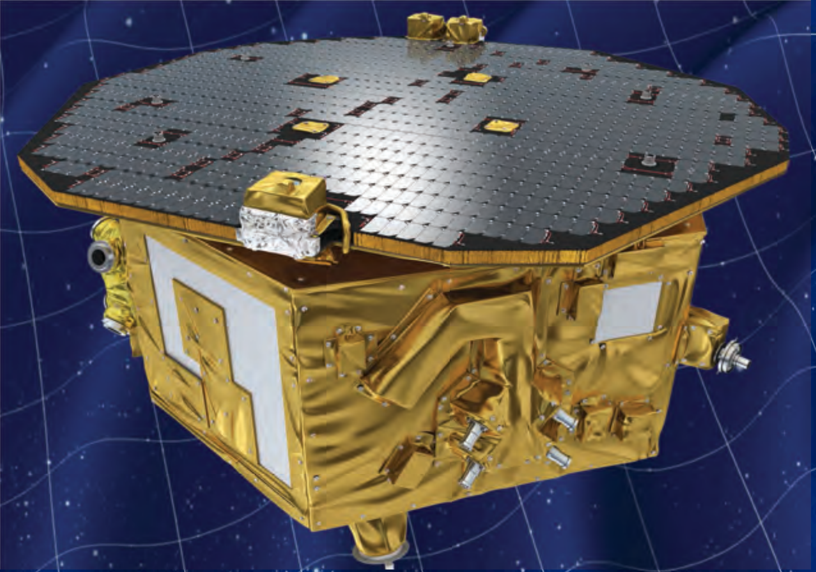
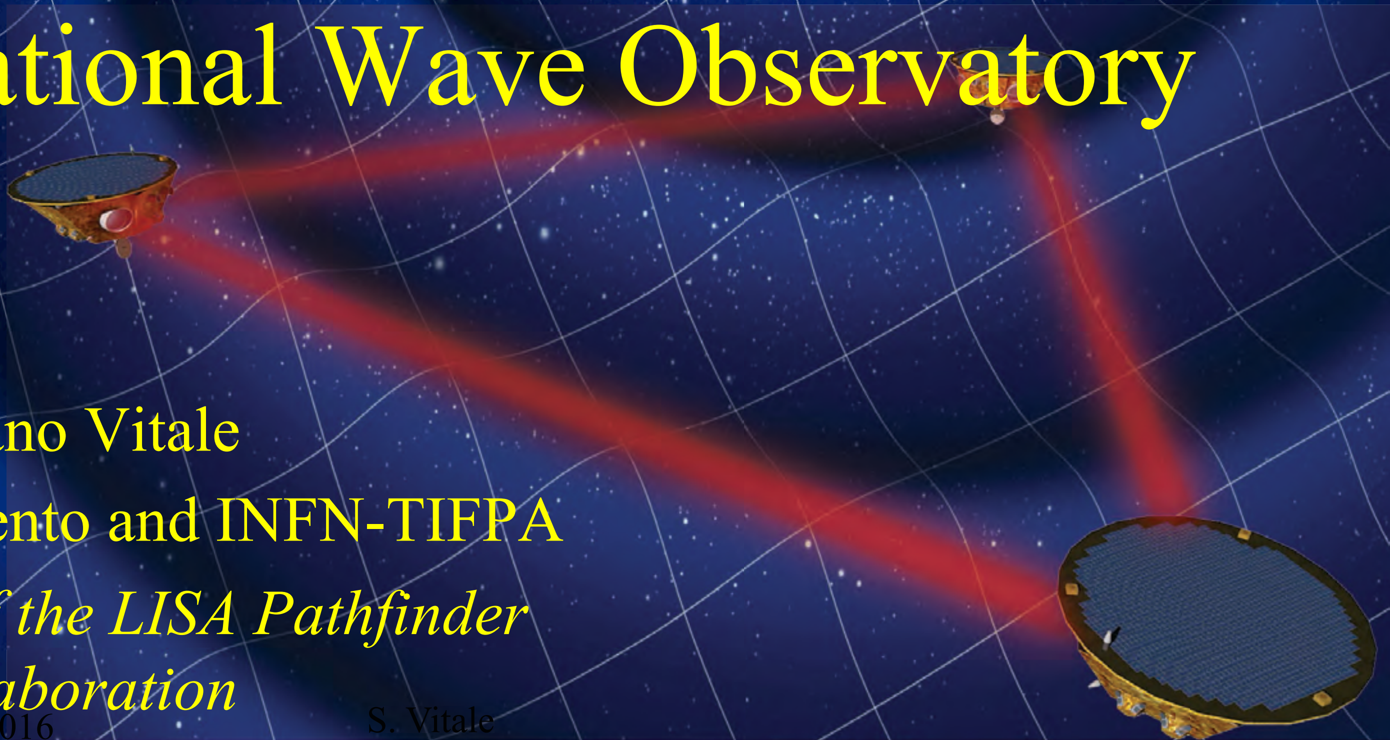


LISA Pathfinder and ESA's Gravitational Wave Observatory

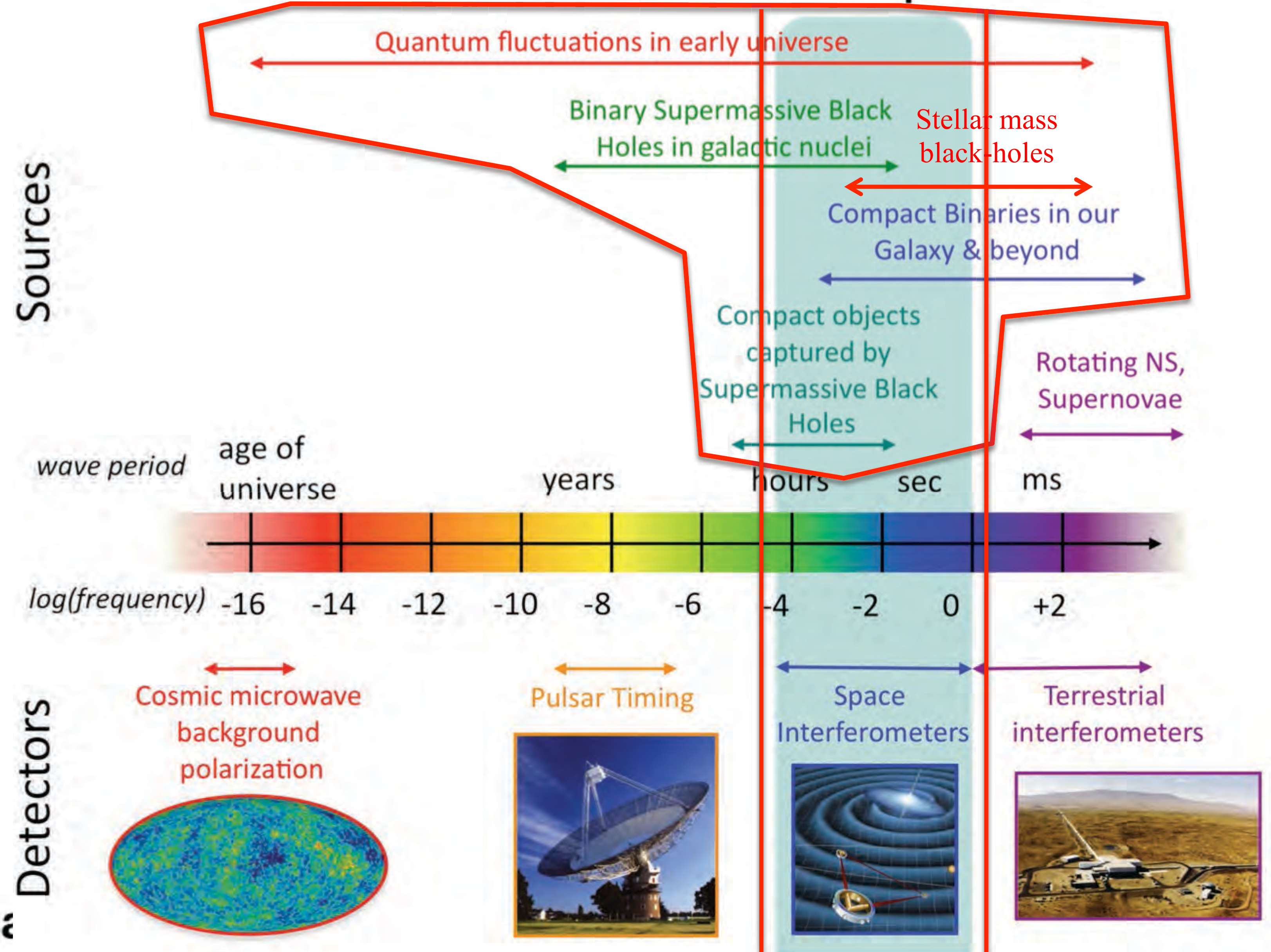


Stefano Vitale
University of Trento and INFN-TIFPA

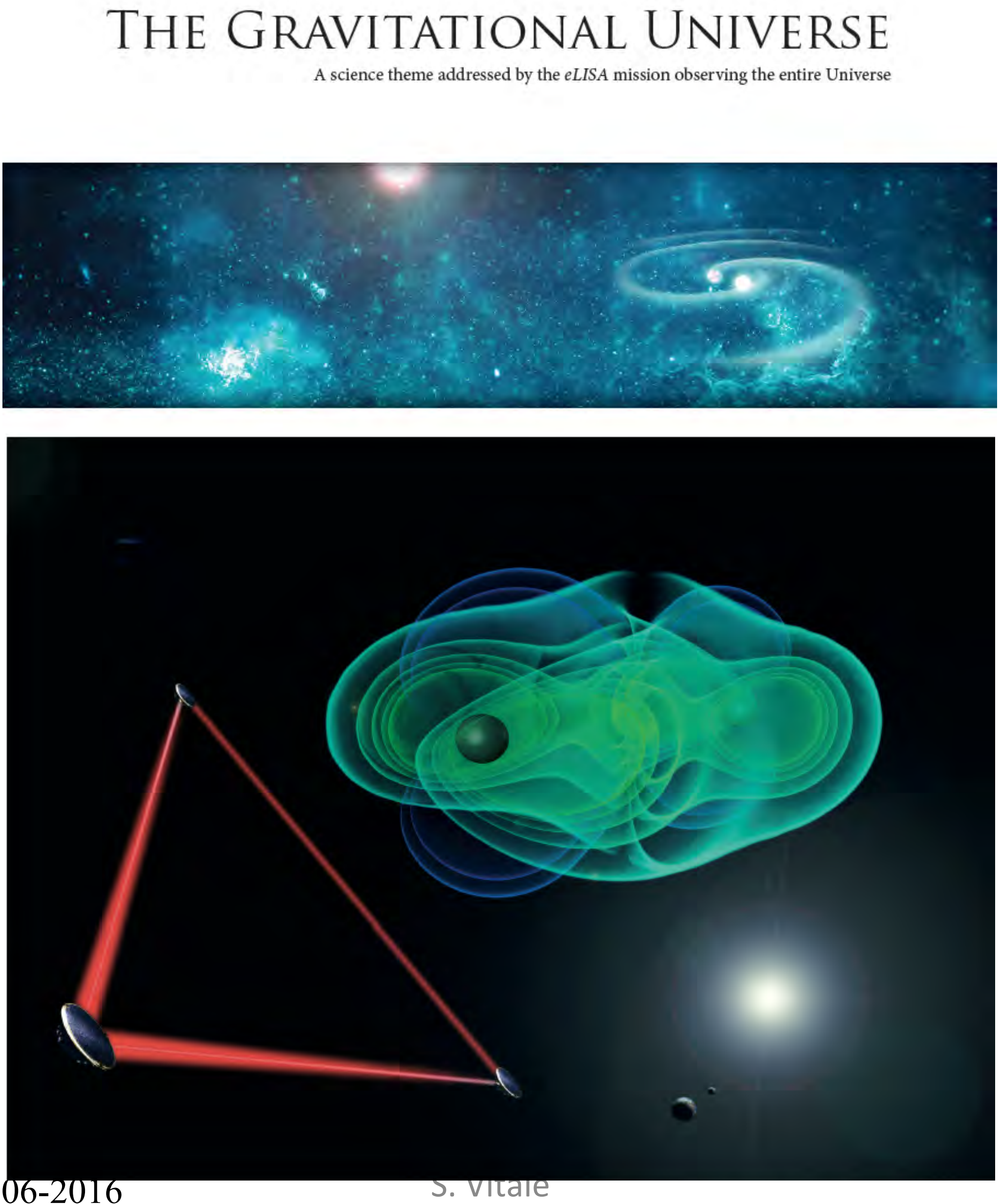
On the behalf of the LISA Pathfinder Collaboration

Space-based observatories

The Gravitational Wave Spectrum



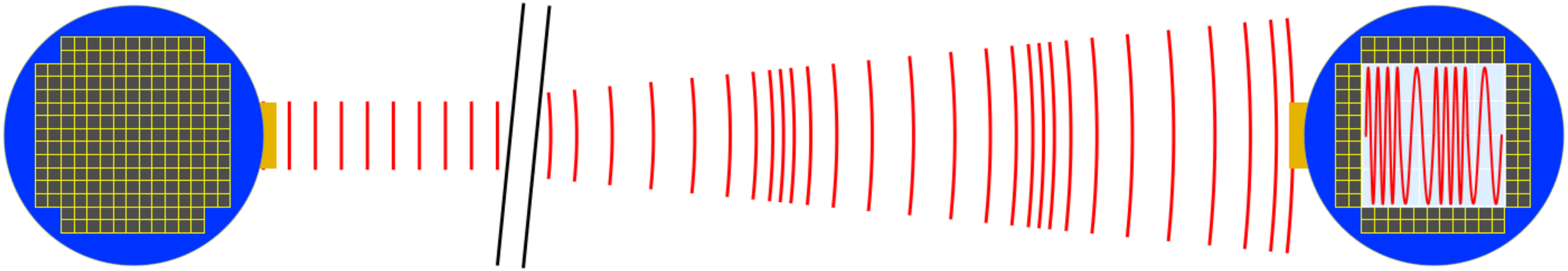
ESA 3rd large class mission



THE GRAVITATIONAL UNIVERSE

A science theme addressed by the *eLISA* mission observing the entire Universe

The LISA link



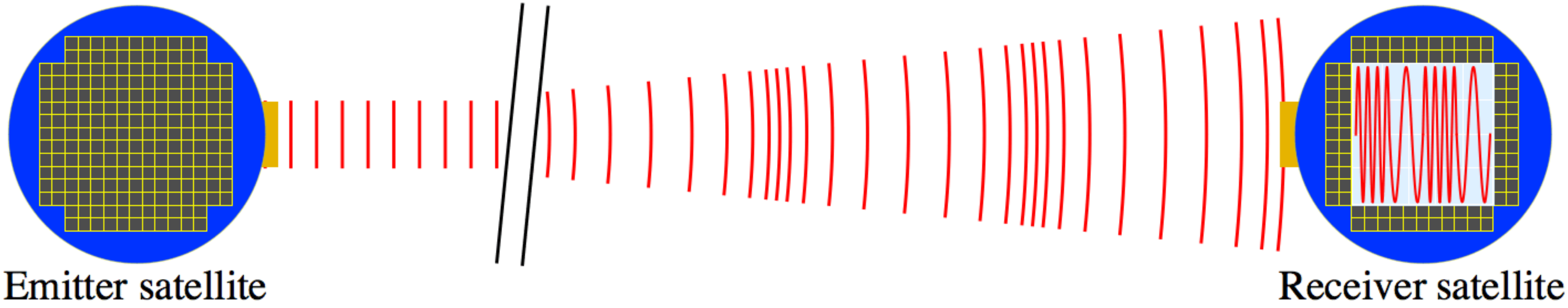
- GW curvature modulates the frequency of the received beam

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

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

Space-borne gravitational-wave detectors as time-delayed differential dynamometers

The eLISA link: a time delayed differential accelerometer



- Accelerations of satellites, *relative to their local inertial frame,* modulate frequency as curvature does.

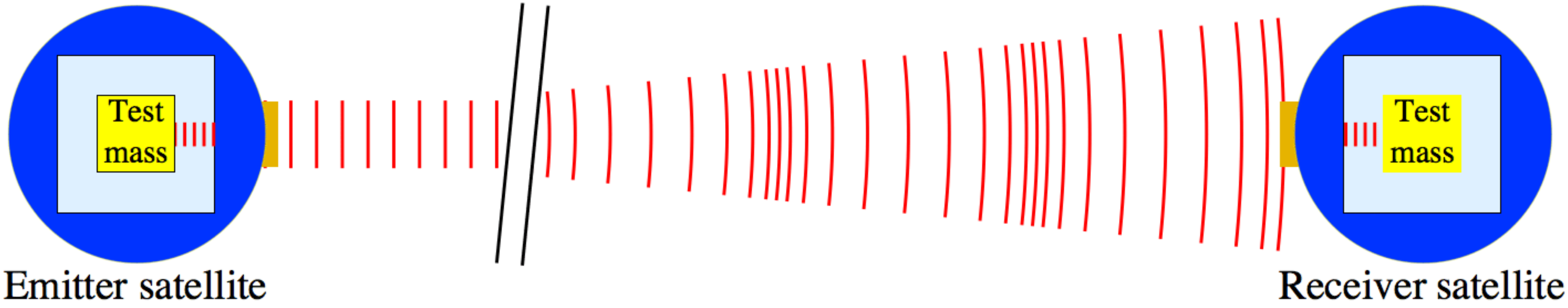
$$\left(c/\nu_{\mathrm{o}}\right)\left(\dot{\nu}_{\mathrm{receiver}}-\dot{\nu}_{\mathrm{emitter}}\right)=c\left\{\dot{h}_{\mathrm{receiver}}(t)-\dot{h}_{\mathrm{emitter}}(t-L/c)\right\}+$$

$$+a_{\mathrm{receiver}}(t)-a_{\mathrm{emitter}}(t-L/c)$$

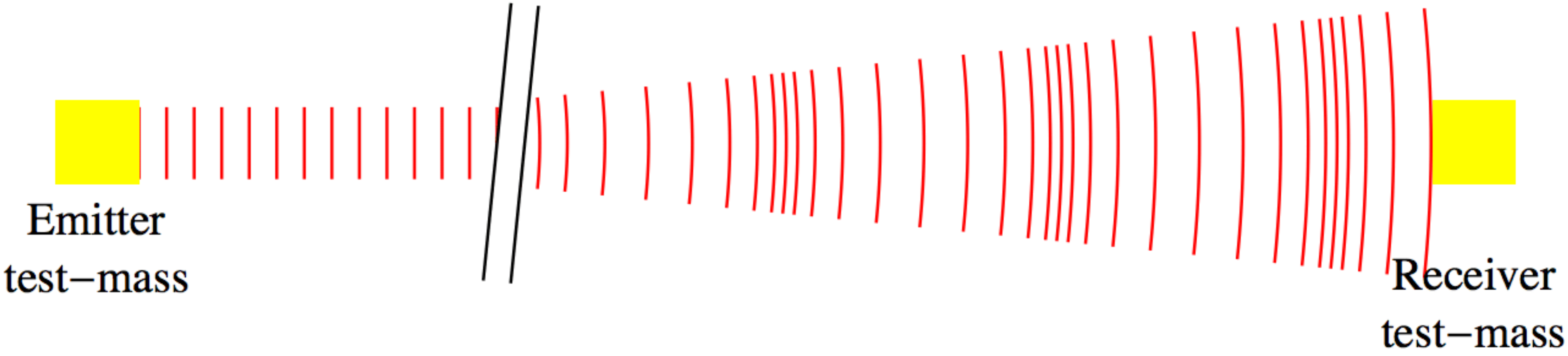
PHYSICAL REVIEW D **88,** 082003 (2013)

Space-borne gravitational-wave detectors as time-delayed differential dynamometers

The eLISA link: a time delayed differential accelerometer

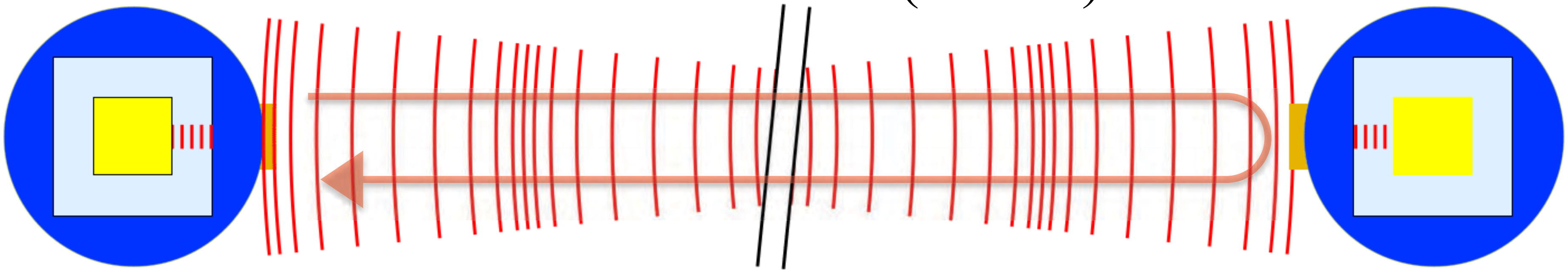


- Inertial reference test-masses are used to correct for satellite acceleration

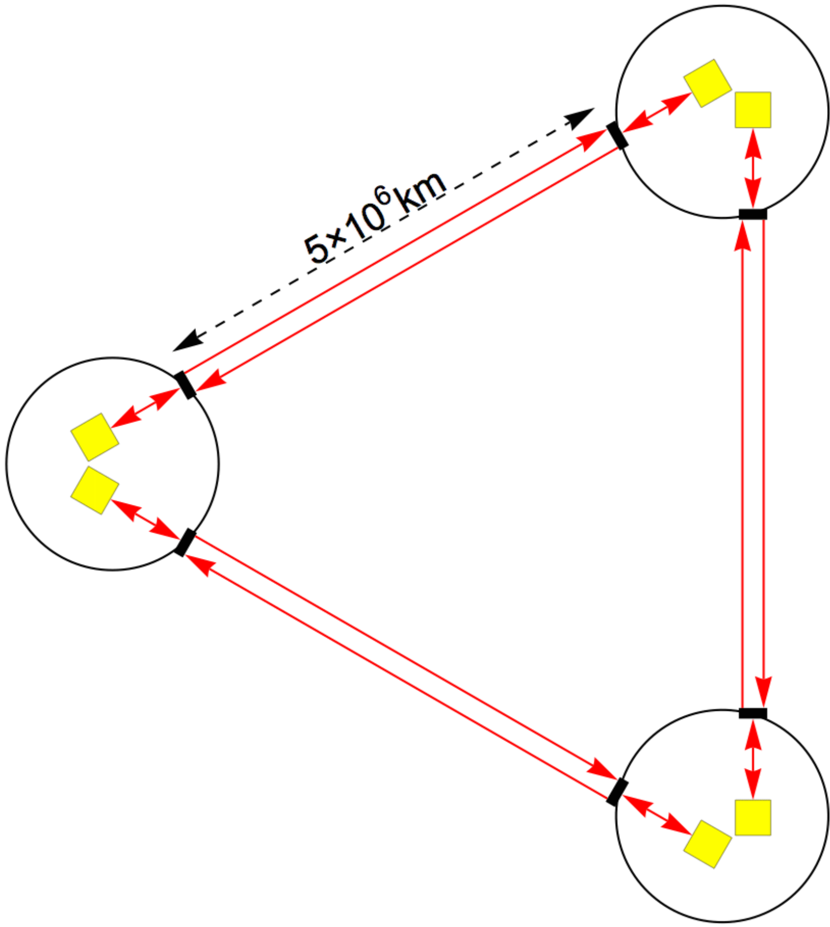


- Equivalent to directly tracking test-masses

The detector arm (eLISA)



- Two counter-propagating, phase-locked links
- LISA: 3 arms 5 Mo km
- 10 pm/√Hz single-link interferometry @1 mHz
- Forces (per unit mass) on test-masses < 3 fm/(s^2√Hz) @ 0.1 mHz
- 3 non-contacting ("drag-free") satellites



.e

Two or three interferometric arms for L3?

Parametric analysis performed by GOAT

- by varying: the number of arms (2 or 3), inter-S/C distance; mission duration; and noise level. See GOAT intermediate report.

