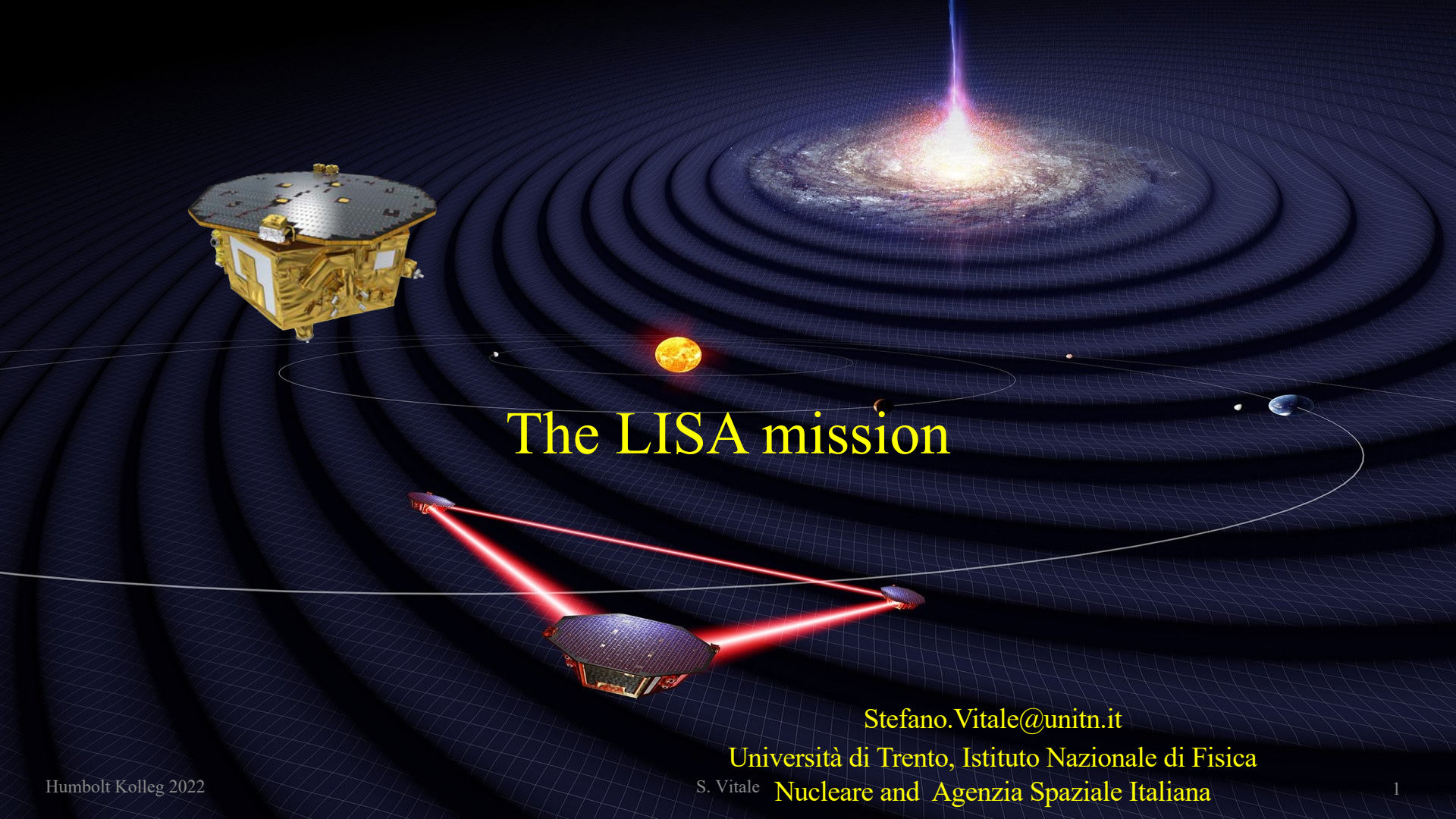
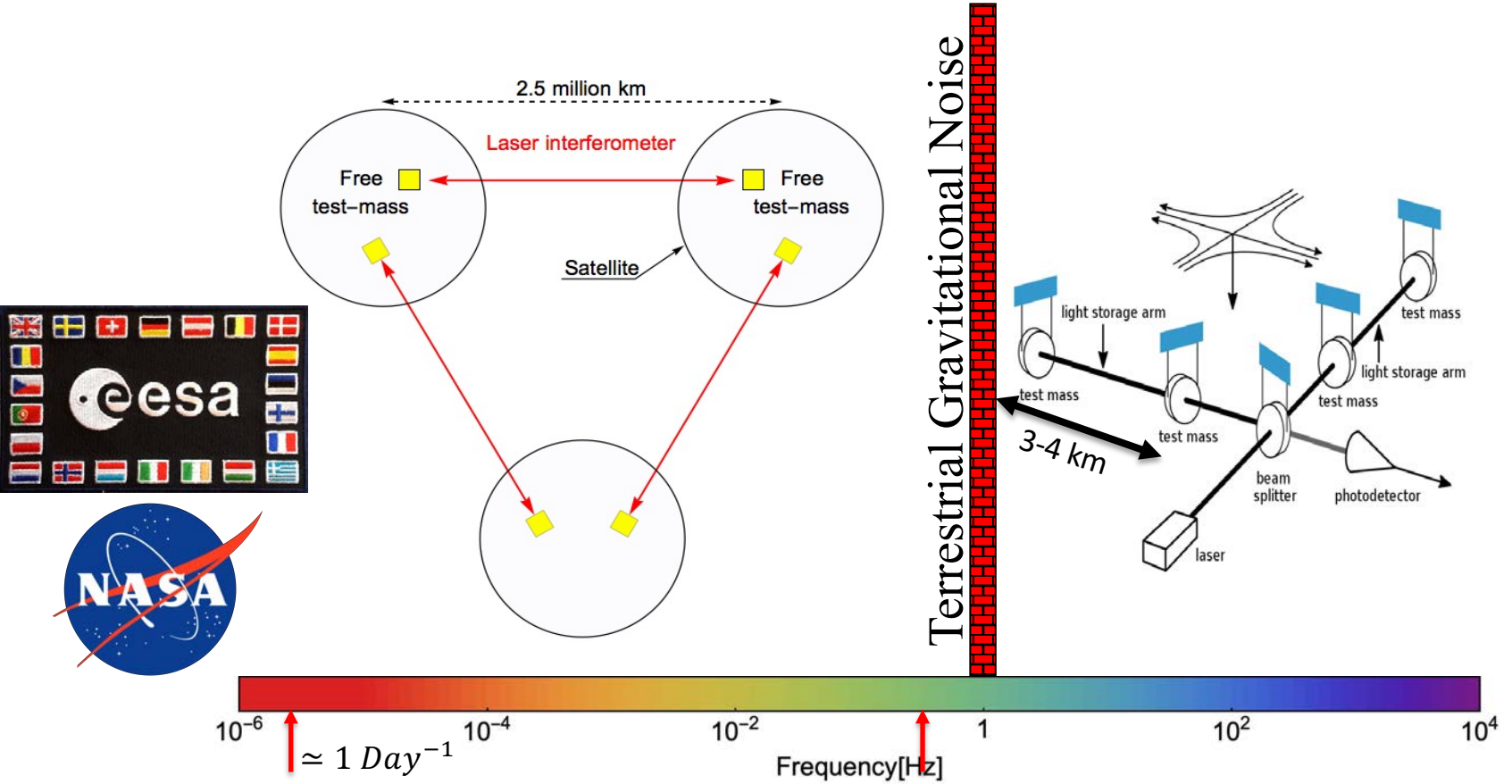


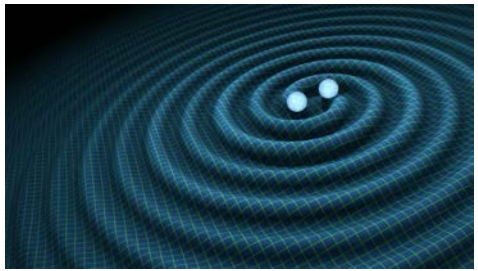
The LISA mission

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

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

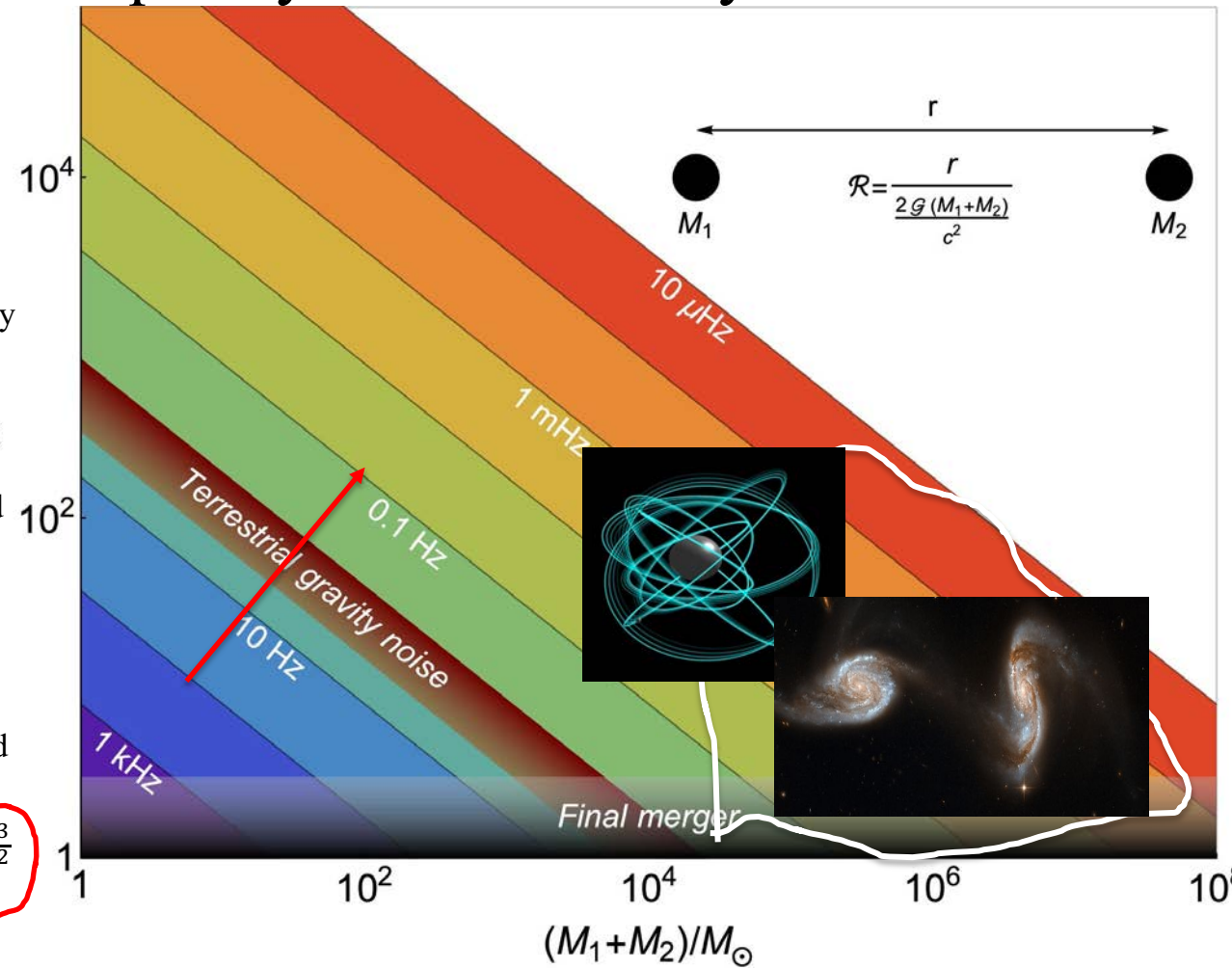
- Separation normalized to Schwarzschild radii:

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

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

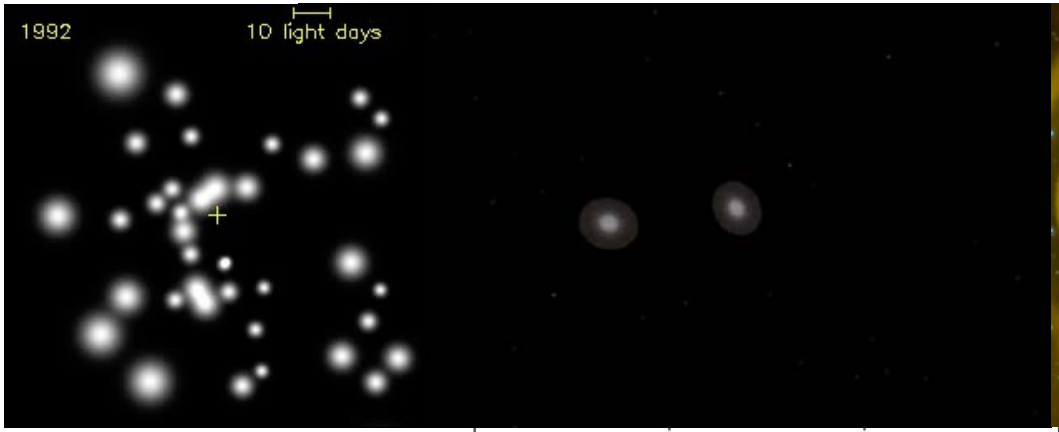
- Frequency decreases with both mass and $\mathcal{R}$

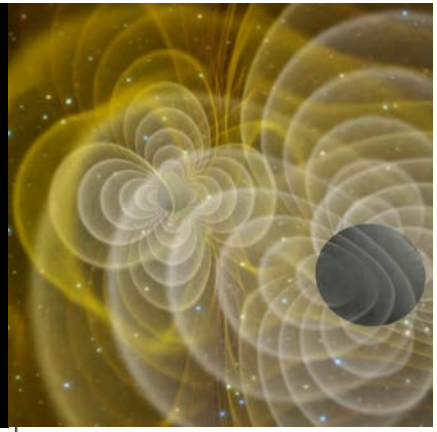
$$f_{GW} = \frac{c}{\pi\sqrt{2}\,R_\odot}\left(\frac{M_1 + M_2}{M_\odot}\right)^{-1}\mathcal{R}^{-\frac{3}{2}}$$

