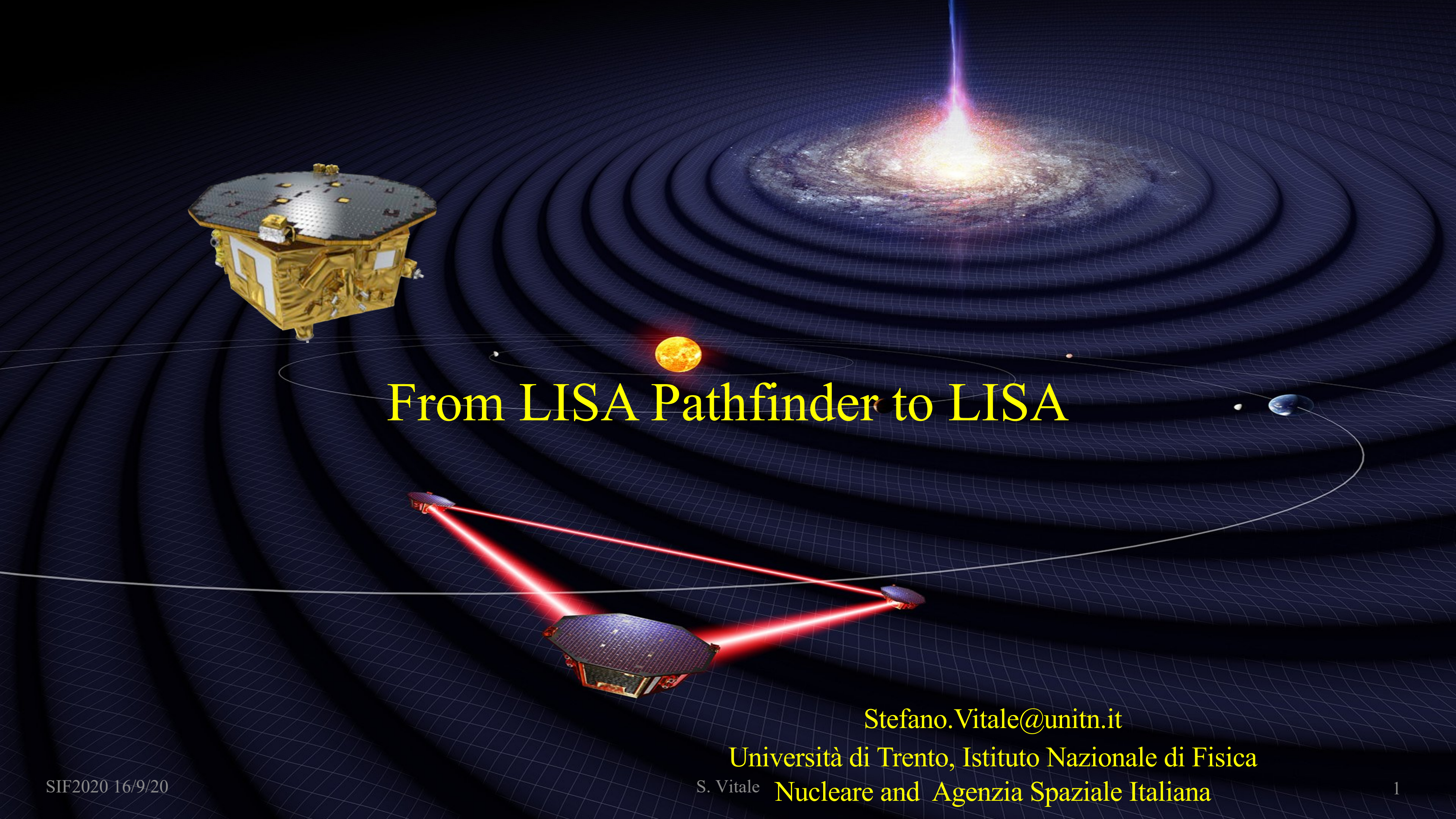
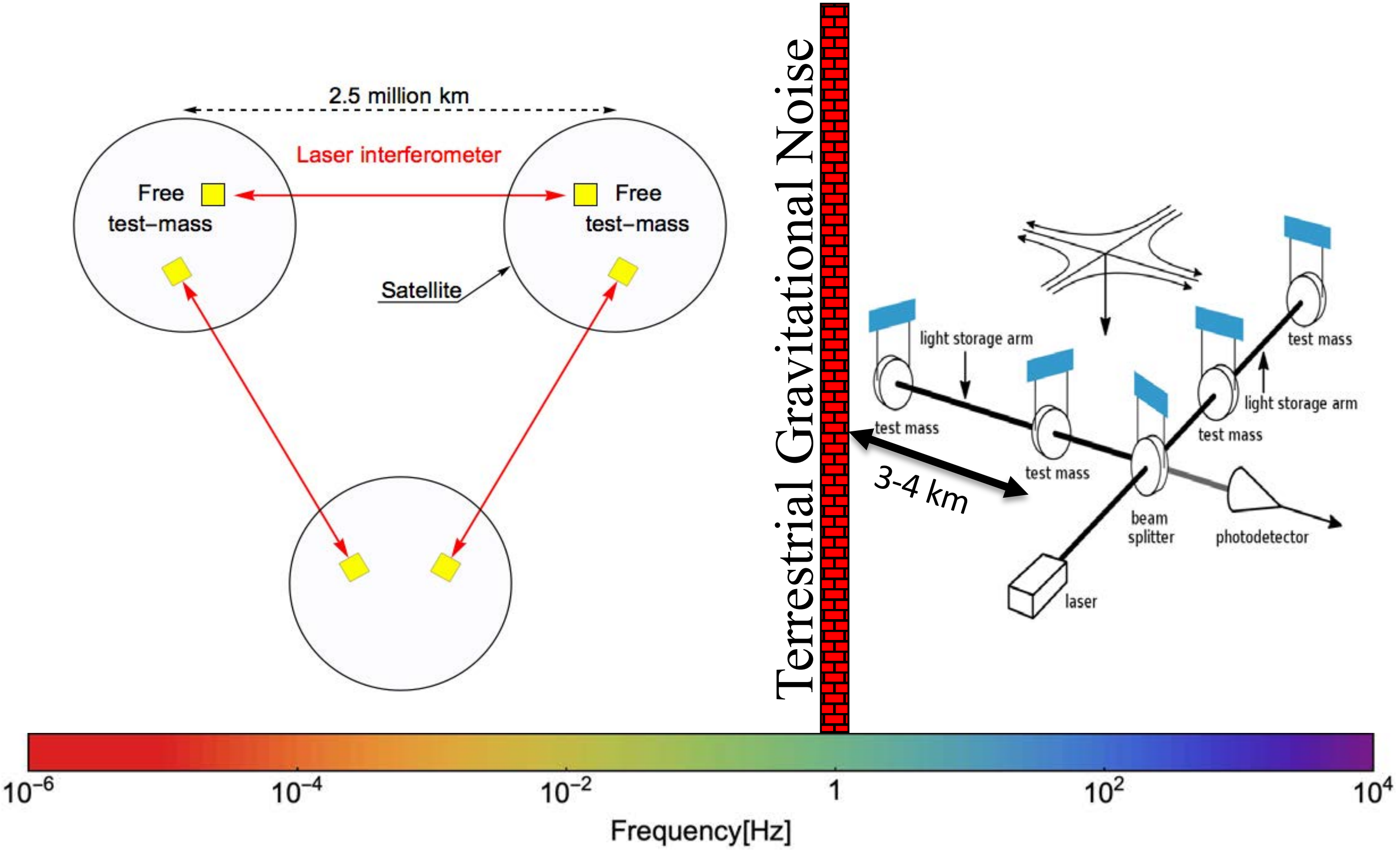


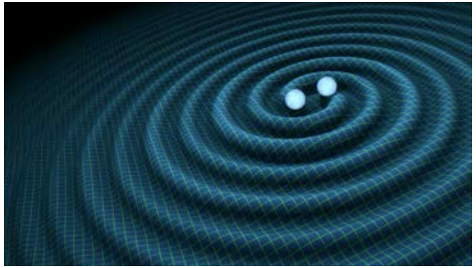
From LISA Pathfinder to LISA

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

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

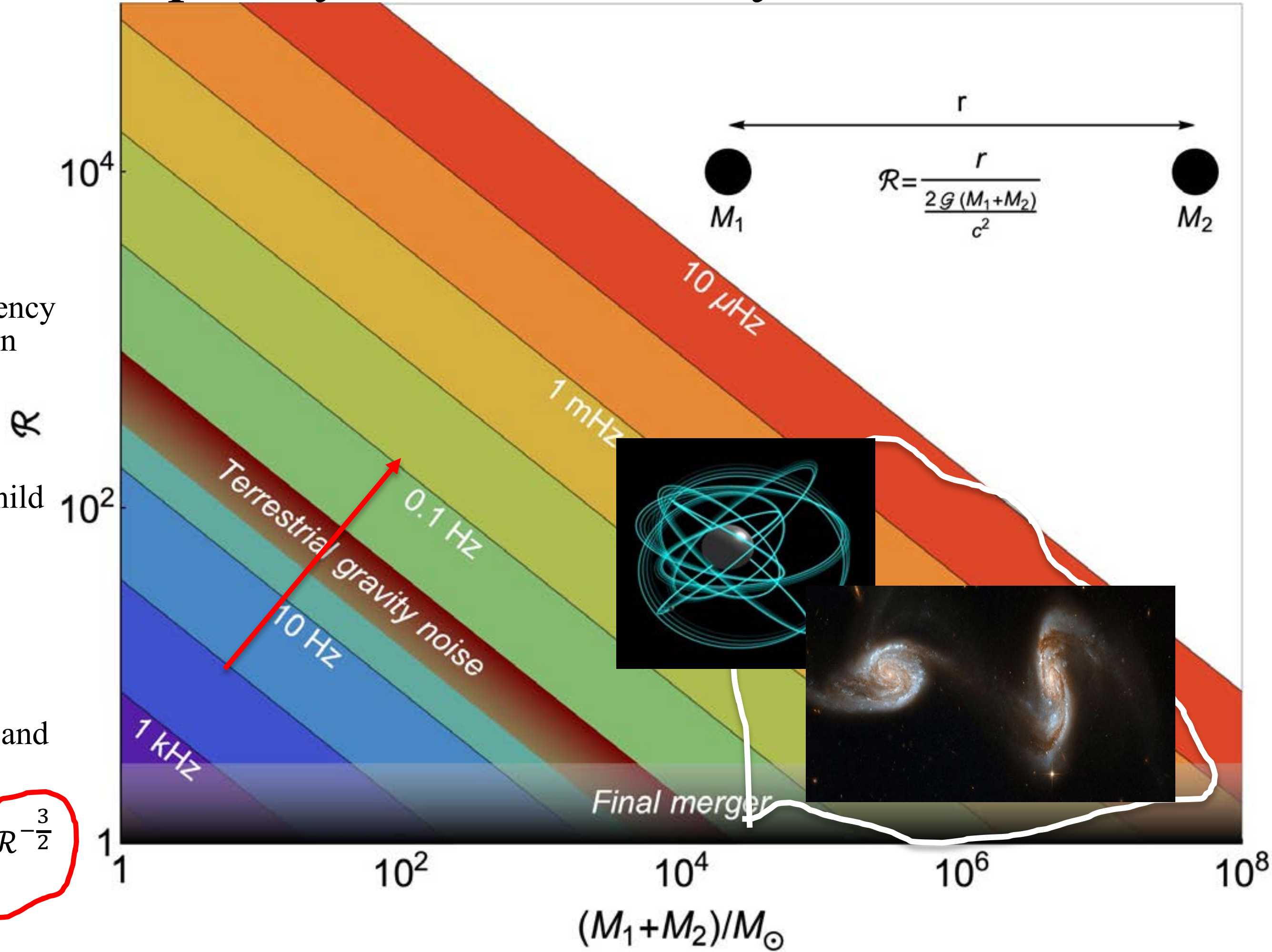
- Separation normalized to Schwarzschild radii:

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

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

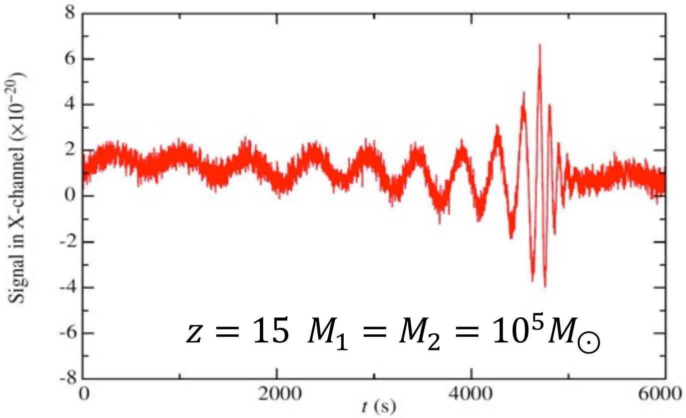
- Frequency decreases with both mass and $\mathcal{R}$

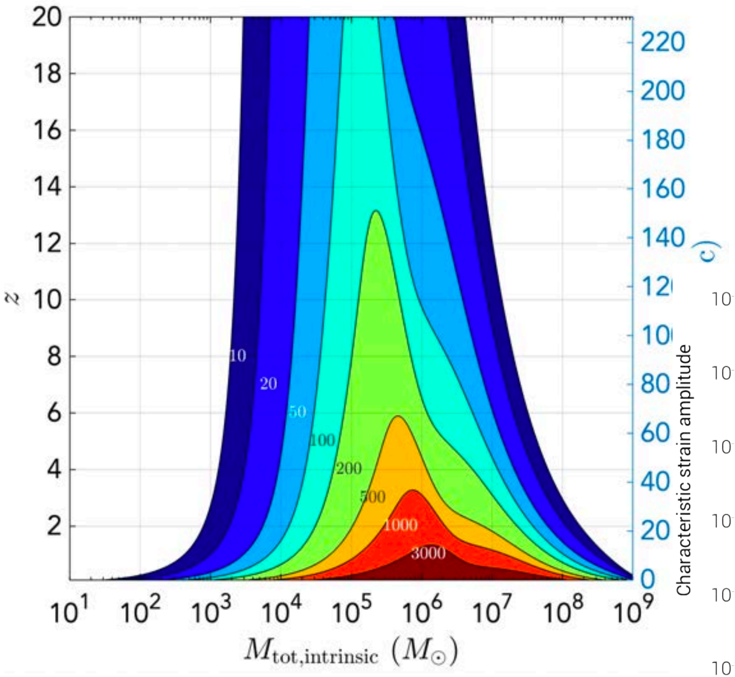
$$f_{GW} = \frac{c}{\pi\sqrt{2}\,R_\odot}\left(\frac{M_1 + M_2}{M_\odot}\right)^{-1}\mathcal{R}^{-\frac{3}{2}}$$

