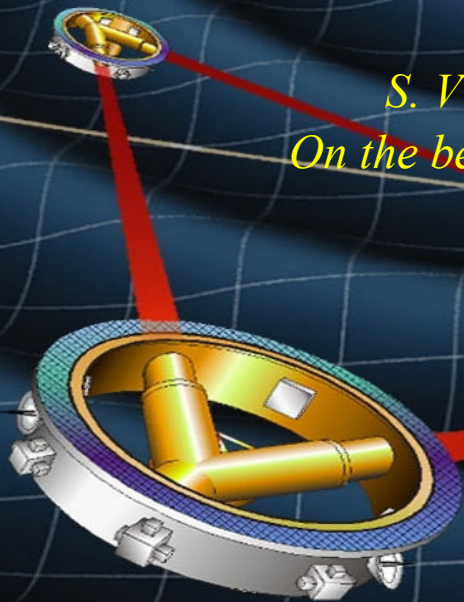
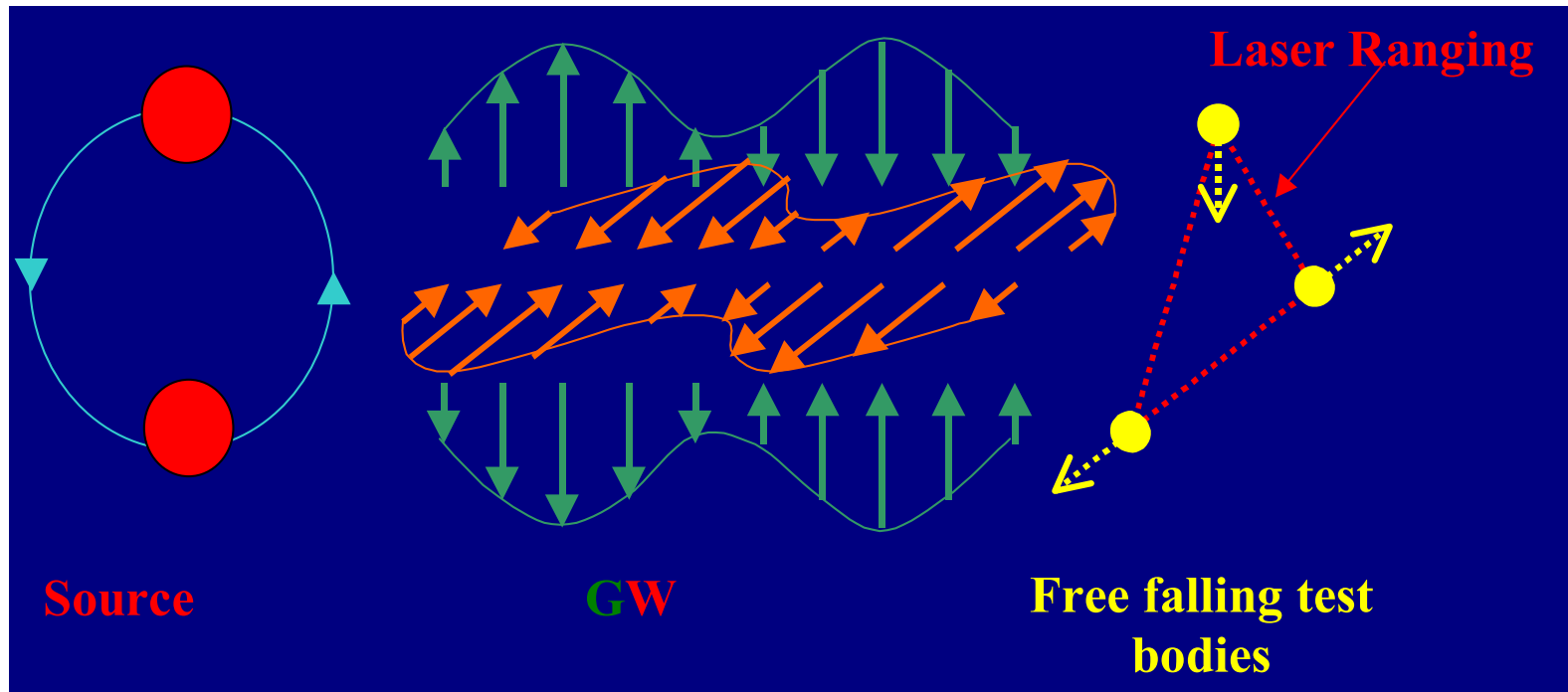


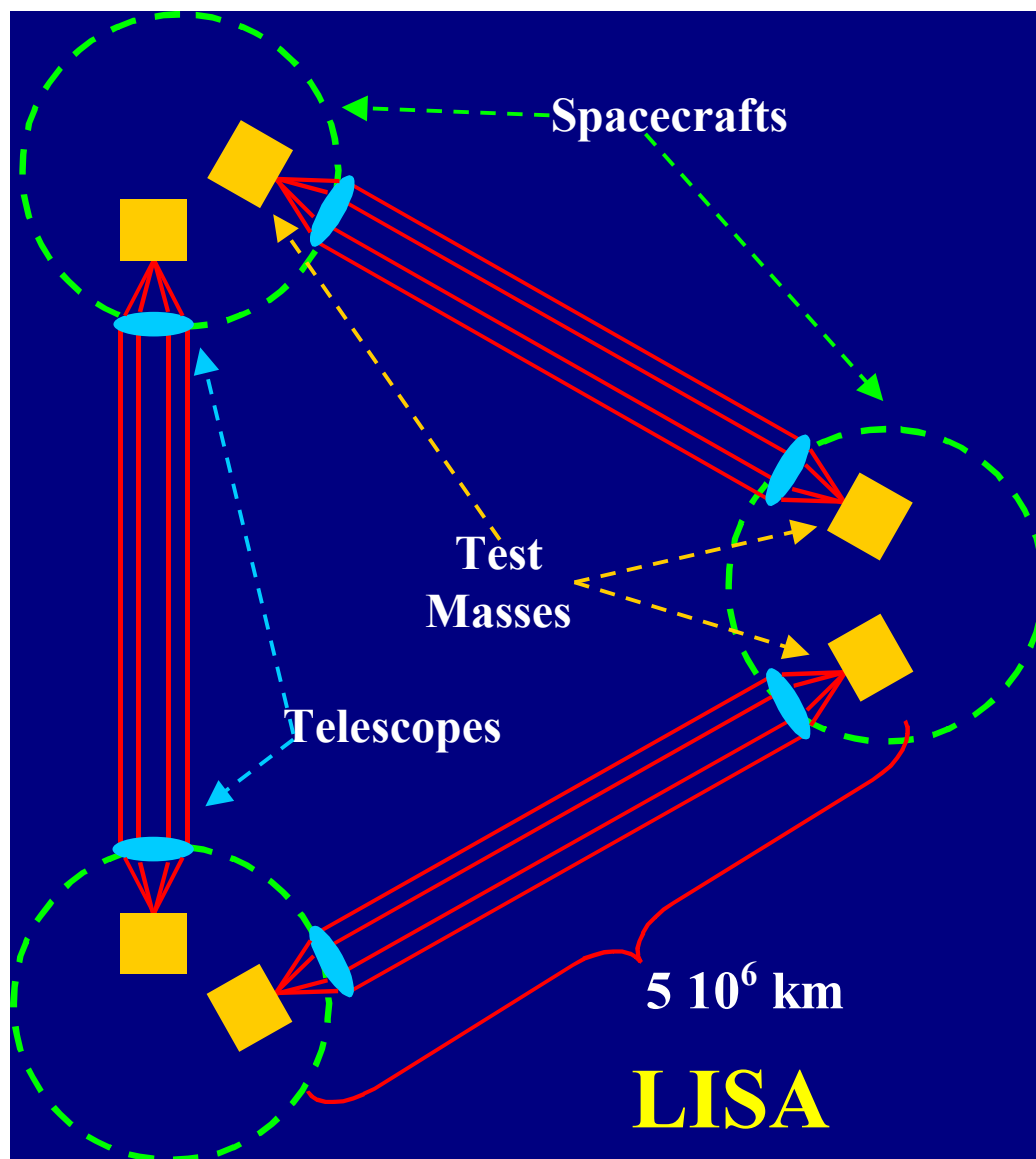
LISA

S. Vitale, University of Trento/INFN Trento
On the behalf of the LISA International Science Team
Vitale@science.unitn.it



LISA basics





3 pairs of “free falling” test masses
($3 \cdot 10^{-15} \text{ ms}^{-2} \text{ Hz}^{-1/2}$ @ 0.1 mHz)

3 “test-mass follower” shielding spacecraft

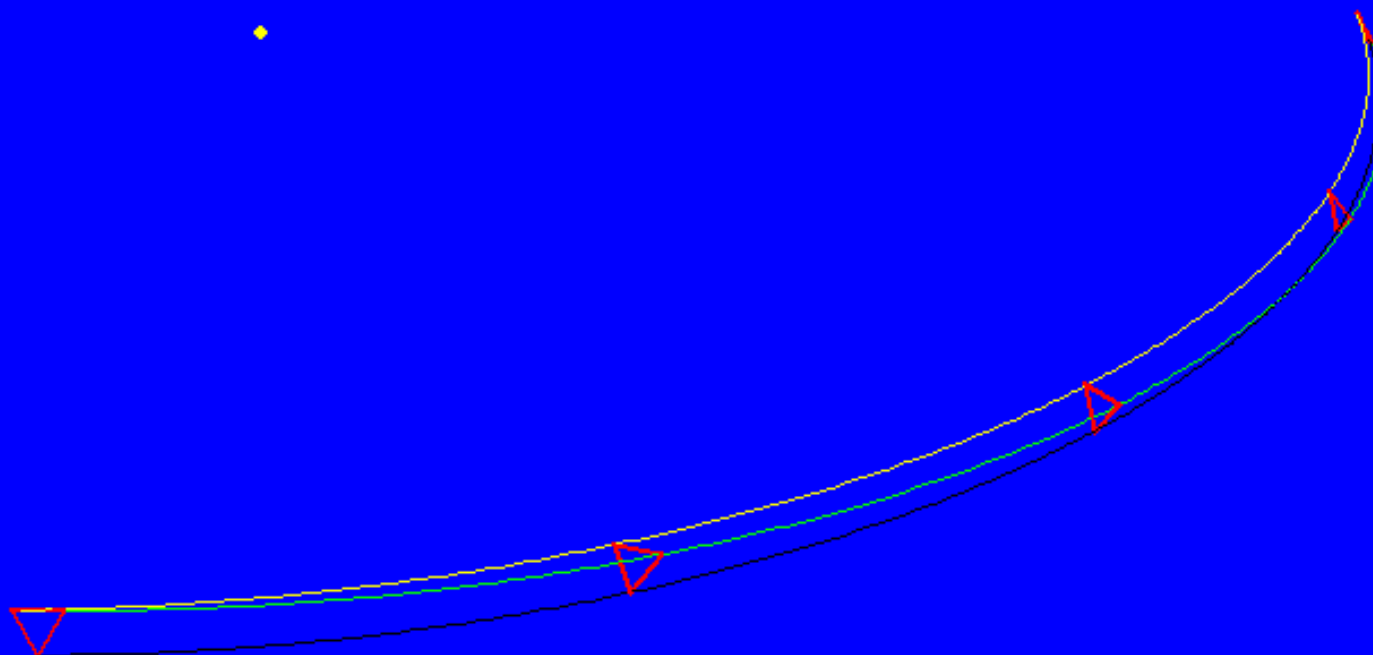
2 semi-independent $5 \cdot 10^6$ km Michelson Interferometers with Laser Transponders

($40 \text{ pm Hz}^{-1/2}$)

Goal: GW at
0.1 mHz – 0.1 Hz

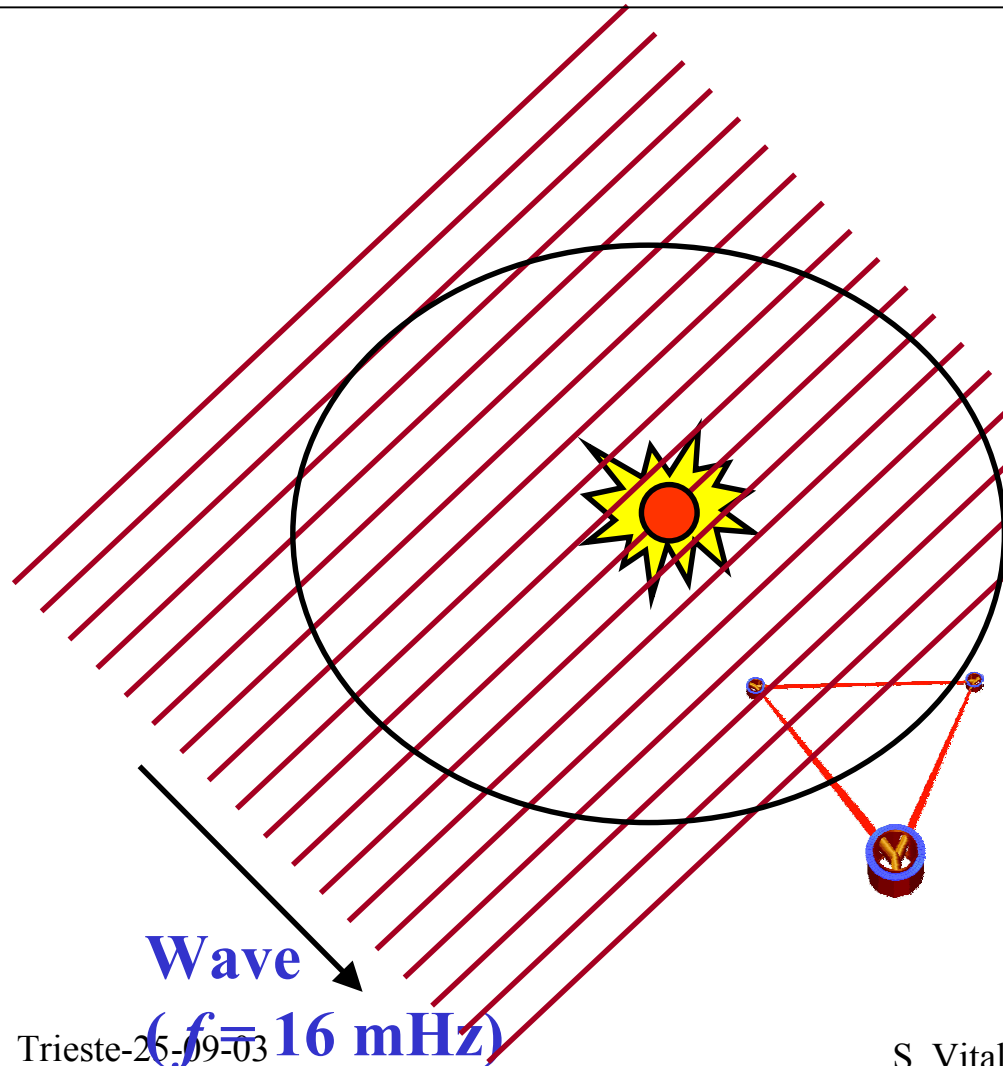
Strain sensitivity $\approx 3 \times 10^{-21} / \sqrt{\text{Hz}}$ @ 10^{-3} Hz

LISA essentials 1: the smart orbits



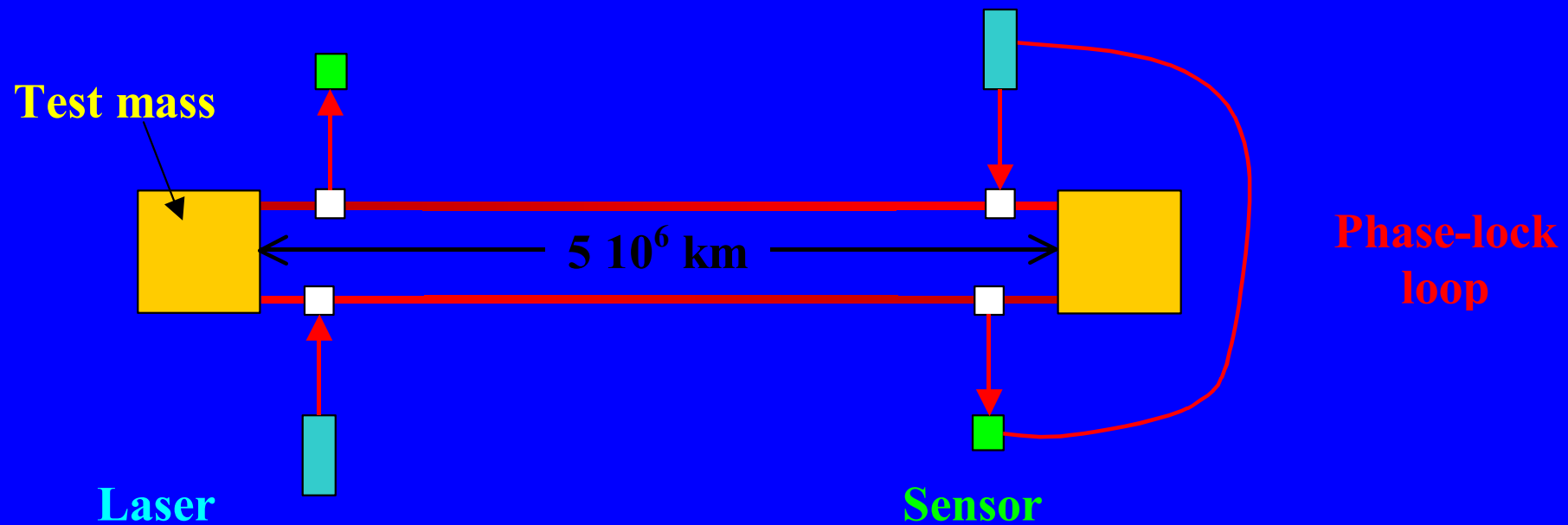


Angular Resolution with LISA



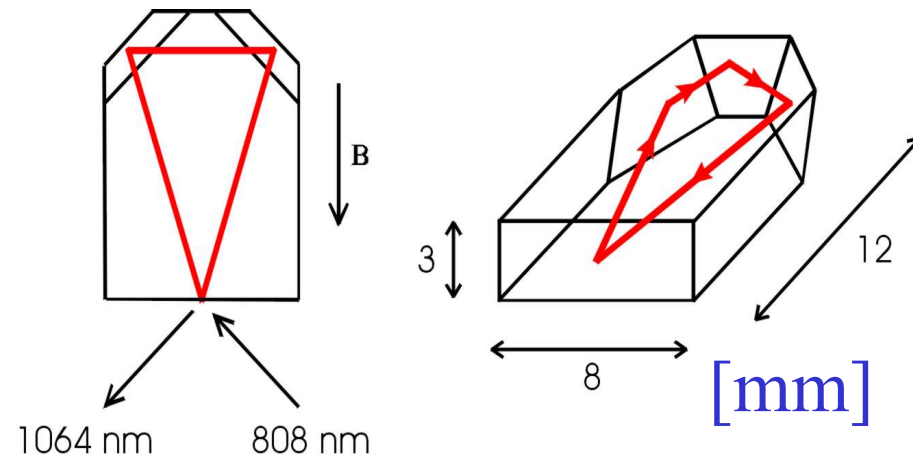
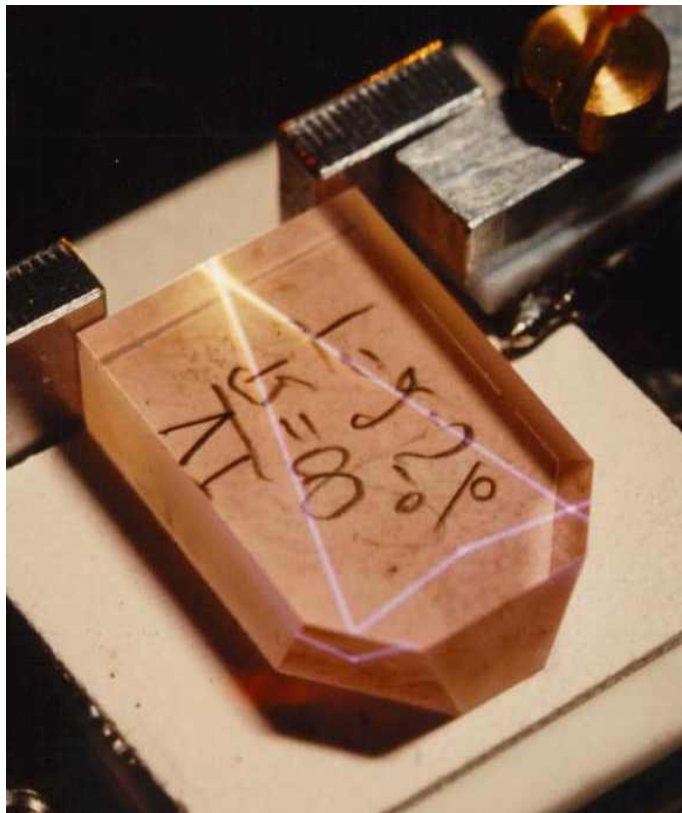
- Using phase modulation due to orbital motion is equivalent to **aperture synthesis**.
- Gives diffraction limit $\Delta\theta = \lambda / 1 \text{ AU}$.
- **Measurements on detected sources:**
 - $\Delta\theta \sim 1' - 1^\circ$
 - $\Delta(\text{mass, distance}) \leq 1\%$

LISA essentials 2: the laser transponding scheme



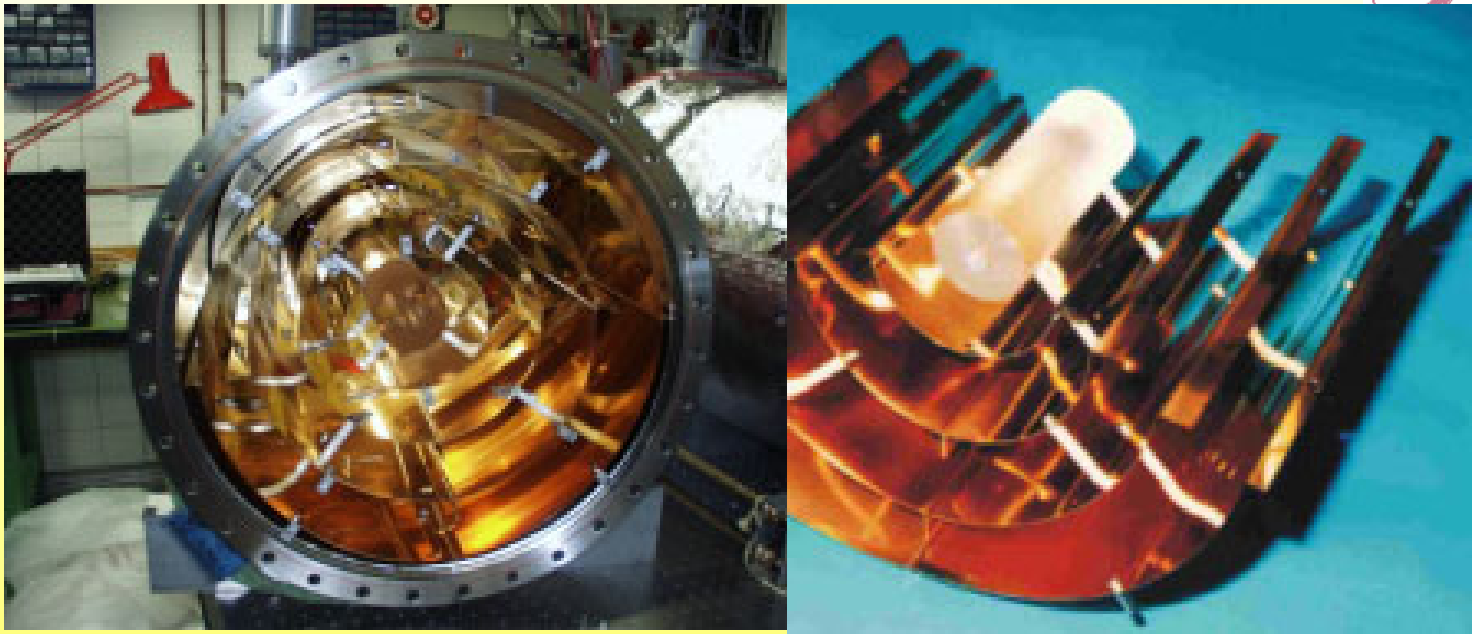
Beating power loss due to beam divergence

Non-planar Nd:YAG Ring Laser



Material	Nd:YAG
Dimensions	12 x 8 x 3 mm ³
Threshold	150 mW
Slope Efficiency	70 %
Power Dissipation (Supply Unit)	12 W
Max. Single Frequency Output	3.5 W

Thermal isolation of cavity

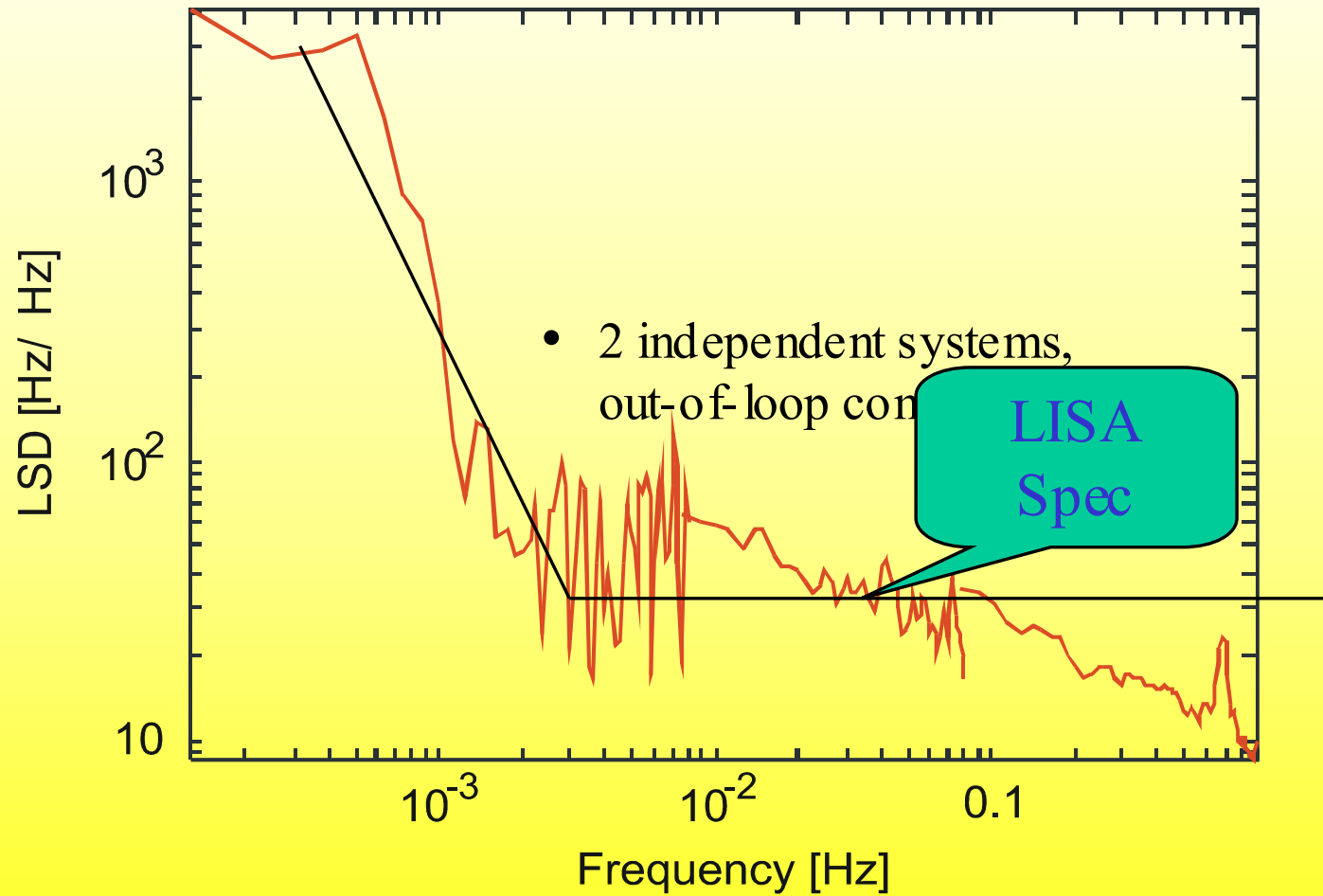


- Cavity length 20 cm, finesse 9000
- Vacuum 2×10^{-7} mbar
- Gold-coated thermal isolation layers
- Spacers from ceramics with low thermal conduction

Amaldi2003

63

Preliminary AEI Results



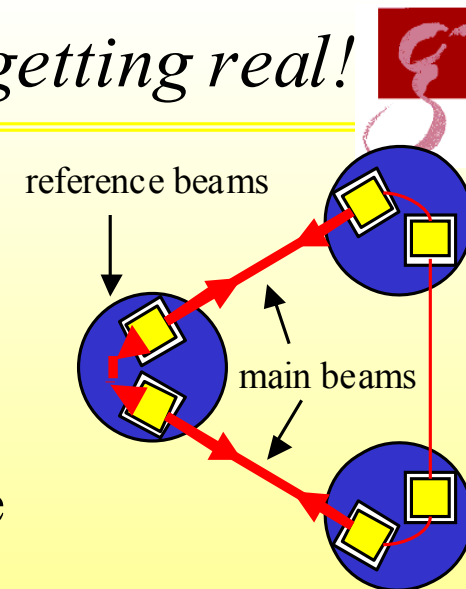
Amaldi2003

64

LISA: Technology and Mission getting real!

LISA Interferometry (1)

- Each signal heterodyned separately with local laser on diode
- Main beams heterodyned on quadrant diodes
- Phase difference between quadrants gives pointing information for main beams (same technology as used on ground-based detectors)



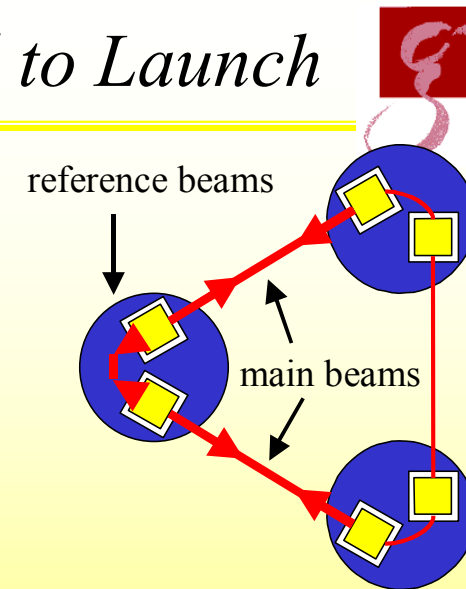
Amaldi2003

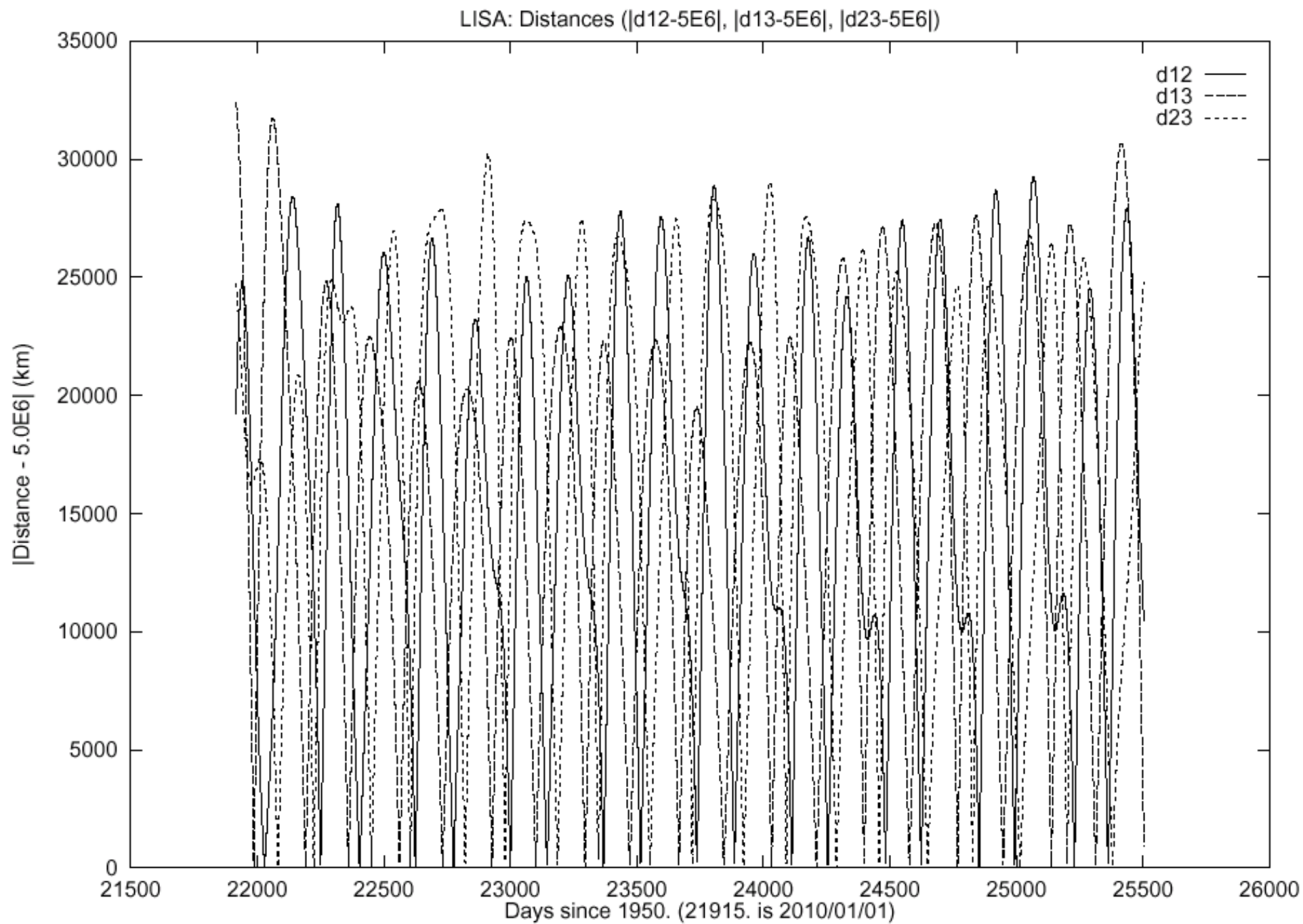
1

LISA: Half-time from Proposal to Launch

LISA Interferometry (2)

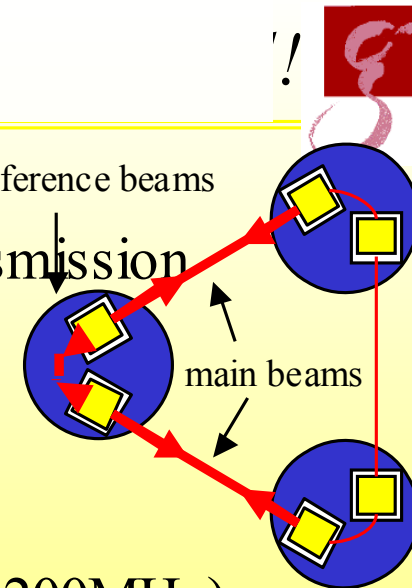
- 6 main beat signals plus
6 reference beat signals
- Reference beam beat signals
used to phase-lock lasers in same S/C
- Laser noise from sum of main beat signals
- Gravitational wave signal from difference





LISA Interferometry (4)

- Need Ultrastable Oscillator to remove Doppler shift of a few MHz before transmission to the ground, but USO noise too high (10^{-13} over 1000 sec for Mars Observer vs. 10^{-16} needed)
- USO transmitted as laser sideband ($\Delta\nu \sim 200\text{MHz}$) to be stabilised on armlength
- Remove laser and USO noise
- Gravitational wave signal from difference of main beat signals minus laser and USO noise



FUNDAMENTALS OF LISA INTERFEROMETRY

1.064 μm Nd:YAG, ≈ 1 W diode pumped monolithic lasers

Laser transponding technique: local laser locked to incoming phase

Master laser (SC1) phase noise ($30 \text{ Hz}^{1/2}$) measured and corrected on board.

Arm lengths difference ΔL known at ± 20 m from ground tracking and laser ranging

$$\delta h \approx \delta \varphi \frac{8\pi}{\lambda} \Delta L$$

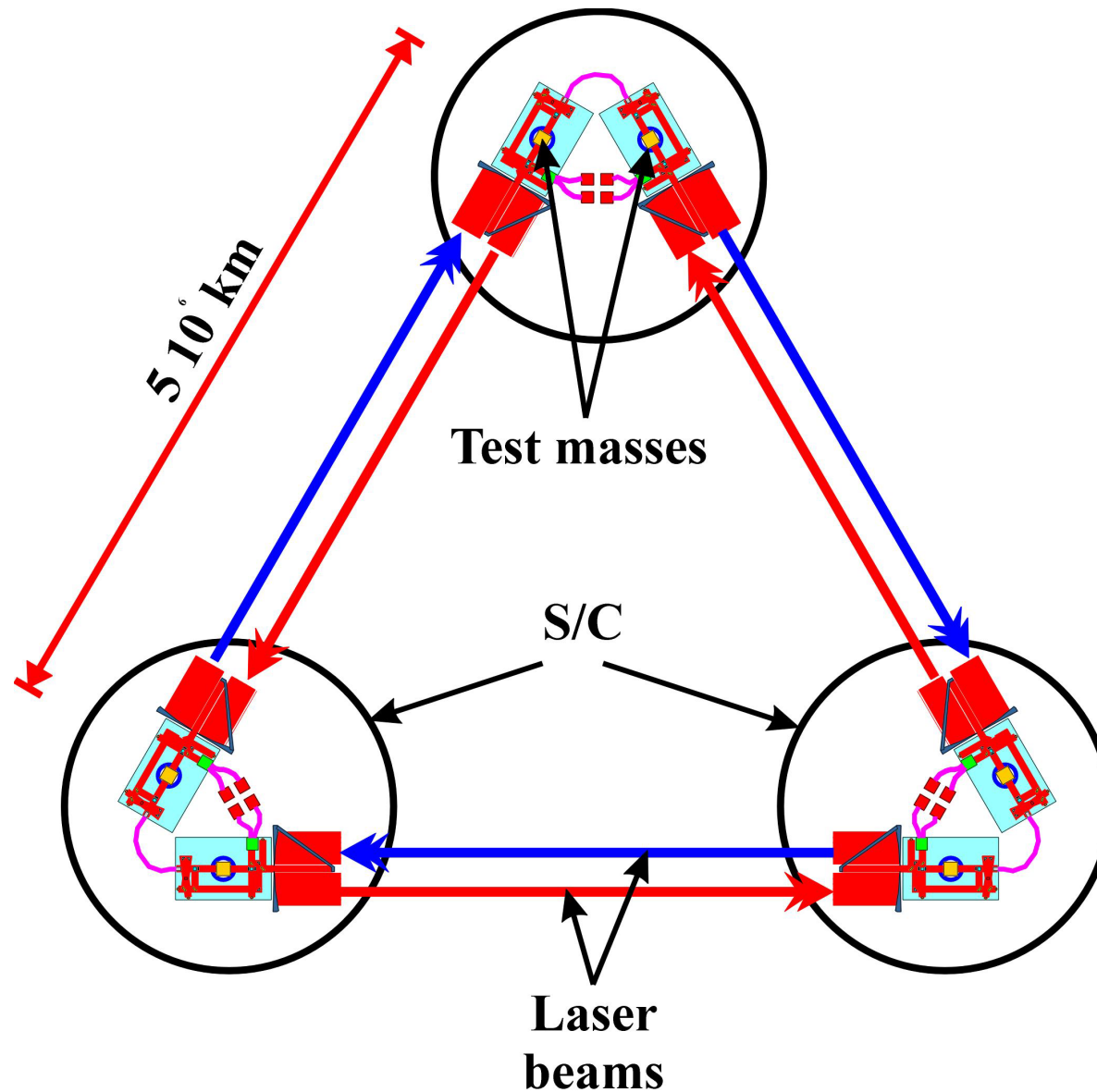
FUNDAMENTALS OF LISA INTERFEROMETRY

USO on board each spacecraft for phase measurements

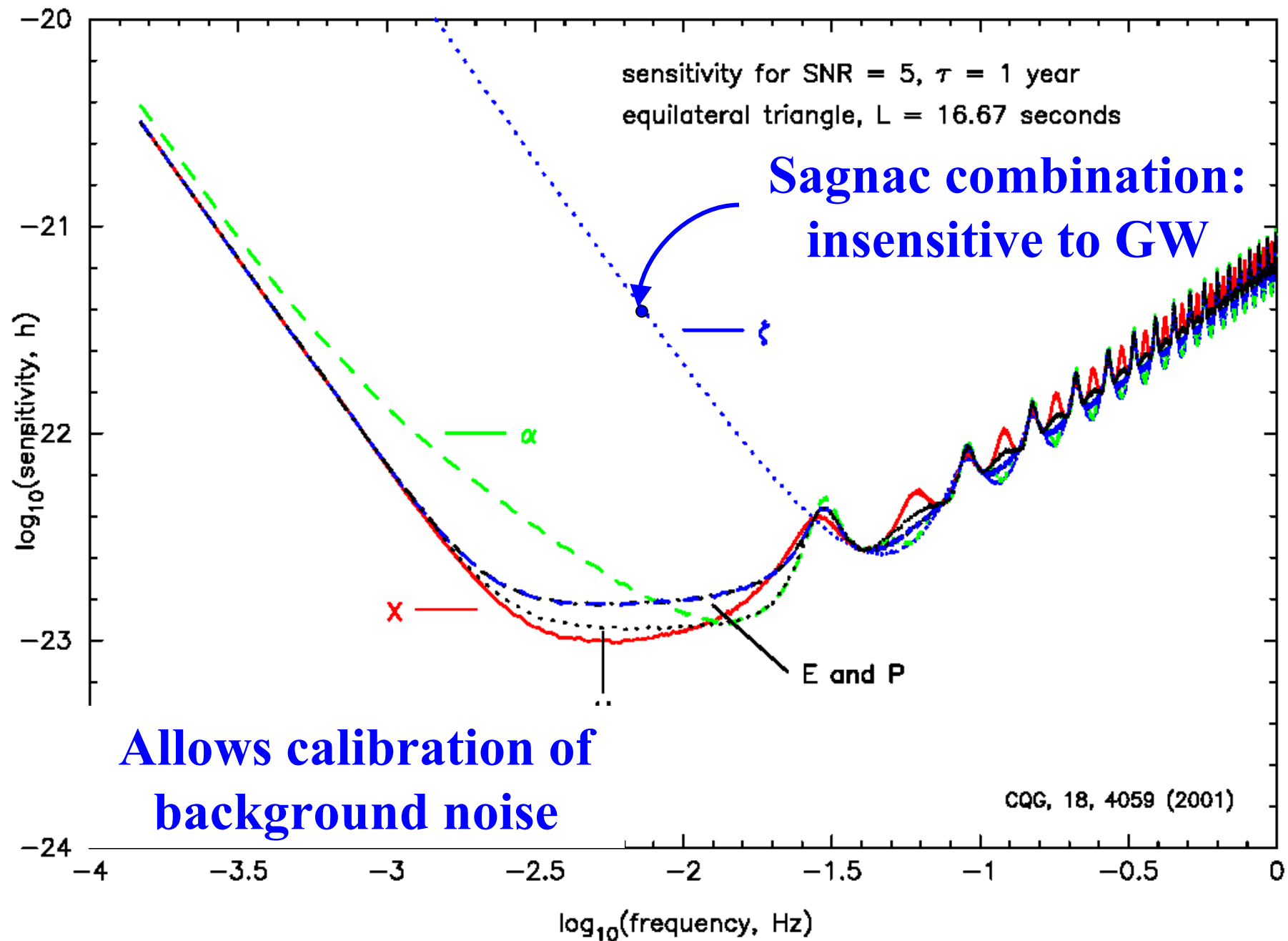
(10^{-13} relative stability 1-1000s; relative phase noise of USO's measured and corrected)

