LISA Pathfinder and LISA

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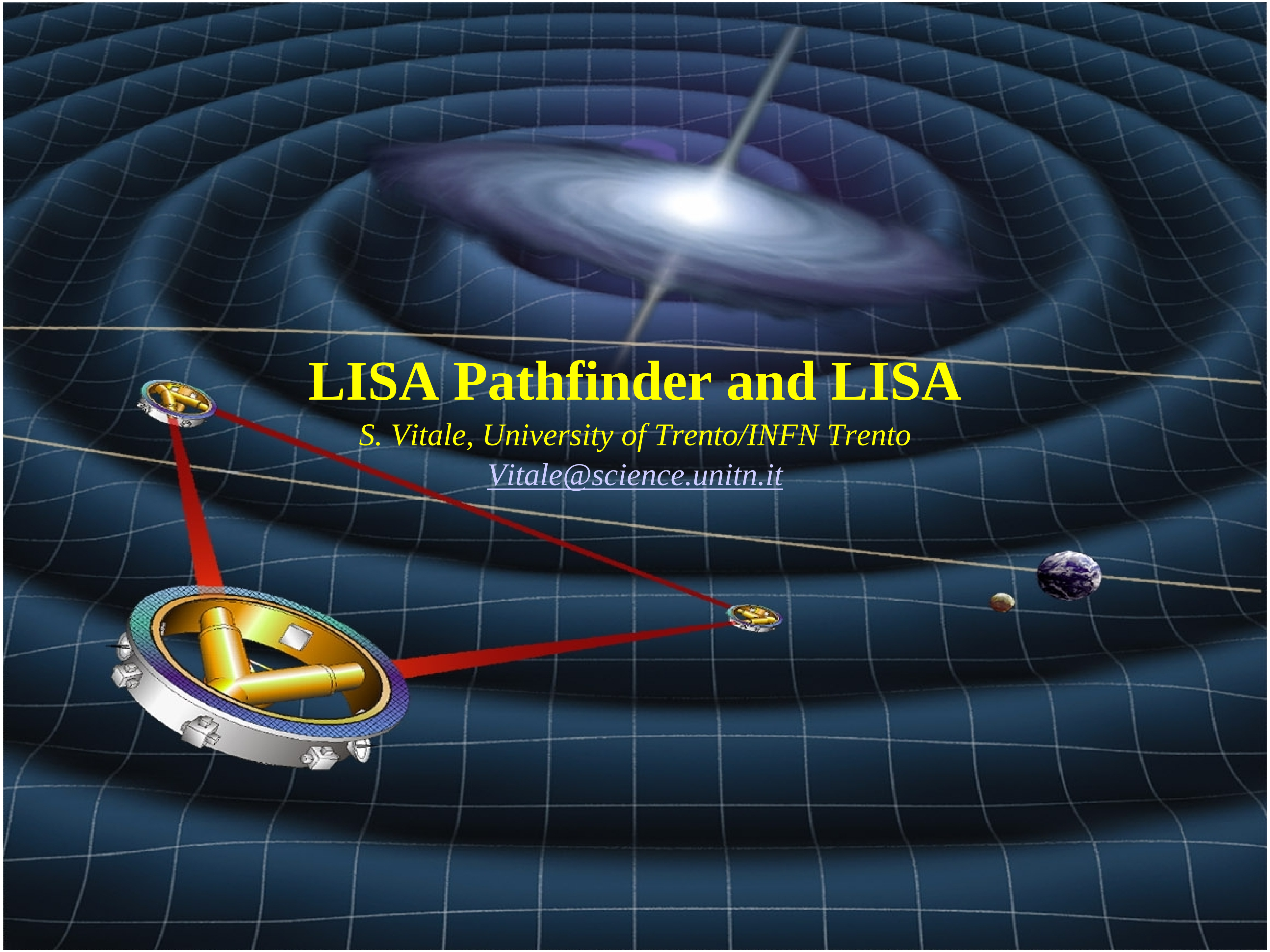
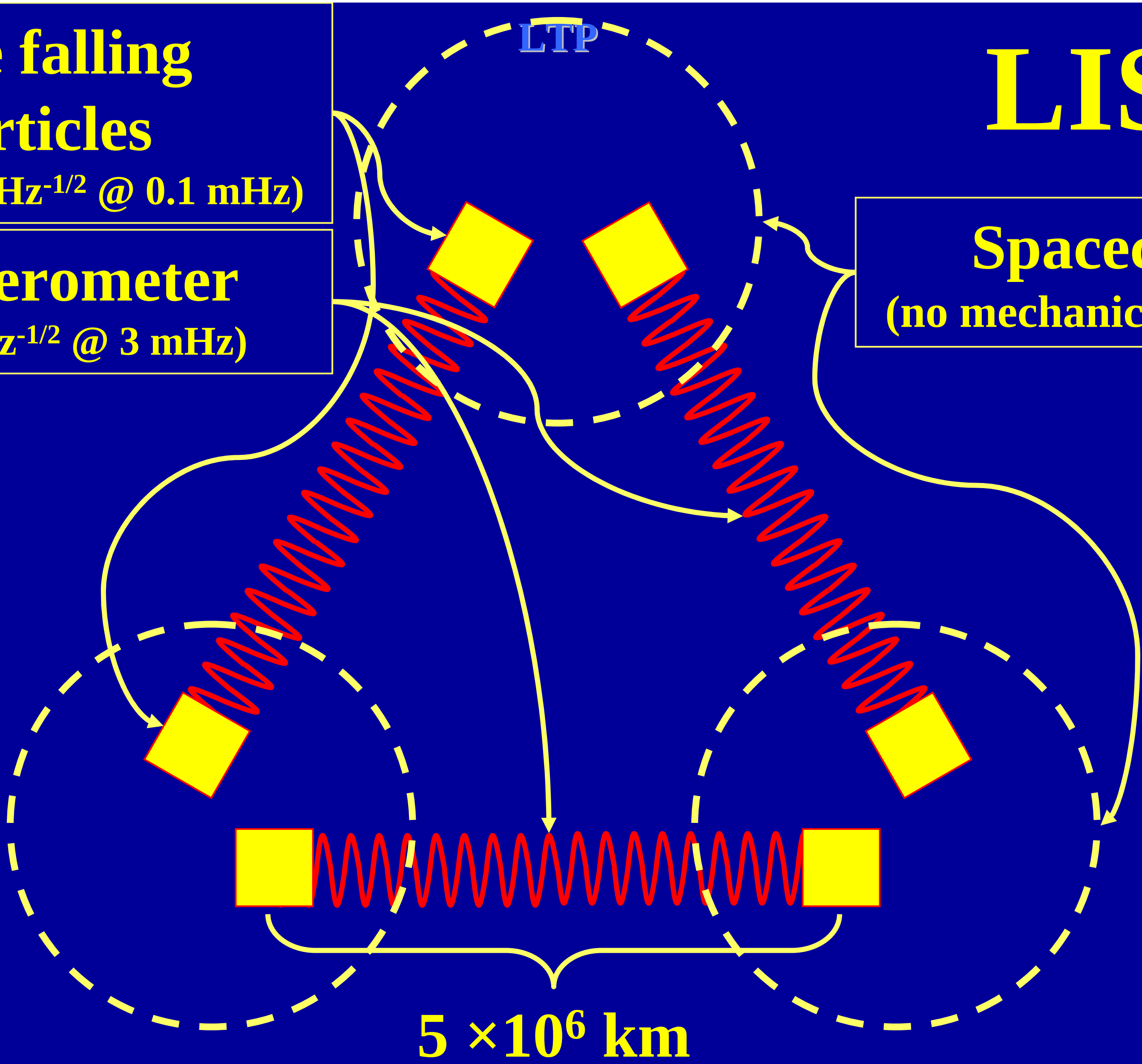


LISA

Free falling particles
(3 10^{-15} ms^{-2} $Hz^{-1/2}$ @ 0.1 mHz)

Interferometer
(40 pm $Hz^{-1/2}$ @ 3 mHz)

Spacecraft
(no mechanical contact)



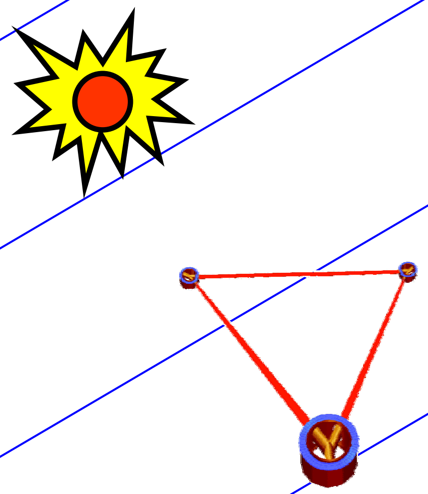
GW at
0.1 mHz – 0.1 Hz

Strain sensitivity
$h \approx 10^{-20} / \sqrt{Hz}$ @ 10^{-3}Hz

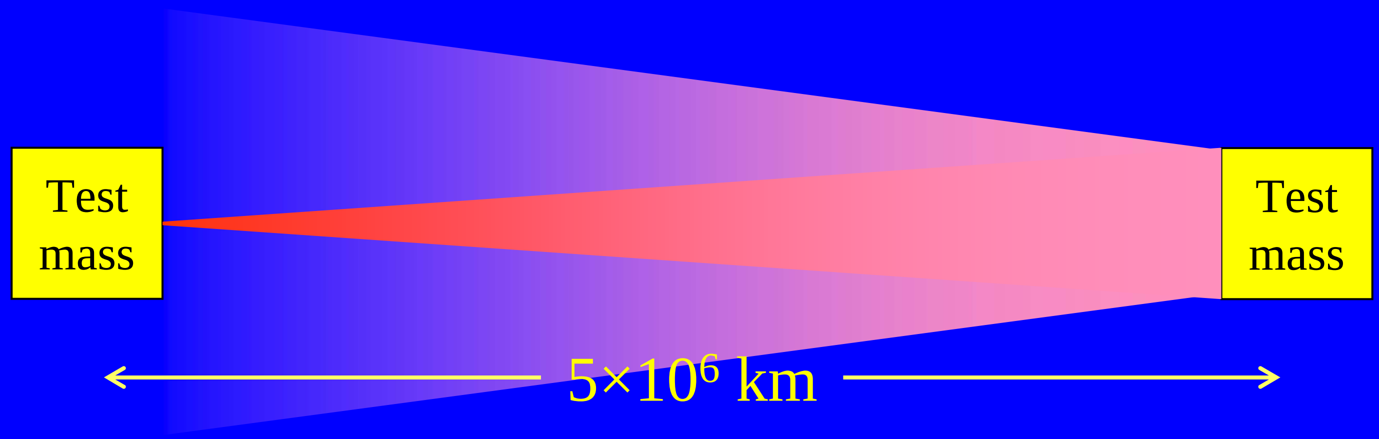
LISA essentials 1: the smart orbits

Angular Resolution with LISA

- Measurements on detected sources:
  - $\Delta\theta \sim 1' - 1^{o}$
  - Δ(mass,distance) $\leq$ 1%

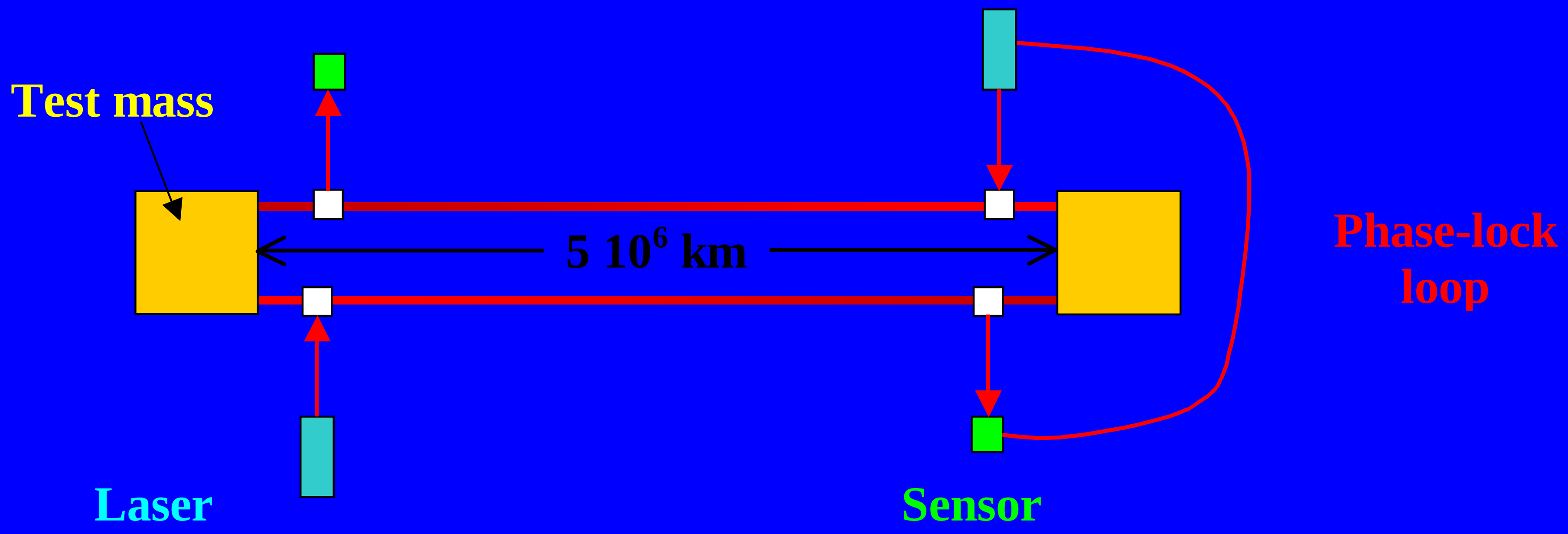


LISA essentials 2: the laser transponding scheme



Power loss due to beam divergence makes interferometry by reflection impossible

LISA essentials 2: the laser transponding scheme



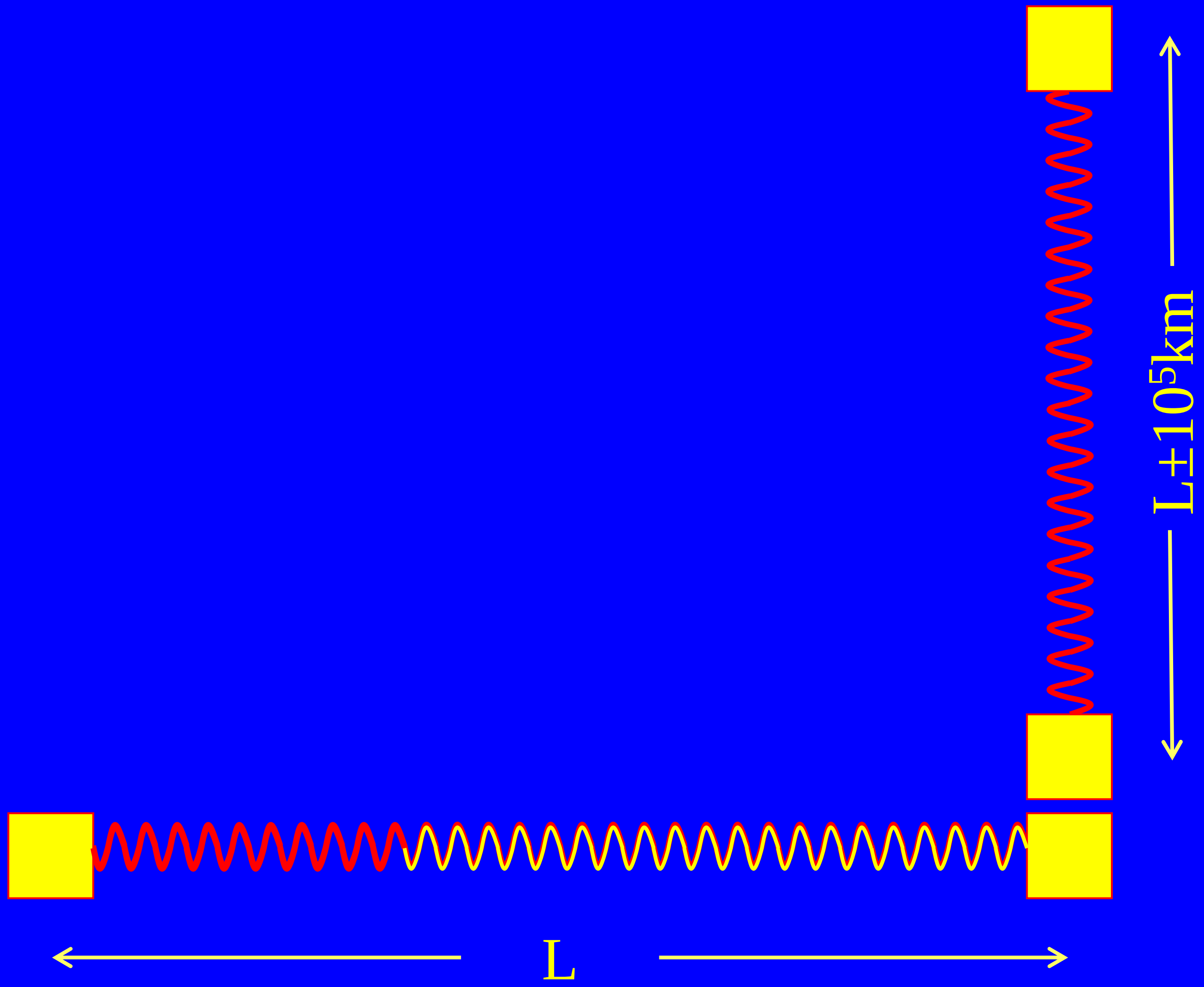
Beating power loss due to beam divergence

The GW from difference of phase in adjacent arms

The standard GW interferometer

Laser phase noise common to both arms:
GW signal from difference: laser noise is suppressed

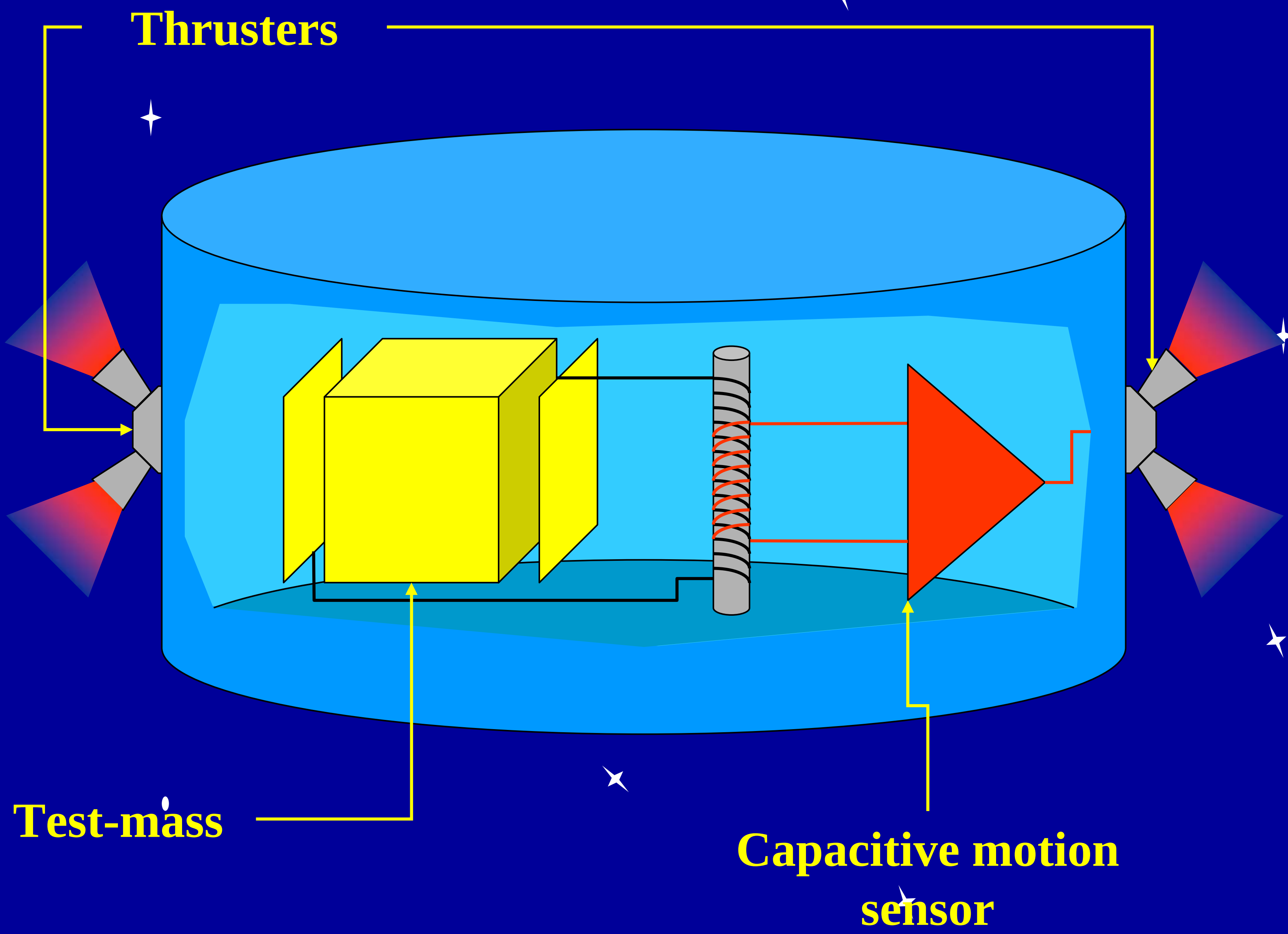
LISA unequal arms confuse phases



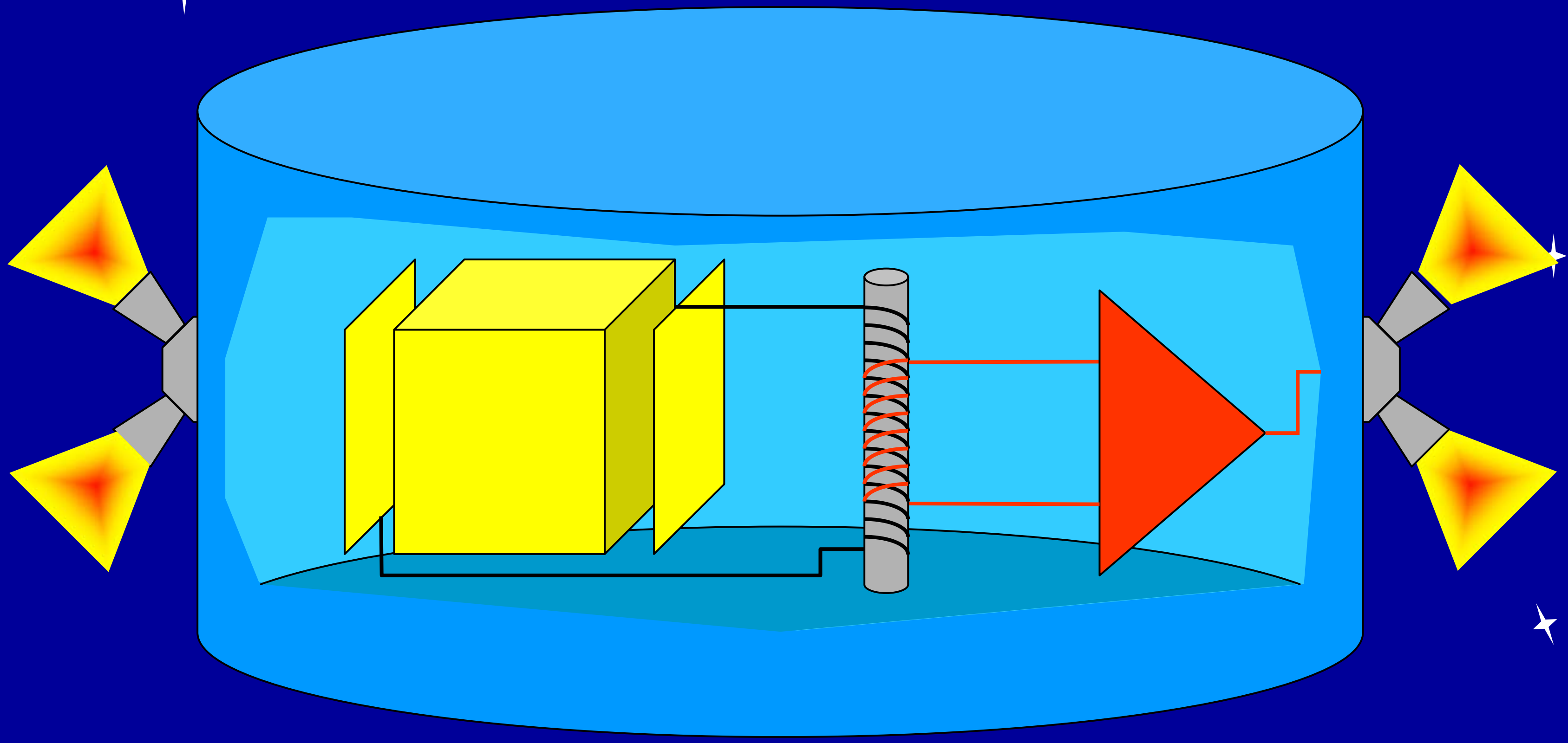
Need to recombine light emitted at equal times

Needs knowledge of armlength with ± 20 m

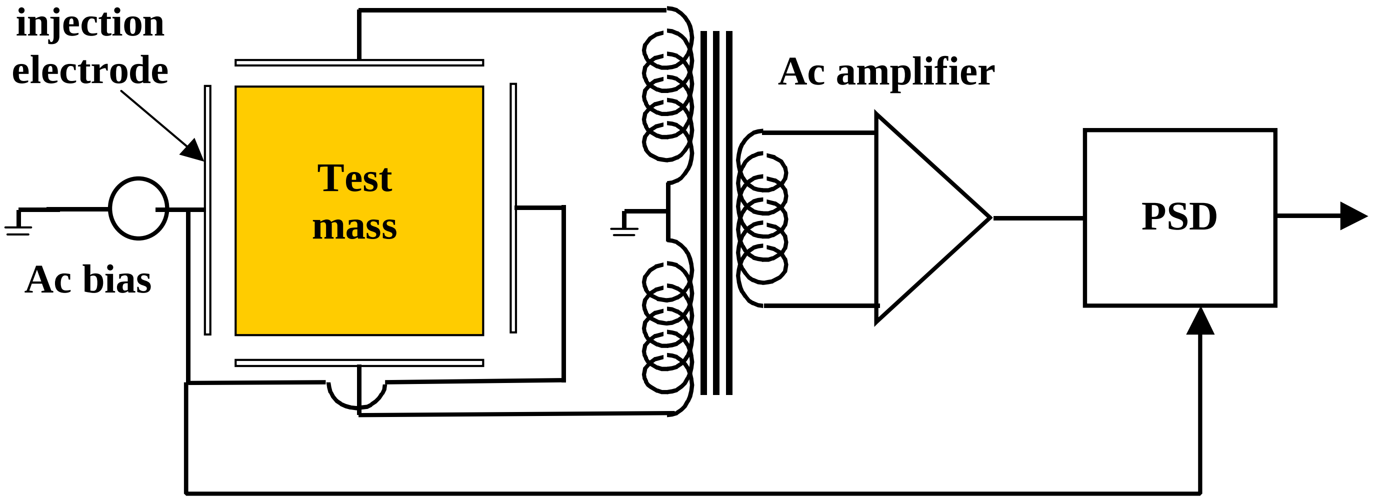
Lisa essential 3: Drag-free control loop



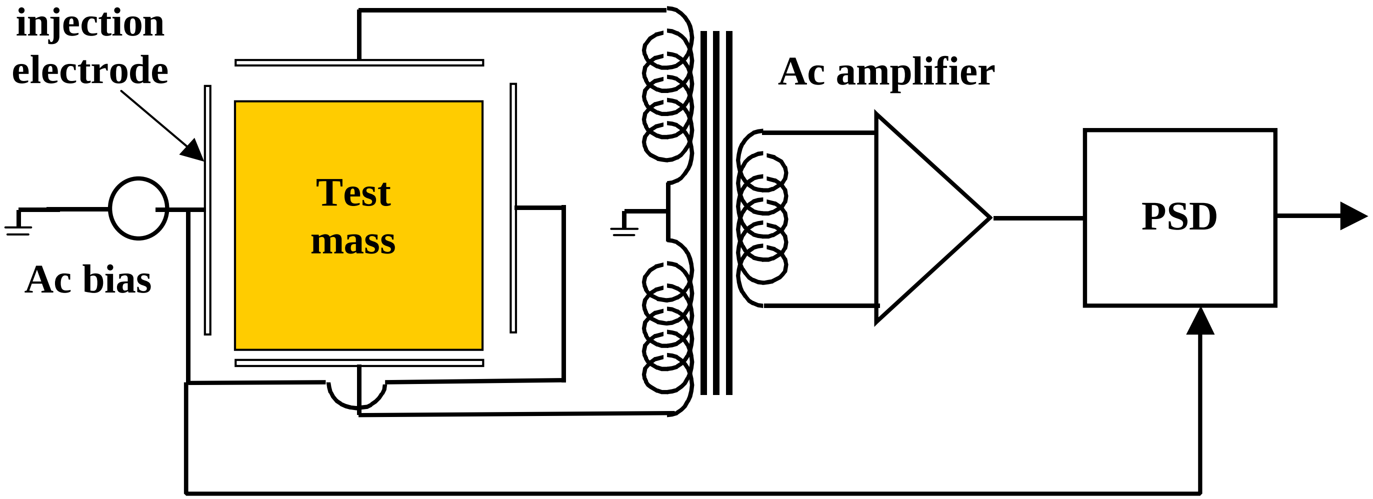
LTP



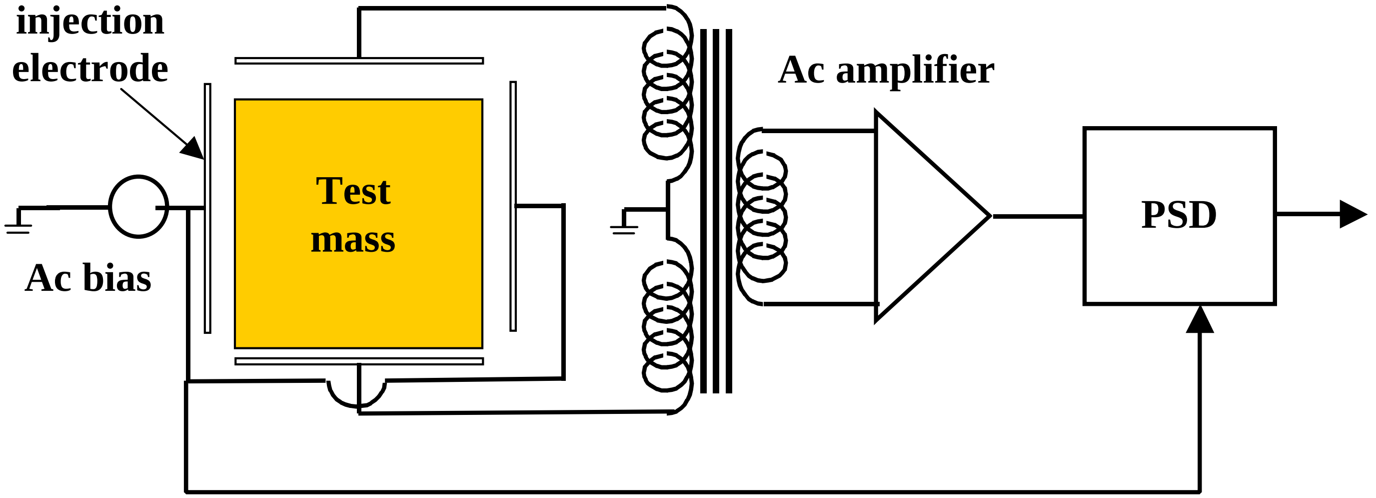
The drag-free key elements: 1 the displacement sensor

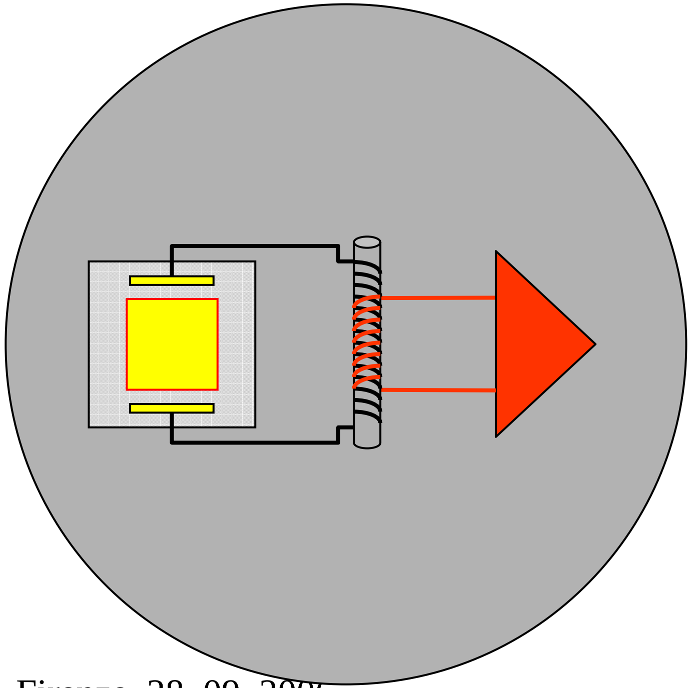


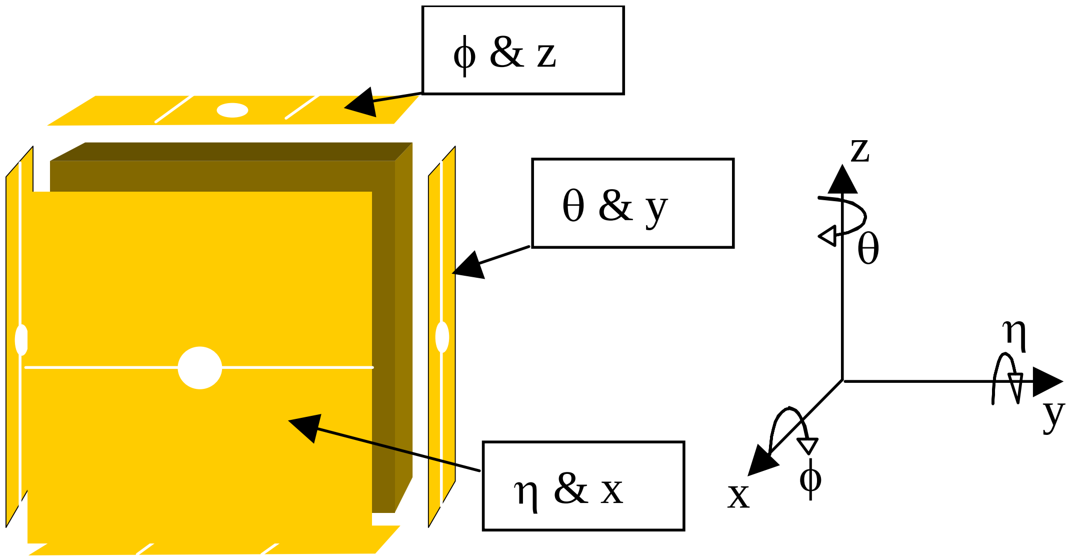
The drag-free key elements: 1 the displacement sensor

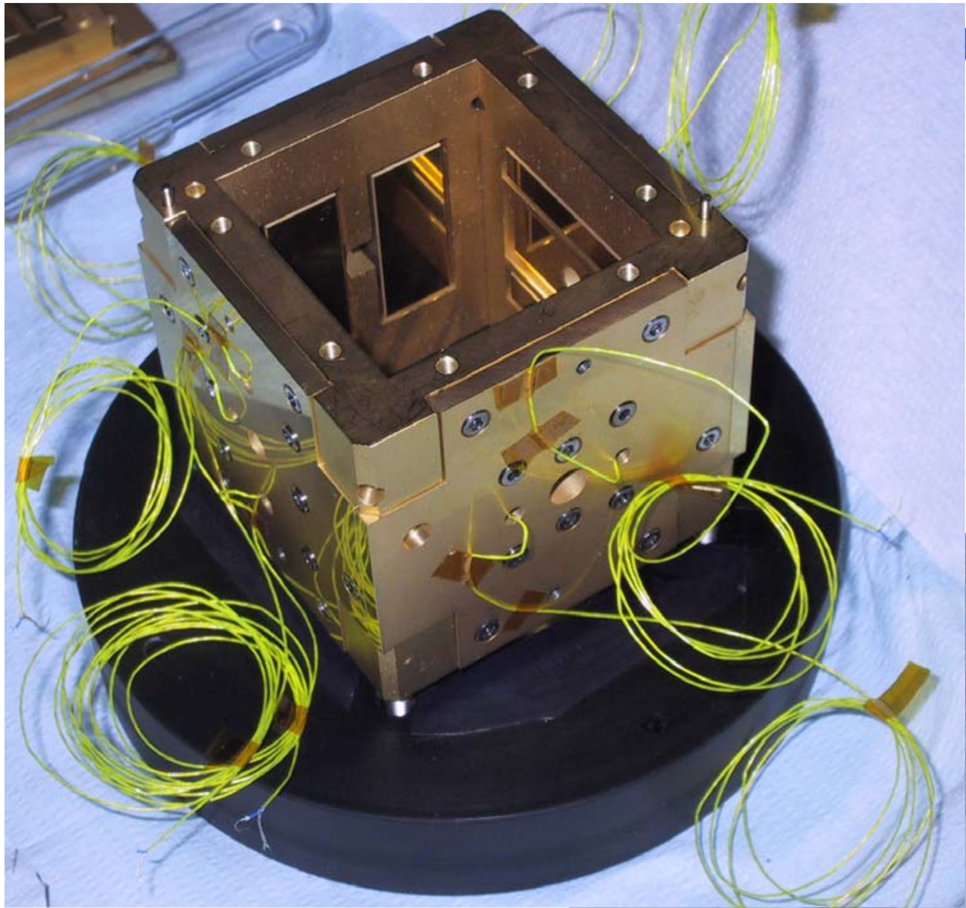


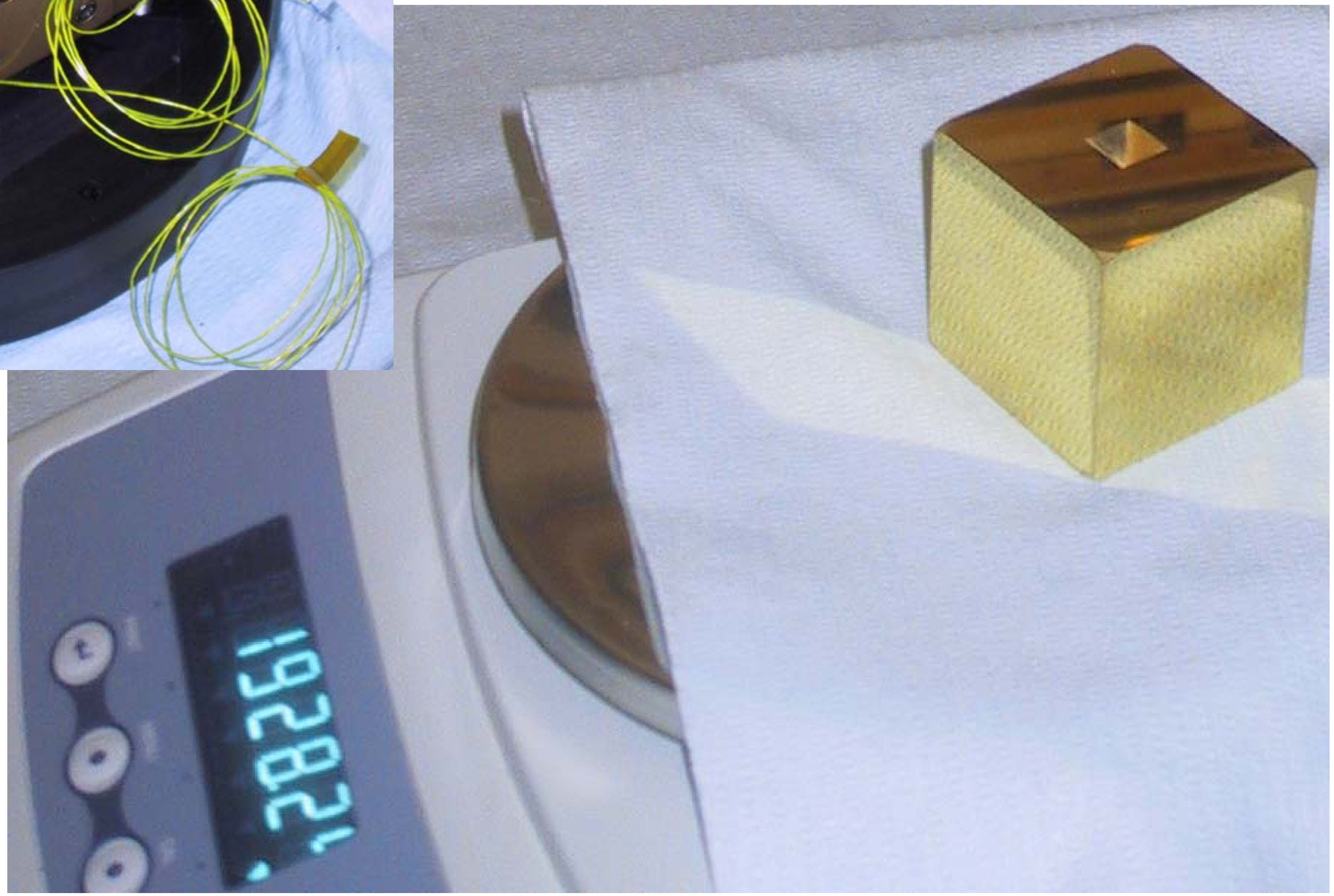
The drag-free key elements: the displacement sensor

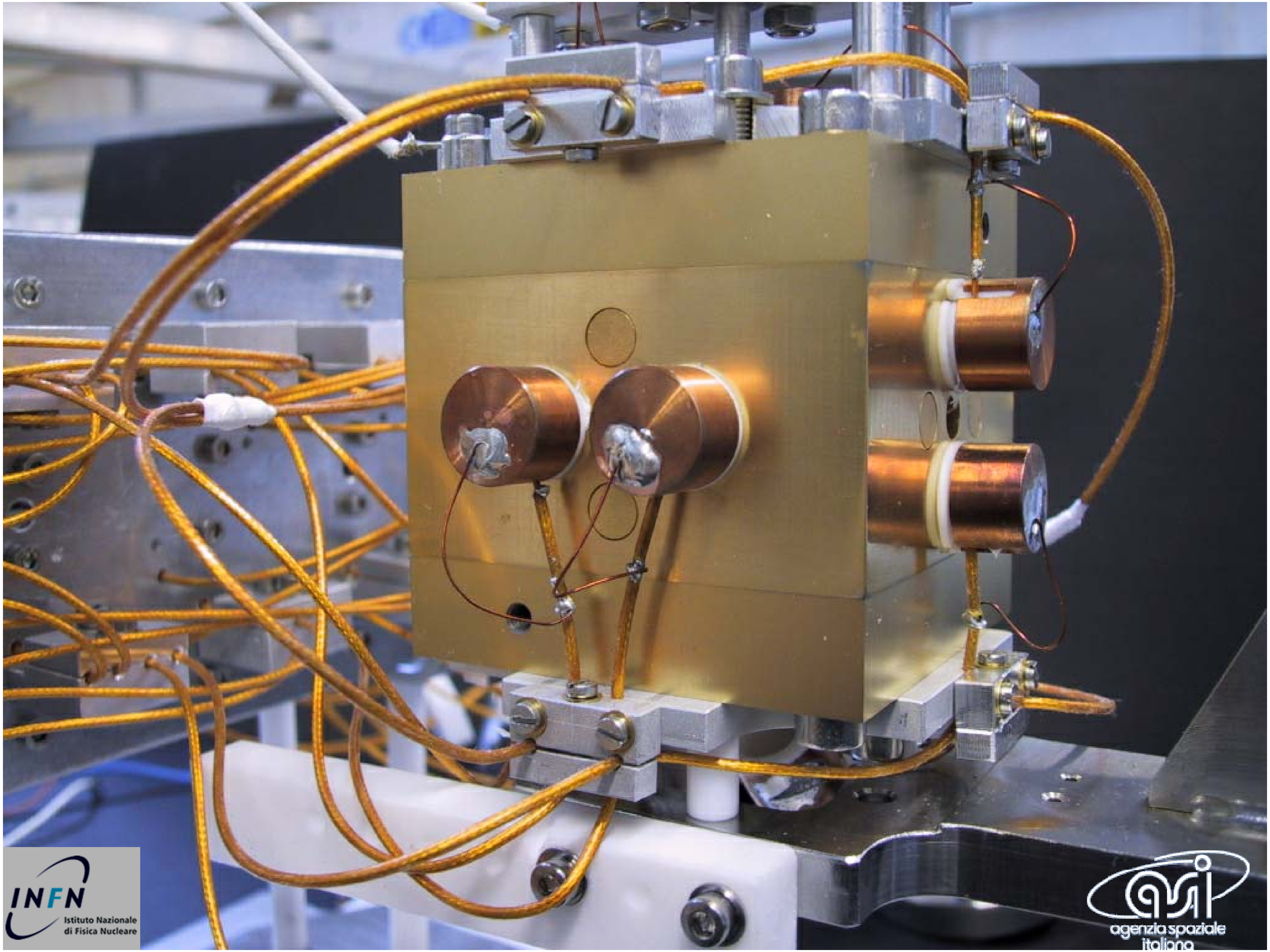








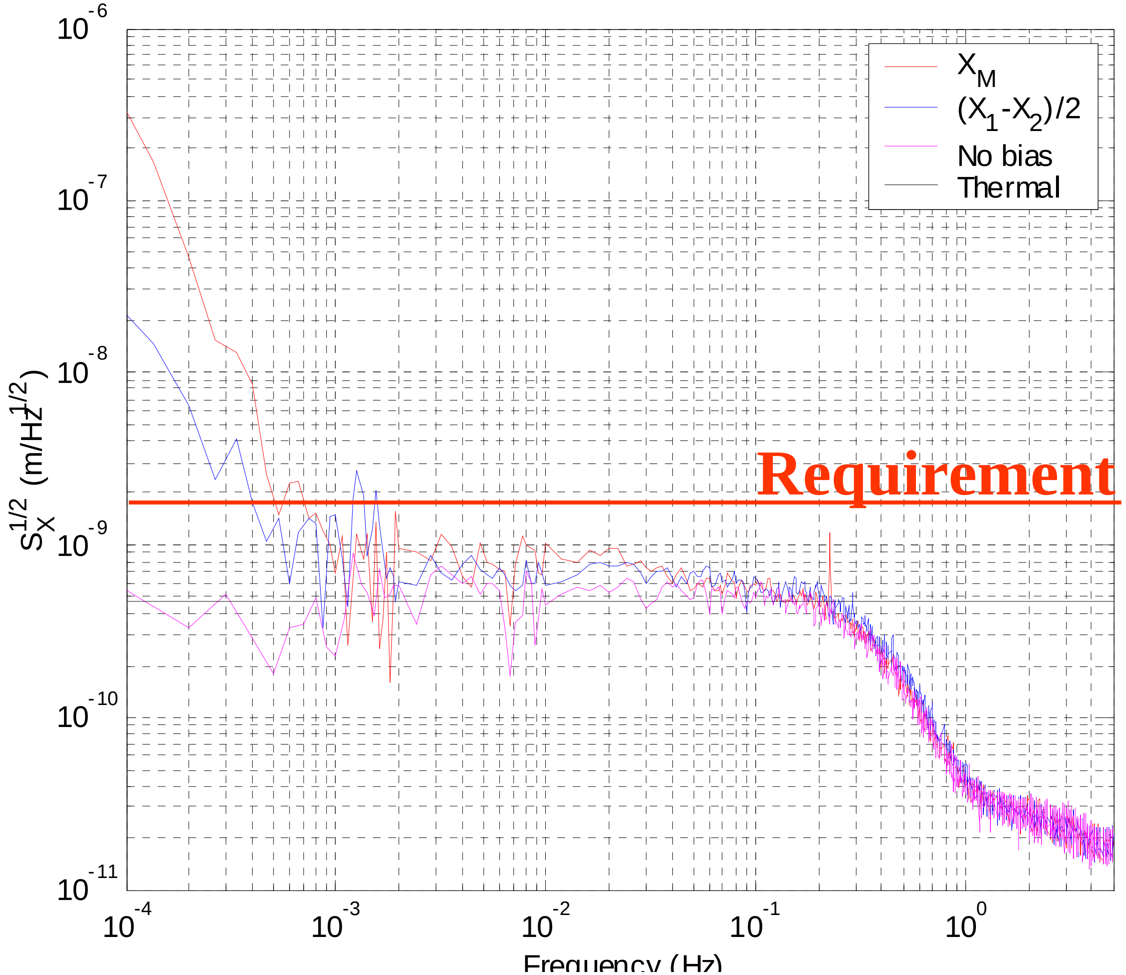



INFN
Istituto Nazionale
di Fisica Nucleare
agenzia spaziale
italiana

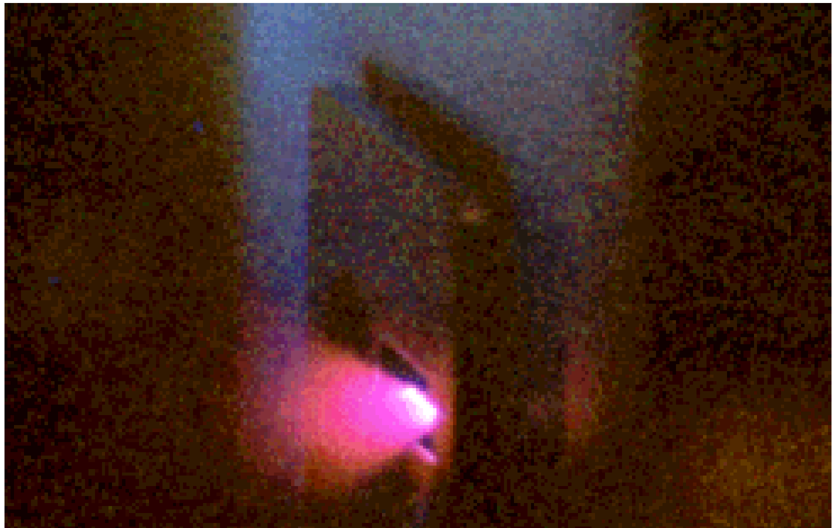
1 nm/√Hz resolution

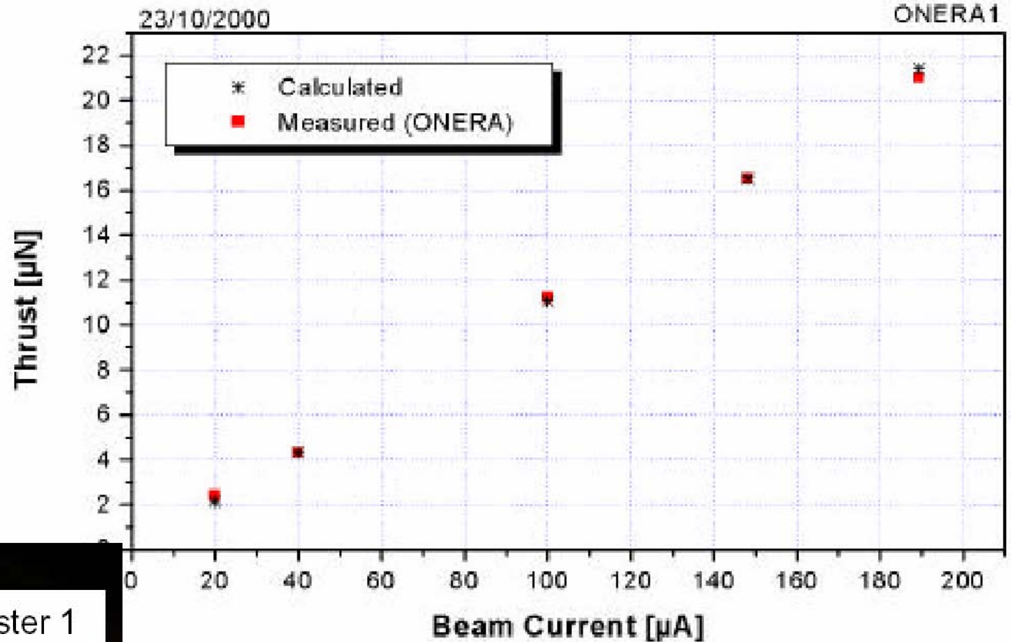
LTP

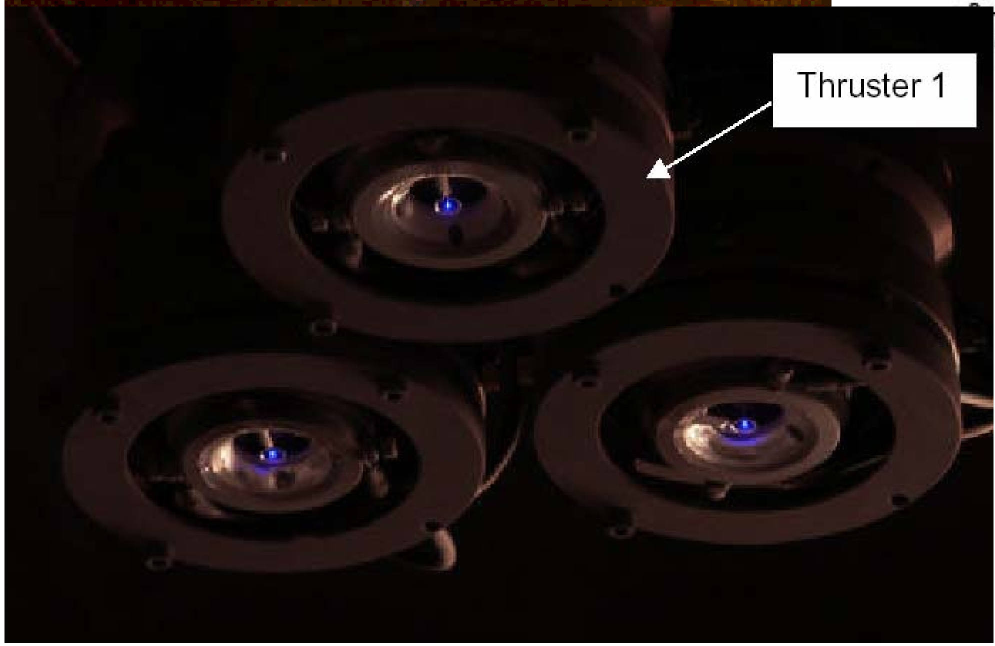
4 mm gaps and 0.3 Volt bias



Drag-free key elements 2: Microthrusters







In-FEEP Cluster after 1500h of continuous operation (3500h for Thruster 1)

