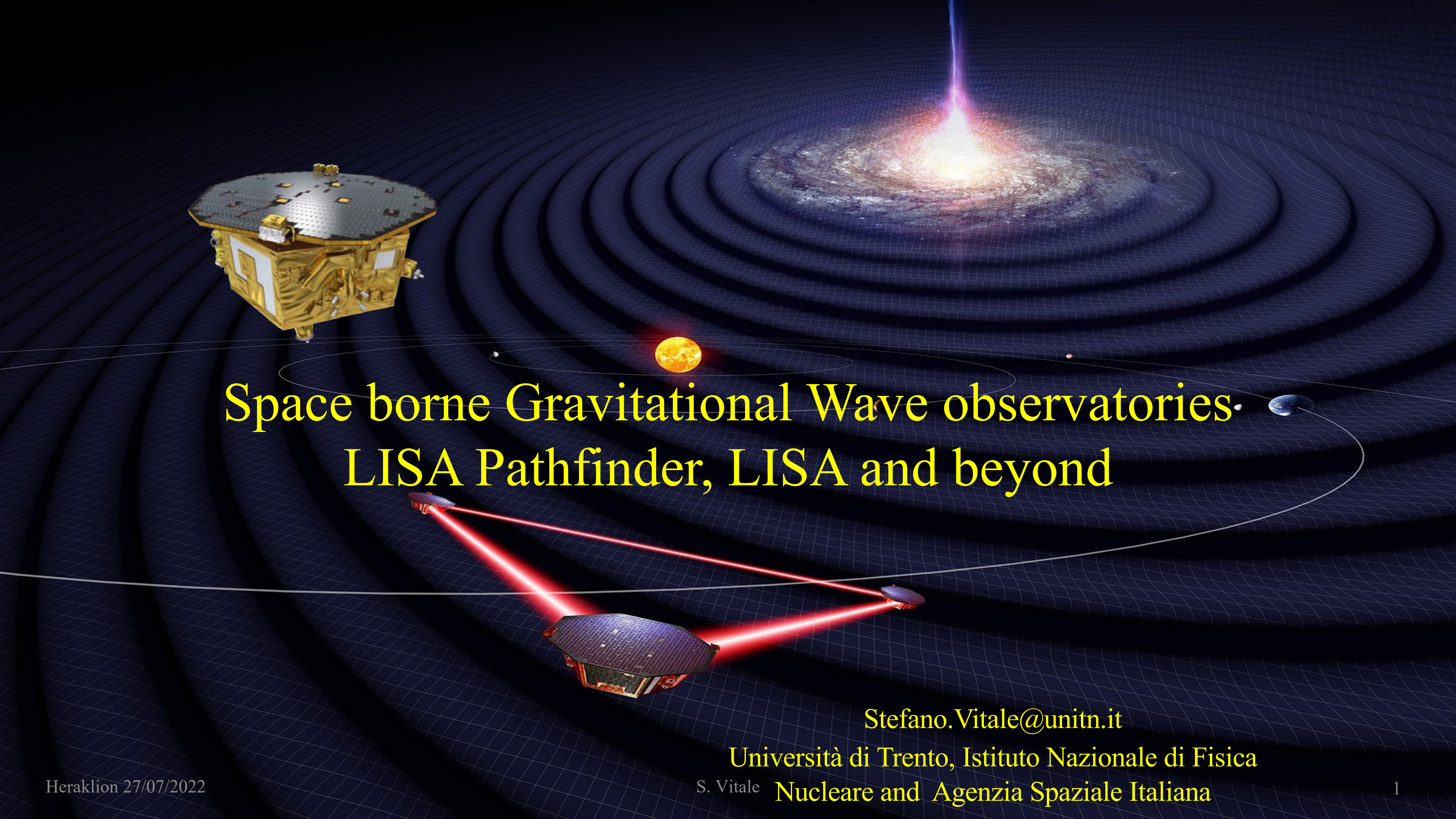
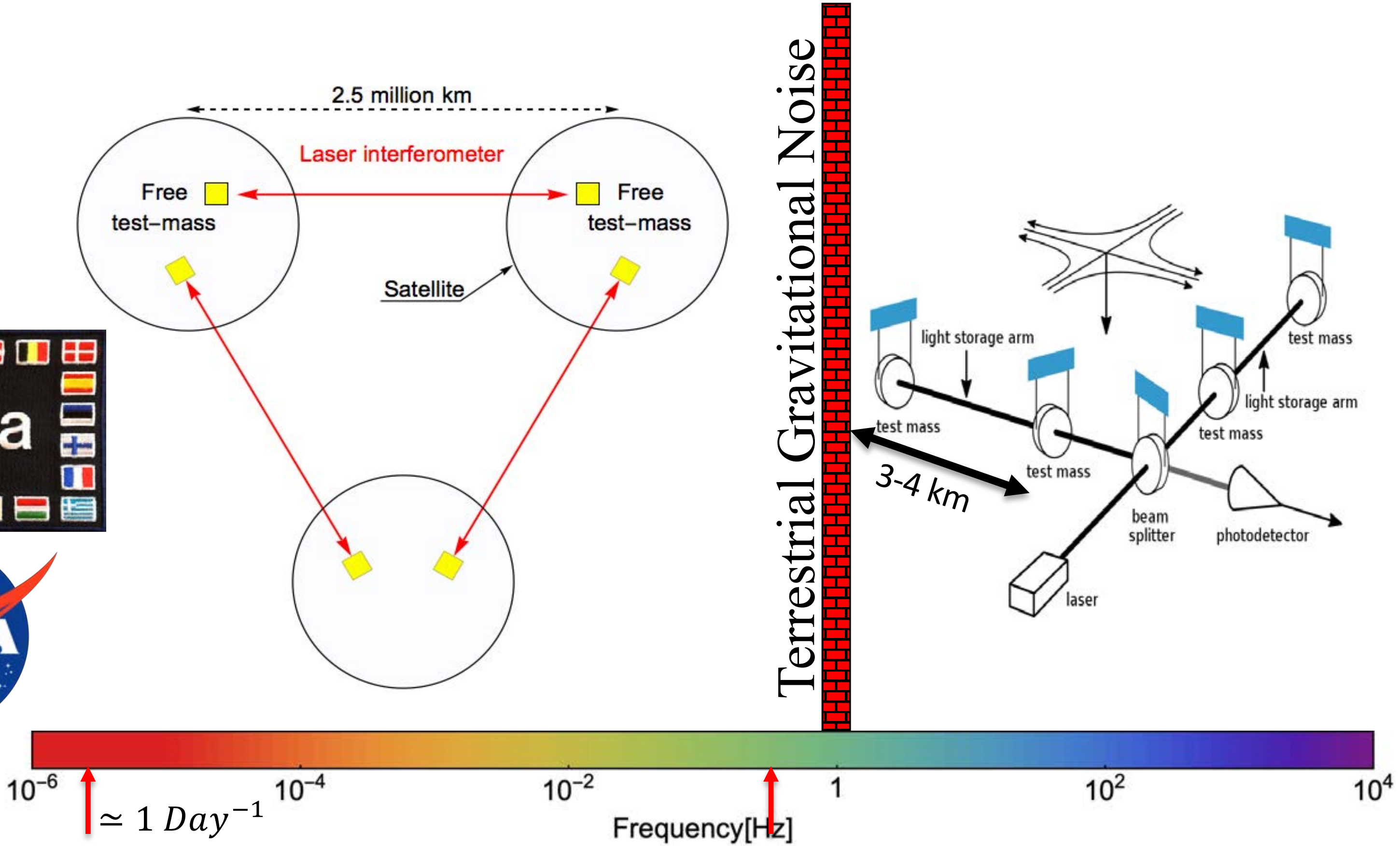


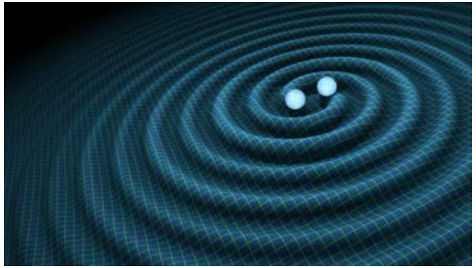
Space borne Gravitational Wave observatories
LISA Pathfinder, LISA and beyond

Stefano.Vitale@unitn.it
Università di Trento, Istituto Nazionale di Fisica Nucleare and Agenzia Spaziale Italiana

LISA: the quest for low-frequency GW



Low frequency GW astronomy



- Binaries are nearly Keplerian, frequency of wave twice frequency of revolution

$$f_{GW} = \frac{1}{\pi}\sqrt{\frac{\mathcal{G}(M_1+M_2)}{r^3}}$$

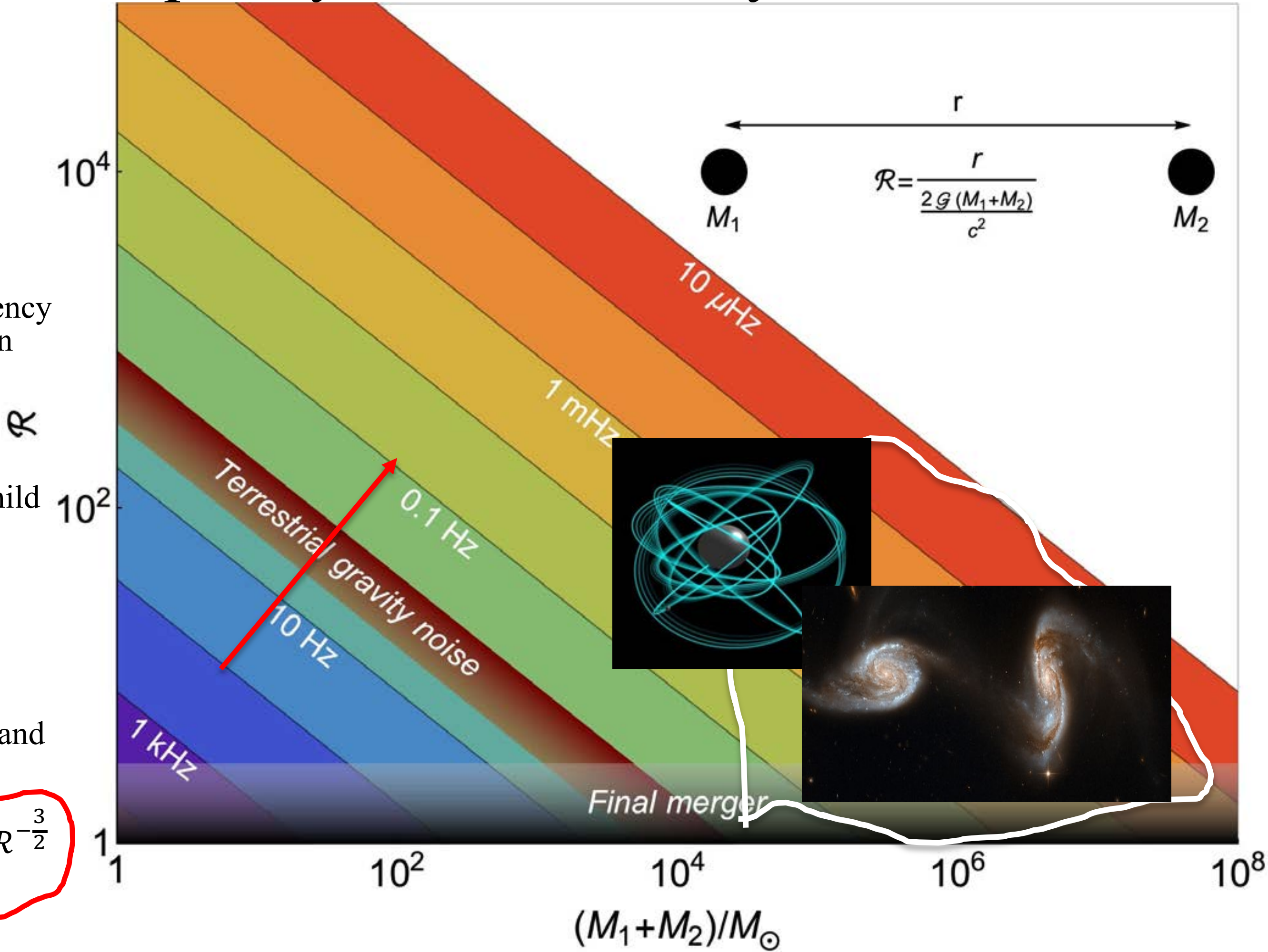
- Separation normalized to Schwarzschild radii:

$$\mathcal{R} = \frac{r}{\left(\frac{2\mathcal{G}(M_1+M_2)}{c^2}\right)}$$

($\mathcal{R} \to 1 \simeq$ final merger)

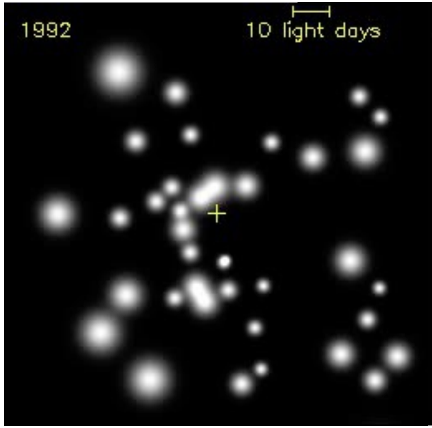
- Frequency decreases with both mass and $\mathcal{R}$

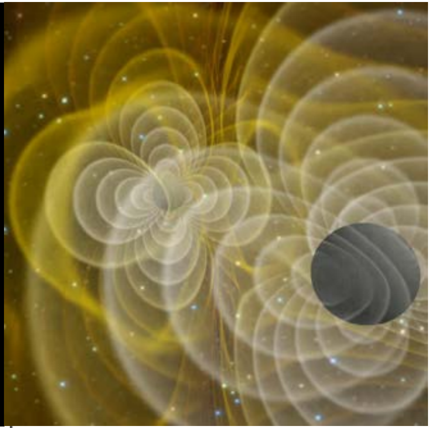
$$f_{GW} = \frac{c}{\pi\sqrt{2}\,R_{\odot}} \left(\frac{M_1+M_2}{M_{\odot}}\right)^{-1} \mathcal{R}^{-\frac{3}{2}}$$

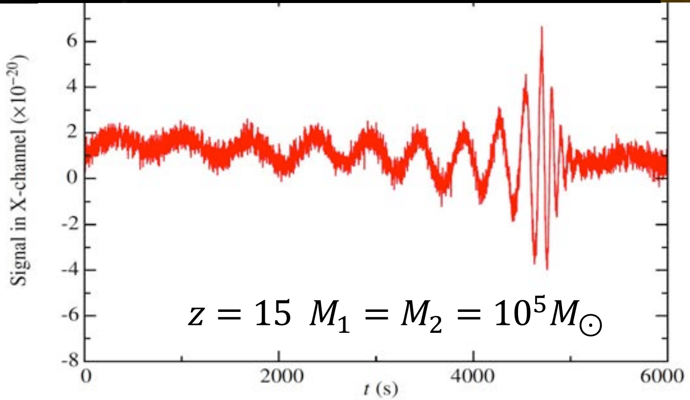


Supermassive BH mergers: the brightest sources

- Wave amplitude scales with $M_1 \times M_2$: detectable “everywhere” in the universe

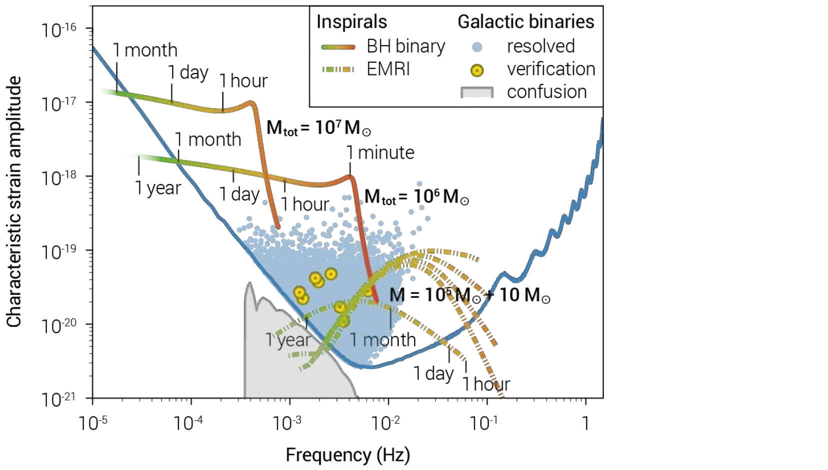


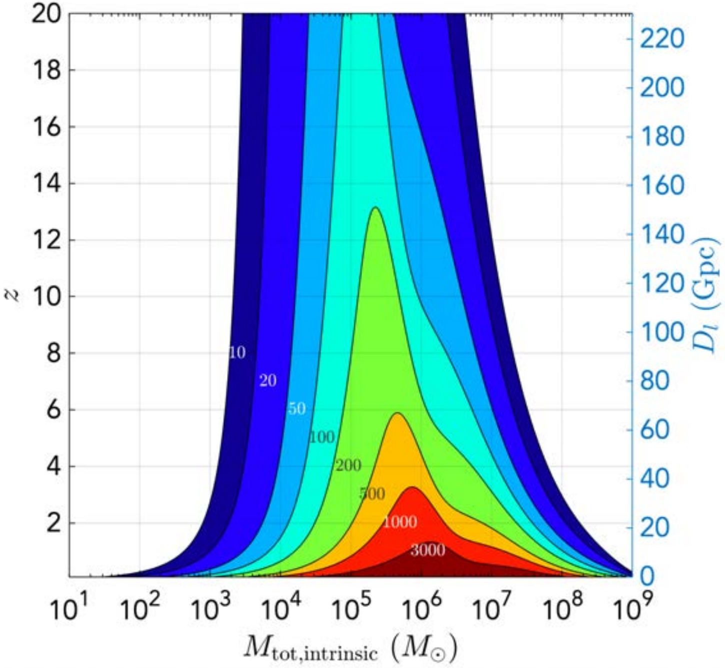


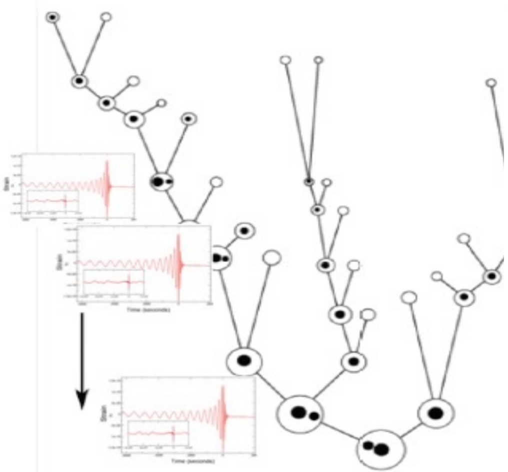


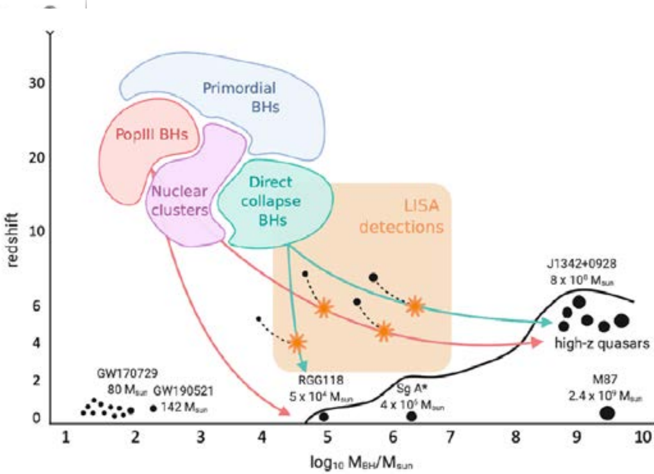
Supermassive BH mergers: the brightest sources

- Detectable “everywhere” in the universe
- Sooner or later frequency crosses LISA band : cosmological stratigraphy



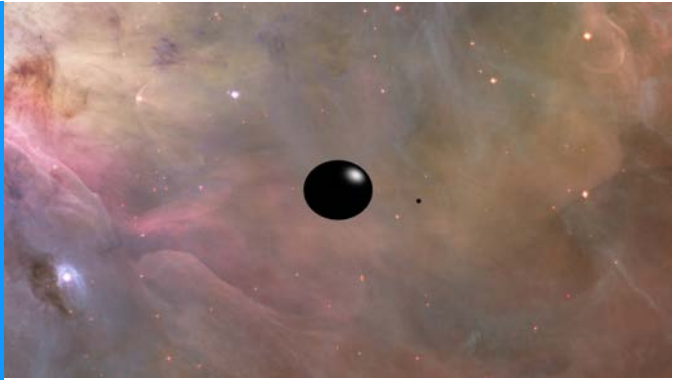


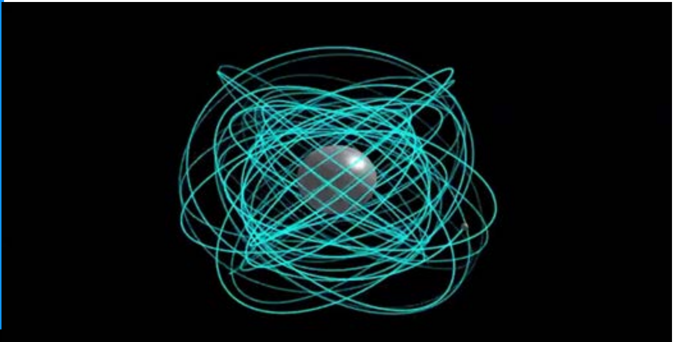


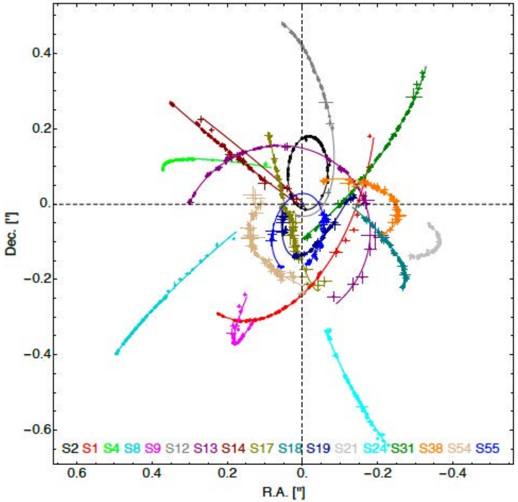


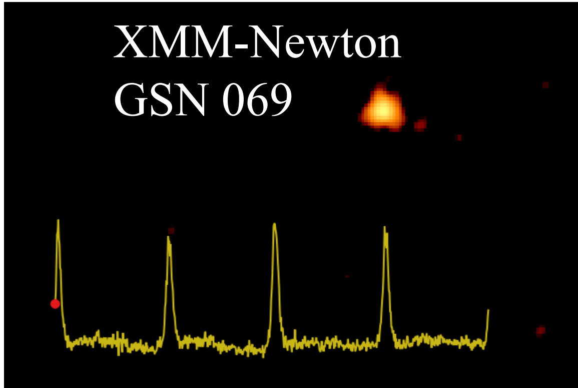
Extreme Mass Ratio Inspirals

- Inspiral of stellar-mass compact object (CO) into massive black hole (MBH): Hils & Bender 95
  - MBH mass $10^4 < M/M_\odot < 10^7$
  - Up to 10^4-10^5 cycles in band
  - If CO is a white dwarf, possible electromagnetic counterpart (Zalamea+10)
- Gravitational waves encode precise information on CO and MBH:
  - $M_{BH}(1+z)$, a_{BH} measurable to extreme precision
  - Detectable to z~few; sky localization ~1-10 deg^2 (Babak+17)
- Precise mapping of MBH spacetime
  - MBH multipole measurement -> test of no-hair theorem (Ryan 95)



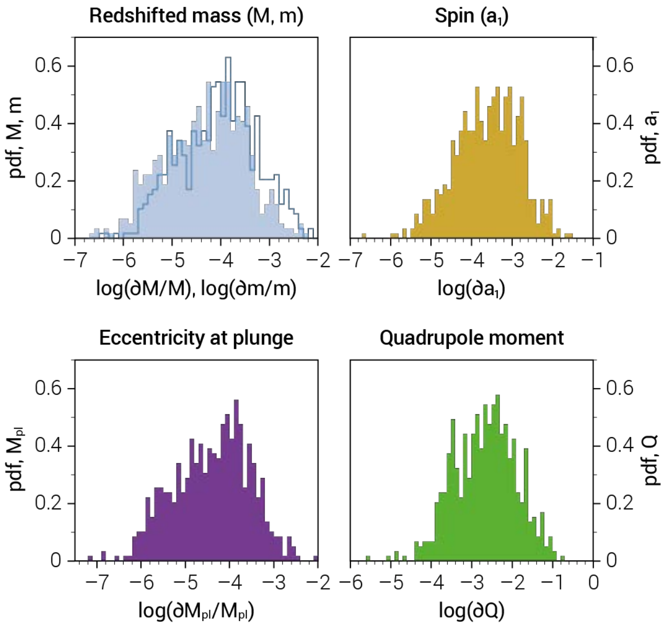






EMRIs as a GRG lab

- The no-hair theorem: spacetime around BH determined by mass and spin
- No deformability
- 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…

