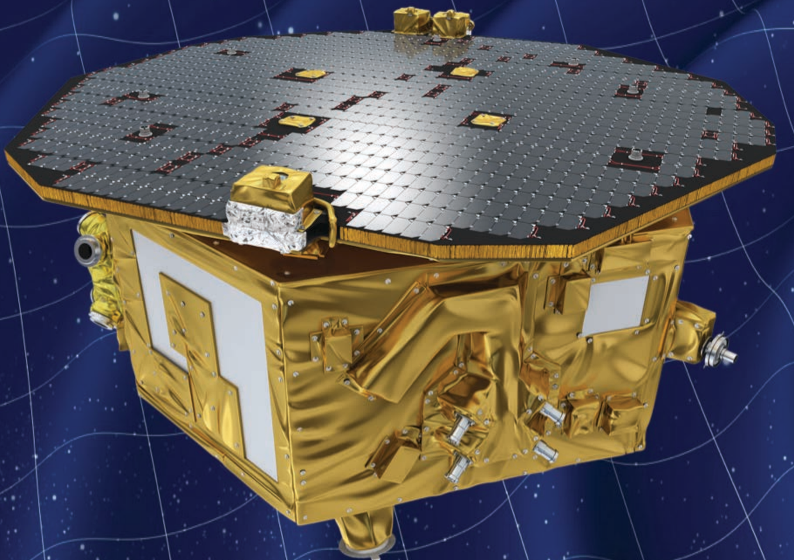


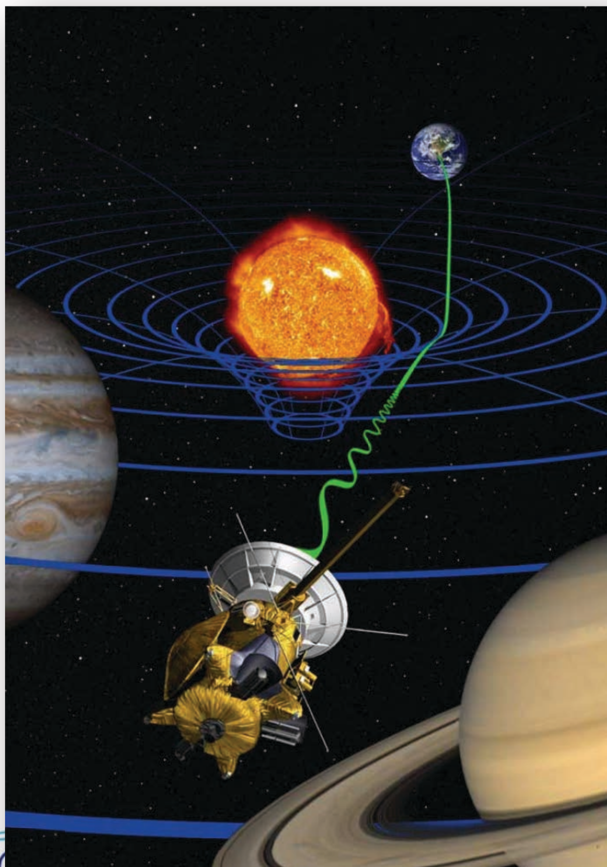
The LTP experiment on LISA Pathfinder and its first results

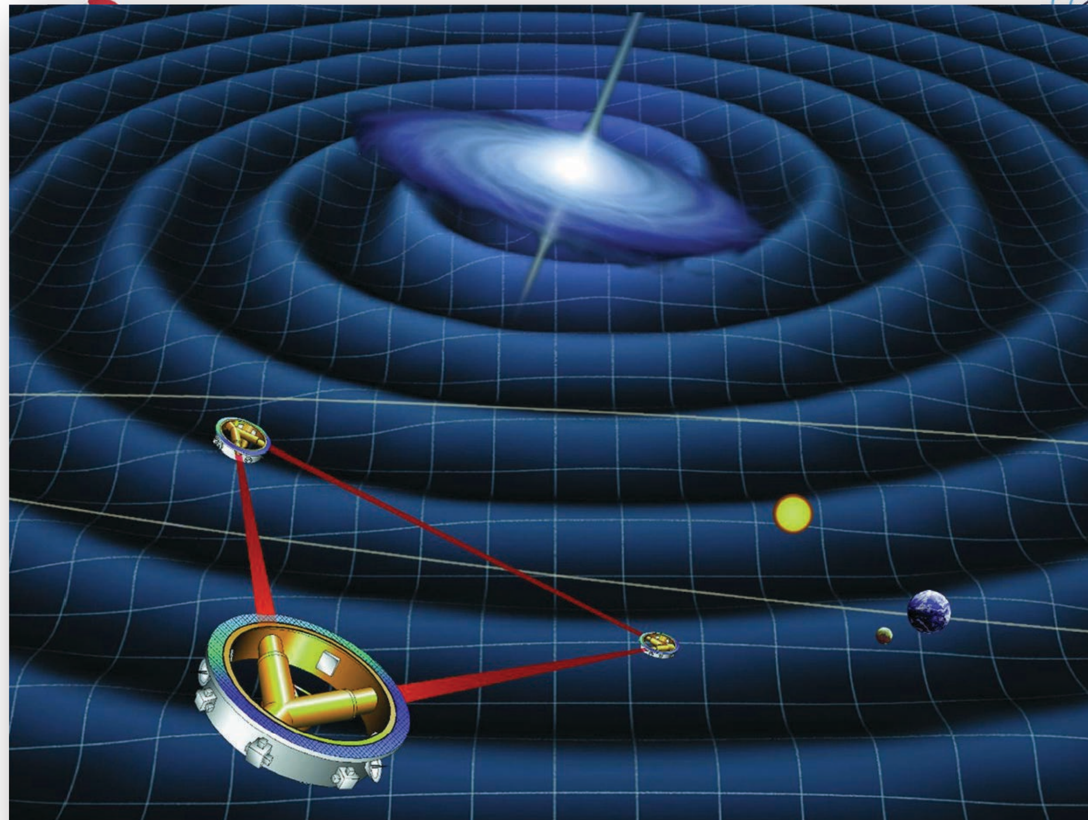
Stefano Vitale

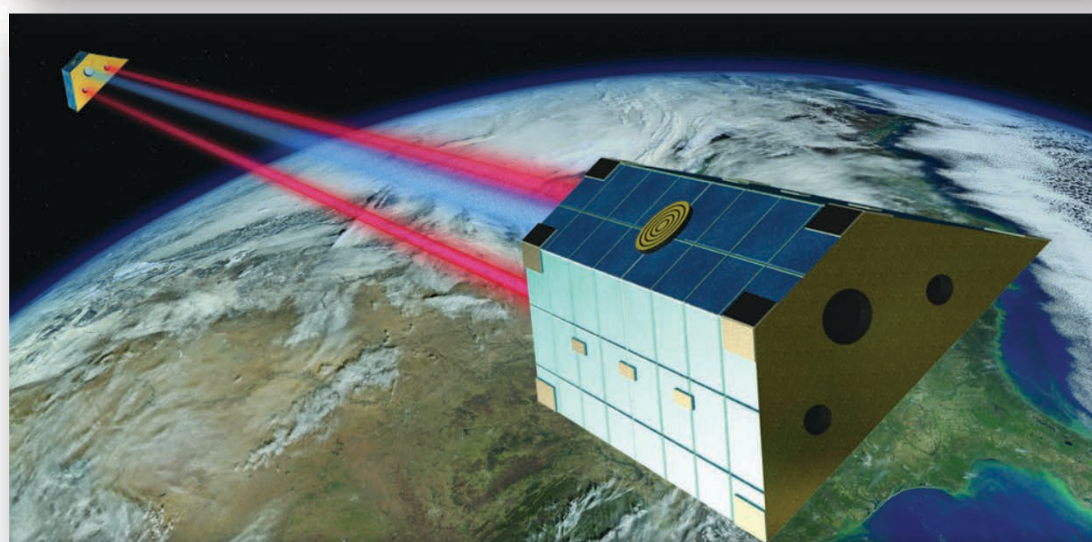
University of Trento and INFN-TIFPA

On the behalf of the LISA Pathfinder Collaboration

Curvature: time-varying Doppler shift between *free falling* observers

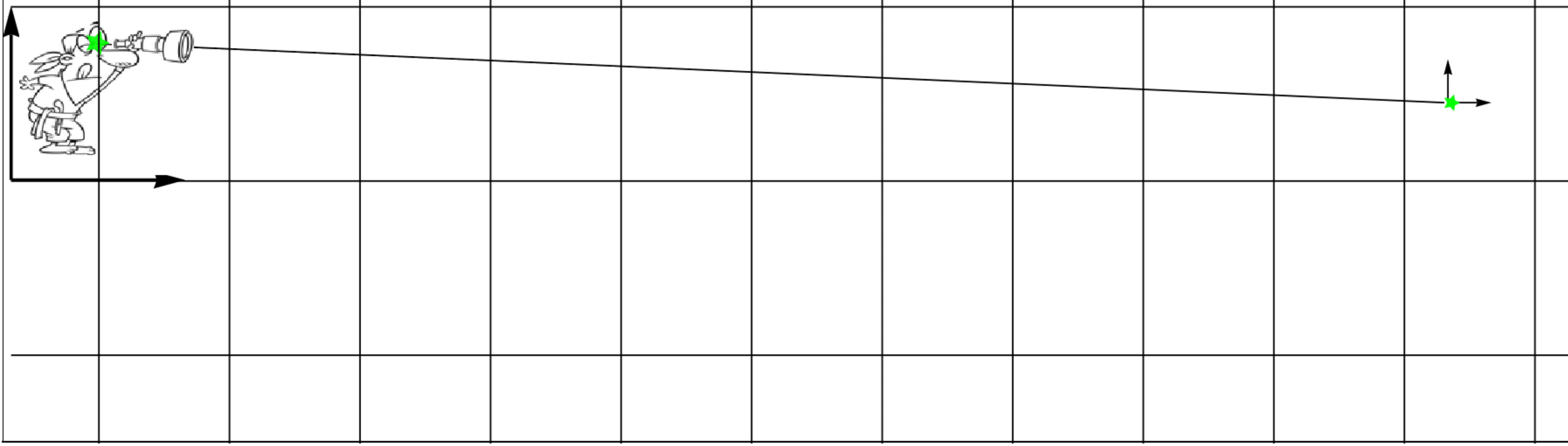






agenzia spaziale italiana

The Doppler link

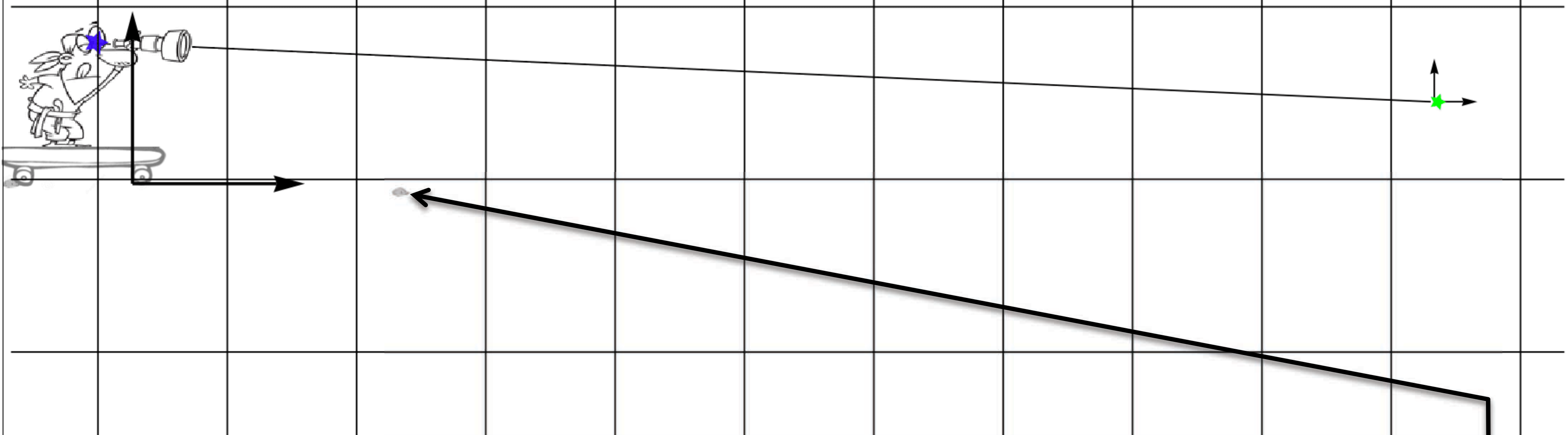


- A constant frequency light beam is sent out by one free-falling observer to a second one far away in space-time.
- GW curvature distorts space-time (accelerates far away free-falling frames) and modulate frequency of beam for second observer.

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

PHYSICAL REVIEW D **88,** 082003 (2013)

The need for free-fall



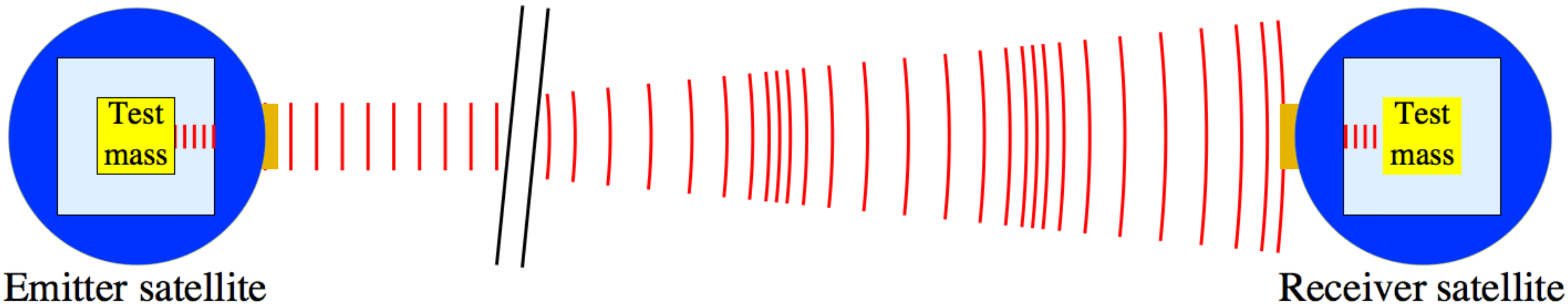
- Doppler due to curvature indistinguishable from acceleration of receiver along the beam, *relative to its local inertial frame*.

$$\left(c/\nu_o\right)\left(\dot{v}_{receiver} - \dot{v}_{emitter}\right) = c\left\{\dot{h}_{receiver}\left(t\right) - \dot{h}_{emitter}\left(t - L/c\right)\right\} +$$
$$+ a_{receiver}\left(t\right) - a_{emitter}\left(t - L/c\right)$$

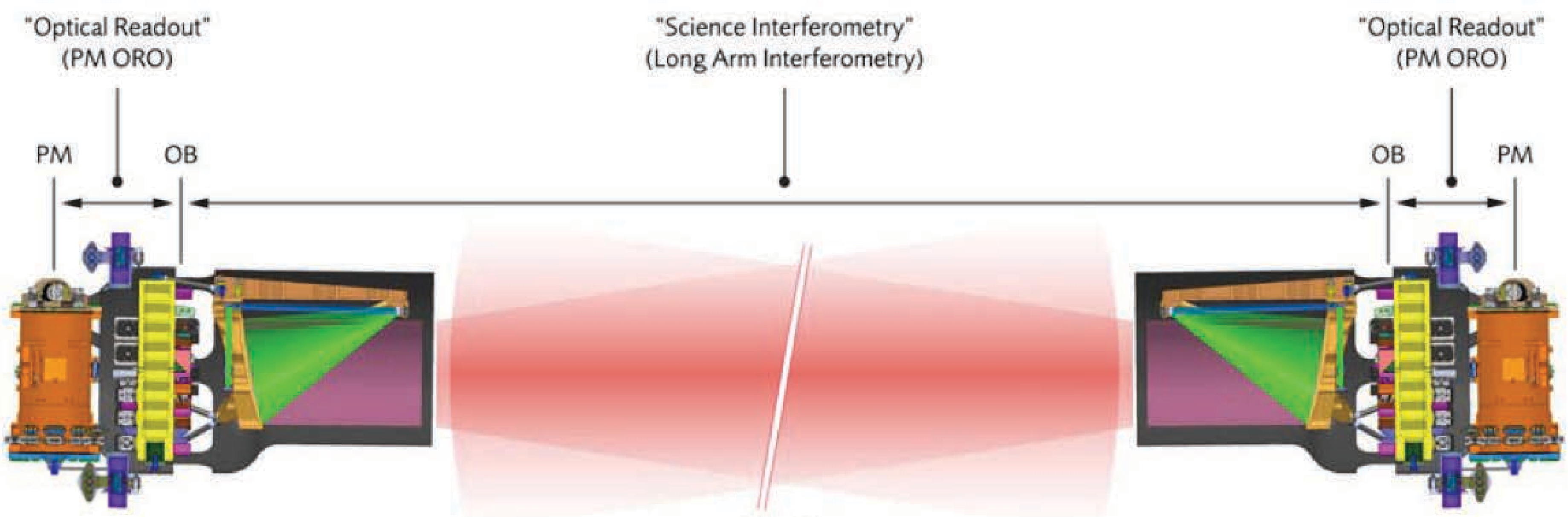
- Same applies to emitter
- Acceleration relative to local inertial frame is due to *true forces*.

PHYSICAL REVIEW D **88**, 082003 (2013)

The LISA link

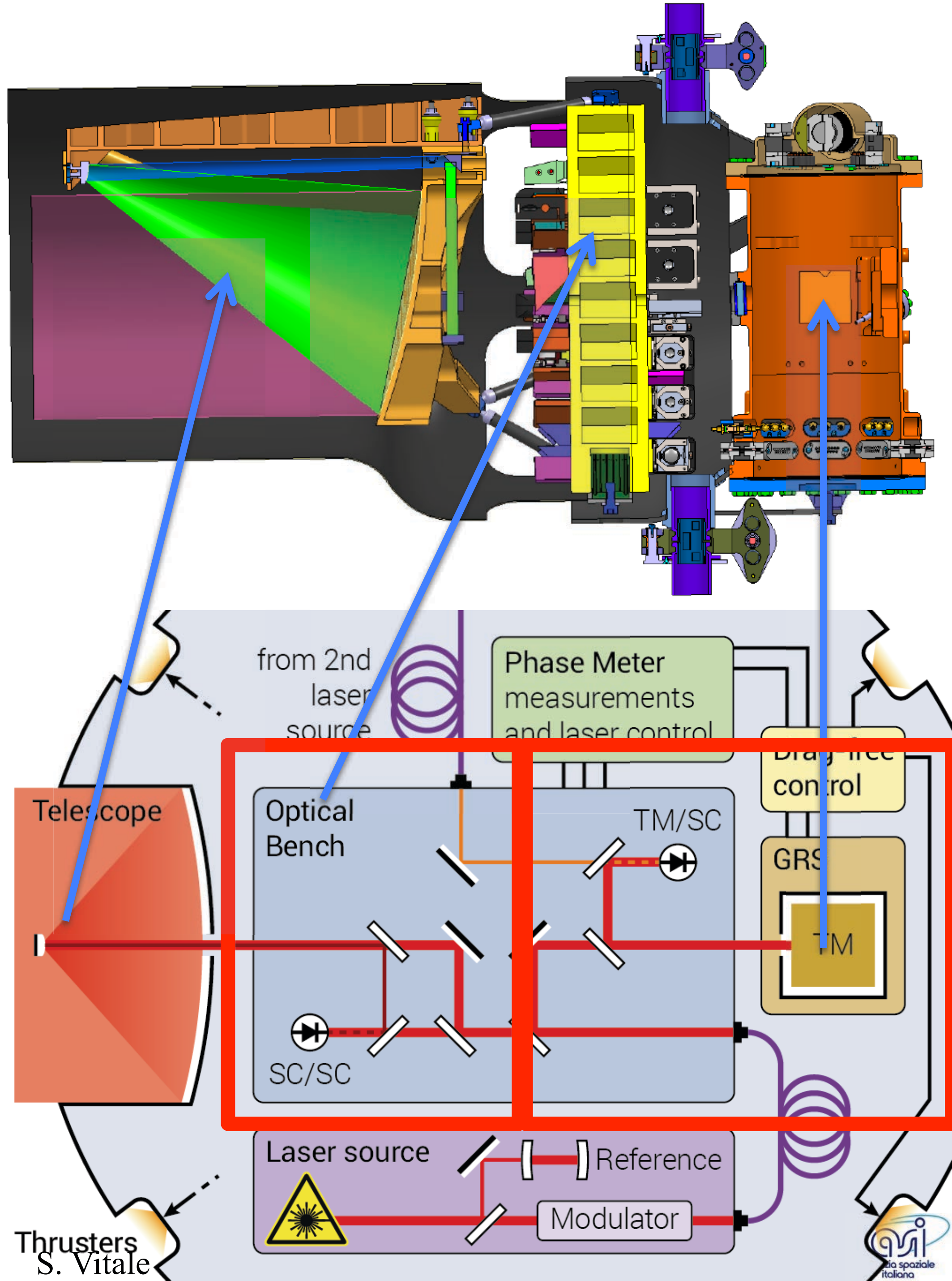


- Inertial observer are replaced by test-masses
- (Satellites accelerate too much because of solar radiation pressure)

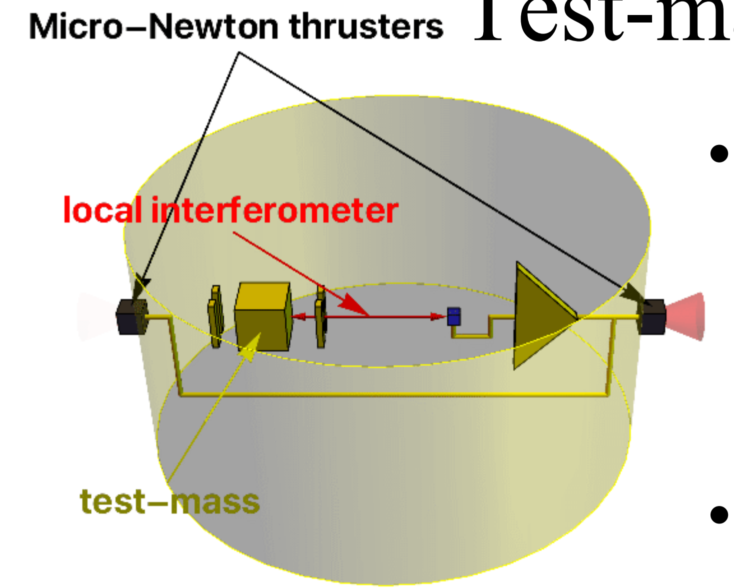


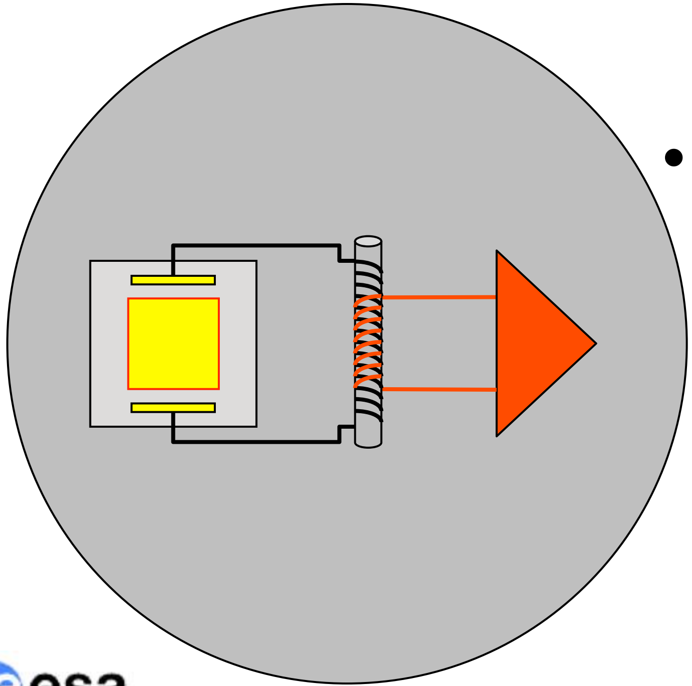
LISA Instrument

- The Gravitational Reference Sensor with the test-mass
- The Optical Bench with:
  - Local interferometer
  - Spacecraft to spacecraft interferometer
- Telescope for the spacecraft to spacecraft interferometer