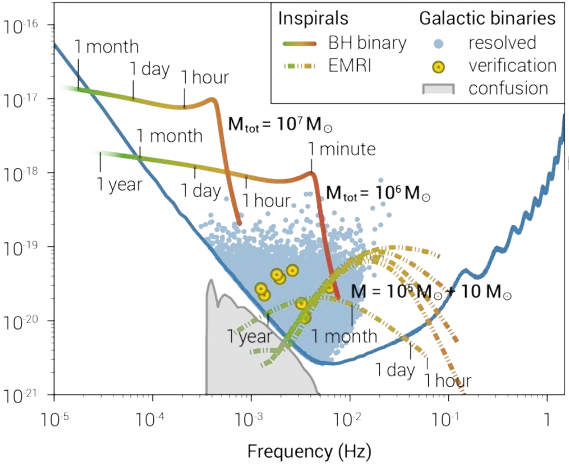


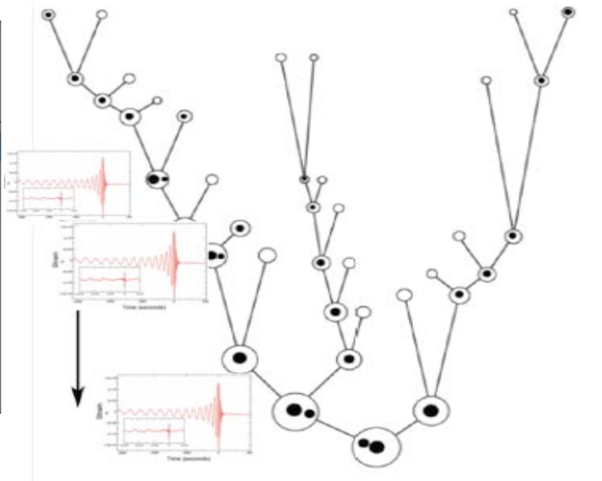
Supermassive BH: the brightest sources

- Wave amplitude scales with $M_1 \times M_2$
- Detectable "everywhere" in the universe
- Sooner or later frequency crosses LISA band : cosmological stratigraphy



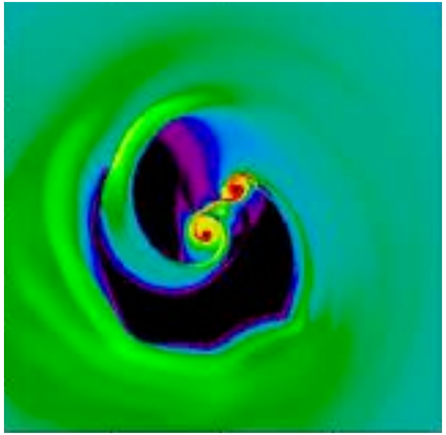


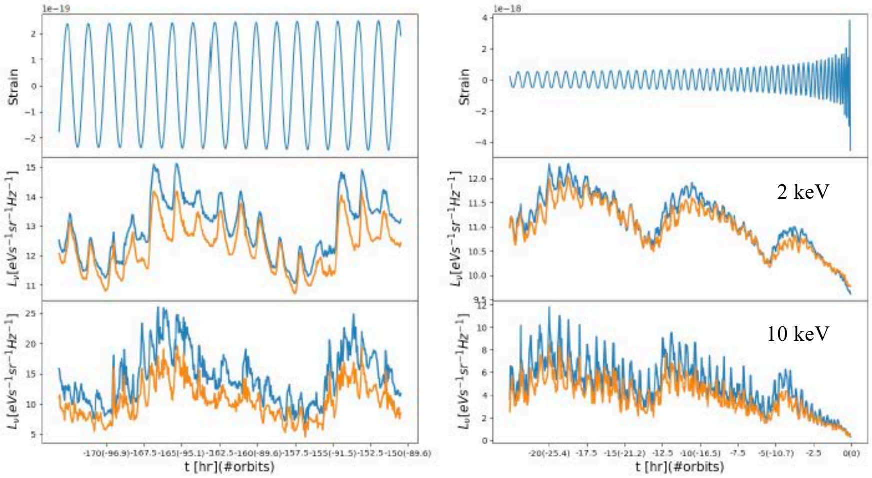




Detecting SMBH mergers with LISA and Athena

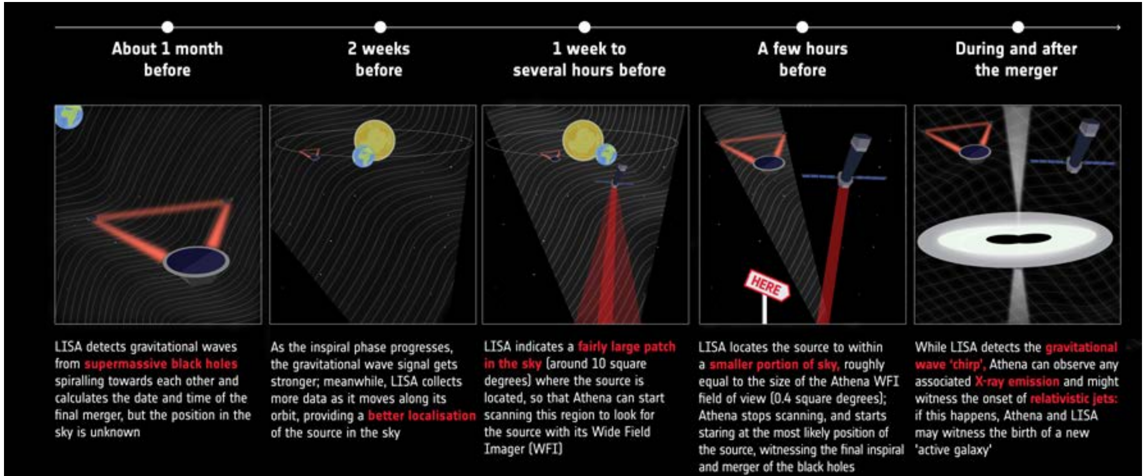
Tang et al. 2018





Gravitational Waves

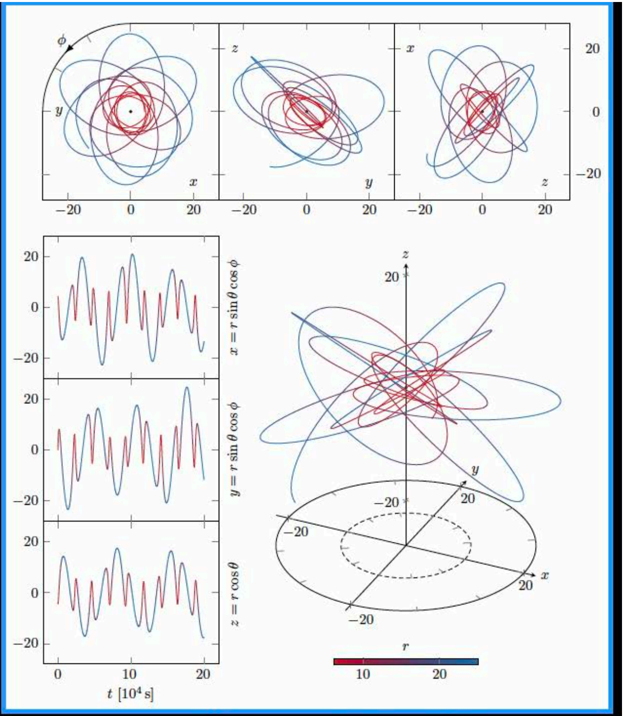
X-rays



lisa pathfinder

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)



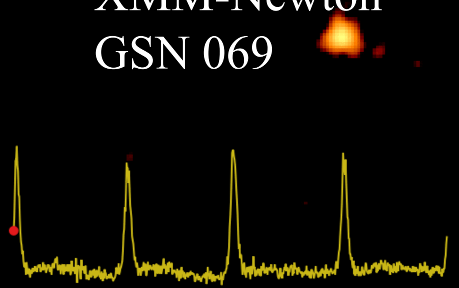
(Mihaylov & Gair 17)

Classes of EMRIs

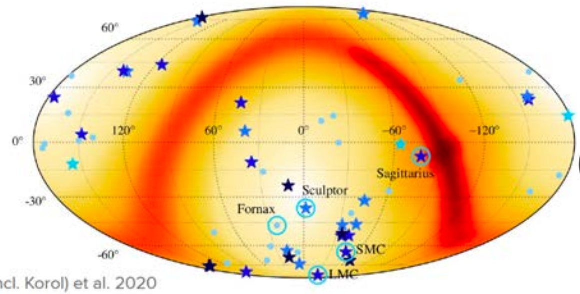
1. Relaxation to high-eccentricity orbits ("loss cone")
2. Binary detachment (Hills mechanism)
3. Hydrodynamic inspiral in AGN disk

- COs embedded in gas disk can inspiral hydrodynamically (Levin 07)
  - Enters LISA band with e~0 (i~0?)
  - Gas torques visible in waveform for some disk models (Kocsis+11)
- **Possible electromagnetic counterparts**:
  - AGN variability
  - Statistical EM counterpart (Bartos+17)
- **Unusually large EMRIs possible** (even "IMRIs")