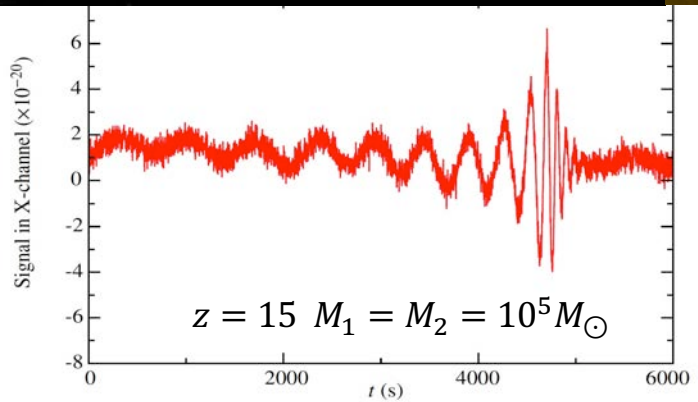


Supermassive BH mergers: the brightest sources

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

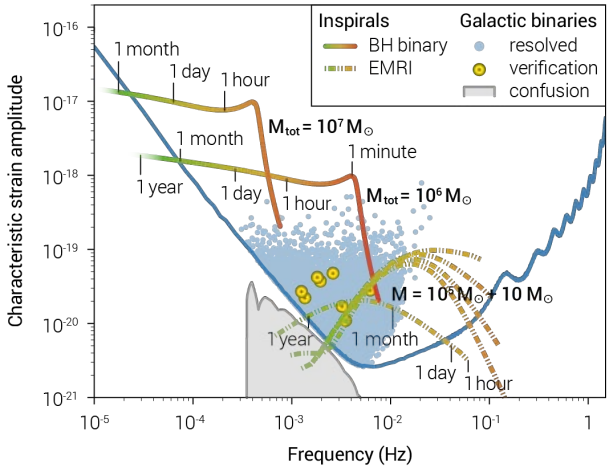


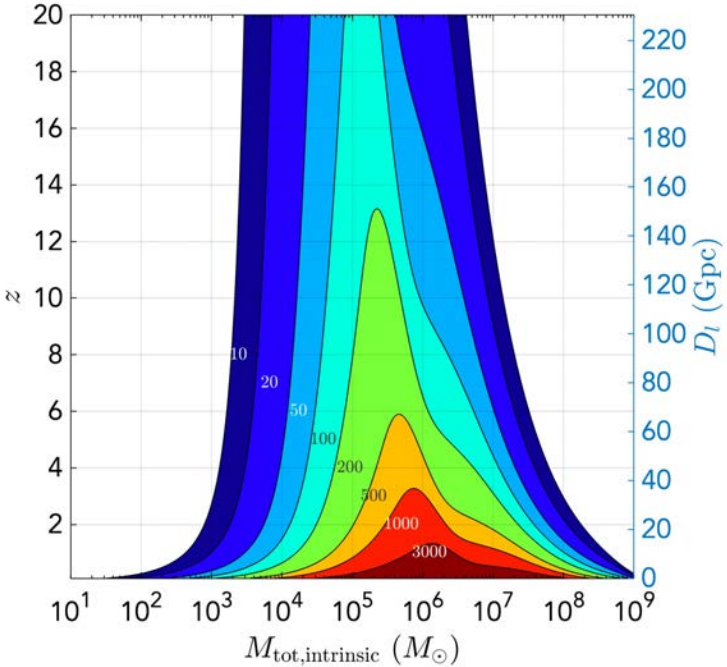


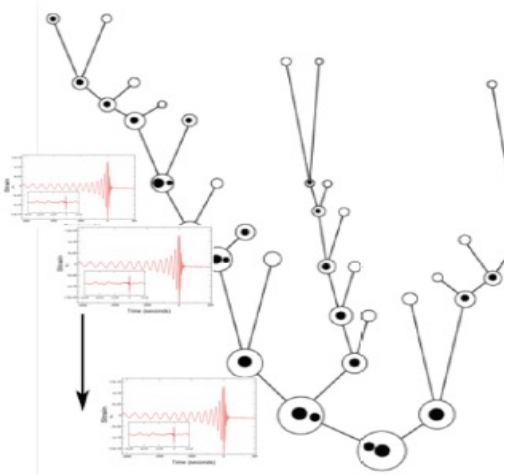


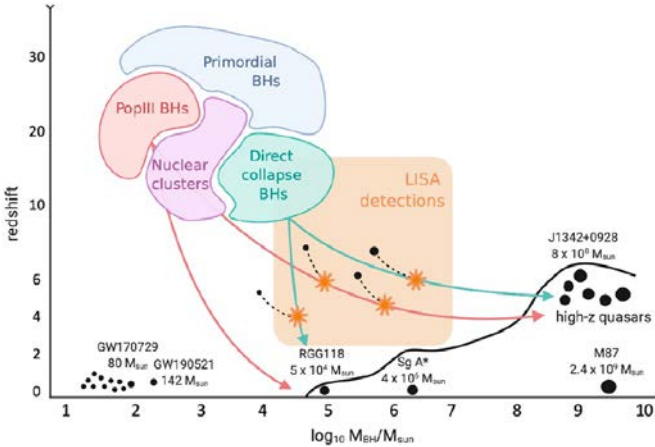
Supermassive BH mergers: the brightest sources

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



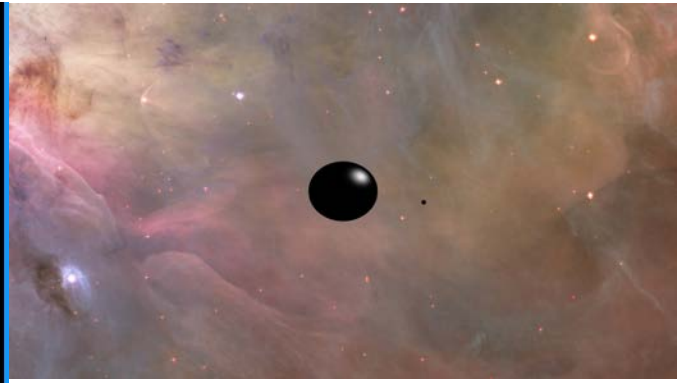


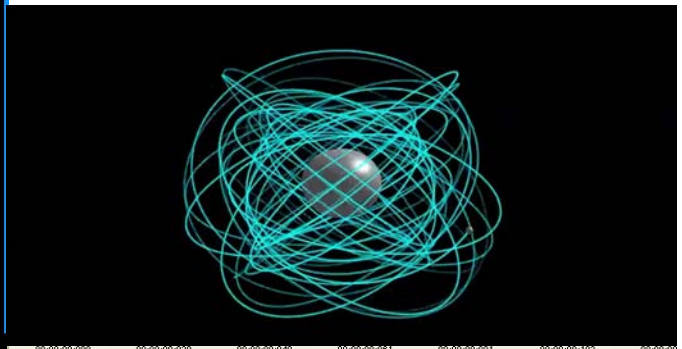


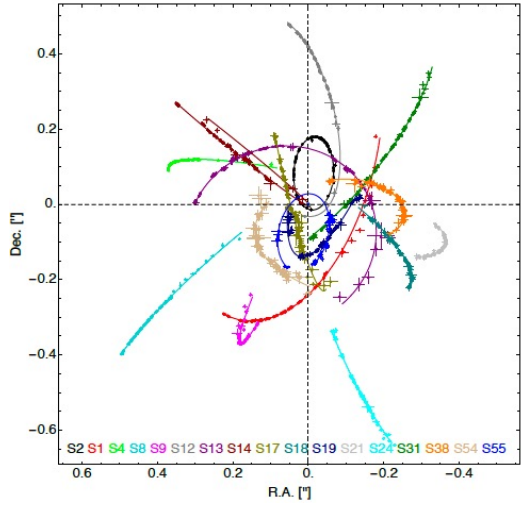


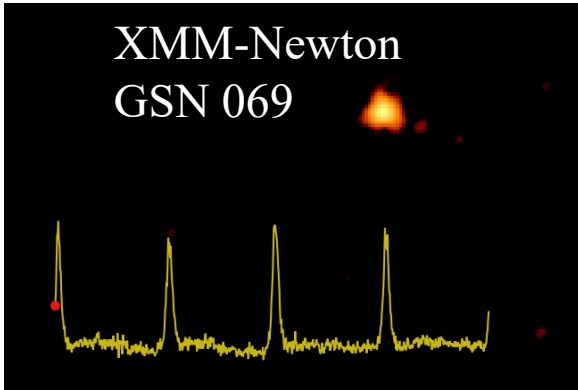
Extreme Mass Ratio Inspirals

- 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)

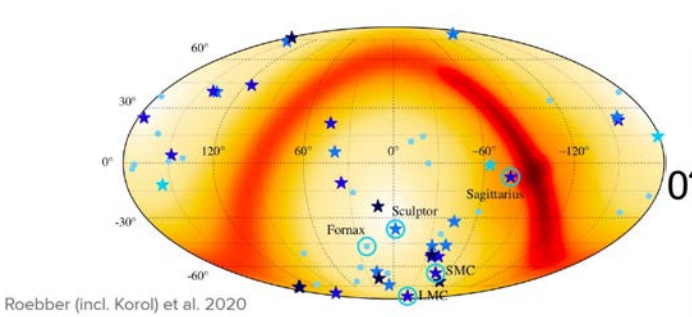






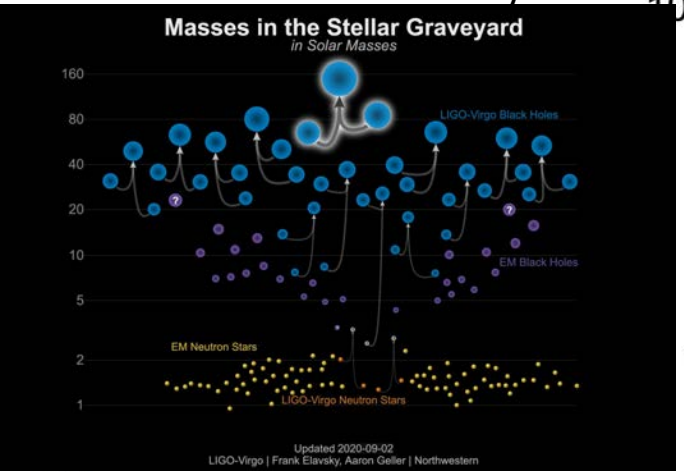


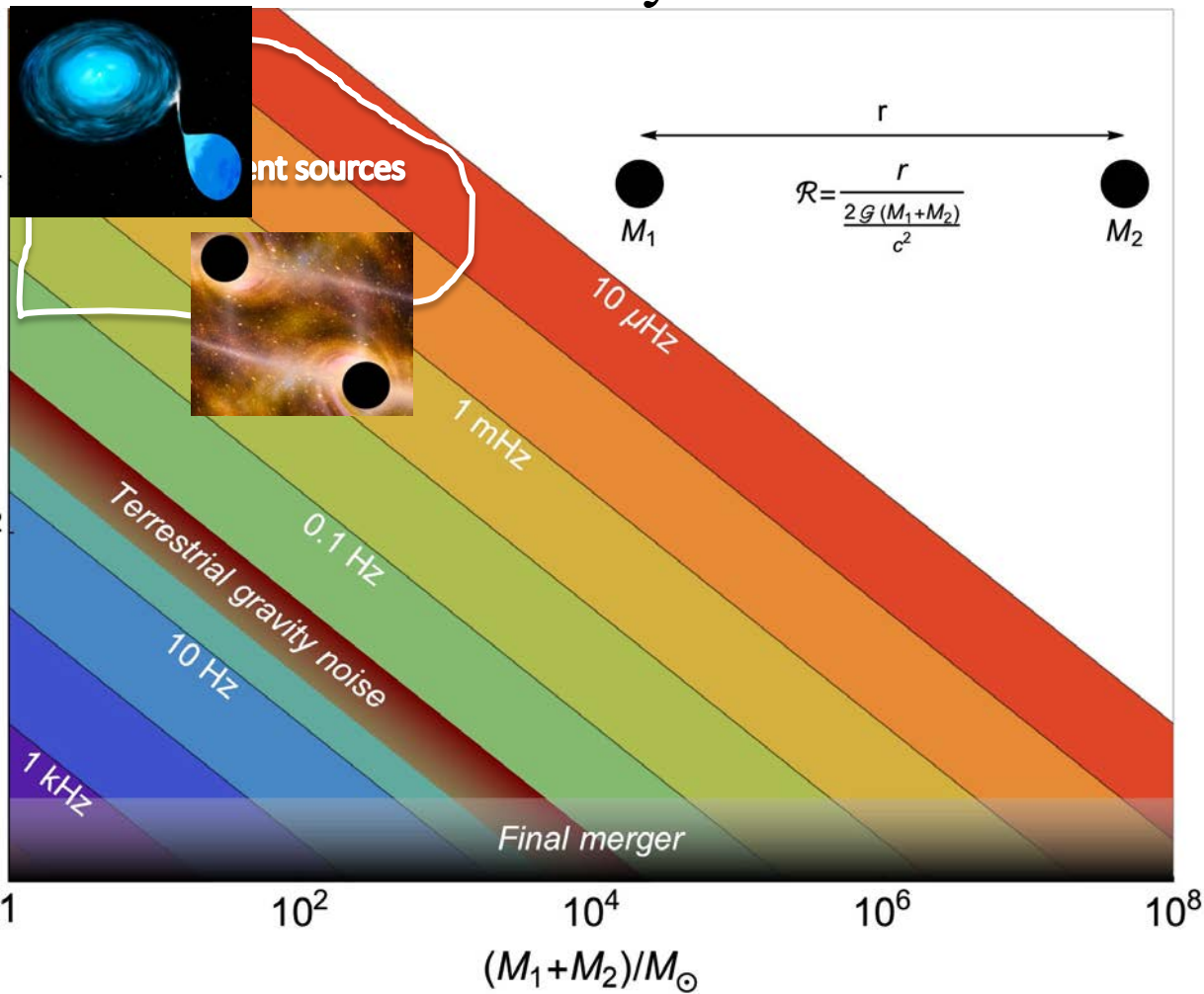
Non-transient GW astronomy



Roebber (incl. Korol) et al. 2020

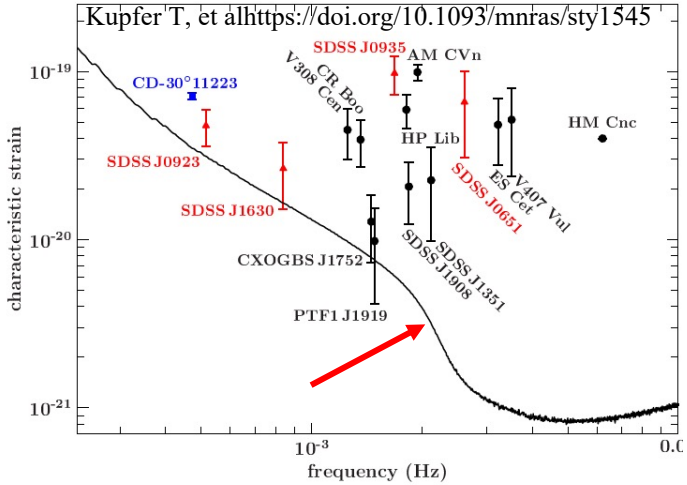
- GW-binary astronomy of local group
- BH multi-band astronomy

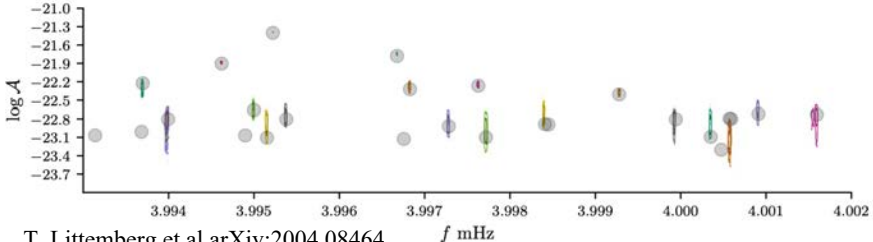




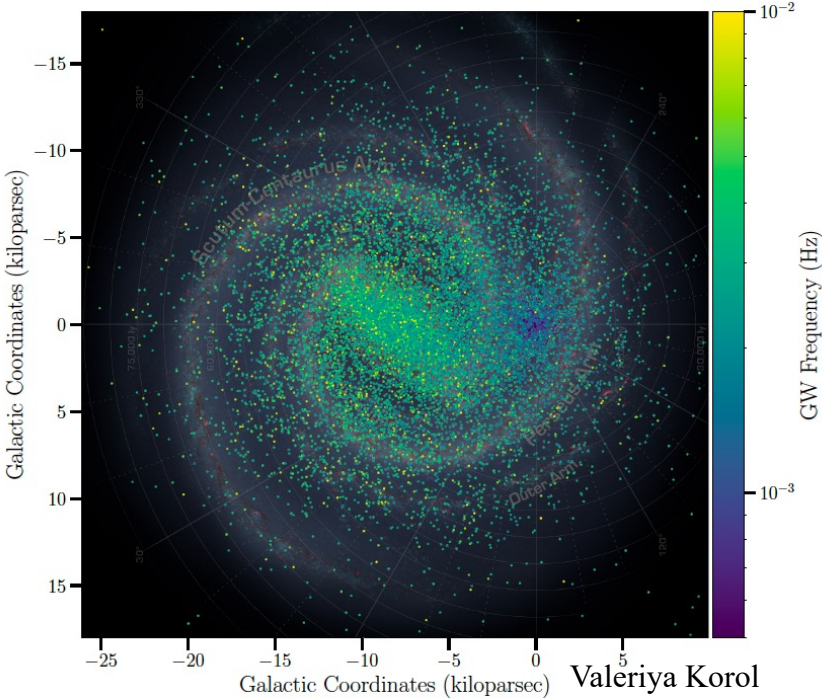
The high $\mathcal{R}$ end: the GW Milky Way

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





T. Littenberg et al arXiv:2004.08464



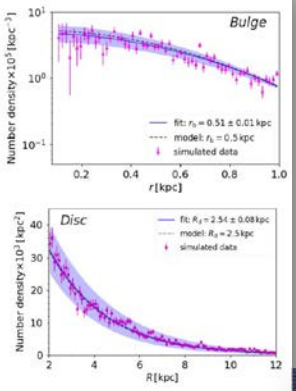
Expectations

The shape of the Milky Way's components

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

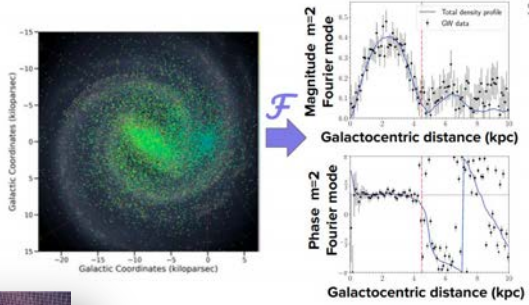
- Bulge scale radius to 2%
- Disc scale radius to 3%
- Disc scale height to 16%