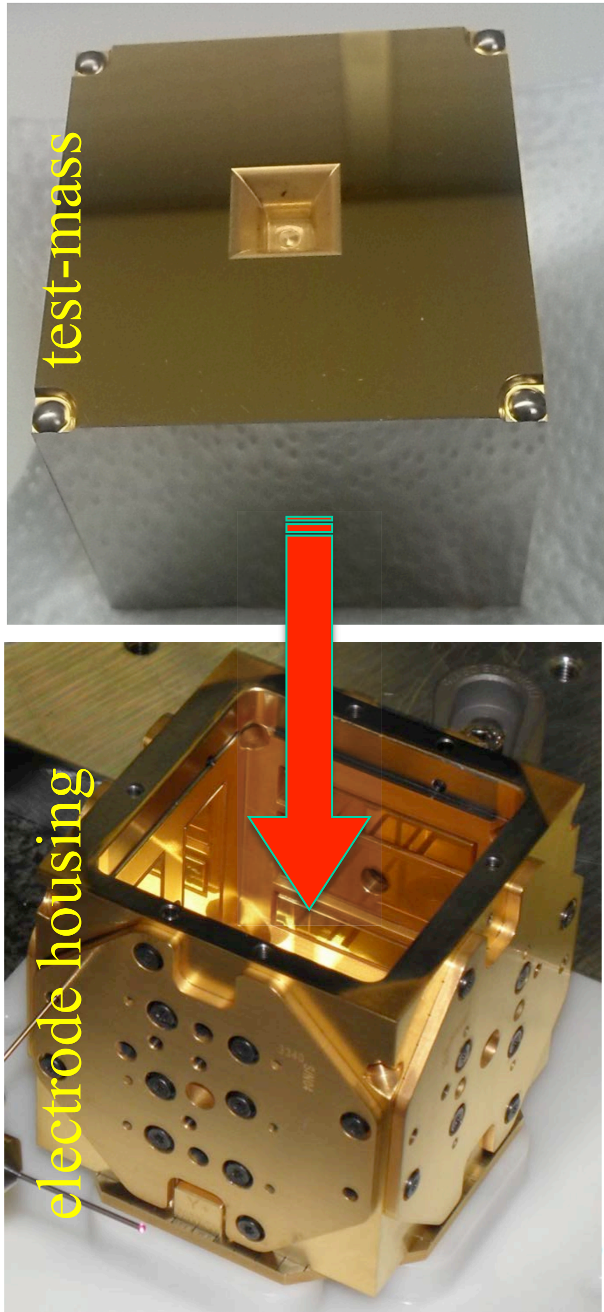


Test-masses and drag-free





- Spacecraft chases test-mass along sensitive direction (drag-free)
- 3-4 mm clearance between test-mass and electrodes
- Some test-mass degrees of freedom controlled via electrostatic forces



Free fall in LISA

- Acceleration relative to local inertial frame are due to true forces.

$$\left(c/\nu_o\right)\left(\dot{\nu}_{receiver}-\dot{\nu}_{emitter}\right)=c\left\{\dot{h}_{receiver}\left(t\right)-\dot{h}_{emitter}\left(t-L/c\right)\right\}+\Delta g$$

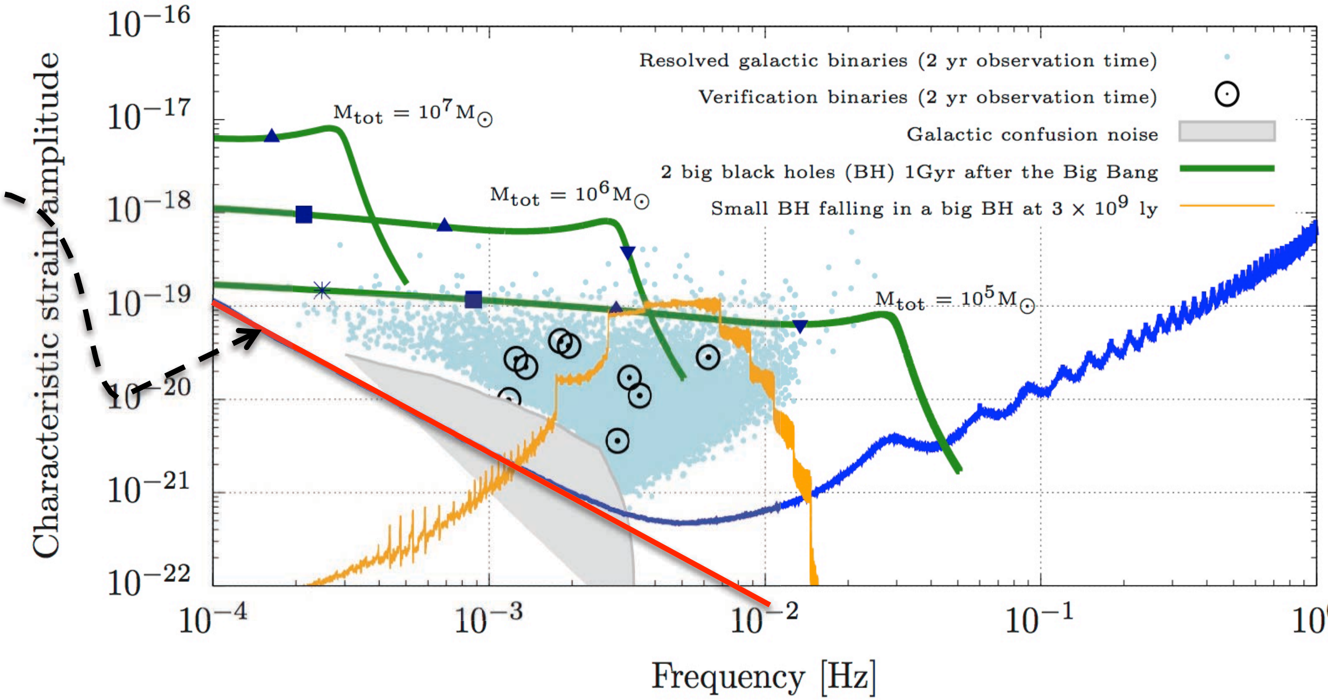
$$\Delta g\equiv f_{receiver}\left(t\right)/m-f_{emitter}\left(t-L/c\right)/m$$

- LISA: Δg noise to be suppressed at $<\sqrt{2}\times 3$ fm $s^{-2}/\sqrt{Hz}$

$\Delta g \rightarrow$ effective strain

$$\left(c/\nu_o\right)\Delta\dot{\nu}\simeq L\ddot{h}+\Delta g$$

$$h_{\Delta g}\left(\omega\right)\rightarrow\Delta g/L\omega^2$$



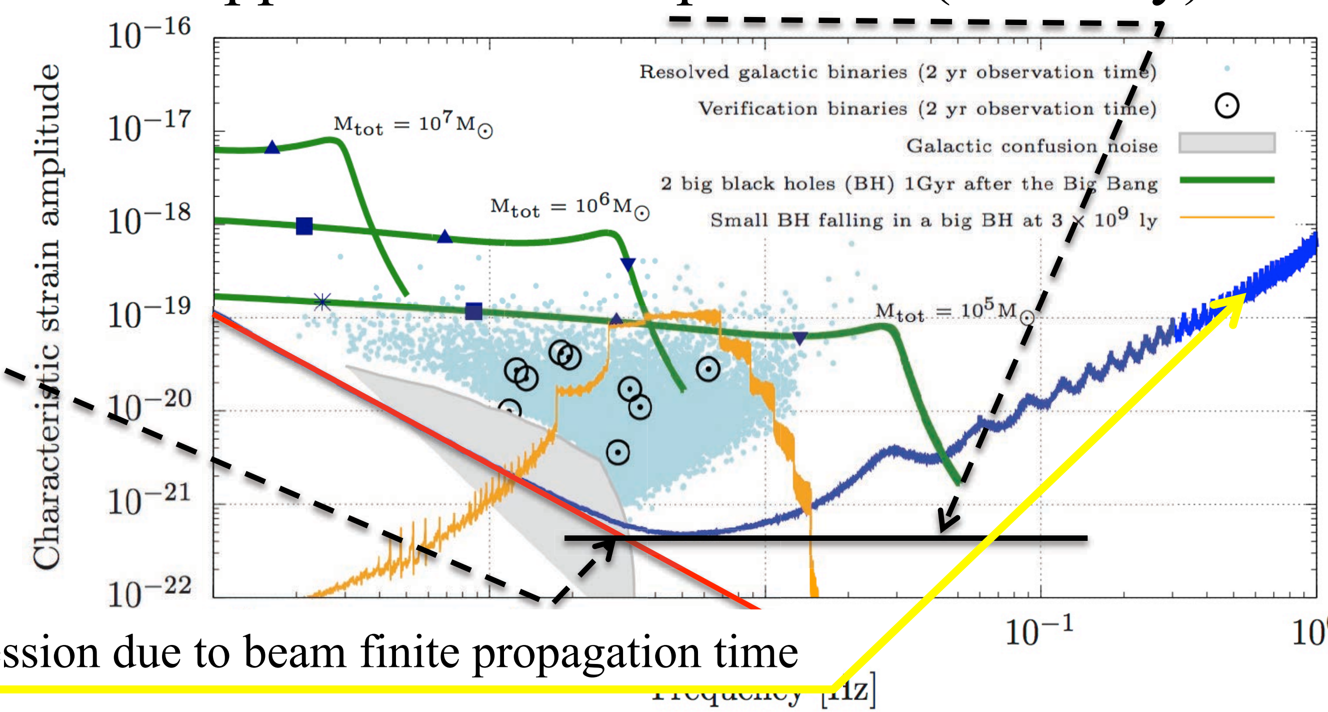
Measuring Doppler shift

- Doppler shift measured by laser interferometer displacement (phase) signal
- Interferometer noise:

$$(c/\nu_o)\Delta\dot{\nu} \simeq L\ddot{h} + \Delta g + \delta\ddot{x}_{noise} \qquad h_{\delta x}(\omega) = \delta x(\omega)/L$$

- LISA: δx noise to be suppressed at < 13 pm /√Hz (two-way)

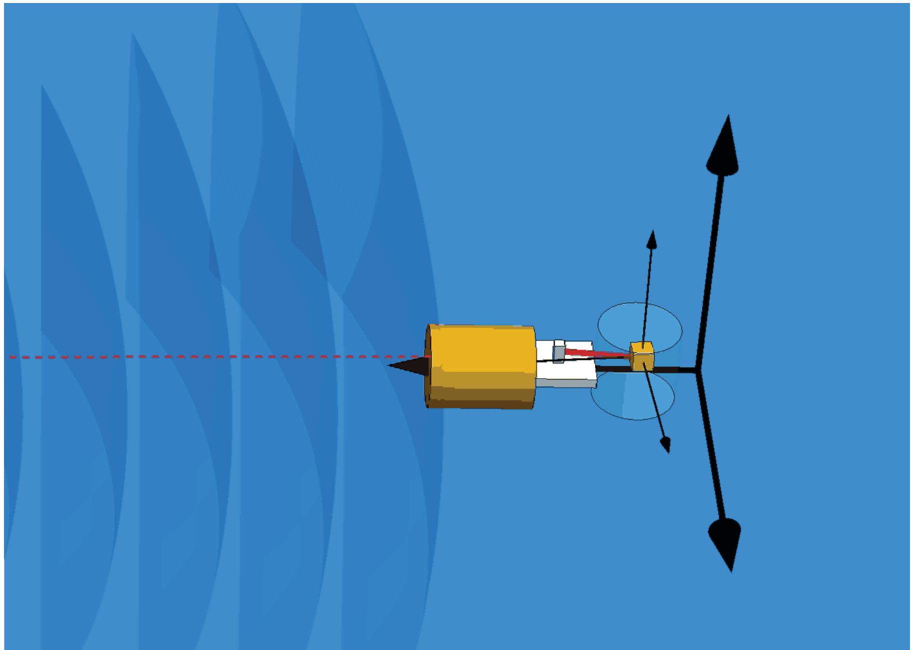
Δg requirements may be relaxed above ~2-3 mHz



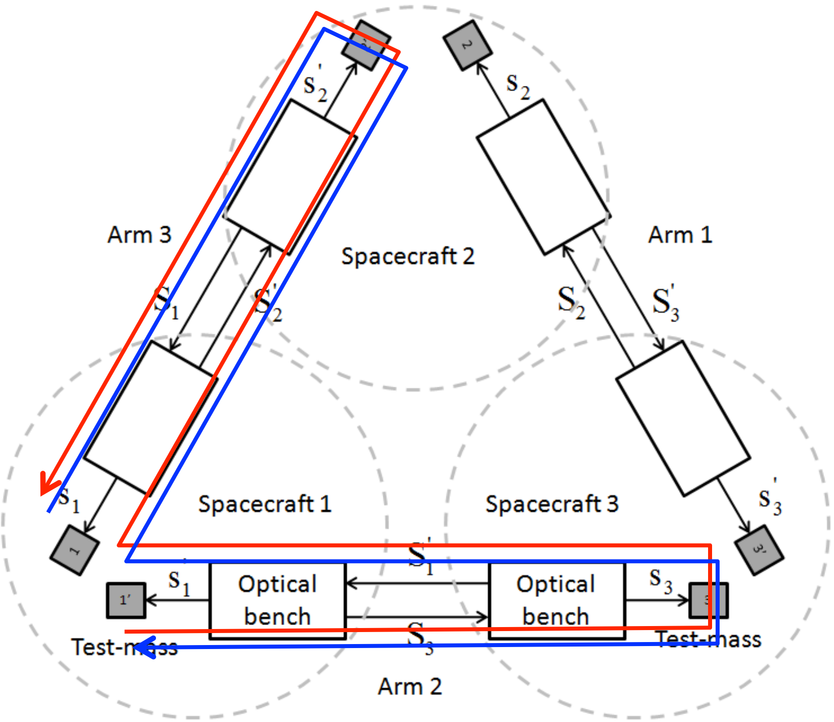
Signal suppression due to beam finite propagation time

Most of noise in LISA is generated inside each spacecraft independently

- Disturbance force is local
- Opto-electronic noise is local
- Pick-up of spacecraft motion due to optical misalignments relative to local laser wave-front

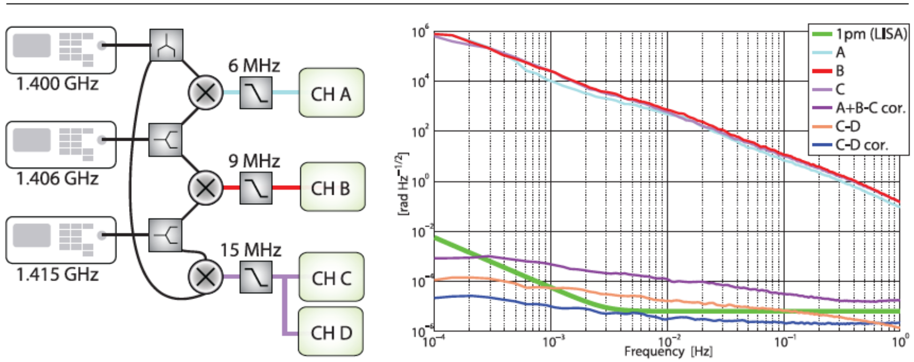


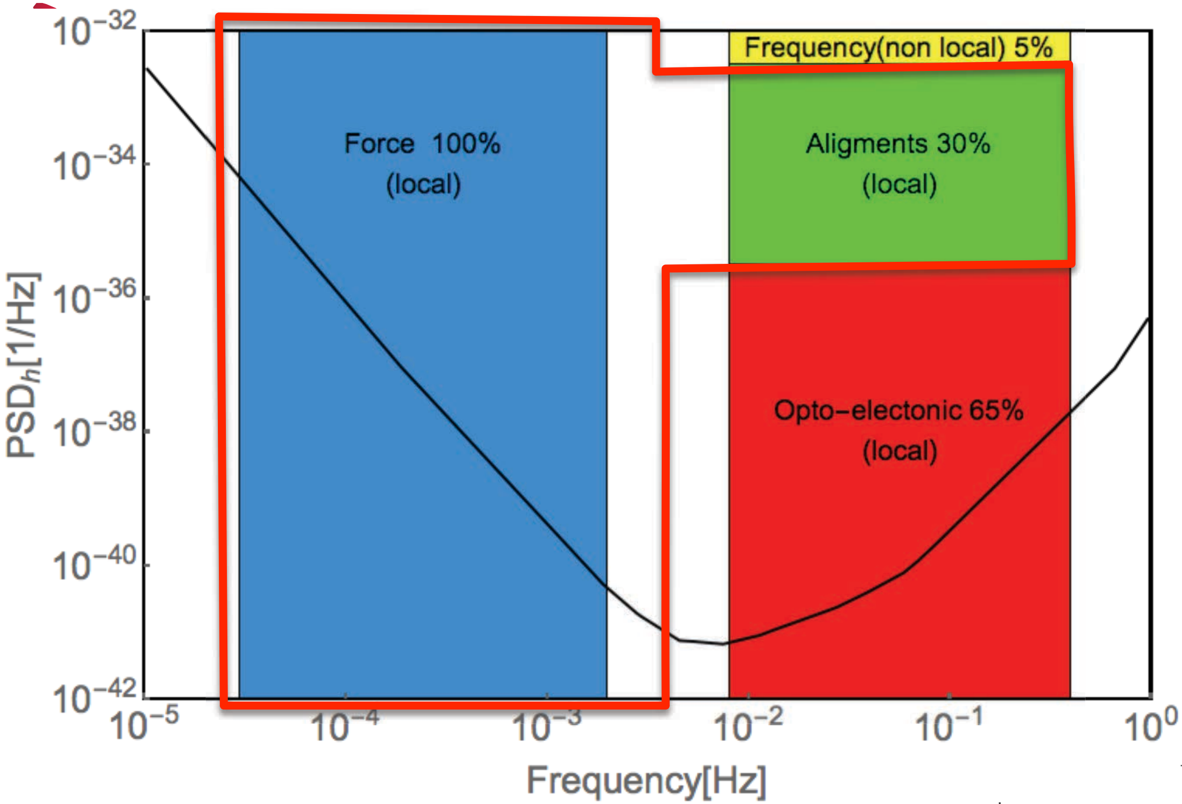
Non-local disturbance: Frequency noise



- Laser frequency noise suppressed by comparing light beam that have traveled along both (unequal) arms
- Done in data post-processing with high accuracy phase-meter
- *Frequency noise is the single noise source that involves the entire constellation*

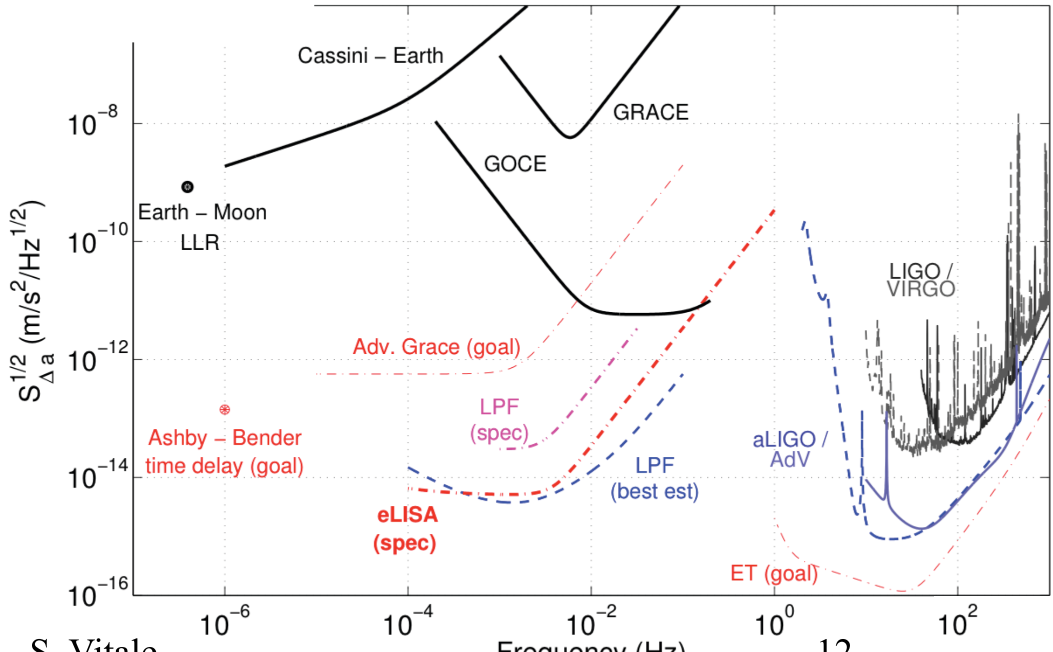
Class. Quantum Grav. 30 (2013) 235029 O Gerberding *et al*





Most of disturbances can be tested within one satellite

- Some can only be tested in 0-g
- And their suppression ~~requires~~ required order of magnitudes improvement relative to state of art



LISA Pathfinder

1. A test of most of the local measurement (95 % of noise)
2. A verification step in the development of LISA using same hardware/processes to carry them at TRL 8-9.
3. In-orbit consolidation test for our physical model of free fall. Integrates the results of extensive ground testing

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

EUROPEAN SPACE AGENCY

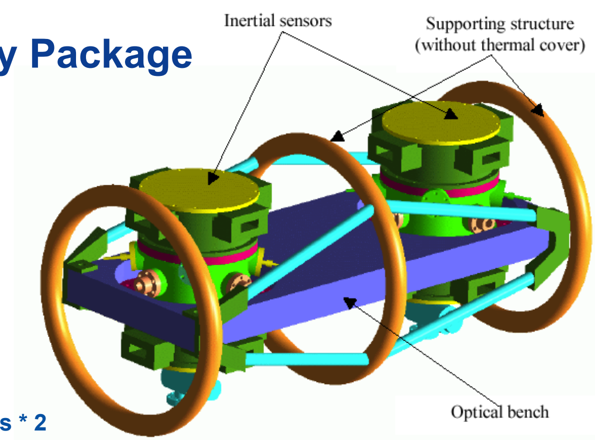
SPACE SCIENCE ADVISORY COMMITTEE

Recommendation on SMART 2

The SSAC unanimously endorses the Executive's proposal to use the SMART 2 mission, as currently scheduled, as a timely opportunity to test the technologies which are crucial to the LISA cornerstone mission, and to also test within the same mission elements of the technologies needed for the DARWIN/IRSI cornerstone.