XMM-Newton
GSN 069



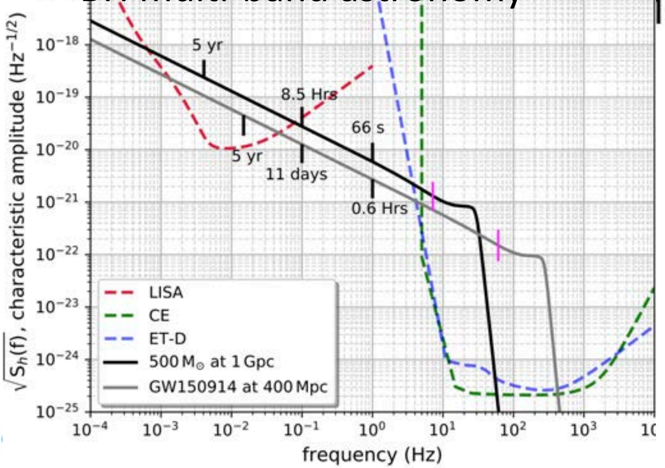
Non-transient GW astronomy

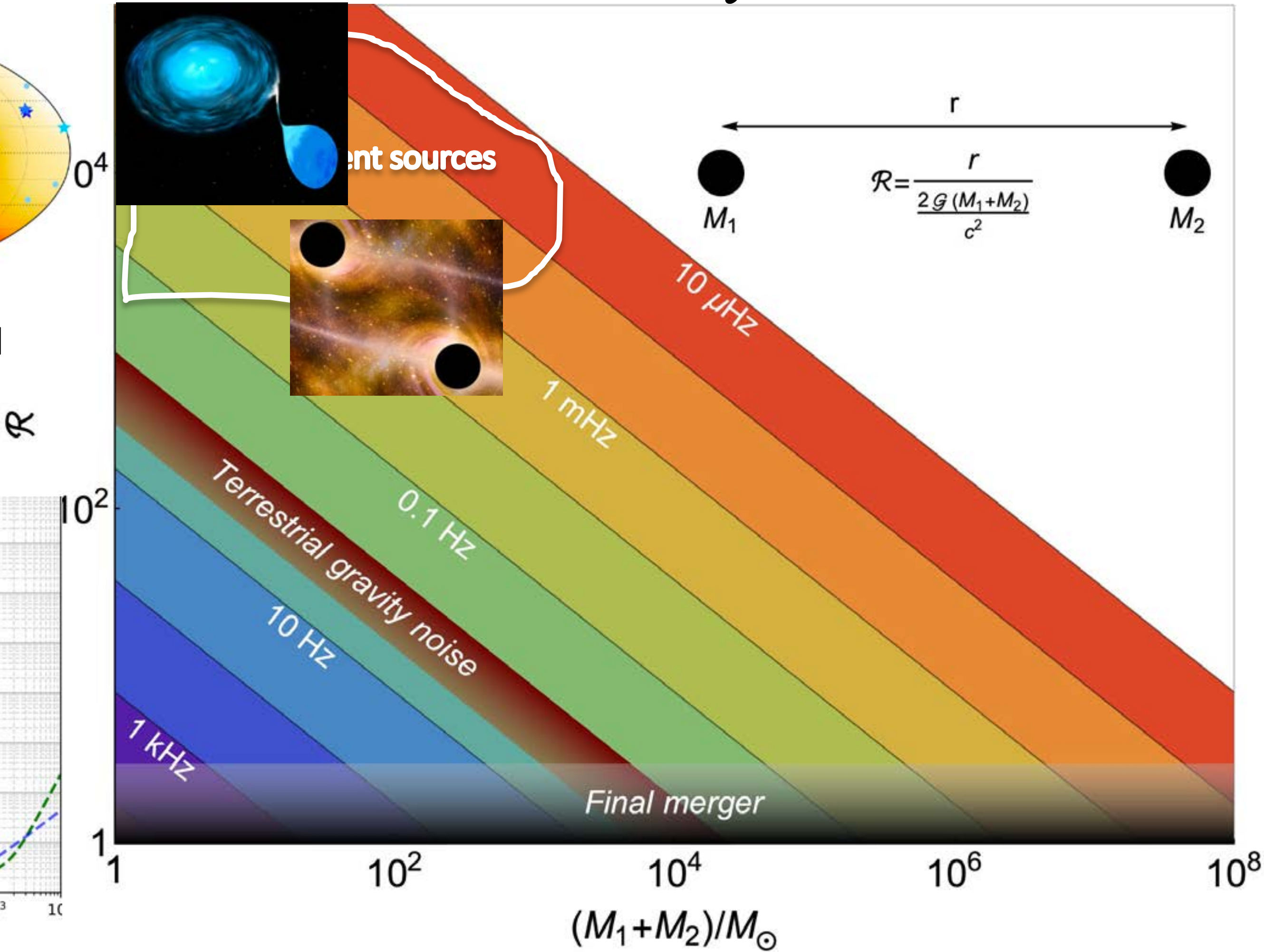


Roebber (incl. Korol) et al. 2020

- GW-binary astronomy of local group

- BH multi-band astronomy

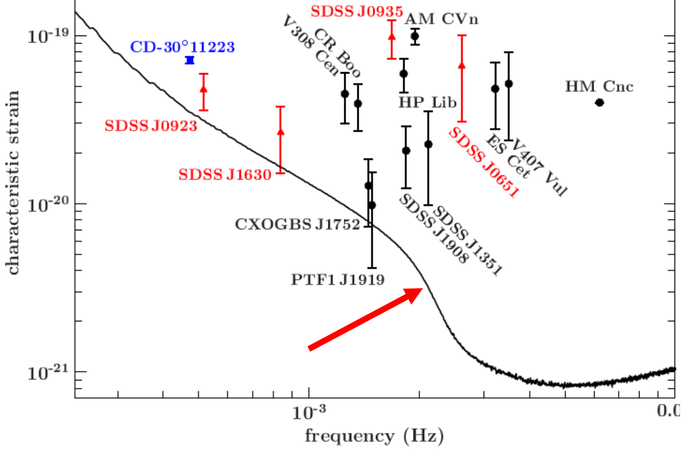


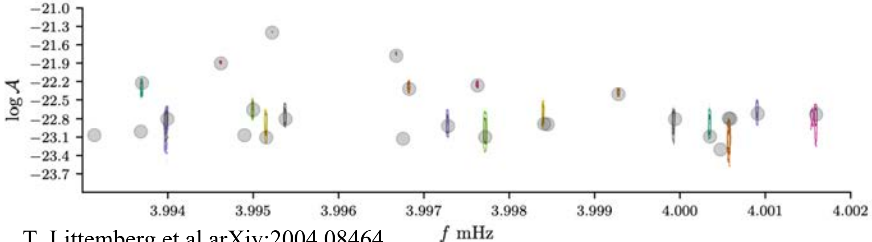


The high $\mathcal{R}$ end: the GW Milky Way

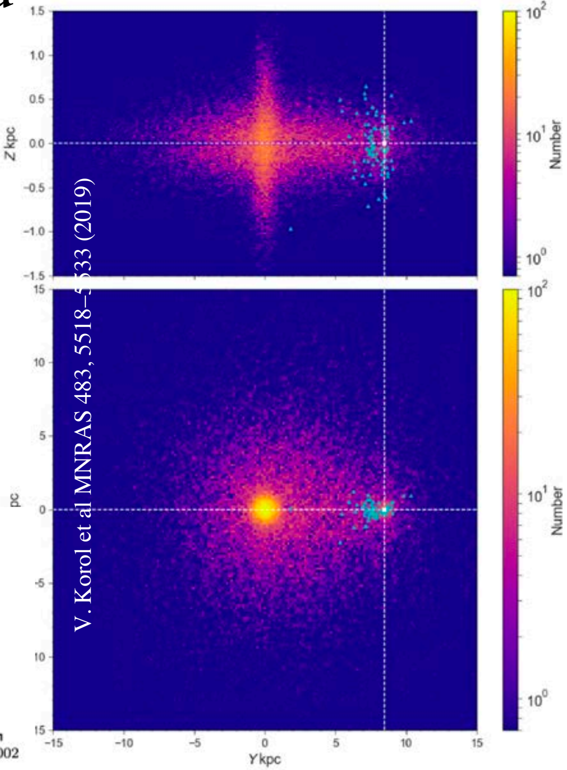
- Tens of thousand of discernible sources
- Plus a stochastic foreground

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





T. Littemberg et al arXiv:2004.08464



V. Korol et al MNRAS 483, 5518–5533 (2019)

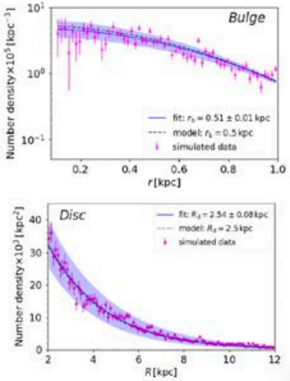
Expectations

The shape of the Milky Way's components

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

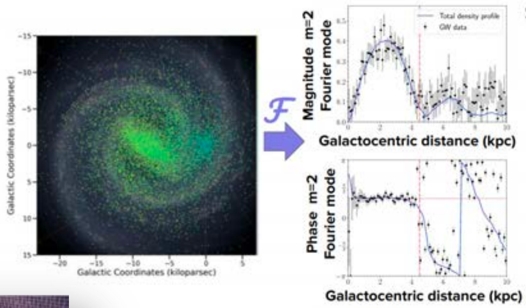
- Bulge scale radius to 2%
- Disc scale radius to 3%
- Disc scale height to 16%

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)

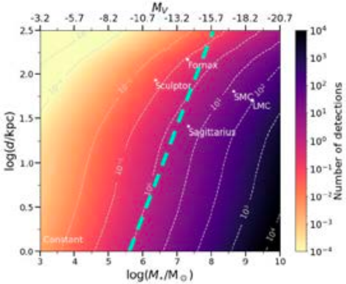
The detection of circumbinary exoplanets

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

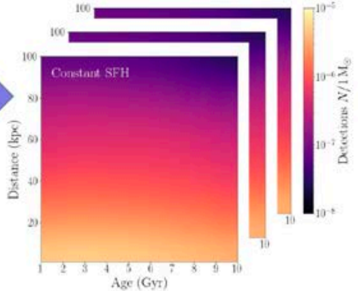


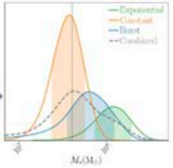
Korol et al. 2020; Roebber et al. (incl.Korol) 2020
See also Lamberts et al. 2019

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.

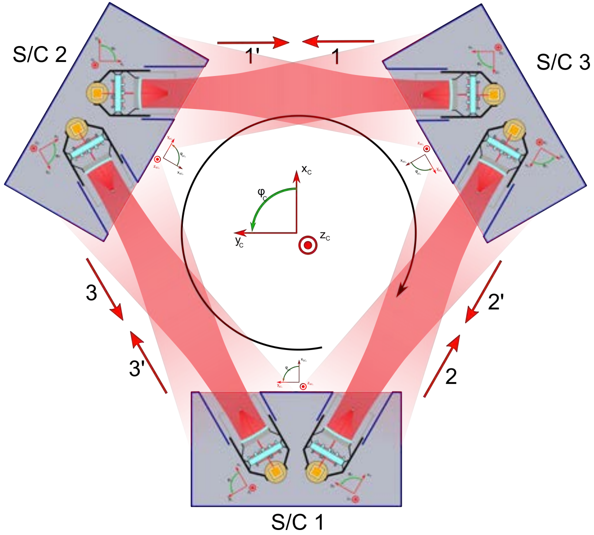
Number of detections $N \pm \sqrt{N}$
Distance $D \pm \Delta D$



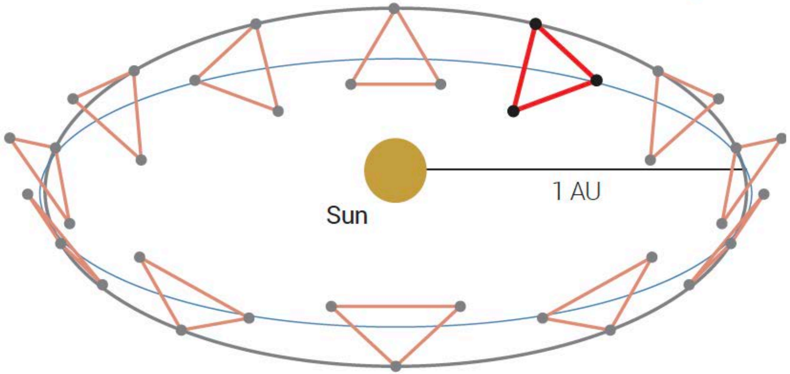


Korol et al. in prep.

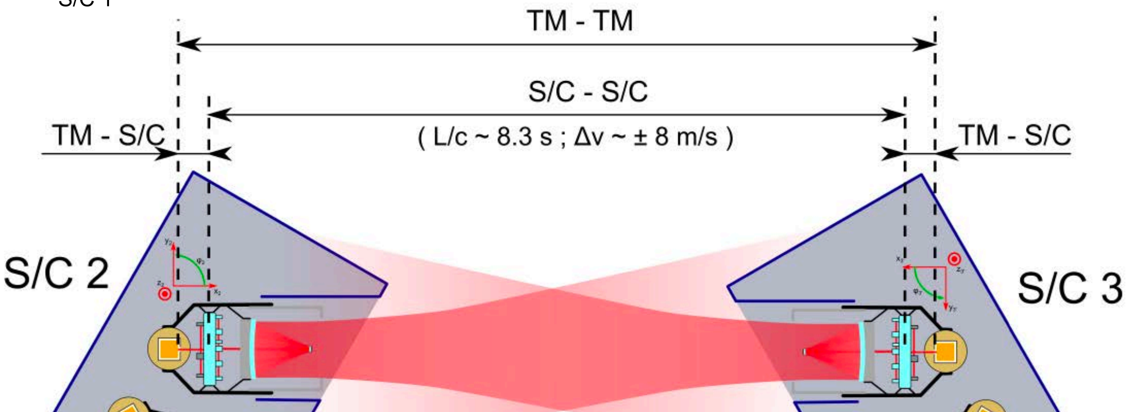
LISA



S/C 2
S/C 3
S/C 1
1'
1
2
2'
3
3'



Sun
1 AU



TM - TM
S/C - S/C
(L/c ~ 8.3 s ; Δv ~ ± 8 m/s)
TM - S/C
TM - S/C
S/C 2
S/C 3

The LISA link

- Laser beam propagates through GW curvature
- Beam frequency ν shifts along propagation

$$\frac{\Delta\nu}{\nu_o}=\frac{1}{2}\left(h(t_{em})-h(t_{rec})\right)$$

Metric tensor perturbation

- Shift is also modulated in time: time derivative directly proportional to curvature

$$\frac{\Delta\dot{\nu}}{\nu_o}=\frac{1}{2}\left(\dot{h}(t_{em})-\dot{h}(t_{rec})\right)\simeq\frac{1}{2}\ddot{h}\frac{L}{c}$$

Riemann tensor

Spacecraft acceleration and Doppler effect

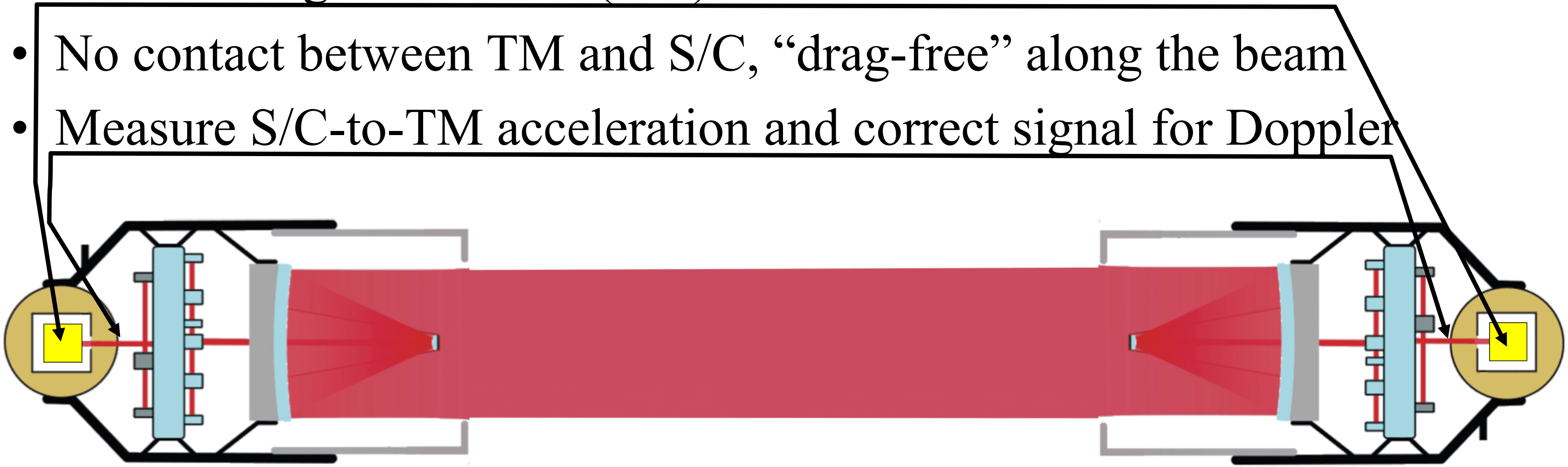
- Standard Doppler effect in flat space-time also shifts frequency and mimics GW
- Time varying shift caused by acceleration along beam of emitter and receiver relative to inertial frame

$$\frac{\Delta\dot{\nu}}{\nu_o}=\frac{1}{2}\ddot{h}\frac{L}{c}+\frac{a_{rec}-a_{em}}{c}$$

- 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 to acceleration of *TM* relative to local inertial frame

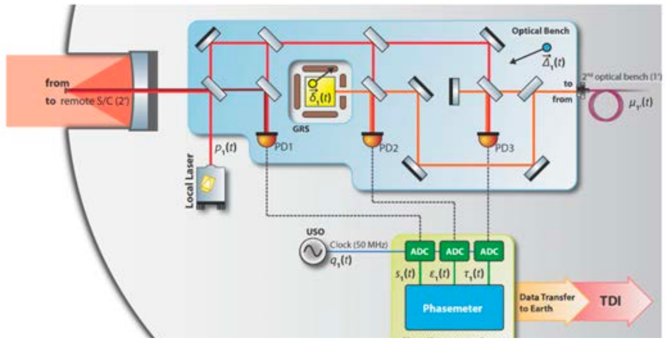
$$\frac{\Delta\dot{\nu}}{\nu_o} = \frac{1}{2}\ddot{h}\frac{L}{c} + \frac{a_{TM,rec} - a_{TM,em}}{c}$$