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)

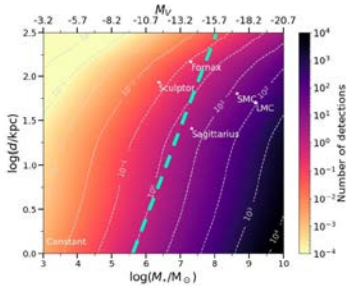
The detection of circumbinary exoplanets

Camilla DANIELSKI

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

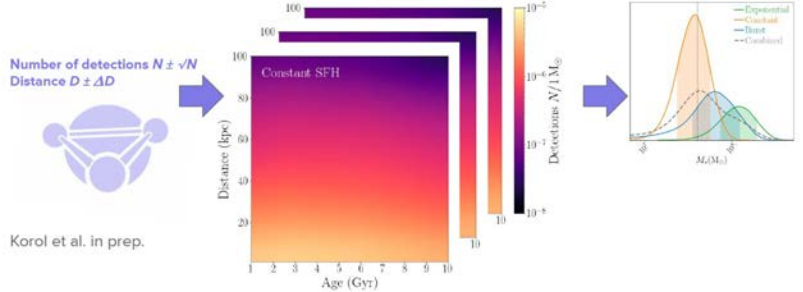
See talk by Riccardo Buscicchio



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

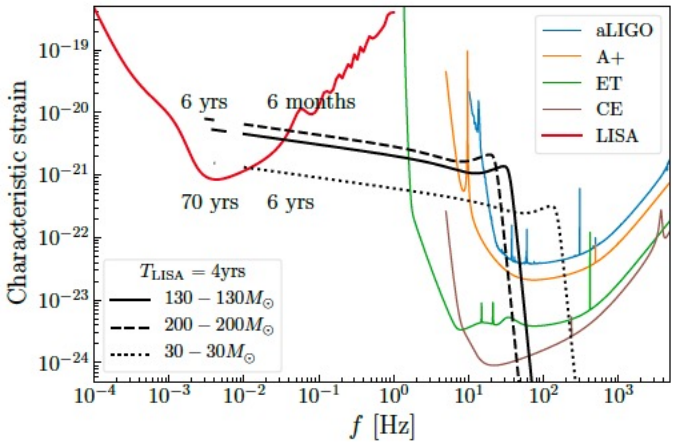
Weighing Milky Way satellites

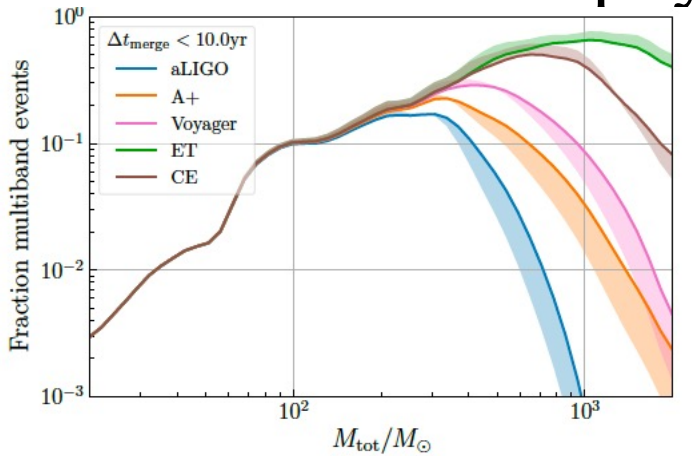
By exploiting our models we can recover the satellite's total stellar mass: to within a factor two if SFH is known and to an order of magnitude when marginalising over different SFH models. If no detections are identified with the satellite we can still place an upper limit on its stellar mass.



Korol et al. in prep.

Multi-band GW astronomy and fundamental physics





Joint observation greatly improves measurement of deviation from GR

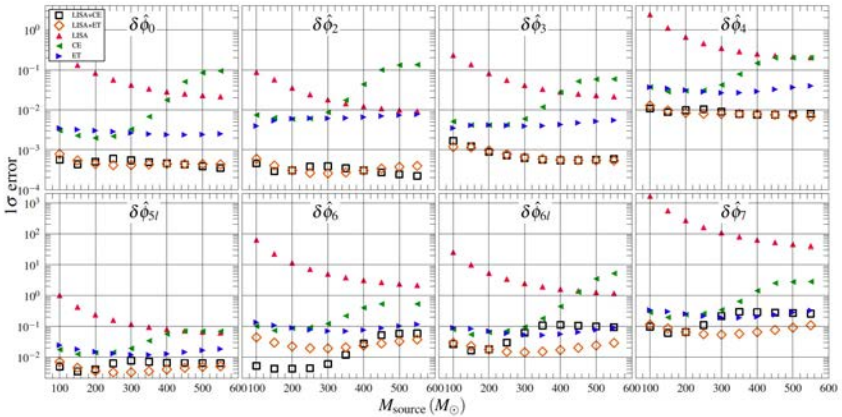
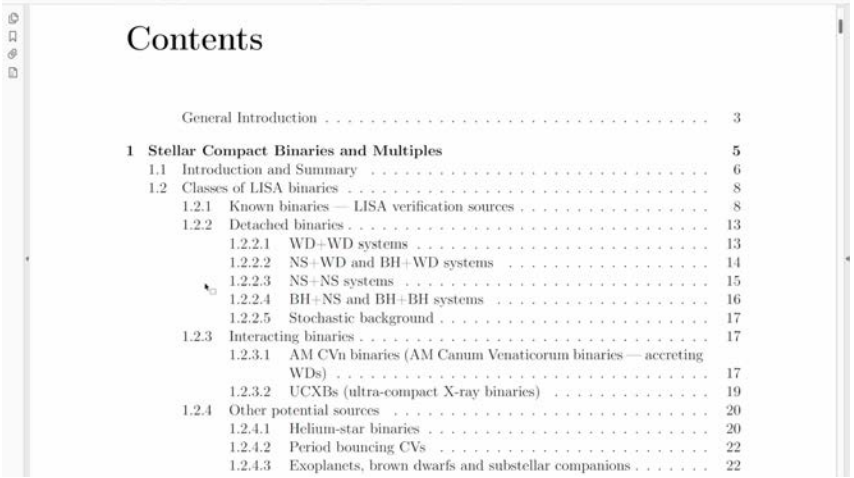


FIG. 3. Top panel shows bounds on deformation parameters at 0PN to 2PN, as a function of total mass in source frame. Bottom panel shows the same but for deformation parameters at 2.5PN to 3.5PN. All the systems have mass-ratio $q = 2$, dimensionless component spins $\chi_1 = 0.2$ and $\chi_2 = 0.1$,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

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

Interesting reading

Astrophysics with the Laser Interferometer Space Antenna



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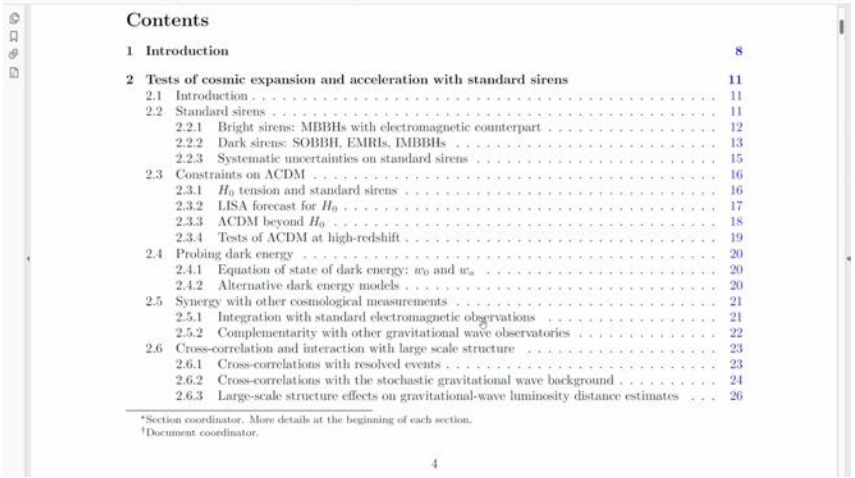
arXiv:2204.05434v1 [astro-ph.CO] 11 Apr 2022

Cosmology with the Laser Interferometer Space Antenna



Contents

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

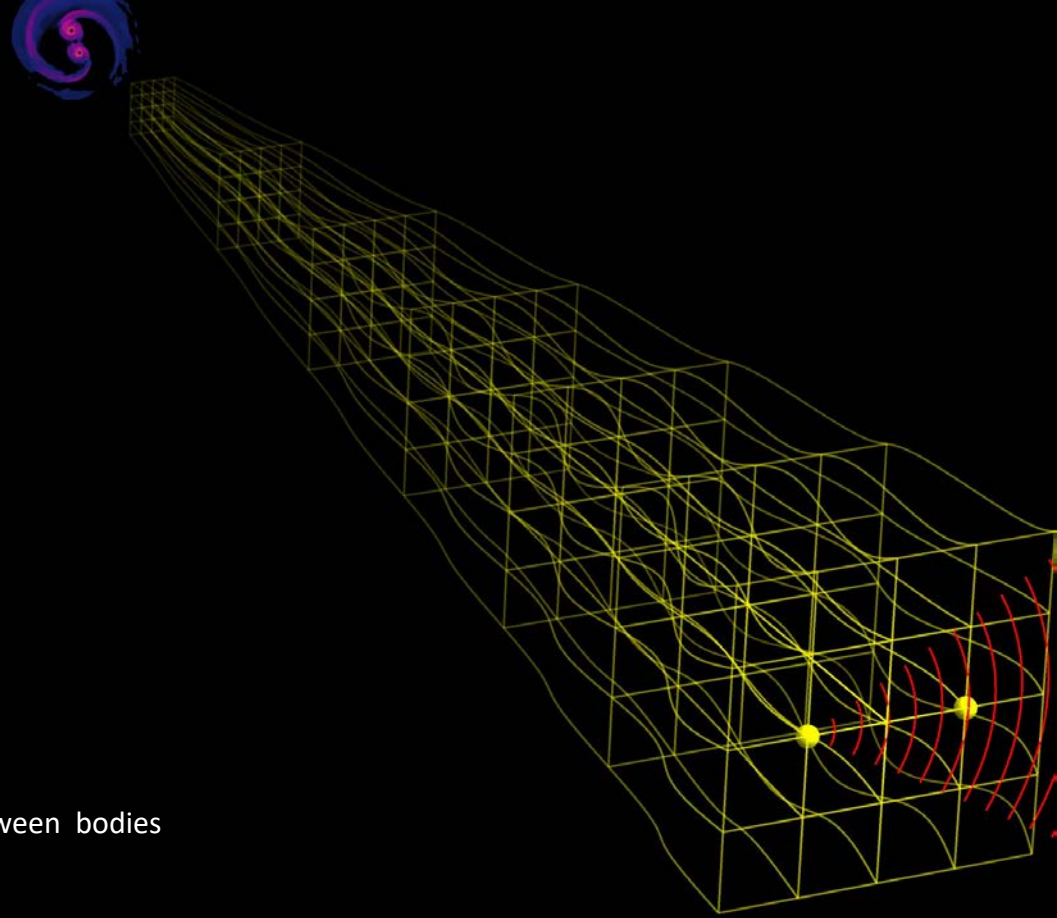
4

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

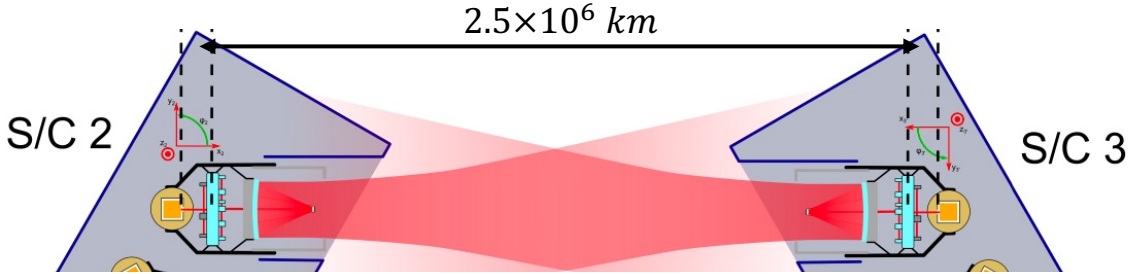
Detecting gravitational wave in space

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

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



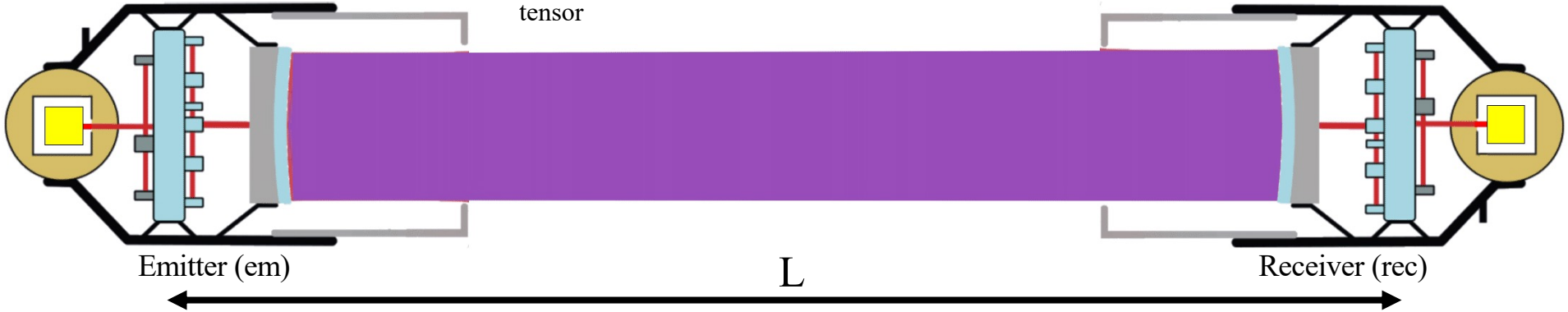
LISA



The LISA link

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

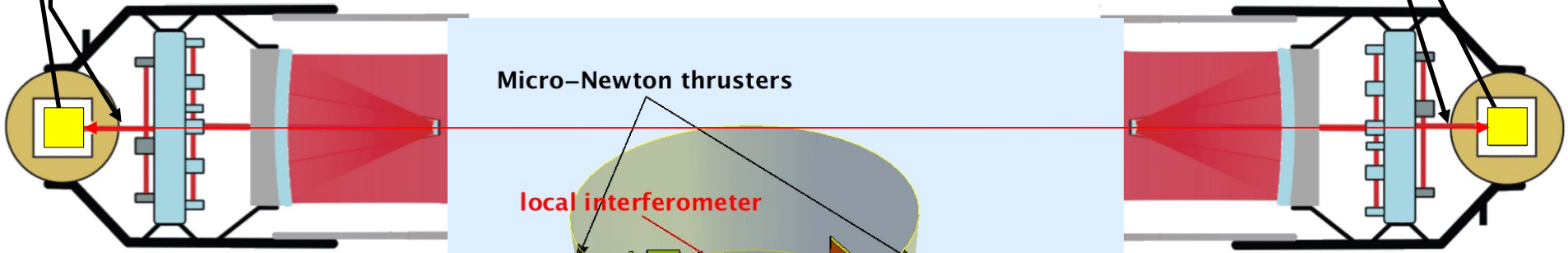
Curvature tensor

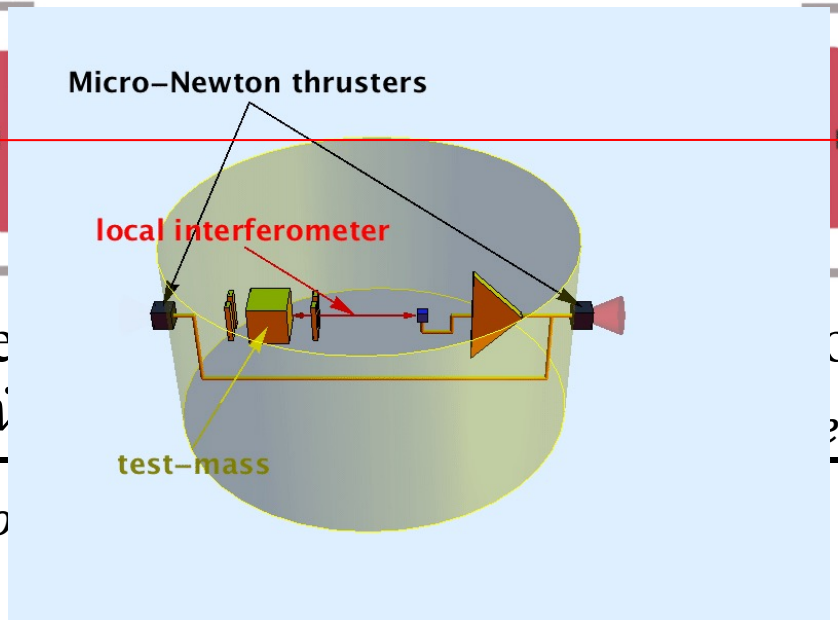


- Acceleration of spacecraft via standard Doppler effect also shifts frequency and mimics GW $\frac{\Delta\dot{\nu}}{\nu_o} = cR^{x}{}_{0\,x\,0}L + \frac{a_{rec}-a_{em}}{c}$
- Spacecraft (S/C) accelerate too much because of solar radiation pressure