The LISA Technology Package

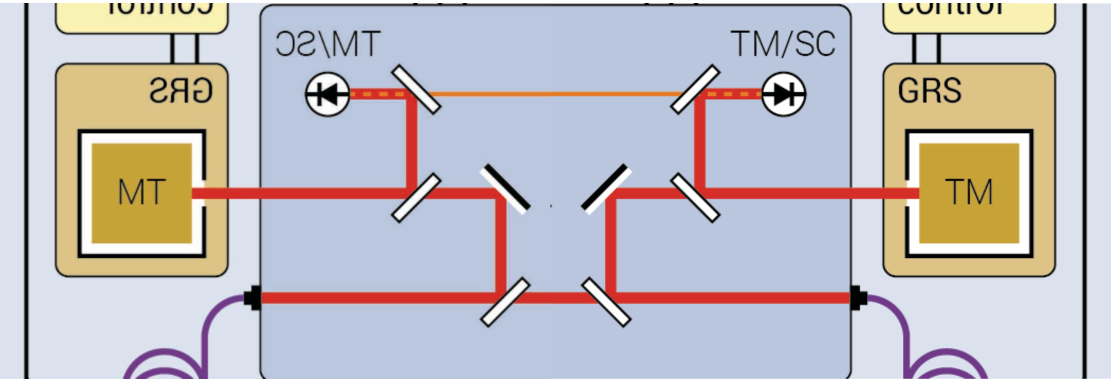
- **The LTP consists of 9 elements:**
- **LTP main assembly, containing:**
  - Two inertial sensors
    - Test mass
    - Caging mechanism
    - Electrostatic position system
    - Vacuum enclosure
  - The optical bench
  - The structure and thermal shield
- **Inertial Sensor Front End Electronics * 2**
- **Caging Mechanism electronics.**
- **Charge Management System electronics and UV lamps.**
- **Phase detector FEE.**
- **Laser system.**
- **Acousto-optic Modulator box.**
- **Processor and diagnostics.**
- **Overall mass ~82 kg, Overall power ~100W**

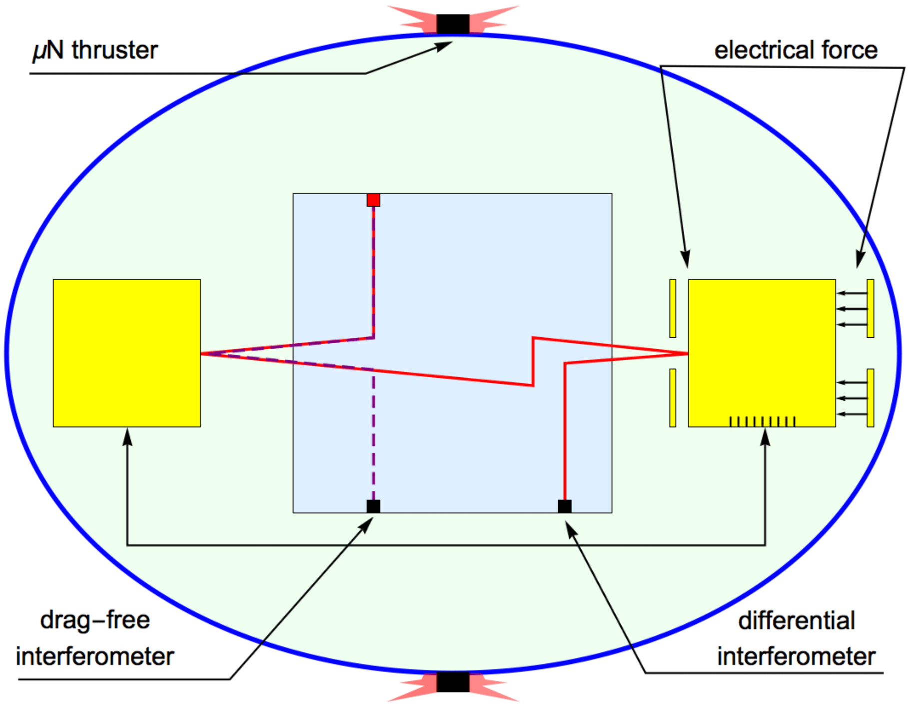


Diameter 354, length 600

LISA Pathfinder concept

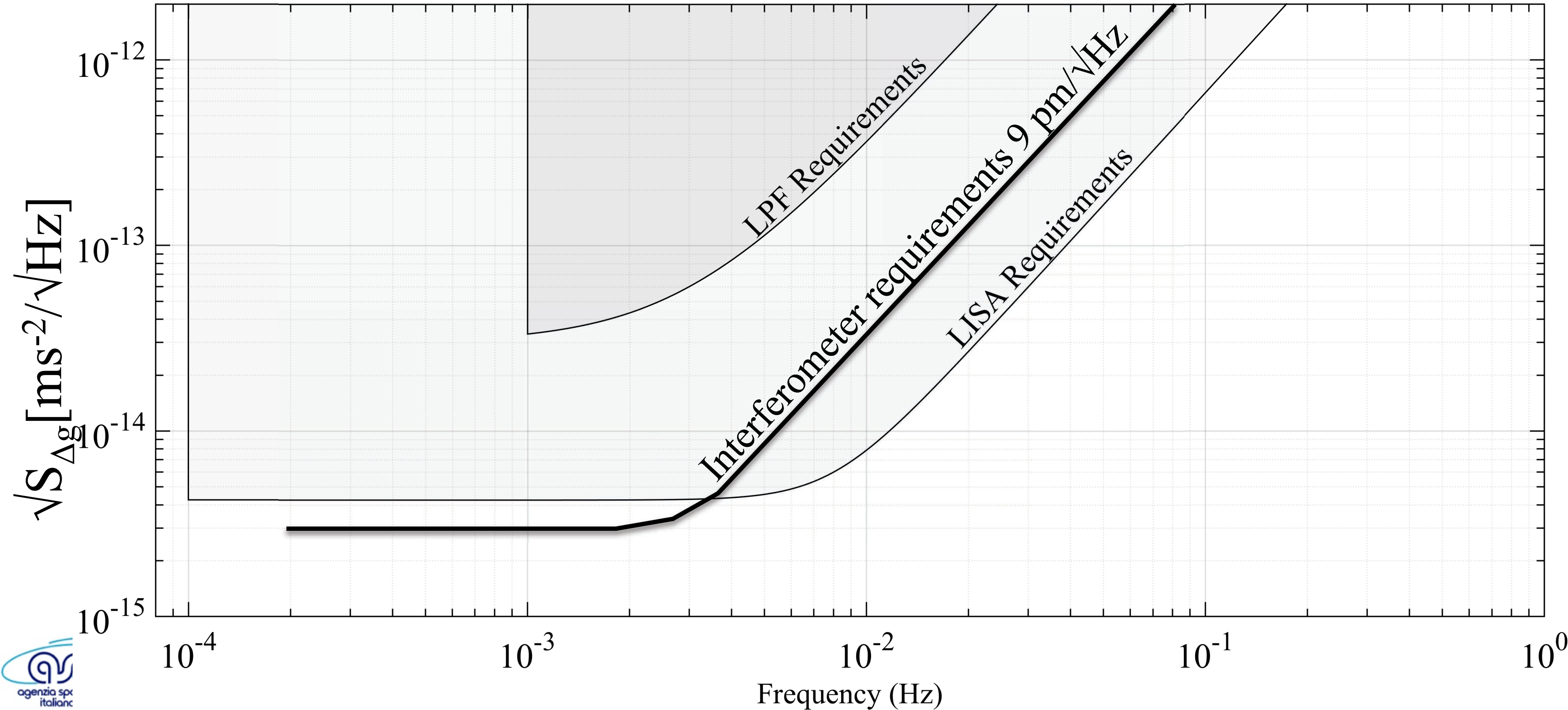
- One LISA link inside a single spacecraft (no million km arm)
- 2 TMs, 2 Ifos
- Satellite chases one test-mass
- Contrary to LISA, second test-mass forced to follow the first at very low frequency by electrostatics





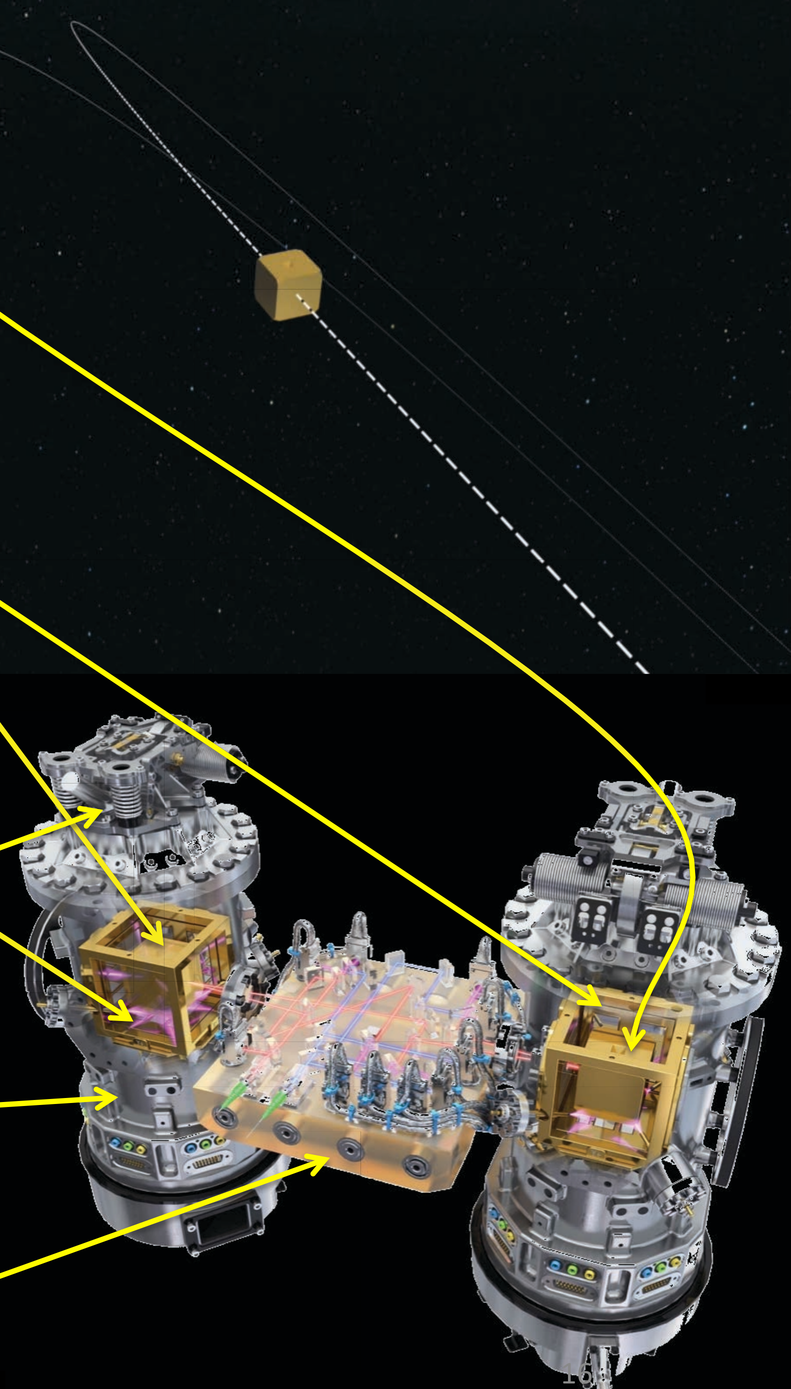
LISA and LISA Pathfinder disturbance acceleration requirements

- LPF amplitude requirement relaxed because single spacecraft experiment more noisy
- Frequency requirement relaxed to cut down ground testing time
- Interferometer requirements to allow for margin and to match LISA sensitivity range



The LTP

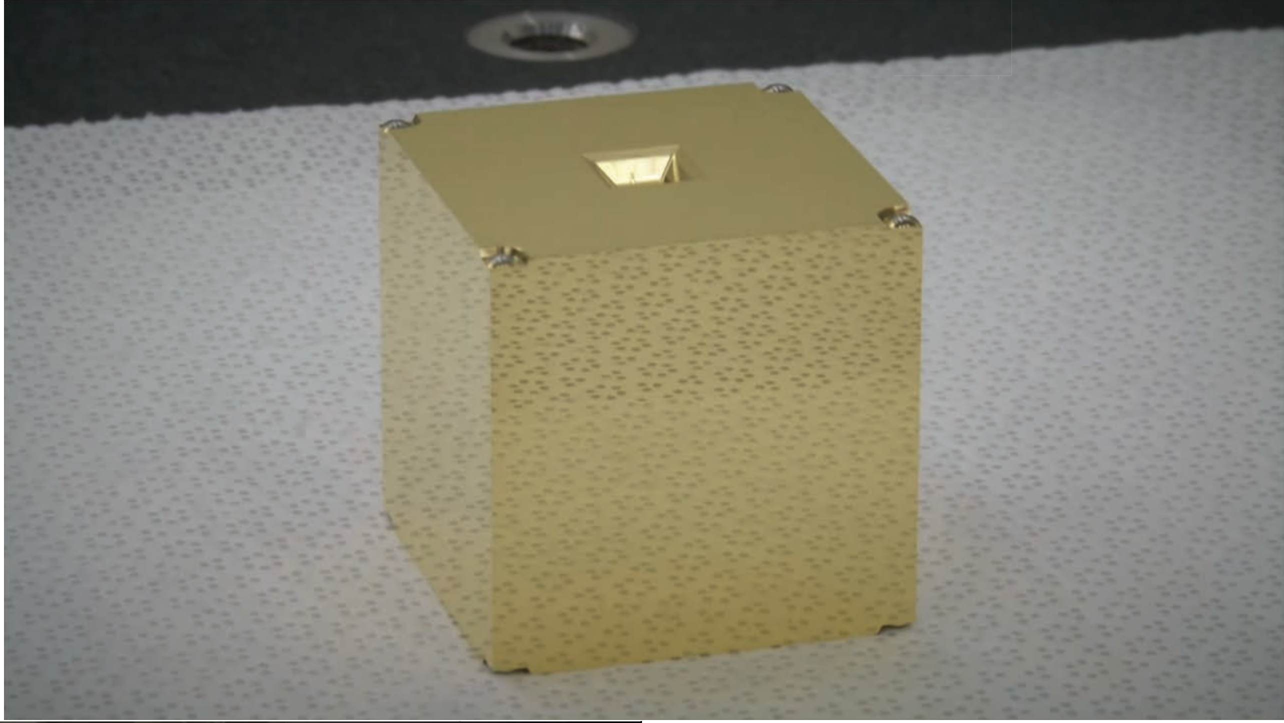
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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