'itale

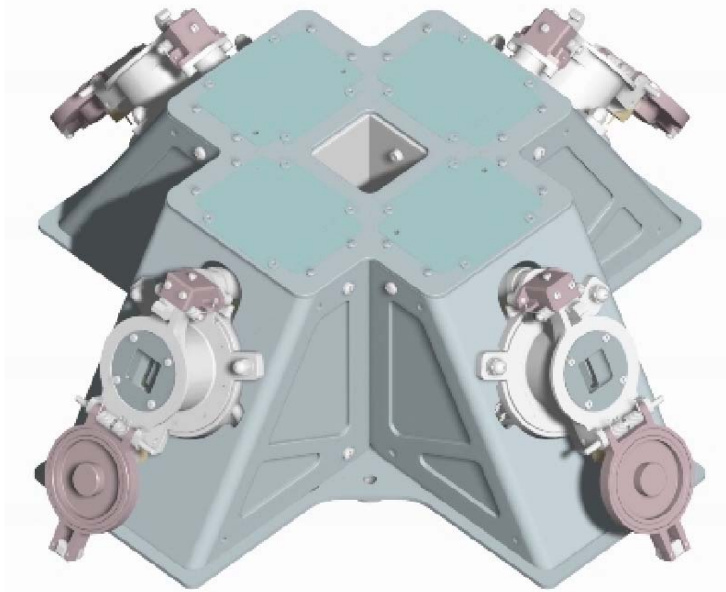
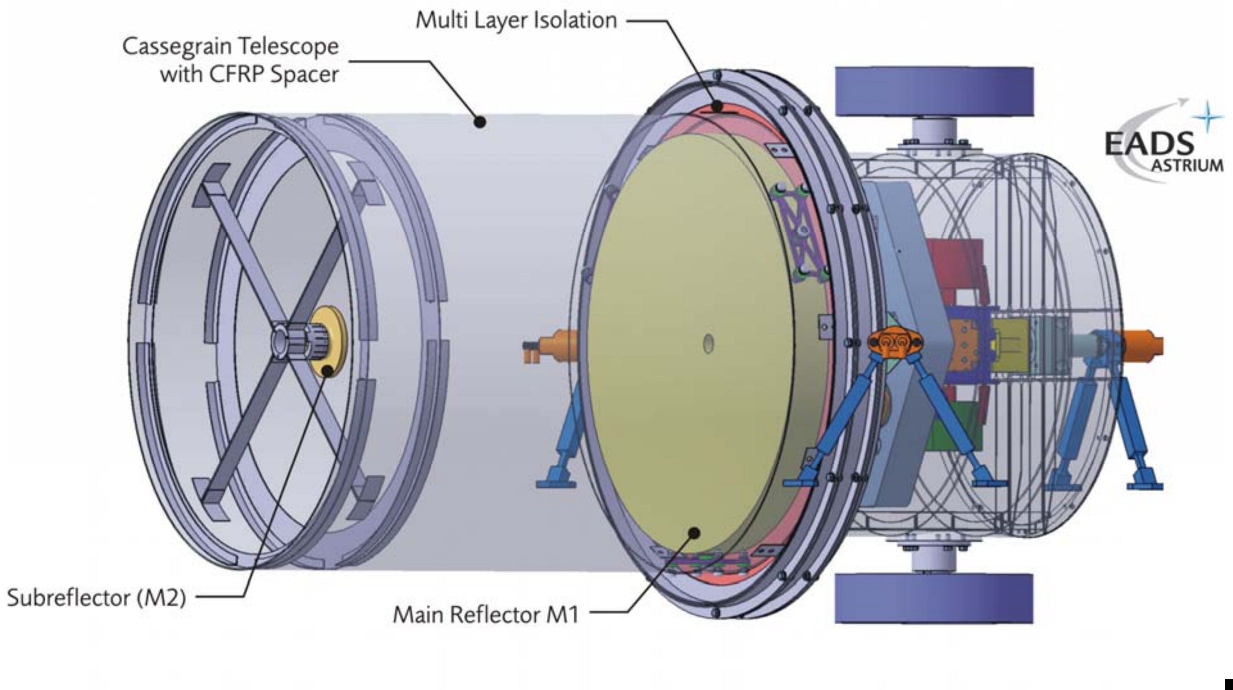
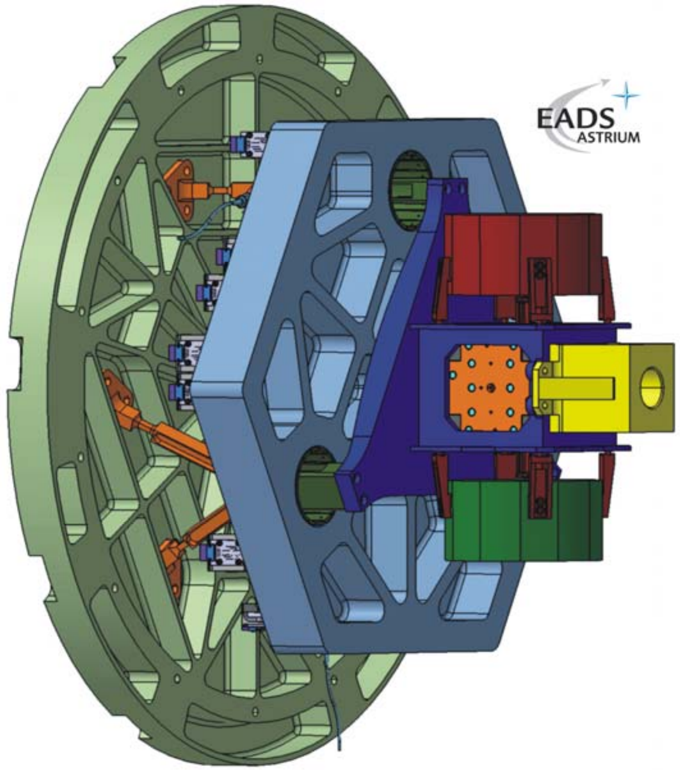


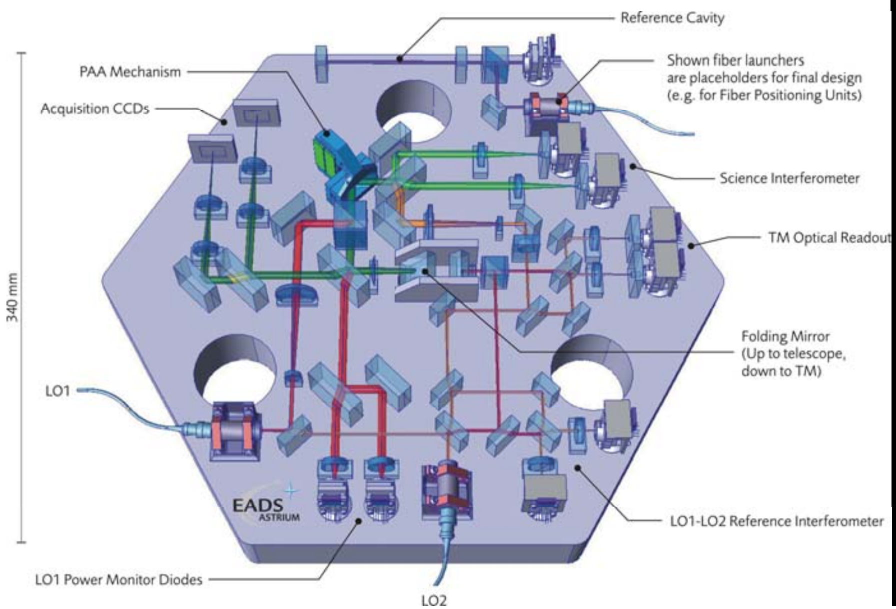
Figure 7.3: The FEEP Cluster


Multi Layer Isolation
Cassegrain Telescope
with CFRP Spacer
EADS
ASTRIUM
Subreflector (M2)
Main Reflector M1

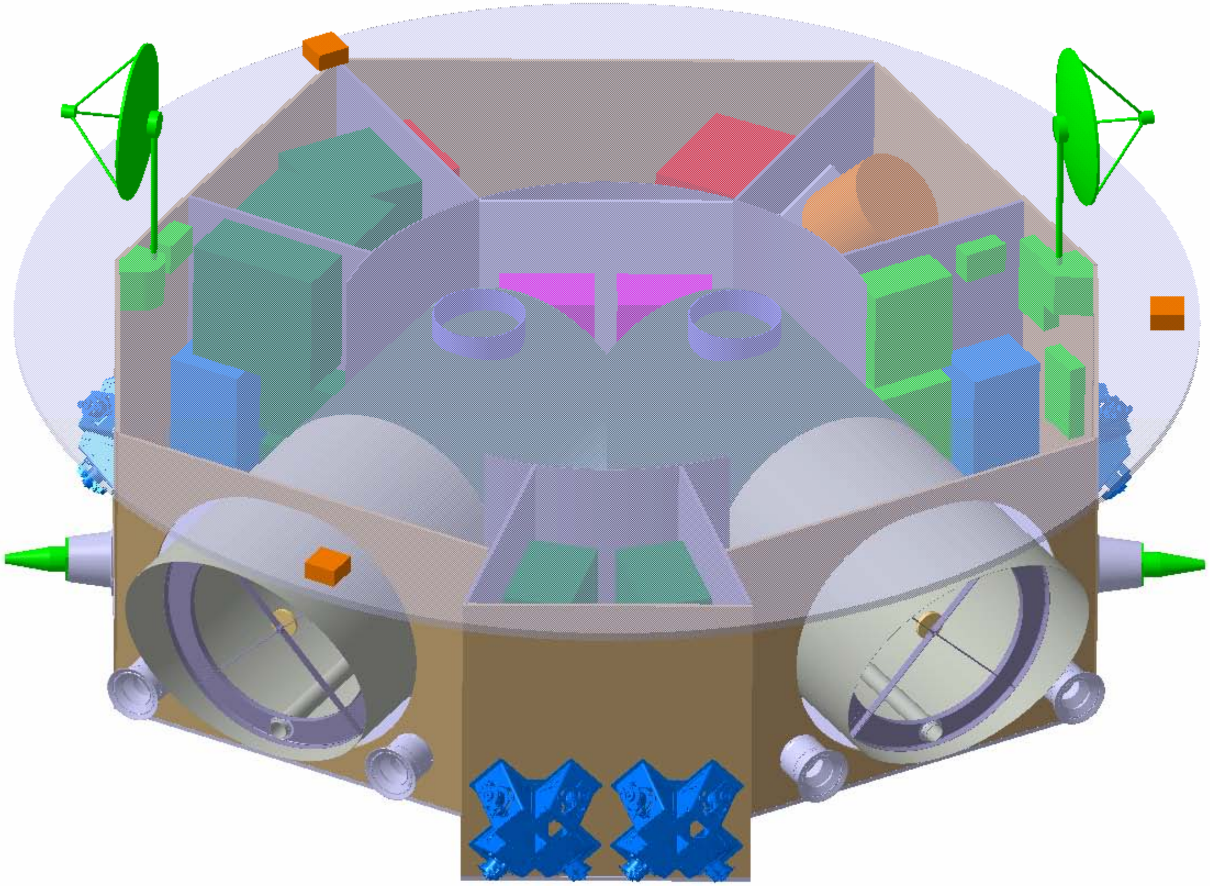
[redacted]

LTP


EADS
ASTRIUM


Reference Cavity
PAA Mechanism
Acquisition CCDs
Shown fiber launchers
are placeholders for final design
(e.g. for Fiber Positioning Units)
Science Interferometer
TM Optical Readout
340 mm
Folding Mirror
(Up to telescope,
down to TM)
LO1
EADS
ASTRIUM
LO1-LO2 Reference Interferometer
LO1 Power Monitor Diodes
LO2

LTP



[redacted]

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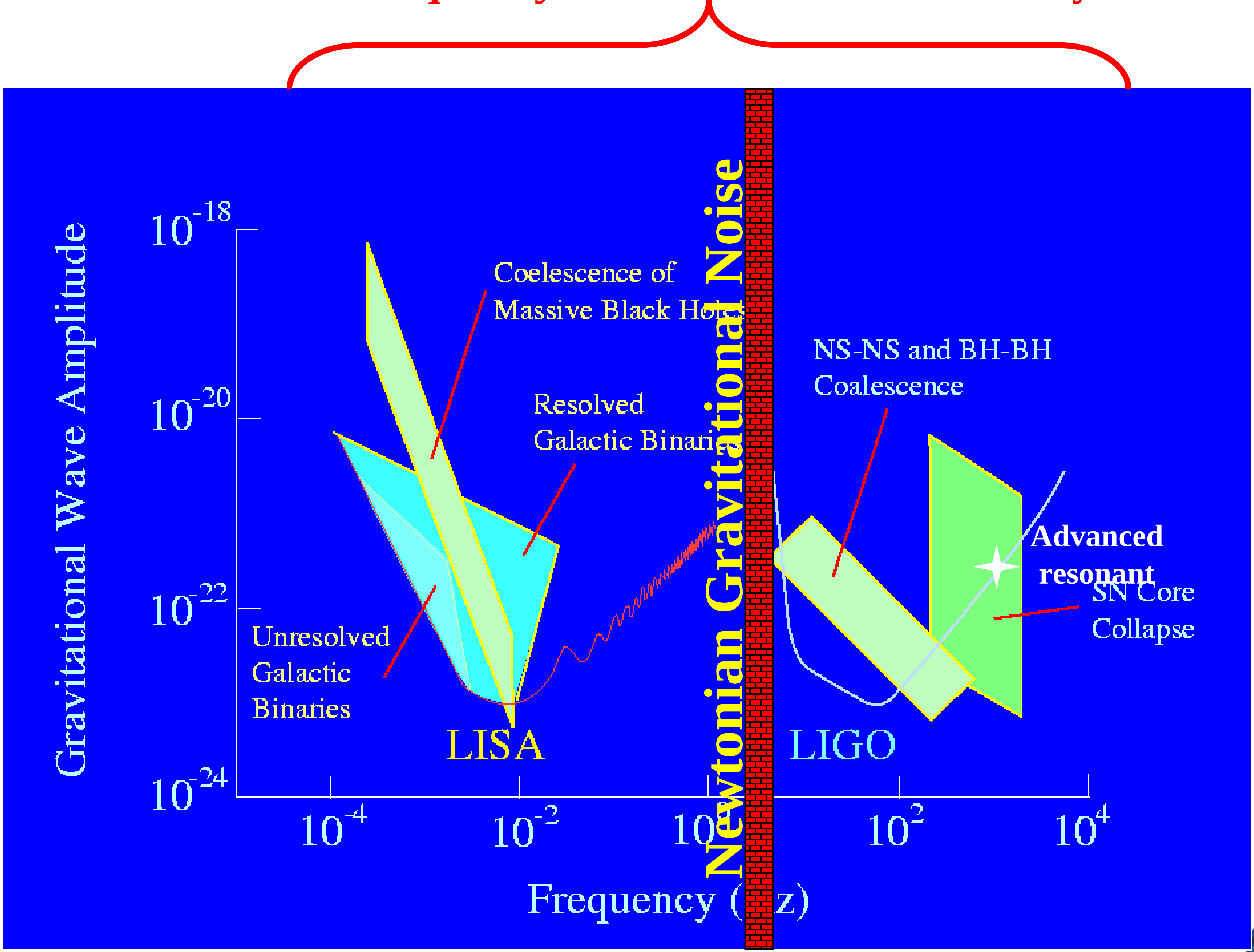
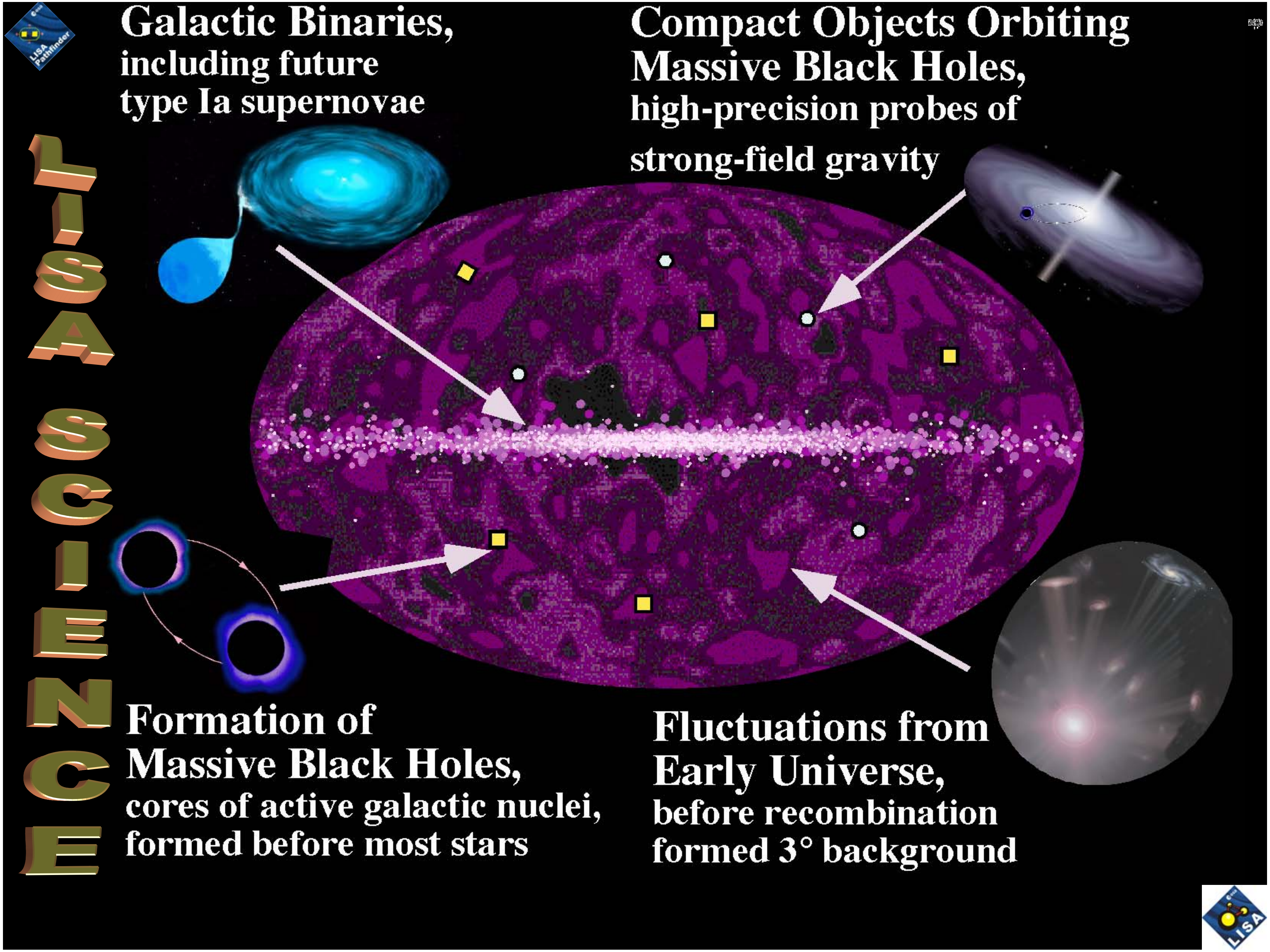
LTP

8 frequency decades of GW astronomy

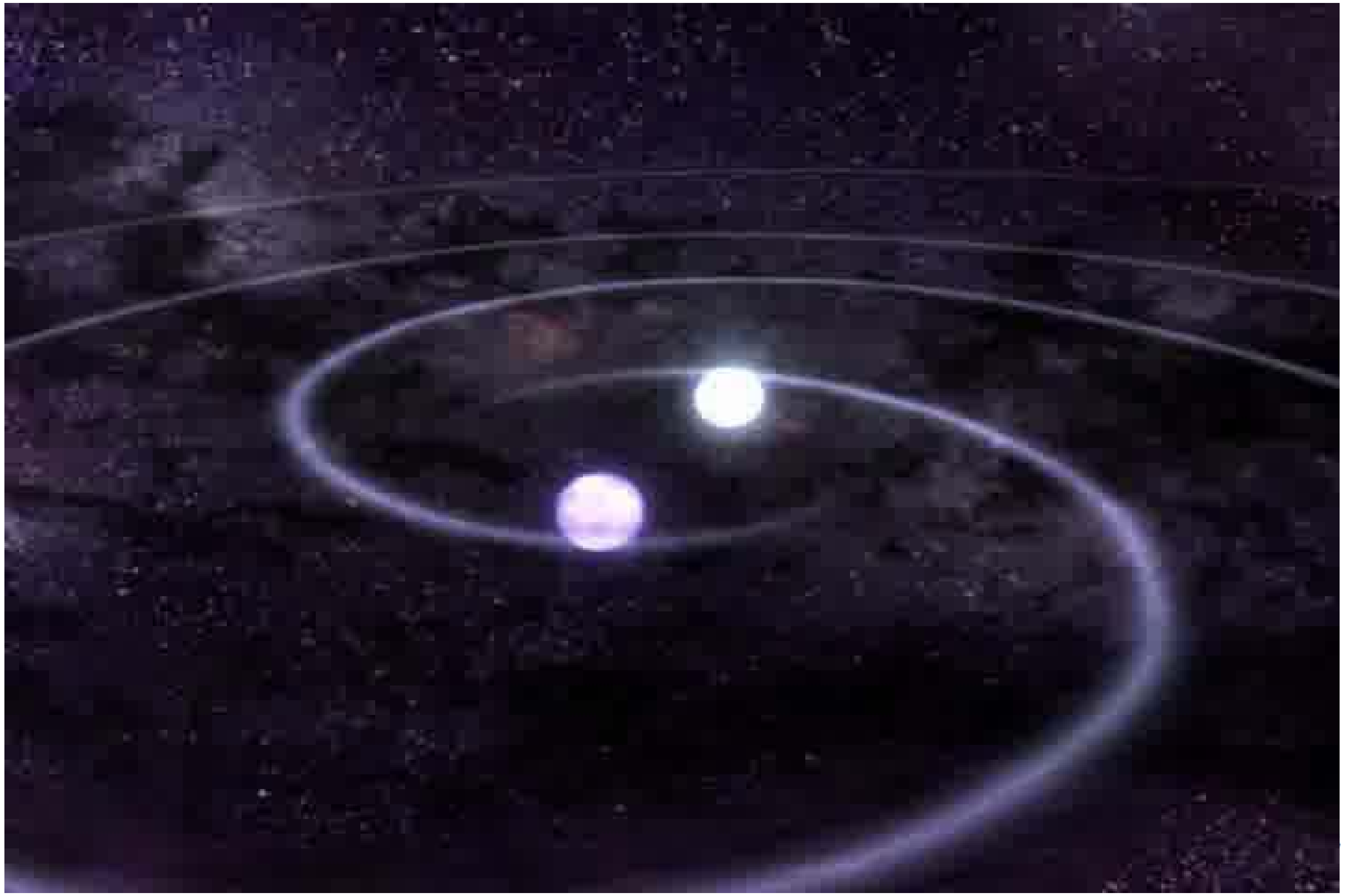


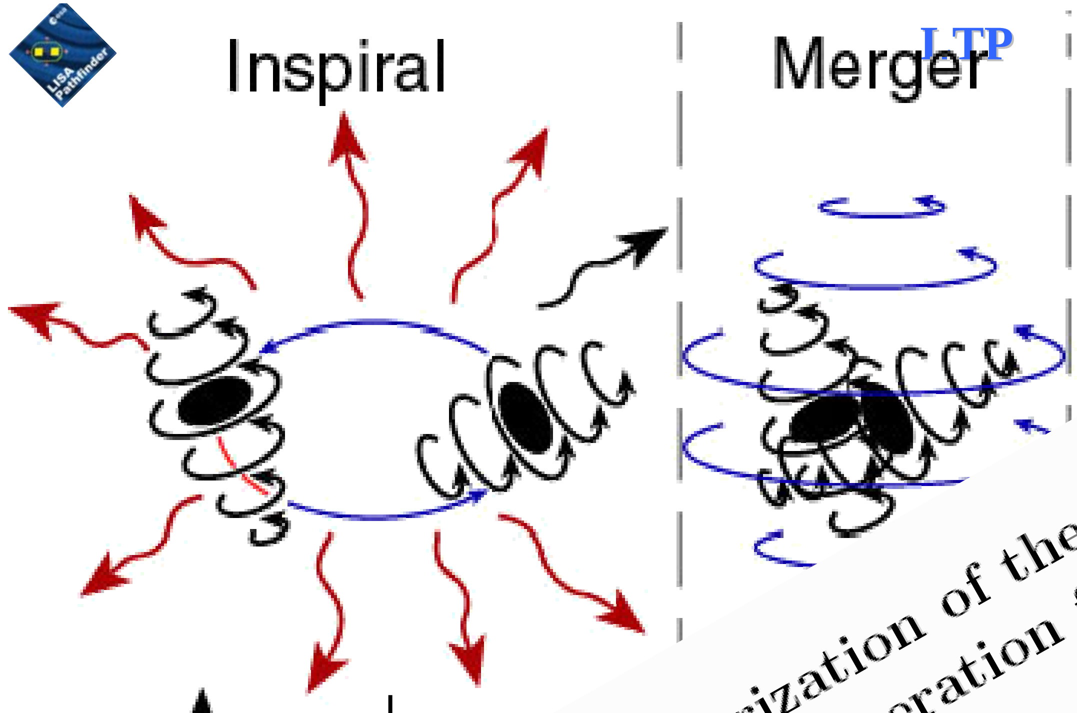

LISA SCIENCE
Galactic Binaries,
including future type Ia supernovae
Compact Objects Orbiting Massive Black Holes,
high-precision probes of strong-field gravity
Formation of Massive Black Holes,
cores of active galactic nuclei, formed before most stars
Fluctuations from Early Universe,
before recombination formed 3° background
LISA
LISA Pathfinder

Binary Star in our Galaxy (White Dwarfs, Neutron Stars)

Very bright signal

List of known sources (verification binaries)

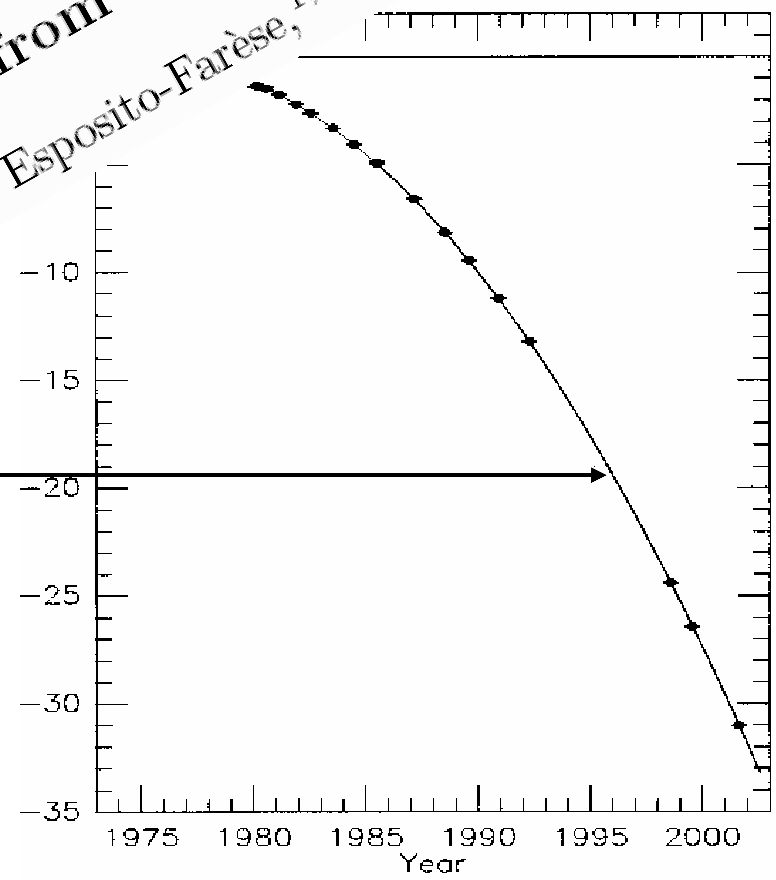




Dimensional regularization of the third post-Newtonian gravitational wave generation from two point masses

Luc Blanchet,[1,*] Thibault Damour,[2,†] Gilles Esposito-Farèse,[1,‡] and Bala R. Iyer[3,§]

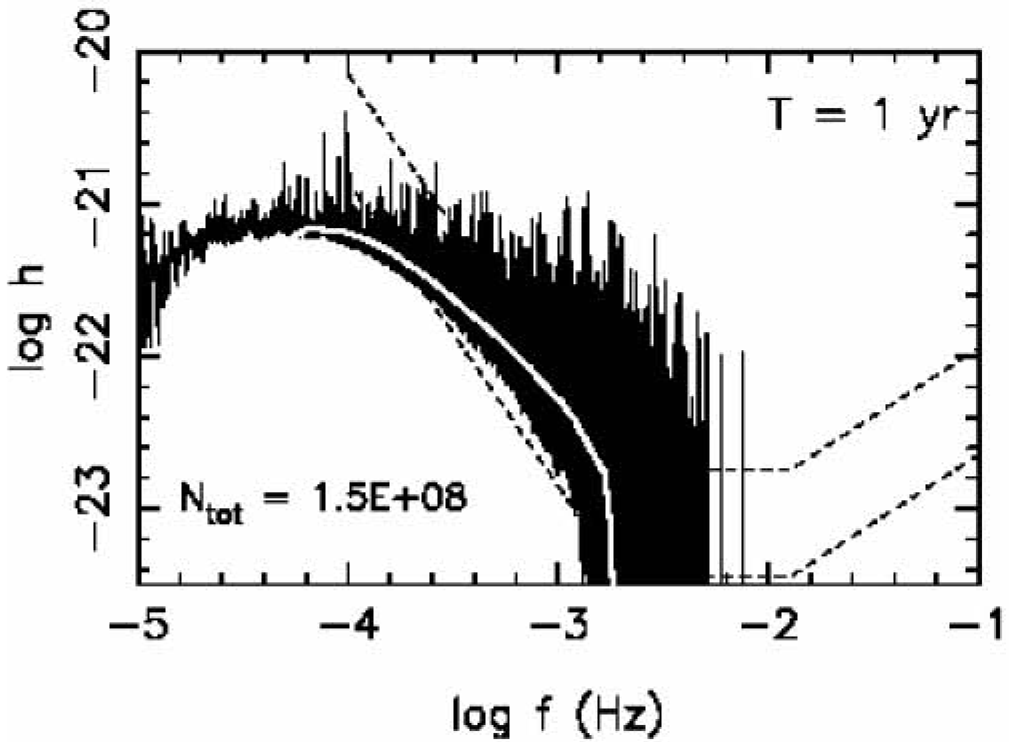
...ary systems



class	source	dist (pc)	$f=2/P_b$ (mHz)	M_1 $M_\odot$	M_2 $M_\odot$	*h*	SNR (1 Year)
WD + WD	WD 0957-666	100	0.38	0.37	0.32	4.00E-22	4.1
	WD1101+364	100	0.16	0.31	0.36	2.00E-22	0.4
	WD 1704+481	100	0.16	0.39	0.56	4.00E-22	0.7
	WD2331+290	100	0.14	0.39	>0.32	2.00E-22	0.3
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	6.00E-22	2.9
	KPD 1930 +2752	100	0.24	0.5	0.97	1.00E-21	4.1
AM CVn	RXJ0806.3+1527	300	6.2	0.4	0.12	4.00E-22	173.2
	RXJ1914+245	100	3.5	0.6	0.07	6.00E-22	195.0
	KUV05184-0939	1000	3.2	0.7	0.092	9.00E-23	27.3
	AM CV n	100	1.94	0.5	0.033	2.00E-22	35.6
	HP Lib	100	1.79	0.6	0.03	2.00E-22	32.0
	CR Boo	100	1.36	0.6	0.02	1.00E-22	10.6
	V803 Cen	100	1.24	0.6	0.02	1.00E-22	9.2
	CP Eri	200	1.16	0.6	0.02	4.00E-23	3.3
	GP Com	200	0.72	0.5	0.02	3.00E-23	1.1
LMXB	4U1820-30	8100	3	1.4	< 0.1	2.00E-23	5.7
	4U1626-67	<8000	0.79	1.4	< 0.03	6.00E-24	0.2
W UM a	CC Com	90	0.105	0.7	0.7	6.00E-22	0.5

THE UNIVERSITY OF BIRMINGHAM

Galactic WD binaries



(Nelemans et al, 2001)

- LISA is expected to provide the largest observational sample of white dwarfs (WDs)
  - Very large number in frequency space

$$\frac{dN}{df} = 2\times 10^{8}\, Hz^{-1}\left(\frac{0.001\, Hz}{f}\right)^{11/3}$$

- WDs are detected as
  - Individual deterministic signals (primarily for f > 3 mHz)
  - Astrophysical foreground (for f < 3 mHz large number of sources per frequency bin)

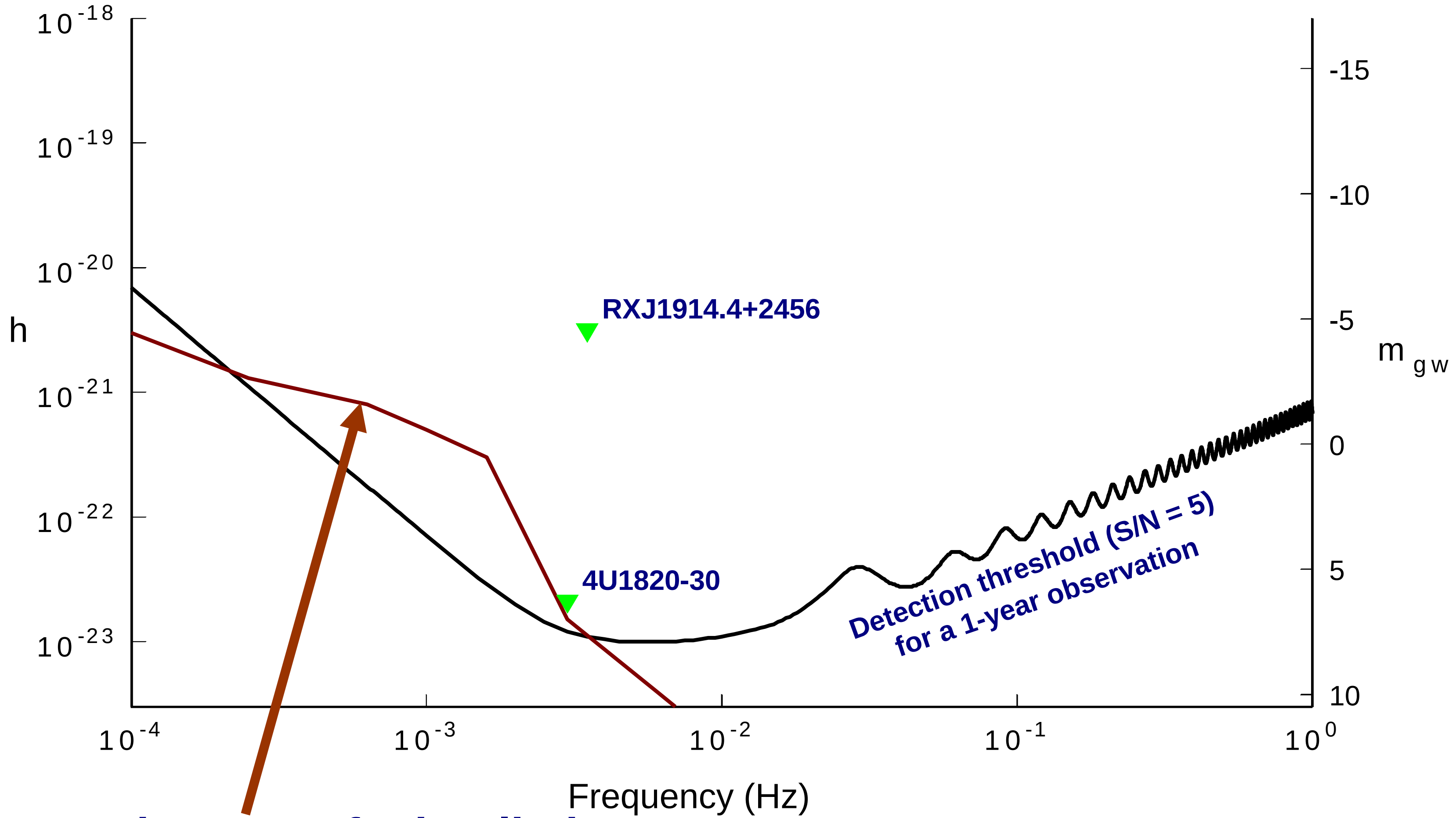
Galactic WD (/NS) binaries

Type	Birth rate (year^{-1})	Resolved systems	With frequency change
(wd, wd)	2.9×10^{-2}	12 163	560
AM CVn	1.8×10^{-3}	10 117	49
(ns, wd)	1.4×10^{-4}	21	3
(ns, ns)	3.2×10^{-5}	1	0
(bh, wd)	3.8×10^{-5}	1	0
(bh, ns)	1.0×10^{-5}	0	0
Total		22 303	614

(Nelemans et al, 2001; Nelemans, 2002)

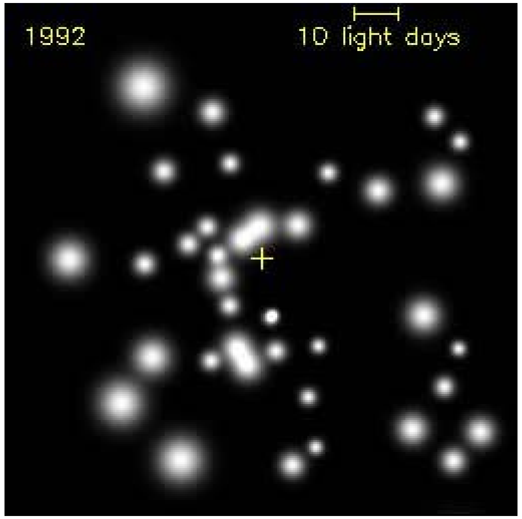
- Map (partially 3D) of WDs in the galaxy
- For ~100 systems, studies of:
  - Tidal interaction
  - Mass transfer
- If follow-on optical observations are available (for some objects):information on M-R relation (Cooray and Seto, 2004)