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

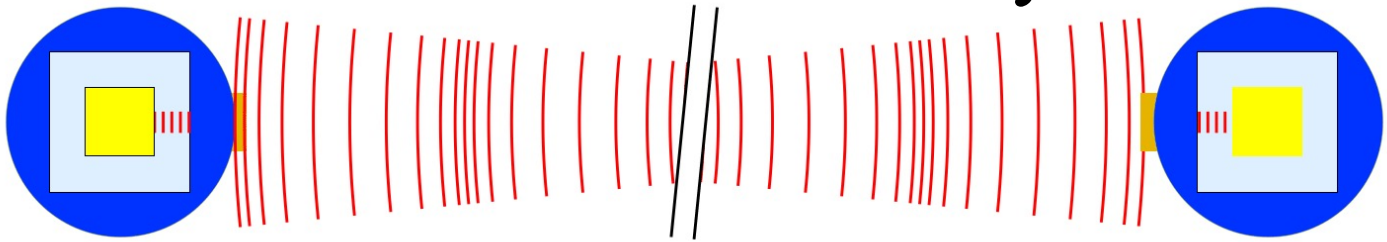




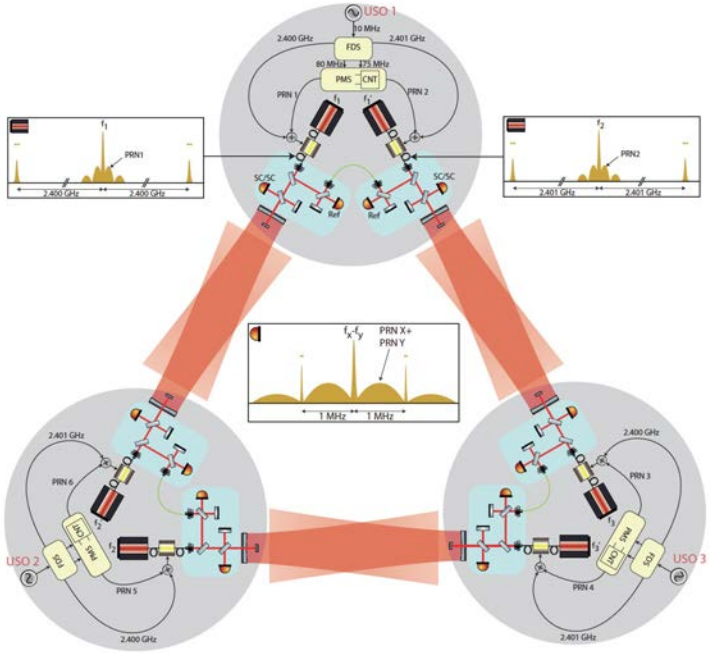
- Residual noise due … o local inertial frame

$$\frac{\Delta v}{v_o} \qquad \ldots em$$

LISA interferometry



- The LISA arm: two counter-propagating links.
- LISA 3 arms: 6 single-link frequency signals, 100 pW interferometry, $\simeq 10\ pm/\sqrt{Hz}$ equivalent test-mass displacement.
- To beat laser noise, data processing requires knowledge of light travel time within 3 ns/1 m. Done with internal "laser GPS"



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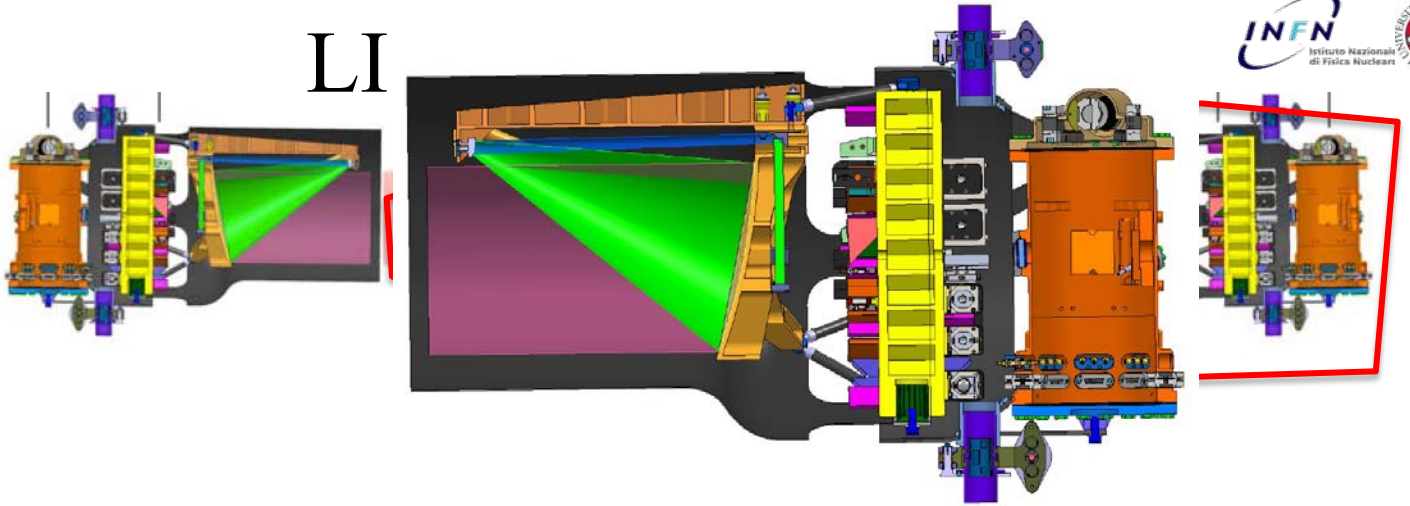
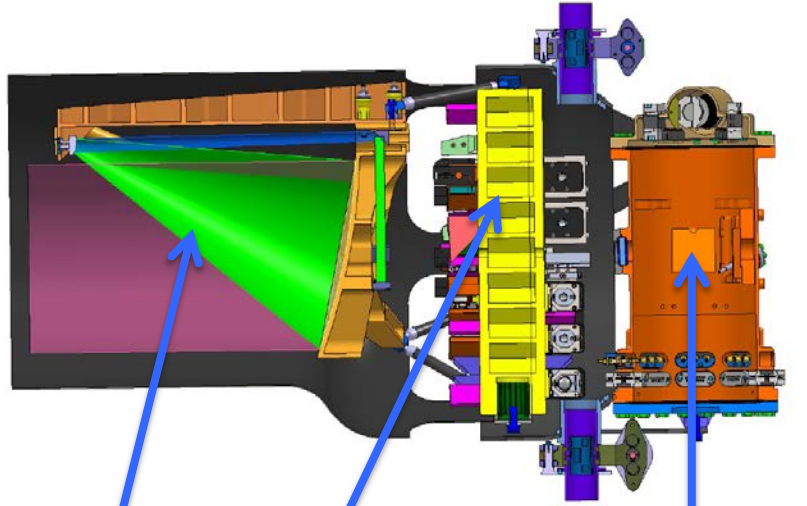
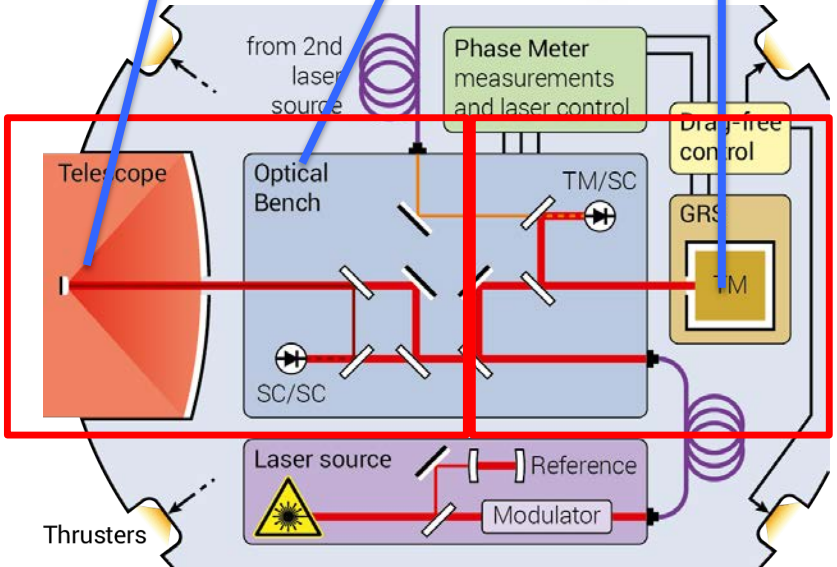
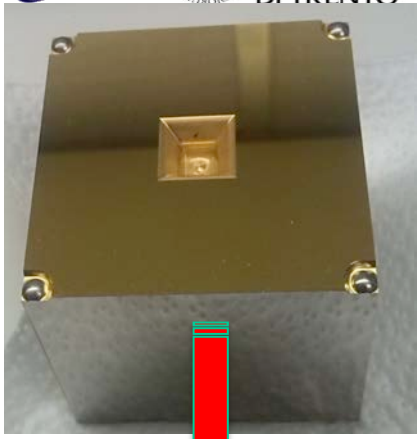


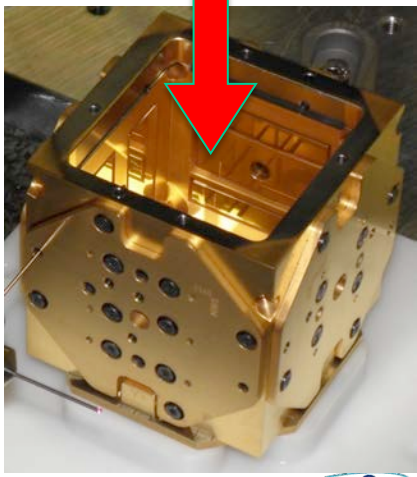
LISA link Instrument

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

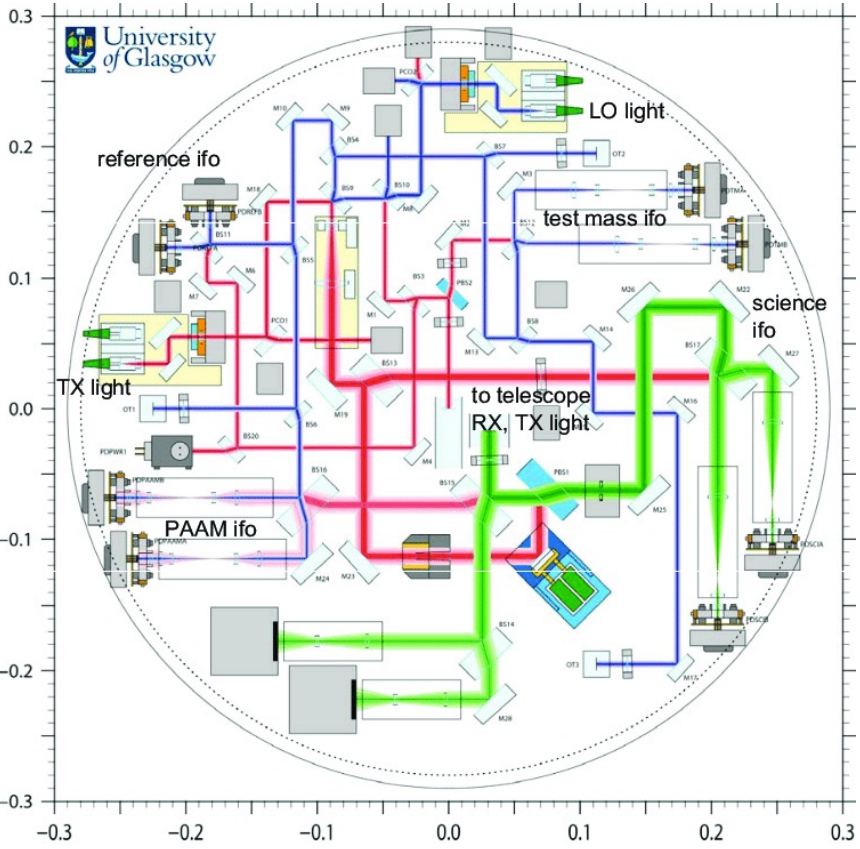








The optical bench



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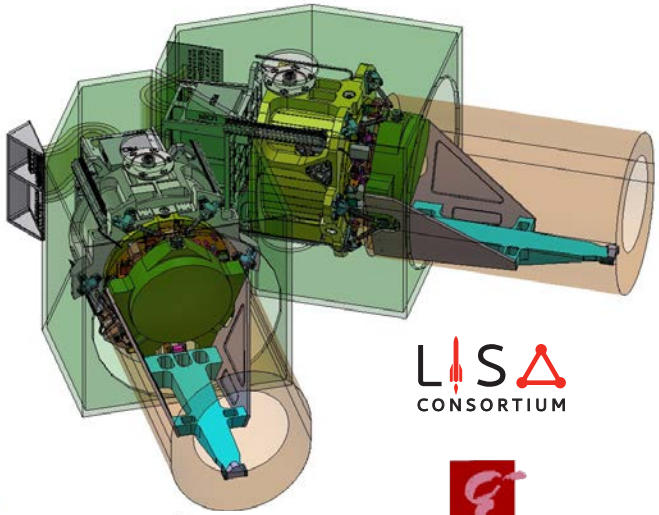
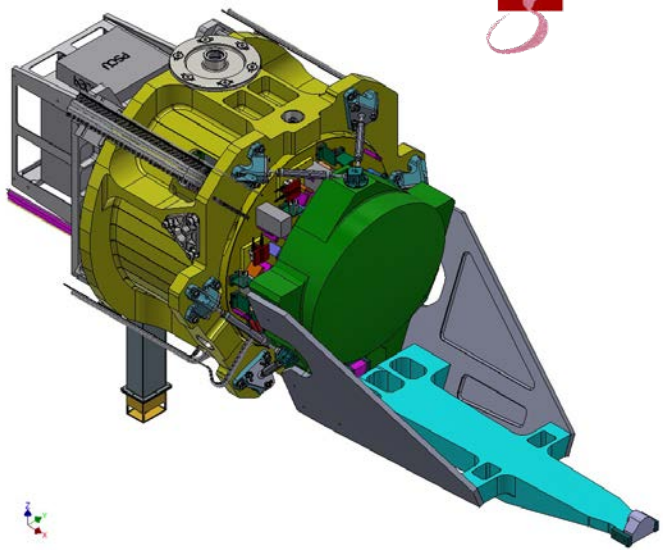
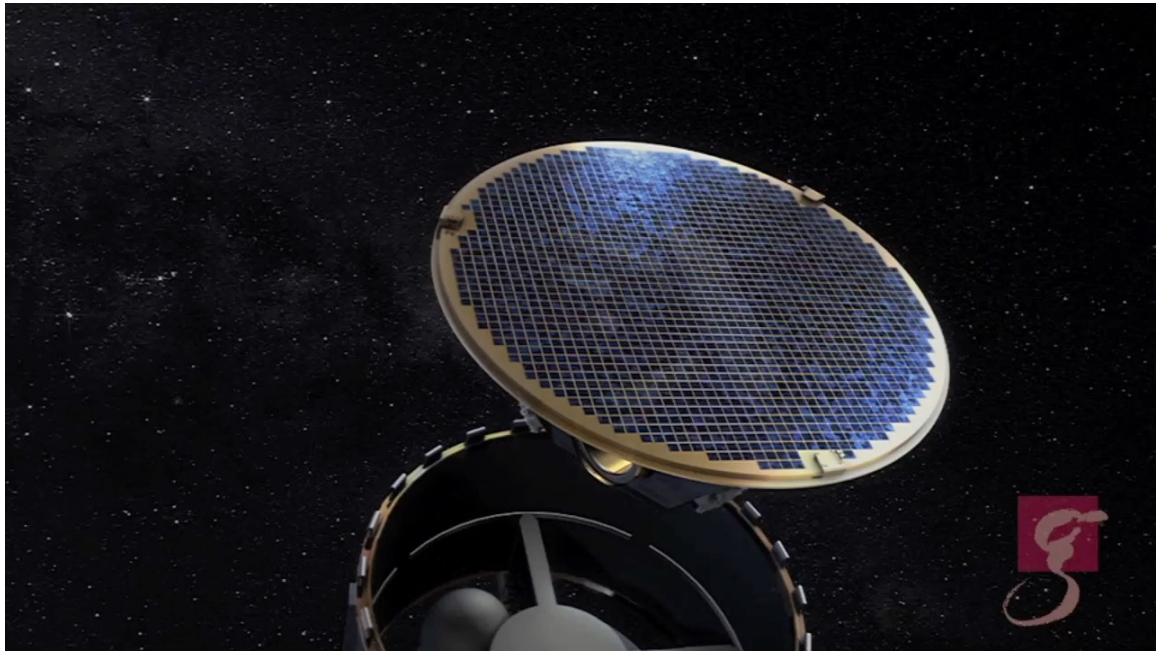
The full complement