Phases due to optics fixed to spacecraft, subtracted

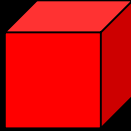
Goal : $40 \frac{\text{pm}}{\sqrt{\text{Hz}}} \quad 0.1 \text{ mHz} \leq f \leq 0.1 \text{ Hz}$



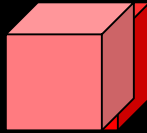
Something more than “an interferometer”: 6 independent beams



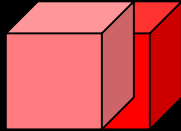
**Trying to be geodesic against
non-gravitational disturbances**



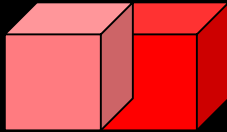
**Trying to be geodesic against
non-gravitational disturbances**



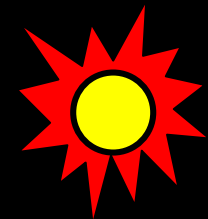
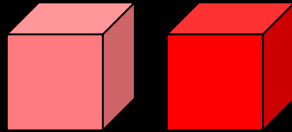
**Trying to be geodesic against
non-gravitational disturbances**



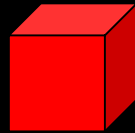
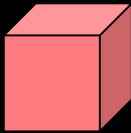
**Trying to be geodesic against
non-gravitational disturbances**



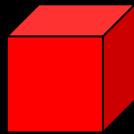
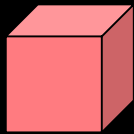
**Trying to be geodesic against
non-gravitational disturbances**



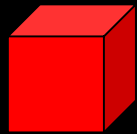
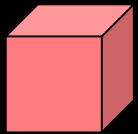
**Trying to be geodesic against
non-gravitational disturbances**



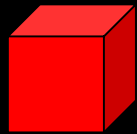
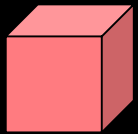
**Trying to be geodesic against
non-gravitational disturbances**



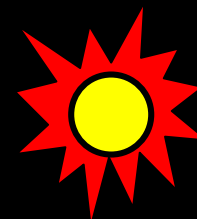
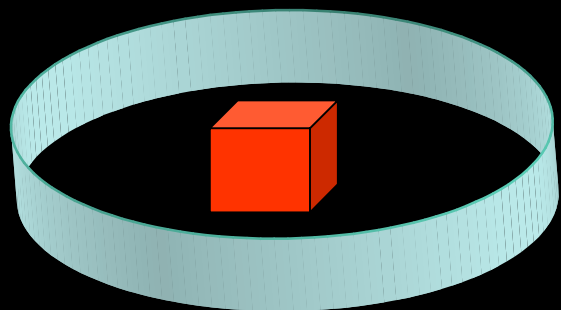
**Trying to be geodesic against
non-gravitational disturbances**



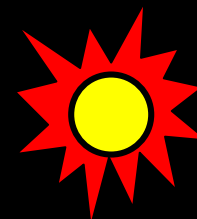
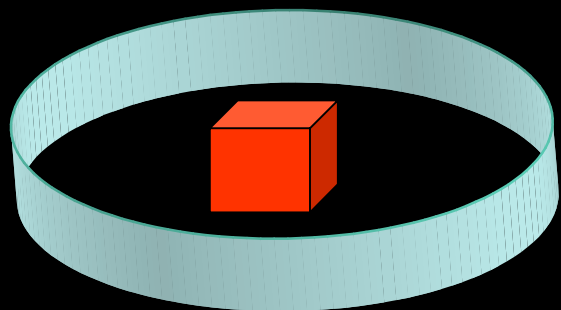
**Trying to be geodesic against
non-gravitational disturbances**



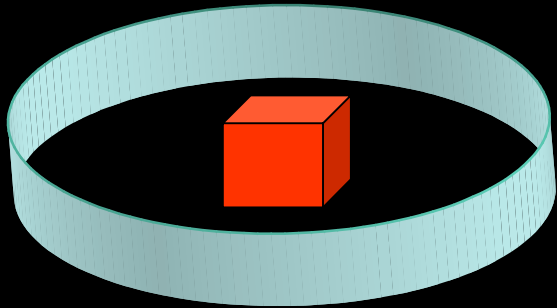
Trying to be geodesic: the spacecraft as a passive shield



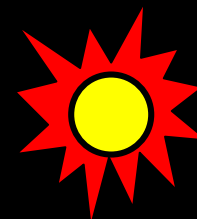
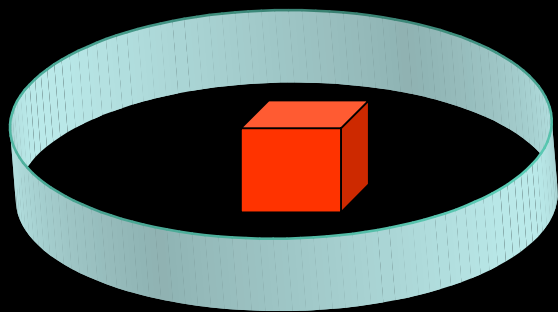
Trying to be geodesic: the spacecraft as a passive shield



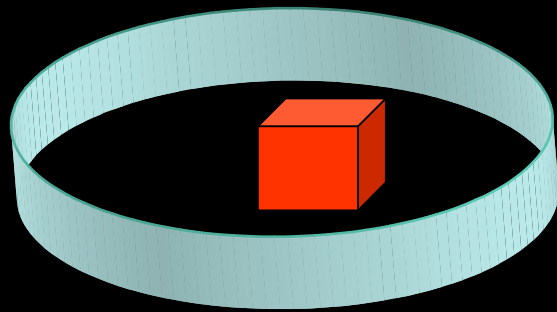
Trying to be geodesic: the spacecraft as a passive shield



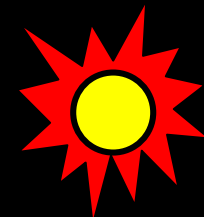
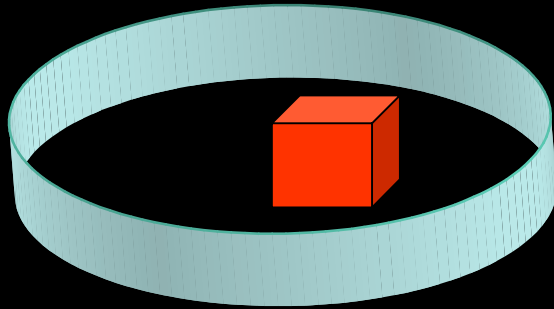
Trying to be geodesic: the spacecraft as a passive shield



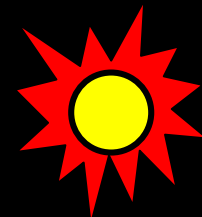
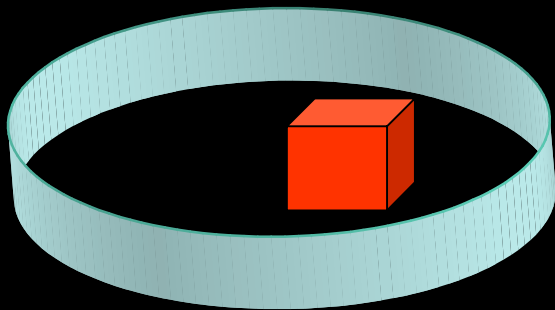
Trying to be geodesic: the spacecraft as a passive shield



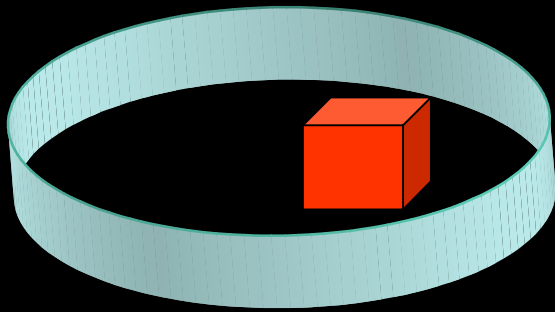
Trying to be geodesic: the spacecraft as a passive shield



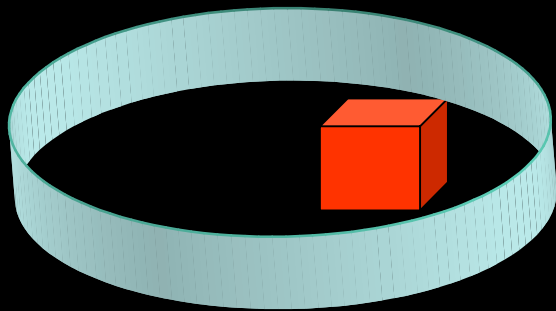
Trying to be geodesic: the spacecraft as a passive shield



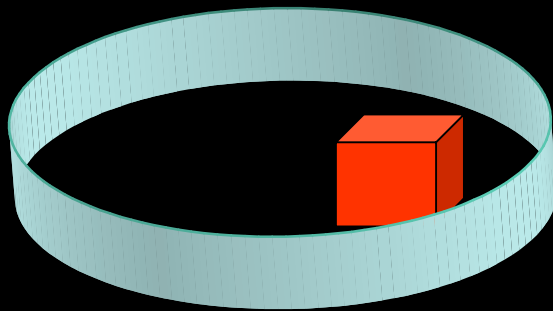
Trying to be geodesic: the spacecraft as a passive shield



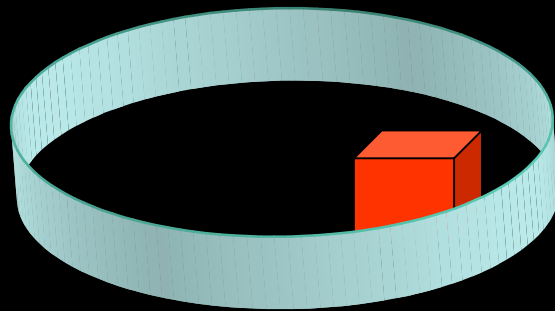
Trying to be geodesic: the spacecraft as a passive shield



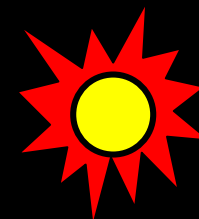
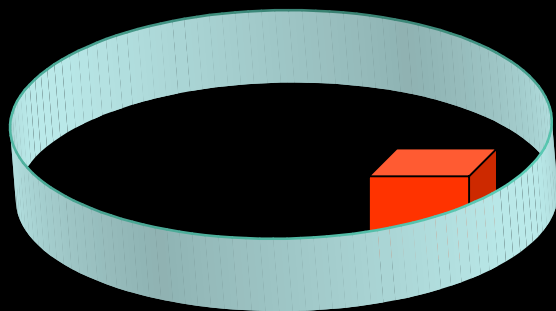
Trying to be geodesic: the spacecraft as a passive shield



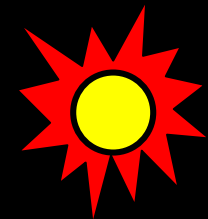
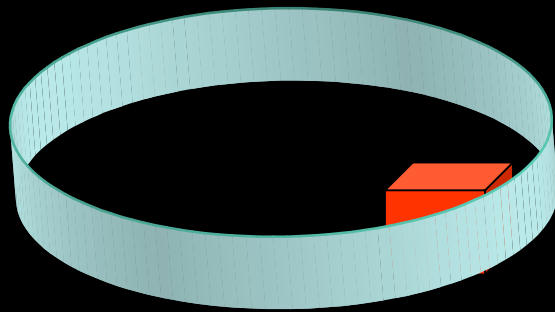
Trying to be geodesic: the spacecraft as a passive shield



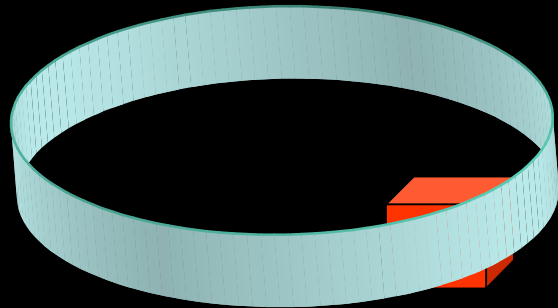
Trying to be geodesic: the spacecraft as a passive shield



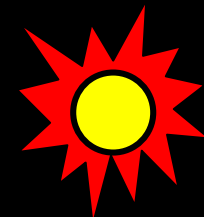
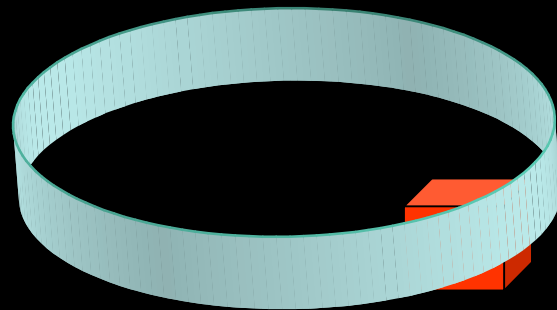
Trying to be geodesic: the spacecraft as a passive shield



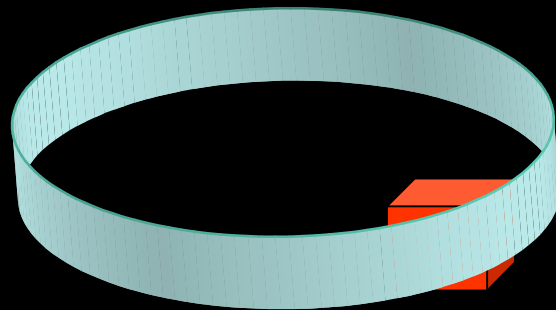
Trying to be geodesic: the spacecraft as a passive shield



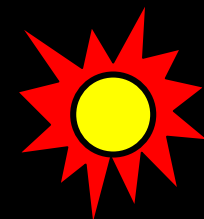
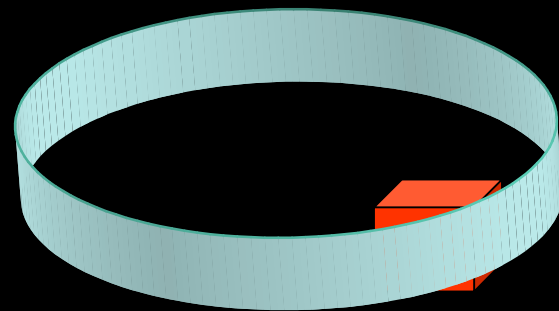
Trying to be geodesic: the spacecraft as a passive shield



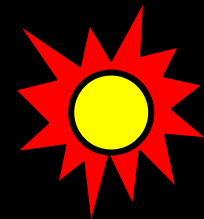
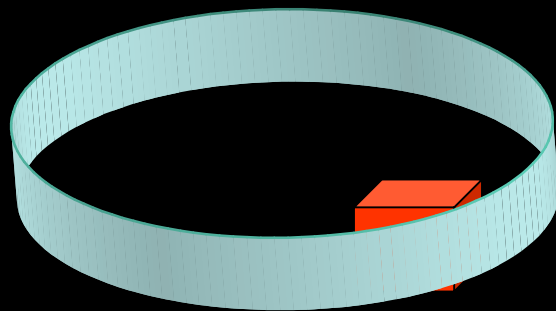
Trying to be geodesic: the spacecraft as a passive shield



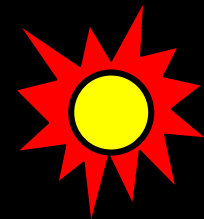
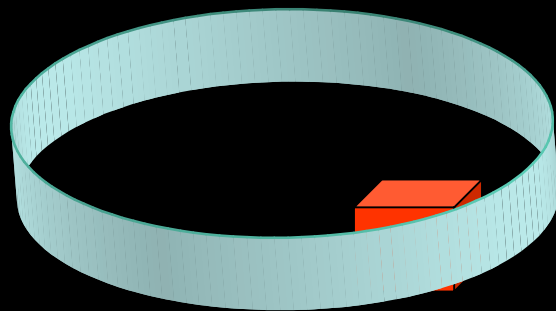
Trying to be geodesic: the spacecraft as a passive shield



Trying to be geodesic: the spacecraft as a passive shield



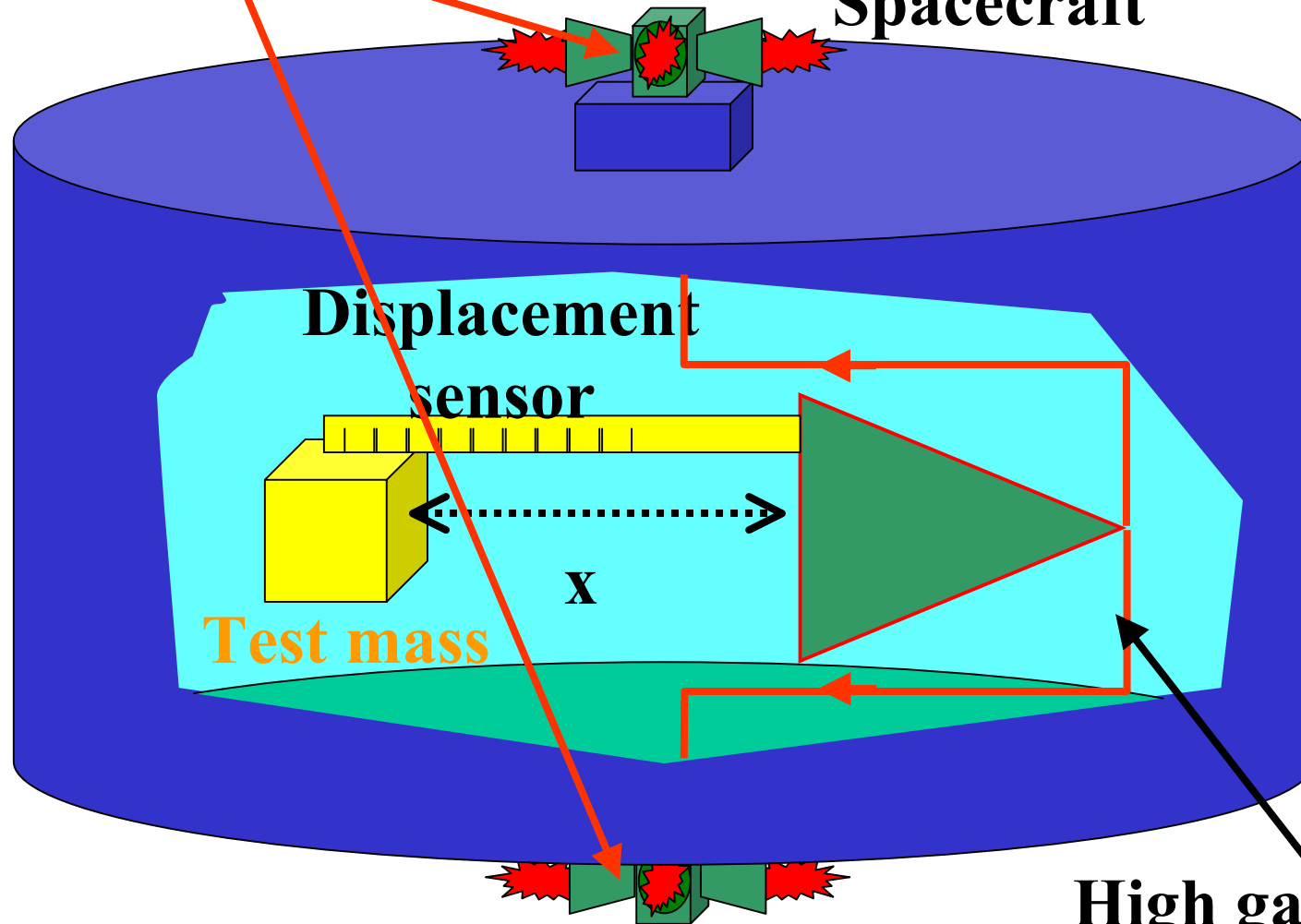
Trying to be geodesic: the spacecraft as a passive shield



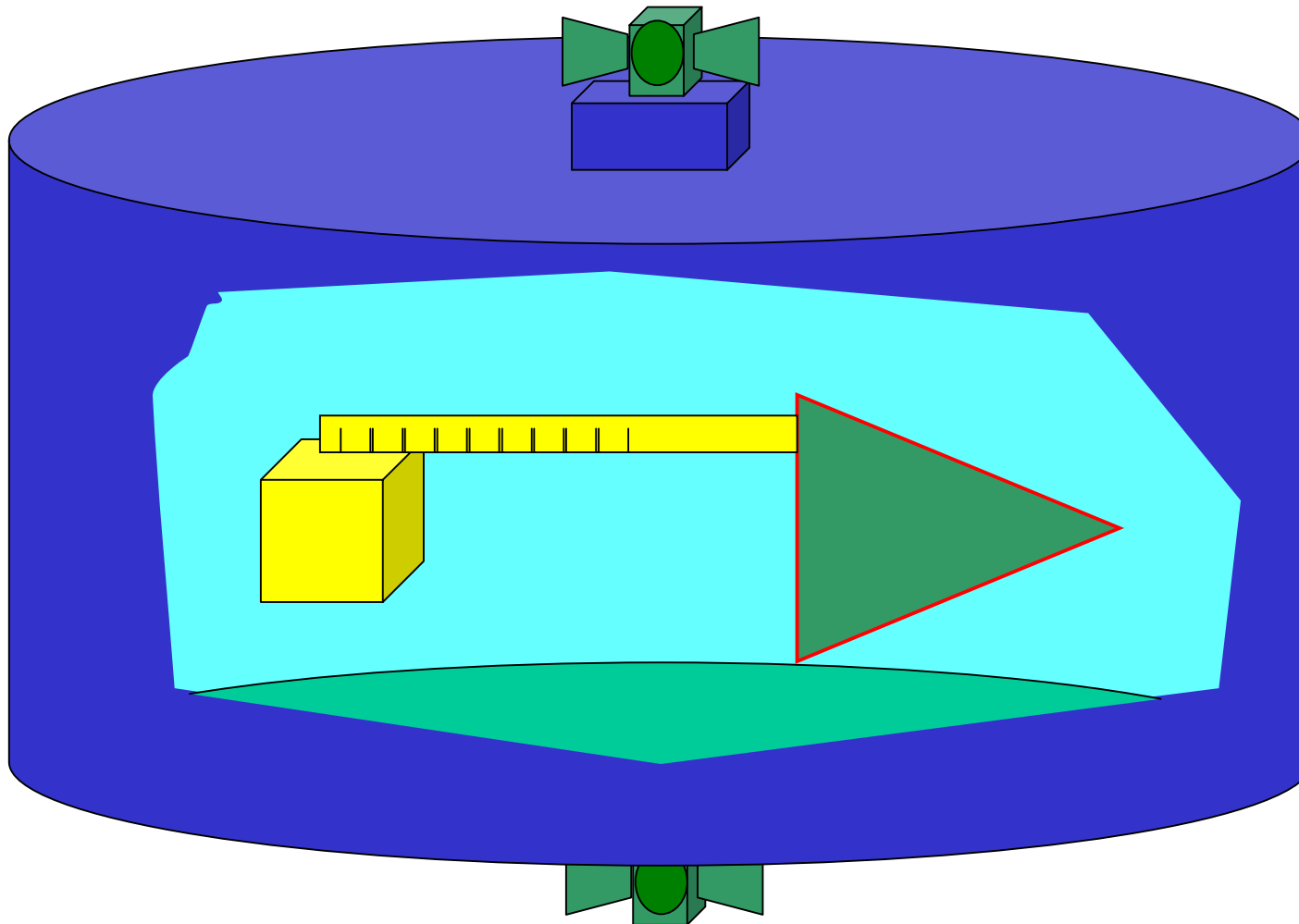
Drag-free: keeping the spacecraft with the proof-mass