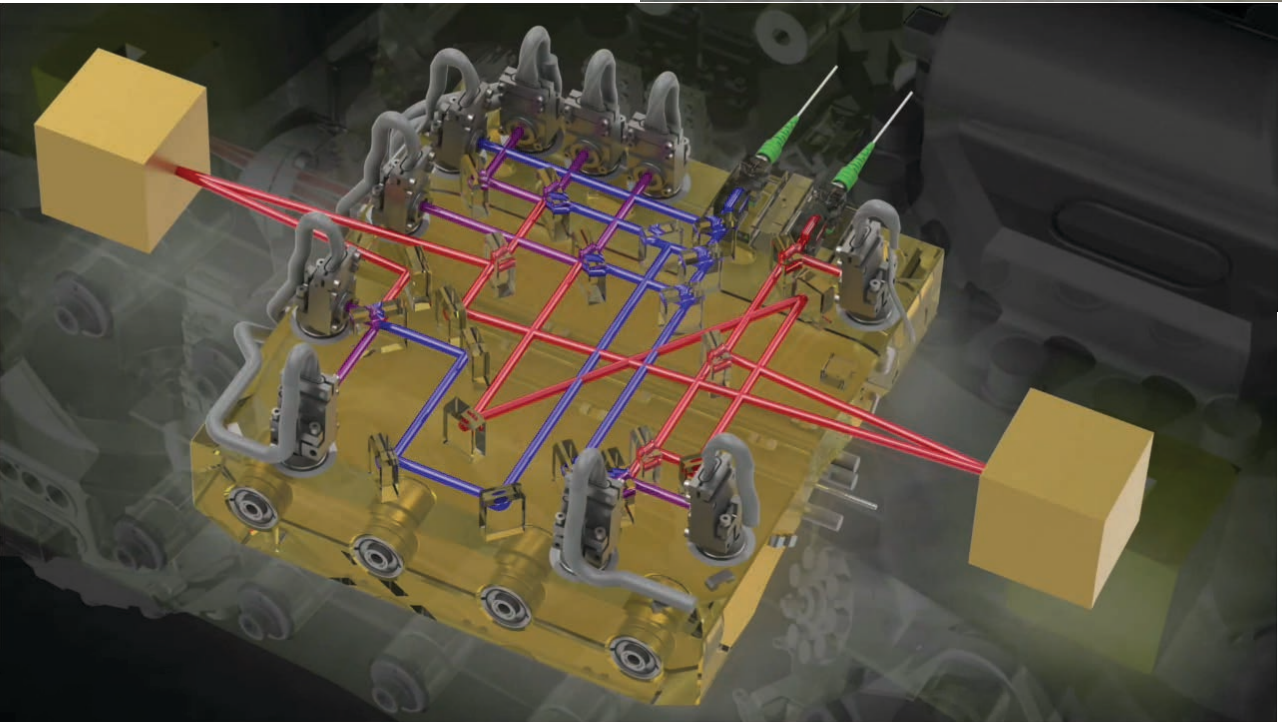


lisa pathfinder

Test-mass and accessories: the gravity reference sensor

CGS-OHB, U.Trento-INFN, ETH Zurich, Ruag, TAS-I, Imperial College, IEEC





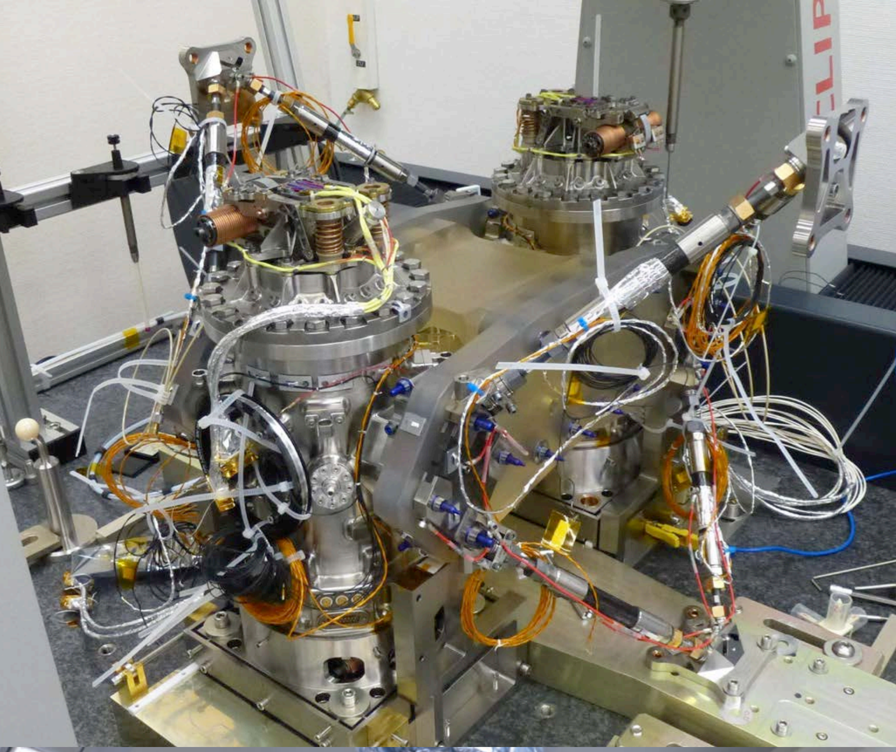
Laser interferometer

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

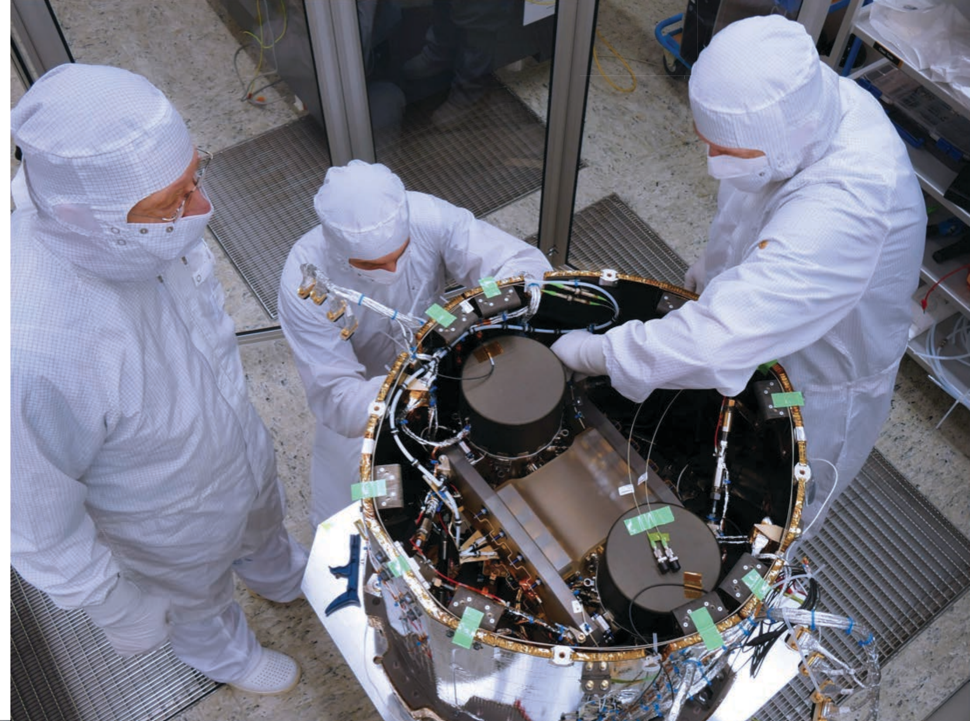
H. Ward talk

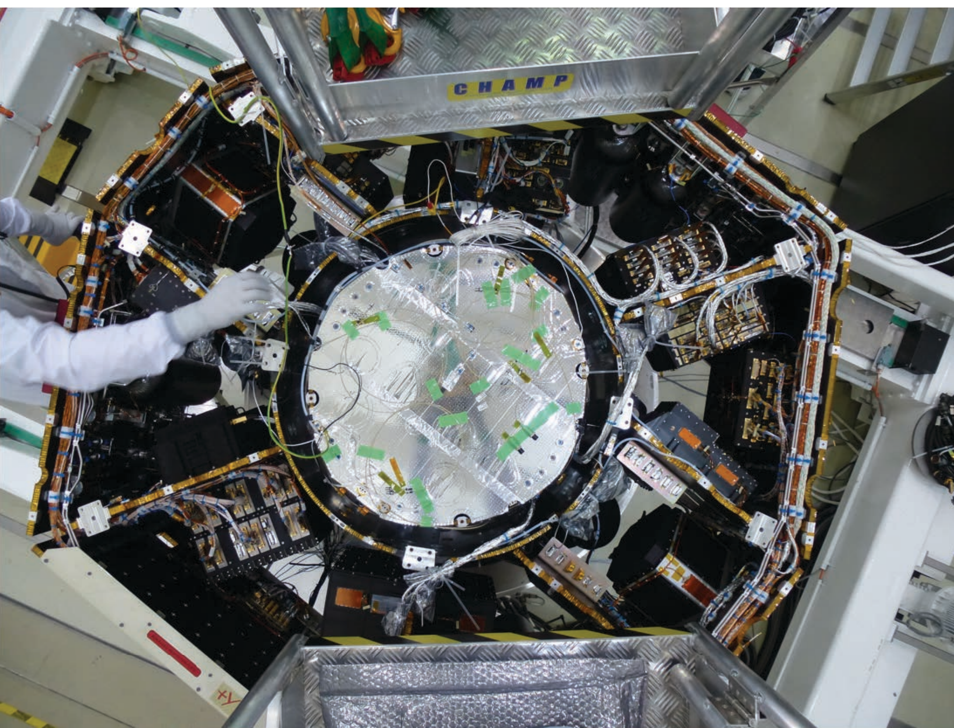
agenzia spaziale italiana

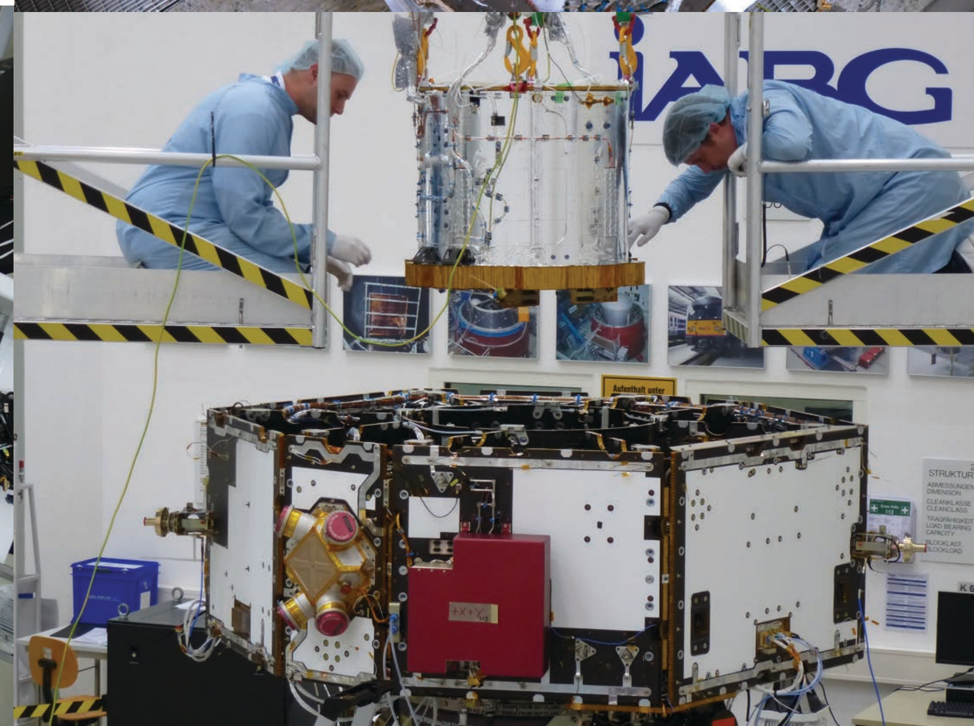
LTP Core assembly



Integration with satellite







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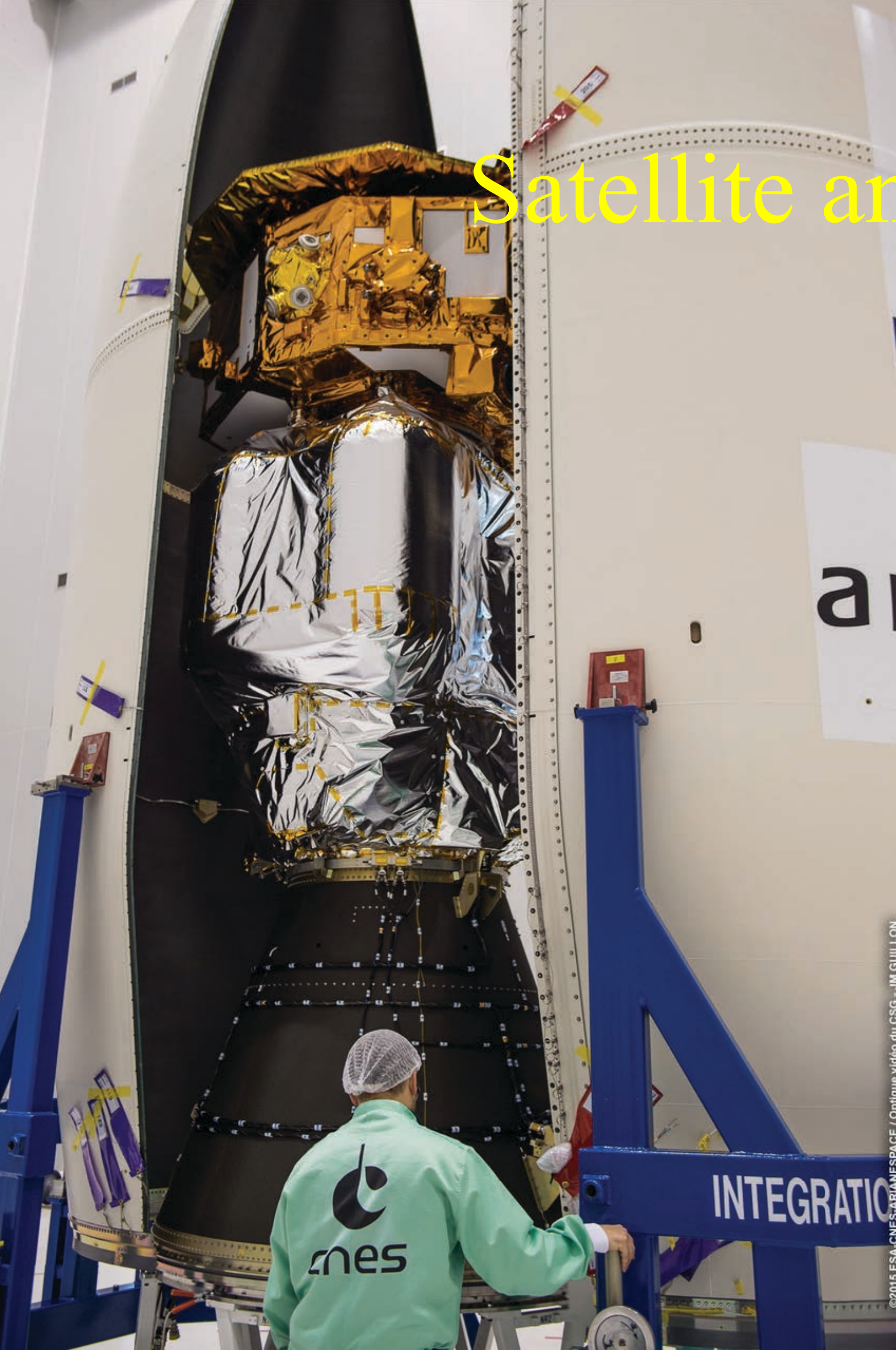
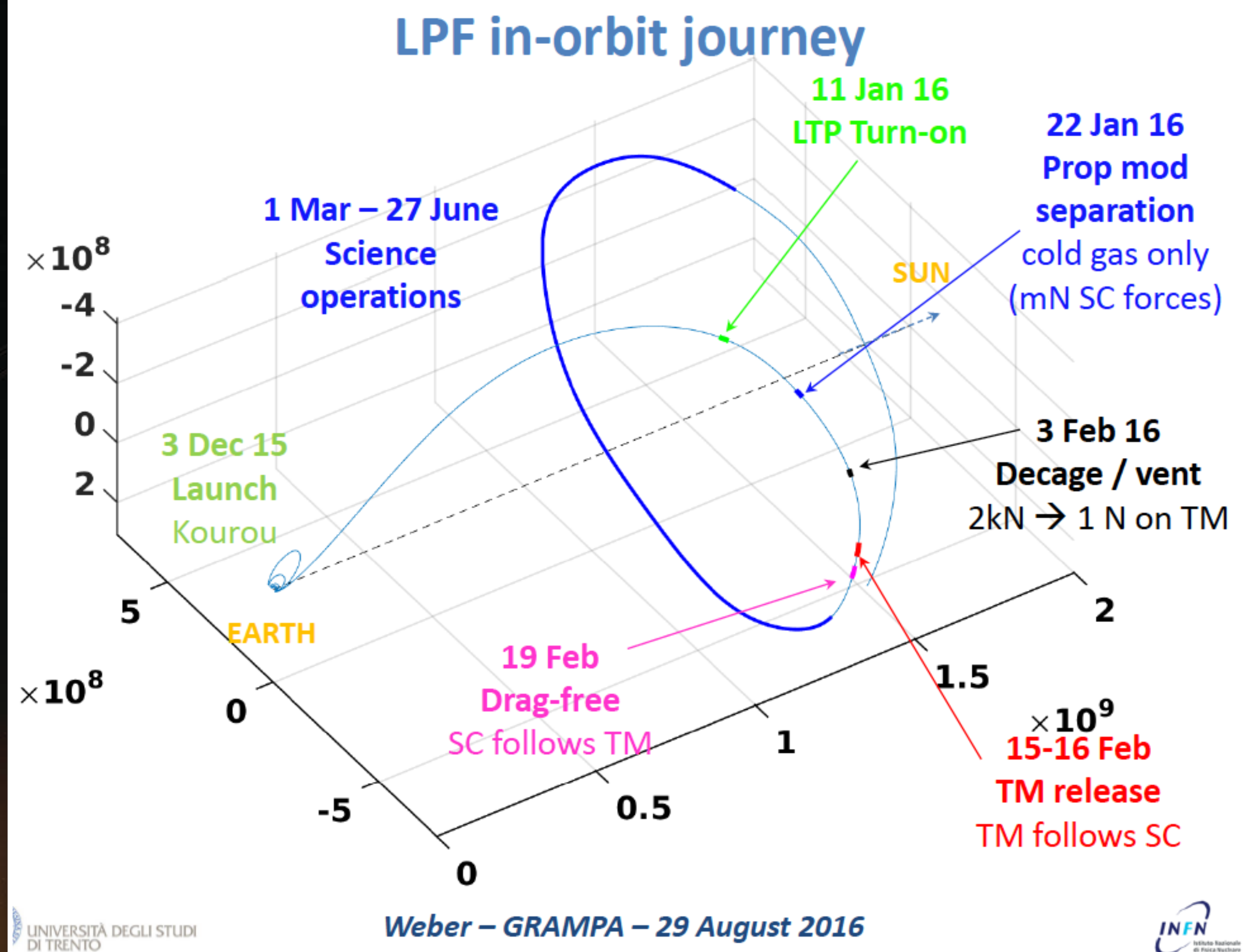
LISA PATHFINDER
Gravitational wave detection technology for LISA

Satellite and launcher



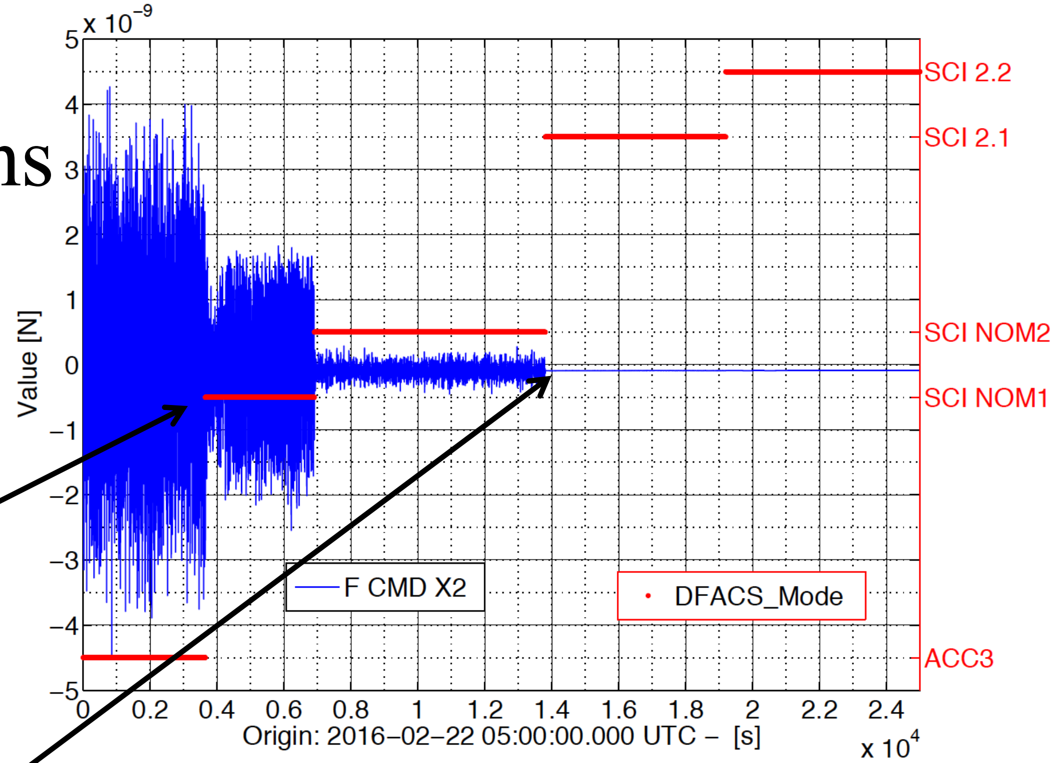


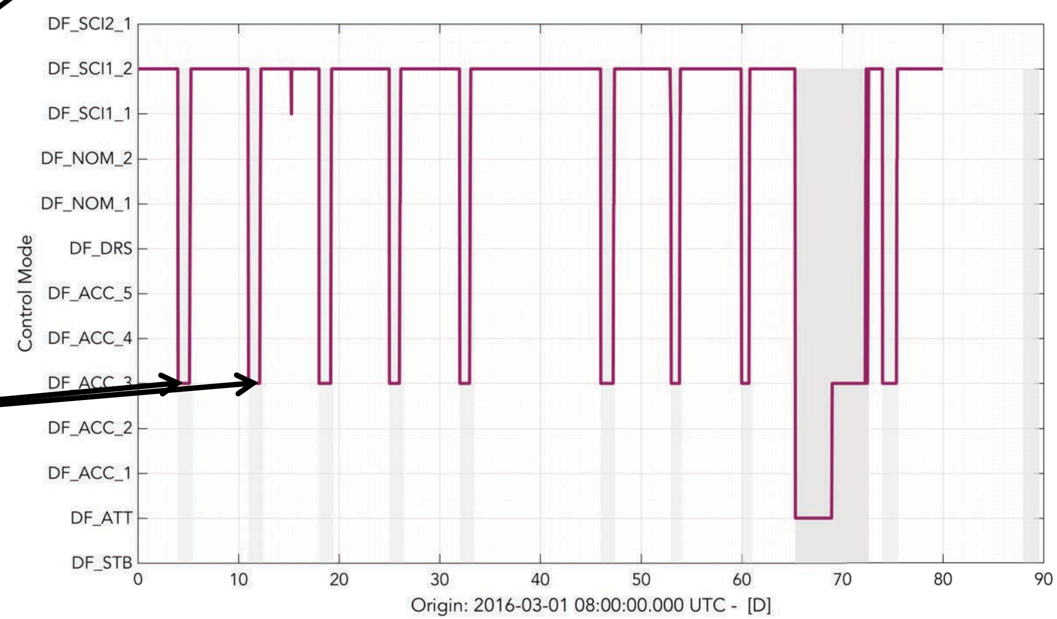
Currently in NASA-DRS operation. LTP extension granted to May 31, 2017

P. McNamara talk

Rather smooth operations

- Transition to Drag-free control
- Transition to low-noise science mode
- Station keeping maneuvers

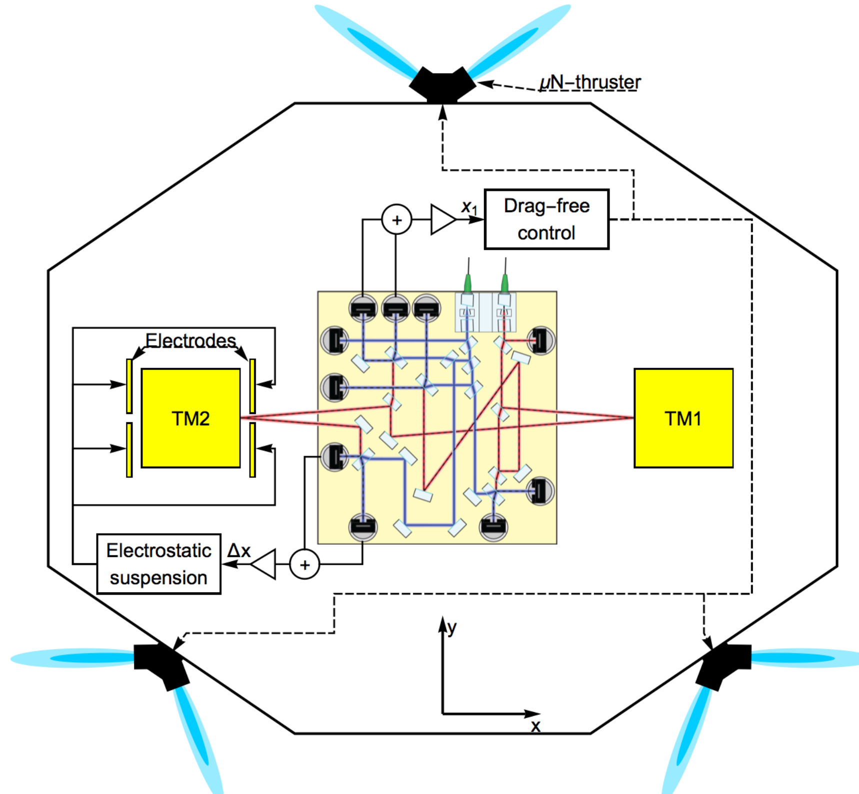




Test mass control and commanded forces

- Acceleration depend on parasitic forces (measurement target) but also on feedback forces

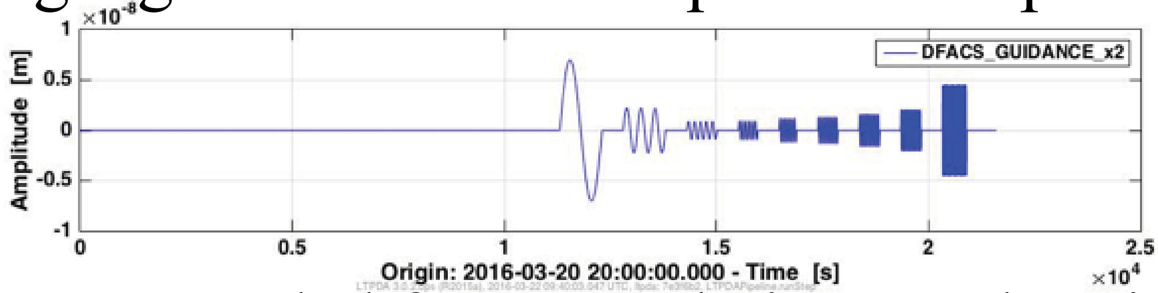
$$a_2 - a_1 = \underbrace{\frac{f_2}{m} - \frac{f_1}{m}}_{\text{Parasitics forces on free test-masses}} + \frac{f_c}{m}$$



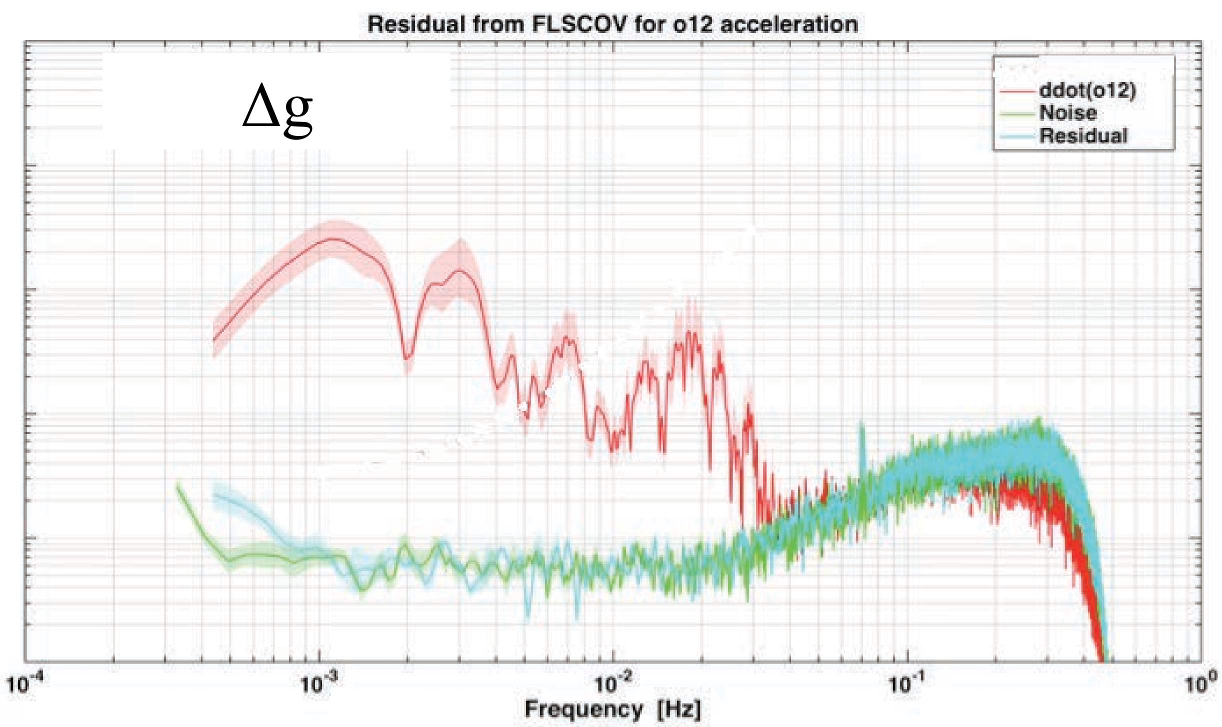
- f_c is known within a calibration factor (that we measure)

Calibrating

- Injecting a guidance in the suspension loop



- Fitting commanded force to relative acceleration

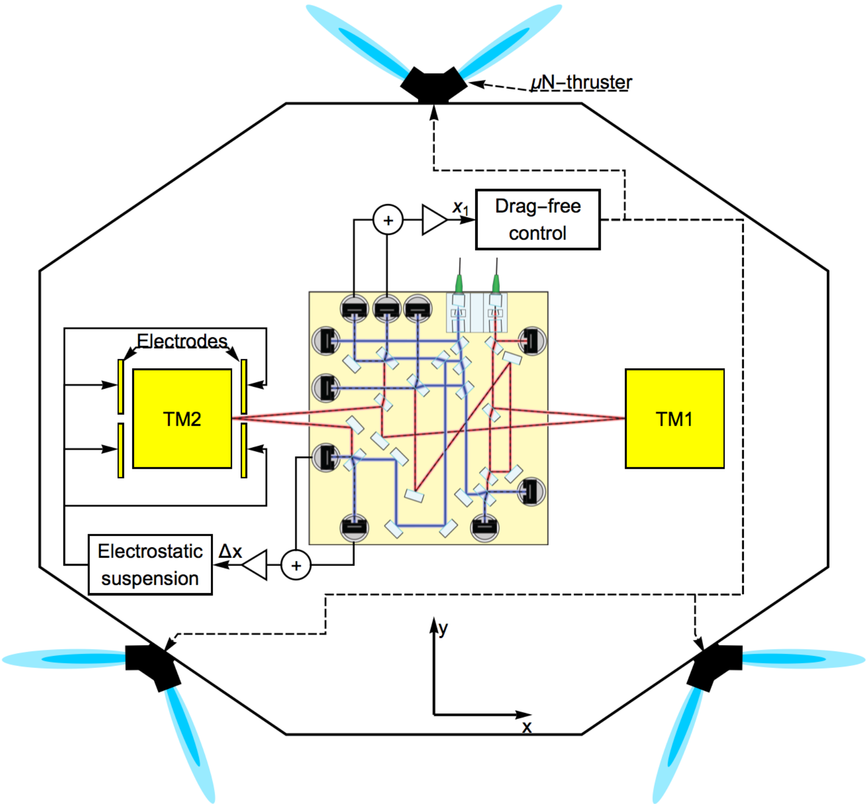


N. Karnesis poster

Generating Δg data

- Acceleration depend on parasitic forces (measurement target) but also on feedback forces

$$a_2 - a_1 = \underbrace{\frac{f_2}{m} - \frac{f_1}{m}}_{\text{Parasitics forces on free test-masses}} + \frac{f_c}{m}$$



