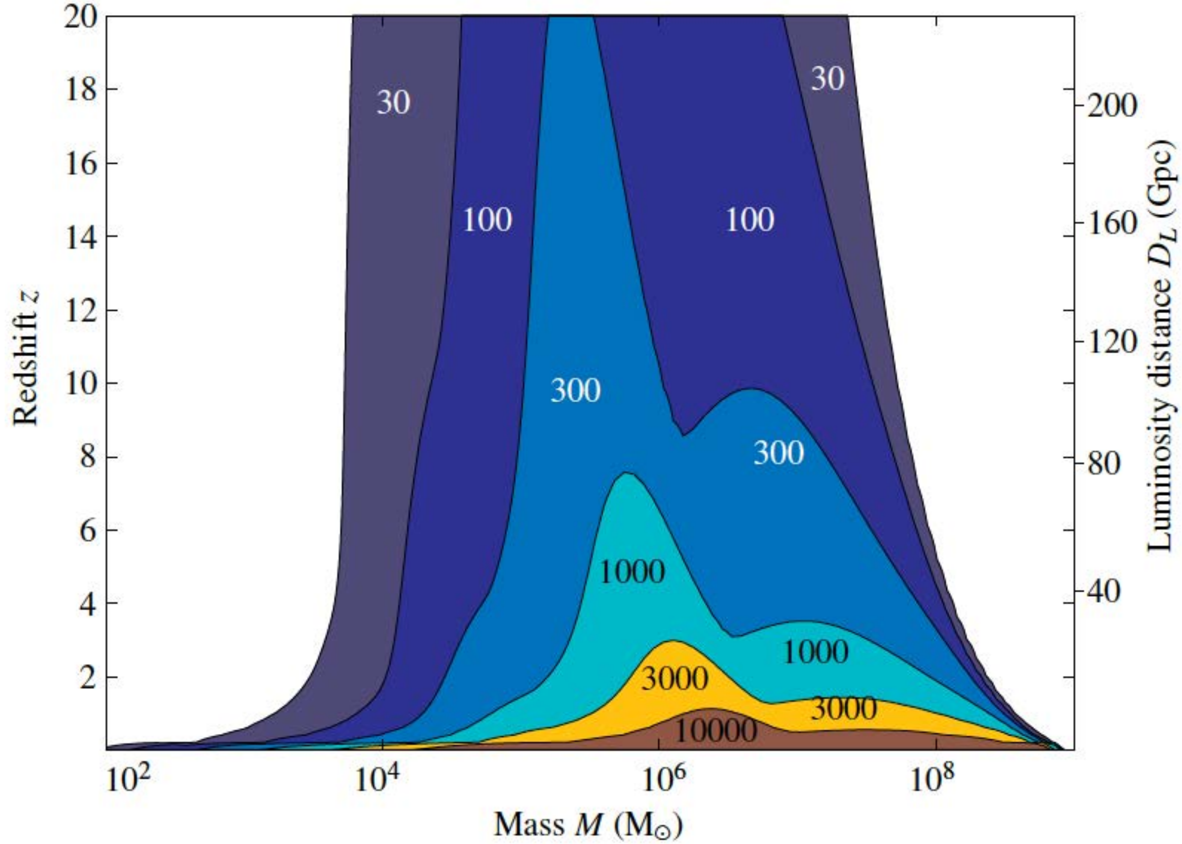
- Galaxies host > million solar mass Black-Holes
- Galaxy collide and form binary Black-Holes
- Binaries coalesce: more GW energy than all light in the Universe
- 10^4-10^6 times the energy of a LIGO/Virgo merger



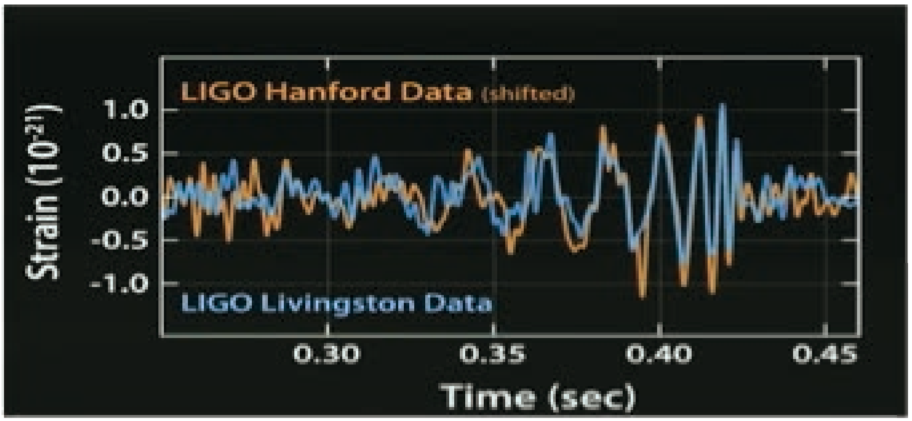


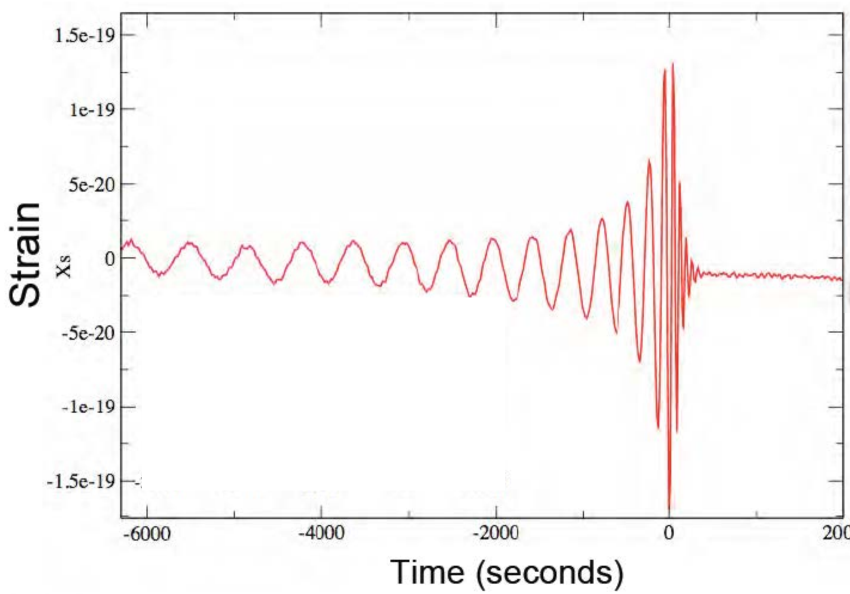
High-precision gravitation

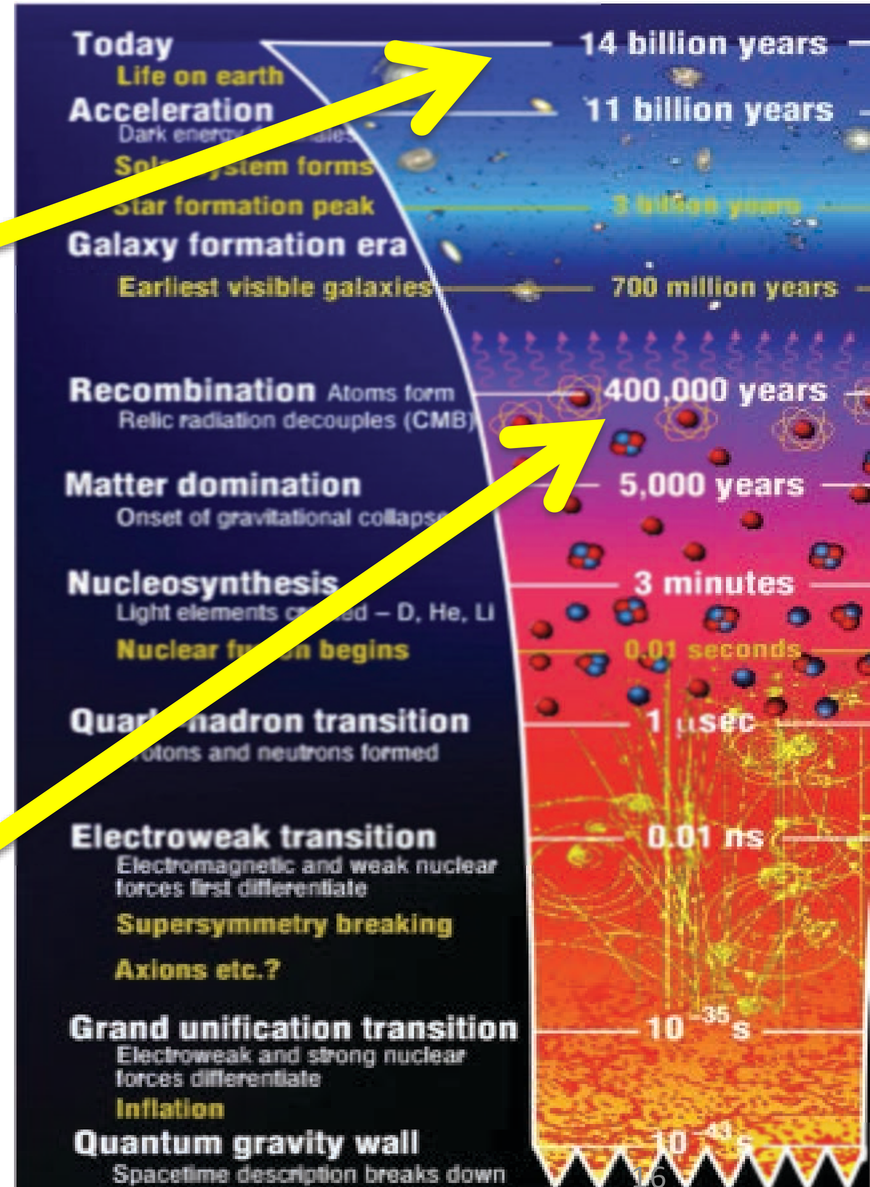
- All mergers in the universe in its frequency band, even out to z=20, if they were happening.
- Measures: luminosity distance 1 – 5 %
- Sky location 0.1° - 5 °
- Masses to ±0.1-0.5%
- Spin magnitudes to ±0.01.
- Spin *vectors* to ±3-5%



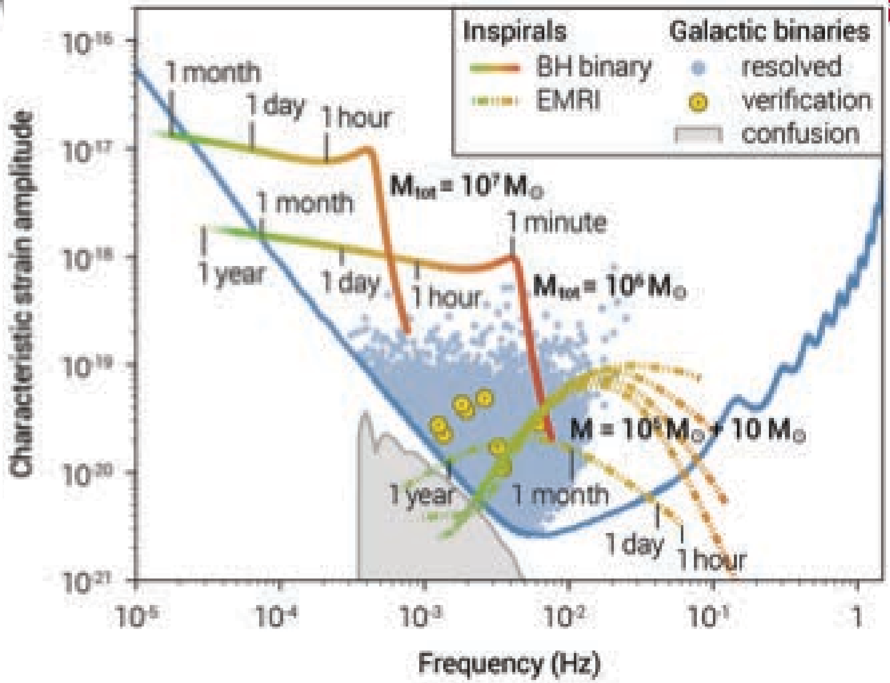
A deep universe, high resolution observatory