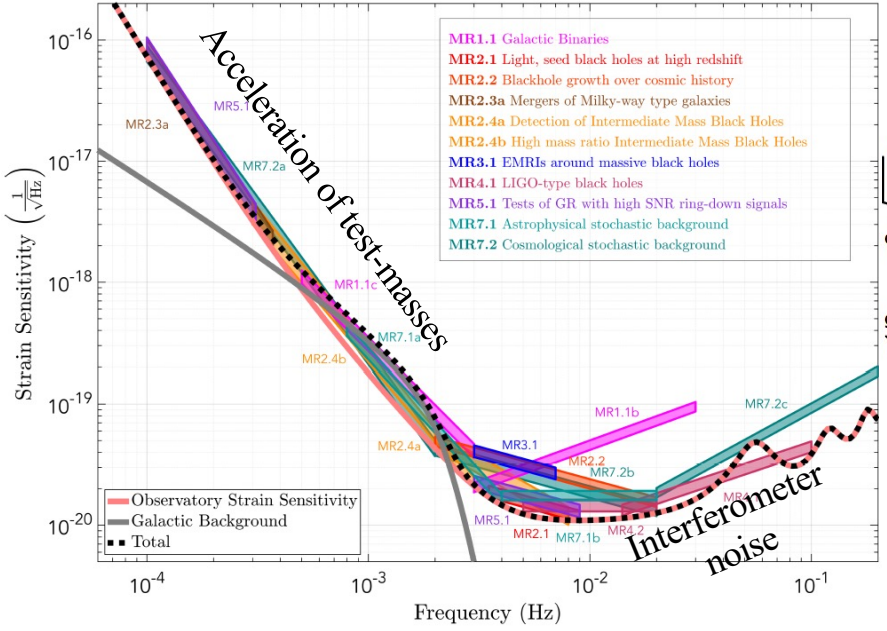


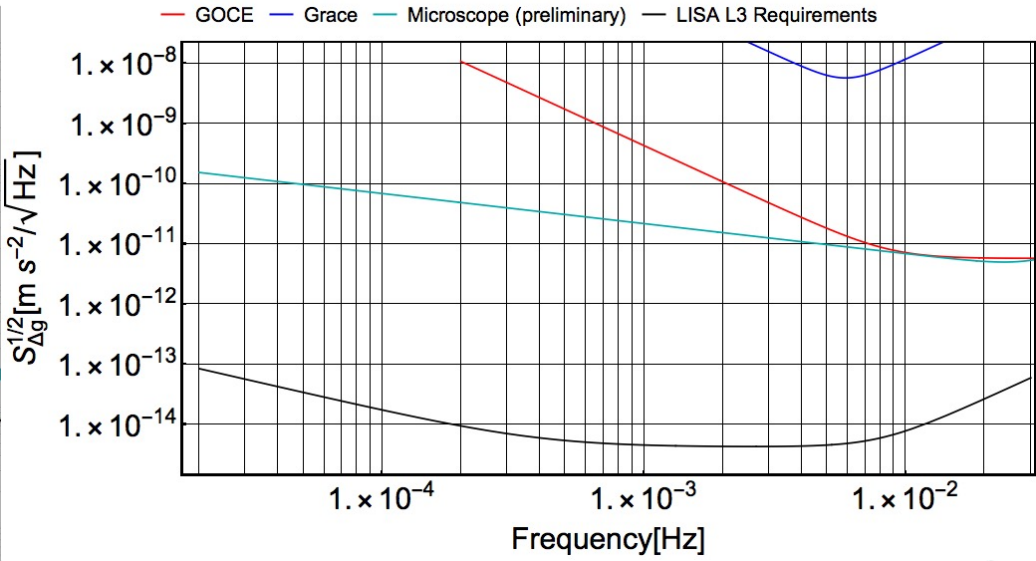




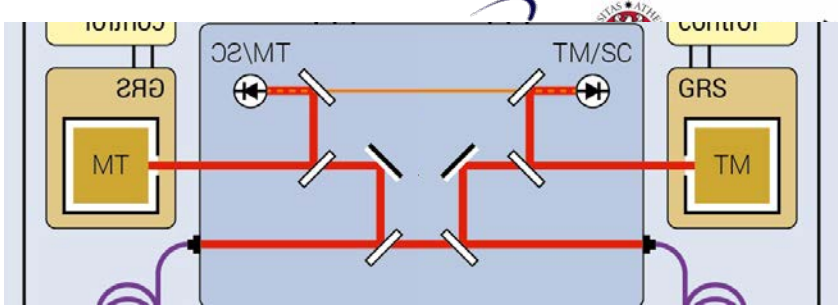
Acceleration noise and LISA science

- 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 $\preccurlyeq 10$ mHz
- Acceleration noise $\leq femto\ g/\sqrt{Hz}$
- Cannot be demonstrated on ground or in LEO

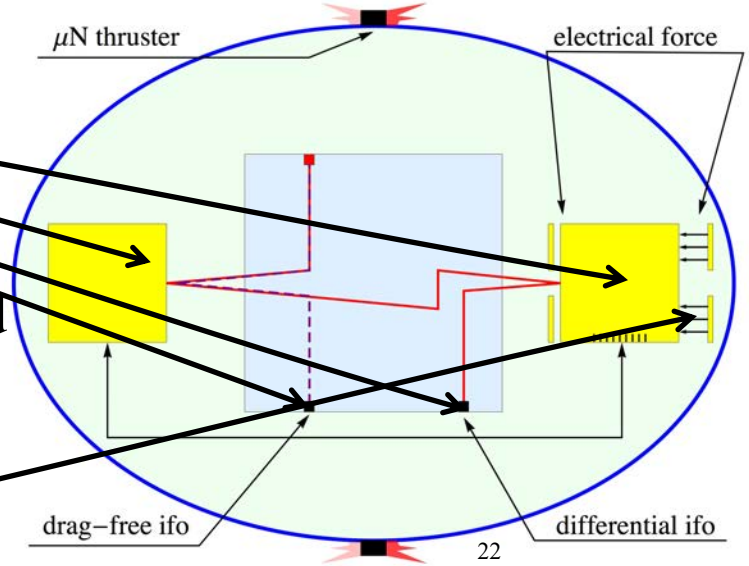




LISA Pathfinder

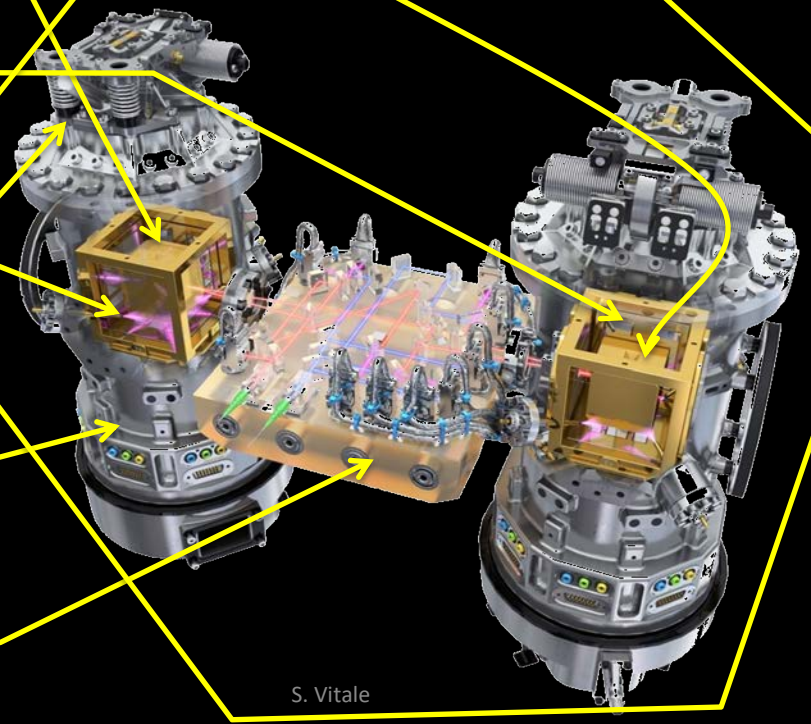


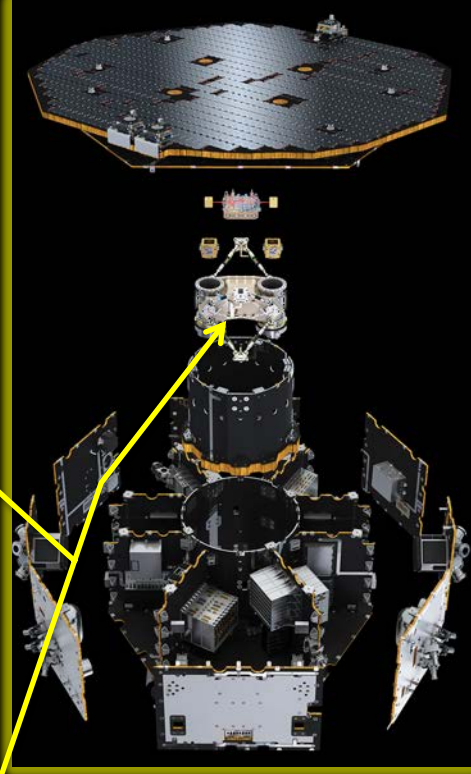
- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- 2 Interferometers (Ifo)
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



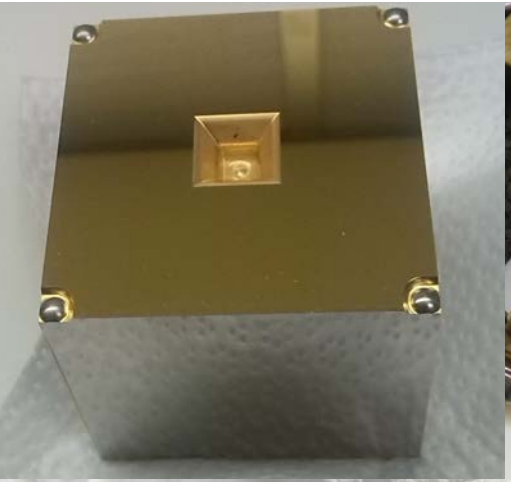
The LTP

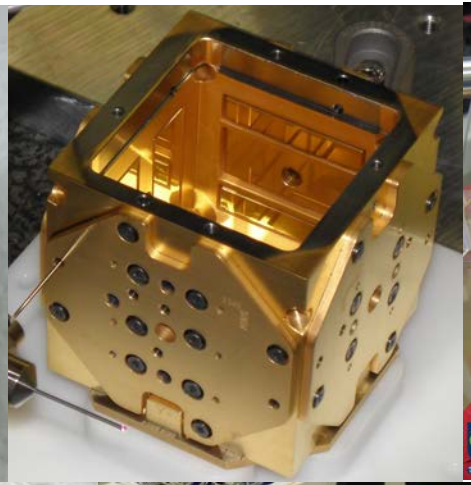
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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