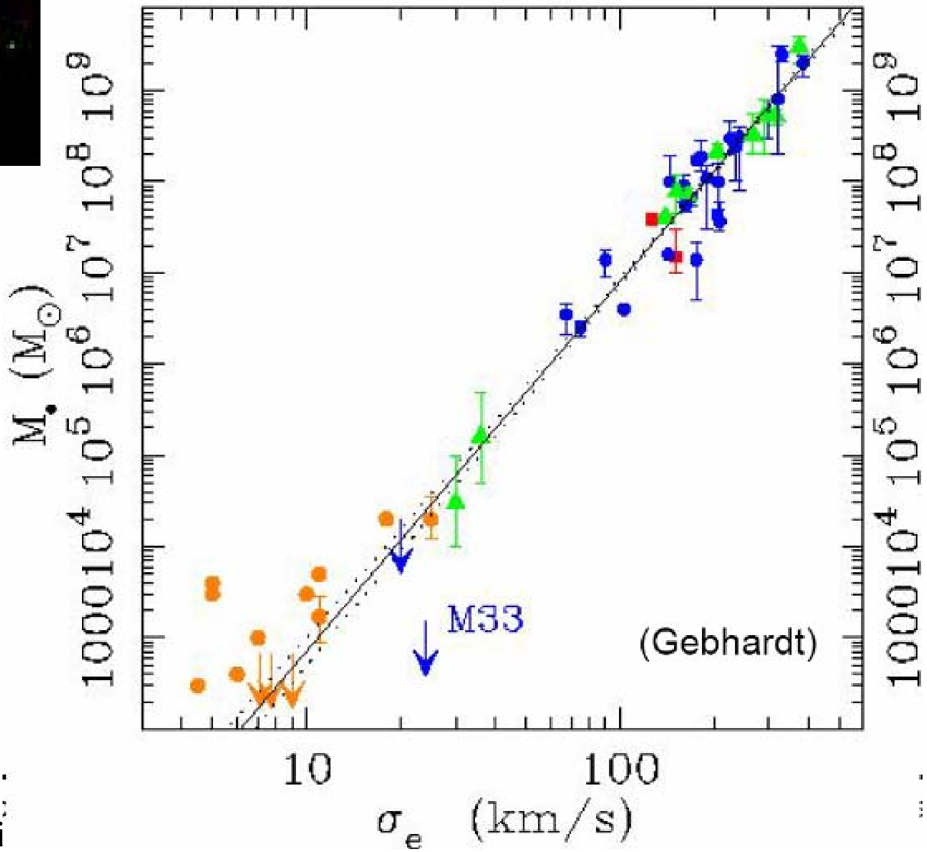
LTP



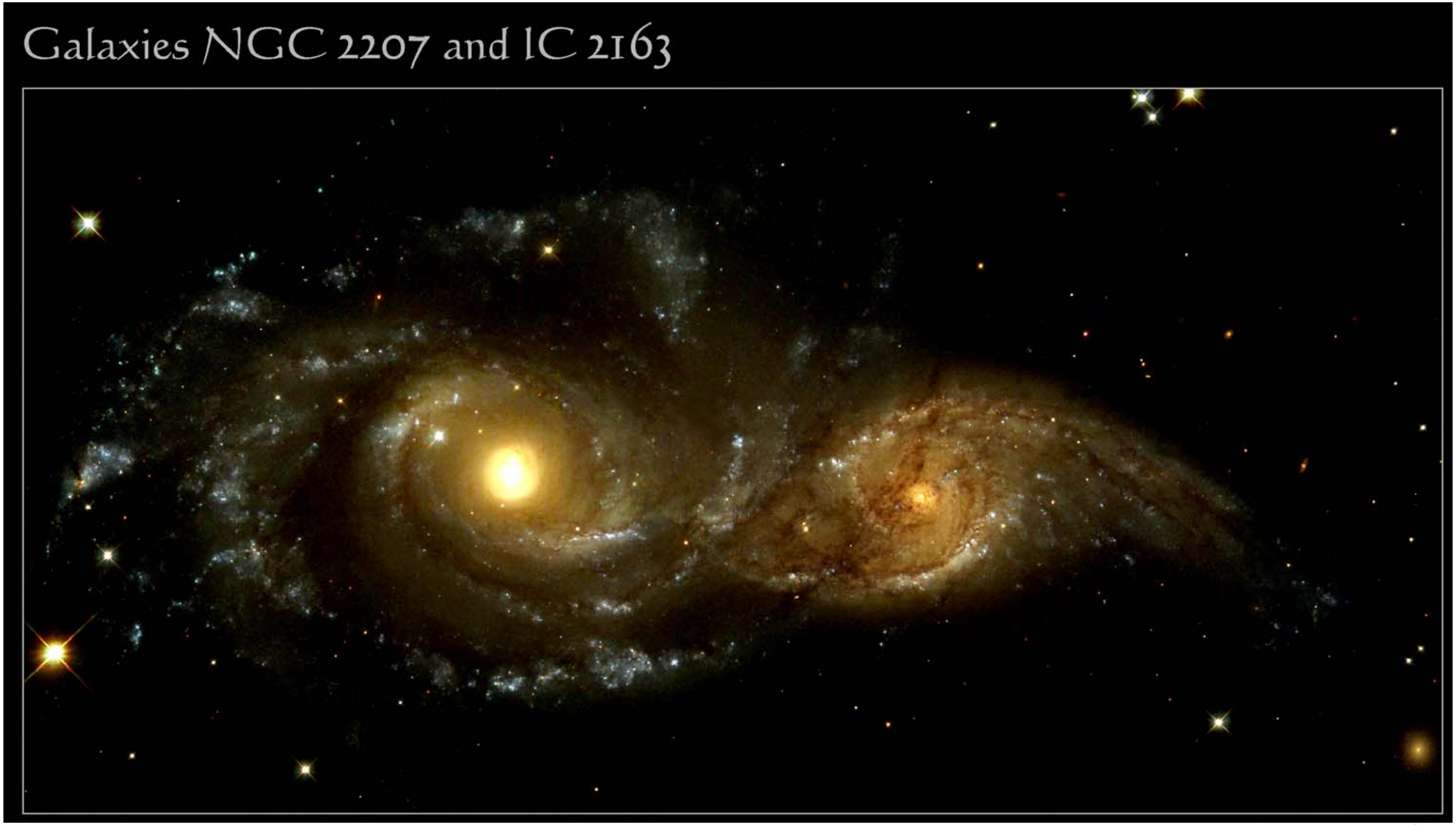
WD Binary confusion limit

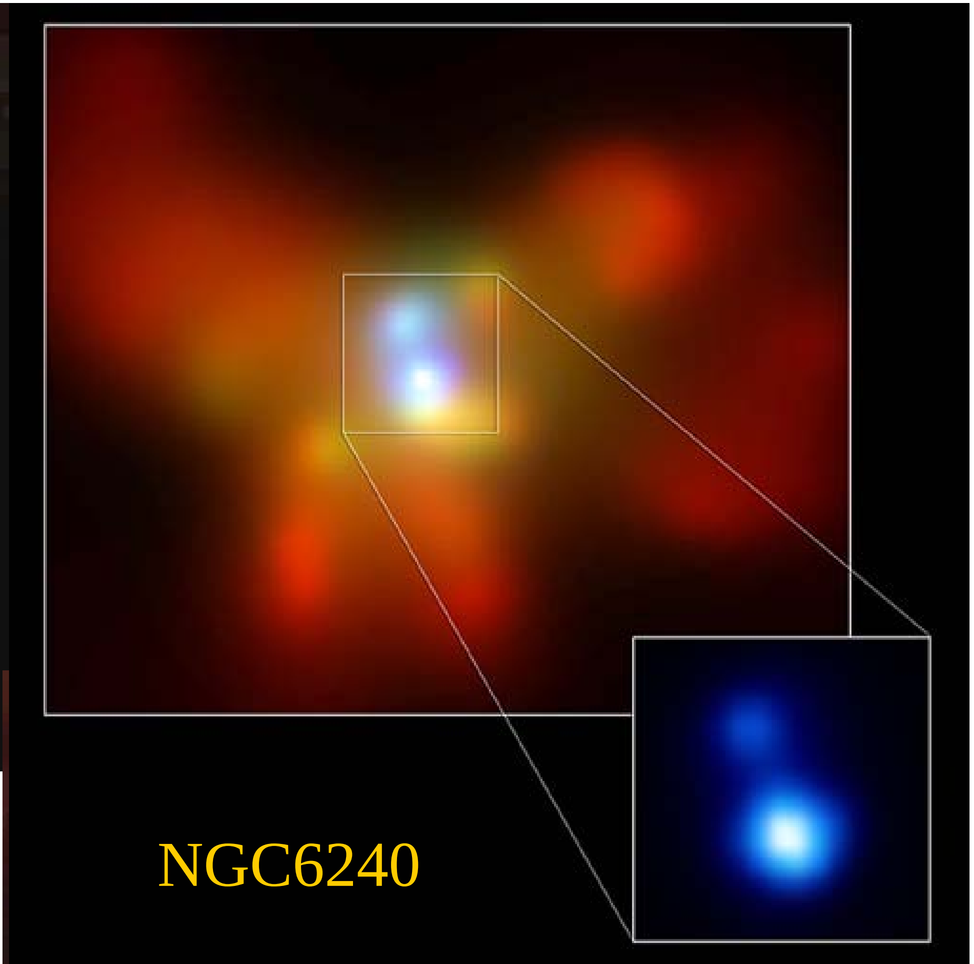
Supermassive Black-Hole Mergers



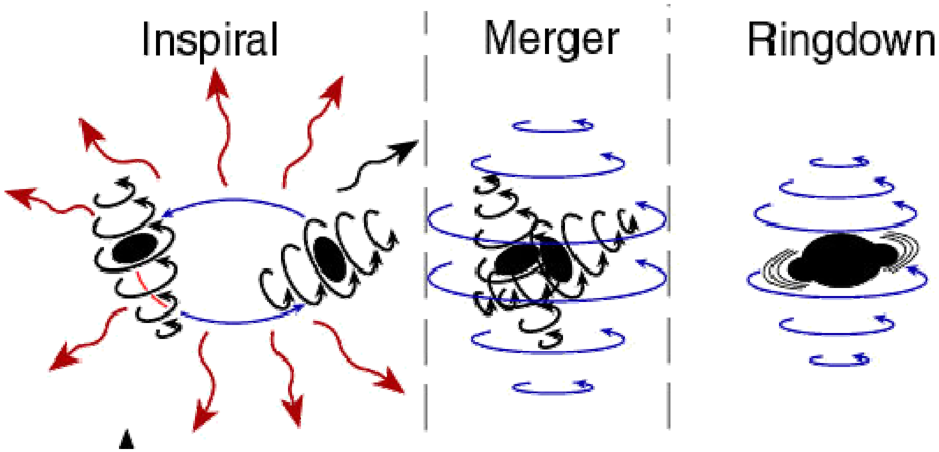


SMBH Binary formation





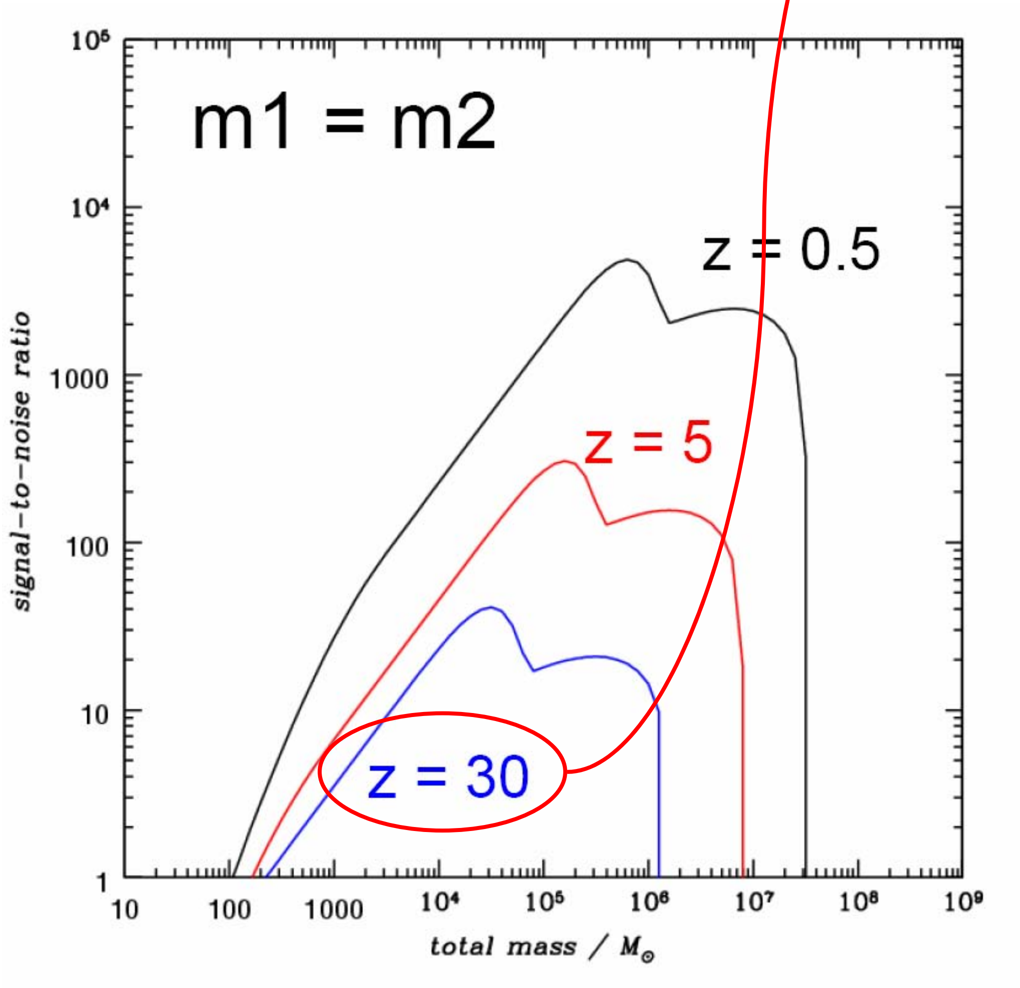
NGC6240



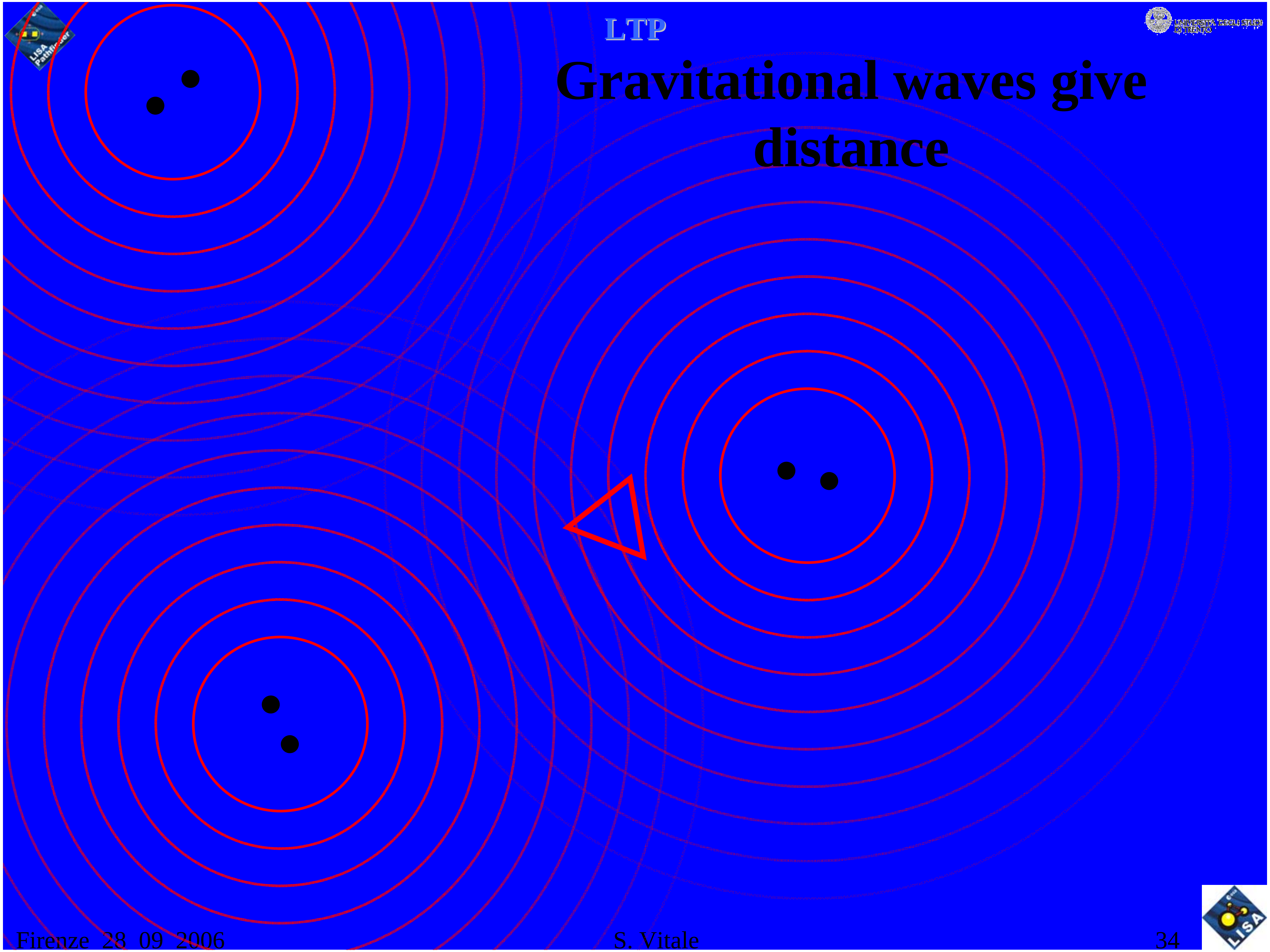
Inspiral
Merger
Ringdown

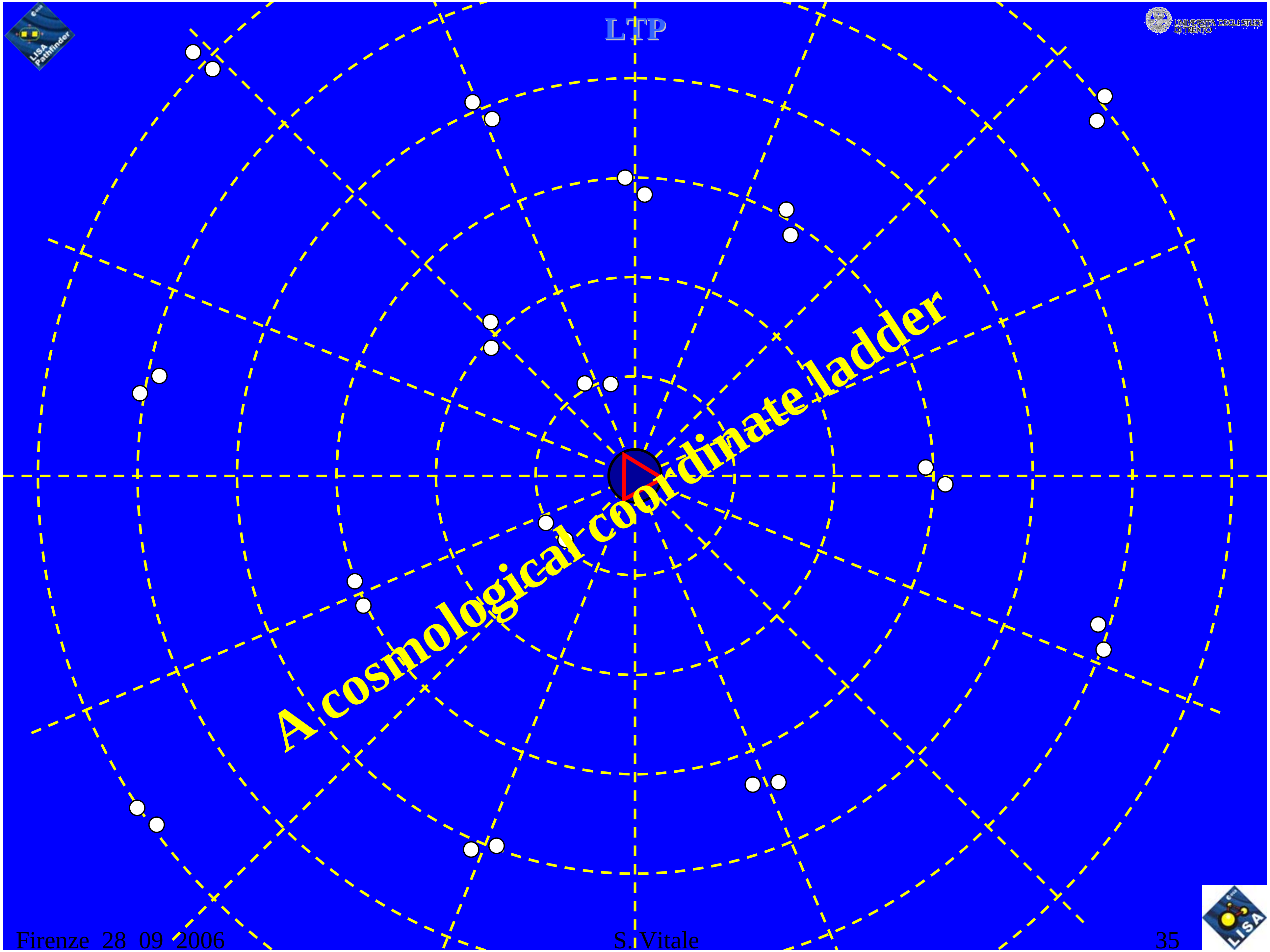
So bright to be visible
"everywhere" in the Universe

Angular resolution up to 1'

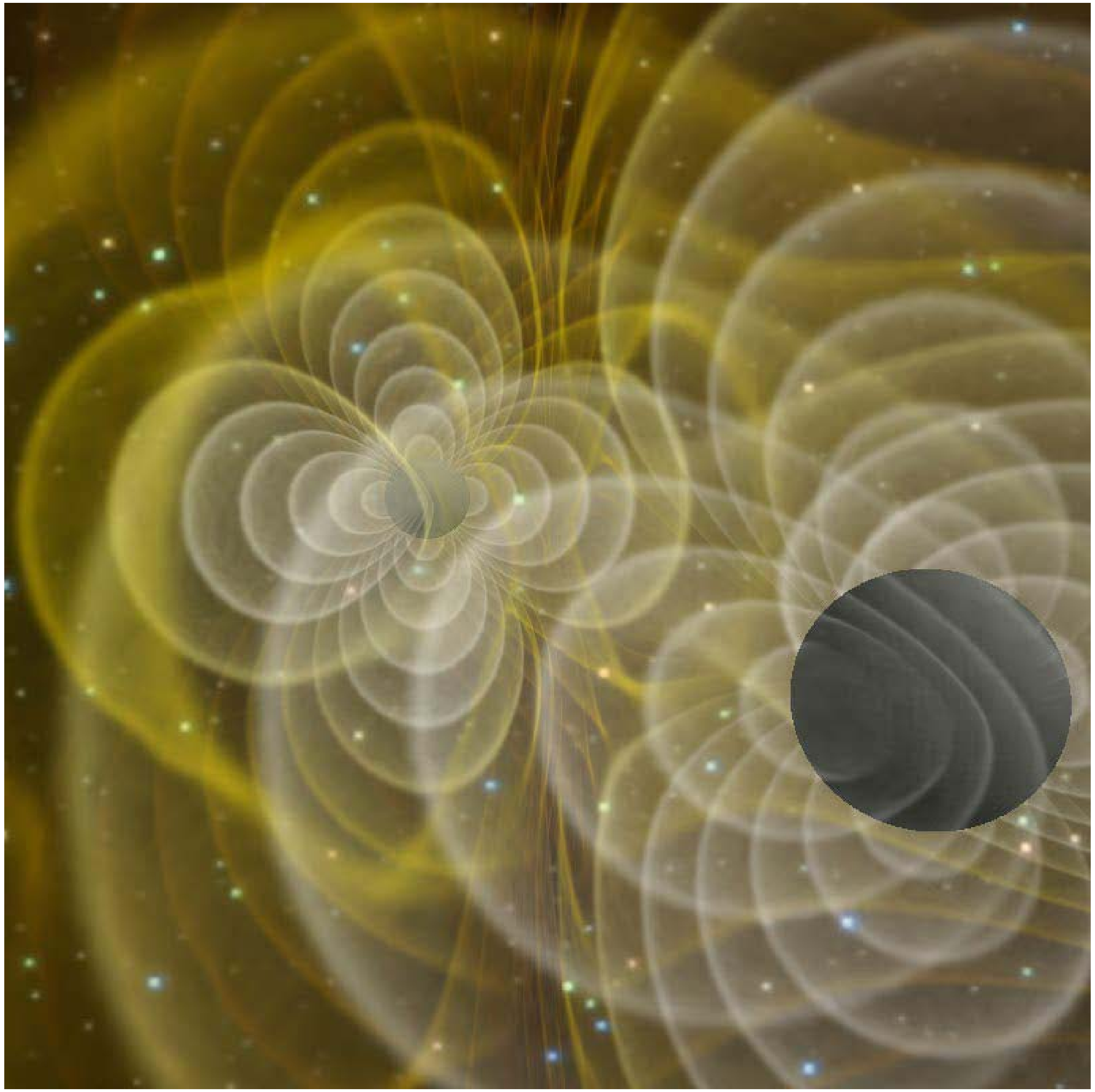


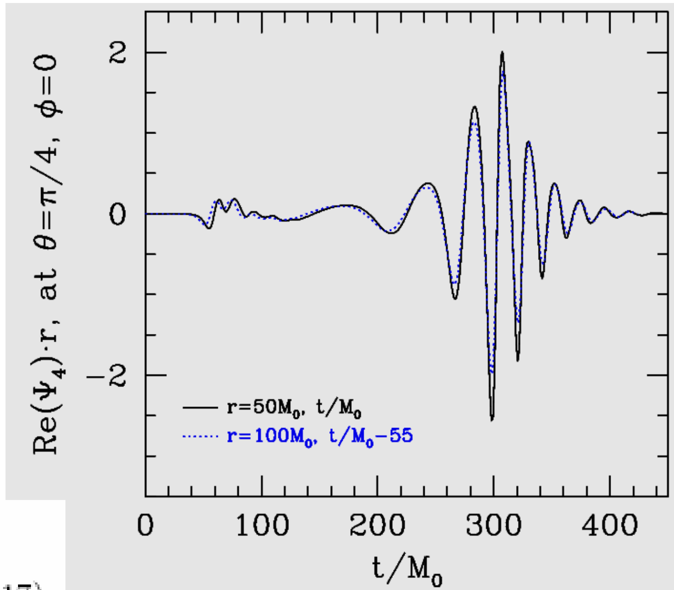
Gravitational waves give distance




A cosmological coordinate ladder

A recent result in numerical relativity:





Although the mass of the system must decrease because of radiative losses,

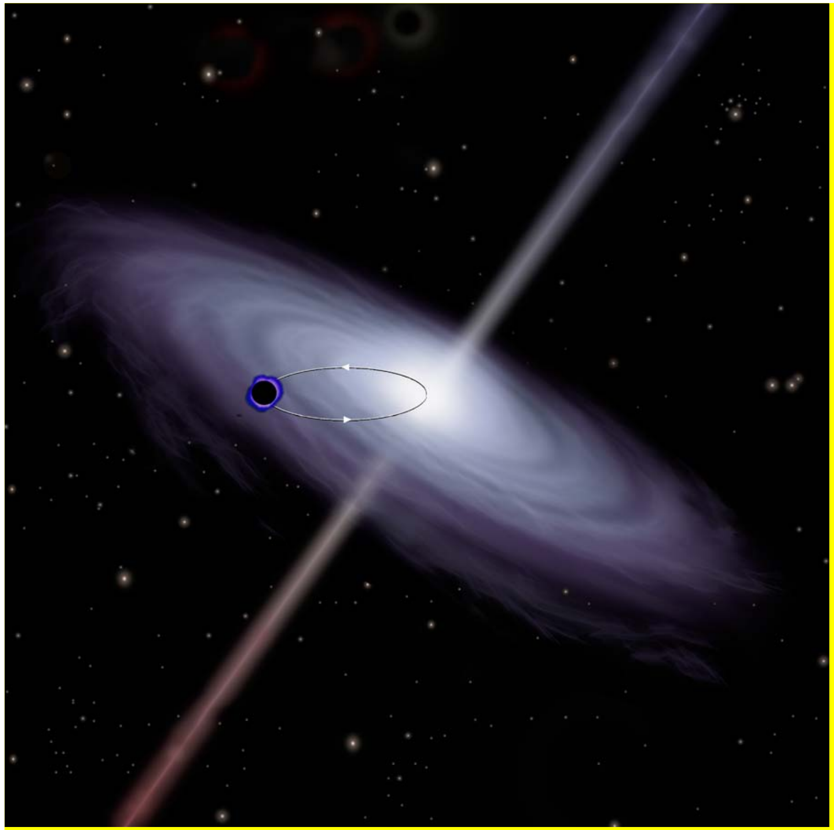
$$M_i = M_1 + M_2 > M_f \ , \tag{17}$$

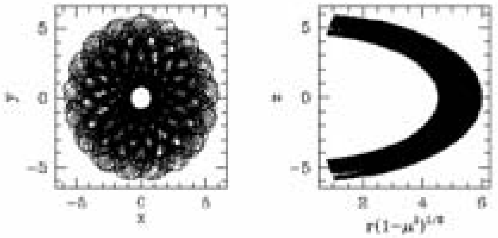
the area of all event horizons in the system must *increase* during the coalescence:

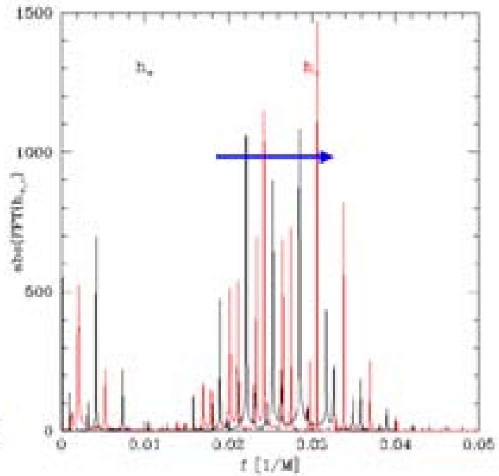
$$A_i = A_1 + A_2 < A_f \ . \tag{18}$$

LTP

Signal from EMRIs



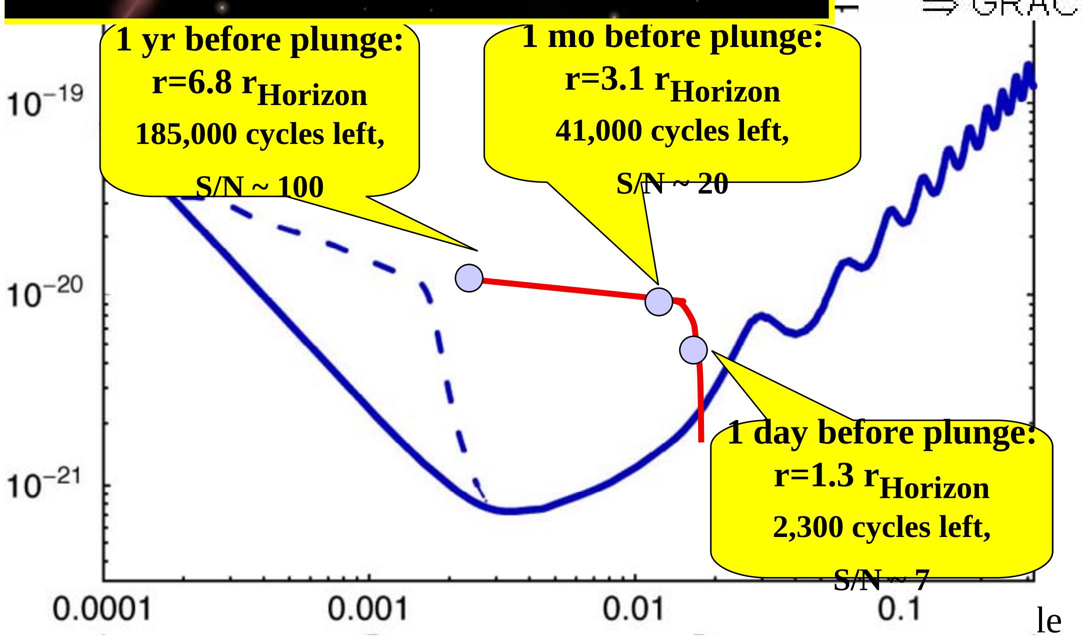




Frequencies sweep and shift slowly as compact object spirals in, mapping space-time outside the horizon.

⇒ Like a Geodesy satellite mapping Geopotential!

⇒ GRACE for Black Holes!

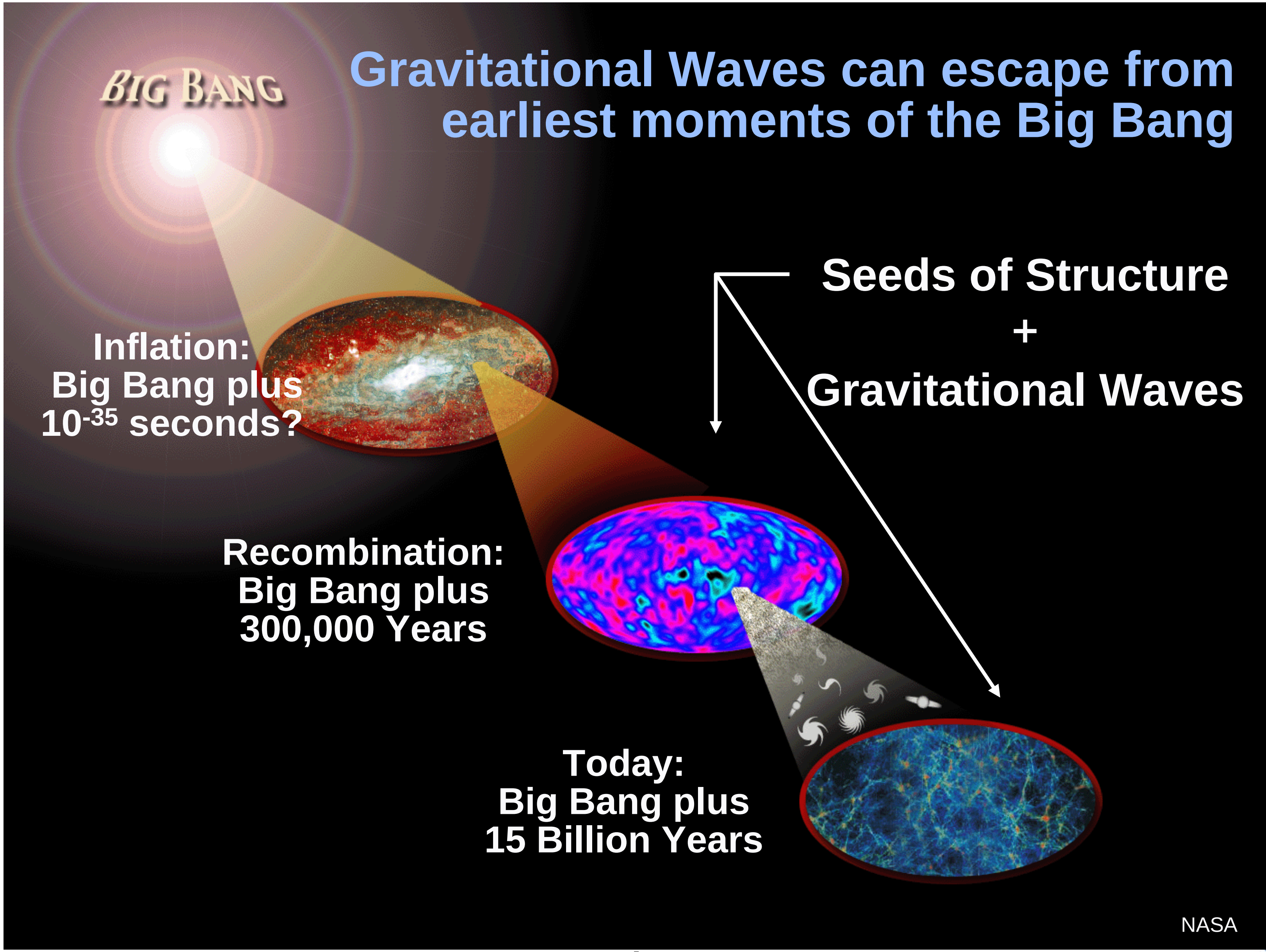


Do Black Holes really have no hair?

$M_\bullet$	m	LISA		Short LISA	
		Optimistic	Pessimistic	Optimistic	Pessimistic
300 000	0.6	8	0.7	14	1
300 000	10	739	89	902	115
300 000	100	1*	1*	1*	1*
1 000 000	0.6	94	9	80	7
1 000 000	10	1000*	800	1000*	502
1 000 000	100	1*	1*	1*	1*
3 000 000	0.6	67	2	11	0.3
3 000 000	10	1700*	134	816	25
3 000 000	100	2*	1*	2*	1

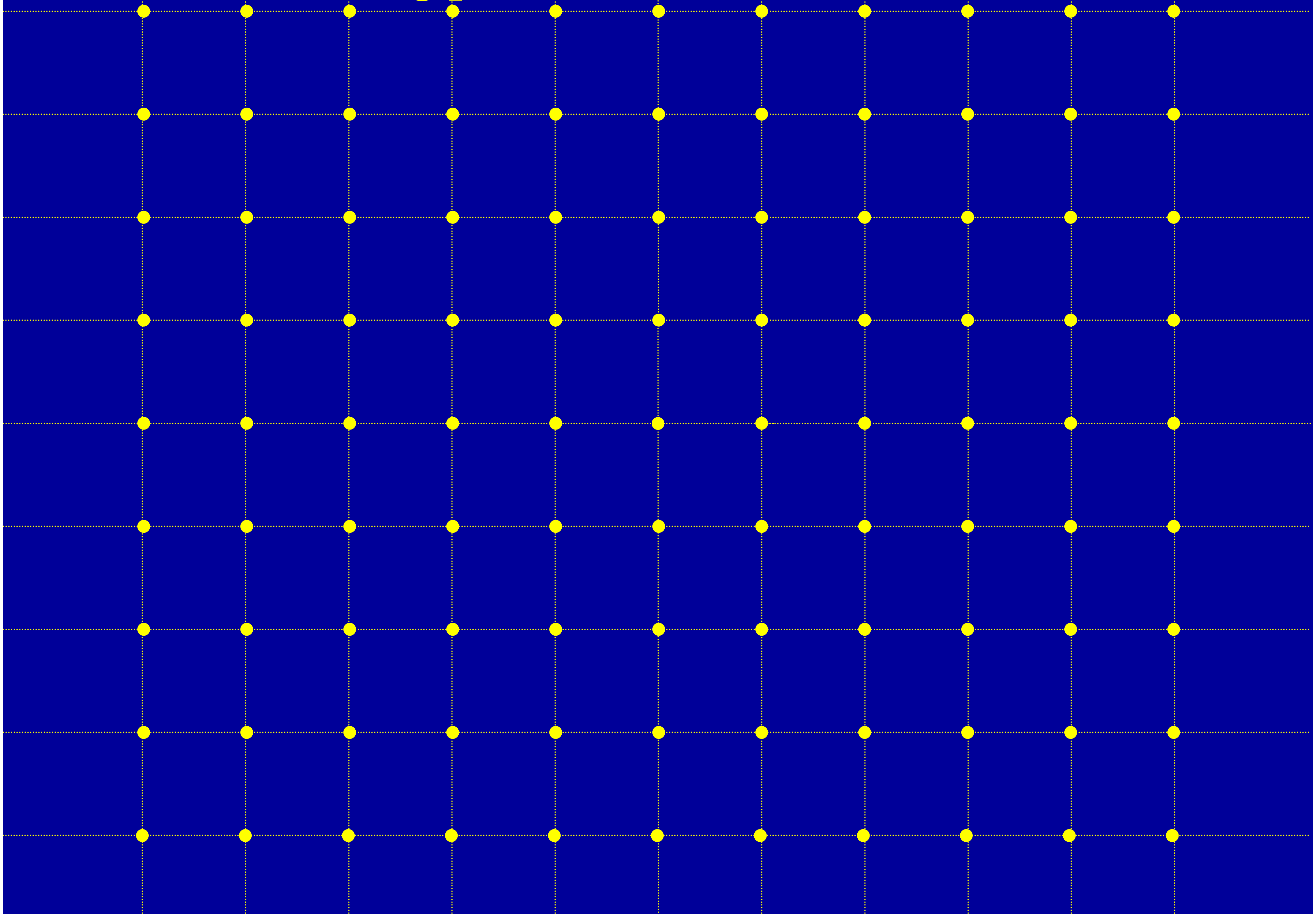
TABLE X: Columns 3-6 give the number of EMRI events LISA can see for merger of body of mass. Columns 3-4 are for the normal 5×10^6km baseline. Columns 5-6 are for a 1.6×10^6km baseline. *Optimistic* uses all 3 TDI variables for 5 years, with ideal white dwarf background removal. *Pessimistic* uses only a single pair of arms for 3 years, with current gCLEAN white dwarf removal. m (column 2) into supermassive black hole of mass $M_\bullet$ (column 1). Entries marked with a * are $z < 1$ lower limits computed from equation 43, since LISA can detect all sources out to $z \gg 1$, and evolution is unknown. All other entries computed from the Euclidean equation 42, since LISA cannot see the sources to cosmological distances.

Cutler, Phinney et al.

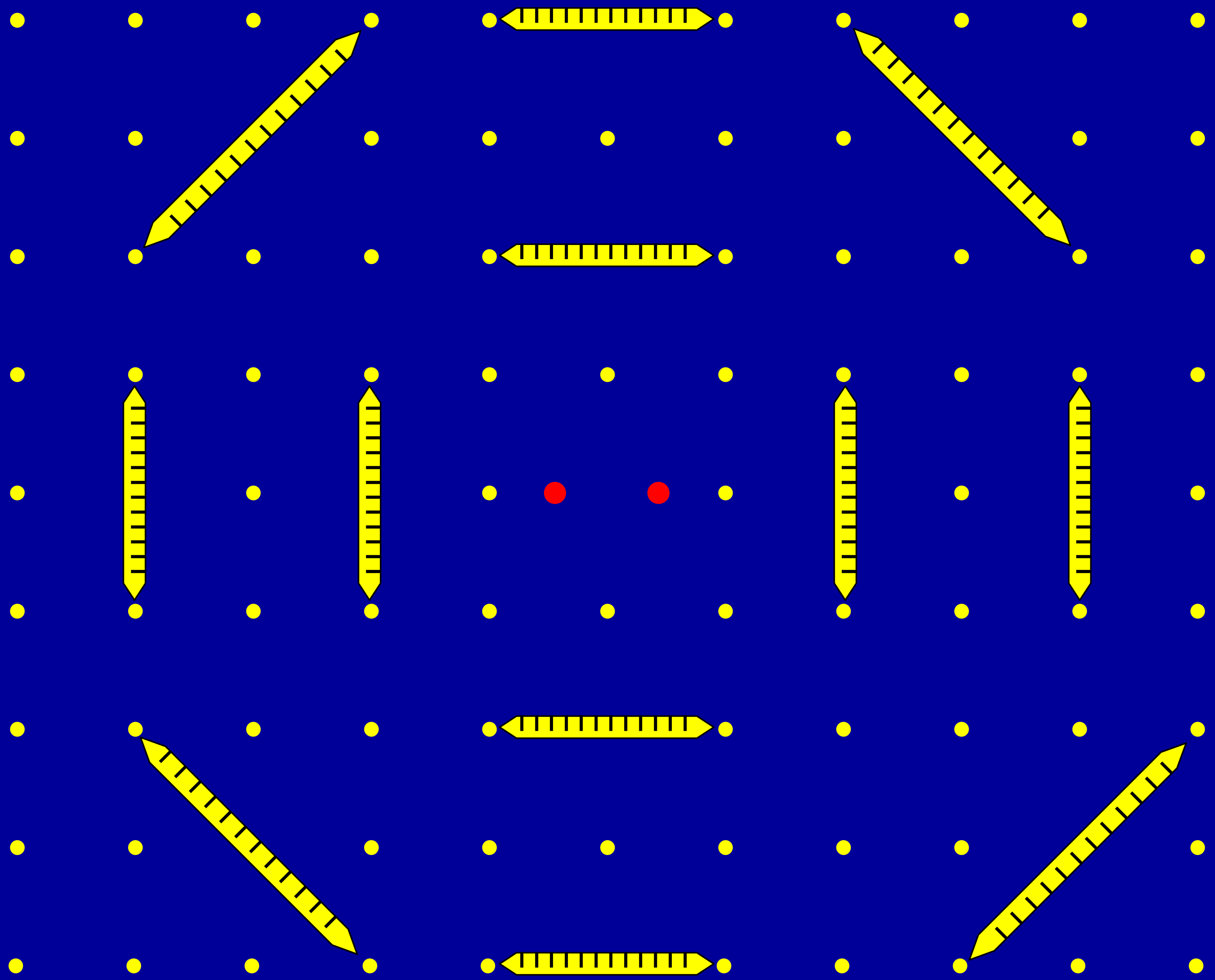

BIG BANG
Gravitational Waves can escape from earliest moments of the Big Bang
Seeds of Structure
+
Gravitational Waves
Inflation:
Big Bang plus
10-35 seconds?
Recombination:
Big Bang plus
300,000 Years
Today:
Big Bang plus
15 Billion Years
NASA

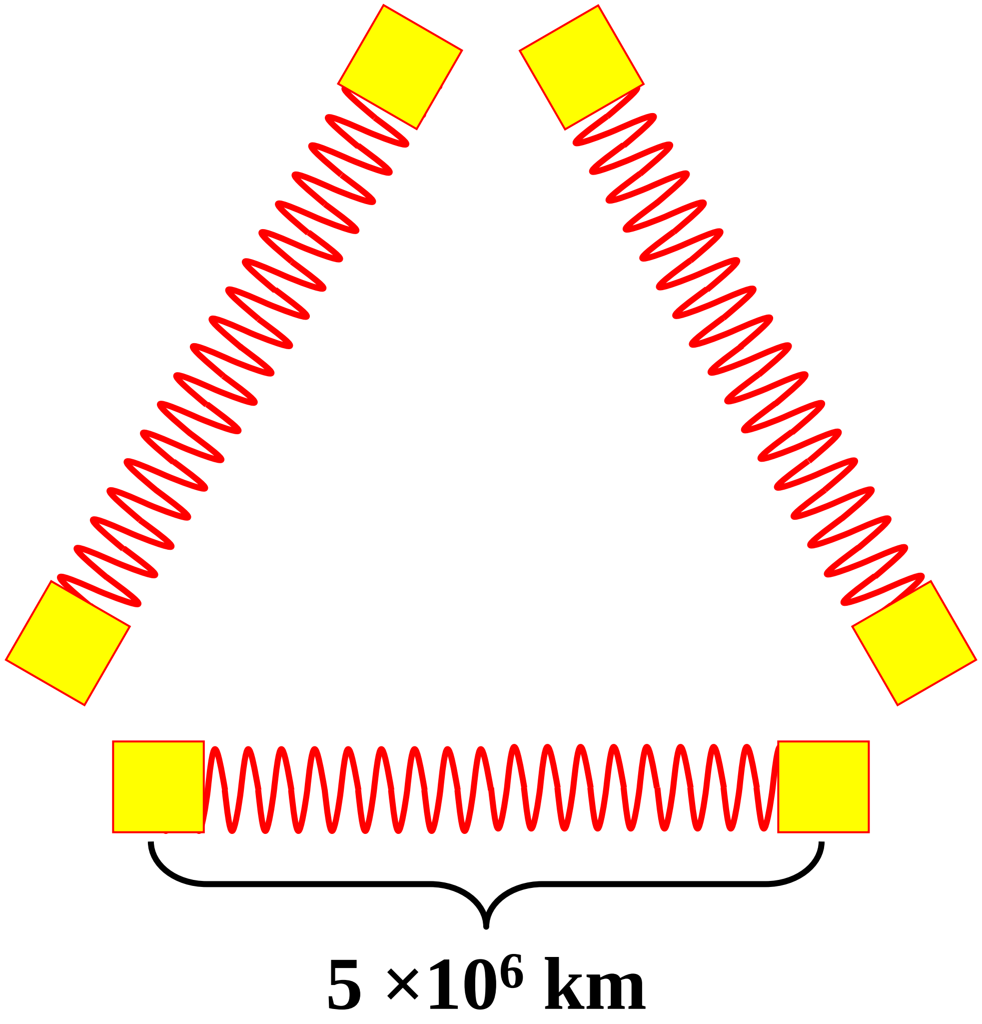
Is LISA feasible?

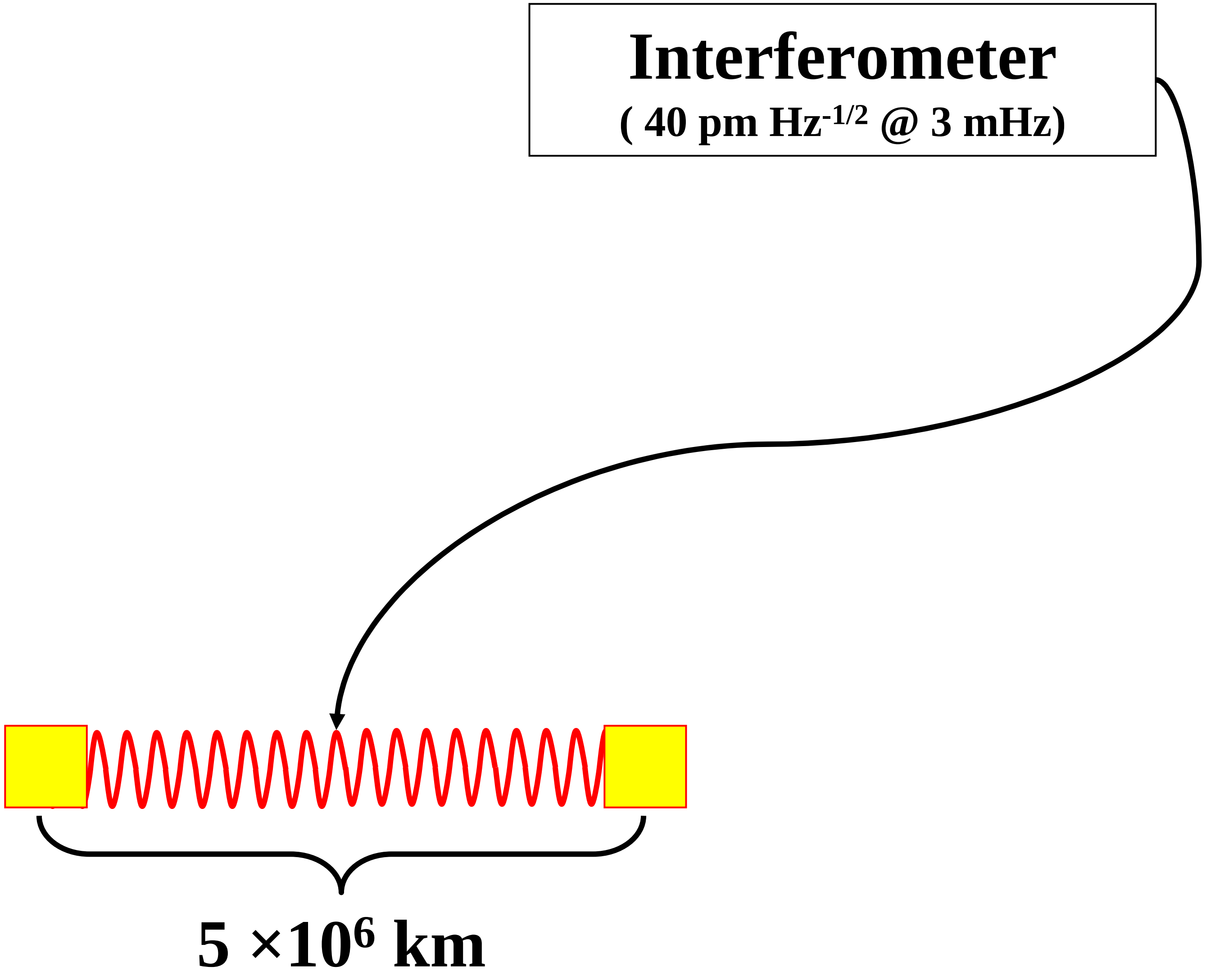
Free falling particles mark TT coordinates



Mass-energy distort distances (metric tensor)




5×10^6 km


Interferometer
(40 pm $Hz^{-1/2}$ @ 3 mHz)
5×10^{6} km

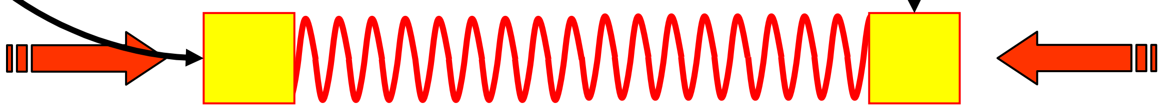
Free falling particles

Parasitic force fluctuations

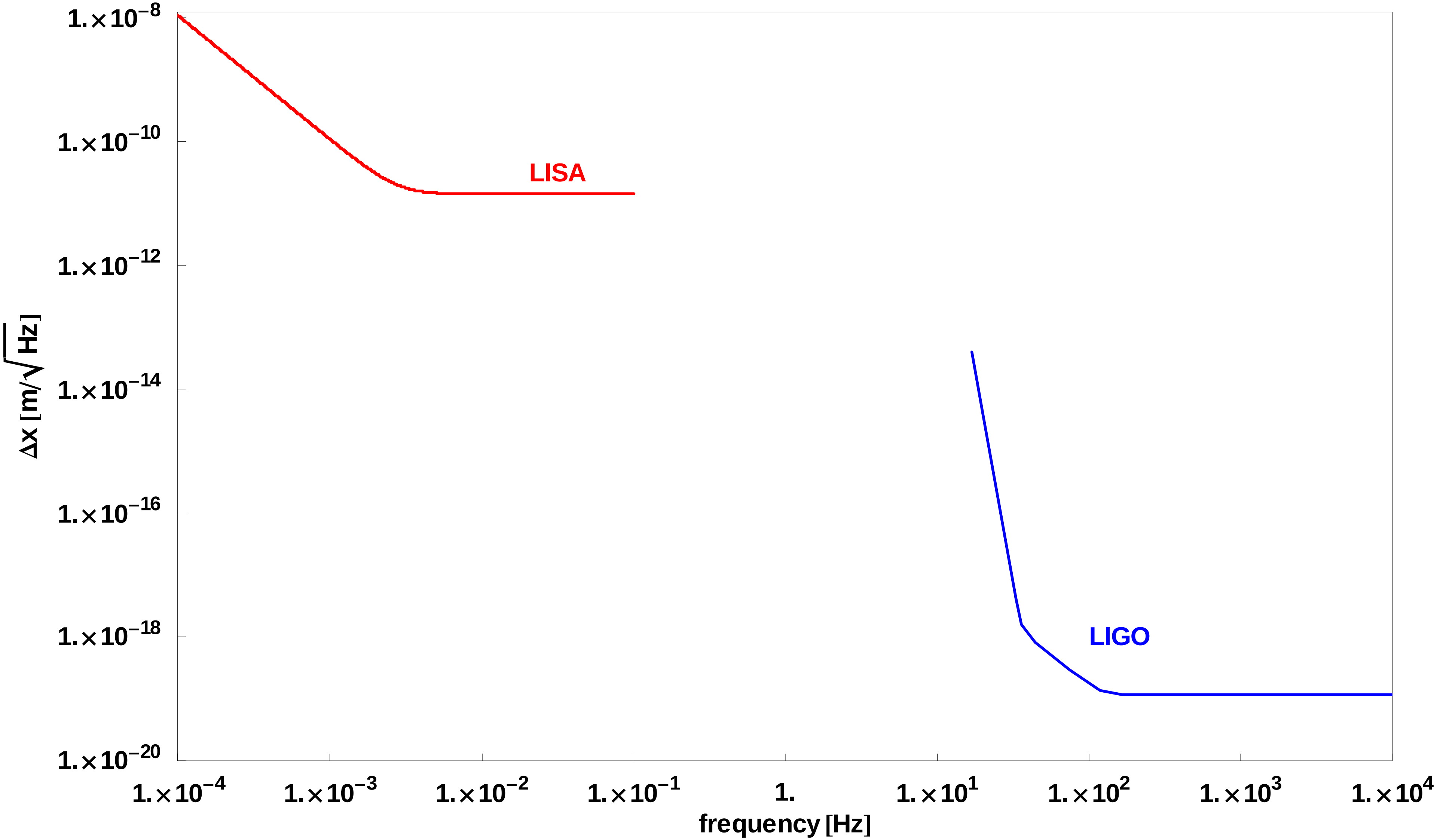
change distances and mimic gravitational waves

No parasitic force (acceleration) beyond

$3\times10^{-15}\,\mathrm{ms^{-2}}/\sqrt{\mathrm{Hz}}$ @ 0.1 mHz (3 hours)

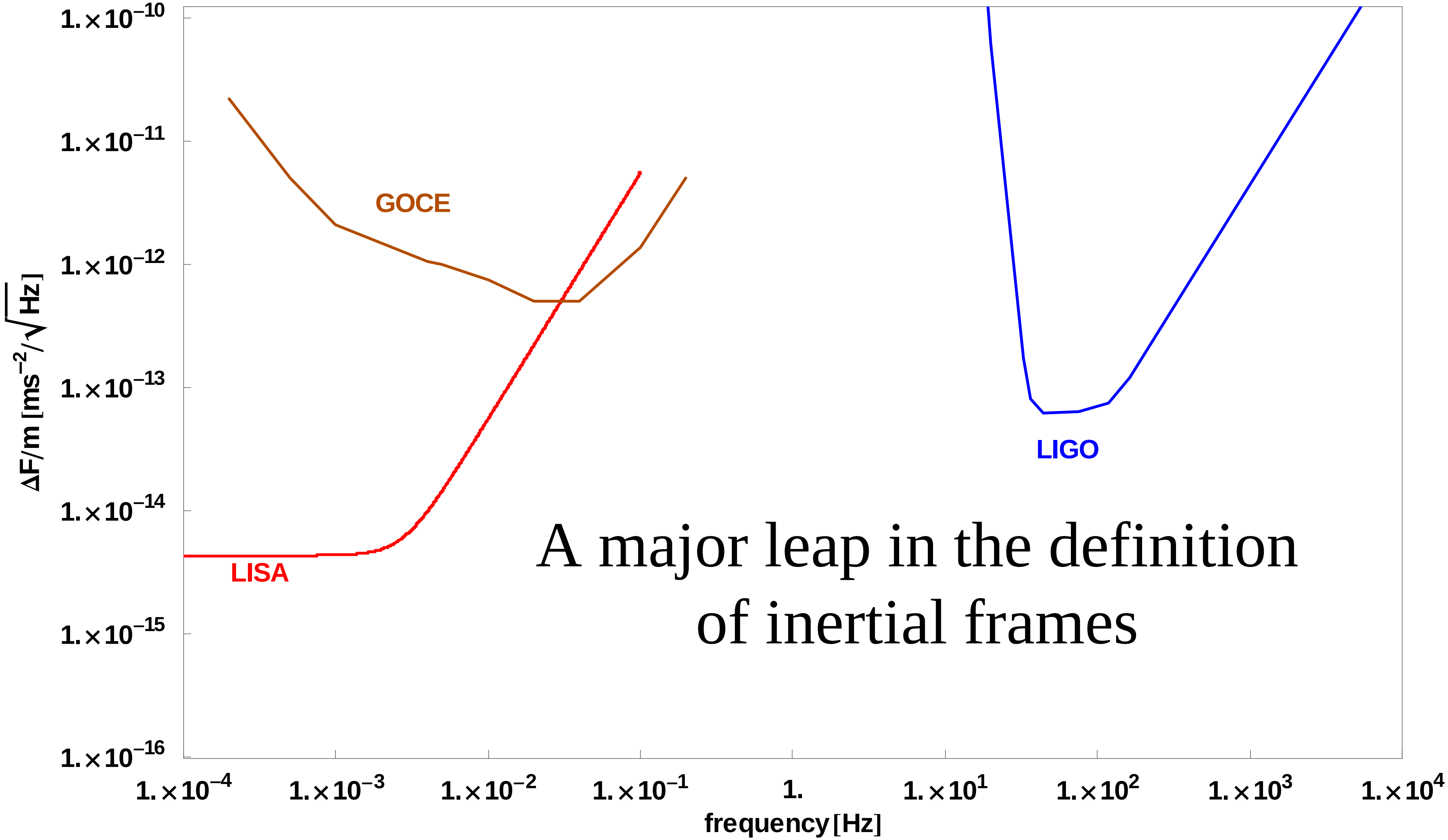


How accurately coordinate frame must be marked by free-falling particles?