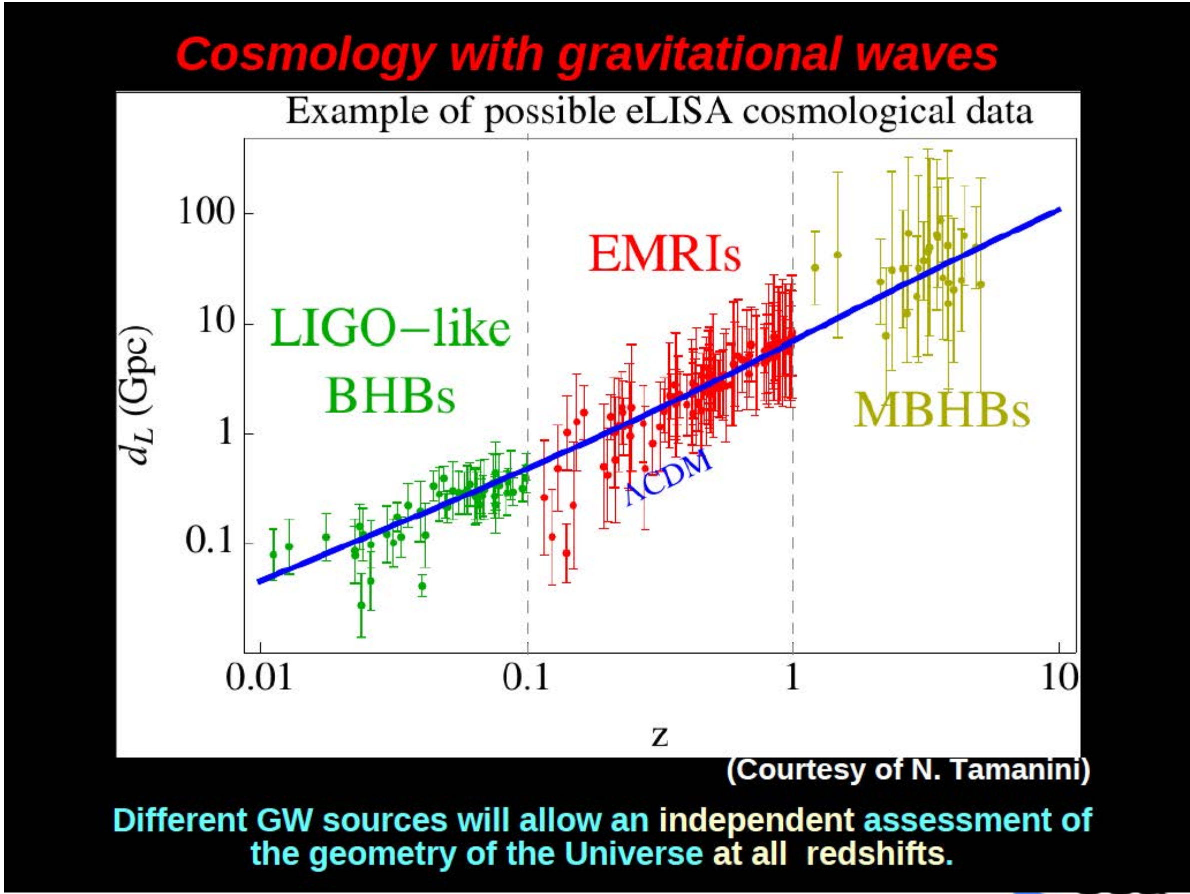


Cosmography with GW

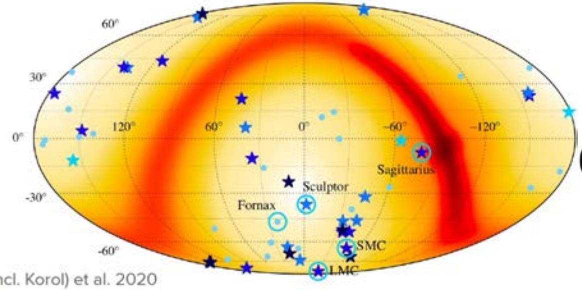
- GW from chirping binary systems are standard sirens: *absolute* luminosity distances D_L from period P and amplitude h:

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

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

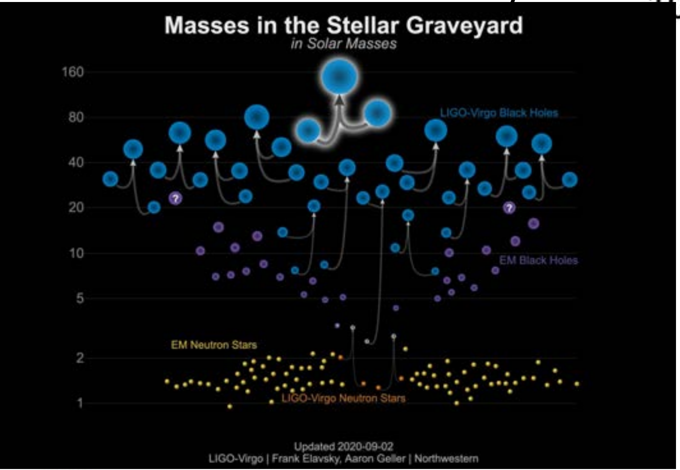


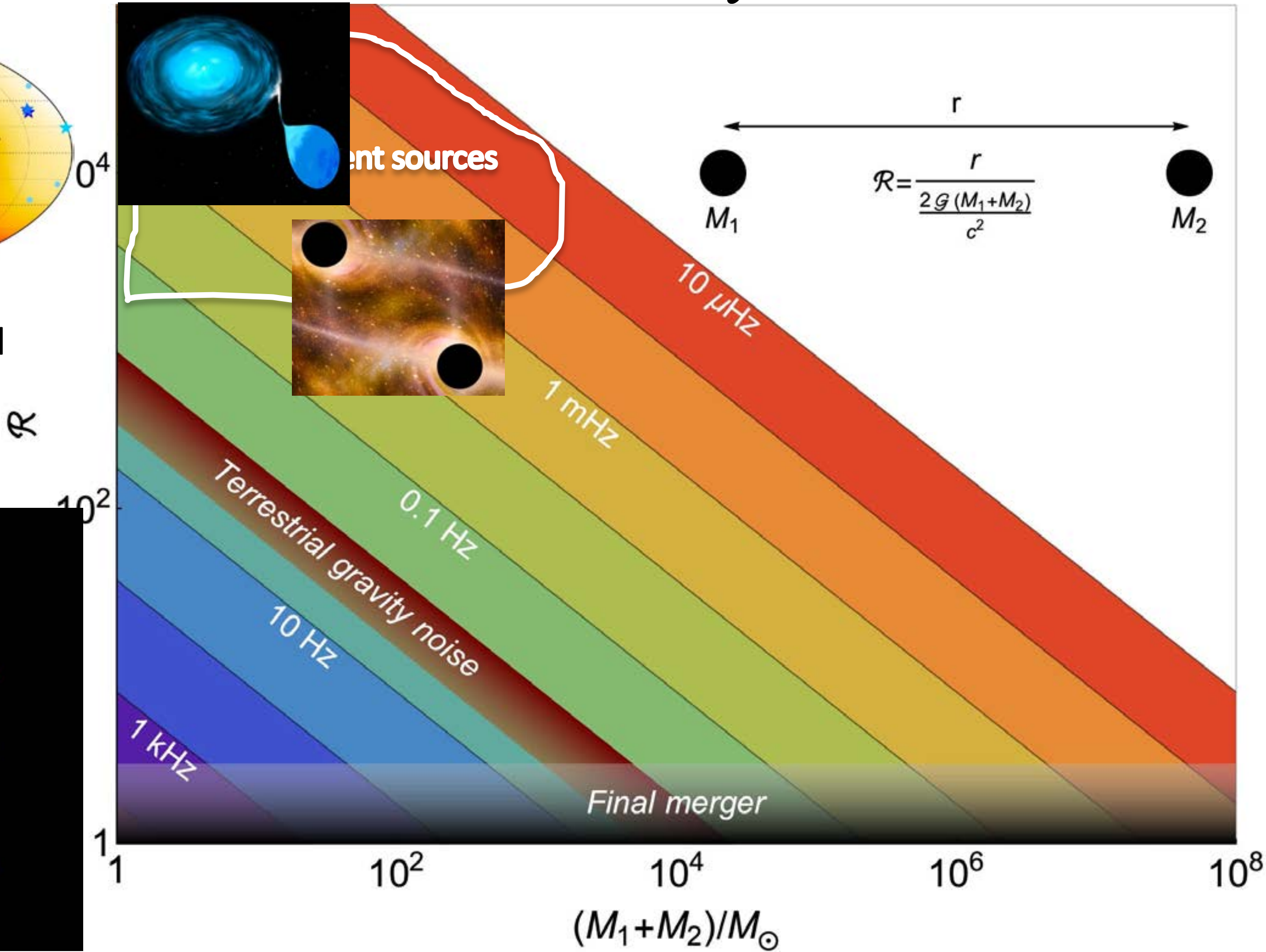
Non-transient GW astronomy



Roebber (incl. Korol) et al. 2020

- GW-binary astronomy of local group
- BH multi-band astronomy

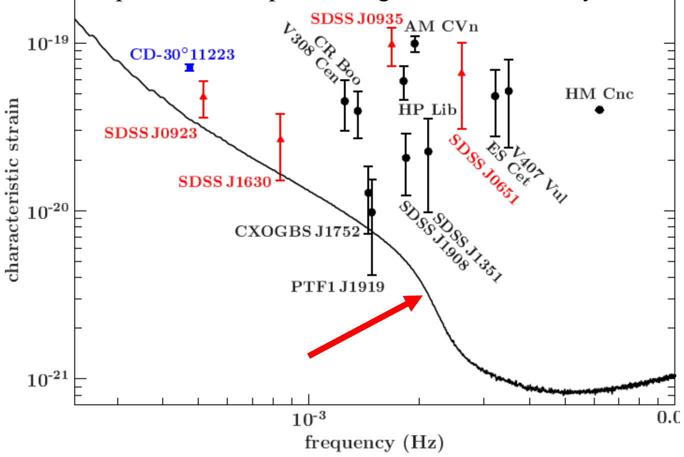


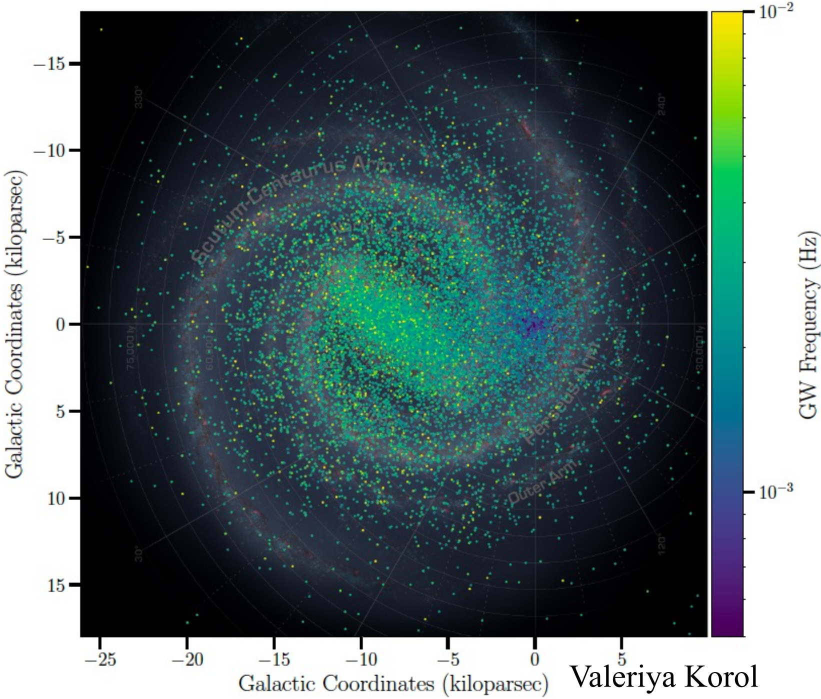


The high $\mathcal{R}$ end: the GW Milky Way

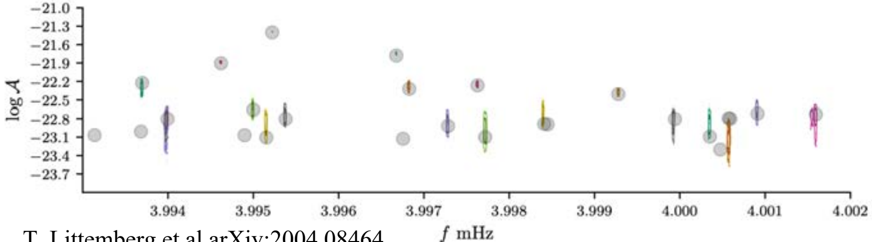
- Tens of thousand of discernible sources
- Plus a stochastic foreground

Kupfer T, et alhttps://doi.org/10.1093/mnras/sty1545





Valeriya Korol



T. Littemberg et al arXiv:2004.08464

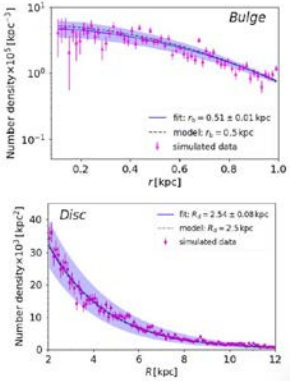
Expectations

The shape of the Milky Way's components

The spatial distribution of DWDs with measured distances (several thousand) constrains:

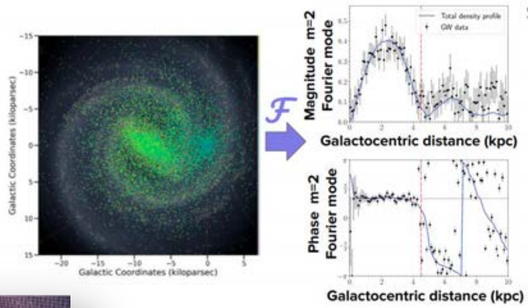
- Bulge scale radius to 2%
- Disc scale radius to 3%
- Disc scale height to 16%

Korol et al 2019
See also Adams et al. 2012



Structural parameters of the central bar

Fourier transformation of the DWD spatial distribution can reveals shape of the bar.



Specifically, It will constrain:

- axis ratio to 10%
- length to < 1%
- orientation angle to < 1°

(Wilhelm, Korol et al. 2020)

The detection of circumbinary exoplanets

Camilla DANIELSKI

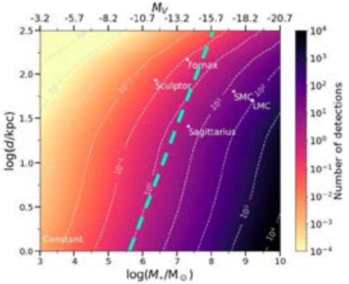
LISA XIII - Sep 3 2020

Valeriya Korol

Discovering Milky Way satellites in gravitational waves

- Satellites with stellar mass > 10^6 $M_\odot$ host detectable LISA sources
- LISA detections can inform us about the total stellar mass and star formation history of the satellites
- Discovery of satellites invisible to electromagnetic observatories

See talk by Riccardo Buscicchio

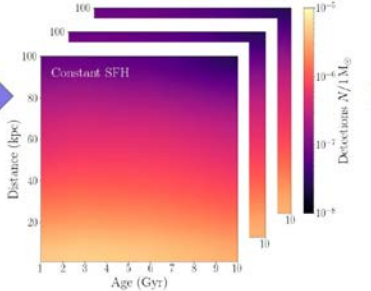


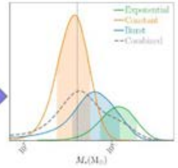
Korol et al. 2020; Roebber et al. (incl.Korol) 2020
See also Lamberts et al. 2019

Weighing Milky Way satellites

By exploiting our models we can recover the satellite's total stellar mass: to within a factor two if SFH is known and to an order of magnitude when marginalising over different SFH models. If no detections are identified with the satellite we can still place an upper limit on its stellar mass.

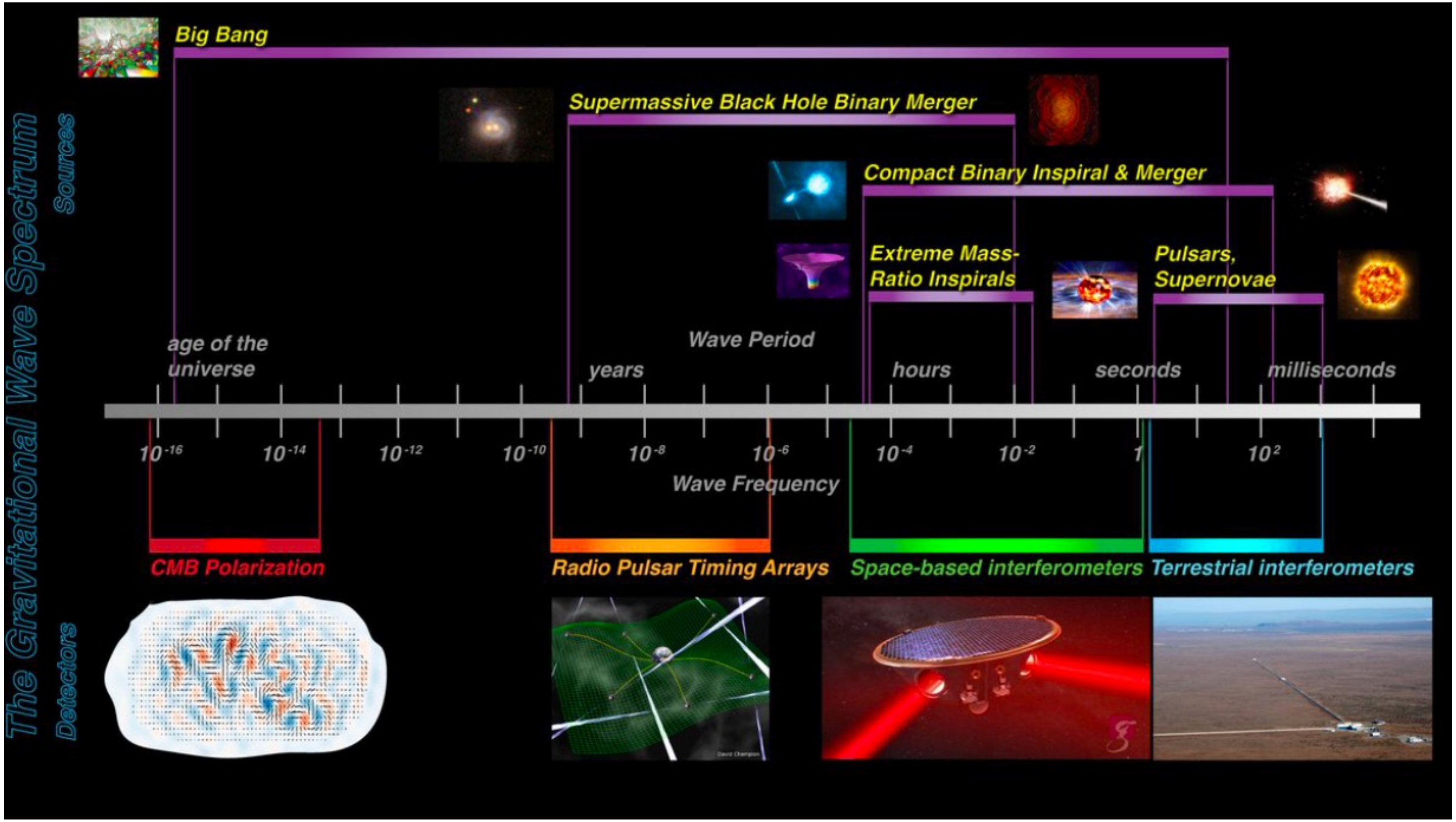
Number of detections $N \pm \sqrt{N}$
Distance $D \pm \Delta D$





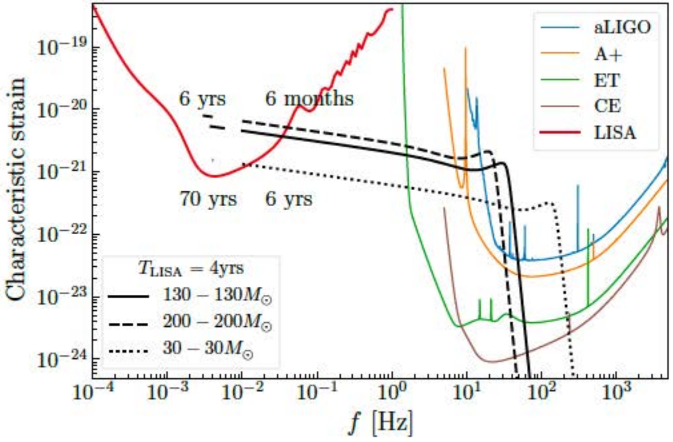
Korol et al. in prep.

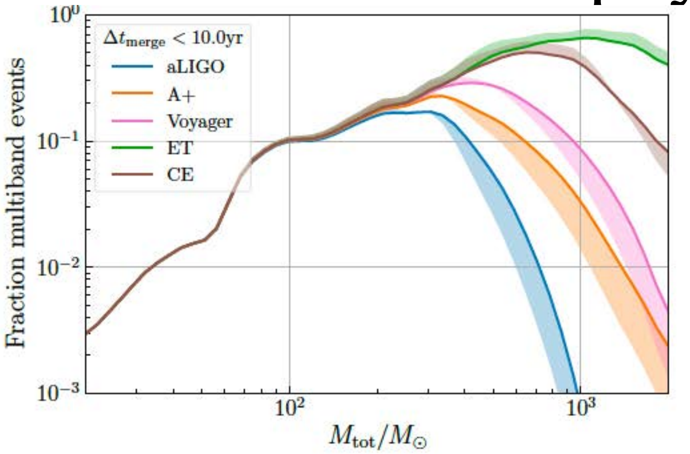
Multi-band GW astronomy



(credit: K. Jani)

Multi-band GW astronomy and fundamental physics





Joint observation greatly improves measurement of deviation from GR

S. Datta et al arXiv:2006.12137v1 [gr-qc] 22 Jun 2020

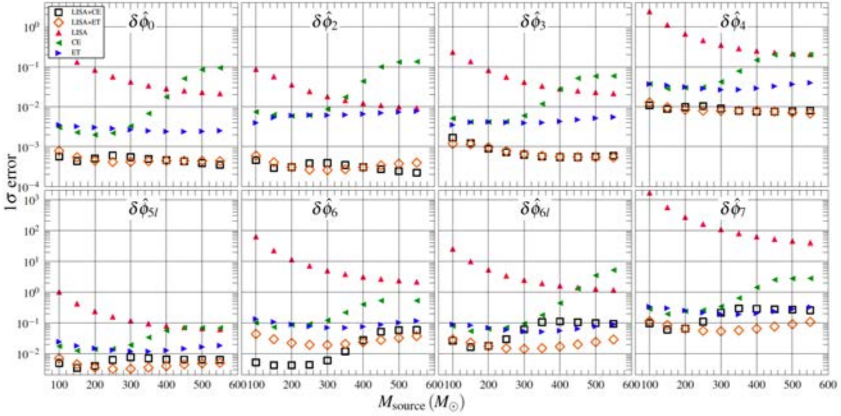
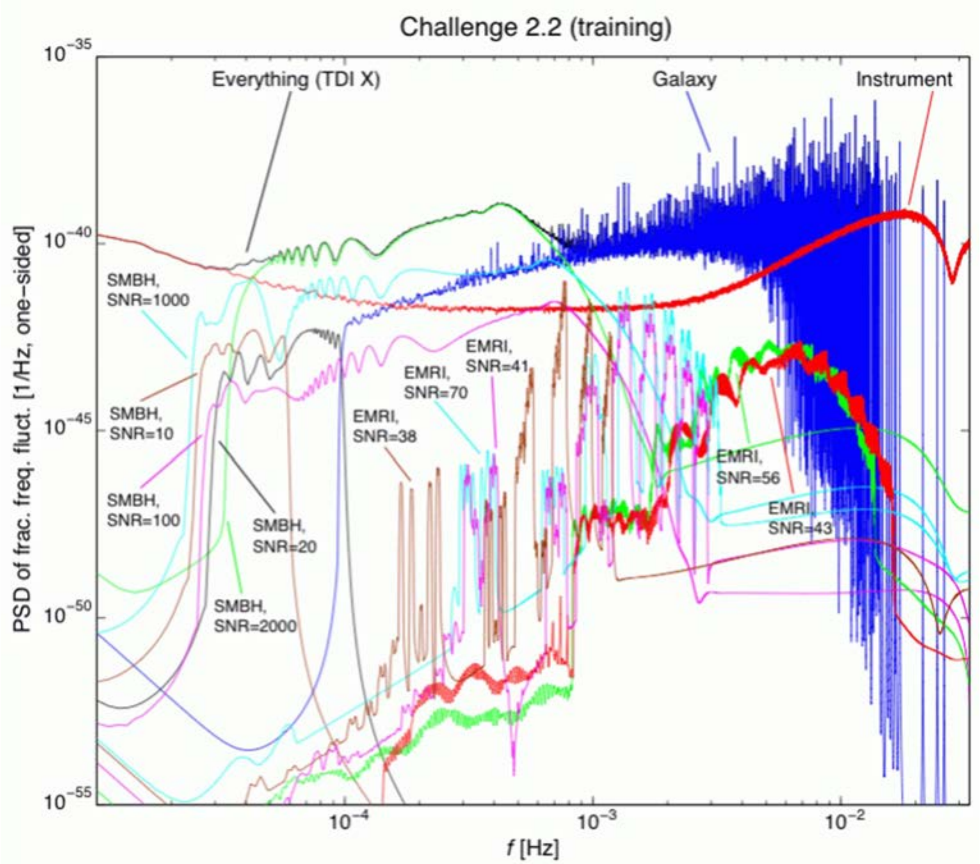
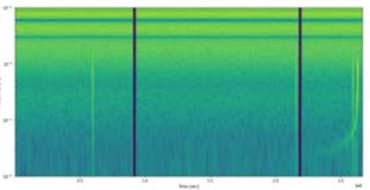


FIG. 3. Top panel shows bounds on deformation parameters at 0PN to 2PN, as a function of total mass in source frame. Bottom panel shows the same but for deformation parameters at 2.5PN to 3.5PN. All the systems have mass-ratio $q = 2$, dimensionless component spins $\chi_1 = 0.2$ and $\chi_2 = 0.1$, and luminosity distance $D_L = 1$ Gpc.

lisa pathfinder

Data analysis a formidable challenge





LDC Challenges Meetings Contact Admin Login Sign up

LISA Data Challenge 2b: *Spritz*

Log in to download »

LDC-2 documentation »

Log in to get LDC-2 code »

Ask for help »

We are glad to announce the release of several datasets in the second LISA Data Challenge, codenamed **Spritz**.

The purpose of this challenge is to address for the first time the realistic instrumental and environmental noise. The datasets are rather easy in the astrophysical content, moreover, the training data contain the sources that were used in the Sangria training dataset. If you are new to the Challenges, we strongly advise that you first complete the first data challenge **Radler** before moving to **Spritz**, specifically, challenges containing the merger of massive black hole binaries (MBHBs) and verification Galactic binaries.

The training **Spritz** data contain three sets. All three datasets were generated with the … pipeline used in the **Sangria** production. All GW sources follow conventions described in the … **documentation** and the same models (PhenomD for MBHB and Taylor-expanded … we have varied the noise level (assuming the same acceleration and optical met… spacecraft) within the same prior as in Sangria. Noise levels are given in the …

Features common to all datasets.