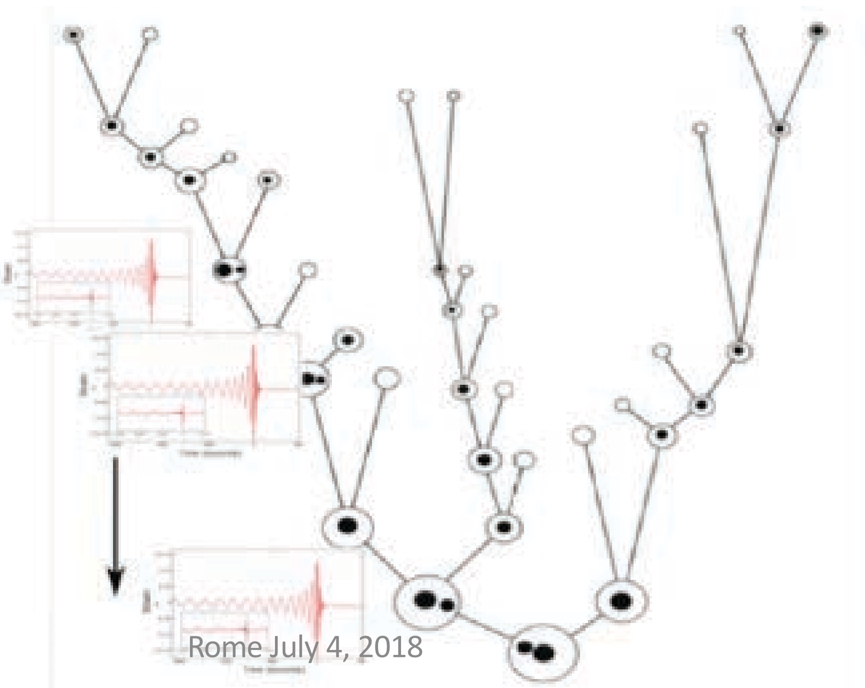


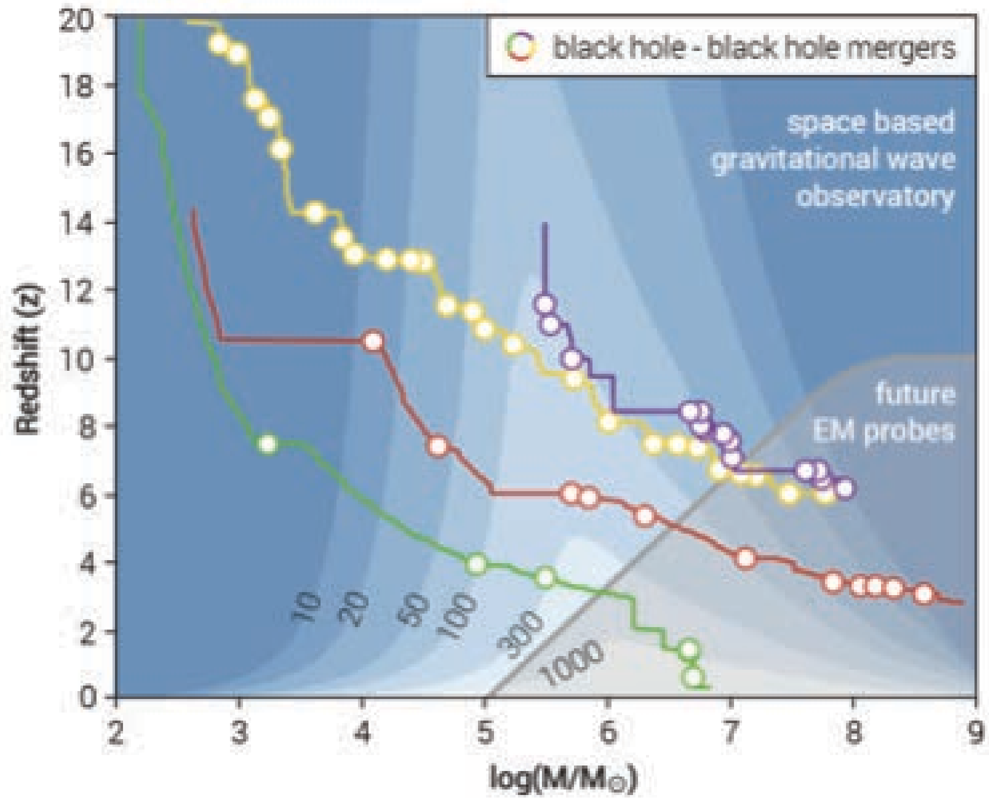


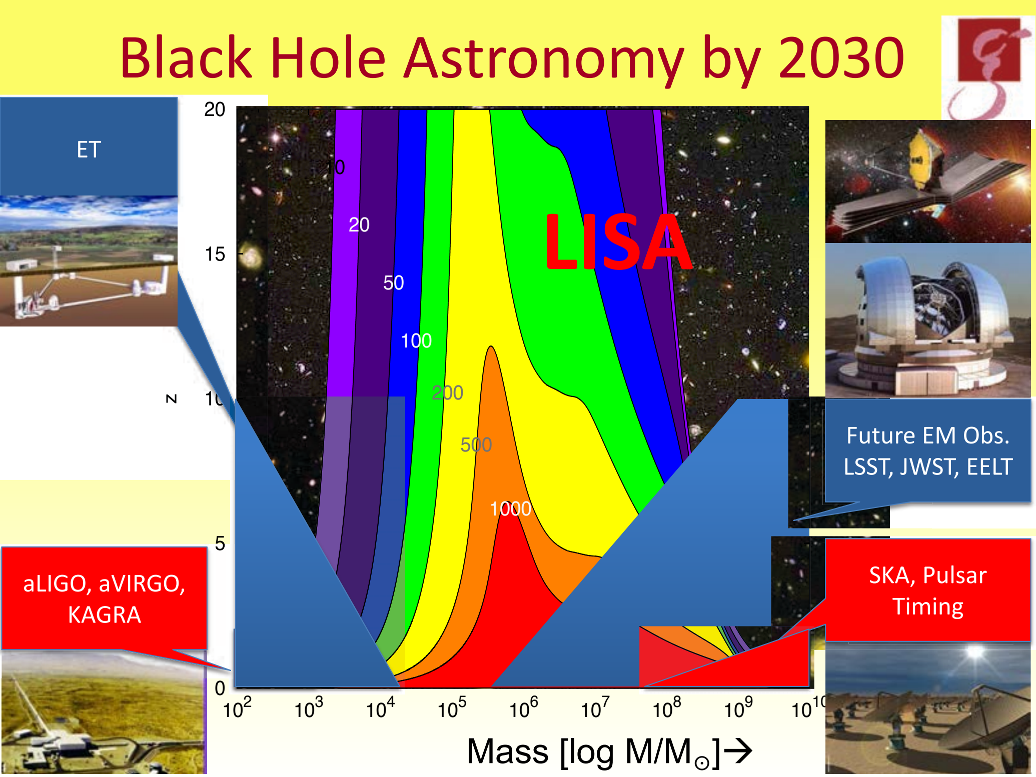
Cosmological stratigraphy



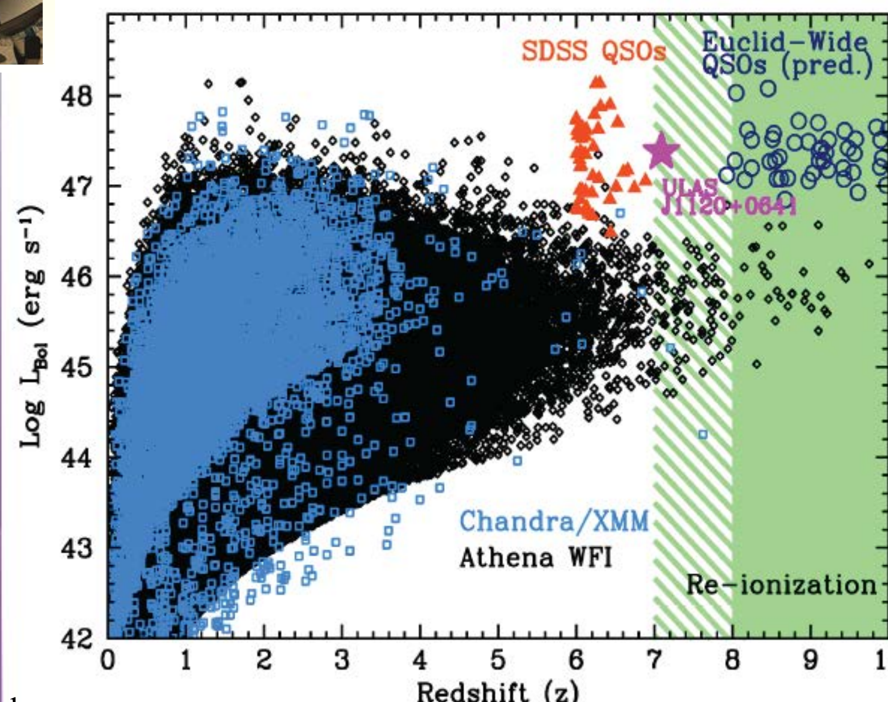
- Almost all BBH in their evolution cross LISA band (hundreds expected)
- Allows discriminating different model of galaxy formation.







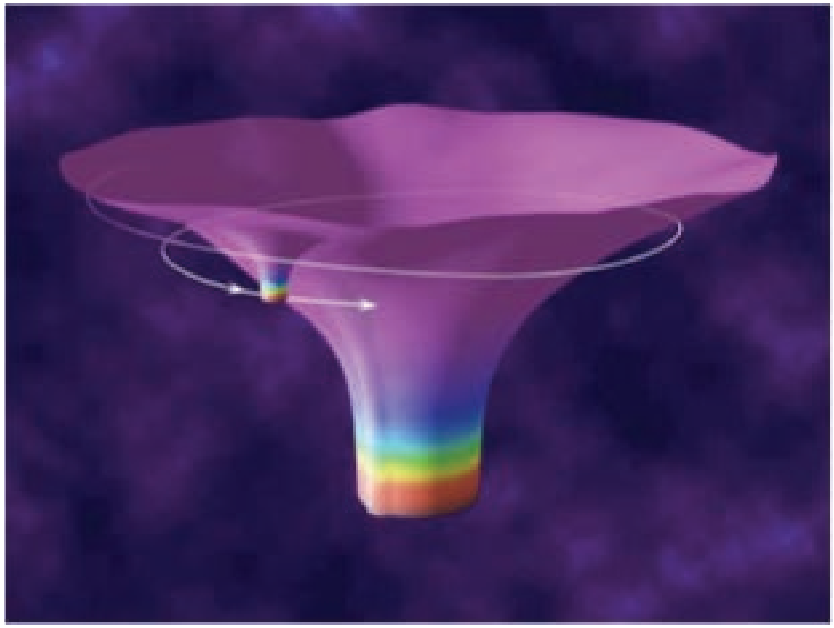
ESA's MBH programme

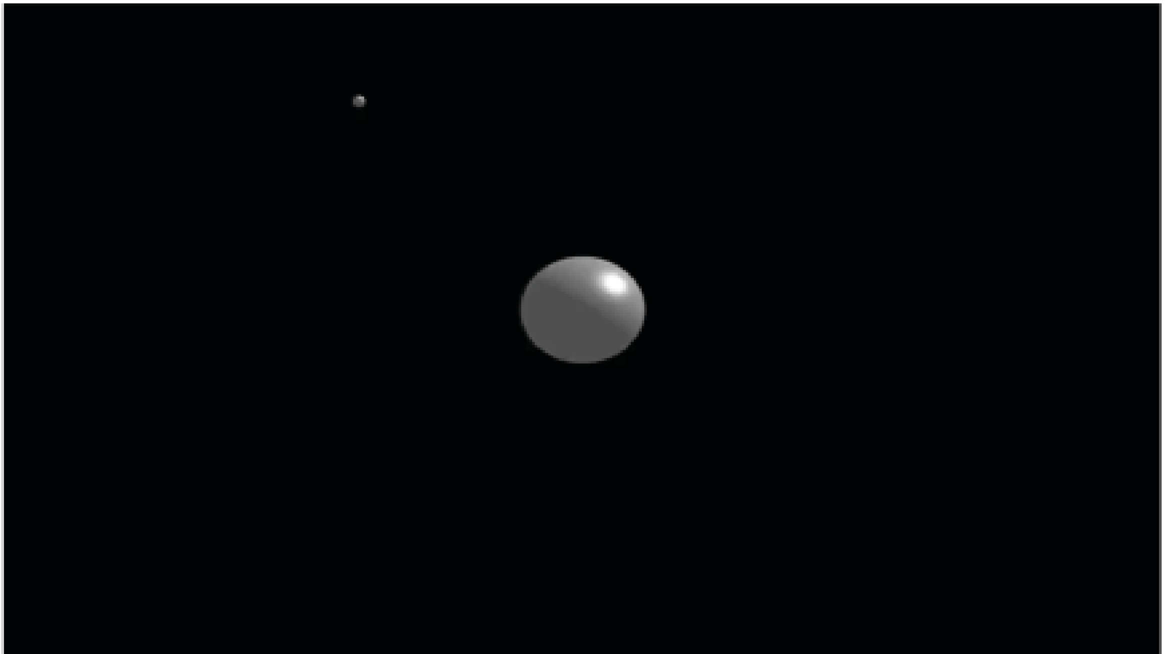


Athena

Extreme Mass-Ratio Inspirals: EMRIs

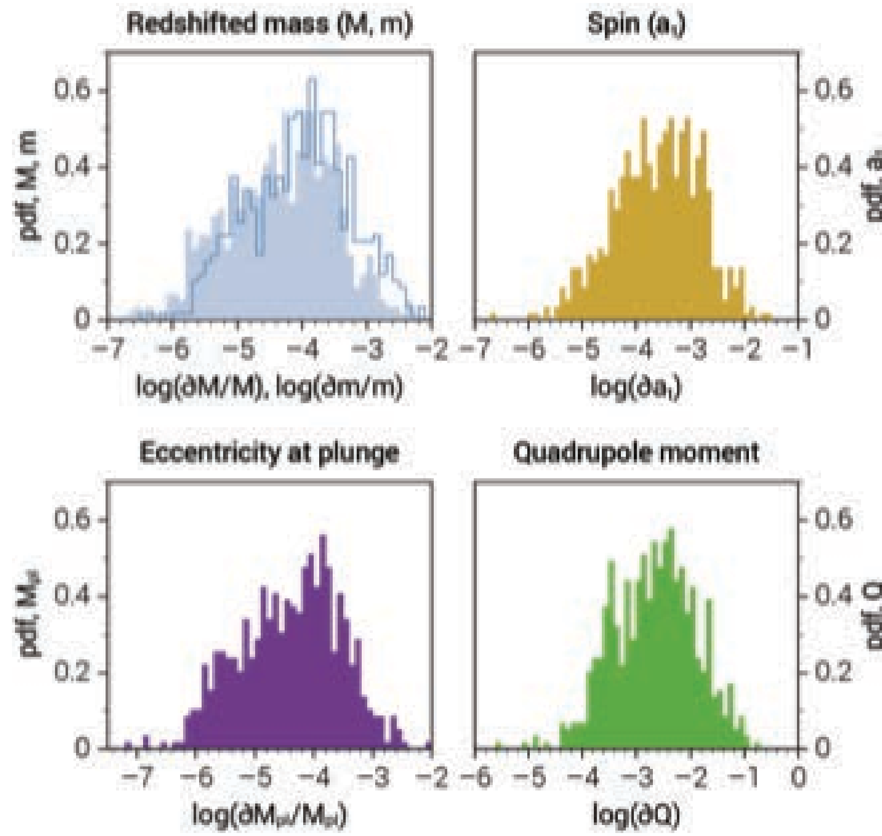
- Stellar-mass BH capture by a massive BH: dozens per year.
- 10^5 orbits very close to horizon. GRACE/GOCE for massive BHs.
  - Prove horizon exists.
  - Test the no-hair theorem to 1%.
  - Masses of holes to 0.1%
  - Spin of central BH to 0.001.



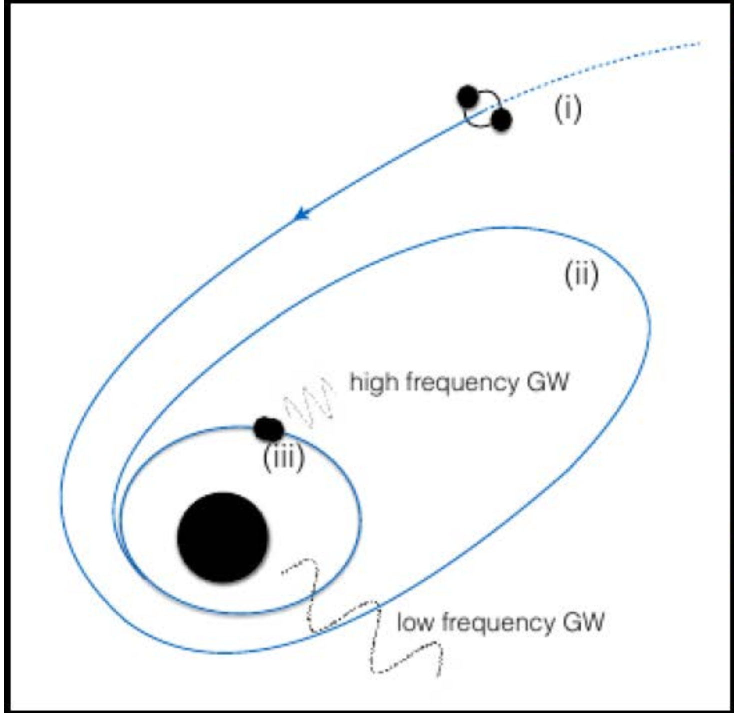


EMRIs as a GRG lab

- 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…



Multiband EMRIs? (Chen & Han 2018)



BHB scattered onto a MBH in a galactic nucleus.

50% of the binaries (if compact enough) can survive and form an EMRI)

T EMRI < T BHB

Kozai-Lidov oscillation canceled by GR precession up to the very last orbits

KL excitation in the last orbits of the inspiral:

Almost coincident
BHB merger + EMRI

Cosmography with GW

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

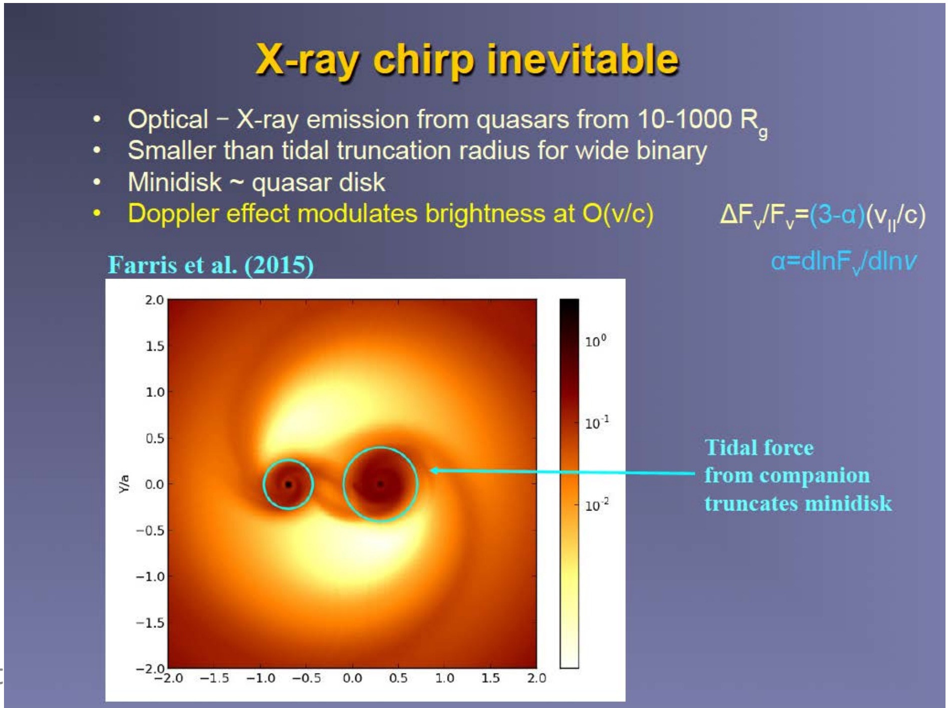
$$D_L \propto cP\dot{P}/h$$

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

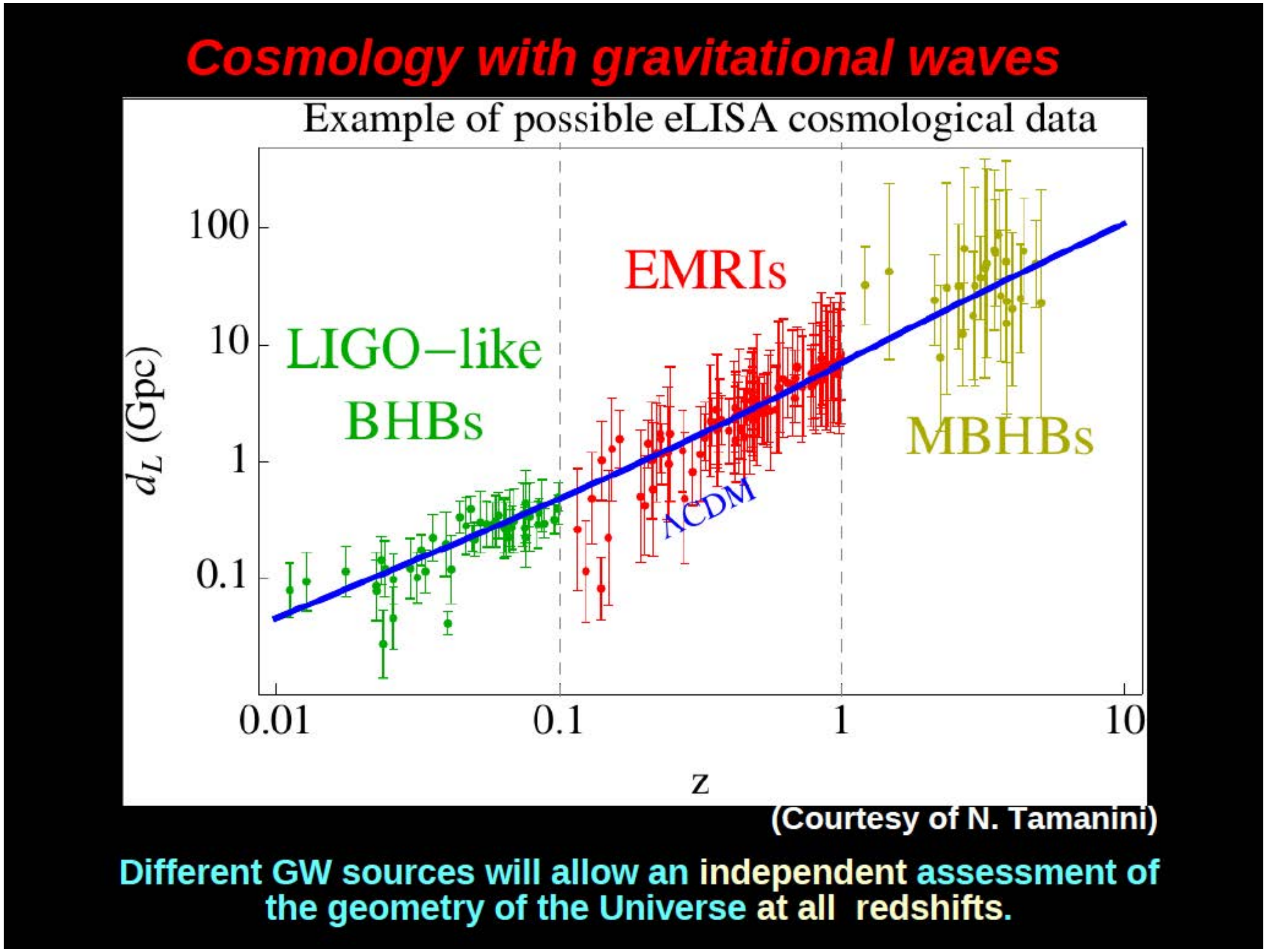
The late inspiral of supermassive black hole binaries with circumbinary gas discs in the LISA band