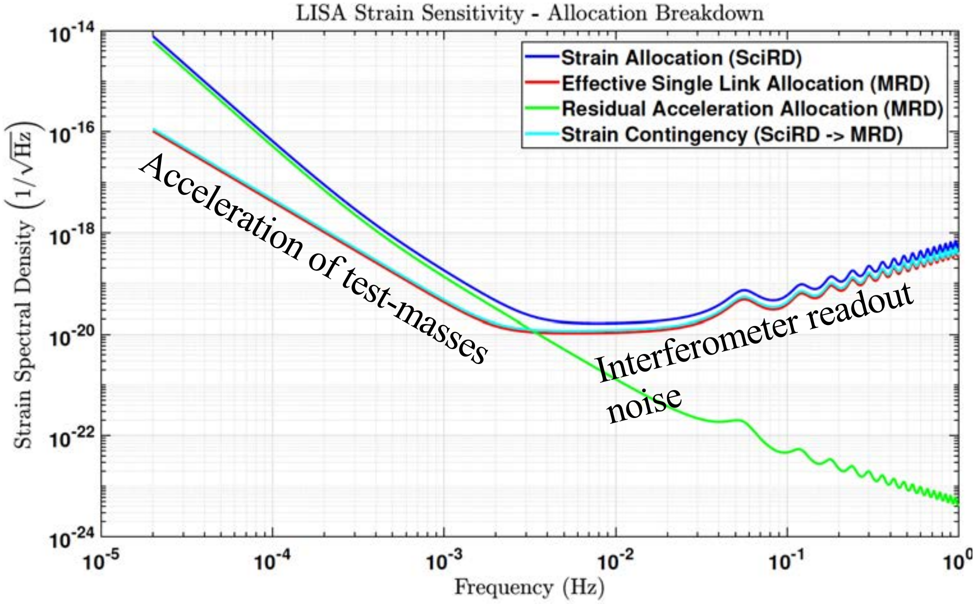
lisa pathfinder

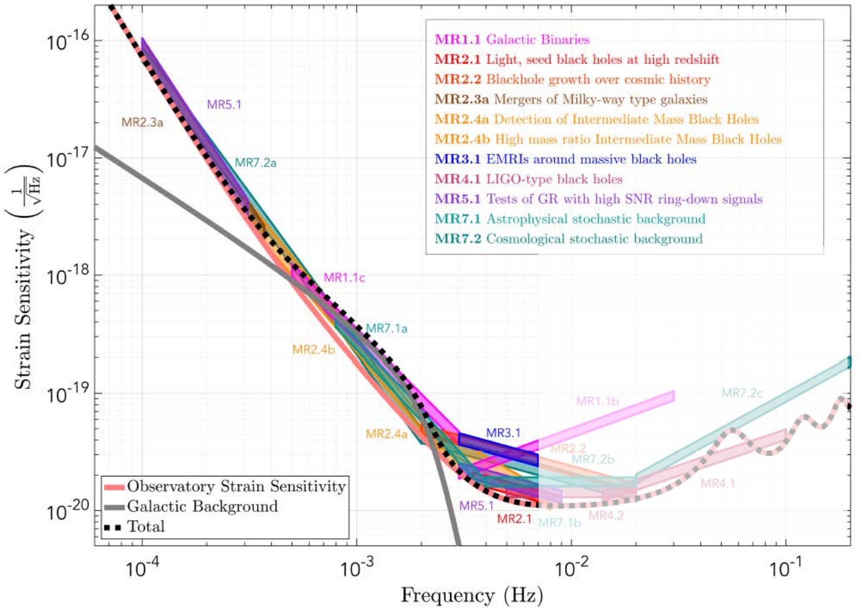
Noise in a LISA link

- Frequency measurements are noisy: interferometer readout noise
- Total noise

Class. Quantum Grav. 29 (2012) 205003 M Otto et al

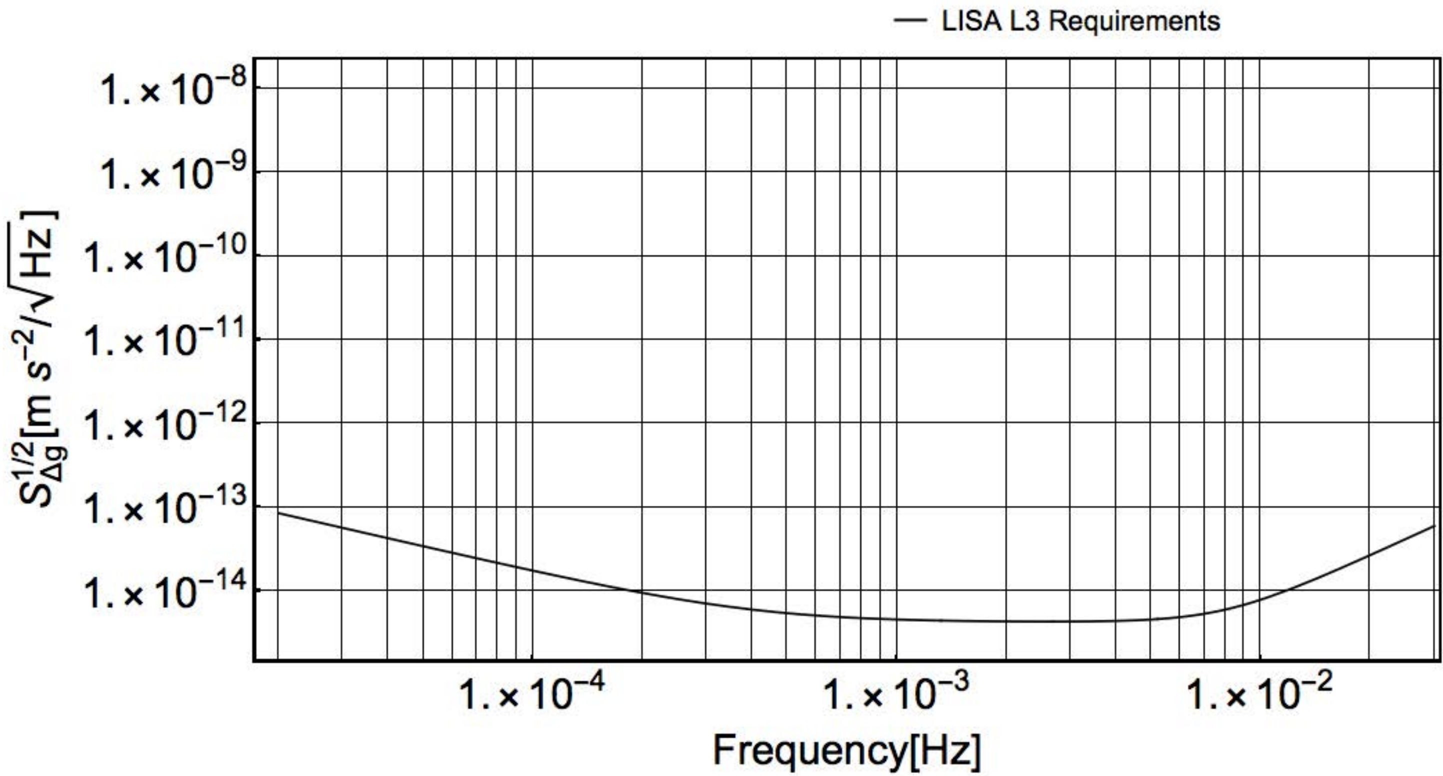






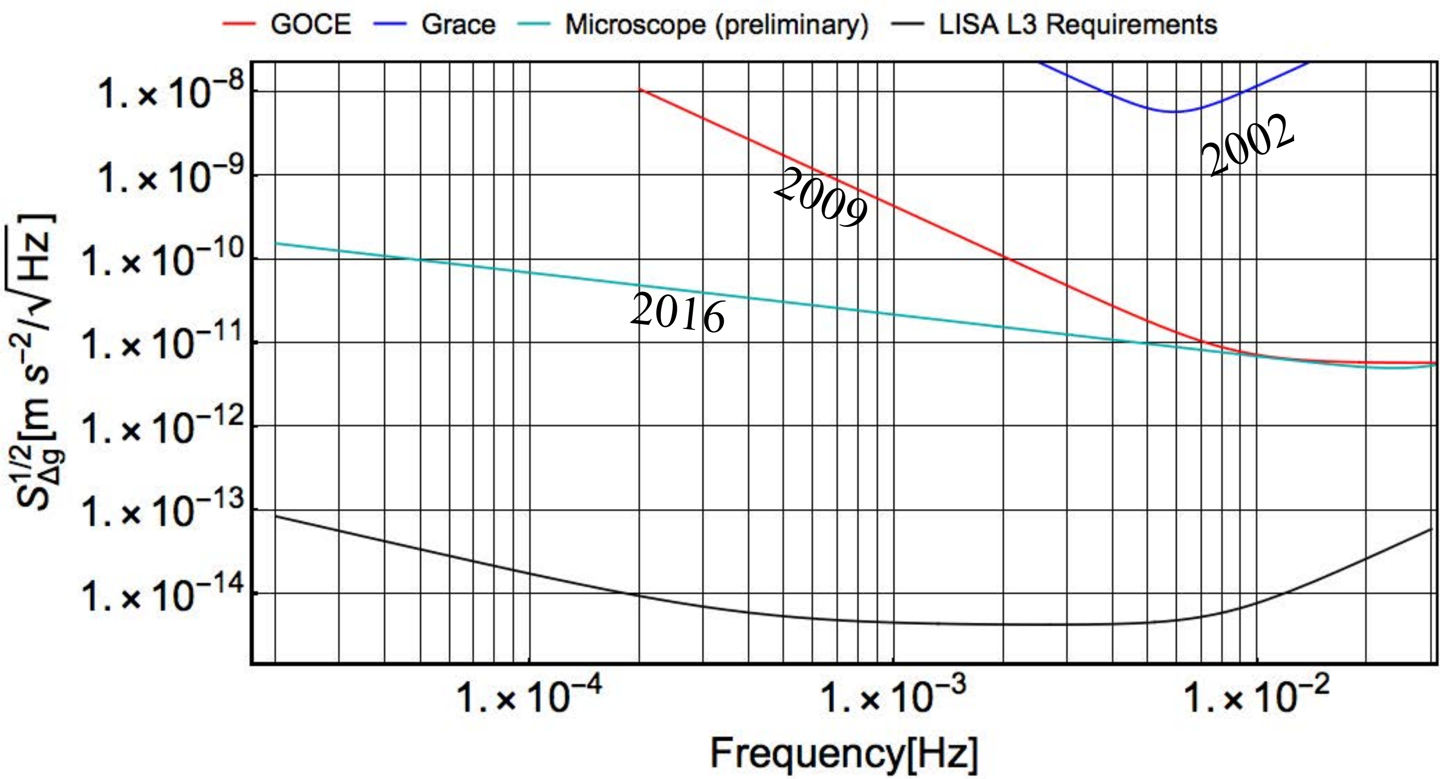
LISA: Sub-femto-g force suppression required

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



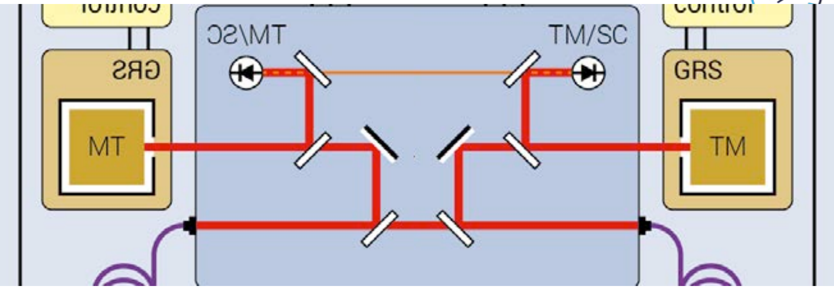
LISA: Sub-femto-g force suppression required

- 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

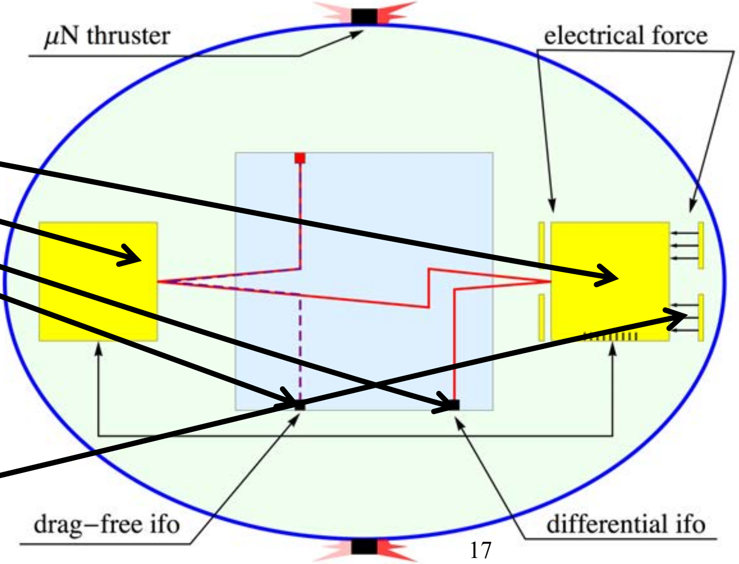


lisa pathfinder

LISA Pathfinder

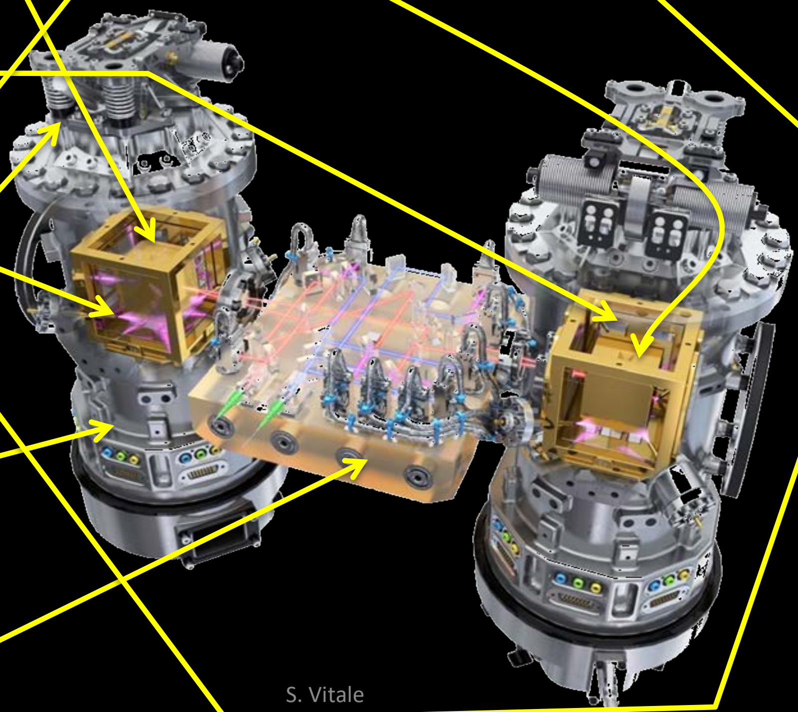


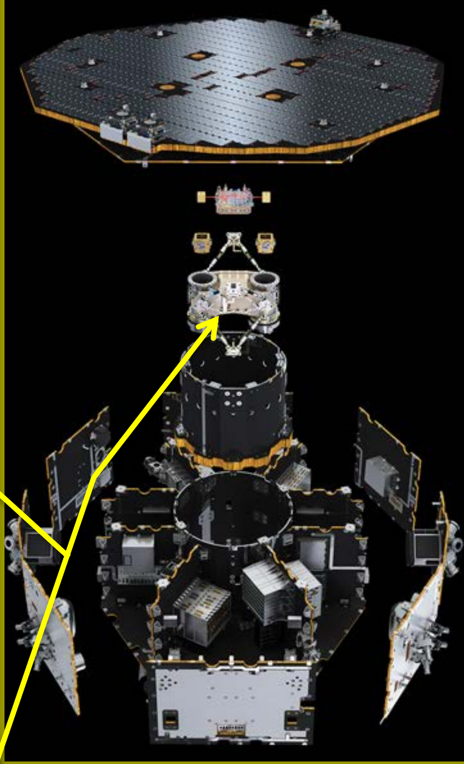
- Force disturbance is local. Test does not require million km size
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs,
- 2 Interferometers (Ifo)
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics



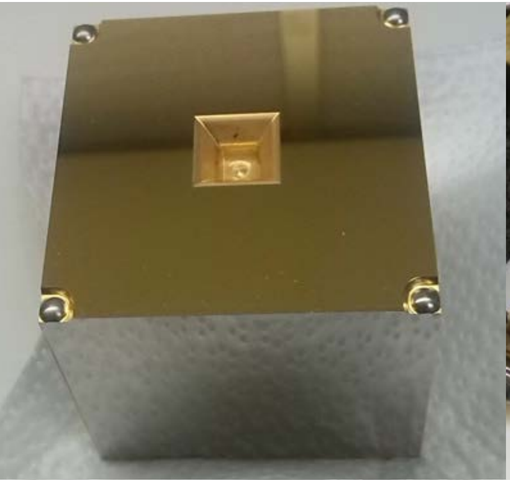
The LTP

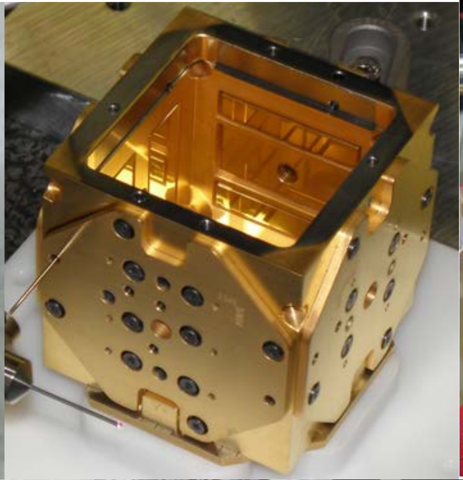
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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