- f_c is known within a calibration factor (that we measure)
- f_c can be subtracted
- Correction very relevant at low frequency. *Missing correction underestimates noise*

$$\Delta g \equiv a_2 - a_1 - \frac{f_c}{m} = \underbrace{\frac{f_2}{m} - \frac{f_1}{m}}_{\text{Parasitics forces on free test-masses}}$$

D. Vetrugno talk

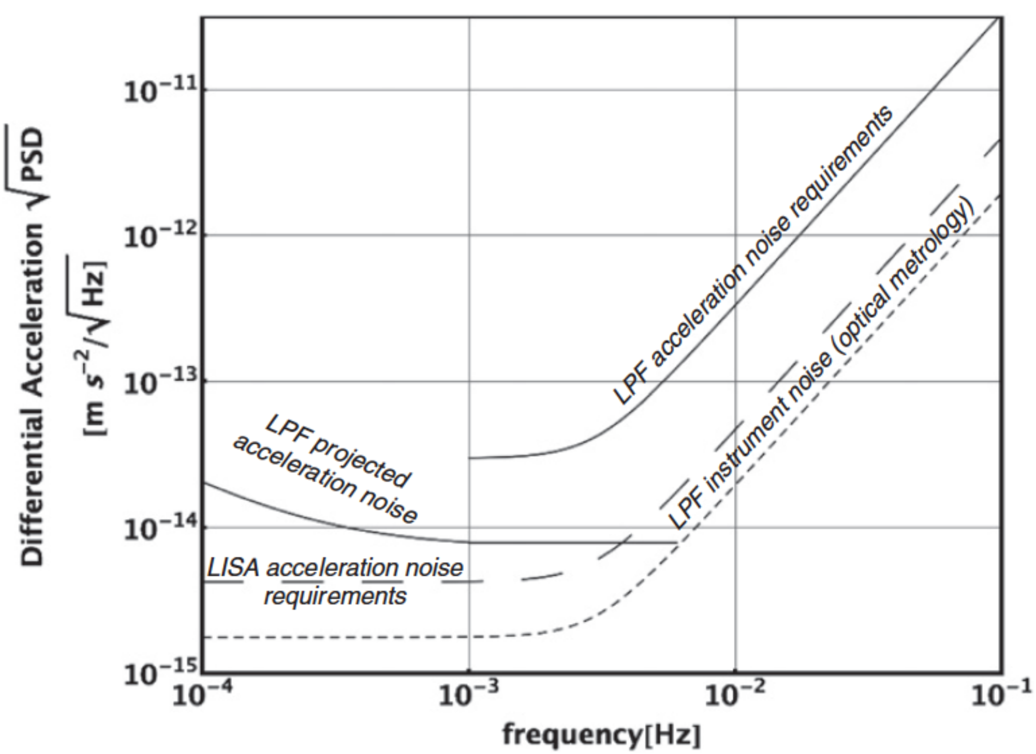
Best Estimate before flight

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

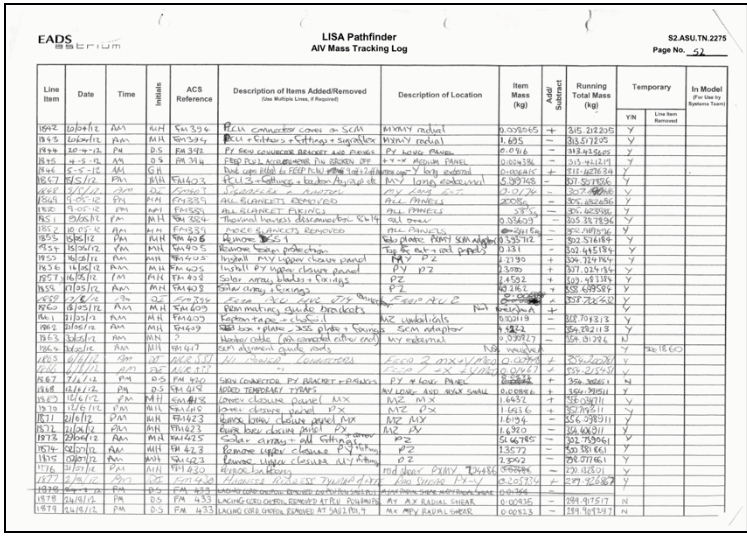
Grav. **28** (2011) 094002



- Electrostatic feedback mostly compensates unbalanced static gravitational force
- Gain fluctuations: noise scales with required compensation force

Gravitational compensation

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

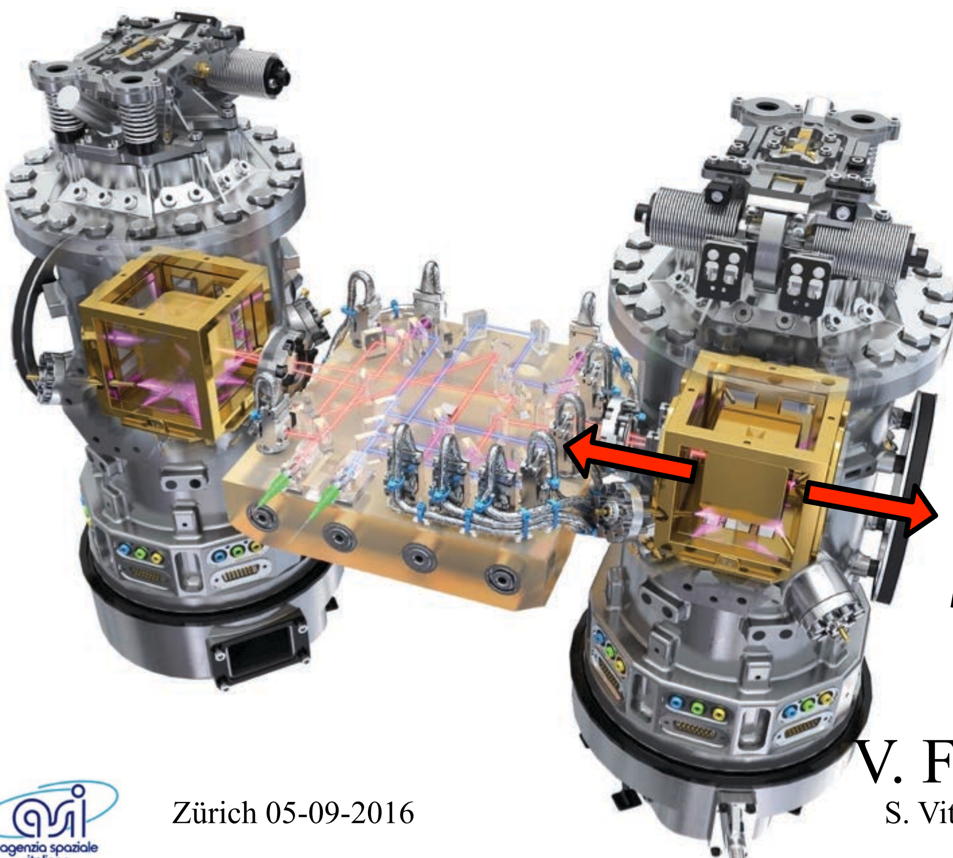


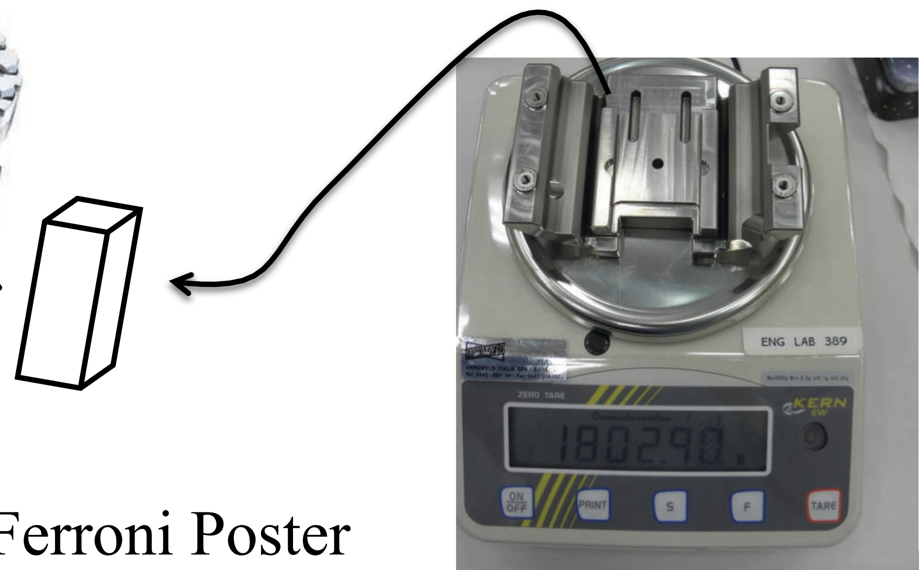
EADS astrium

LISA Pathfinder
AIV Mass Tracking Log

S2.ASU.TN.2275
Page No. 52

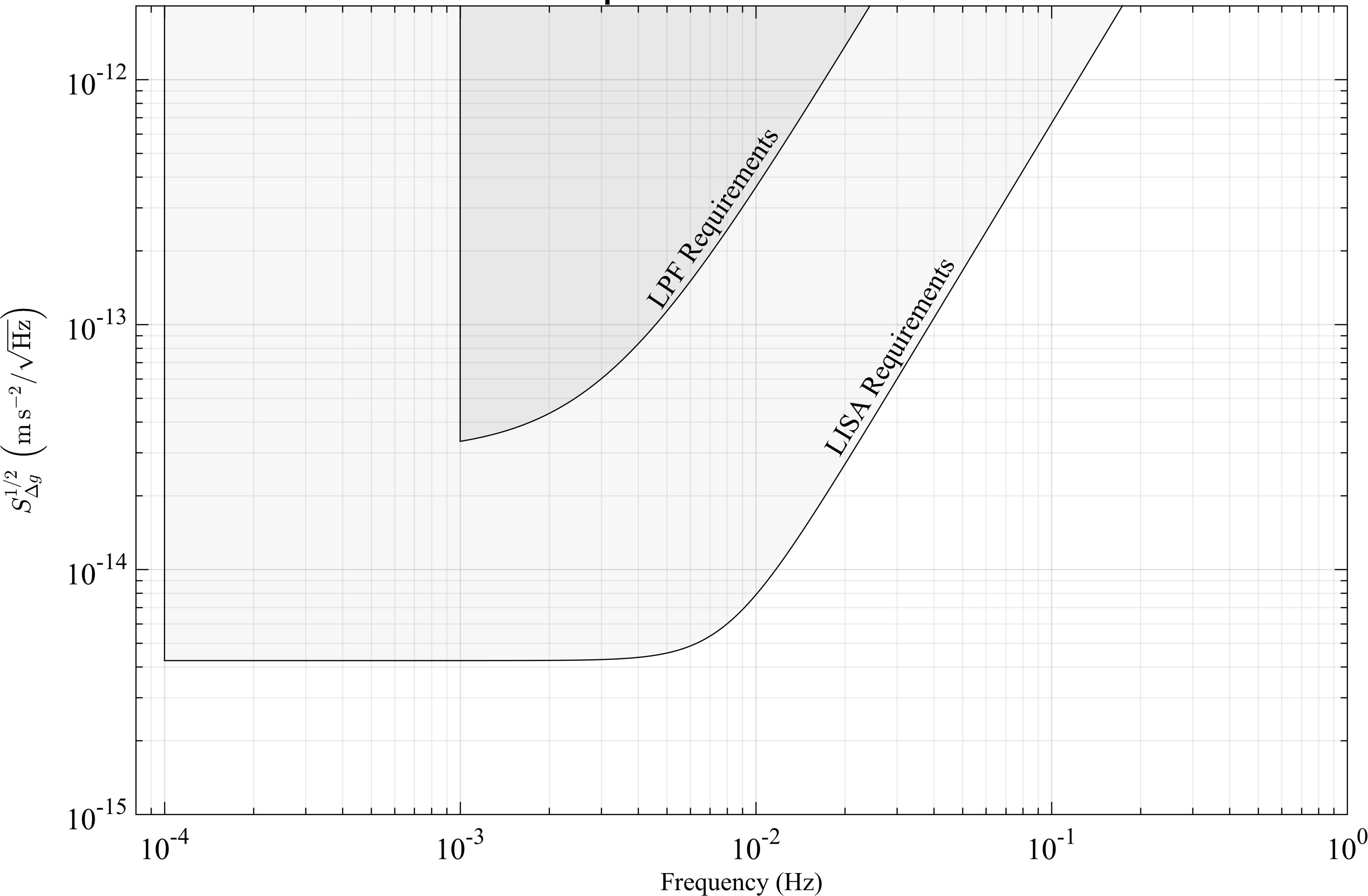
Line Item	Date	Time	Initials	ACS Reference	Description of Items Added/Removed (Use Multiple Lines, if Required)	Description of Location	Item Mass (kg)	Add/ Subtract	Running Total Mass (kg)	Temporary Y/N	Temporary Line Item Removed	In Model (For Use by Systems Team)
1842	20/04/12	AM	MH	FM 394	PCU connector cover on SCM	MXMY radial	0.008065	+	315.212205	Y		
1843	20/04/12	AM	MH	FM394	PCU + filters + fittings + sigraflex	MXMY radial	1.695	−	313.517205	Y		
1844	20-4-12	PM	D.S	FM 392	PY SKIN CONNECTOR BRACKET AND FIXINGS	PY LONG PANEL	0.0916	−	313.425605	Y		
1845	4-5-12	AM	D.S	FM 394	FEEP PCU2 ACCELEROMETER PIN BROKEN OFF	+Y −X MEDIUM PANEL	0.004386	−	313.421219	Y		
1846	5-5-12	AM	GH		Dust caps fitted to FEEP PCU [illegible]	[illegible] −Y long external	0.006415	+	313.427634	Y		
1847	8/5/12	PM	MH	FM403	PCU3 + fittings + [illegible]	MY long external	5.919748	−	307.507886	Y		
1848	9/5/12	AM	DJ	FM403	SIGRAFLEX + [illegible]	MY LONG EXT.	0.0174	−	307.[illegible]	Y		
1849	9-05-12	PM	MM	FM339	ALL BLANKETS REMOVED	ALL PANELS	2008g	−	305.482686	Y		
1850	9-05-12	PM	MM	FM339	ALL BLANKET FIXINGS	ALL PANELS	58.5g	−	305.423986	Y		
1851	9/05/12	PM	MH	FM 384	Thermal harness disconnector [illegible]	all over	0.03609	−	305.387896	Y		
1852	10-05-12	AM	MM	FM339	MORE BLANKETS REMOVED	ALL PANELS	[illegible]	−	302.969896	Y		
1853	15/05/12	PM	MH	FM 406	Remove DSS1	[illegible] plate PXMY SCM adaptor	0.393712	−	302.576184	Y		
1854	15/05/12	PM	MH	FM405	Remove [illegible] protection	Top [illegible] ext + rad [illegible]	0.131	−	302.445184	Y		
1855	16/05/12	AM	MH	FM405	Install MY upper closure panel	MY PZ	2.2790	+	304.724184	Y		
1856	16/05/12	AM	MH	FM 405	Install PY upper closure panel	PY PZ	2.3000	+	307.024184	Y		
1857	16/05/12	PM	MH	FM 408	Solar array blades + fixings	PZ	2.4592	+	309.483384	Y		
1858	17/05/12	AM	MH	FM408	Solar array + fixings	PZ	49.2162	+	358.699584	Y		
1859	17/5/12	PM	DJ	FM 394	FEEP PCU HVC J14 connector	FEEP PCU 2	[illegible]	+	358.706432	Y		
1860	18/05/12	AM	MH	FM409	PPM mating guide brackets	Not weighed		+		Y		
1861	21/05/12	AM	MH	FM409	Kapton tape + chofoil	MZ umbilicals	0.002119	−	358.704313	Y		
1862	21/05/12	AM	MH	FM409	[illegible] box + plate, DSS plate + fixings	SCM adaptor	4.4222	−	354.282113	Y		
1863	30/05/12	AM	MN	?	Heater cable (not connected either end)	MY external	0.090827	−	354.191286	N		
1864	30/05/12	AM	MH	FM 417	SCM alignment guide rods	Not weighed				Y	see 1860	
1865	6/6/12	AM	DJ	NCR 533	HI POWER CONNECTORS	FEEP 2 MX+Y MED	0.00[illegible]	+	354.200[illegible]	Y		
1866	6/6/12	AM	DJ	NCR 533	"	FEEP 1 +X +Y MED	0.01467	+	354.215451	Y		
1867	7/6/12	PM	D.S	FM 420	SKIN CONNECTOR PY BRACKET + FIXINGS	PY + LONG PANEL	[illegible]	+	354.30265[illegible]	N		
1868	12/6/12	PM	D.S	FM 418	ADDED TEMPORARY TYRAPS	MY LONG AND MY+X SMALL	0.00886	+	354.391511	Y		
1869	12/6/12	PM	MH	FM 418	Lower closure panel MX	MZ MX	1.6432	+	356.034711	Y		
1870	12/6/12	PM	MH	FM 418	Lower closure panel PX	MZ PX	1.6836	+	357.718311	Y		
1871	21/6/12	PM	MH	FM423	Remove lower closure panel MX	MZ MX	1.6194	−	356.098911	Y		
1872	21/06/12	PM	MH	FM423	Remove lower closure panel PX	MZ PX	1.6920	−	354.406911	Y		
1873	29/06/12	AM	MH	FM425	Solar array + all fittings + cover	PZ	51.66785	−	302.739061	Y		
1874	02/07/12	AM	MH	FM 423	Remove upper closure PY + fitting	PZ	2.3572	−	300.381861	Y		
1875	02/07/12	AM	MH	FM423	Remove upper closure MY fitting	PZ	2.3042	−	298.077661	Y		
1876	31/07/12	PM	MH	FM 430	Remove battery	mid shear PXMY [illegible]	[illegible]	−	290.132801	Y		
1877	2/8/12	PM	DJ	FM 430	HARNESS REDRESS TYWRAP [illegible]	RAD SHEAR PX-Y	0.205934	+	289.926867	Y		
~~1878~~	~~[illegible]~~	~~PM~~	~~D.S~~	~~FM 433~~	~~LACING CORD CHOFOIL REMOVED [illegible]~~	~~[illegible] RADIAL SHEAR [illegible]~~	~~0.01764~~	~~−~~				
1878	24/8/12	PM	D.S	FM 433	LACING CORD CHOFOIL REMOVED AT PCU [illegible]	MY MX RADIAL SHEAR	0.00935	−	289.917517	N		
1879	24/8/12	PM	D.S	FM 433	LACING CORD CHOFOIL REMOVED AT SAU2 POL 4	MX MPY RADIAL SHEAR	0.00823	−	289.909287	N		