For the first time, we have used second-generation Michelson TDI … combinations, expressed as fractional frequency deviations, do… 5-second cadence. We have used a Keplerian model for the … data contain scheduled gaps of 7 hours duration each, dist… with intervals between 10 and 15 days. We have include… noise from the unresolved population of Galactic binar… with SNR<7 with respect to the total noise budget). … included laser frequency noise, which is strongly … levels in the TDI combinations. In addition to th… datasets also contain partial versions of the … retrieve the total signal: with and without … (including gaps, glitches and non-statio… as input to the simulator are given, t…

MBHBs in Spritz data.

We have two datasets with merging MBHBs. (i) Dataset with a loud (SNR ~2000) GW signal, lasting for about 31 days. The signal is expected to be detectable a few weeks before the merger and, therefore, is suitable for testing low-latency algorithms. We have added three short loud glitches distributed in the inspiral, late inspiral and near merger parts of the signal. (ii) Dataset with a quiet (SNR ~100) GW signal lasting for one week, with a several-hour-long glitch placed near the merger. Parameters of both MBHBs are available in the training data, as well as the information about glitches The glitches injected in the two MBHB datasets correspond to events detected and fitted during the LISA Pathfinder operations (*Phys. Rev. Lett.* 120, 061101).

Verification GBs in Spritz.

A 1-year long dataset contains 36 verification binaries, with parameters available in the same data file. We have placed glitches according to a Poisson distribution with a rate of 4 glitches per day, whose model is described in the Spritz documentation.

The LDC working-gro… conduct their own analysis using algorithms of their choice, … you to join them (to do so, e-mail us so we can pair you appropriately, … course, you may organize to work on your own, or with your collaborators. For usage tracking purposes, we request that you set up a login for this website before downloading the datasets (your LDC-1 login will work fine). Please **submit your results by October 1st, 2022**, using the submission interface and format to be found on this website. Plan to include a description of your methods (or a link to a methods paper) with your submission. We would also greatly appreciate it if you were to share your code (e.g., on GitHub, or on our GitLab). To simplify a bit your life we have made several tutorials which, we hope, you will find useful: Tutorial notebooks link, LISANode simulation model.

While we did our best to check the datasets for correctness, small problems or inconsistencies may have escaped us. The best way to validate the data is to analyze it, so let us know of any problems!

Spectrogram of the 1st MBHB dataset, with a loud signal at day 30, 3 glitches at the beginning, middle and end of the time series, and 2 gaps seen as deep blue chunks.

https://lisa-ldc.lal.in2p3.fr

agenzia spaziale italiana

Interesting reading

lisa pathfinder

Astrophysics with LISA

Contents

arXiv:2204.05434v1 [astro-ph.CO] 11 Apr 2022

Cosmology with LISA

Contents

*Section coordinator. More details at the beginning of each section.
†Document coordinator.

arXiv:2203.06016v1 [gr-qc] 11 Mar 2022

Fundamental Physics with LISA

CONTENTS

arXiv:2205.01597v1 [gr-qc] 3 May 2022

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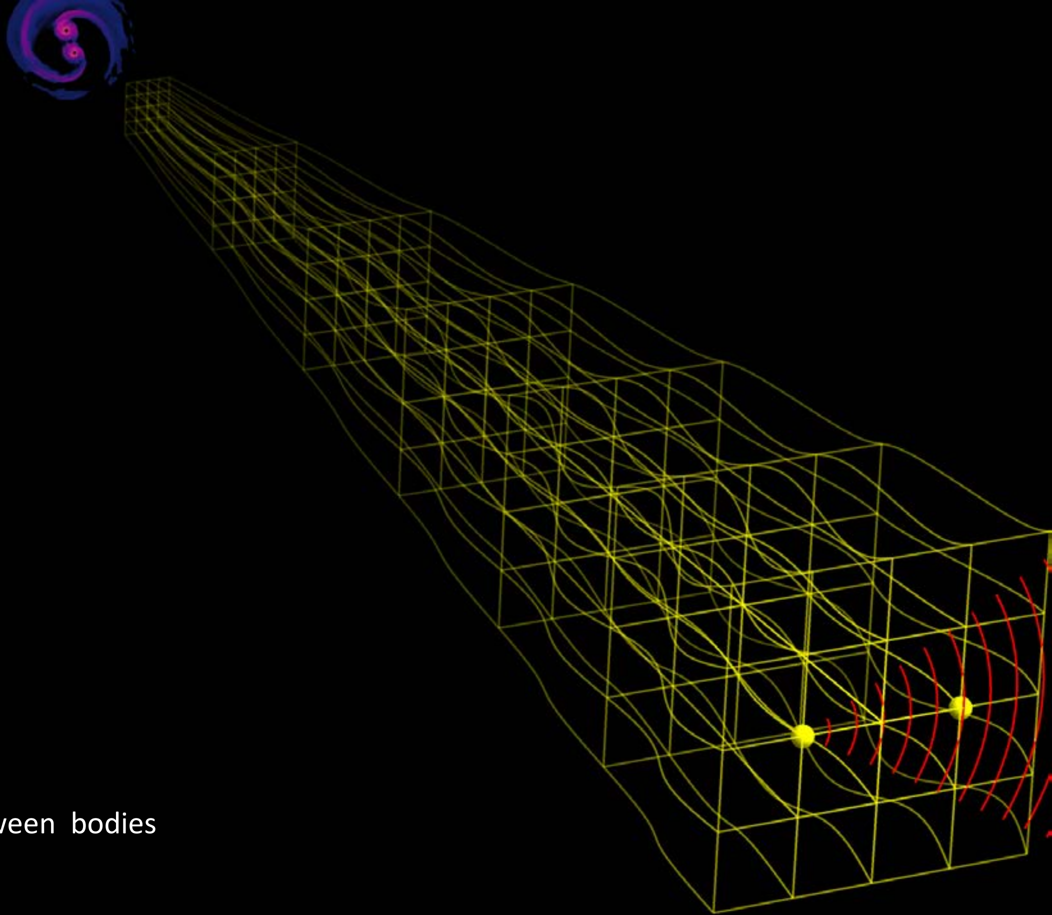
esa

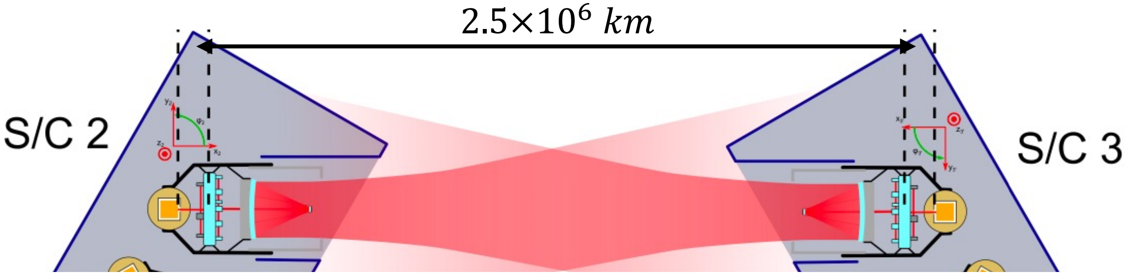
Detecting gravitational wave in space

- Waves of space-time curvature that propagate at speed of light
- Doppler tracking of free orbiting bodies modulated at period of gravitational wave

$$\frac{\Delta\dot{\nu}}{\nu_o} \simeq c\underbrace{R^{x}{}_{0x0}}_{\text{Curvature tensor}}\underbrace{L}_{\text{Separation between bodies}}$$

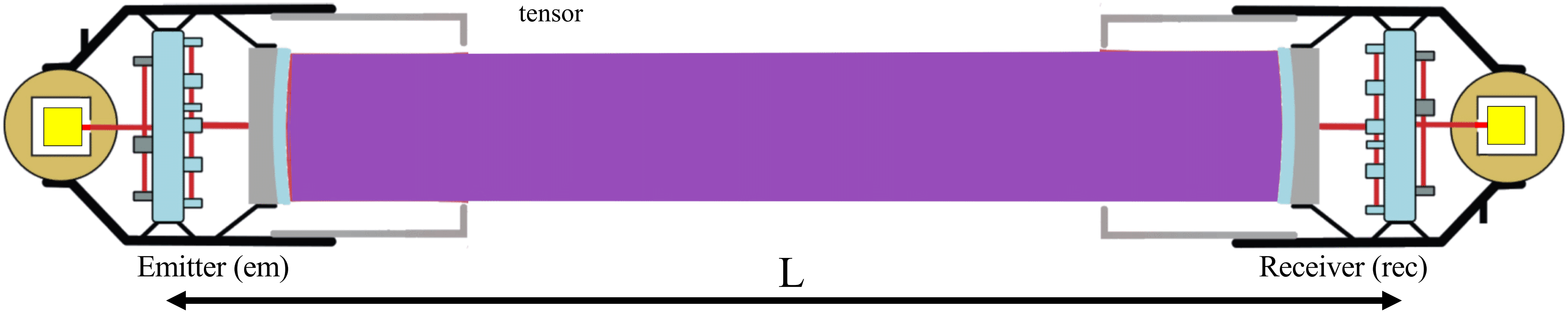


LISA



The LISA link

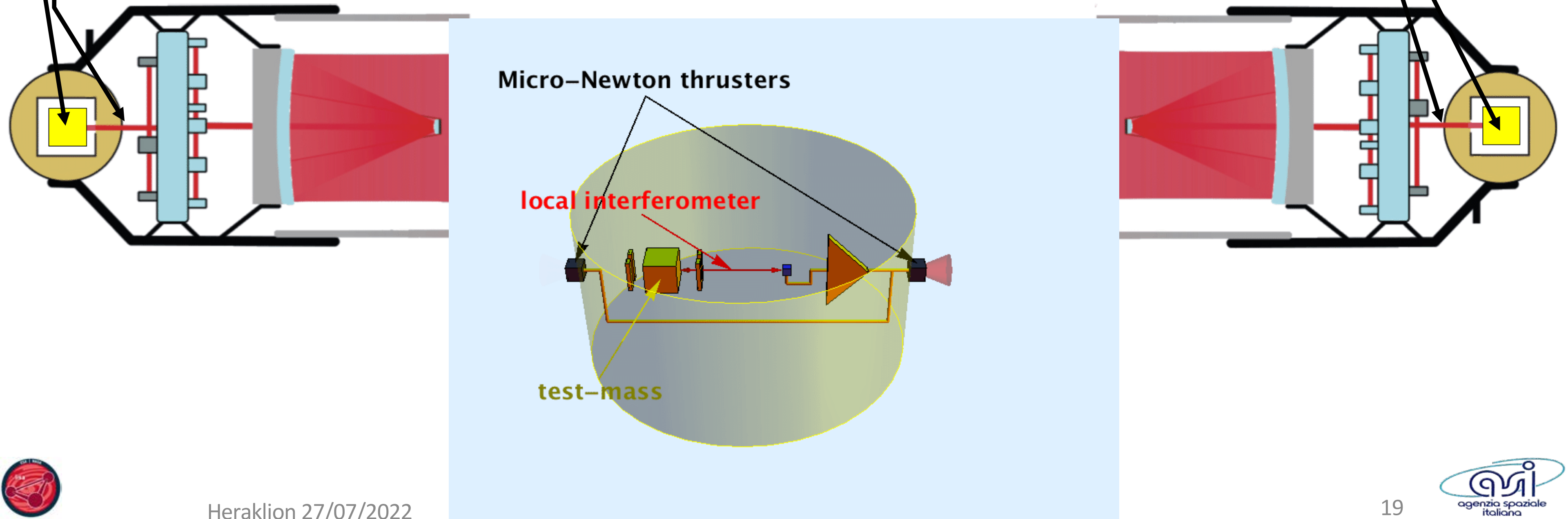
- Propagating throughout GW curvature, beam accumulates a time modulated frequency shift $\frac{\Delta\dot{\nu}}{\nu_o} \simeq cR^{x}{}_{0\,x\,0}L$



- Acceleration of spacecraft via standard Doppler effect also shifts frequency and mimics GW $\frac{\Delta\dot{\nu}}{\nu_o} = cR^{x}{}_{0\,x\,0}L + \frac{a_{rec}-a_{em}}{c}$
- Spacecraft (S/C) accelerate too much because of solar radiation pressure

Coping with S/C acceleration

- Free-floating test-masses (TM) are carried inside S/C
- No contact between TM and S/C, “drag-free” along the beam
- Measure S/C-to-TM acceleration and correct signal for Doppler



LISA link: combination of three independent measurements

2 × test-mass to spacecraft measurements

1 × spacecraft to spacecraft interferometer

$$\frac{\Delta\dot{\nu}_{local,1}}{\nu_o}=\frac{a_{TM1}-a_{SC1}}{c} \qquad \frac{\Delta\dot{\nu}_{local,2}}{\nu_o}=\frac{a_{TM2}-a_{SC2}}{c}$$

$$\frac{\Delta\dot{\nu}_{SC\leftrightarrow SC}}{\nu_o}=\frac{a_{SC2}-a_{SC1}}{c}+\frac{\Delta\dot{\nu}_{GW}}{\nu_o}$$

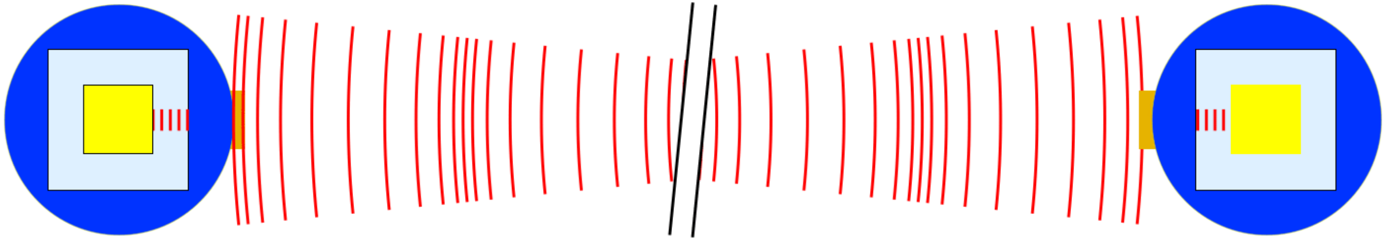
- Combining:

$$\frac{\Delta\dot{\nu}_{local,2}}{\nu_o}+\frac{\Delta\dot{\nu}_{SC\leftrightarrow SC}}{\nu_o}-\frac{\Delta\dot{\nu}_{local,1}}{\nu_o}=\frac{a_{TM2}-a_{SC2}+a_{SC2}-a_{SC1}+a_{SC1}-a_{TM1}}{c}+\Delta\dot{\nu}_{GW}=$$

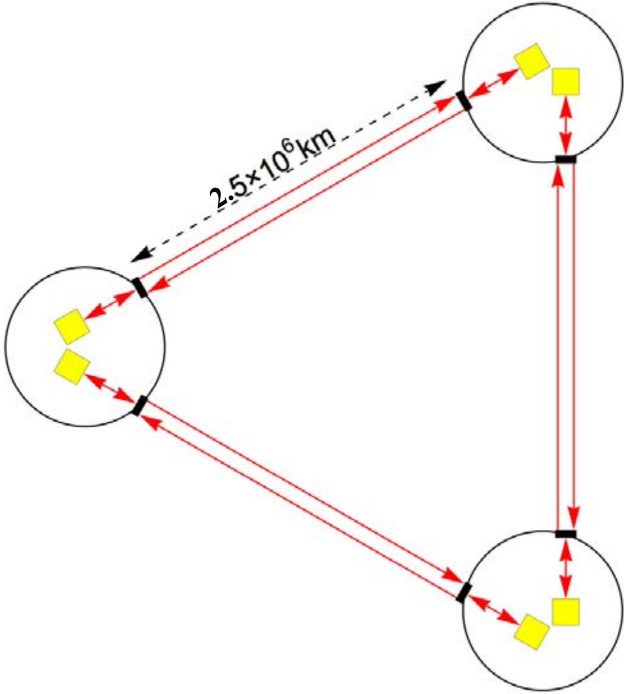
$$=\frac{a_{TM2}-a_{TM1}}{c}+\Delta\dot{\nu}_{GW}$$

Equivalent to a direct test-mass to test-mass measurement

The LISA arm

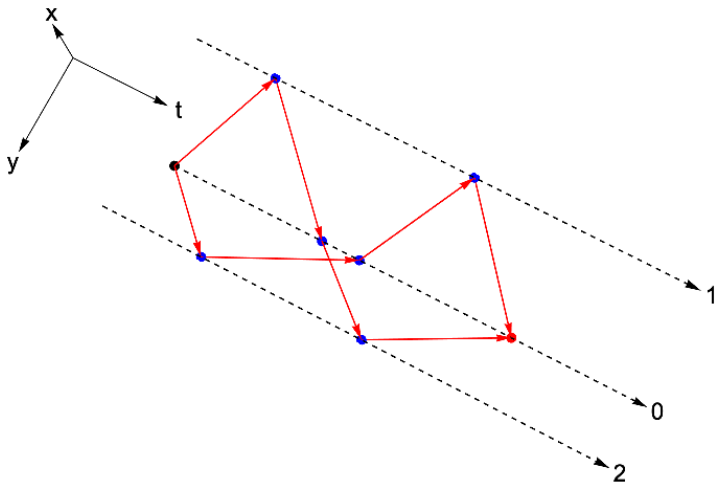


- True reflection impossible. The LISA arm: two counter-propagating links.
- LISA: 3 arms=6 links
- LISA science signals: 1 frequency signal per link, i.e. 6 single-link signals

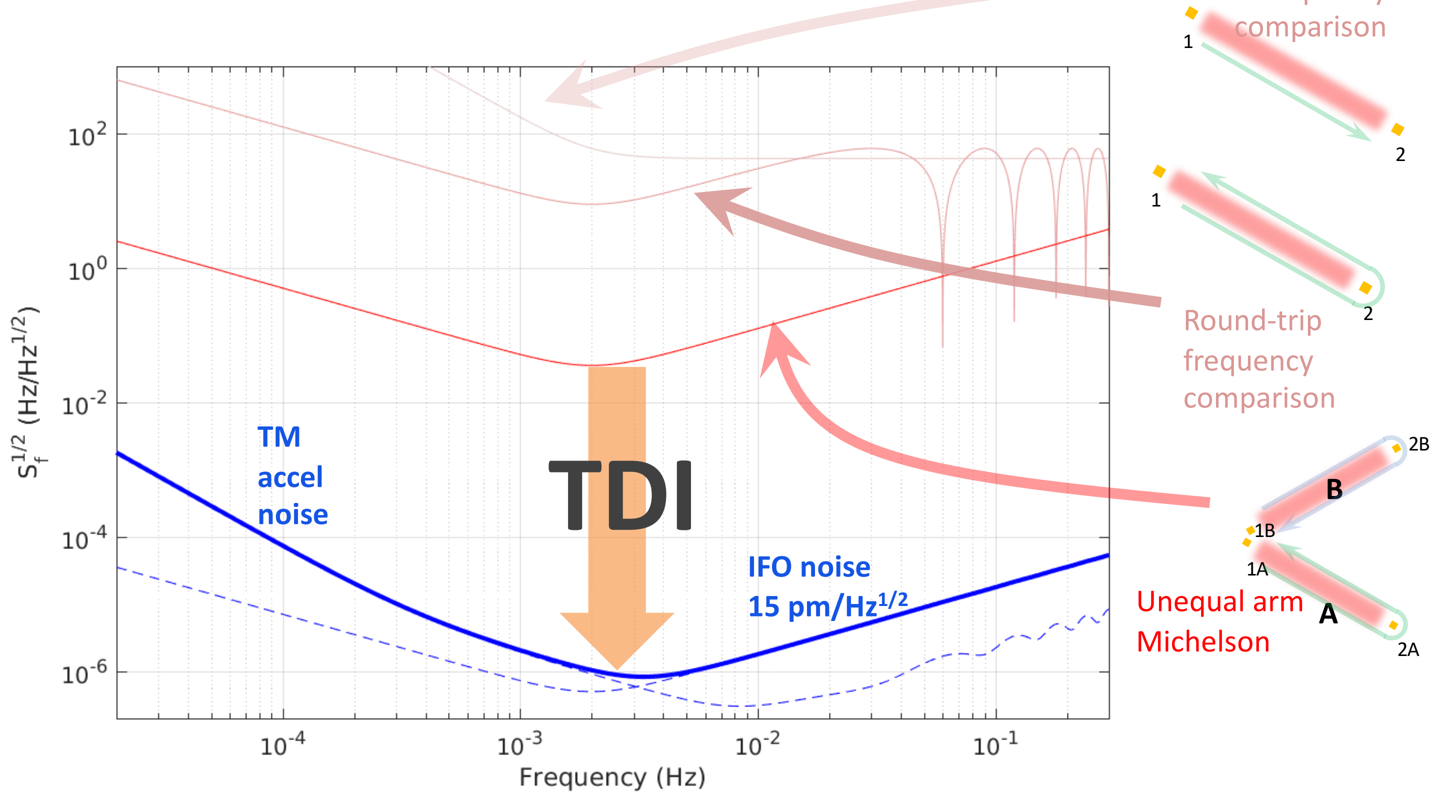


Laser frequency noise & time delay interferometry

- Best stabilized laser frequency noise off scale:
  - Required ≲ $1\ \mu Hz/\sqrt{Hz}$
  - Available ≲ $1\ kHz/\sqrt{Hz}$
- Ground based interferometers beat noise comparing beams emitted at same time (equal arms)
- LISA: arms are unequal ($\Delta L \simeq 10^5 km$) and time varying over the year.
- Combine single-link signals to mimic light beams that have traveled equal lengths

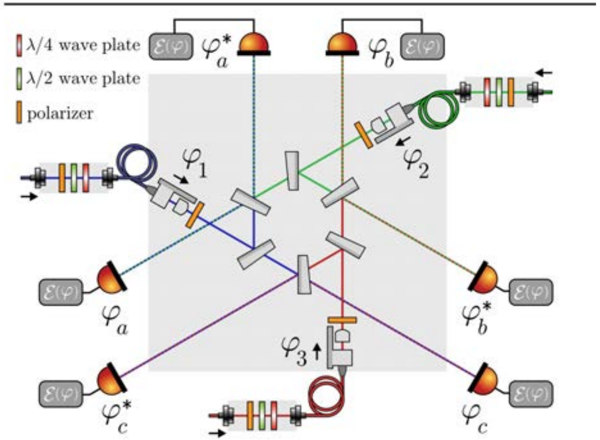


8 orders of magnitude suppression



Requires high accuracy measurement of phase

- Demonstrated in lab by many teams
- For instance



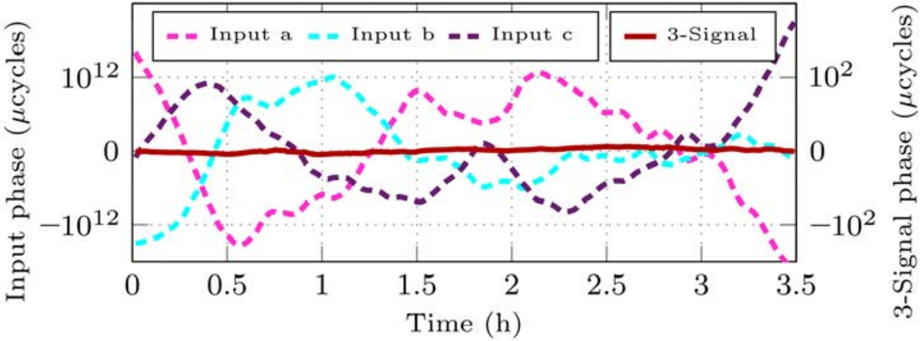


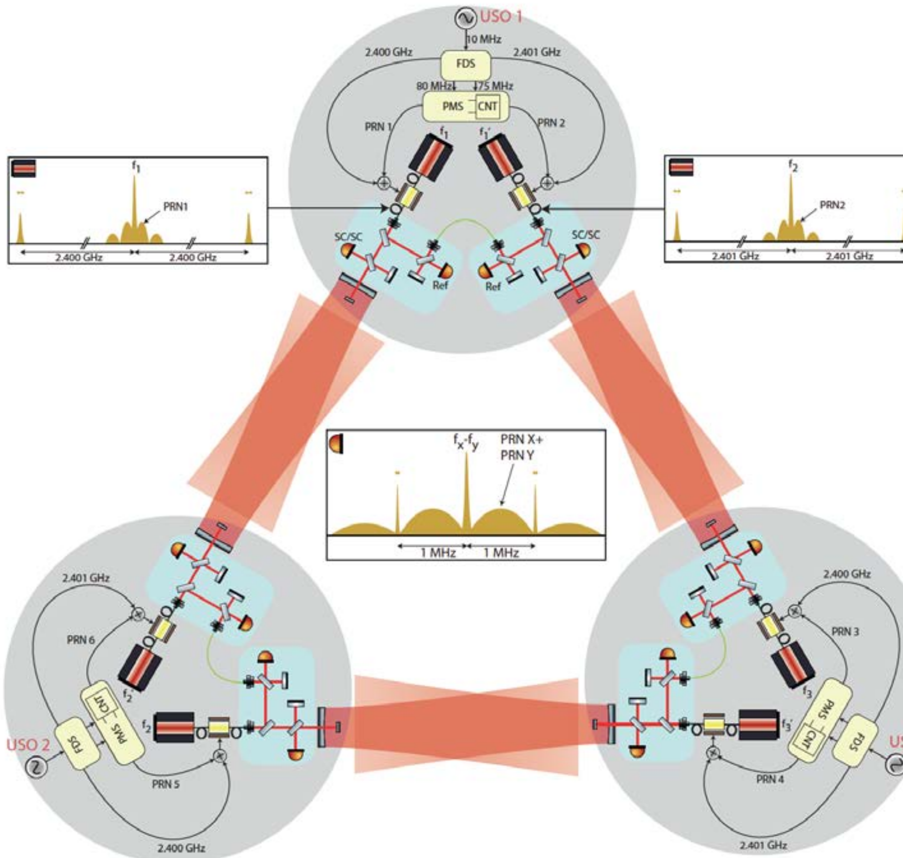
FIG. 4. Time series of input phase fluctuations and resulting three-signal combination, illustrating the high dynamic range essential for TDI.