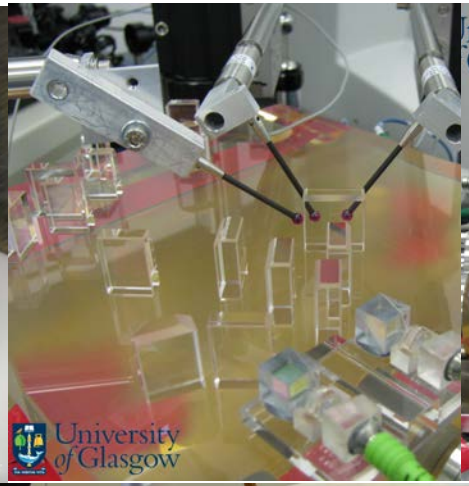


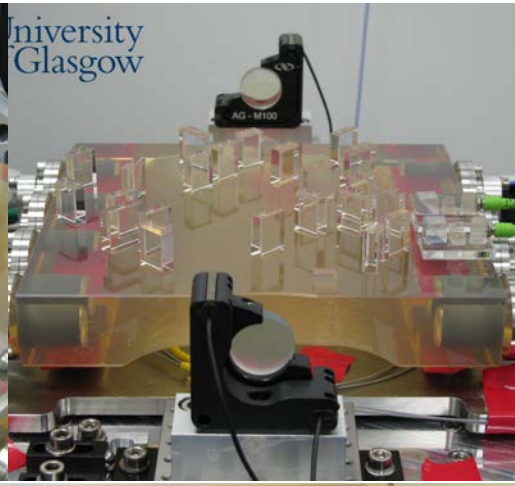


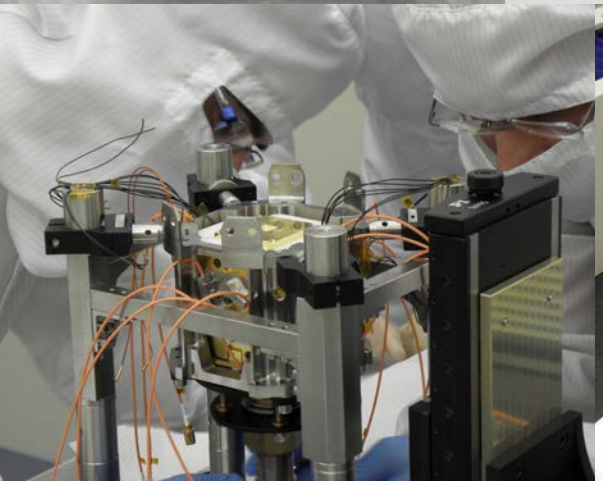
The real H/W

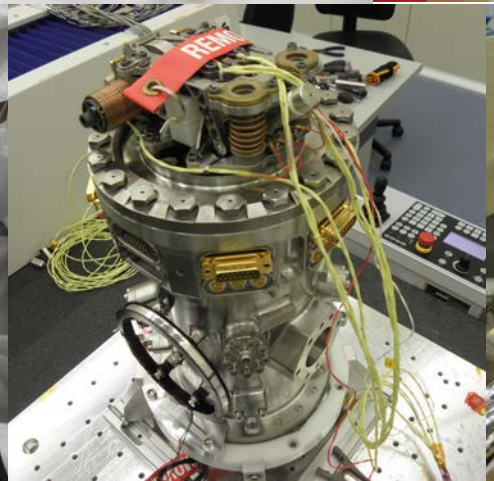




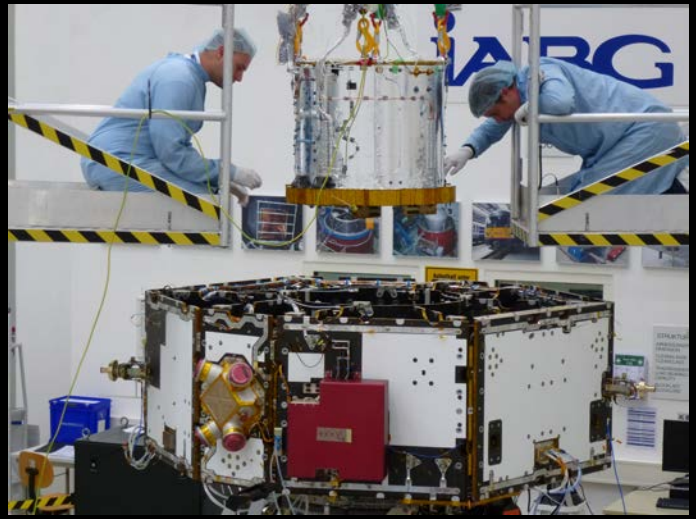


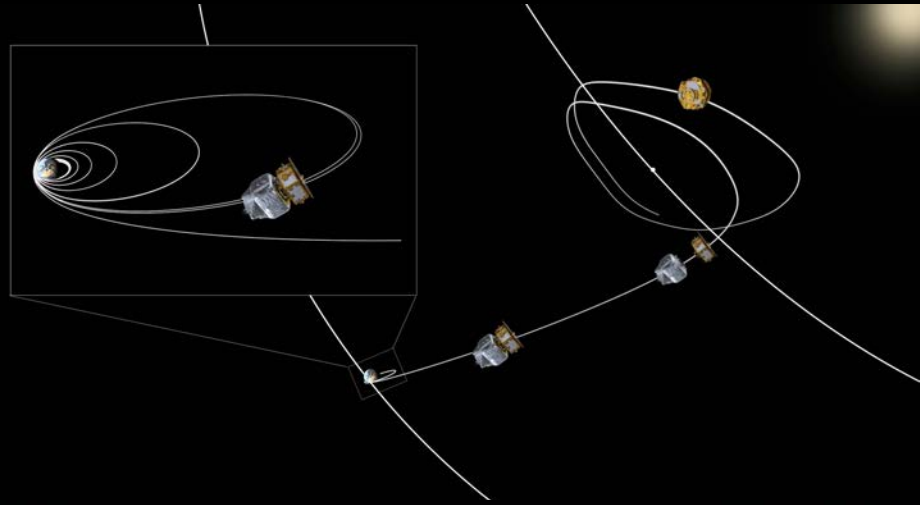






Instrument integration

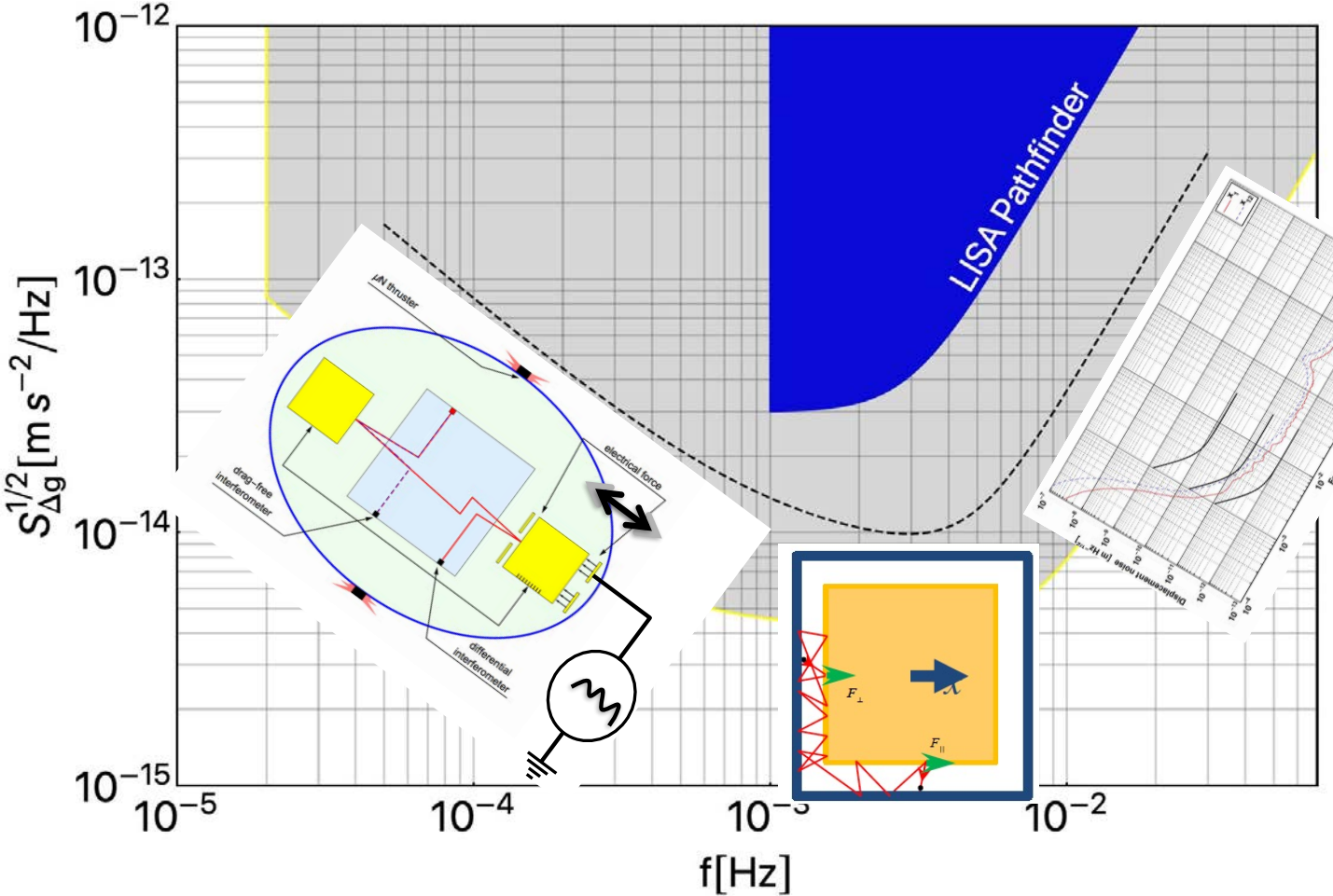




From instrument integration to orbit

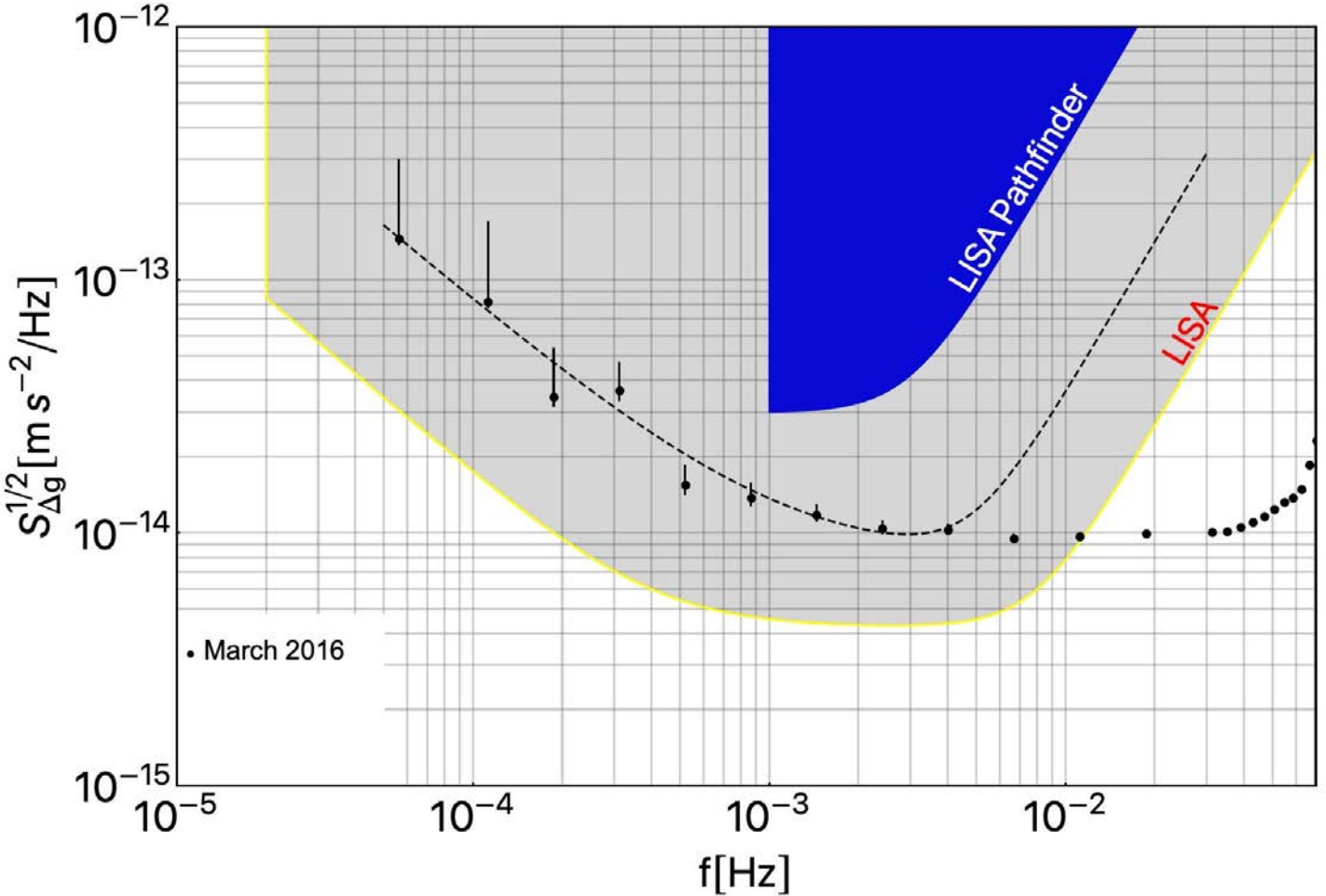
Requirements and expected performance

- Electrostatic actuation noise:
  - For a given voltage source noise, the larger the needed force you set, the larger the force noise.
  - Required force set by accuracy of gravitational balance
- 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

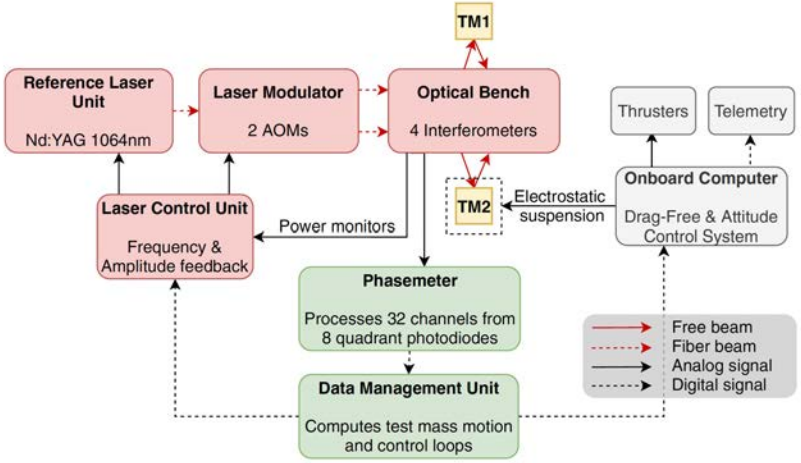


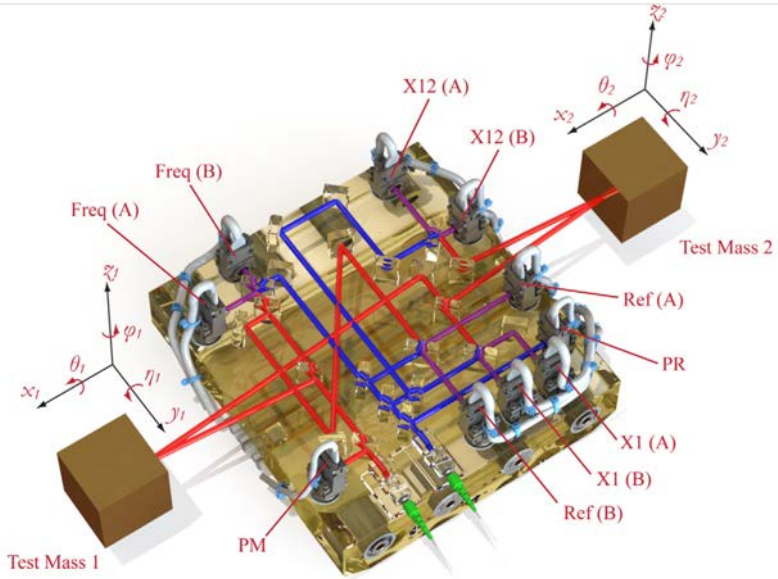
First day of operations: March 1st 2016

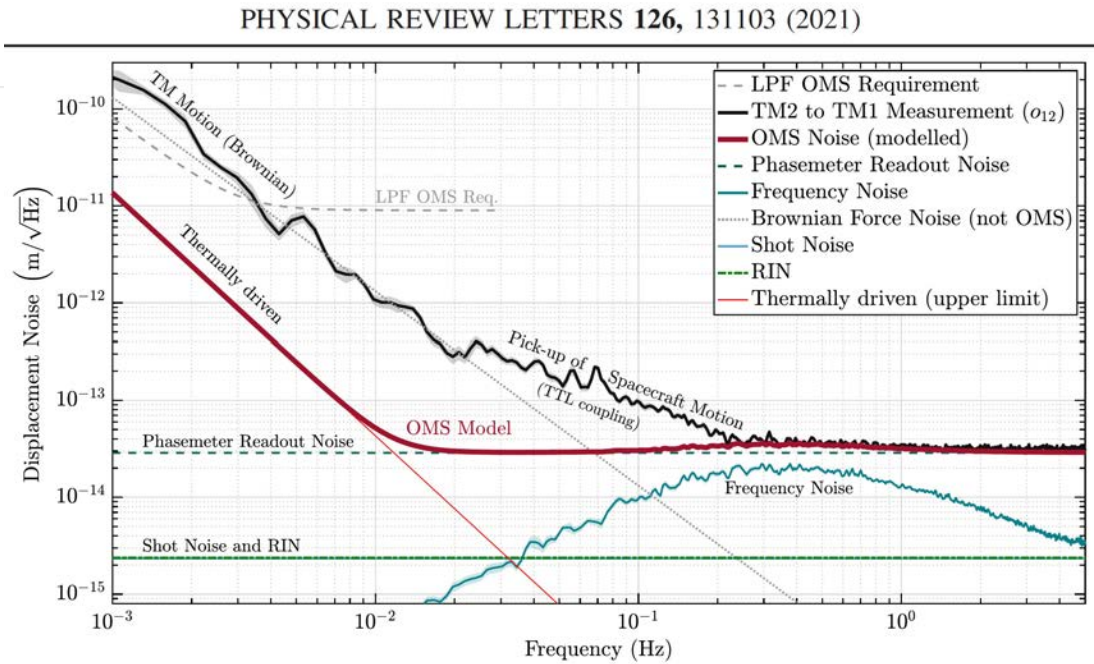
- Close to prediction
- Except for interferometer noise at 35 fm/√Hz instead of 10 pm/√Hz we could show on ground!