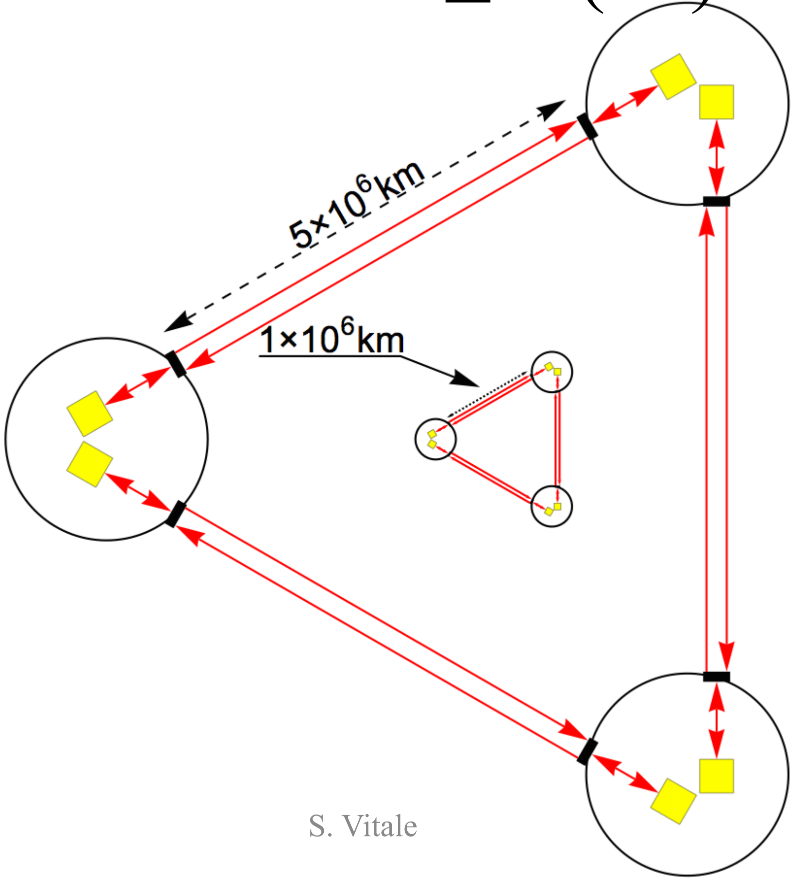
ESA would baseline the 3-arm configuration for the upcoming study activities –affordability TBC!

- Fully recurring spacecraft development; failure tolerance.
- Some arguments suggested in 2011 for two arms not valid, e.g. lower launch costs with 2 Soyuz launches vs single Ariane 5…the 3 Spacecraft configuration may be compatible with a single Ariane 6.2!
- Note that some of NGO/eLISA simplifications will probably be maintained, even when moving back to 3 arms

No urgent decision needed: short/medium term technology developments are devoted to payload subsystems

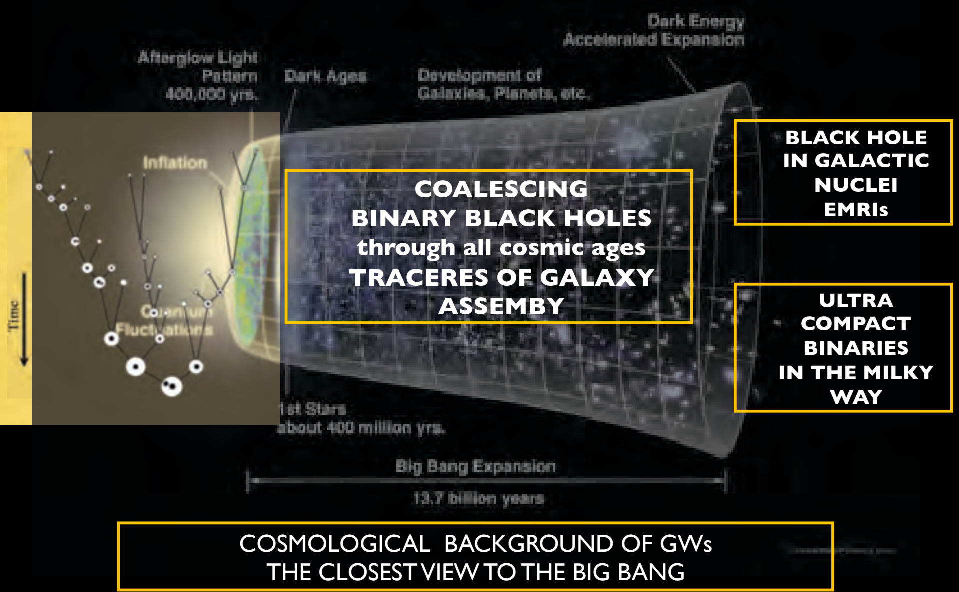
L3 Design parameter space

- 1 Mo km ≤ arm-length≤5 Mo km
- 2 (6) ≤ Mission duration ≤ 5 (10)



A mission in astrophysics, cosmology and fundamental physics

THE GRAVITATIONAL UNIVERSE



COALESCING BINARY BLACK HOLES
through all cosmic ages
TRACERES OF GALAXY ASSEMBY

BLACK HOLE IN GALACTIC NUCLEI
EMRIs

ULTRA COMPACT BINARIES IN THE MILKY WAY

COSMOLOGICAL BACKGROUND OF GWs
THE CLOSEST VIEW TO THE BIG BANG

The Gravitational Laboratory

- Does gravity travel at the speed of light ?
- Does the graviton have mass?
- How does gravitational information propagate: Are there more than two transverse modes of propagation?
- Does gravity couple to other dynamical fields, such as, massless or massive scalars?
- What is the structure of spacetime just outside astrophysical black holes? Do their spacetimes have horizons?
- Are astrophysical black holes fully described by the Kerr metric, as predicted by General Relativity?

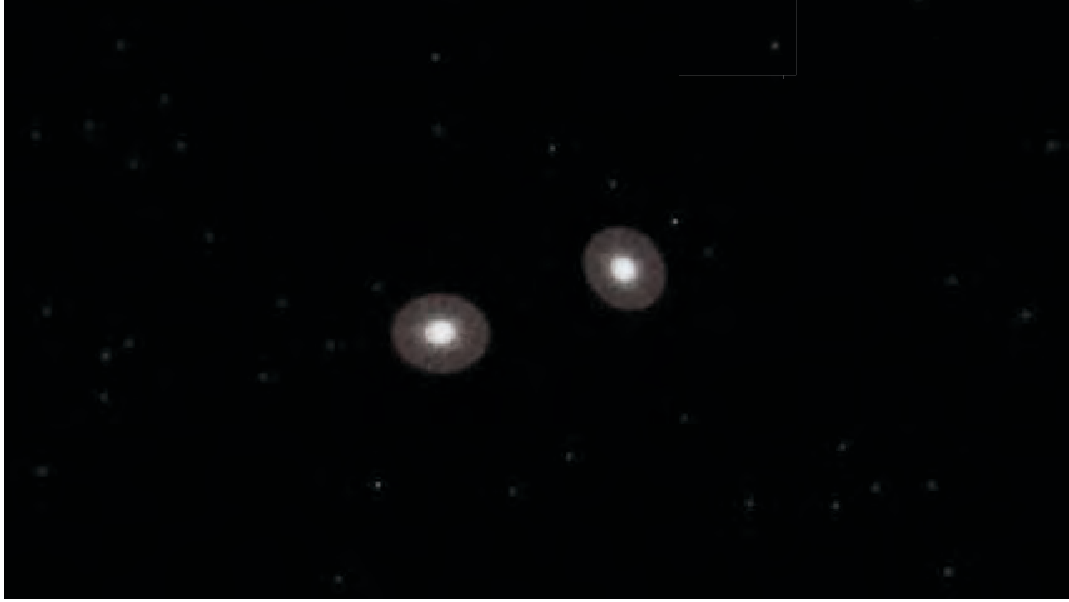
Event Rates and Event Numbers

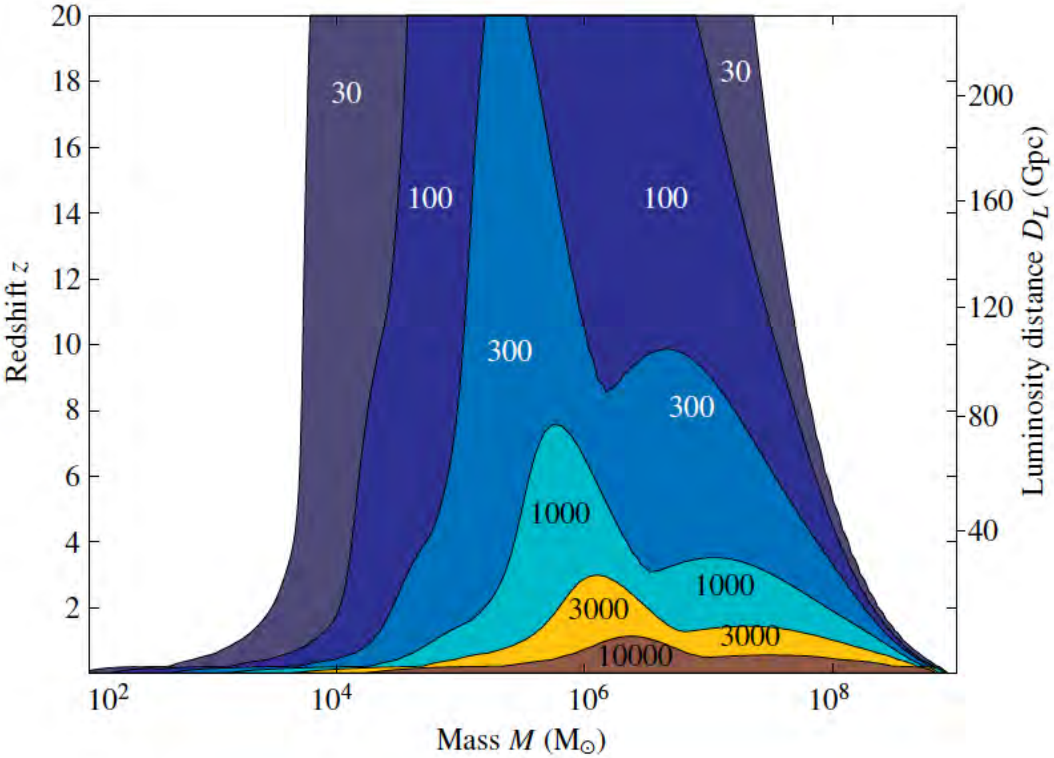
Frequency band	1×10^{-4} Hz to 1 Hz, (3×10^{-5} Hz to 1 Hz as a goal)
Massive black hole mergers	10 yr^{-1} to 100 yr^{-1}
Extreme mass ratio inspirals	5 yr^{-1} to 50 yr^{-1}
Galactic Binaries	~ 3000 resolvable out of a total of ~ 30×10^{6} in the *eLISA* band

+ what we cannot predict

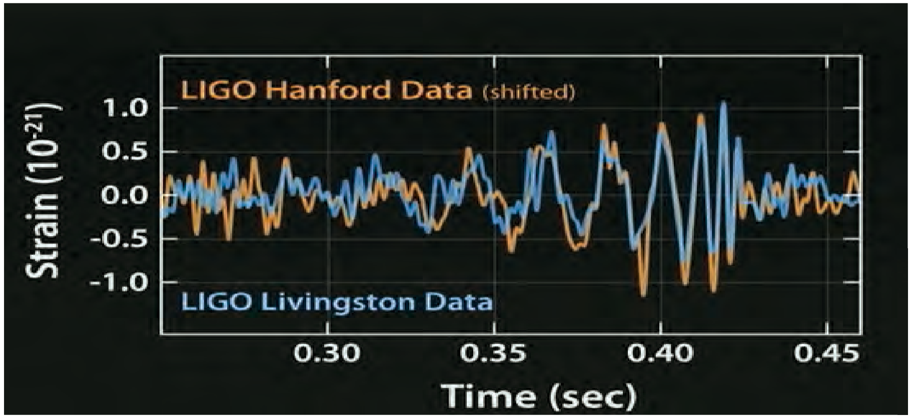
Super-massive black-hole mergers

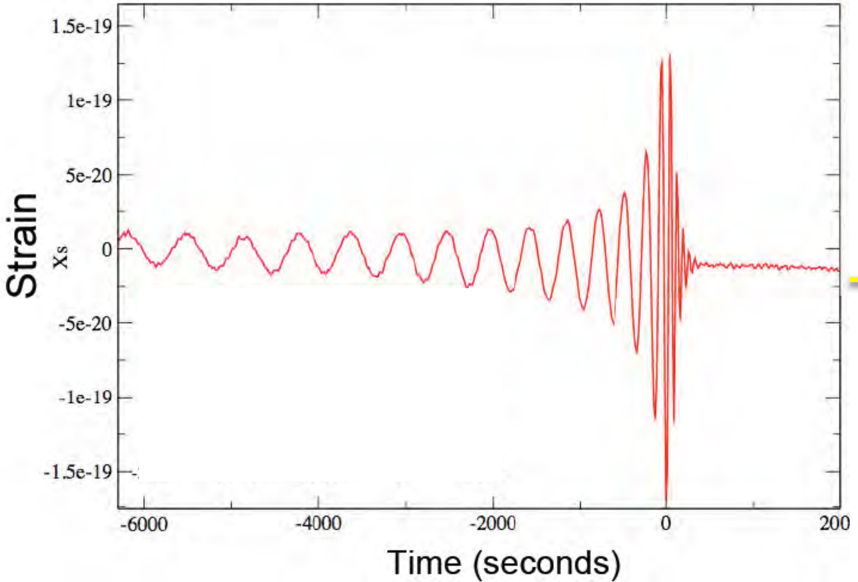
- All mergers in the universe in its frequency band, even out to z=20, if they were happening.
- Measures: luminosity distance 1 – 5 %
- Sky location 1‘ - 5 °
- Masses to ±0.1-0.5%
- Spin magnitudes to ±0.01.
- Spin *vectors* to ±3-5%

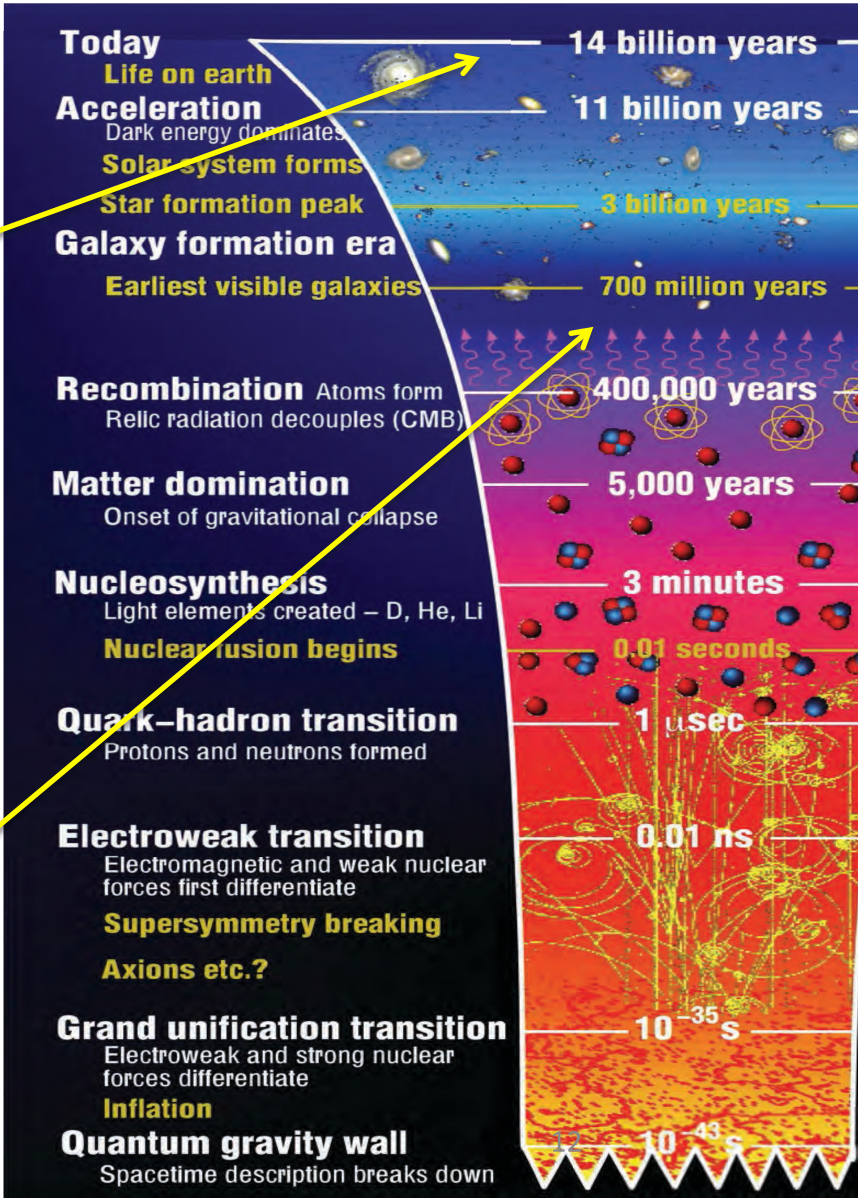




A deep universe observatory







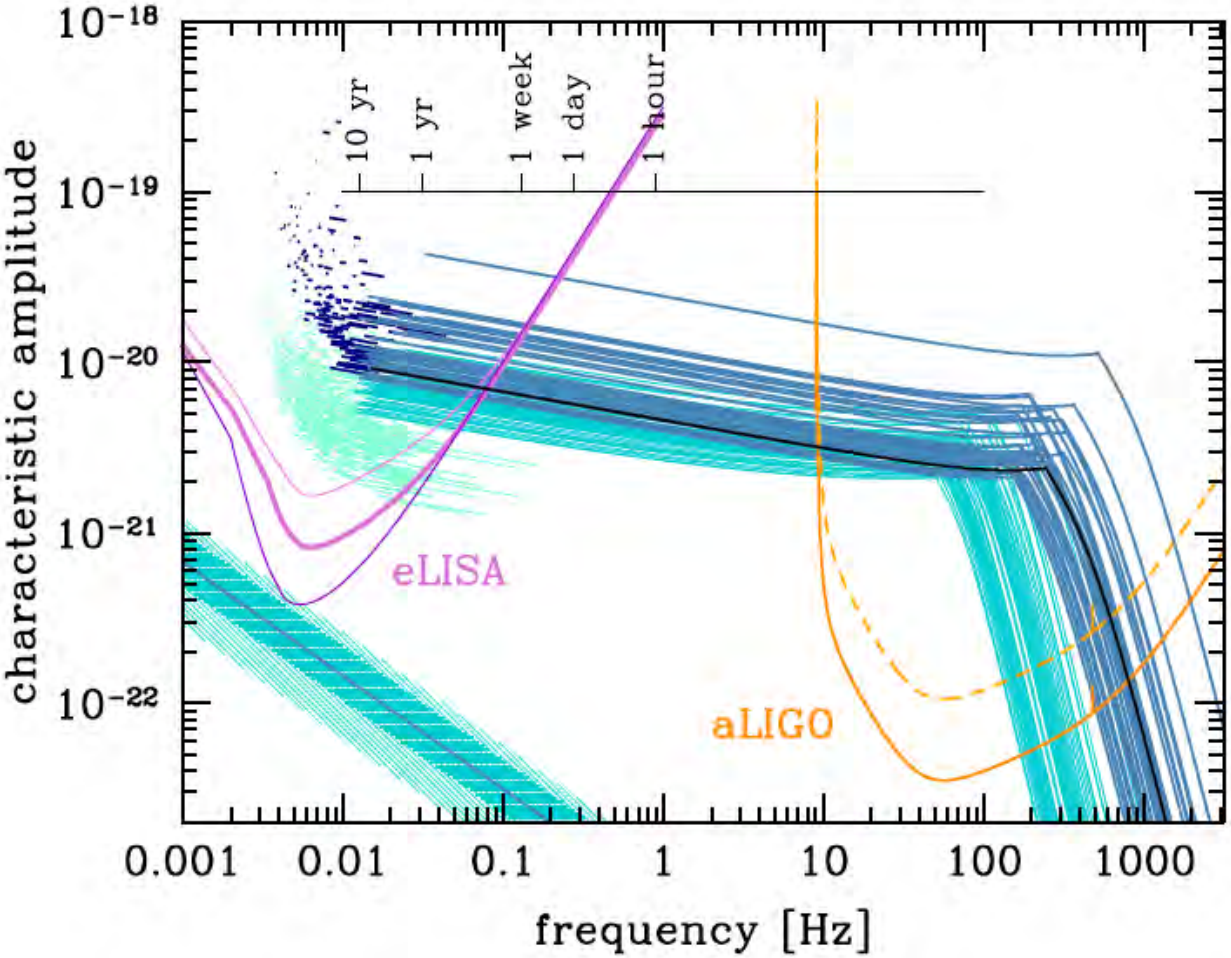
Editors' Suggestion

Prospects for Multiband Gravitational-Wave Astronomy after GW150914

Alberto Sesana

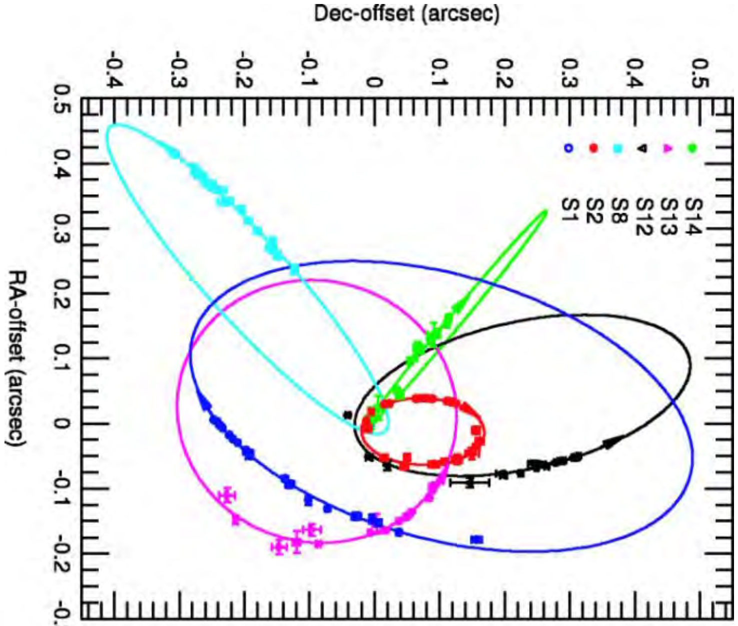
Phys. Rev. Lett. **116**, 231102 (2016) – Published 8 June 2016

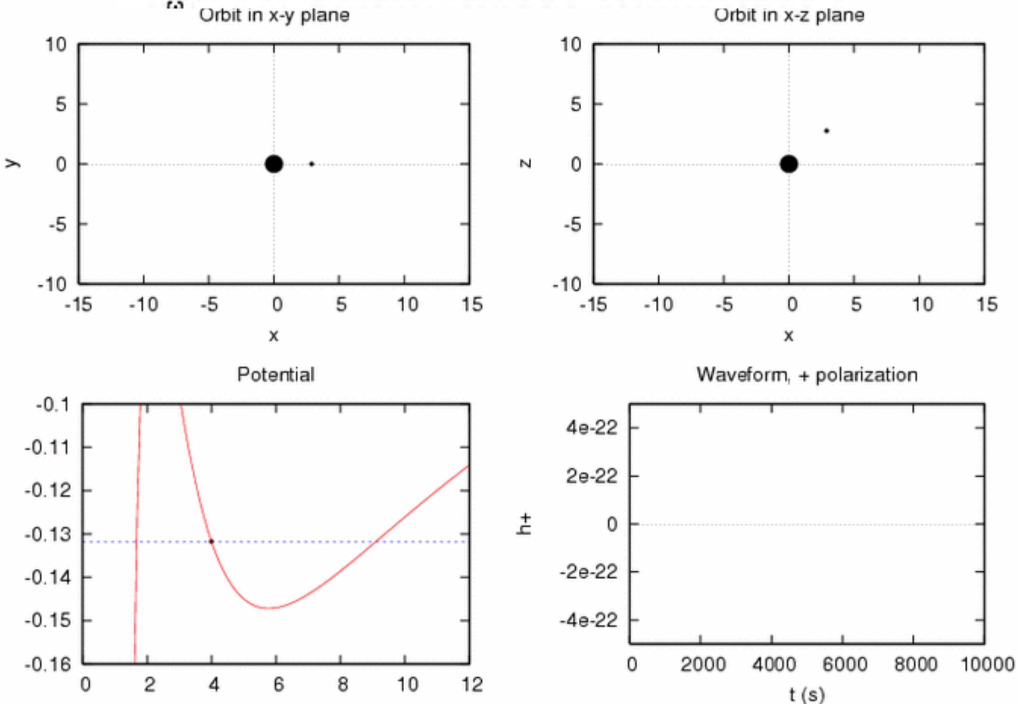
Rates of black hole merger formations inferred from the recent detection of gravitational waves suggest that a future space based facility like eLISA can efficiently inform LIGO and other facilitates about locations of potential black hole mergers weeks in advance.