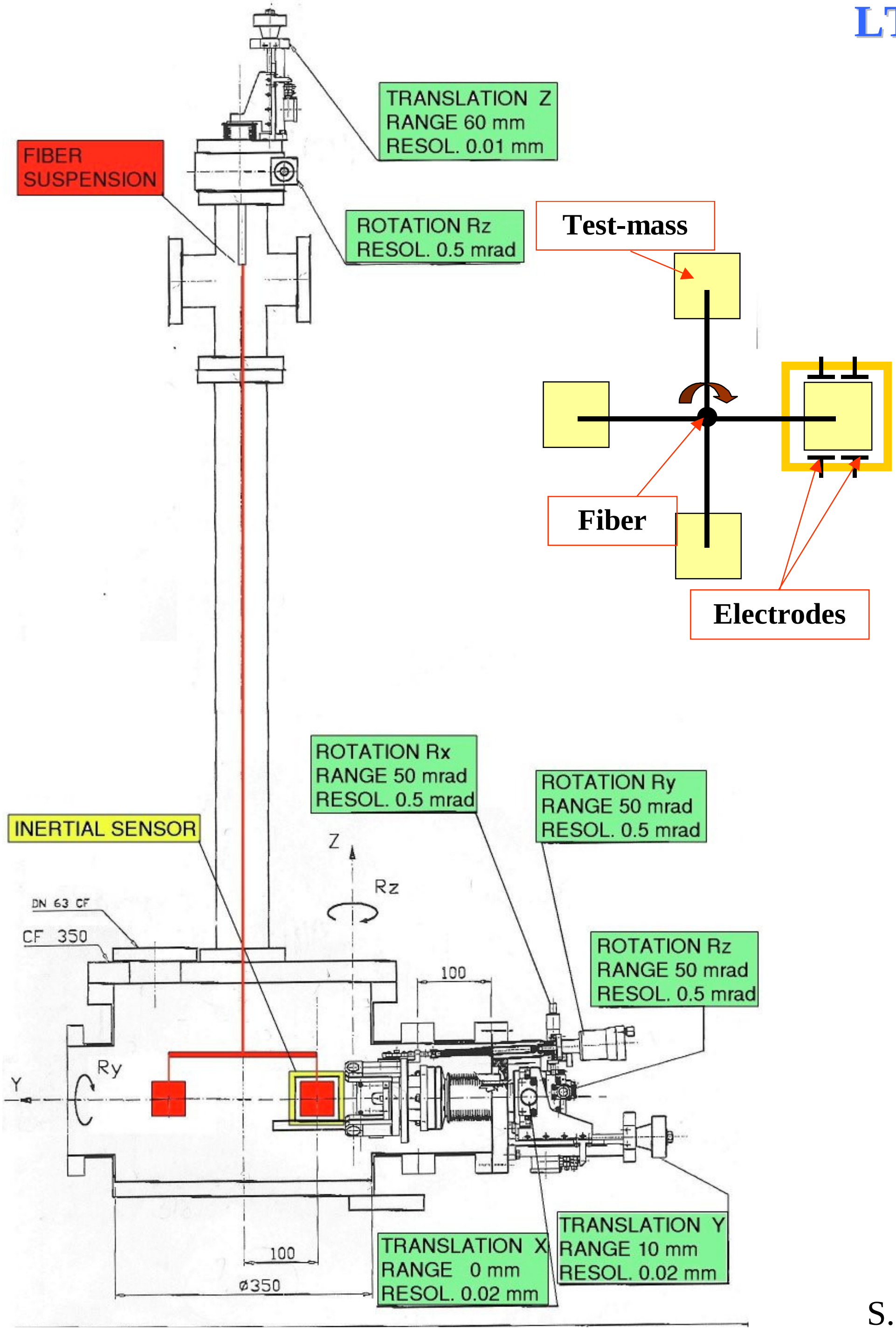
LTP

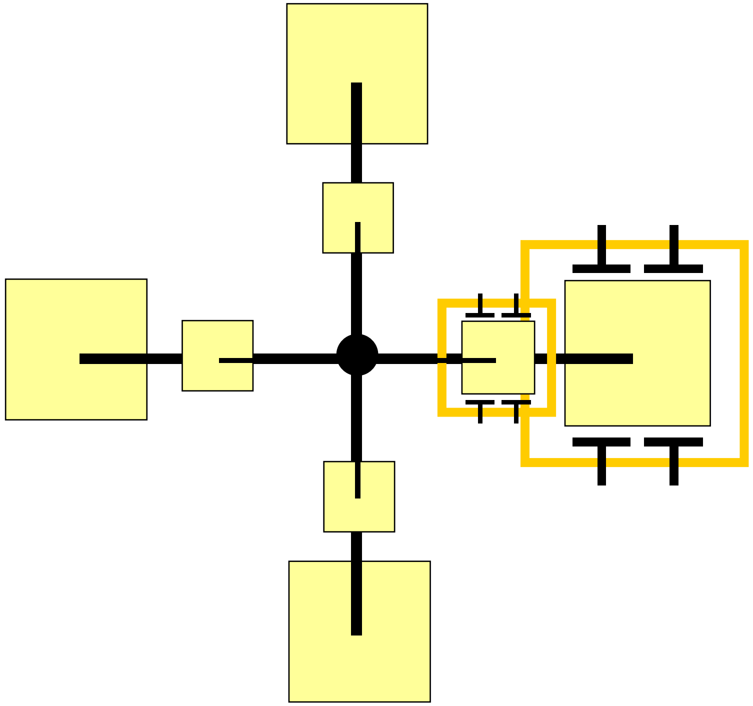
How accurate must be free-fall of particles? (lack of spurious relative acceleration)



A major leap in the definition of inertial frames

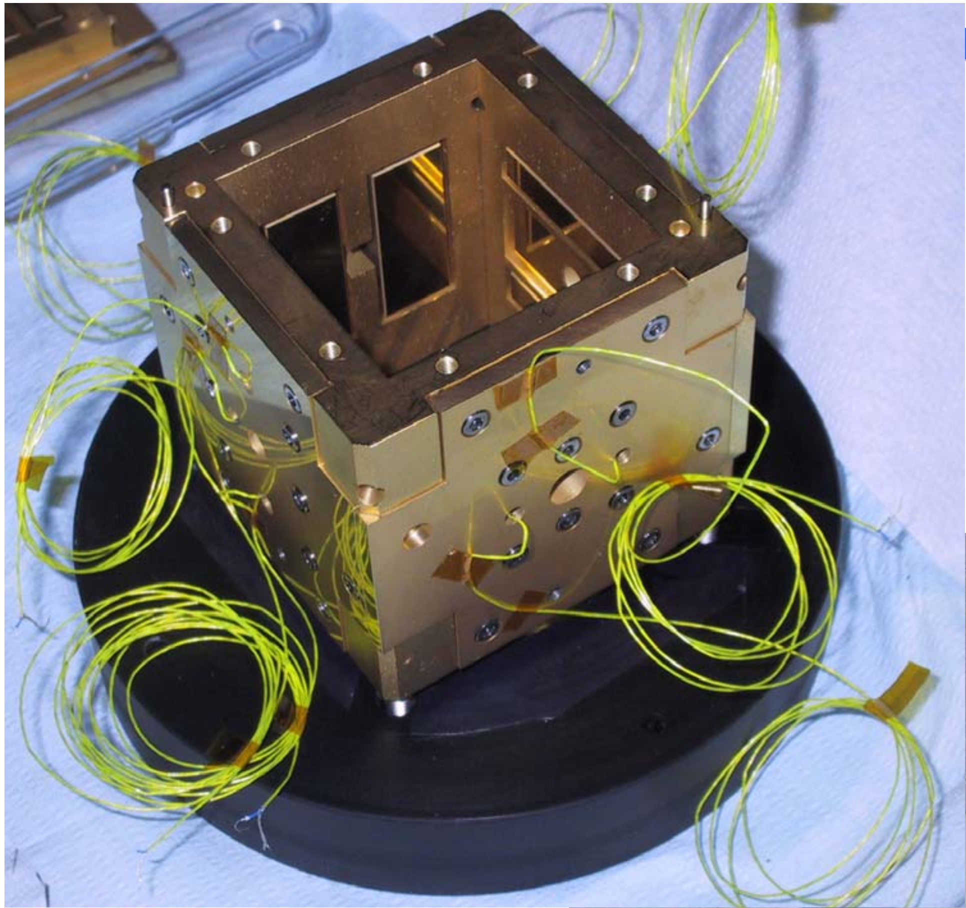
What can be done on ground: torsion pendulum

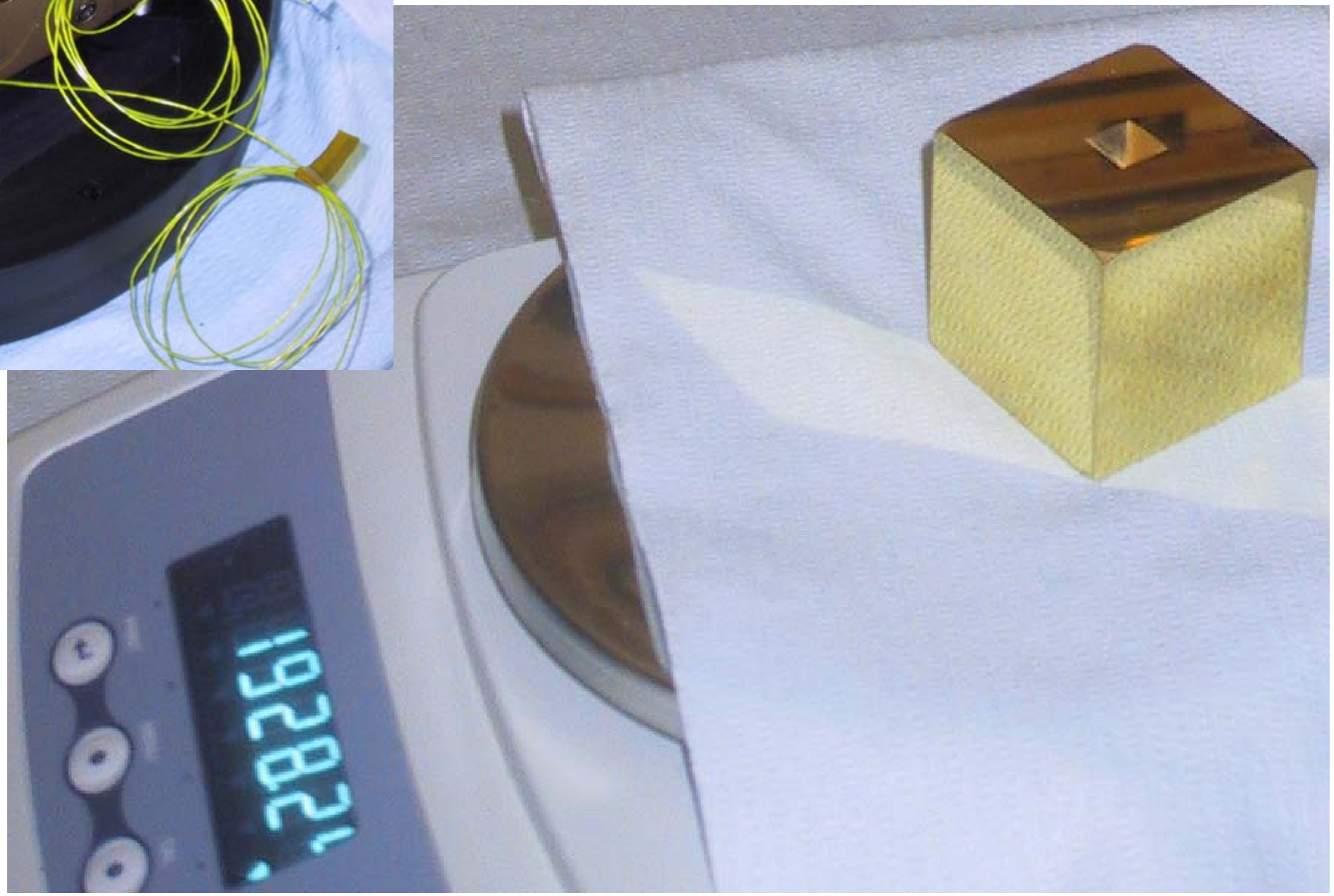


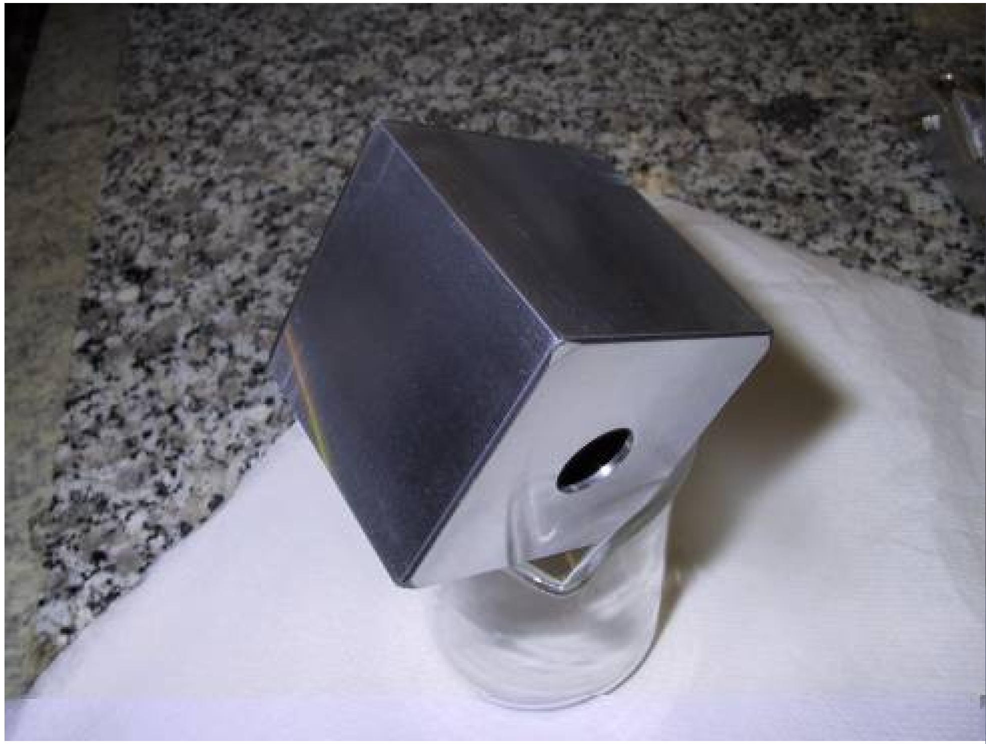


Achieving free motion in the horizontal plane (0 g)

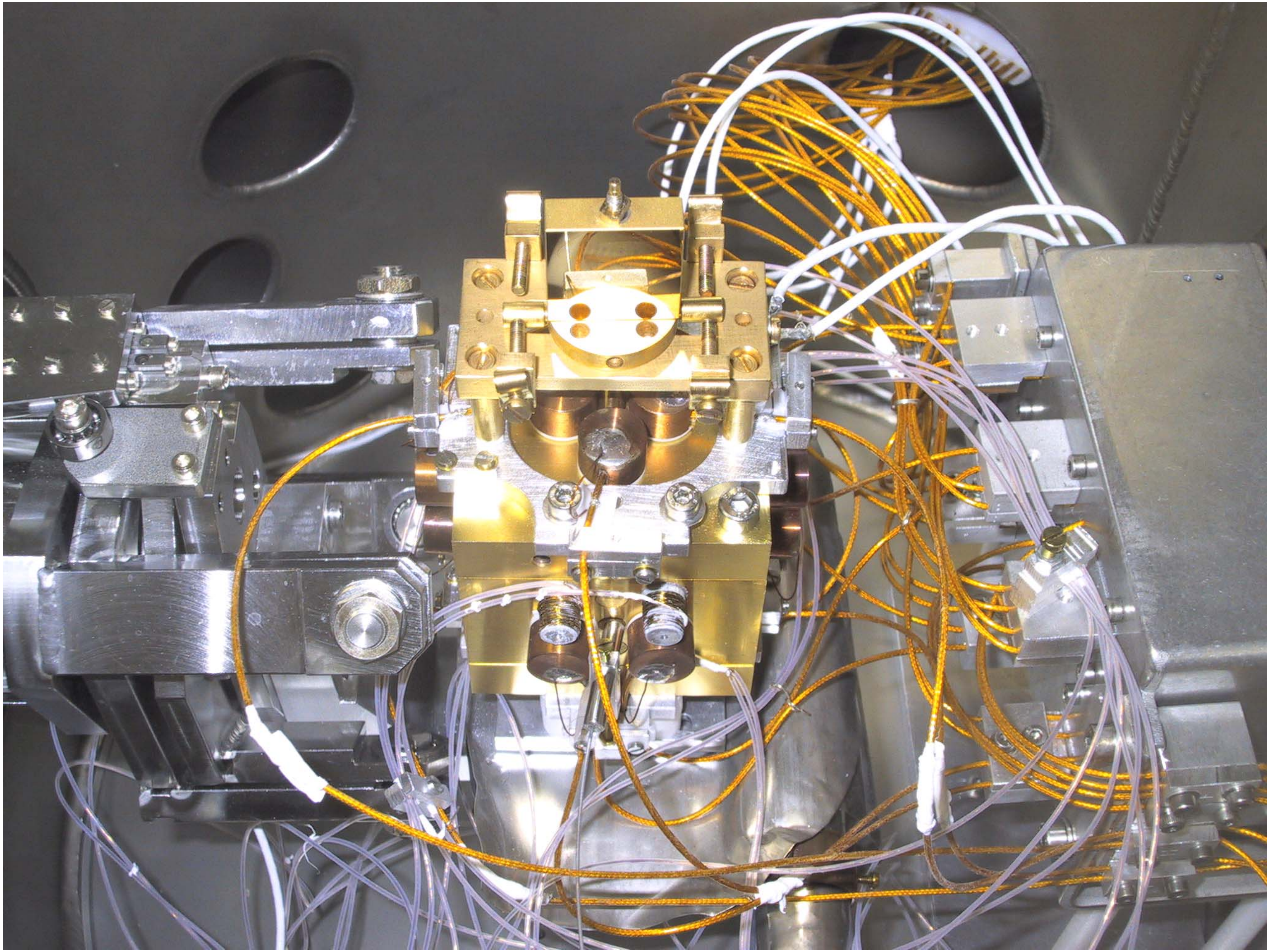
TP



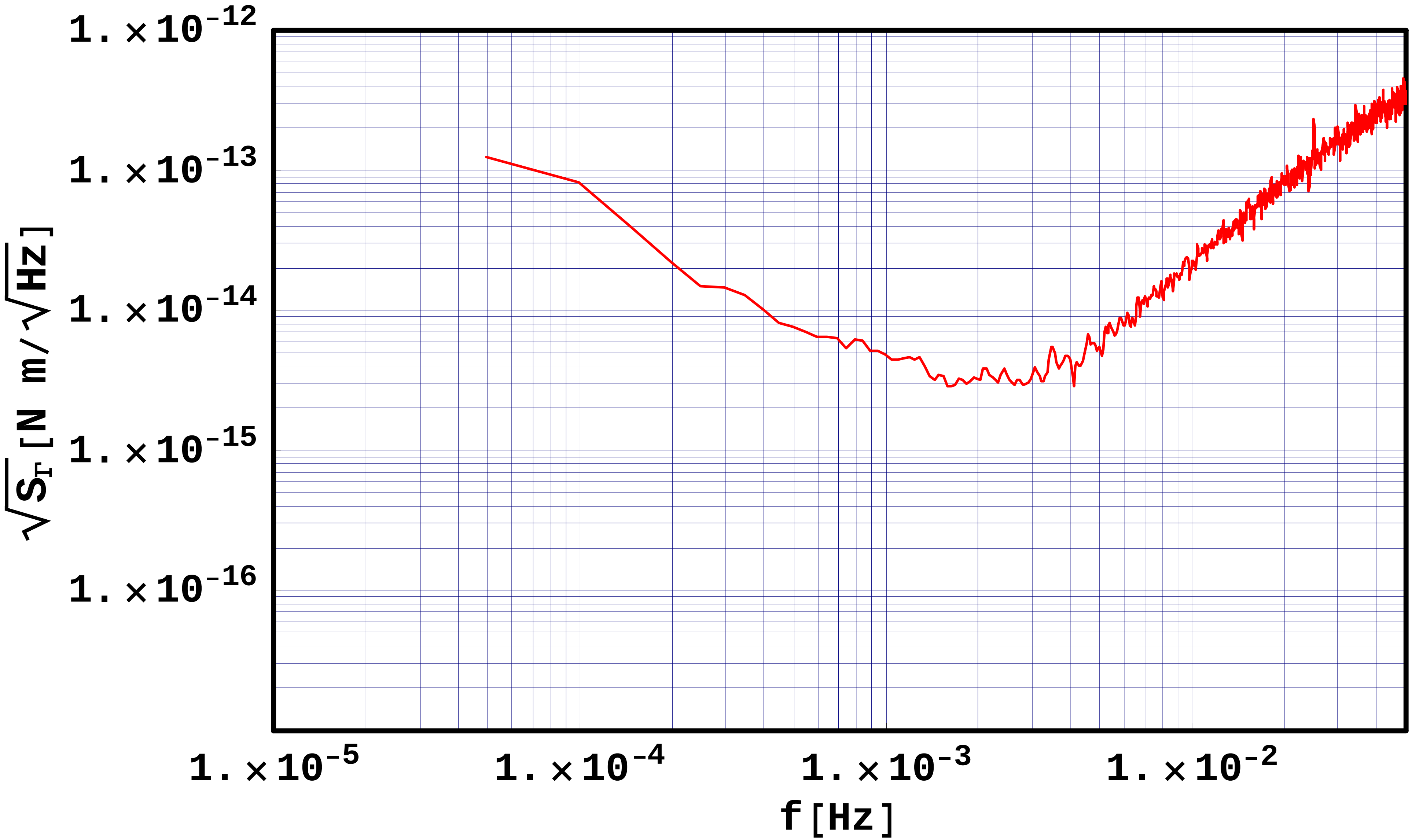




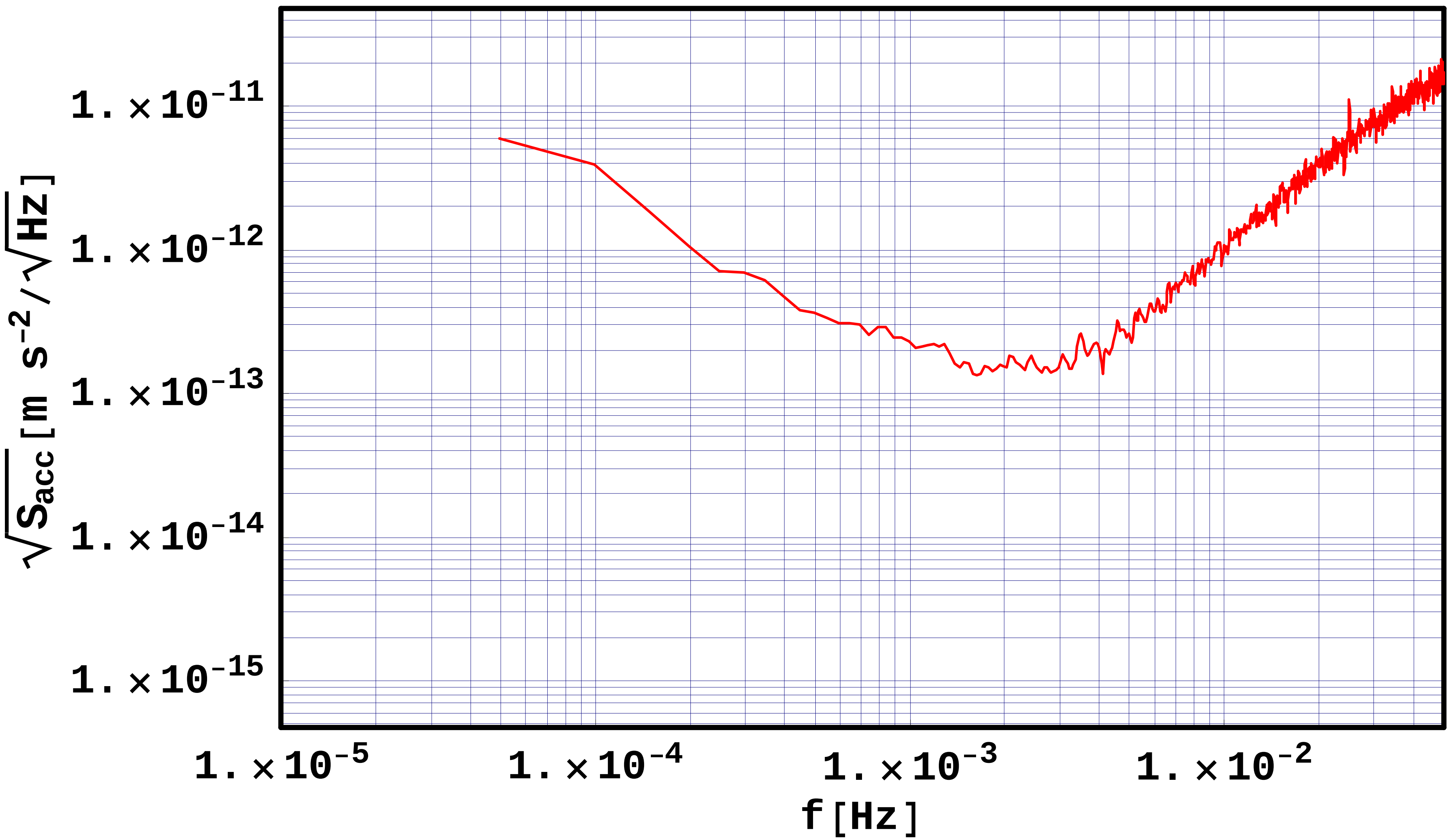
Hollow proof-mass for torsion pendulum testing



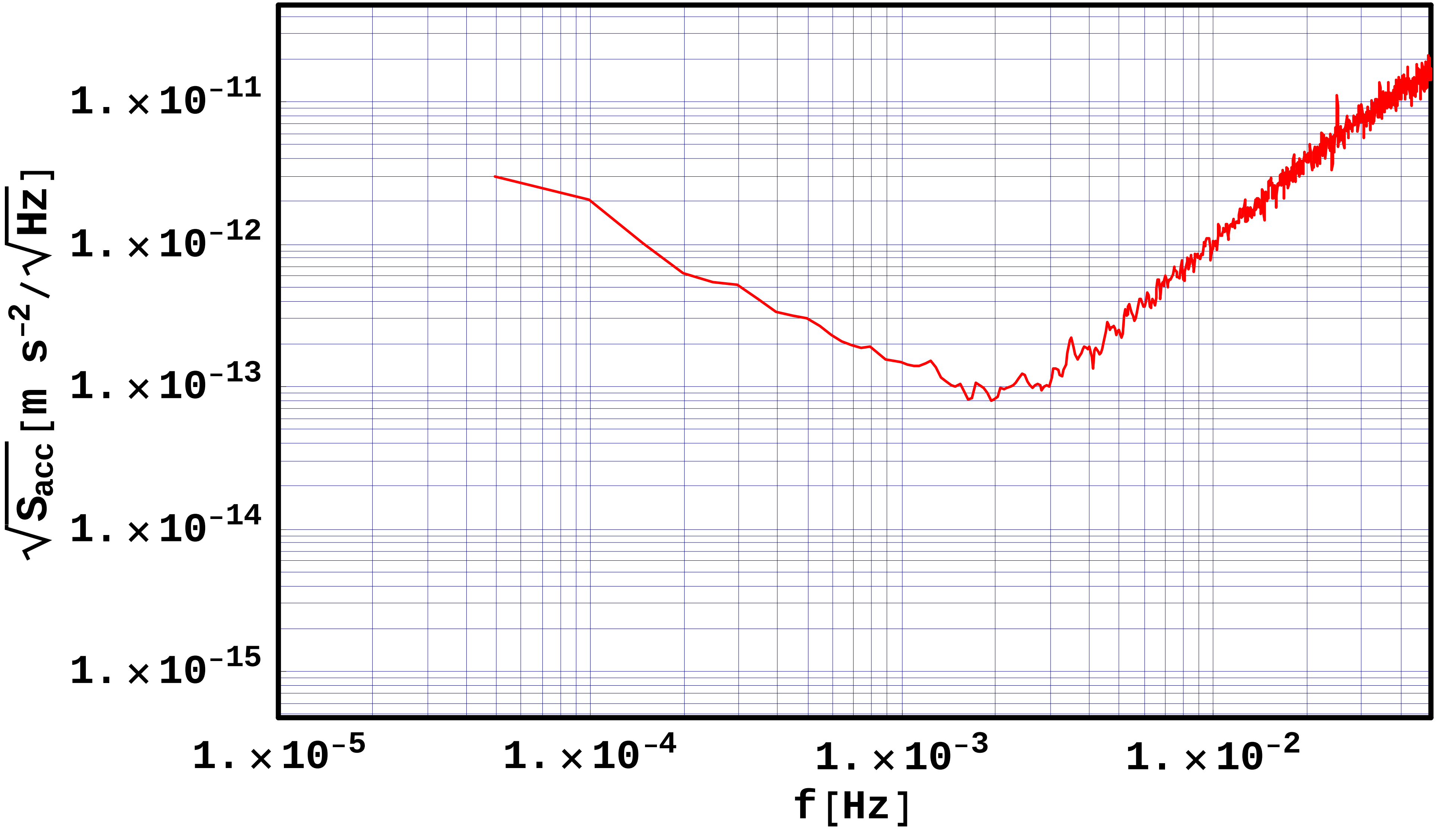
Best Noise


1. × 10^-12
1. × 10^-13
1. × 10^-14
1. × 10^-15
1. × 10^-16
√S_Γ [N m/√Hz]
1. × 10^-5
1. × 10^-4
1. × 10^-3
1. × 10^-2
f [Hz]

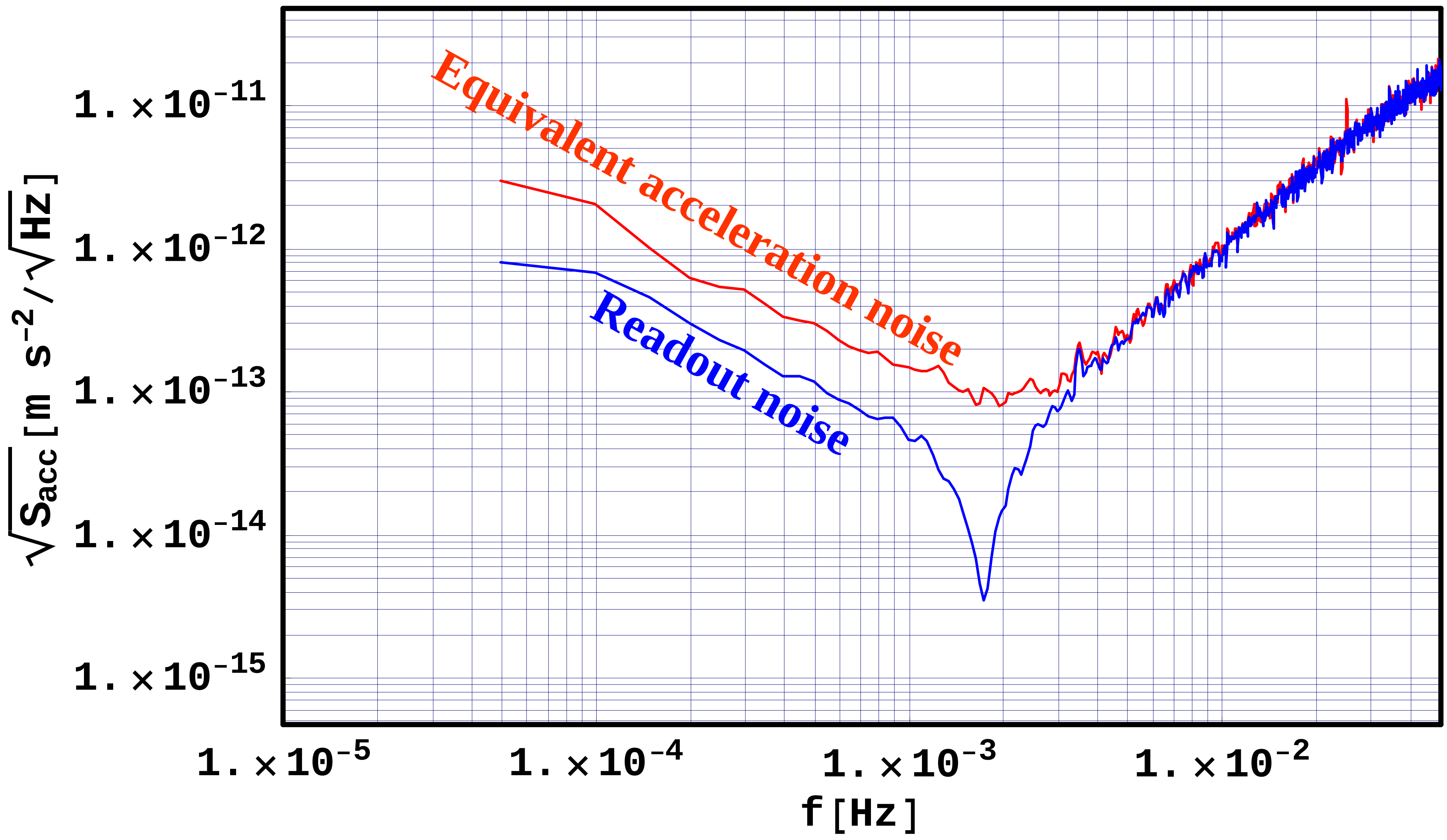
Converted into acceleration for LISA



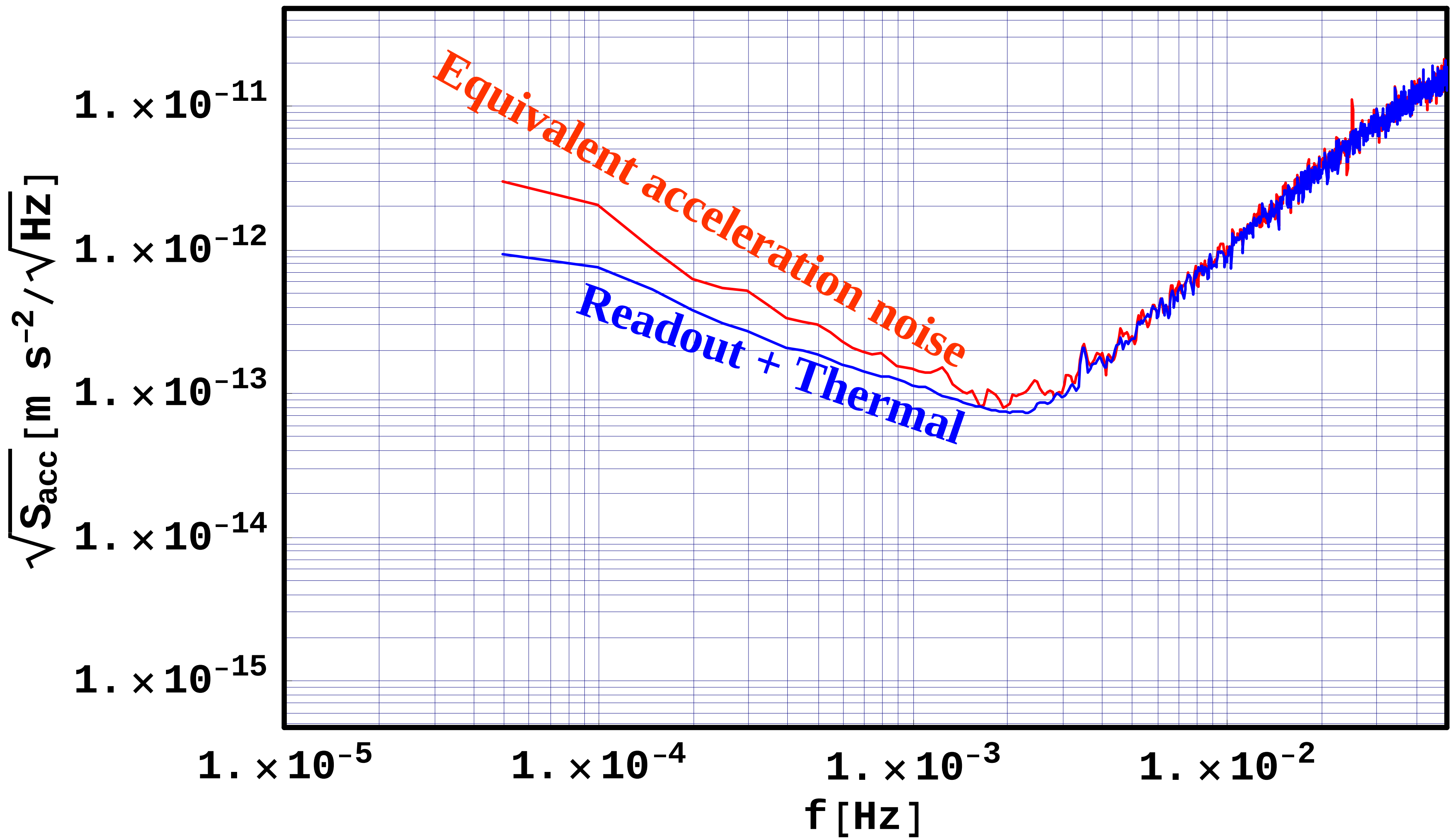
Tilt and temperature subtracted



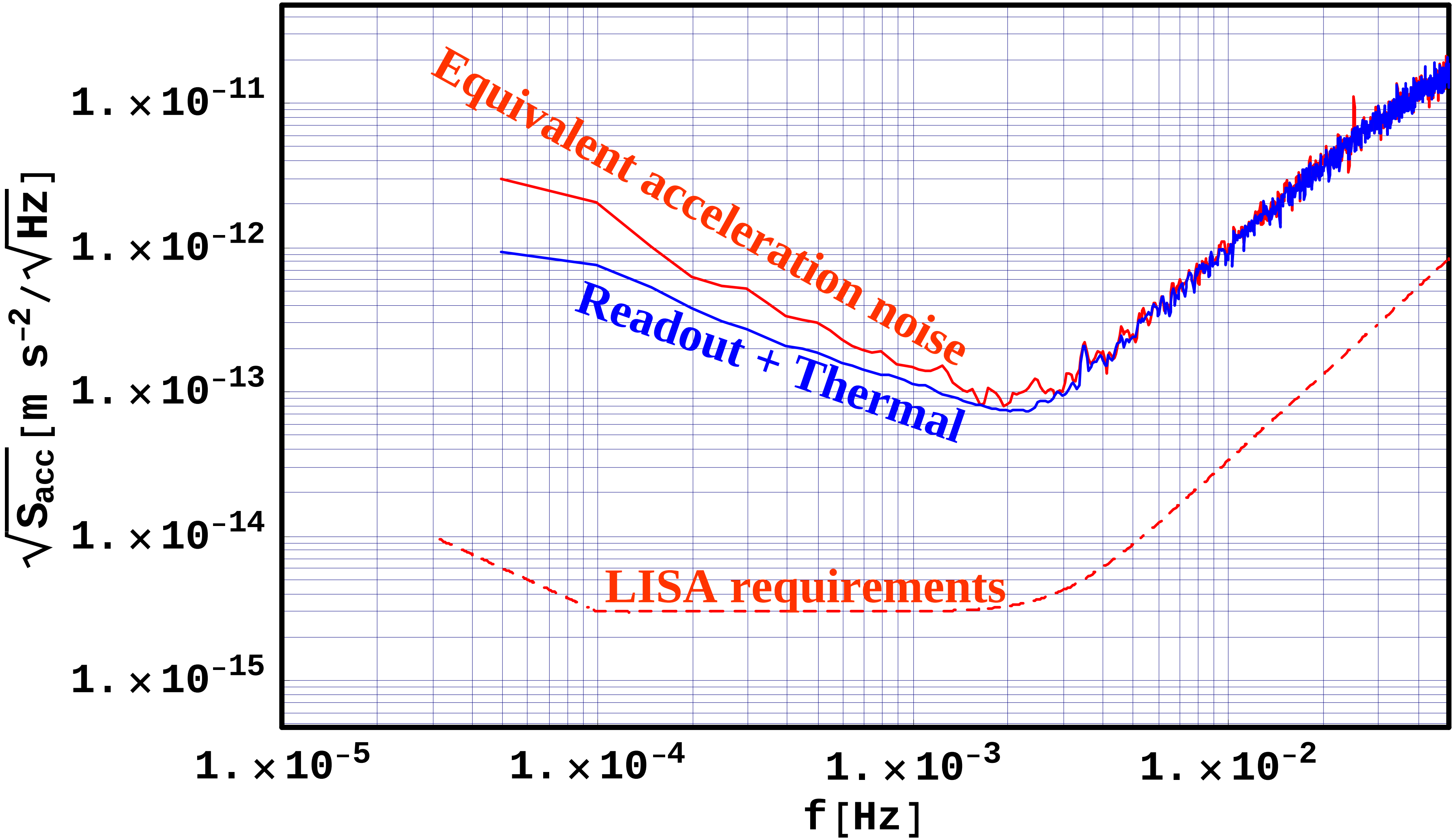
Read-out noise



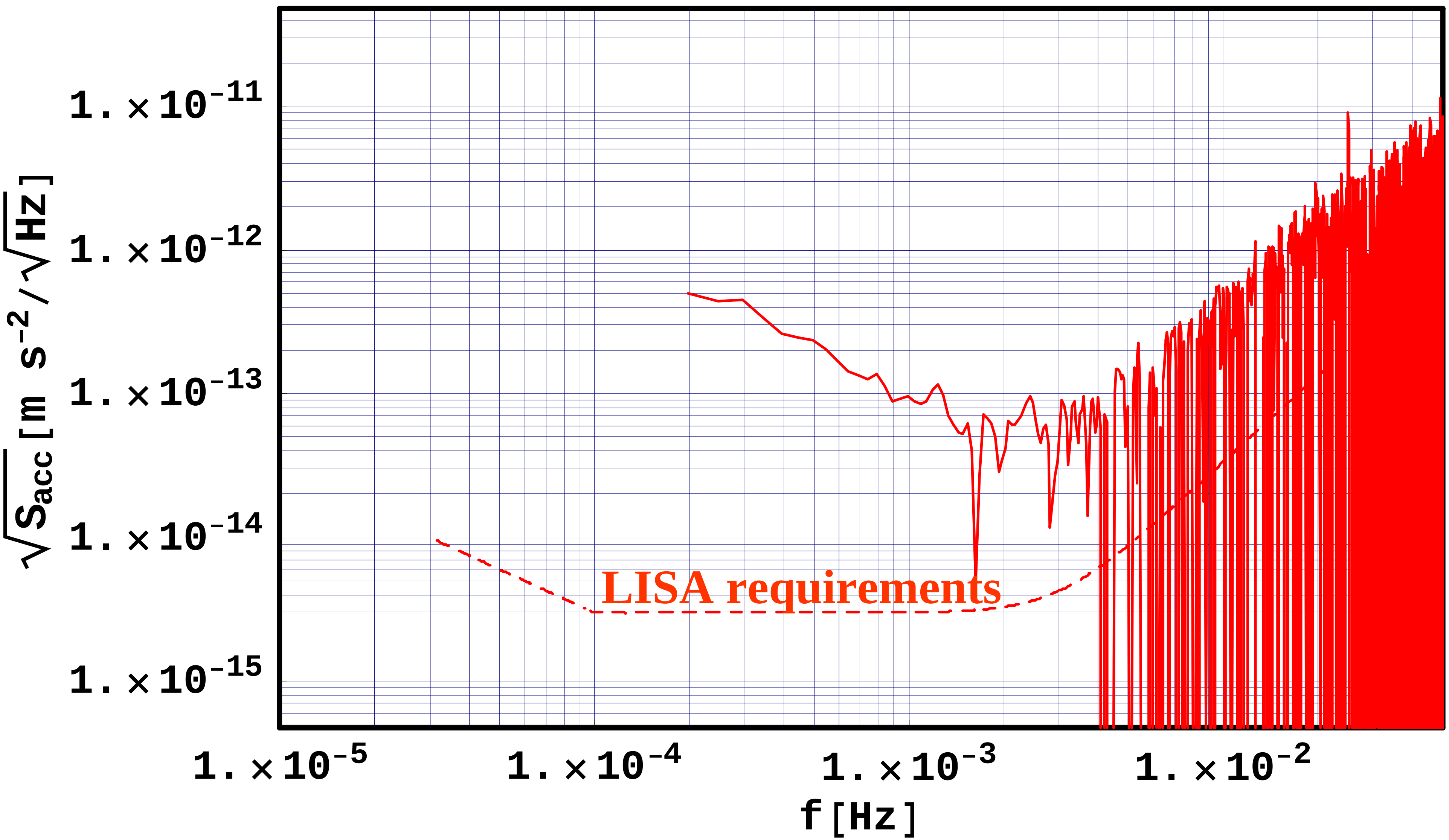
Thermal noise form measured parameters



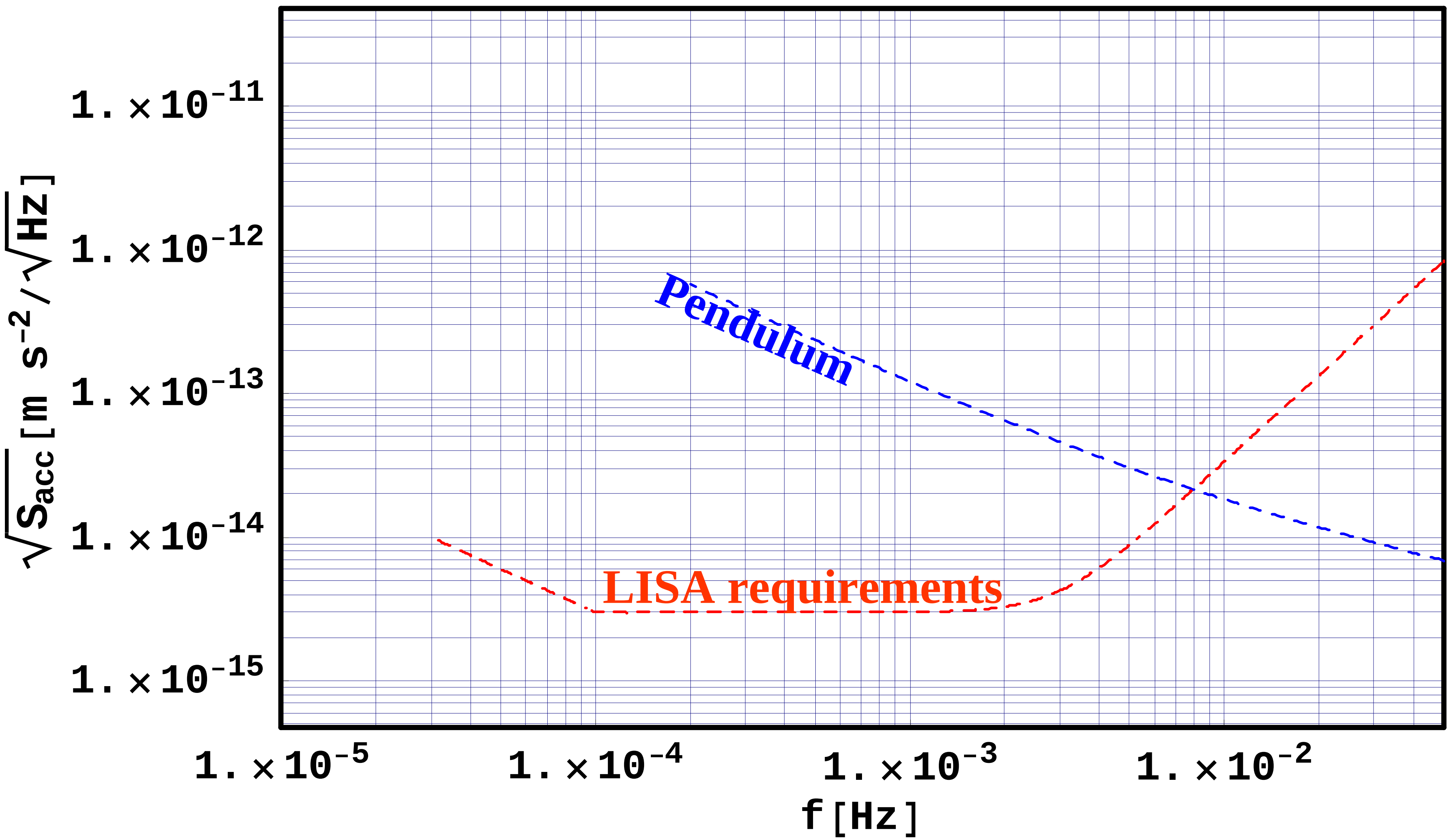
LISA requirements



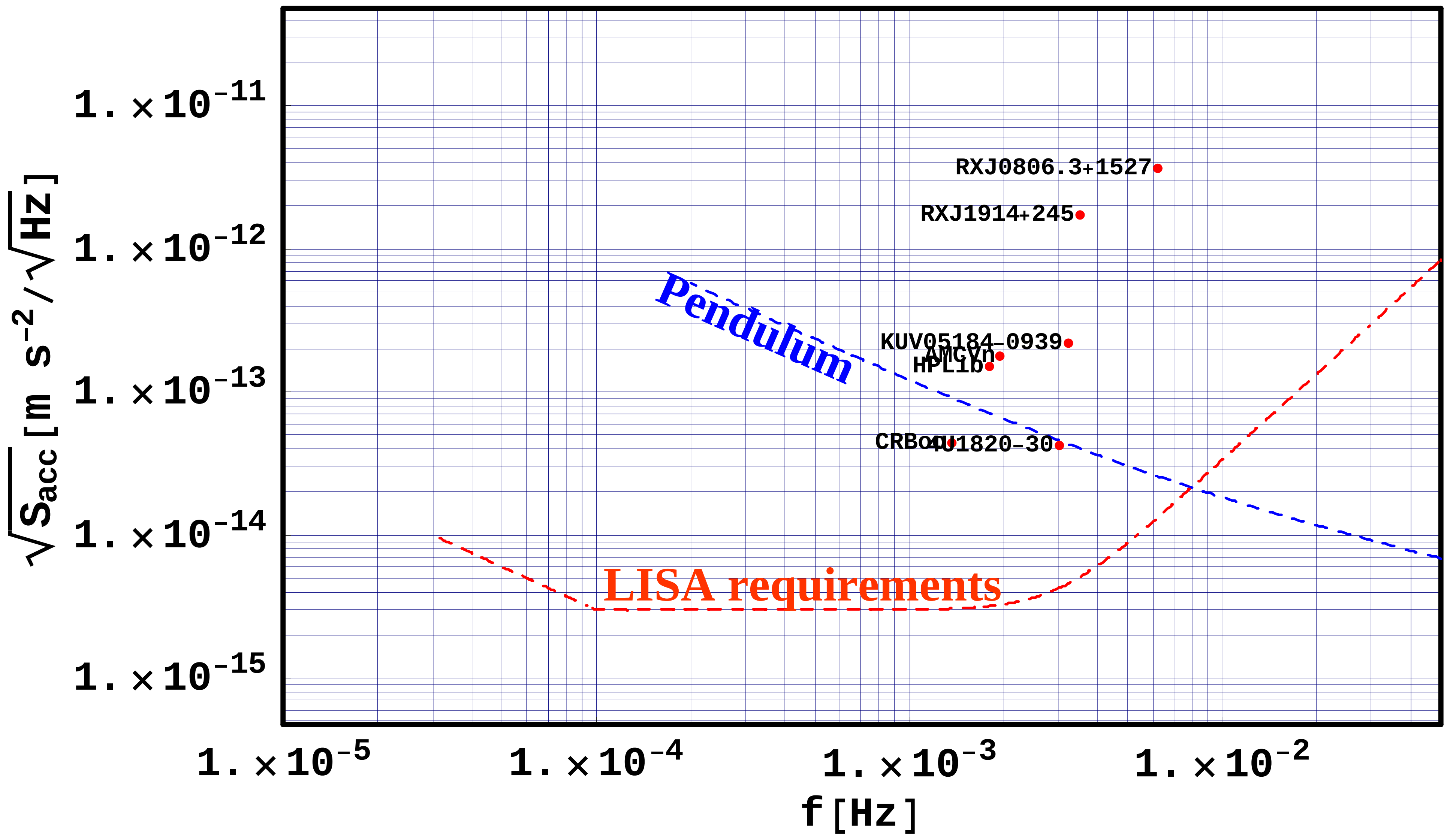
The measured excess

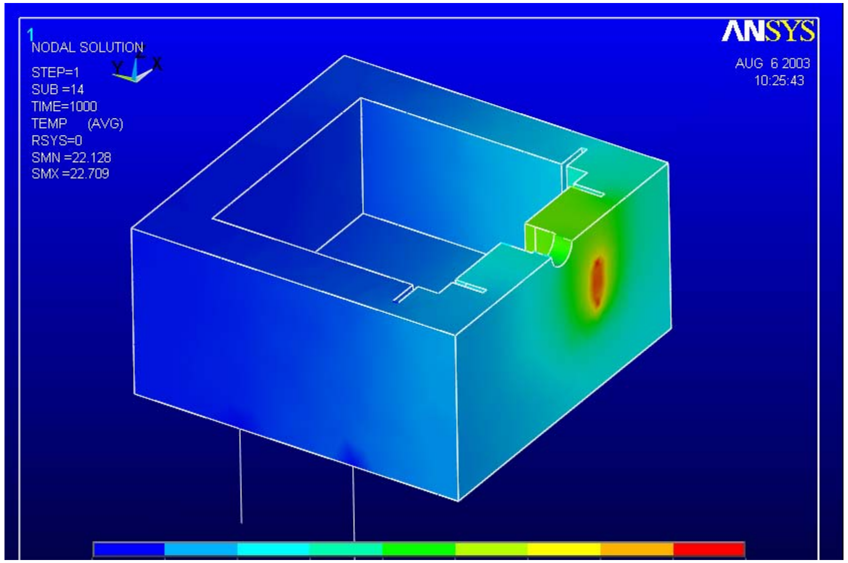


Upper limit form fit and uncertainties



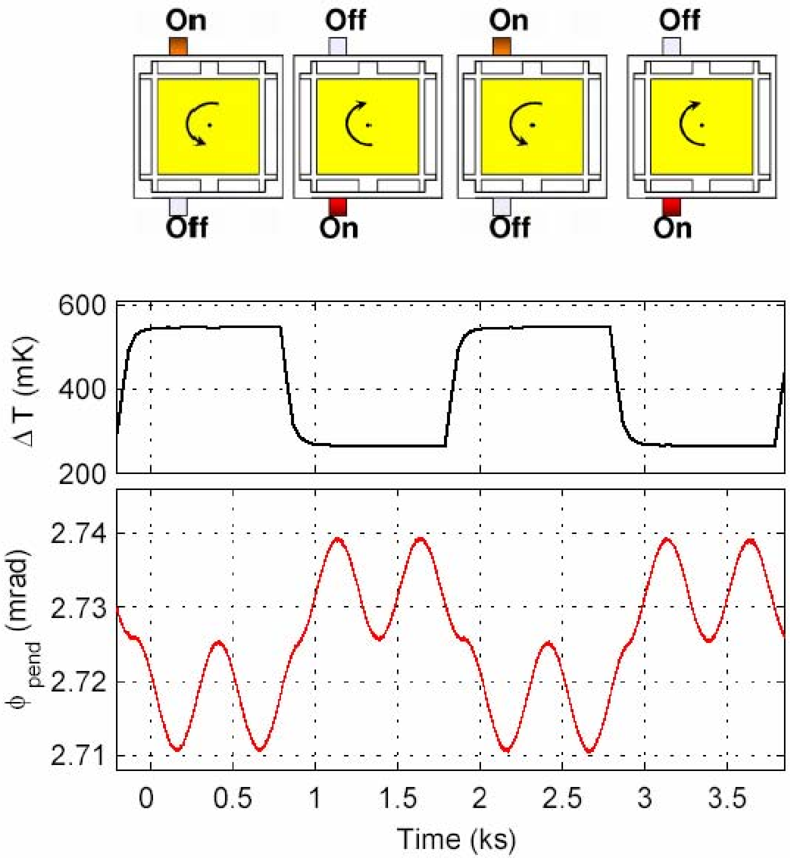
Galactic binaries signals





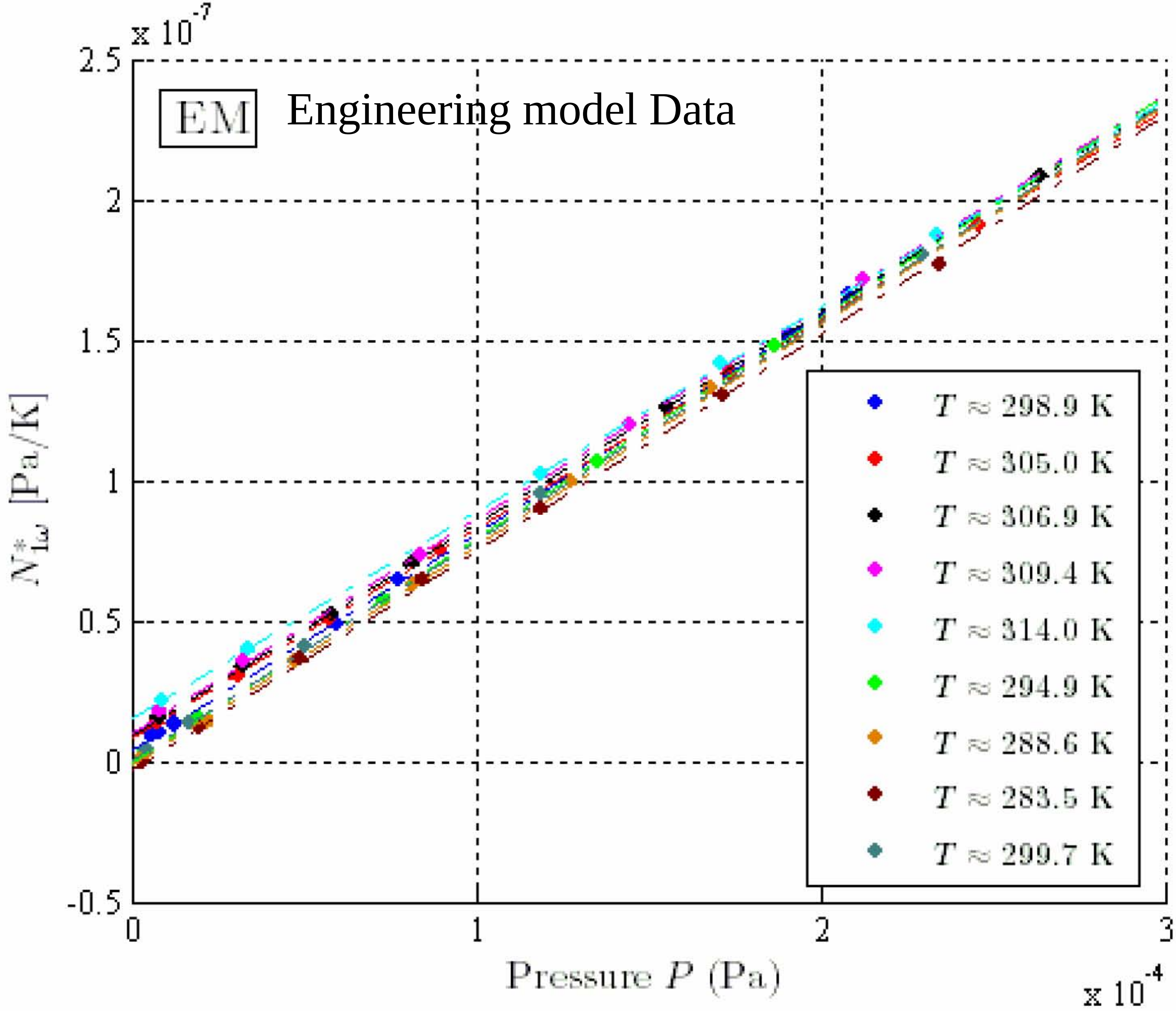
LTP

Testing specific disturbances. One example: temperature gradients



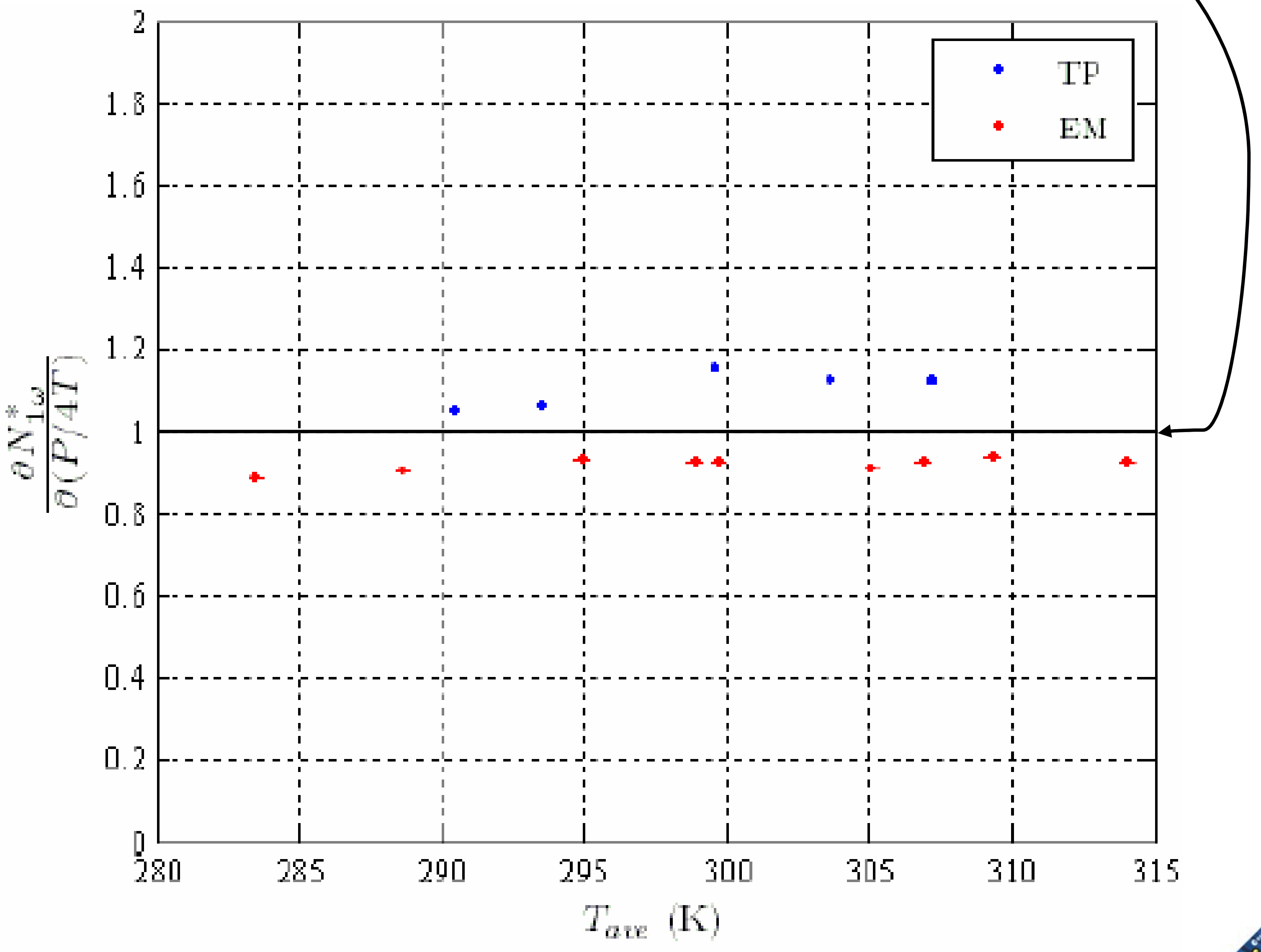
tale

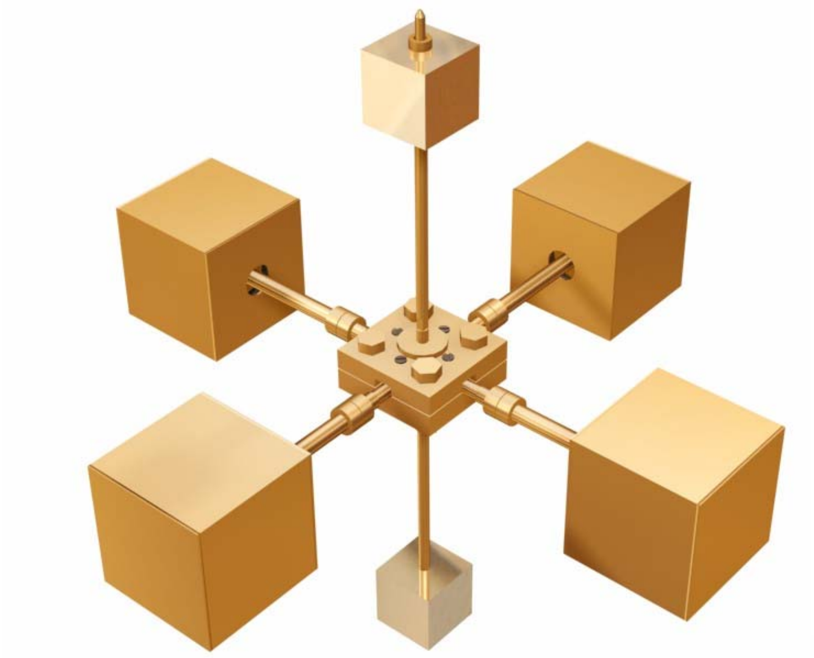
$$\begin{cases} N_{radiom} \propto P_{out} \dfrac{\Delta T_{eff}}{T_s} \\ N_{outgas} \propto \dfrac{\Delta T_{eff}}{T_s^{\,2}} \Theta Q_{outgas} \\ N_{rad\ press} \propto T_s^3 \Delta T_{eff} \end{cases}$$