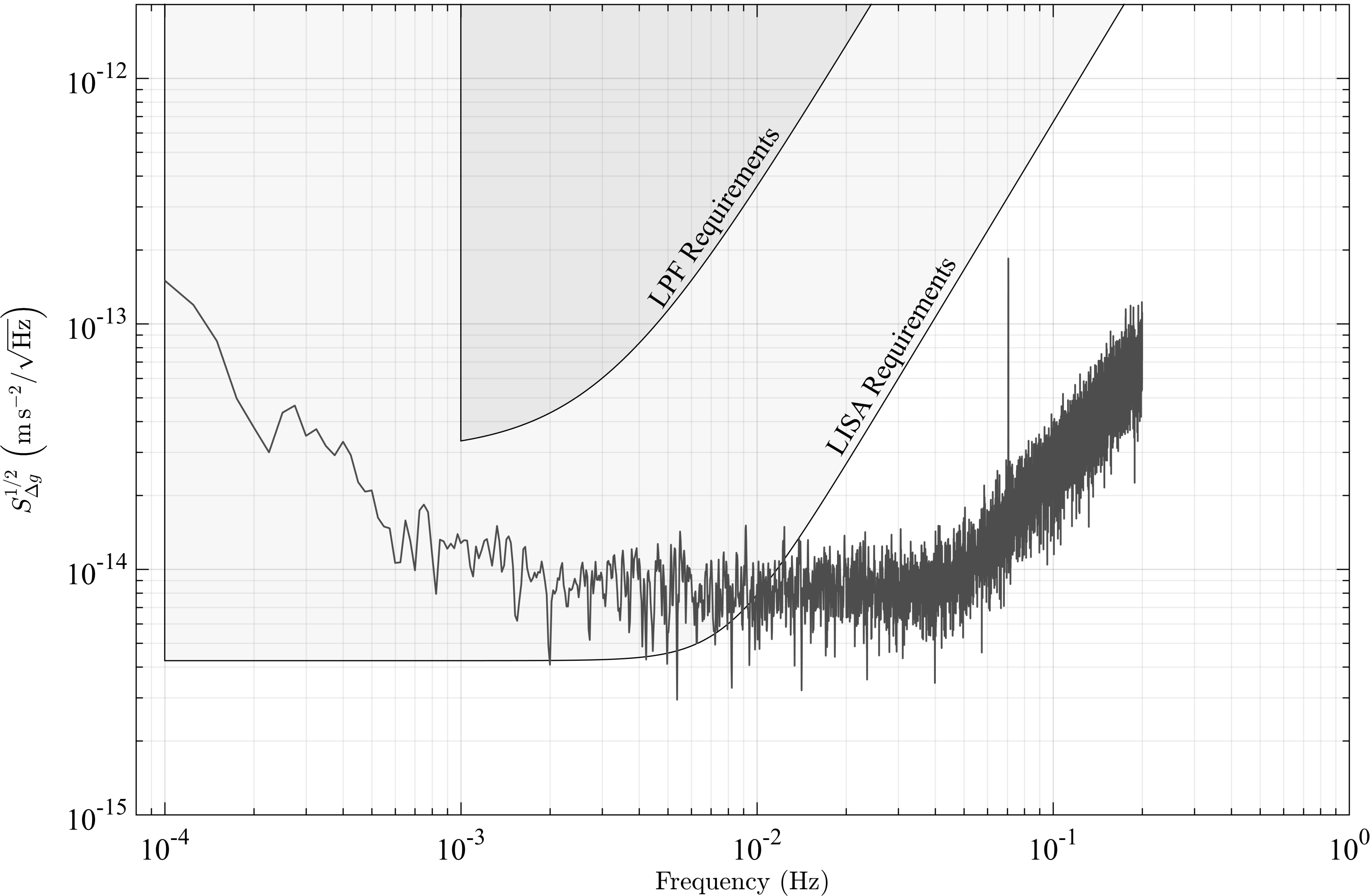


V. Ferroni Poster

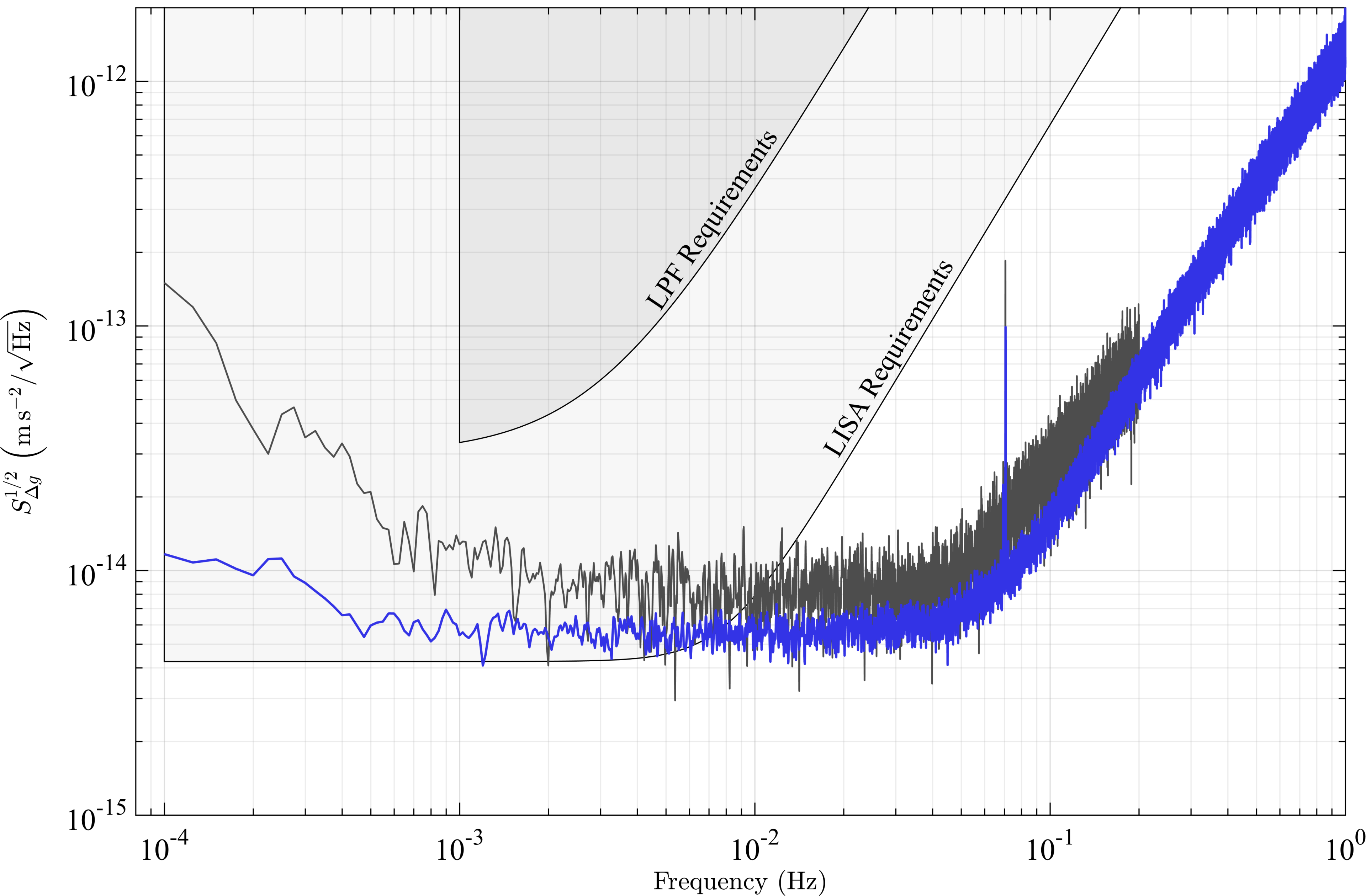
LISA and LISA Pathfinder disturbance acceleration requirements



First day of operation. March 1st, 2016

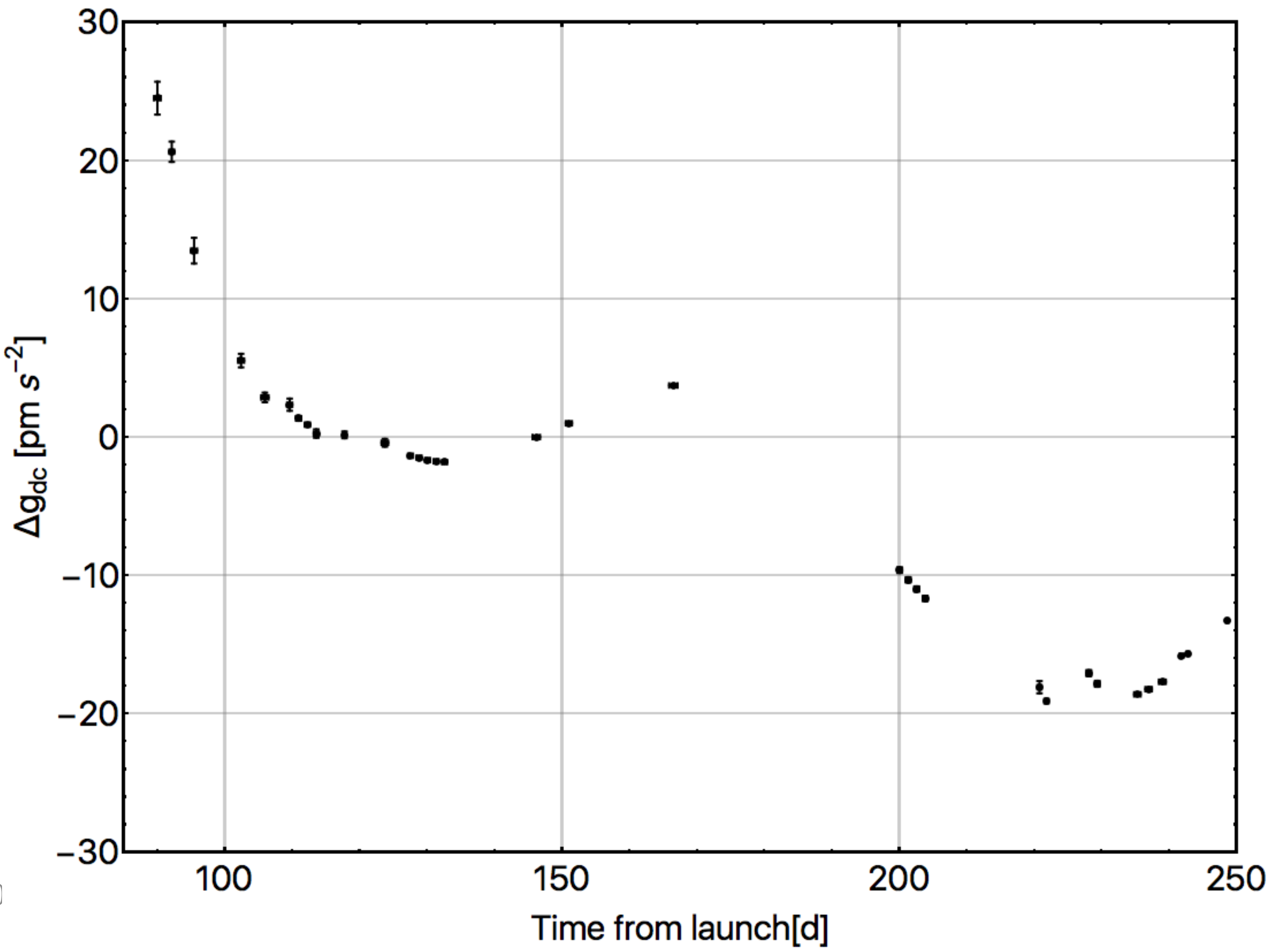


April 8-14, 2016.

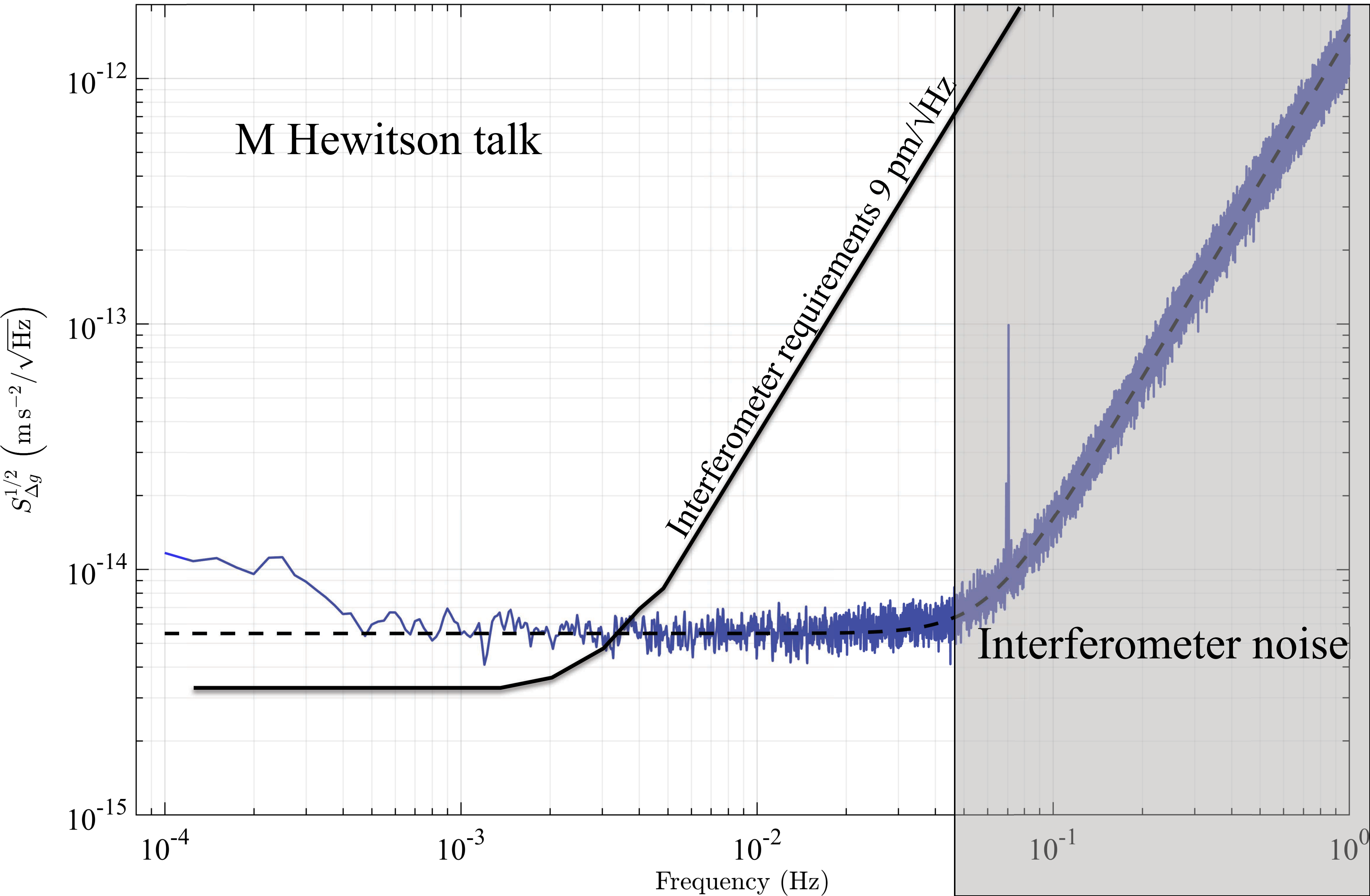


Very effective gravitational compensation

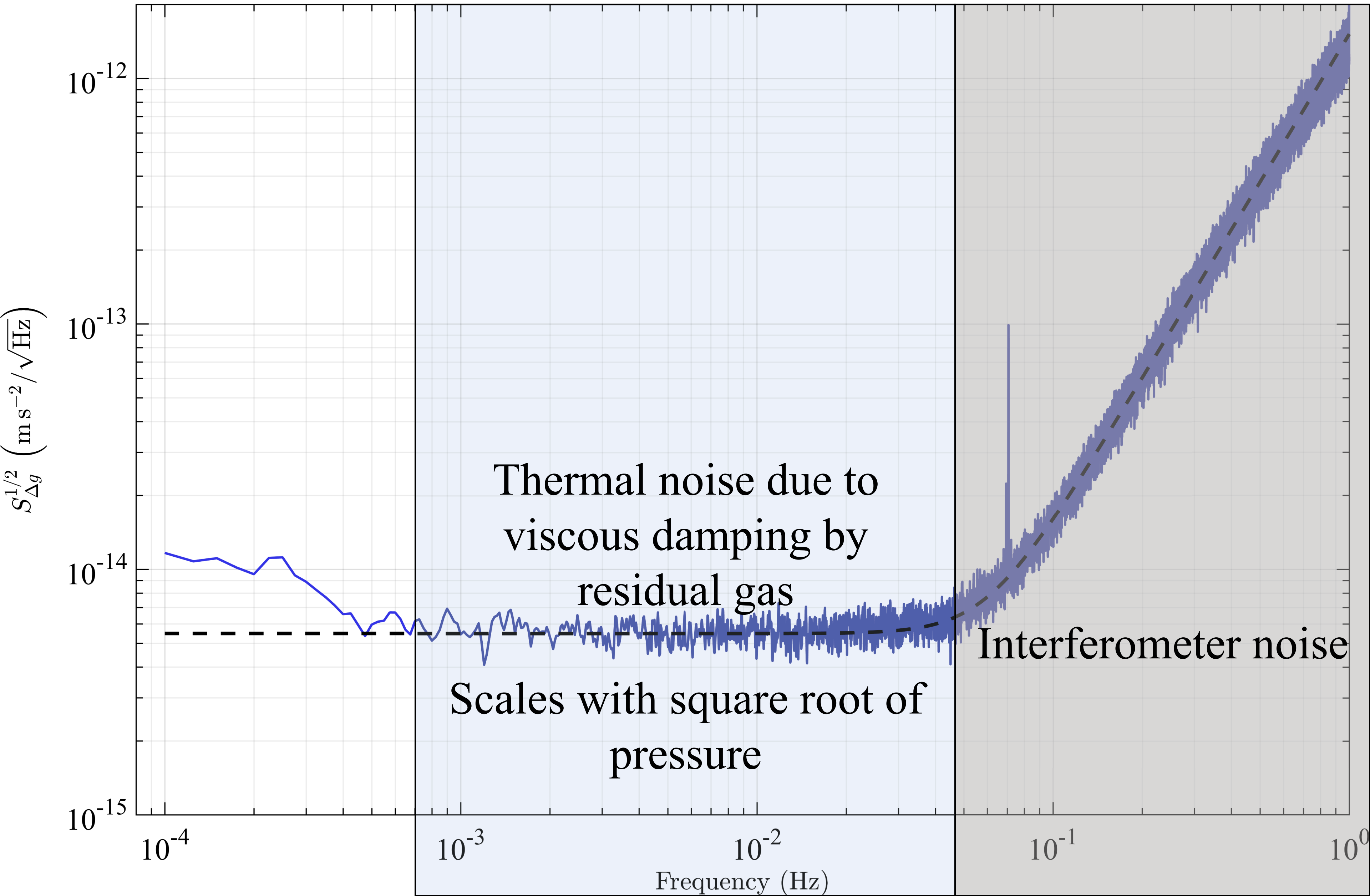
- Static forces found within ±25 pm s^{-2}
- Voltage settings decreased from those required to accommodate >650 pm s^{-2} to those for 25 pm s^{-2}



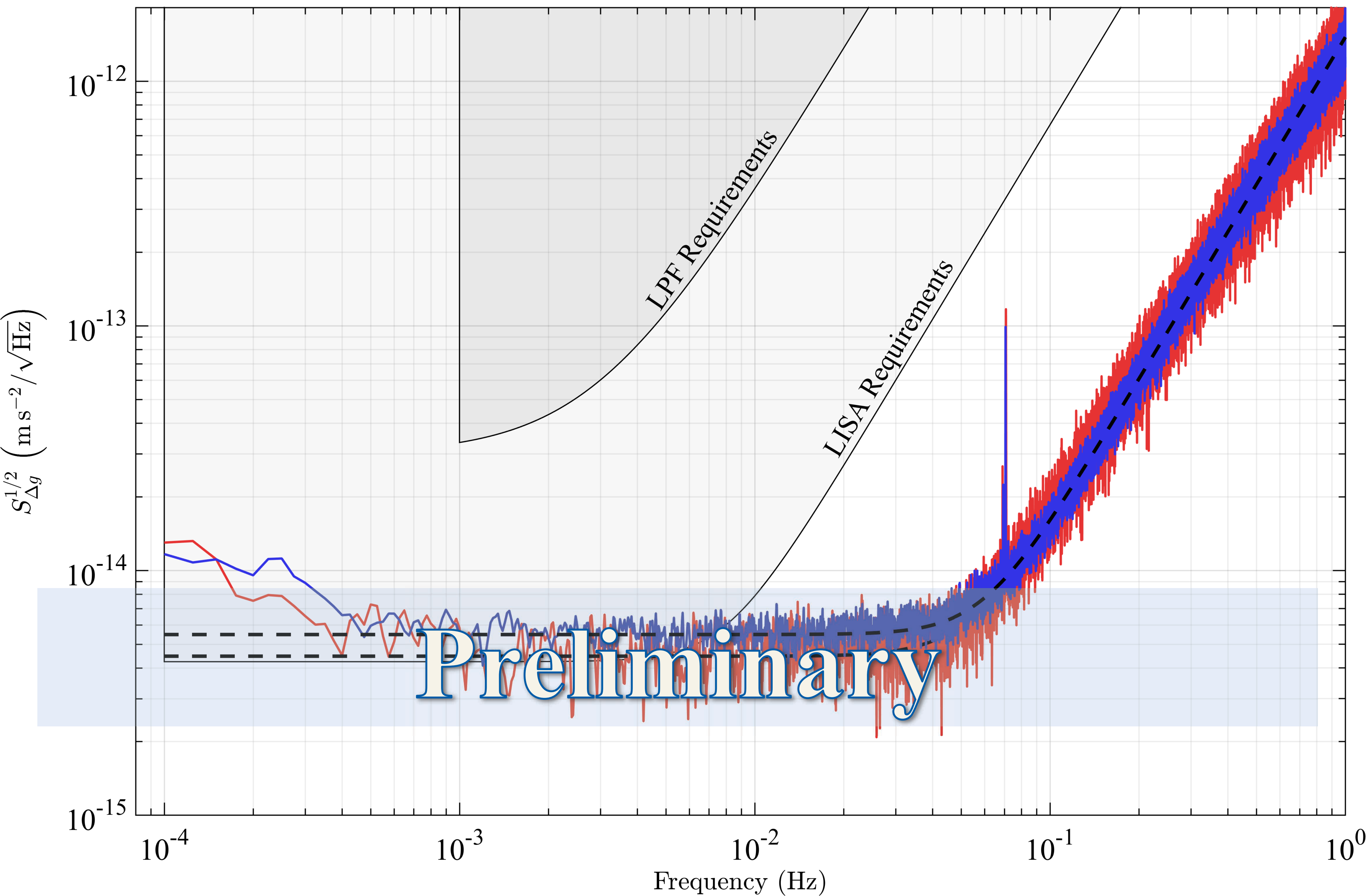
The limiting disturbances



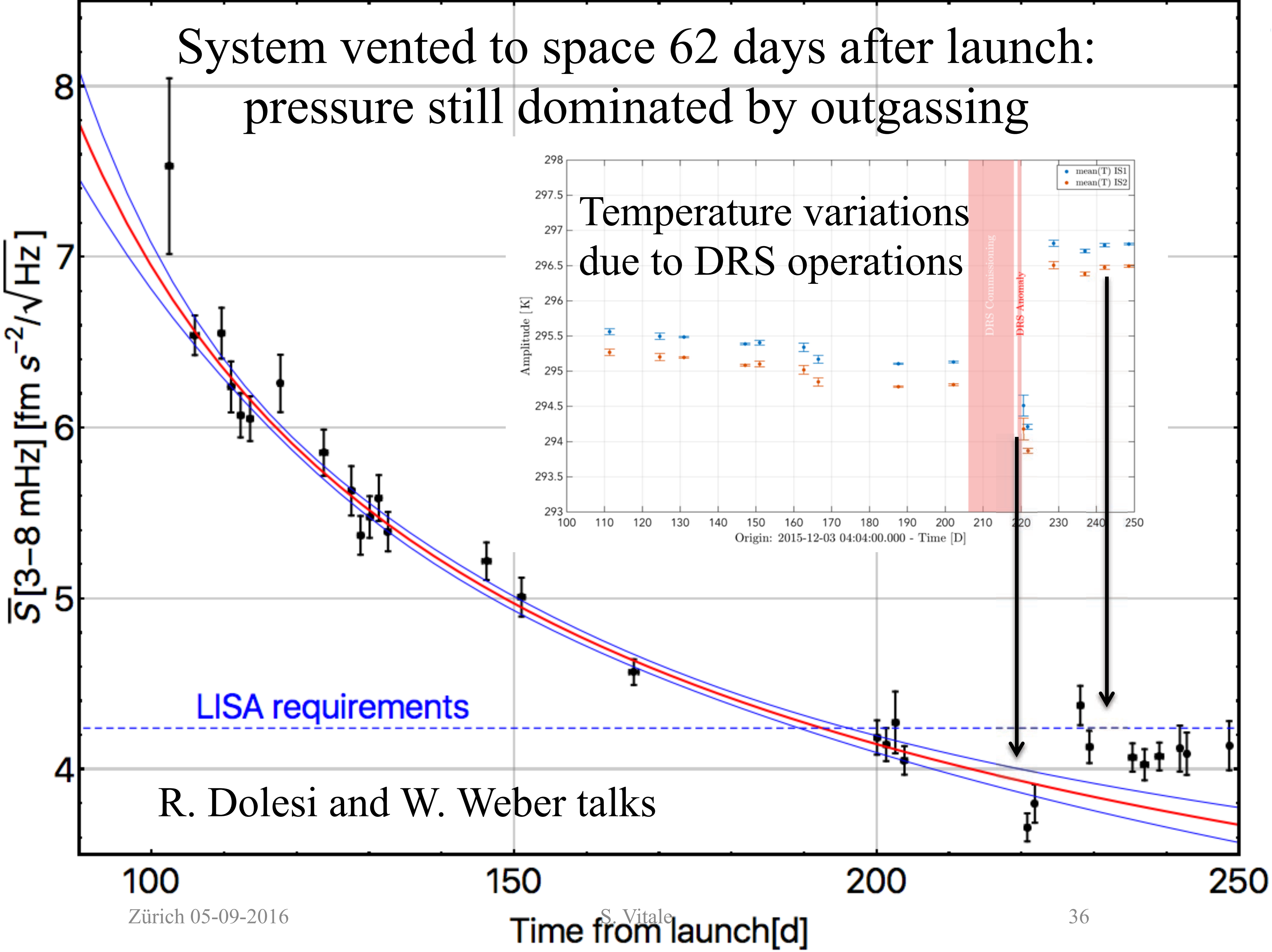
The limiting disturbances



May 16-18, 2016.