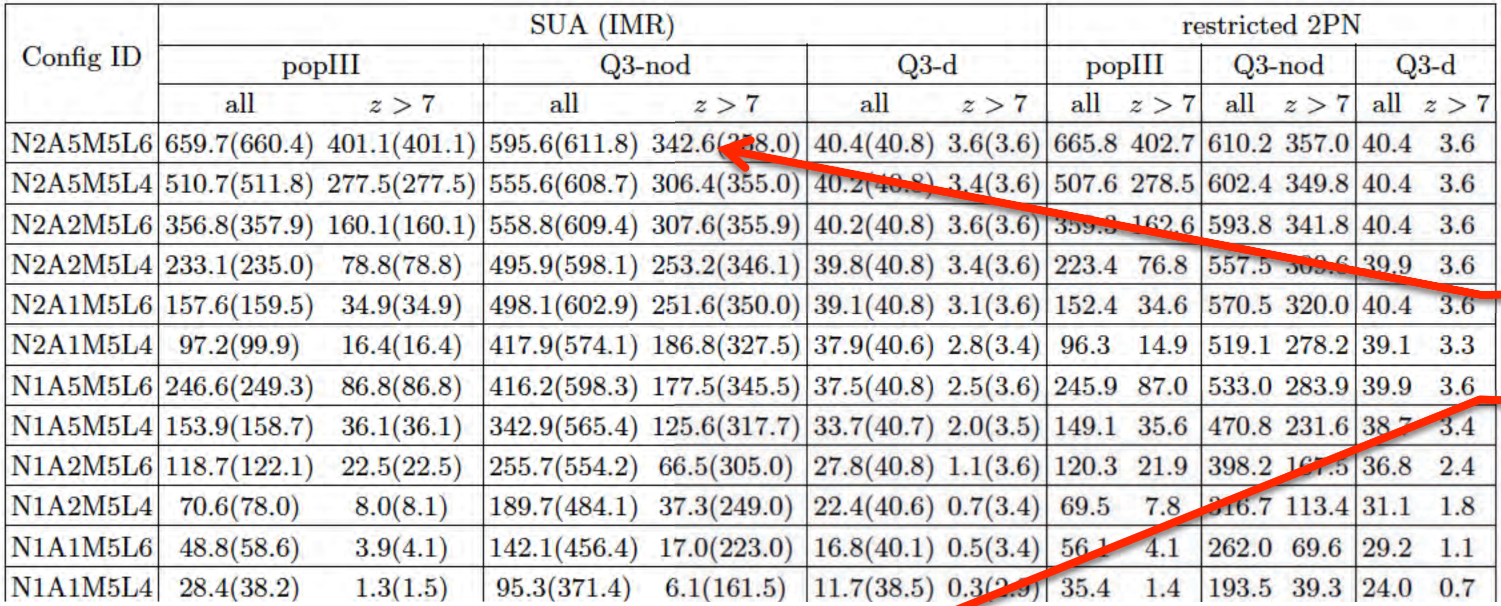


Extreme Mass-Ratio Inspirals: EMRIs

- Stellar-mass BH capture by a massive BH: dozens per year to z~0.7.
- 10^5 orbits very close to horizon. GRACE/GOCE for massive BHs.
  - Prove horizon exists.
  - Test the no-hair theorem to 1%.
  - Masses of holes to 0.1%
  - Spin of central BH to 0.001.
- Probes environment of central black-hole
  - mass and spin spectrum of stellar mass black holes
  - density and mechanism of formation





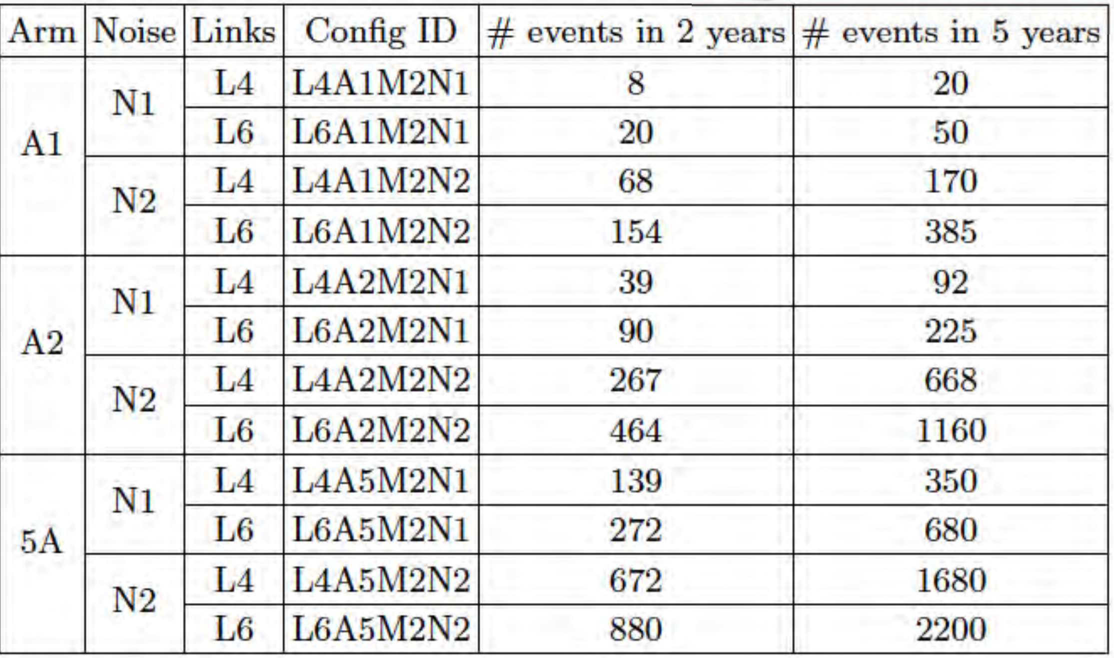


Config ID	SUA (IMR)						restricted 2PN					
	popIII		Q3-nod		Q3-d		popIII		Q3-nod		Q3-d	
	all	$z > 7$	all	$z > 7$	all	$z > 7$	all	$z > 7$	all	$z > 7$	all	$z > 7$
N2A5M5L6	659.7(660.4)	401.1(401.1)	595.6(611.8)	342.6(358.0)	40.4(40.8)	3.6(3.6)	665.8	402.7	610.2	357.0	40.4	3.6
N2A5M5L4	510.7(511.8)	277.5(277.5)	555.6(608.7)	306.4(355.0)	40.2(40.8)	3.4(3.6)	507.6	278.5	602.4	349.8	40.4	3.6
N2A2M5L6	356.8(357.9)	160.1(160.1)	558.8(609.4)	307.6(355.9)	40.2(40.8)	3.6(3.6)	359.3	162.6	593.8	341.8	40.4	3.6
N2A2M5L4	233.1(235.0)	78.8(78.8)	495.9(598.1)	253.2(346.1)	39.8(40.8)	3.4(3.6)	223.4	76.8	557.5	309.6	39.9	3.6
N2A1M5L6	157.6(159.5)	34.9(34.9)	498.1(602.9)	251.6(350.0)	39.1(40.8)	3.1(3.6)	152.4	34.6	570.5	320.0	40.4	3.6
N2A1M5L4	97.2(99.9)	16.4(16.4)	417.9(574.1)	186.8(327.5)	37.9(40.6)	2.8(3.4)	96.3	14.9	519.1	278.2	39.1	3.3
N1A5M5L6	246.6(249.3)	86.8(86.8)	416.2(598.3)	177.5(345.5)	37.5(40.8)	2.5(3.6)	245.9	87.0	533.0	283.9	39.9	3.6
N1A5M5L4	153.9(158.7)	36.1(36.1)	342.9(565.4)	125.6(317.7)	33.7(40.7)	2.0(3.5)	149.1	35.6	470.8	231.6	38.7	3.4
N1A2M5L6	118.7(122.1)	22.5(22.5)	255.7(554.2)	66.5(305.0)	27.8(40.8)	1.1(3.6)	120.3	21.9	398.2	167.5	36.8	2.4
N1A2M5L4	70.6(78.0)	8.0(8.1)	189.7(484.1)	37.3(249.0)	22.4(40.6)	0.7(3.4)	69.5	7.8	316.7	113.4	31.1	1.8
N1A1M5L6	48.8(58.6)	3.9(4.1)	142.1(456.4)	17.0(223.0)	16.8(40.1)	0.5(3.4)	56.1	4.1	262.0	69.6	29.2	1.1
N1A1M5L4	28.4(38.2)	1.3(1.5)	95.3(371.4)	6.1(161.5)	11.7(38.5)	0.3(2.9)	35.4	1.4	193.5	39.3	24.0	0.7

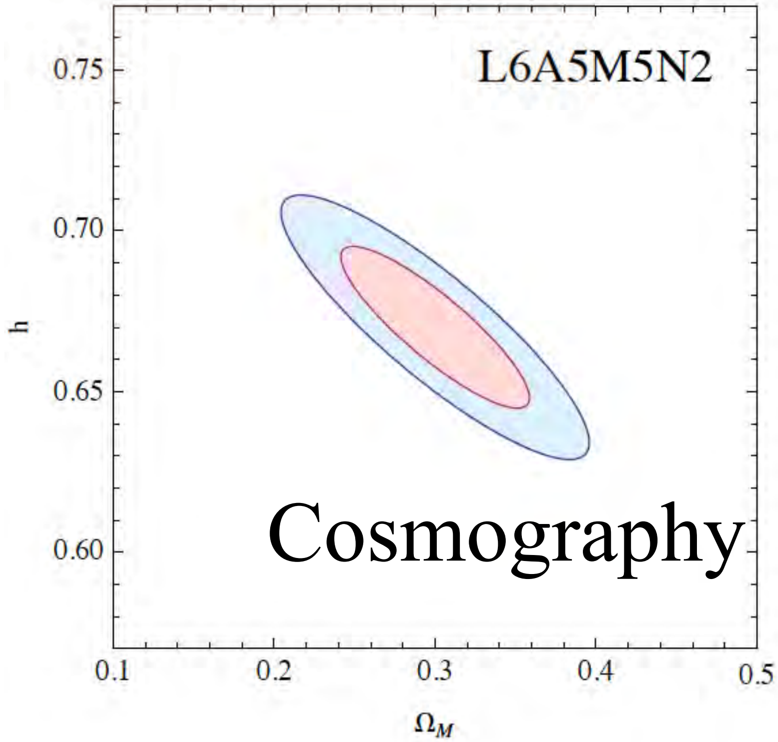
Rates:

SMBH

EMRI



Arm	Noise	Links	Config ID	# events in 2 years	# events in 5 years
A1	N1	L4	L4A1M2N1	8	20
		L6	L6A1M2N1	20	50
	N2	L4	L4A1M2N2	68	170
		L6	L6A1M2N2	154	385
A2	N1	L4	L4A2M2N1	39	92
		L6	L6A2M2N1	90	225
	N2	L4	L4A2M2N2	267	668
		L6	L6A2M2N2	464	1160
5A	N1	L4	L4A5M2N1	139	350
		L6	L6A5M2N1	272	680
	N2	L4	L4A5M2N2	672	1680
		L6	L6A5M2N2	880	2200



Cosmography

Stochastic GW background

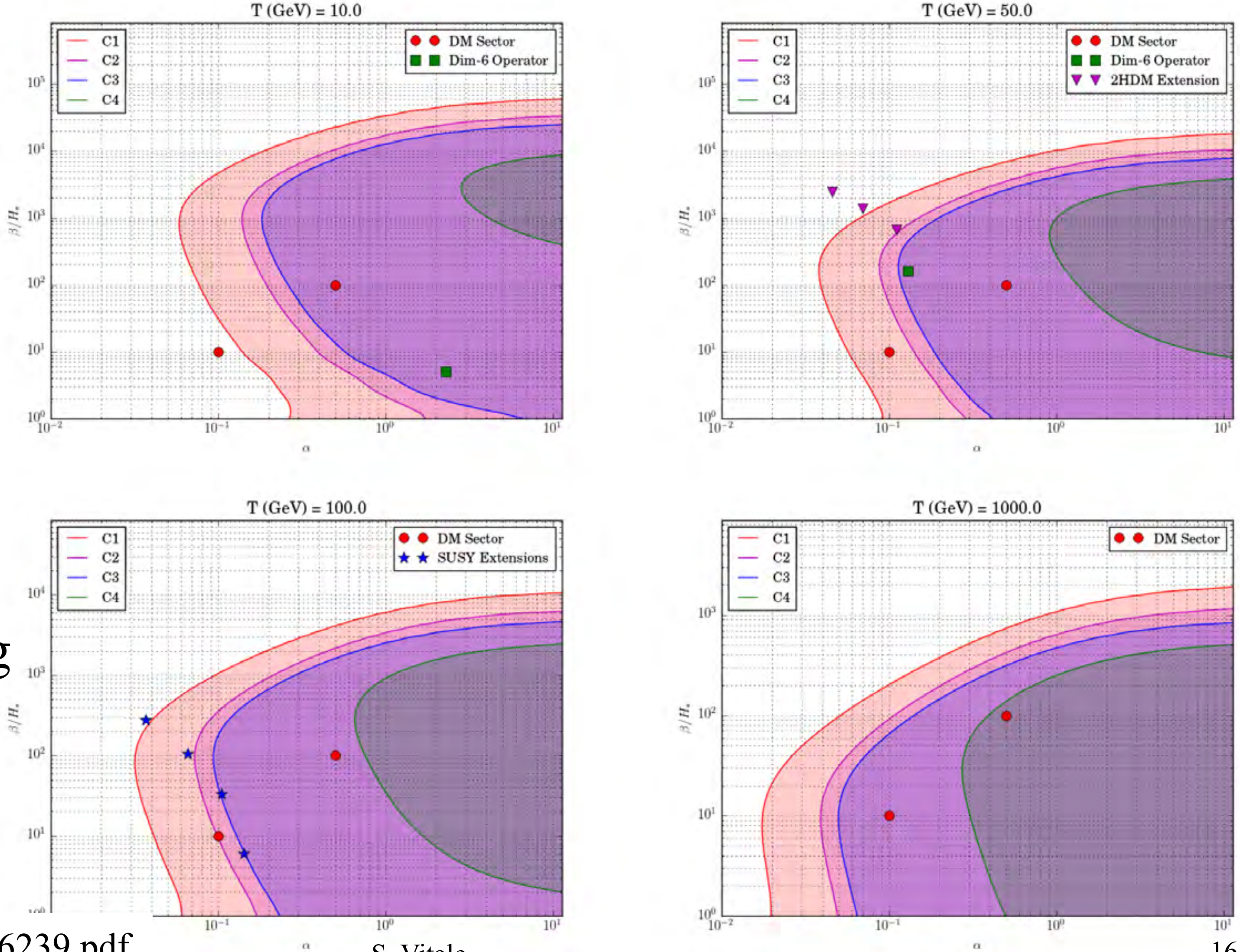
- Assuming wavelength of relic GW set by horizon scale at time of emission (with temperature T) $f \simeq 0.1\,\mathrm{mHz}\left(k_B T/1\,\mathrm{Tev}\right)$

LISA band:
0.1-100 mHz $\Longrightarrow$
1-1000 TeV scale
(LHC)

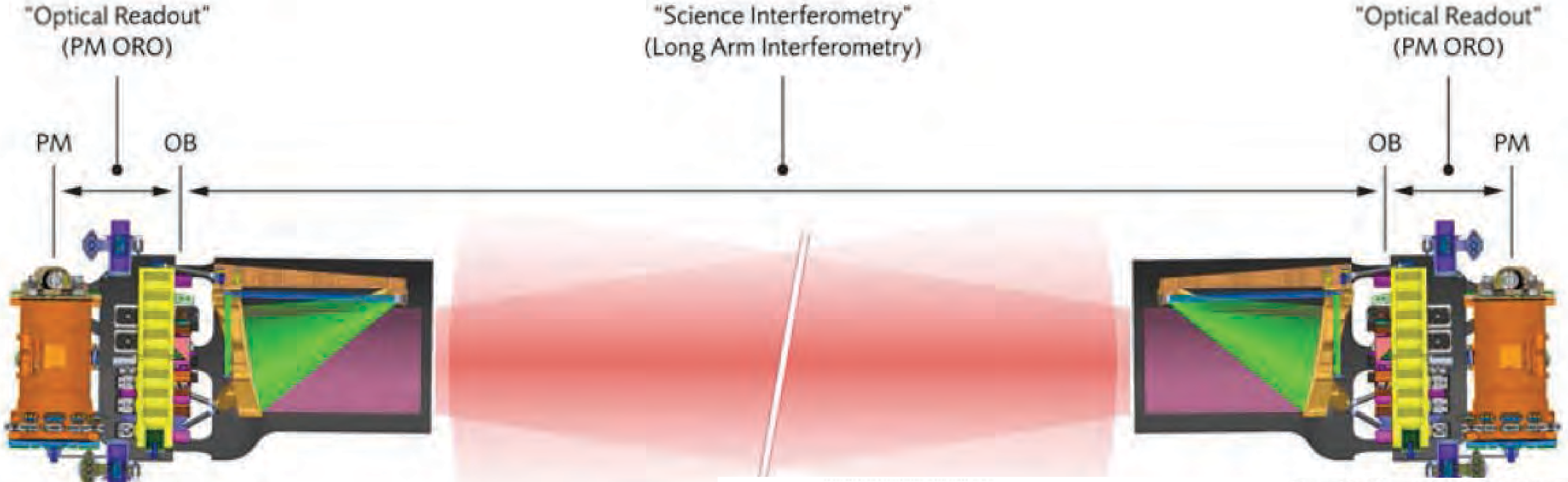
1 mm Horizon scale

3×10^{-18}-3×10^{-10} s after the Big Bang

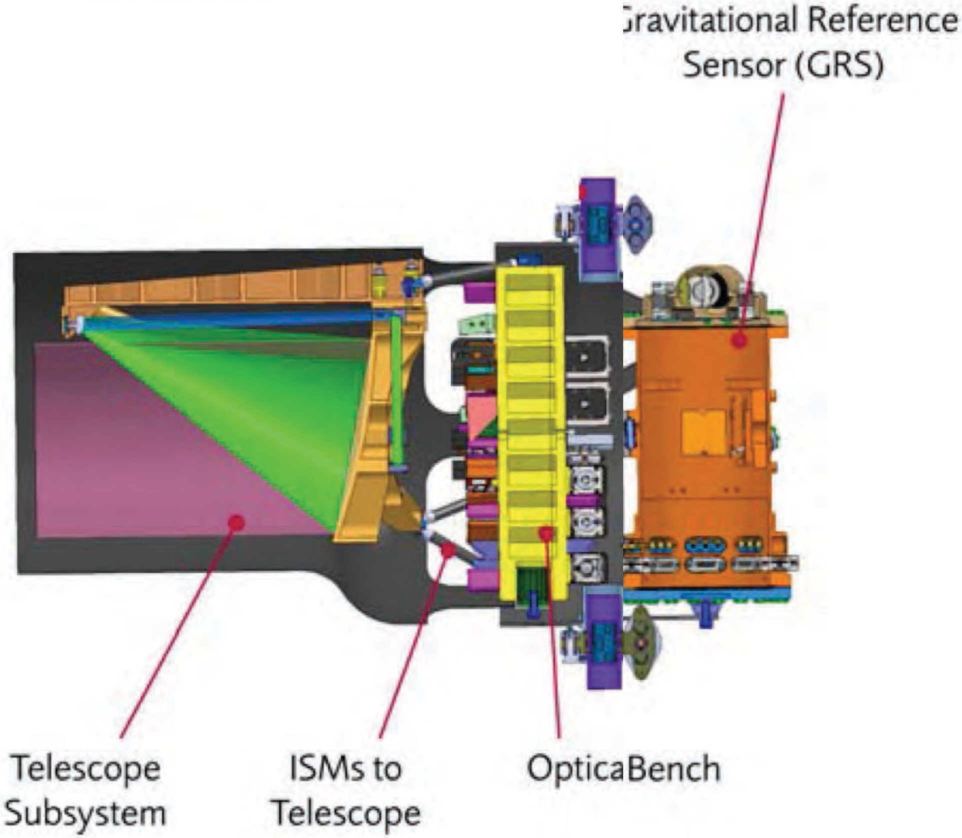
LISA sensitivity
$\Omega_{GW}<10^{-11}\,\Omega$



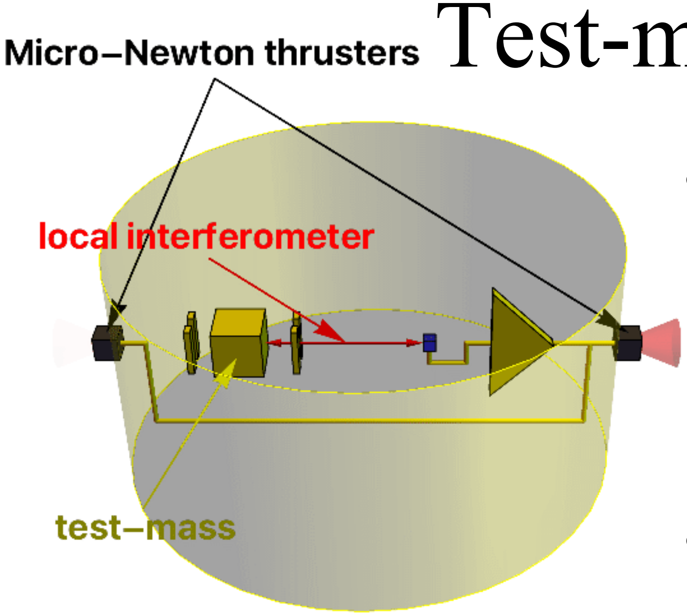
http://arxiv.org/pdf/1512.06239.pdf



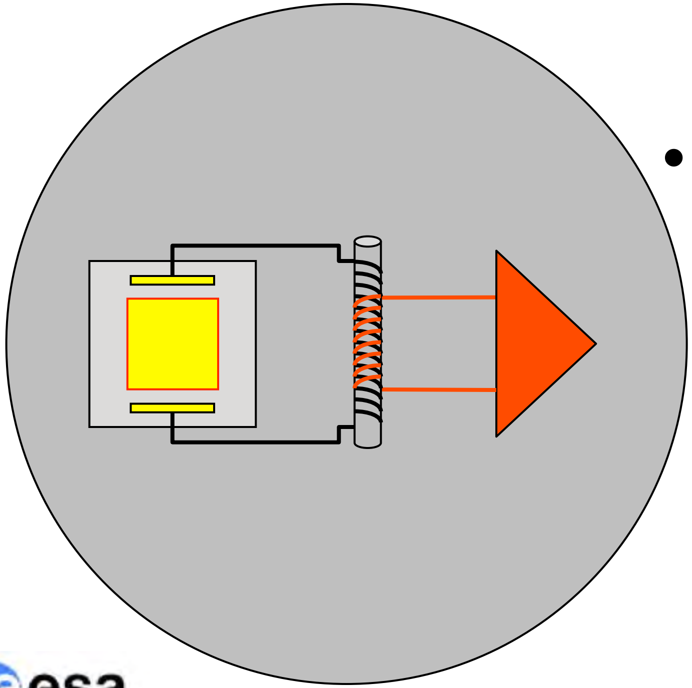
- eLISA instrument key elements:
  - The Gravitational Reference Sensor with the test-mass (also called Inertial Sensor)
  - The Optical Bench with the complete interferometry
  - A telescope to exchange light with the far satellite