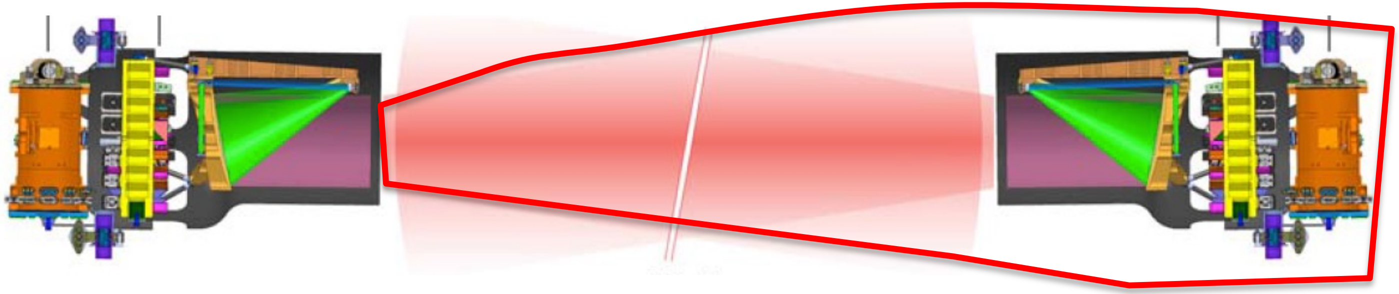
$10^8 - 10^{11}$ dynamic range

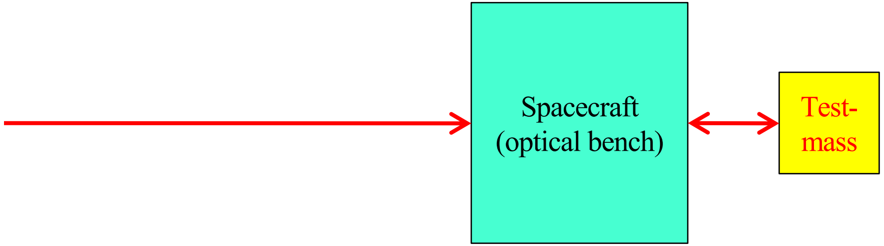
PHYSICAL REVIEW LETTERS **122,** 081104 (2019)

Time delay interferometry

- Requires knowledge of light travel time within 3 ns/1 m
- Done with "laser GPS":
  - Pseudo-random code transmitted as modulation of laser frequency
  - Received signal correlated locally with same code to find true delay
- Predicted accuracy $1 - 10\ cm$



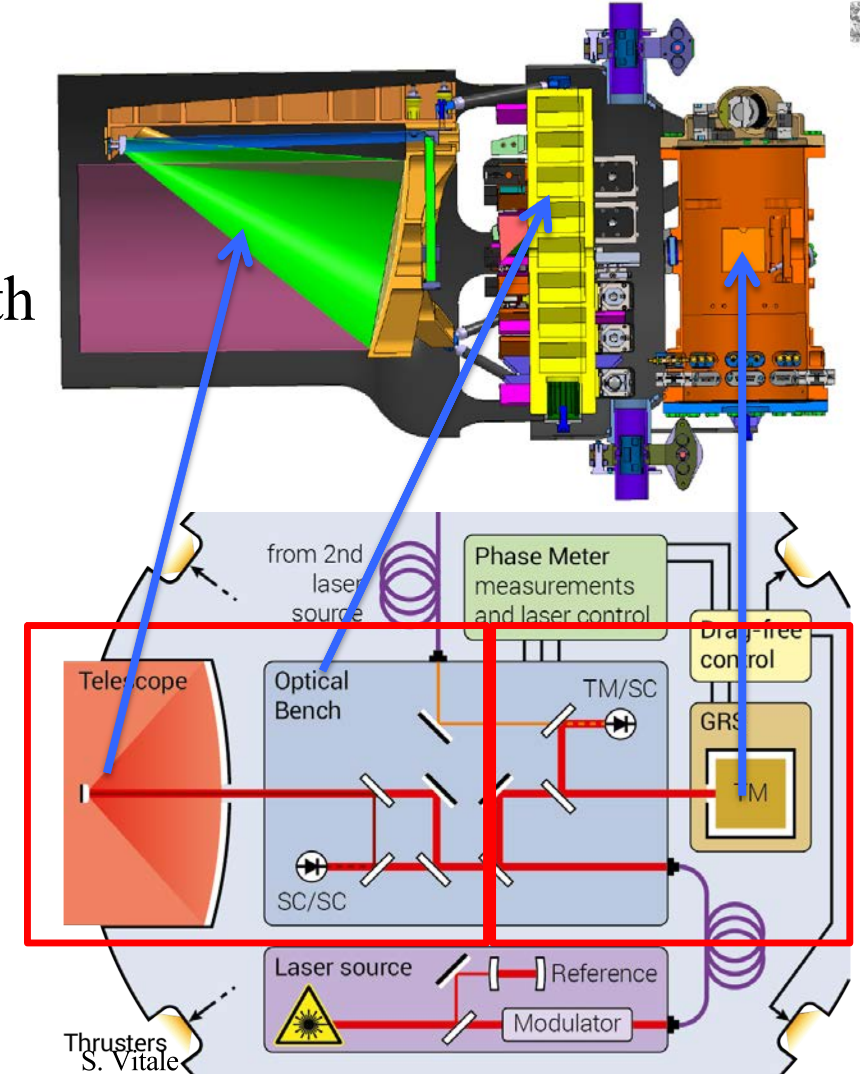




The LISA link instrument

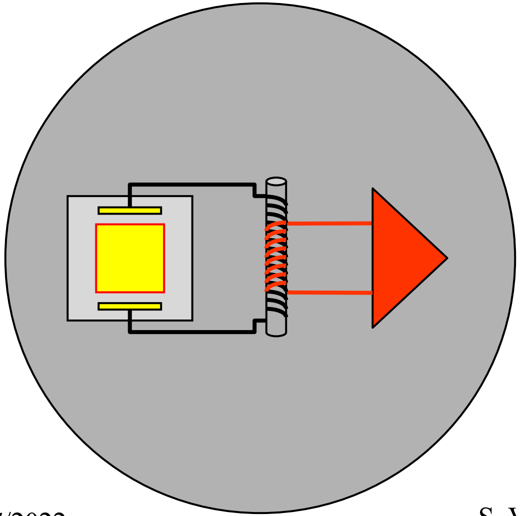
LISA link Instrument

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



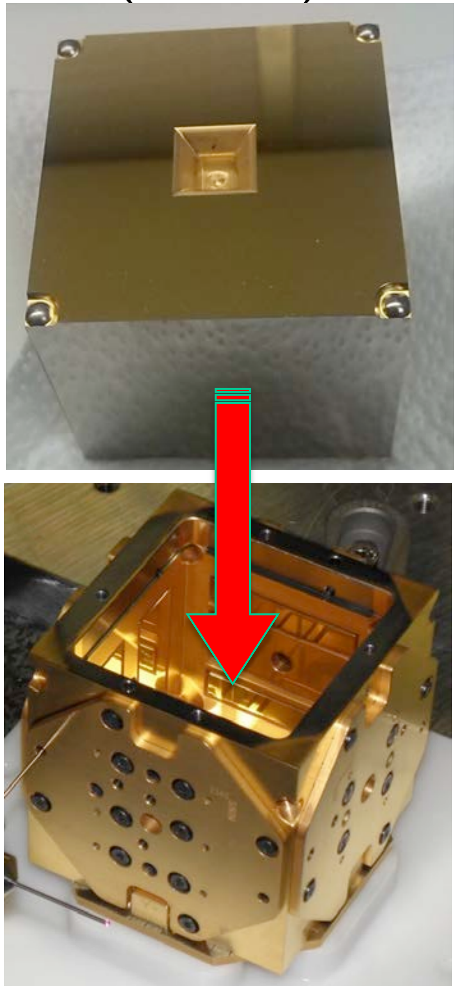
The Gravity reference Sensor (GRS)

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

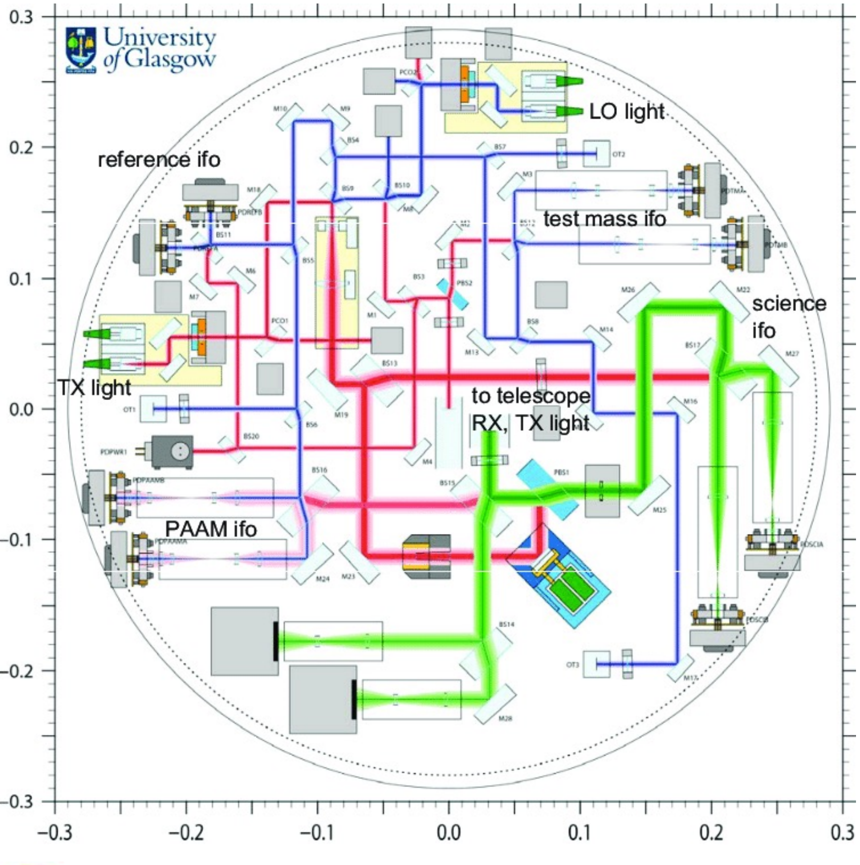


test-mass

electrode housing

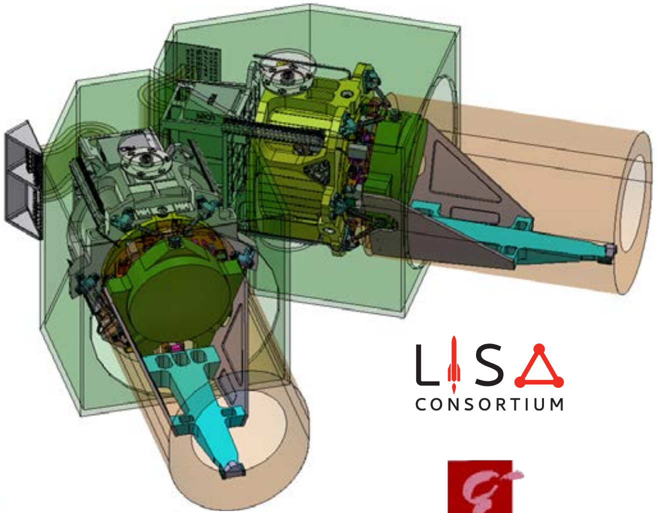


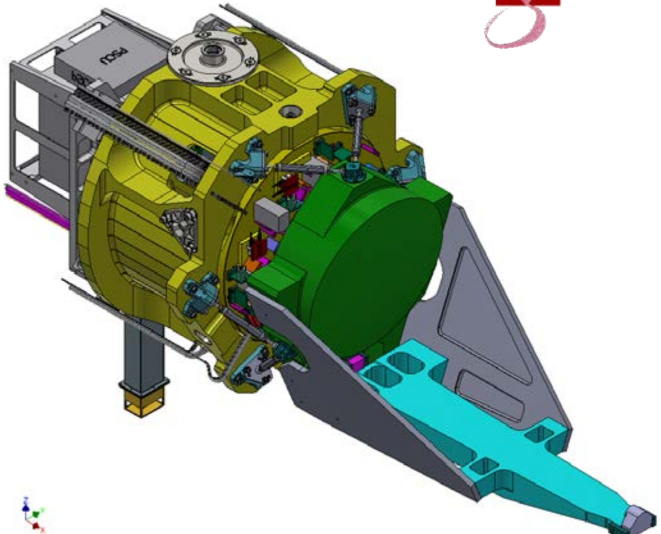
The optical bench

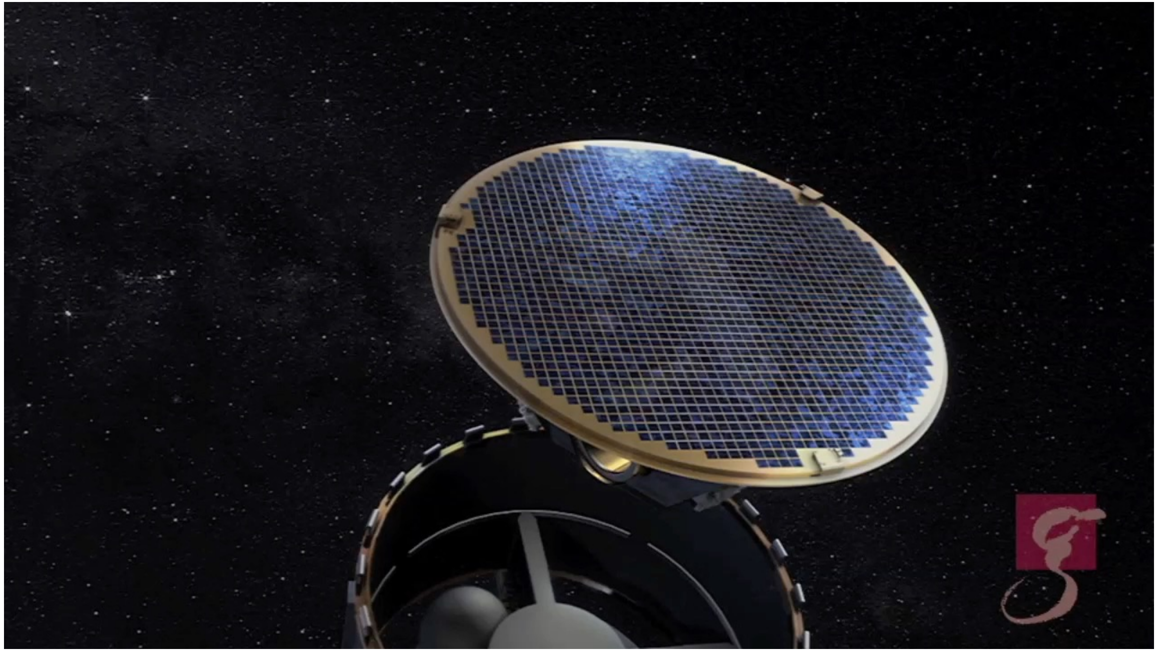


$\simeq$

The full complement

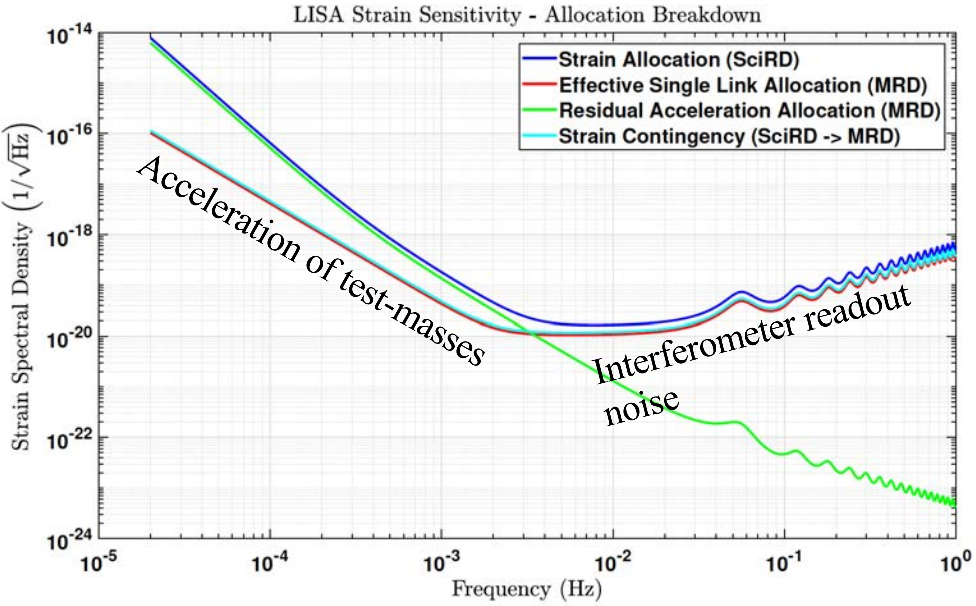


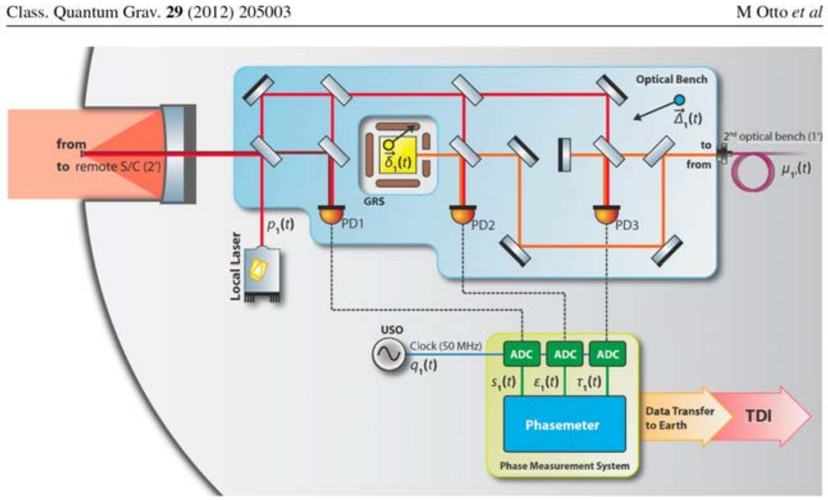




Noise in a LISA link

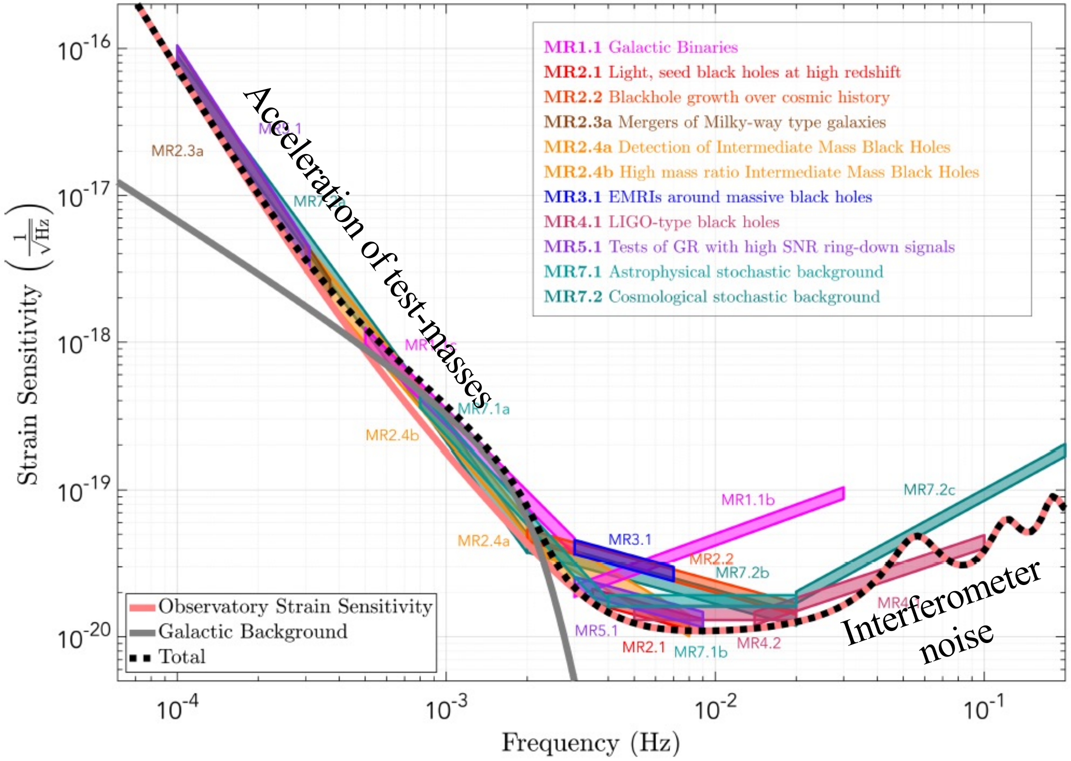
- Once frequency noise has been suppressed, LISA sensitivity limited at low frequency by acceleration of test-masses
- Only at higher frequencies interferometer readout noise sets in





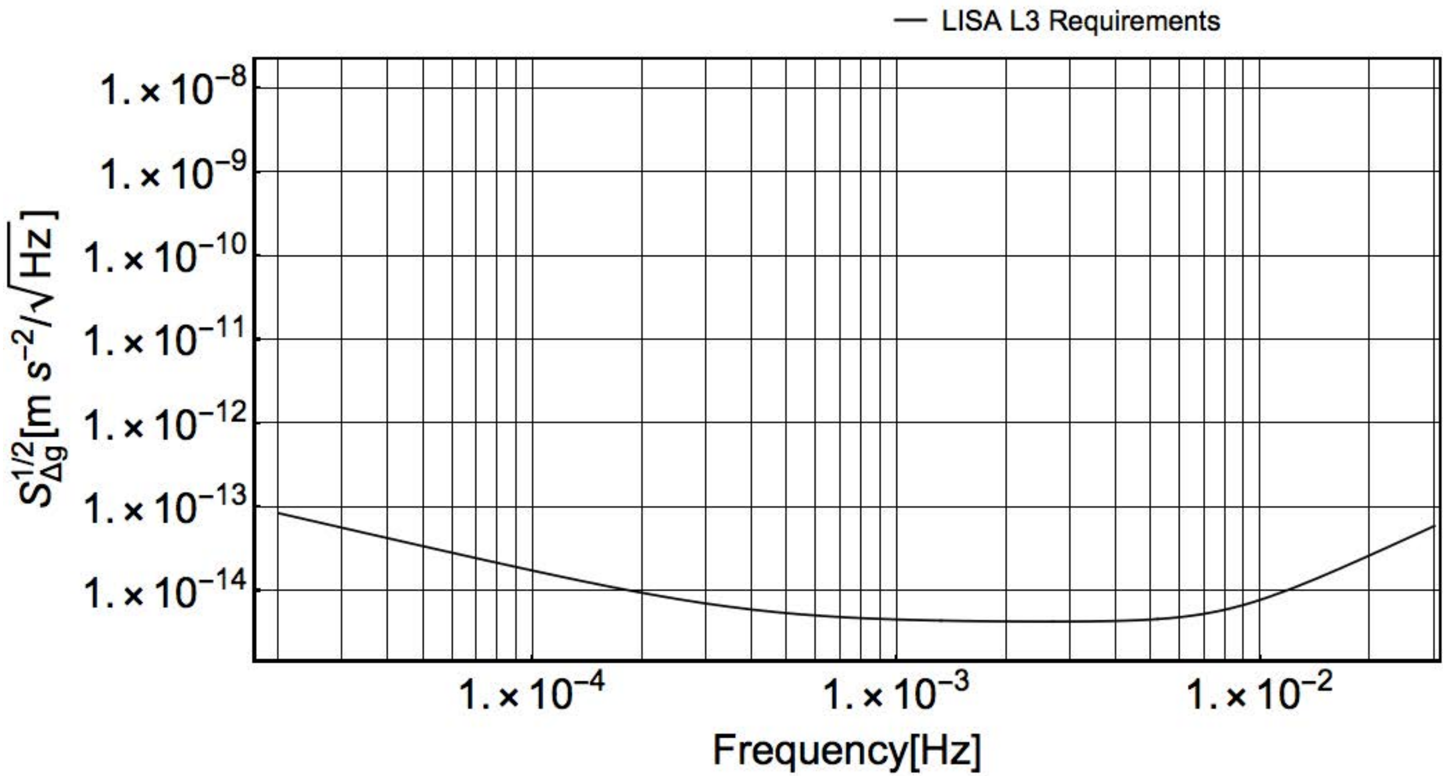
Acceleration noise and LISA science

- LISA sensitivity limited at low frequency by acceleration of test-masses
- LISA is a low frequency instrument: much of SNR for most interesting sources accumulated ≲ 10 mHz



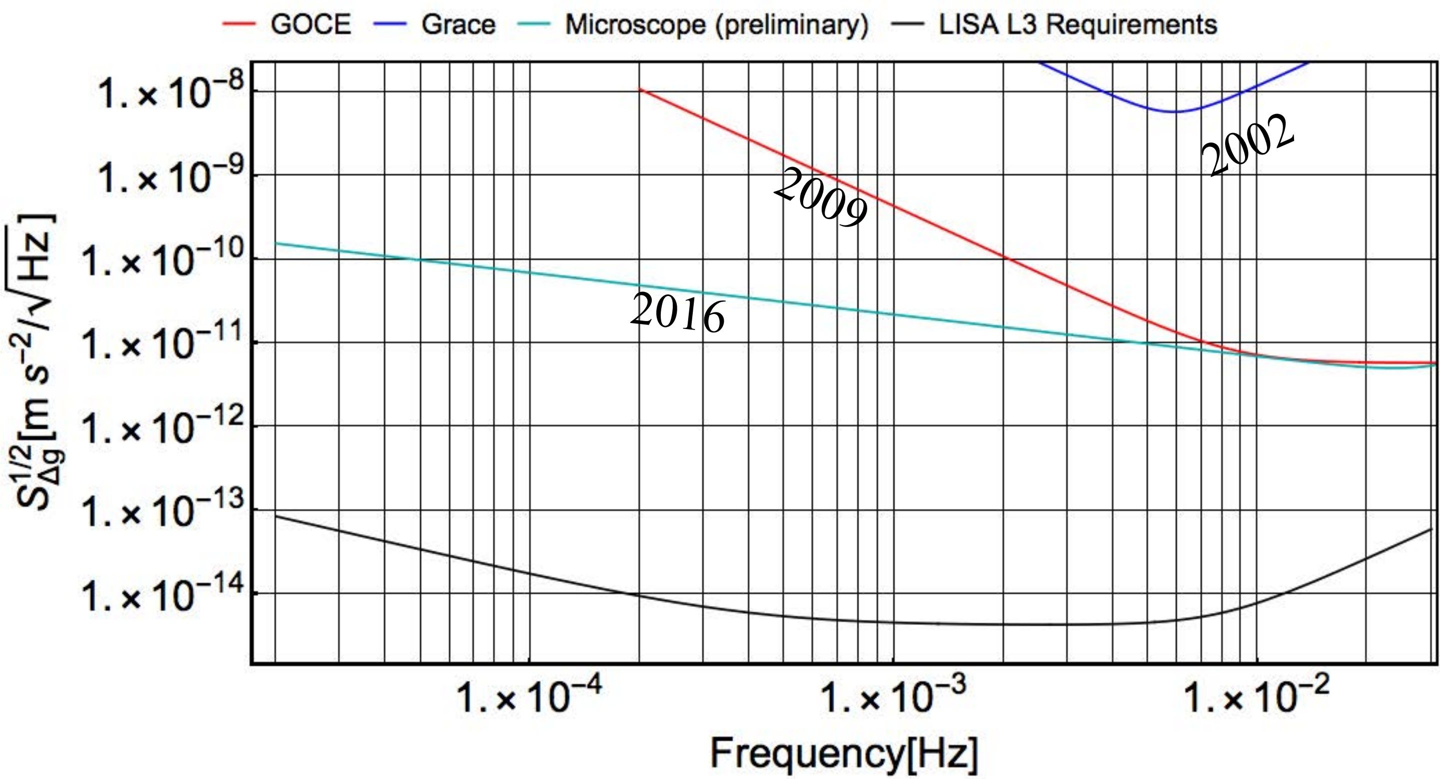
LISA: Sub-femto-g force suppression required