The magic interferometer

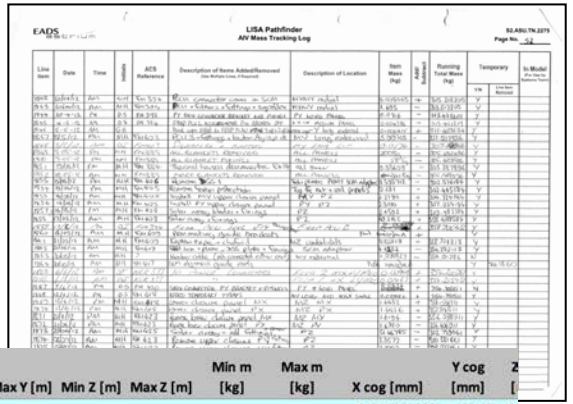




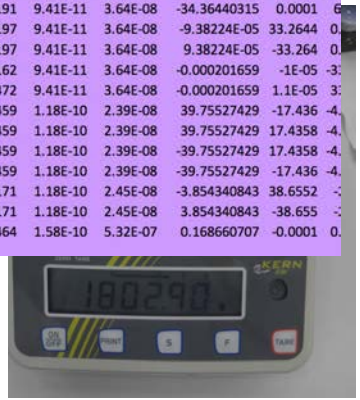


Gravitational control and actuation

- 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	-3
	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	-3
	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												



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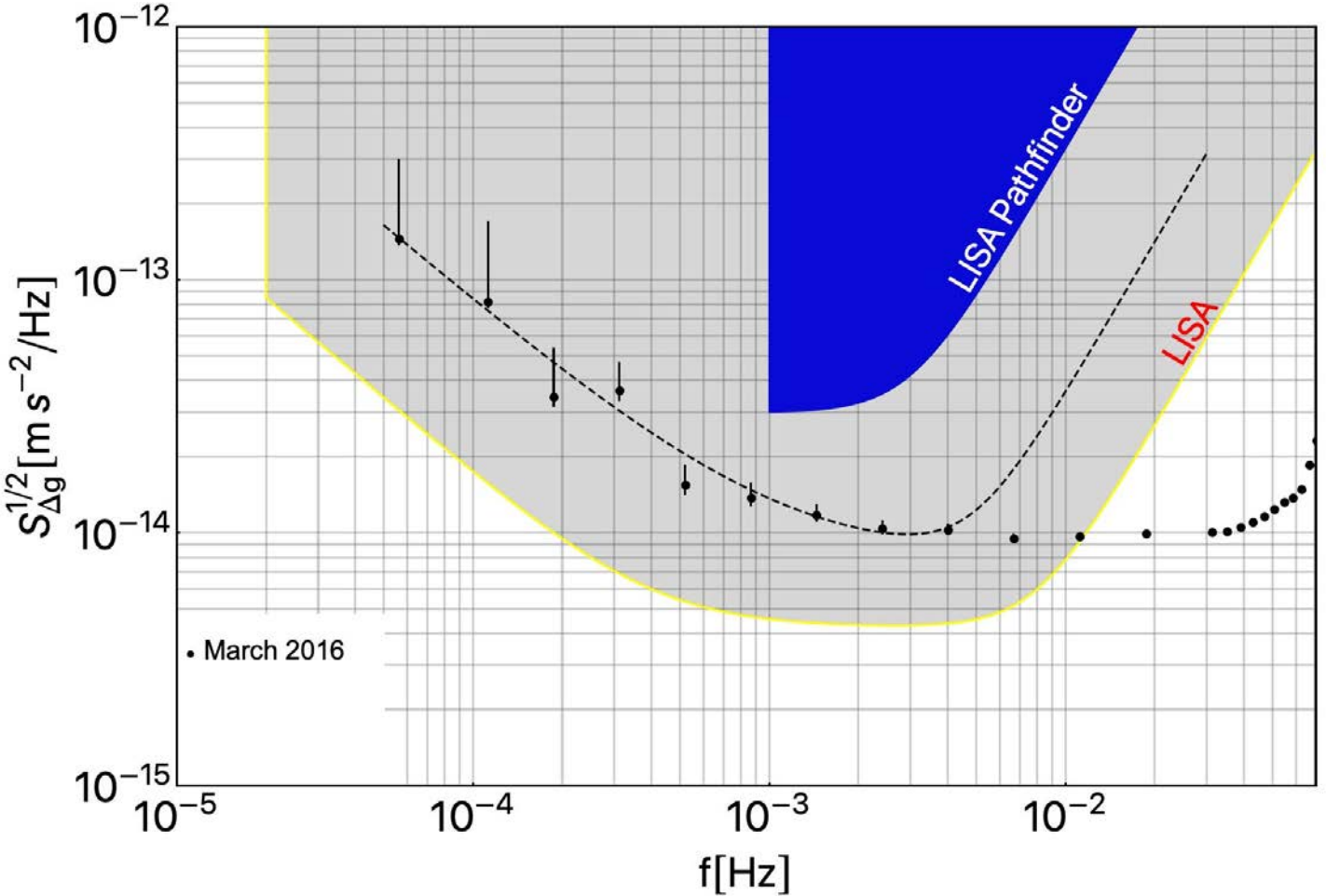
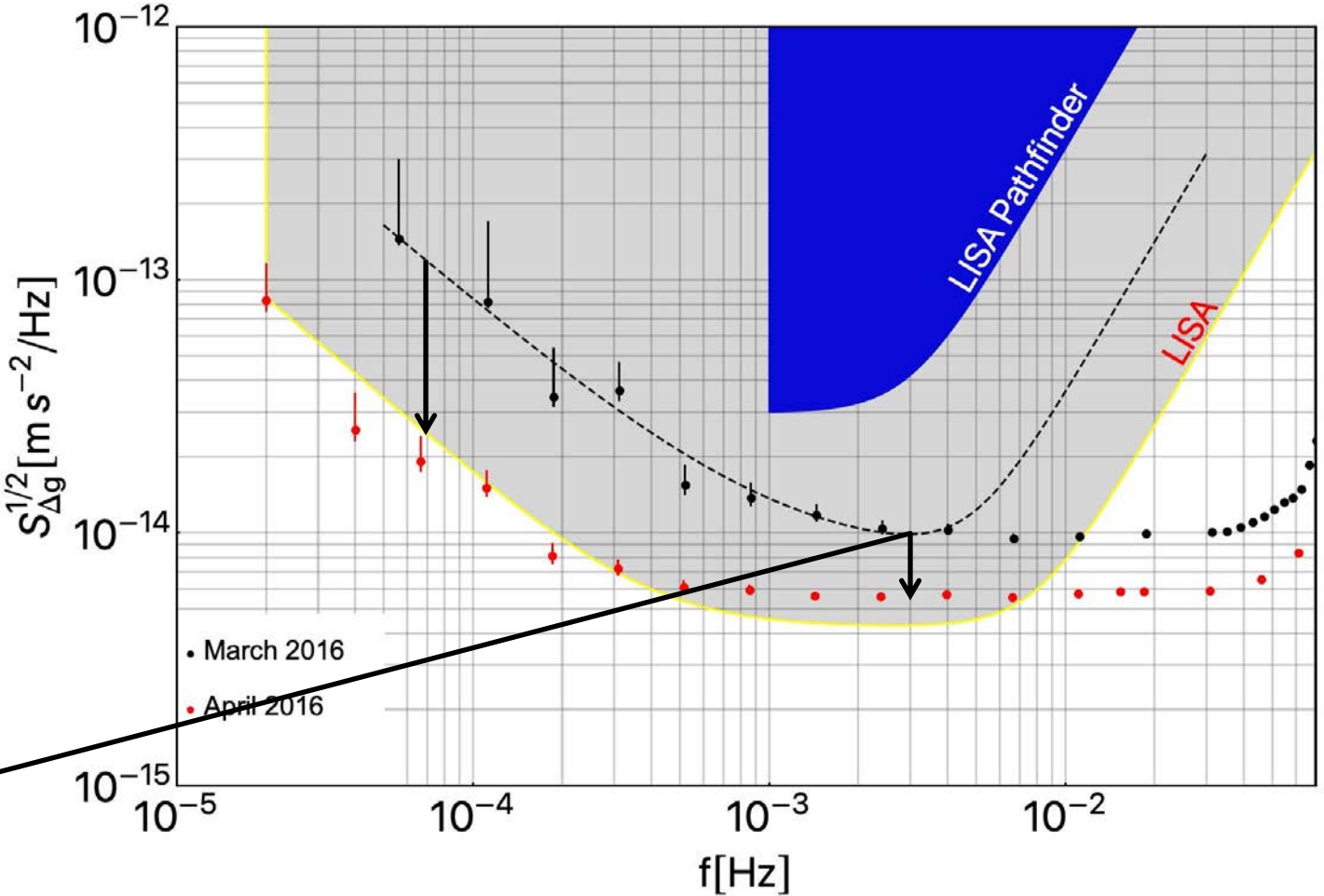
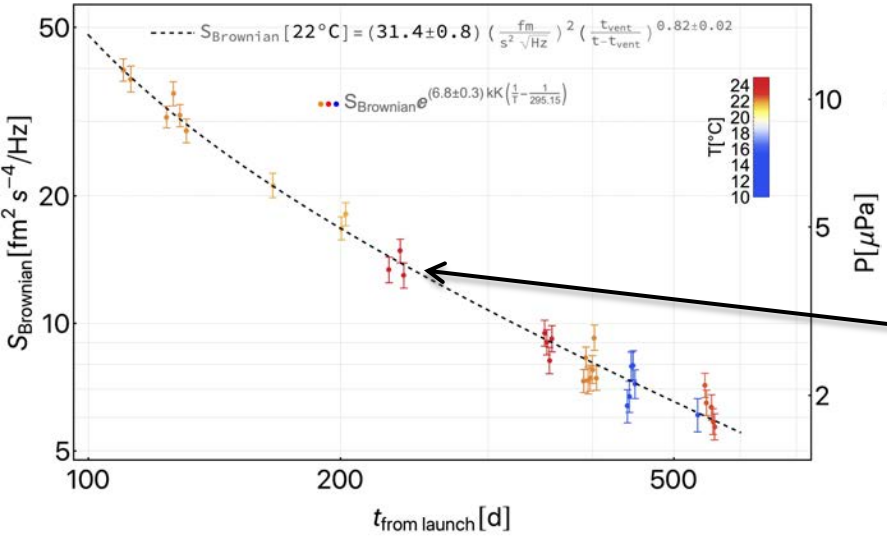
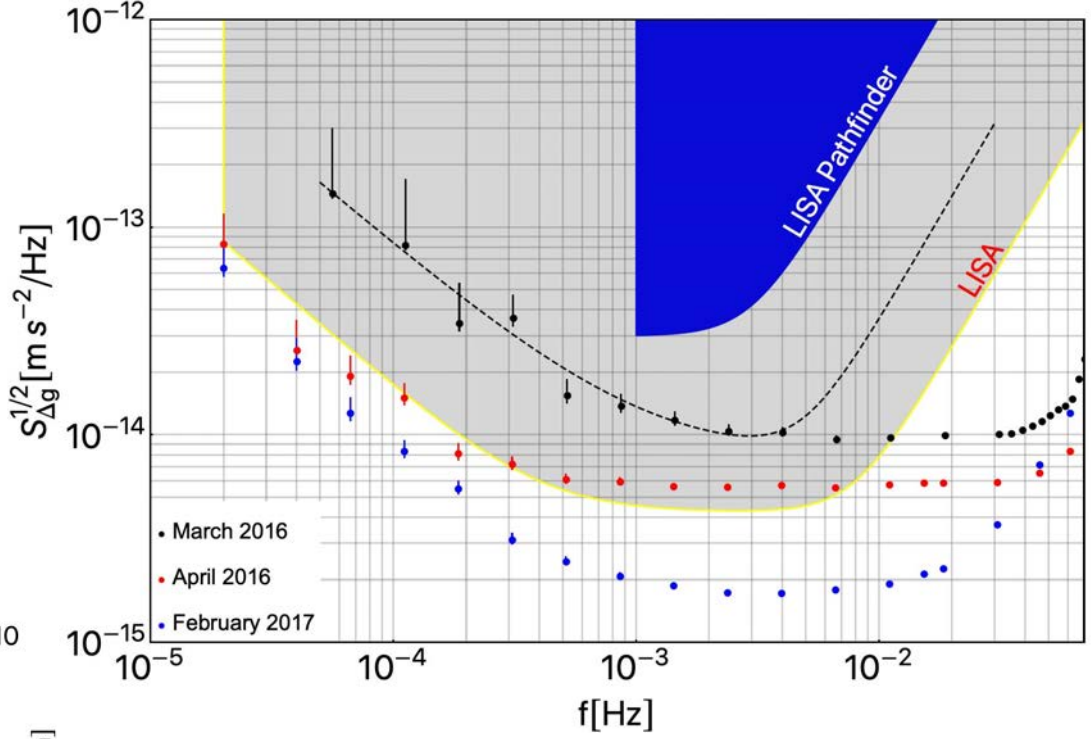


- Brownian noise decreases with pressure as the system is vented to outer space



LISA requirements met with some margin





Brownian noise (pressure) vs time throughout the mission

Consolidating the noise model: LPF 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.

[17] M. Armano, et al. Analysis of the accuracy of actuation electronics in the laser interferometer space antenna pathfinder. *Review of Scientific Instruments*, 91(4):045003, 2020.

[18] M Armano, et al. Spacecraft and interplanetary contributions to the magnetic environment on-board LISA Pathfinder. *Monthly Notices of the Royal Astronomical Society*, 494(2):3014–3027, 04 2020.

[19] M. Armano, et al. Sensor noise in lisa pathfinder: In-flight performance of the optical test mass readout. *Phys. Rev. Lett.*, 126:131103, Apr 2021.

Phase A Conclusions – MFR outcome

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

for their valuable contributions to the Review.

Timeline

October 2013:

October 2016:

June 2017:

May 2018:

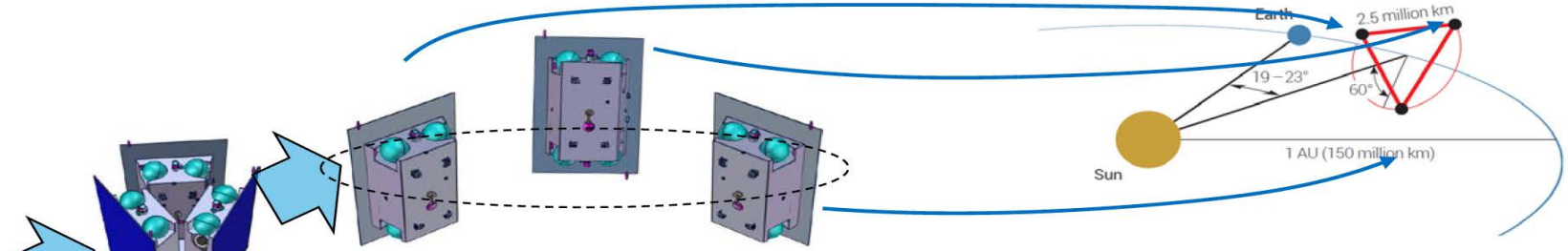
2018-2021:

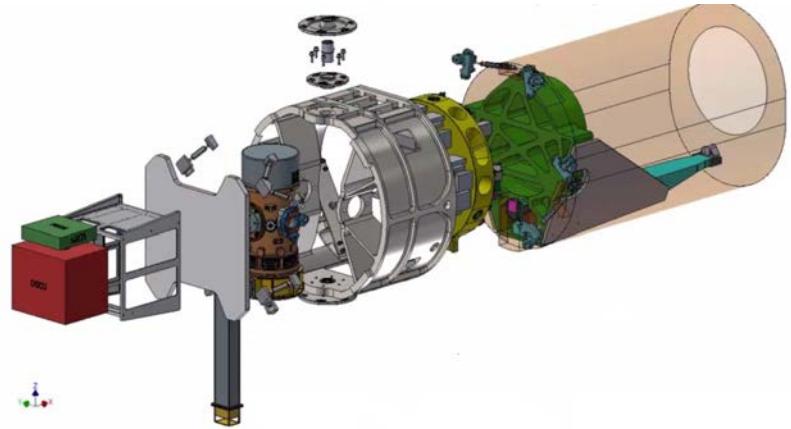
Oct '20-Oct '2:

<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

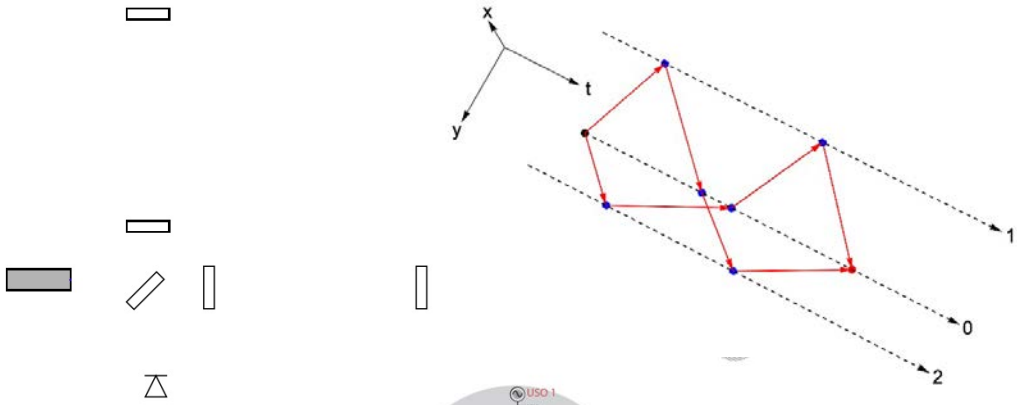
- Phase-A study competitive: cannot show much!
- A rather stable concept, working out the details