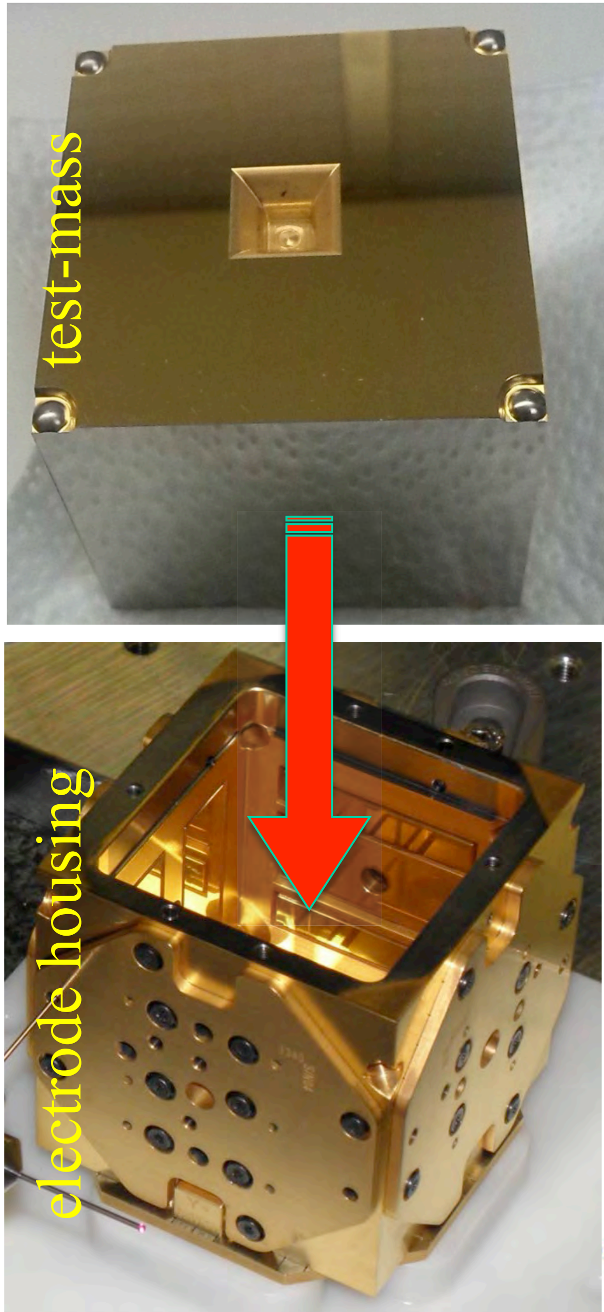


Test-masses and drag-free

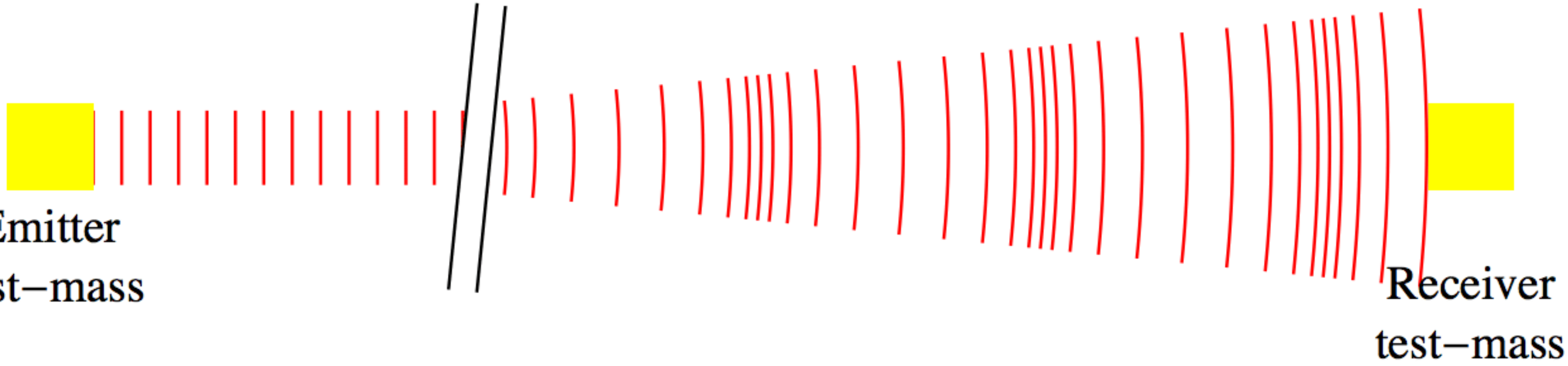


- Spacecraft chases test-mass along sensitive direction (drag-free)
- 3-4 mm clearance between test-mass and electrodes
- Other test-mass degrees of freedom controlled via electrostatic forces





Disturbances in LISA: 1 *Force noise*



- Accelerations of test-masse relative to ***local*** inertial frame: due to *true force noise.*

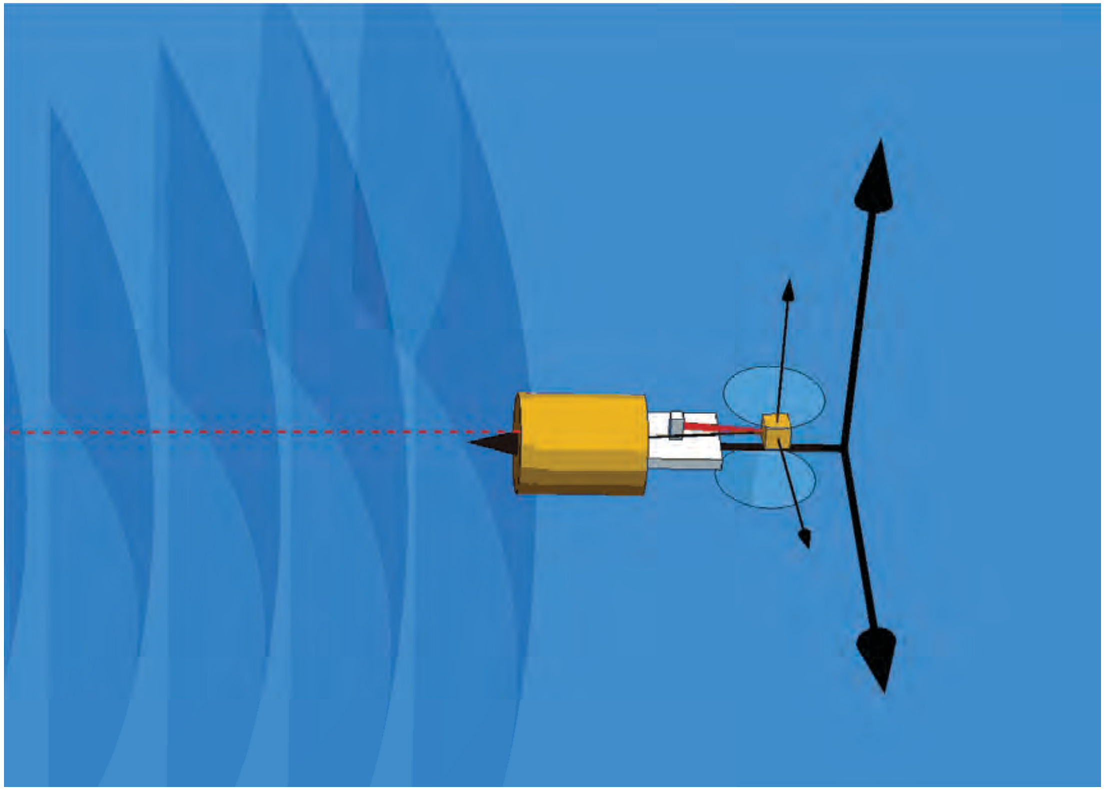
$$\Delta g \equiv (c/\nu_o)(\dot{\nu}_{receiver} - \dot{\nu}_{emitter}) = \underbrace{c\left\{\dot{h}_{receiver}(t) - \dot{h}_{emitter}(t - L/c)\right\}}_{GW} +$$

$$+ \underbrace{\frac{f_{receiver}}{m}(t) - \frac{f_{emitter}}{m}(t - L/c)}_{\text{Acceleration relative to local inertial frame}}$$

Disturbance in LISA: 2 *Reference noise*

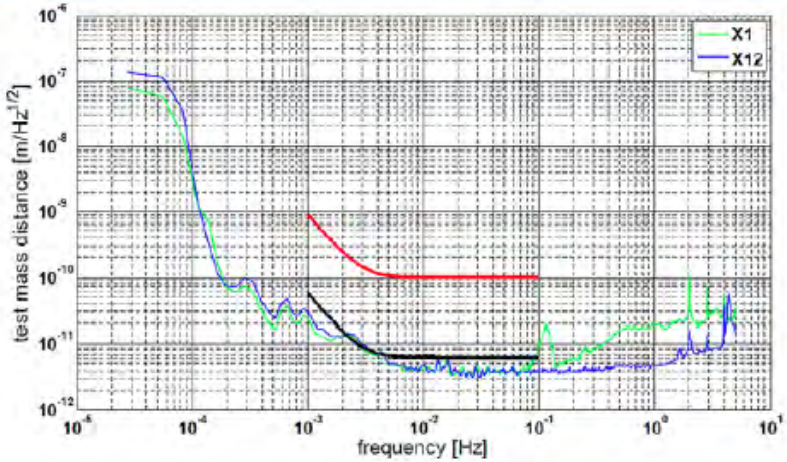
- Goal: acceleration of point particle relative to ***local*** wave front

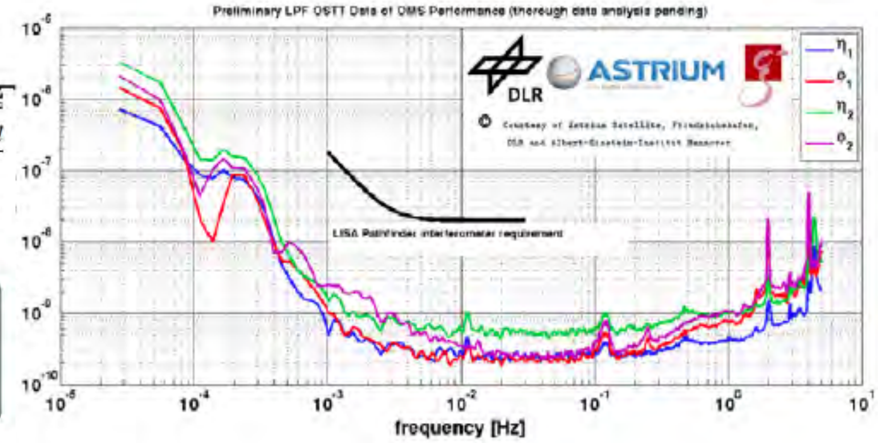
- True signal: relative accelerations of *some points* on various reference frames. Sensitive to *noisy* degrees of freedom of satellite and test-mass



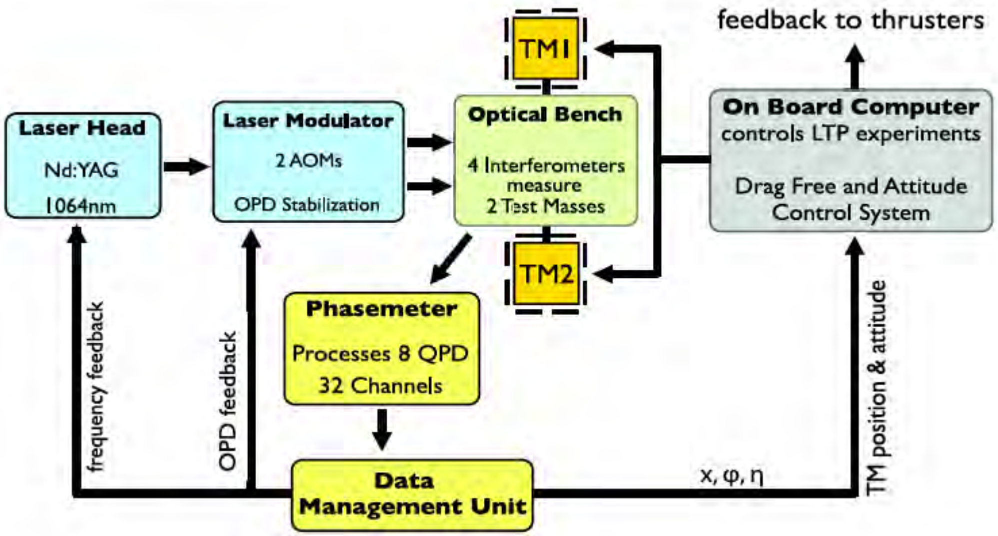
Disturbance in LISA: 3 Readout noise

- ***Local*** contributions: phase-meter electronics, clock, AOM's….

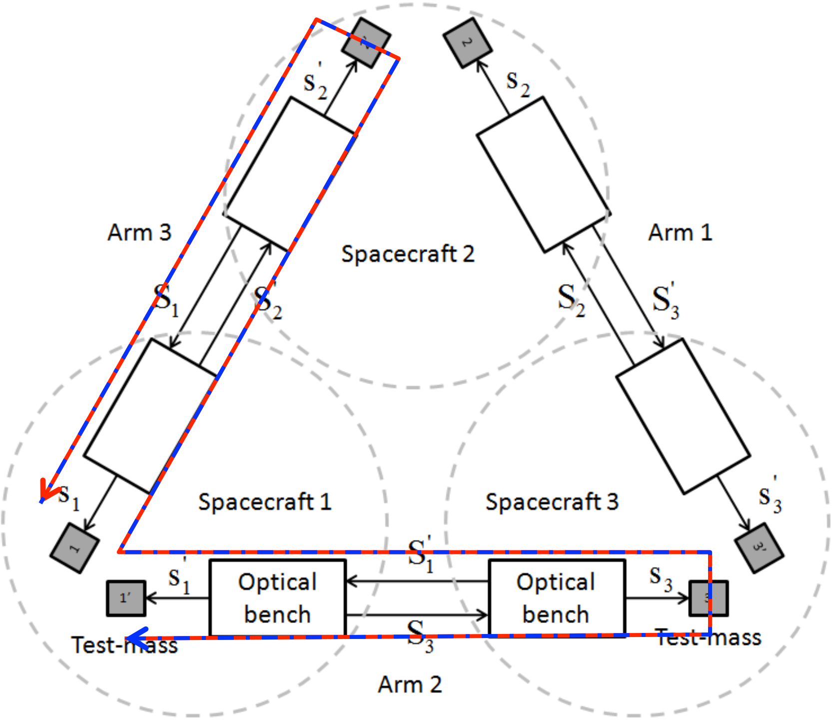




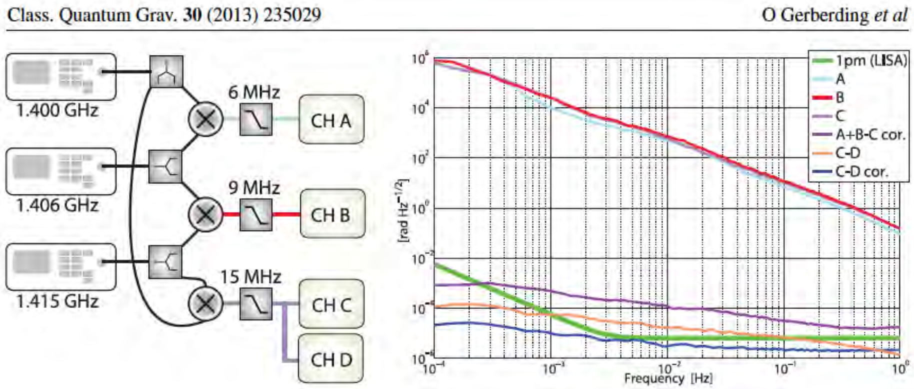
Class. Quantum Grav. 28 (2011) 094003 H Audley *et al*



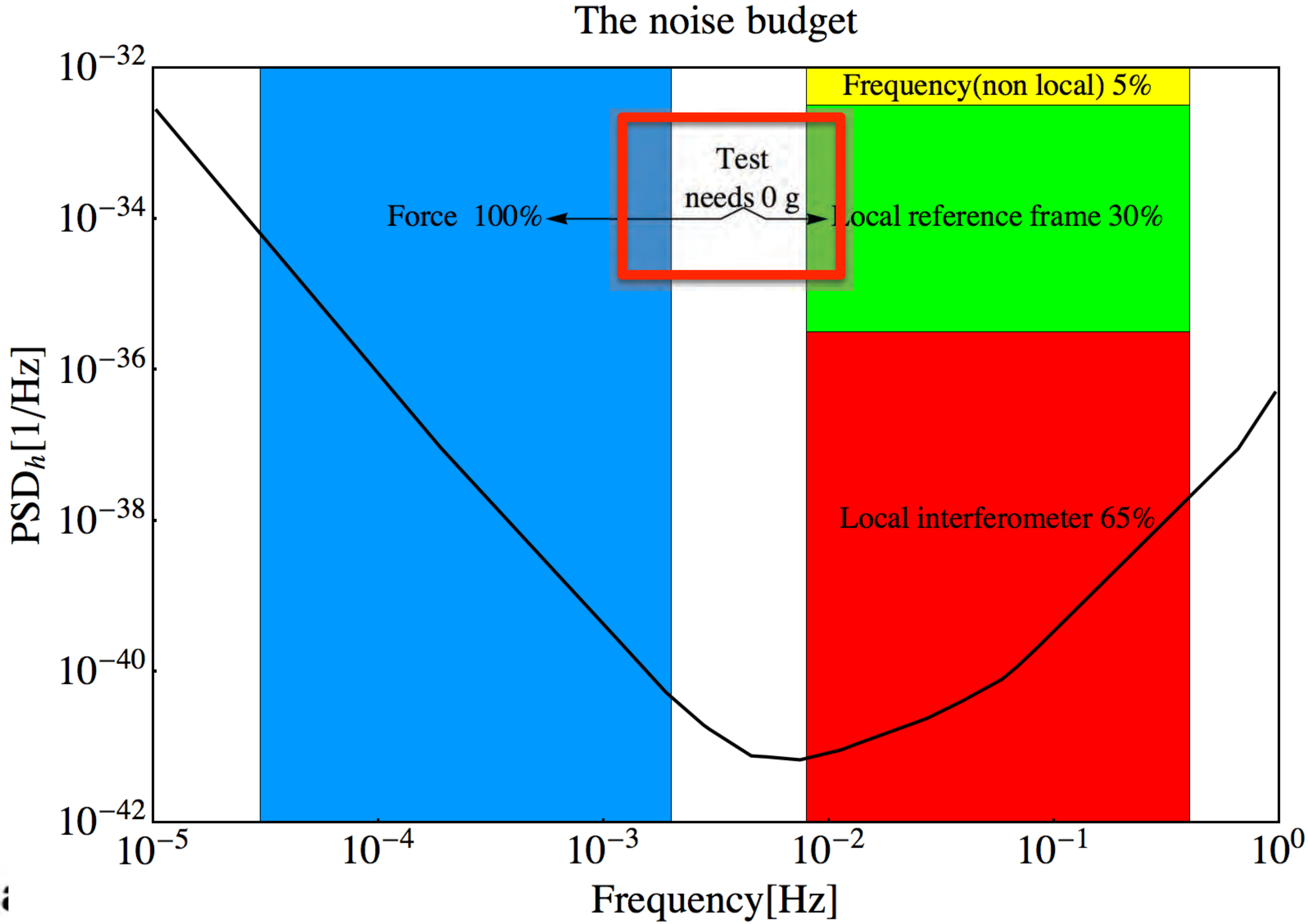
Disturbances in eLISA: 4 Frequency noise



- Laser frequency noise suppressed by comparing light beam that have traveled along both (unequal) arms
- Done in data post-processing
- Requires high accuracy phase-meter
- At least two fully demonstrated in the lab
- *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 are local and can be tested within one satellite!



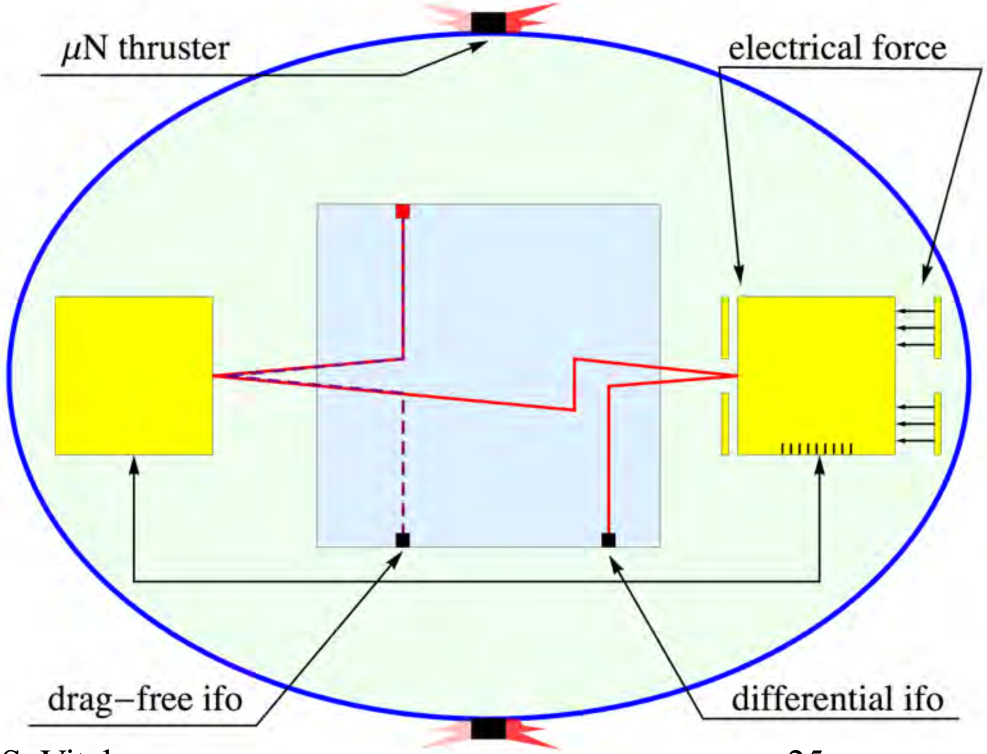
LISA Pathfinder

1. A test of the entire local measurement (95 % of noise) with a requirement at 3 fg/√Hz @ 1 mHz
2. A verification step in the development of LISA using same hardware/processes to carry them at TRL 8-9.
3. A final in-orbit consolidation test for our physical model of free fall. Integrates the results of extensive ground testing

Notice : Requirements in 1. are relaxed relative to LISA, but relaxation only applies to allow for less demanding test conditions, not to H/W design.

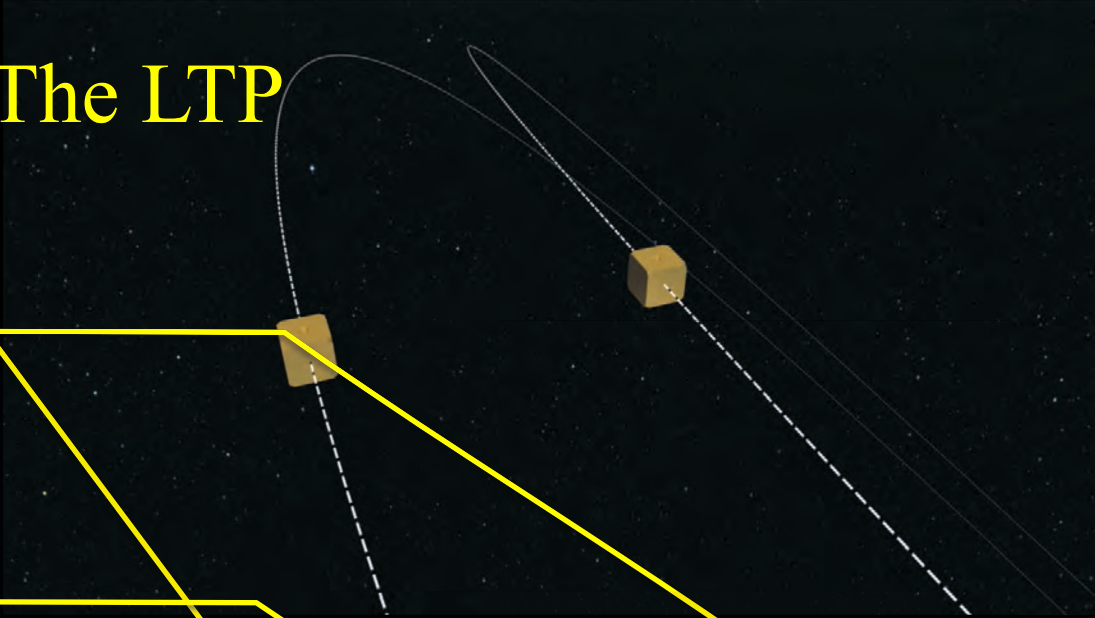
LISA Pathfinder concept

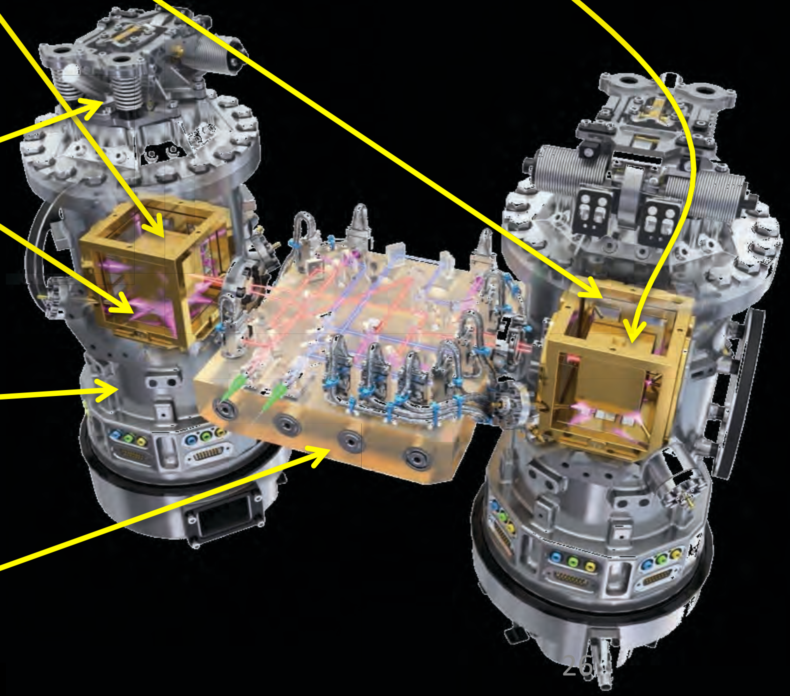
- Test of 95% of noise does not need Million km separation
- Requires free-falling test-masses inside a single spacecraft
- LPF 2 TMs, 2 Ifos, Satellite chases one test-mass
- Second test-mass forced to follow the first at very low frequency by electrostatics (different from LISA)