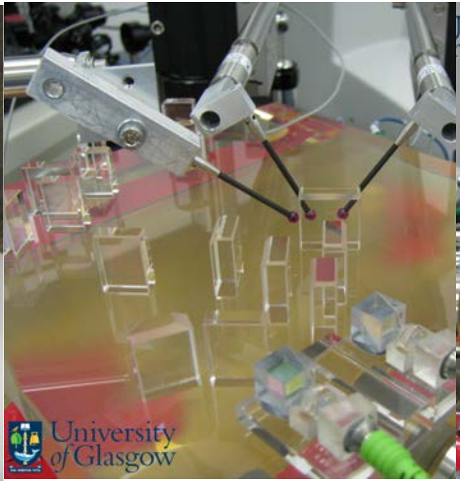


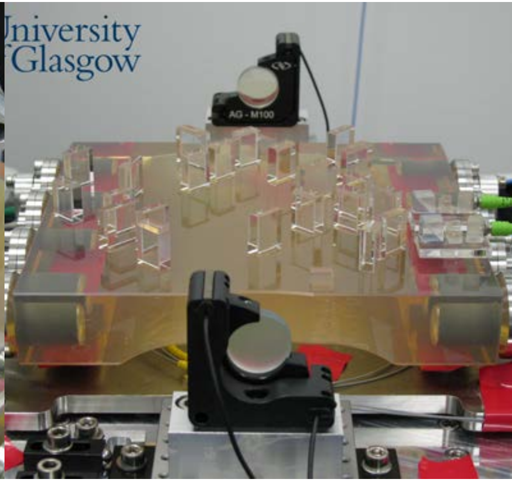


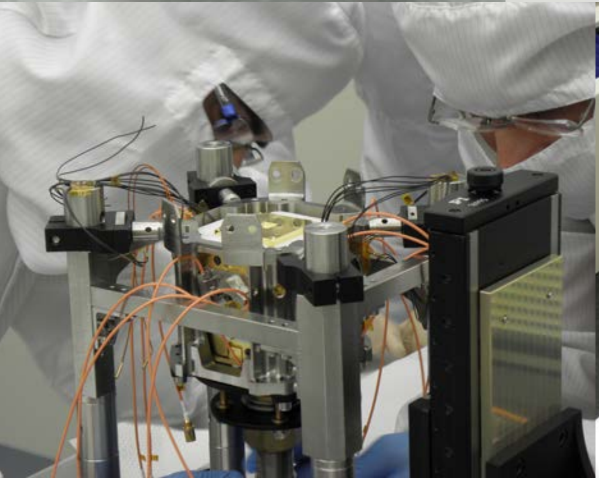
The real H/W

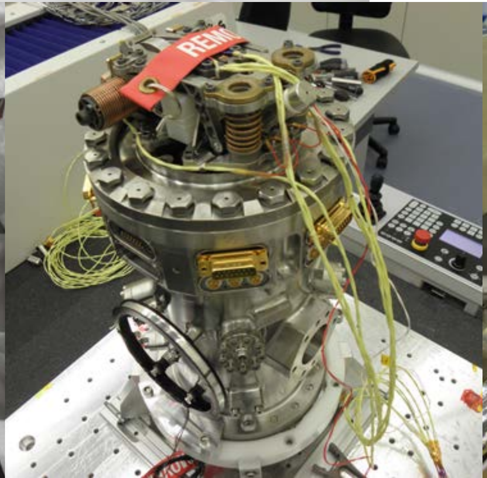




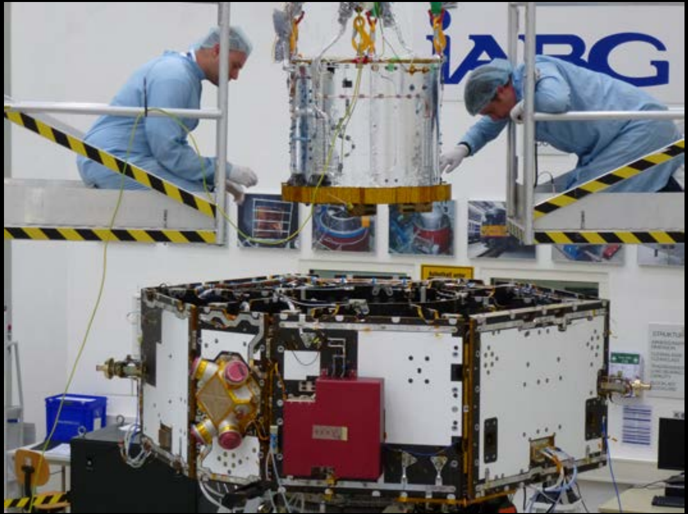




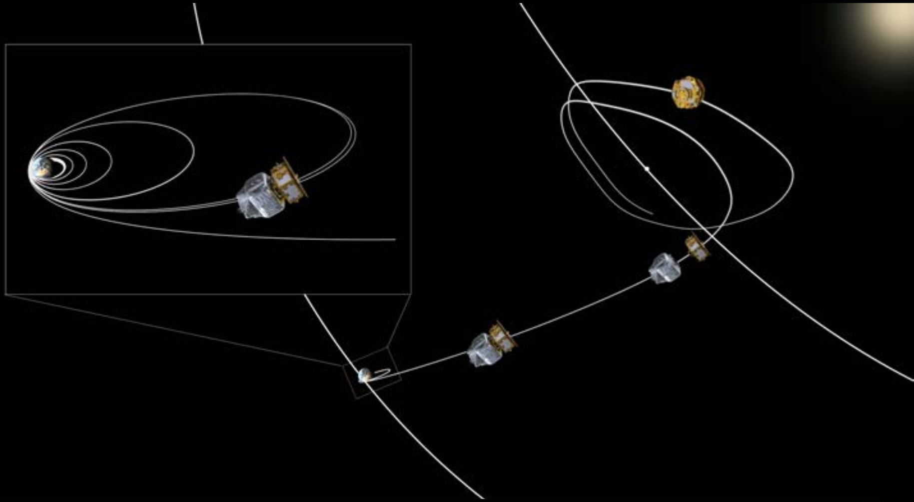




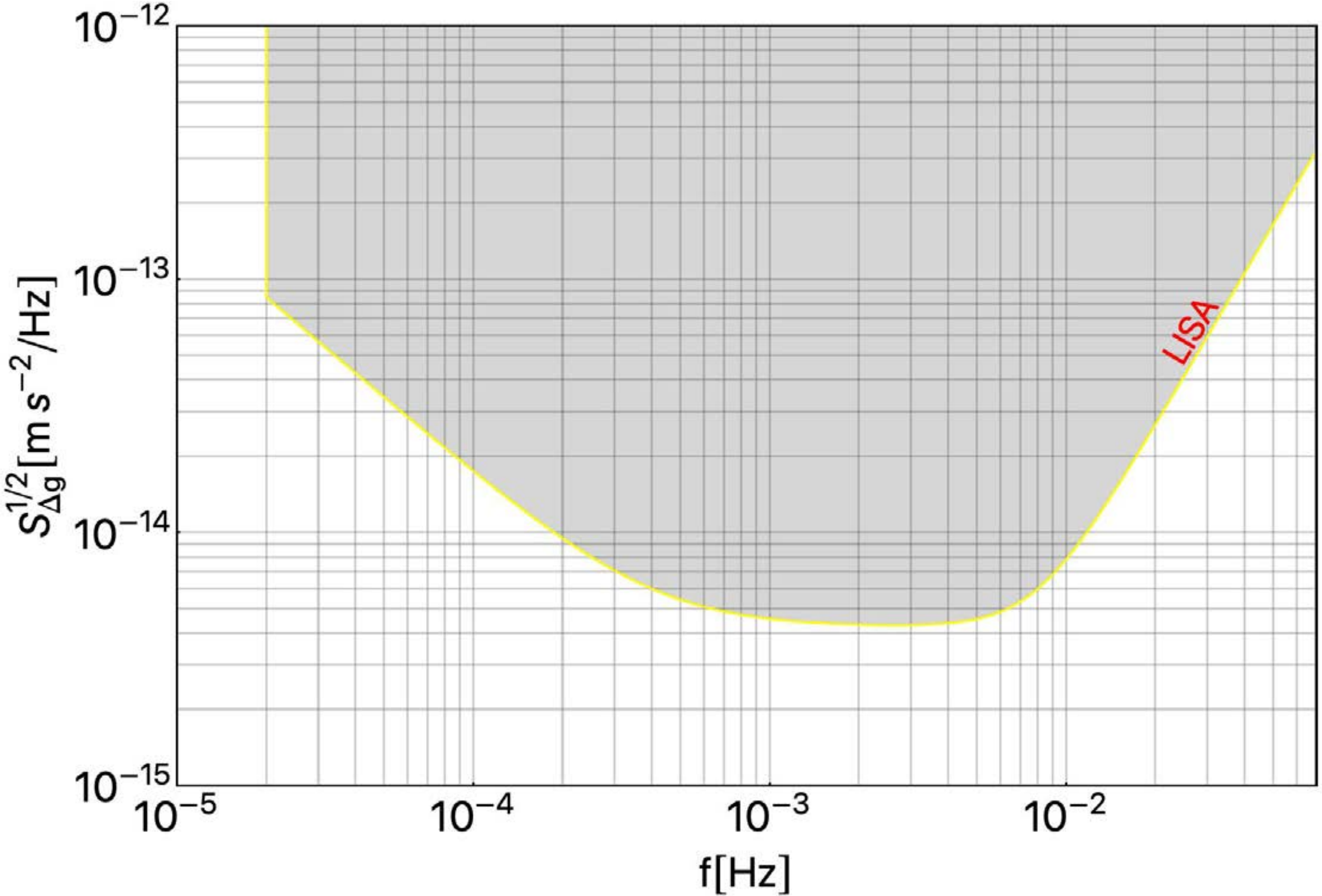
Instrument integration



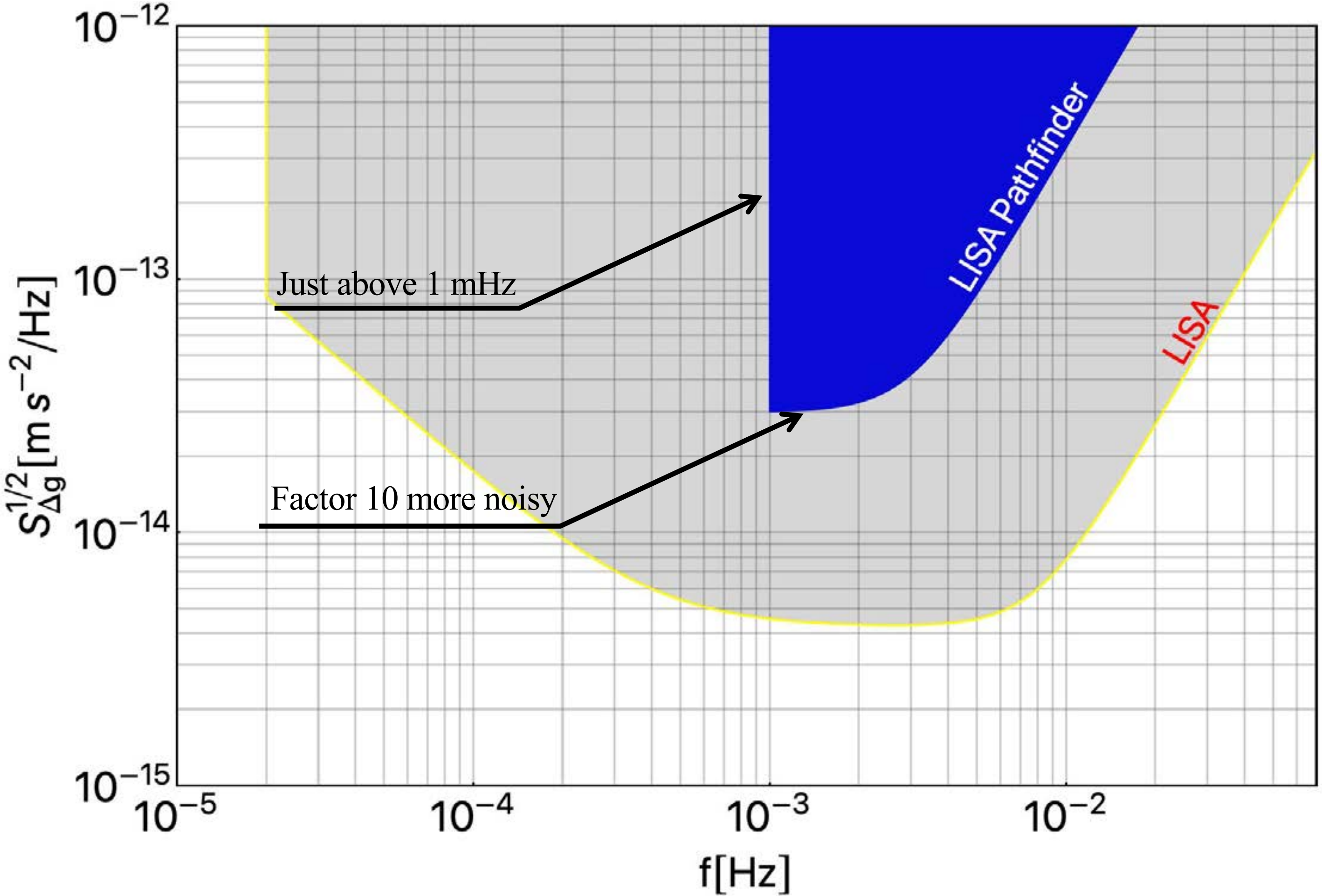
From instrument integration to orbit



LISA acceleration requirements

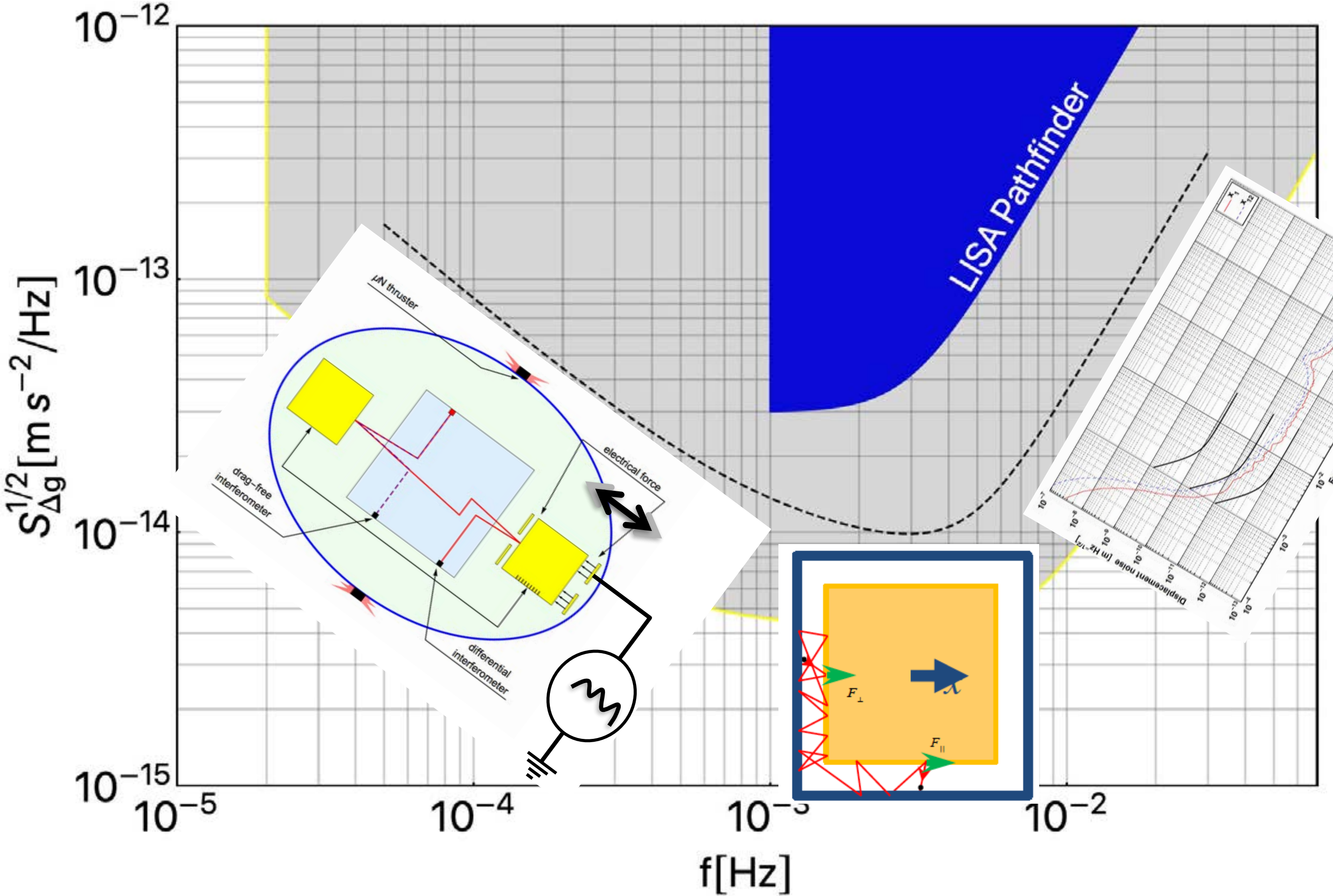


Relaxed LISA Pathfinder requirements



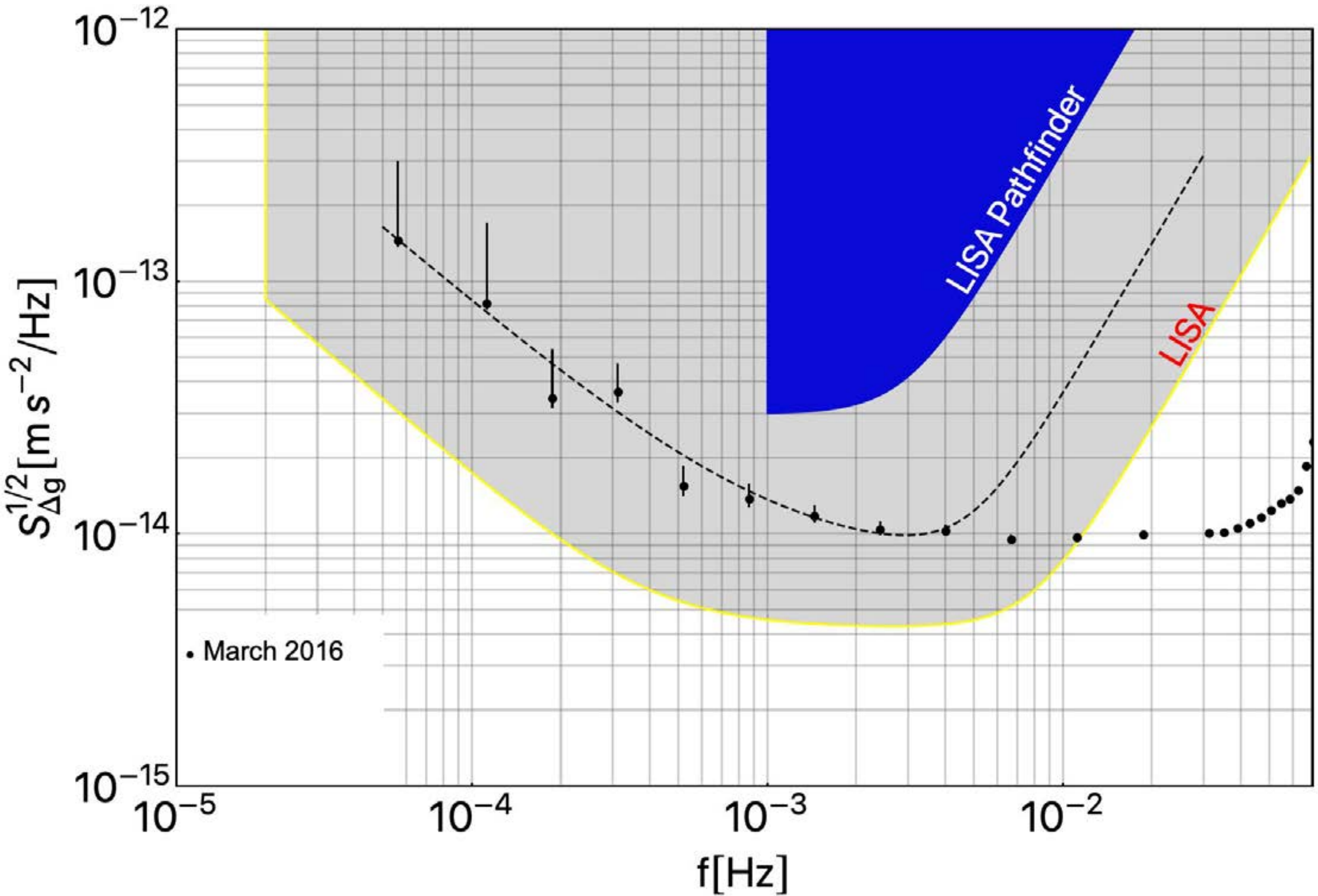
Expected performance

- 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



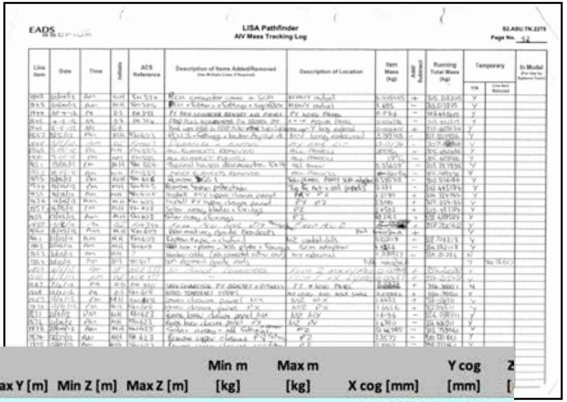
First day of operations: March 1st 2016

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

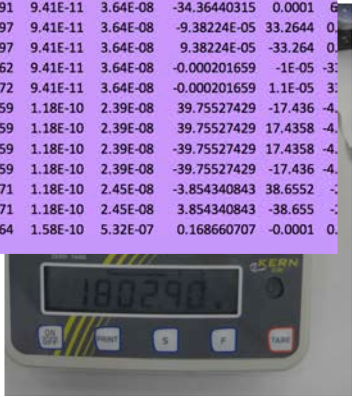


Gravitational control and actuation

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



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



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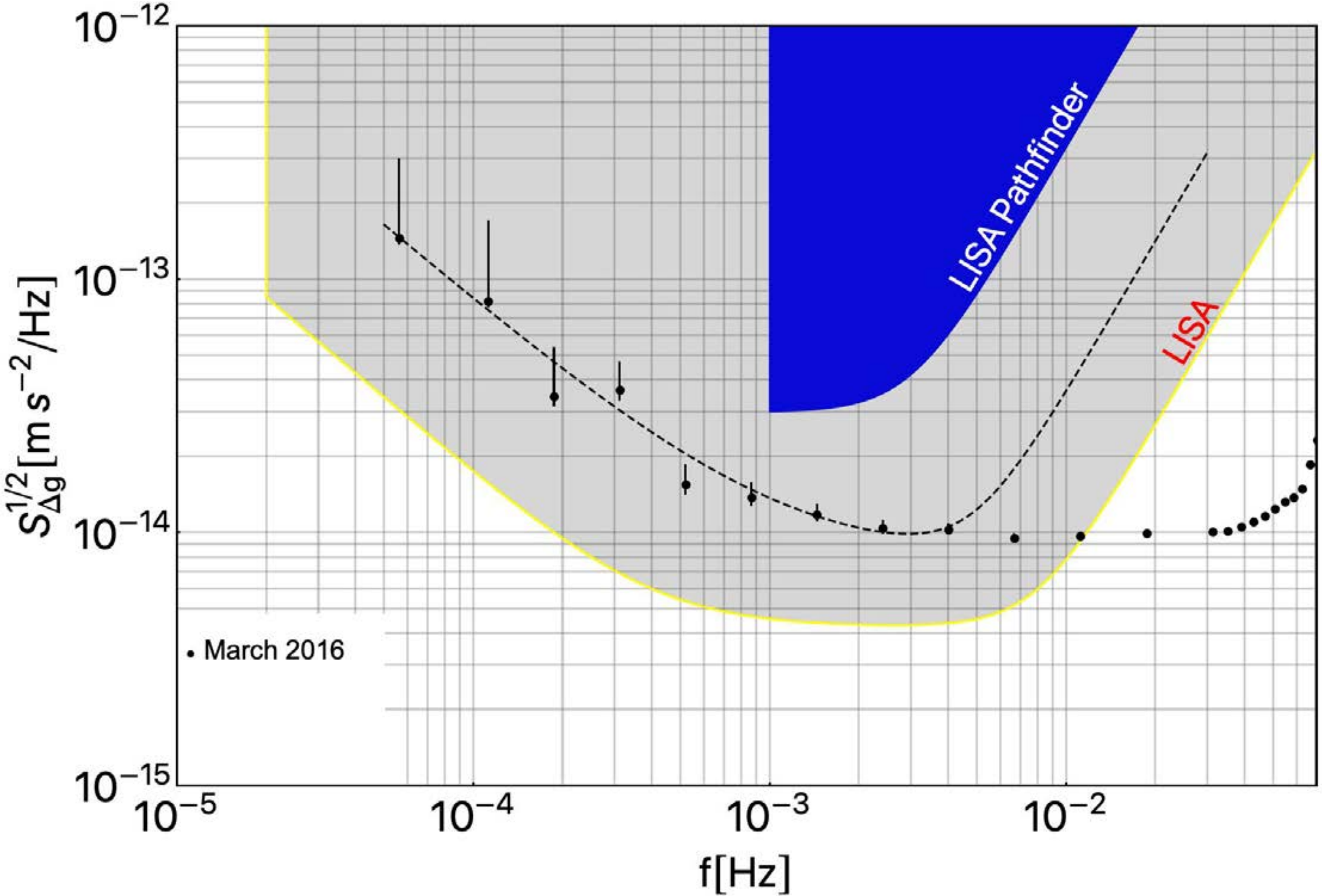