Yike Tang[1], Zoltán Haiman[2], Andrew MacFadyen[1]★
[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

both the GW and the X-ray chirp signals. In the future, it would be interesting to compute the accuracy to which the phase difference can be measured in practice, if the absolute phase is unknown ab-initio, given realistic observational S/N from LISA, and from an X-ray instrument such as Athena[2],



Cosmography with GW

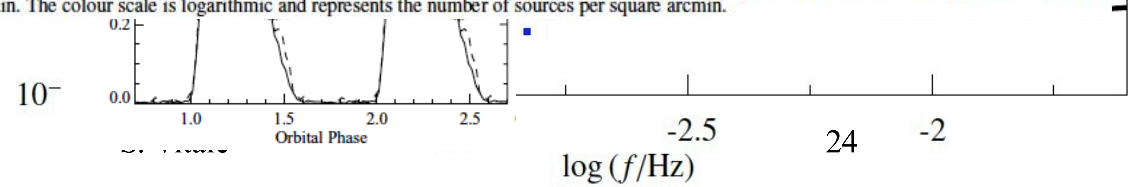


- Complementary to and totally independent of ESA's Euclid

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

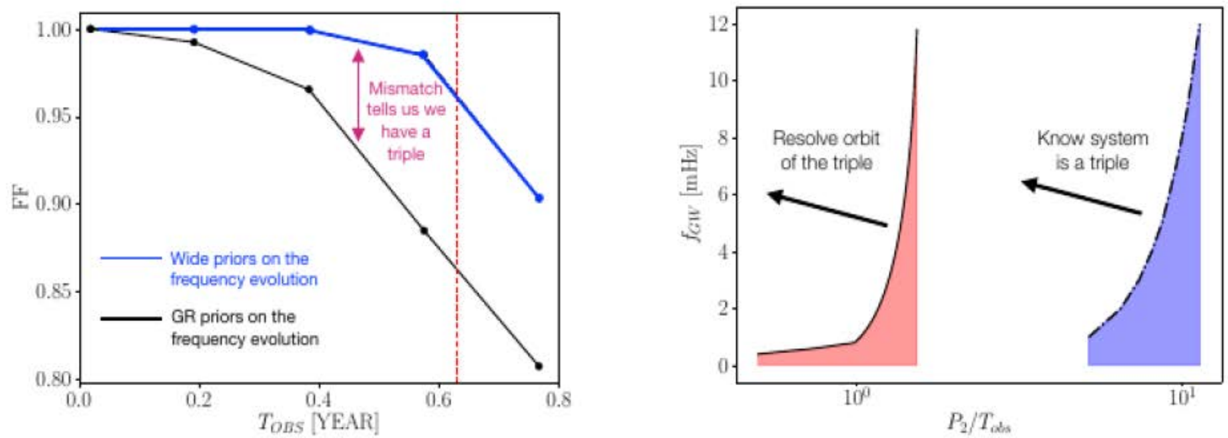
Fig. 3. Sky distribution of all *Gaia* DR2 sources in Galactic coordinates. This image and the one in Fig. 4 are Hammer projections of the full sky. This projection was chosen in order to have the same area per pixel (not strictly true because of pixel discretisation). Each pixel is ~ 5.9 square arcmin.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



LISA observations of Hierarchical Galactic Triples

T. Robson, N. Cornish, Valeriya Korol, Nicola Tamanini & Silvia Toonen (paper in prep)

- Detection - how much do triples complicate the analysis?
  - Not too much. Revealed by a larger than expected frequency evolution in the usual binary model
  - Can distinguish between binaries and triples for outer orbits up to 10 times the mission lifetime (at SNR=10)
- Parameter estimation - what can we learn about these systems?
  - Can measure eccentricity and period of outer orbit if shorter than 2 times the mission lifetime (at SNR=10)
  - Can potentially measure the relative inclination of the inner/outer orbits and mass ratio if the systems are eclipsing



lisa pathfinder

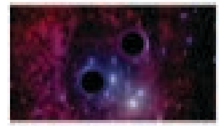
VIRGO/LIGO BH in their Keplerian phase

Editors' Suggestion

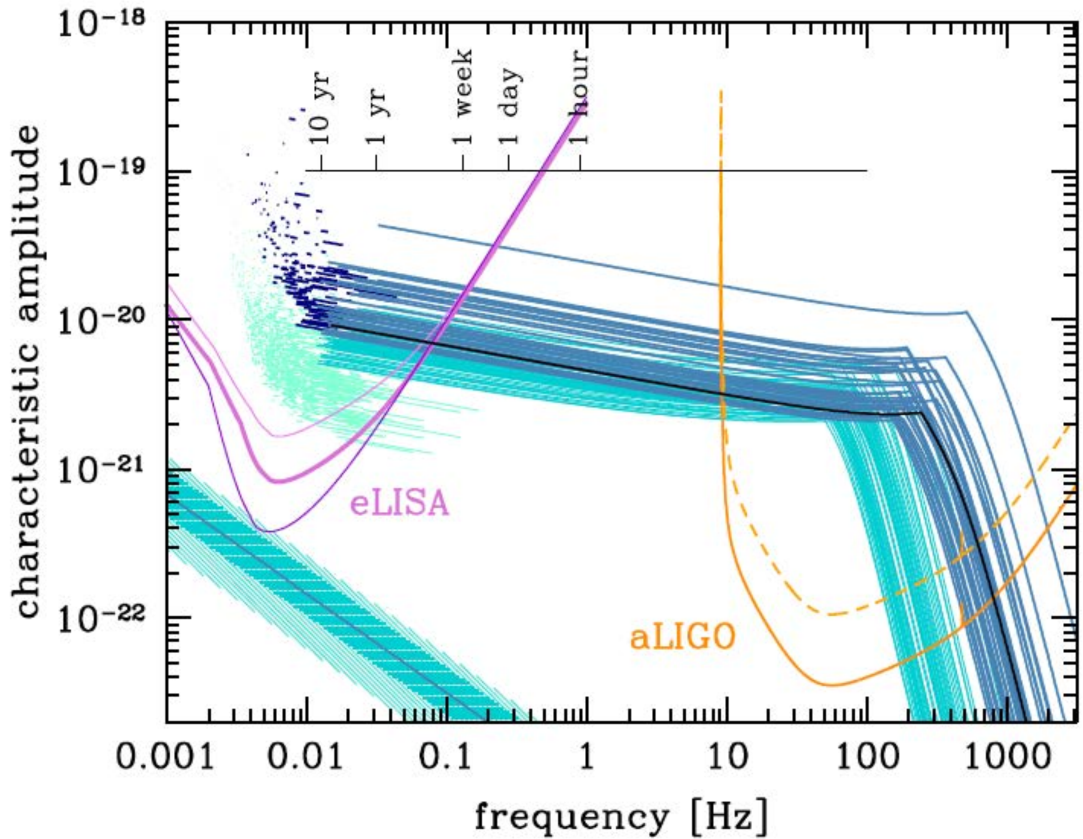
Prospects for Multiband Gravitational-Wave Astronomy after GW150914

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 weeks in advance.



2. Detecting LIGO events before they happen

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) coal 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 t*

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)*

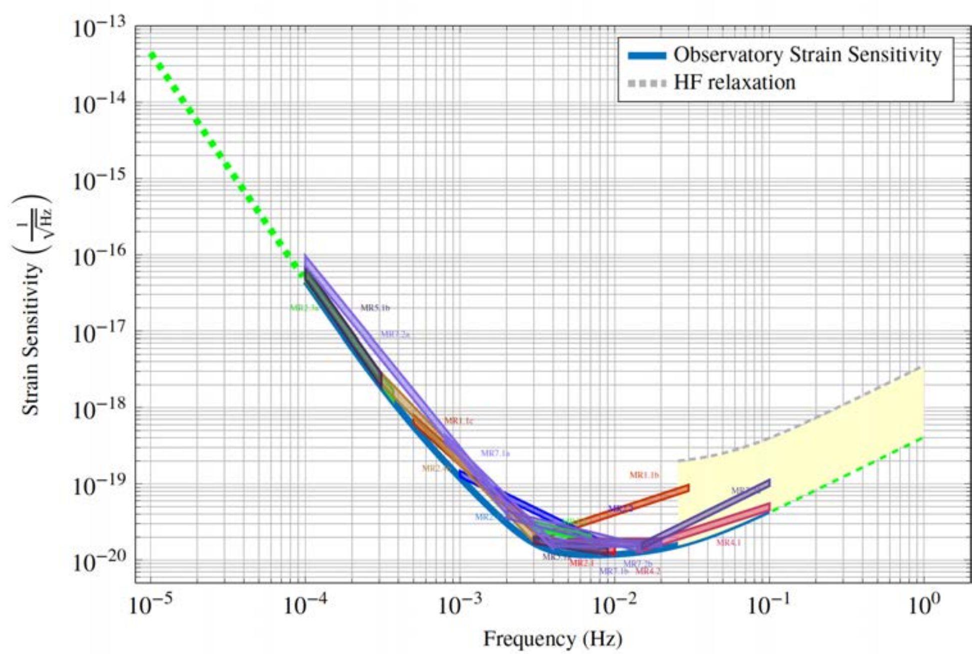
SO 7 Understand stochastic GW backgrounds and their implications for the early Universe and Te physics

- *SI 7.1 Characterise the astrophysical stochastic GW background*

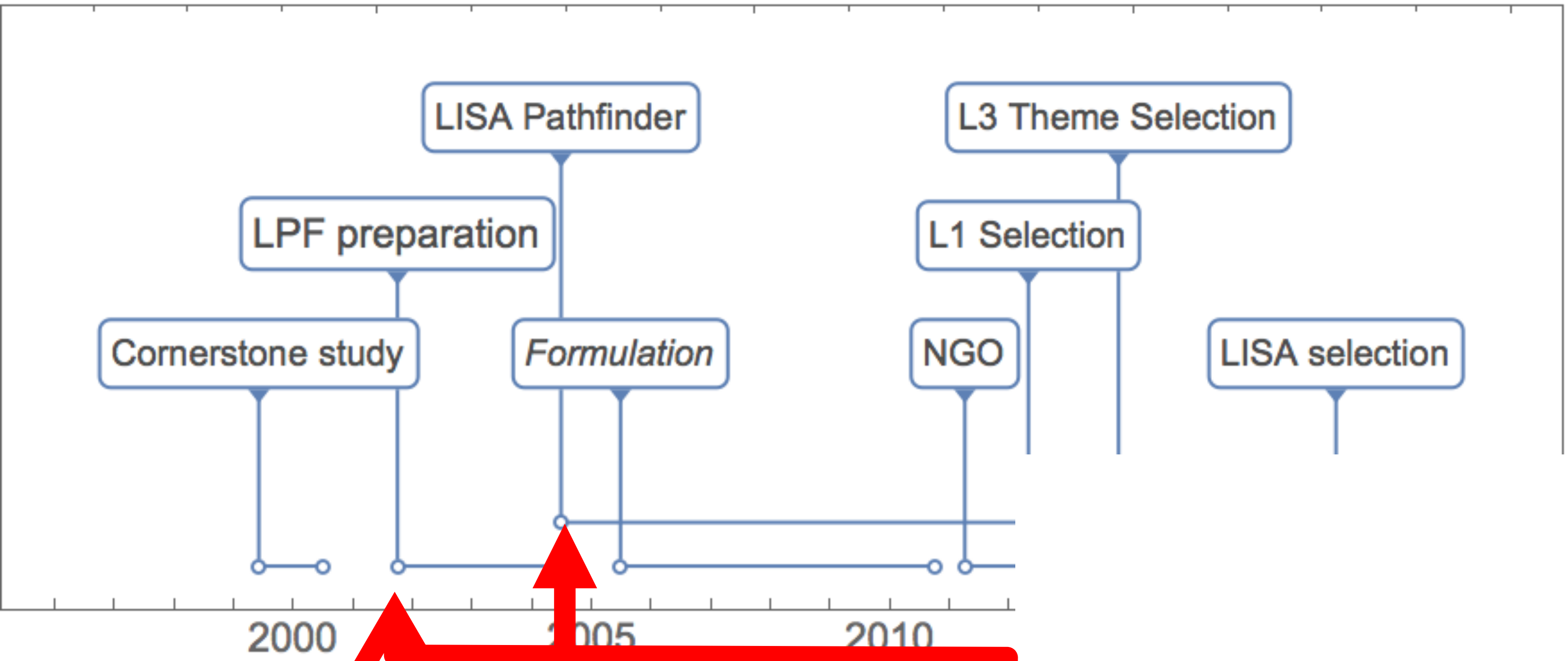
SO 8 Search for GW bursts and unforeseen sources

- *SI 8.1 Search for cusps and kinks of cosmic strings*
- *SI 8.2 Search for unmodelled sources*

And so on and so forth



LISA development and LISA Pathfinder



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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.

Lisa Pathfinder should launch in 2008

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

EUROPEAN SPACE AGENCY

SPACE SCIENCE ADVISORY COMMITTEE

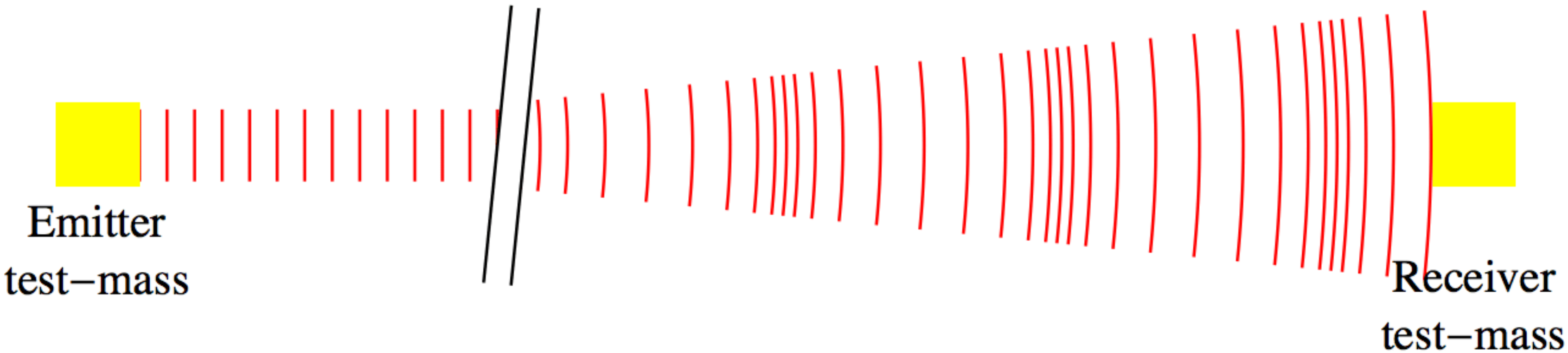
Recommendation on SMART 2

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.

free falling masses: must accelerate just because of curvature

Accelerations relative to local frames must be negligible

Force vs curvature



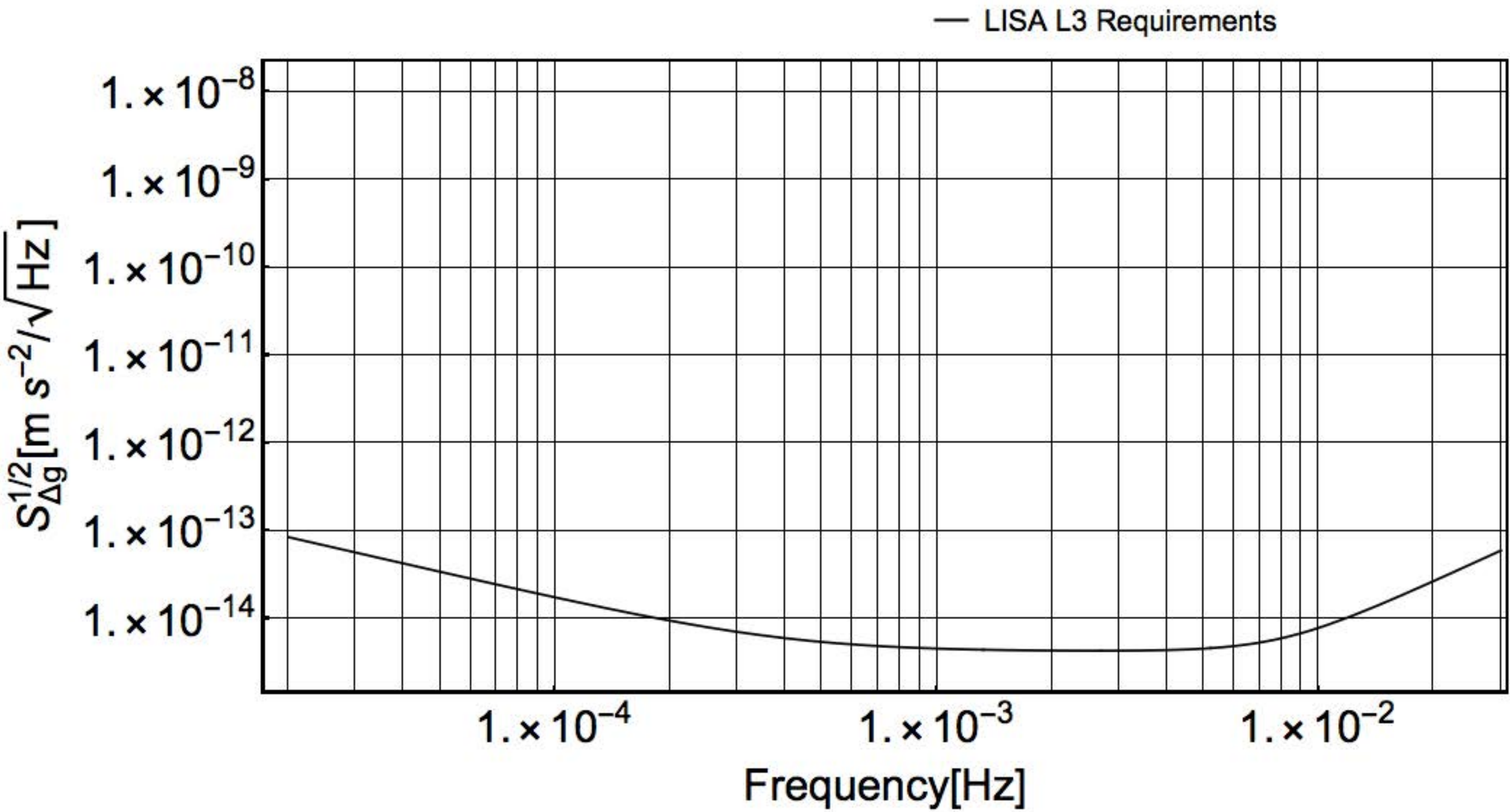
- Acceleration of test masses, *relative to their local free-falling frames*, cannot be distinguished from the effect of curvature