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

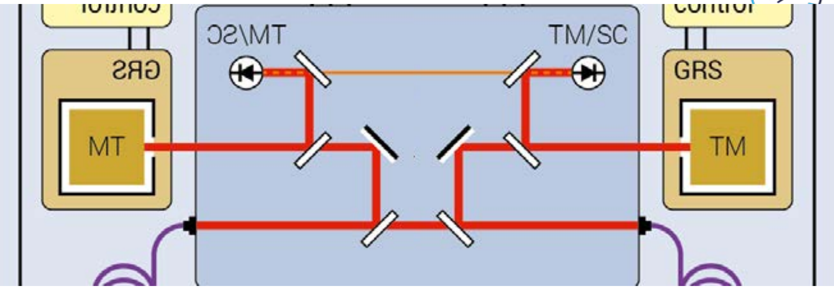


LISA: Sub-femto-g force suppression required

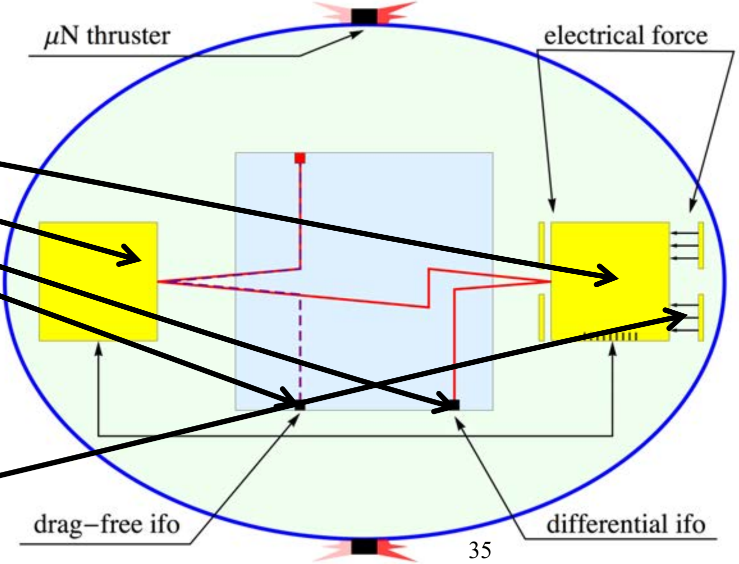
- Cannot be tested on ground $\lesssim$ 0.1 Hz
- Not even in low Earth orbit: orders (>3) of magnitude better than any other space mission



LISA Pathfinder

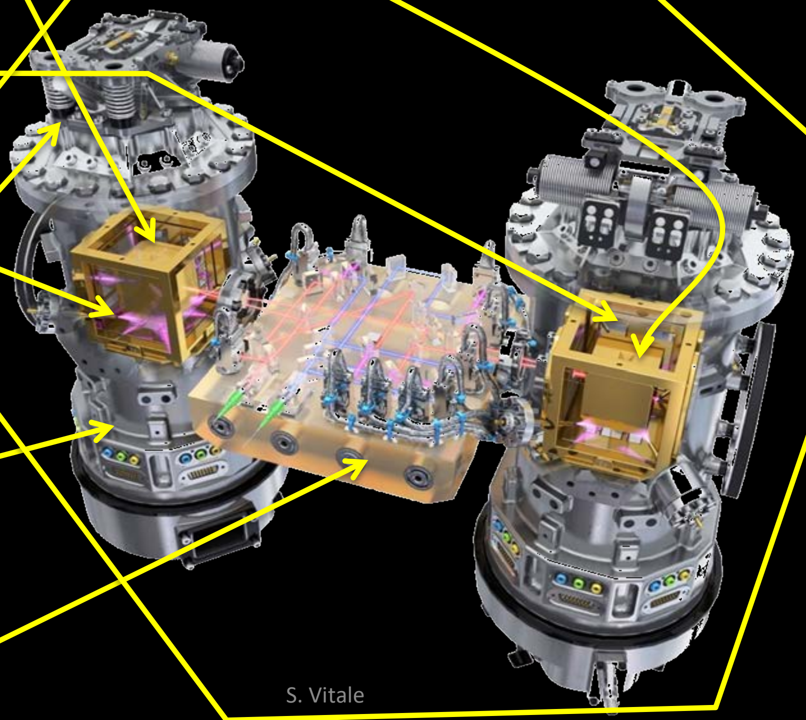


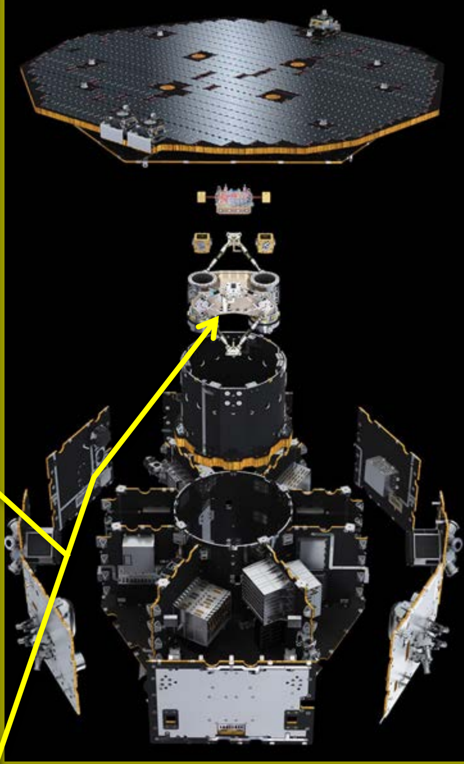
- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- 2 Interferometers (Ifo)
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



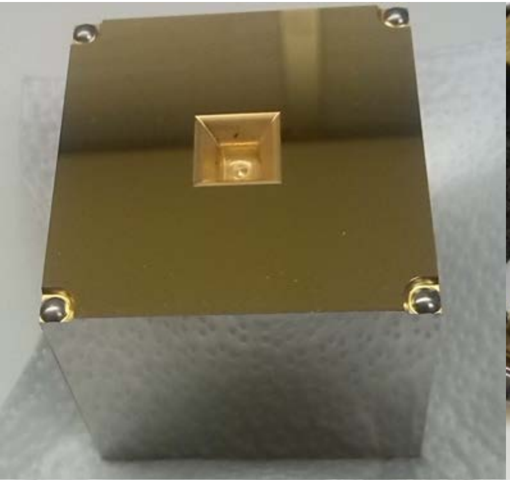
The LTP

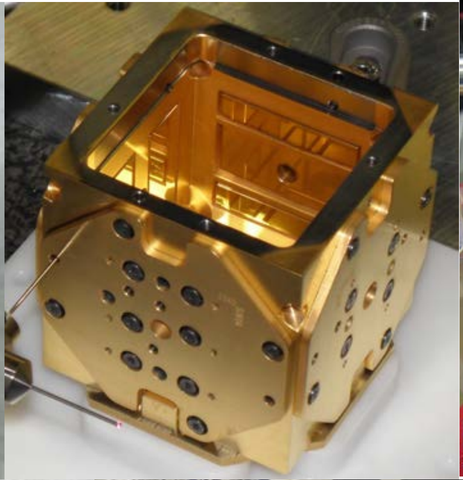
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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

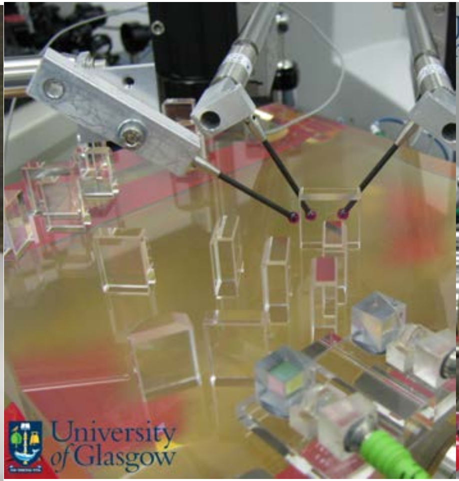


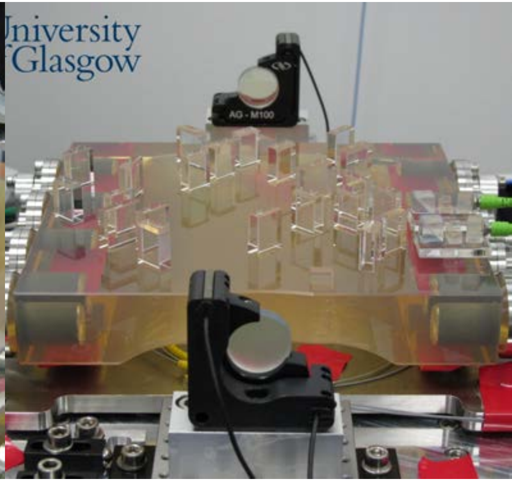


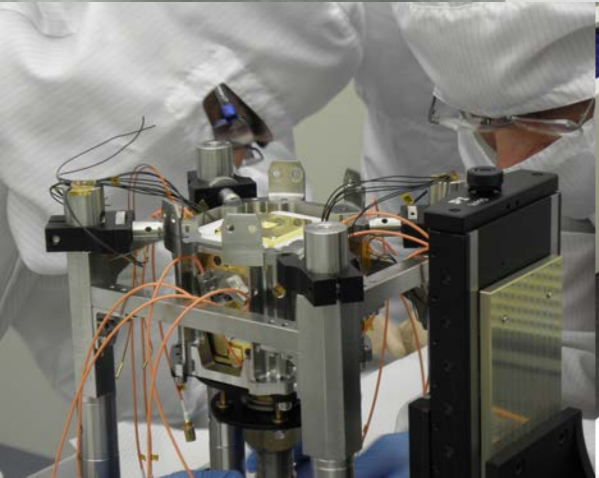
The real H/W

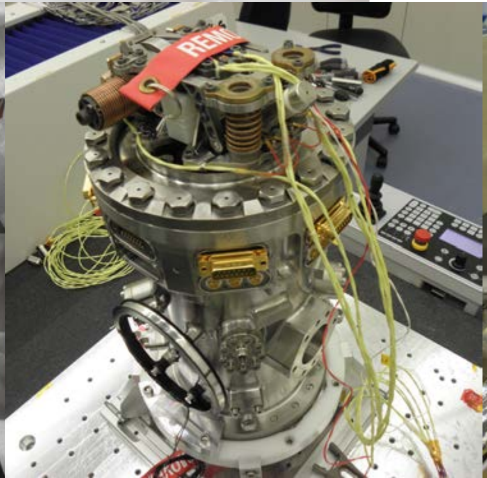




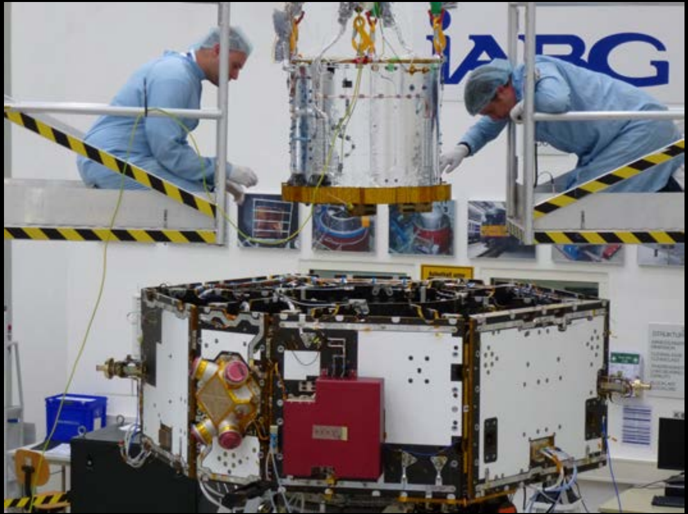


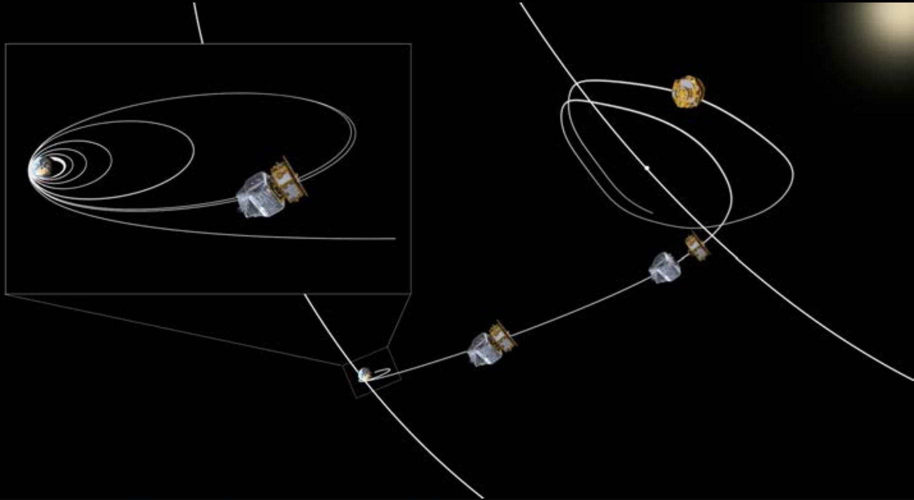




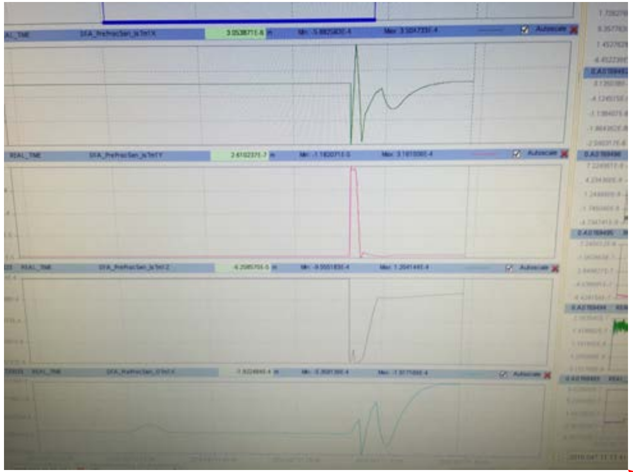


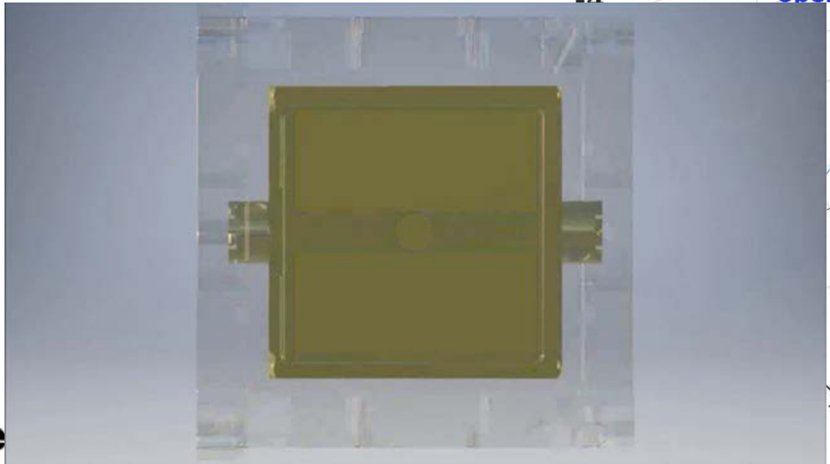
Instrument integration

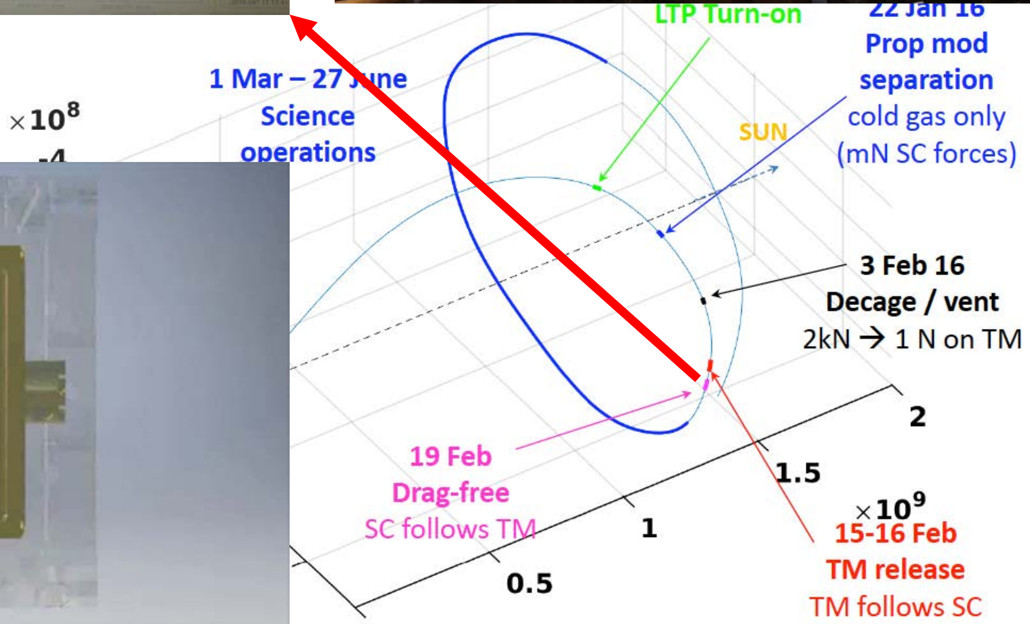




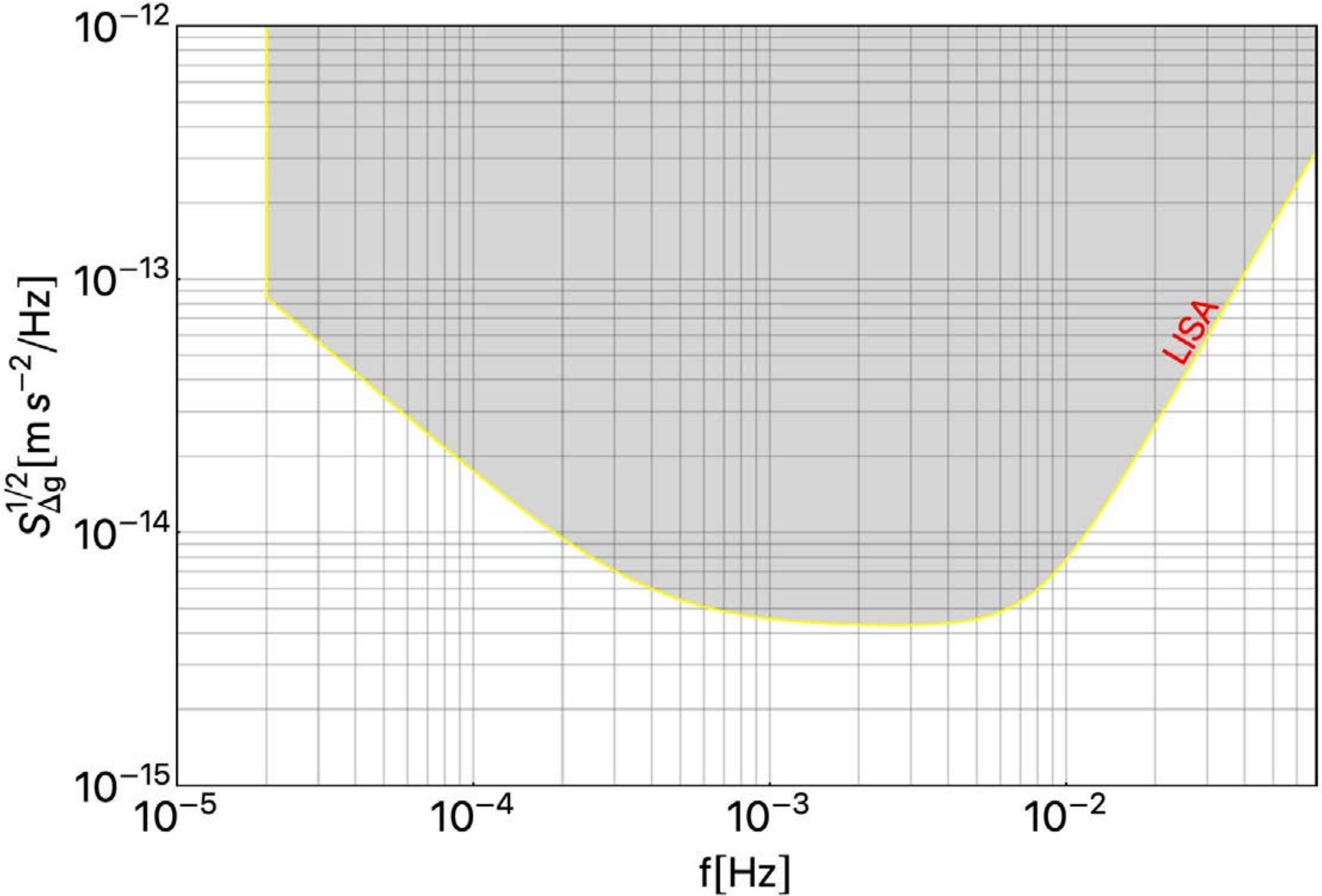
From instrument integration to orbit



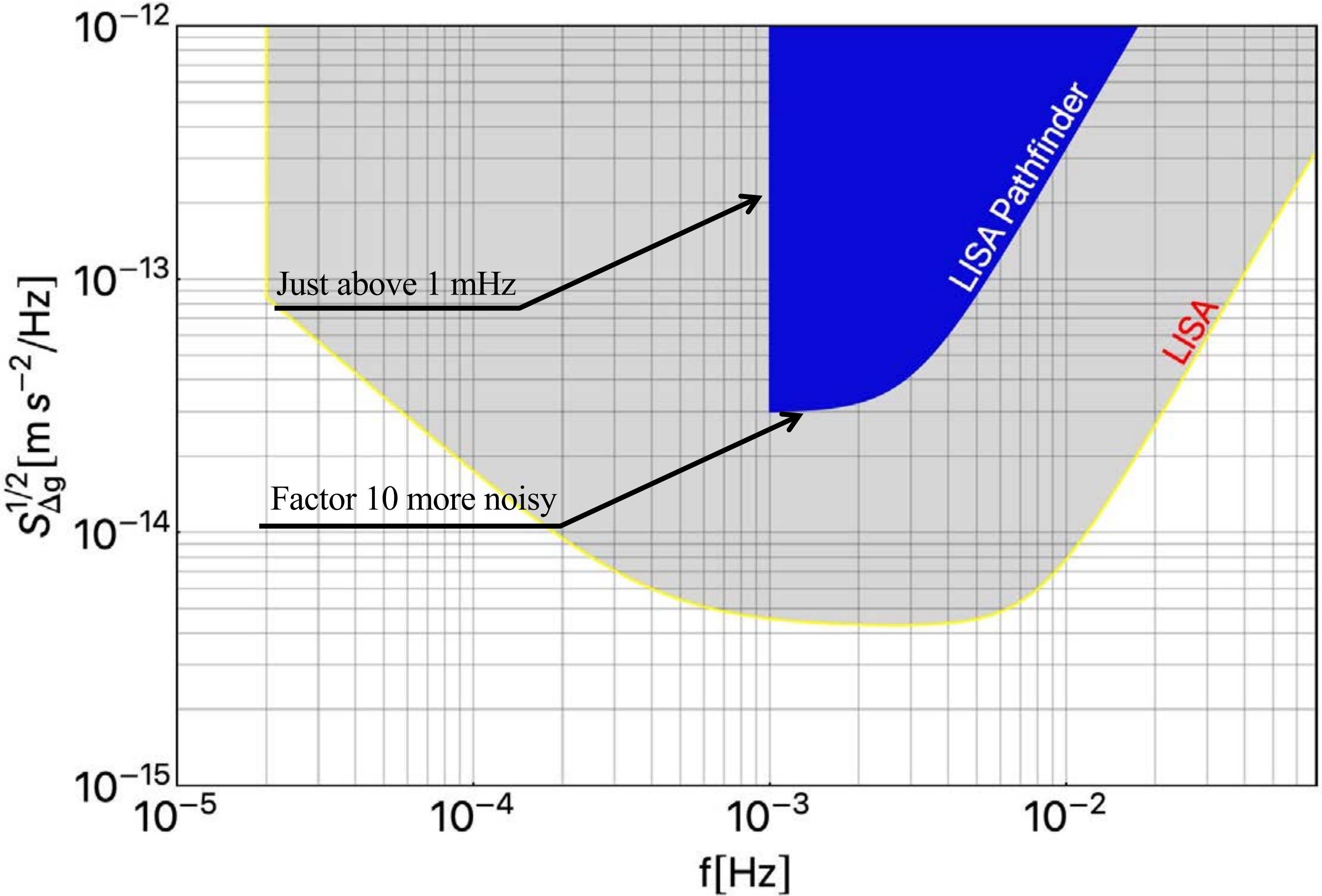



$\times 10^8$
1 Mar – 27 June
Science
operations
LTP Turn-on
22 Jan 16
Prop mod
separation
cold gas only
(mN SC forces)
SUN
3 Feb 16
Decage / vent
2kN → 1 N on TM
19 Feb
Drag-free
SC follows TM
15-16 Feb
TM release
TM follows SC
$\times 10^9$
0.5
1
1.5
2