The LTP

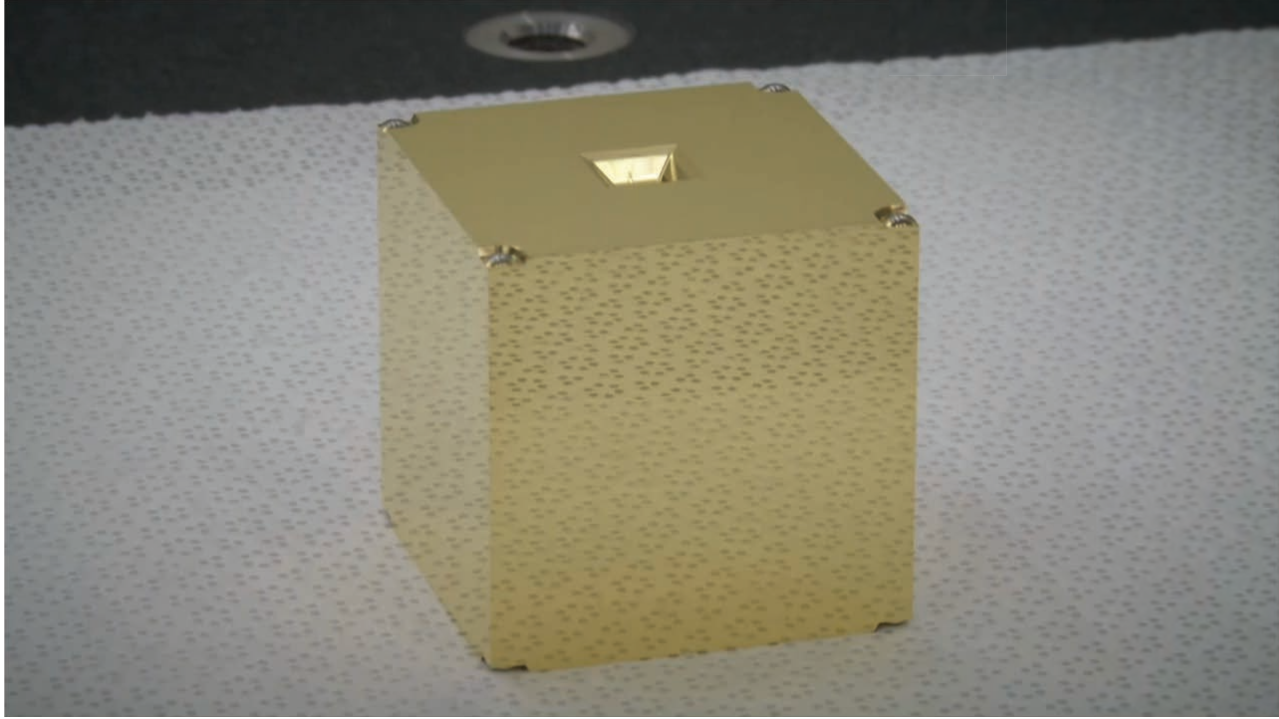
- Test masses gold-platinum, highly non-magnetic, very dense
- Electrode housing: electrodes are used to exert very weak electrostatic force
- UV light, neutralize the charging due to cosmic rays
- Caging mechanism: holds the test-masses and avoid them damaging the satellite at launch
- Vacuum enclosure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

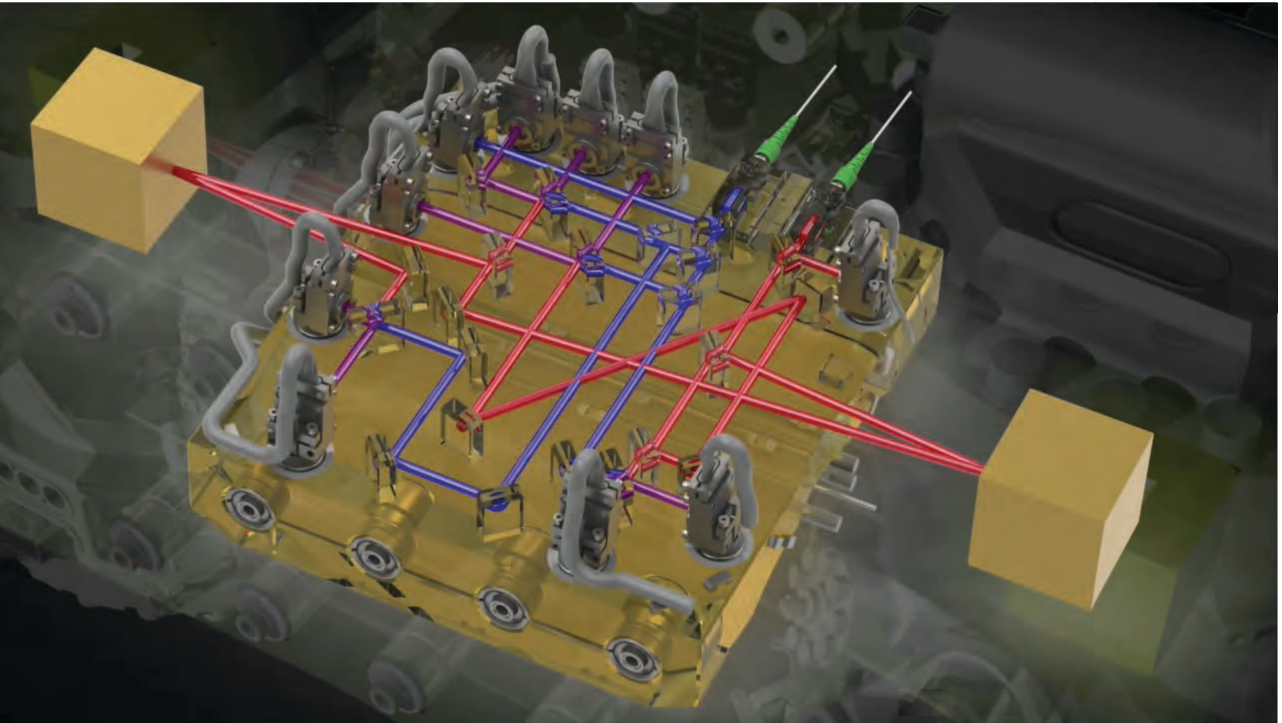




Test-mass and accessories: the gravity reference sensor

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

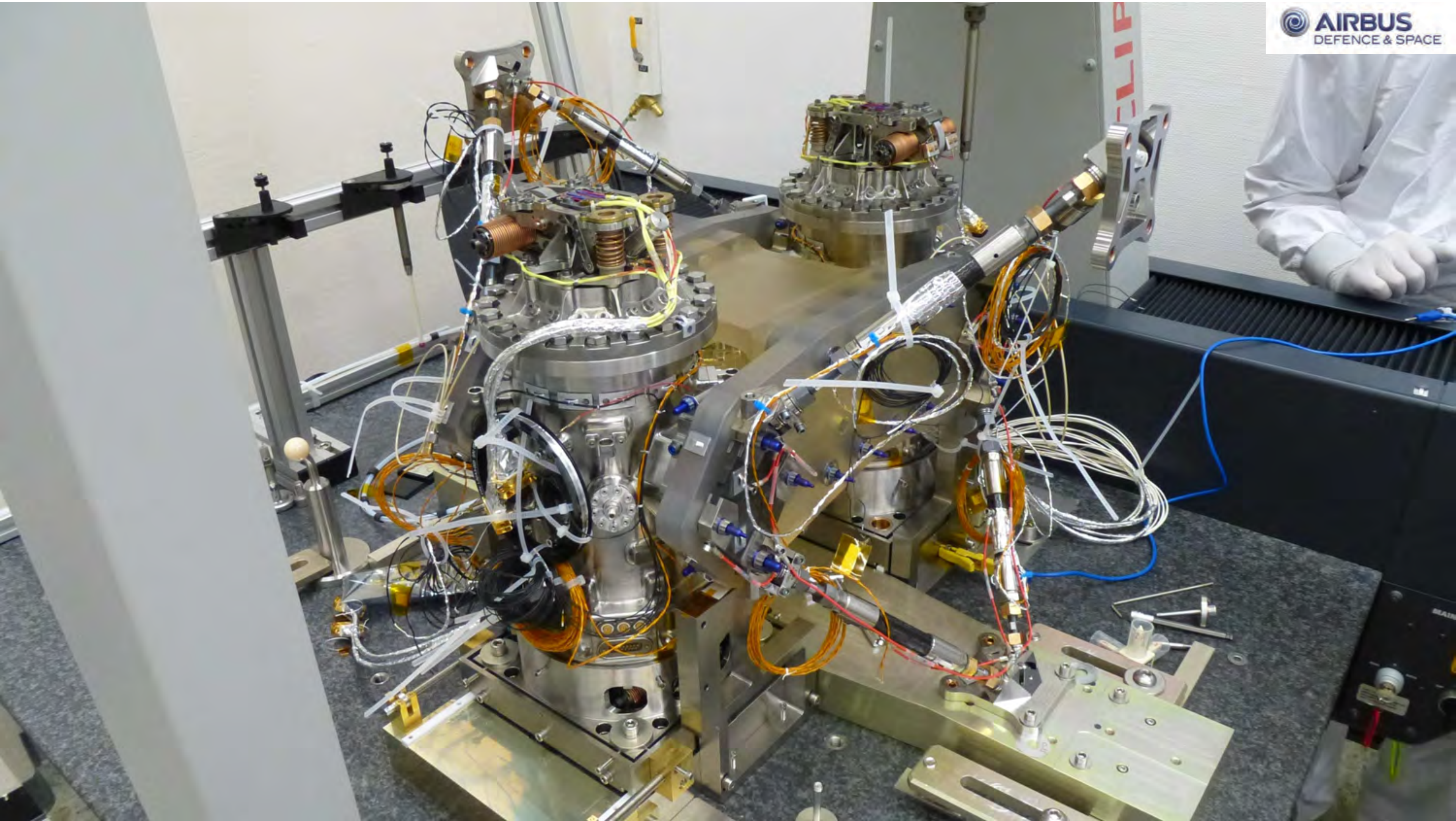




Laser interferometer

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

LTP Core assembly



Integration with satellite


S
W
IABG
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SOUTH
IABG
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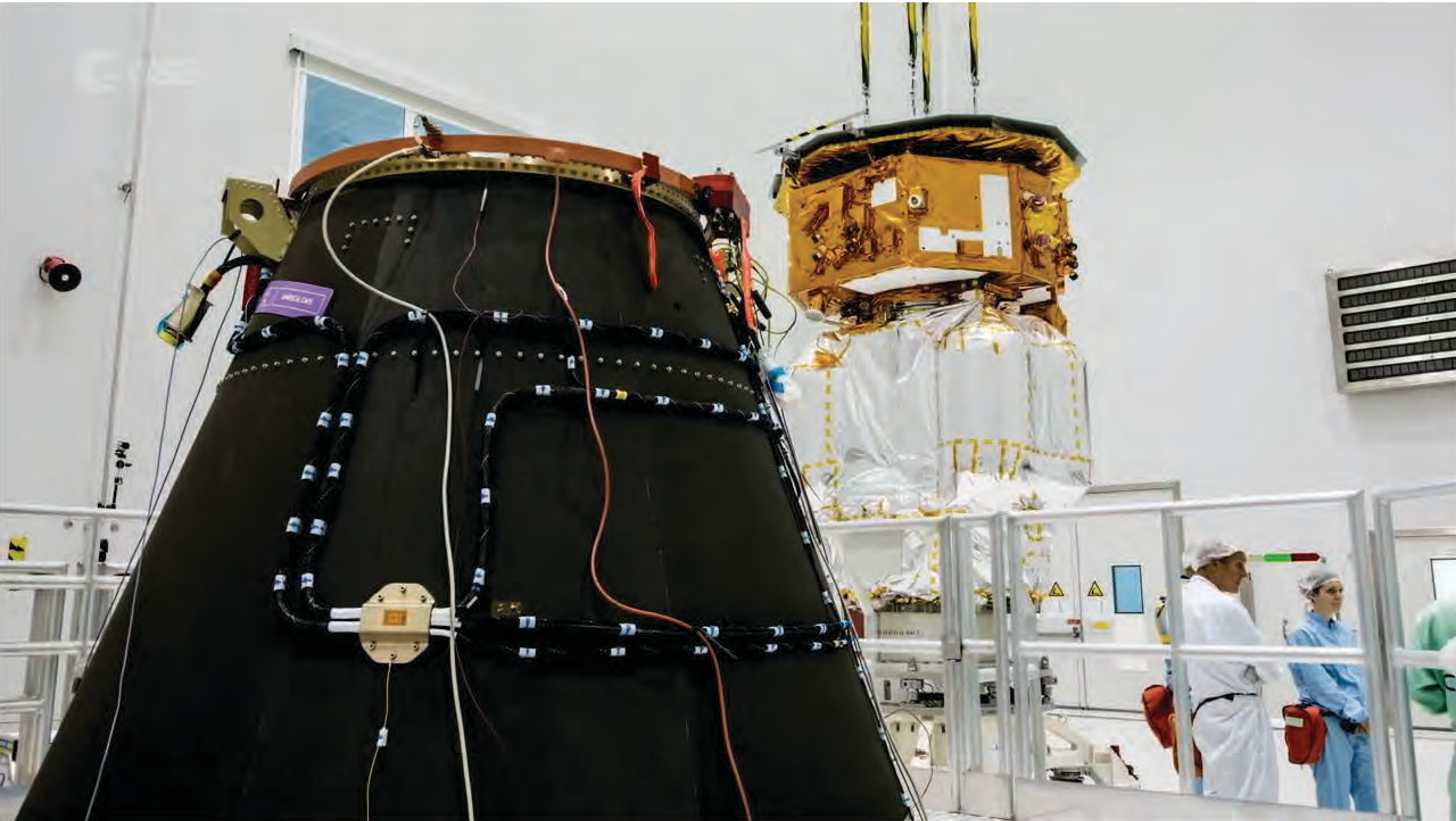
WEST
esa
LISA PATHFINDER
Gravitational wave detection technology for LISA

Satellite and launcher



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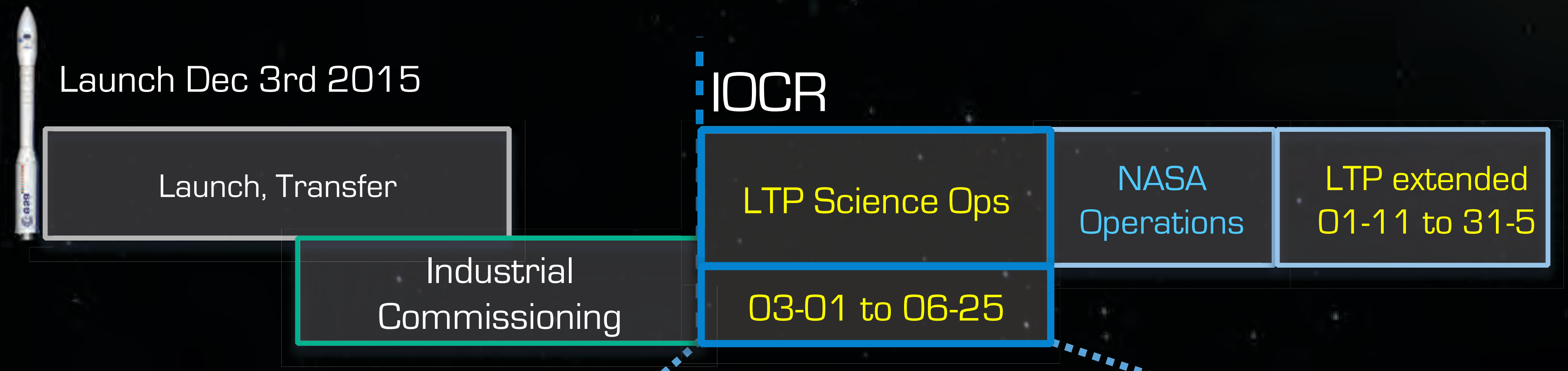
The launch


arianespace
esa
00:29
esa
lisa pathfinder
arianespace
service & solutions

Sequence of events



Launch Dec 3rd 2015

Launch, Transfer

Industrial Commissioning

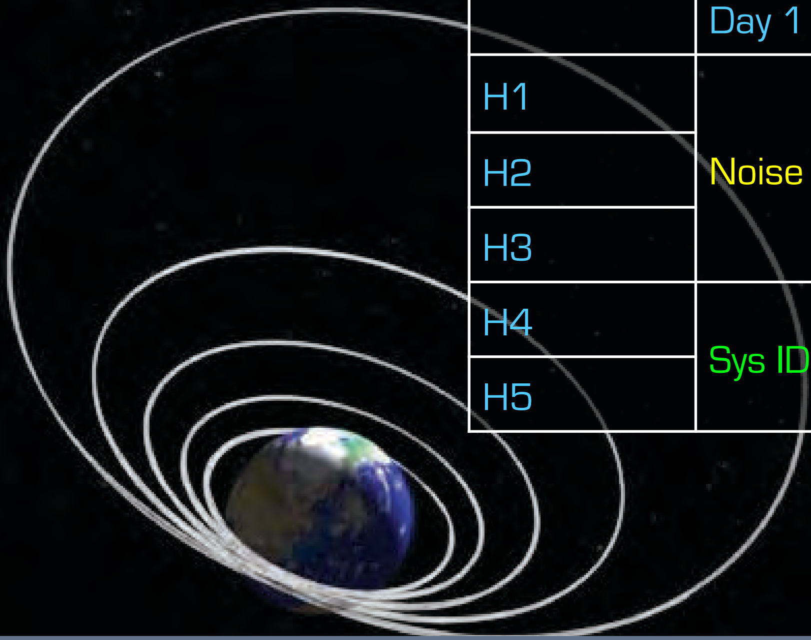
IOCR

LTP Science Ops

03-01 to 06-25

NASA Operations

LTP extended 01-11 to 31-5

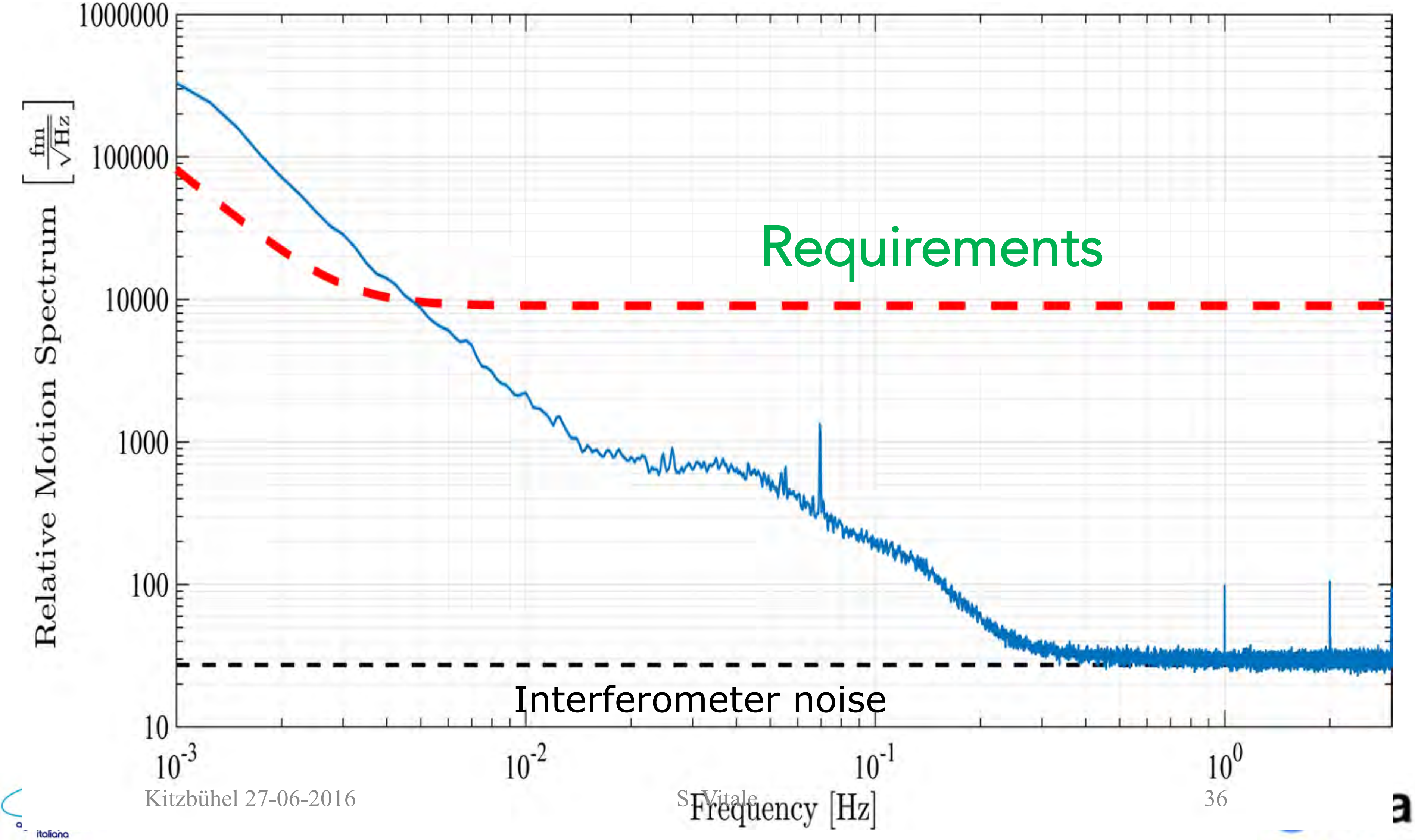


	Day 1	Day 2	Day 3	Day 4
H1	Noise Run	Discharge	Noise Run	Discharge
H2		Working Point		Stray Potentials
H3				
H4	Sys ID			
H5				

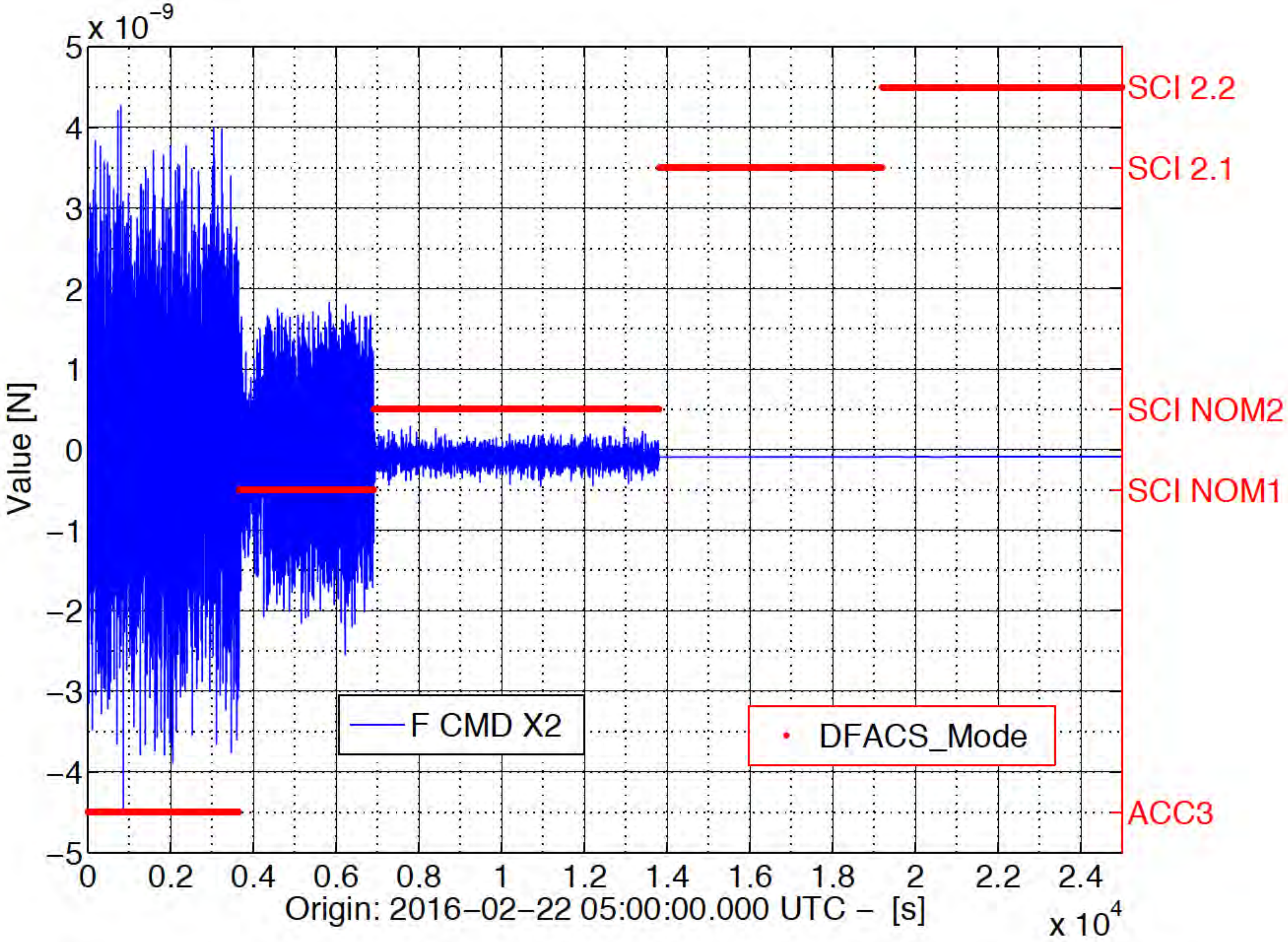
Commissioning timeline

Date	Milestone
11 January	Switch-on of LISA Technology Package
2 February	Release of test mass launch locks and opening of venting valve
15 & 16 February	Test Mass r
18 February	Alignment o
22 February	First entry t
1 March	Start of Scie