System vented to space 62 days after launch: pressure still dominated by outgassing

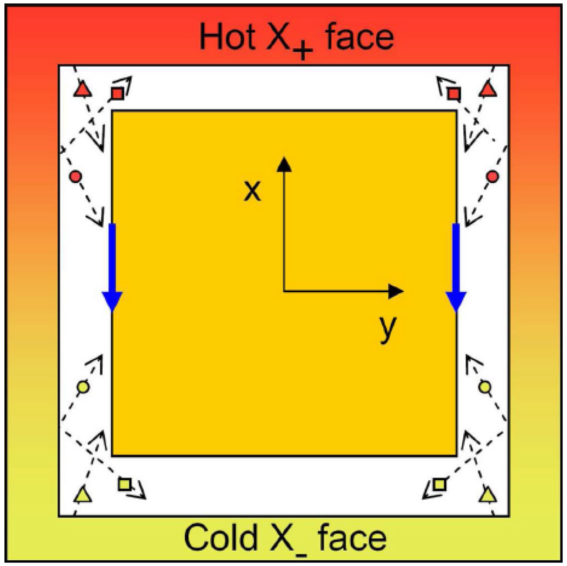


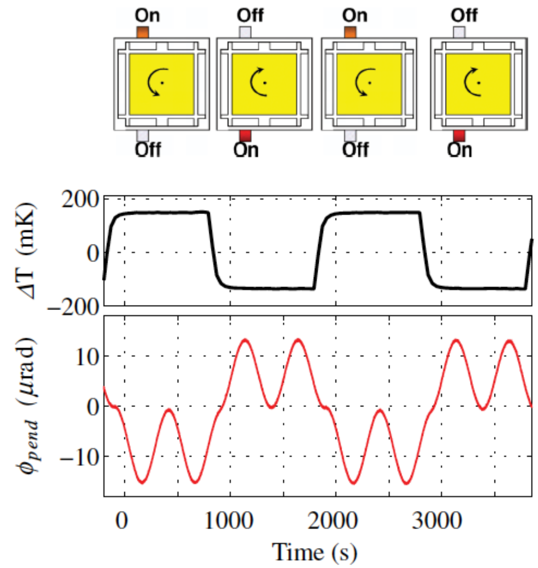
R. Dolesi and W. Weber talks

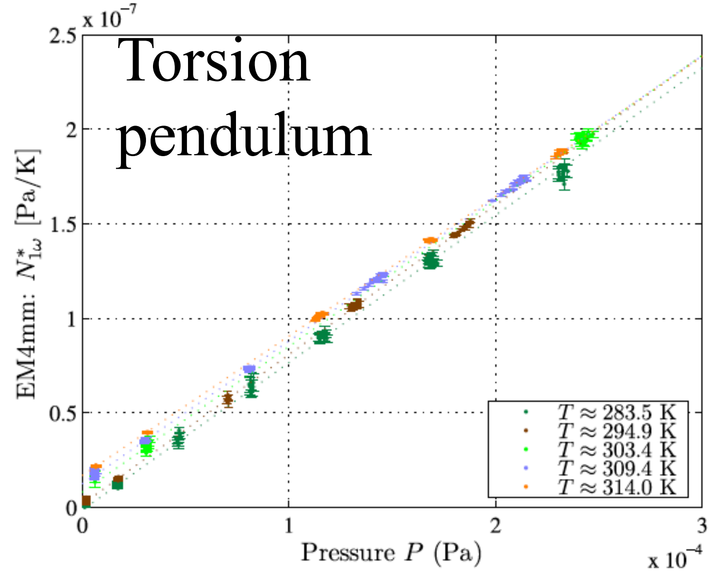
Pressure estimated from radiometer effect

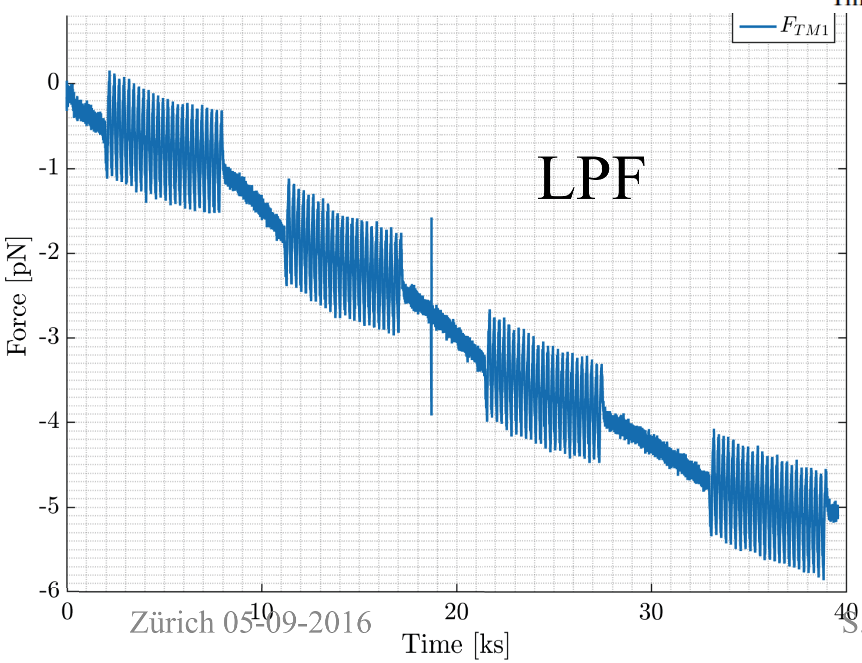
PHYSICAL REVIEW D 76, 102003 (2007)

L. CARBONE et al.





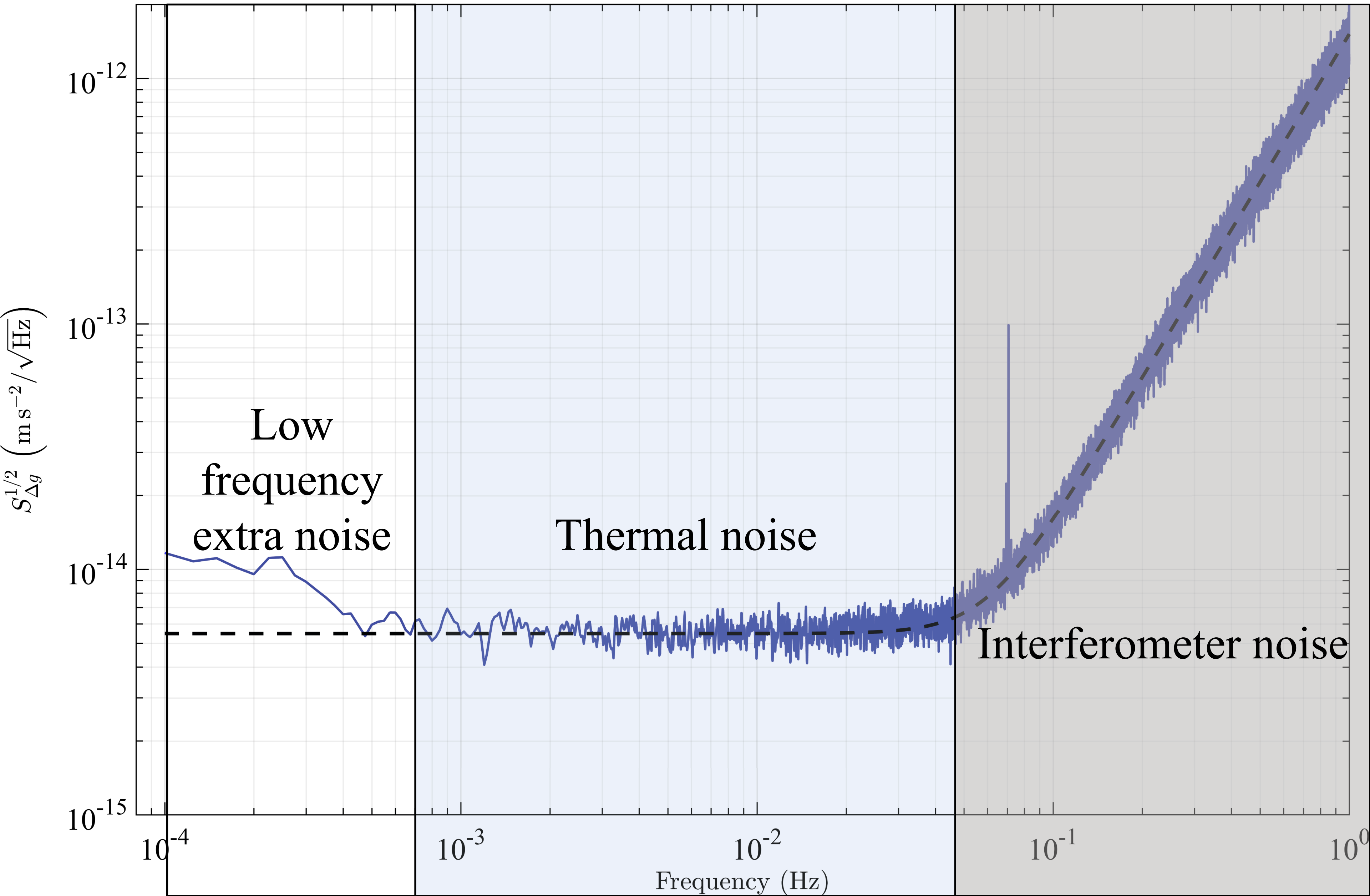




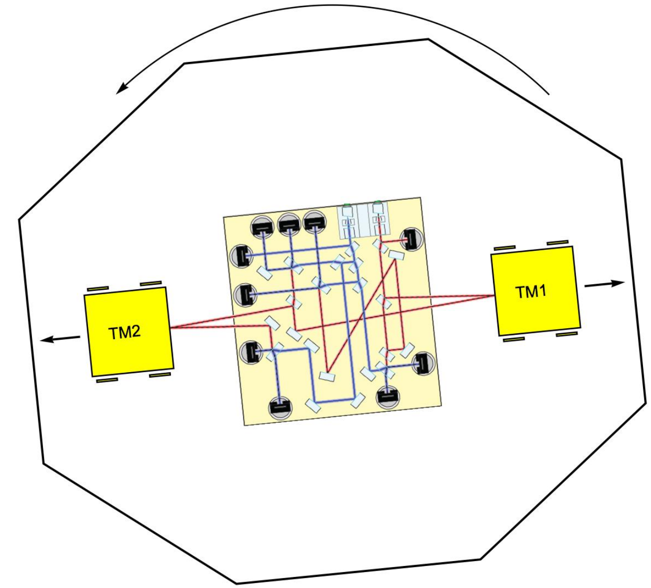
- Reasonable agreement with Brownian prediction

F. Gibert poster

The limiting disturbances



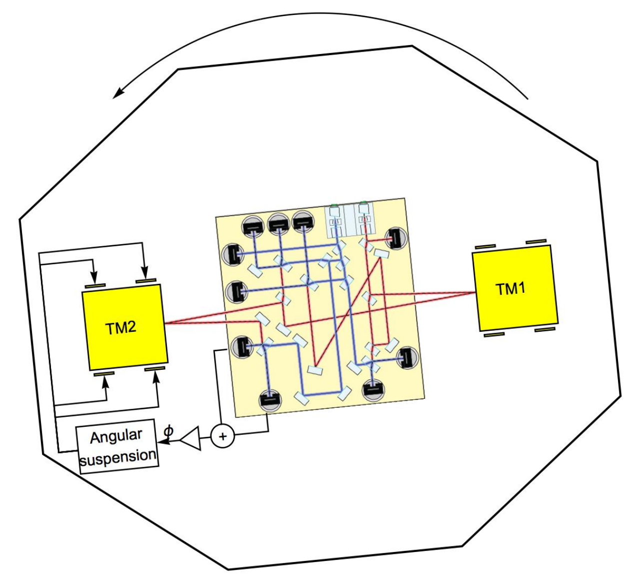
Centrifugal correction at low frequency



- Accelerations measured relative to spacecraft frame: centrifugal force is differential
- Centrifugal noise: mixing of quasi-static rotation and angular noise from noisy star-trackers (mrad /√Hz)

$$\Delta g_{\substack{\text{centrifugal}\\ \text{noise}}} \simeq 2\Delta r\Omega_{\substack{\text{quasi-}\\ \text{static}}}\Omega_{\text{noise}}$$

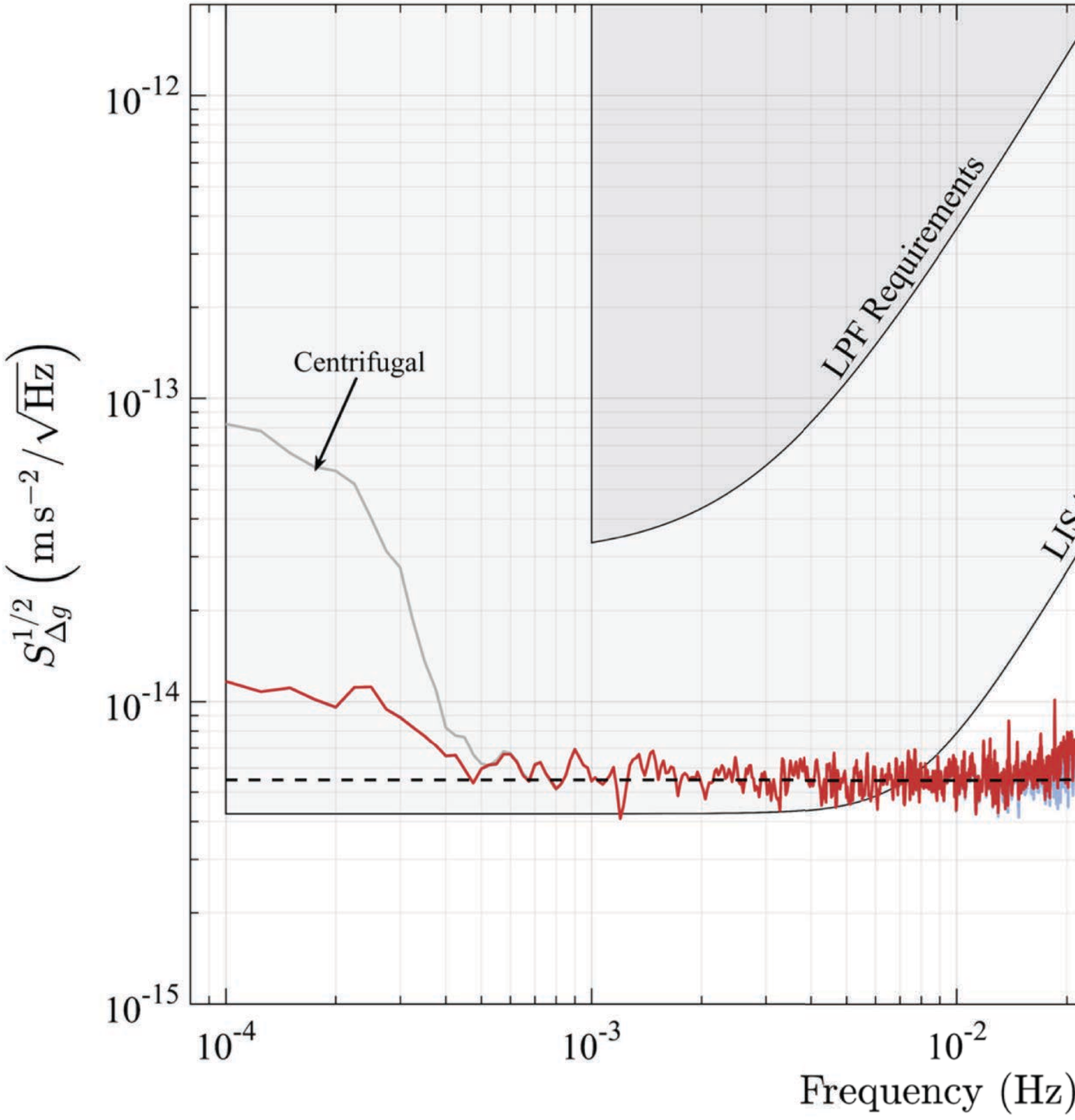
- Irrelevant for LISA: angular control of spacecraft on laser wave-front: nrad/√Hz
- Can be corrected:
  - Ω_{qs} measured from star-trackers
  - Ω_{noise} measured using test-masses as gyroscopes, i.e. integrating torque needed to keep them fixed to spacecraft



D. Vetrugno talk

An example of one of the largest corrections

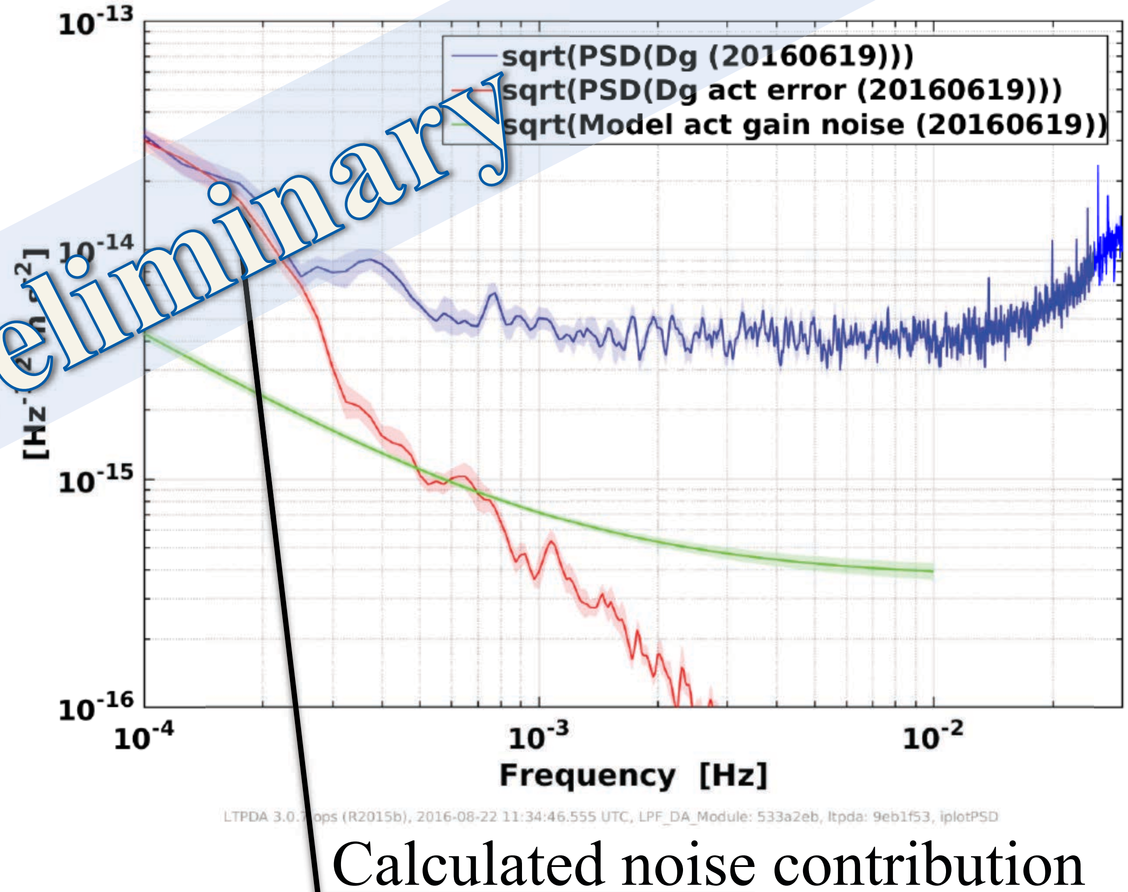
- Due to large quasi-static angular velocity of spacecraft during this specific run (antenna pointing)
- Affects data only below ~0.5 mHz
- For other runs at low angular velocity the correction is found to be negligible



Low frequency tail and stationarity

- Power at low frequency found dependent on static drift of commanded force
- Very likely due to identified quantization non-linearity in feedback-force

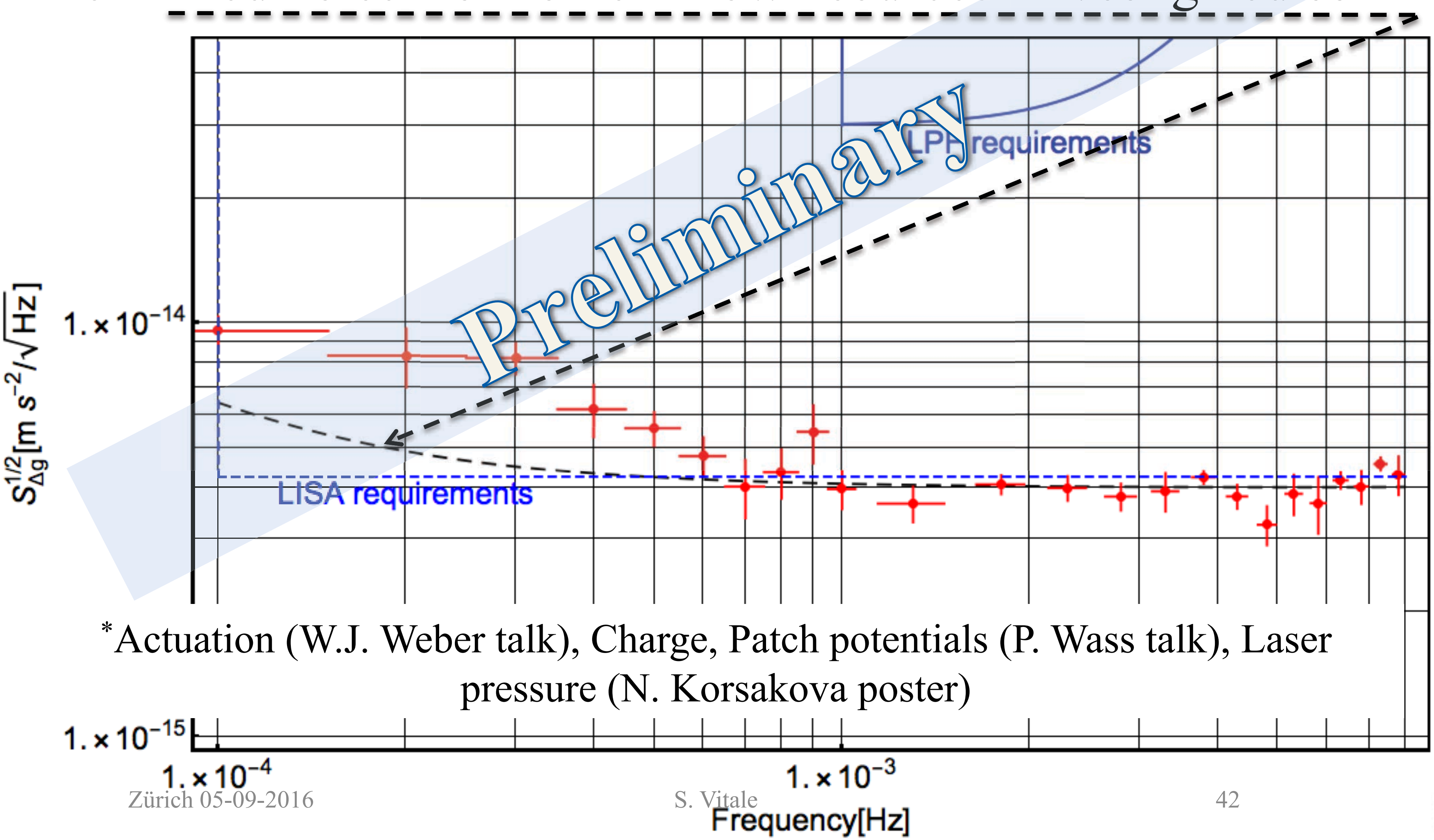
Run 19 June: $d\Delta g/dt \sim -0.5$ pm/s²/day