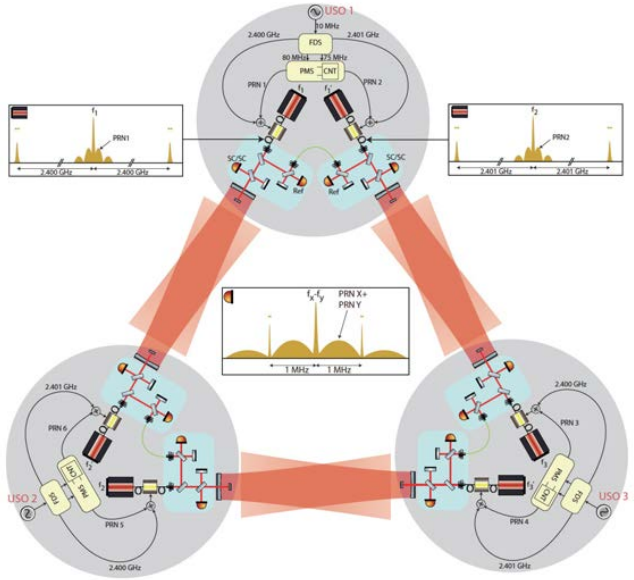




Laser frequency noise & time delay interferometry

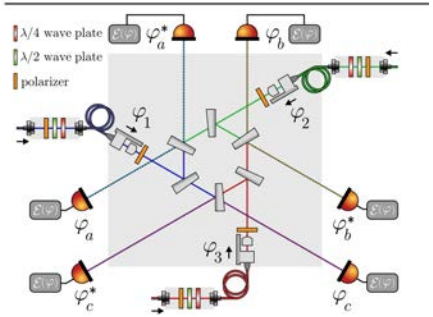
- Laser frequency stability:
  - Required $\simeq 1\ \mu Hz/\sqrt{Hz}$
  - Available $\preccurlyeq 30\ Hz/\sqrt{Hz}$
- Ground based interferometers beat noise comparing beams emitted at same time (equal arms)
- LISA: arms are unequal ($\Delta L \simeq 10^5 km$) and time varying over the year.
- Combine single-link signals to mimic light beams that have traveled equal lengths



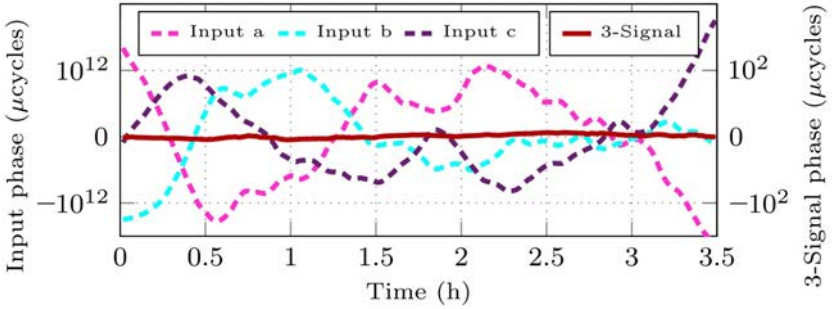


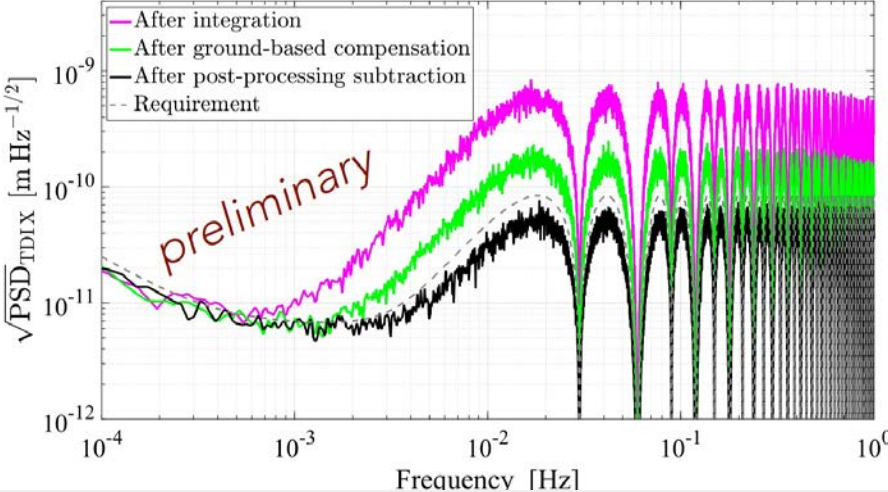
Progress on Interferometry

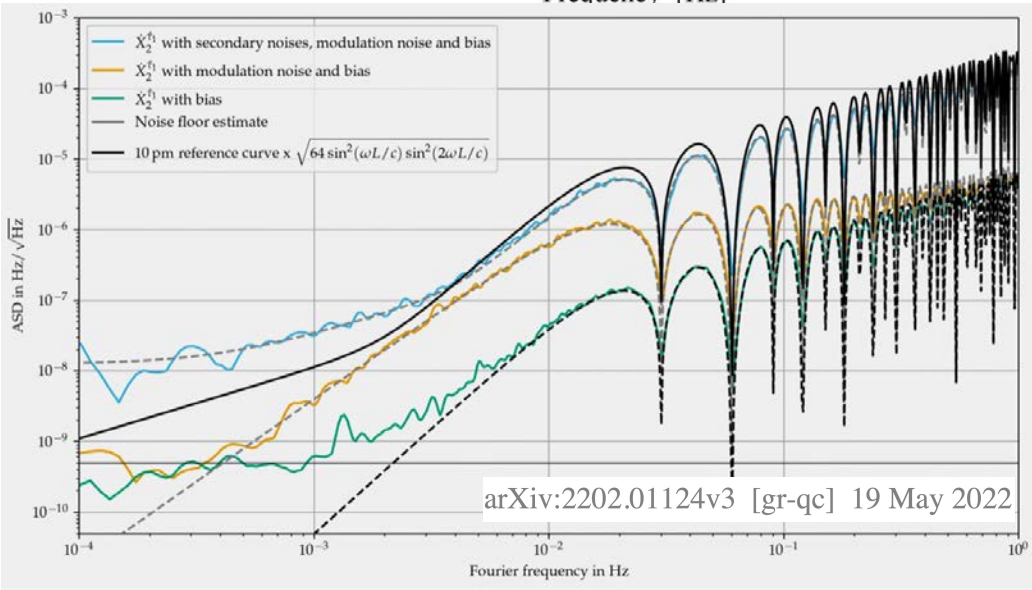
- Beating misalignments
- Beating frequency and clock noise



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

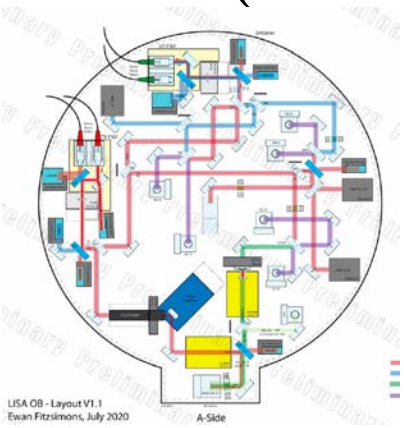


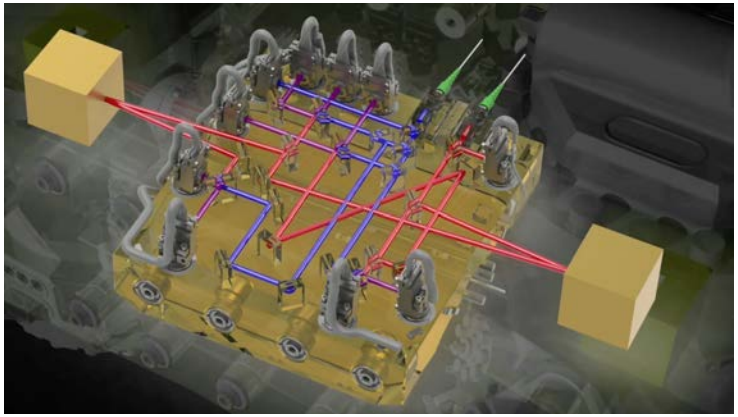


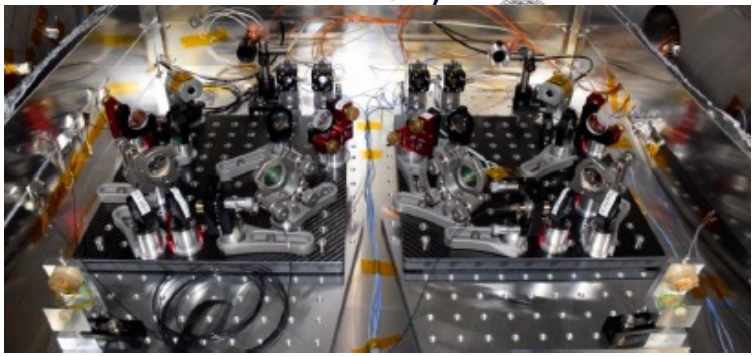


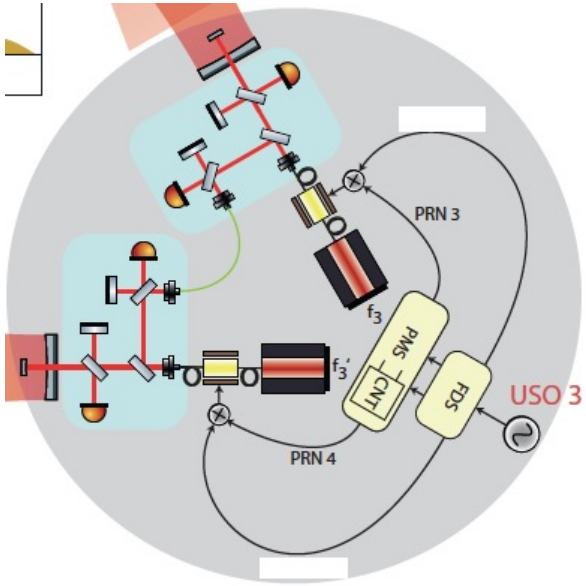
arXiv:2202.01124v3 [gr-qc] 19 May 2022

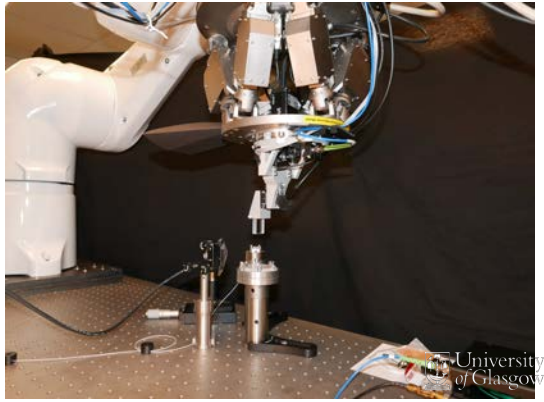
Technology developments (TRL 6 by adoption)



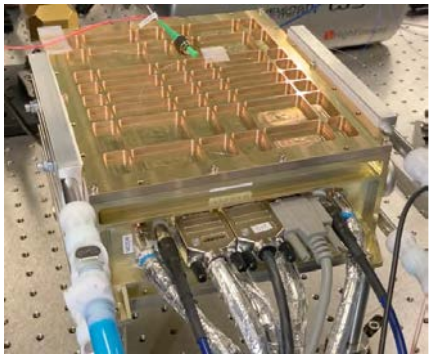




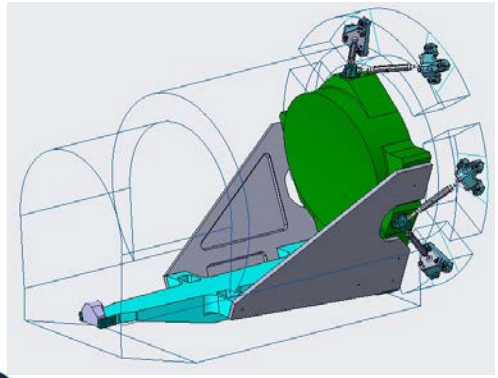




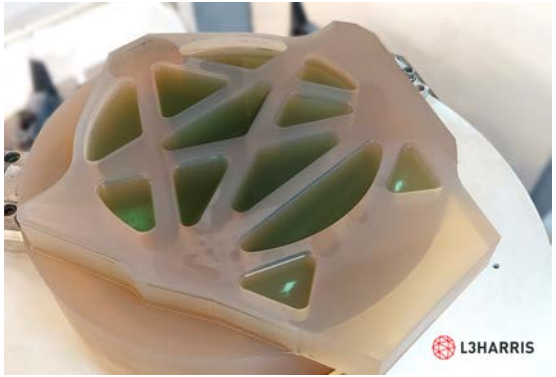
Technology developments (TRL6 by adoption)



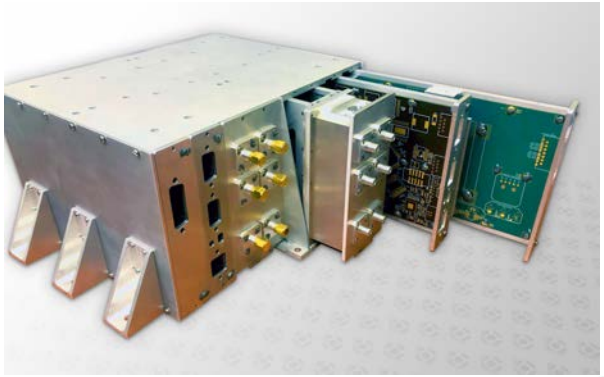
Laser



Telescope

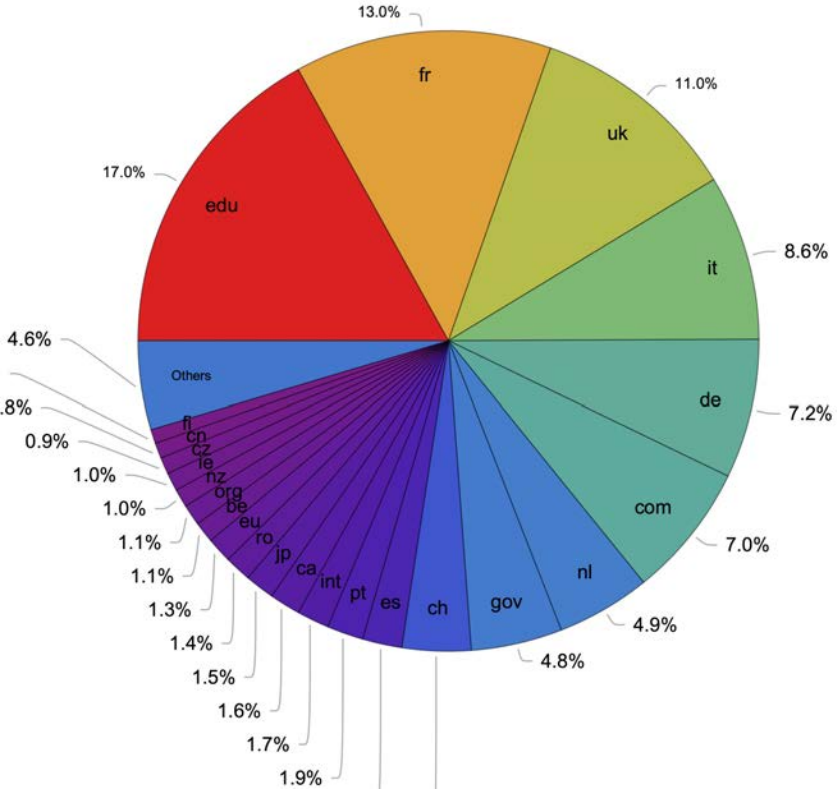


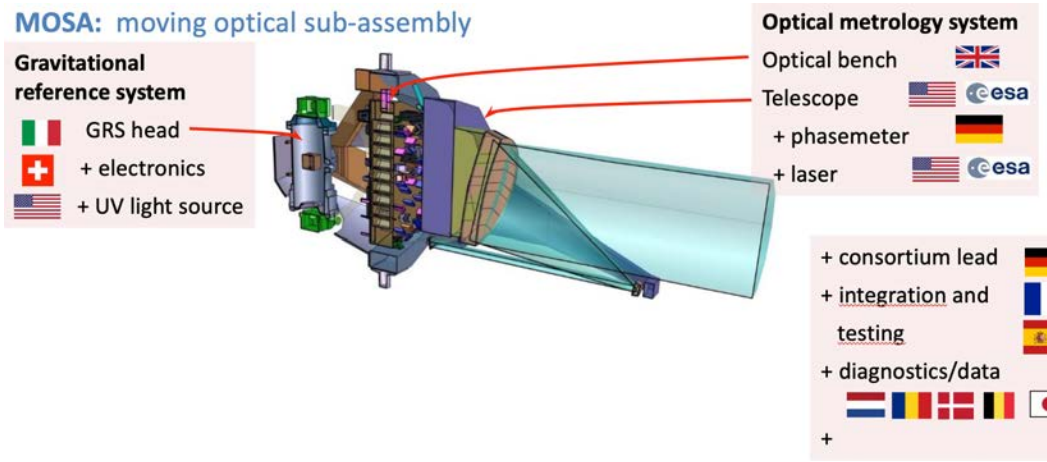
Charge management



The International Collaboration

- The LISA Consortium (~~1437~~ 1548 members)






Thank you!