Interferometer performance



Transition to drag-free: force commanded on test-mass 2

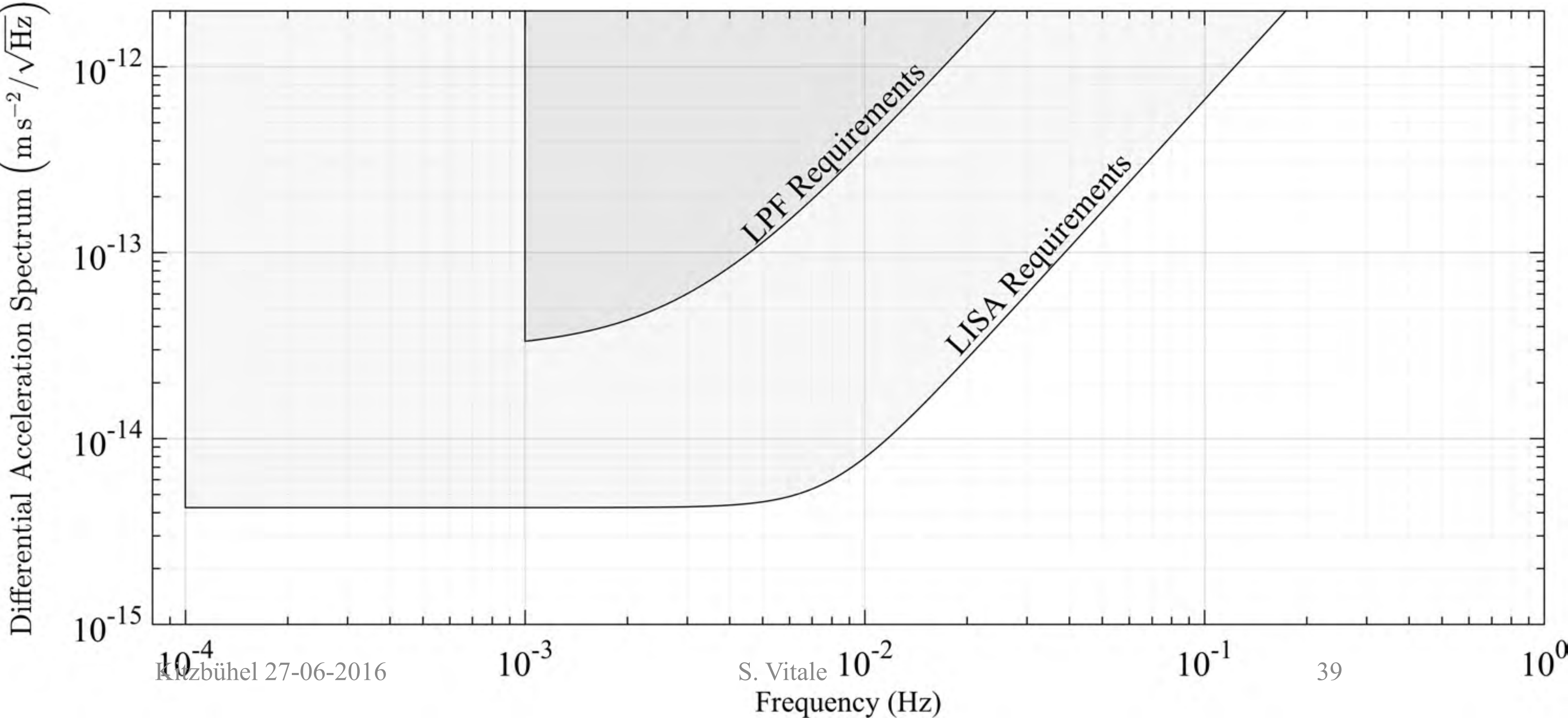


A remote laboratory

08:00	–	08:01	DC compensation voltages via CMS. Set to 0 for simulation.	con_cms_dccoef0_:V001	[1']
08:01	–	09:00	<59 minutes>		
09:00	–	12:00	Stray Potentials (POTVAVZ) TM1 [-20mV 0 +20mV]	inv04113_003	[180']
12:00	–	15:00	Stray Potentials (POTVAVY) TM1 [-20mV 0 +20mV]	inv04112_003	[180']
15:00	–	18:00	Stray Potentials (POTVAVX) TM1 [-20mV 0 +20mV]	inv04111_003	[180']
18:00	–	21:00	Stray Potentials (POTVAVZ) TM2 [-20mV 0 +20mV]	inv04123_003	[180']
21:00	–	00:00	Stray Potentials (POTVAVX) TM2 [-20mV 0 +20mV]	inv04121_003	[180']
00:00	–	03:00	Stray Potentials (POTVAVY) TM2 [-20mV 0 +20mV]	inv04122_003	[180']
03:00	–	04:00	Charge Estimate TM1	inv04011_001	[60']
04:00	–	05:00	Charge Estimate TM2	inv04021_001	[60']
05:00	–	07:00	Acceleration Noise Measurement	inv00002	[120']
07:00	–	07:01	Set max force TM2 x to 600pN, phi1 = 3pNm, phi2 = 3pNm	con_fee_maxf____:V15	[1']
07:01	–	08:00	<59 minutes>		

LISA and LISA Pathfinder disturbance acceleration requirements

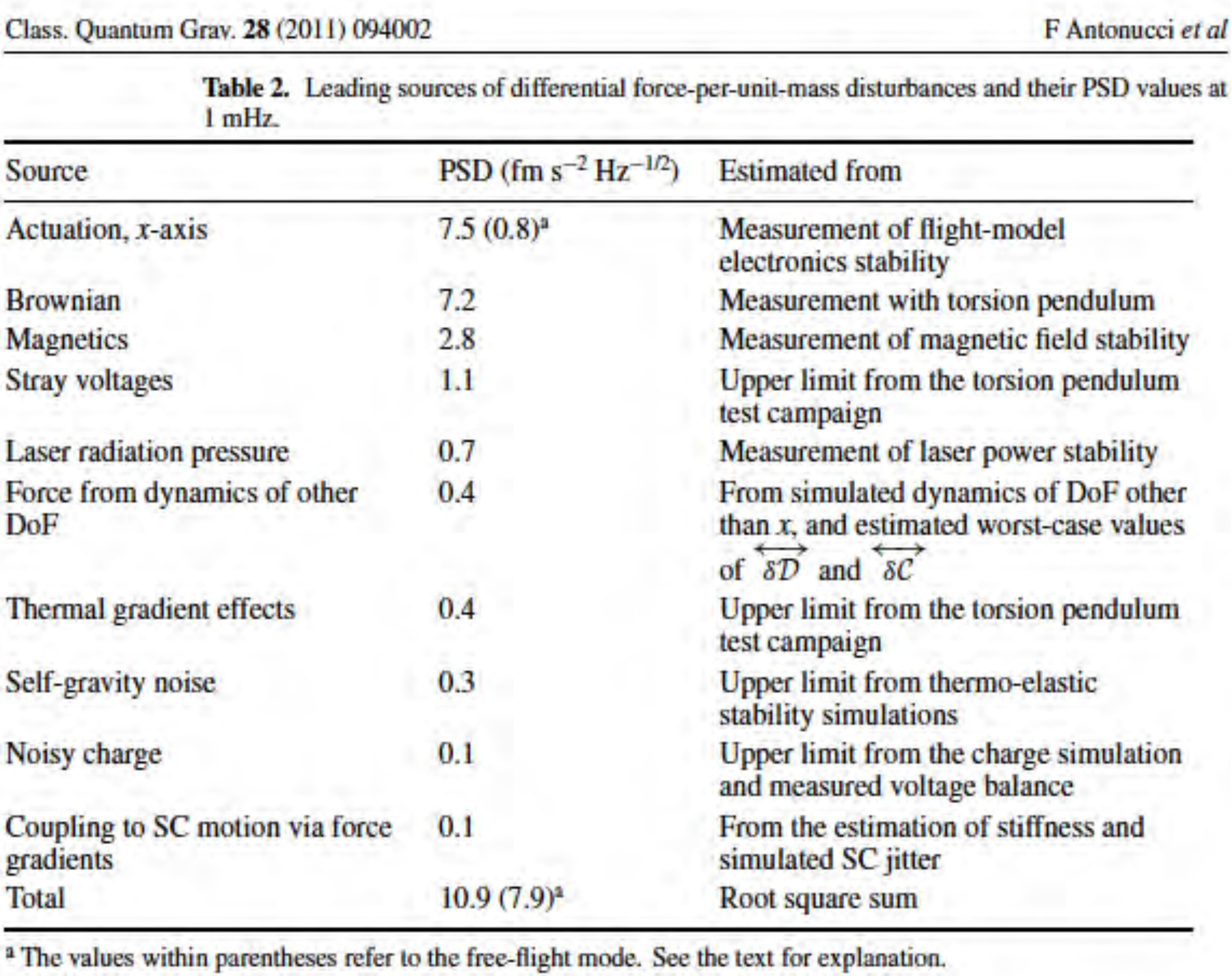
- LPF amplitude requirement relaxed because single spacecraft experiment more noisy
- Frequency requirement relaxed to cut down ground testing time



Limitation of a single satellite test

LISA	**LISA Pathfinder**
• Each test-mass in one link is drag-free	• Spacecraft cannot follow both test-masses at once. One test mass is controlled (noisy)
• Inertial forces are negligible	• Spacecraft reference frame is significantly non-inertial → centrifugal force
• Force gradients couple each test-mass to its own spacecraft	• Force gradients couple both test-masses to same spacecraft

Best Estimate Before Launch



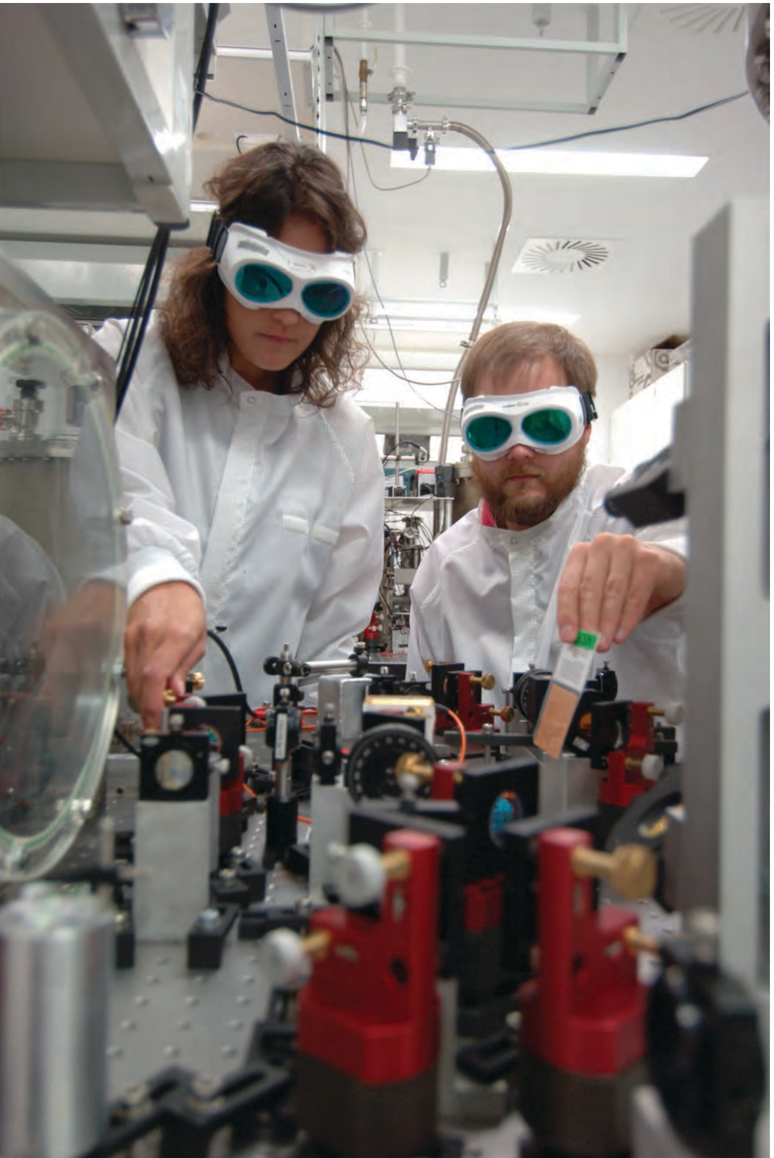
Class. Quantum Grav. **28** (2011) 094002 F Antonucci *et al*

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

Source	PSD (fm s^{-2} $Hz^{-1/2}$)	Estimated from
Actuation, *x*-axis	7.5 (0.8)[a]	Measurement of flight-model electronics stability
Brownian	7.2	Measurement with torsion pendulum
Magnetics	2.8	Measurement of magnetic field stability
Stray voltages	1.1	Upper limit from the torsion pendulum test campaign
Laser radiation pressure	0.7	Measurement of laser power stability
Force from dynamics of other DoF	0.4	From simulated dynamics of DoF other than *x*, and estimated worst-case values of $\overleftrightarrow{\delta D}$ and $\overleftrightarrow{\delta C}$
Thermal gradient effects	0.4	Upper limit from the torsion pendulum test campaign
Self-gravity noise	0.3	Upper limit from thermo-elastic stability simulations
Noisy charge	0.1	Upper limit from the charge simulation and measured voltage balance
Coupling to SC motion via force gradients	0.1	From the estimation of stiffness and simulated SC jitter
Total	10.9 (7.9)[a]	Root square sum

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

Effects studied over years in the laboratory: Knowledge pushed forward in different fields of physics



1, NUMBER 15 PHYSICAL REVIEW LETTERS w 10 O

Achieving Geodetic Motion for LISA Test Masses: Ground Testing Results

PHYSICAL REVIEW D 76, 102003 (2007)

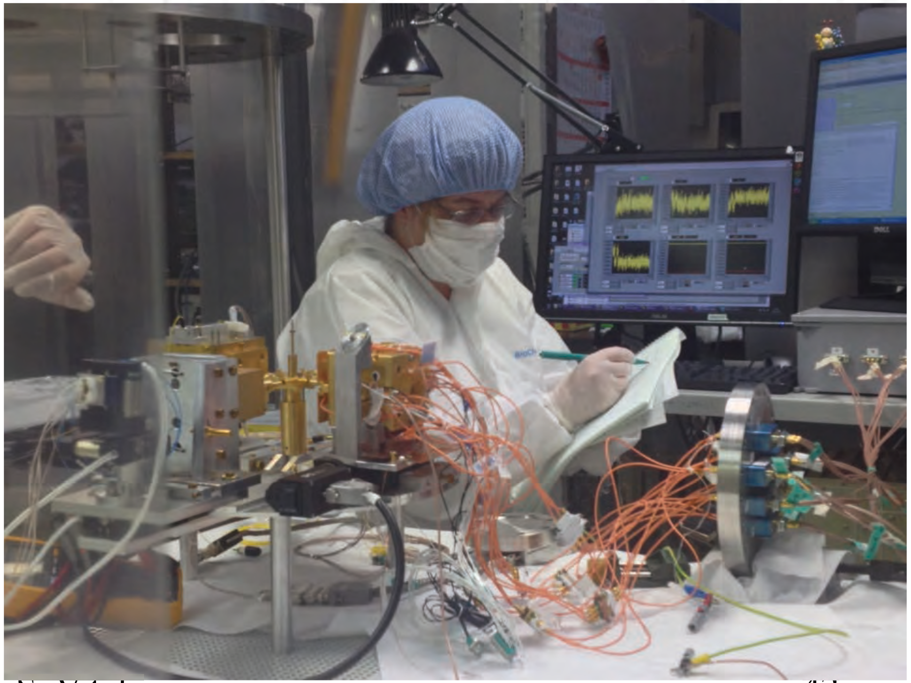
Thermal gradient-induced forces on geodesic reference masses for LISA

03, 140601 (2009) PHYSICAL REVIEW LETTERS week endi 2 OCTOBER

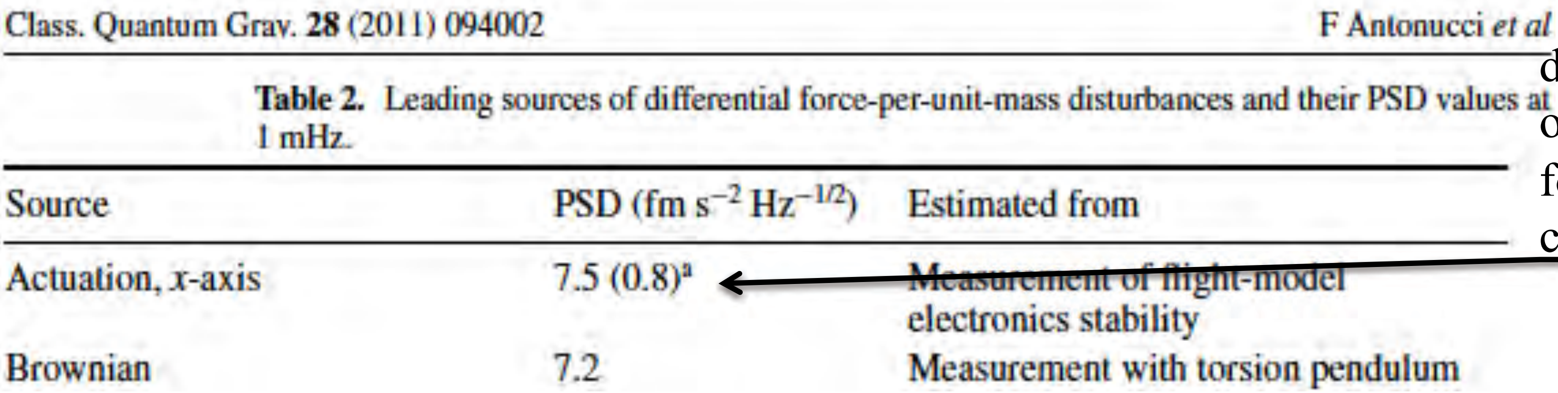
Increased Brownian Force Noise from Molecular Impacts in a Constrained Volume

108, 181101 (2012) PHYSICAL REVIEW LETTERS week 4 MA

Interaction between Stray Electrostatic Fields and a Charged Free-Falling Test Mass



Last Best Estimate



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

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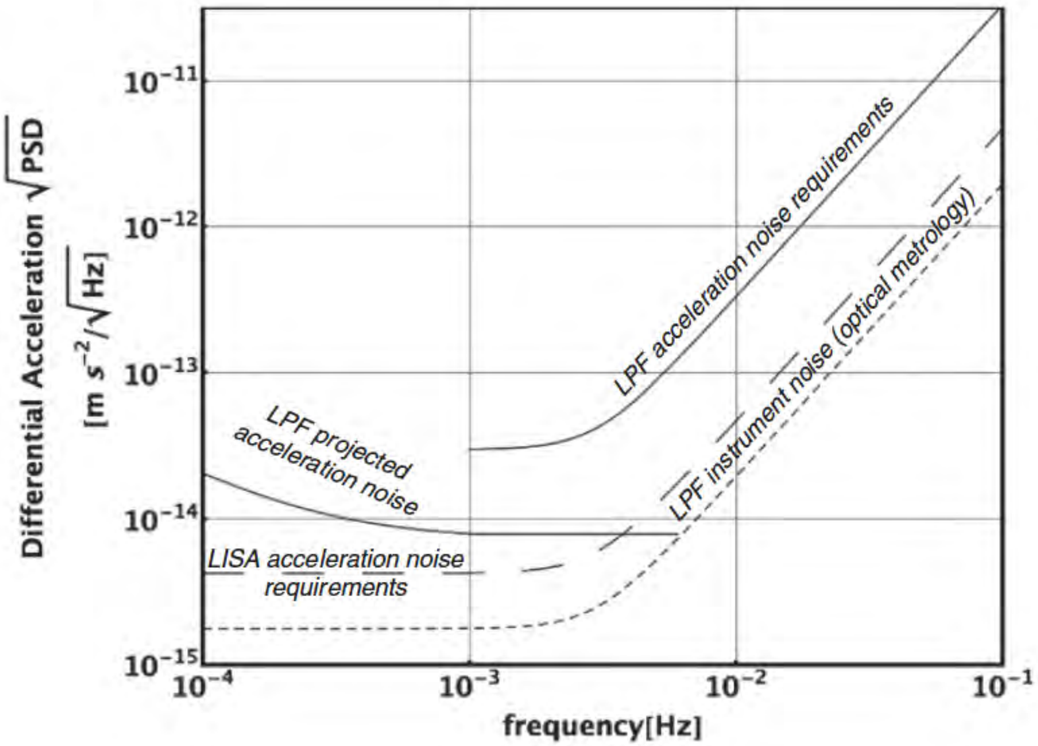
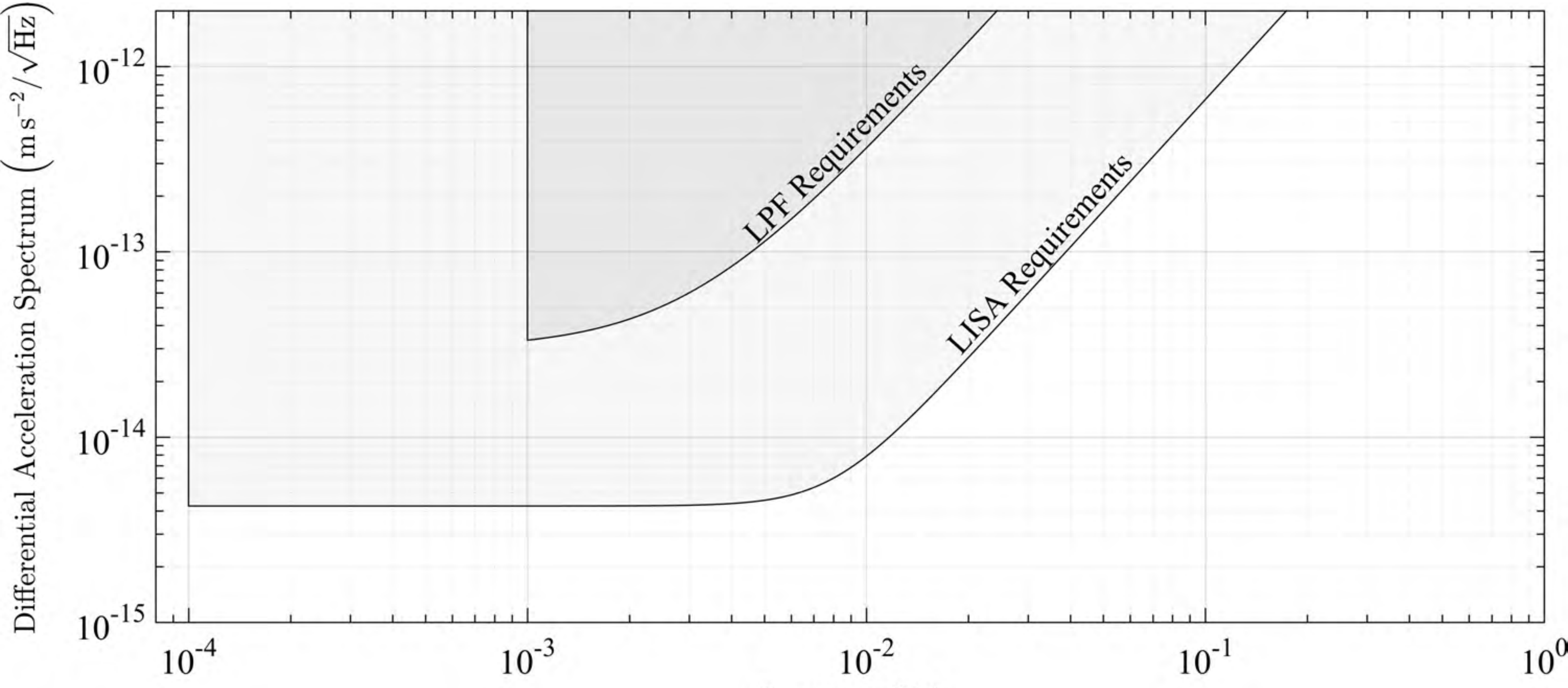
Actuation, *x*-axis	7.5 (0.8)[a]	Measurement of flight-model electronics stability
Brownian	7.2	Measurement with torsion pendulum