W. J. Weber talk

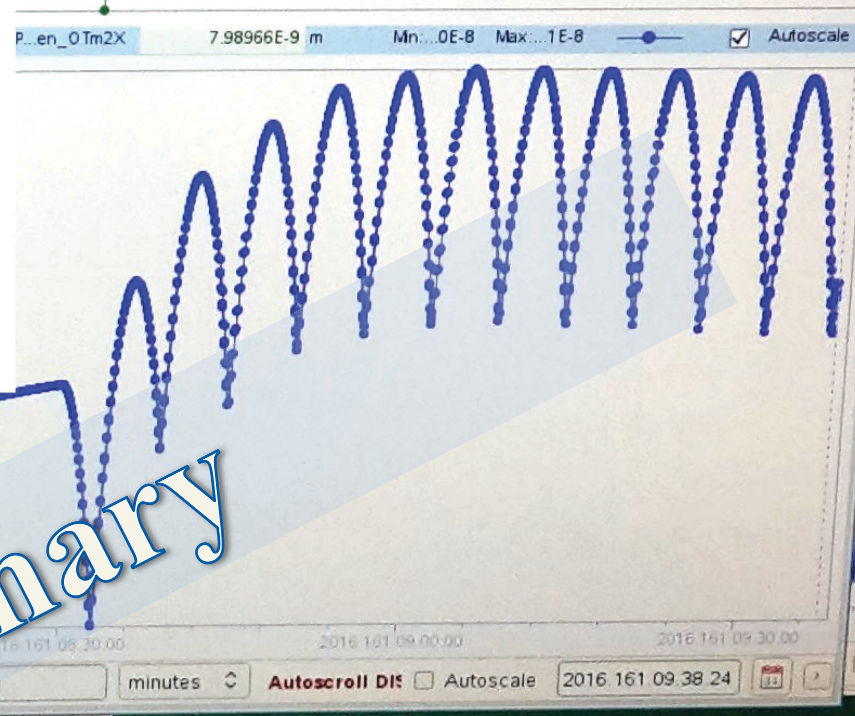
Current Performance Estimate

- Performance at times with drift less than 0.05 pm s^{-2}/d
- Normalized to Brownian at 4 fm $s^{-2}/\sqrt{Hz}$
- Estimated noise from other known sources* investigated so far



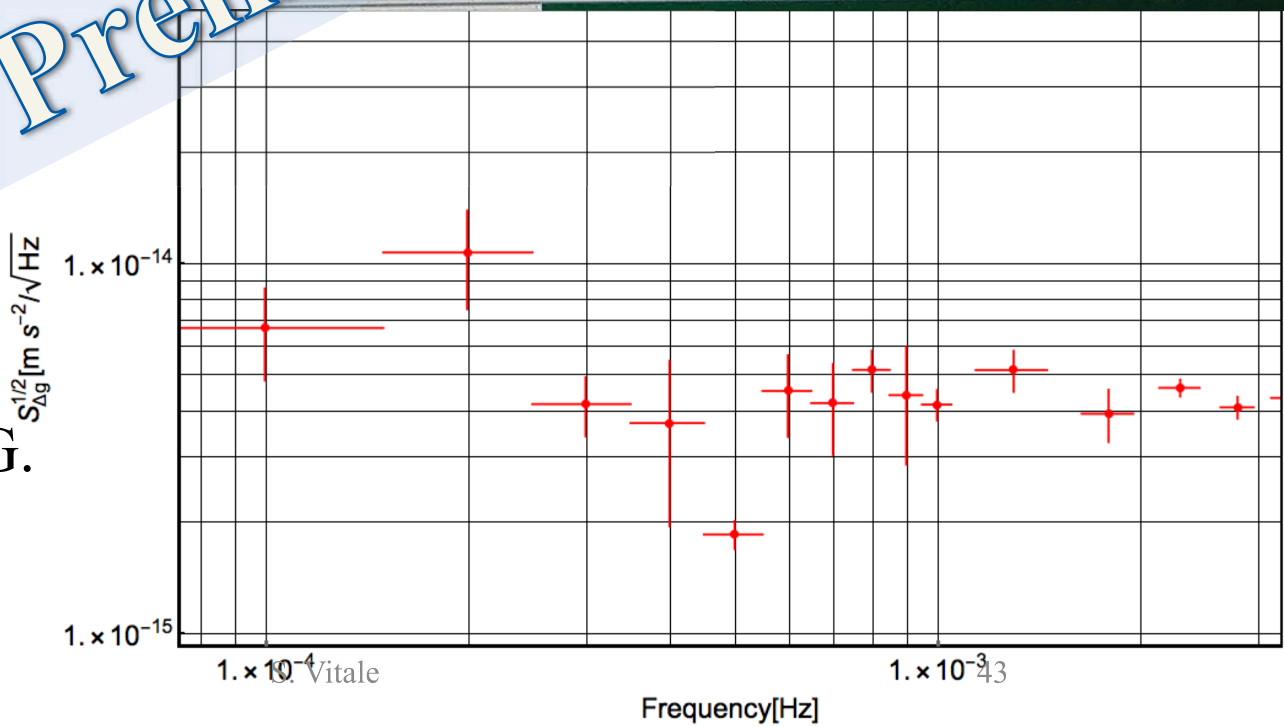
*Actuation (W.J. Weber talk), Charge, Patch potentials (P. Wass talk), Laser pressure (N. Korsakova poster)

Free-flight experiment: x-actuation off



- *Preliminary* results consistent with low-drift runs
- (spectral bias under consolidation)
- R. Giusteri talk and G. Russano Poster

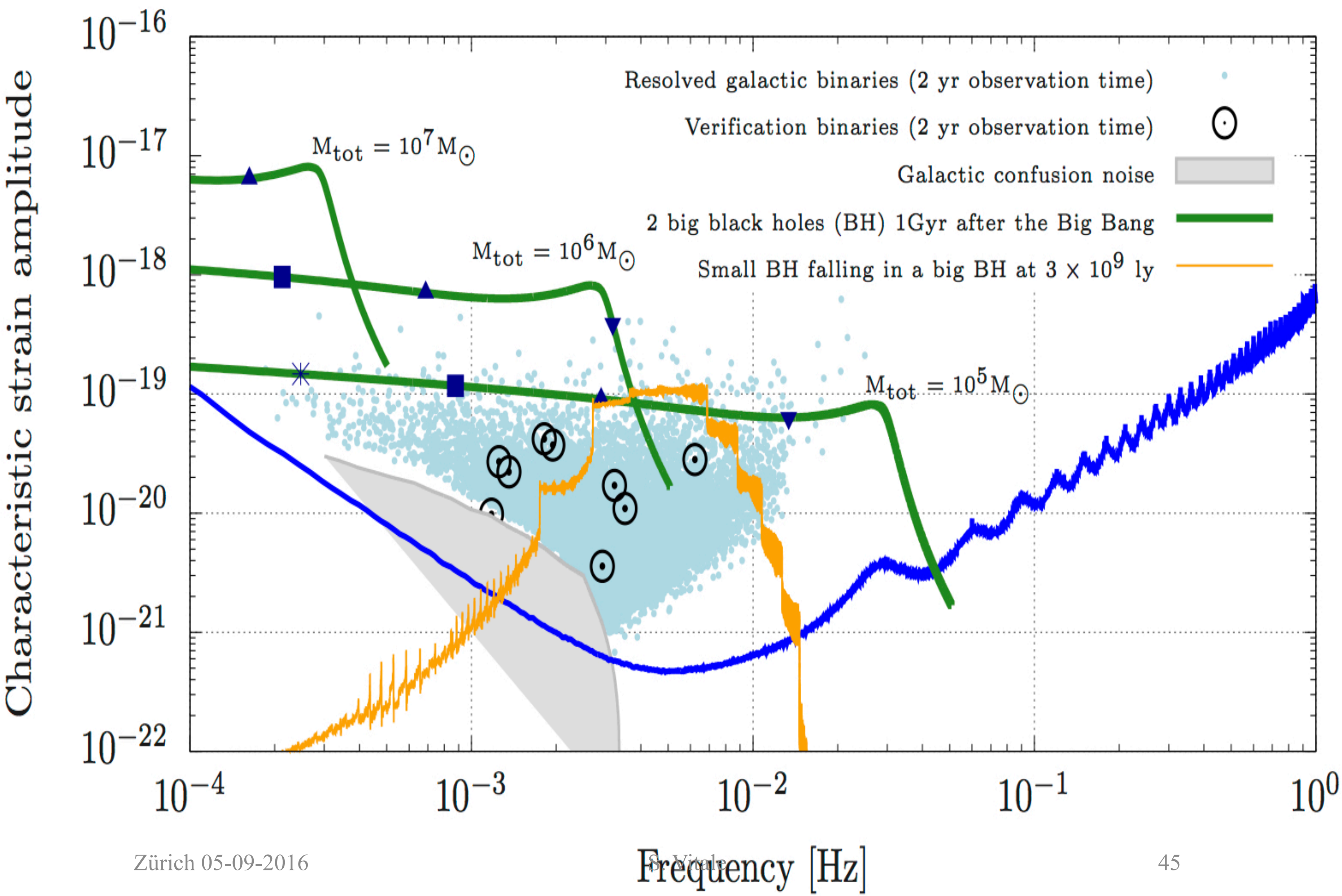
Preliminary



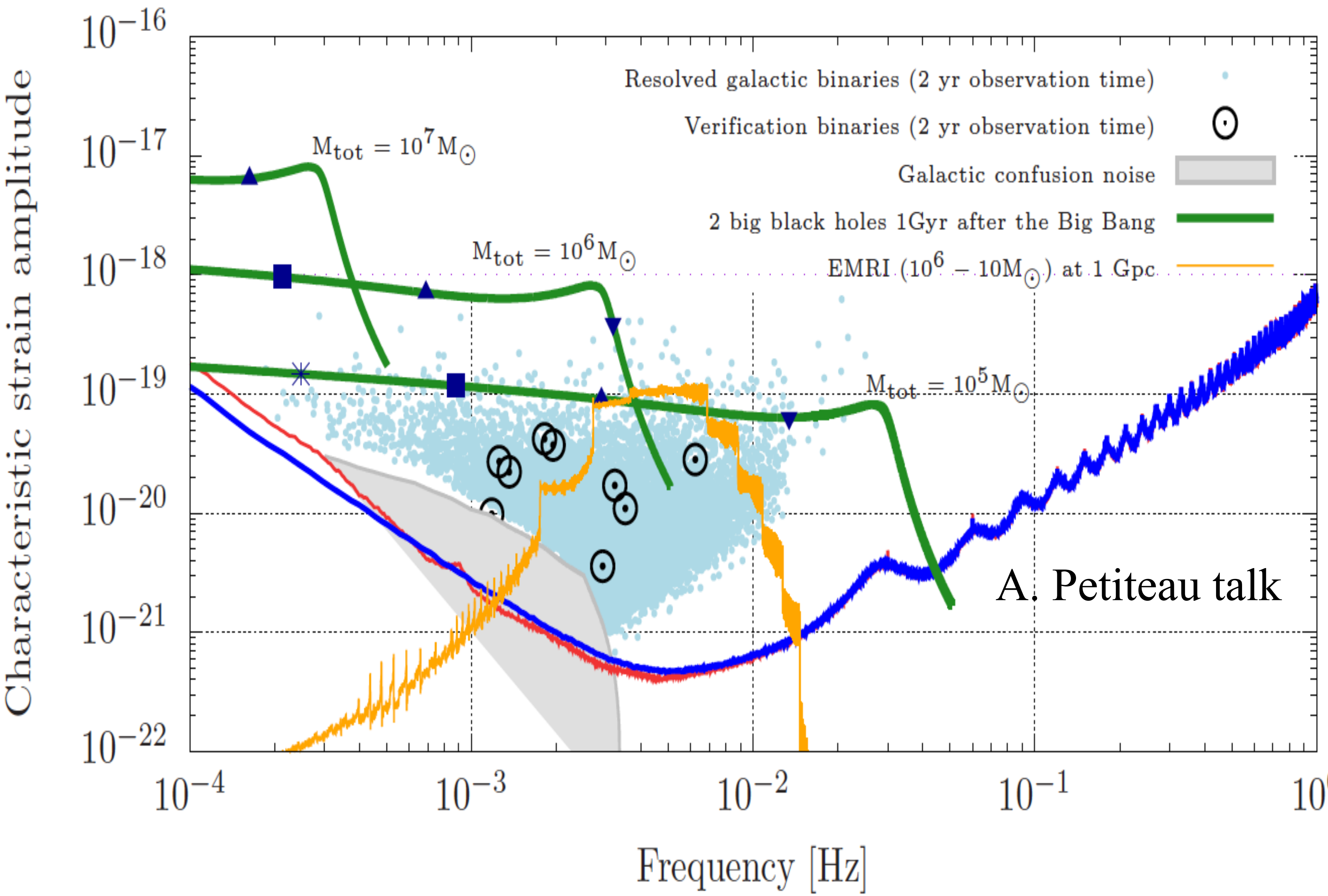
Other sources under investigation

- Residual non linear actuation noise
- Calibration inaccuracies
- Clock synchronization effects
- Interplanetary magnetic field (M. Nofrarias talk)
- Temperature fluctuations
- …………..

Noise almost entirely modeled: original LISA requirements at hand

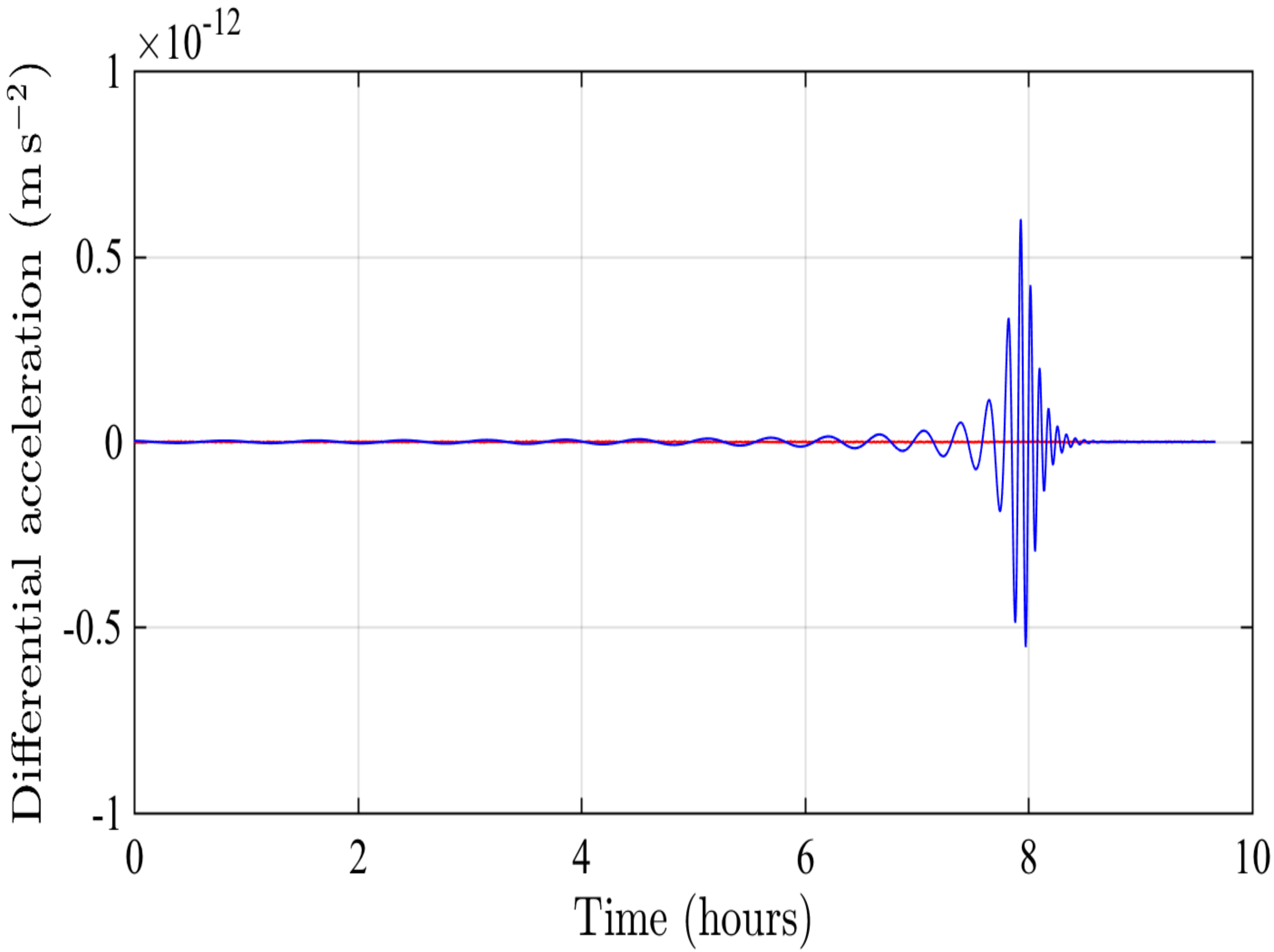


With current demonstrated sensitivity most science obtained anyway



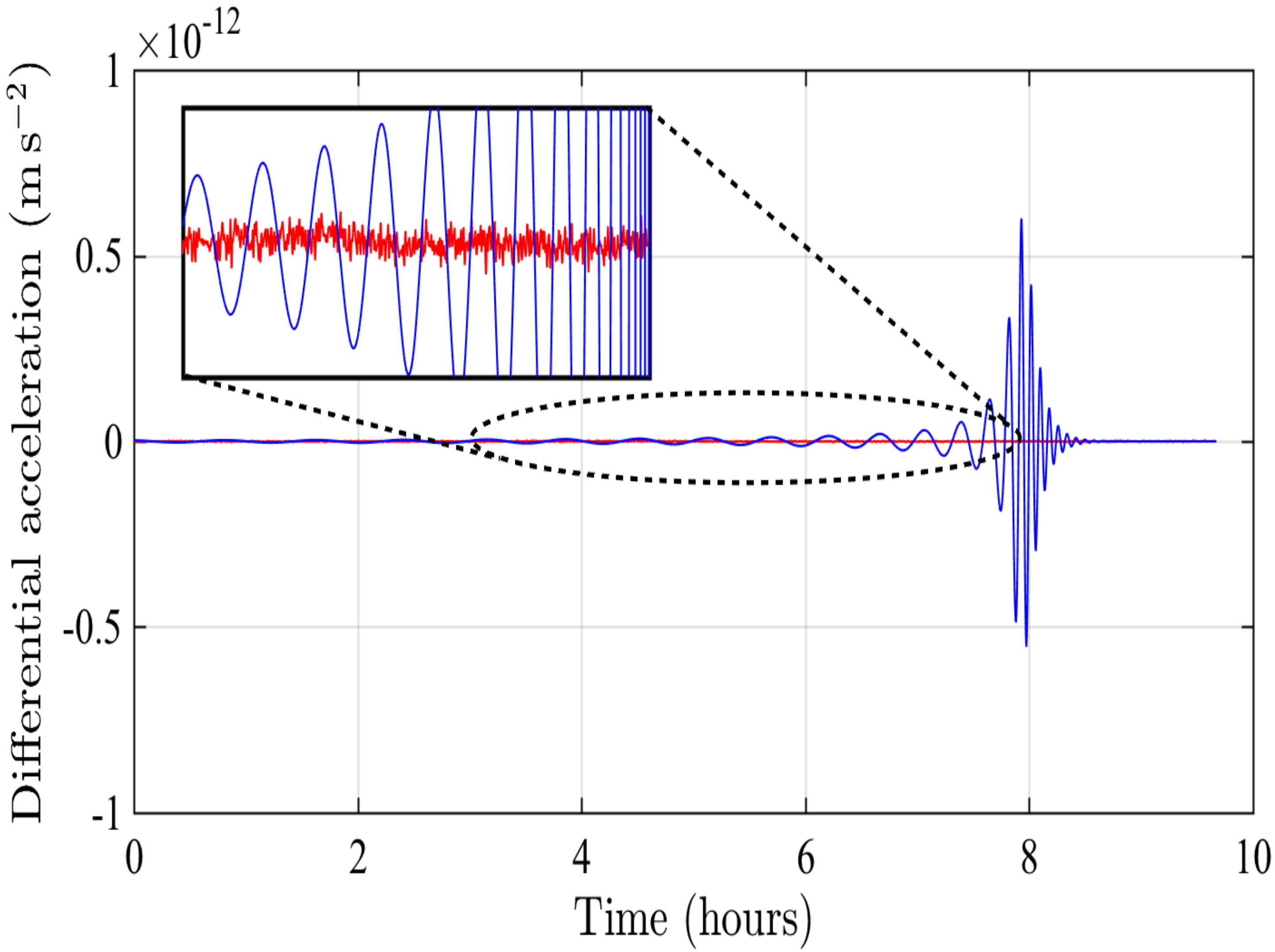
Simulated LISA acceleration signal for two $5\times10^5\ M_\odot$ black-holes with their galaxies merging at z=5

LISA Pathfinder acceleration data



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

LISA Pathfinder acceleration data



lisa pathfinder

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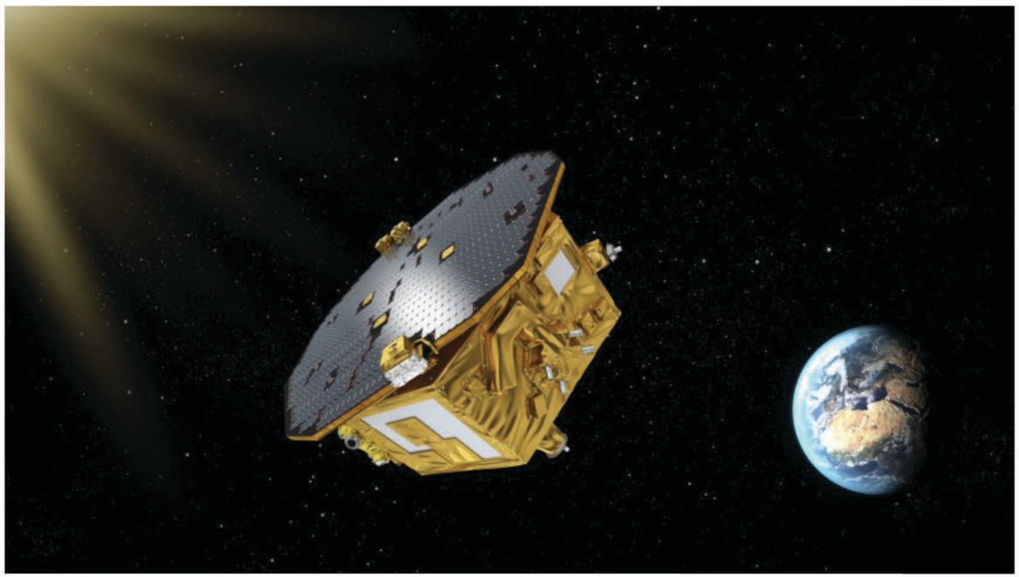

Artist's rendition of LISA Pathfinder. ESA

Green light for space-based gravitational wave detector

agenzia spaziale italiana

esa

OHB CGS

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)

INFN Istituto Nazionale di Fisica Nucleare

University of Glasgow

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Universitat de Barcelona

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SRON Netherlands Institute for Space Research

CDTI

UK SPACE AGENCY

asi agenzia spaziale italiana

DLR Deutsches Zentrum für Luft- und Raumfahrt

cnes

Züric

Thank you!!!!!!