LISA acceleration requirements



Relaxed LISA Pathfinder requirements



Expected performance

- LISA Pathfinder performance budget: 276pages
- A short list of dominating effects

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

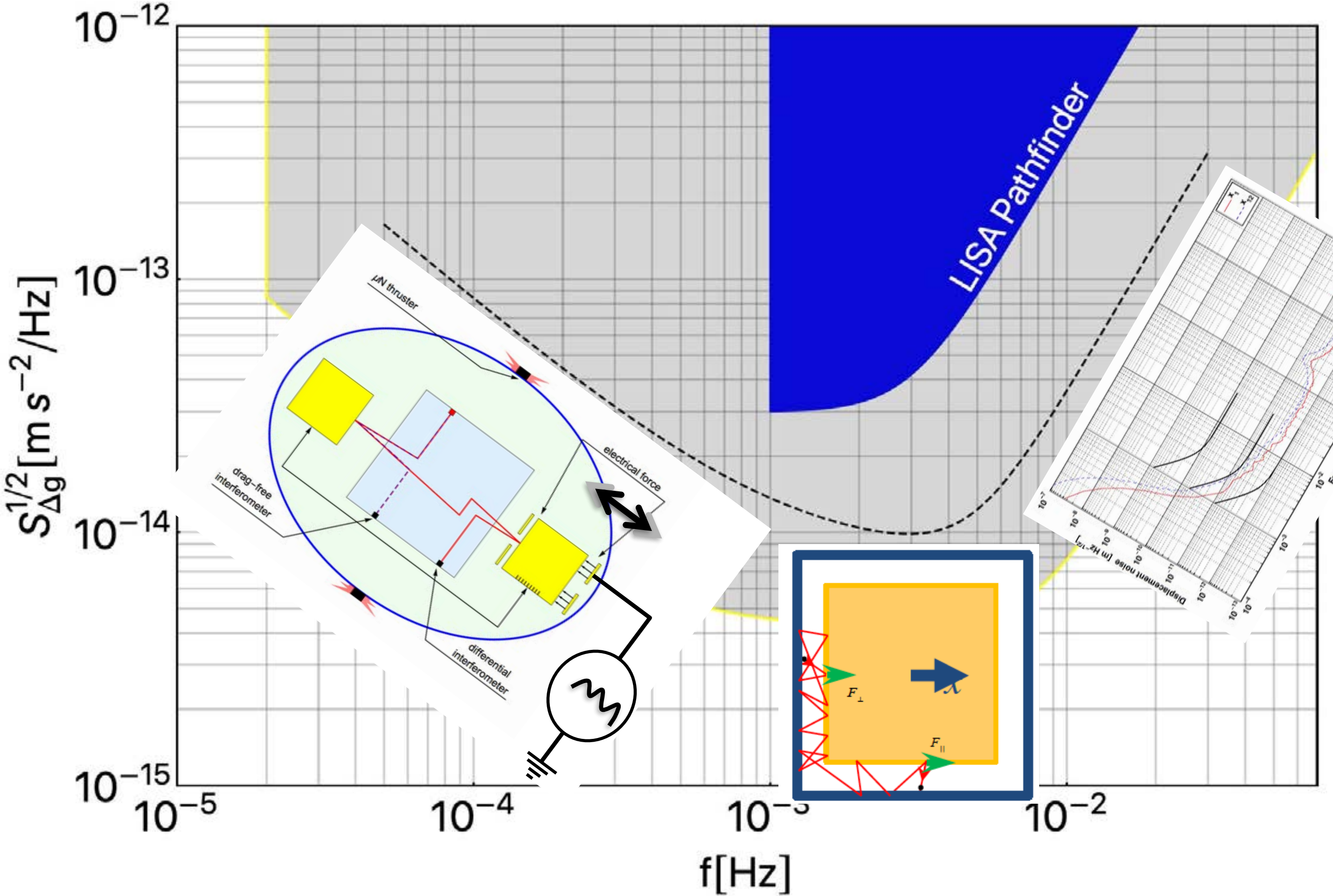
Table 2. Leading sources of differential force-per-unit-mass disturbances and their PSD values at 1 mHz.

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.

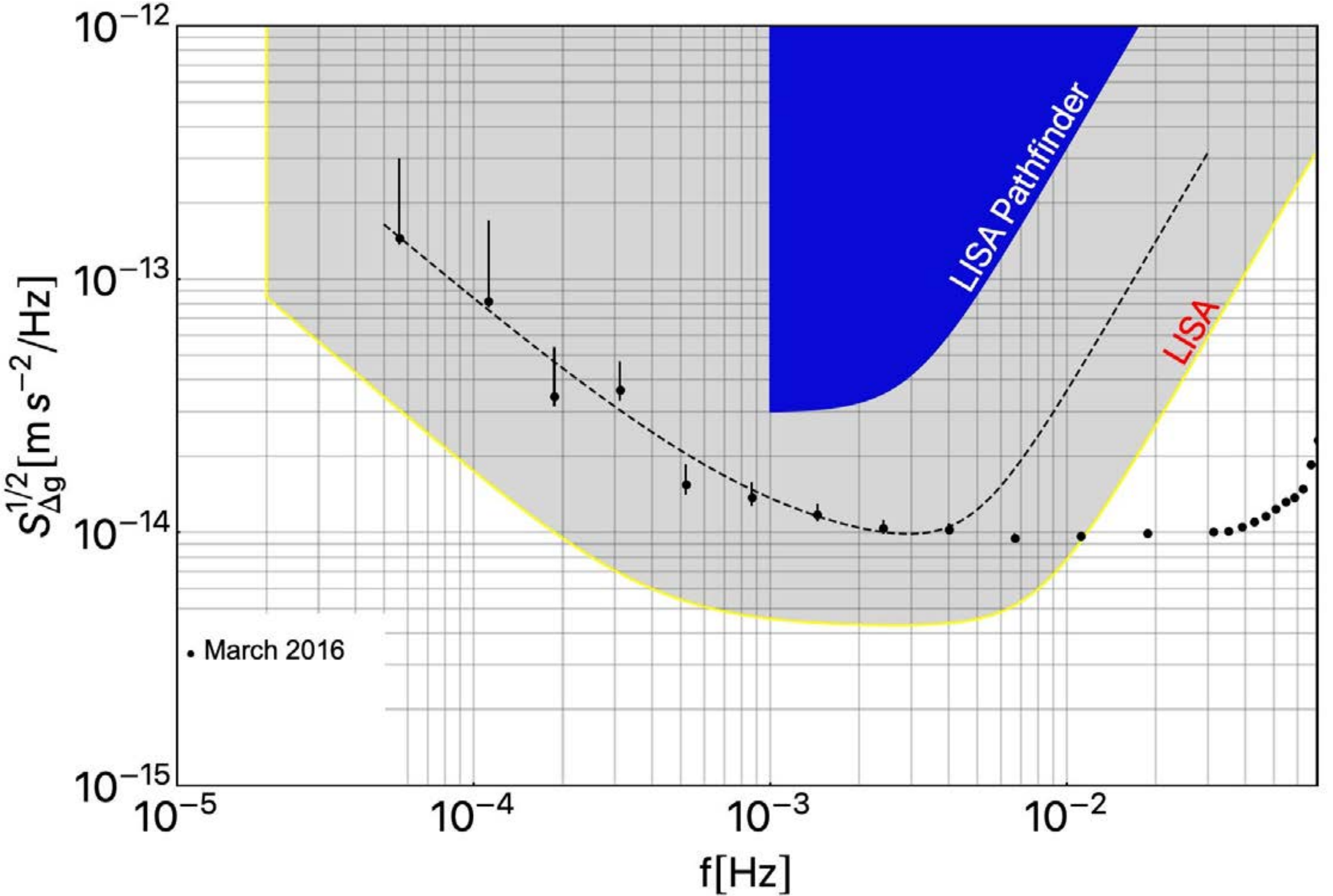
Expected performance

- Electrostatic actuation noise:
  - For a given voltage source noise, the larger the needed force you set, the larger the force noise.
- Brownian noise from residual gas:
  - The larger the pressure surrounding the test-mass the larger the noise
- Interferometer readout noise: $\simeq 10\ pm/\sqrt{Hz}$ as for LISA

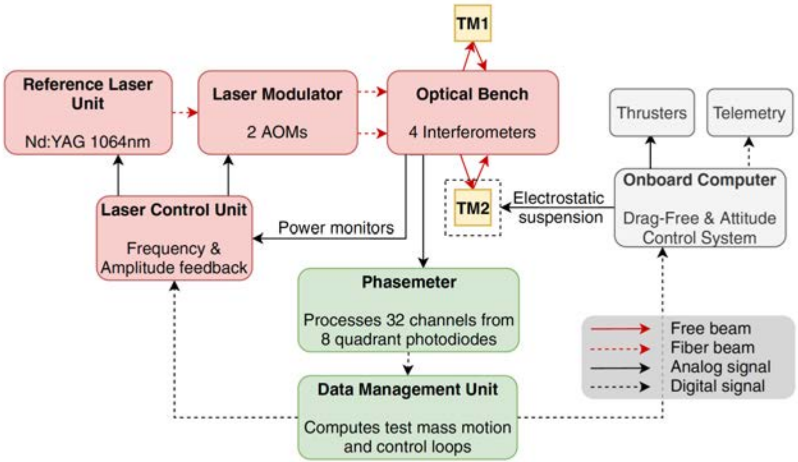


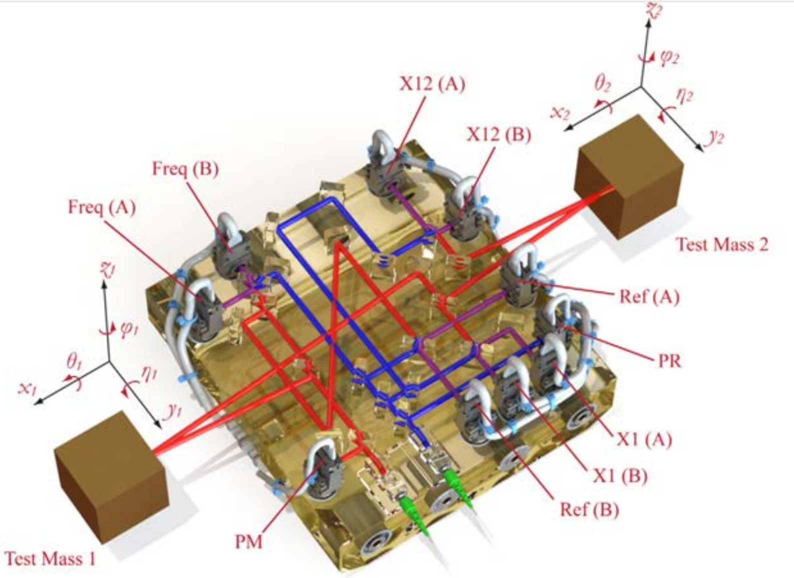
First day of operations: March 1st 2016

- Better than requirement.
- Close to prediction
- Except for interferometer noise at 35 fm/√Hz instead of 10 pm/√Hz

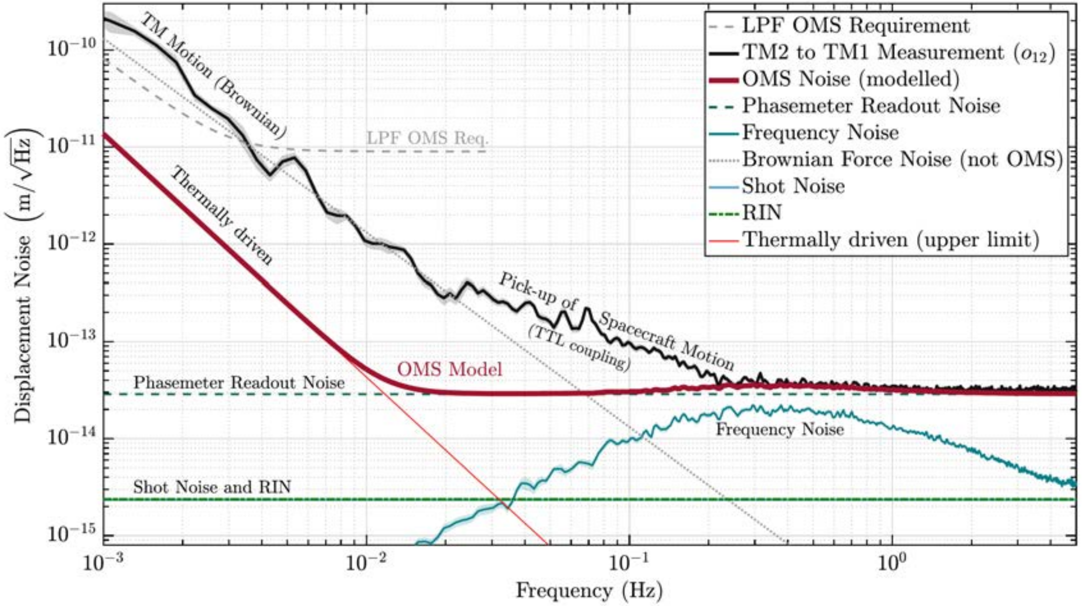


The magic interferometer





PHYSICAL REVIEW LETTERS **126,** 131103 (2021)



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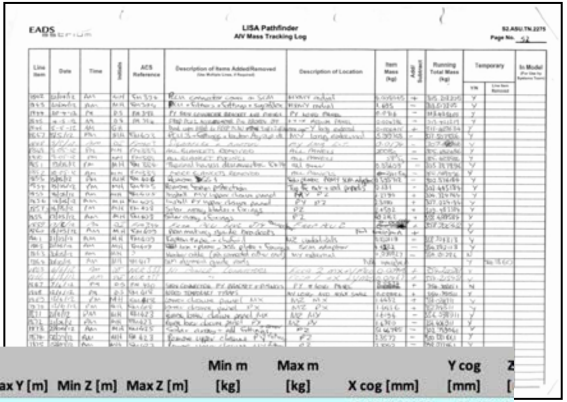
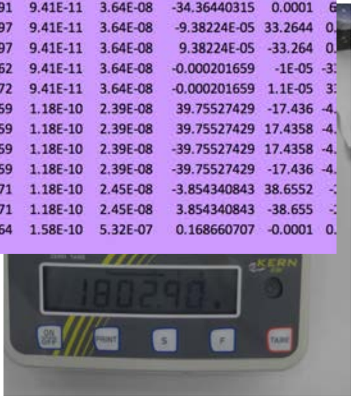
Gravitational control and actuation

- 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)
-



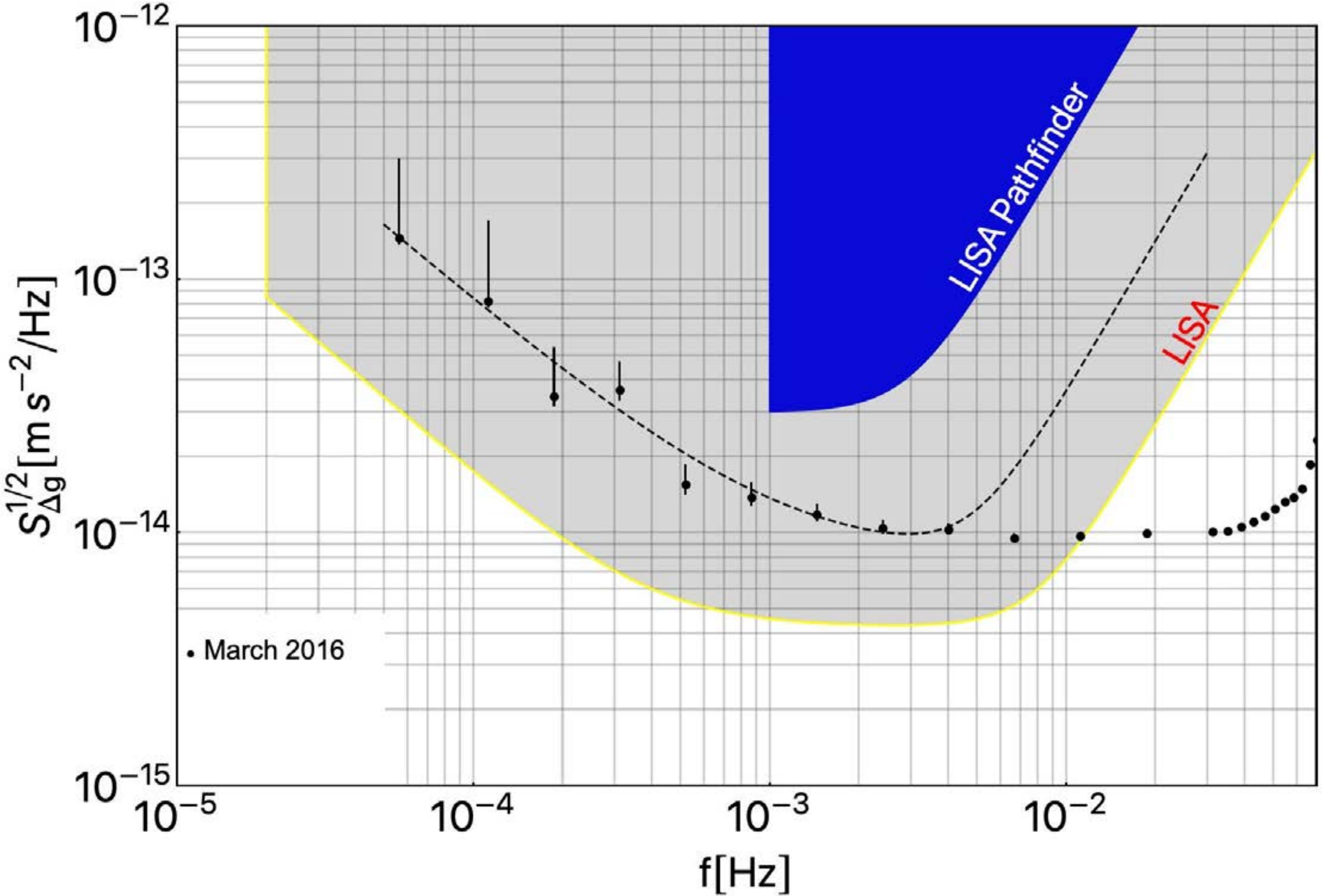
1 Do not touch!