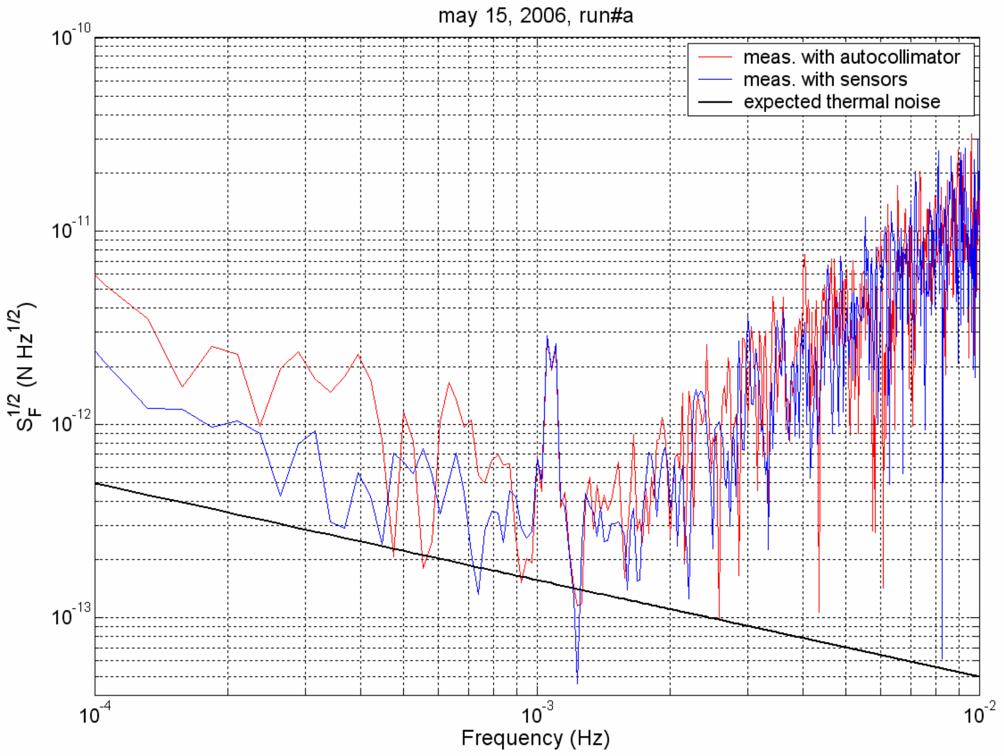
EM
Engineering model Data
x 10^-7
2.5
2
1.5
1
0.5
0
-0.5
$N^*_{1\omega}$ [Pa/K]
0
1
2
3
Pressure P (Pa)
x 10^-4
$T \approx 298.9$ K
$T \approx 305.0$ K
$T \approx 306.9$ K
$T \approx 309.4$ K
$T \approx 314.0$ K
$T \approx 294.9$ K
$T \approx 288.6$ K
$T \approx 283.5$ K
$T \approx 299.7$ K

Knudsen formula





4-TM pendulum



Testing quality of free fall

LTP

10^{-12}

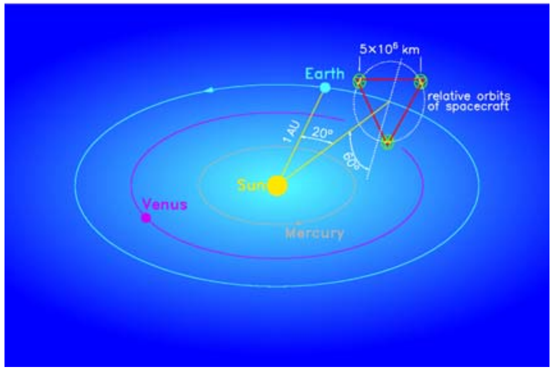
$\sqrt{S_F}\left(\frac{N}{\sqrt{Hz}}\right)$

10^{-13}

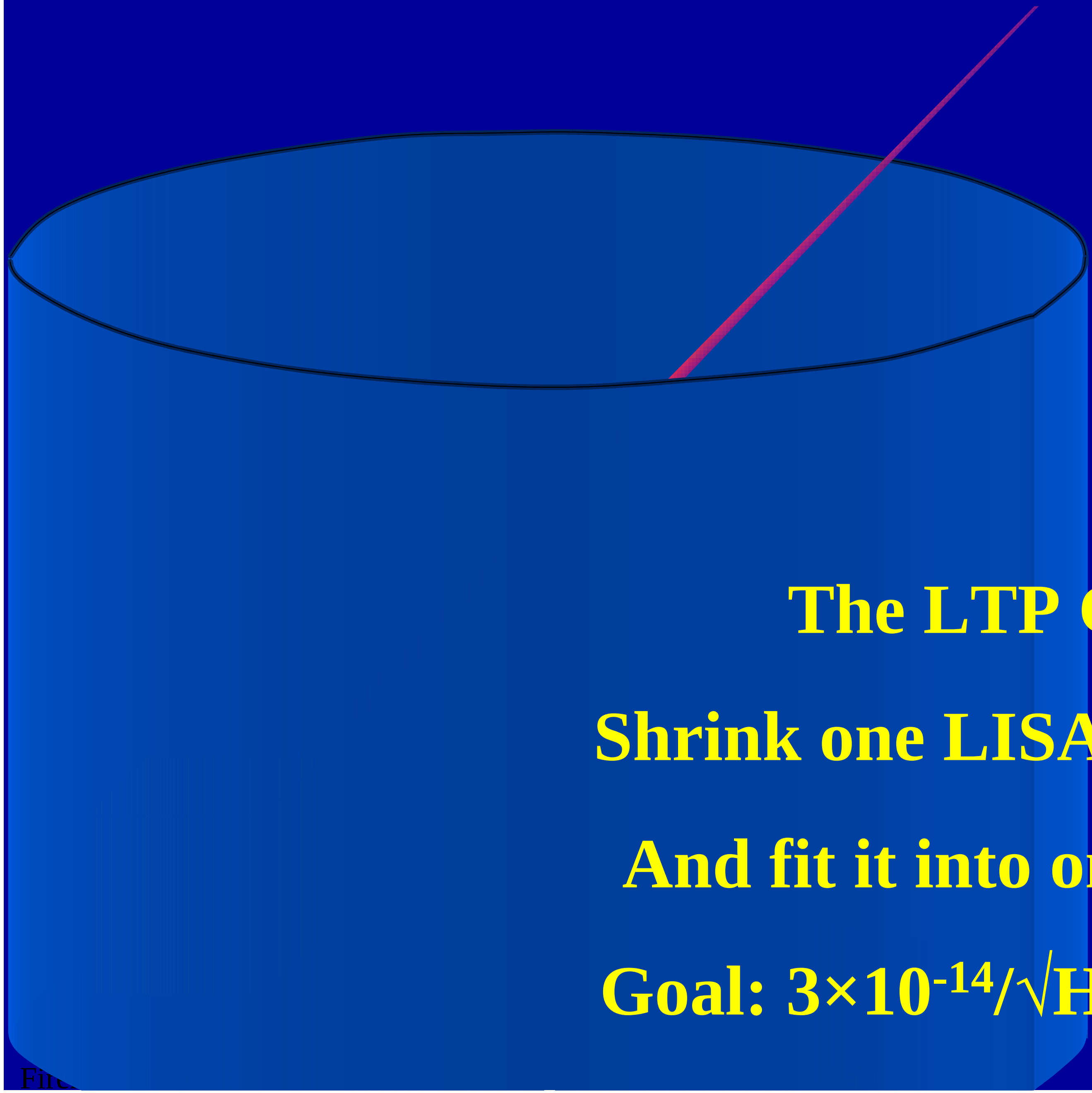
Torsion pendulum
(surface disturbances)

10^{-14}

10^{-15}



LISA

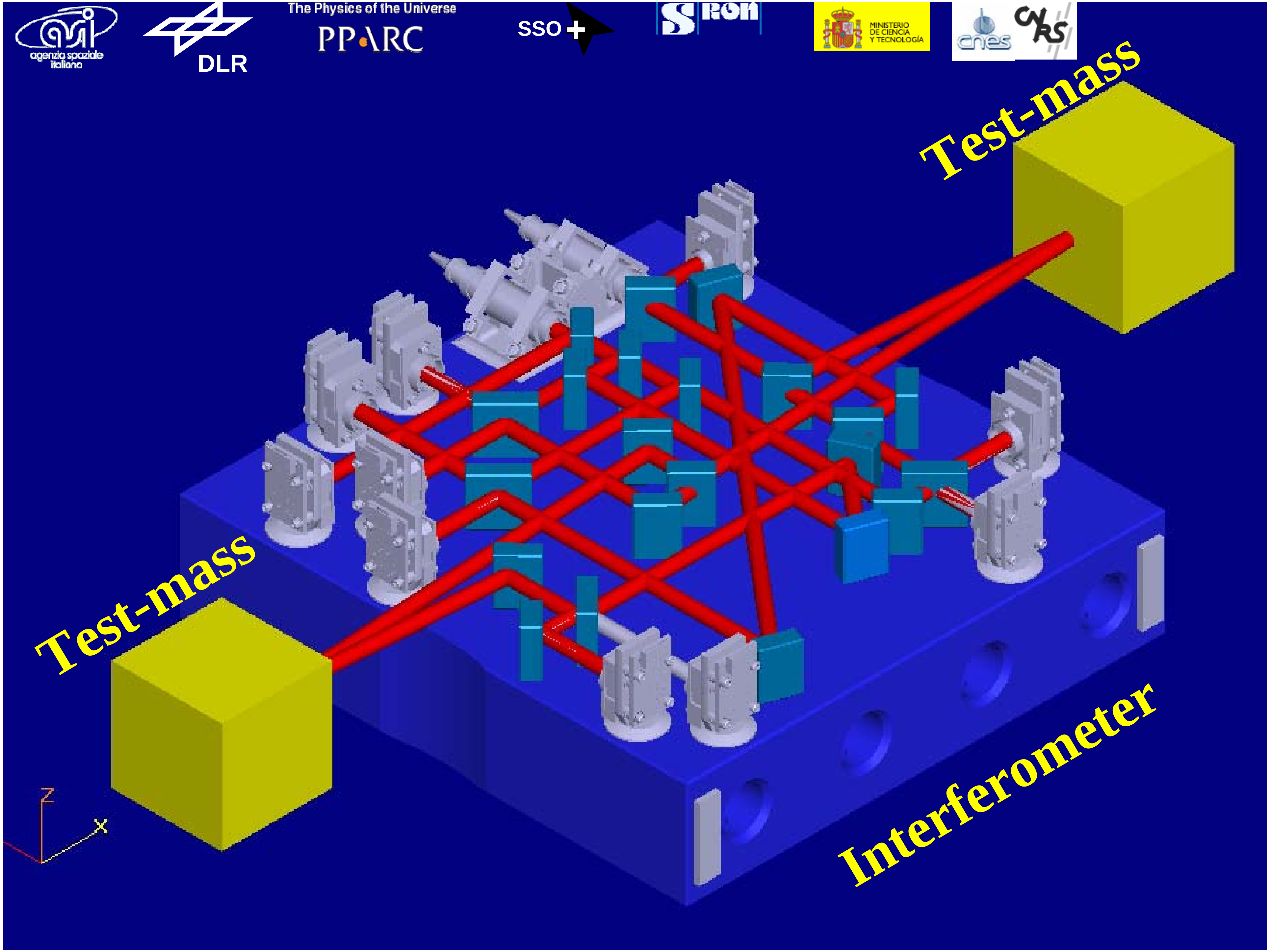


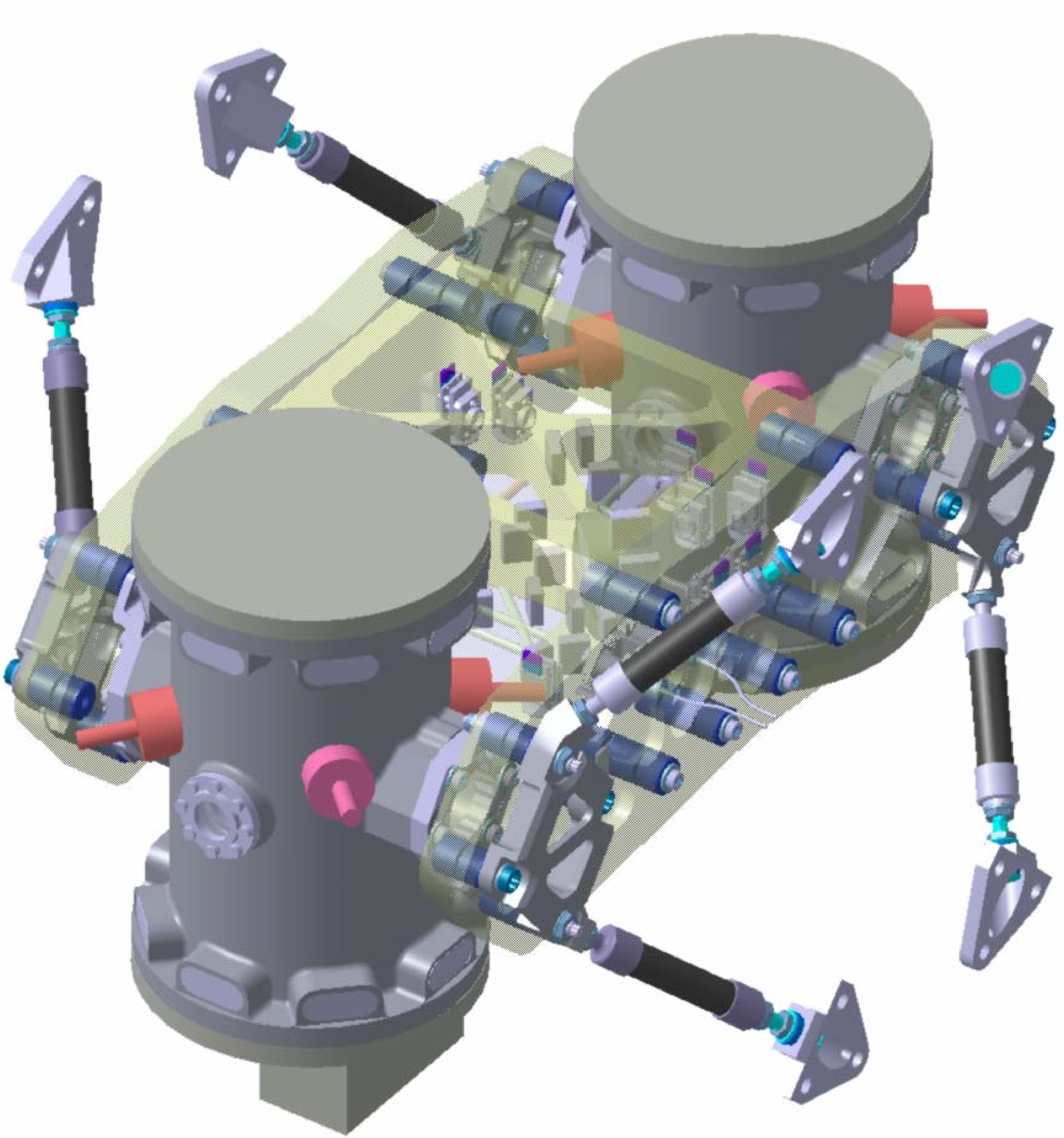
The LTP Concept

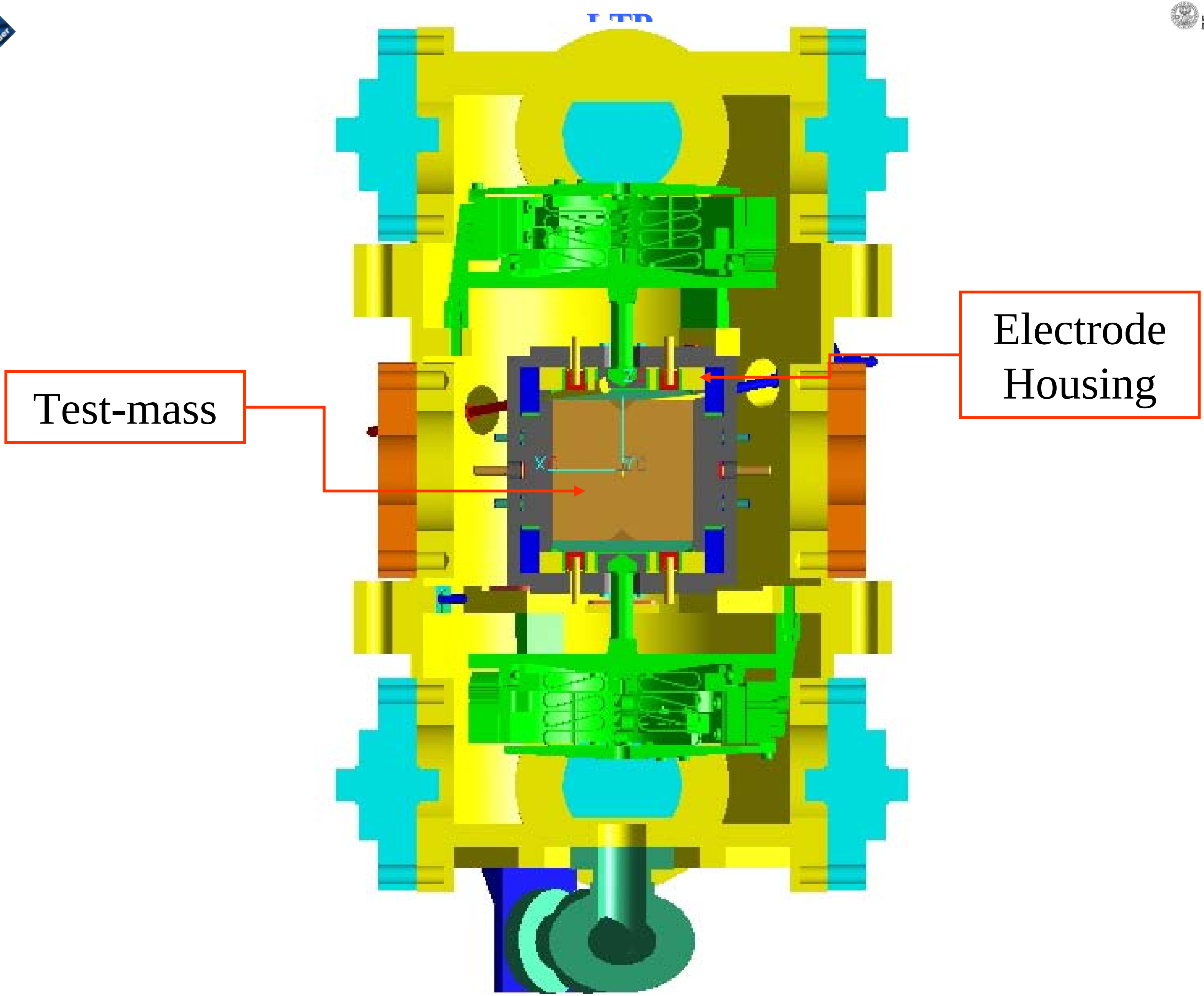
Shrink one LISA arm to 38 cm

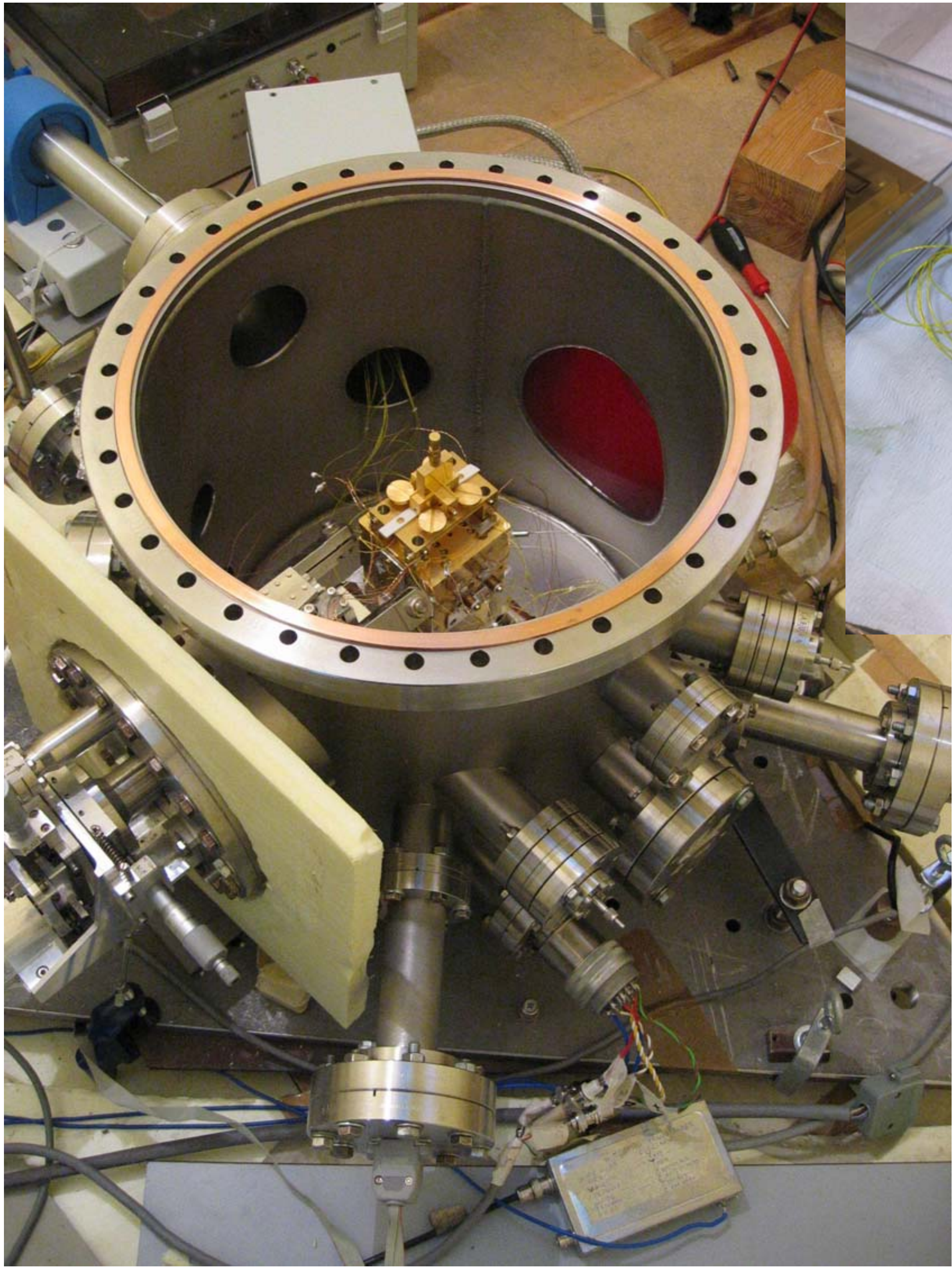
And fit it into one Spacecraft

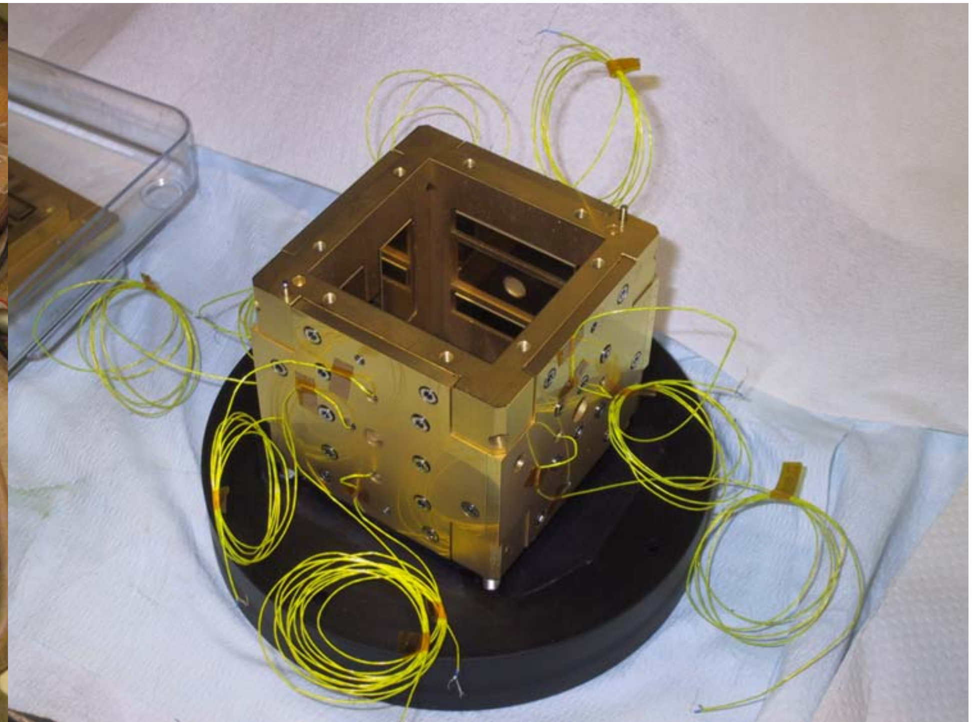
Goal: $3\times10^{-14}/\sqrt{Hz}$ $f > 1mHz$

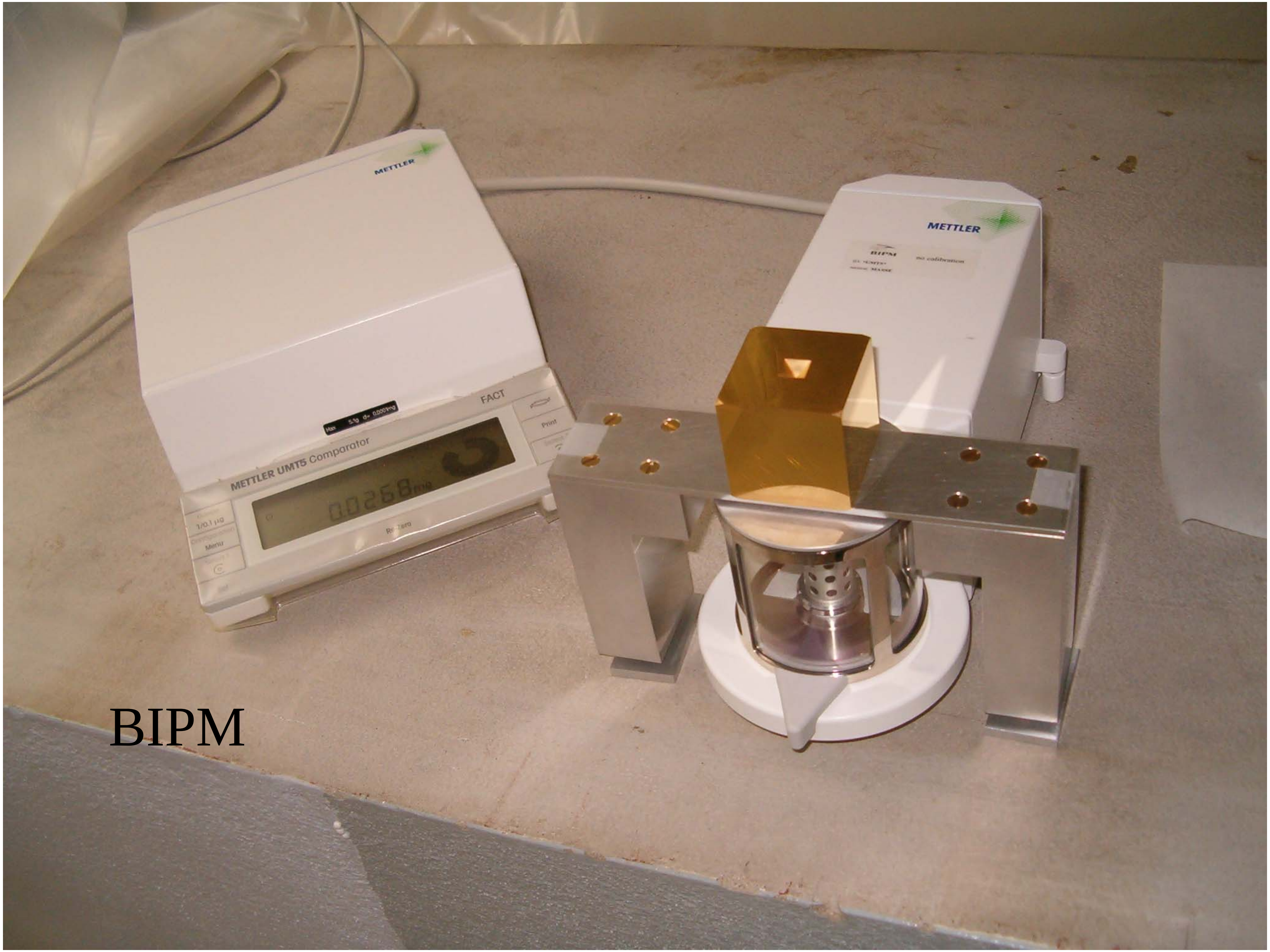

agenzia spaziale italiana
DLR
The Physics of the Universe
PPARC
SSO
MINISTERIO DE CIENCIA Y TECNOLOGÍA
cnes
Test-mass
Test-mass
Interferometer
Z
X

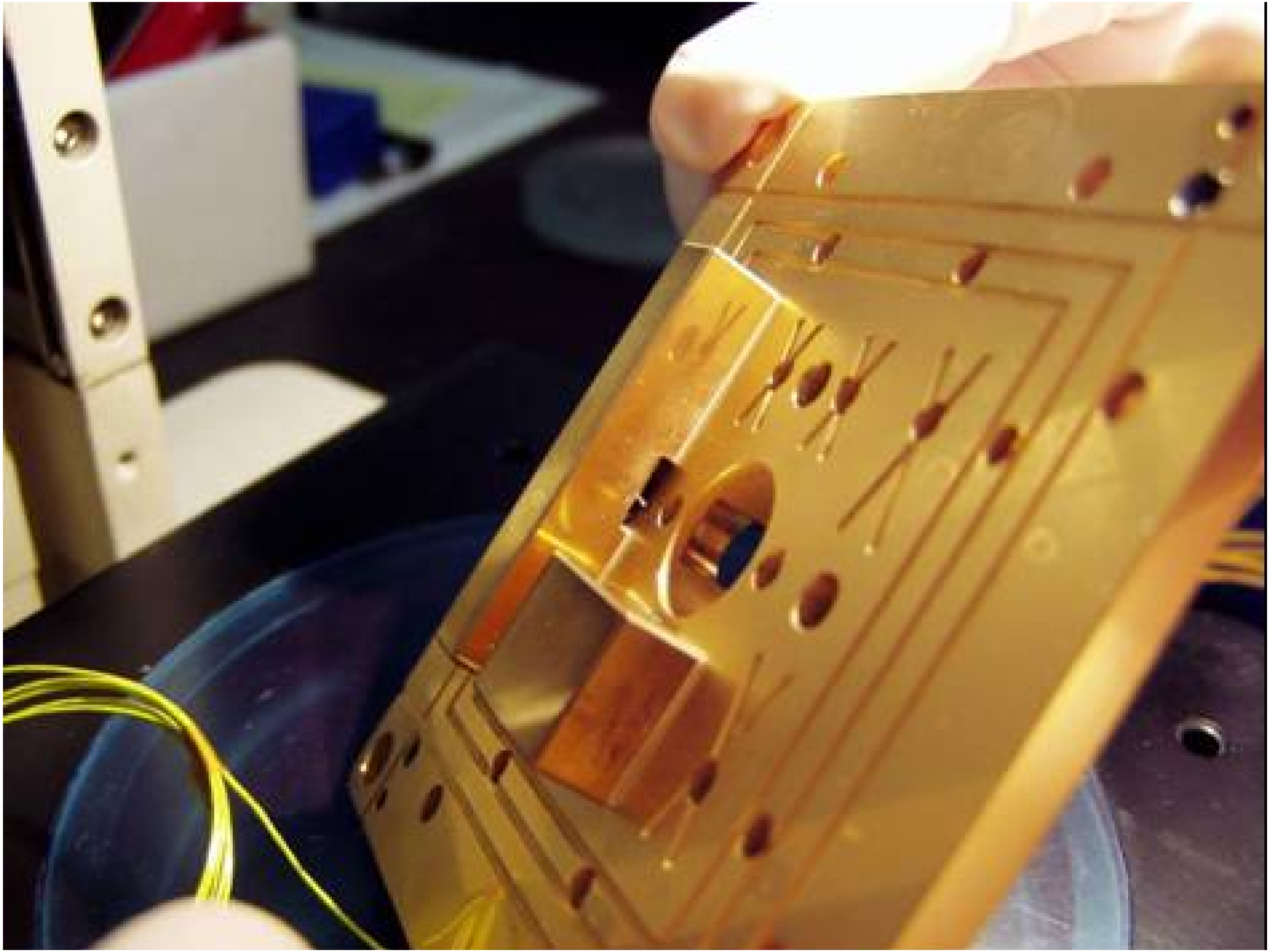



Test-mass
Electrode Housing






METTLER
METTLER UMT5 Comparator
FACT
Print
0.0268 mg
METTLER
BIPM
no calibration
BIPM



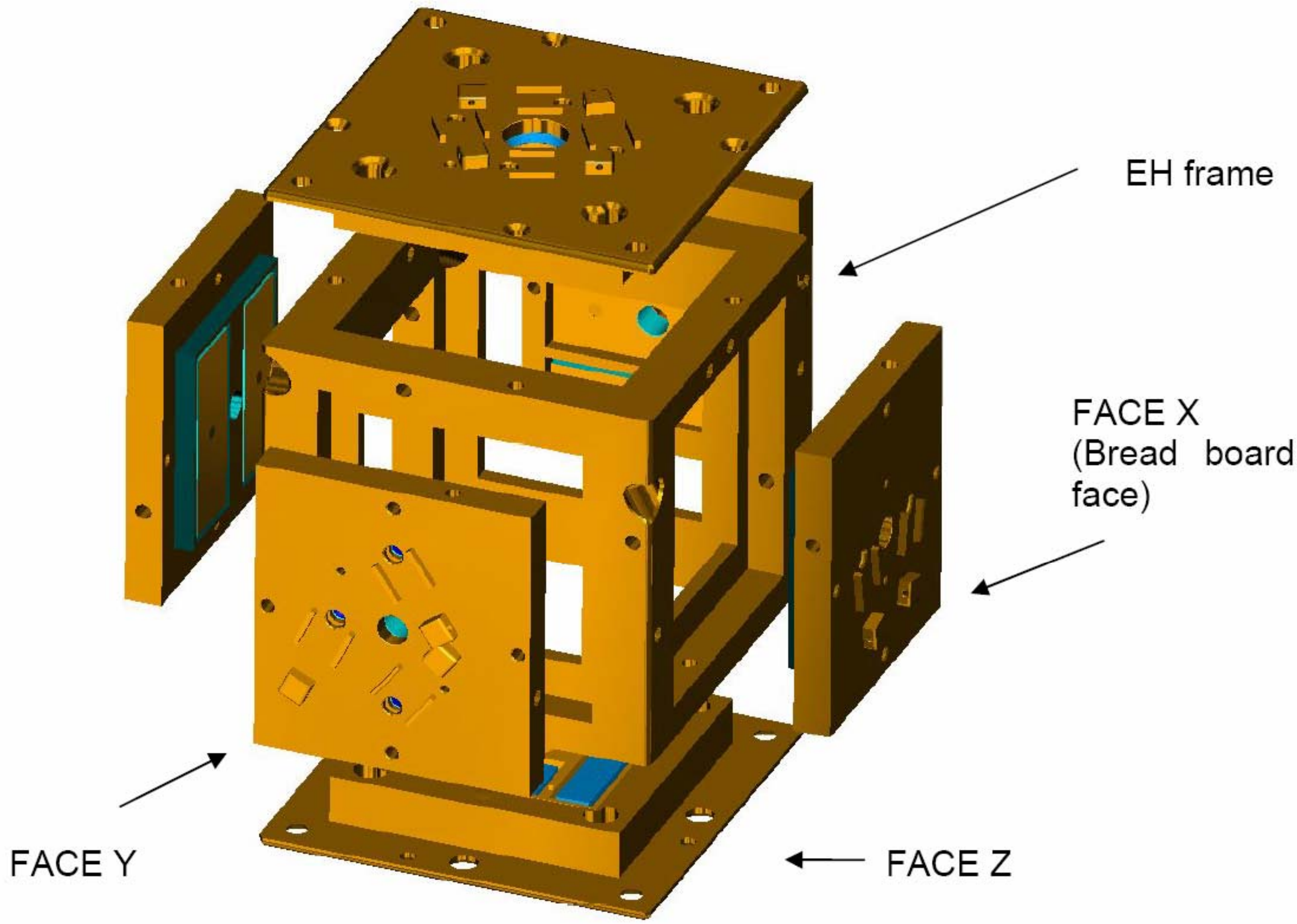
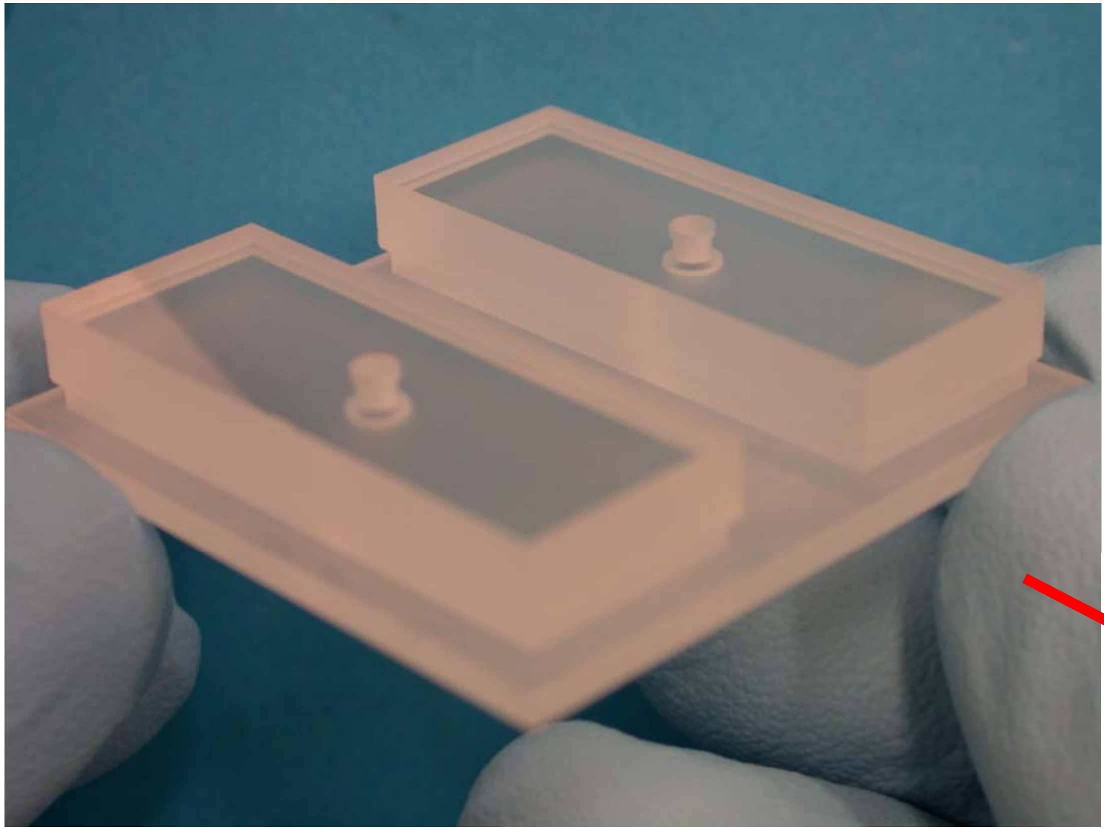
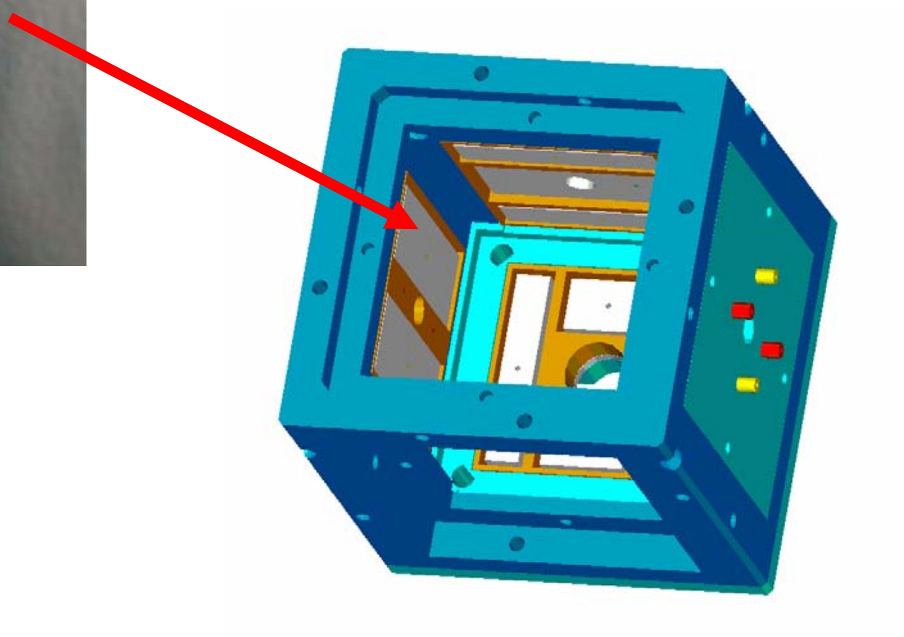
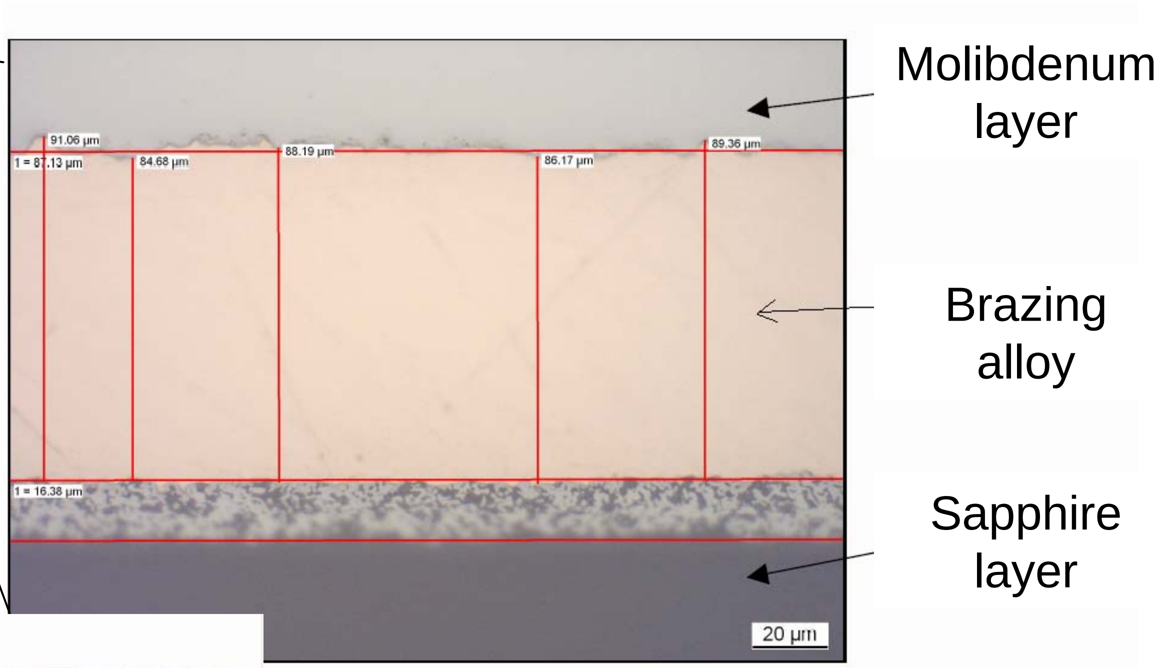


Figure 2-1 LISA Electrode housing exploded view

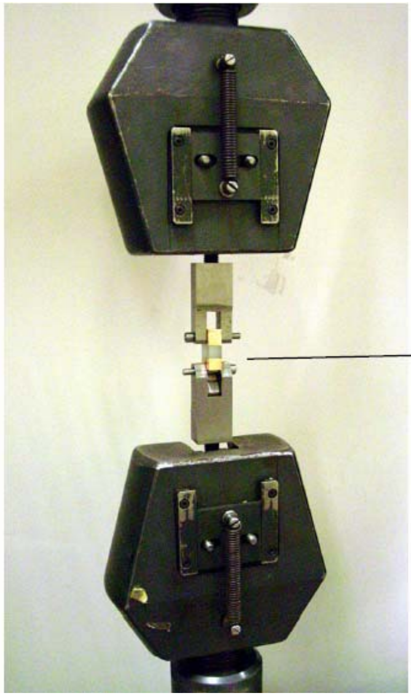


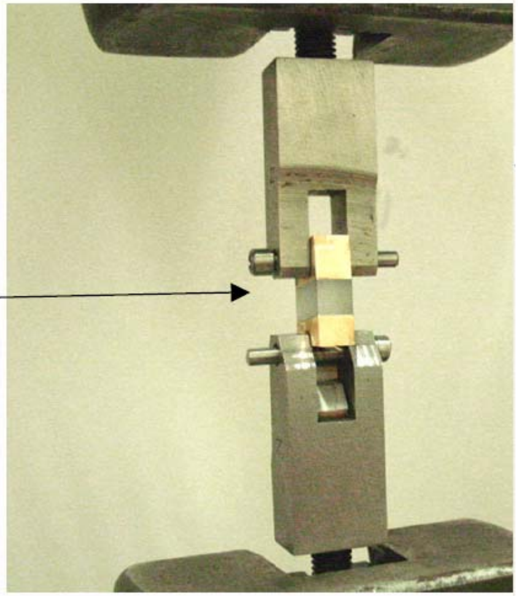


LTP



91.06 µm
1 = 87.13 µm
84.68 µm
88.19 µm
86.17 µm
89.36 µm
1 = 16.38 µm
20 µm
Molibdenum layer
Brazing alloy
Sapphire layer