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

$$\Delta g$$

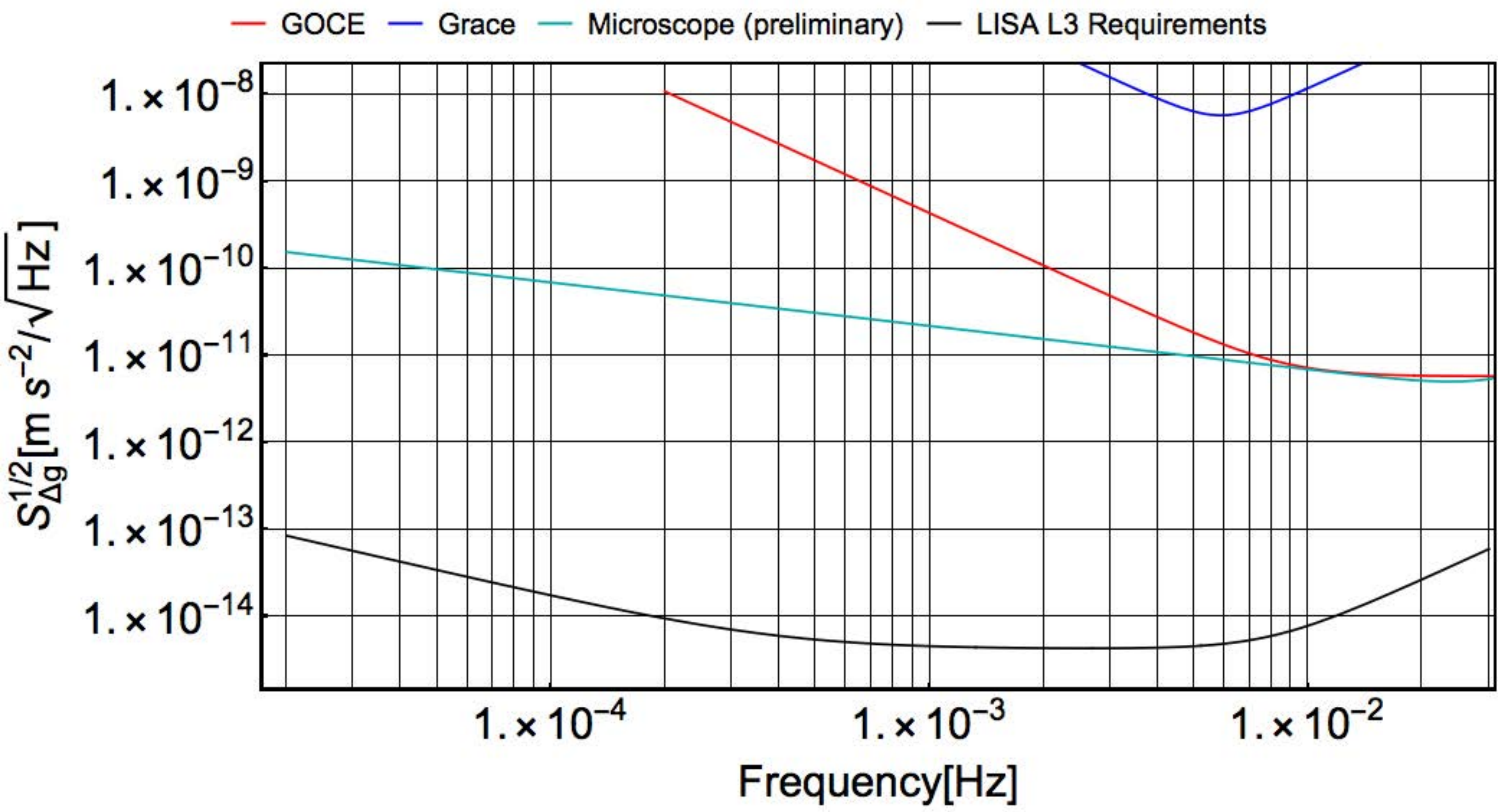
Sub-femto-g force suppression for LISA

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

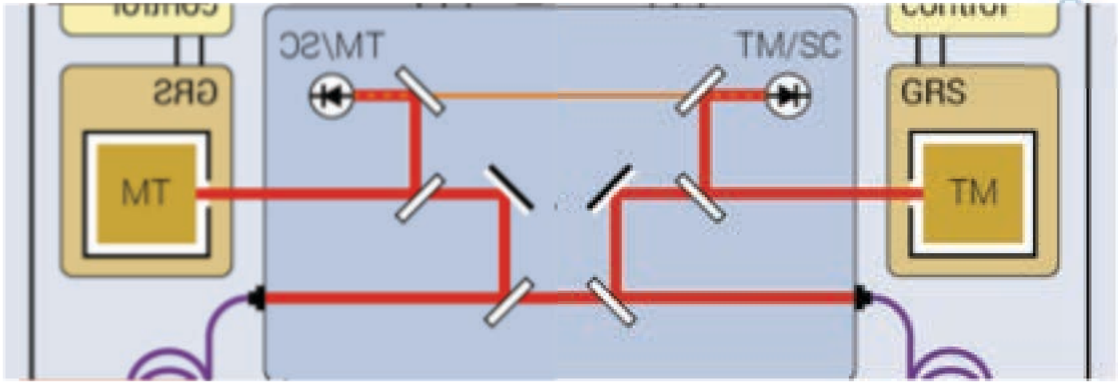


Sub-femto-g force suppression for LISA

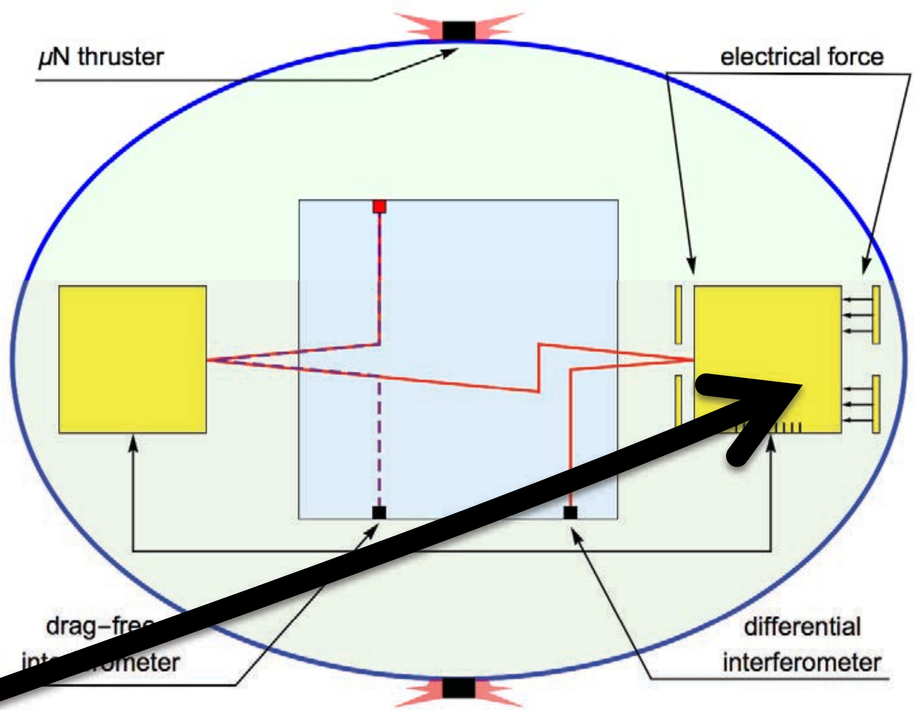
- Cannot be tested on ground $\lesssim 0.1$ Hz
- Orders of magnitude better than any other space mission



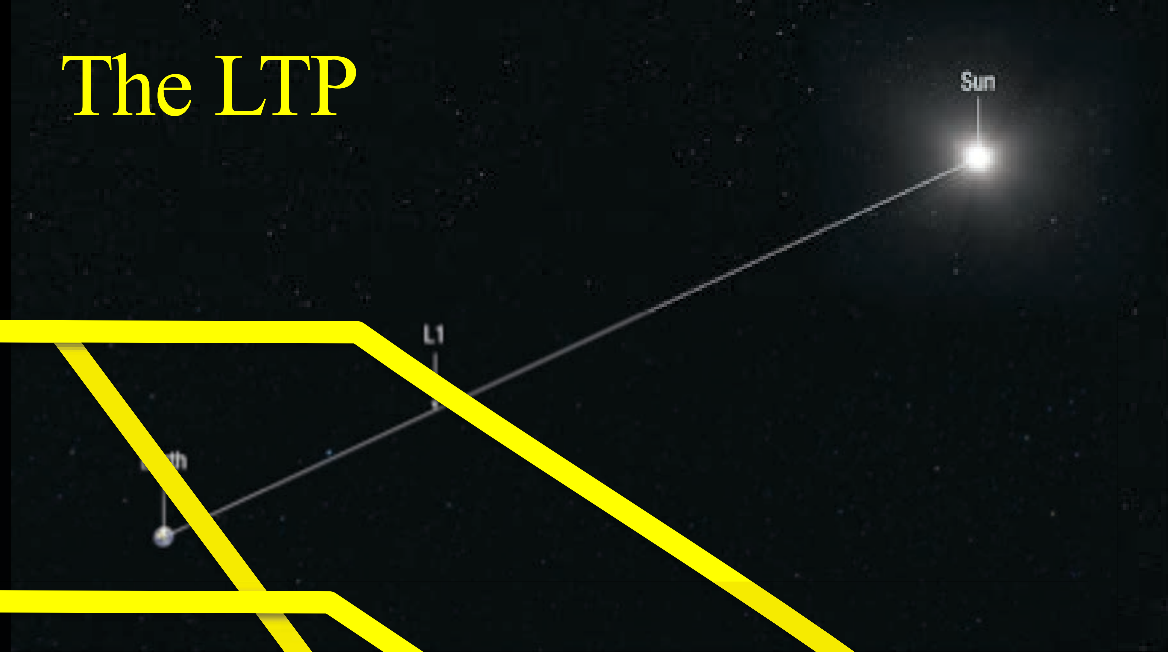
LISA Pathfinder concept



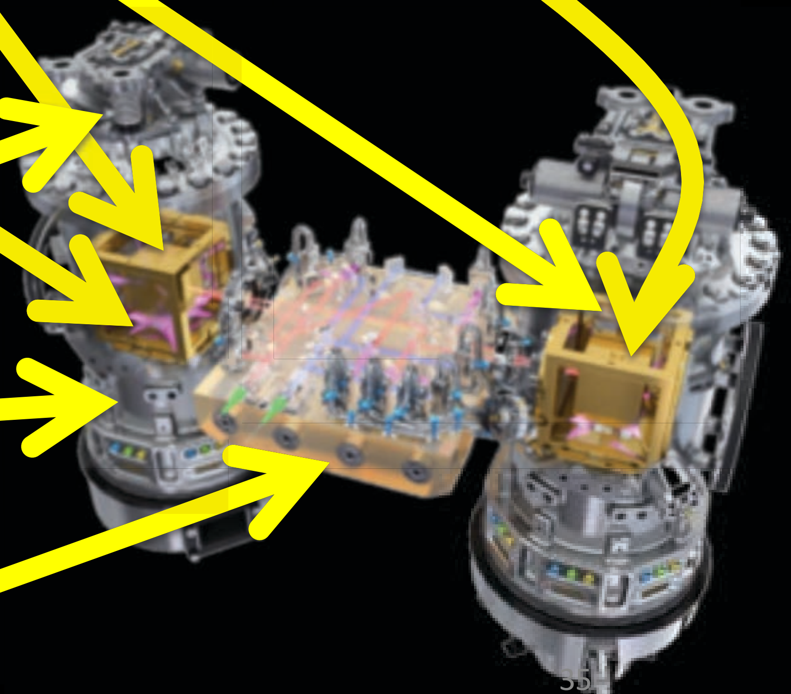
- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- 2 Interferometers (Ifo)
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



The LTP

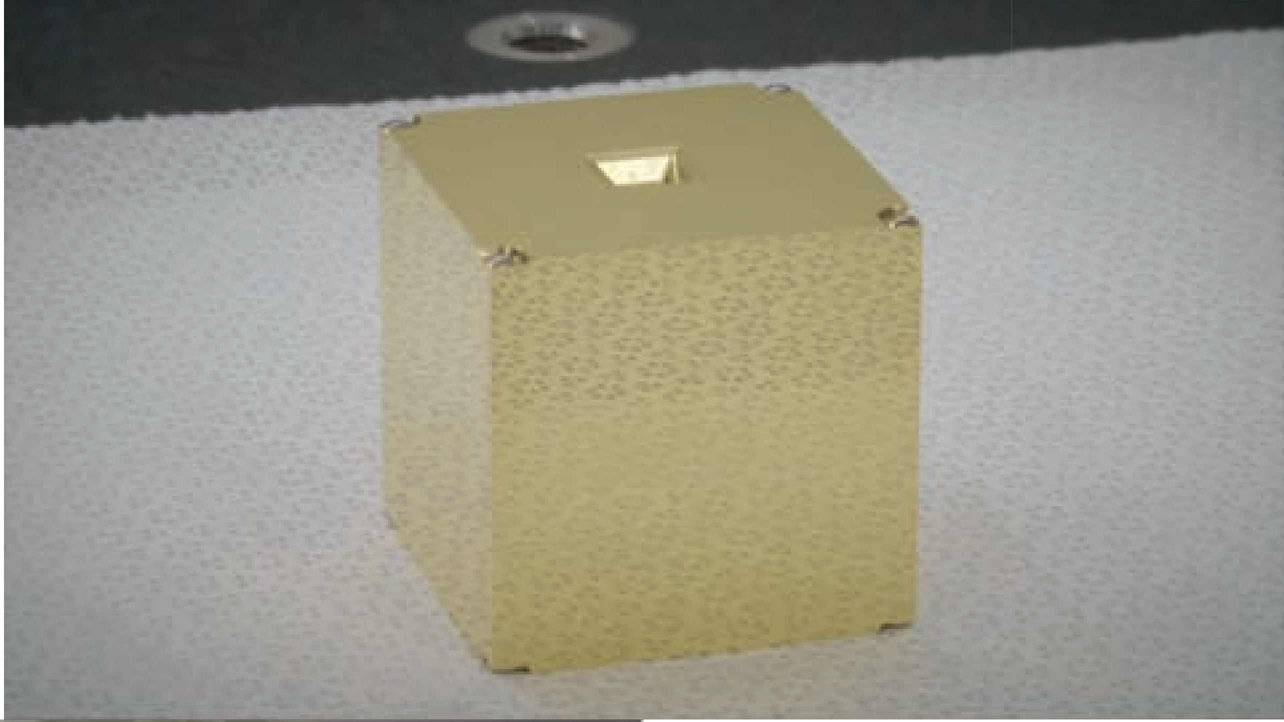


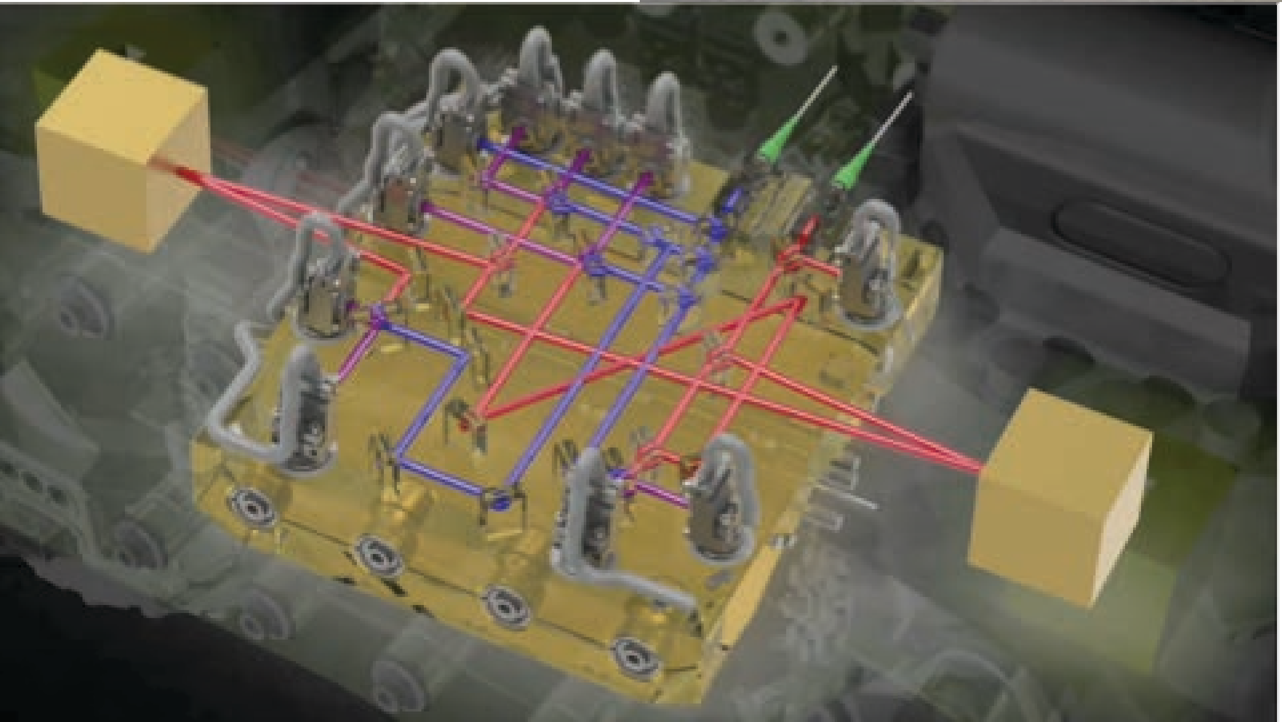
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure 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