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												

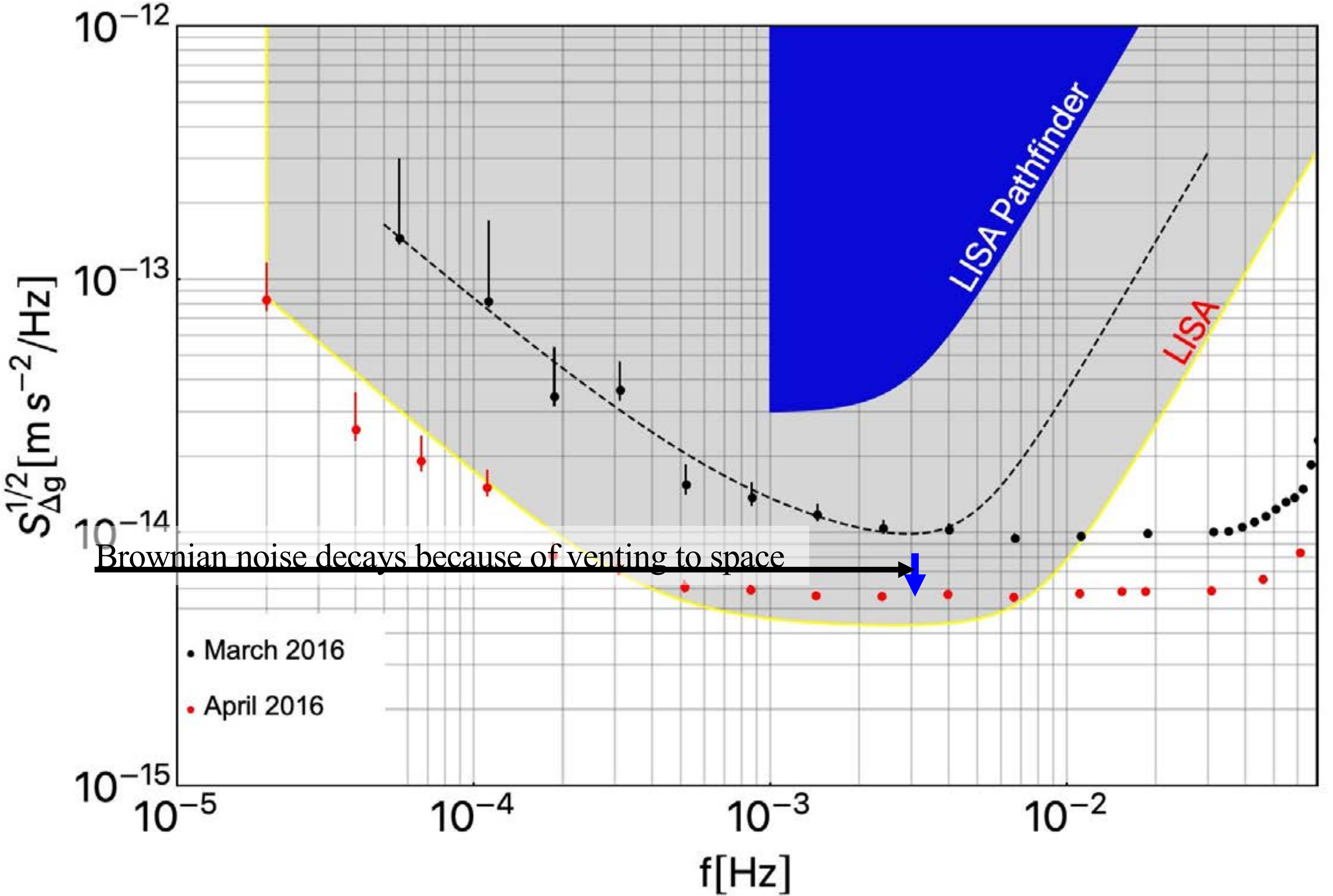


esa
agenzia spaziale italiana

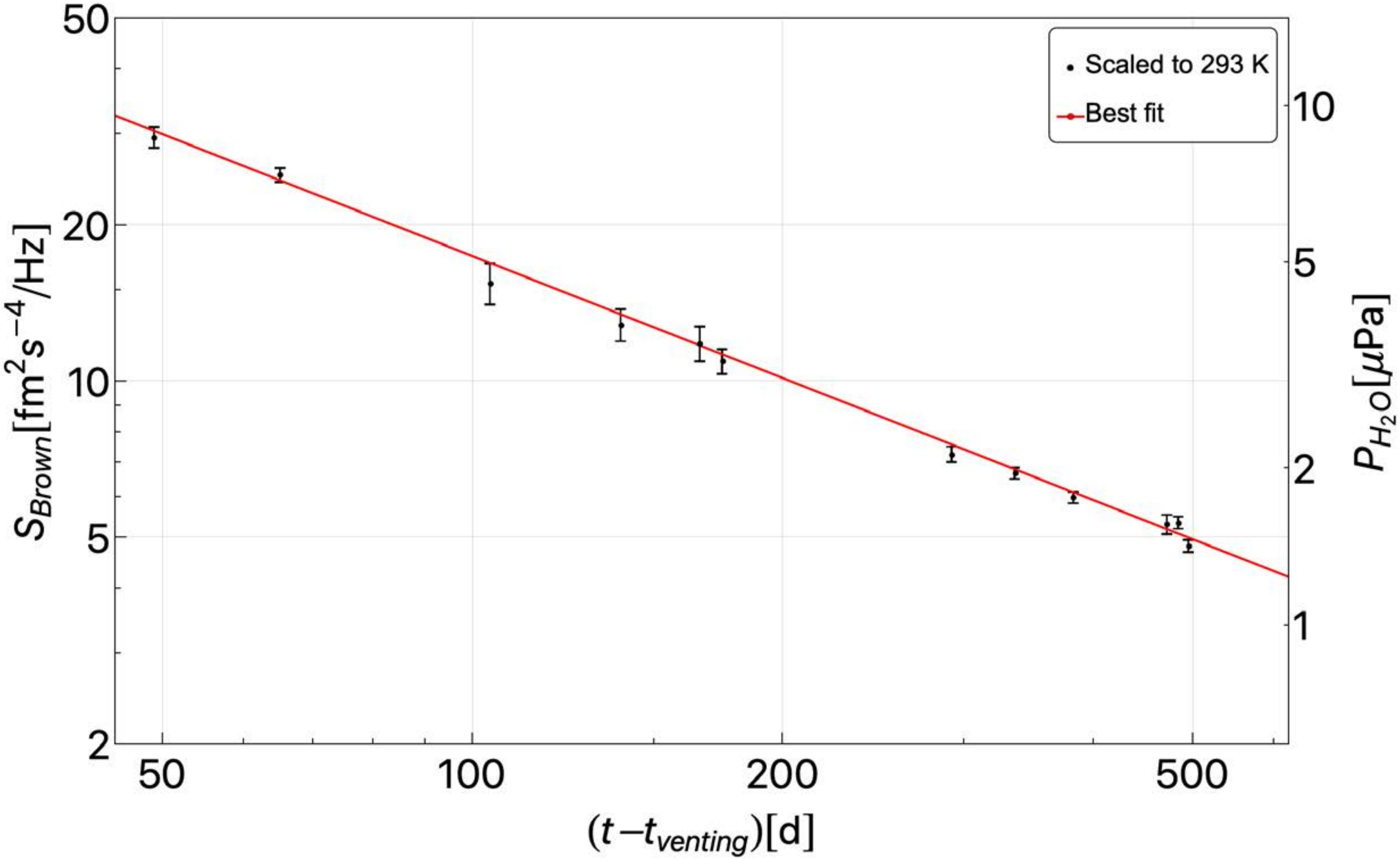
Authority 650 pm s^{-2}



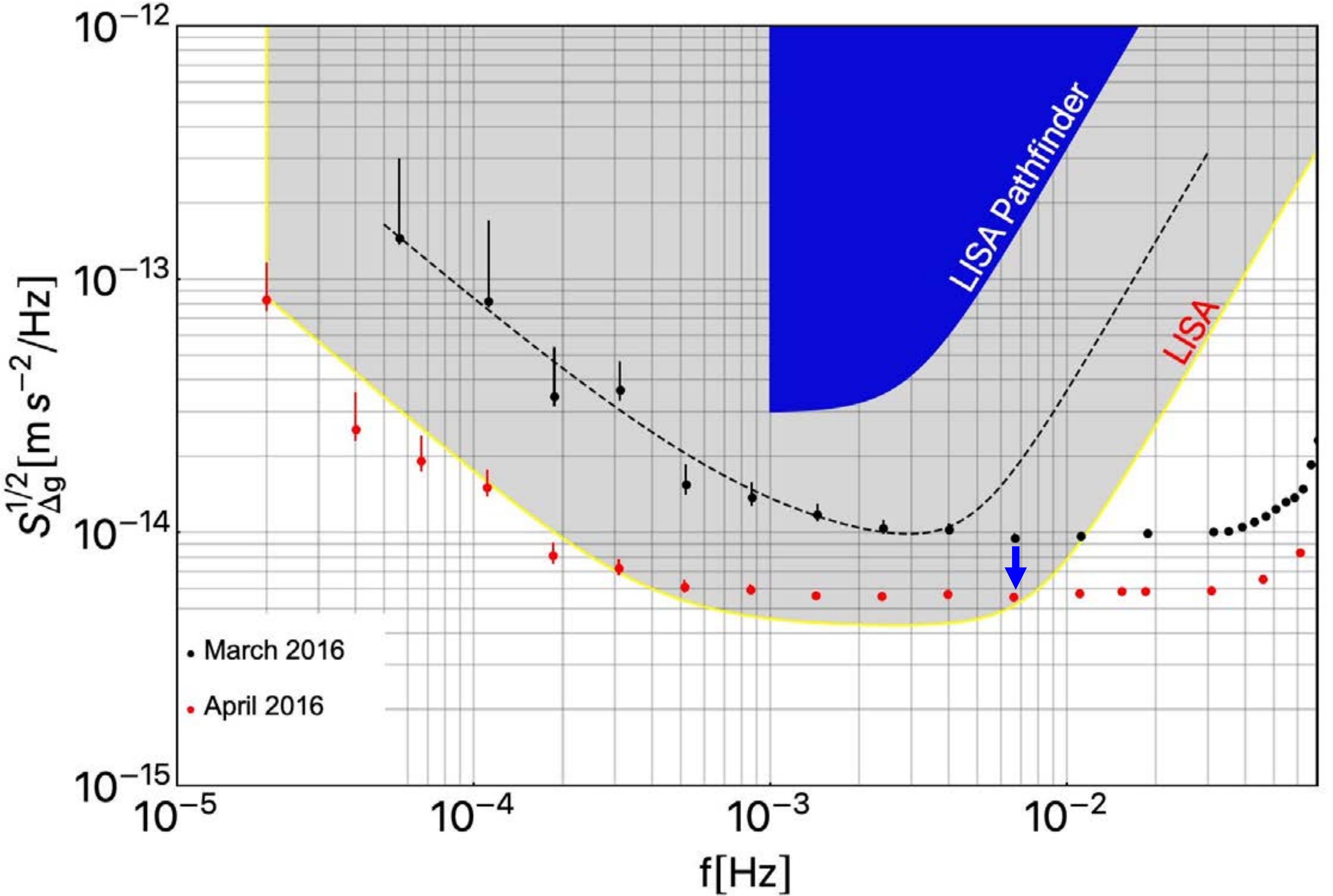
Authority 50 pm s^{-2}



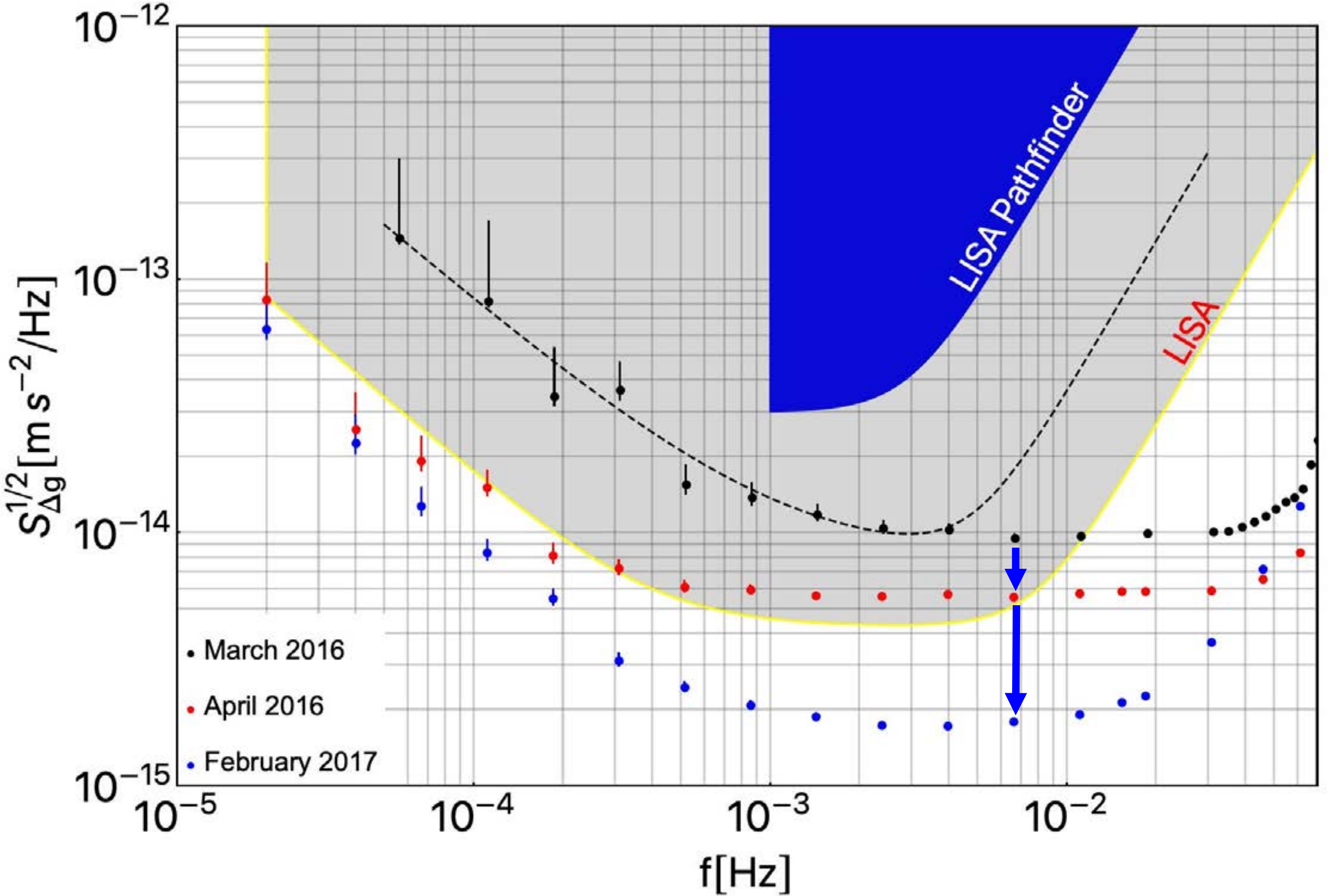
Pressure and Brownian decay



Authority 50 pm s^{-2}



The ultimate performance



LISA CONSORTIUM

INFN Istituto Nazionale di Fisica Nucleare — UNIVERSITÀ DI TRENTO

Consolidating the noise m… LPF full m… of experiments

In depth analysis of LISA Pathfinder performance results: time evolution, noise projection, physical models and implications for LISA

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 24 May 2022]

Transient acceleration events in LISA Pathfinder: properties and possible physical origin

LISA Pathfinder Collaboration

Sensor Noise in LISA Pathfinder: An Extensive In-Flight Review of the Angular and Longitudinal Interferometric Measurement System

[1] M. Armano, et al. Sub-femto-*g* free fall for spa… …itational wave observatories: Lisa pathfinder results. *Phys. Re…* …231101, Jun 2016.

[2] D. Vetrugno et al. Lisa pathfinder first result… …*al Journal of Modern Physics D*, 26(05):1741023, 2017.

[3] M. Armano, et al. Charge-induced f… …ree-falling test ma… sults from lisa pathfinder. *Phys. …* …:171101, Apr 2017.

[4] M. Armano, et al. Capacitive … mass motion with… cision over millimeter-wide … …or space-borne gr… …nce sensors. *Phys. Rev. D*, … 2017.

[5] M. Armano, et al. C… …, and energy depe… …nt galactic cosmic-ray flux d… …d of a forbush d… …A pathfinder. *The Astrophy…* 854(2):113, Feb …

[6] M. Arma… …ond the require… …erformance: New lisa pathfin… …wn to 20 μHz … 120:061101, Feb 201…

[7] M. … …l. Calibrating … …nics of lisa pathfind… *Rev.* … 002, Jun 2018.

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Test mass charging

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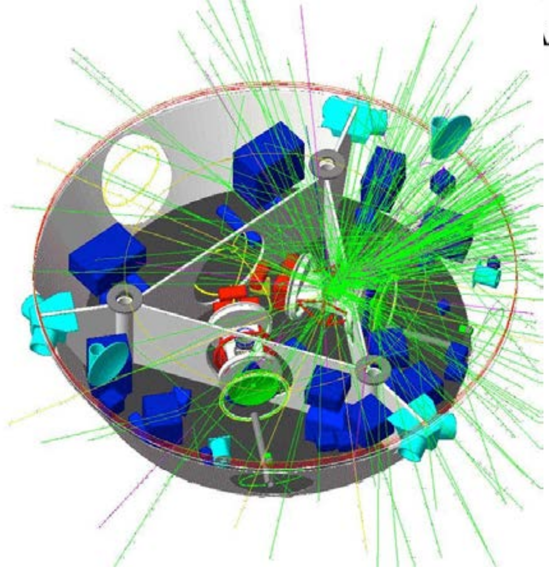
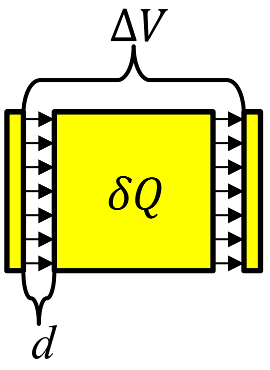


- Cosmic rays keep charging up the test-mass
- Random charge δQ interact with parasitic potentials ΔV and produces force noise $\delta F_Q = \frac{\delta Q \Delta V}{d}$
- Charging events random and uncorrelated: Poisson statistics expected.
- Force noise with $1/f$ spectrum

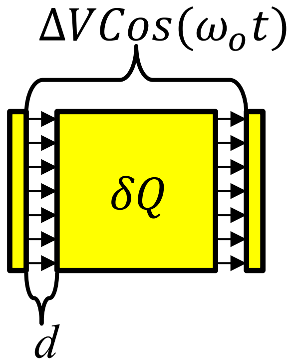


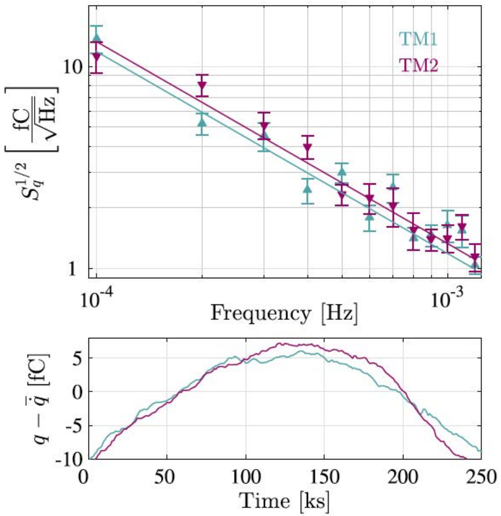
Test mass charging

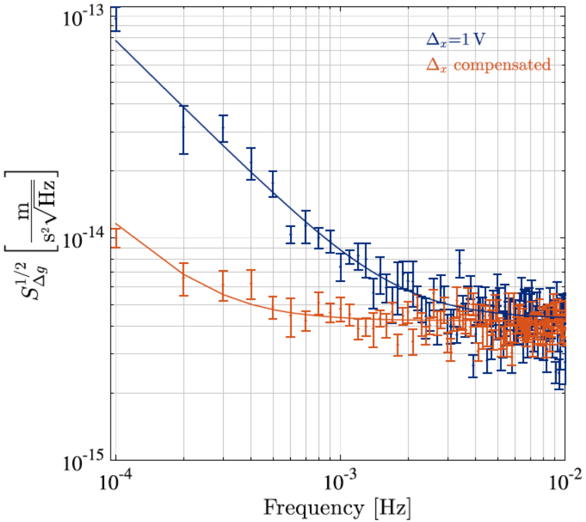
- We were able to measure charge by using an oscillating potential
- Oscillating force produced

$$\delta F_Q = \frac{\delta Q}{d} \Delta V Cos(\omega_o t)$$

- $\delta Q(t)$, at frequencies $\ll \omega_o/2\pi$, from induced test-mass motion





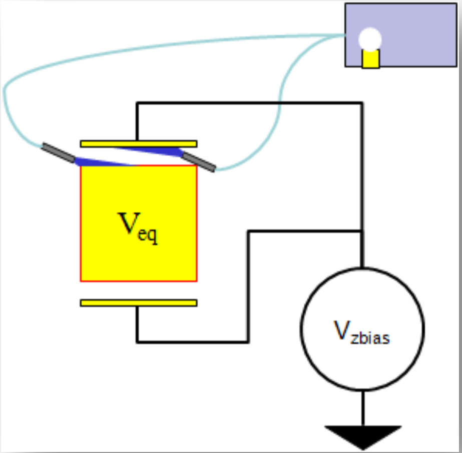


Suppressing force noise due to charge by balancing the parasitic potential

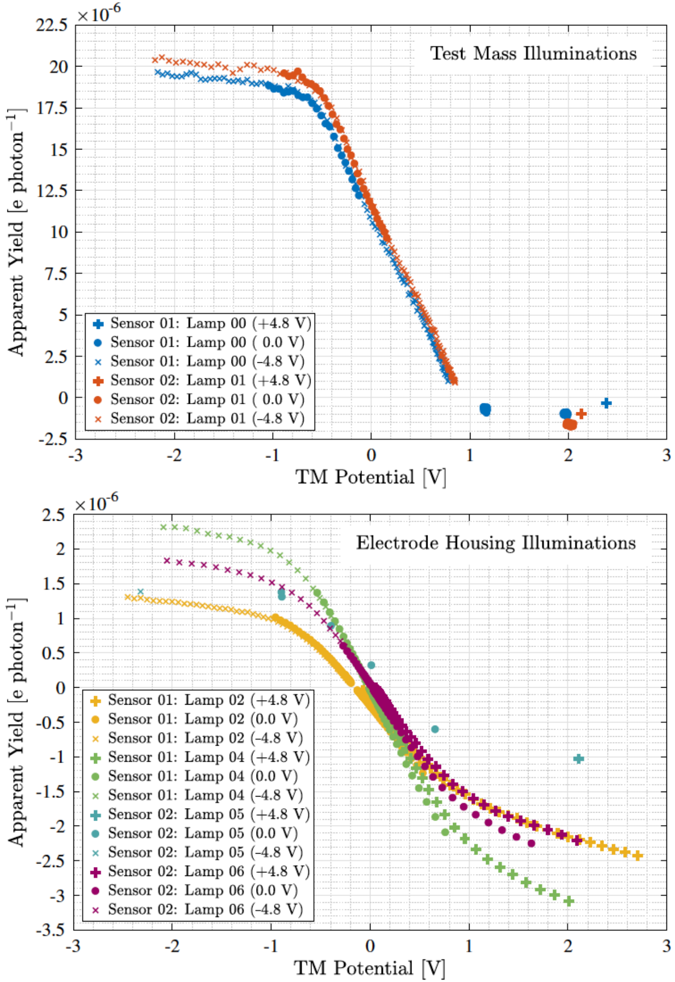
PRL 118, 171101 (2017) PHYSICAL REVIEW LETTERS week ending 28 APRIL 2017

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



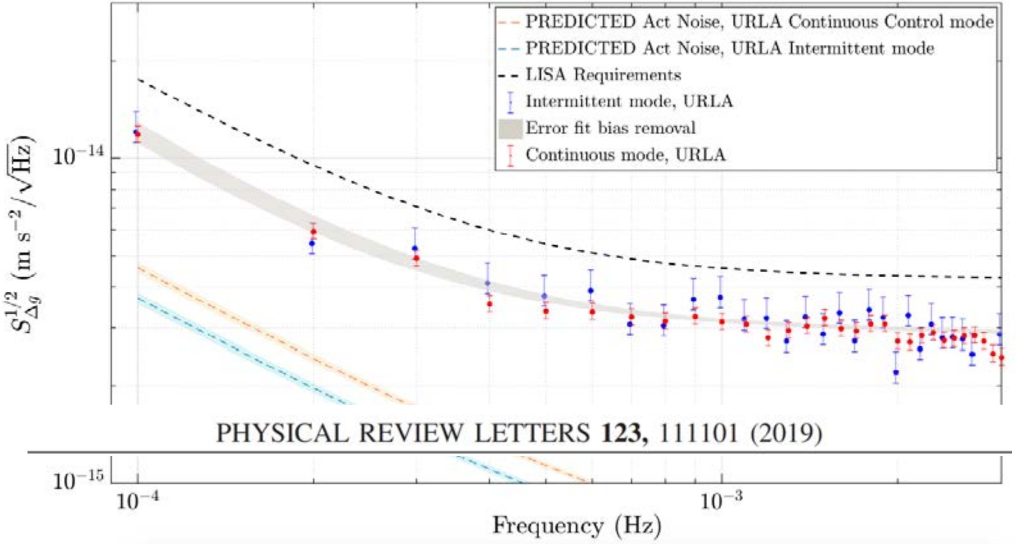
M. ARMANO *et al.*



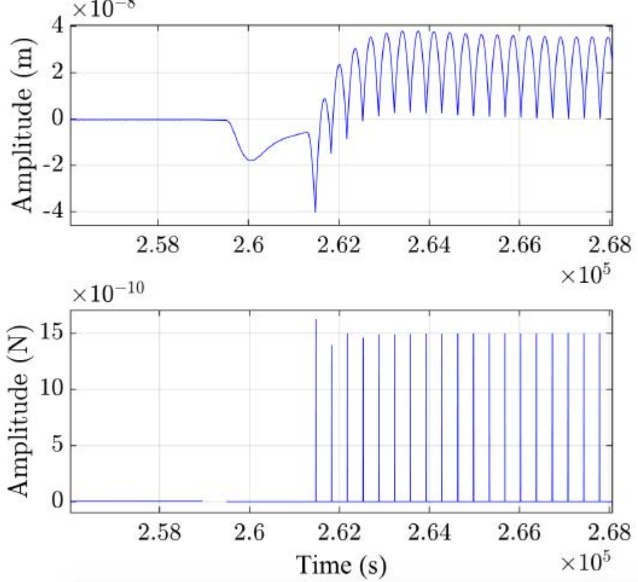
PHYSICAL REVIEW D **98**, 062001 (2018)

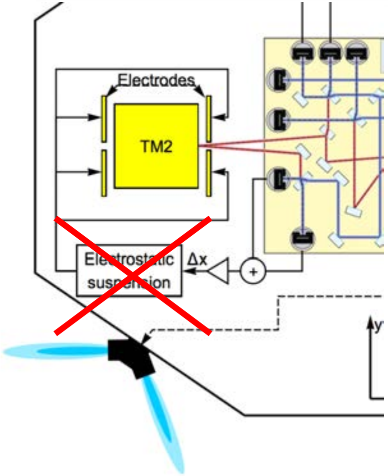
An independent check of performance: gravimeter vs accelerometer

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



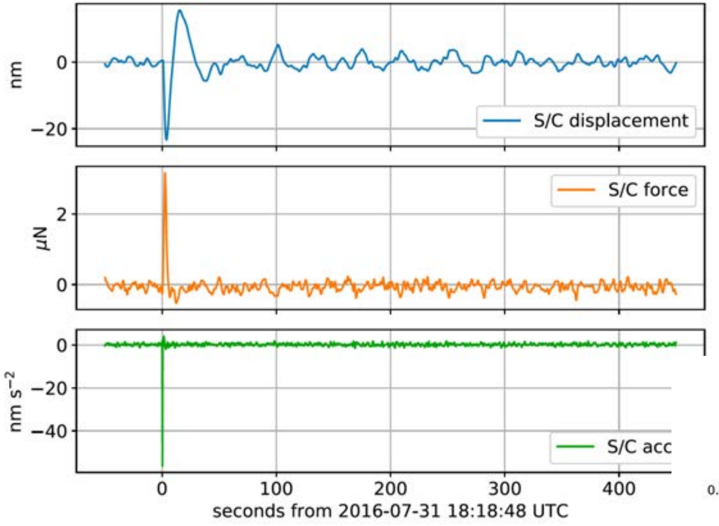
PHYSICAL REVIEW LETTERS **123,** 111101 (2019)

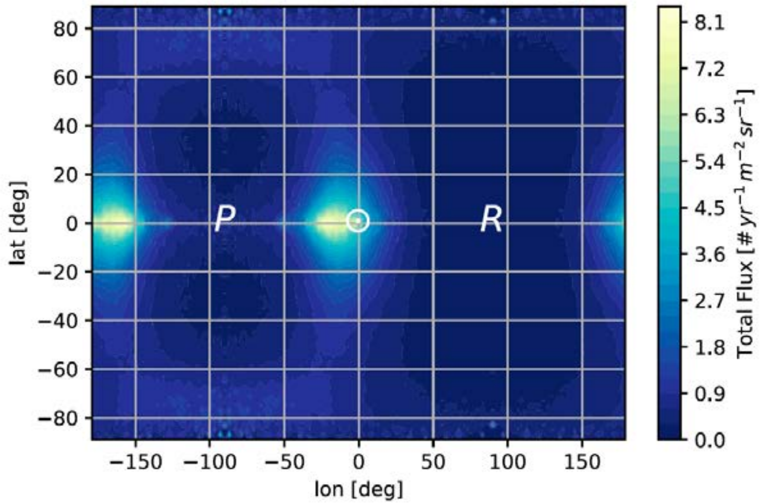




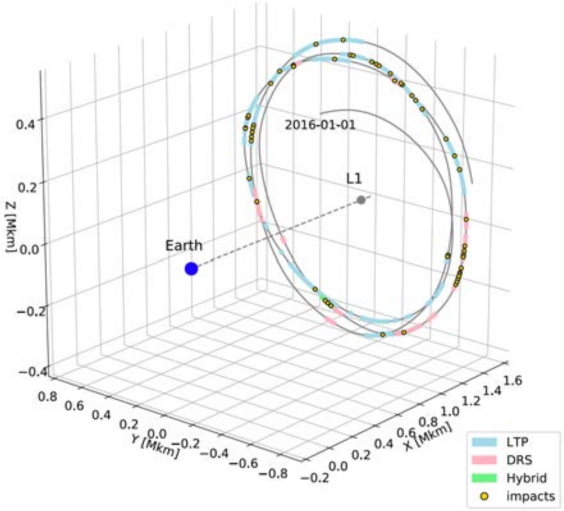
The Astrophysical Journal, 883:53 (15pp), 2019 September 20

Micrometeoroid impacts on LPF



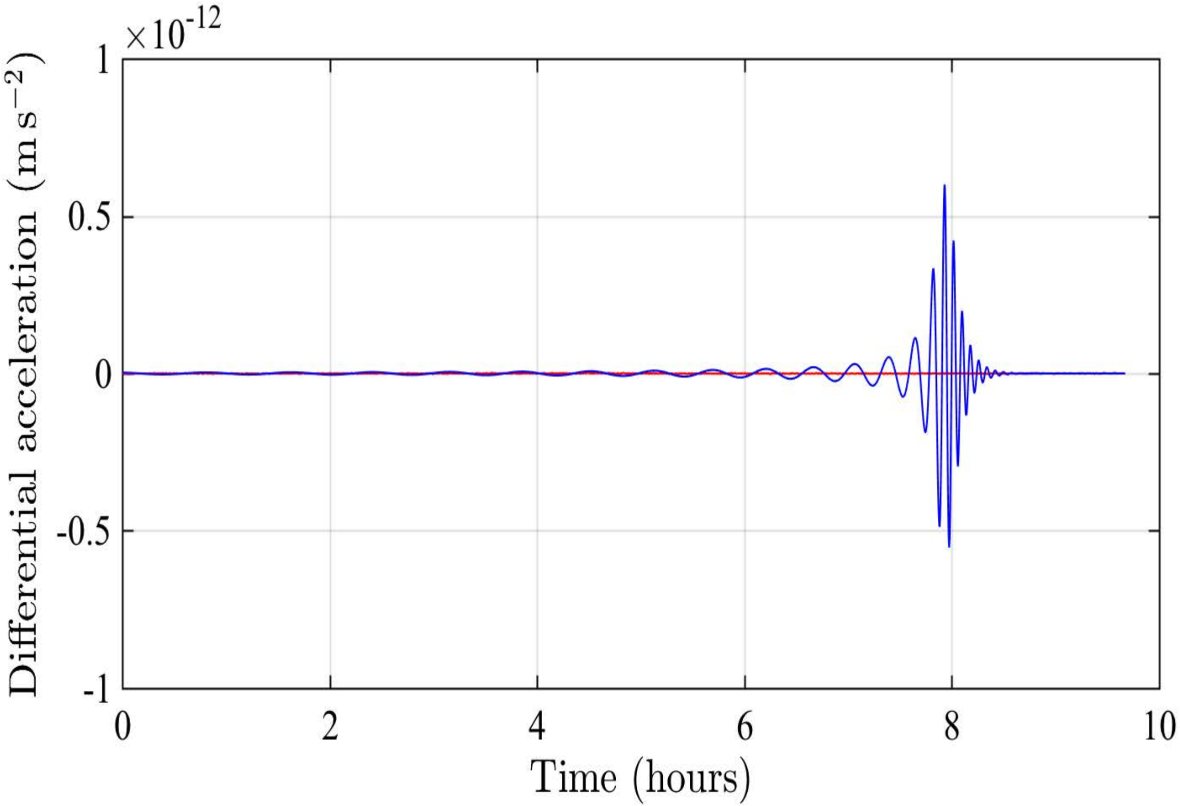


(a) Jupiter-Family Comets (JFC)