LTP

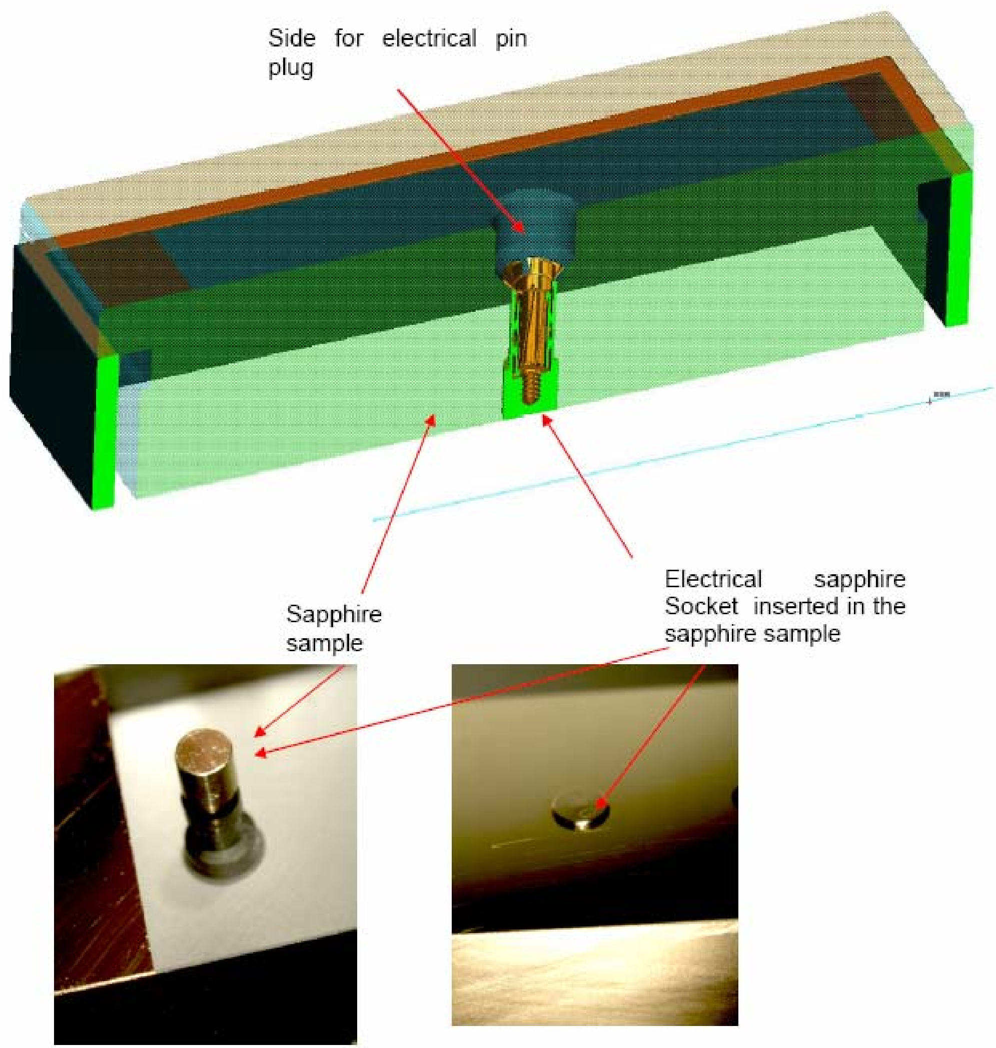
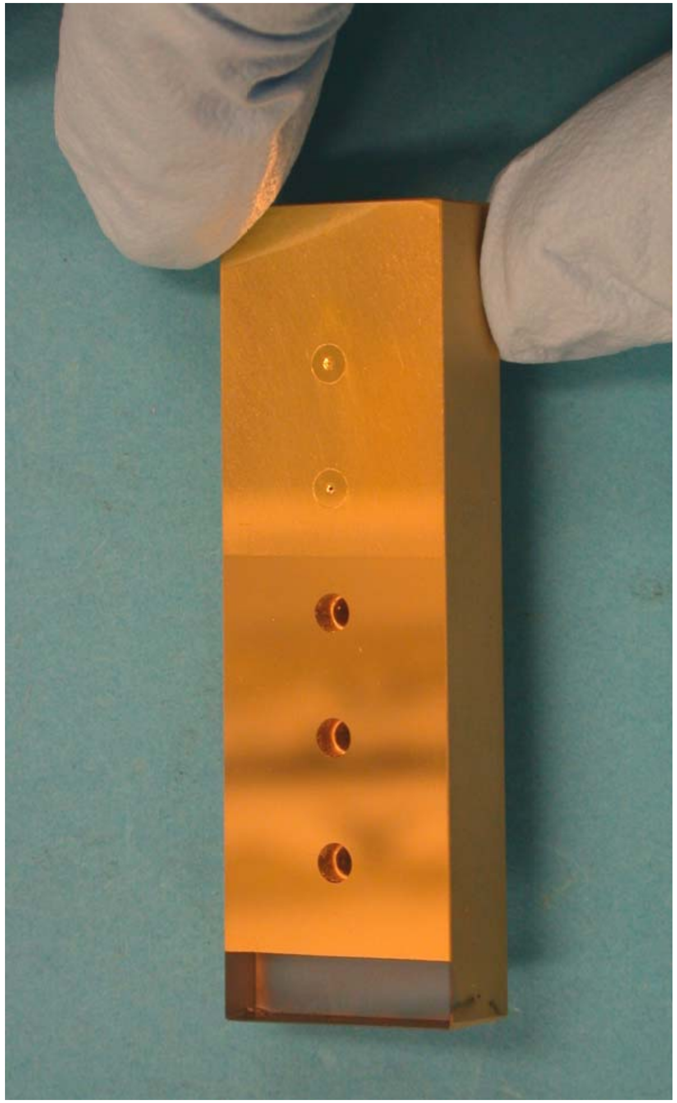
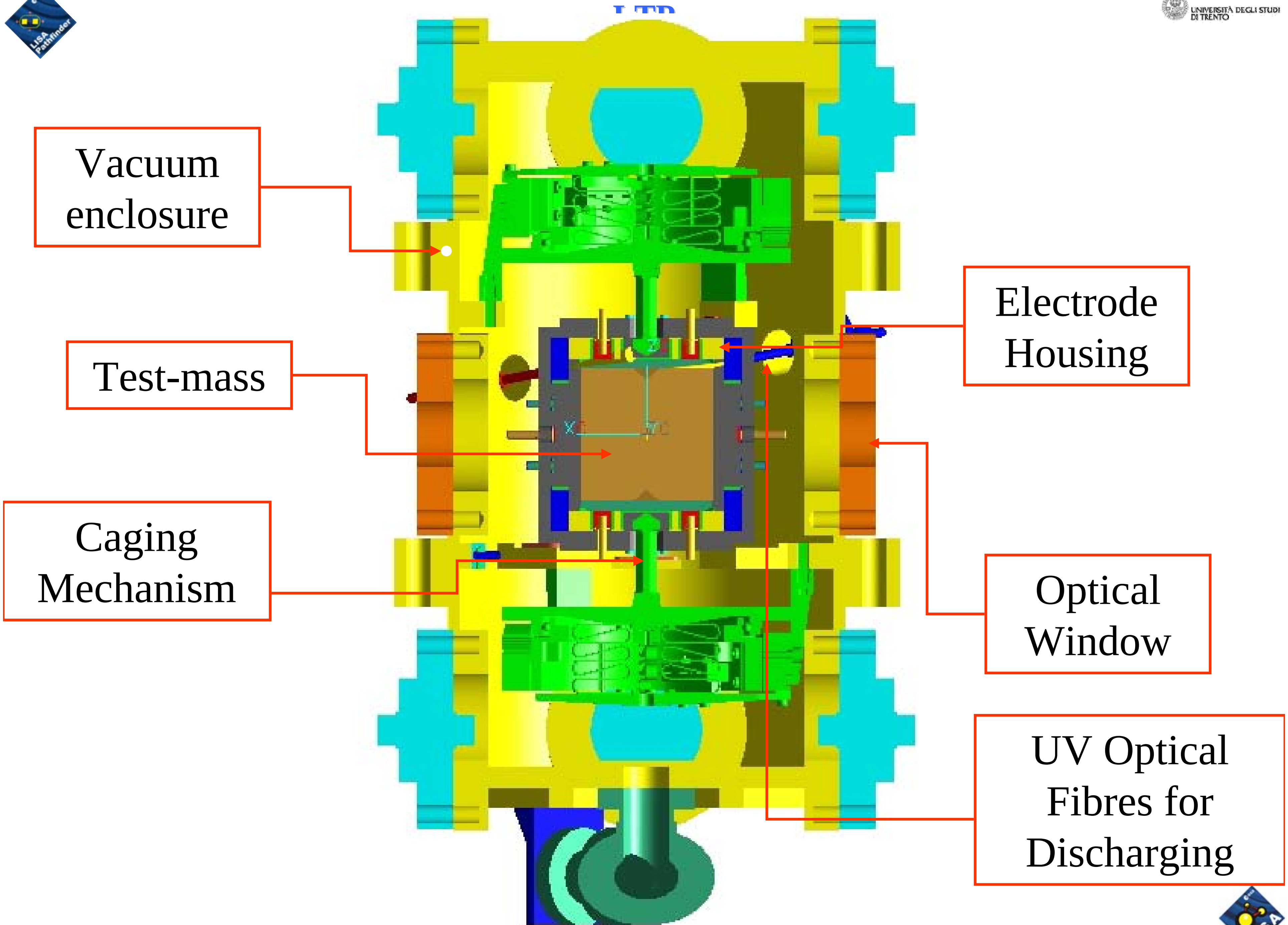
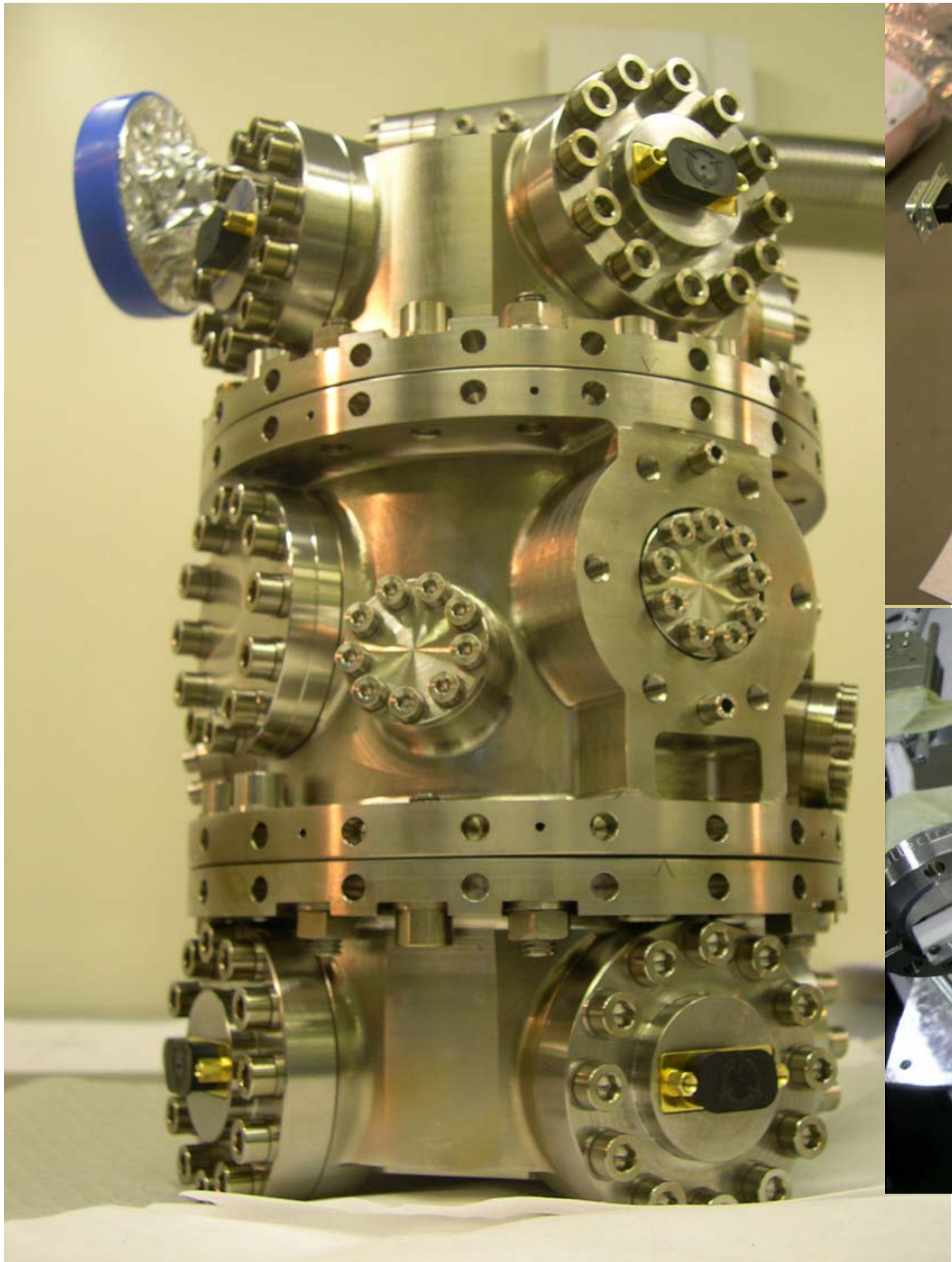
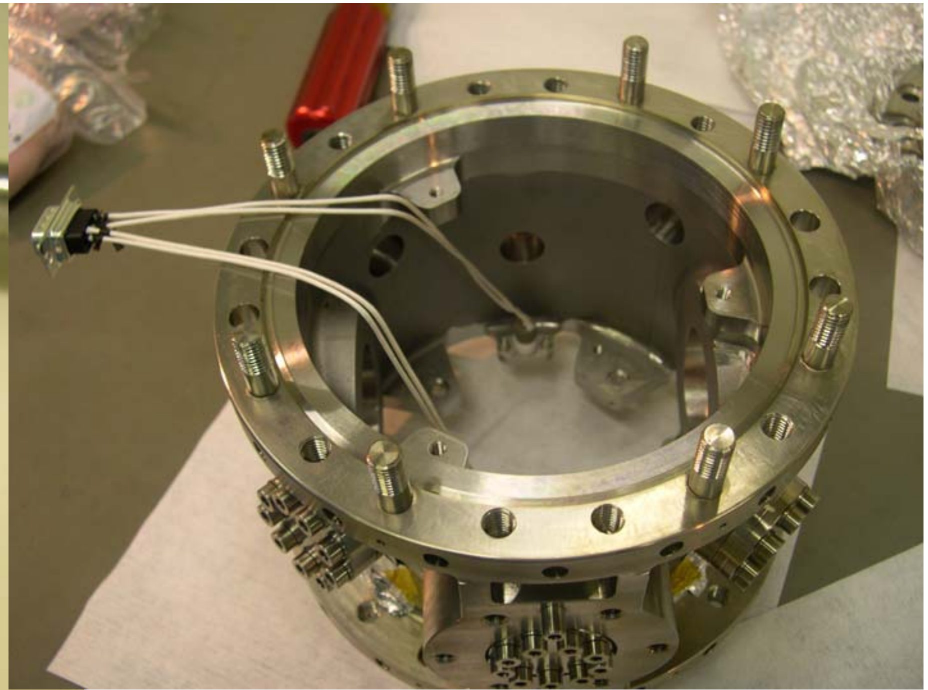
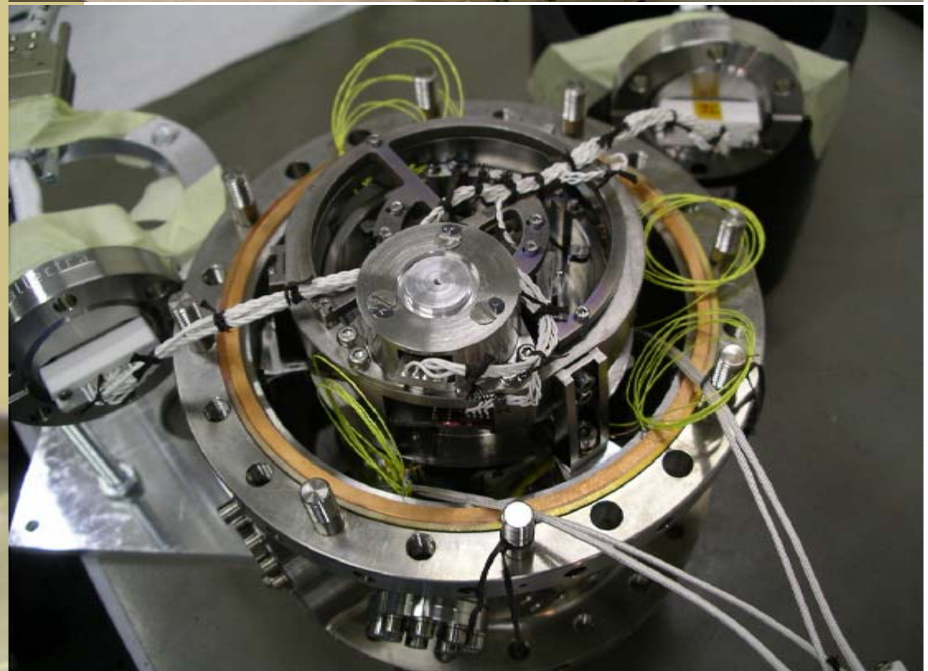
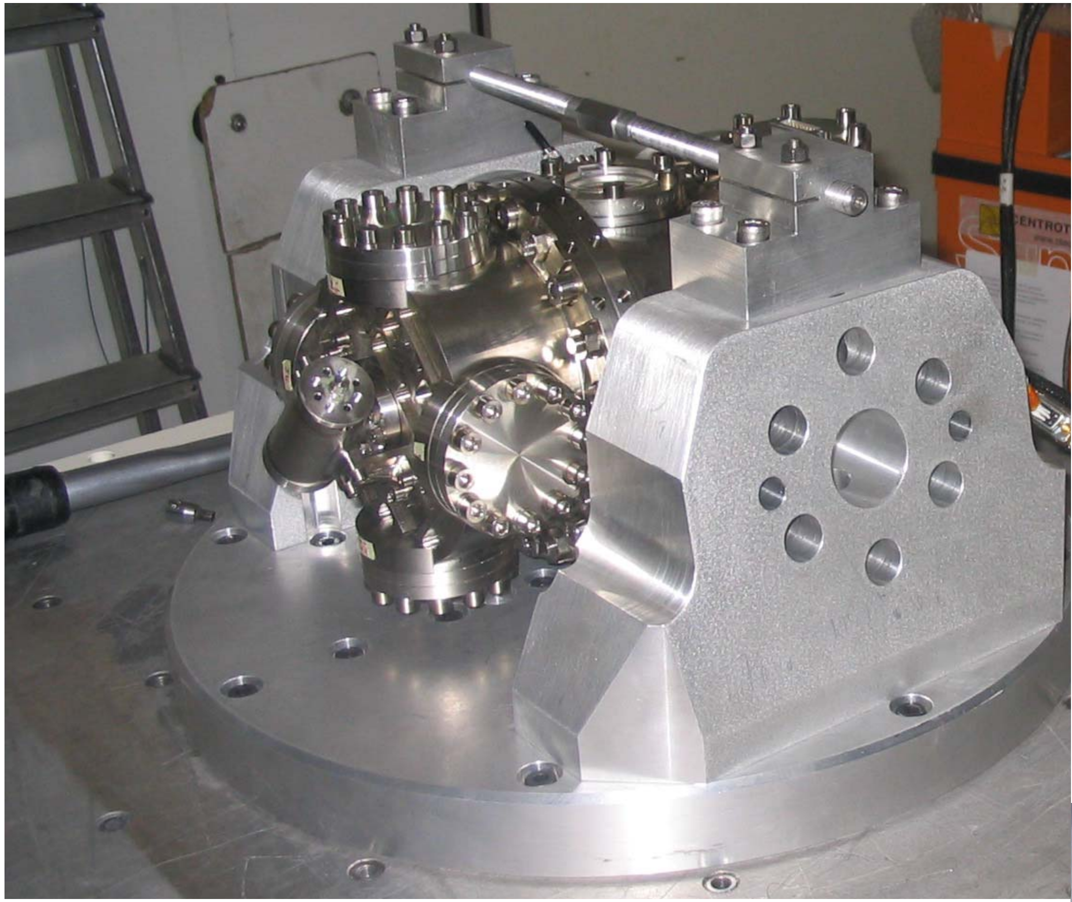


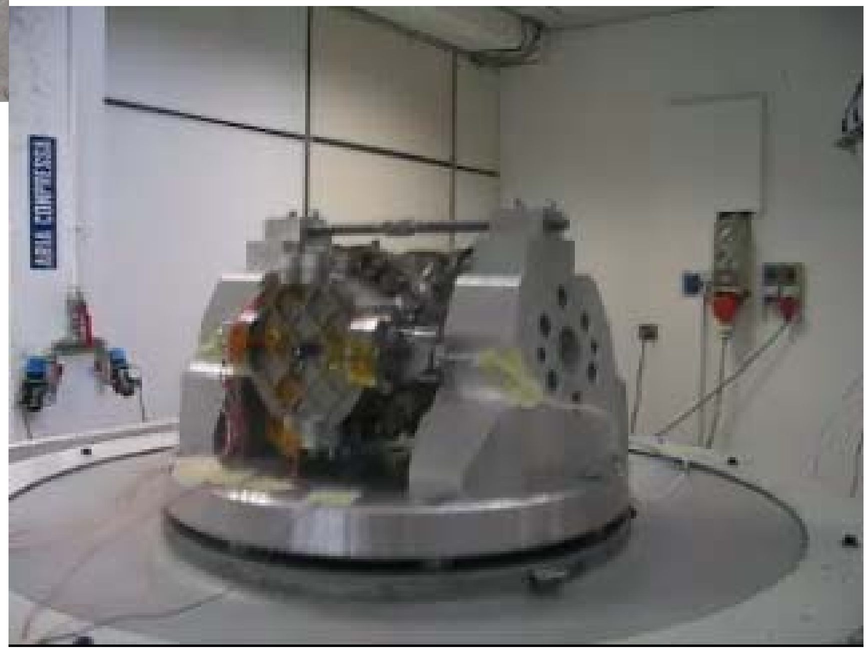
Figure 3-16 Details of sapphire electrical socket inserted in the sample for insertion test

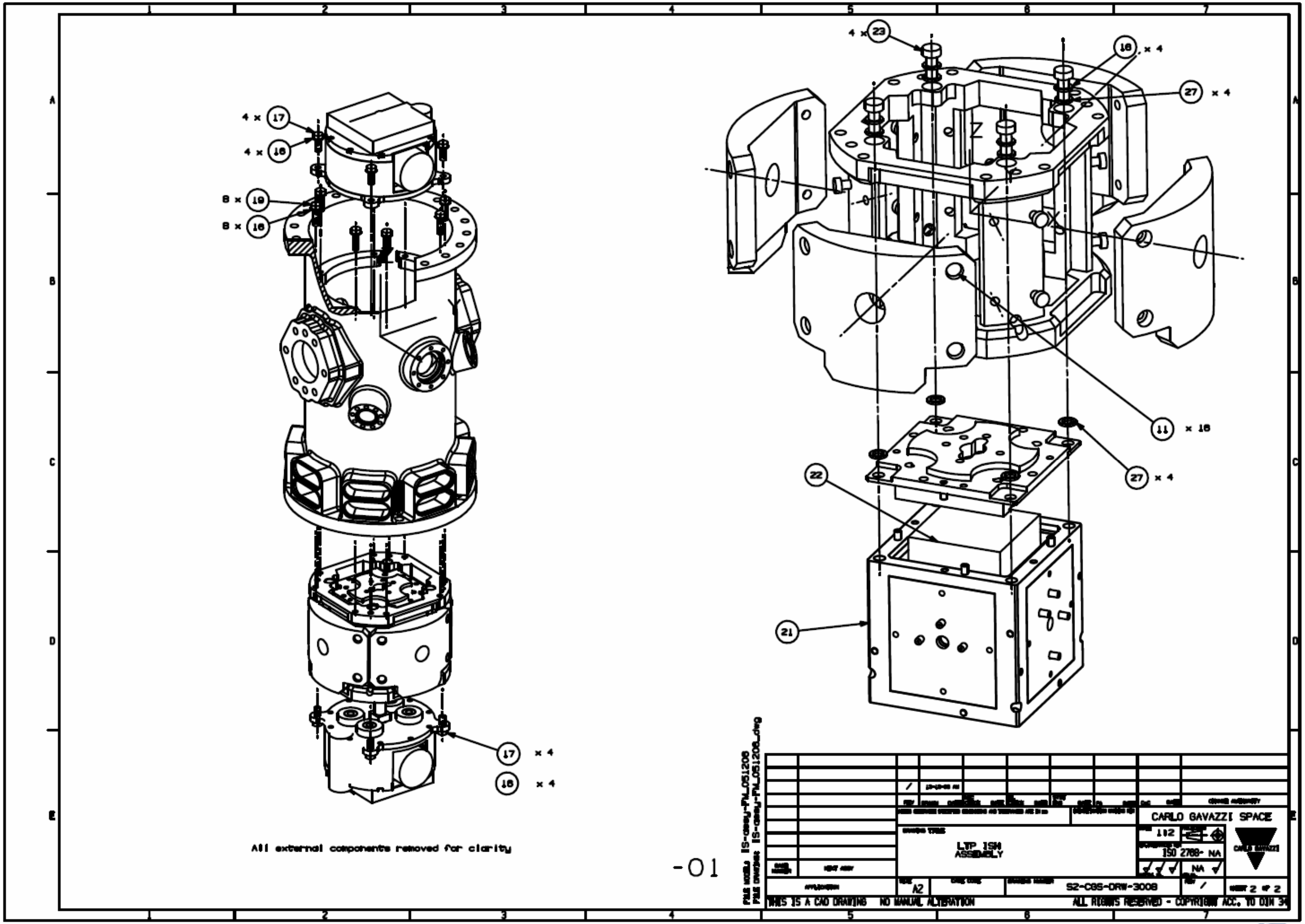


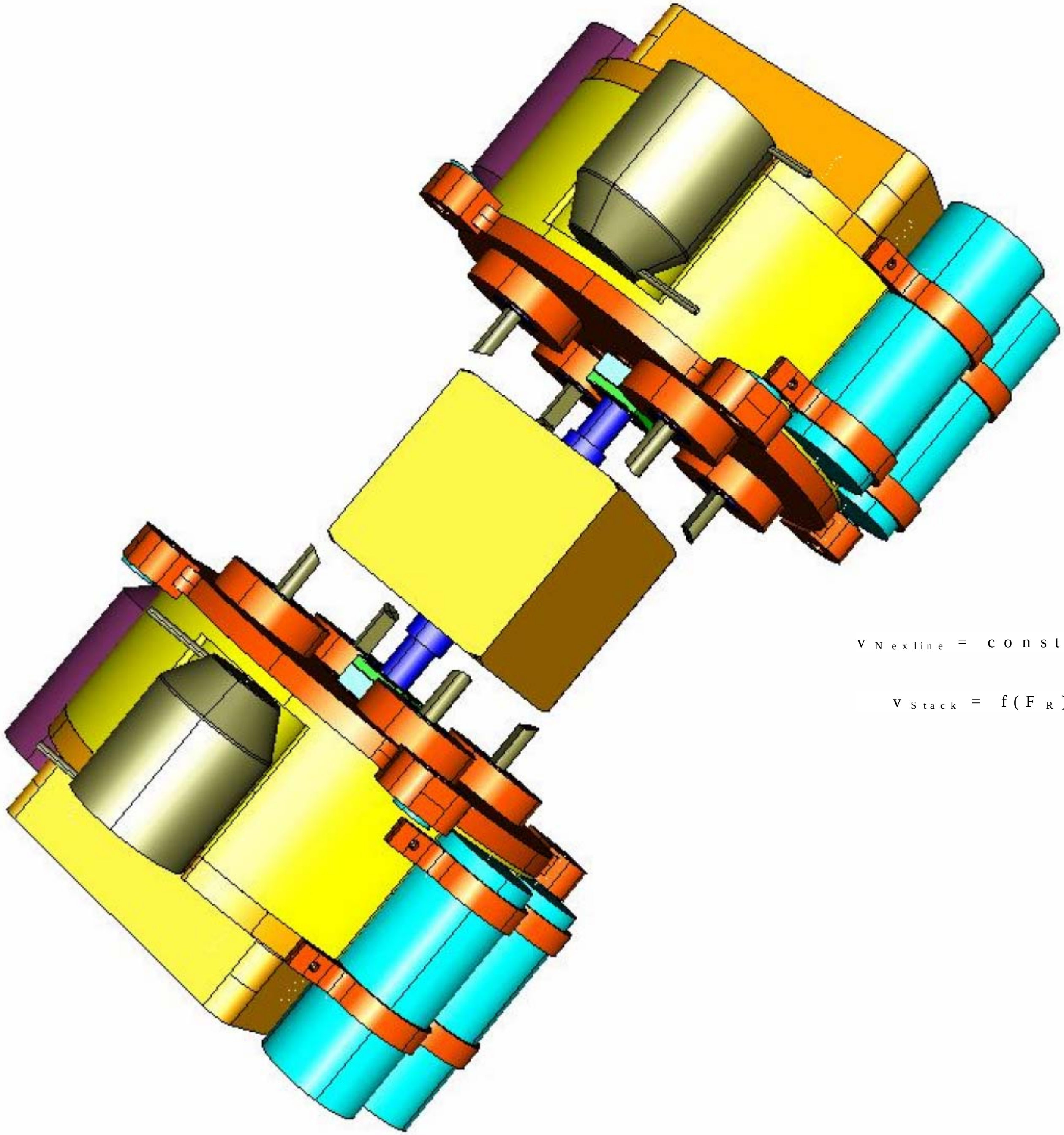

Vacuum enclosure
Electrode Housing
Test-mass
Caging Mechanism
Optical Window
UV Optical Fibres for Discharging

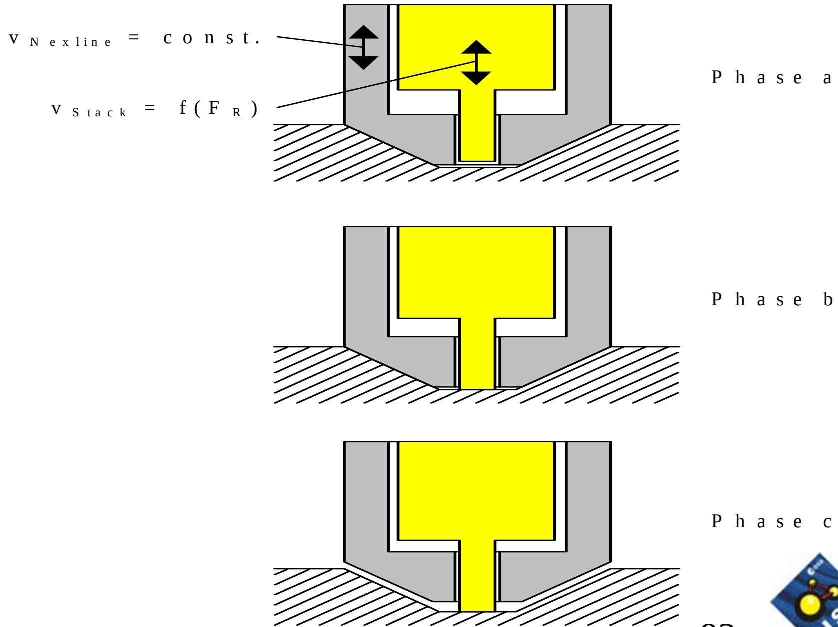






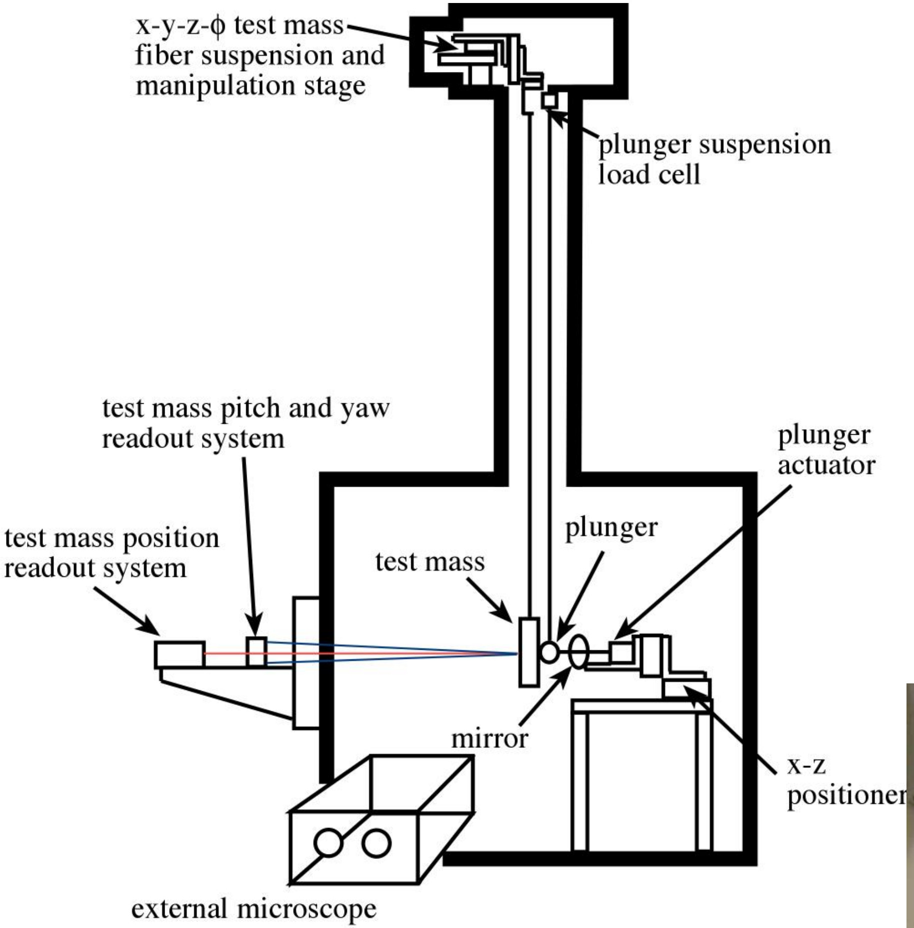



4 × 17
4 × 18
8 × 19
8 × 18
17 × 4
18 × 4
All external components removed for clarity
-01
4 × 23
18 × 4
27 × 4
11 × 16
27 × 4
22
21
CARLO GAVAZZI SPACE
LTP ISH
ASSEMBLY
1:2
ISO 2768- NA
A2
S2-CGS-DRW-3008
SHEET 2 OF 2
THIS IS A CAD DRAWING
NO MANUAL ALTERATION
ALL RIGHTS RESERVED - COPYRIGHT ACC. TO DIN 34

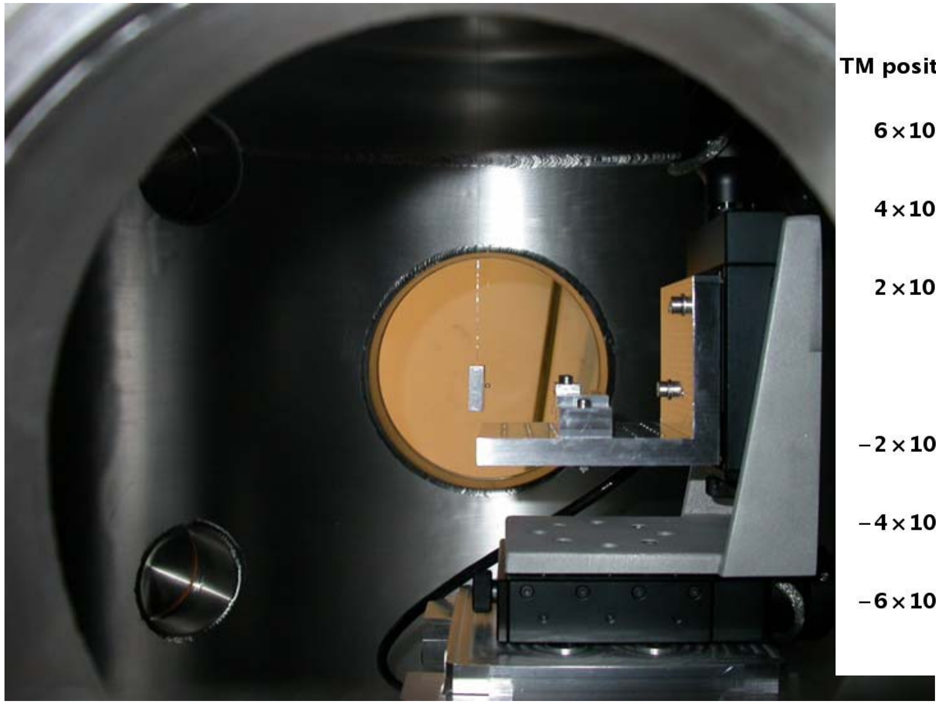


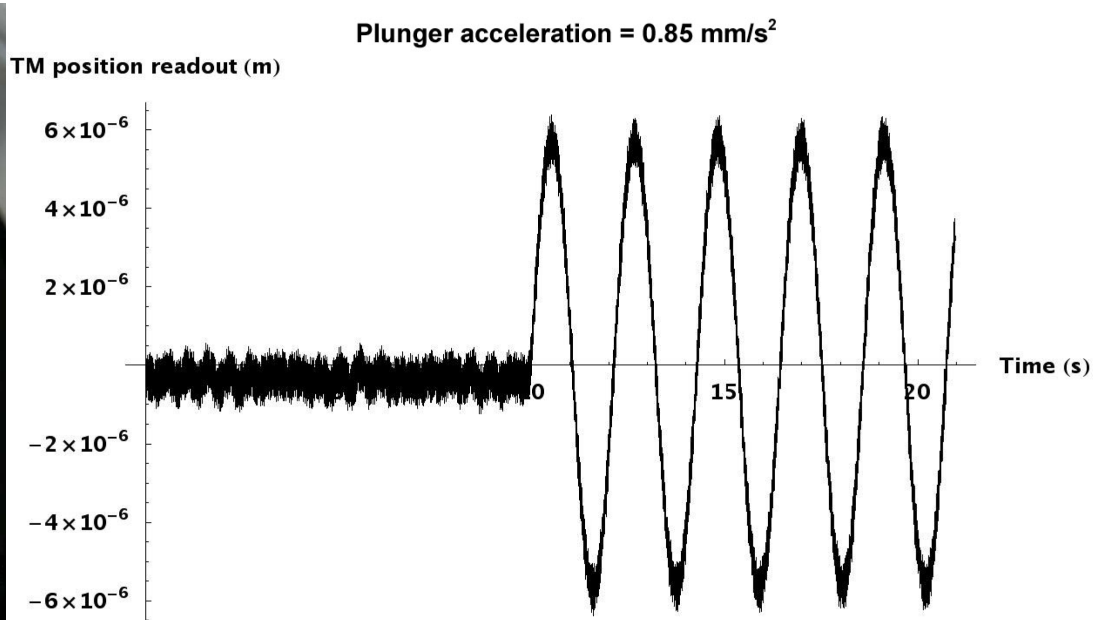

$v_{Nexline}$ = const.
$v_{Stack} = f(F_R)$
Phase a
Phase b
Phase c

LTP

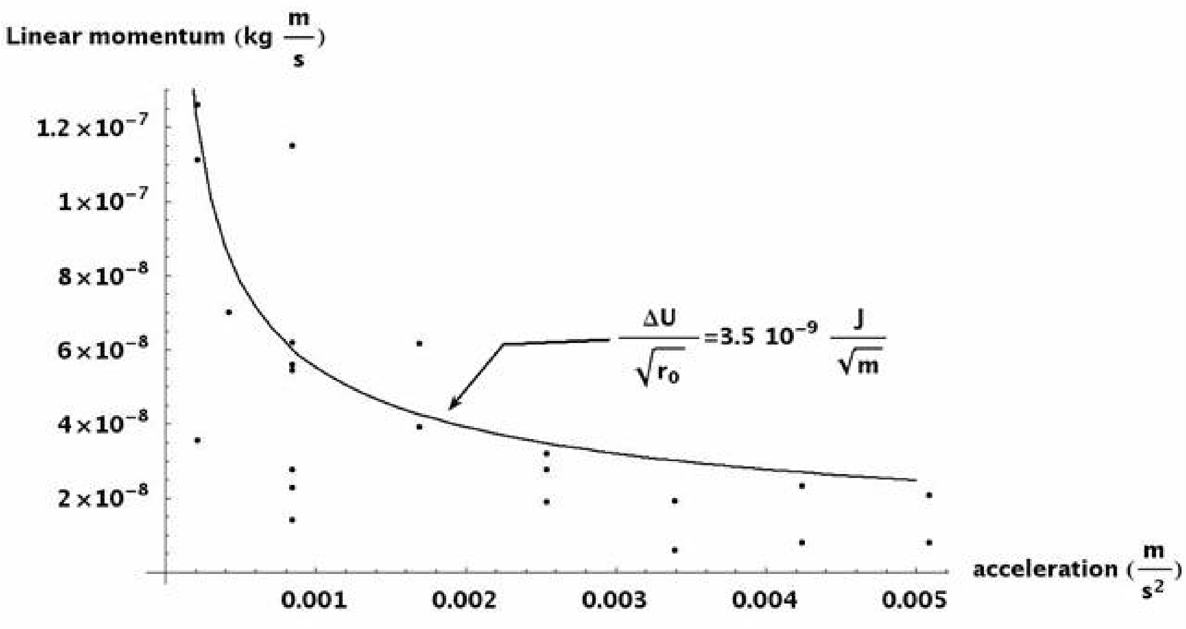


x-y-z-ϕ test mass
fiber suspension and
manipulation stage
plunger suspension
load cell
test mass pitch and yaw
readout system
plunger
actuator
test mass position
readout system
test mass
plunger
mirror
x-z
positioner
external microscope

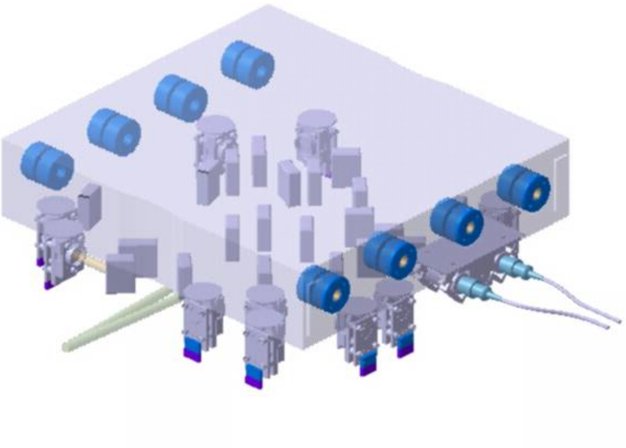


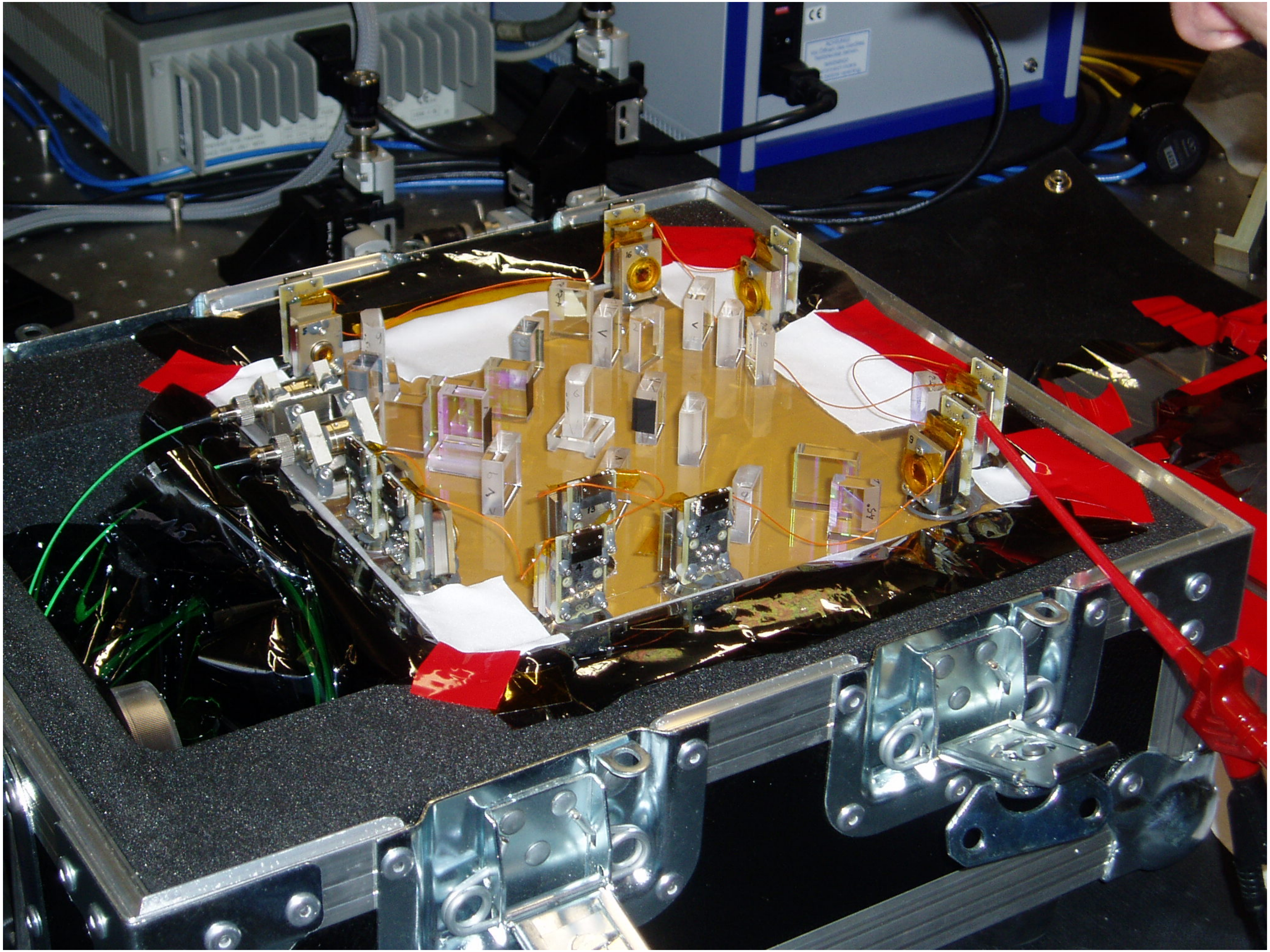


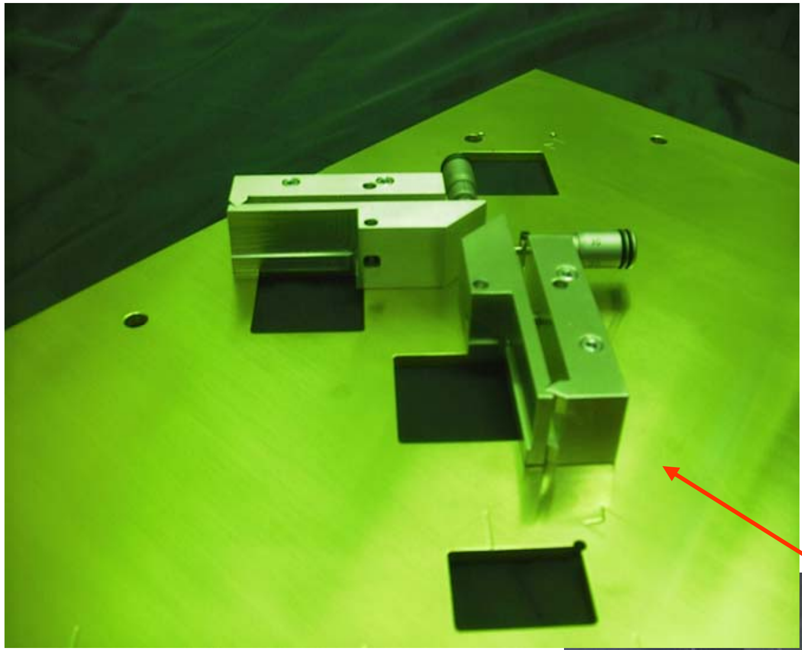
Plunger acceleration = 0.85 mm/s^2
TM position readout (m)
6×10^{-6}
4×10^{-6}
2×10^{-6}
-2×10^{-6}
-4×10^{-6}
-6×10^{-6}
Time (s)
10
15
20



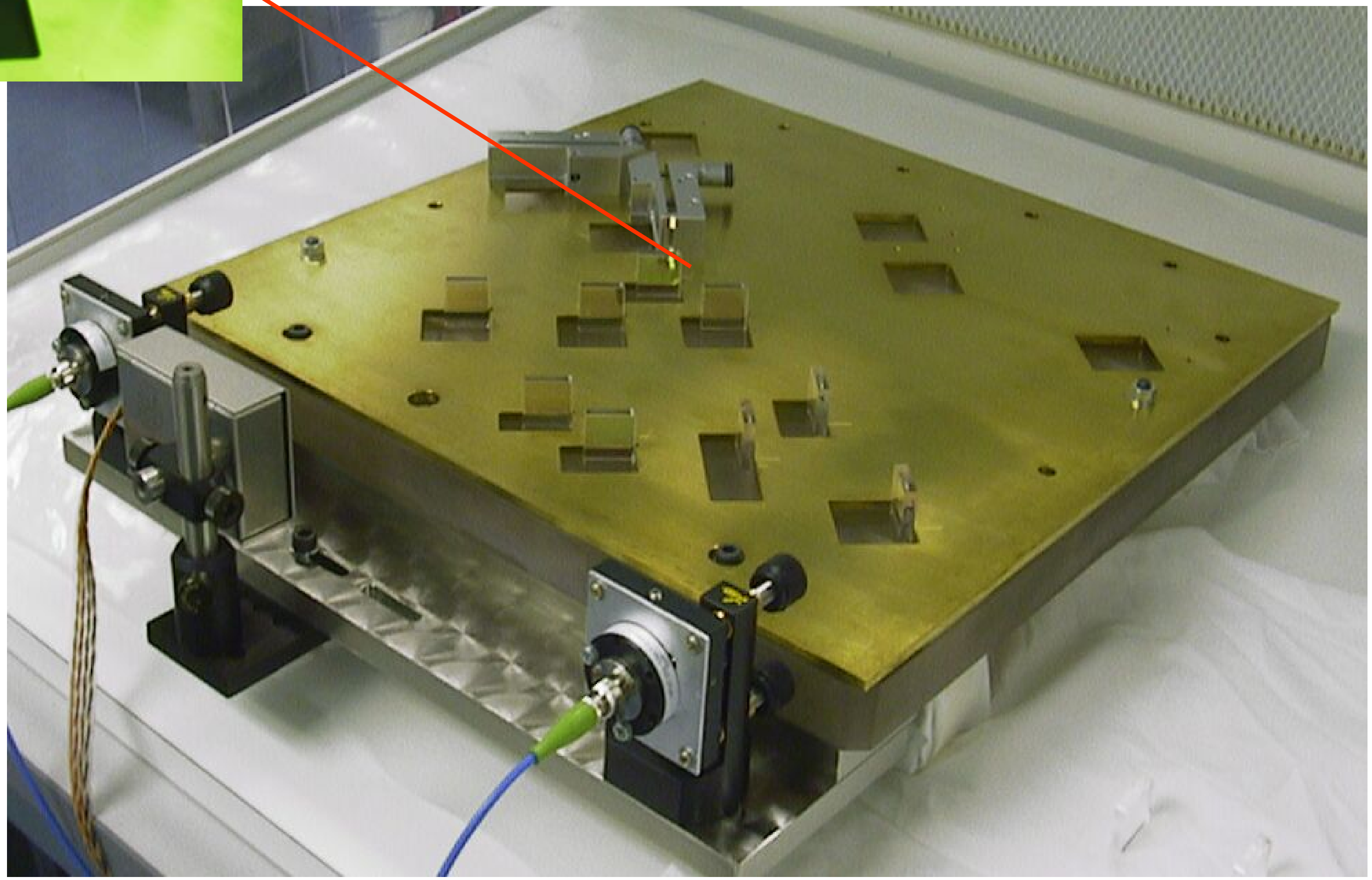
Linear momentum (kg $\frac{m}{s}$)
1.2×10^{-7}
1×10^{-7}
8×10^{-8}
6×10^{-8}
4×10^{-8}
2×10^{-8}
$\frac{\Delta U}{\sqrt{r_0}} = 3.5\ 10^{-9}\ \frac{J}{\sqrt{m}}$
acceleration ($\frac{m}{s^2}$)
0.001
0.002
0.003
0.004
0.005