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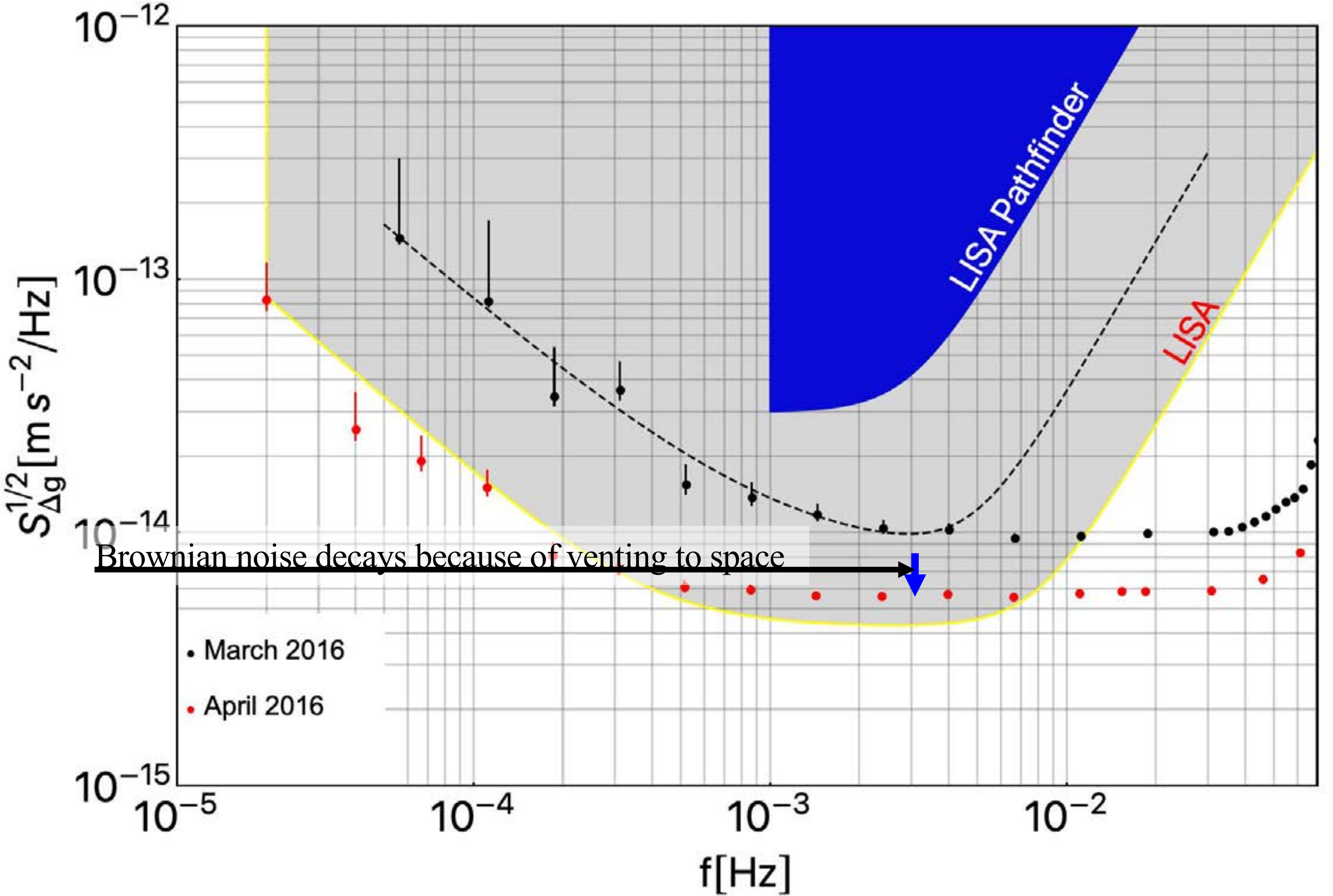
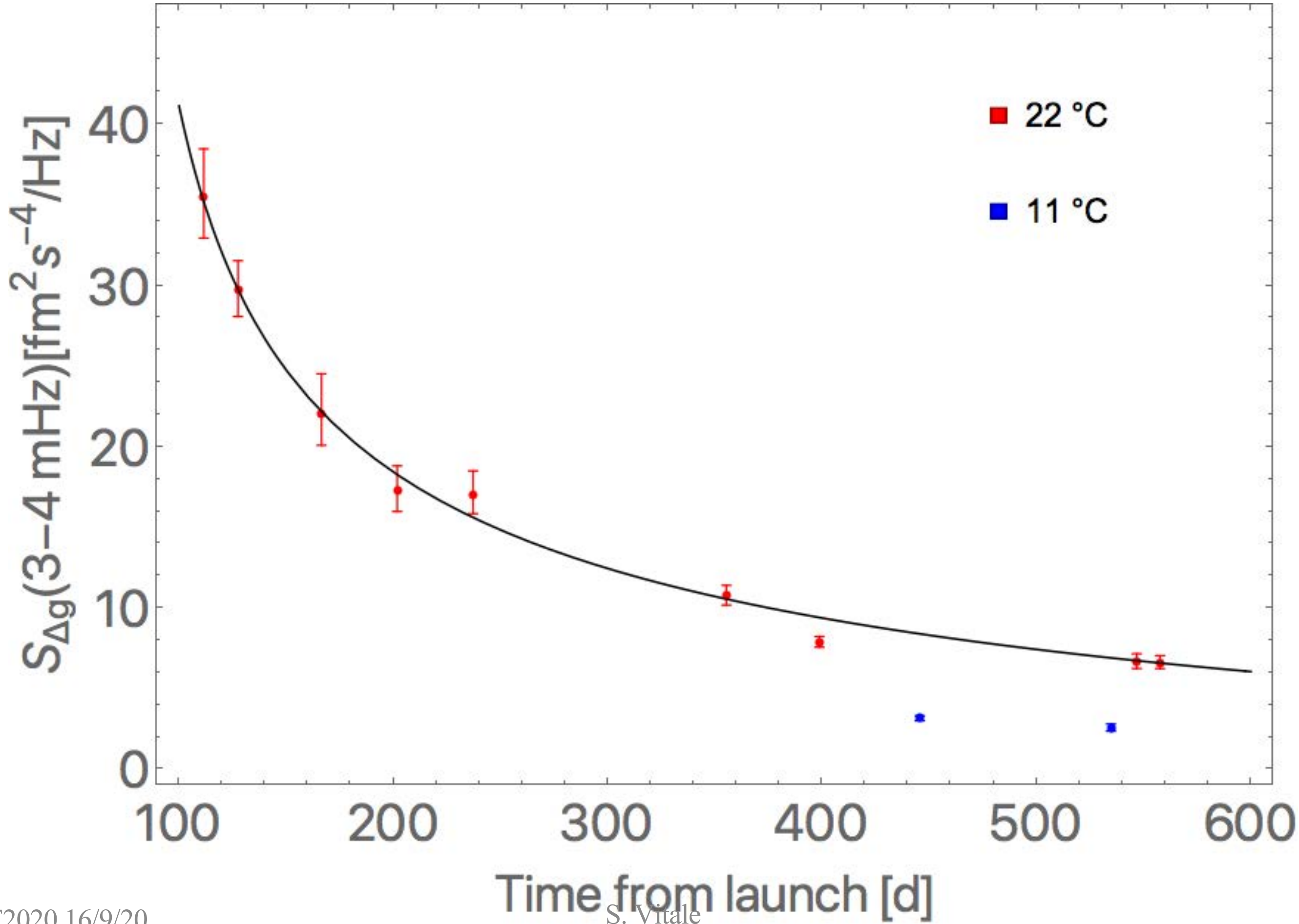


Pressure and Brownian decay



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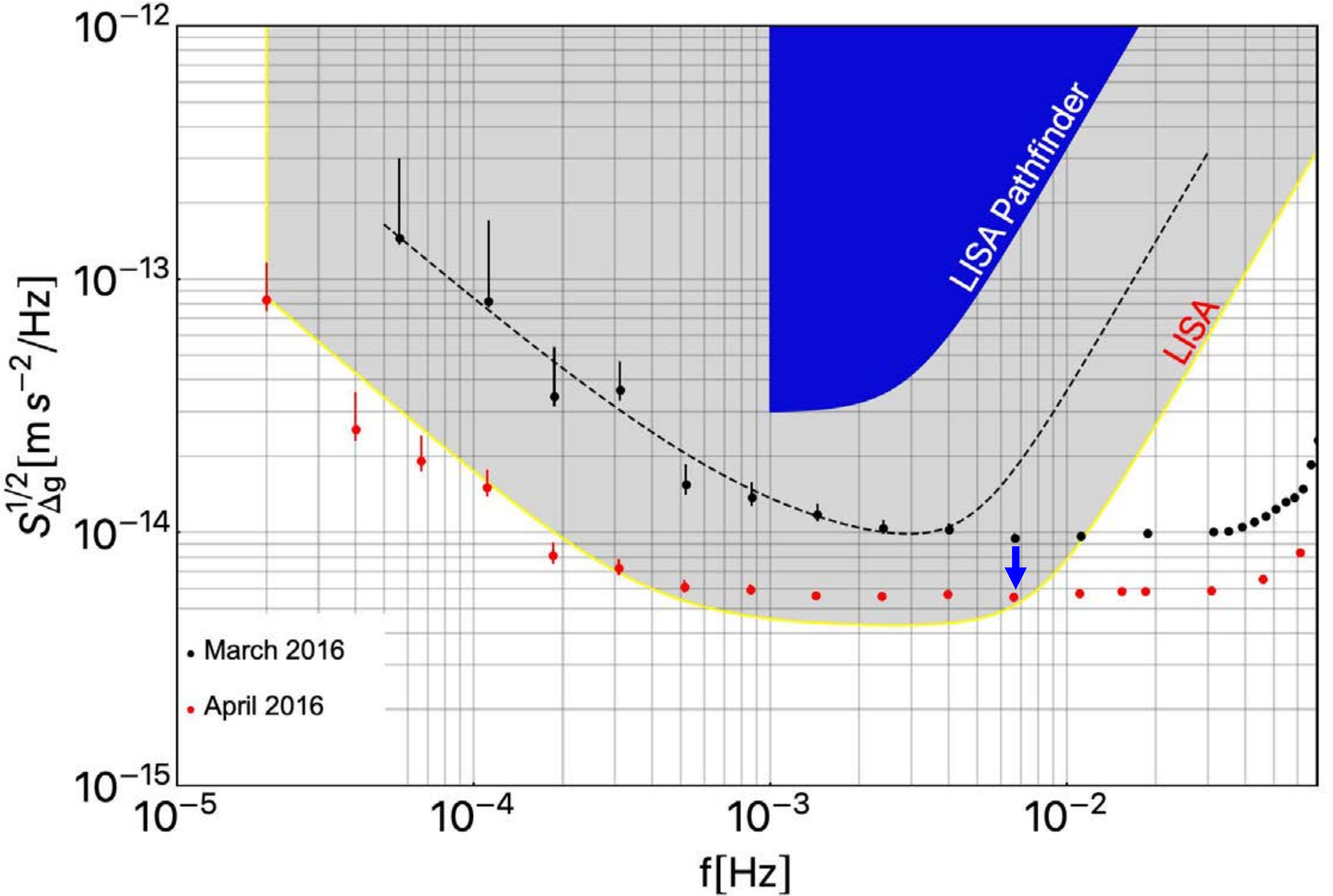
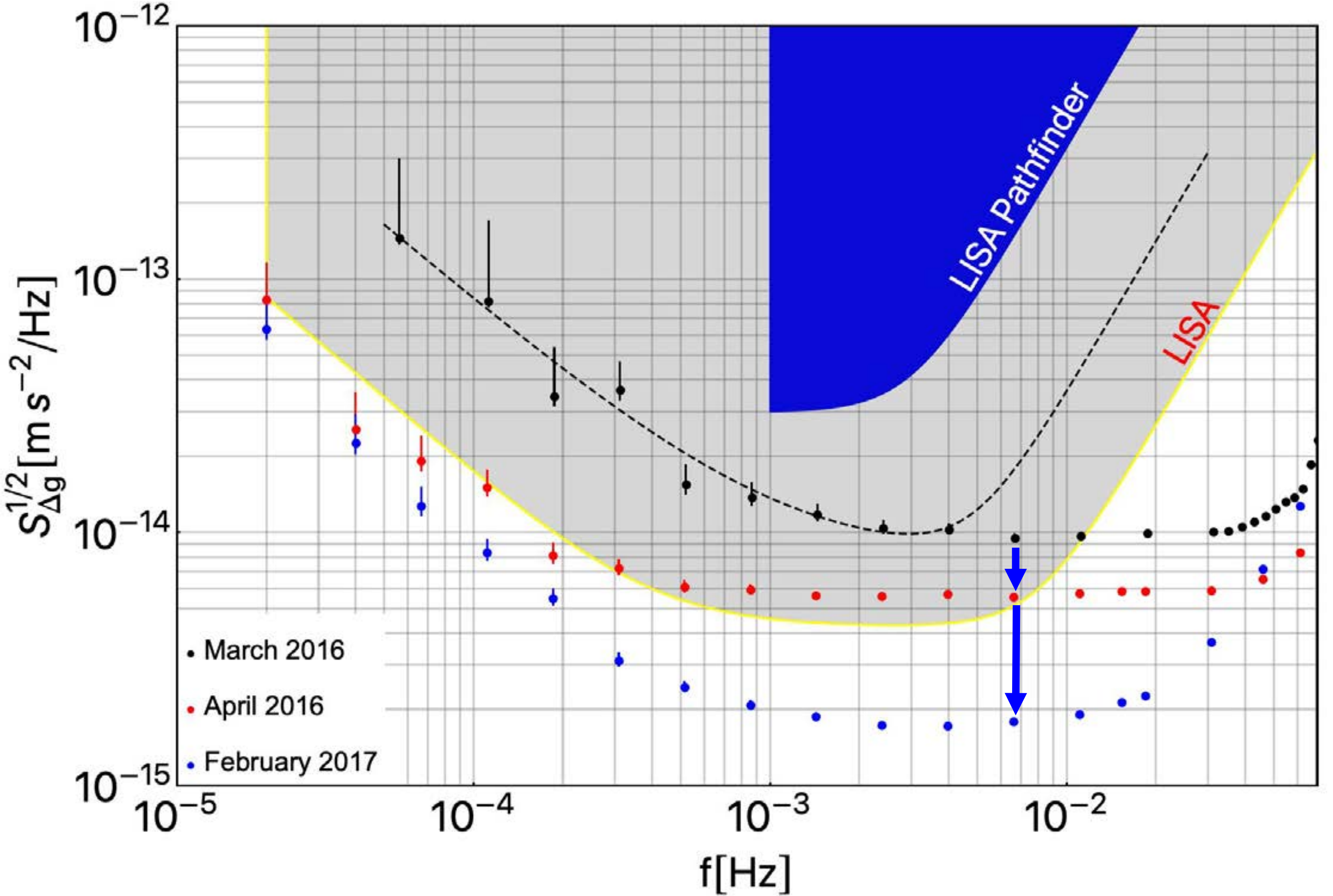
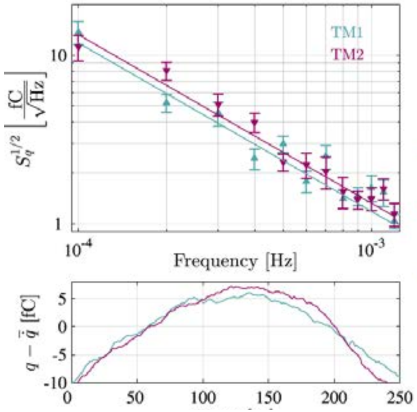