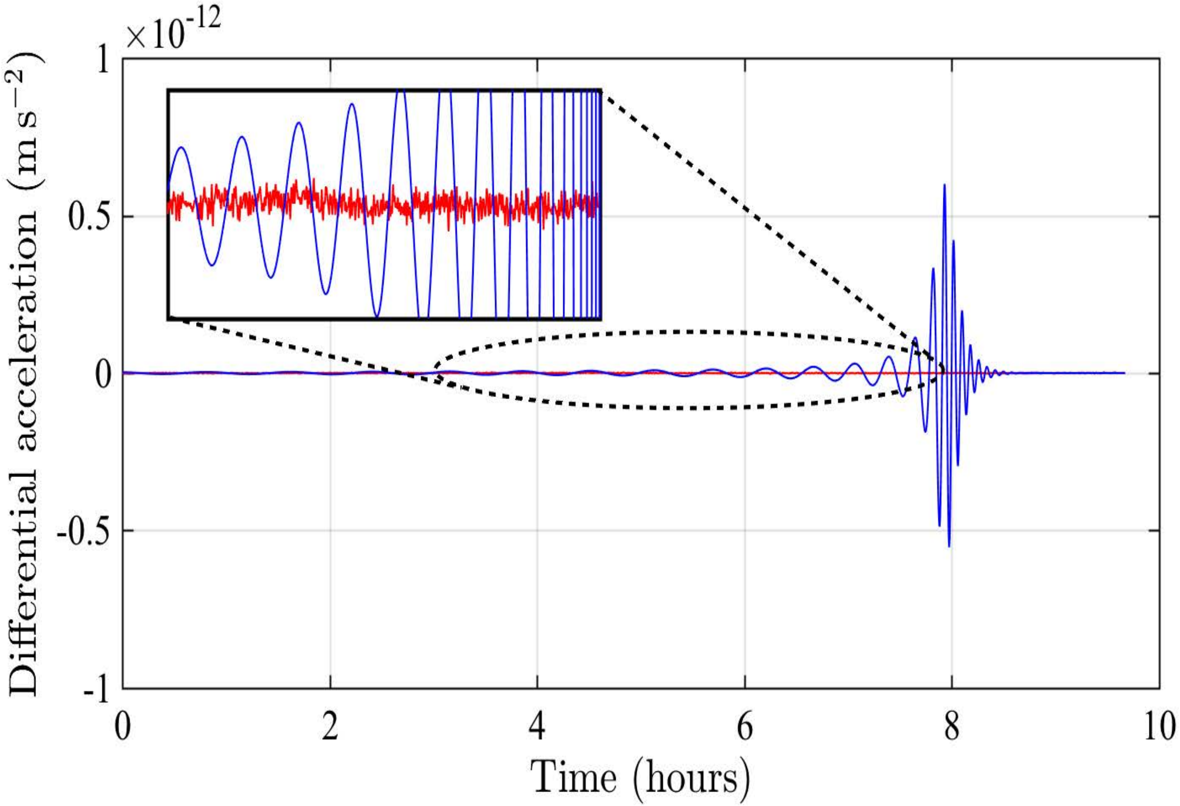
Simulated LISA acceleration signal for two $5\times10^5\ M_\odot$ black-holes with their galaxies merging at z=5

LISA Pathfinder acceleration data



Simulated LISA acceleration signal for two 5×10^5 $M_\odot$ black-holes with their galaxies merging at z=5

LISA Pathfinder acceleration data



Green Light for LISA

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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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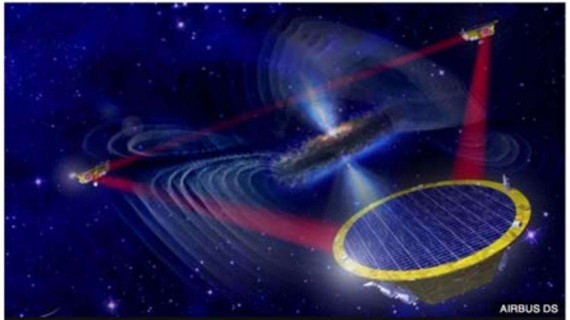

Artwork: LISA envisages three spacecraft linked by laser arms that are 2.5 million km in length

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.).

Phase A Conclusions – MFR outcome

6. C

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April 2022	**Phase B1 Kick-Off** (New Requirements Architecture ready)
Q4 / 2022	Intermediate Review (Consolidation of requirements to CFIs)
Q2 / 2023	**Instrument SRR ("Adoption review for CFIs")**
~~Q4 / 2023~~	Mission Adoption Review — Q3 2023
~~Q1 / 2024~~	Mission **Adoption (TBC)** — Q4 2023

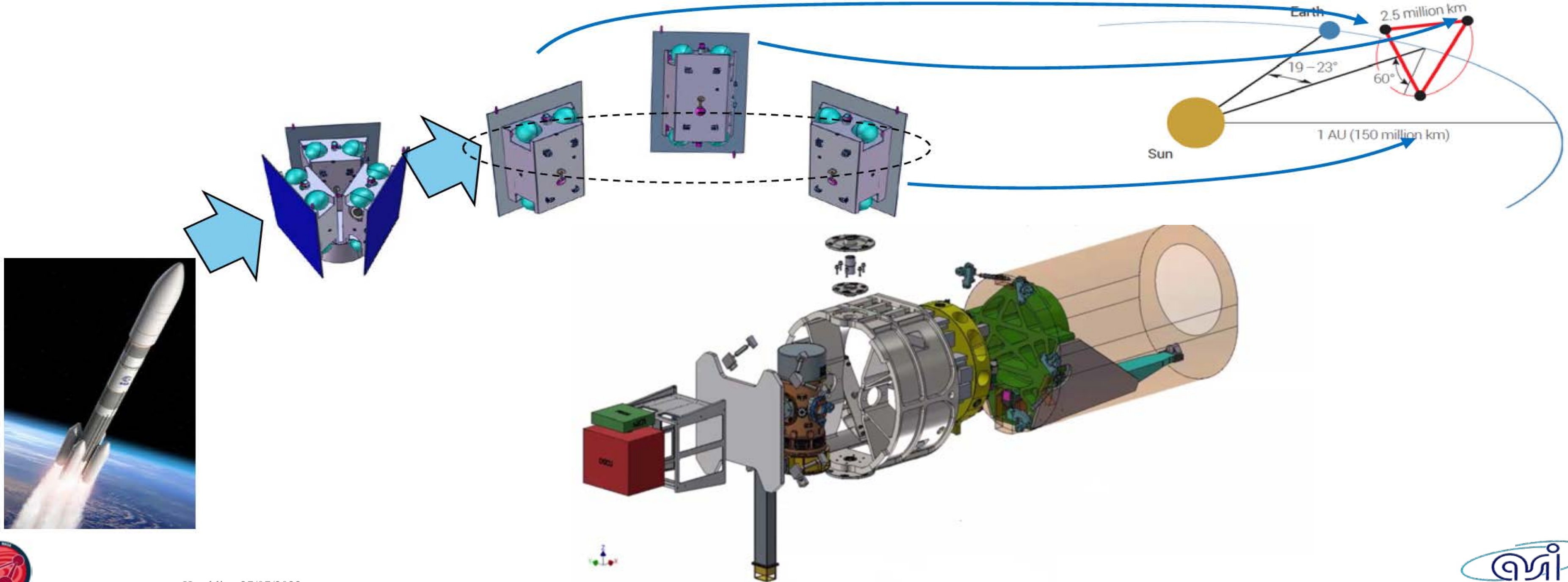
The ... well as
the p ... sortium.
The ... icipants
for their valuable contributions to the Review.

Timeline

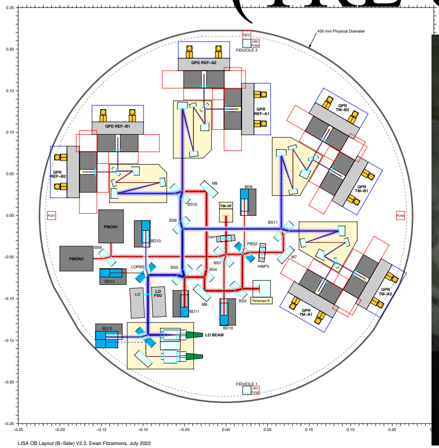
October 2013:	
October 2016:	
June 2017:	
May 2018:	
2018-2021:	
Oct '20-Oct '2	
<end 2021:	Formulation Review (end Phase A)
>2021:	Mission Phase B1
<2024:	Mission Adoption
>Adoption:	Mission Implementation (Phase B2/C/D)
<2034:	Launch
>Launch:	6.5 years operations (+6 years potential extension)

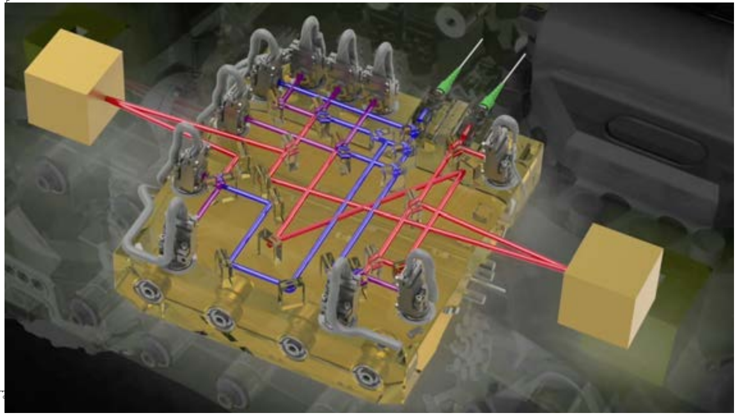
LISA currently in phase B1

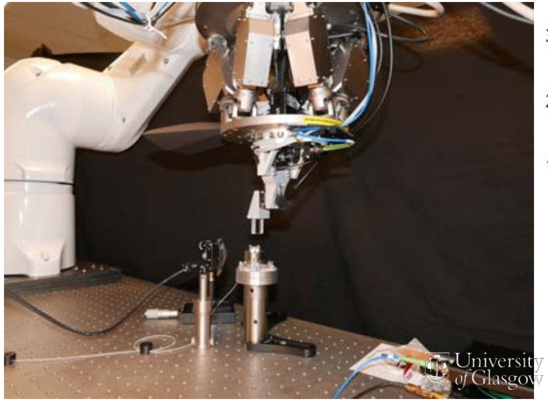
- Phase-A study competitive: cannot show much!
- A rather stable concept, working out the details

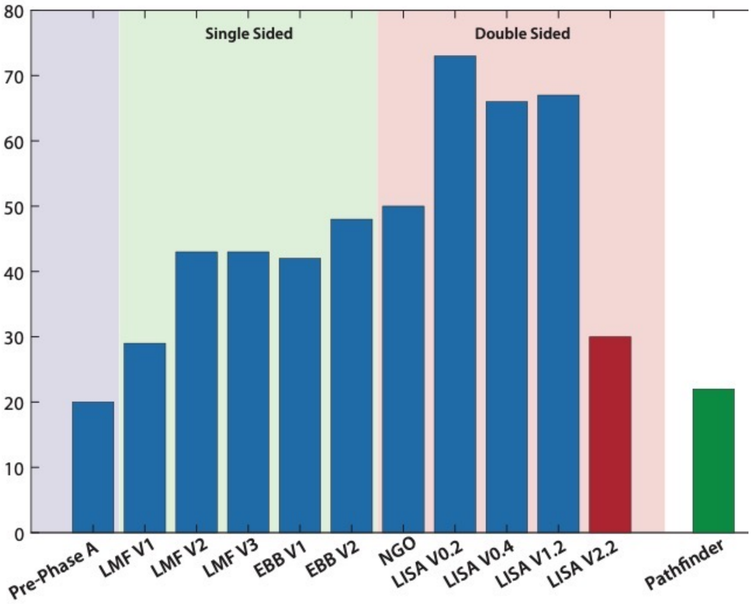


Technology developments (TRL 6 by adoption)

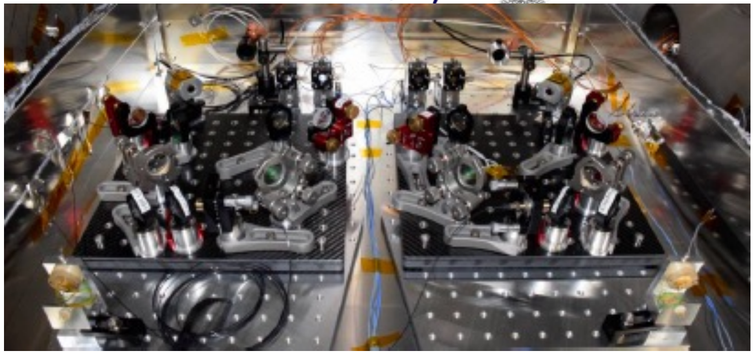






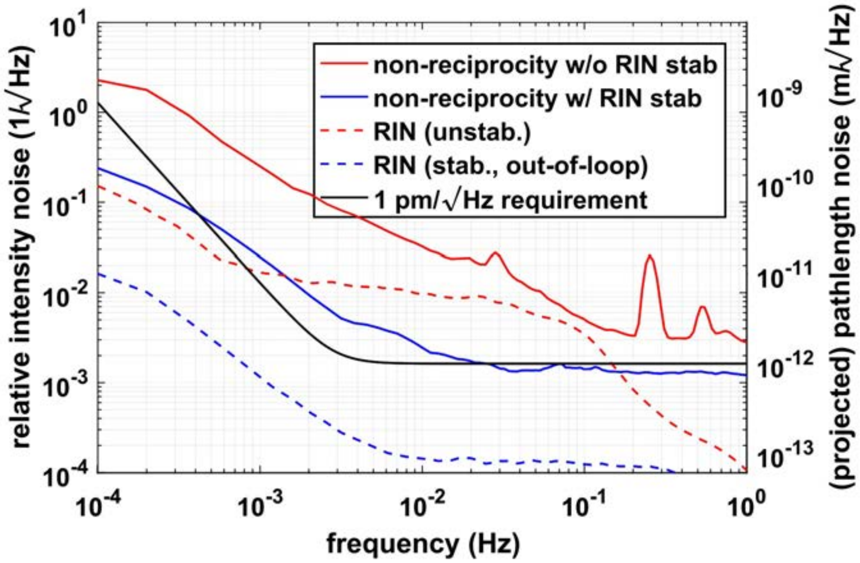


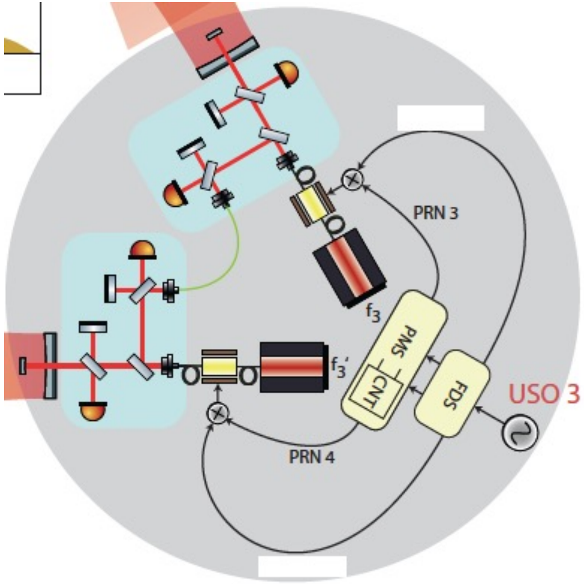
Technology developments (TRL 6 by adoption)



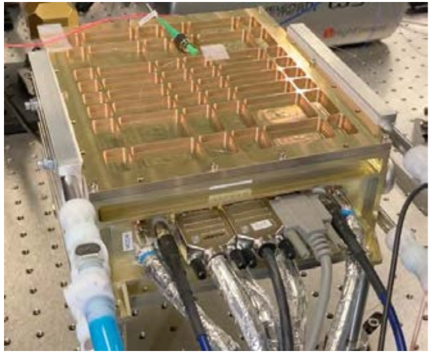
- The back link systems

Class. Quantum Grav. **35** (2018) 075007 R Fleddermann *et al*



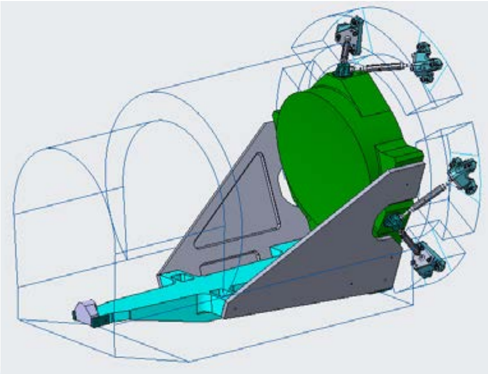


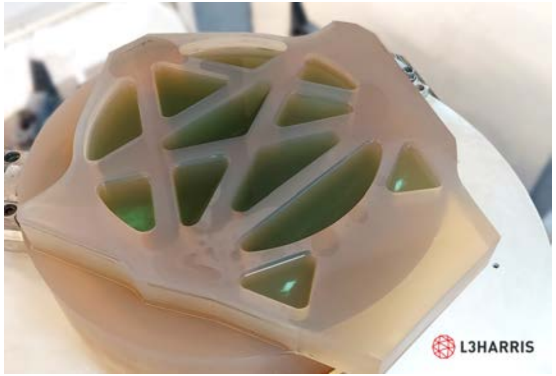
Technology developments (TRL6 by adoption)



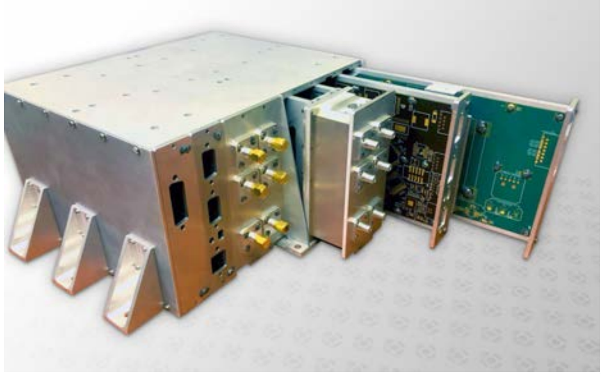
Laser

Telescope



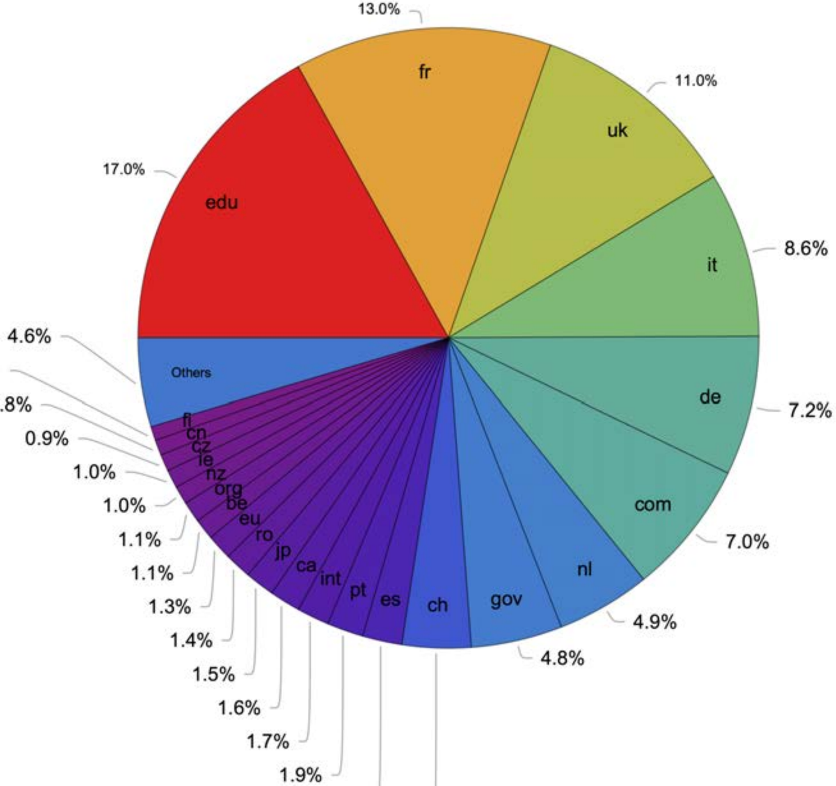


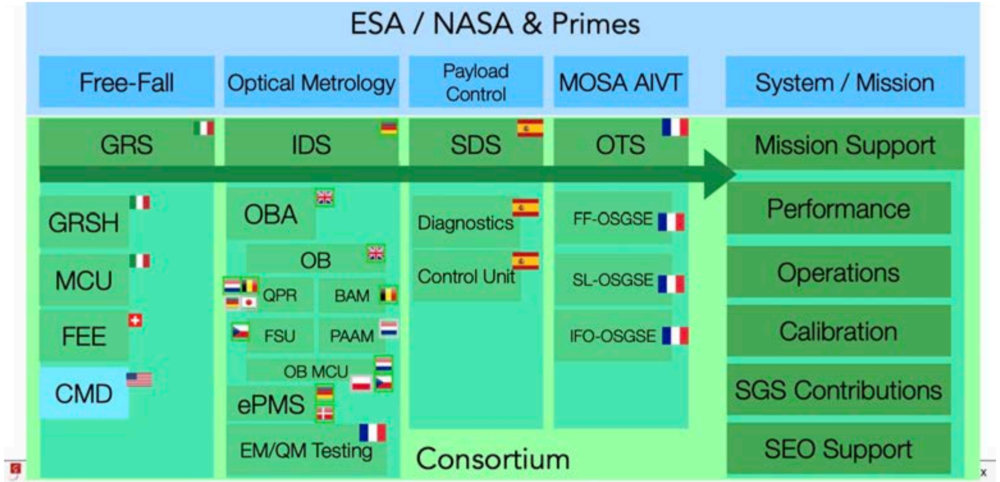
Charge management



The International Collaboration

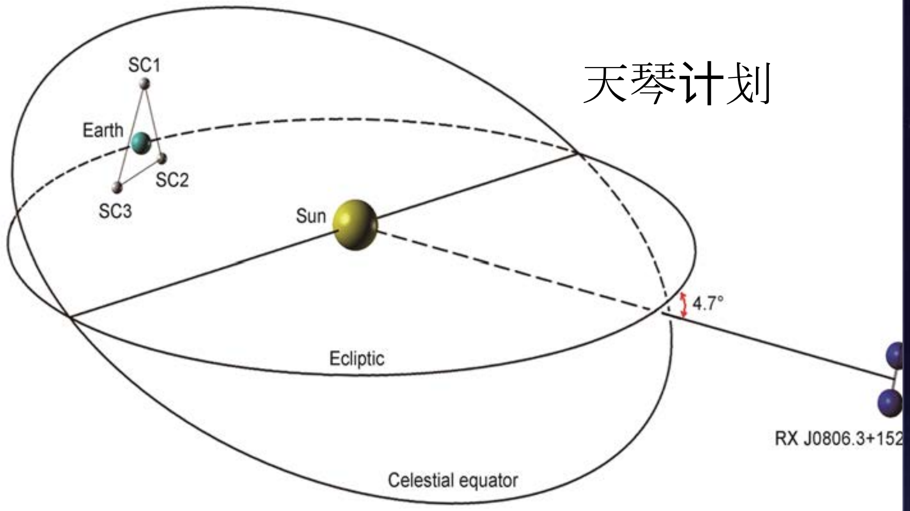
- The LISA Consortium (~~1437~~ 1612 members)





Beyond and besides LISA

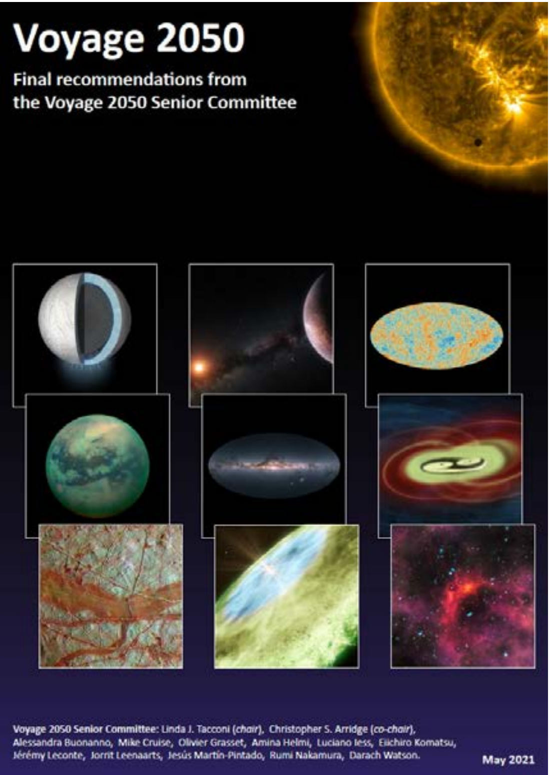
- Efforts in China



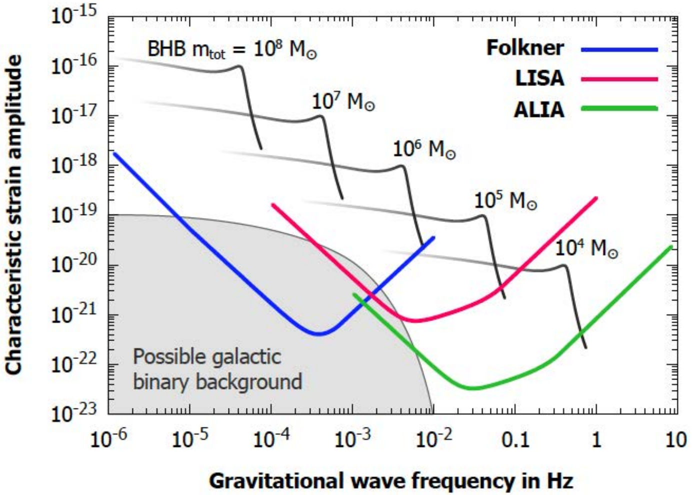
天琴计划

Beyond and besides LISA

- Planning for the future



- **New Physical Probes of the Early Universe.** How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from *Planck* and the expected scientific return from *LISA*.



Thank you!