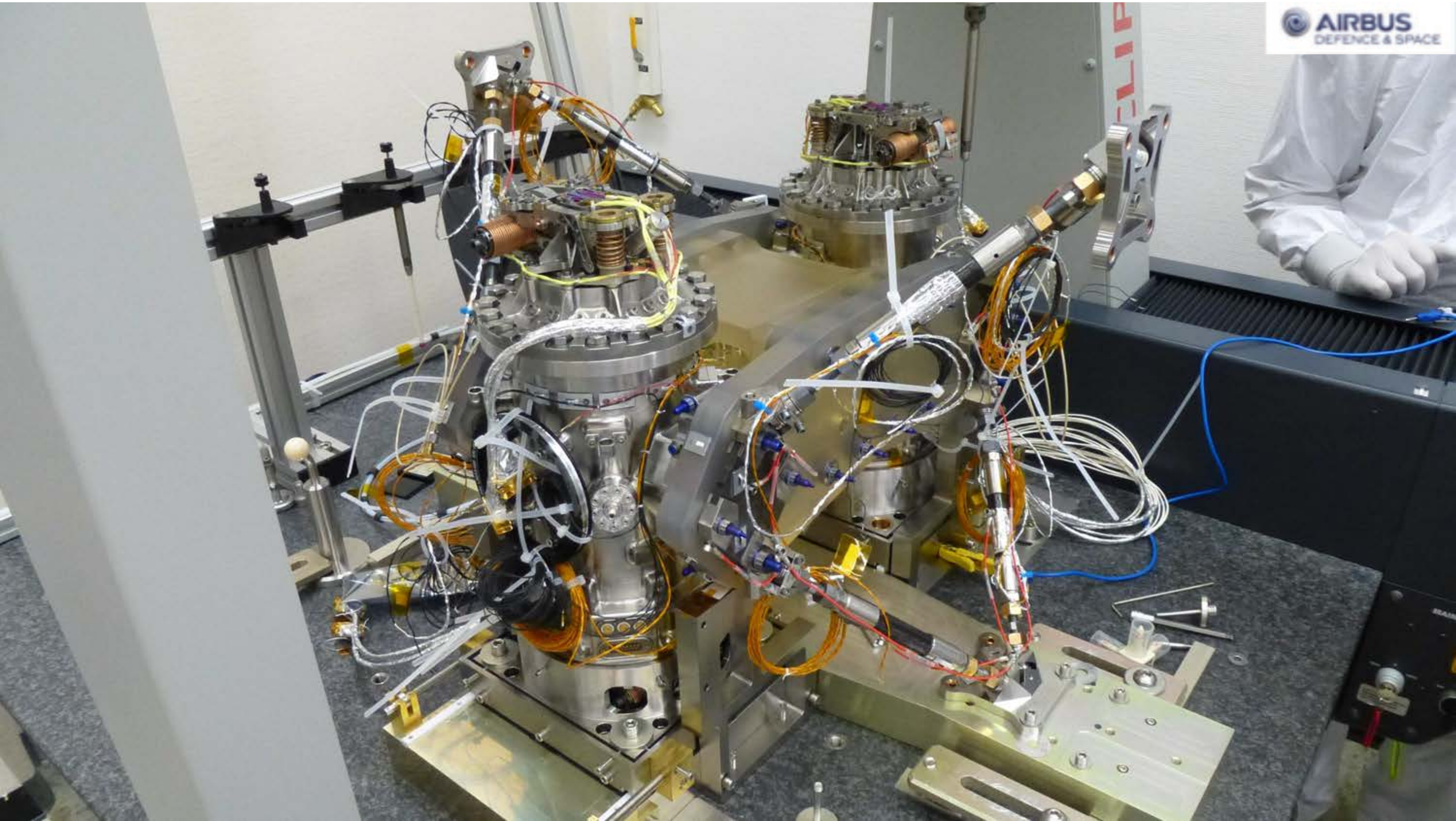


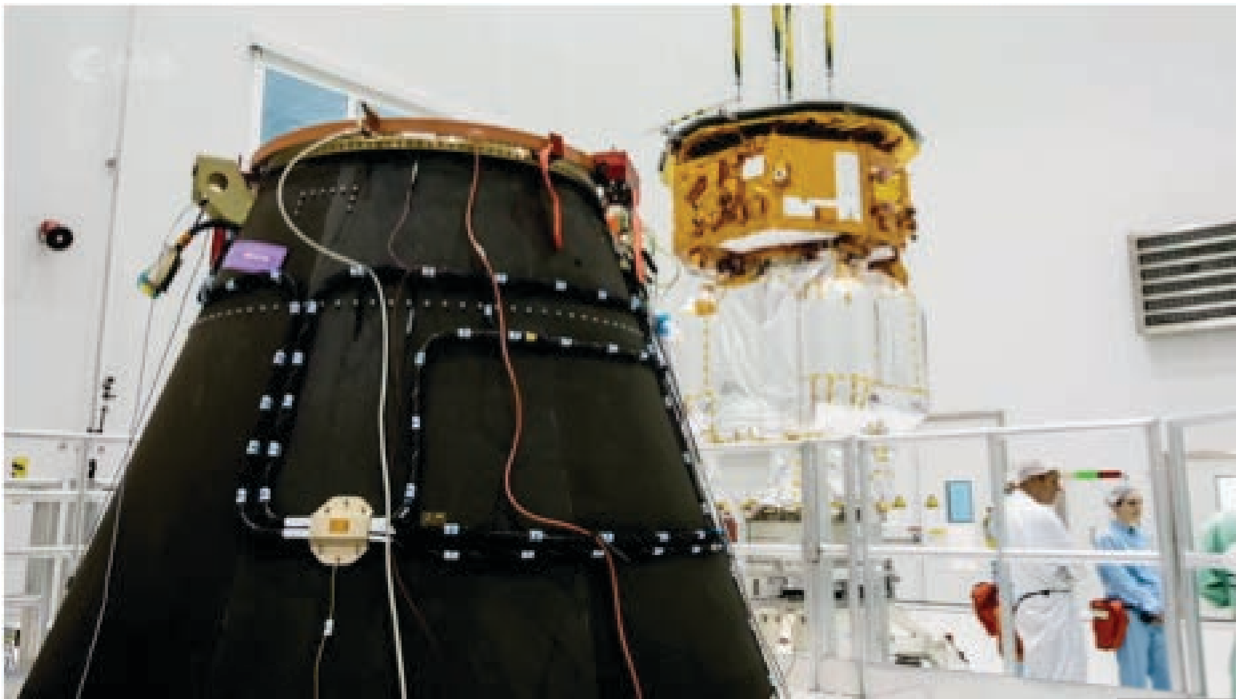


Laser interferometer

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

LTP Core assembly

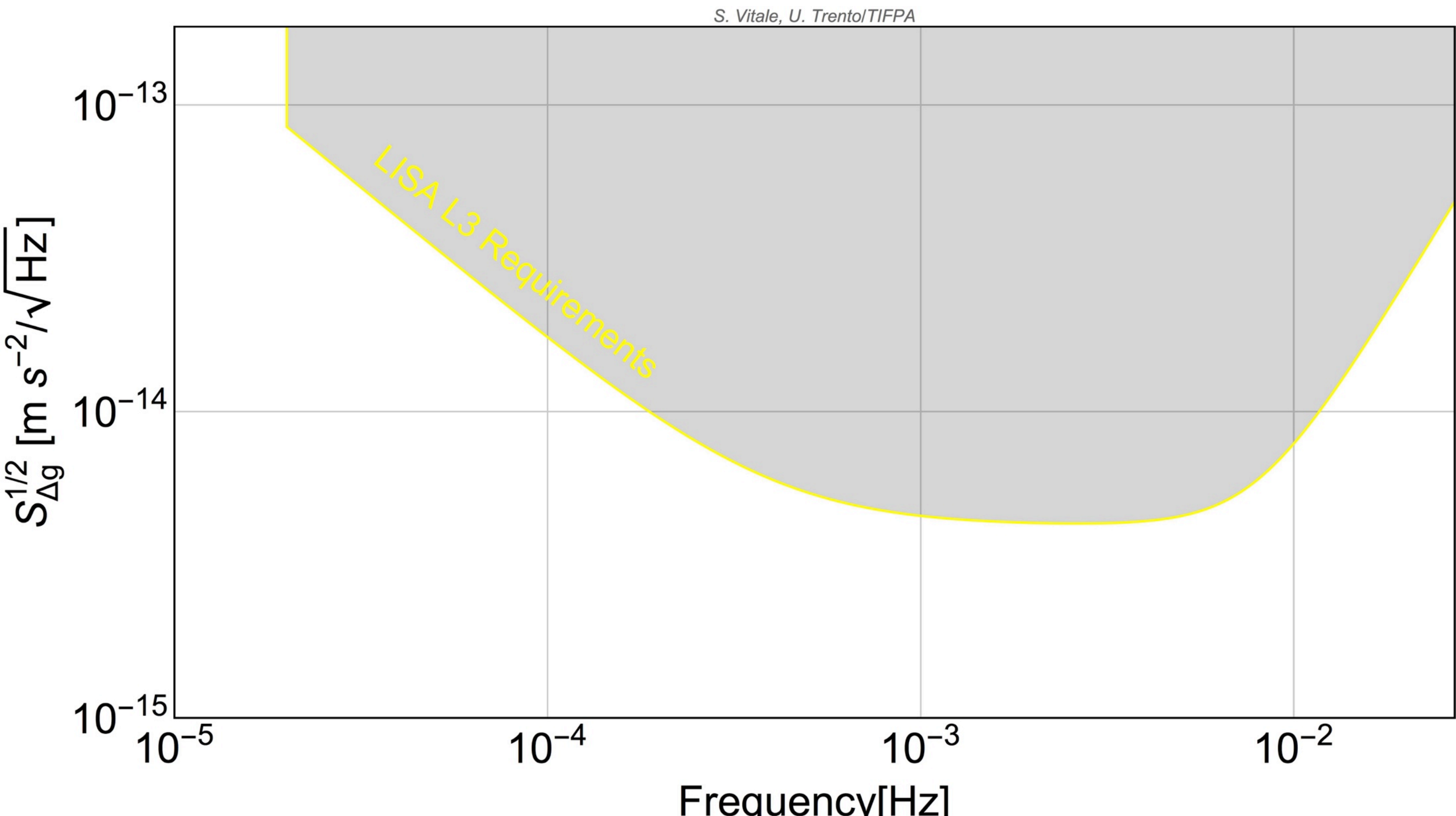





esa
00:29
esa
lisa pathfinder
arianespace

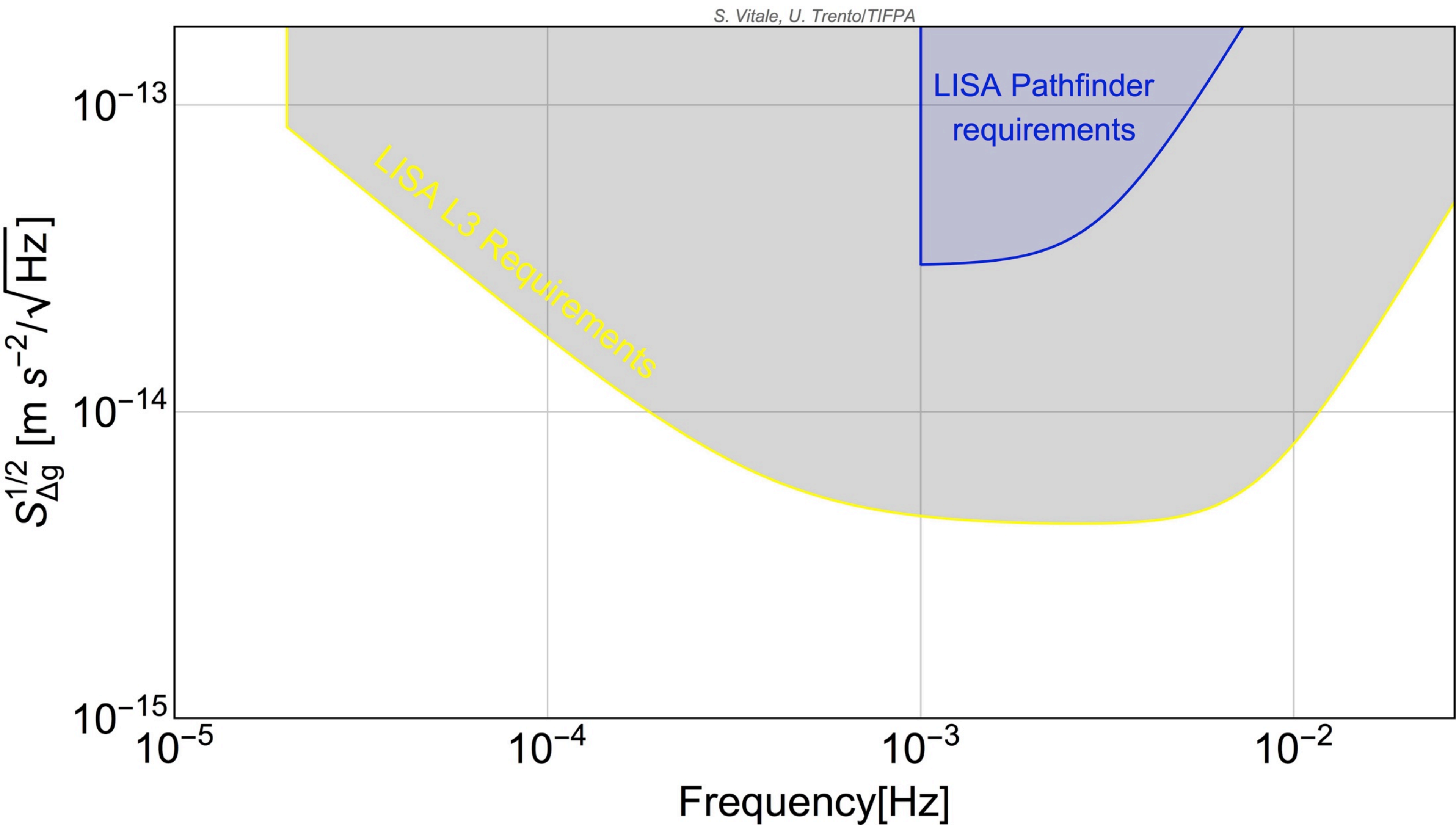

11 Jan 16
LTP Turn-on
22 Jan 16
$\times 10^8$
-4
-2
0
2
5
$\times 10^8$

LISA (L3) disturbance acceleration requirements



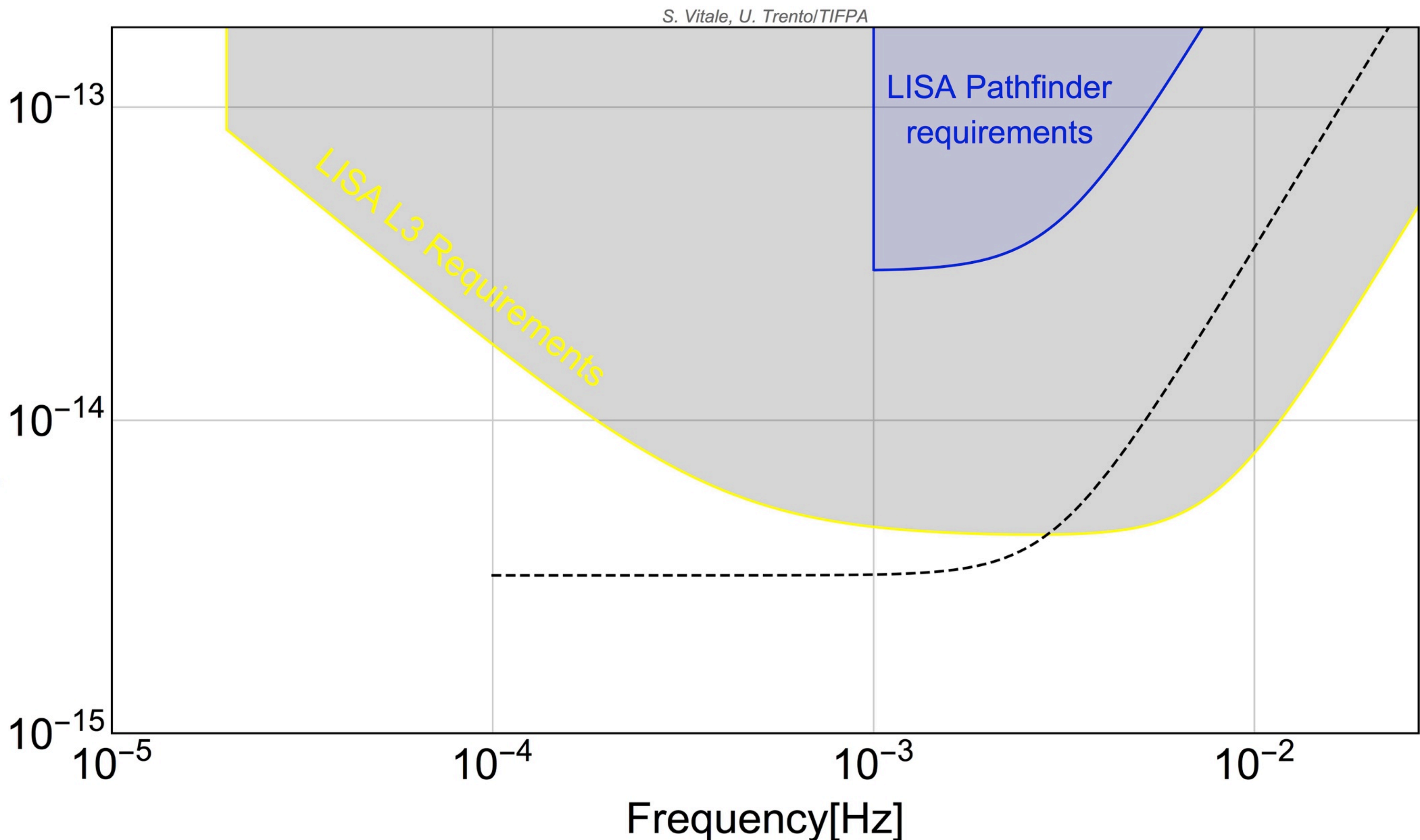
LISA Pathfinder requirements

- 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 pm/√Hz ~ as in LISA



What were we expecting?