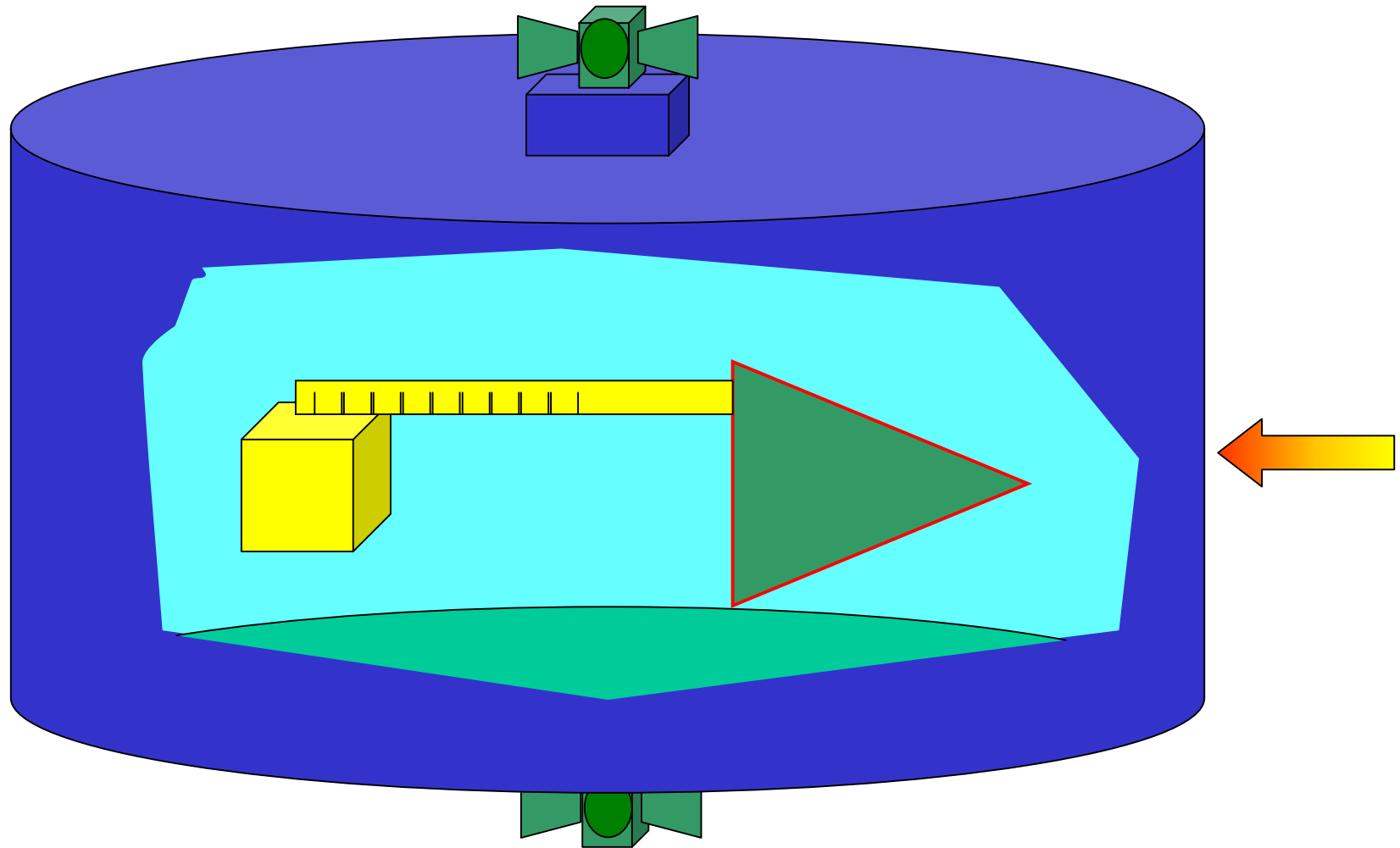
Thrusters

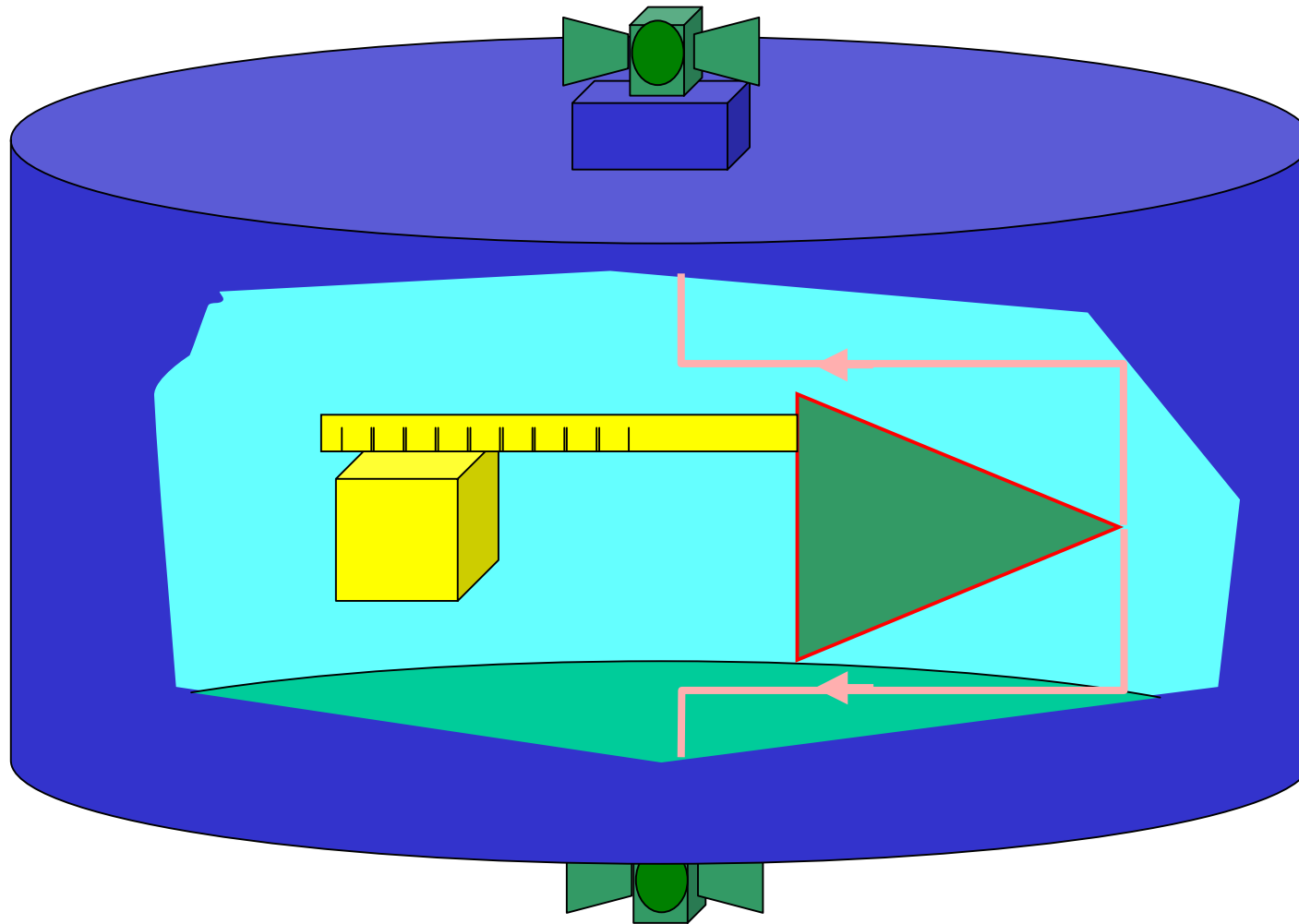
Spacecraft

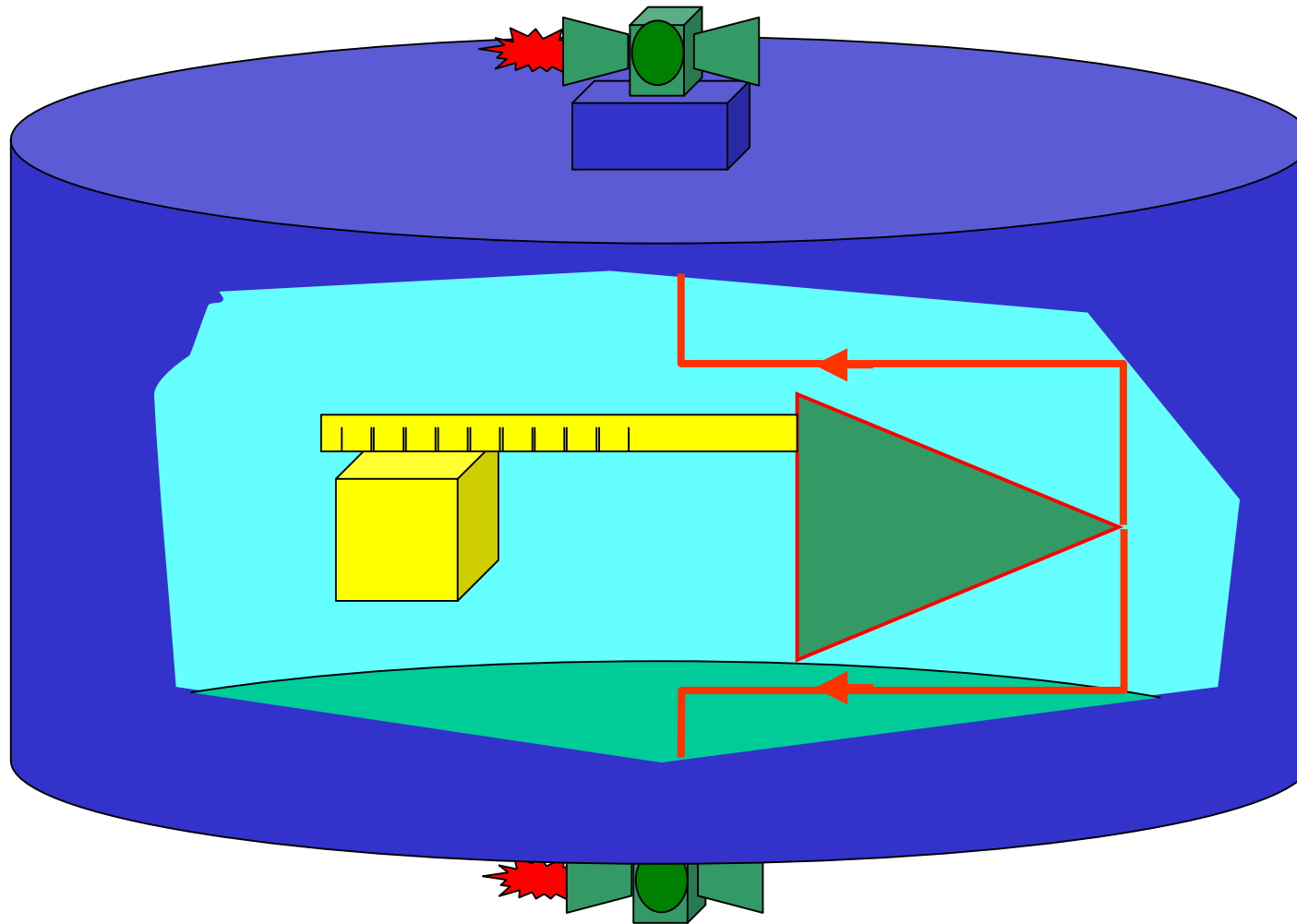


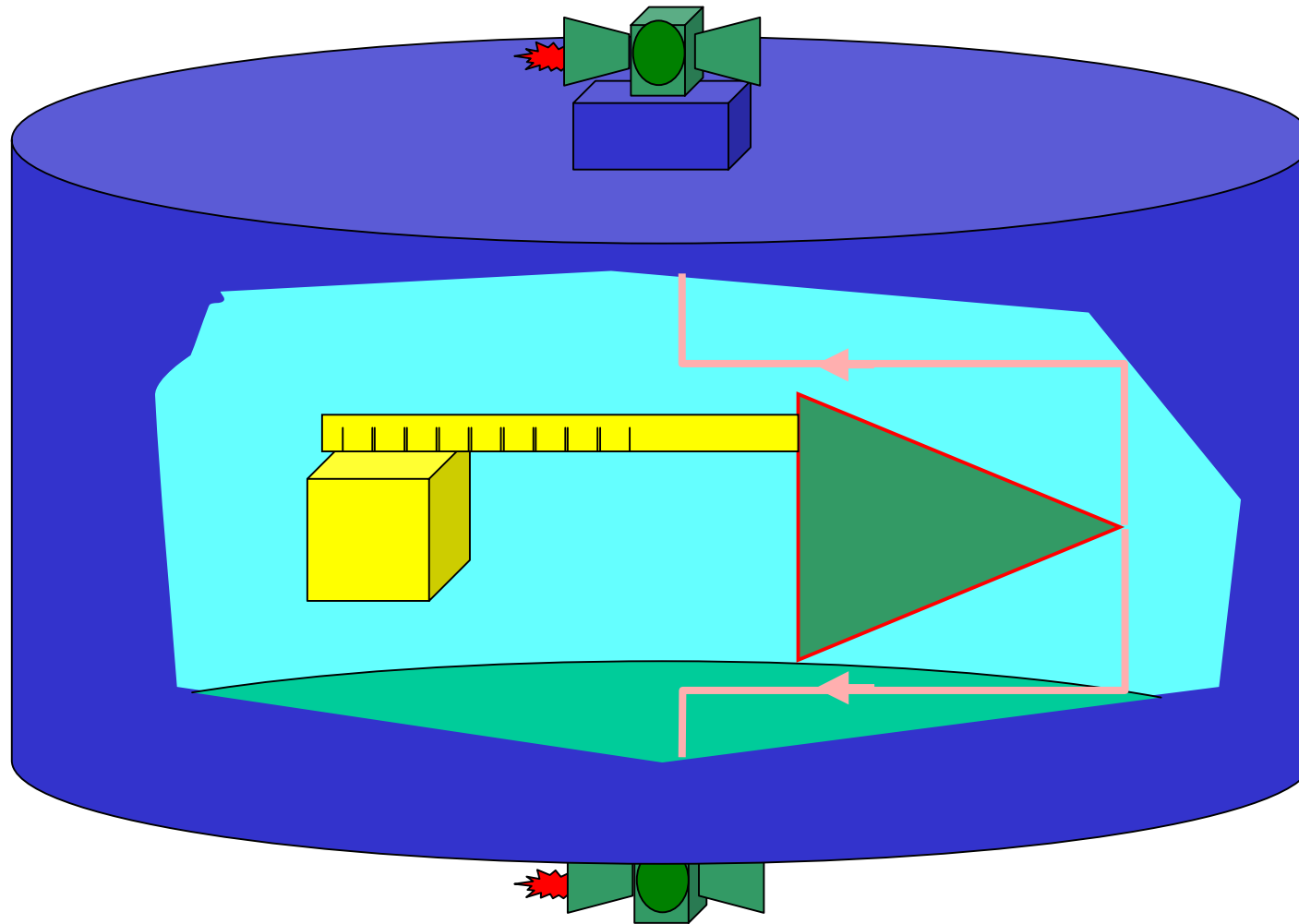
High gain force
feedback

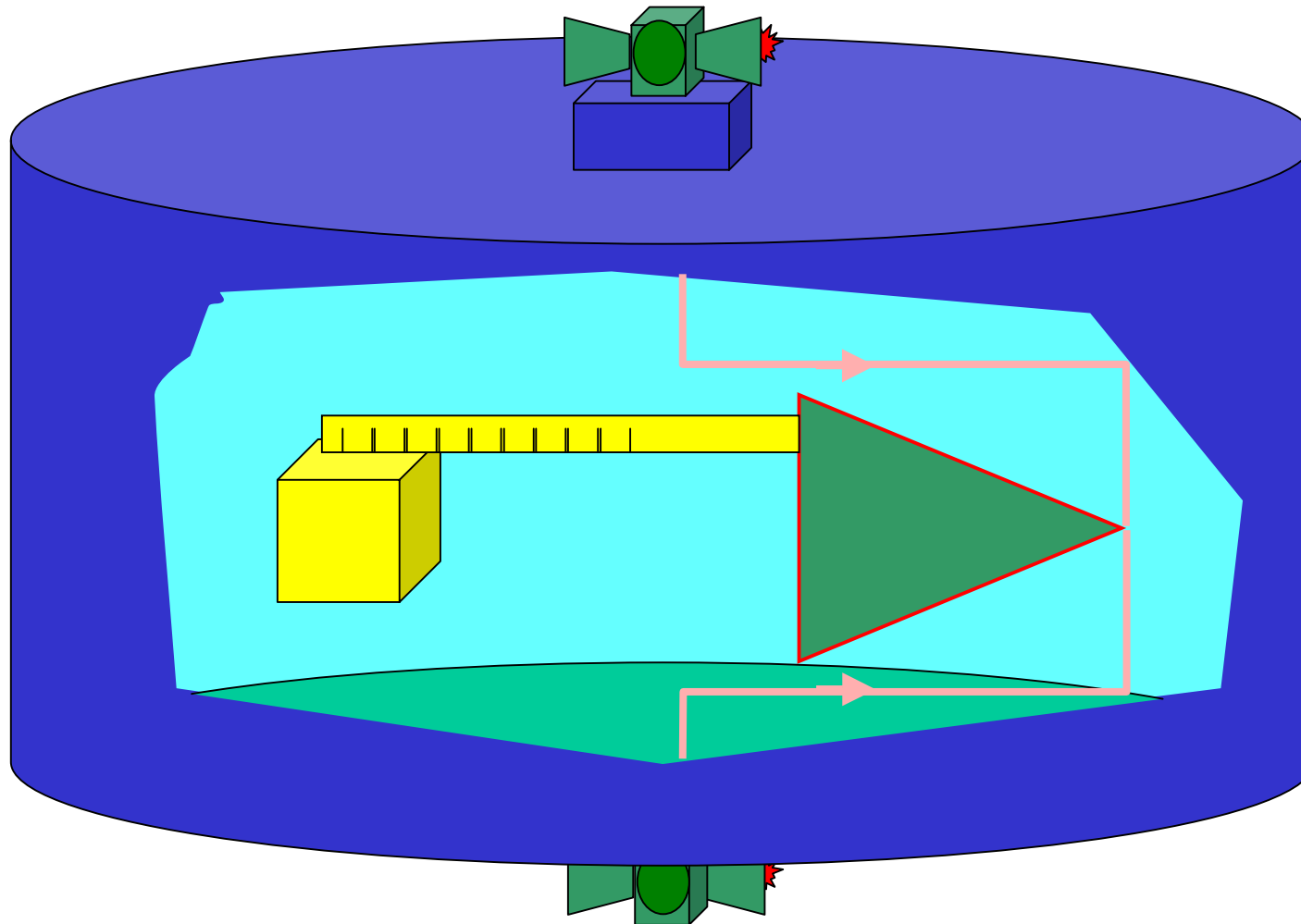


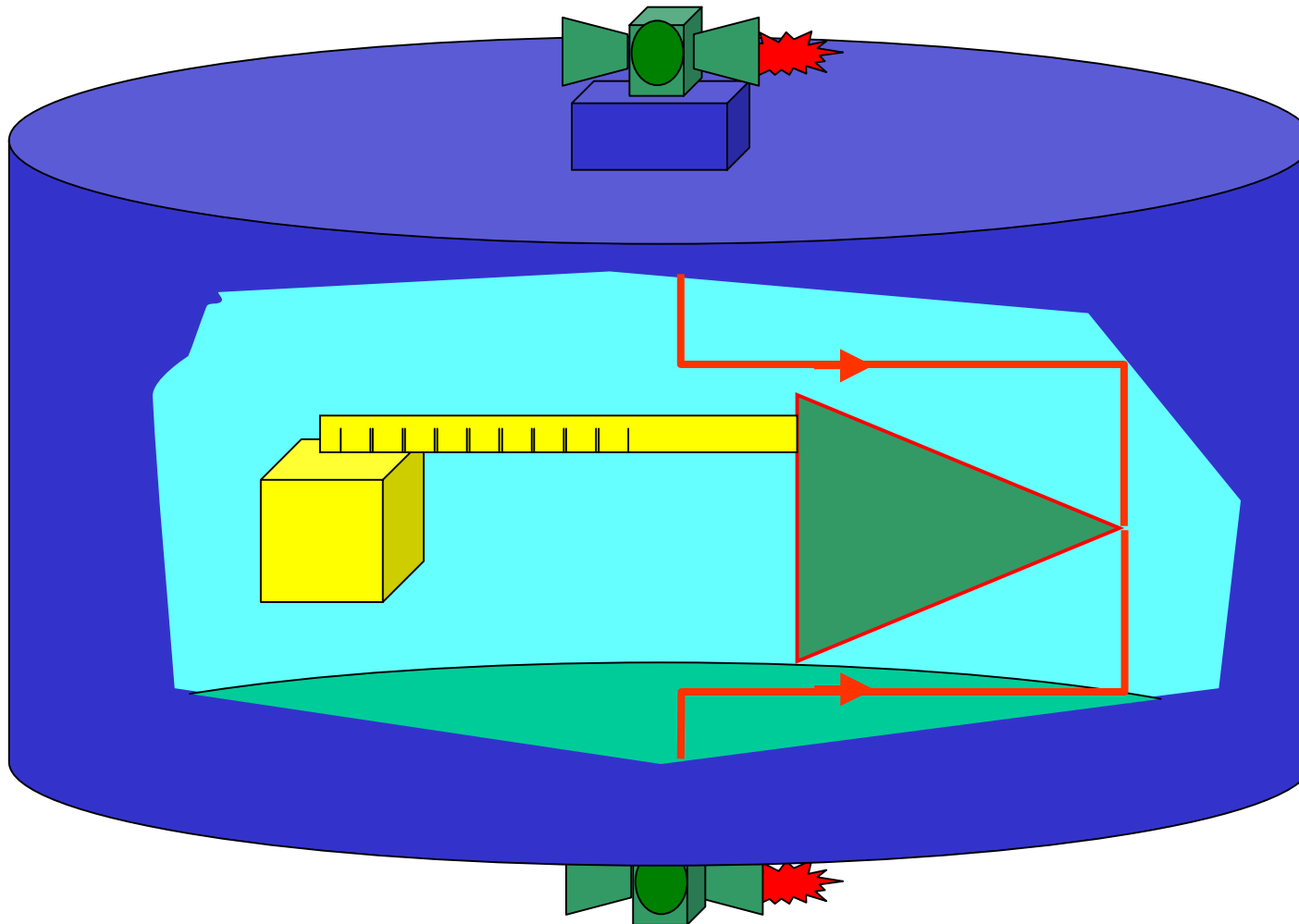


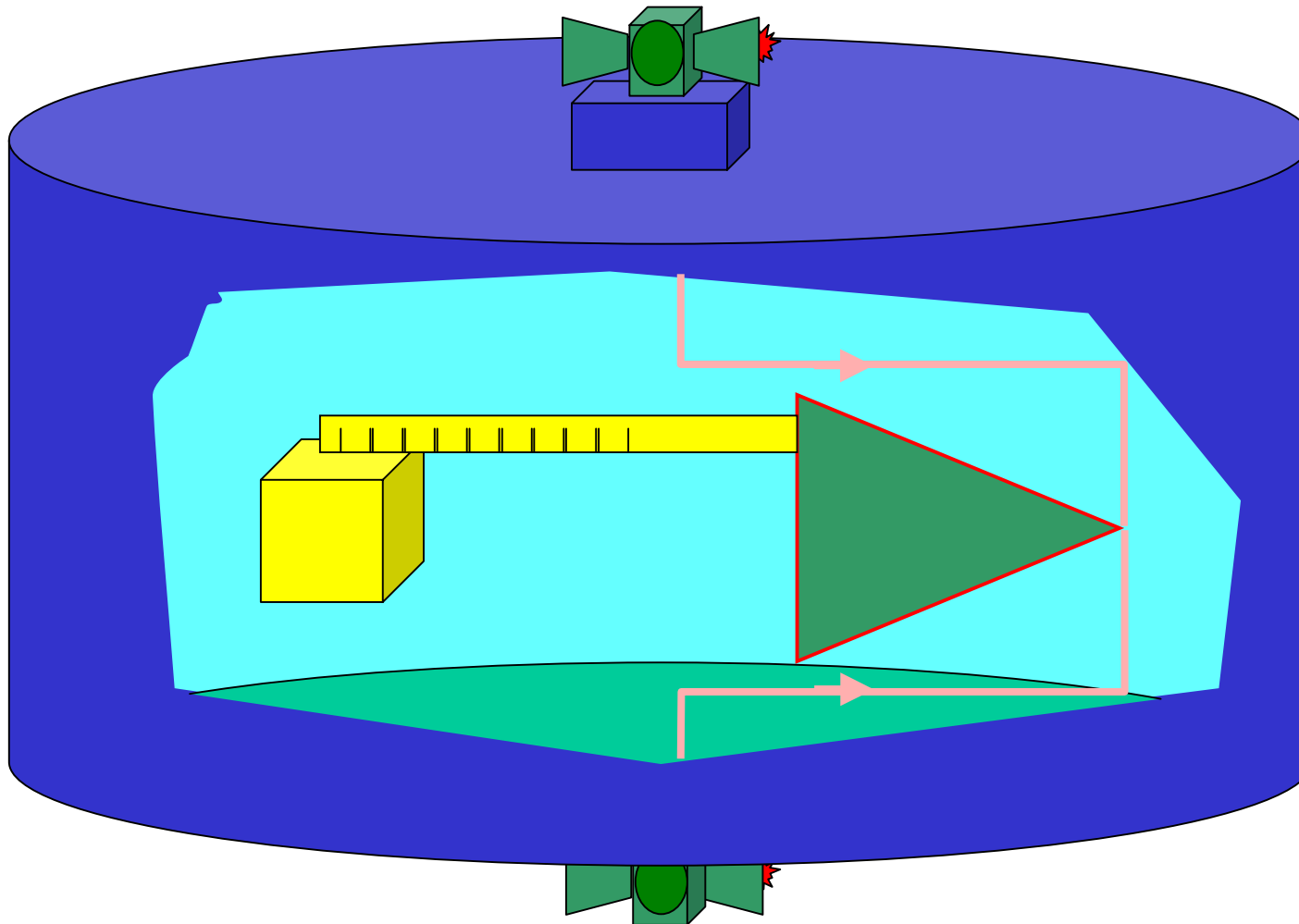


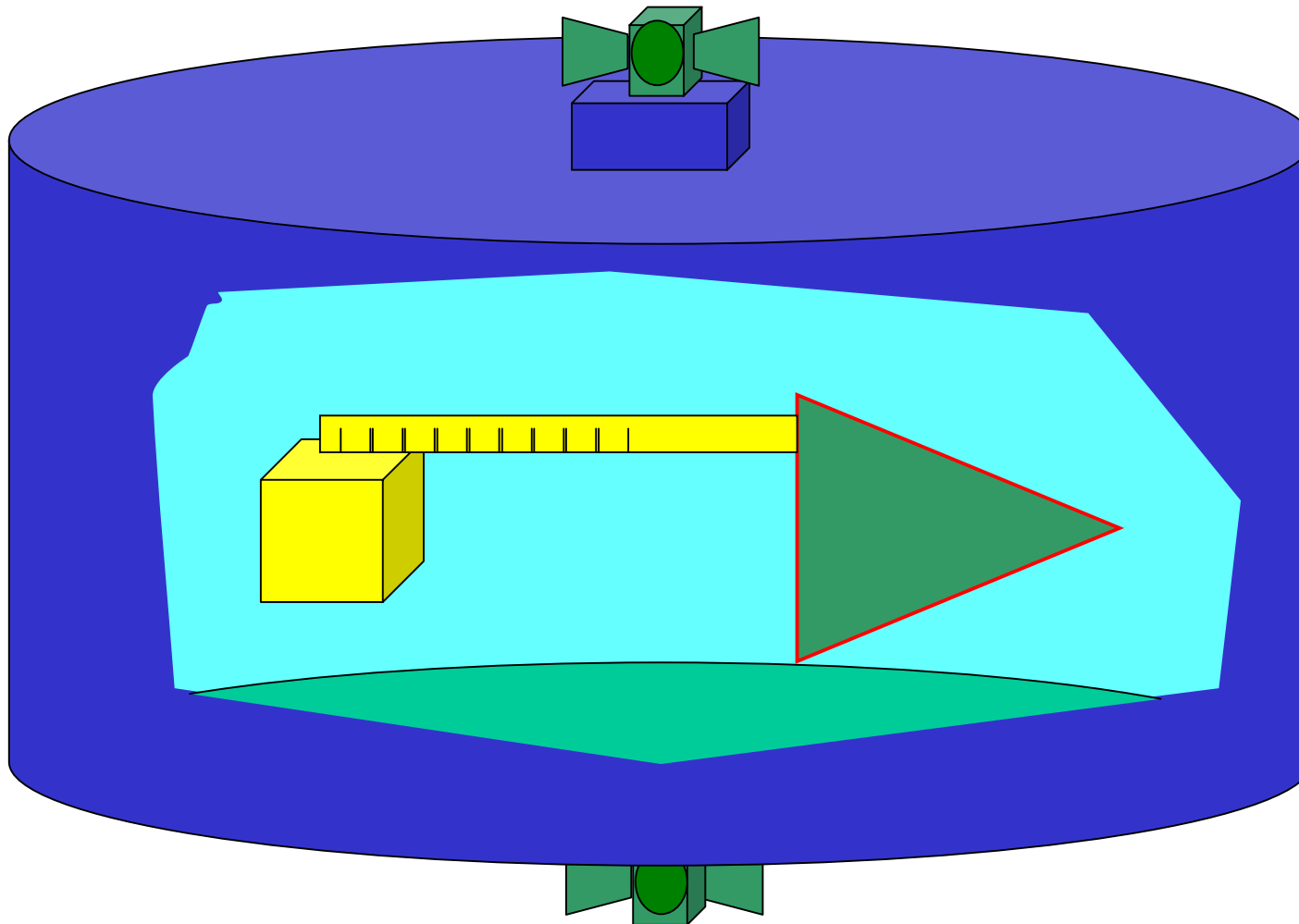




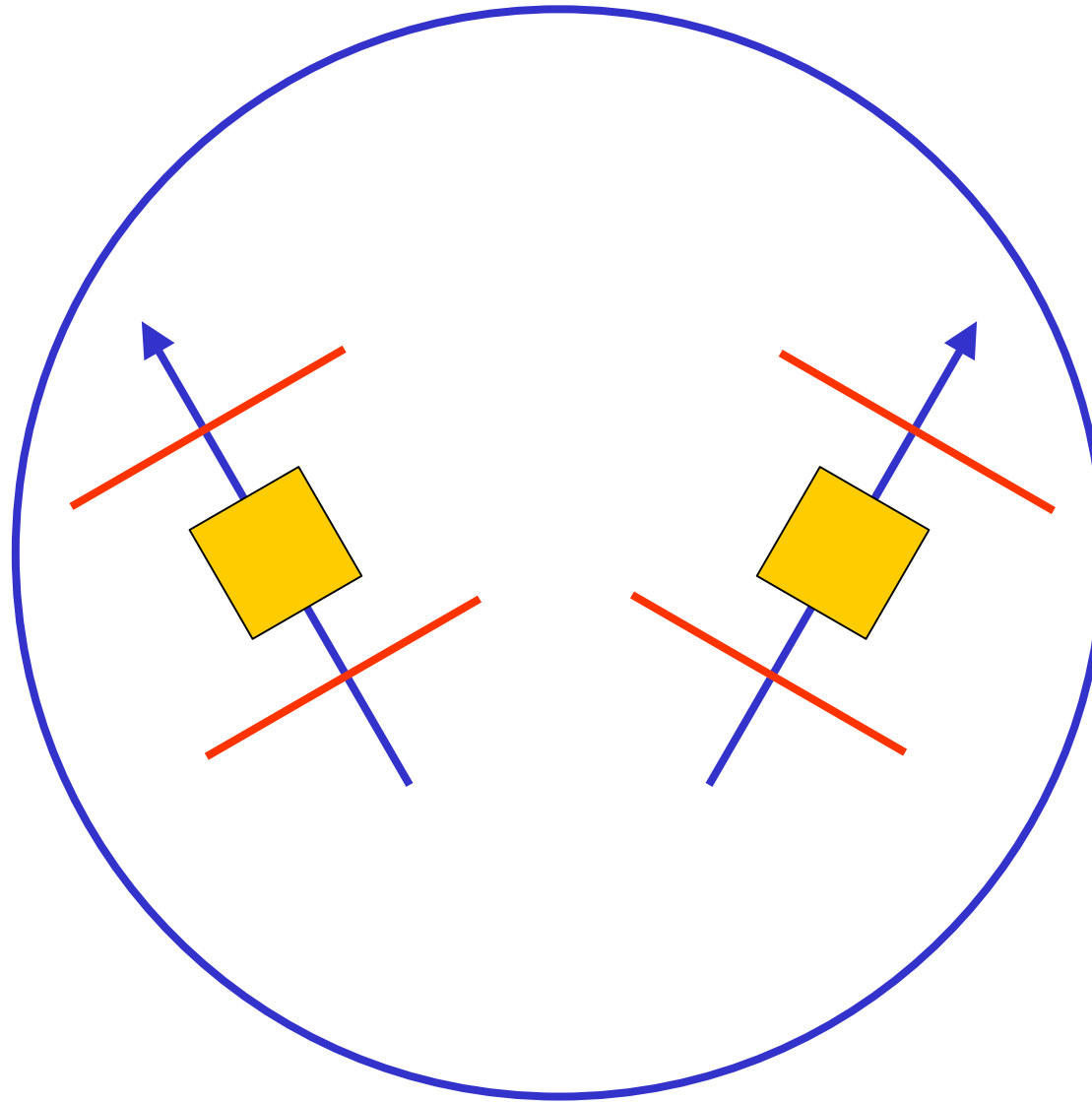




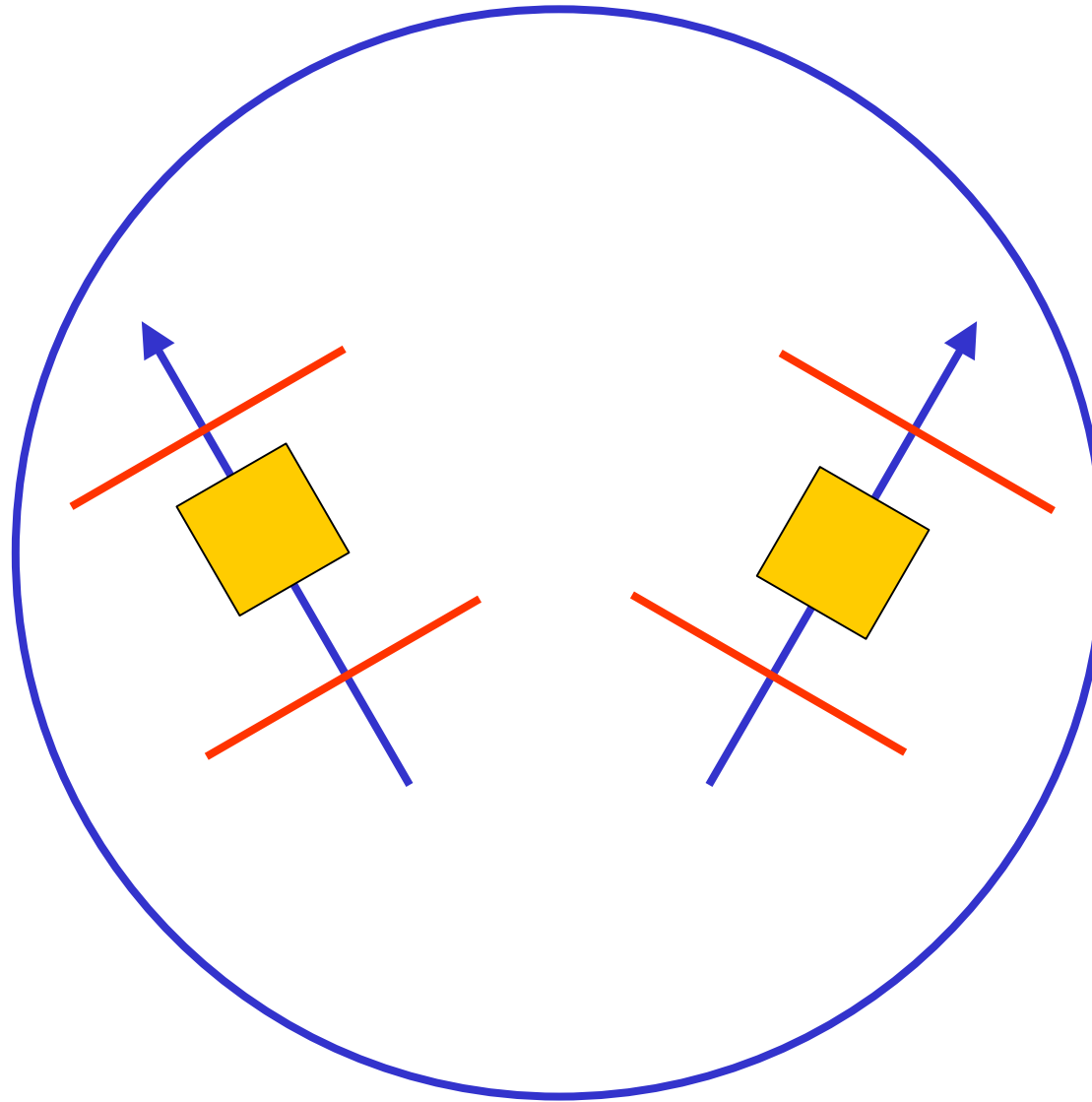




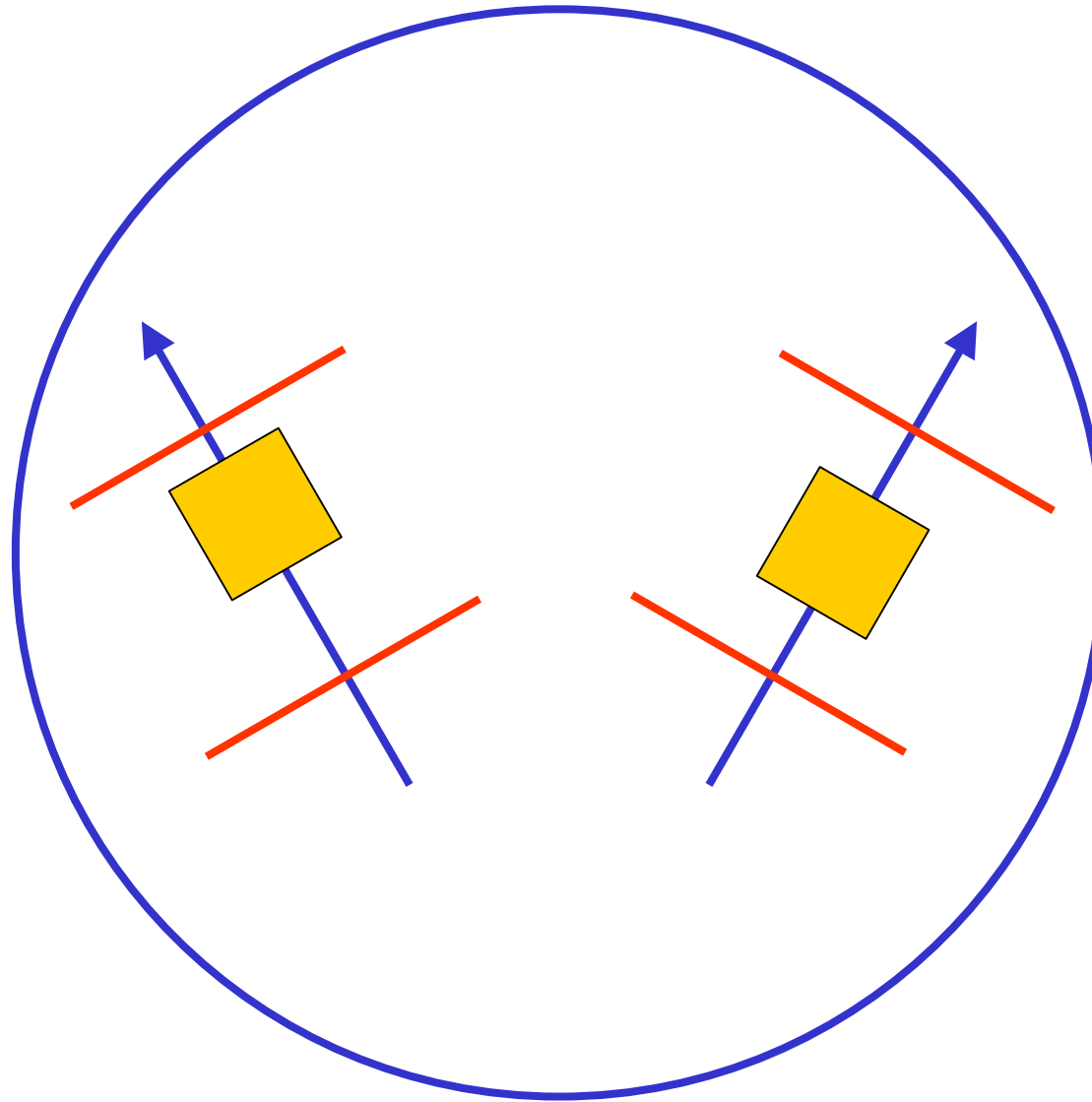
LISA control: spacecraft follows 2 masses at once



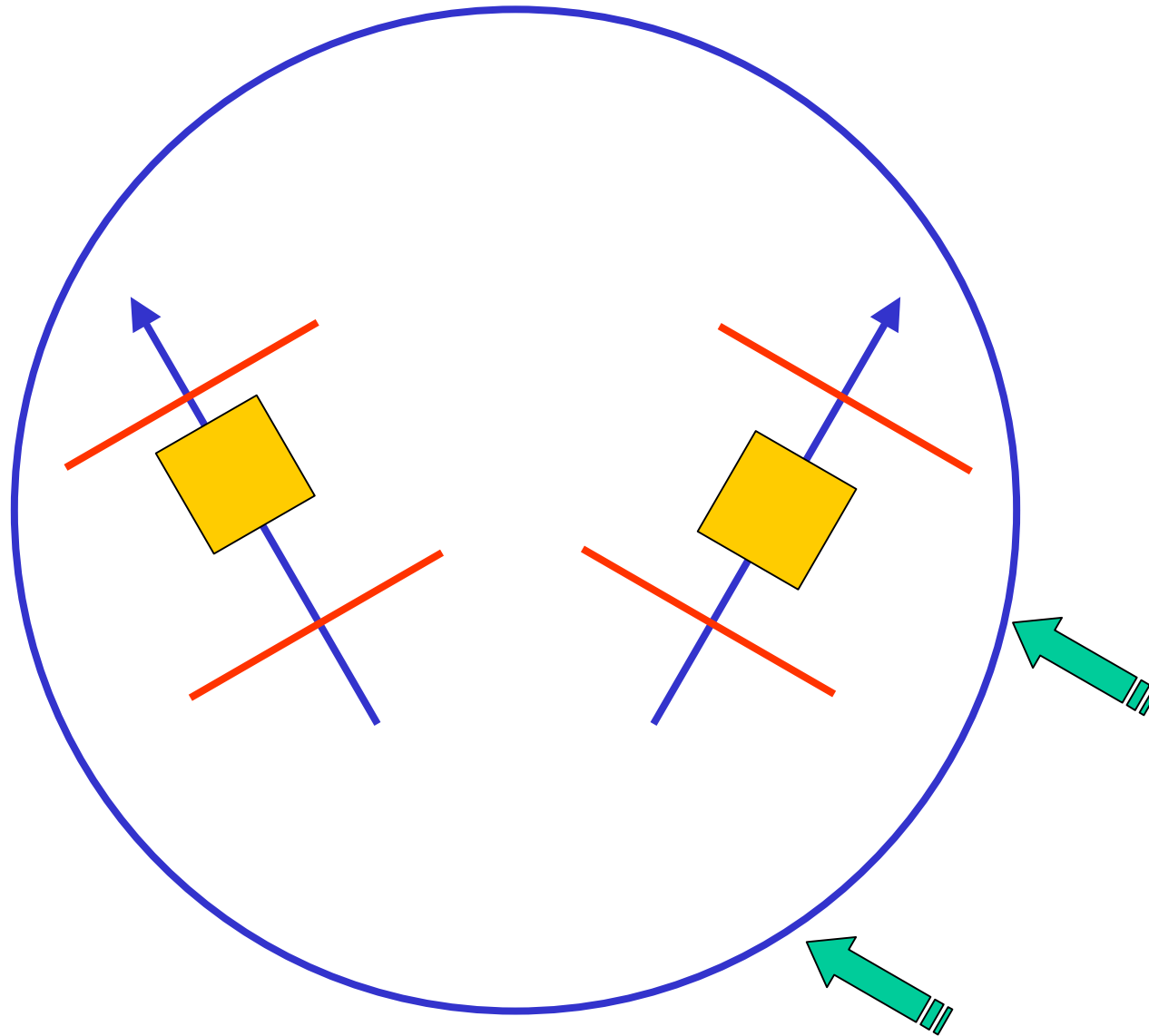
LISA control: spacecraft follows 2 masses at once



LISA control: spacecraft follows 2 masses at once

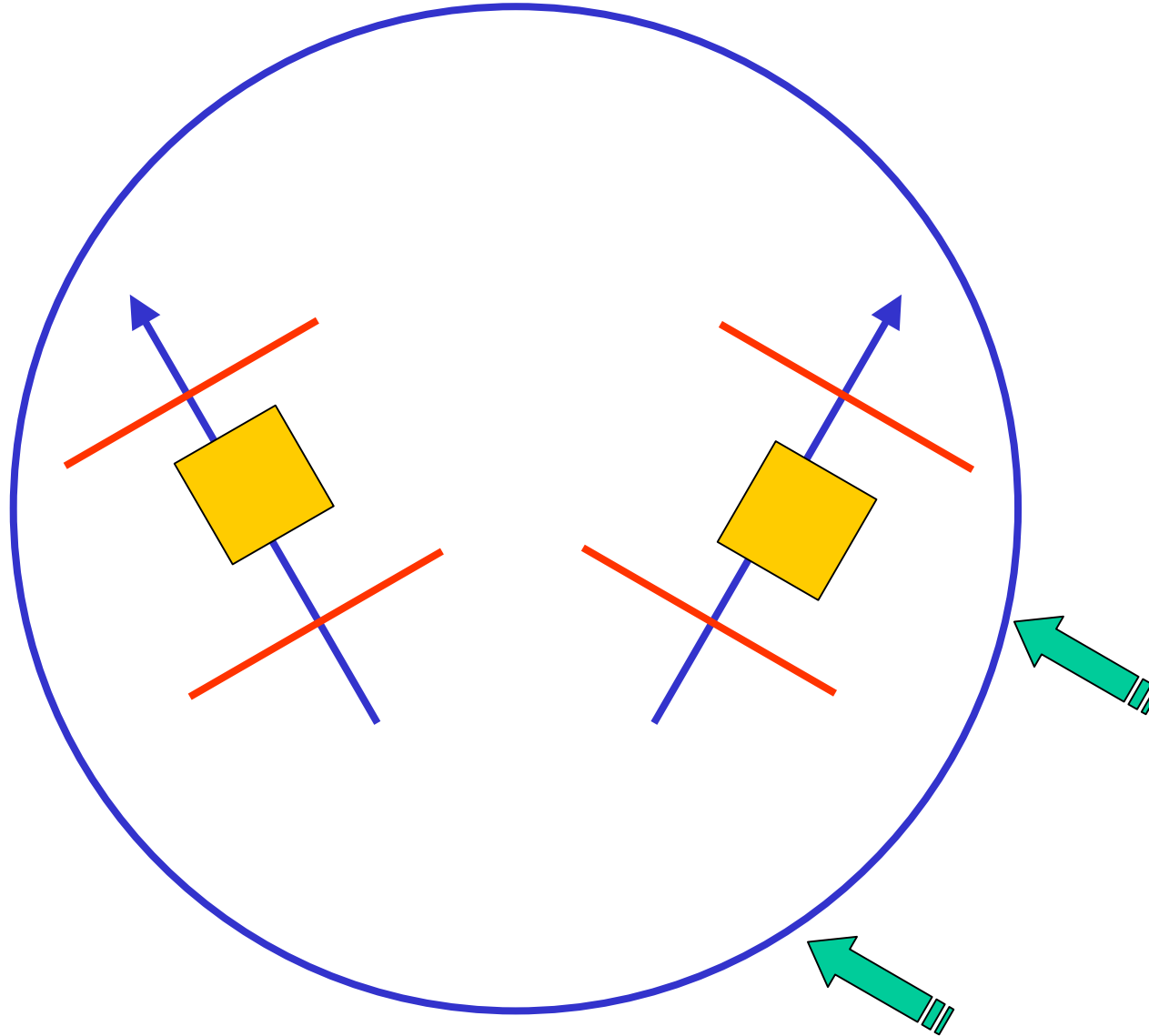


LISA control: spacecraft follows 2 masses at once



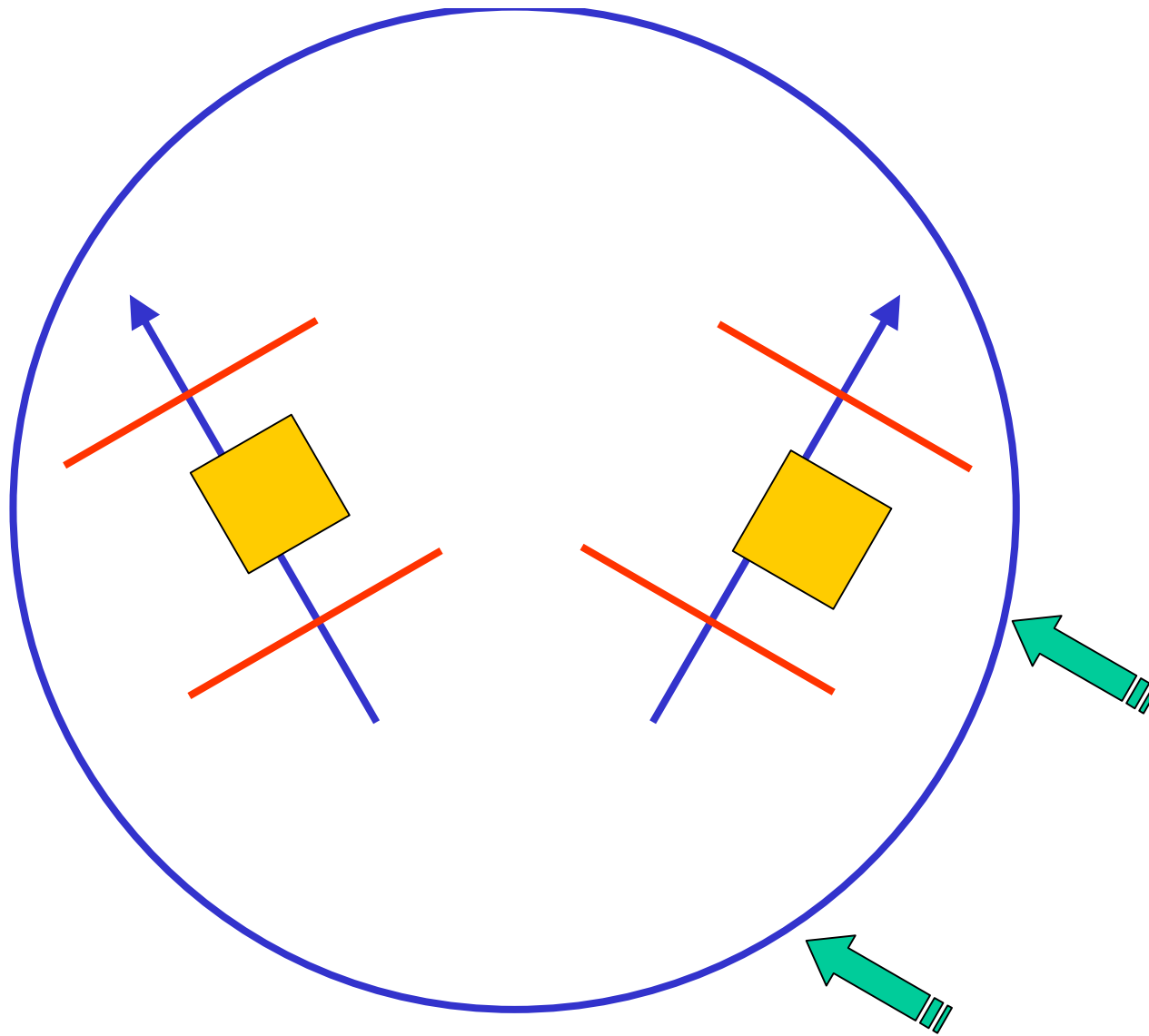
1: Move the spacecraft and centre the masses along laser beams

LISA control: spacecraft follows 2 masses at once



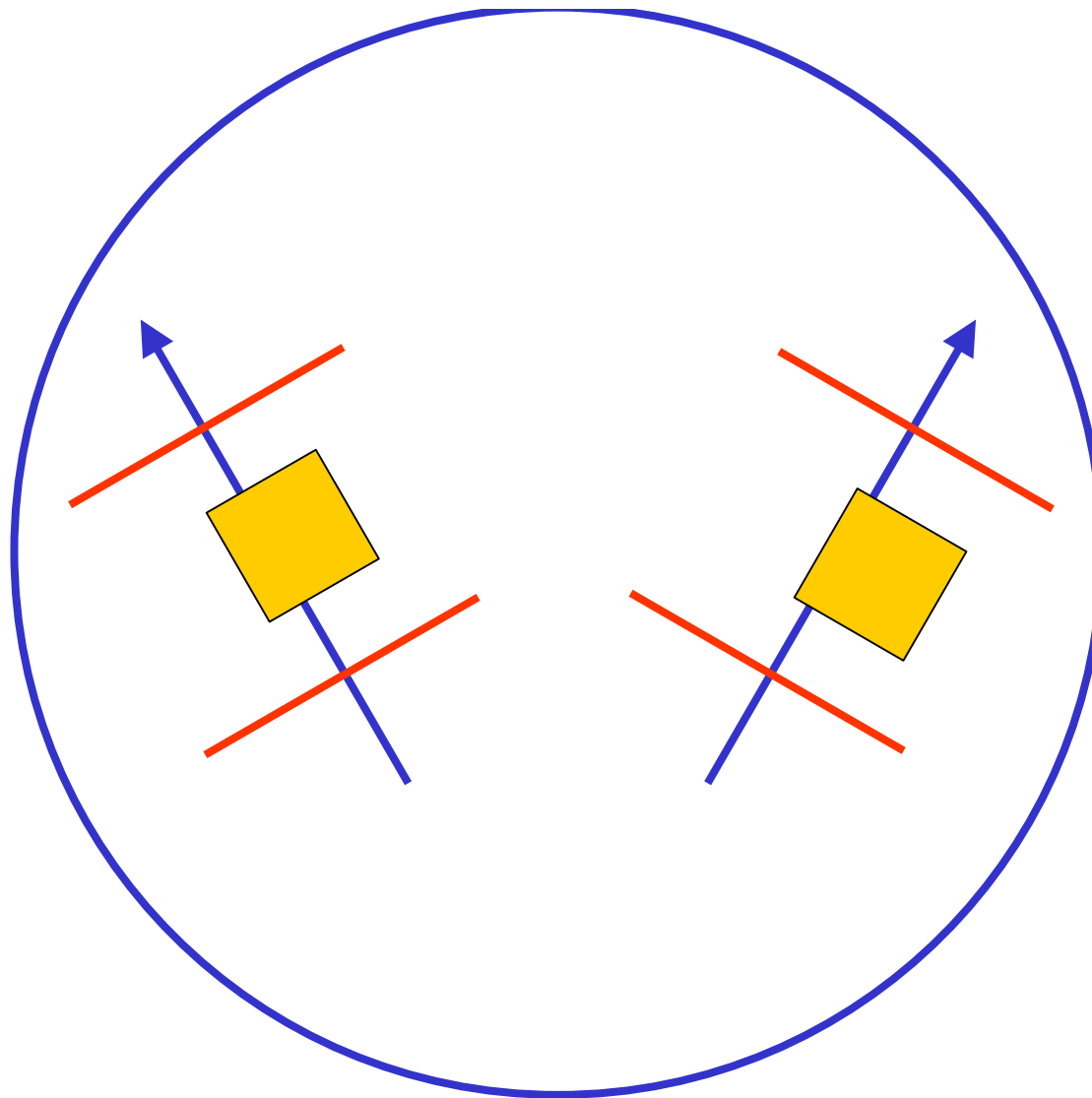
1: Move the spacecraft and centre the masses along laser beams

LISA control: spacecraft follows 2 masses at once



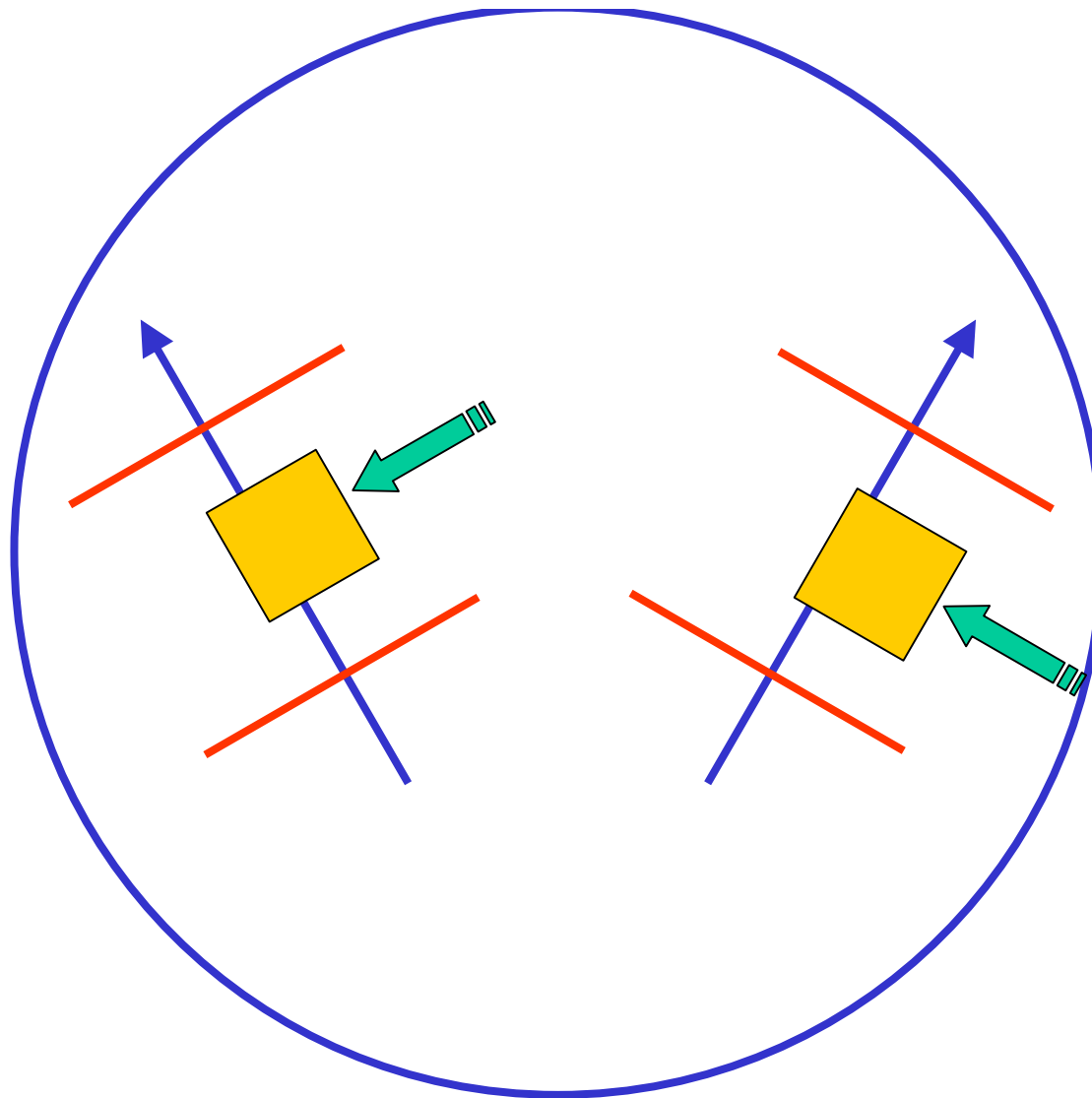
1: Move the spacecraft and centre the masses along laser beams

LISA control: spacecraft follows 2 masses at once



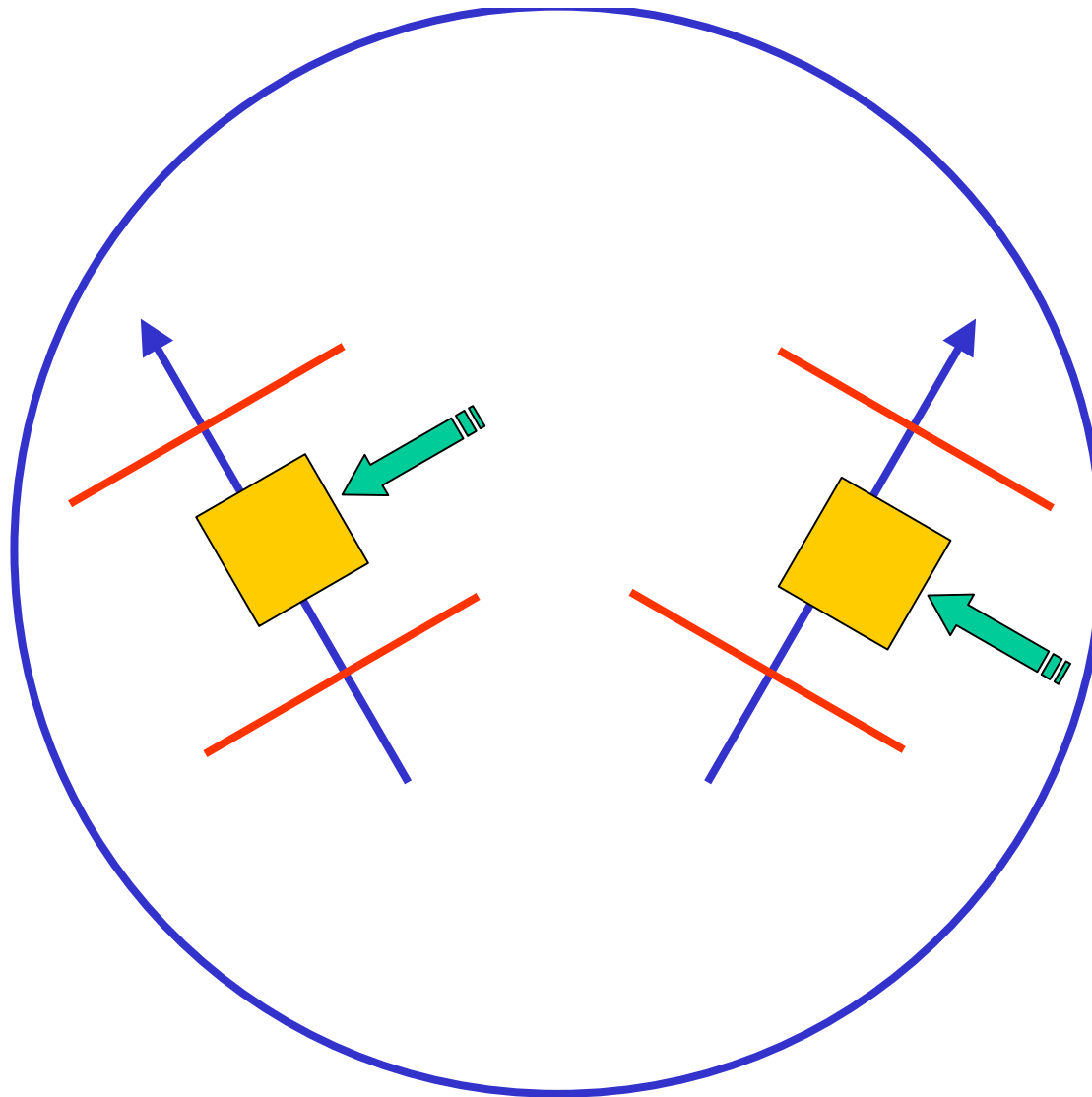
1: Move the spacecraft and centre the masses along laser beams