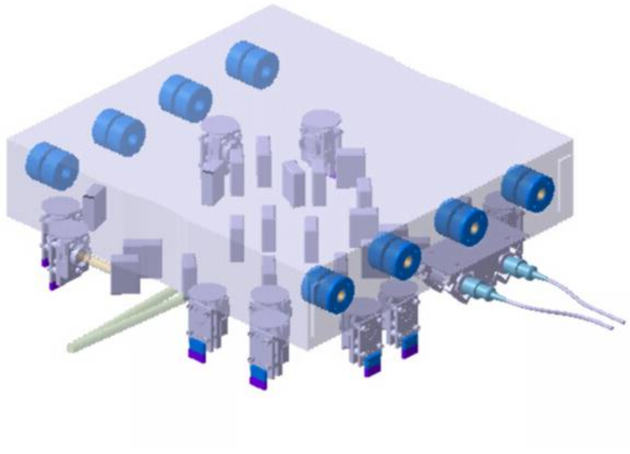


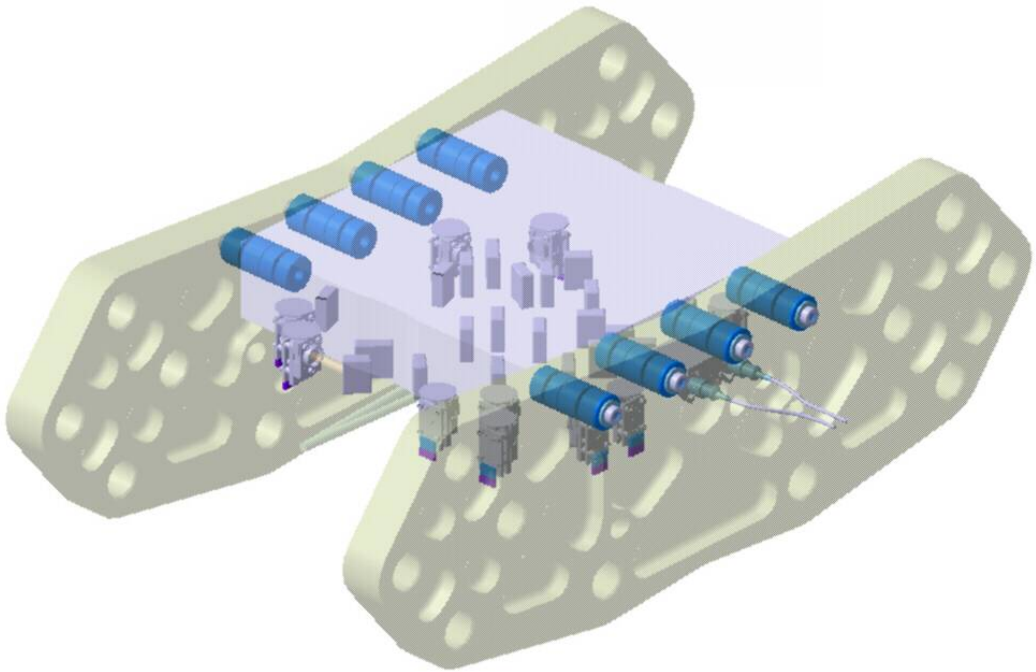


Fine alignment jig

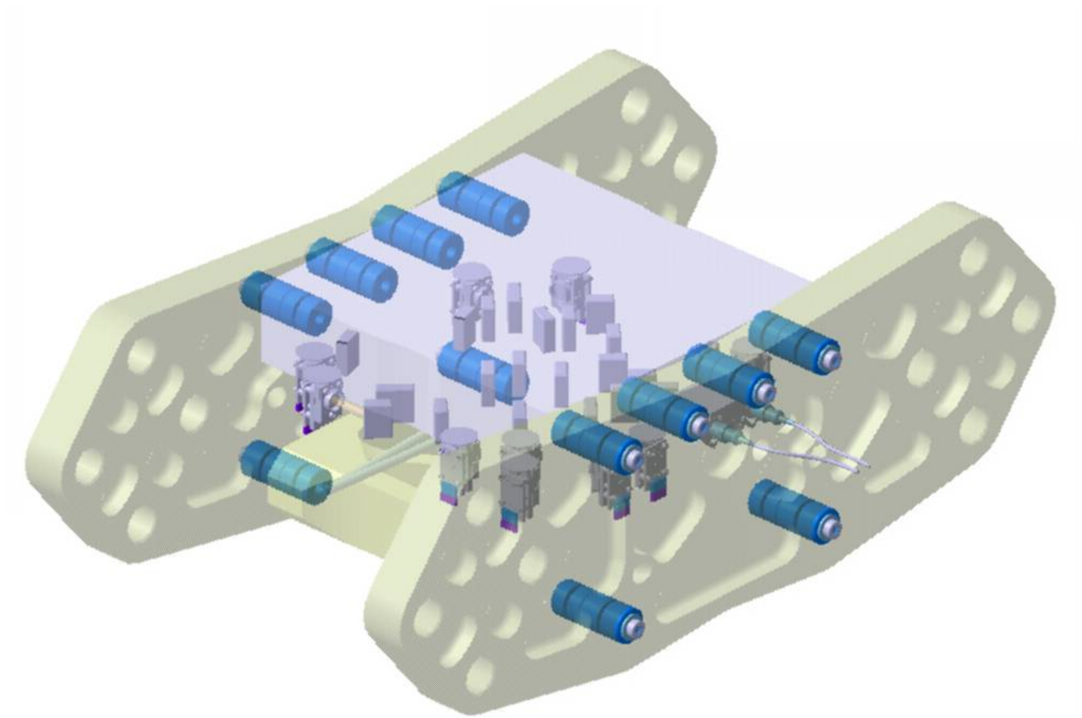


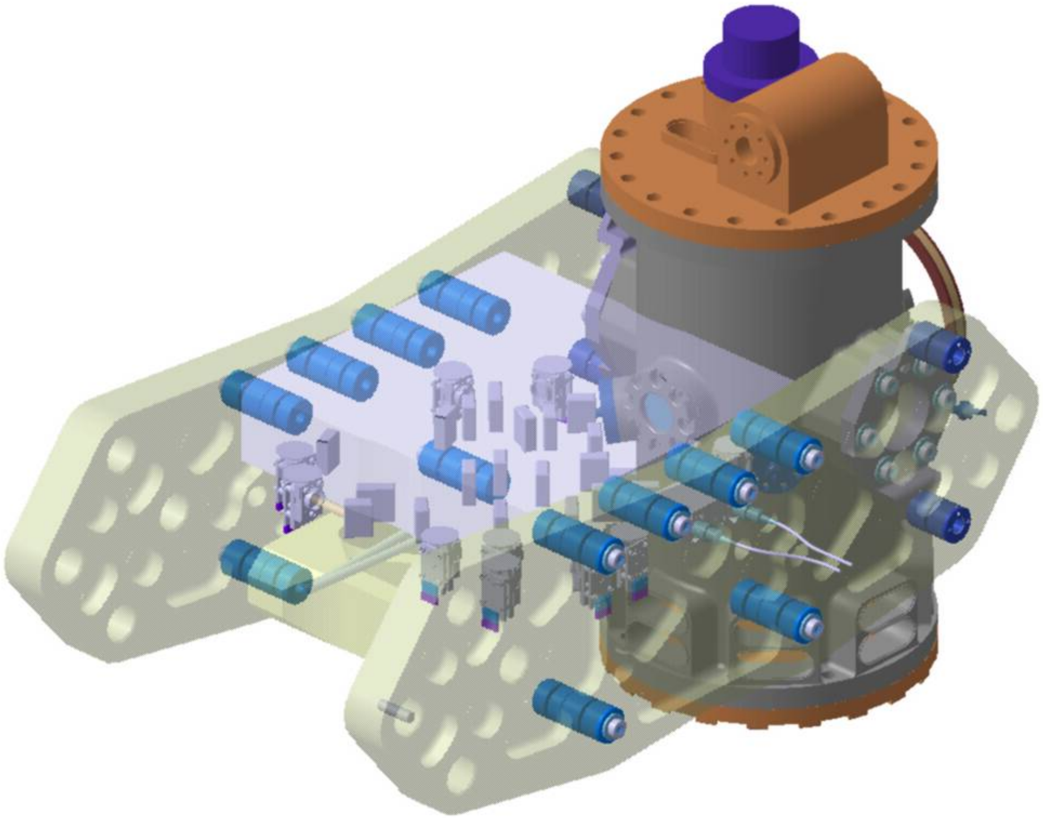
Template assembly

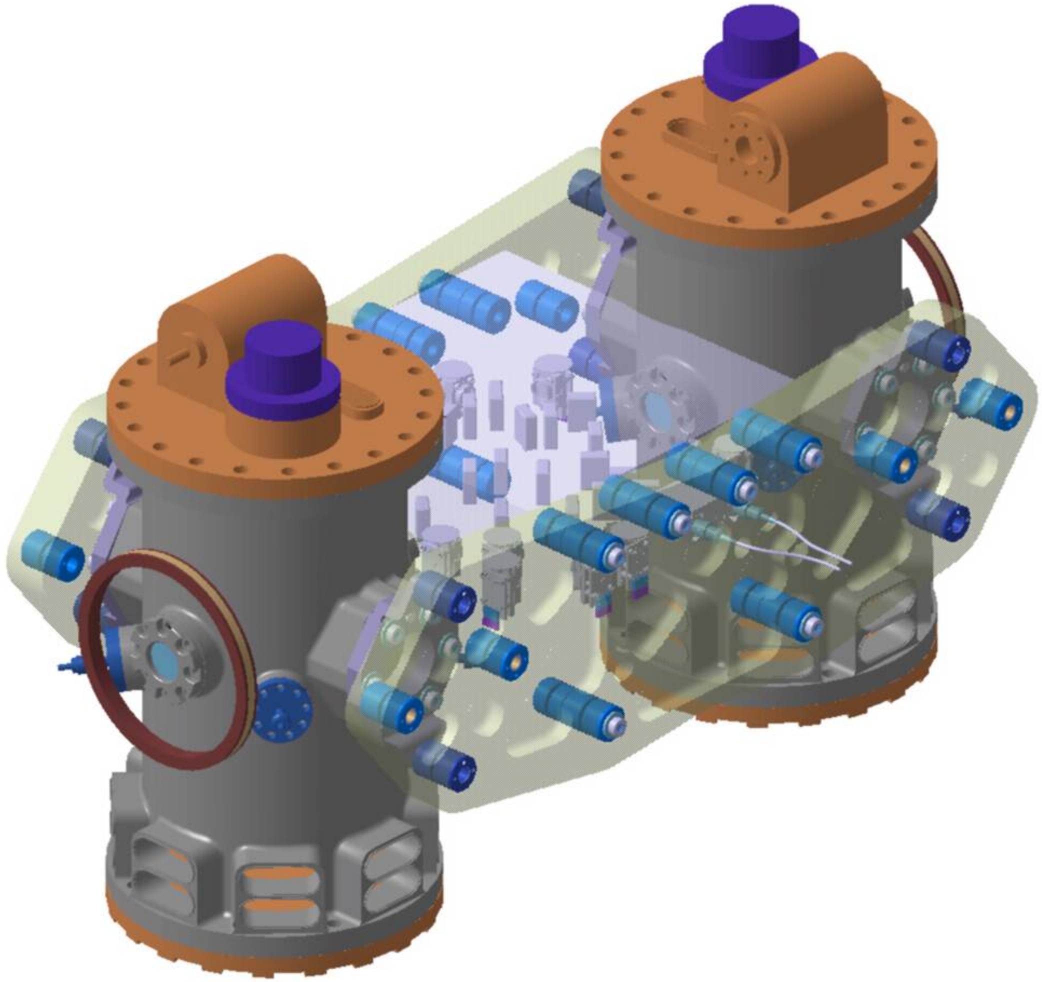




LTP







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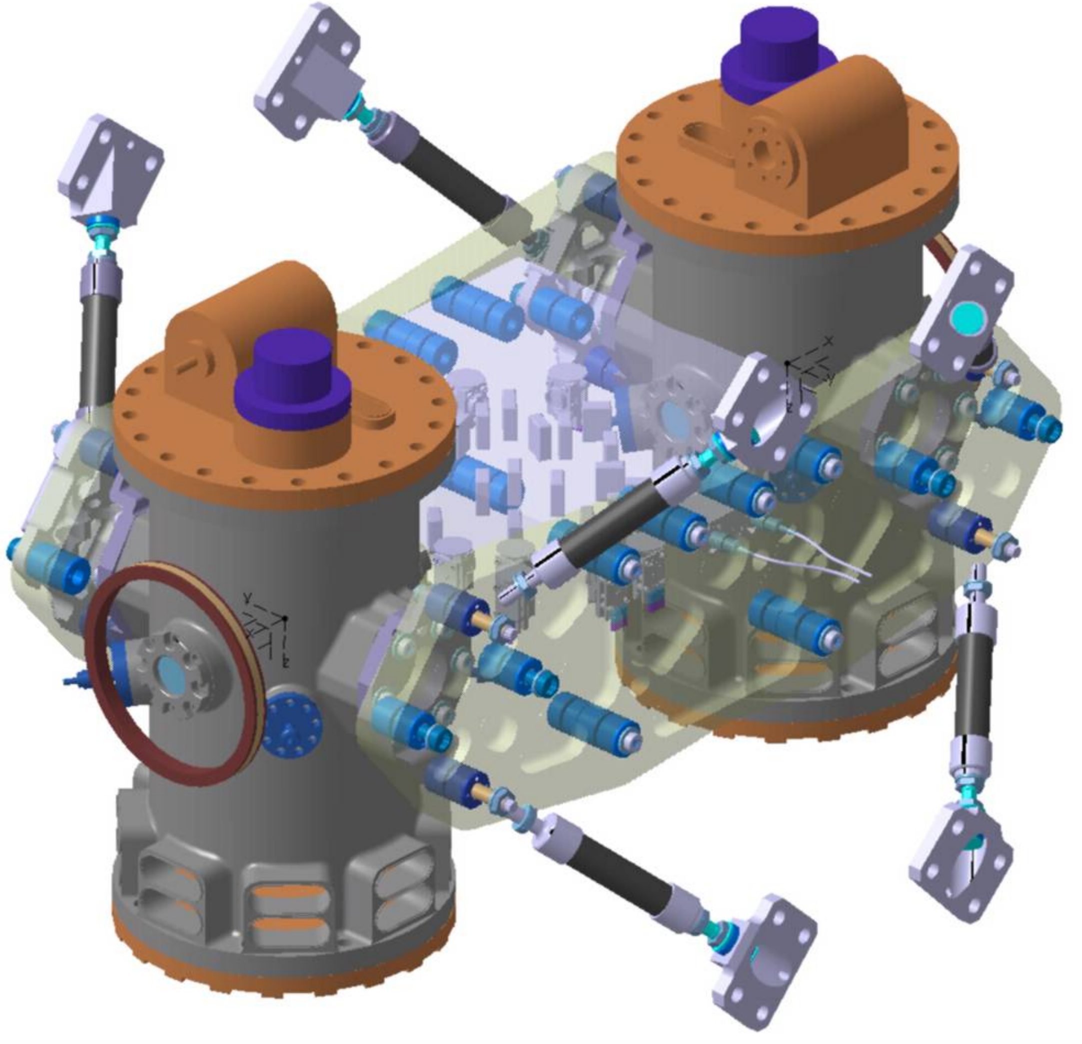

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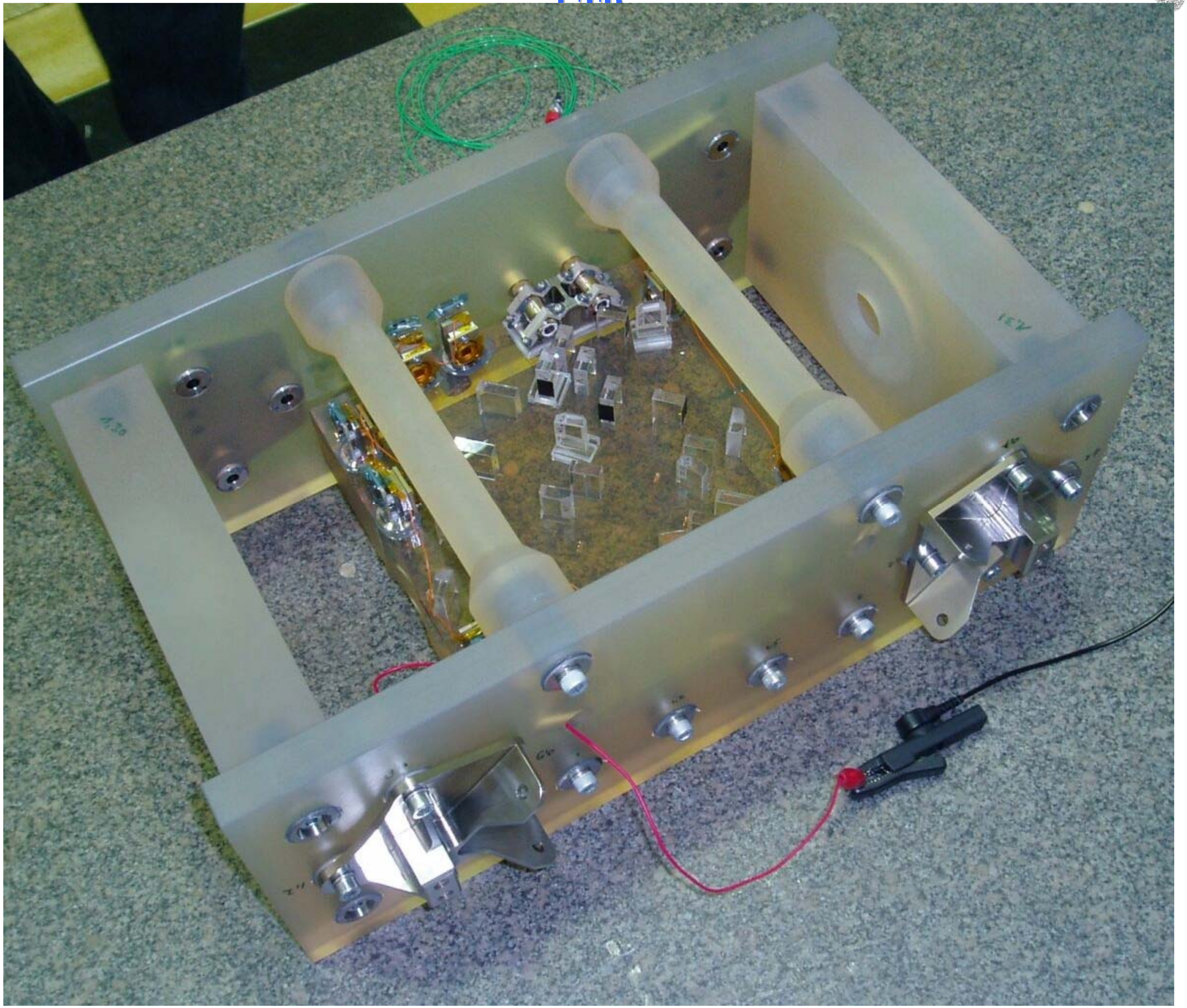
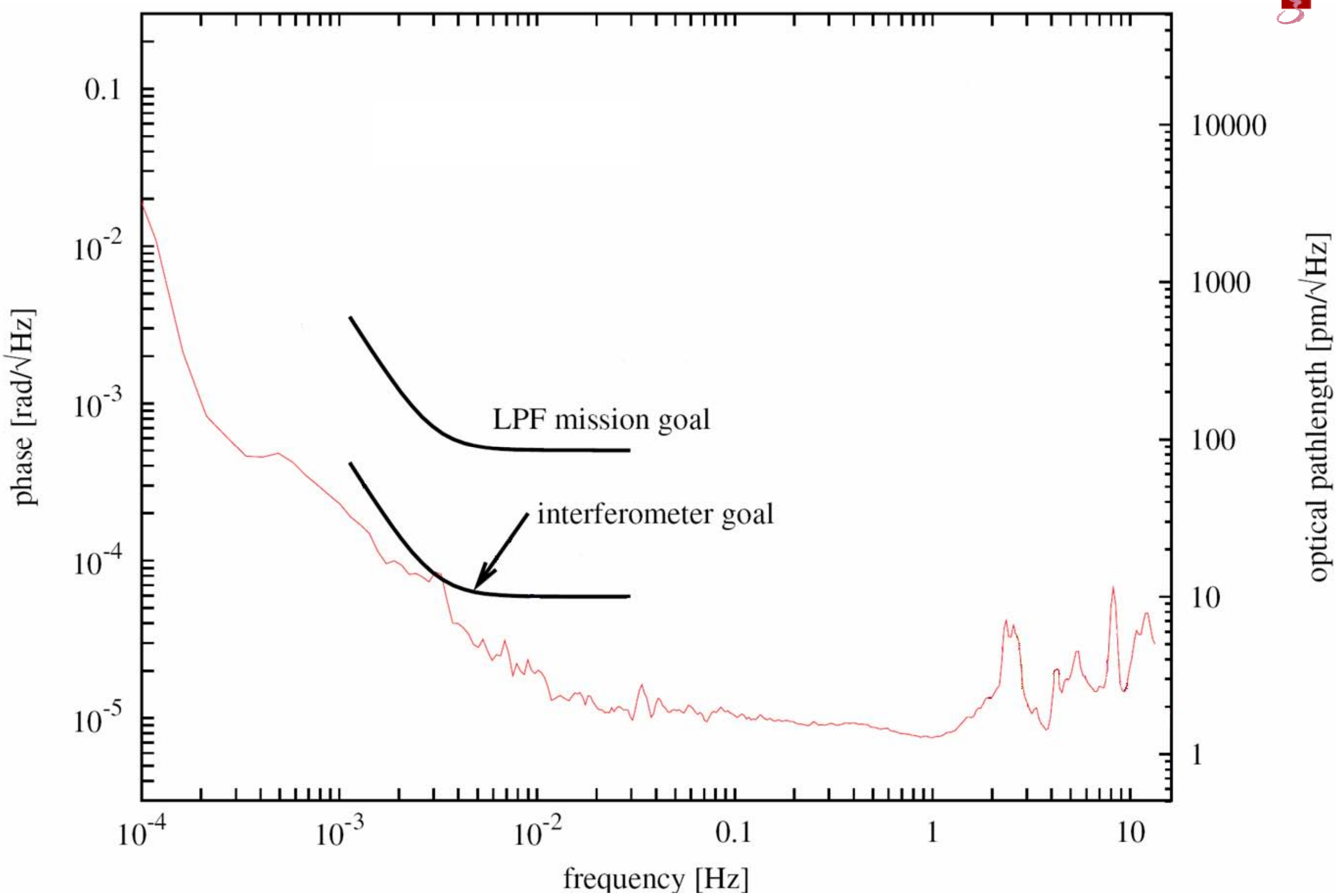
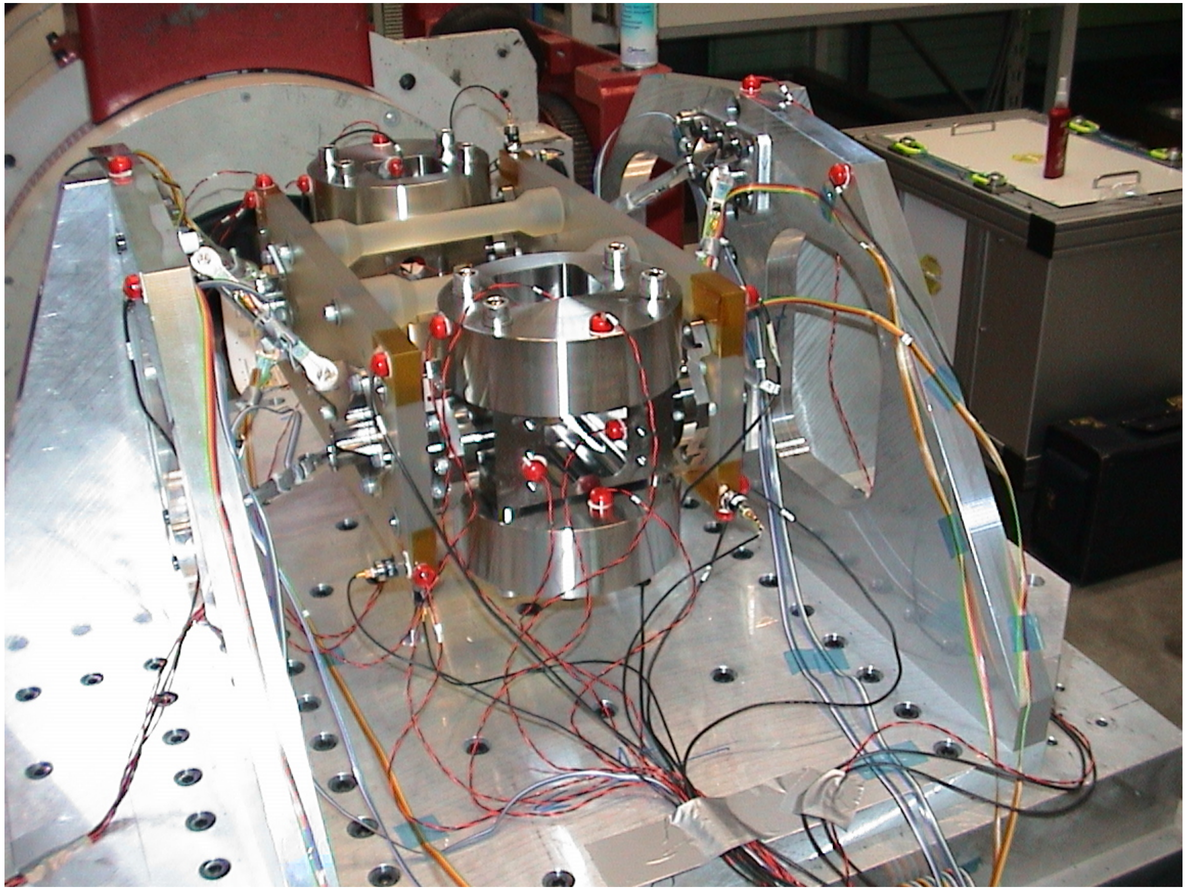
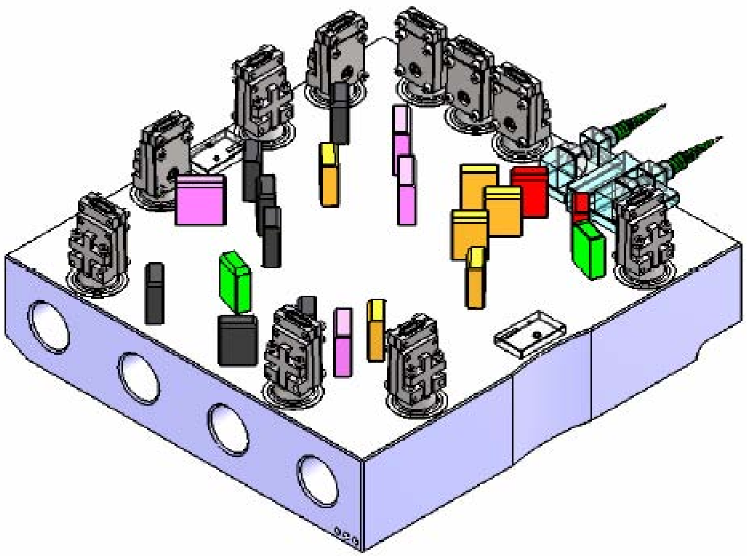


LTP



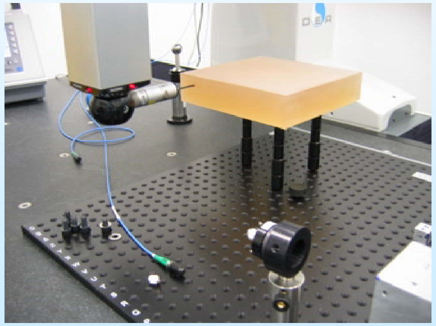
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
phase [rad/√Hz]
10000
1000
100
10
1
optical pathlength [pm/√Hz]
LPF mission goal
interferometer goal
10^{-4}
10^{-3}
10^{-2}
0.1
1
10
frequency [Hz]





LTP lab in operation

CMM operation – metrology with 2.5 μm precision over 20 cm distances



Class 1000 cleanroom with large ultra-clean laminar flow cabinet for bonding operations

LTP Team Workshop, Trento, 10 - 12 October 2005

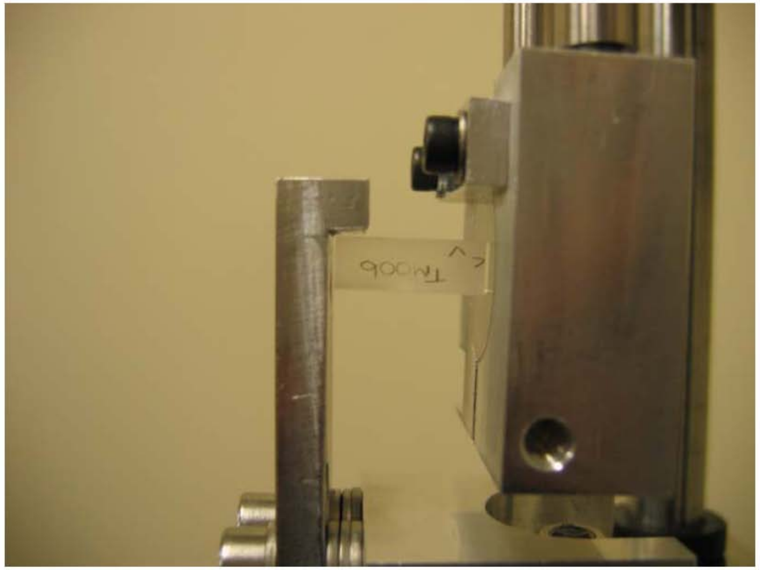
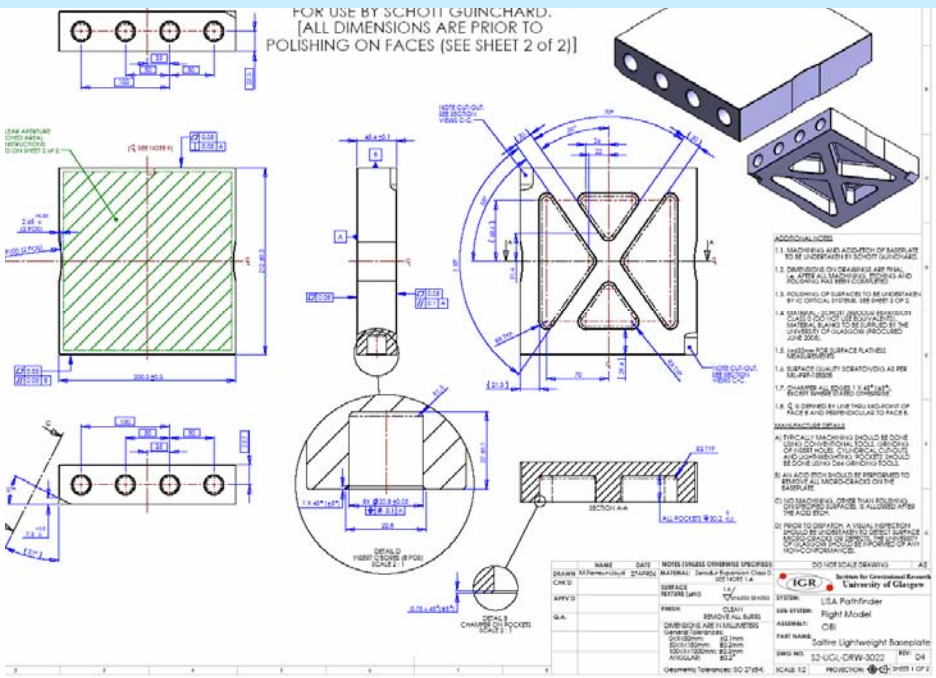
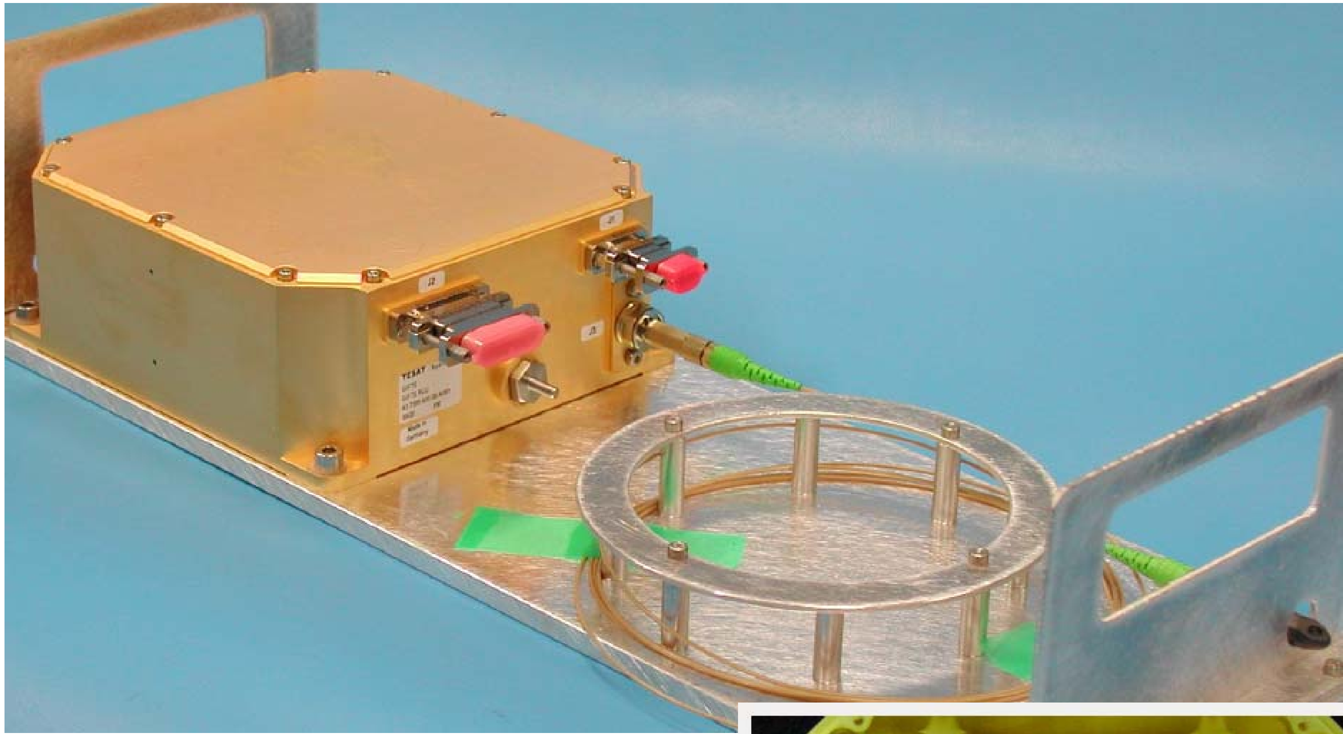
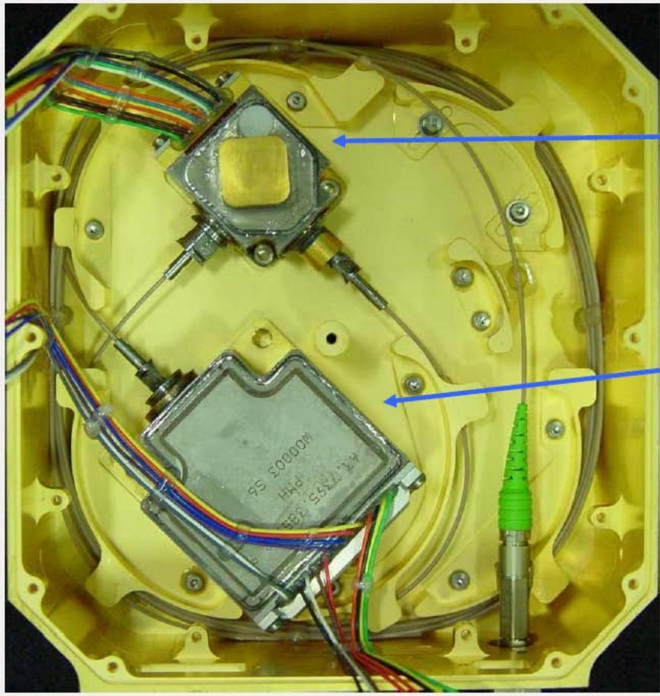


Figure 3 TM-006 ground-polished bonded to TS-018 in the strength testing pulling machine





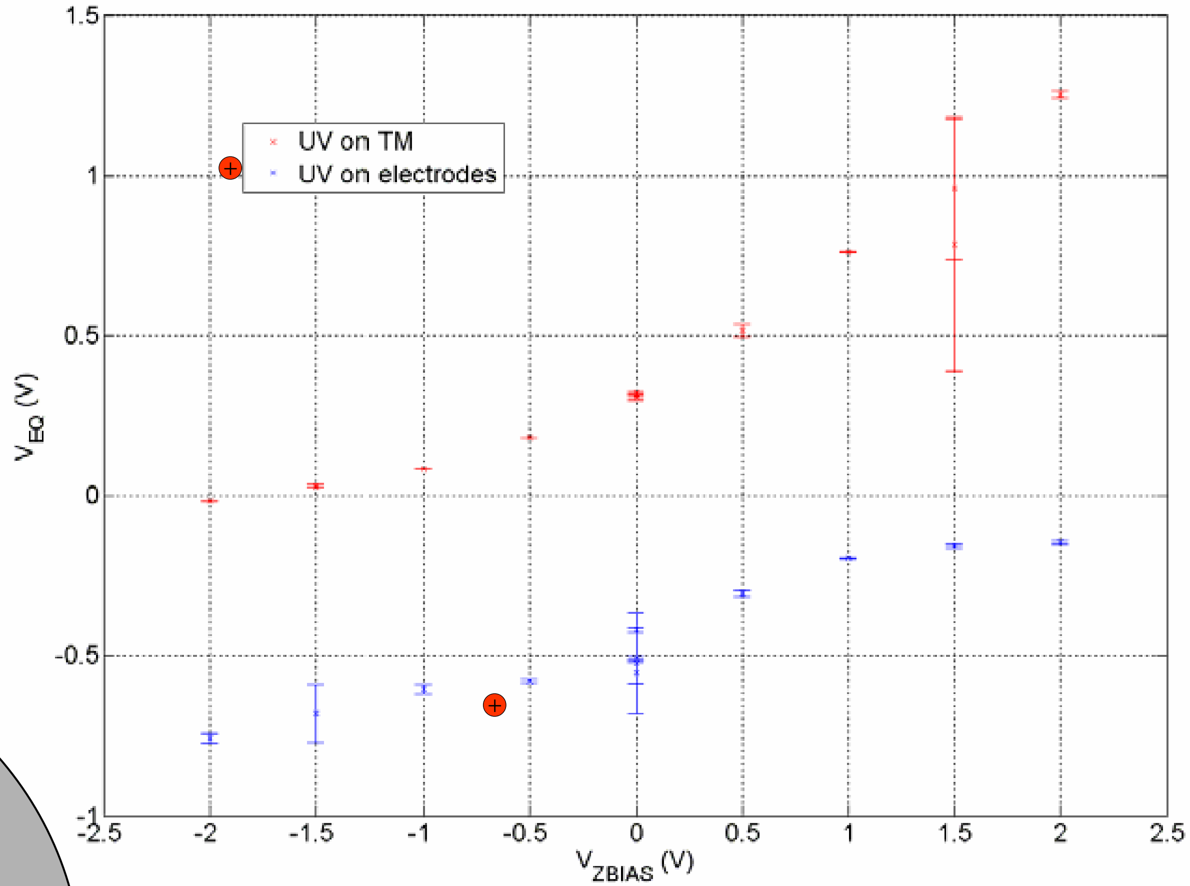


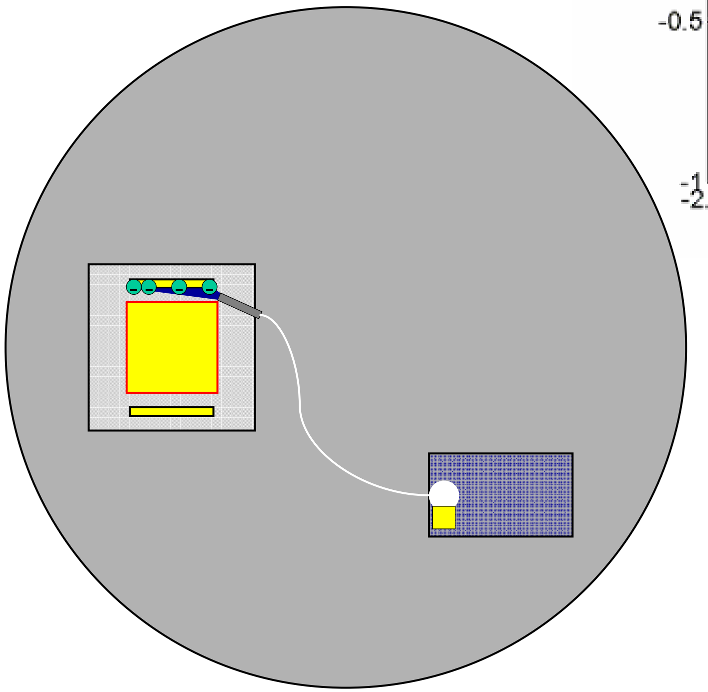
Laserhead
Nd:YAG 1064nm

Pumpmodule
bragg-stabilized 808nm
with redundant bench

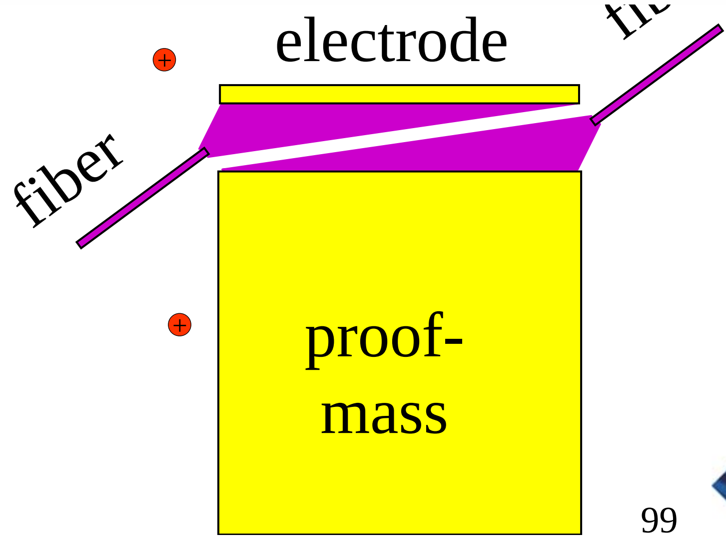
all optical units in direct
thermal contact with
RLU housing

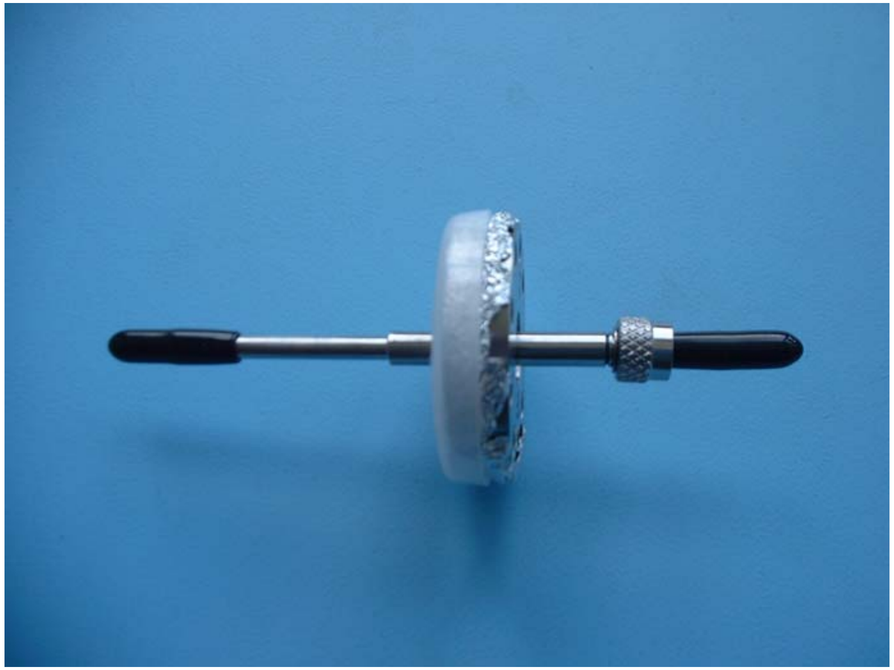
•**Fighting cosmic rays with UV-light non-contacting discharging system**