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

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

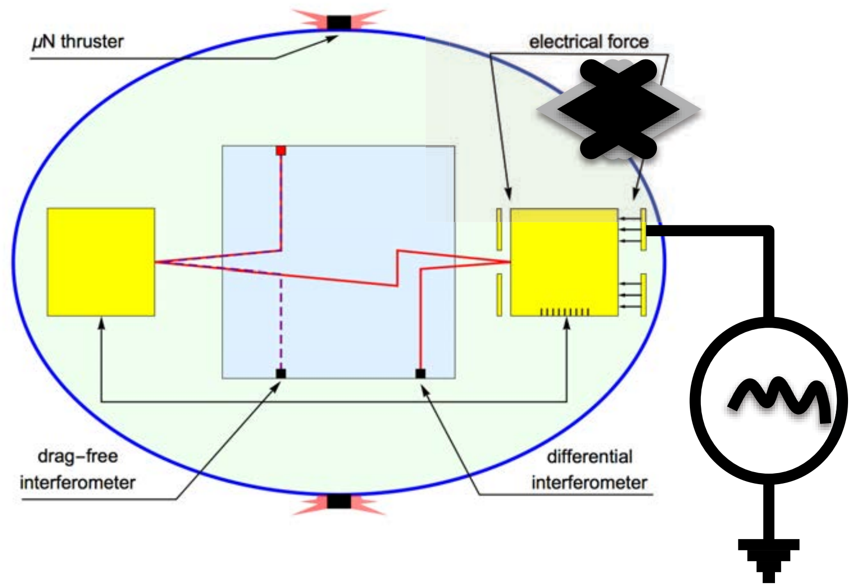
Source	PSD (fm s^{-2} $Hz^{-1/2}$)	Estimated from
Actuation, x-axis	7.5 (0.8)[a]	Measurement of flight-model electronics stability
Brownian	7.2	Measurement with torsion pendulum
Magnetics	2.8	Measurement of magnetic field stability
Stray voltages	1.1	Upper limit from the torsion pendulum test campaign
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 $\overleftrightarrow{\delta D}$ 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

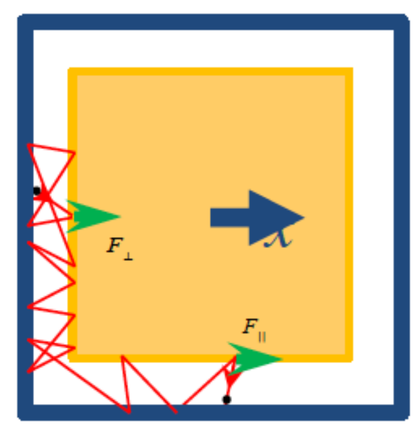
[a] The values within parentheses refer to the free-flight mode. See the text for explanation.

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

Source	PSD (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

- 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





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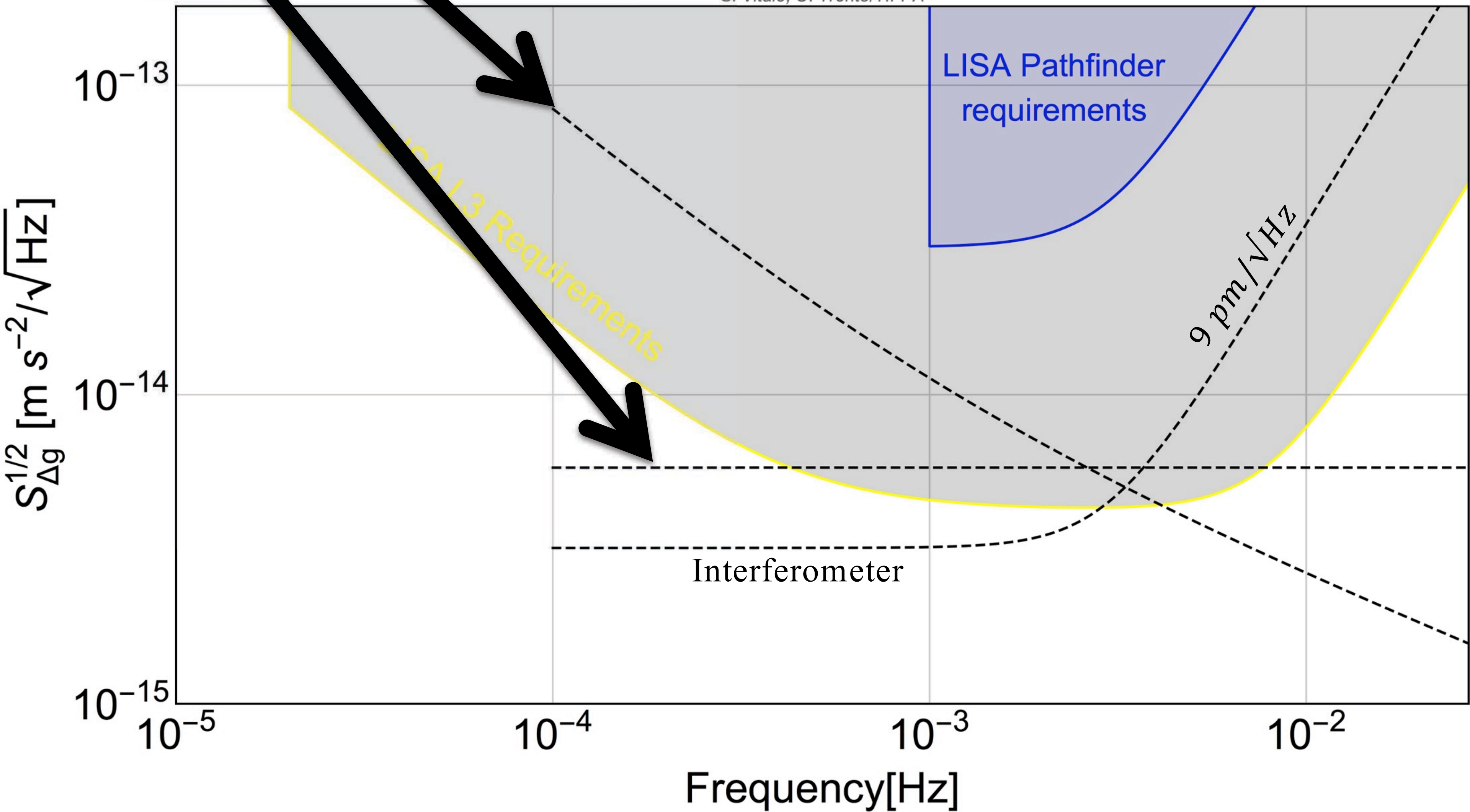
S. Vitale, U. Trento/TIFPA



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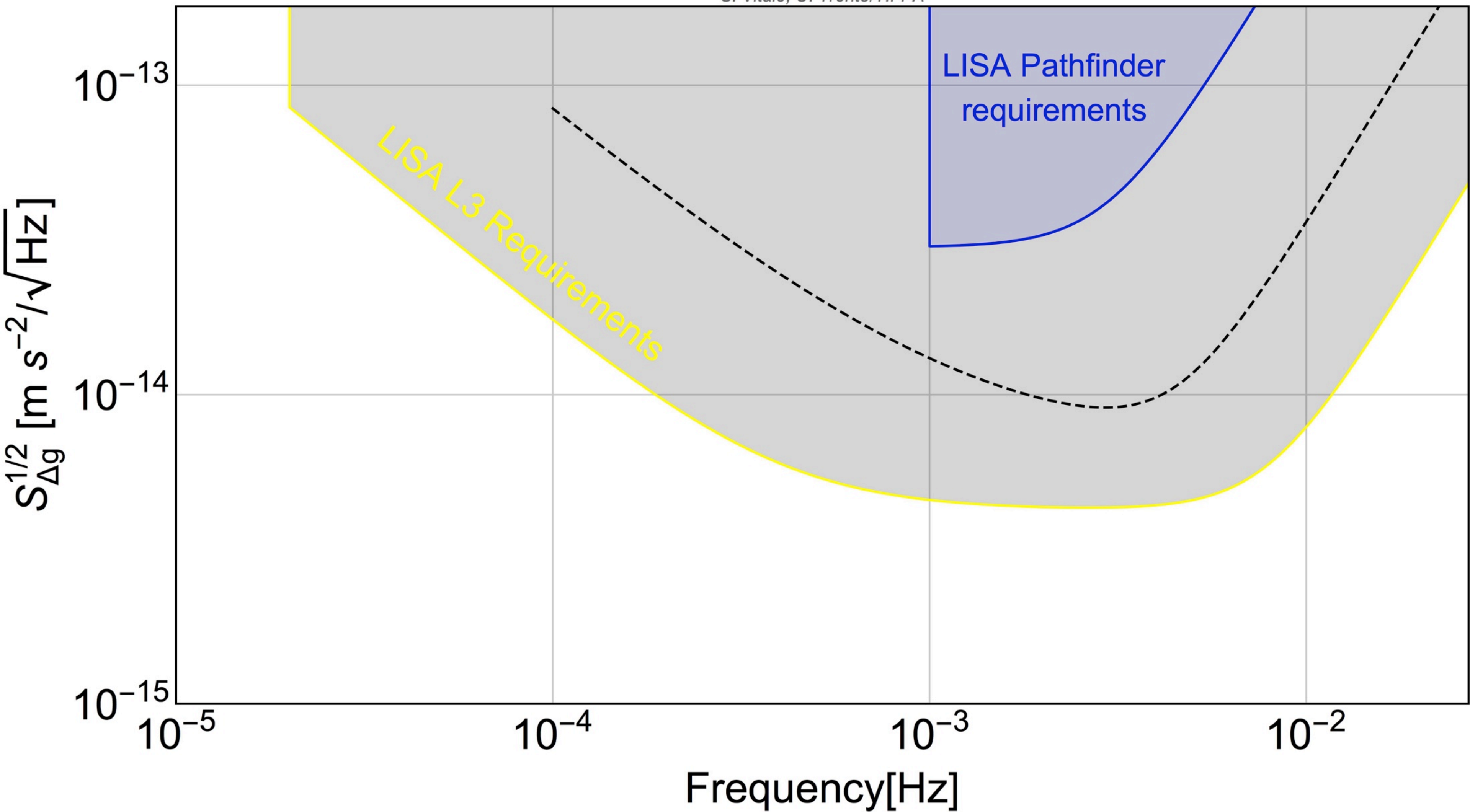
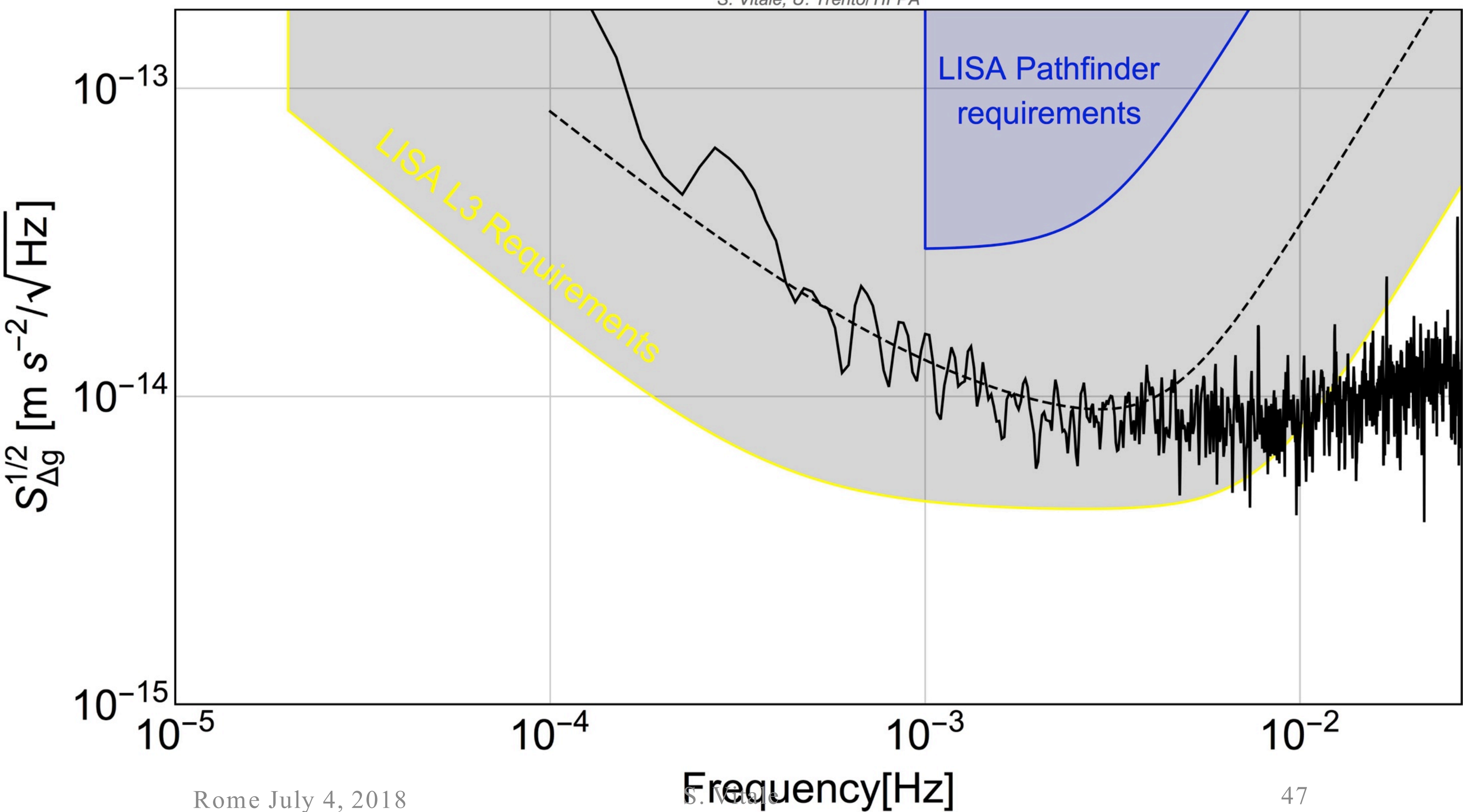


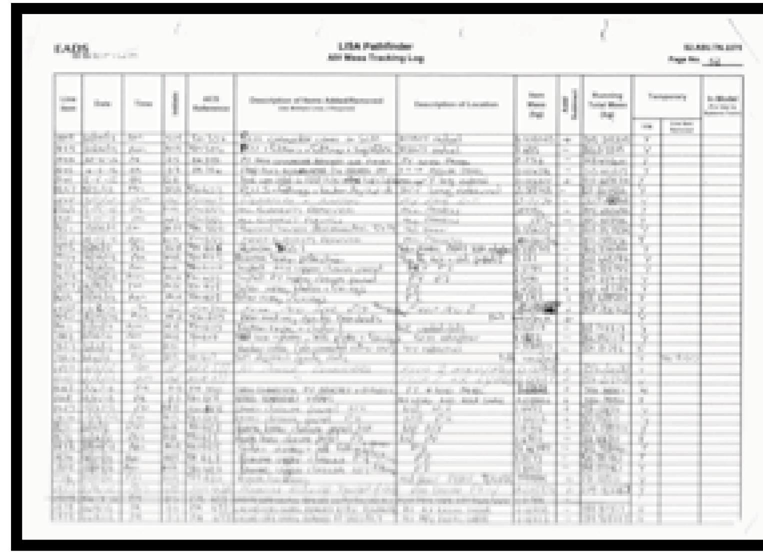
First day of operations, March 1st 2016

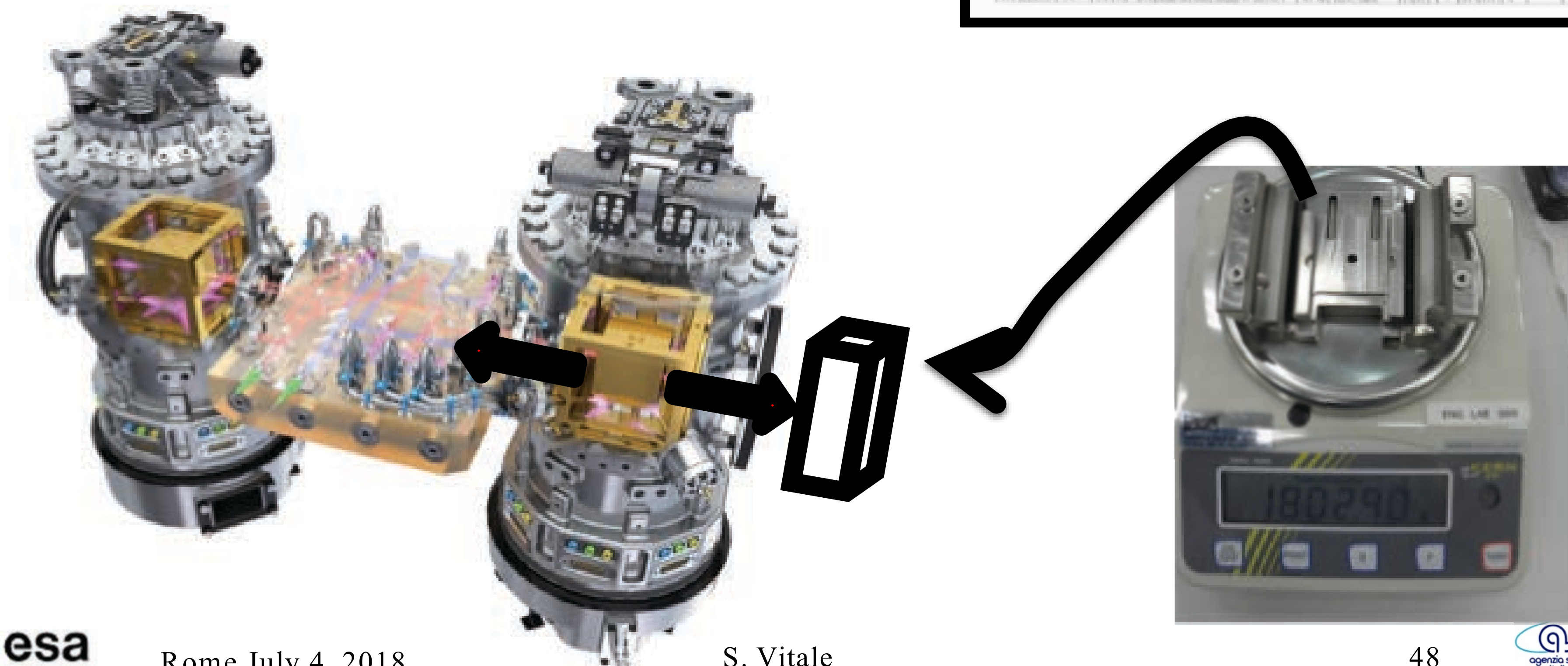
- Better than requirement.
- Close to prediction
- Except interferometer noise at 35 fm/√Hz!