LISA control: spacecraft follows 2 masses at once



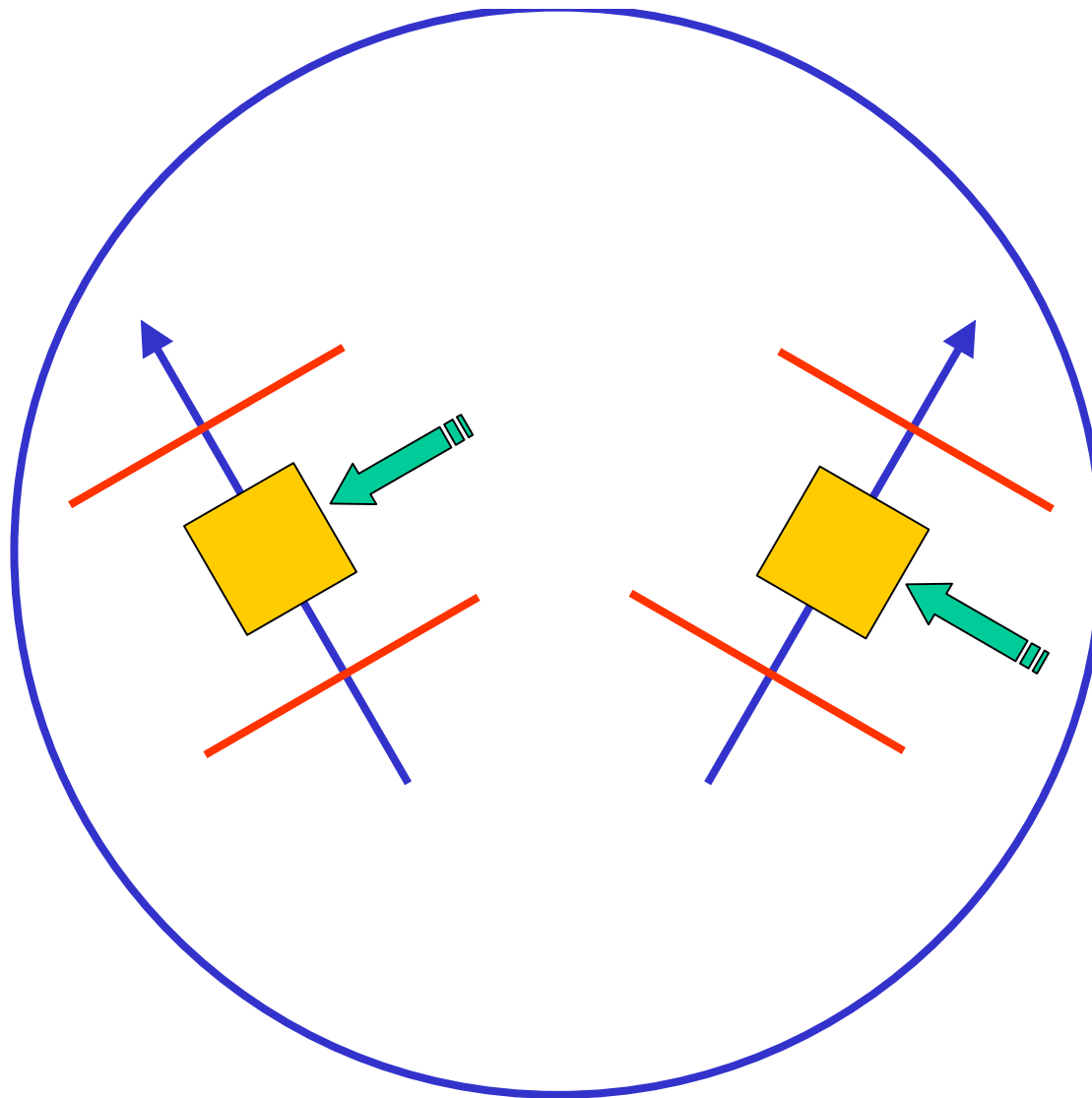
2: Re-center the masses at 90° from the laser beam

LISA control: spacecraft follows 2 masses at once



2: Re-center the masses at 90° from the laser beam

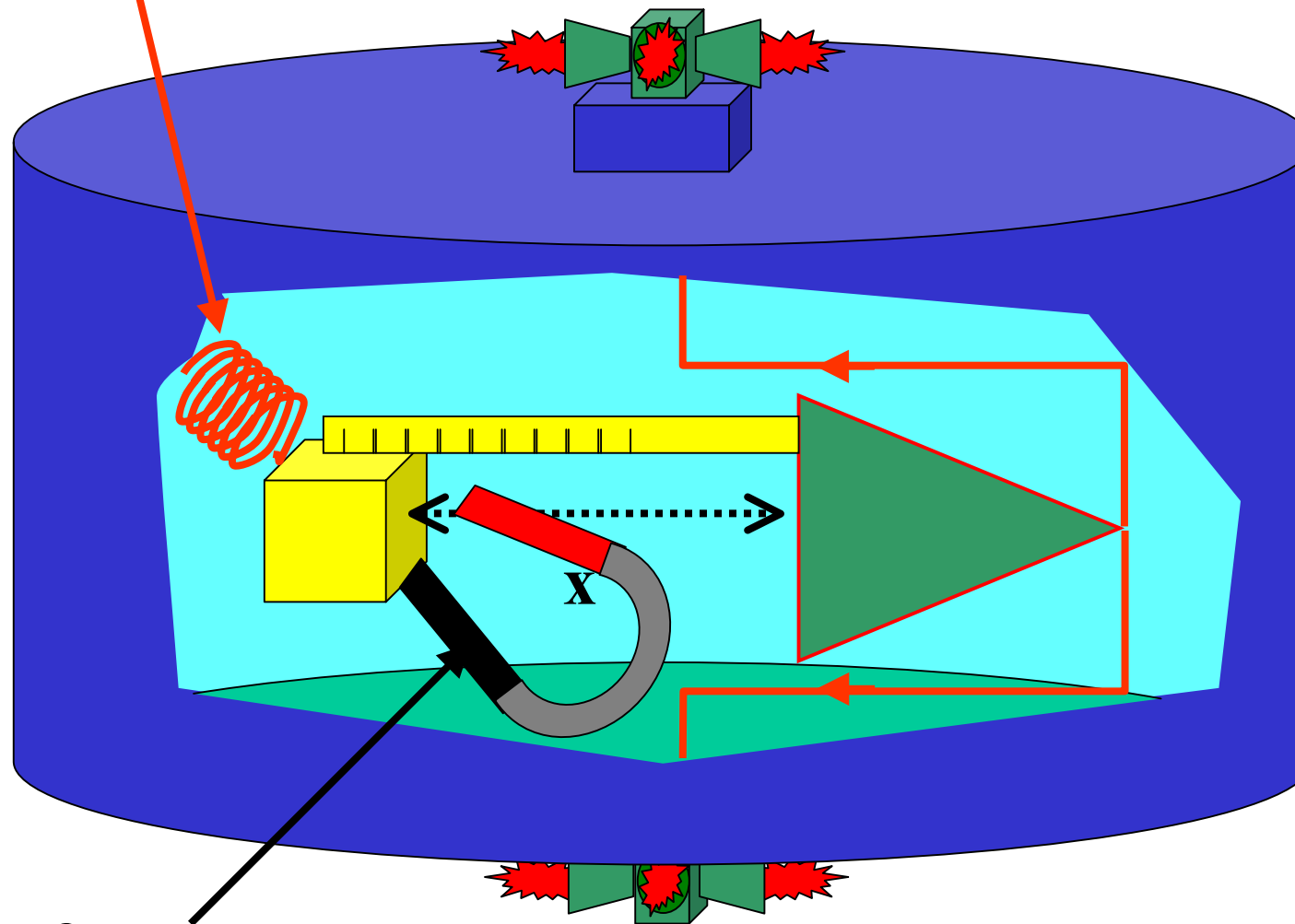
LISA control: spacecraft follows 2 masses at once



2: Re-center the masses at 90° from the laser beam

**Parasitic
coupling**

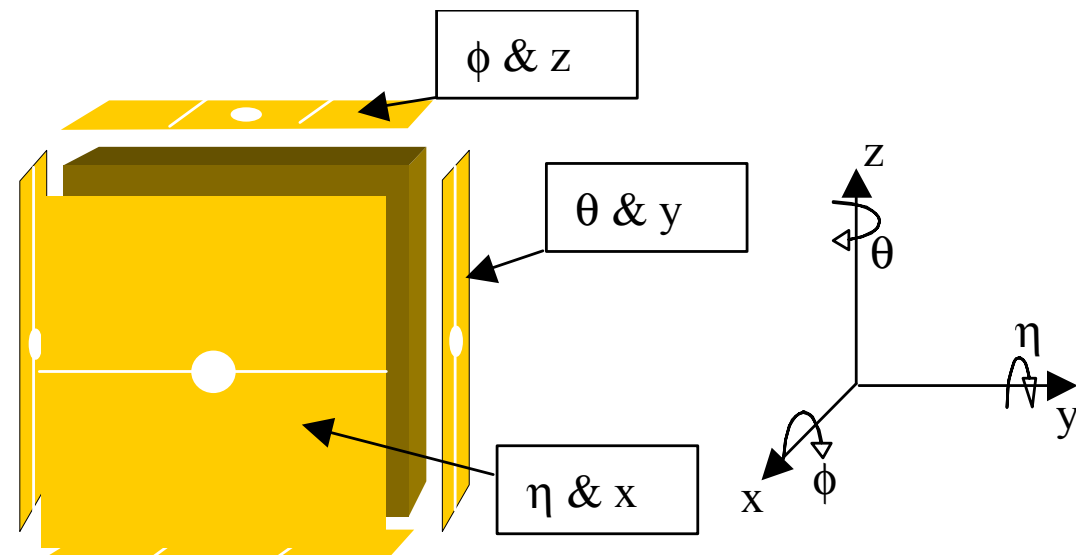
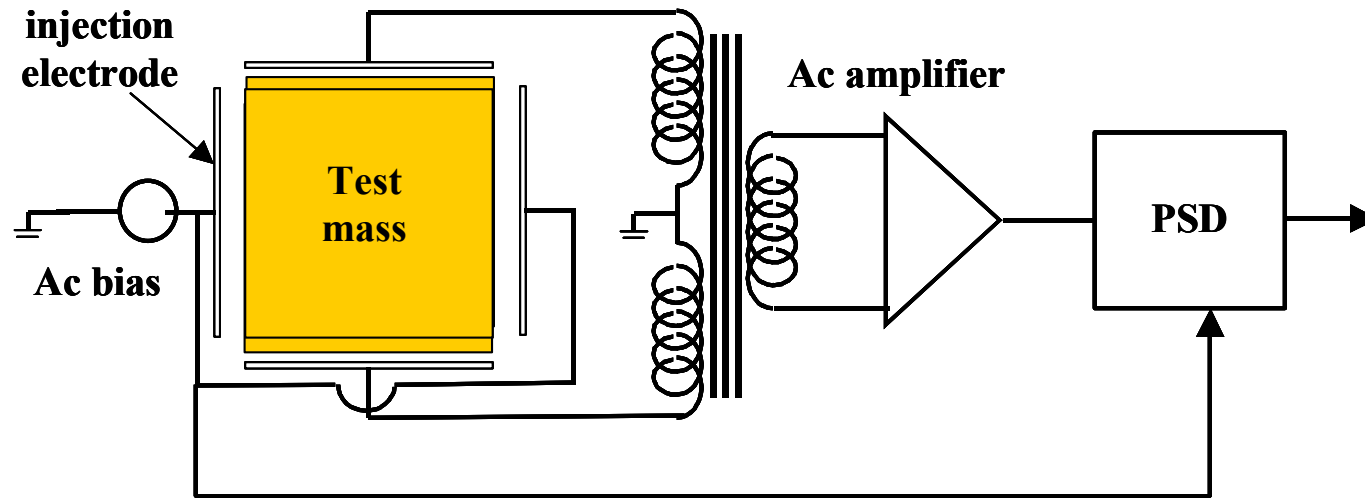
The reality



Stray forces

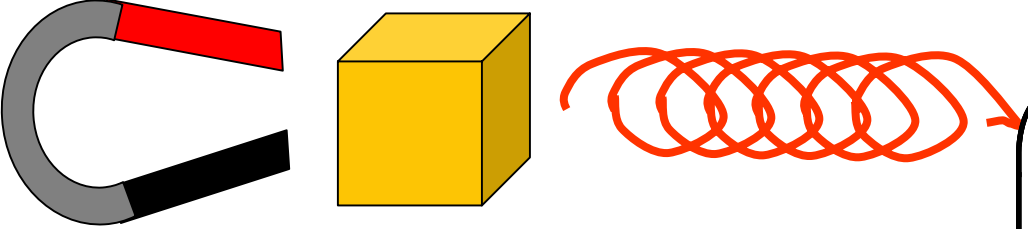
The drag-free key elements: 1 the displacement

sensor



Main disturbances to free-fall and design guidelines

The residual test-mass acceleration noise



$$\mathbf{a}_{\text{noise}} = \underbrace{\frac{\mathbf{f}_{\text{T/M}}}{\mathbf{m}}}_{\text{Force on Test-Mass}} + \underbrace{\omega_p^2}_{\text{Parasitic stiffness}} \left[\underbrace{\mathbf{x}_n}_{\text{Sensor noise}} + \underbrace{\frac{\mathbf{F}_{\text{S/C}}}{\mathbf{M}\omega_{\text{fb}}^2}}_{\text{Drag-free gain}} \right]$$

Relative displacement
TM wrt S/C

Main disturbances to free-fall and design guidelines

Large gaps, low voltage → low sensitivity

$$\mathbf{a}_{\text{noise}} = \underbrace{\frac{\mathbf{f}_{\text{T/M}}}{\mathbf{m}}}_{\text{Force on Test-Mass}} + \underbrace{\left[\underbrace{\omega_p^2}_{\text{Parasitic stiffness}} + \underbrace{\left(\underbrace{\mathbf{x}_n}_{\text{Sensor noise}} + \underbrace{\frac{\mathbf{F}_{\text{S/C}}}{\mathbf{M}\omega_{\text{fb}}^2}}_{\text{Drag-free gain}} \right)}_{\text{Relative displacement TM wrt S/C}} \right]}_{\text{Relative displacement TM wrt S/C}}$$

The diagram illustrates the components of the noise acceleration $\mathbf{a}_{\text{noise}}$. The first term is the force on the test mass divided by its mass. The second term is the relative displacement of the test mass with respect to the spacecraft, which is composed of parasitic stiffness, sensor noise, and drag-free gain. The sensor noise and drag-free gain terms are further detailed in red boxes, showing their dependence on bias voltage and gap size.

Red boxes and arrows indicate the following relationships:

- Top left box: $\propto \frac{V_{\text{bias}}^2}{\text{gap}^3}$
- Top right box: $\propto \frac{\text{gap}^2}{V_{\text{bias}}}$
- Bottom left box: ω_p^2 (Parasitic stiffness)
- Bottom middle box: $\mathbf{x}_n$ (Sensor noise)
- Bottom right box: $\frac{\mathbf{F}_{\text{S/C}}}{\mathbf{M}\omega_{\text{fb}}^2}$ (Drag-free gain)

A large bracket on the right side groups the sensor noise and drag-free gain terms, labeled "Relative displacement TM wrt S/C".

Main disturbances to free-fall and design guidelines

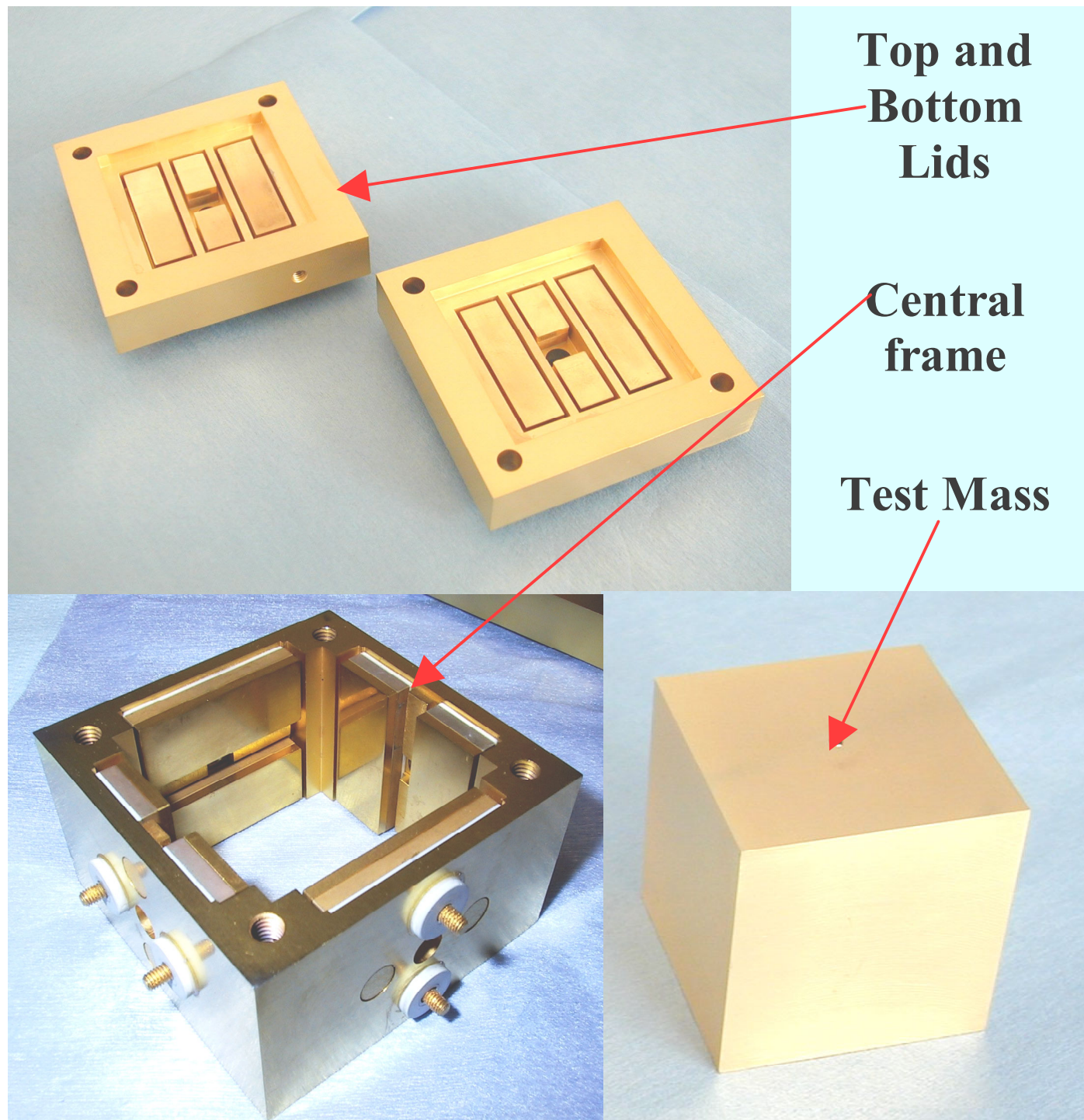
Charge effects, Thermal noise → no dc-voltage

Outgassing, Radiometer effect... → Stable thermal gradients

Magnetic field → Low susceptibility, Low magnetic moment, Cleanliness

.....

$$\mathbf{a}_{\text{noise}} = \underbrace{\frac{\mathbf{f}_{\text{T/M}}}{\mathbf{m}}}_{\text{Force on Test-Mass}} + \underbrace{\omega_p^2}_{\text{Parasitic stiffness}} \underbrace{\left(\underbrace{\mathbf{x}_n}_{\text{Sensor noise}} + \frac{\underbrace{\mathbf{F}_{\text{S/C}}}_{\text{Force on spacecraft}}}{\underbrace{\mathbf{M}\omega_{\text{fb}}^2}_{\text{Drag-free gain}}} \right)}_{\substack{\text{Relative displacement} \\ \text{TM wrt S/C}}}$$



**Top and
Bottom
Lids**

**Central
frame**

Test Mass

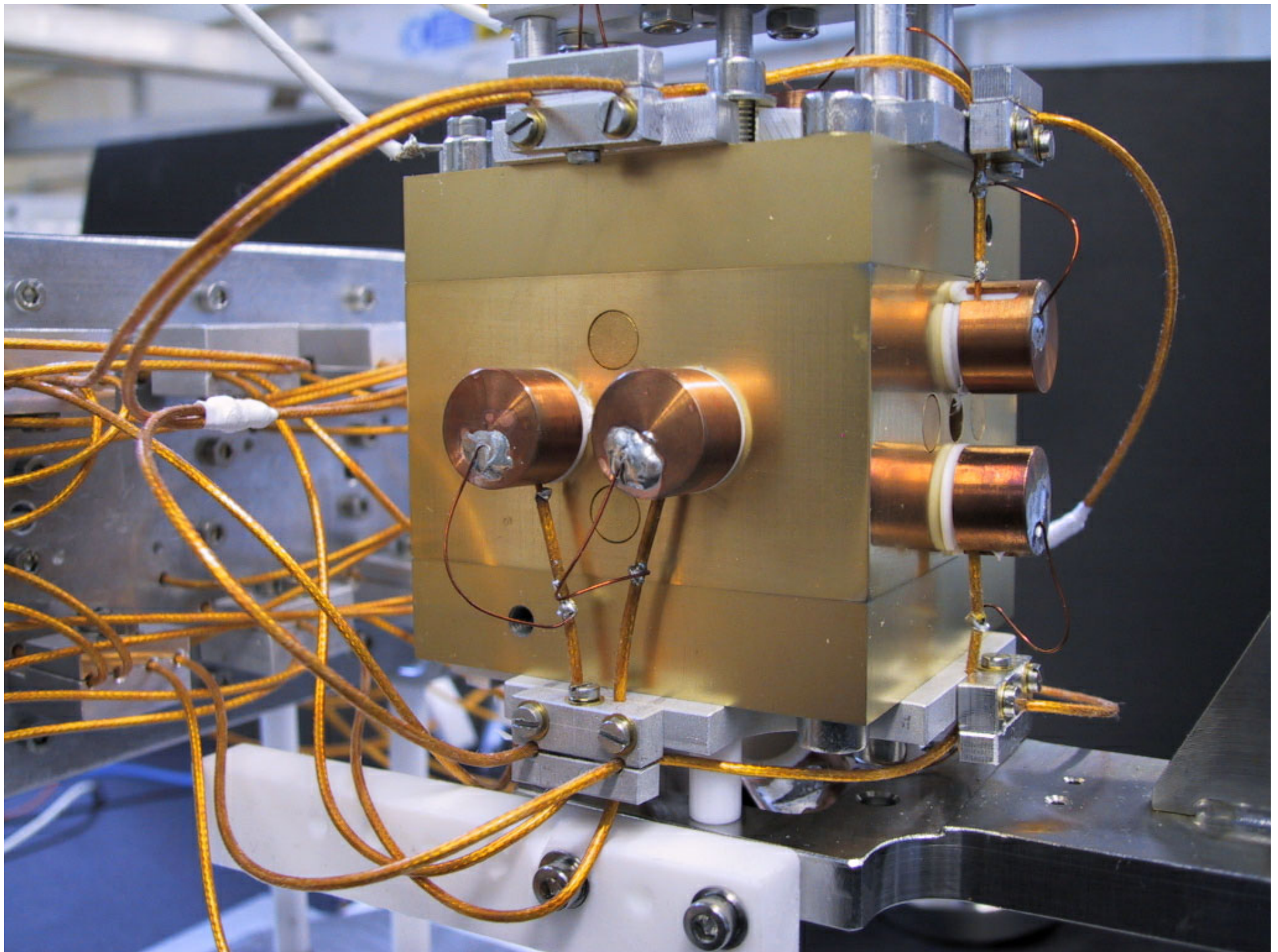
2-4 mm gaps

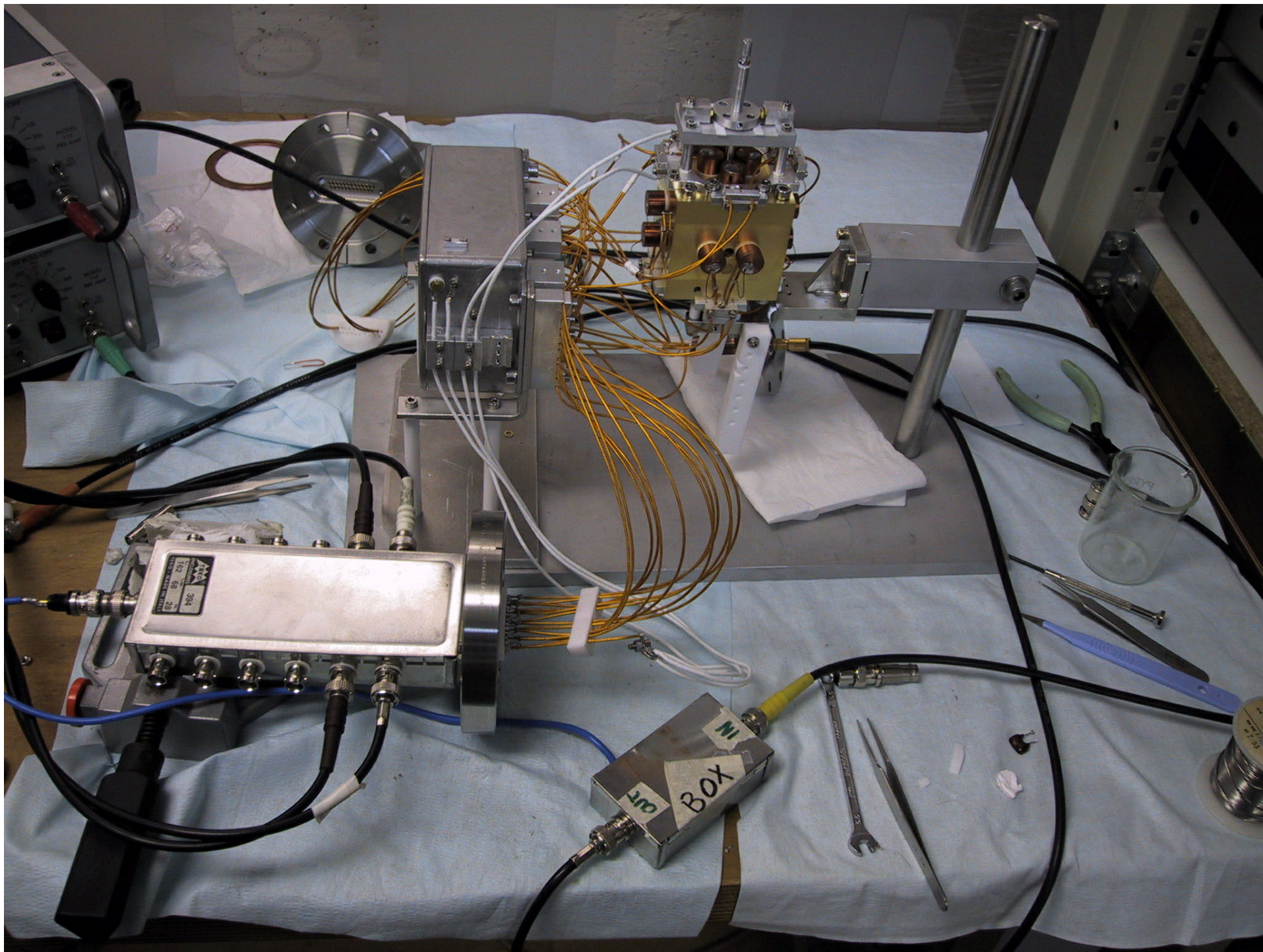
<1 V ac-bias

**No dc-voltage
(charging-losses)**

**Thermally
conducting
ceramics
(thermal
gradients)**

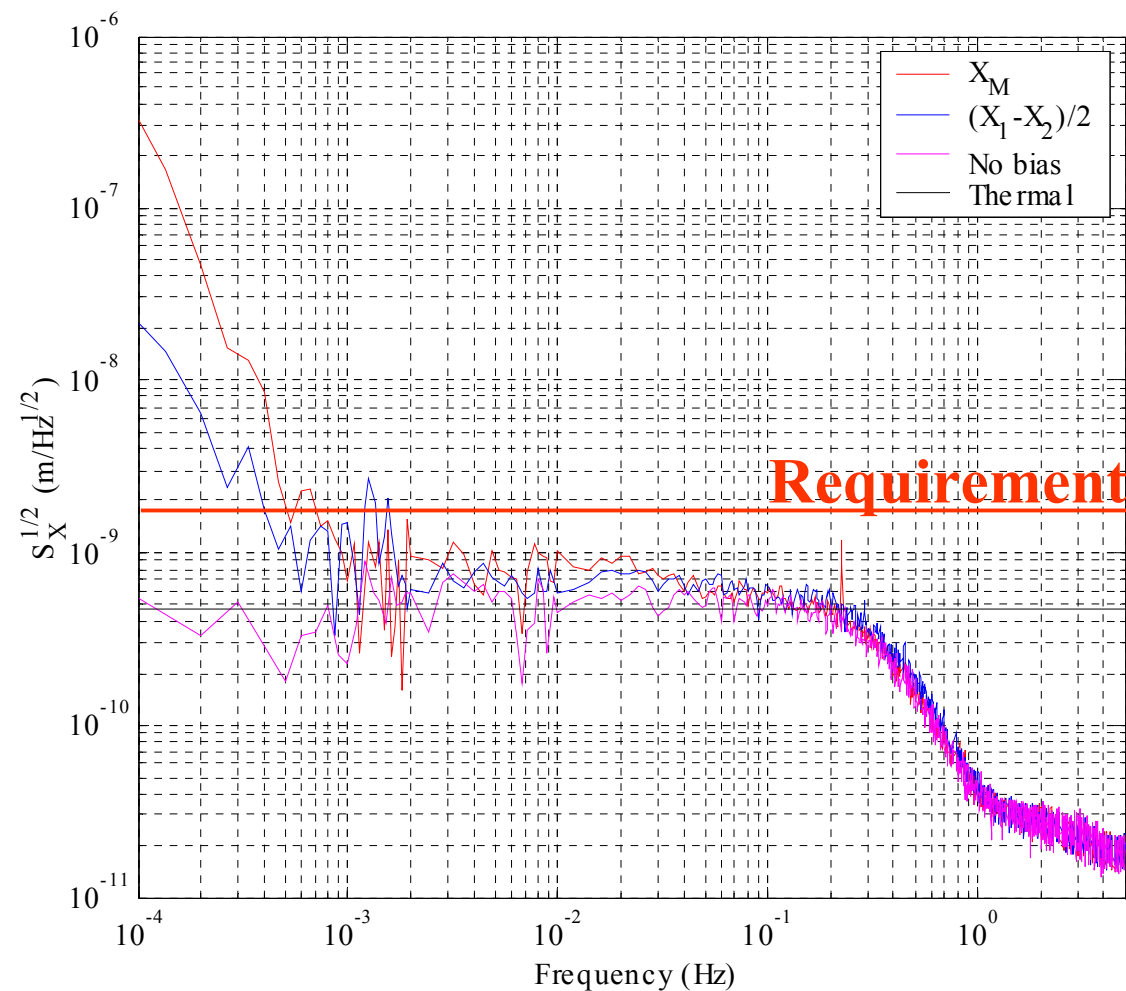
**AuPt low
susceptibility
test-mass
(magnetic noise)**

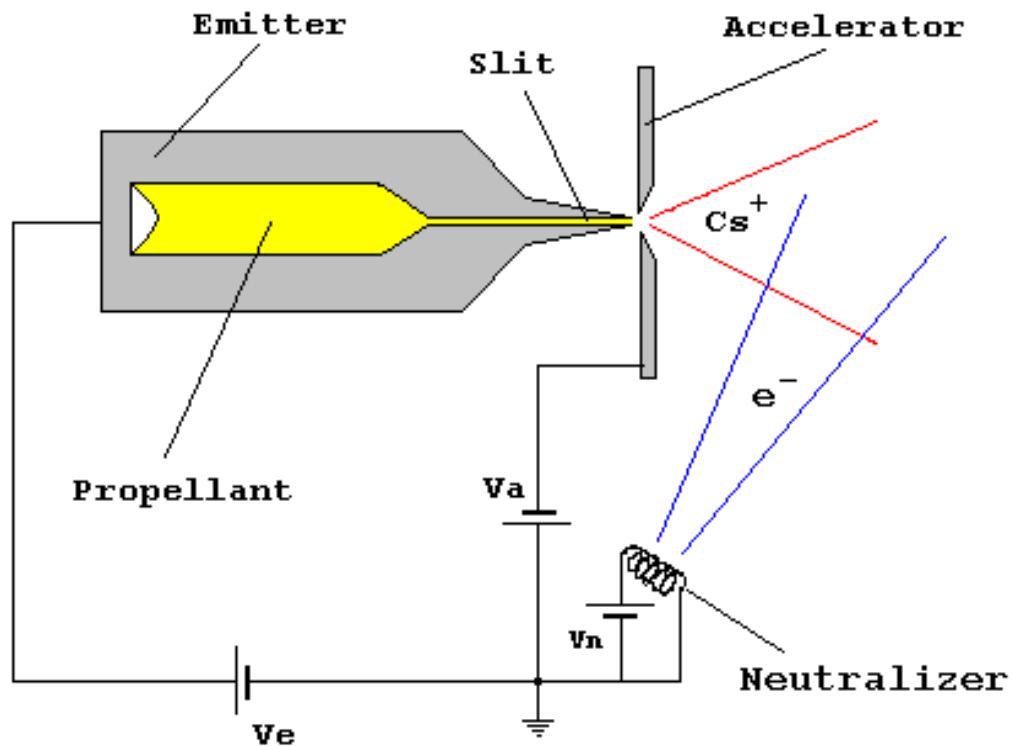
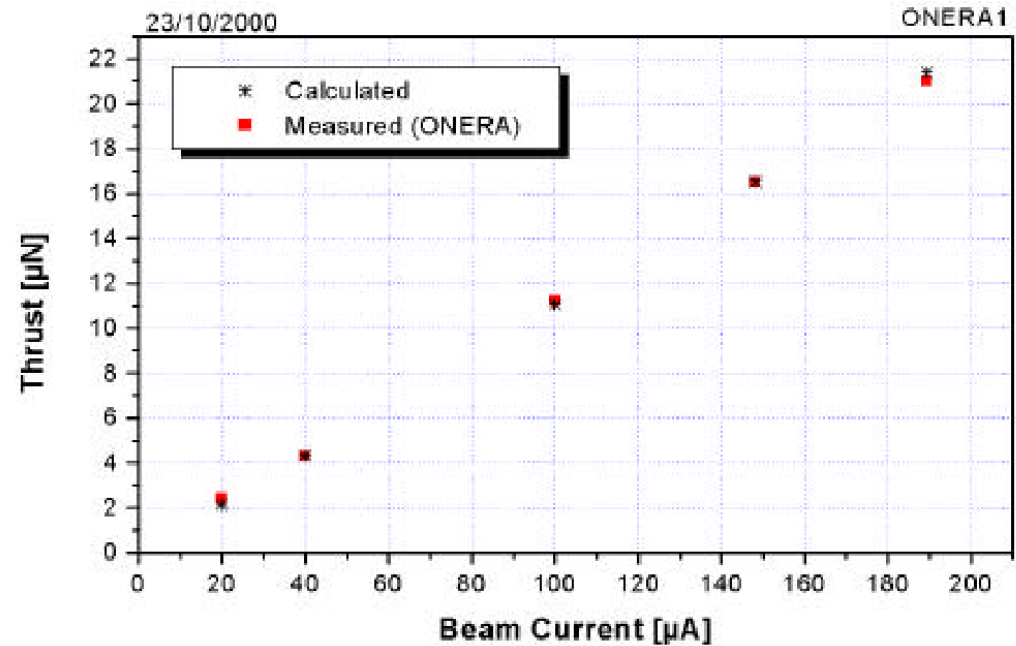




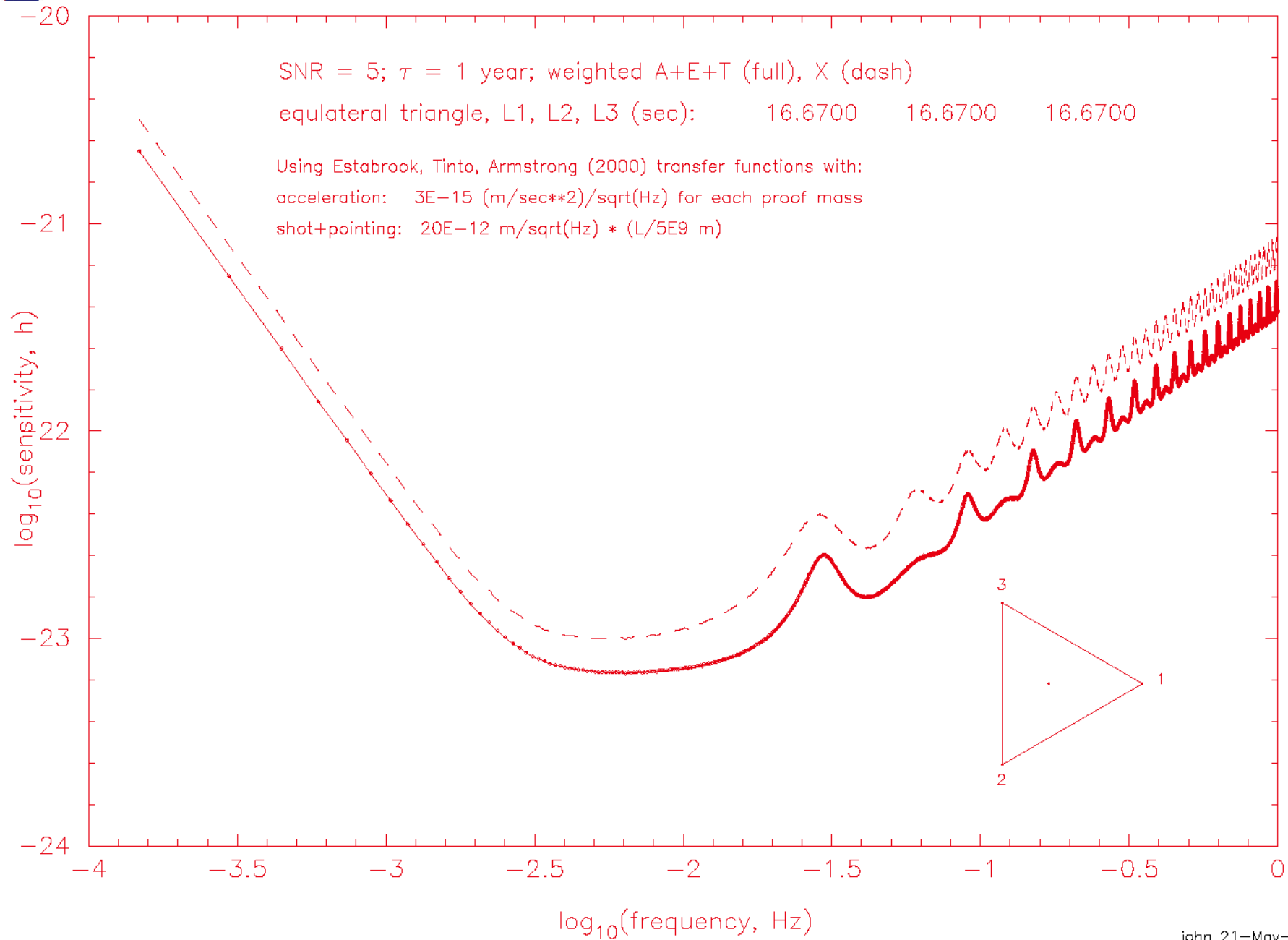
Requirement: $1 \text{ nm}/\sqrt{\text{Hz}}$ resolution