depends on value of gravitational force to be compensated

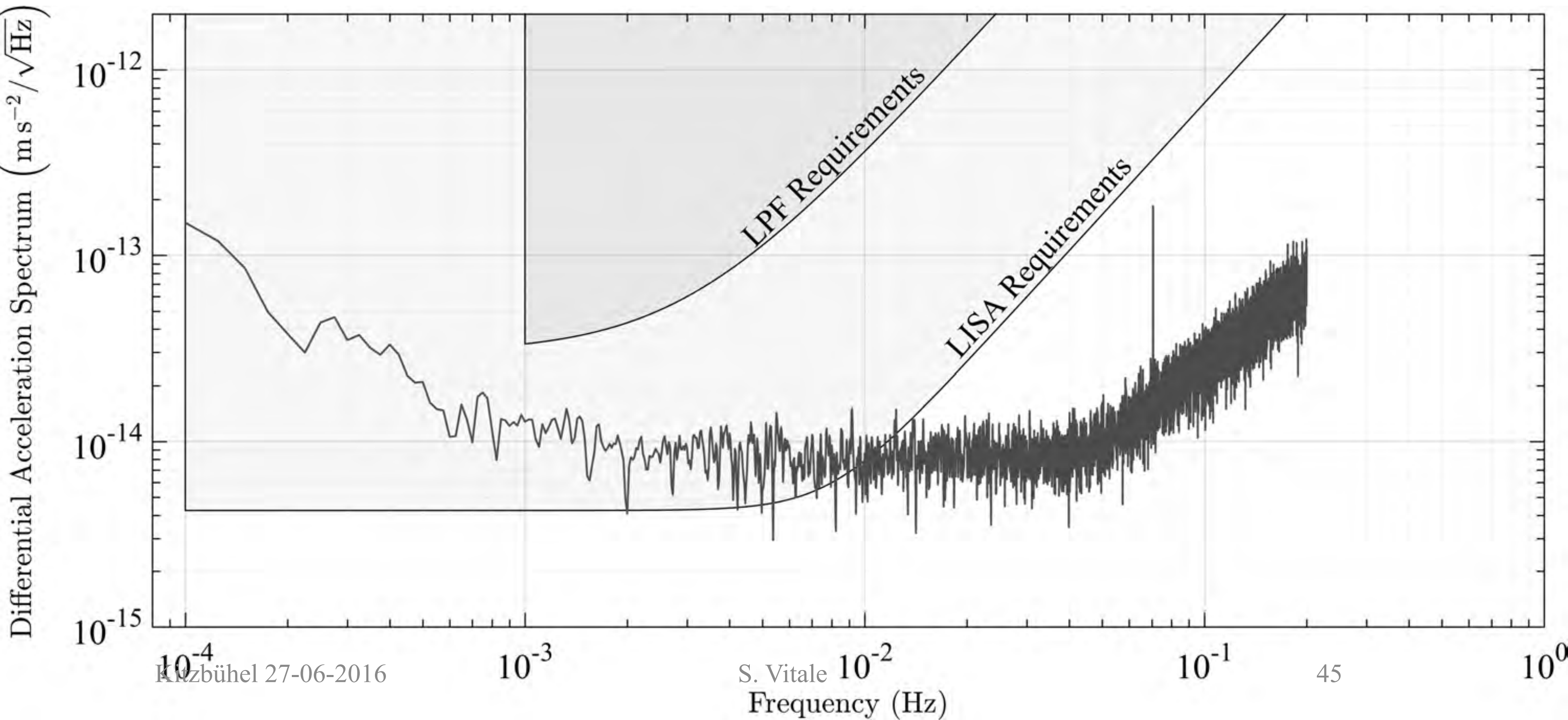
Class. Quantum Grav. **28** (2011) 094002



LISA and LISA Pathfinder disturbance acceleration requirements

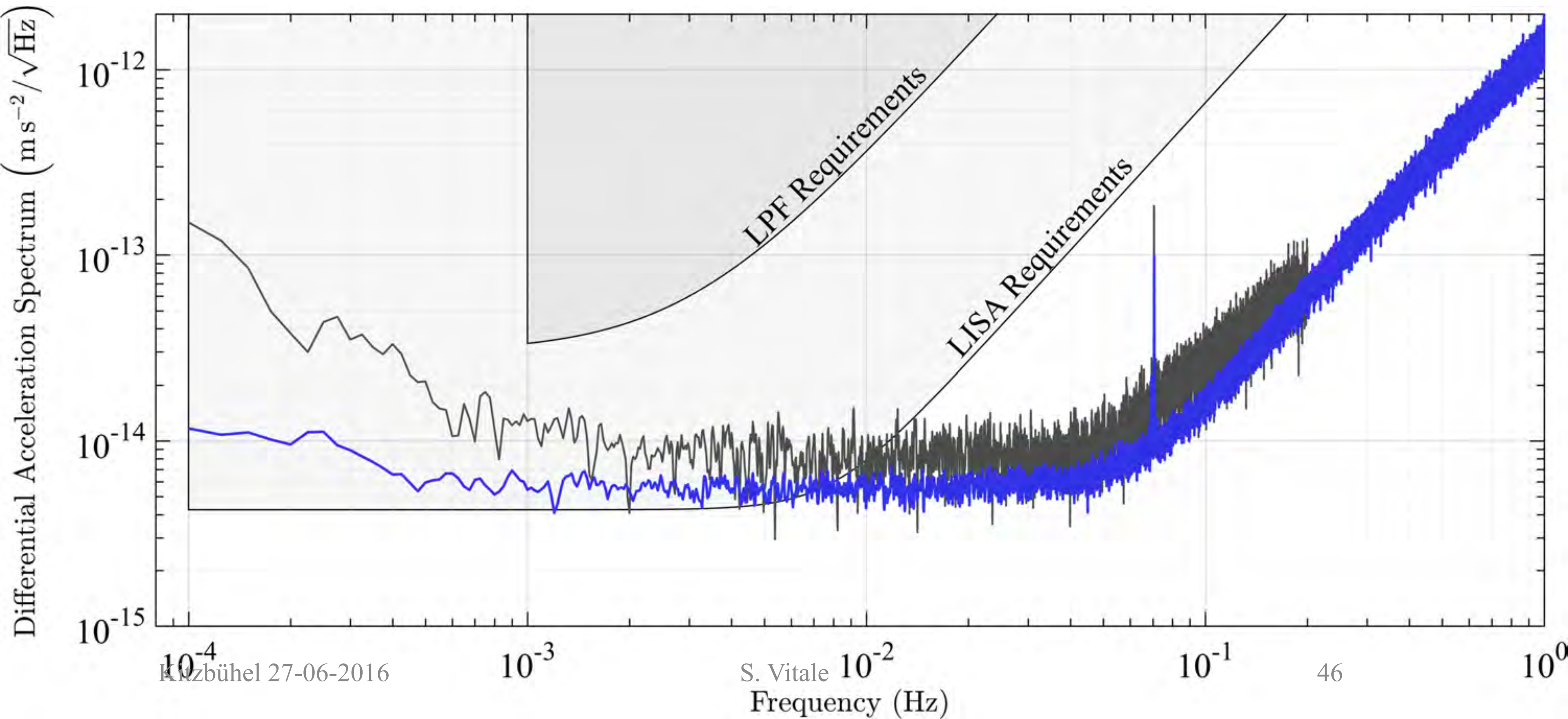


First day of operation. March 1st, 2016

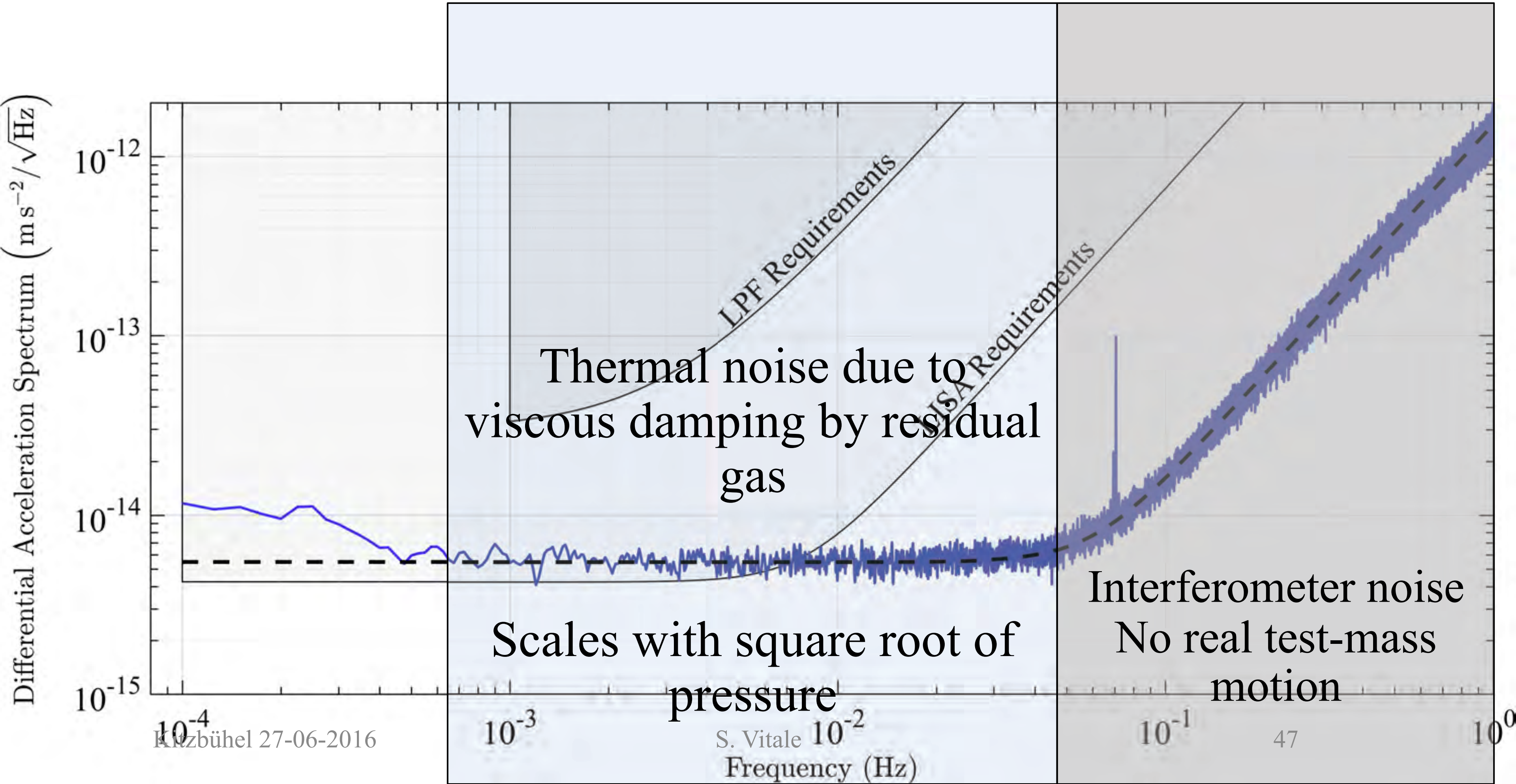


April 8-14, 2016.

- The results in http://link.aps.org/doi/10.1103/PhysRevLett.116.231101
- Decreased because of elapsed time and basic instrument optimization



The limiting disturbances



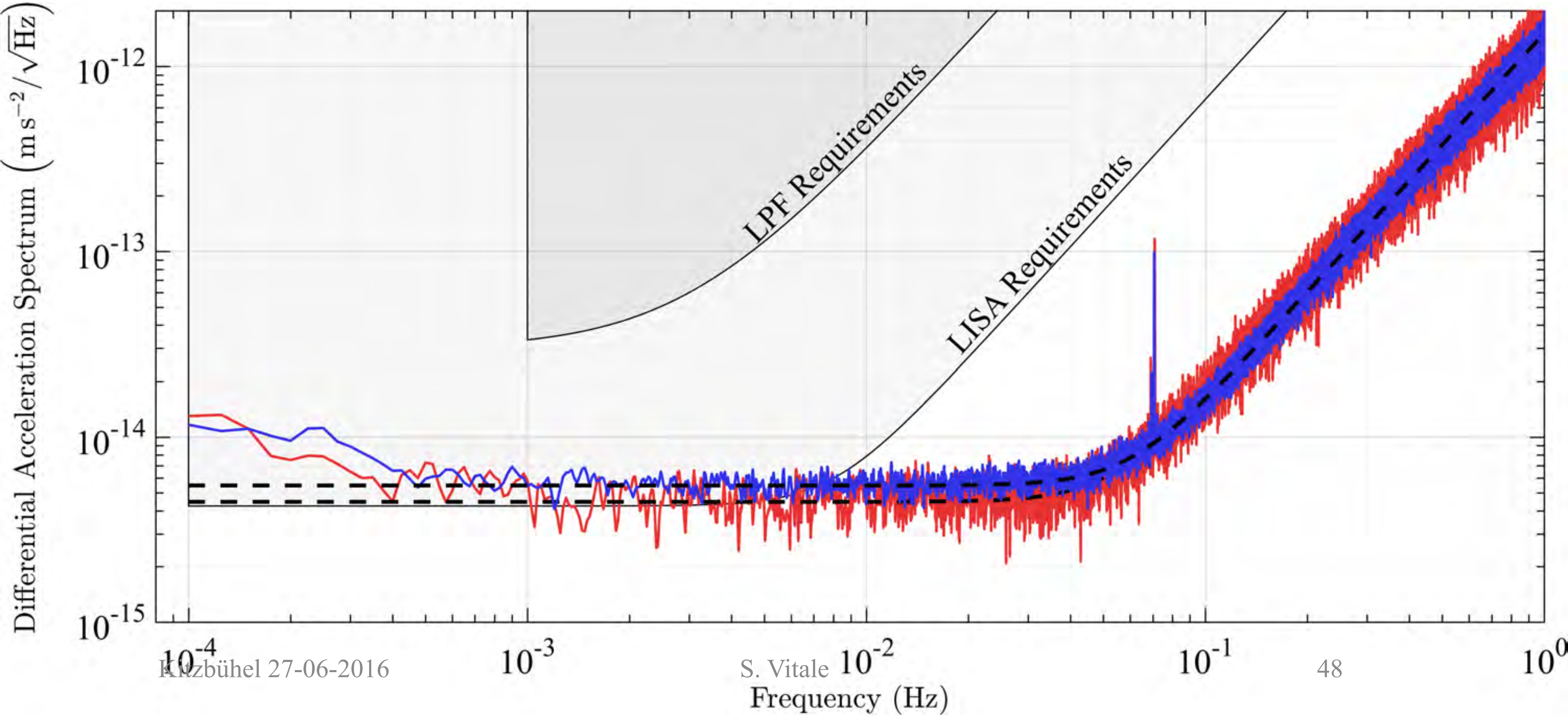
Thermal noise due to viscous damping by residual gas

Scales with square root of pressure

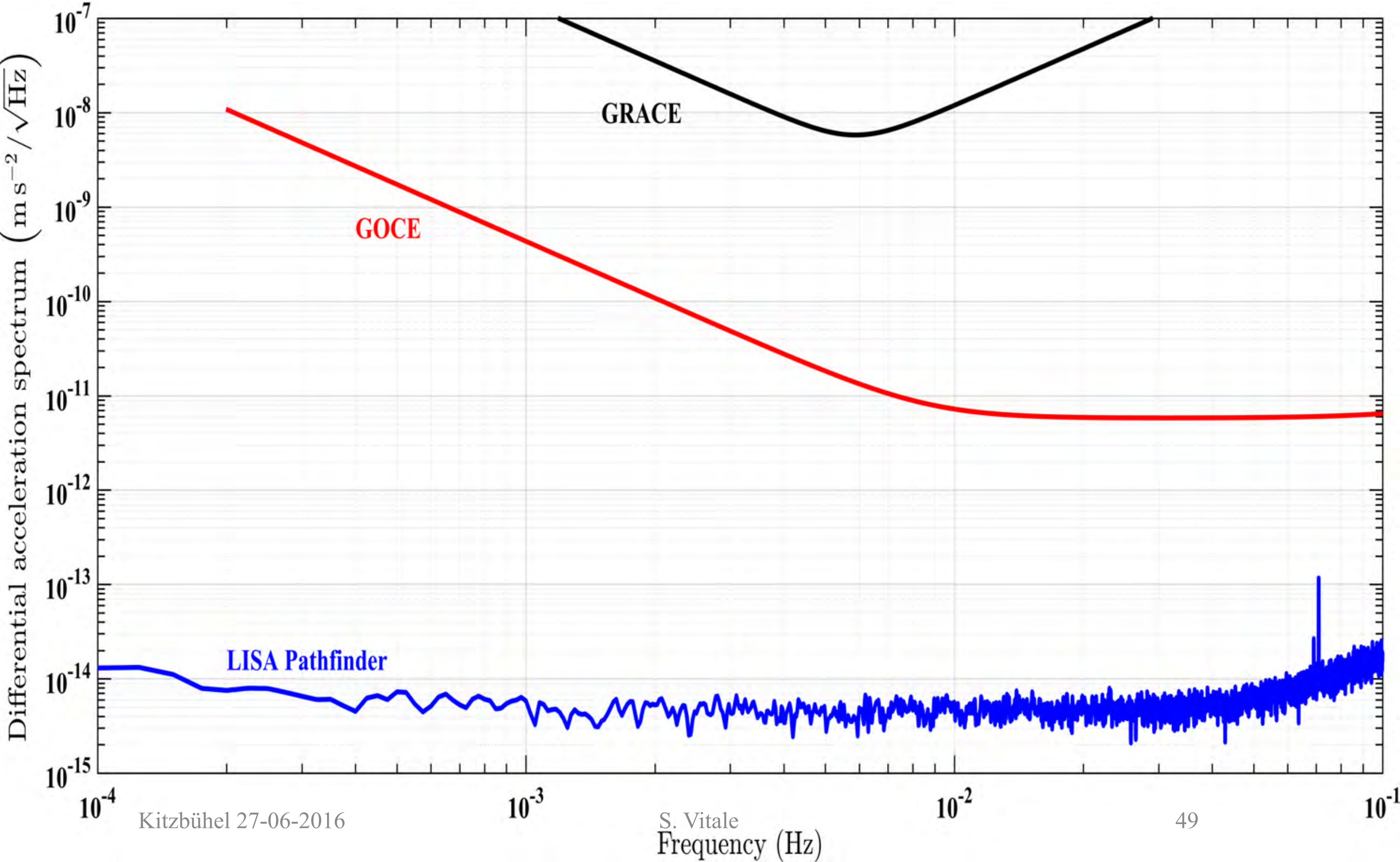
Interferometer noise
No real test-mass motion

May 16-18, 2016.

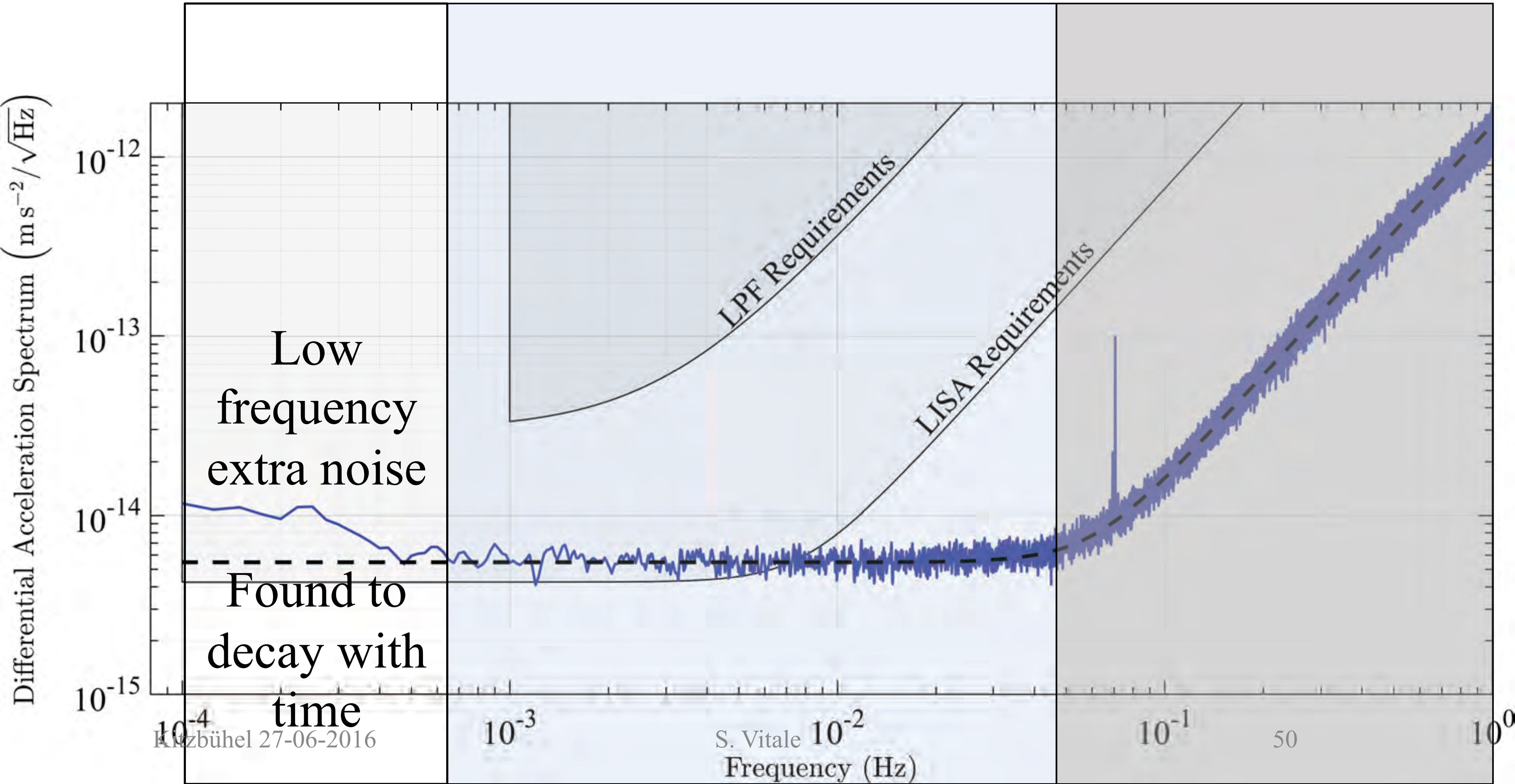
- System continuously vented to outer space
- Pressure gone further down



Sub-femto-g differential accelerometry: orders of magnitude improvement in the field of experimental gravitation