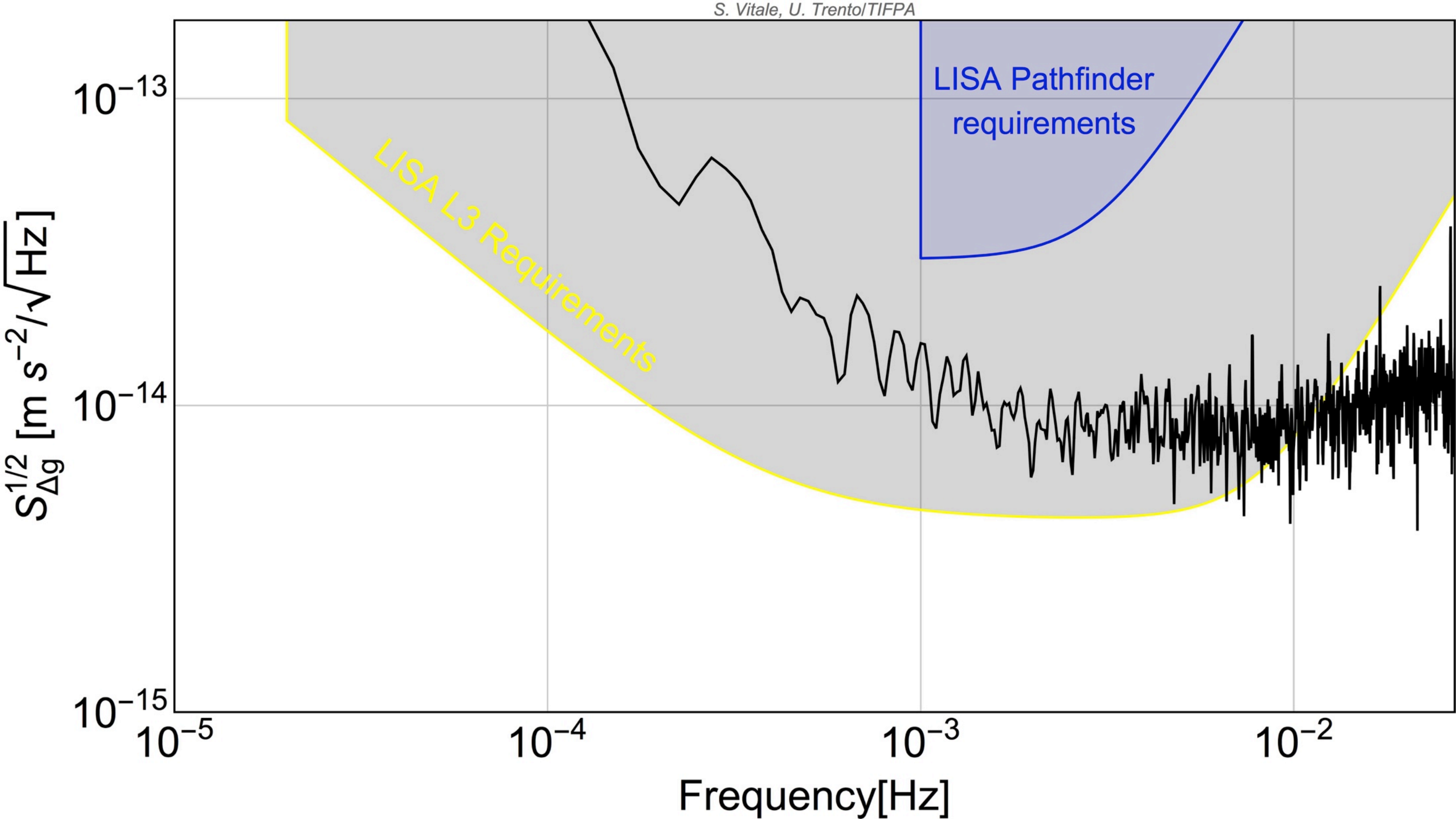
Gravitational compensation and actuation

- 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)
- Actual: g_{max}< 25 pm s^{-2}


LISA Pathfinder
AIV Mass Tracking Log

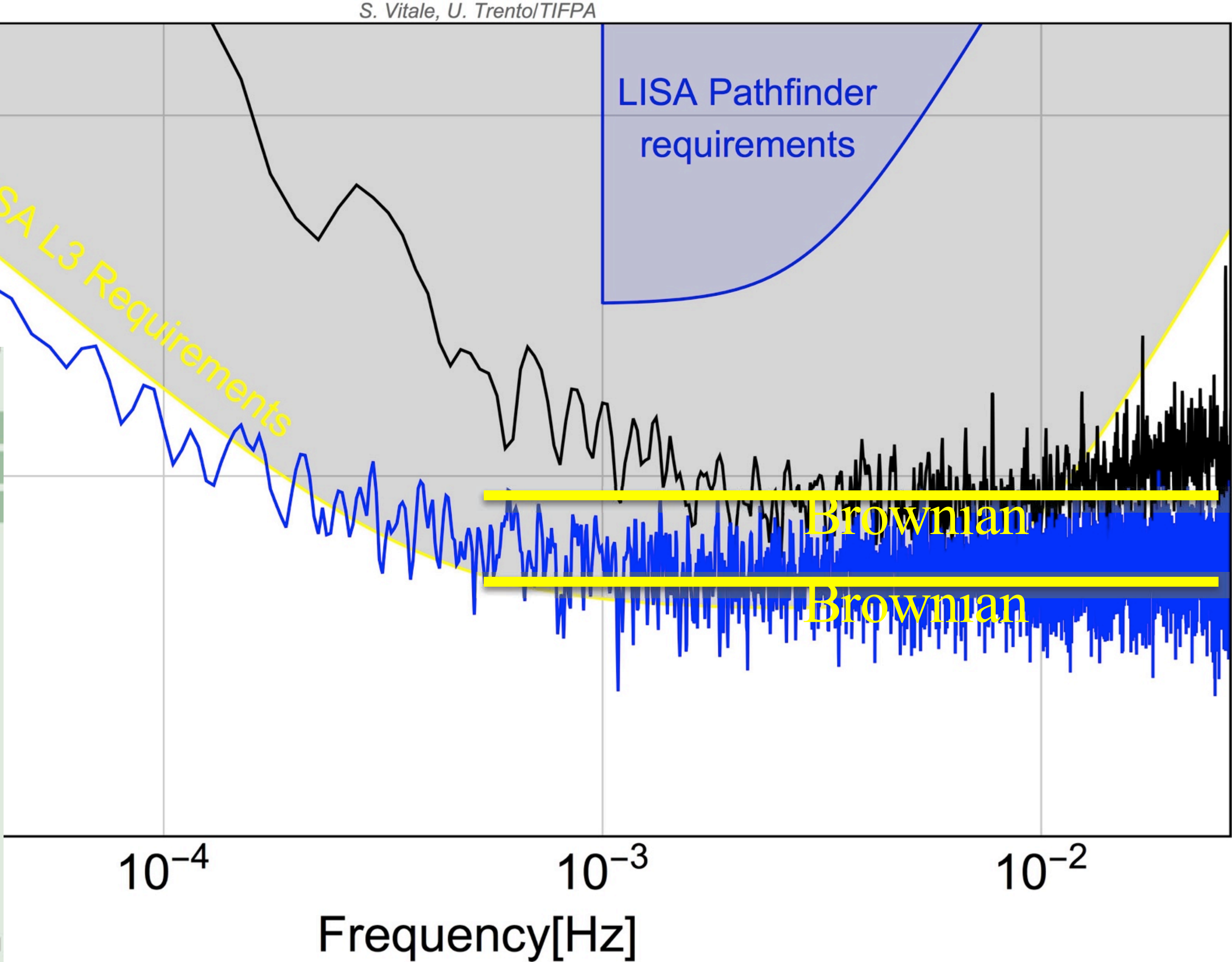


Authority: 650 pm s^{-2}



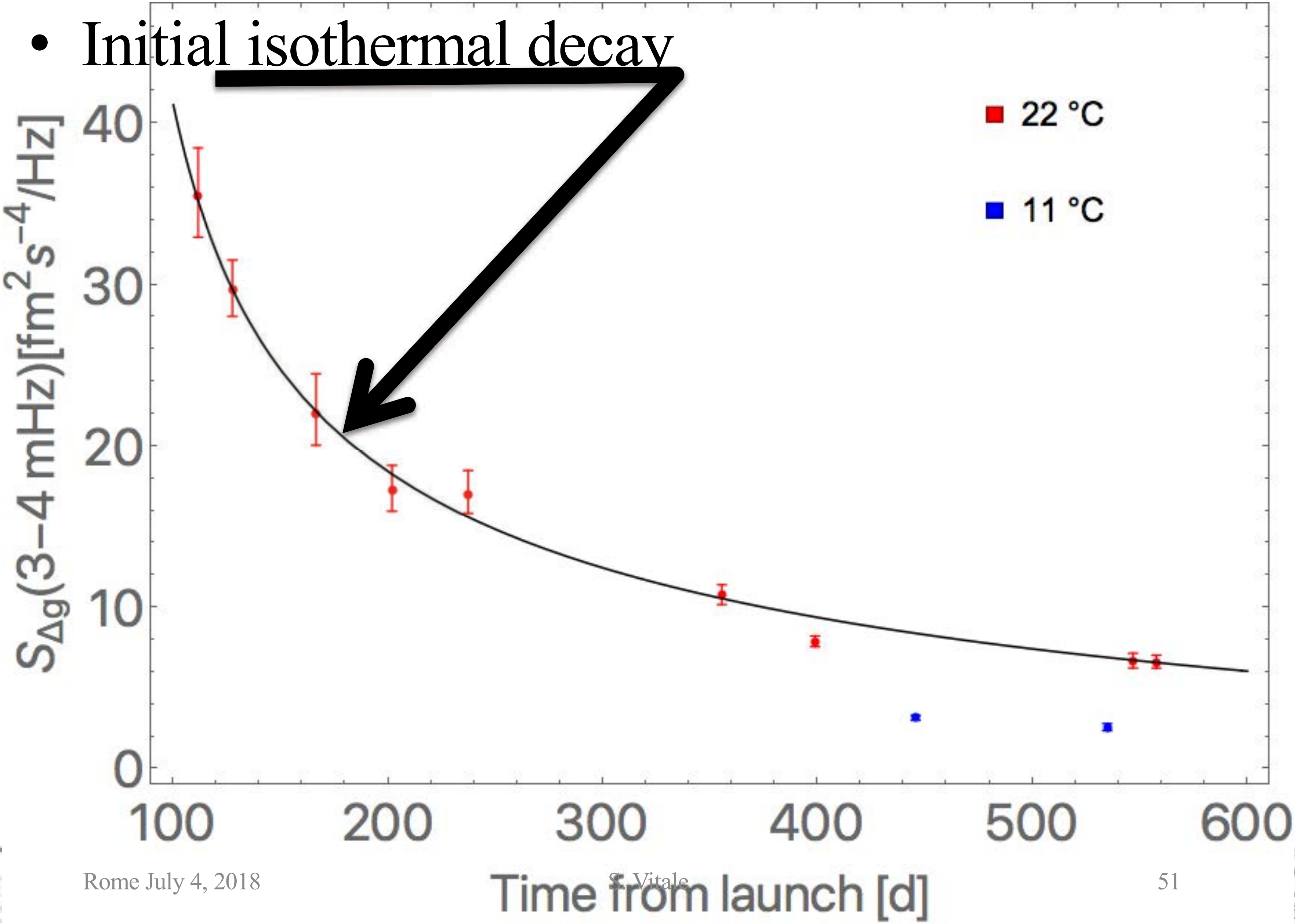
April 2016

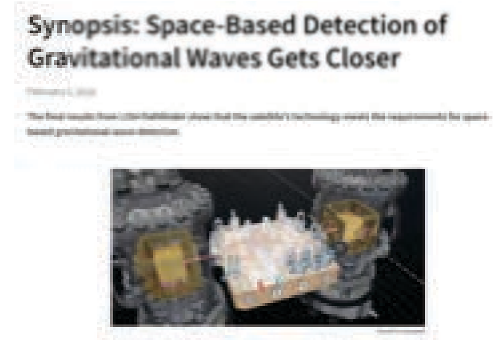
- Authority reduced to 50 pm s^{-2}
- Published in June 2016
- Pressure and Brownian decaying thanks to venting to space



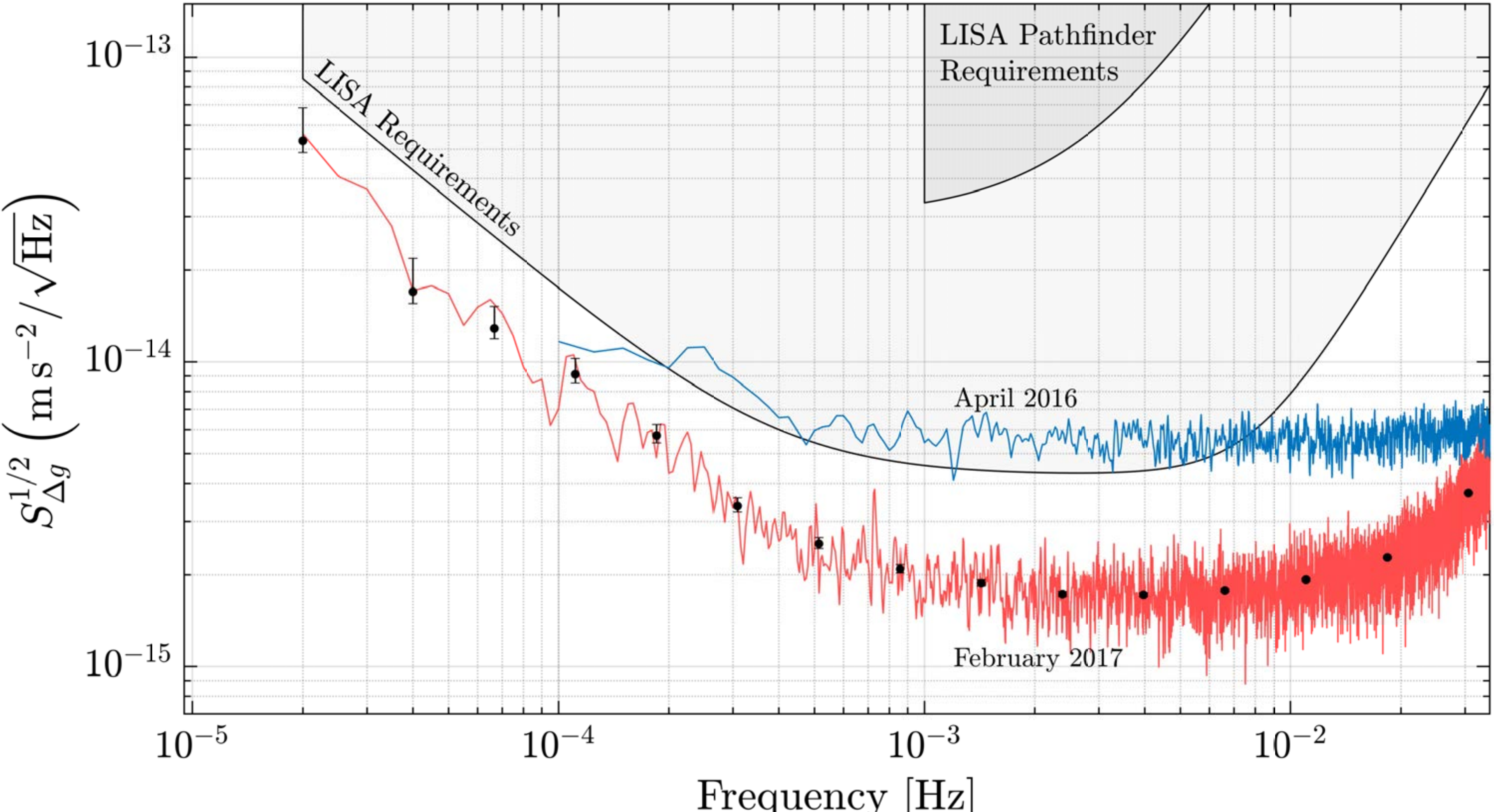
Pressure and Brownian decay

- Initial isothermal decay



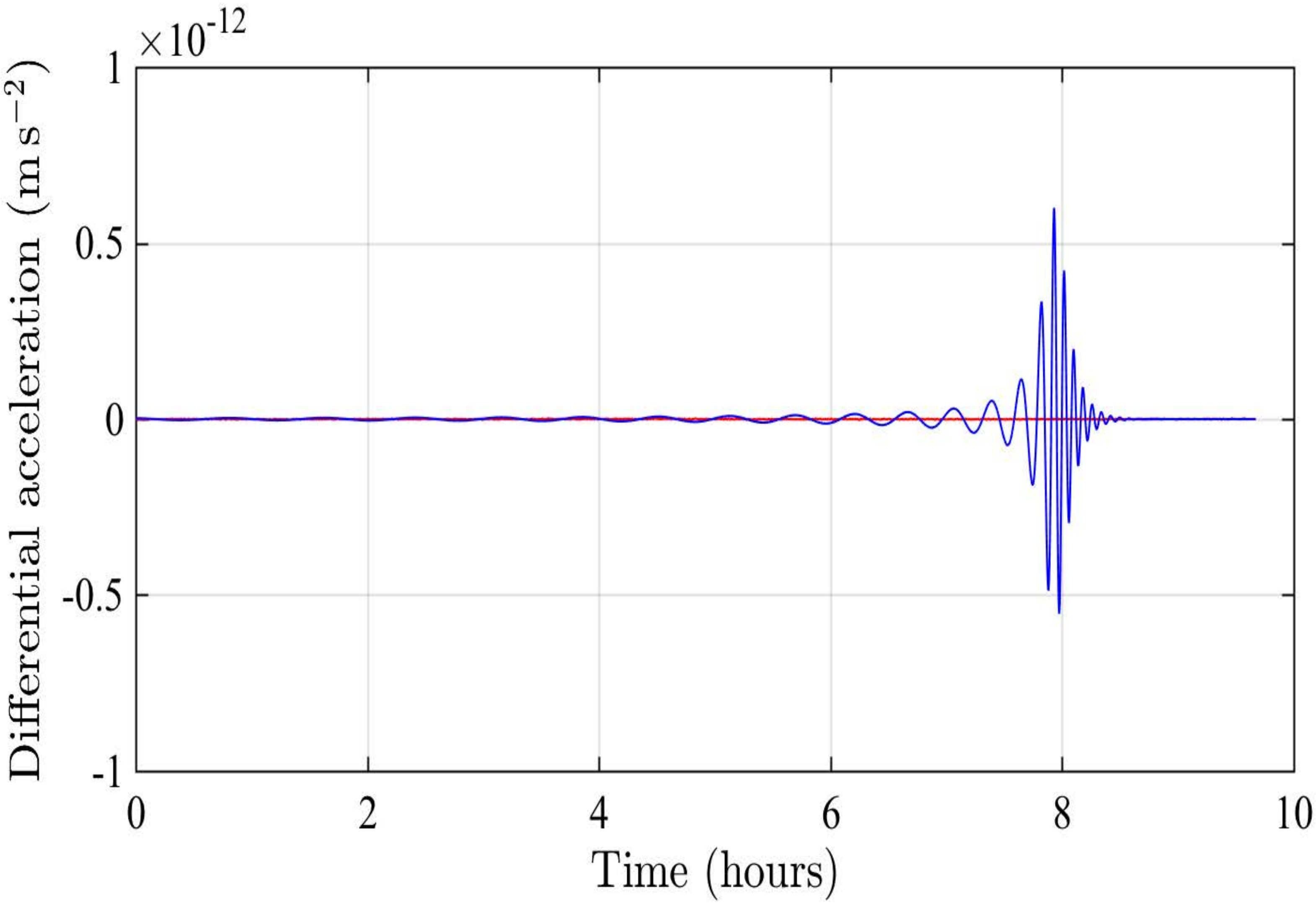

Synopsis: Space-Based Detection of Gravitational Waves Gets Closer

The ultimate performance



Simulated LISA acceleration signal for two 5×10^5 M⊙ black-holes with their galaxies merging at z=5