$>2 \text{ mm}$ gaps and 0.3 Volt bias

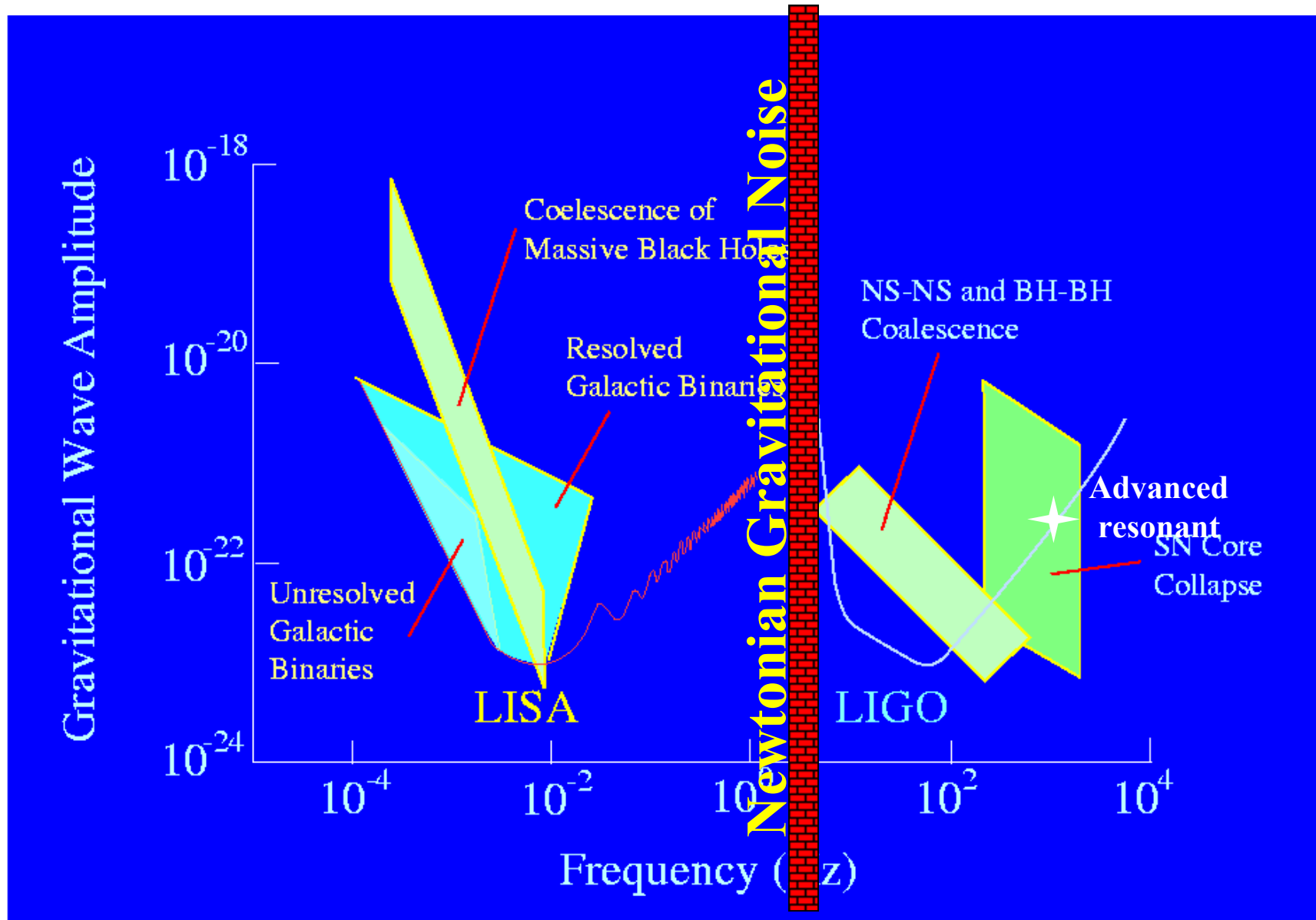




Drag-free key elements 2: Microthrusters

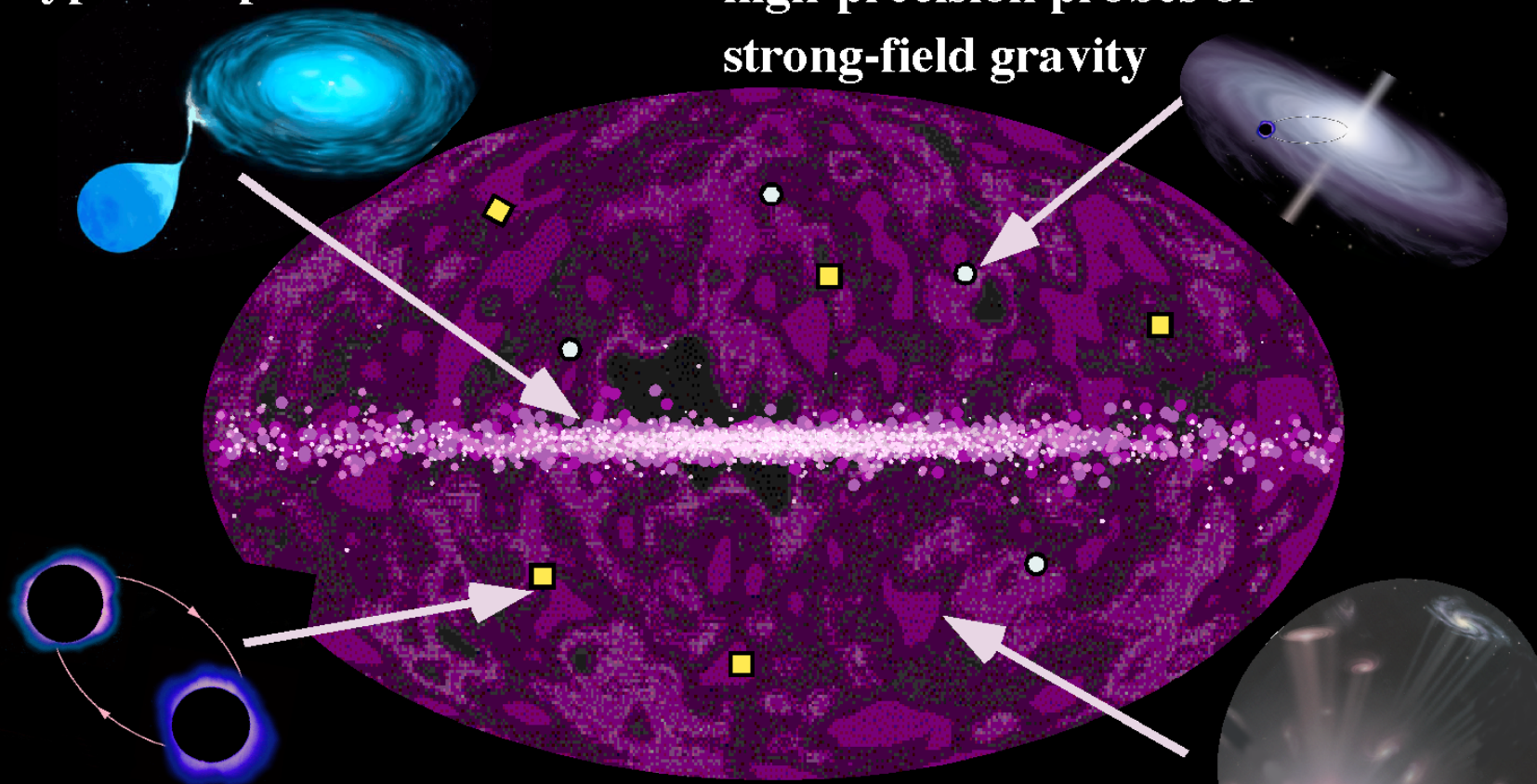


john 21-May-2002 08:09



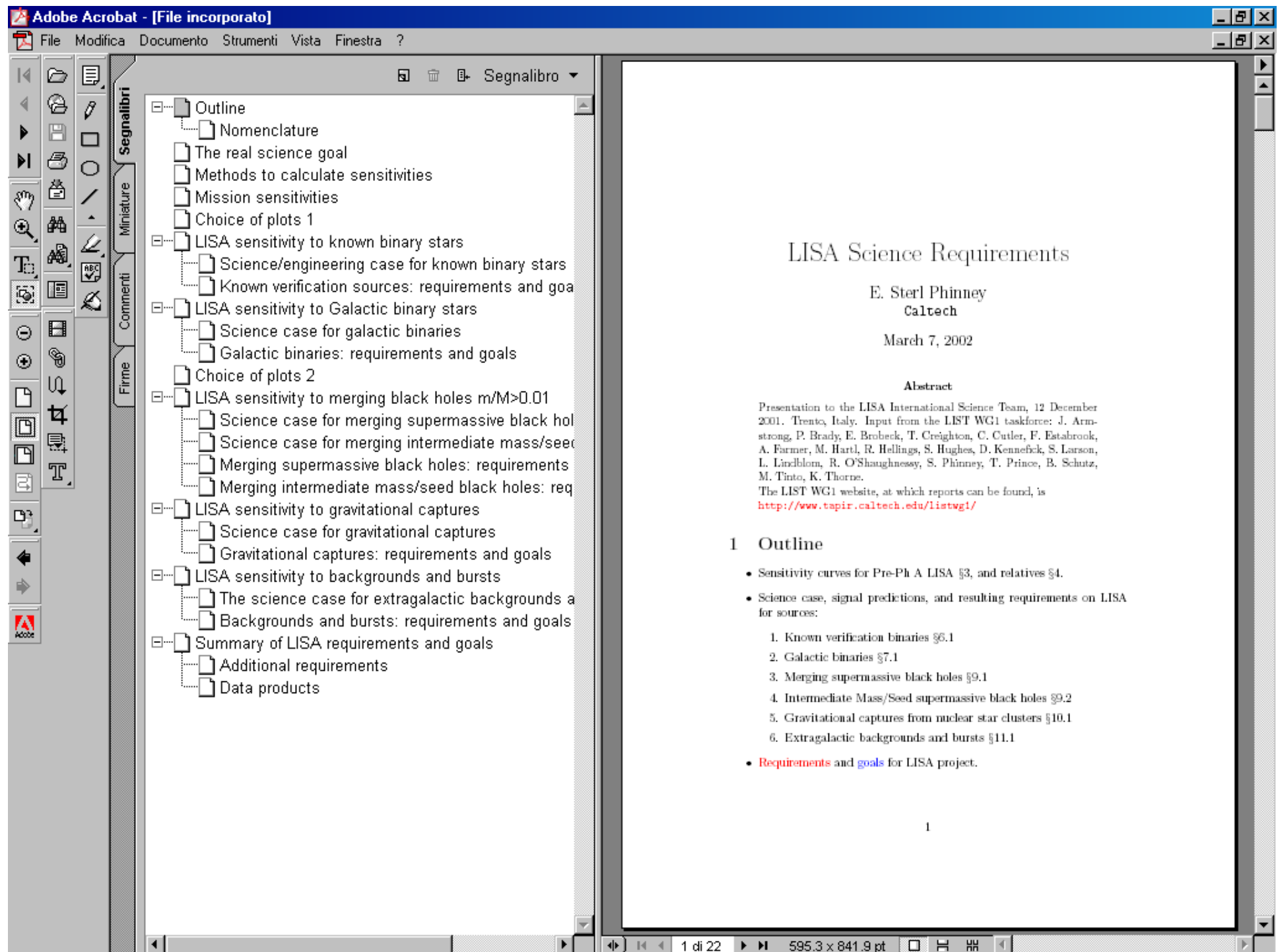
**Galactic Binaries,
including future
type Ia supernovae**

**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**

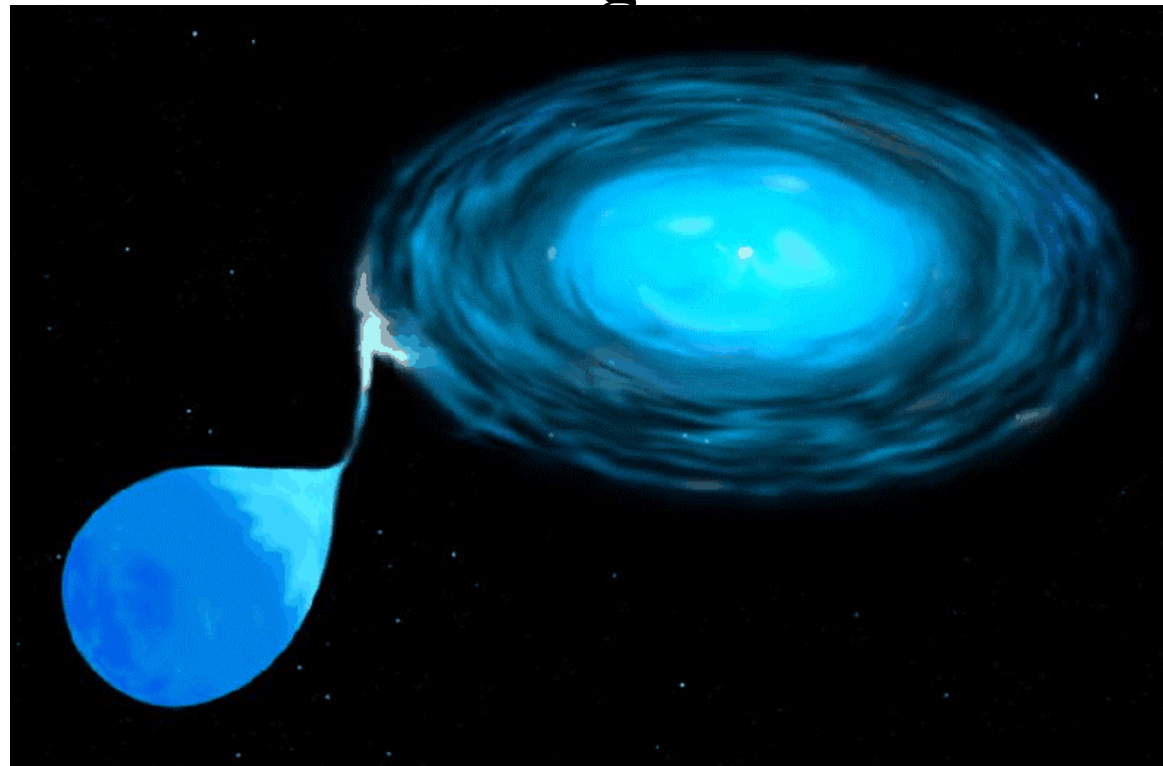
**Fluctuations from
Early Universe,
before recombination
formed 3° background**



Galactic Binaries

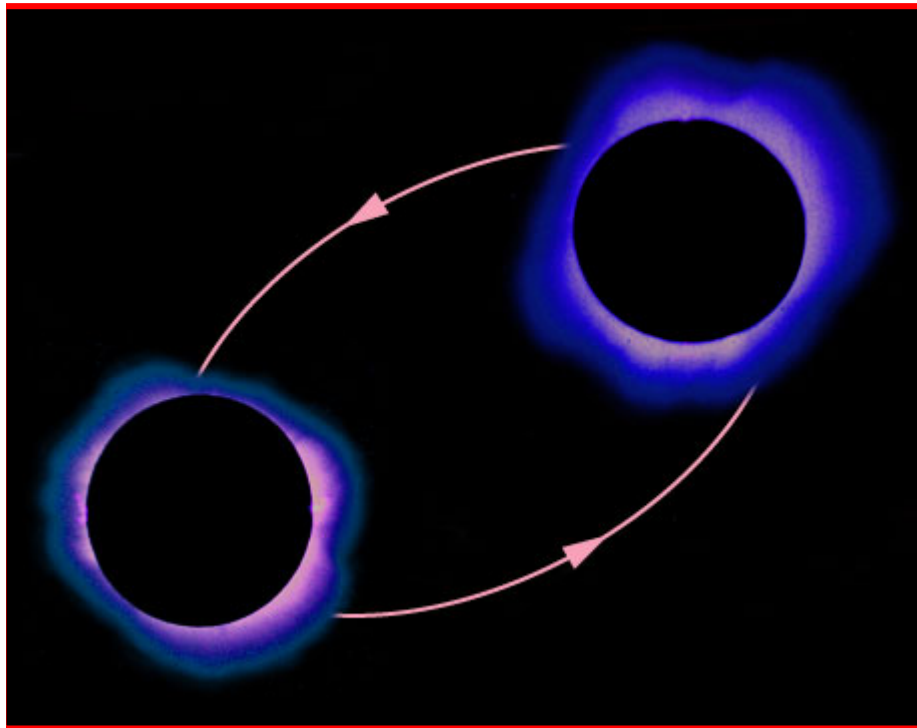
SNR up to 500 in 1 year. Angular resolution 10^{-3} – 10^{-2} srad at SNR ≈ 10

Some are standard candles: everything known about the signal.



LISA calibration binaries

class	source	dist pc	$f = 2/P_b$ mHz	M_1 $M_\odot$	M_2 $M_\odot$	τ_{mrg} 10^8y	h
WD+WD	WD 0957-666	100	0.38	0.37	0.32	2	4×10^{-22}
	WD 1101+364	100	0.16	0.31	0.36	20	2×10^{-22}
	WD 1704+481	100	0.16	0.39	0.56	13	4×10^{-22}
	WD 2331+290	100	0.14	0.39	> 0.32	< 30	$> 2 \times 10^{-22}$
WD+sdB	KPD 0422+4521	100	0.26	0.51	0.53	3	6×10^{-22}
	KPD 1930+2752	100	0.24	0.5	0.97	2	1×10^{-21}
AM CVn	RXJ0806.3+1527	300	6.2	0.4	0.12	—	4×10^{-22}
	RXJ1914+245	100	3.5?	0.6	0.07	—	6×10^{-22}
	KUV05184-0939	1000	3.2	0.7	0.092	—	9×10^{-23}
	AM CVn	100	1.94	0.5	0.033	—	2×10^{-22}
	HP Lib	100	1.79	0.6	0.03	—	2×10^{-22}
	CR Boo	100	1.36	0.6	0.02	—	1×10^{-22}
	V803 Cen	100	1.24	0.6	0.02	—	1×10^{-22}
	CP Eri	200	1.16	0.6	0.02	—	4×10^{-23}
	GP Com	200	0.72	0.5	0.02	—	3×10^{-23}
LMXB	4U1820-30	8100	3.0	1.4	< 0.1	—	2×10^{-23}
	4U1626-67	3-8000	0.79	1.4	< 0.03	—	6×10^{-24}
W UMa	CC Com	90	0.105	0.7	0.7	—	6×10^{-22}

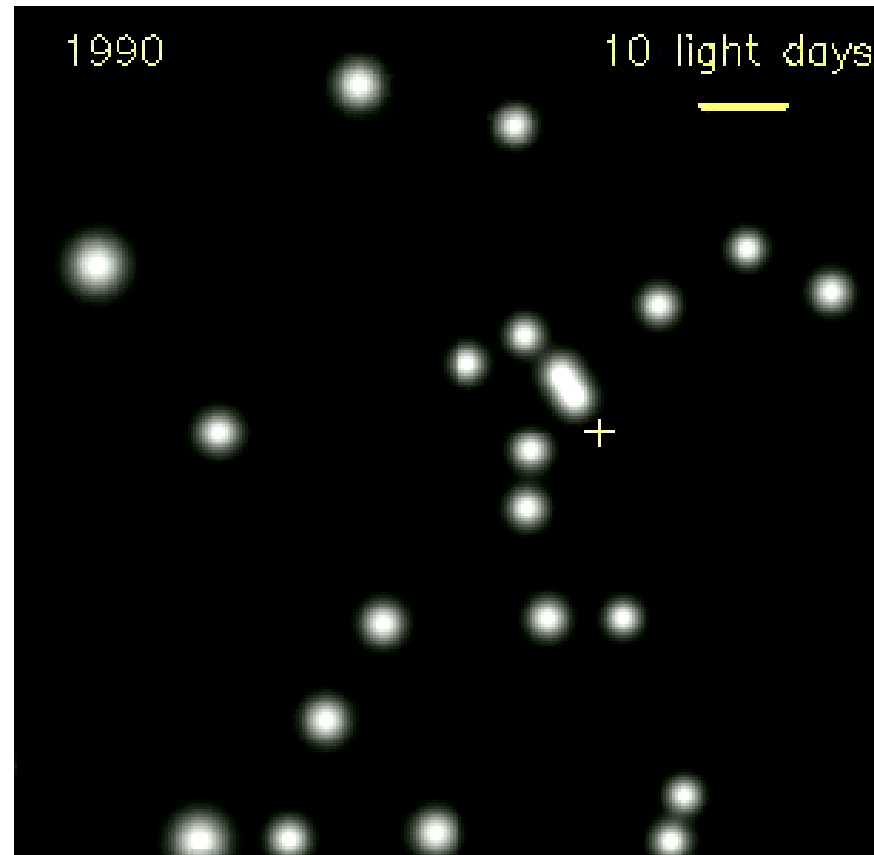


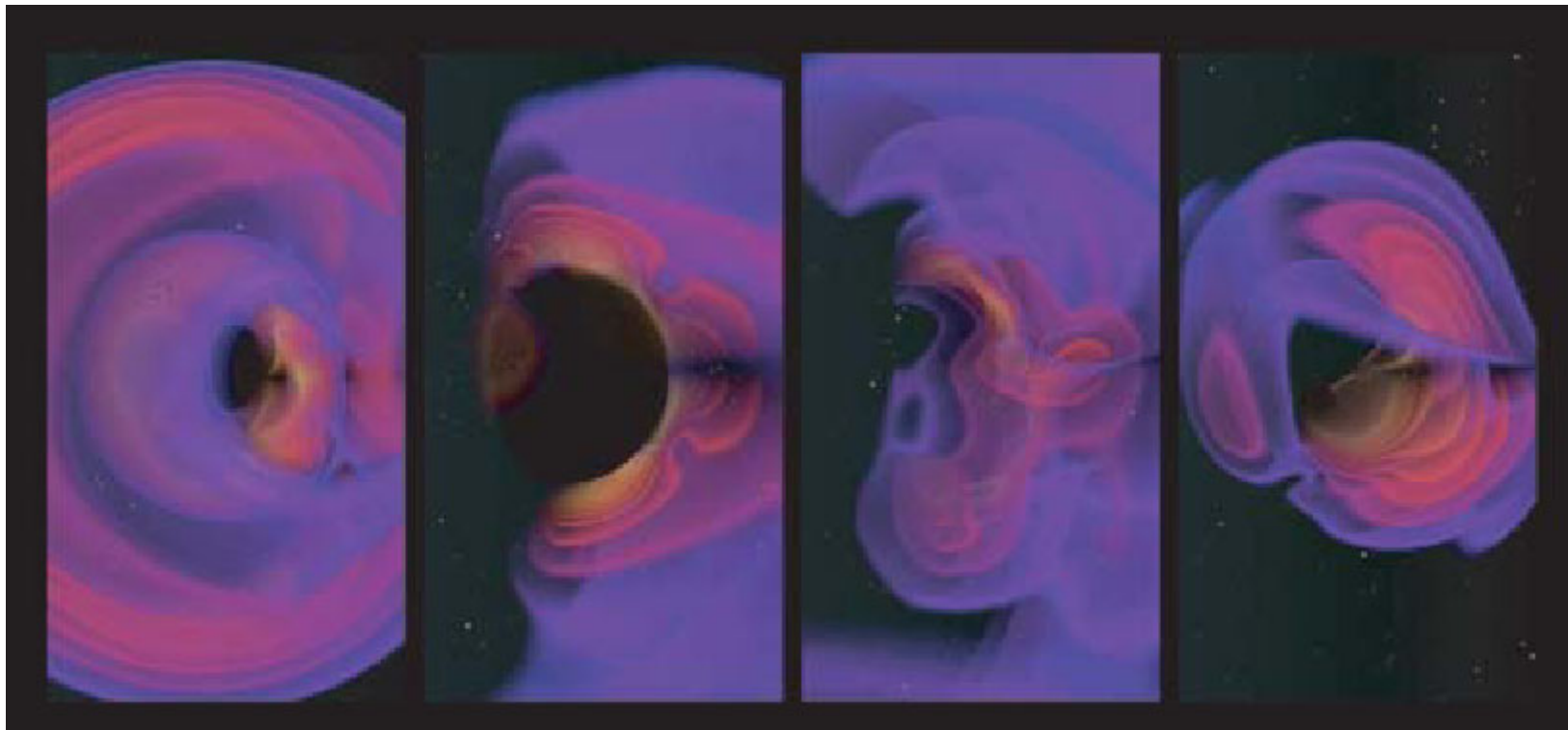
**Massive black hole binaries from
merging galaxies cores**

**SNR up to 2000 in one year at z
 $\approx 1 - 3$**

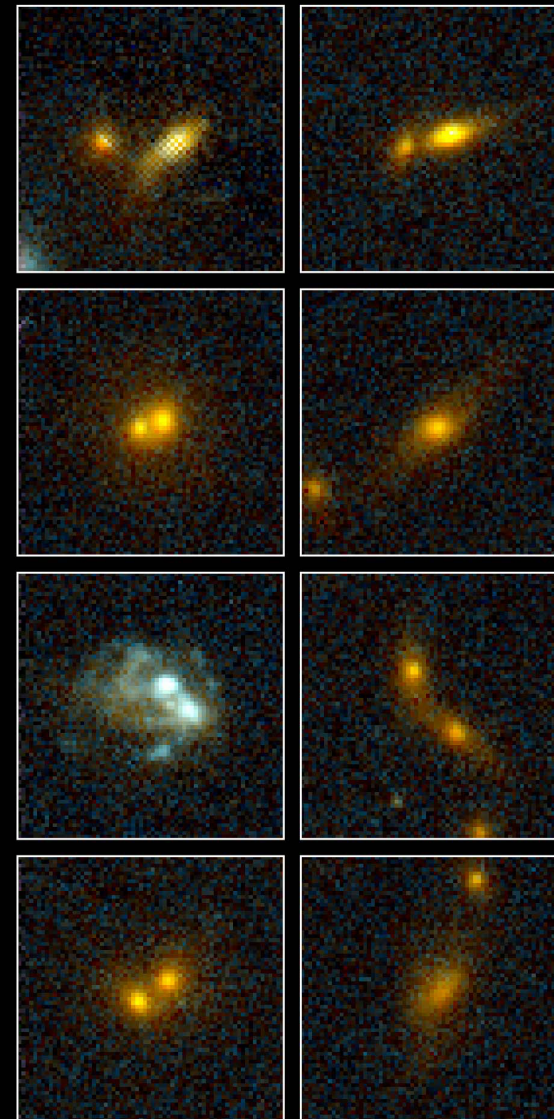
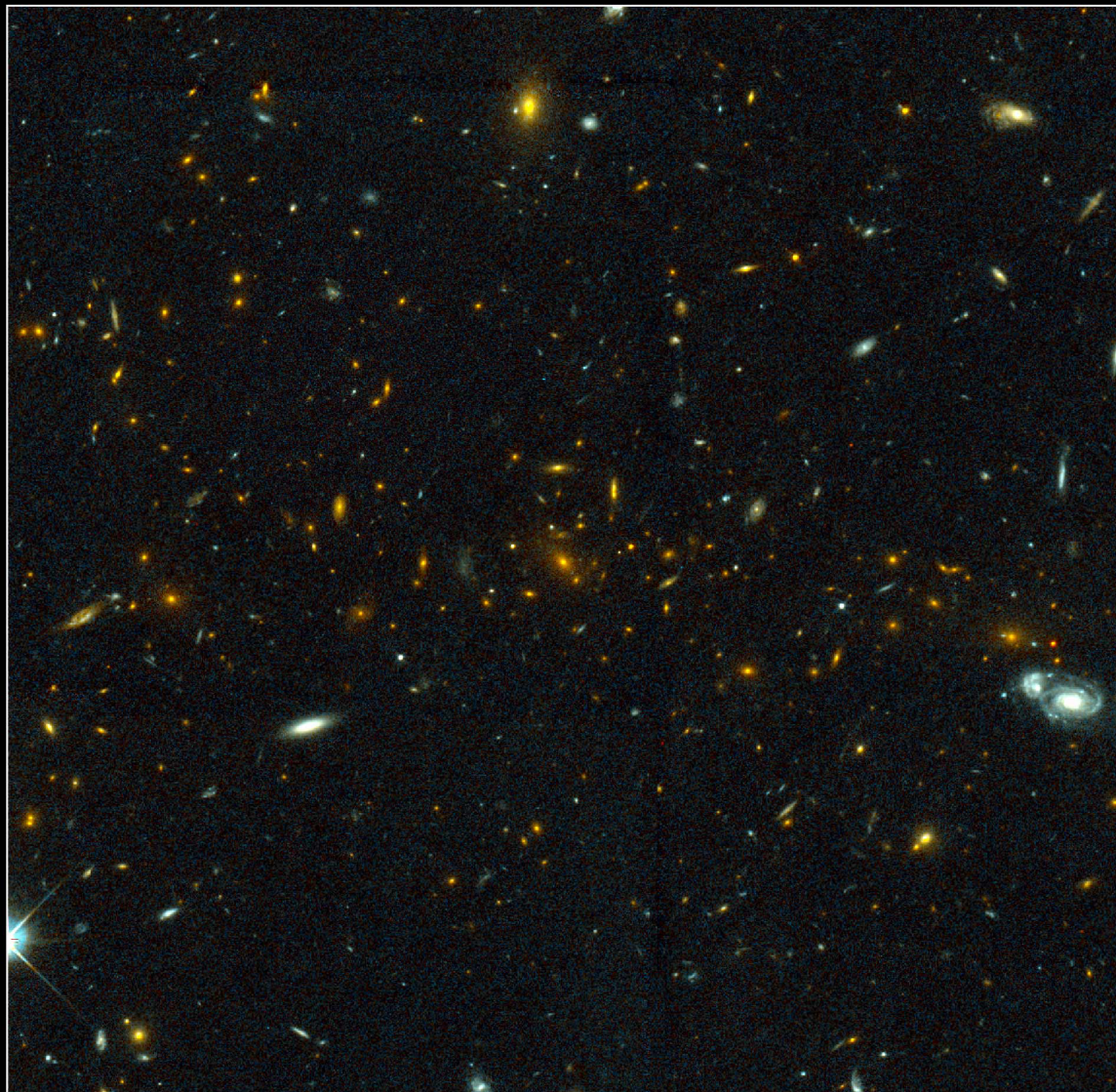
Angular resolution few'-few $^{\circ}$

Our one





Binary SMBH-SMBH

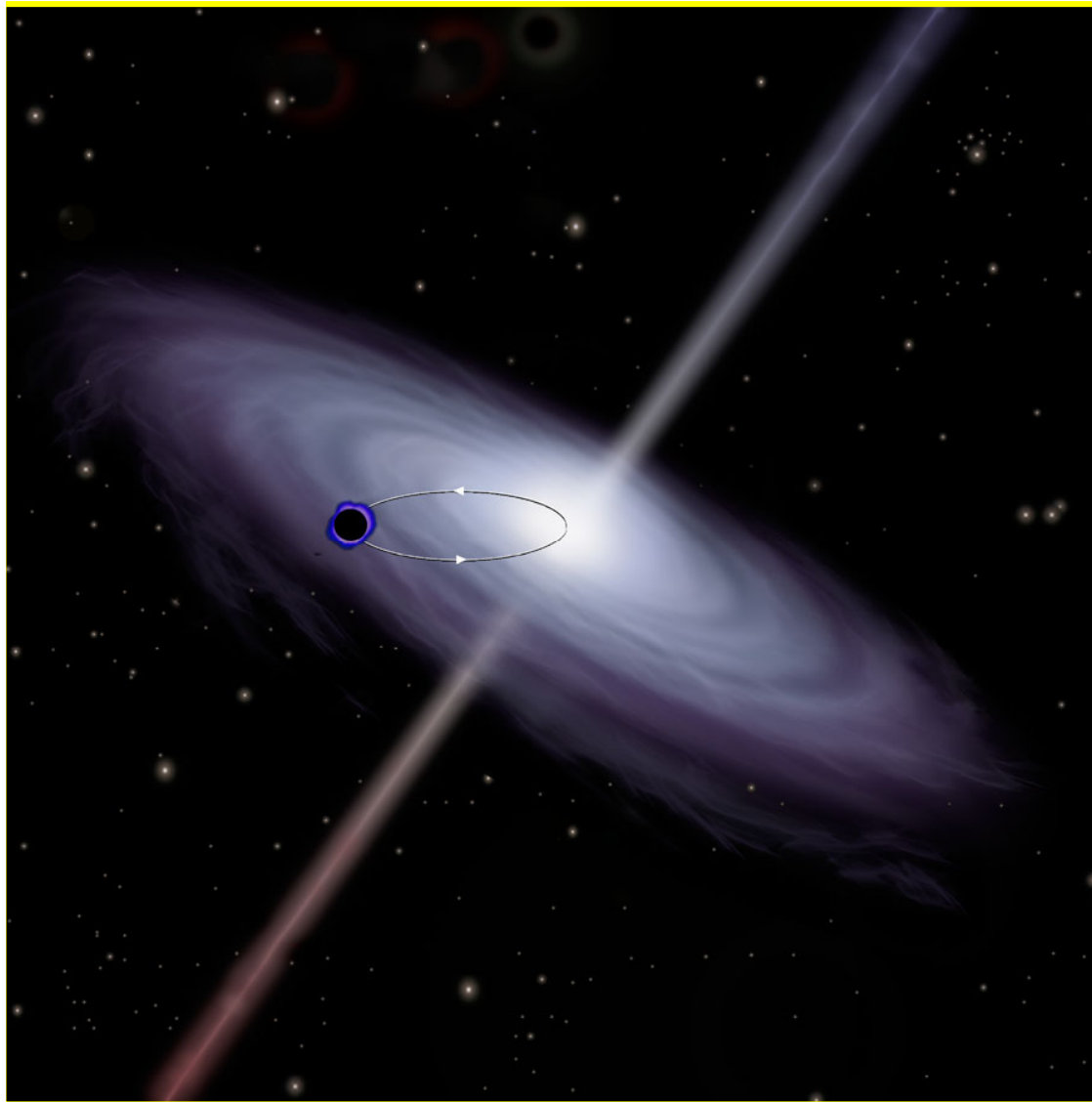


Galaxy Cluster MS1054-03
Hubble Space Telescope • Wide Field Planetary Camera 2

PRC99-28 • STScI OPO • P. van Dokkum (University of Groningen), ESA and NASA

9.1 Science case for merging supermassive black holes

- Precision tests of dynamical nonlinear gravity through comparison with precise numerical simulation of Einstein's equations. Cosmic censorship in horizon merger, ringdown. [ground-based detectors will do this with substantially lower precision with stellar mass BHs, however].
- Determine precision masses, spins for supermassive black holes in galactic nuclei (PN inspiral).
- Determine precision distances to supermassive black holes, get redshifts (if cosmography well-determined). Or if electromagnetic signal gives redshift, determine cosmography.
- Determine combination of merger history of galaxies and protogalactic lumps with nuclear stellar/gas dynamics (black hole binaries vs triples vs clusters, ejection of nuclear stars).



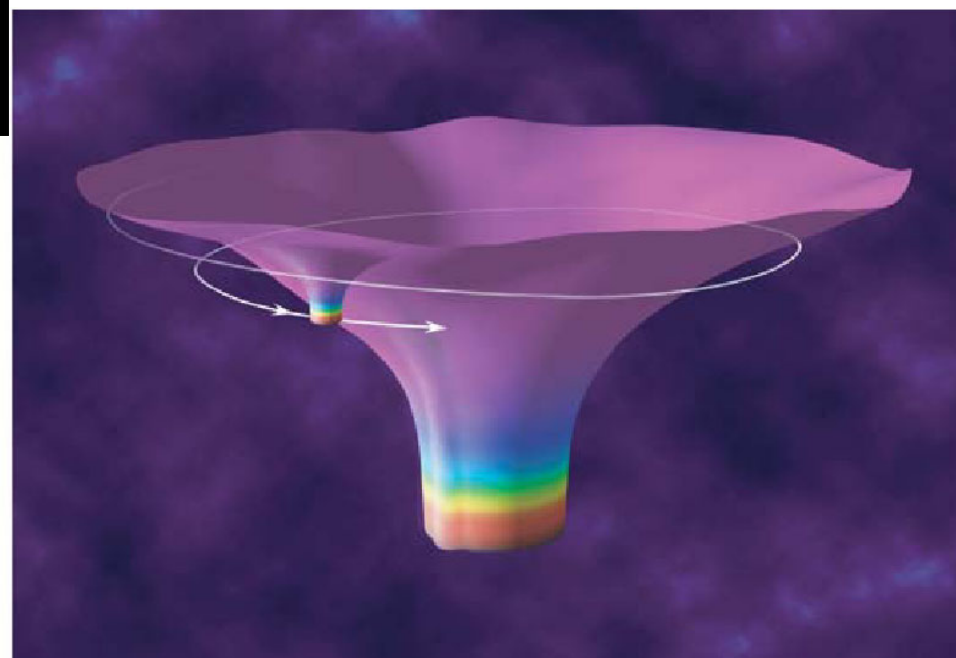
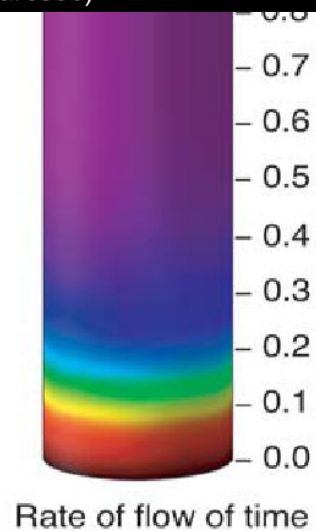
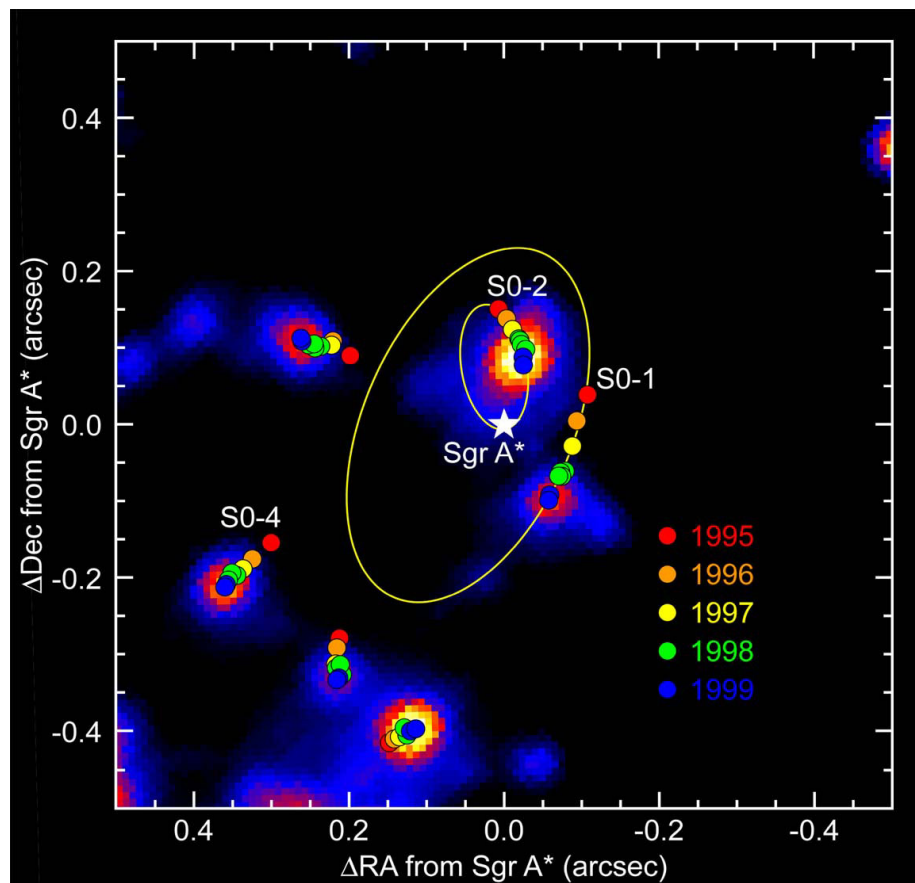
Gravitational capture

High rate. SNR 10-20

**Map of the event
horizon**

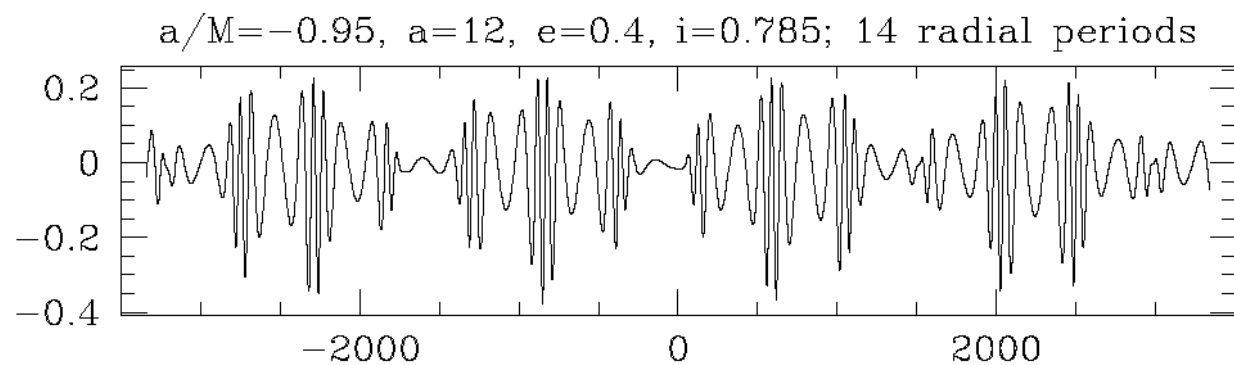
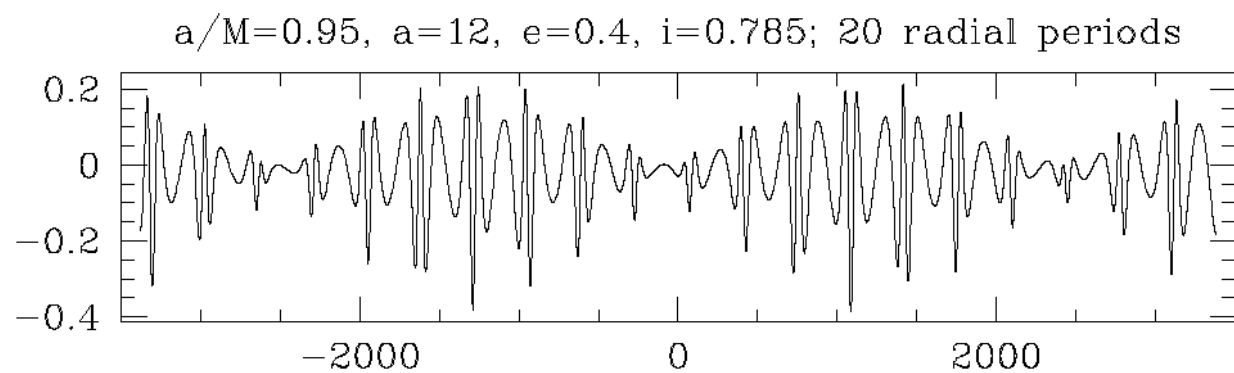
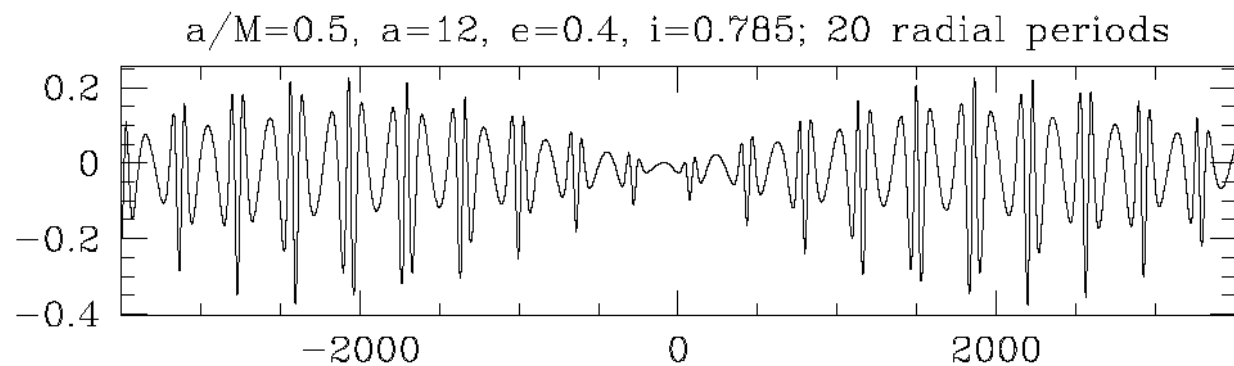
**Proof of no-hair
theorem**

Direct proof of BH



The science case for gravitational capture

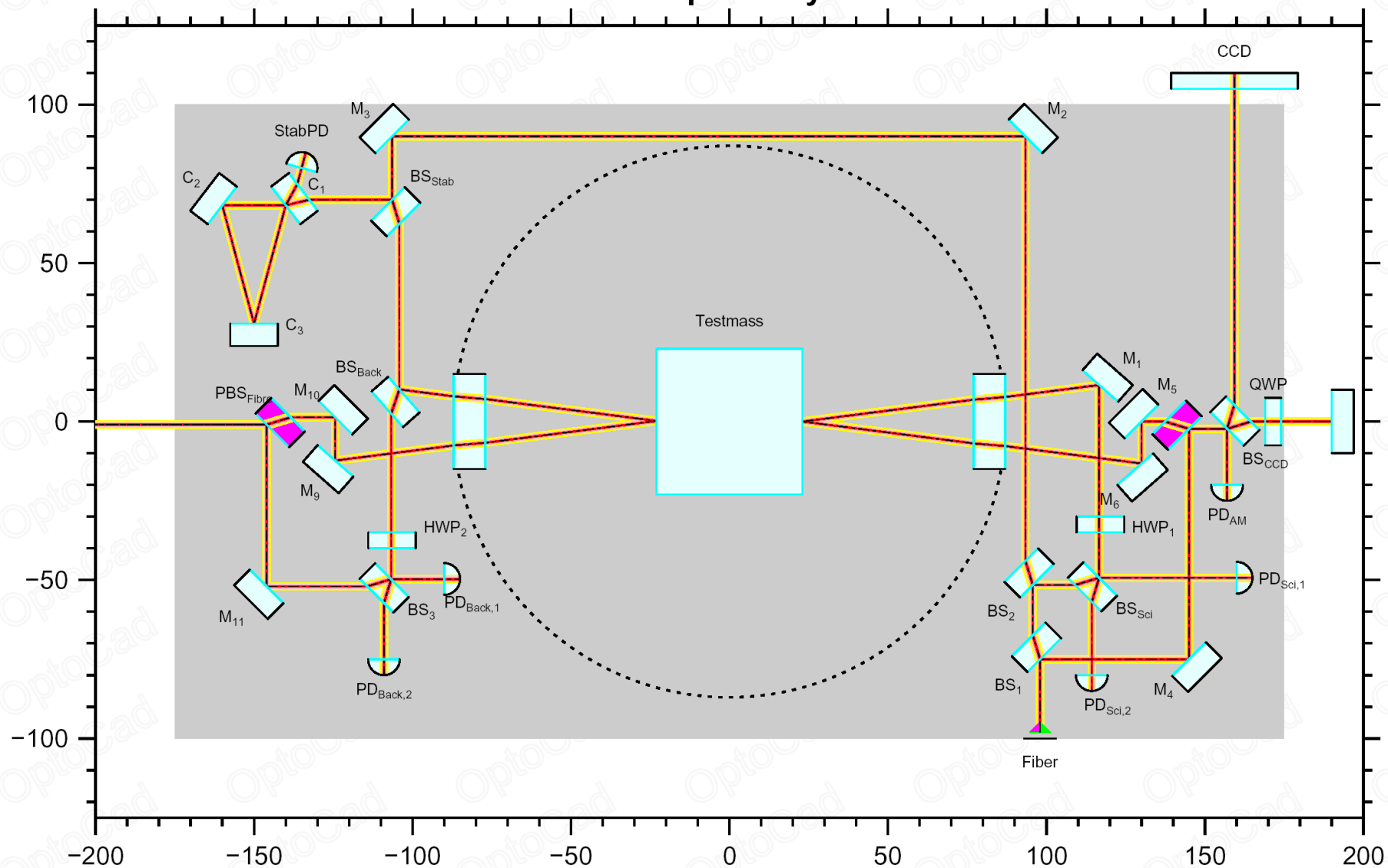
- Measure $M = M_0$, $a/M = S_1$ to $< 1\%$.
- Measure higher mass and current multipoles M_2 , S_3 , etc to sufficient precision to test “no hair theorem” (e.g. Kerr predicts $M_2 = Ma^2$; uniform density slowly rotating Newtonian star, radius R , has $M_2 = (25/8)(R/M)Ma^2$).
 - No hair satisfied: highest precision probe of strong field nonlinear gravity yet envisaged. [Note: black holes almost certainly have non-Abelian hair, and “no hair theorem” strictly false for fields beyond E&M. QCD hair not detectable -femtometer multipoles! But in some models fields in dark hidden sectors of string theory could make measurable effects on bothrodesy.]
 - No hair not satisfied: discovery of hypothetical new types of massive compact bodies —e.g. soliton stars, naked singularities. Inversion of multipoles gives detailed map of spacetime.
- Measure to high precision the orbiting body’s tidal extraction of rotational energy and angular momentum from the black hole (via its $\sim 5 - 10\%$ effect on the rate of inspiral).
- Astrophysical parameters: mass, spin, distance of supermassive bodies, mass, orbital eccentricity, inclination all to better than a few %. Infer population and evolution of supermassive black holes and their surrounding star clusters (mass segregation, IMF, density structure).