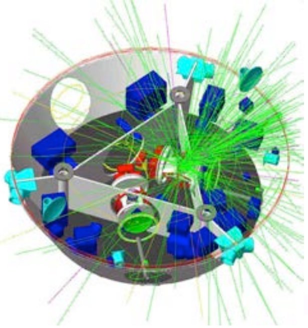
The ultimate performance

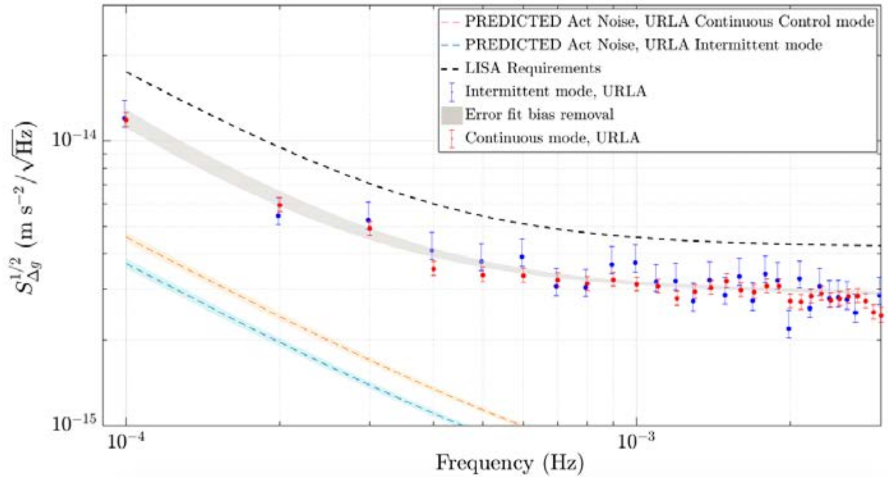


lisa pathfinder

LPF: a full menu of experiments







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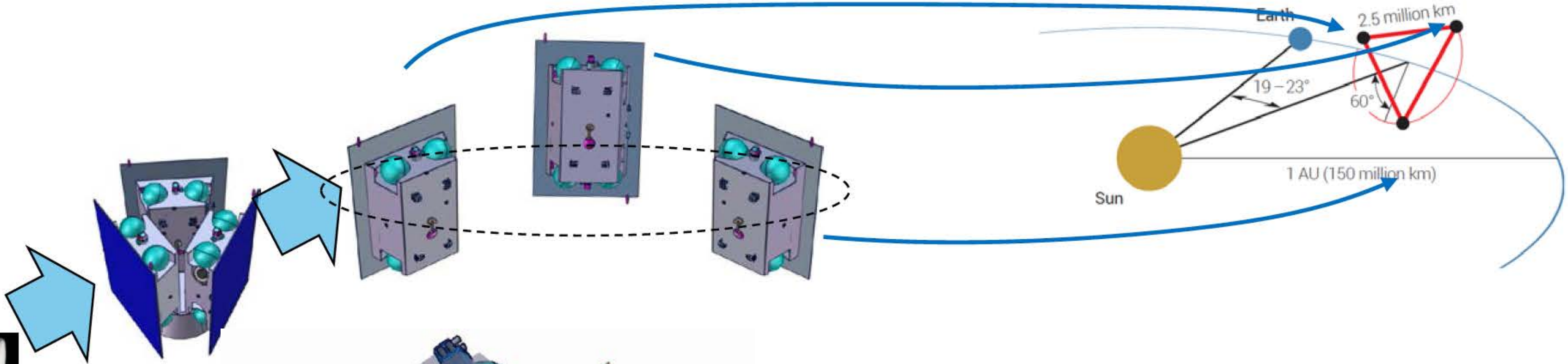
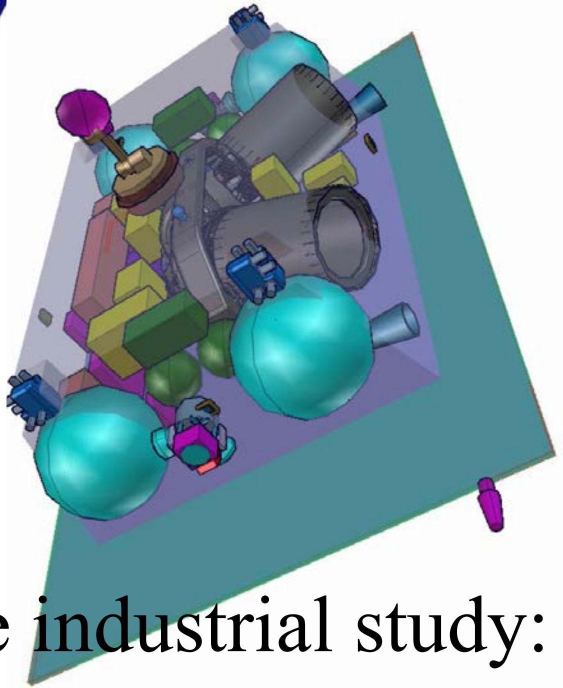
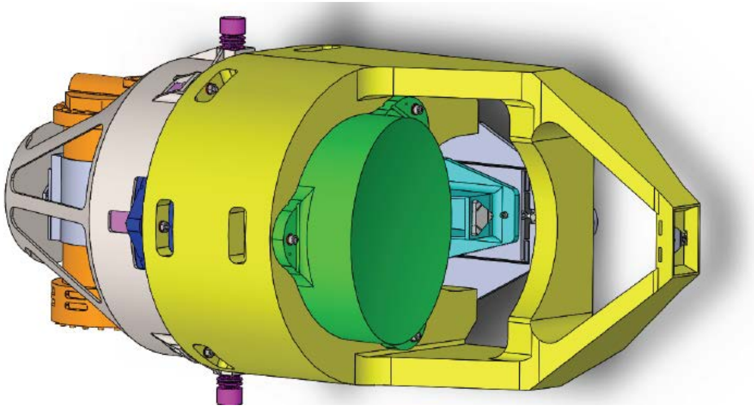
LISA marching ahead

Timeline

October 2013:	Selection of "The Gravitational Universe" as science theme for the 3rd ESA flagship mission (L3)
October 2016:	Call for mission proposals for L3
June 2017:	Selection of LISA as L3 with an anticipated 2034 launch date
May 2018:	Phase A Kick-Off
2018-2021:	**Mission Phase A**
Oct '20-Oct '21:	**Mission Phase A Extension**
<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)





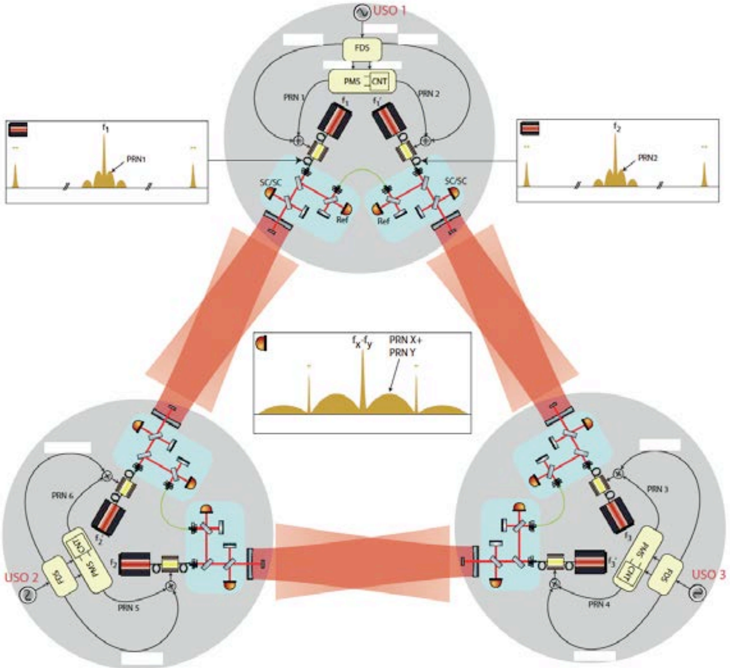


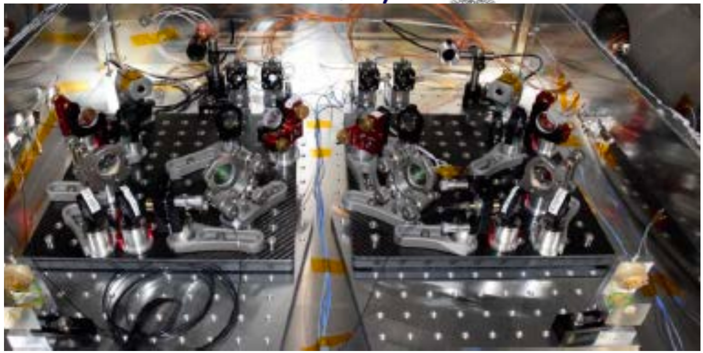
Competitive industrial study: can’t show actual design

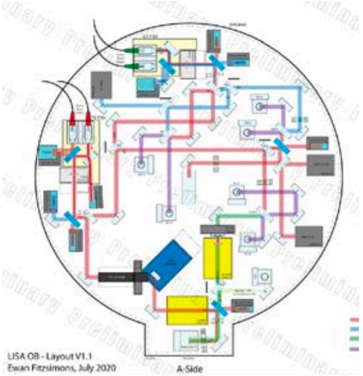
Watchlist of Issues

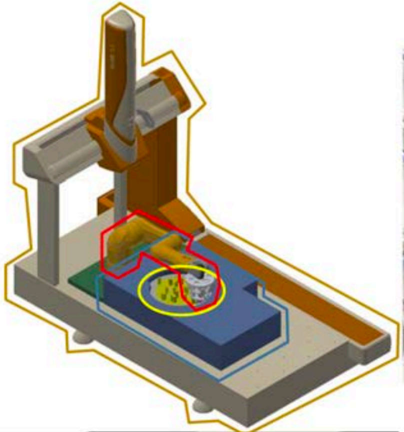
- **Mission**:
  - Schedule: Lengthy instrument integration and testing schedules, as much industrialization as possible required.
  - Cost/Schedule: streamlined model philosophy might incur delays due to problems encountered late
  - Confirmation of baseline TDI performances and requirements (WG in place)
- **Platform**:
  - Mechanisms for assembly tracking and antenna (requirements identified, remaining development risk)
  - Constellation Acquisition (sequence, straylight)
  - **Launch mass currently within updated target.**
- **Instrument**:
  - Mounting and alignment scheme of optical elements and GRS
  - Backlink confirmation
  - Impact of harness
  - Thermal stability at low frequencies

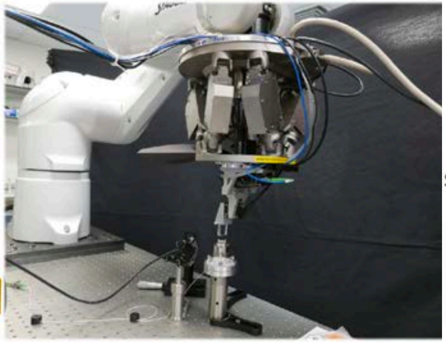
Technology developments

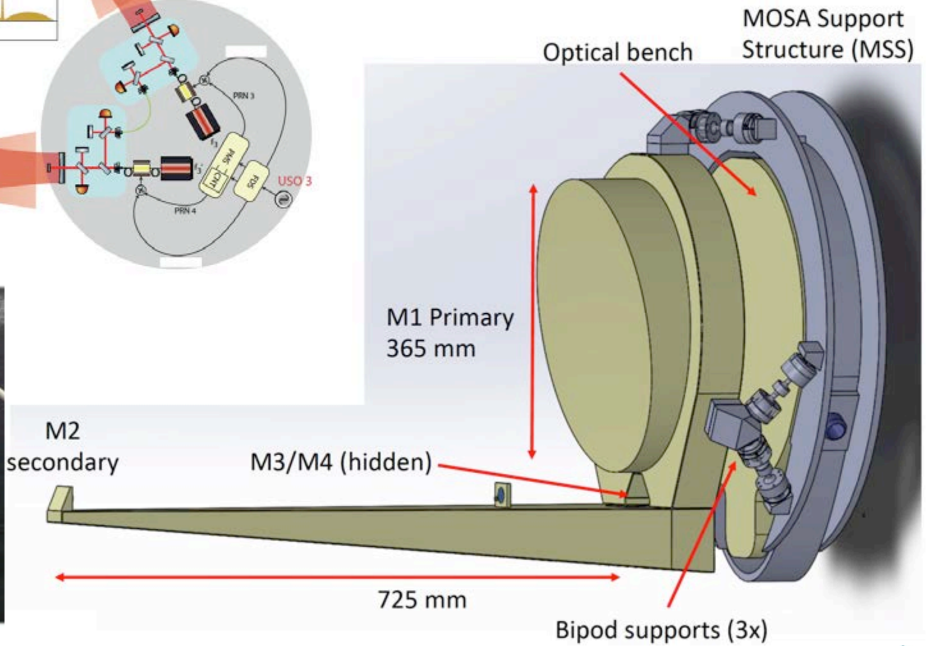













Thank you!
MuSe