LISA Pathfinder acceleration data



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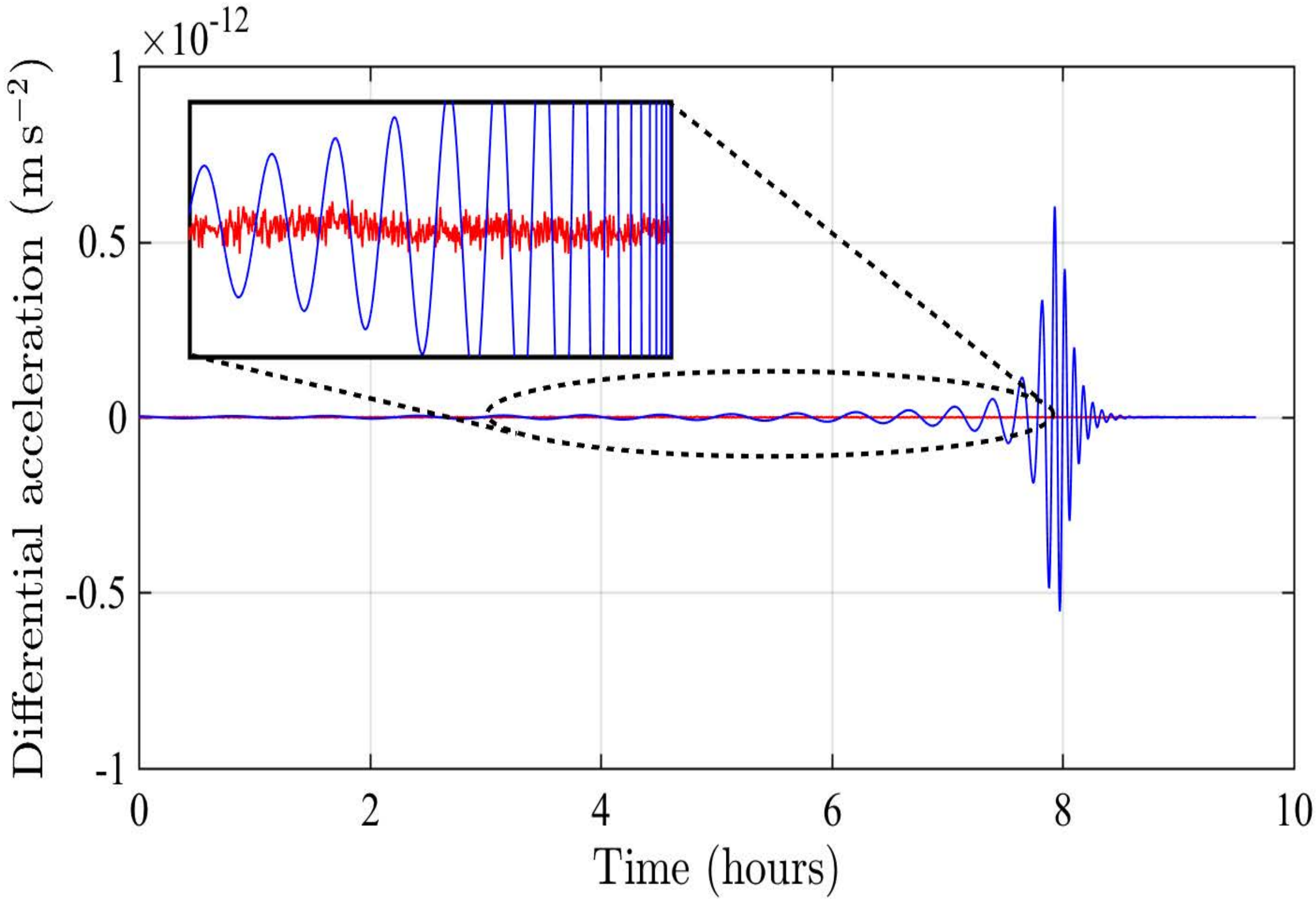

lisa pathfinder

Green Light for LISA

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Science & Environment

Gravity probe exceeds performance goals

By Jonathan Amos
BBC Science Correspondent, Boston

18 February 2017 | Science & Environment

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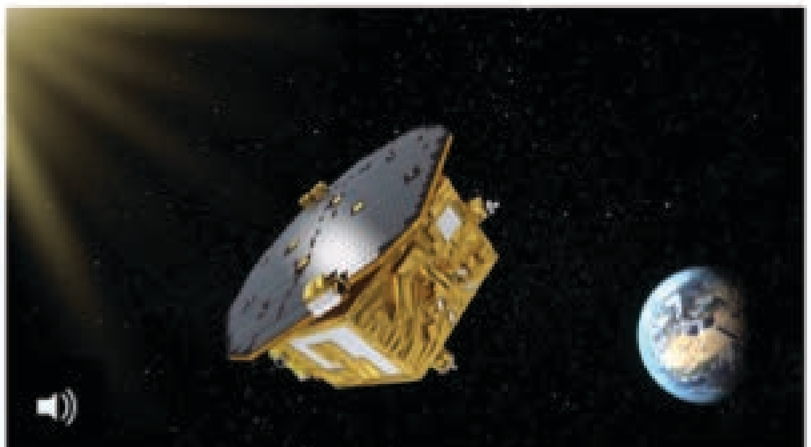

Stefano Vitale: "LISA Pathfinder has been an amazing success"

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

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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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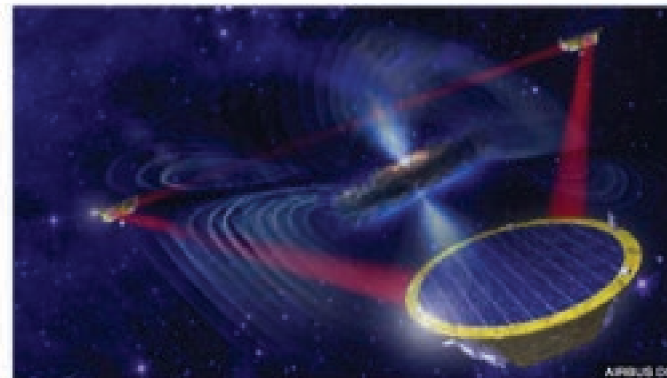


Artwork: LISA envisages three spacecraft linked by laser arms that are 2.5 million km in length

BBC

NEWS

Science & Environment

LISA Pathfinder: Time called on Europe's gravity probe

By Jonathan Amos
BBC Science Correspondent

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

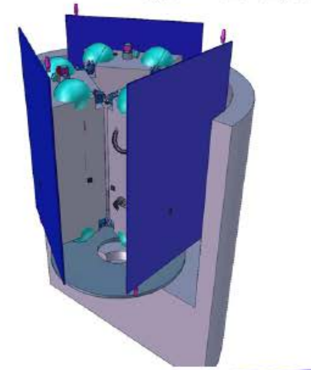
LISA – Status of Activities

Phase 0 activities – completed

- Mission Definition Review passed (go-ahead for Phase A given)

Phase A activities

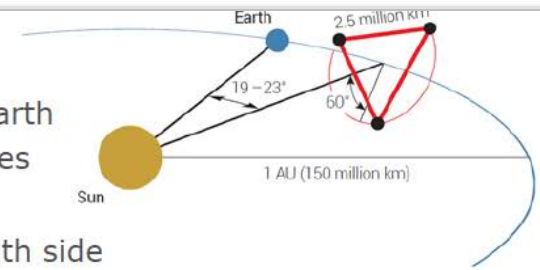
- Parallel industrial Phase A studies starting in Q2/2018 (20 months)
- Single Payload Phase A study contract to Consortium in parallel to industrial activities, supporting the nationally funded Phase A studies of provided instruments – all to start also Q2/2018
- Mission Consolidation Review planned around Mar-19, with the intention to enable the start of critical breadboarding activities
- NASA fully involved in Phase 0/A activities
- System Engineering Office in place (as for ATHENA)



LISA charging ahead

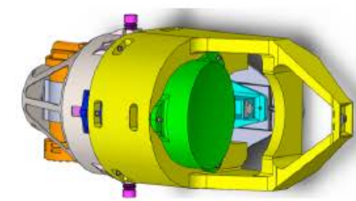
Mission and Spacecraft

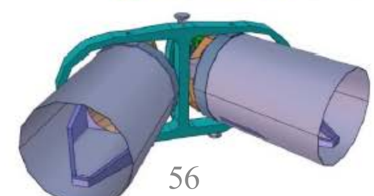
- Launch on Ariane 6.4 direct into escape and transfer to Earth trailing (or heading) heliocentric orbit at 1 AU, ~20 degrees phasing with the Earth.
- Constellation of three spacecraft, ~ equilateral triangle with side length ~2.5 Mkm, inclined at 60 degree w.r.t. ecliptic.
- Spacecraft dry mass ~1950 kg each, trapezoidal 4.5 x 3 x 1.3 m^3



Instrument

- Integrated payload with reference sensor (GRS), optical bench and telescope, plus phasemeter and electronics.
- Total estimated mass ~ 514 kg, Power in science mode: ~615 W
- Use of LPF heritage as far as possible, taking best benefit of previous LISA studies.

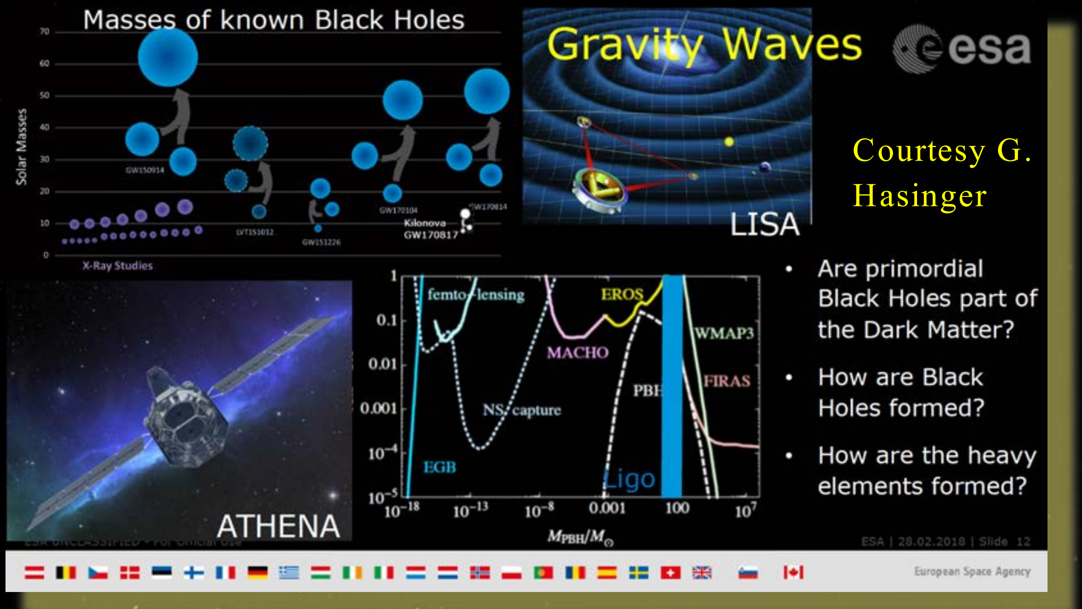


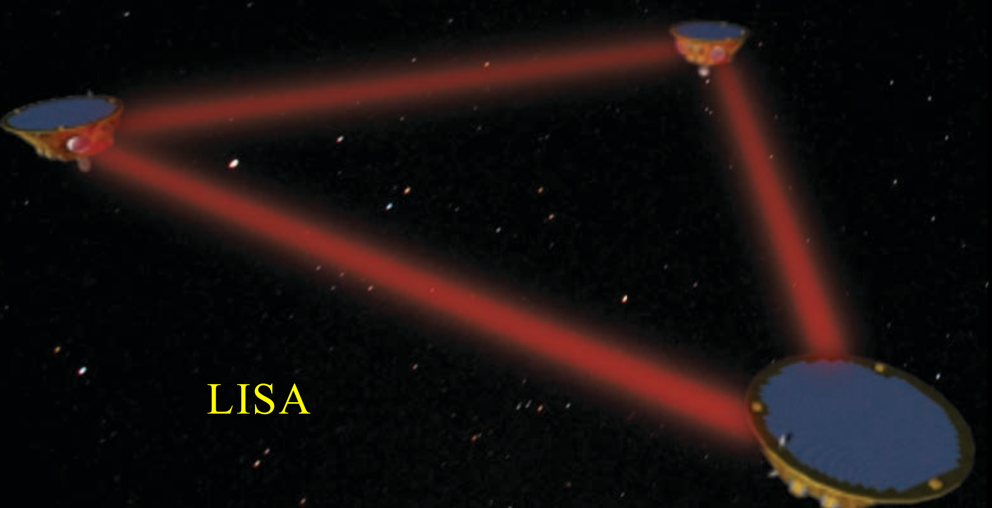


A rather accelerated (initial) schedule of an international effort

Event	From	To	Status
Phase 0 for instrument contributions	**2017-JUL**	**2017-NOV**	Done
Mission Definition Review (MDR)	**2017-NOV-27**		Done
Phase A (mission **& instruments**)	2018-APR	2019-DEC	**Kicked-off**
Mission Consolidation Review (MCR)	2019-FEB	2019-MAR	
Mission Formulation Review (MFR)	2019-OCT	2019-DEC	
Adoption	<=2024		
Implementation (Phase B2/C/D)	8.5-9 years		
Launch			
Transfer & Commissioning	2.5 years		
Operations	4 years		
Extension (TBD)	6 years		10 years total of science

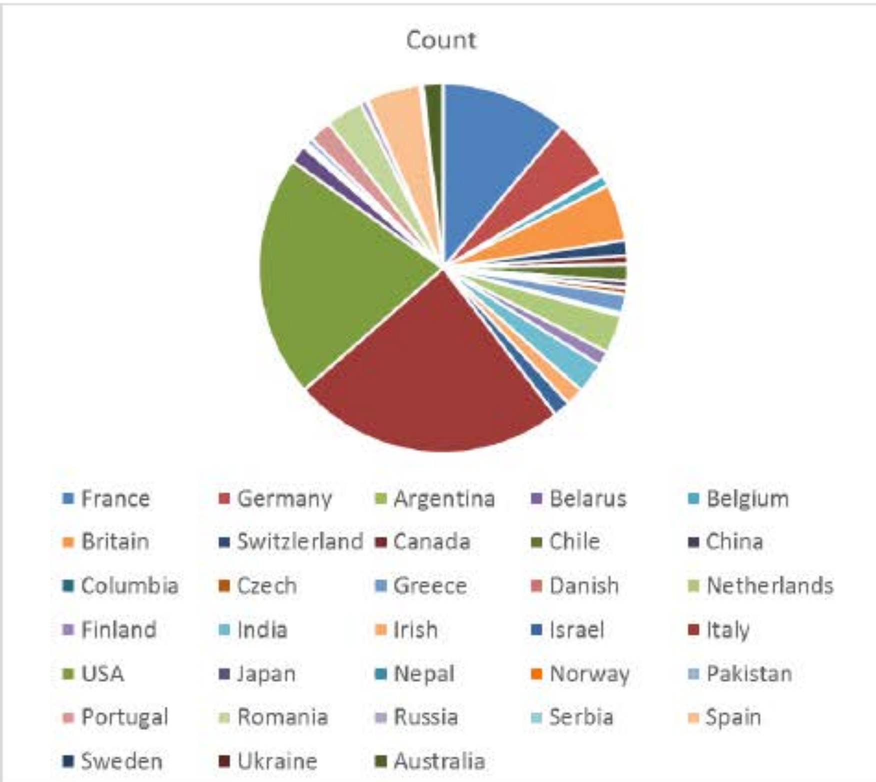
Working toward the ideal scenario: Athena and LISA up together





Athena

A large international scientific consortium



864 members
415 «full» members (with FTE + deliverable assignments)
175 FTE