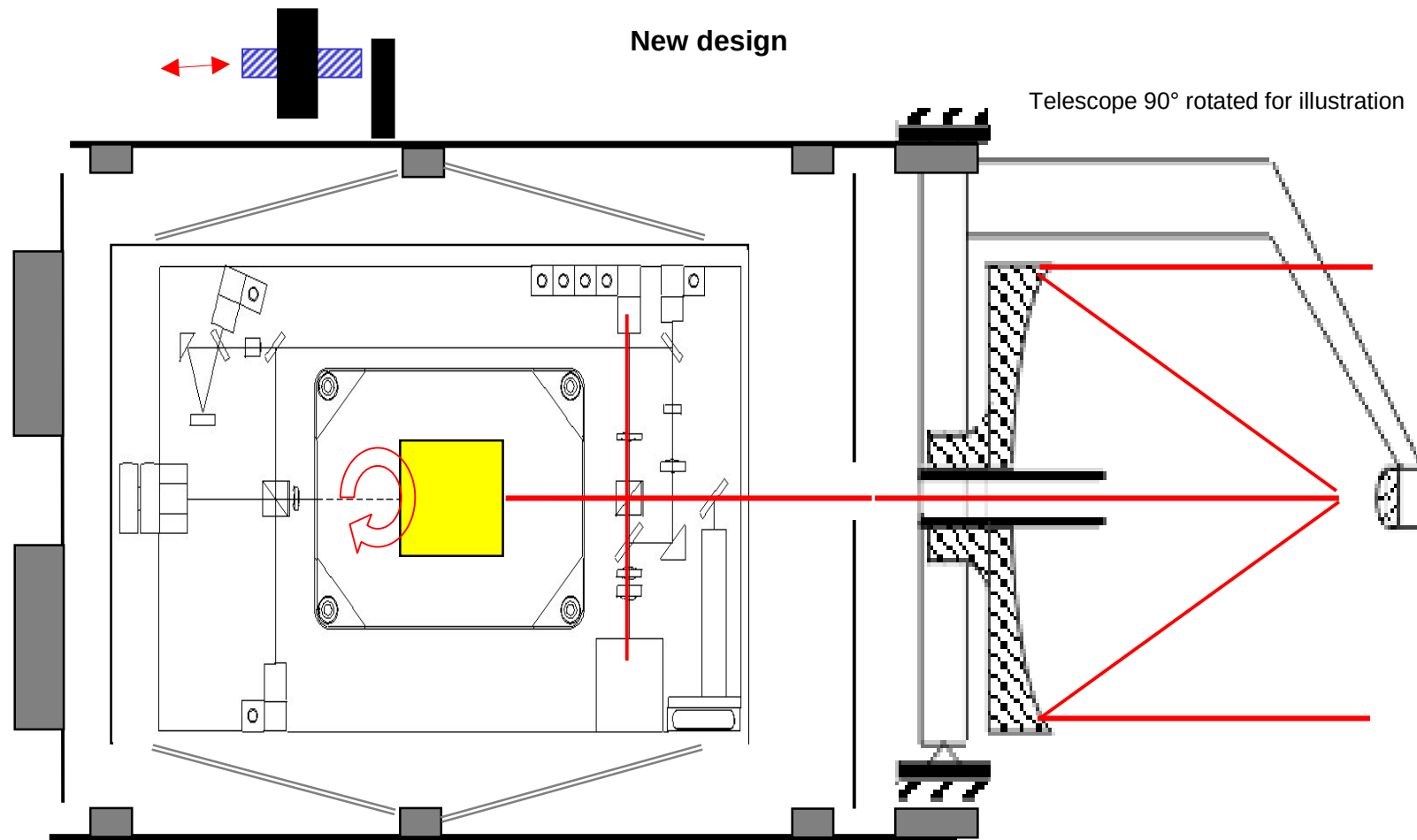


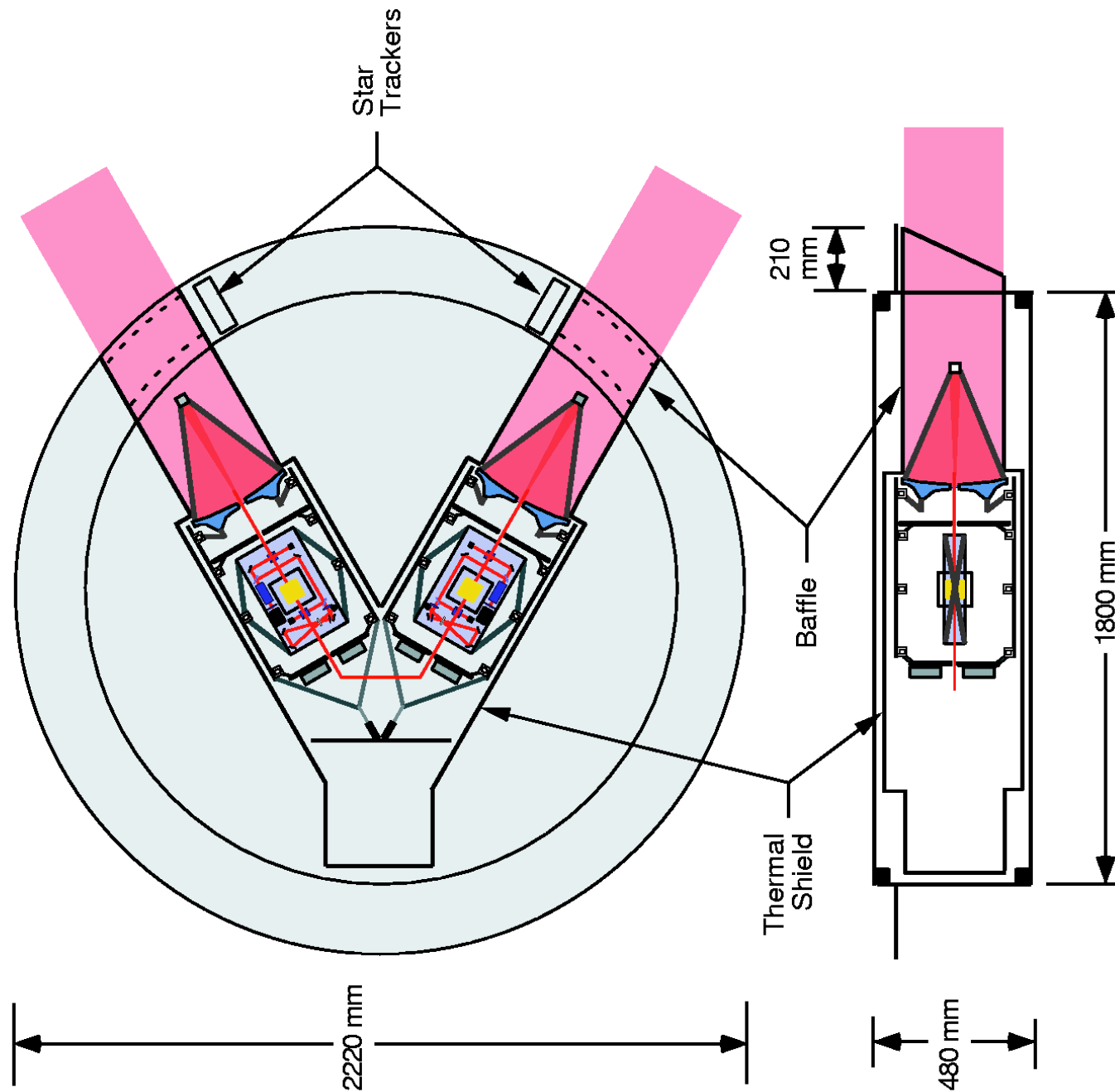
**Signal
extraction
challenging**

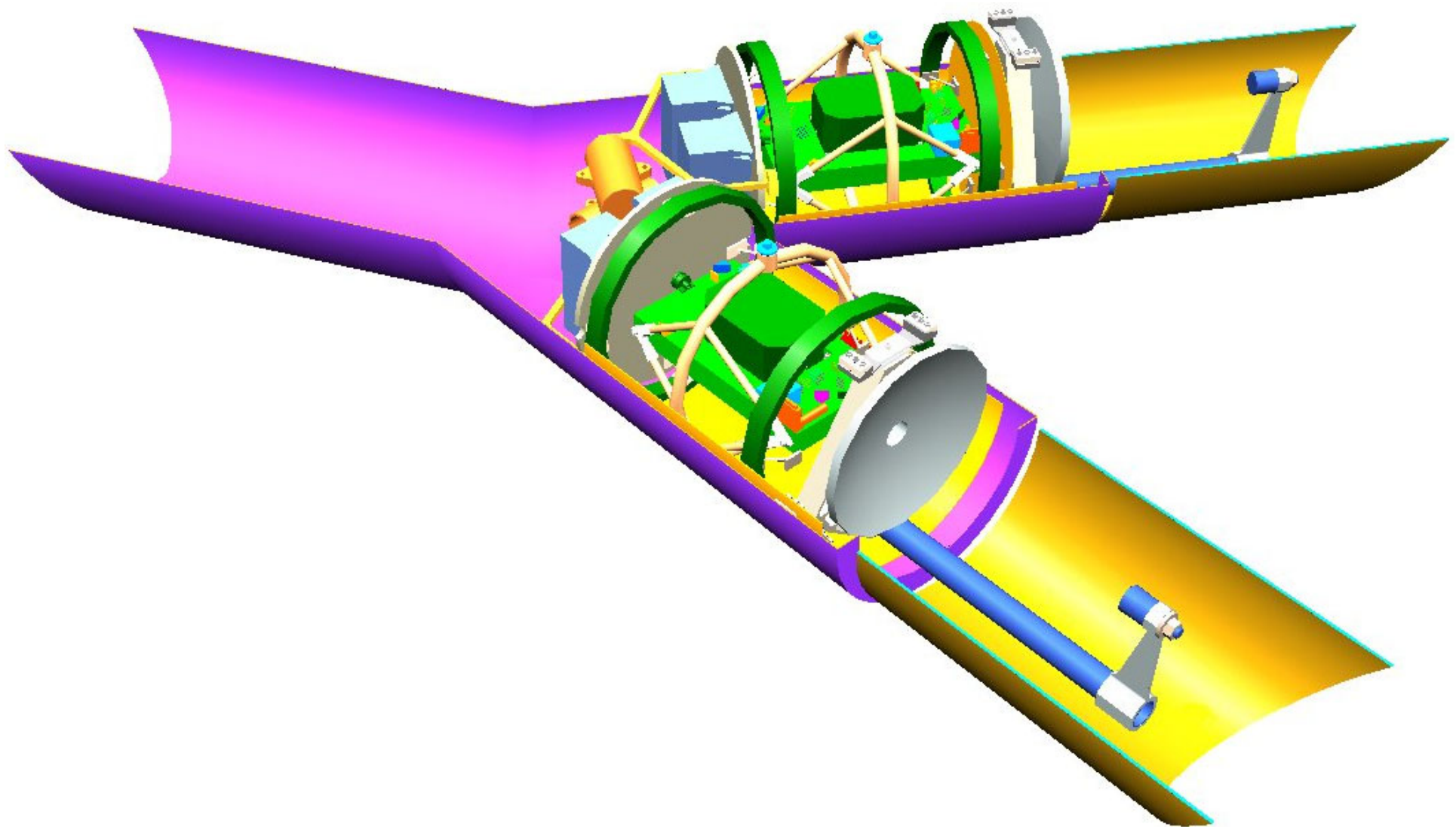
Putting all together

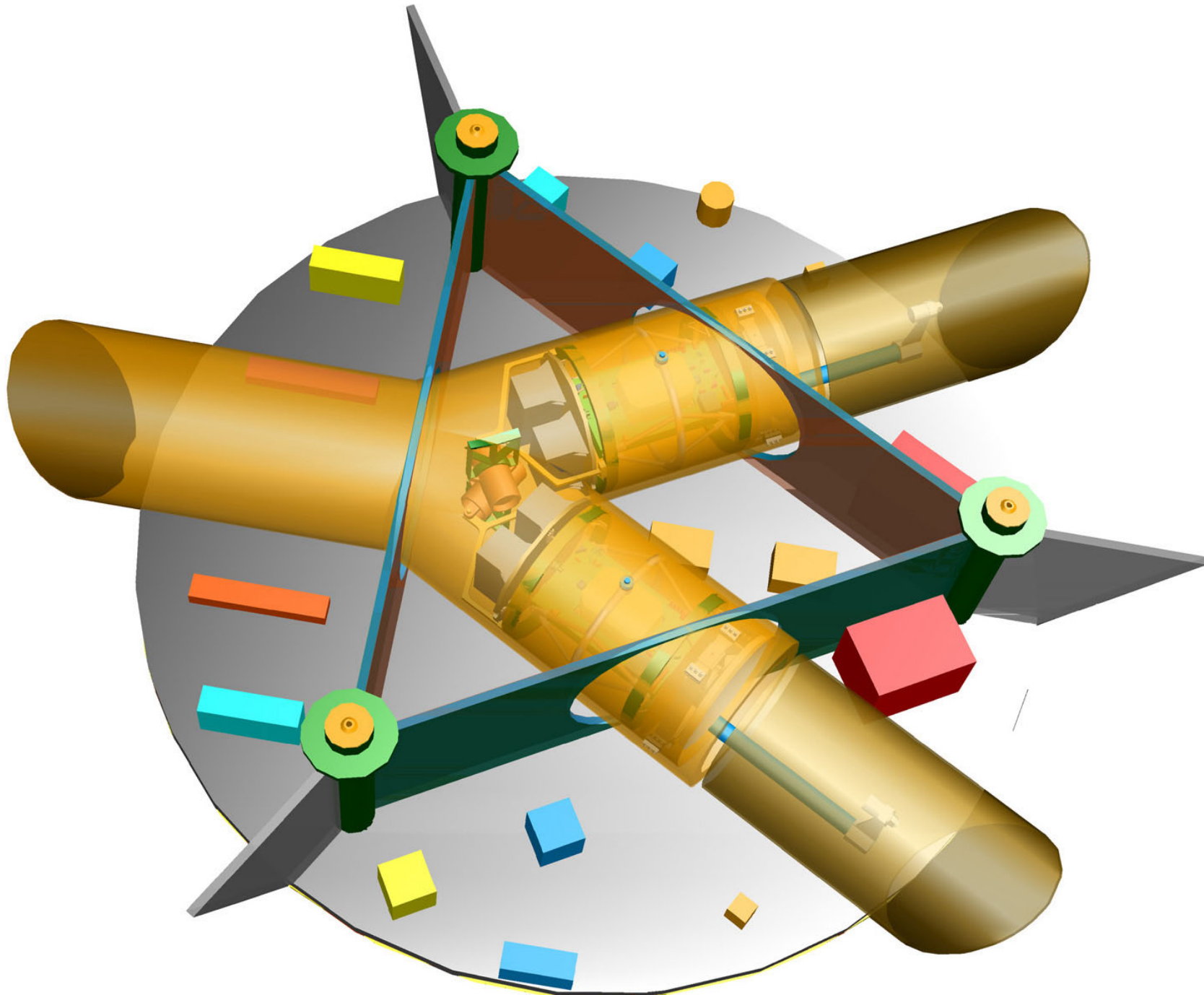
LISA optical layout

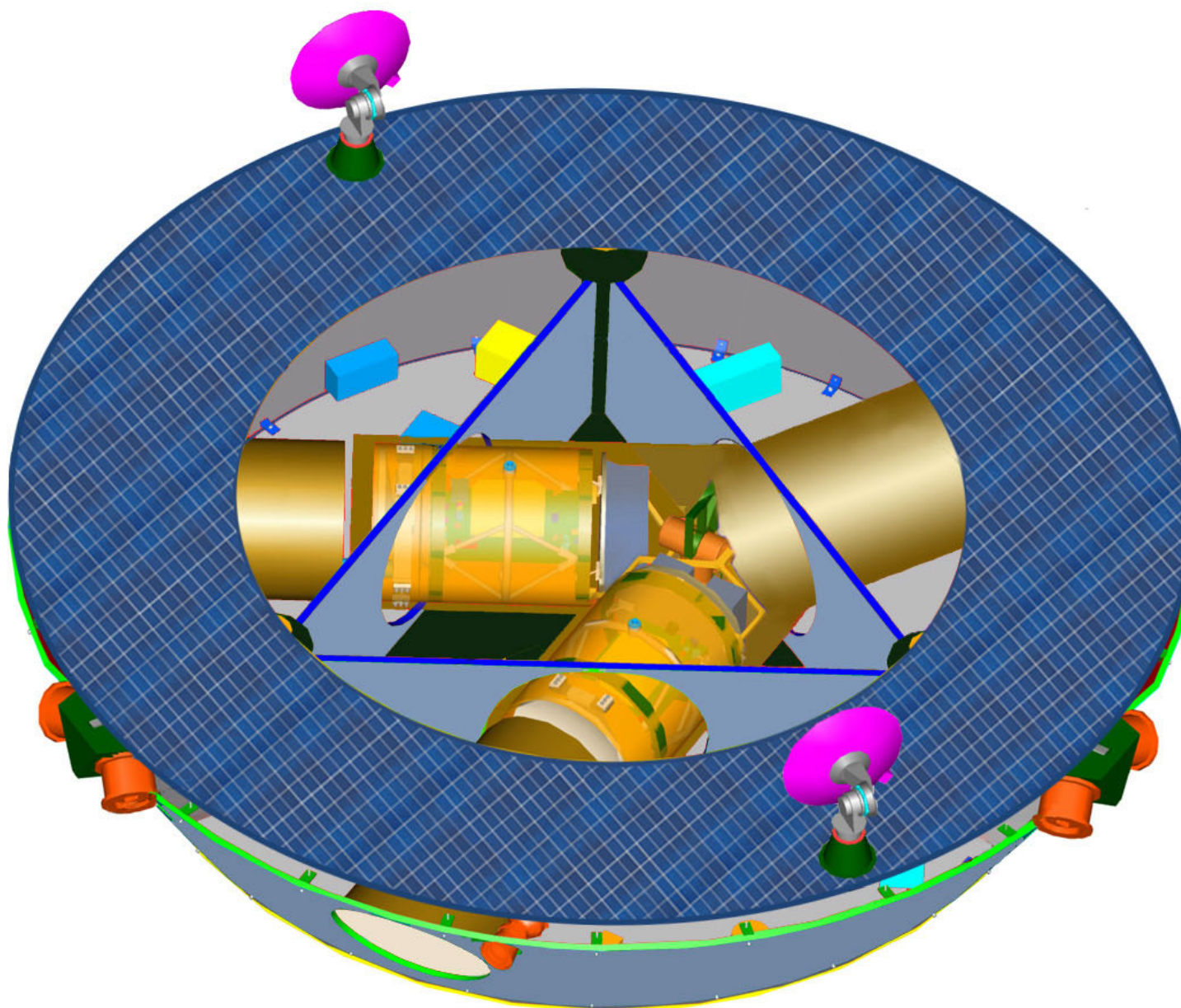


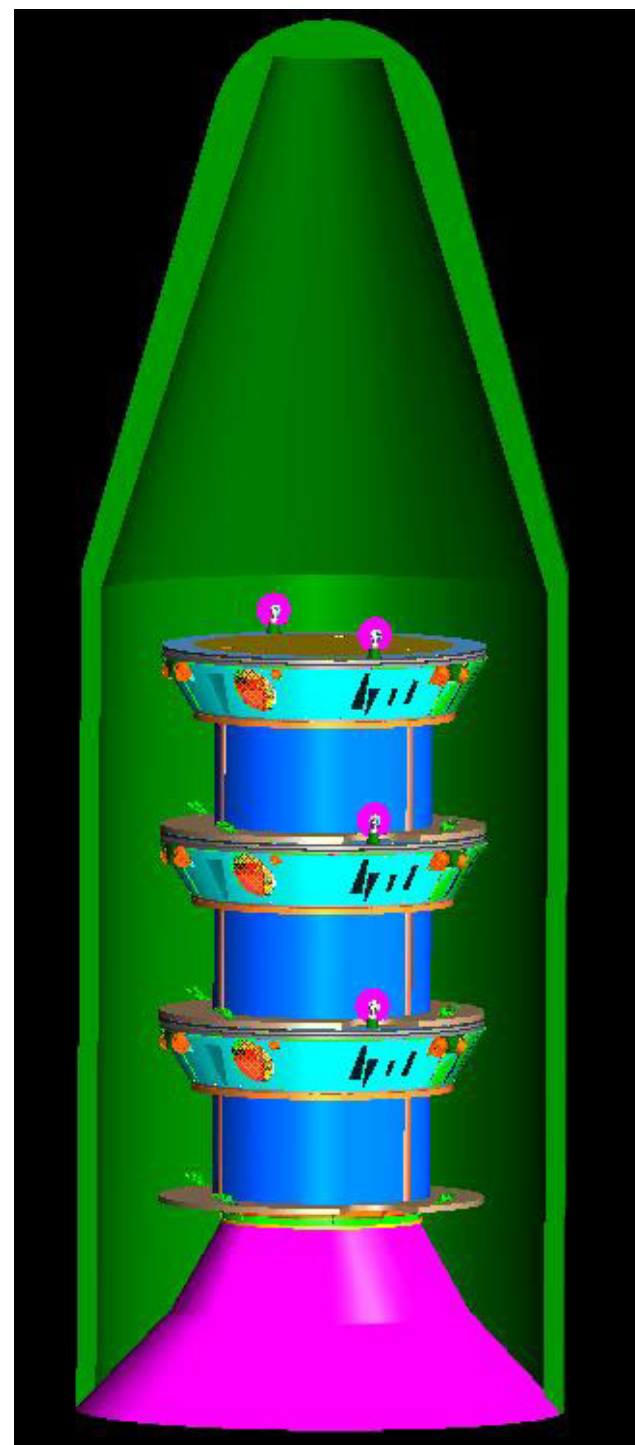
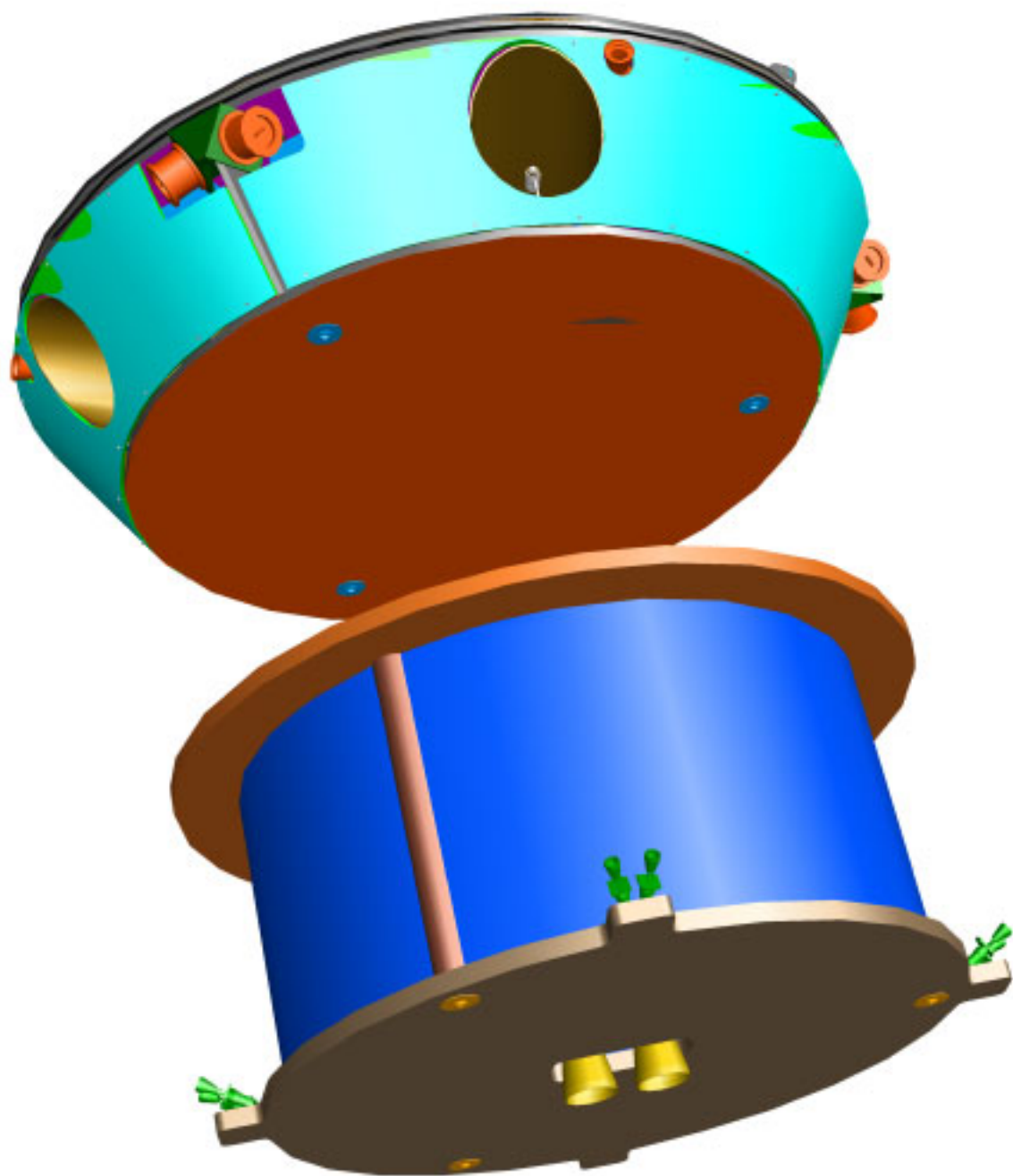


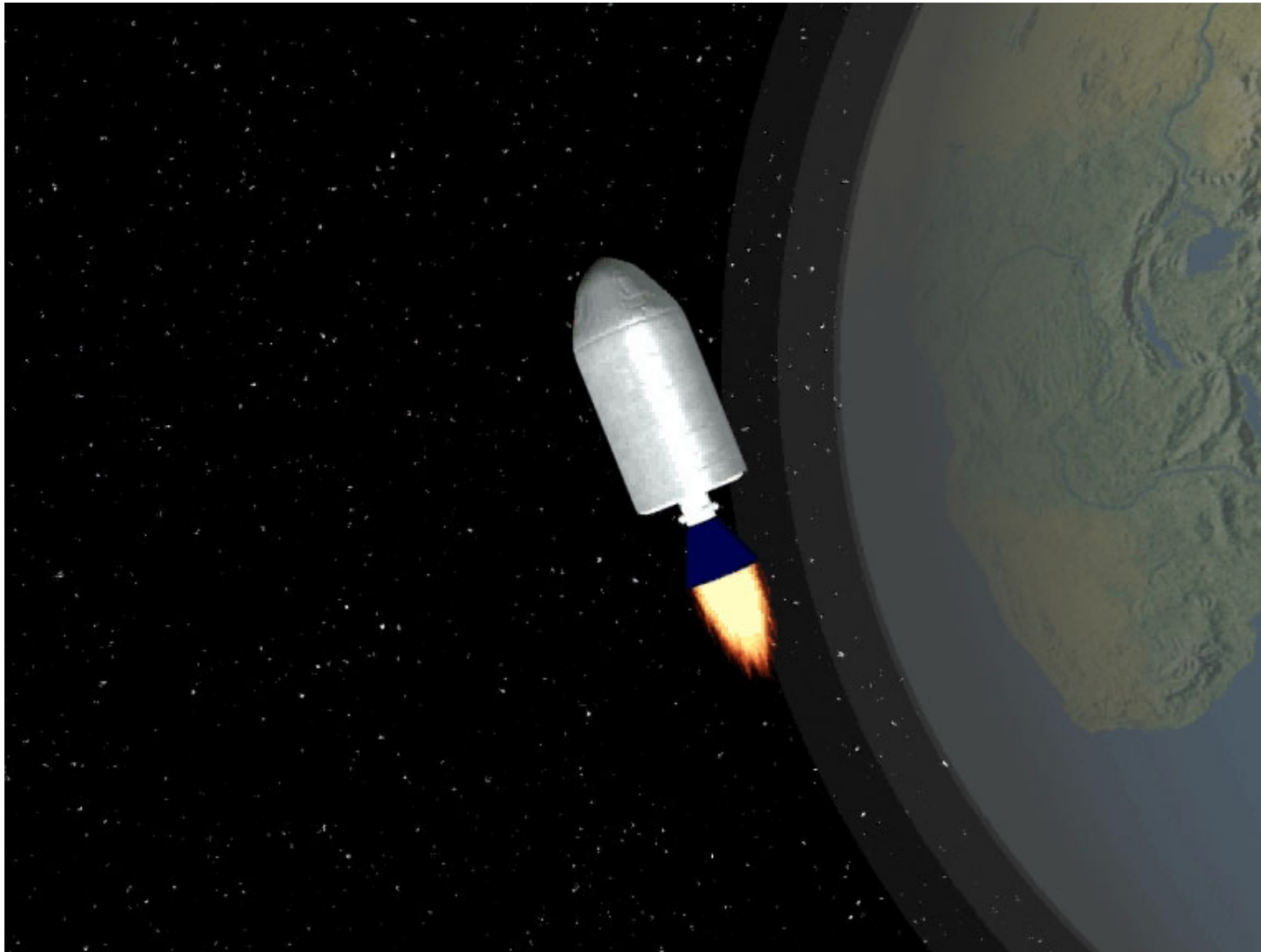


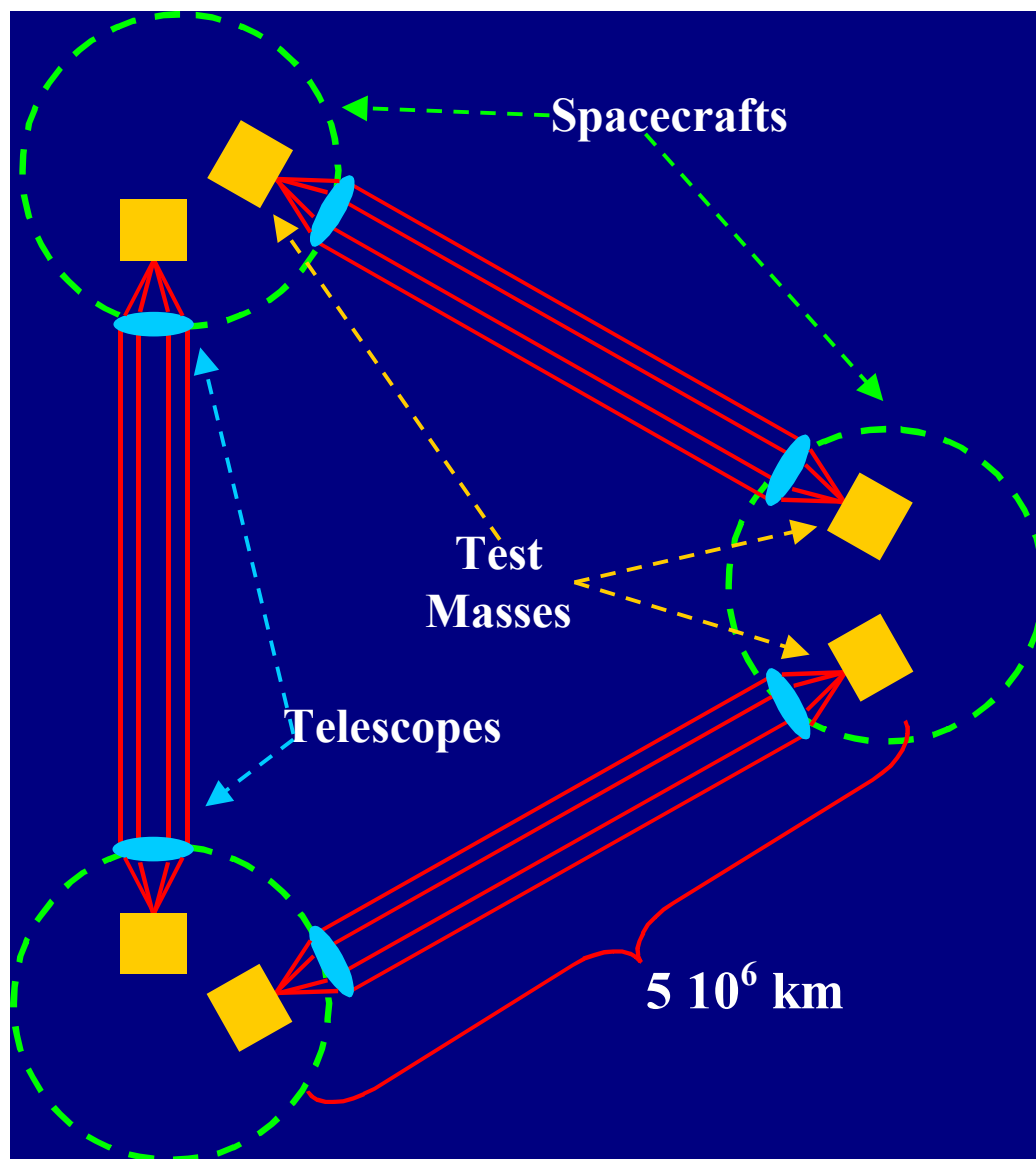










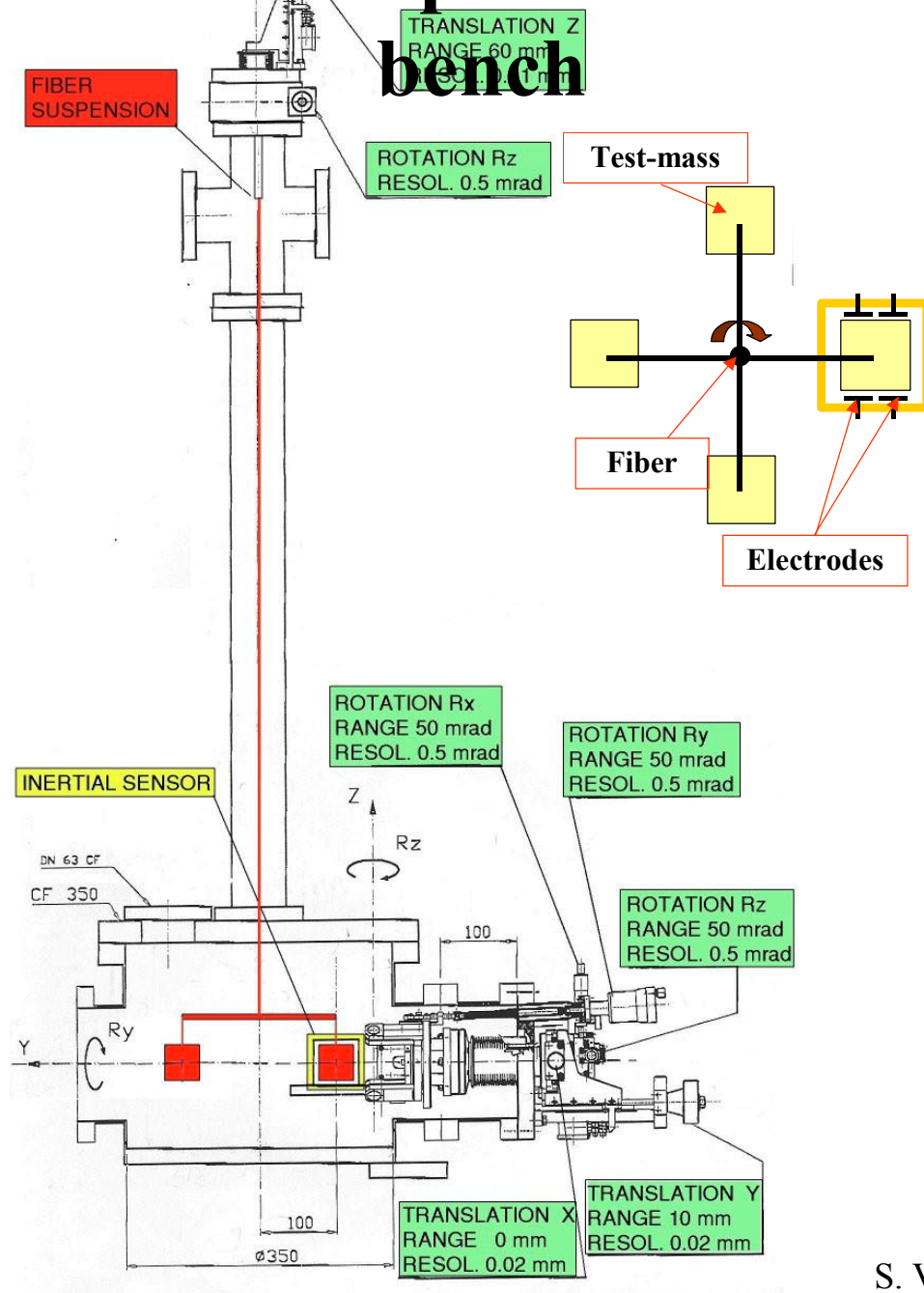


3 pairs of “free falling” test masses
($3 \cdot 10^{-15} \text{ ms}^{-2} \text{ Hz}^{-1/2}$ @ 0.1 mHz)

Can it be achieved?

Can it be tested?

A Torsion pendulum test bench



L. Carbone,¹ A. Cavalleri,² R. Dolesi,¹ C. D. Hoyle,¹ M. Hueller,¹ S. Vitale,¹ and W. J. Weber¹

¹*Dipartimento di Fisica, Università di Trento, and I.N.F.N., Gruppo di Trento, 38050 Povo (TN), Italy*

²*Centro Fisica degli Stati Aggregati, 38050 Povo (TN), Italy*

(Dated: August 14, 2003)

The low-frequency resolution of space-based gravitational wave observatories such as LISA (Laser Interferometry Space Antenna) hinges on the orbital purity of a free-falling reference test mass inside a satellite shield. We present here a torsion pendulum study of the forces that will disturb an orbiting test mass inside a LISA capacitive position sensor. The pendulum, with a measured torque noise floor below $10 \text{ fN m}/\sqrt{\text{Hz}}$ from 0.6 to 10 mHz, has allowed placement of an upper limit on sensor force noise contributions, measurement of the sensor electrostatic stiffness at the 5% level, and detection and compensation of stray DC electrostatic biases at the mV level.