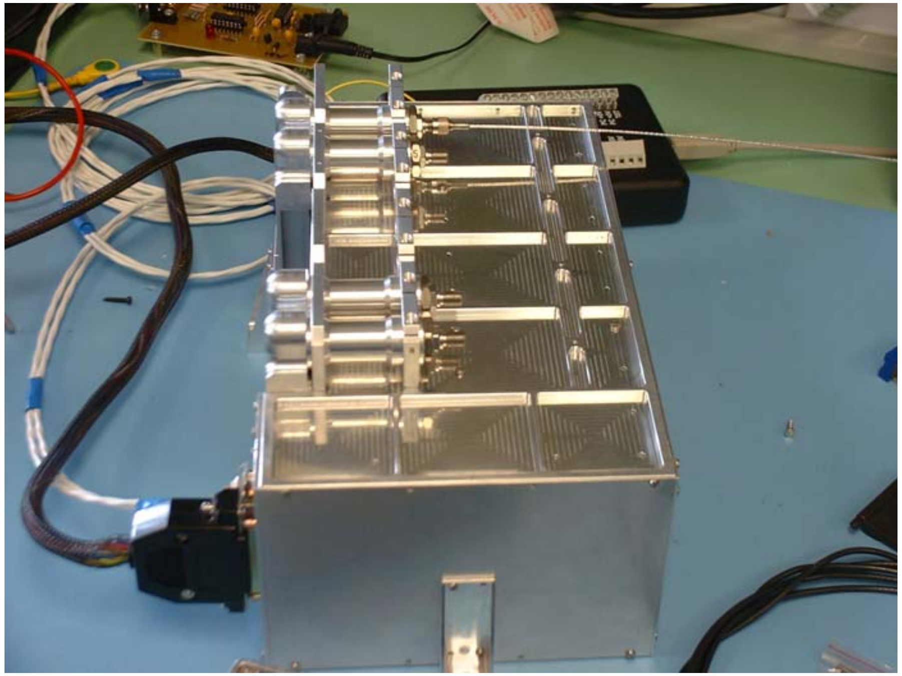


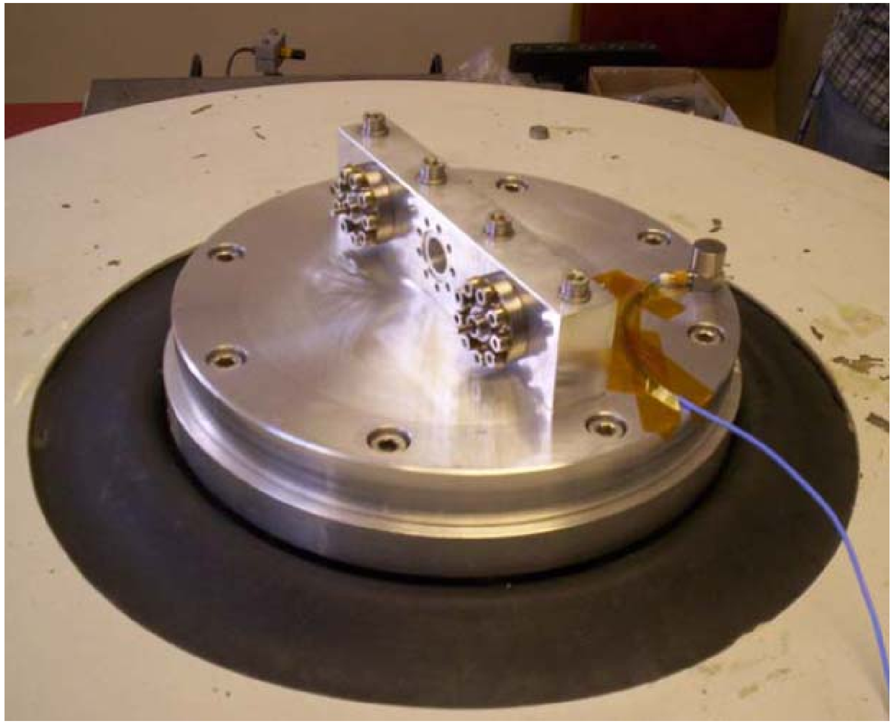
Imperial College

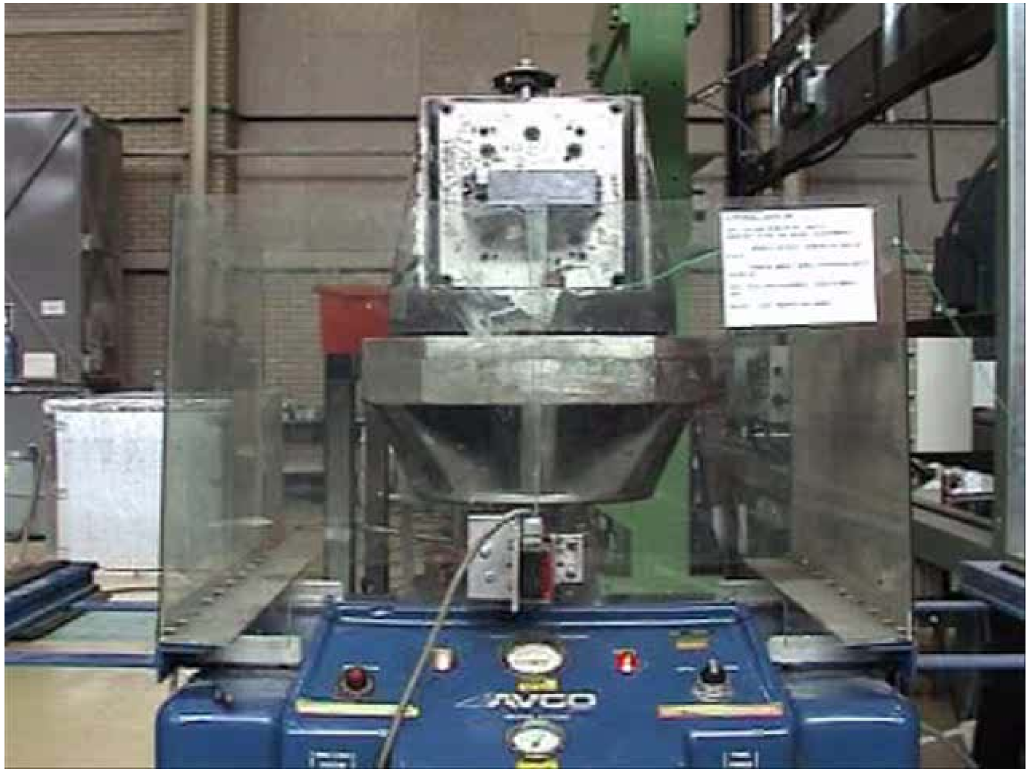




LTP







Firenze 28 09 2006

LTP

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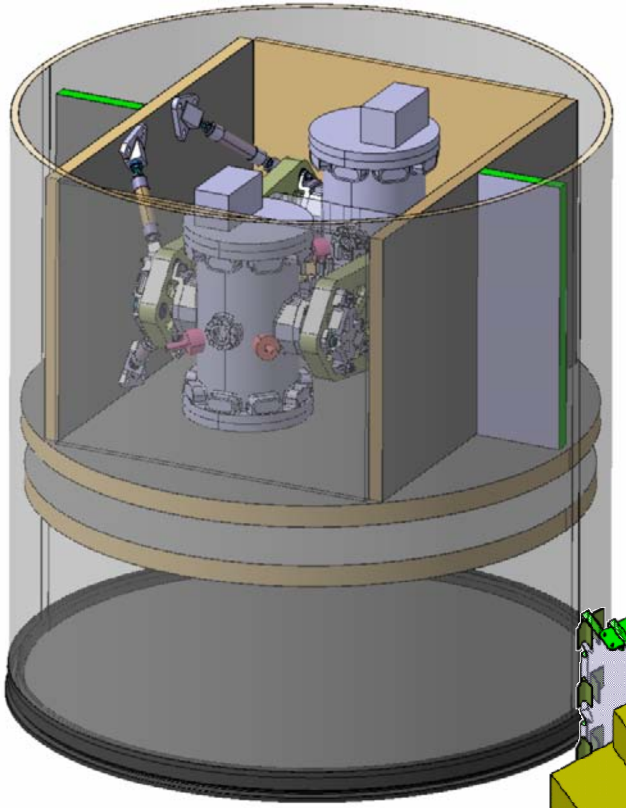
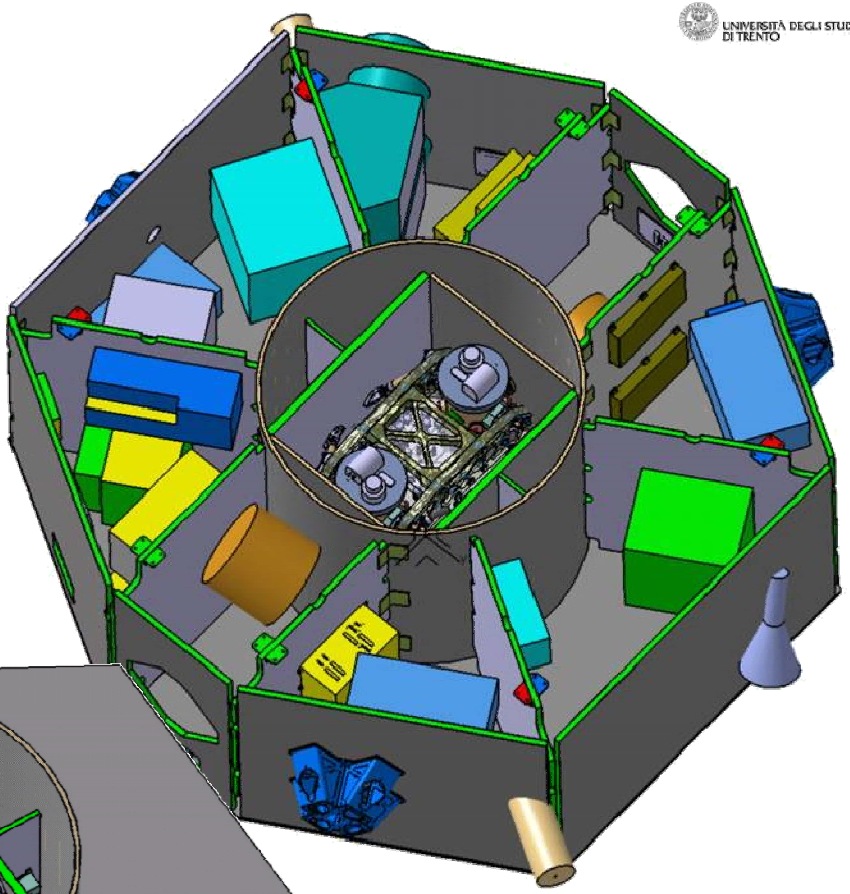
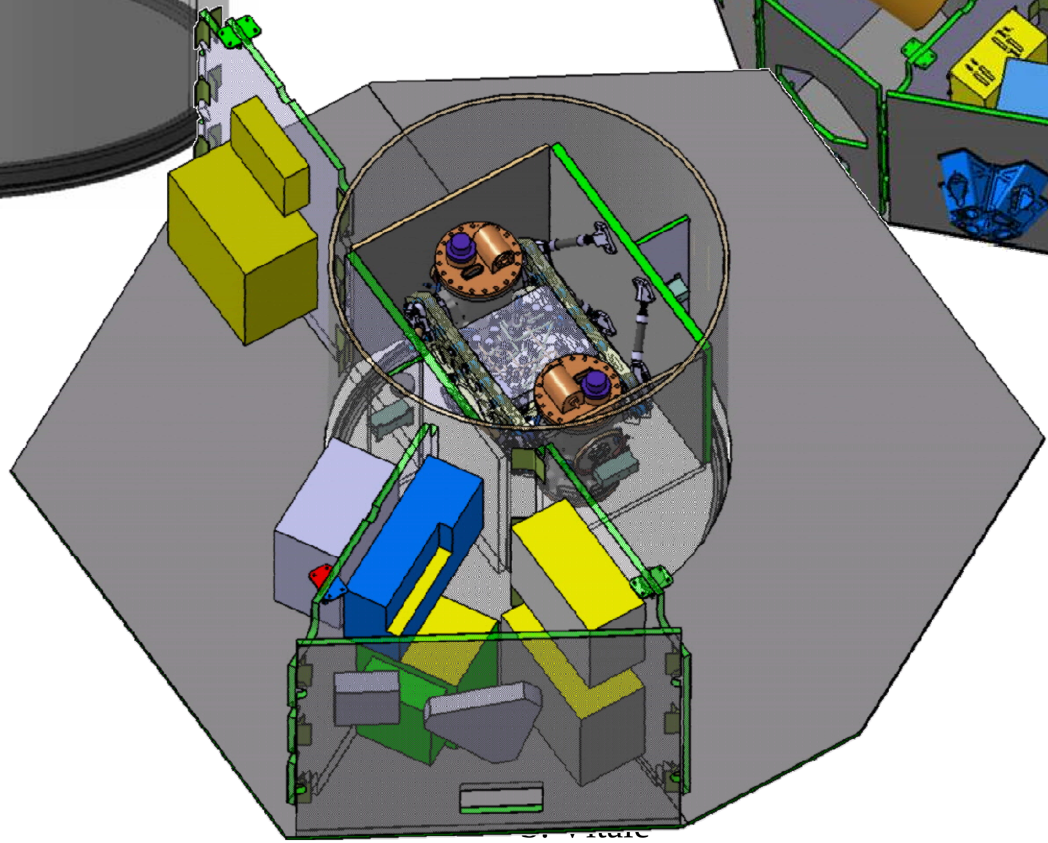
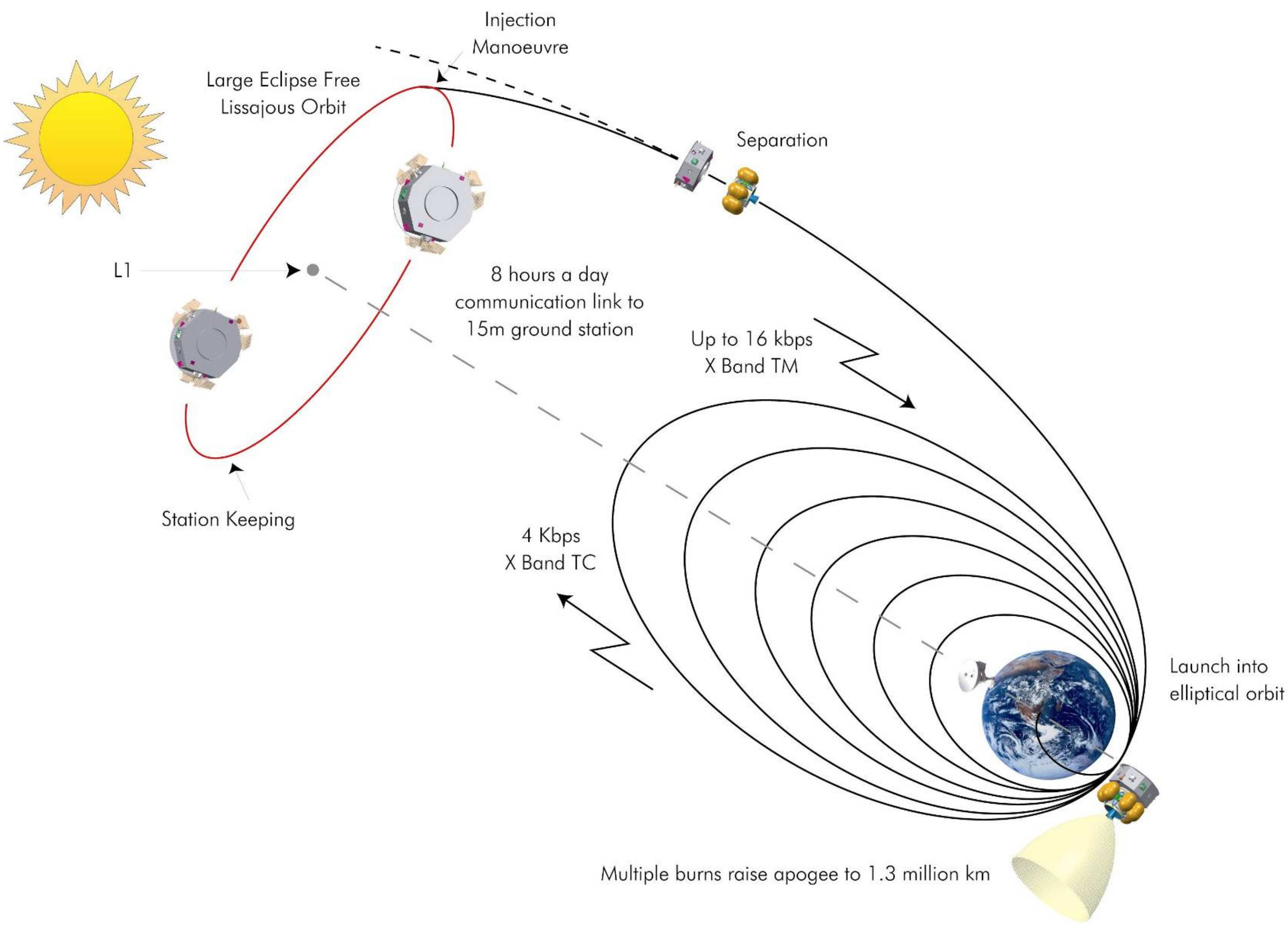






LTP



Injection
Manoeuvre
Large Eclipse Free
Lissajous Orbit
Separation
L1
8 hours a day
communication link to
15m ground station
Up to 16 kbps
X Band TM
Station Keeping
4 Kbps
X Band TC
Launch into
elliptical orbit
Multiple burns raise apogee to 1.3 million km

LTP Experiment Main Goals

1. Demonstrate that total acceleration noise in realistic conditions is not larger than goals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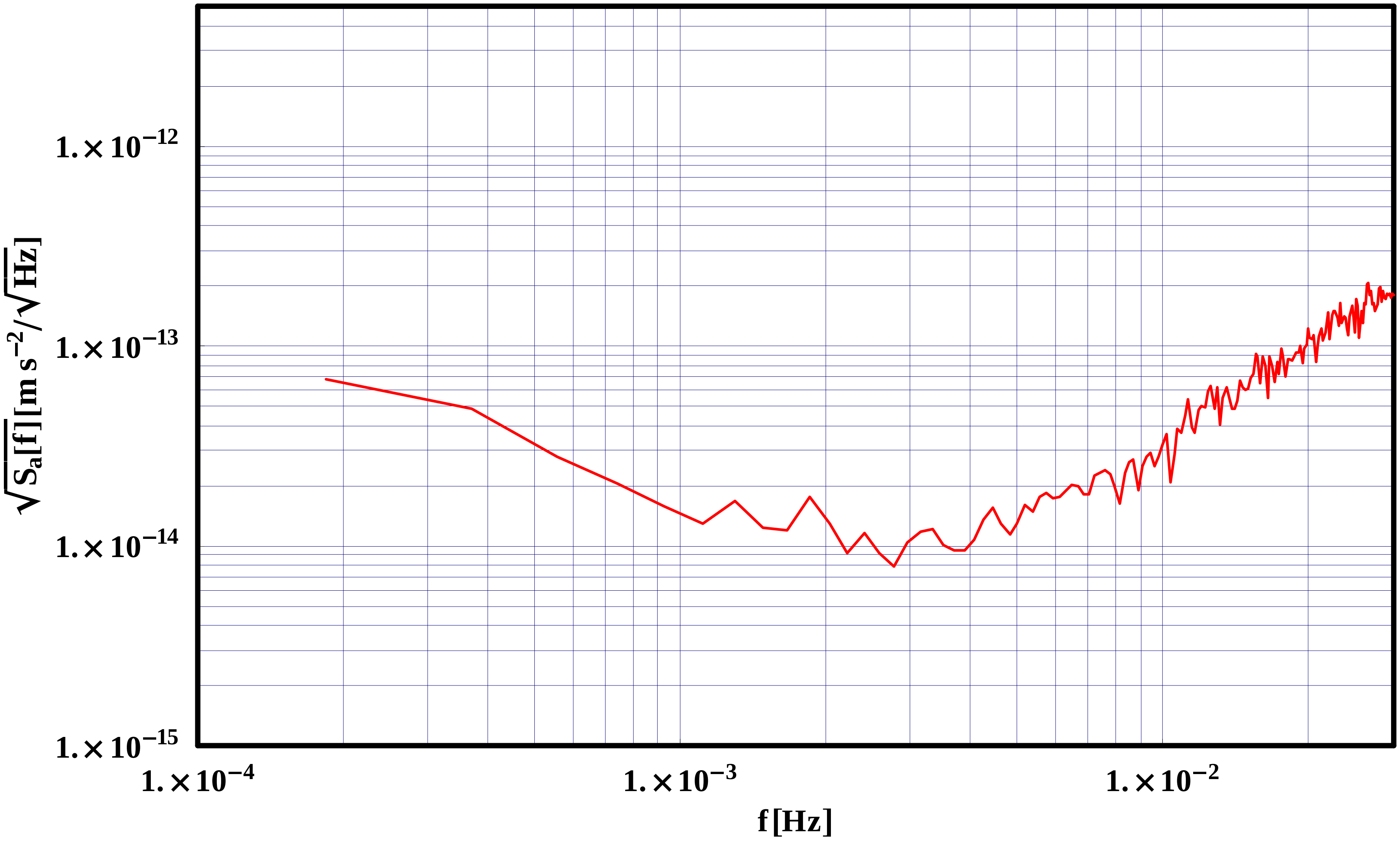
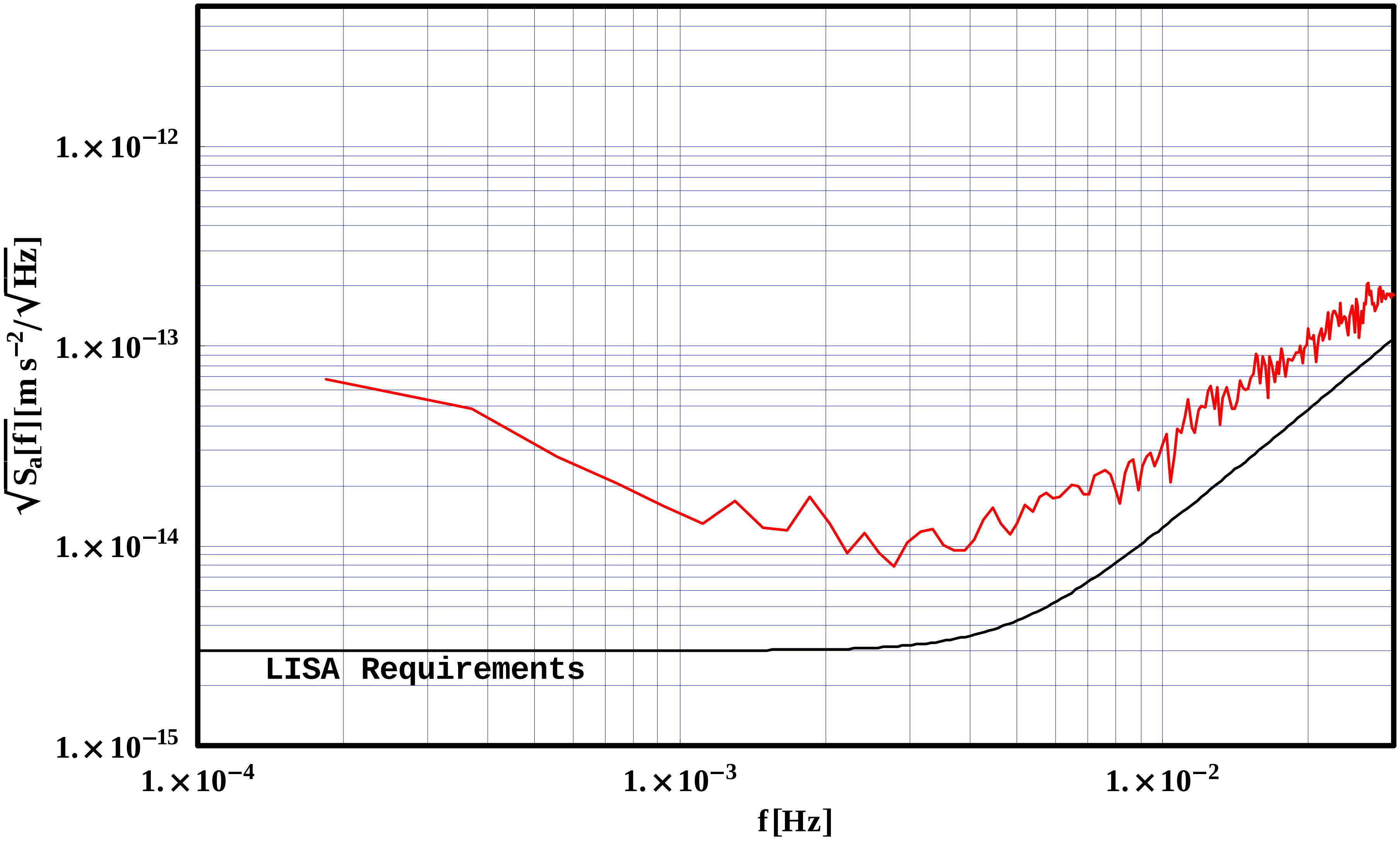
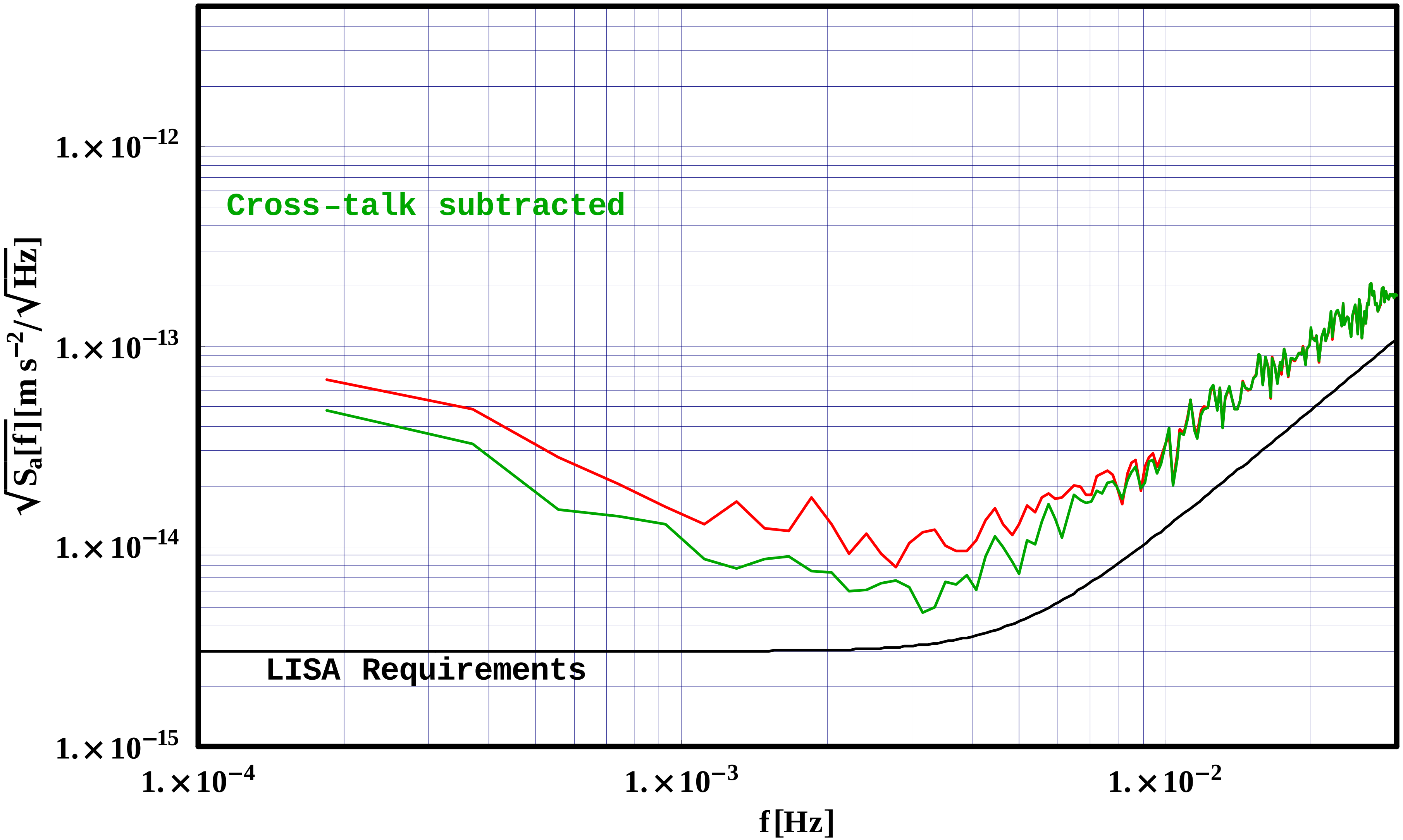
LISA Technology Package

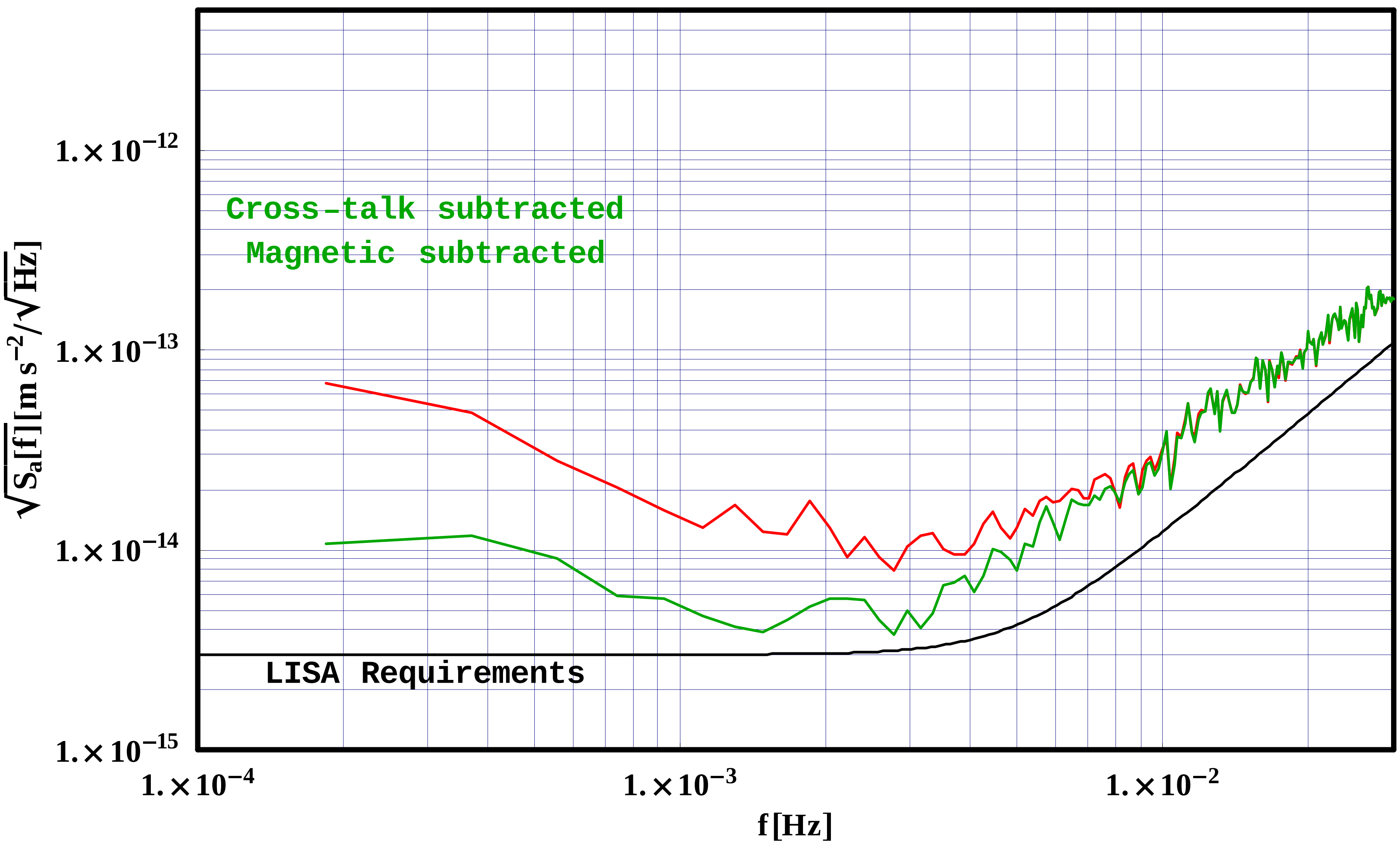
Science Requirements and Top-level Architecture Definition for the Lisa Technology Package (LTP) on Board LISA Pathfinder (SMART-2)

LTPA-UTN-ScRD-Iss003-Rev1

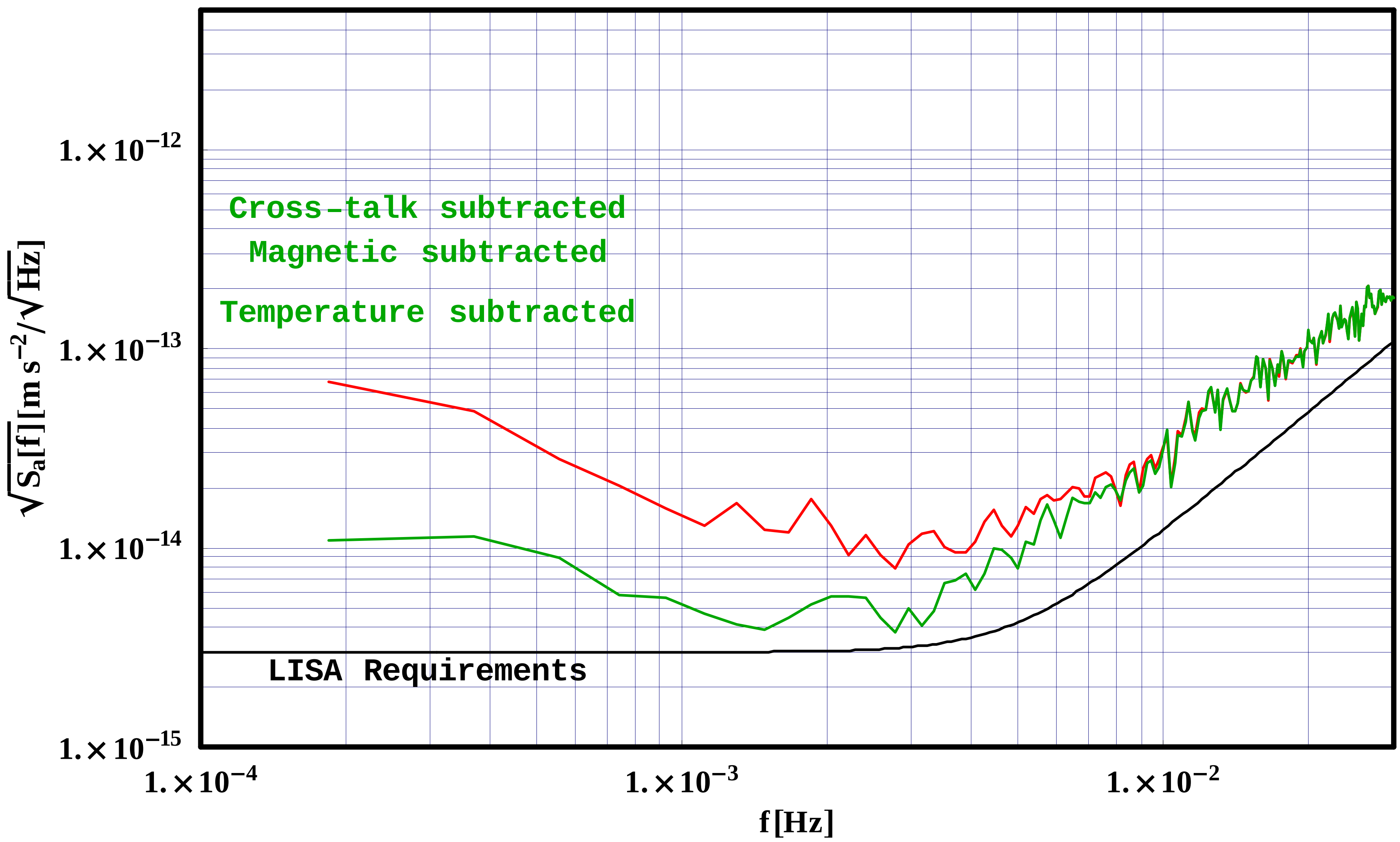

1. × 10^−12
1. × 10^−13
1. × 10^−14
1. × 10^−15
1. × 10^−4
1. × 10^−3
1. × 10^−2
f [Hz]
√S_a[f] [m s^−2/√Hz]


$1.\times 10^{-12}$
$1.\times 10^{-13}$
$1.\times 10^{-14}$
$1.\times 10^{-15}$
$\sqrt{S_a[f]}\,[\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$
LISA Requirements
$1.\times 10^{-4}$
$1.\times 10^{-3}$
$1.\times 10^{-2}$
f [Hz]

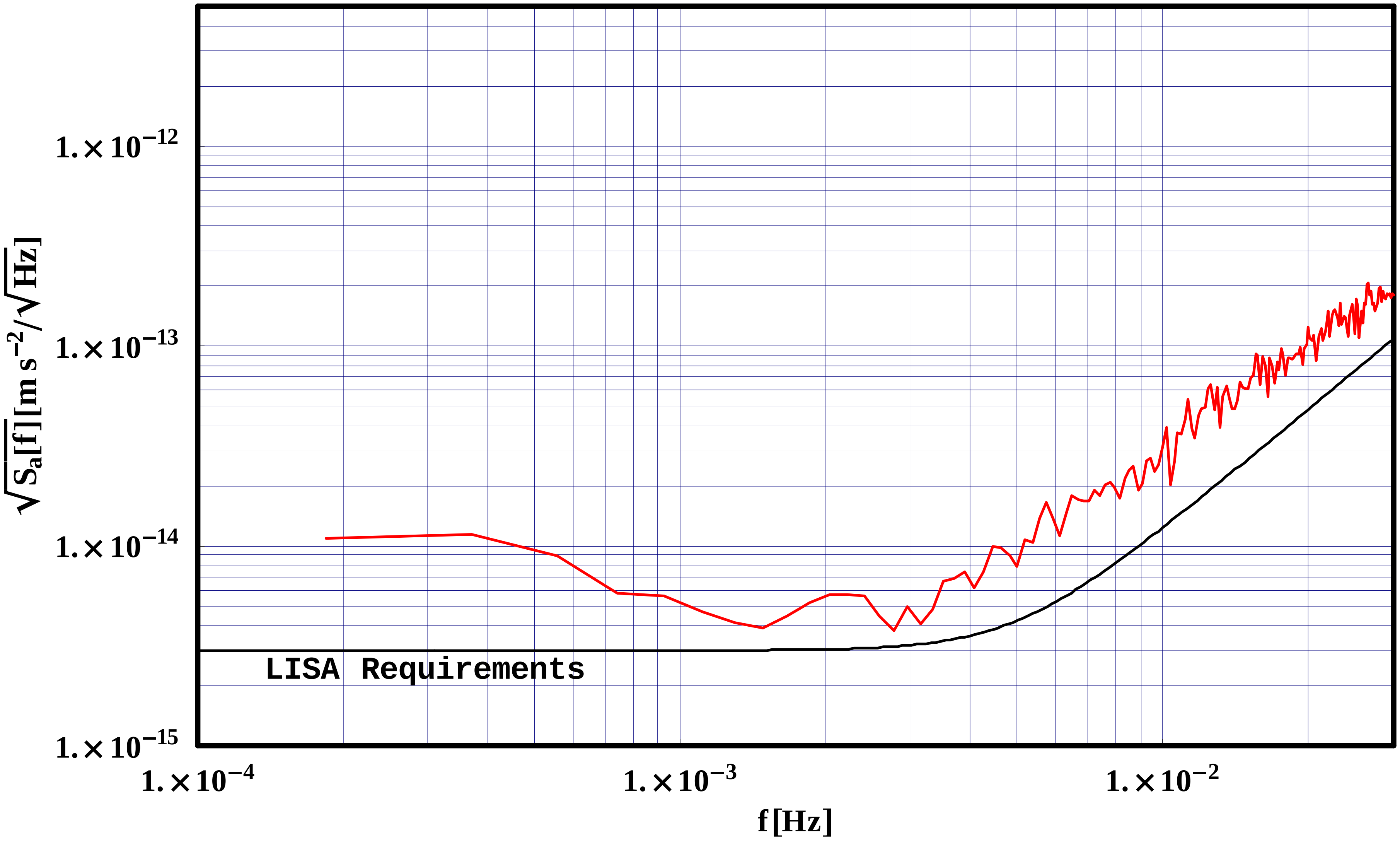

Cross-talk subtracted
LISA Requirements
1. × 10^−12
1. × 10^−13
1. × 10^−14
1. × 10^−15
1. × 10^−4
1. × 10^−3
1. × 10^−2
f [Hz]
√Sa[f] [m s^−2/√Hz]



Cross-talk subtracted
Magnetic subtracted
LISA Requirements
$1.\times 10^{-12}$
$1.\times 10^{-13}$
$1.\times 10^{-14}$
$1.\times 10^{-15}$
$1.\times 10^{-4}$
$1.\times 10^{-3}$
$1.\times 10^{-2}$
f [Hz]
$\sqrt{S_a[f]}\,[\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$

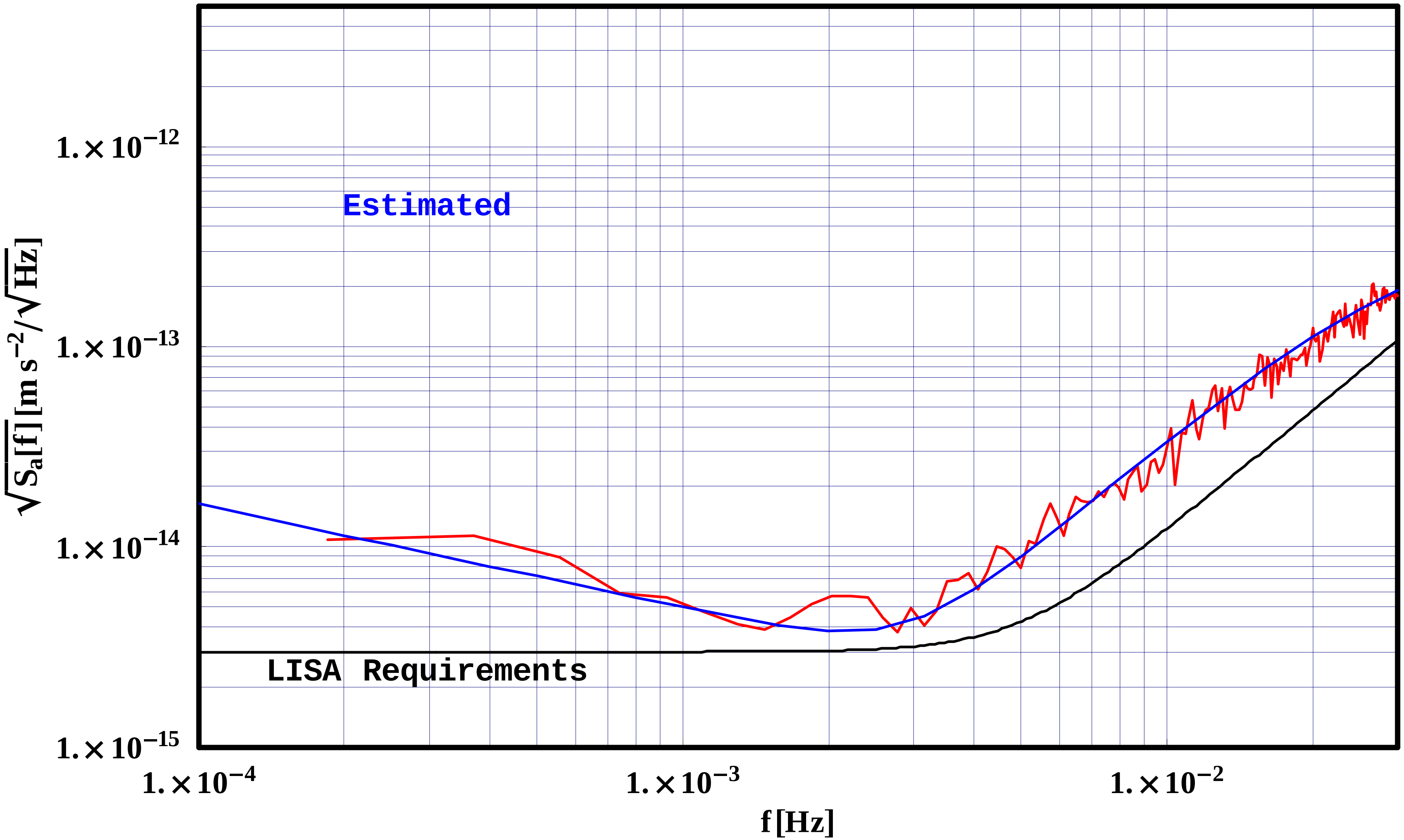

Cross-talk subtracted
Magnetic subtracted
Temperature subtracted
LISA Requirements
$1.\times 10^{-12}$
$1.\times 10^{-13}$
$1.\times 10^{-14}$
$1.\times 10^{-15}$
$1.\times 10^{-4}$
$1.\times 10^{-3}$
$1.\times 10^{-2}$
f [Hz]
$\sqrt{S_a[f]}\,[\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$

LTP

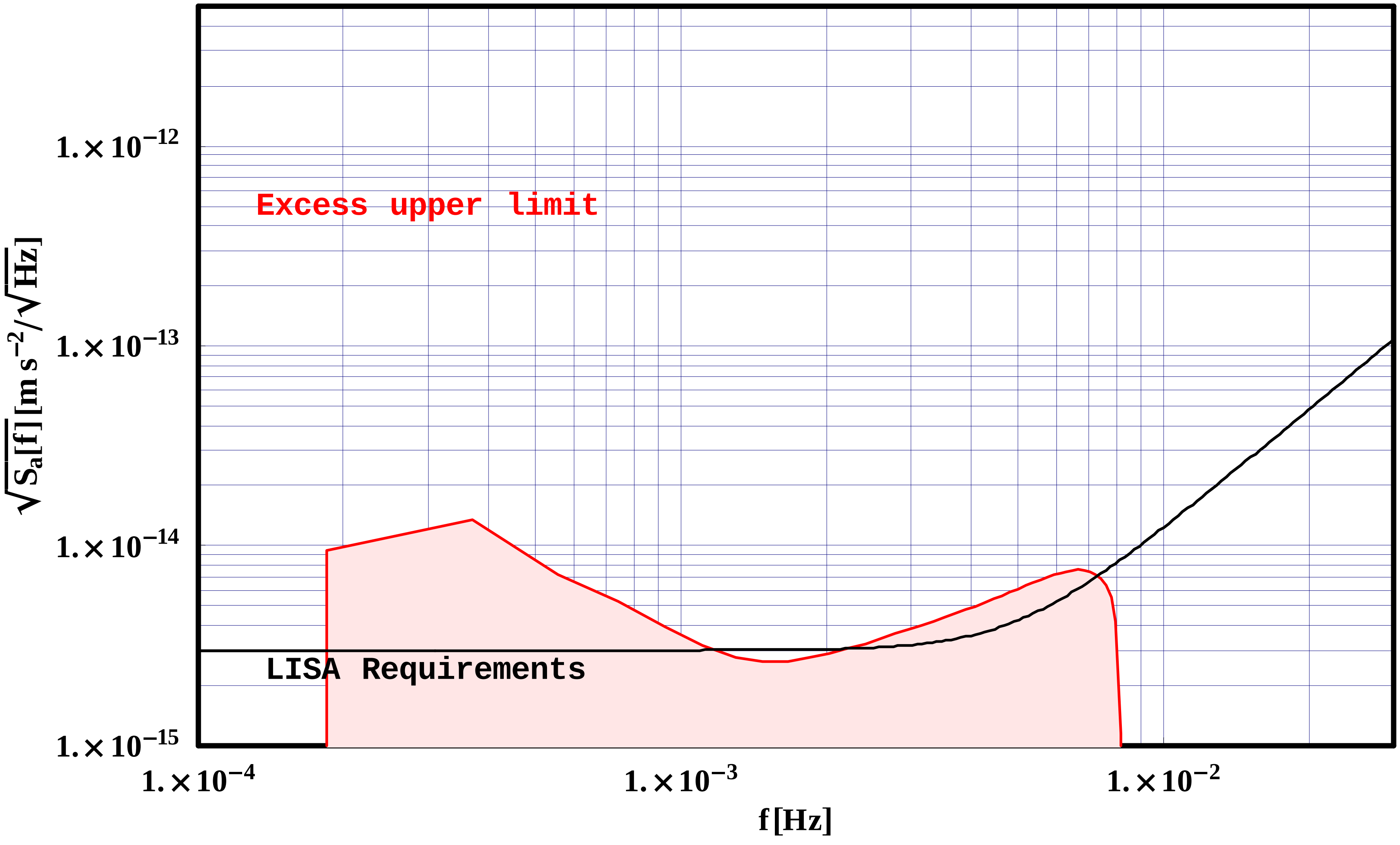


$\sqrt{S_a[f]}\,[\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$
$1.\times 10^{-12}$
$1.\times 10^{-13}$
$1.\times 10^{-14}$
$1.\times 10^{-15}$
LISA Requirements
$1.\times 10^{-4}$
$1.\times 10^{-3}$
$1.\times 10^{-2}$
f [Hz]

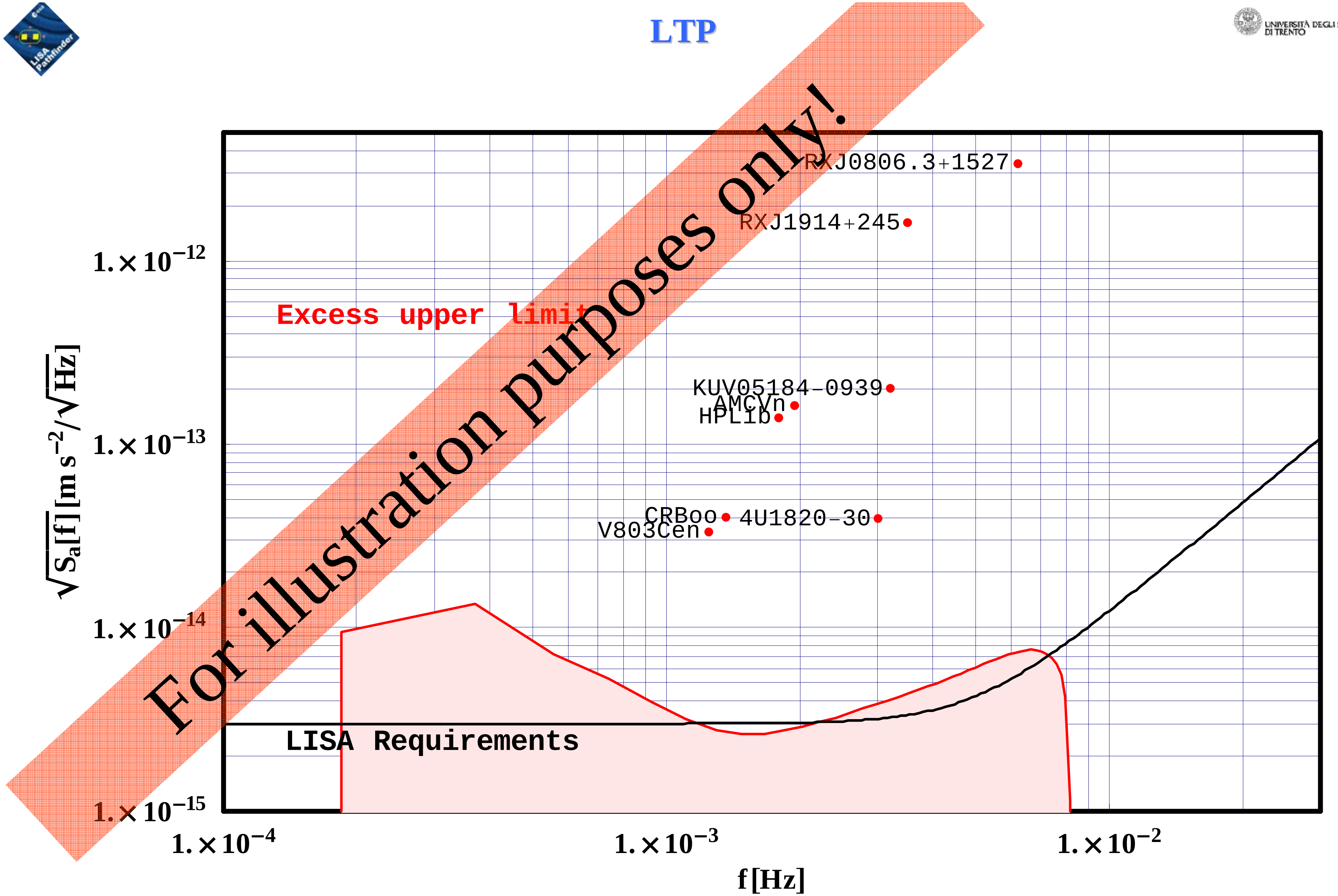
Source	Name	Formula	Value $[\mathrm{m\,s^{-3/2}}]$
Correlated readout noise	f_{corr}	$f_{corr} = \sqrt{2}\sqrt{f_{trip}^2 + f_{ampip}^2 + f_{act100}^2}$	6.36×10^{-18}
Uncorrelated readout noise	f_{unc}	$f_{unc} = \sqrt{2}\sqrt{f_{act0}^2 + f_{actth}^2}$	8.81×10^{-18}
Thermal effects	$f_{thermal}$	$f_{thermal} = 2\,(f_{rad} + f_{radpr} + f_{og} + f_{th} + f_{gravIS})$	4.97×10^{-15}
Brownian Noise	$f_{Brownian}$	$f_{Brownian} = \sqrt{2}\sqrt{f_{diel}^2 + f_{gas}^2 + f_{magdmp}^2 + f_{magimp}^2}$	9.36×10^{-16}
Magnetics S/C	f_{magnSC}	$f_{magnSC} = \sqrt{2}\,(f_B + f_{\Delta B} + f_{Bac})$	8.9×10^{-15}
Magnetics Interplanetary	f_{magnIP}	$f_{magnIP} = \sqrt{2}\,(f_{Bi} + f_{Lz})$	3.25×10^{-16}
Charging and voltage	f_{charge}	$f_{charge} = \sqrt{2}\sqrt{f_q^2 + f_{vs}^2}$	3.61×10^{-15}
Miscellanea	f_{misc}	$f_{misc} = 2\sqrt{f_{VAC}^2 + f_{laser}^2 + f_{grav}^2}$	6.04×10^{-15}
Cross – talk	$f_{cross-talk}$	$f_{cross-talk}$	1.01×10^{-14}
Readout noise	$f_{readout}$	$f_{readout} = \sqrt{f_{corr}^2 + f_{unc}^2}$	1.09×10^{-17}
Drag – free	$f_{dragfree}$	$f_{dragfree} = \mathrm{Abs}[\Delta\omega_x^2]\,x_{tot}$	1.57×10^{-15}
Total	f_{total}	$f_{total} = \sqrt{(f_{dragfree}^2 + f_{corr}^2 + f_{unc}^2 + f_{readout}^2 + f_{thermal}^2 + f_{Brownian}^2 + f_{cross-talk}^2 + f_{magnSC}^2 + f_{magnIP}^2 + f_{charge}^2 + f_{misc}^2)}$	1.61×10^{-14}
Measurement noise	f_{meas}	$f_{meas} = \sqrt{f_{act}^2 + f_{bl}^2 + f_{OM}^2}$	5.06×10^{-15}
Grand Total	f_{gtotal}	$f_{gtotal} = \sqrt{f_{total}^2 + f_{meas}^2}$	1.68×10^{-14}



Estimated
LISA Requirements
1.×10^−12
1.×10^−13
1.×10^−14
1.×10^−15
1.×10^−4
1.×10^−3
1.×10^−2
f [Hz]
√Sa[f] [m s^−2/√Hz]


Excess upper limit
LISA Requirements
1.×10^−12
1.×10^−13
1.×10^−14
1.×10^−15
1.×10^−4
1.×10^−3
1.×10^−2
f [Hz]
√Sa[f] [m s^−2/√Hz]

LTP



For illustration purposes only!
RXJ0806.3+1527
RXJ1914+245
Excess upper limit
KUV05184-0939
AMCVn
HPLib
CRBoo
4U1820-30
V803Cen
LISA Requirements
$1.\times10^{-12}$
$1.\times10^{-13}$
$1.\times10^{-14}$
$1.\times10^{-15}$
$1.\times10^{-4}$
$1.\times10^{-3}$
$1.\times10^{-2}$
f [Hz]
$\sqrt{S_a[f]}\,[\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}]$

Testing quality of free fall

LTP

10^{-12}

$\sqrt{S_F}\left(\frac{N}{\sqrt{Hz}}\right)$

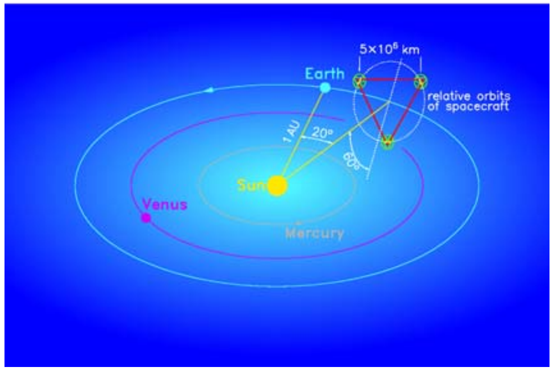
10^{-13}

10^{-14}

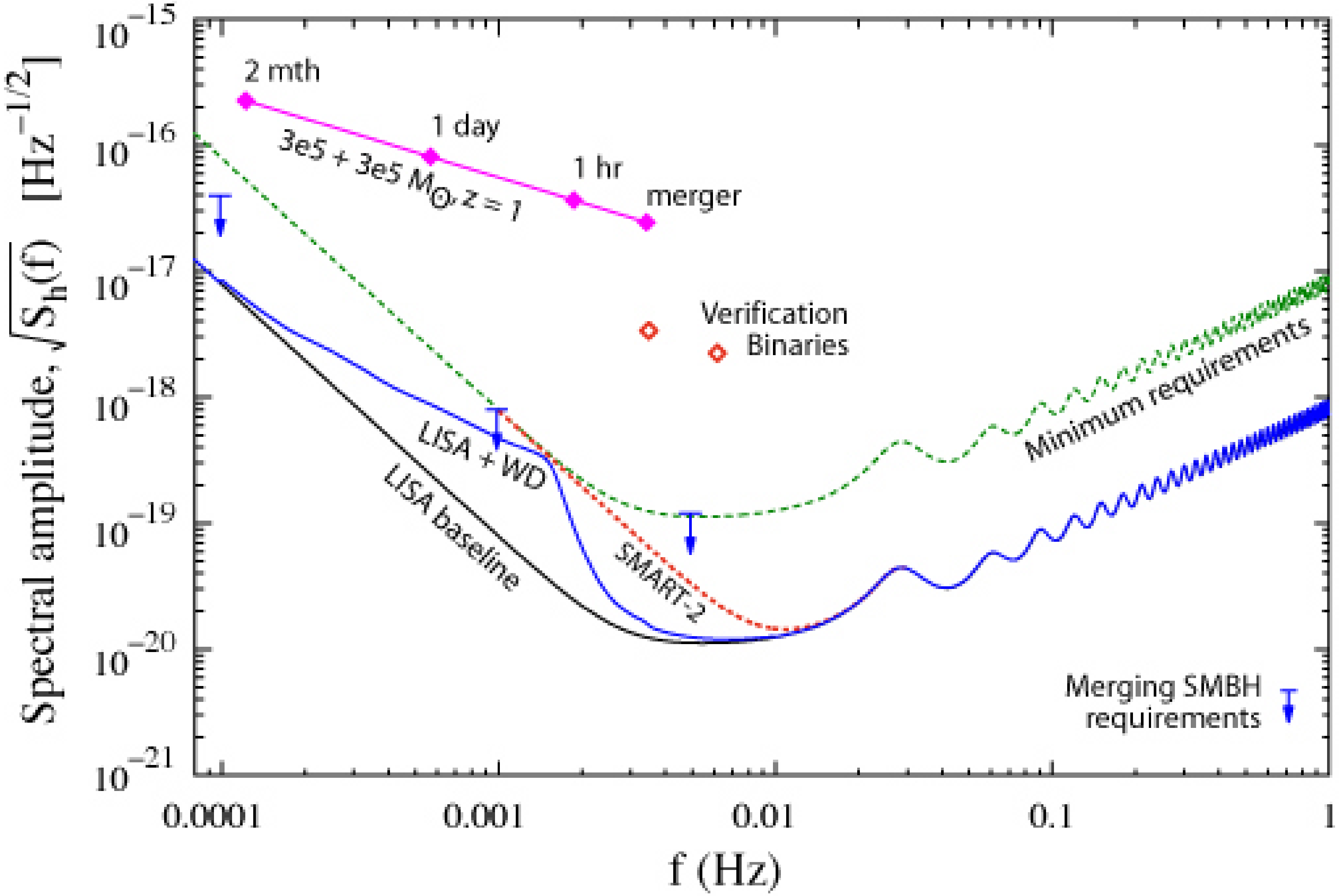
10^{-15}

Torsion pendulum
(surface disturbances)

LISA PF



LISA


2 mth
1 day
3e5 + 3e5 M⊙, z = 1
1 hr
merger
Verification
Binaries
Minimum requirements
LISA + WD
LISA baseline
SMART-2
Merging SMBH
requirements
Spectral amplitude, $\sqrt{S_h(f)}$ [$Hz^{-1/2}$]
f (Hz)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
0.0001
0.001
0.01
0.1
1

The plan:

LISA PF: In flight demonstration of reference frames 2009

LISA PF +6 years: LISA

LISA + 1 year: enjoy listening to black-holes