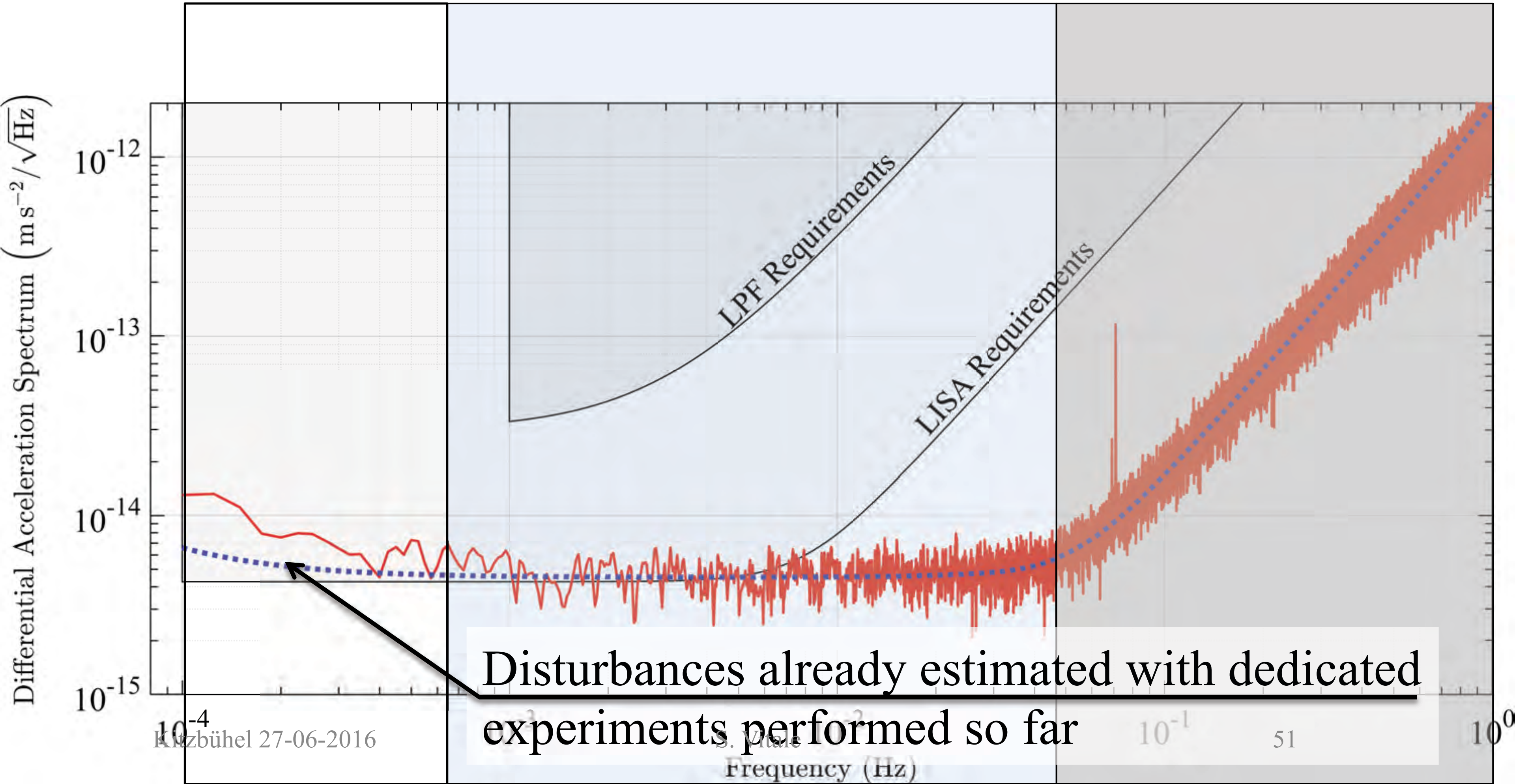
The limiting disturbances



Low frequency extra noise

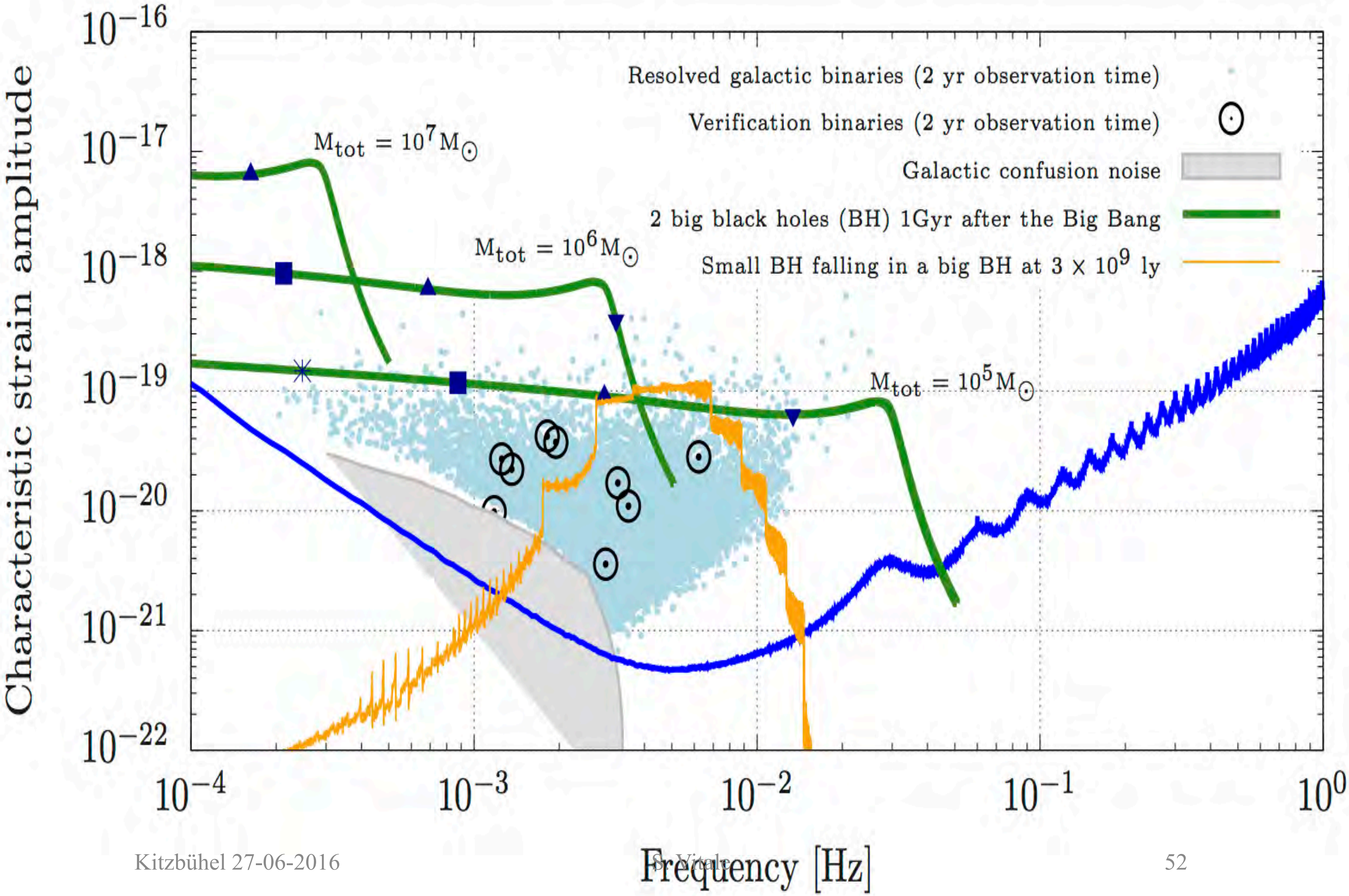
Found to decay with time

The limiting disturbances

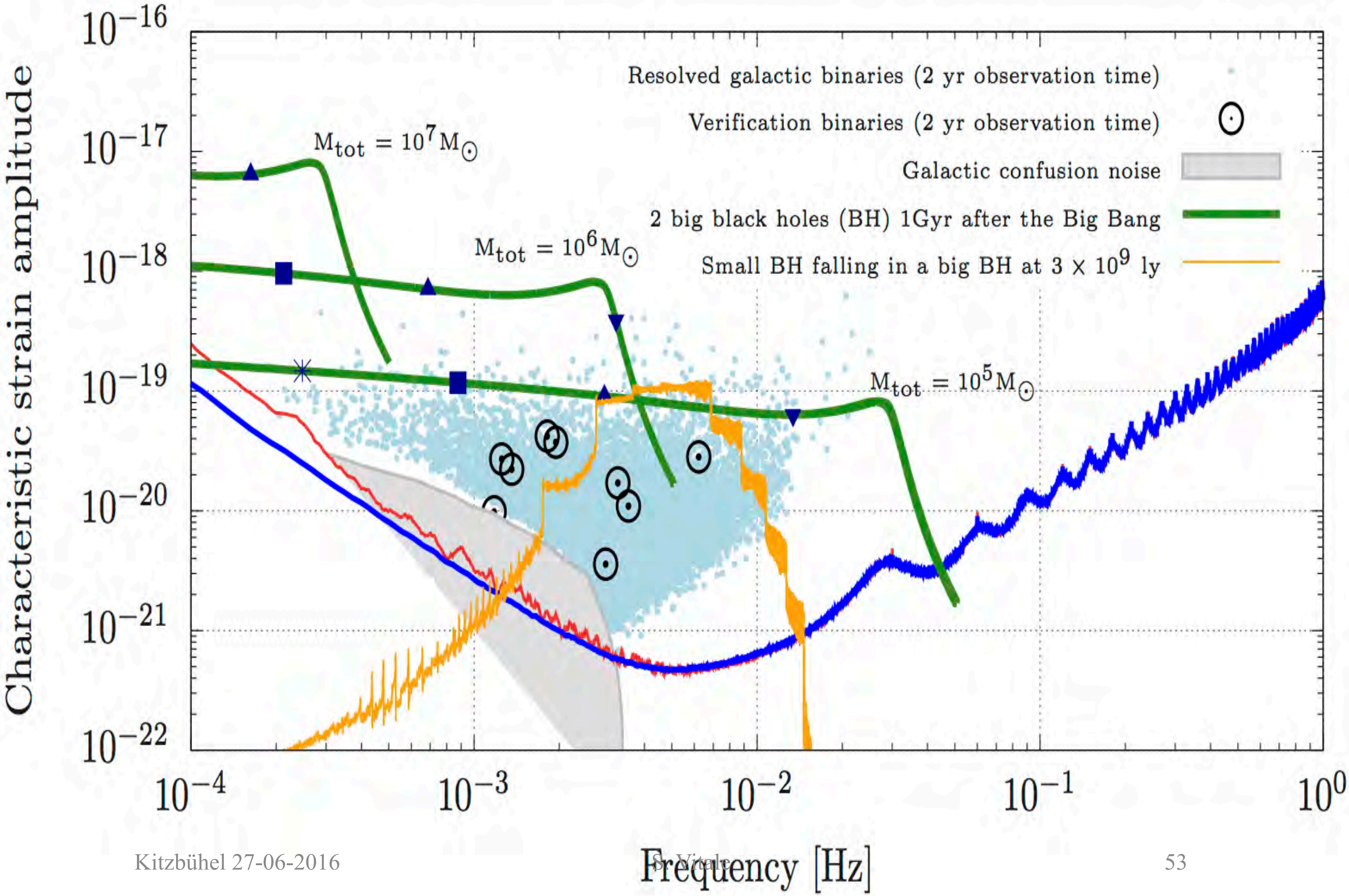


Disturbances already estimated with dedicated experiments performed so far

Noise almost entirely modeled: original LISA requirements at hand

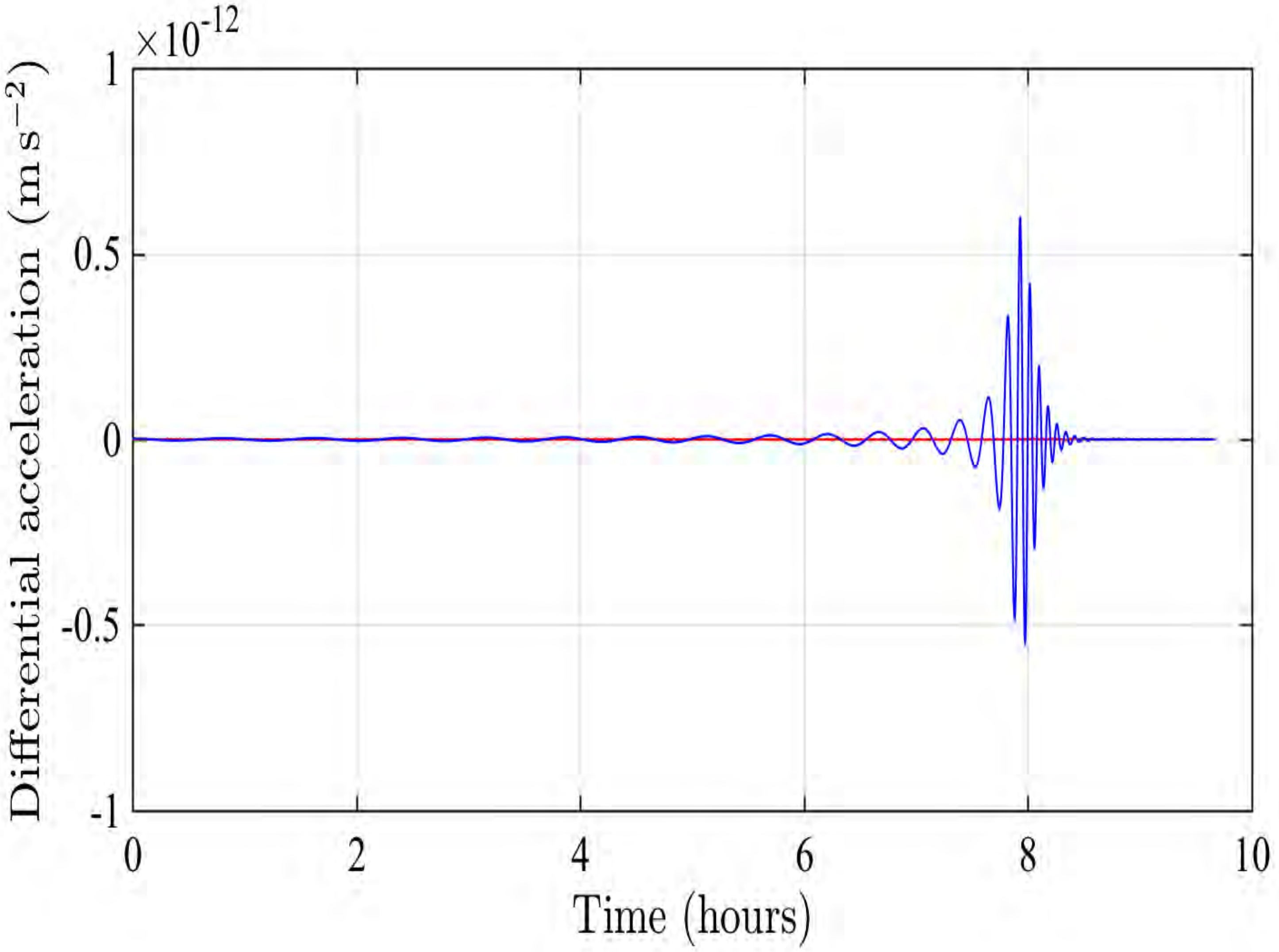


With current demonstrated sensitivity most science obtained anyway



Simulated LISA acceleration signal for two $5\times10^5\ M_\odot$ black-holes with their galaxies merging at 12.5 billion light-years

LISA Pathfinder acceleration data



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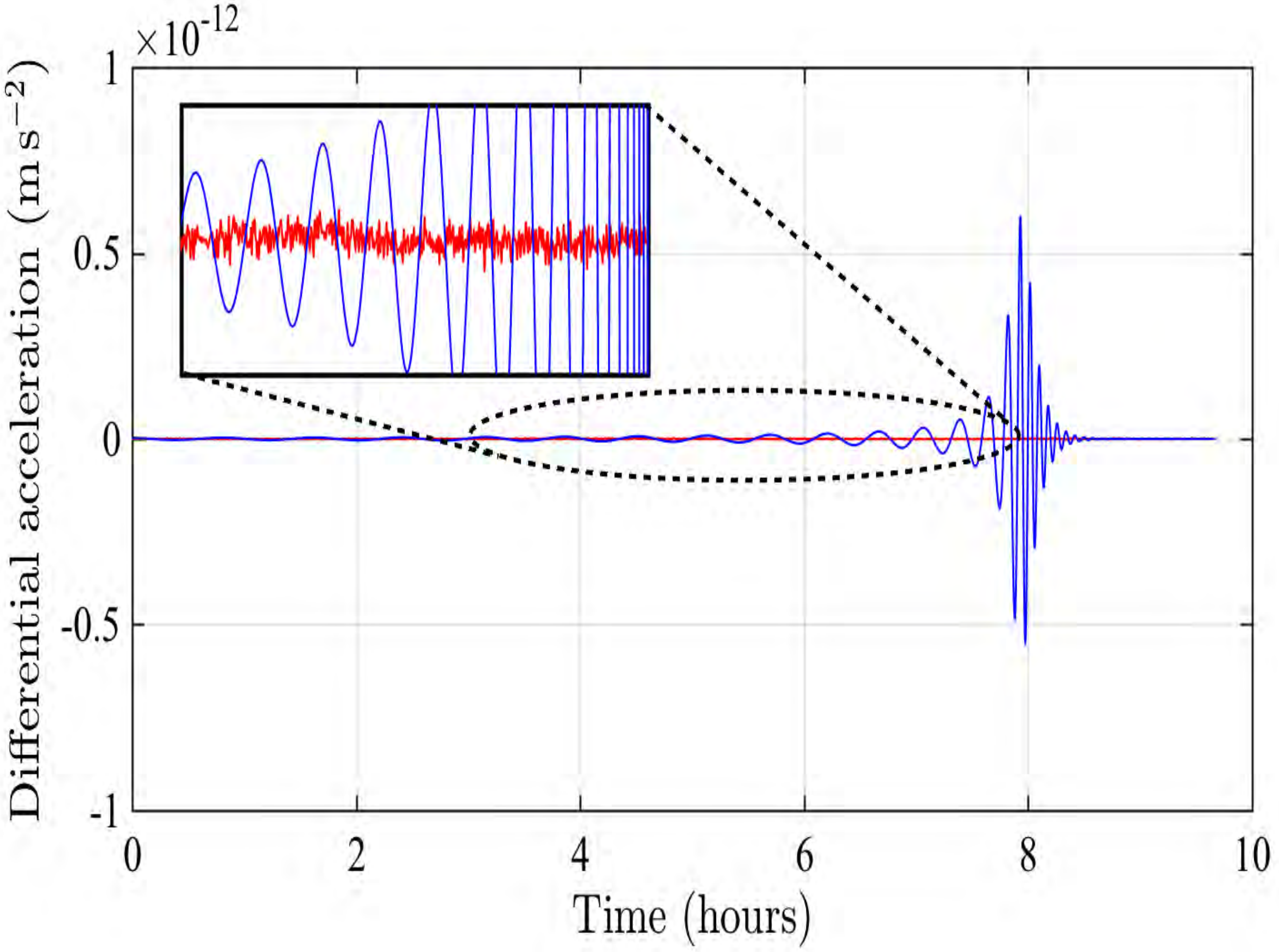
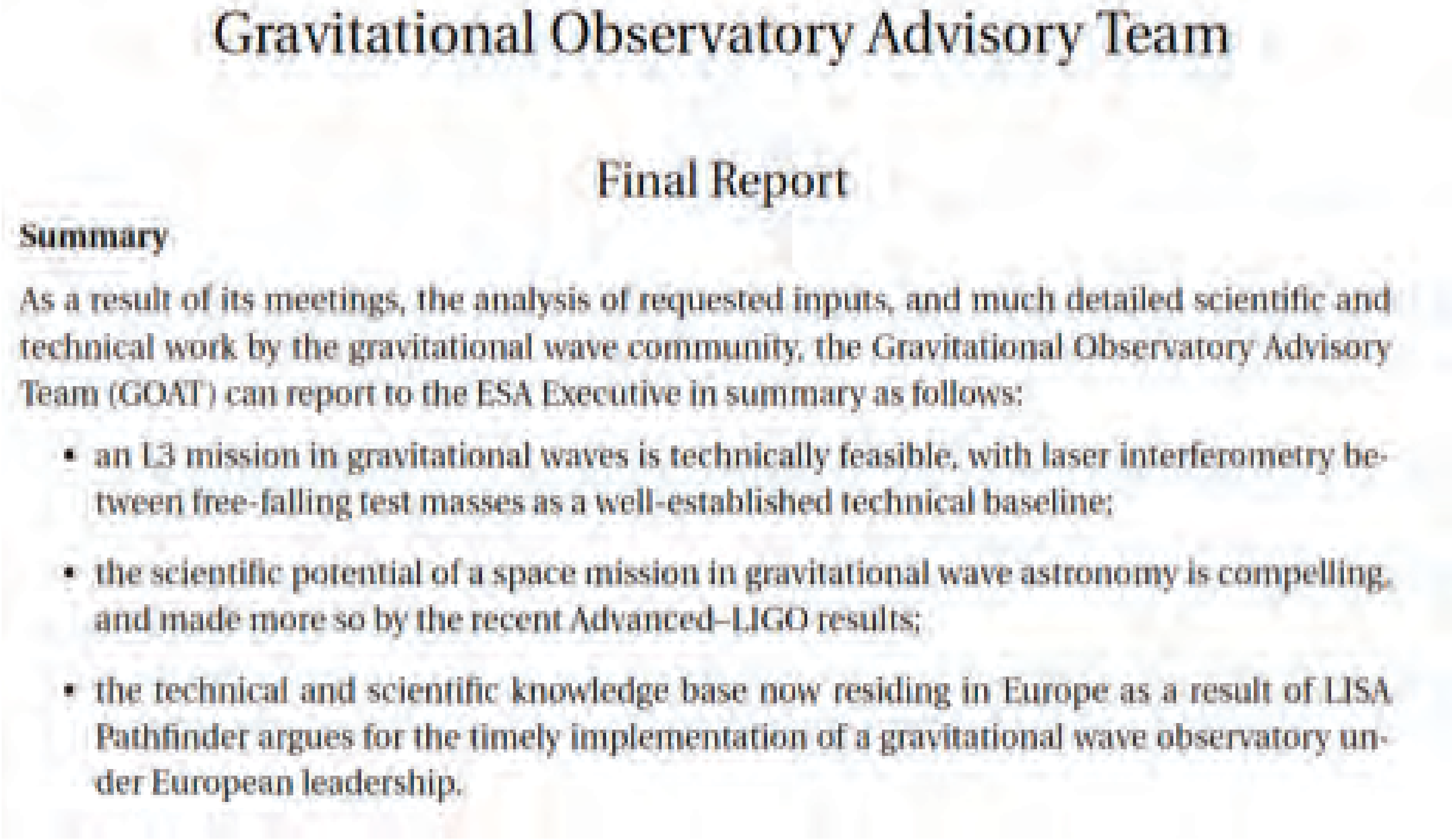
LISA Pathfinder acceleration data



Next

- LISA pathfinder investigations continuing till May 31, 2017
- ESA plans for GW observatory



Gravitational Observatory Advisory Team

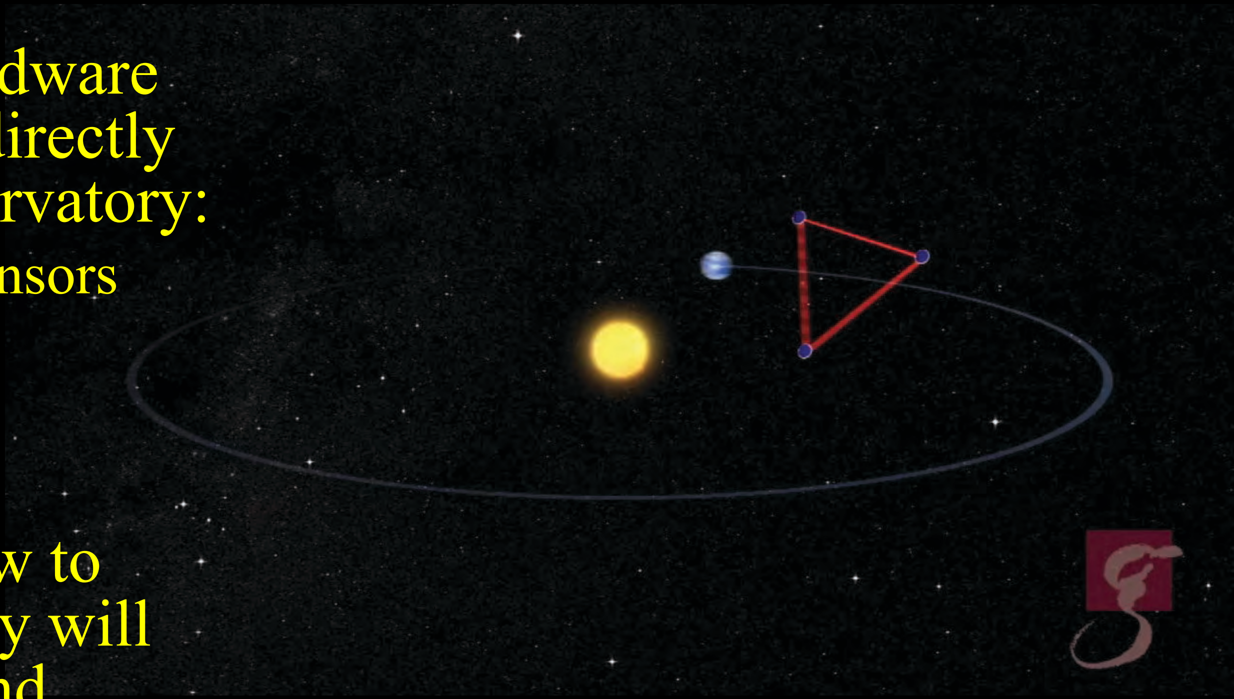
Final Report

Summary

As a result of its meetings, the analysis of requested inputs, and much detailed scientific and technical work by the gravitational wave community, the Gravitational Observatory Advisory Team (GOAT) can report to the ESA Executive in summary as follows:

- an L3 mission in gravitational waves is technically feasible, with laser interferometry between free-falling test masses as a well-established technical baseline;
- the scientific potential of a space mission in gravitational wave astronomy is compelling, and made more so by the recent Advanced-LIGO results;
- the technical and scientific knowledge base now residing in Europe as a result of LISA Pathfinder argues for the timely implementation of a gravitational wave observatory under European leadership.

The Gravitational Wave observatory after LISA Pathfinder



- The physics of the observatory demonstrated down to critical details
- Substantial part of hardware and methods may be directly transferred to the observatory:
  - Gravity Reference Sensors
  - Drag-free control
  - Local interferometer
  - ……..
- Important steps on how to operate the observatory will have been practiced and understood
- A key “go ahead” for LISA