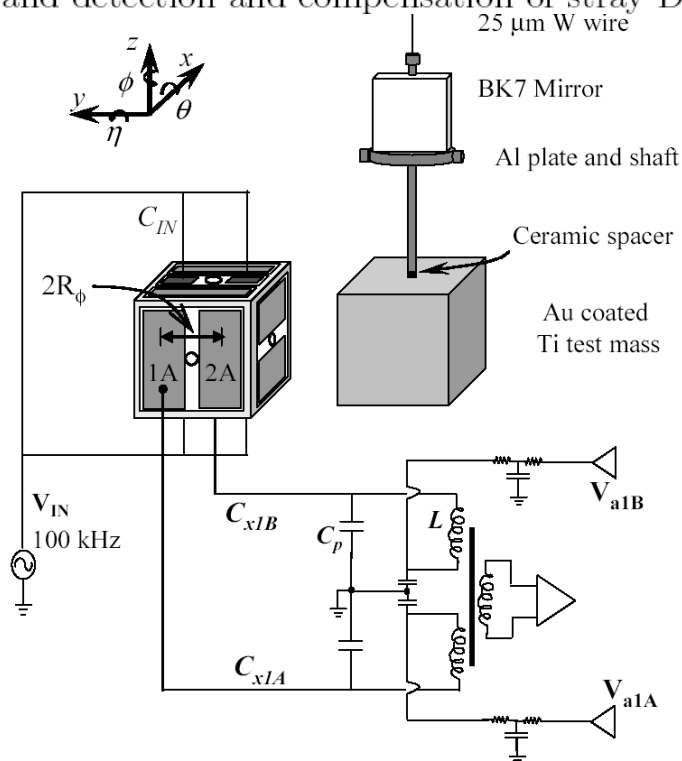


FIG. 1: Sensor electrode configuration and circuitry, with

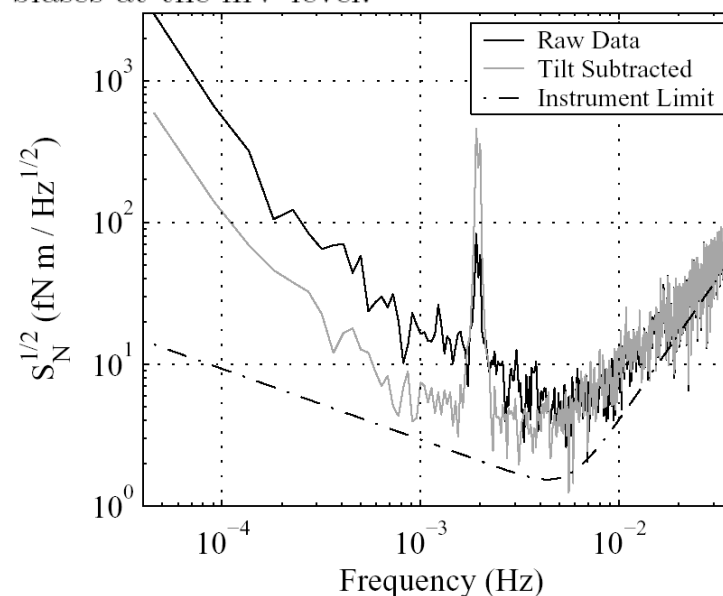
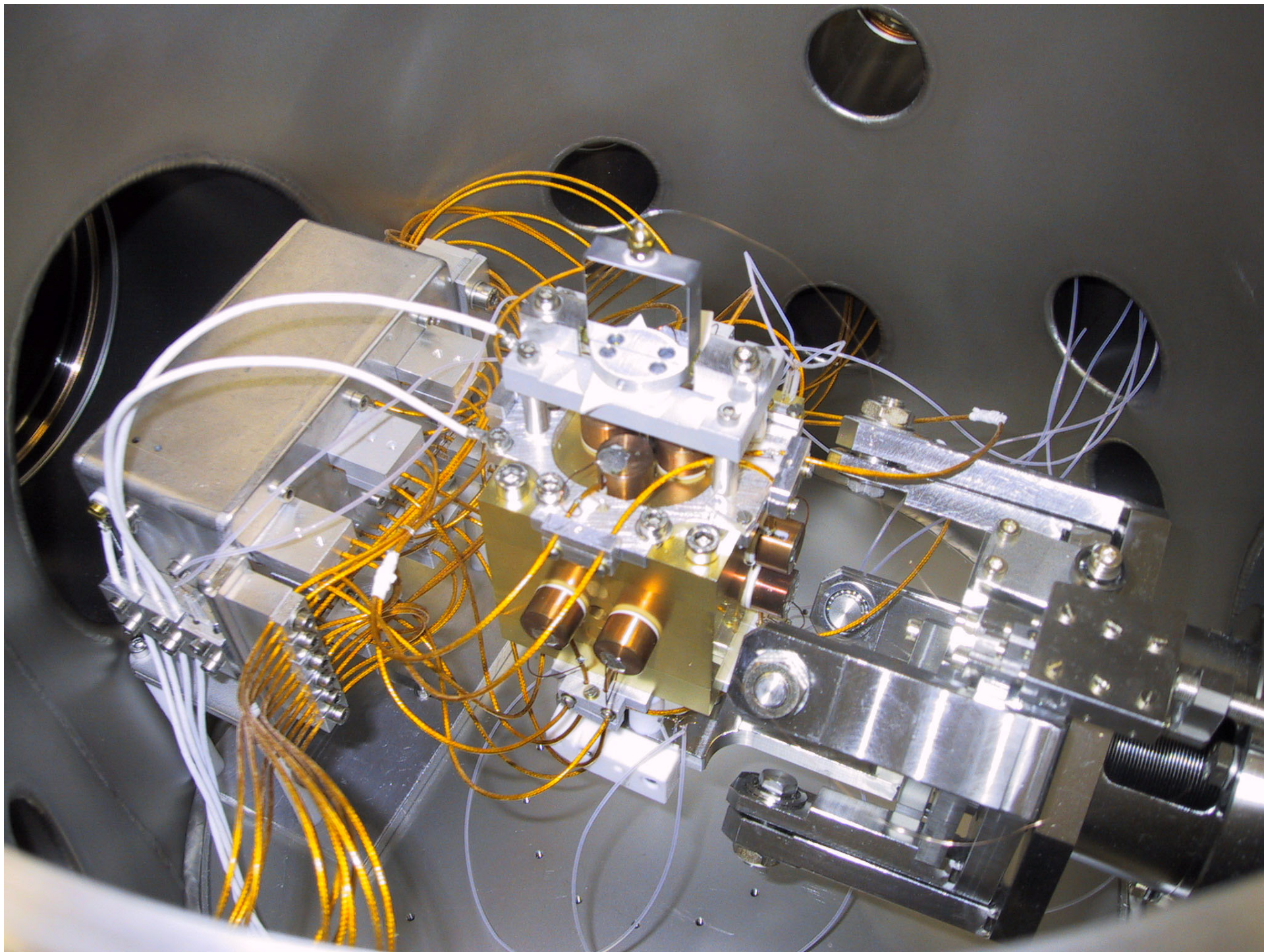
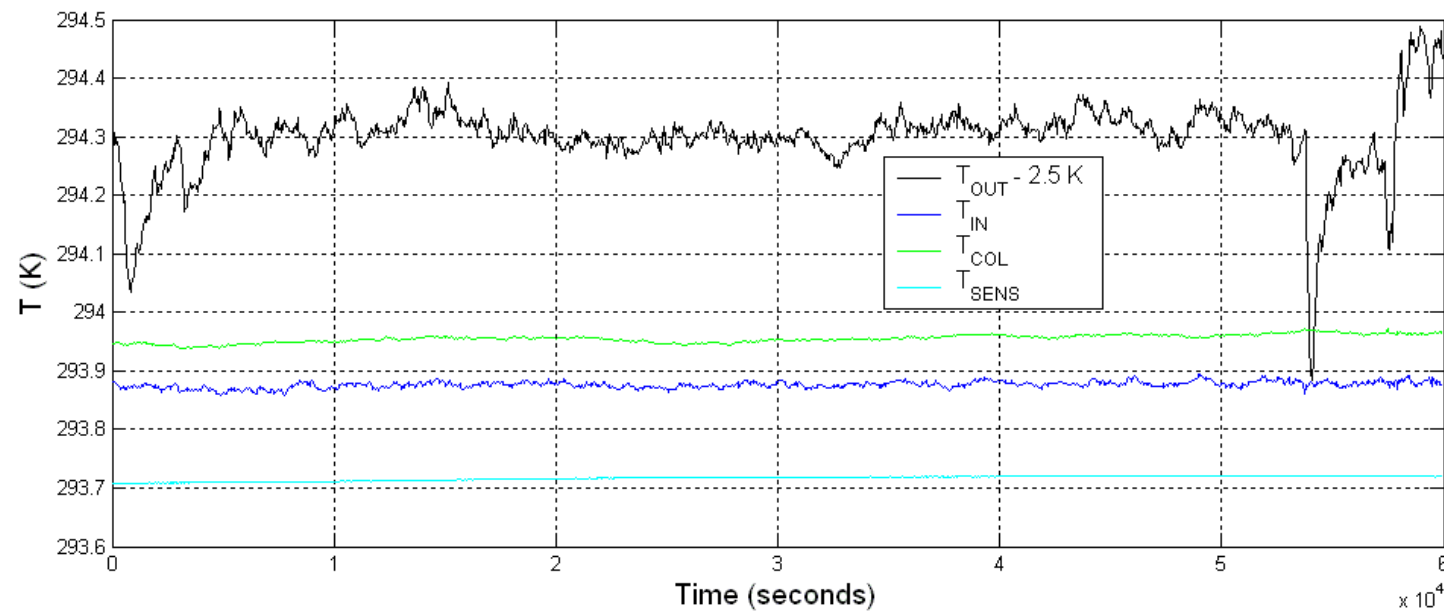
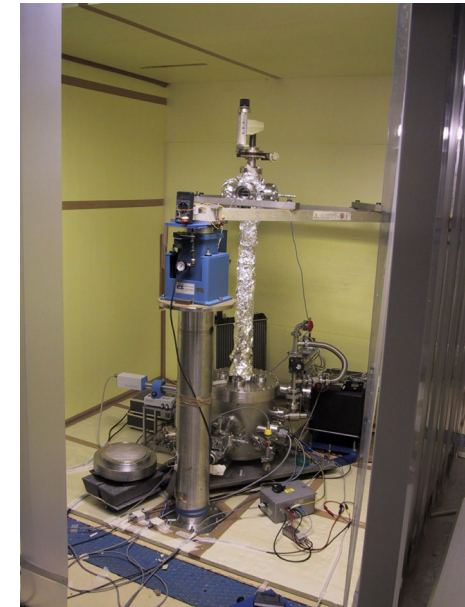


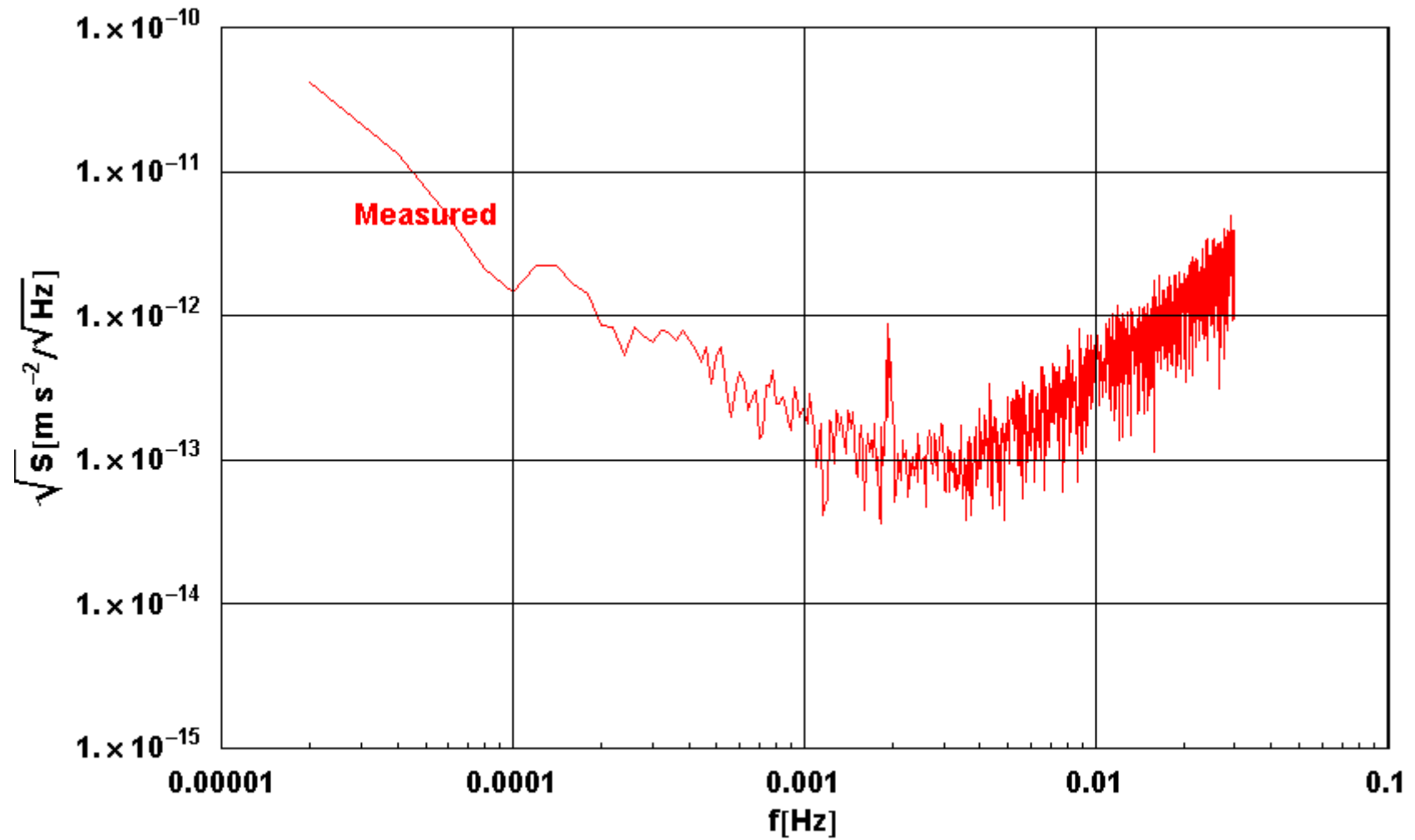
FIG. 2: Plot showing the raw (dark) and tilt subtracted (light) pendulum torque noise, with the instrument limit (dashed). Spectra for this 19 hour measurement are calculated with a 22,000 second Hanning window, which leaves an artificial peak near the 2 mHz pendulum resonance.

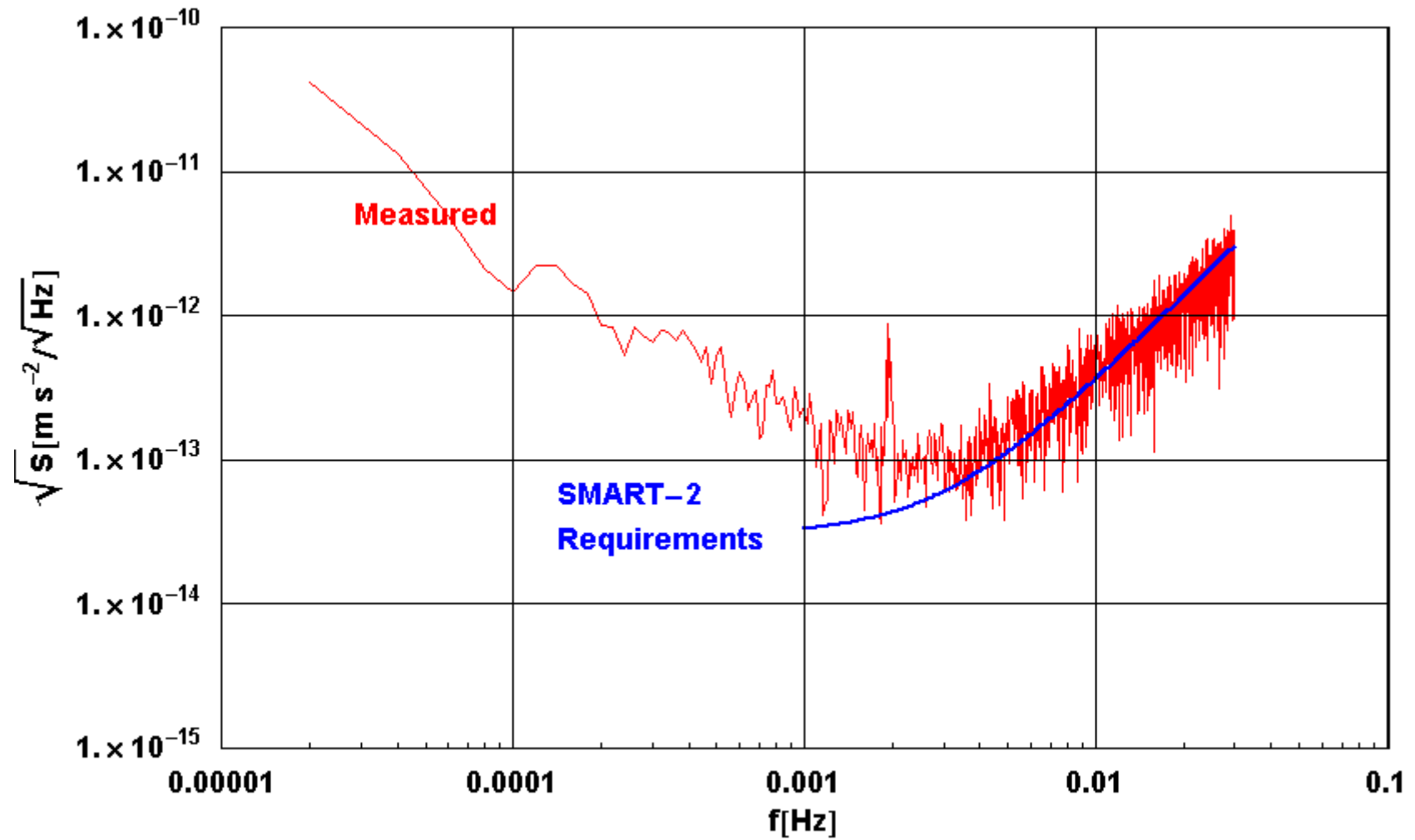


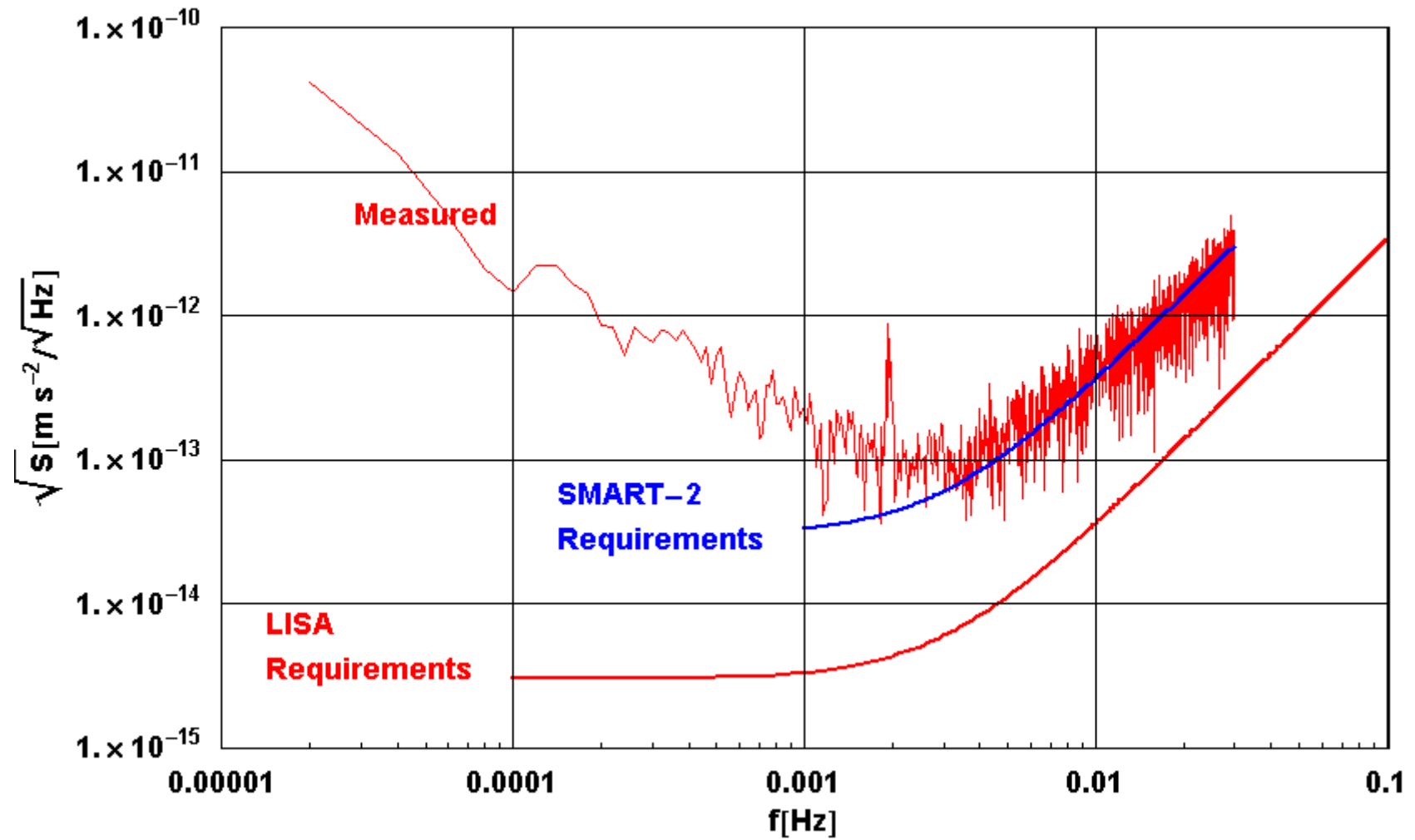
Temperature controlled room

- Long term temperature stability of 50 mK, order of magnitude reduction in sensitivity to room temperature fluctuations
- Allows controlled investigation of temperature effects by modulation of temperature setpoint

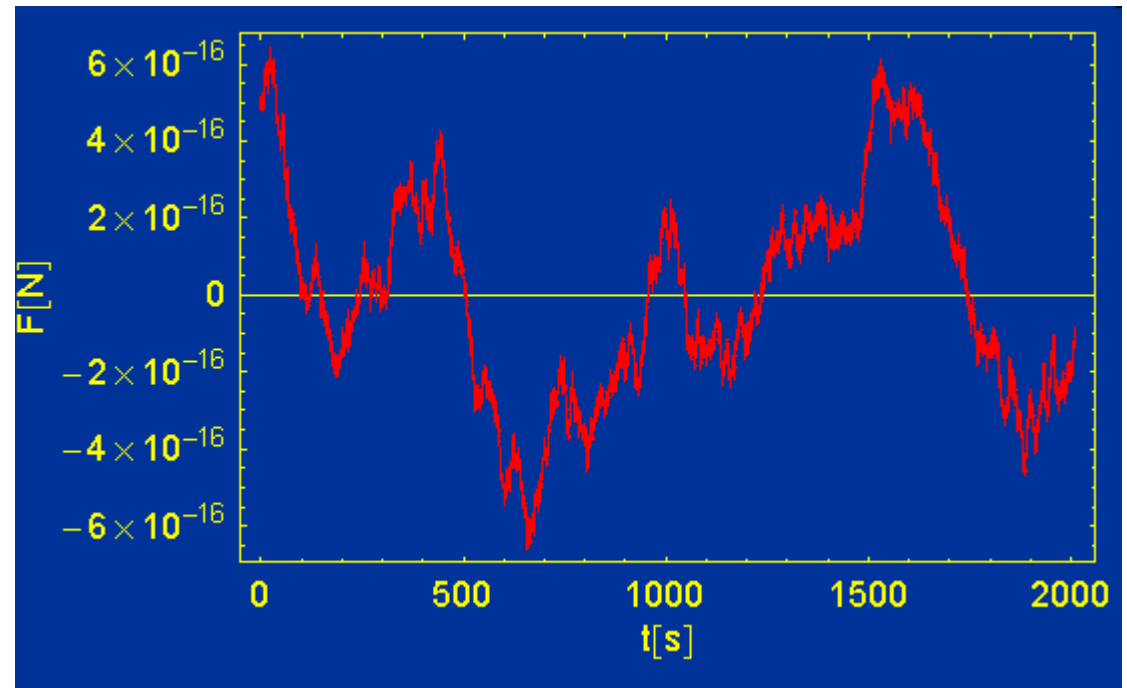
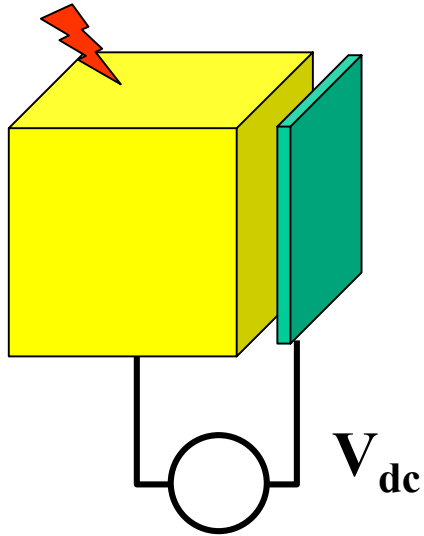






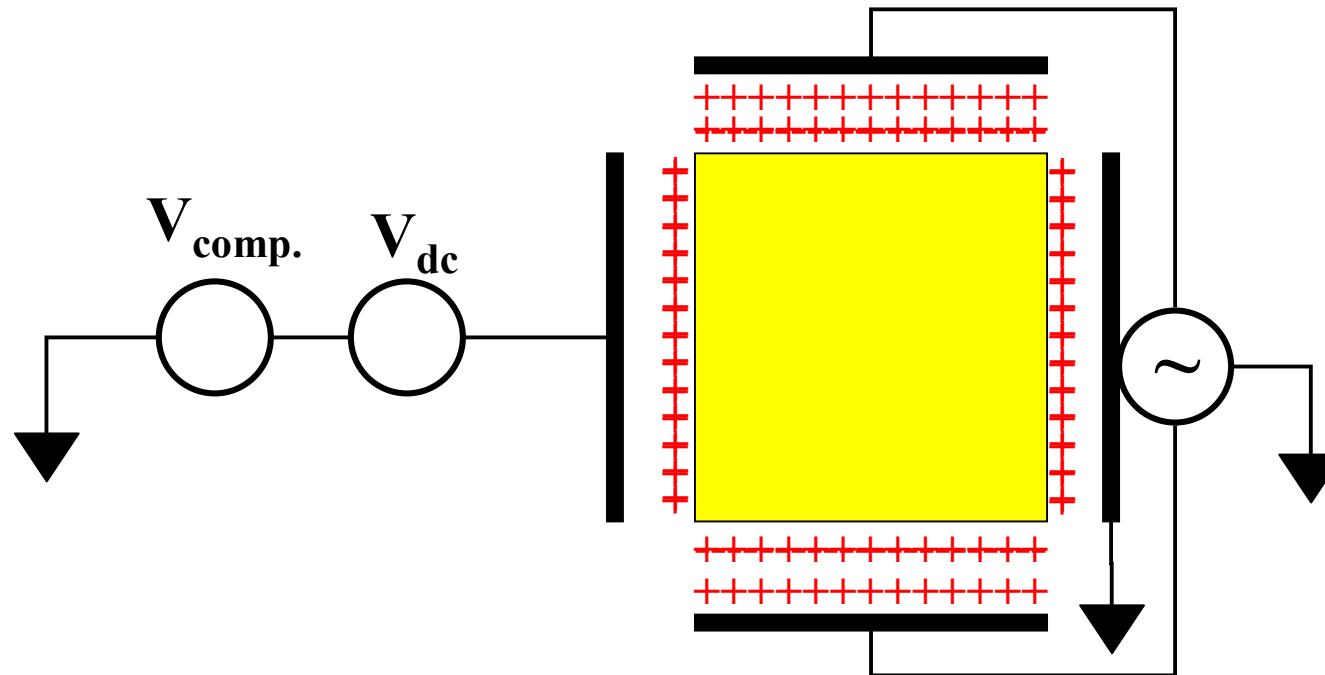


Stray dc voltage



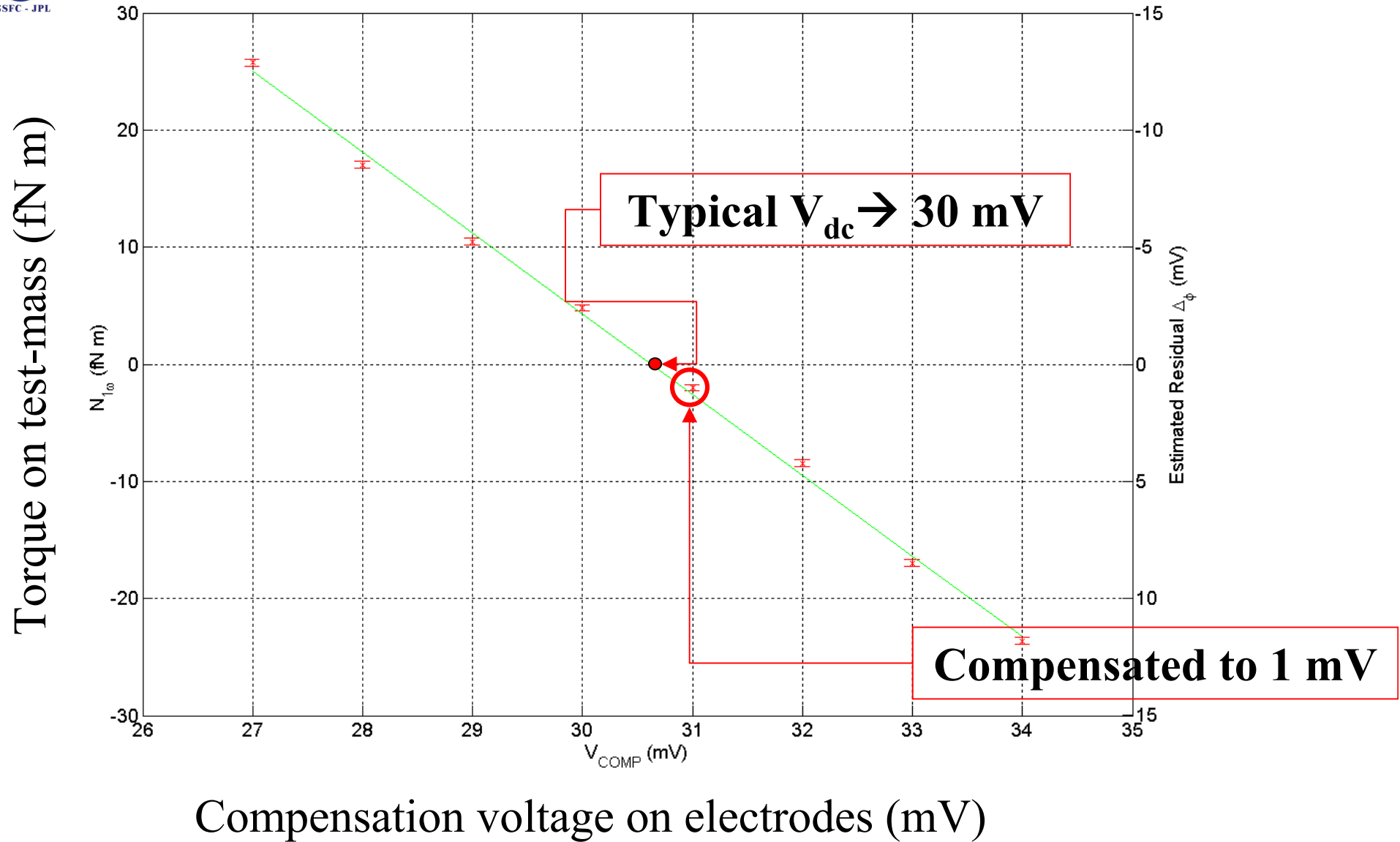
Random arrival of charge

$$\frac{S^{1/2}(\omega)}{m_0} = 0.8 \times 10^{-15} \frac{\text{m}}{\text{s}^2 \sqrt{\text{Hz}}} \left(\frac{4 \text{ mm}}{\text{gap}} \right) \left(\frac{V_{\text{dc}}}{10 \text{ mV}} \right) \left(\frac{\text{event rate}}{300 \text{ s}^{-1}} \right)^{1/2} \left(\frac{0.1 \text{ mHz}}{f} \right)$$

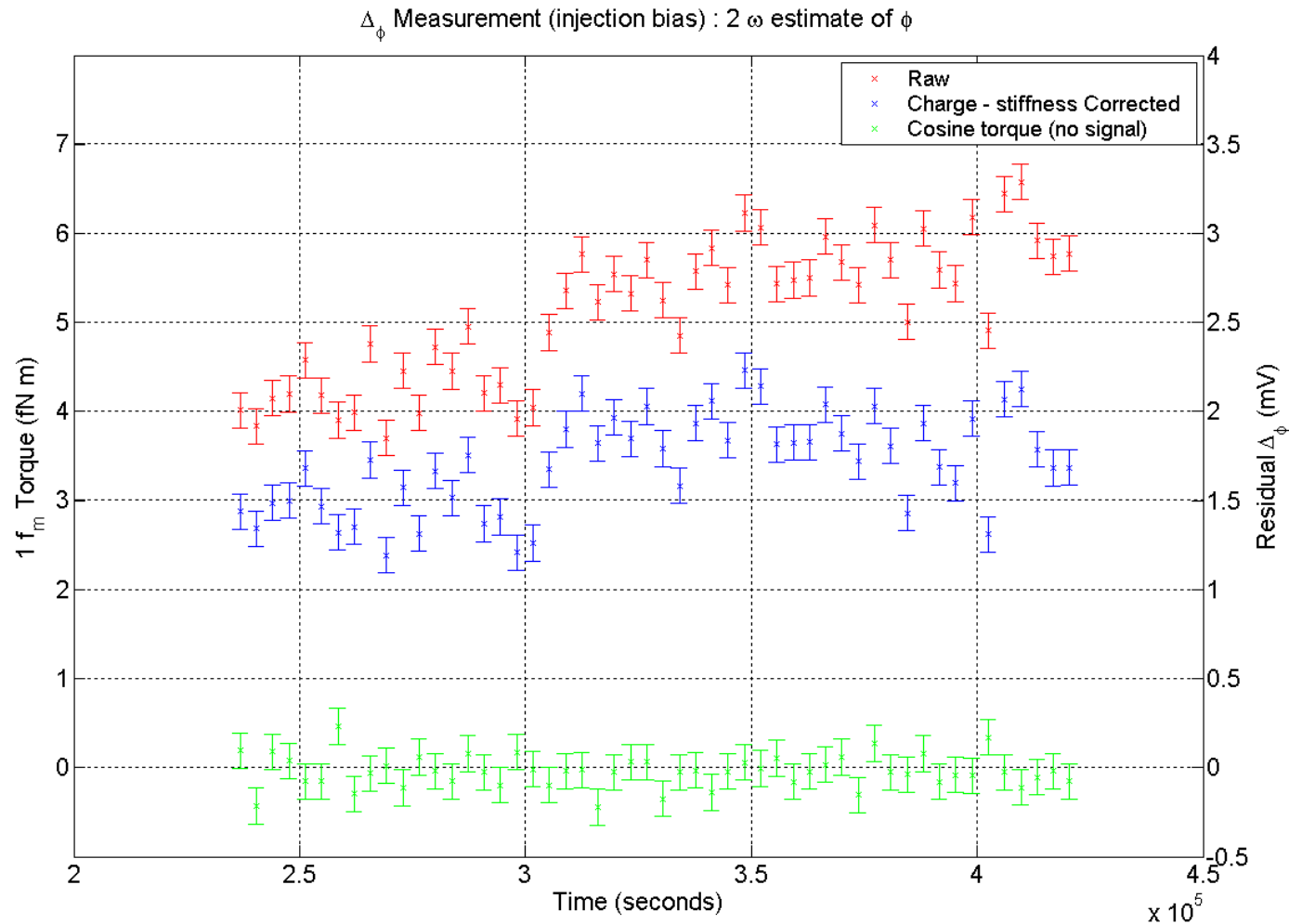


Simulating a varying charge on the test-mass $\rightarrow$ ac-torque induced

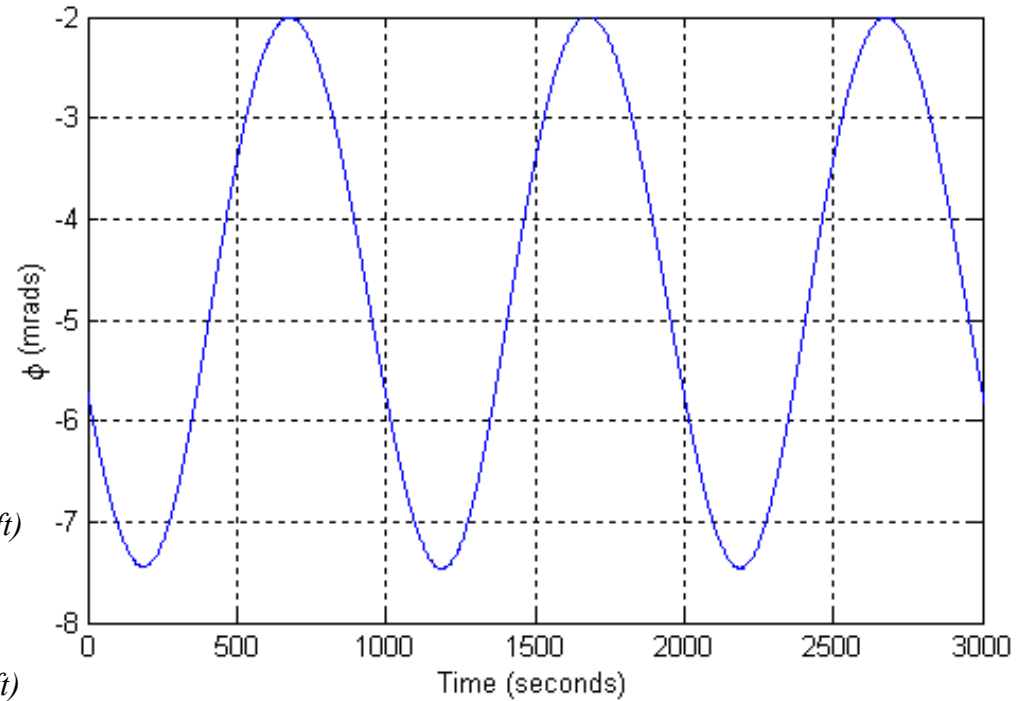
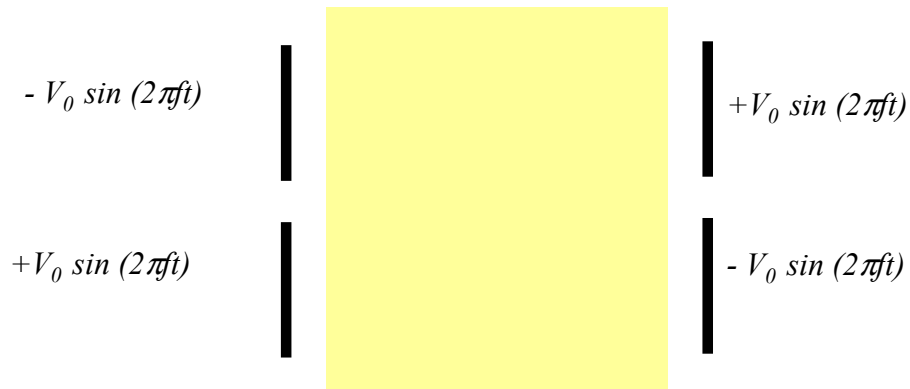
V_{dc} may be compensated $\rightarrow V_{dc} + V_{comp.} = 0$



Measurement of DC Bias Stability



- DC Bias imbalance stable to within 1 mV over 50 hour run
- Note that measurement noise (cosine phase) is below the observed scatter in the electrostatic signal

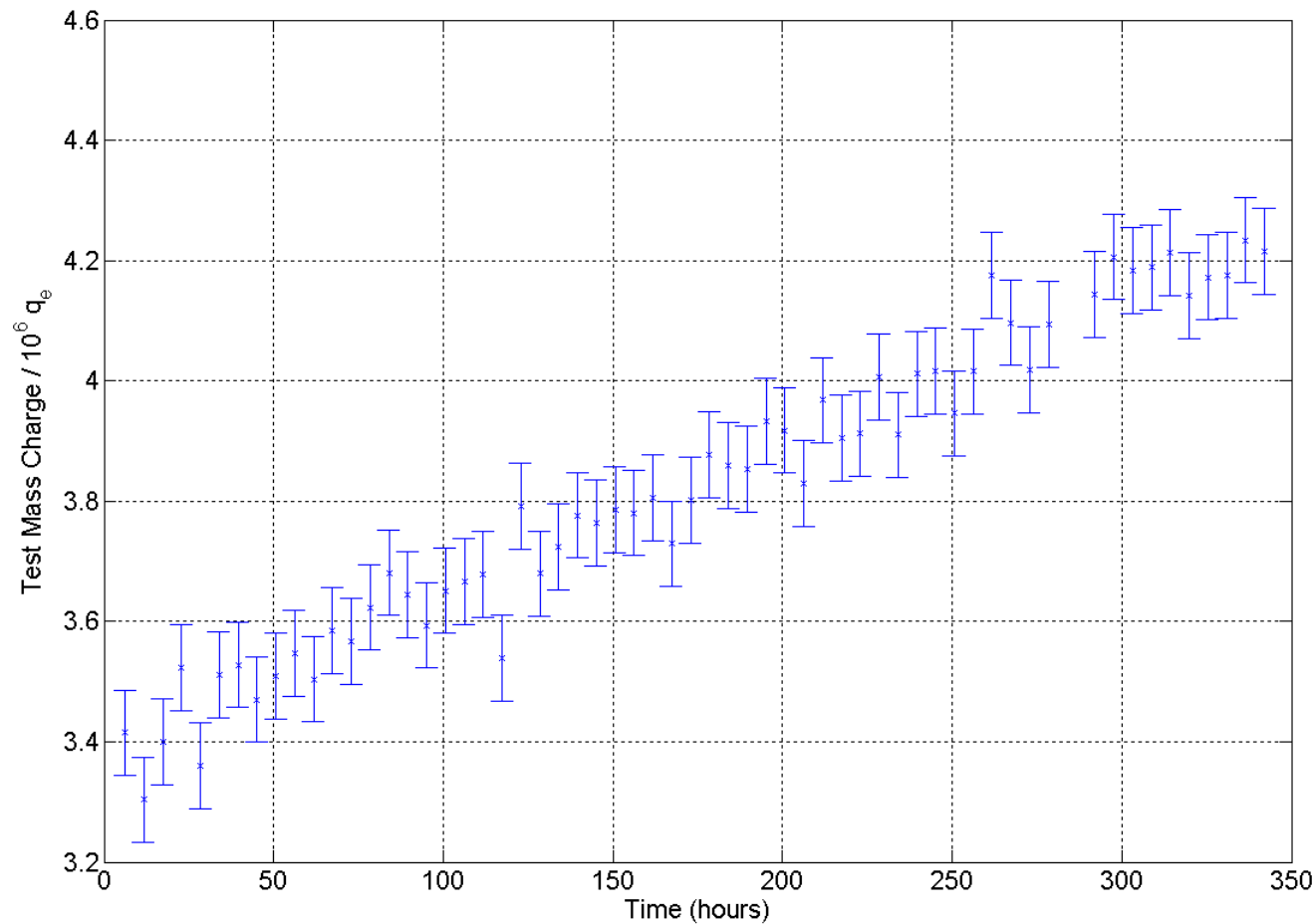


$$5 \times 10^7 e$$

Charge measurement by dither voltage

Resolution: $1000 e$

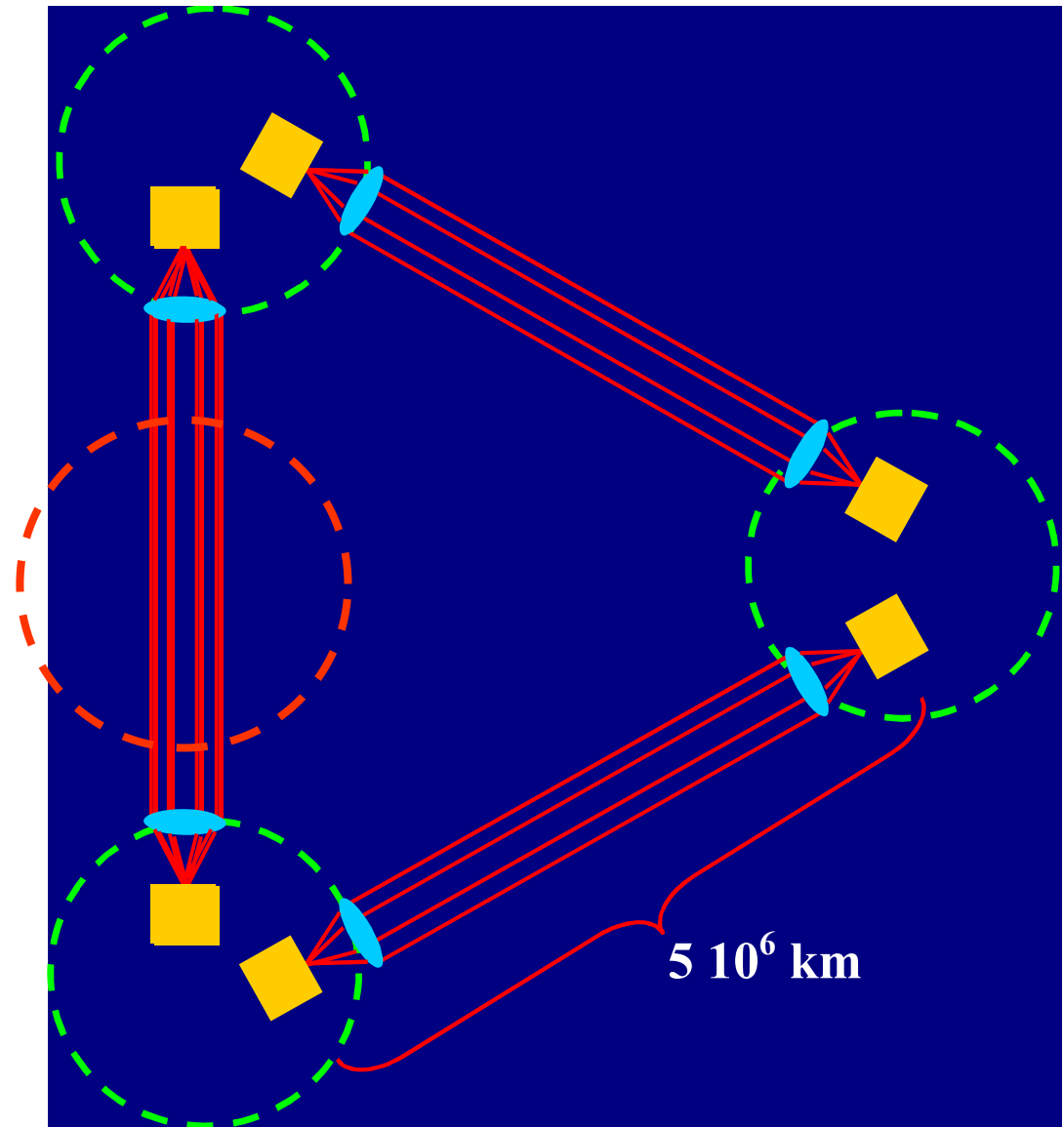
Long term charge measurement



- Roughly +1 e / s charging
- Measurement error of 50000 charges in a 6 hour measurement with 50 mV measurement bias

LISA Path Finder (SMART-2) In-flight test:

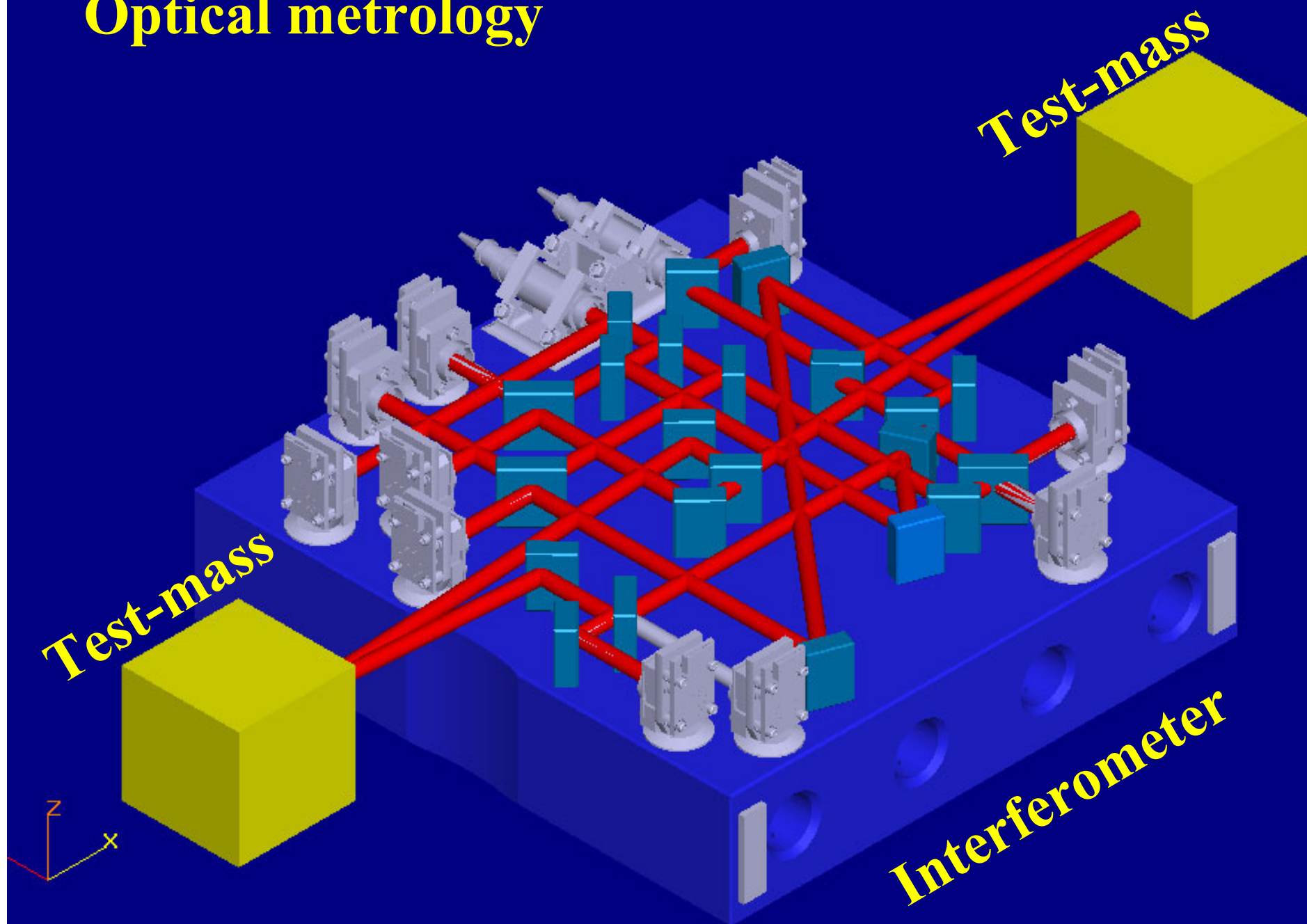
squeezing 1 LISA's
arm to 35 cm
One order of
magnitude from
LISA goals



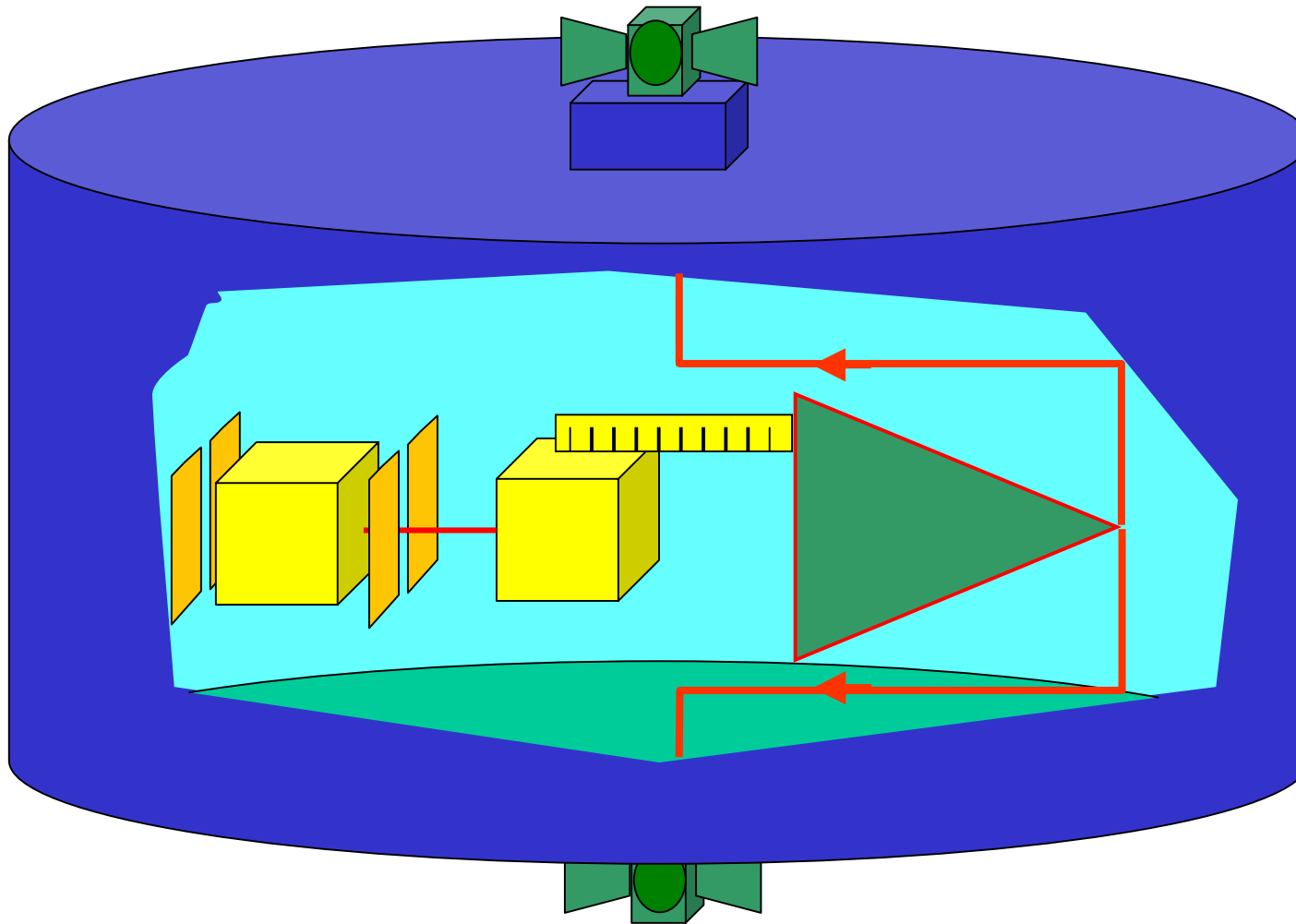
$$\delta a \leq 3 \cdot 10^{-14} \frac{\text{ms}^{-2}}{\sqrt{\text{Hz}}}$$

$$1 \text{ mHz} \leq f \leq 30 \text{ mHz}$$

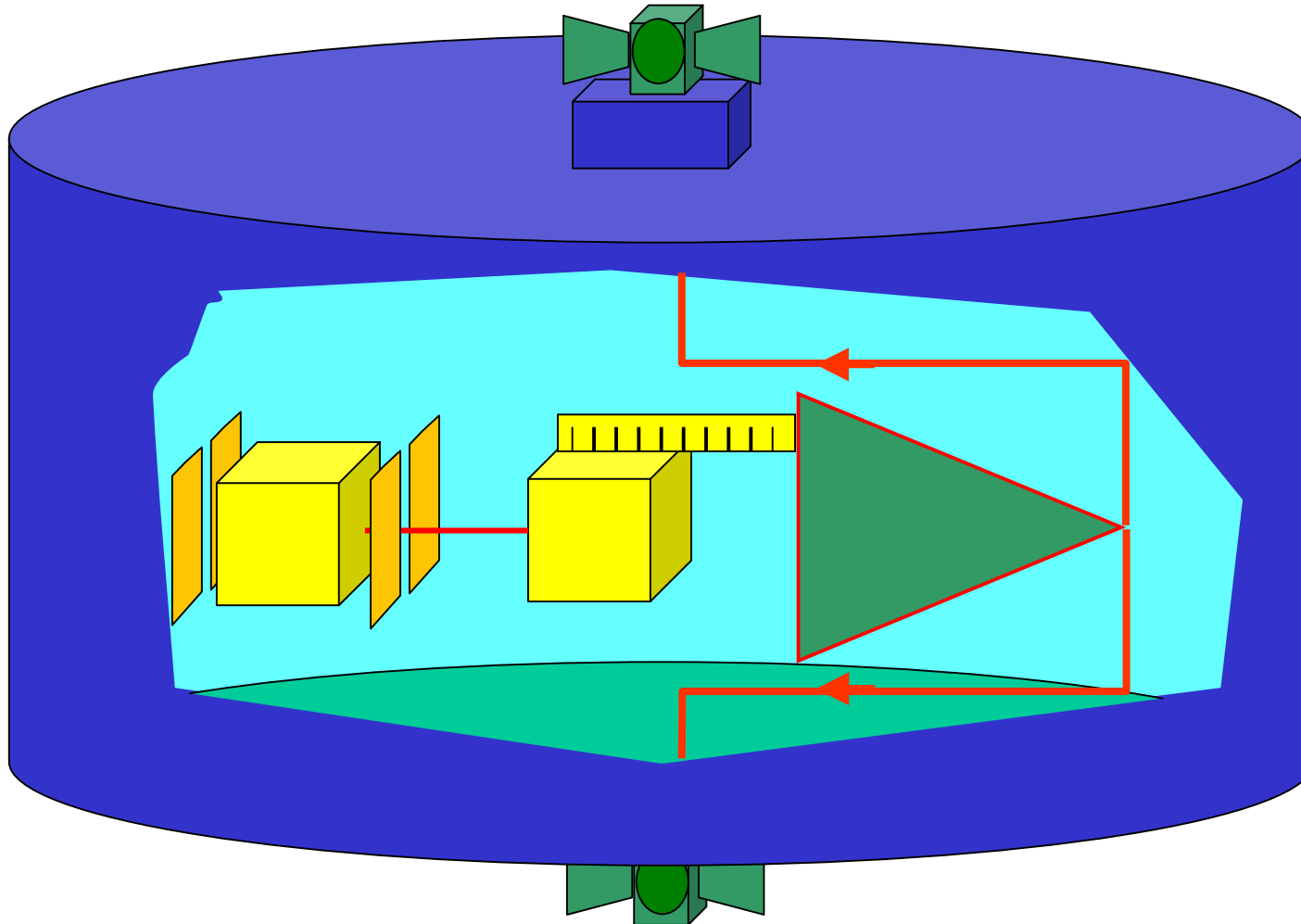
Optical metrology



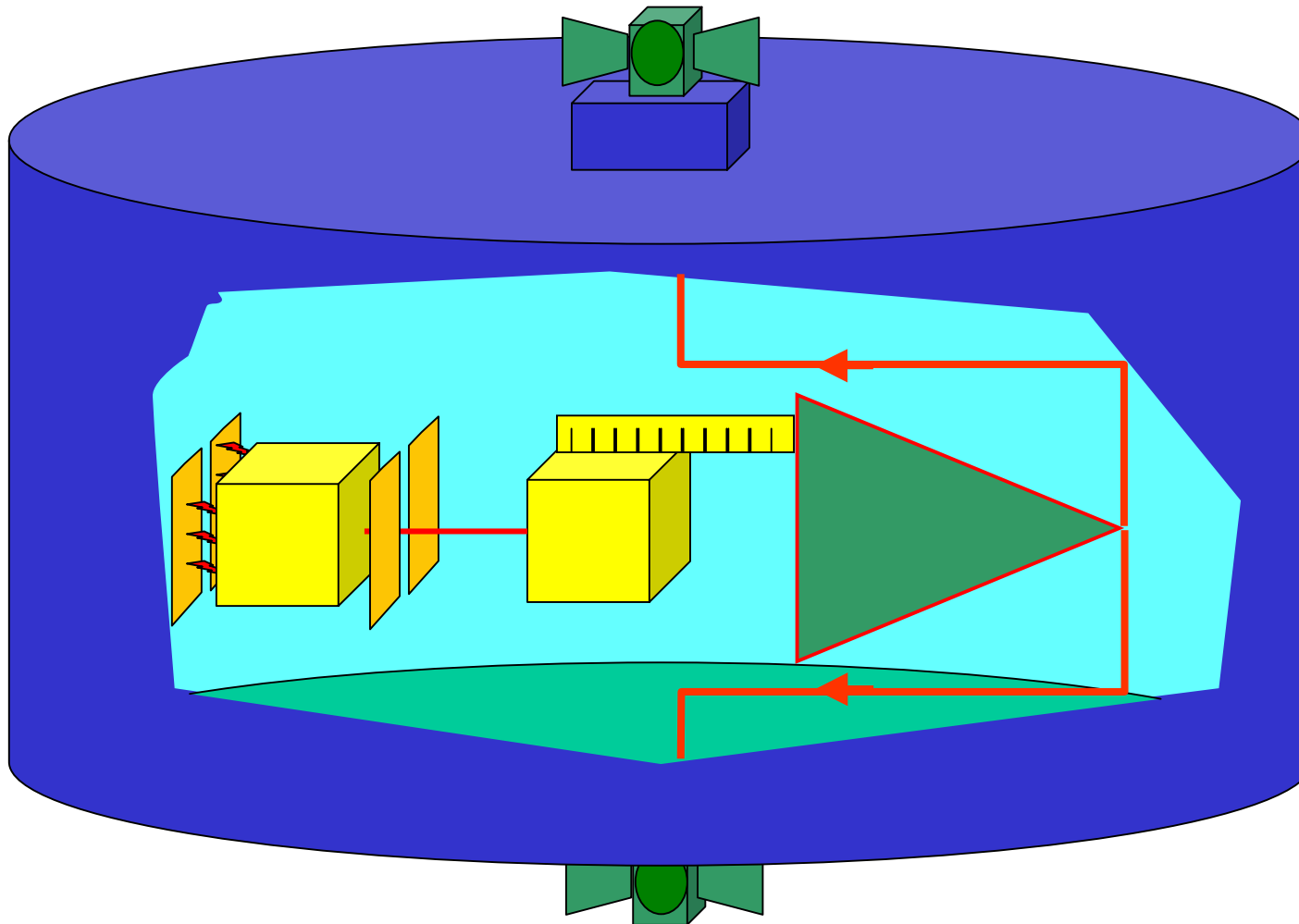
SMART-2 control logic



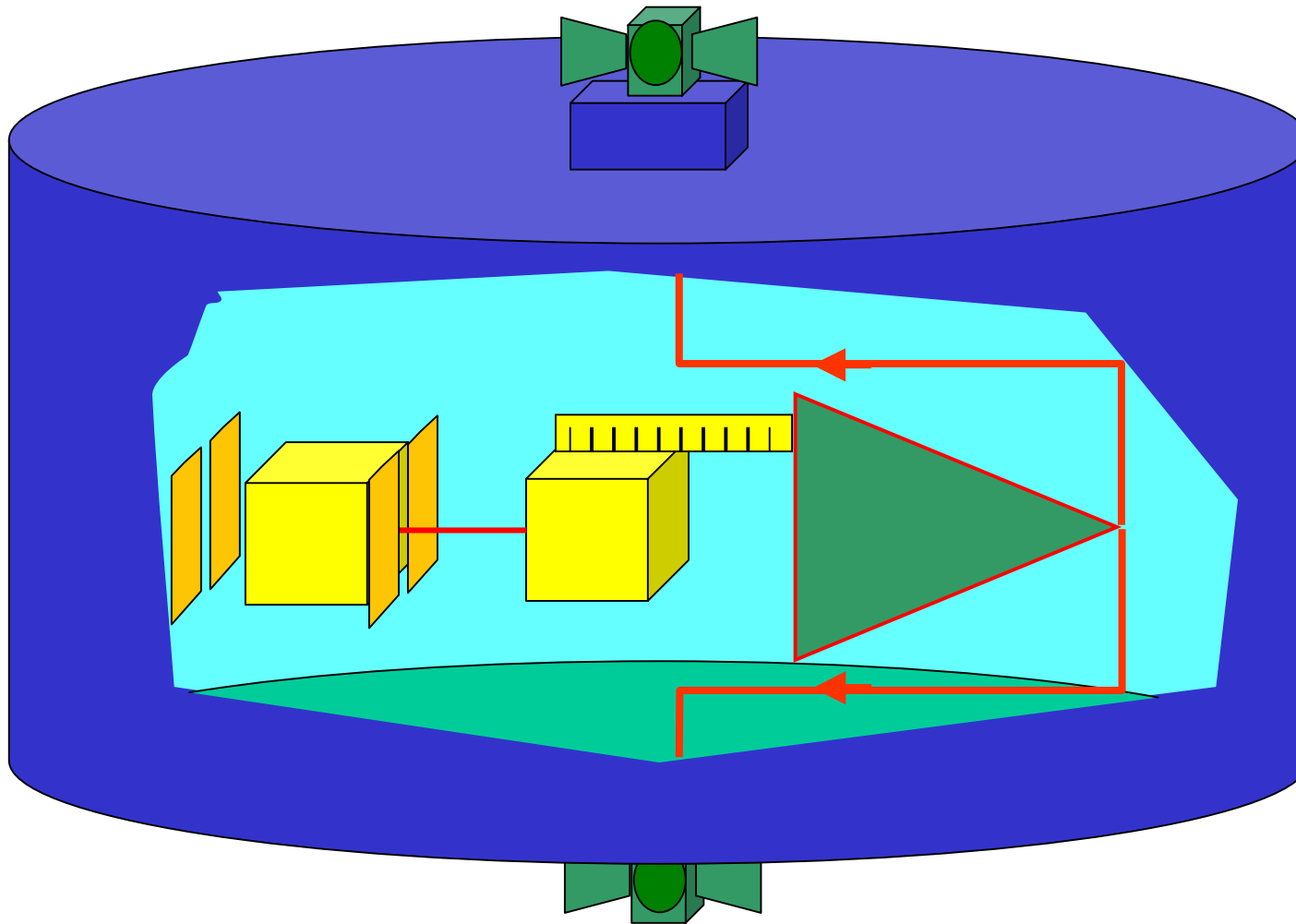
SMART-2 control logic



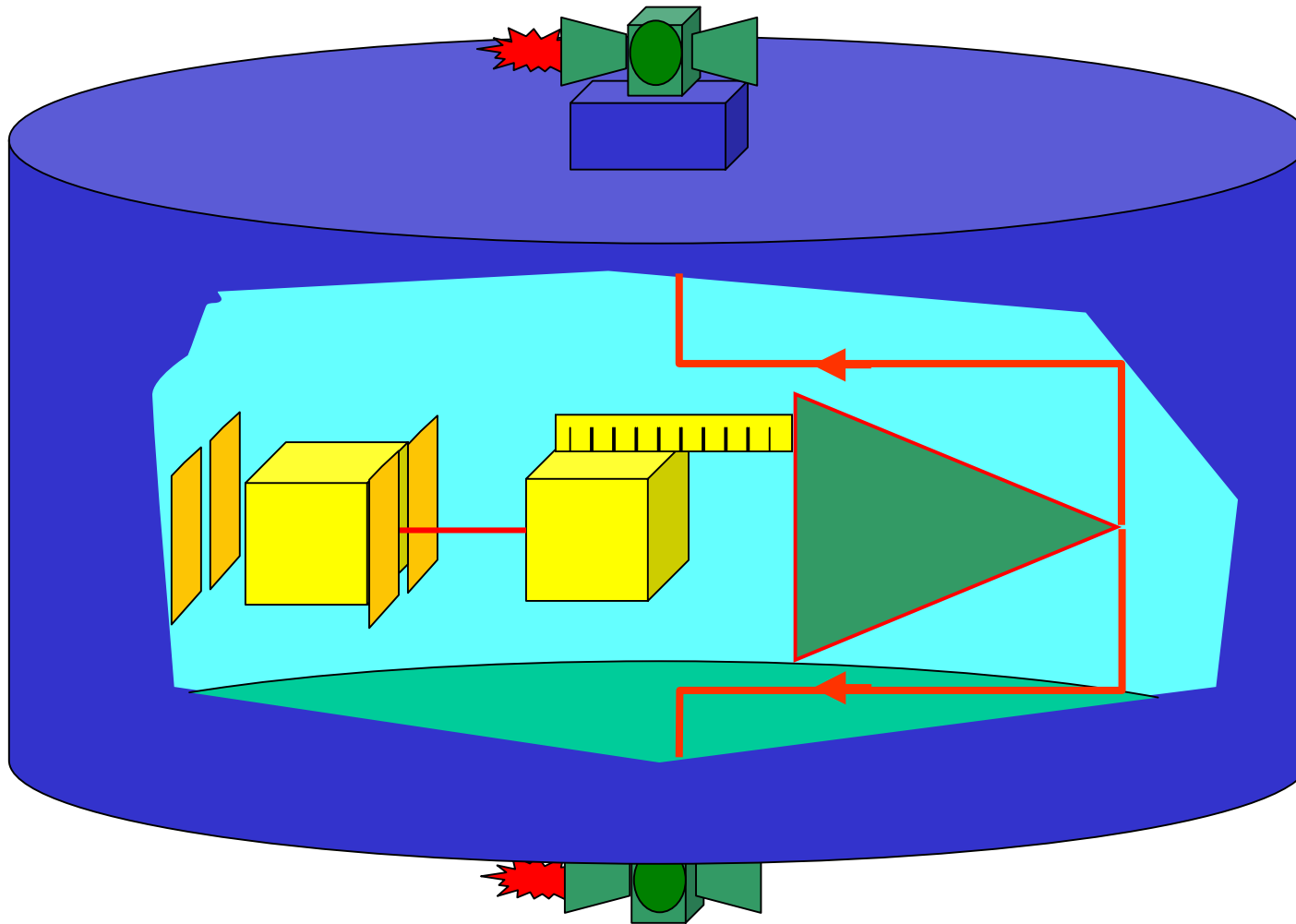
SMART-2 control logic



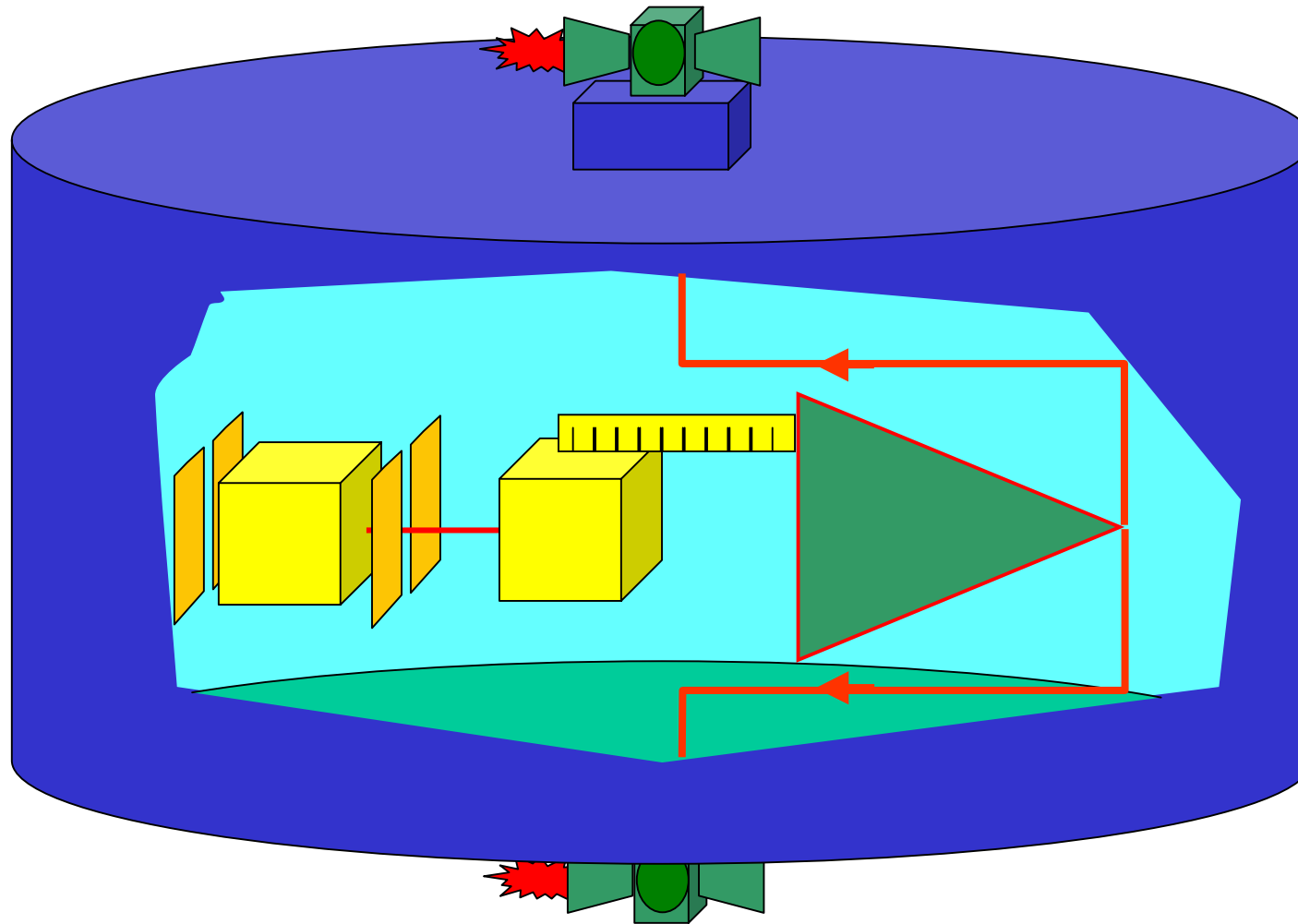
SMART-2 control logic



SMART-2 control logic



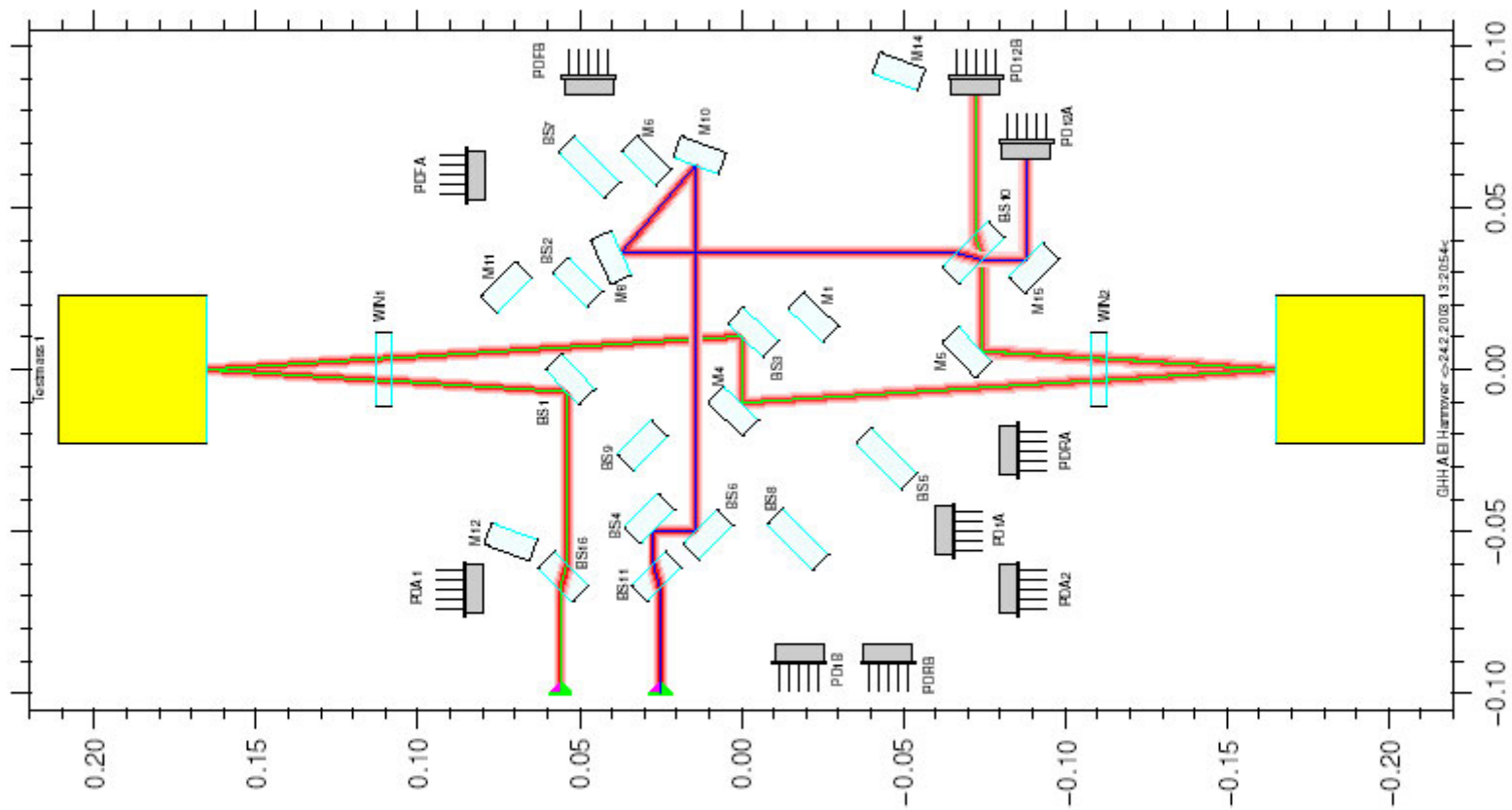
SMART-2 control logic



$$\underbrace{a_n \propto \frac{\overbrace{\mathbf{f}_x}^{\text{Force on test-mass}}}{m} + \overbrace{\omega_p^2}^{\text{Parasitic test-mass coupling}} \left(\mathbf{x}_{n,1} + \frac{\mathbf{F}_{S/C,x}}{M\omega_{fb,x}^2} \right)}_{\text{LISA}}$$

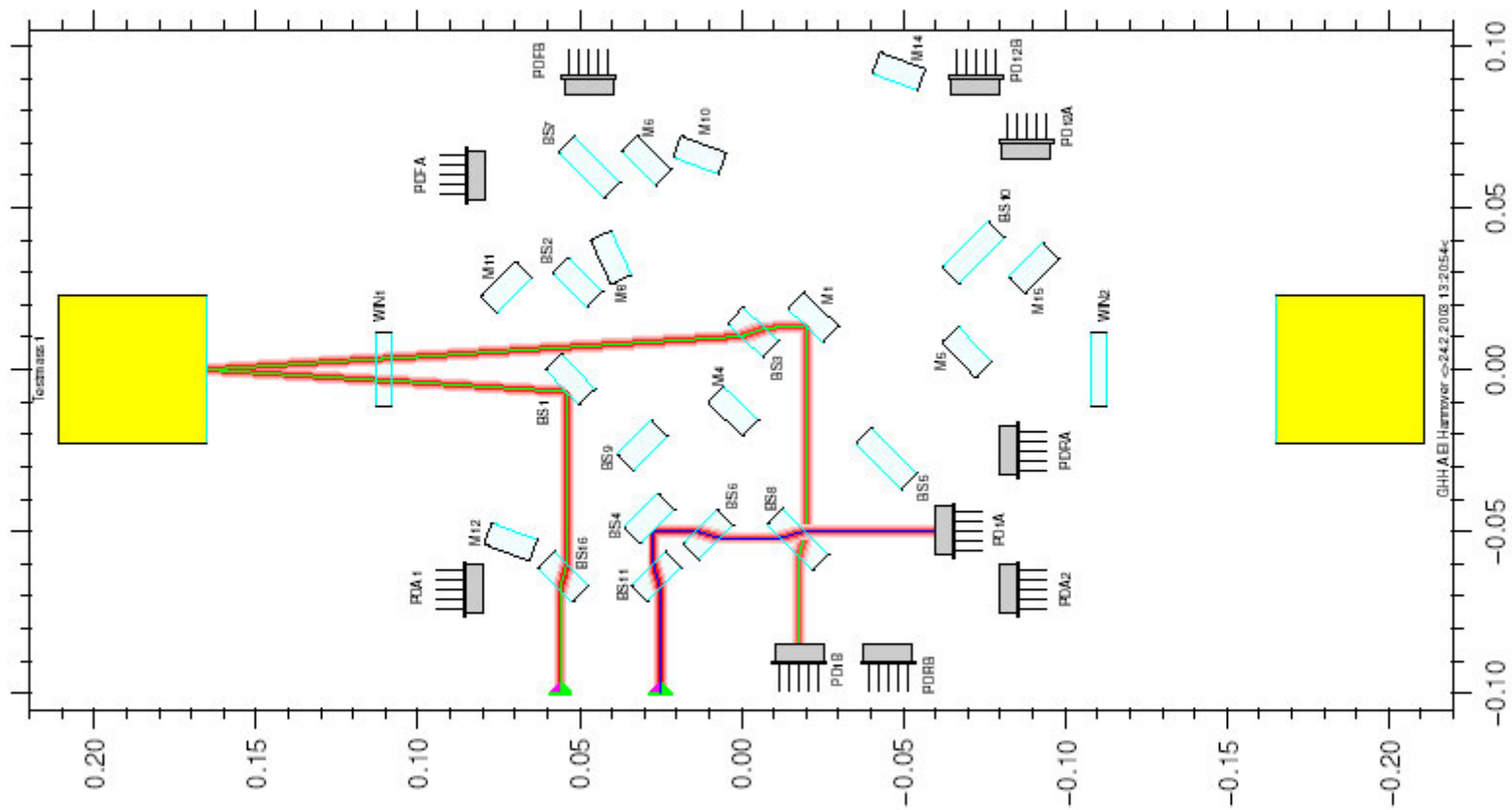
$$\underbrace{\delta \mathbf{x}_{\text{laser}} \propto \frac{\overbrace{\mathbf{f}_{x,1} - \mathbf{f}_{x,2}}^{\text{Difference of force}}}{m} + \overbrace{\left(\omega_{p1}^2 - \omega_{p2}^2 \right)}^{\text{Difference of parasitic coupling}} \left(\mathbf{x}_{n,1} + \frac{\mathbf{F}_{S/C,x}}{M\omega_{fb,x}^2} \right)}_{\text{SMART-2}}$$

No effect on measurement of test-mass control



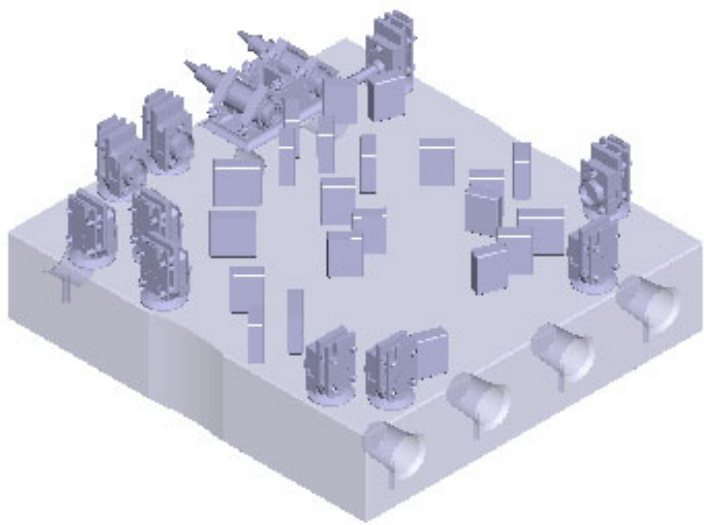
with an extra pathlength of 356.7 mm in the reference fiber, the pathlength difference is 0.000 mm.

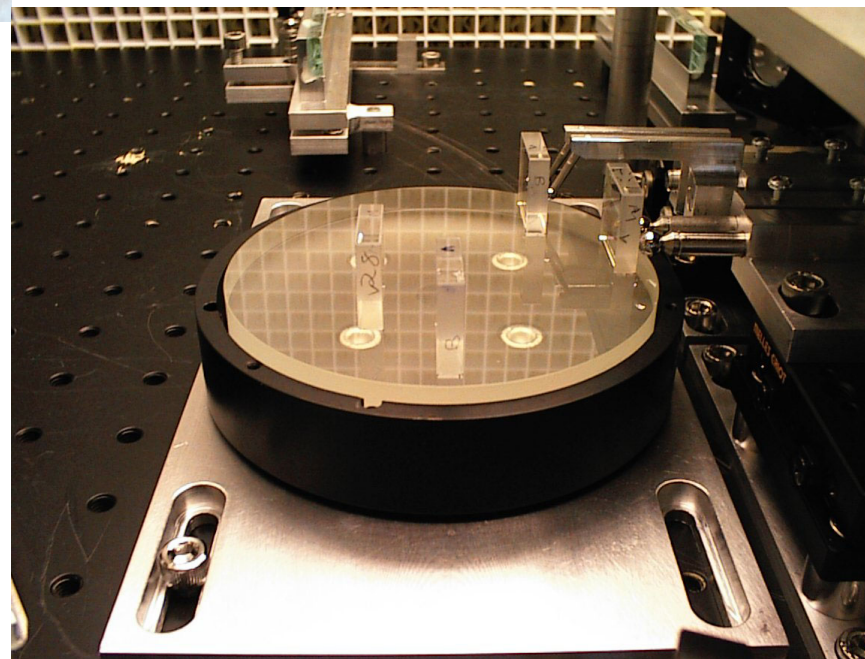
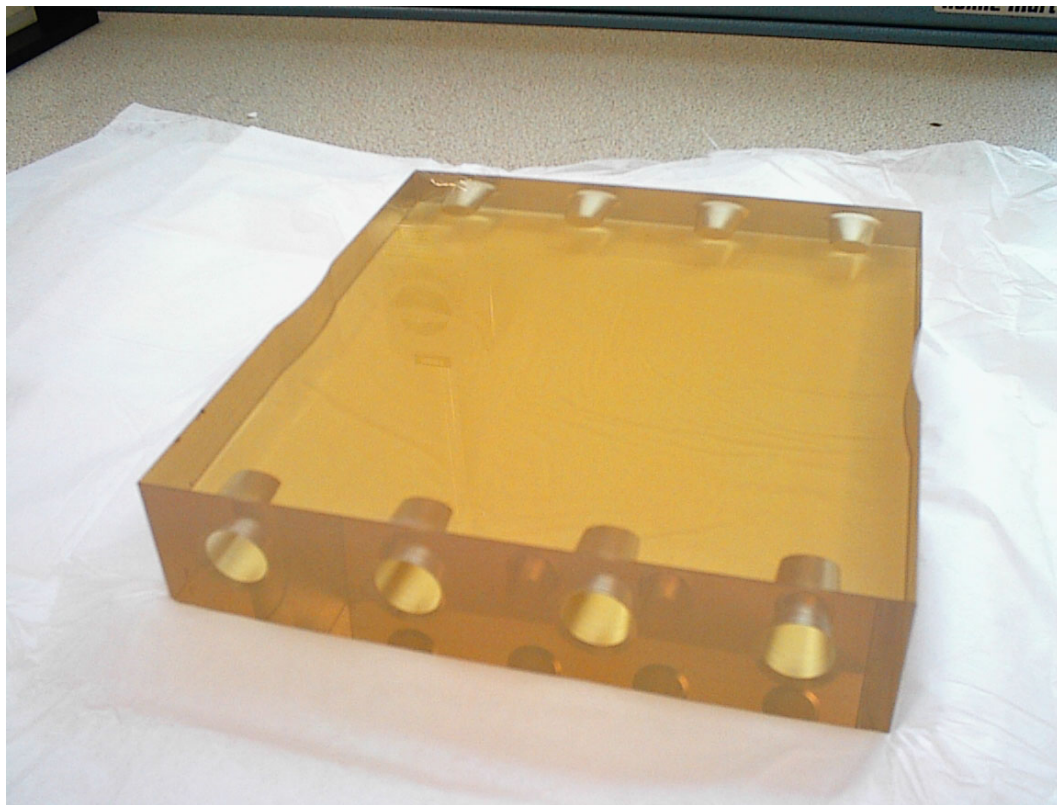
2



with an extra pathlength of 356.7 mm in the reference fiber, the pathlength difference is 0.02 mm.

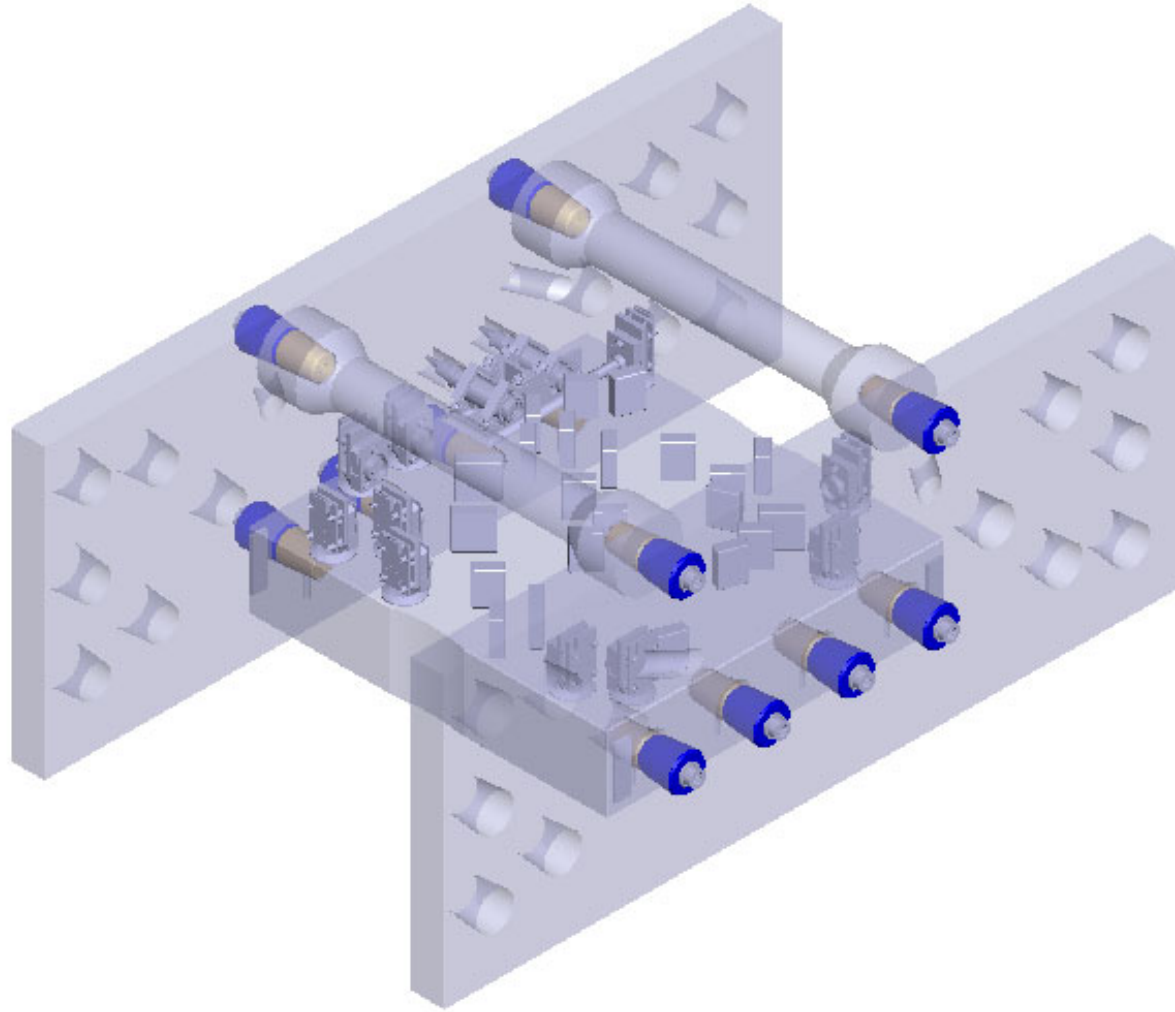
3

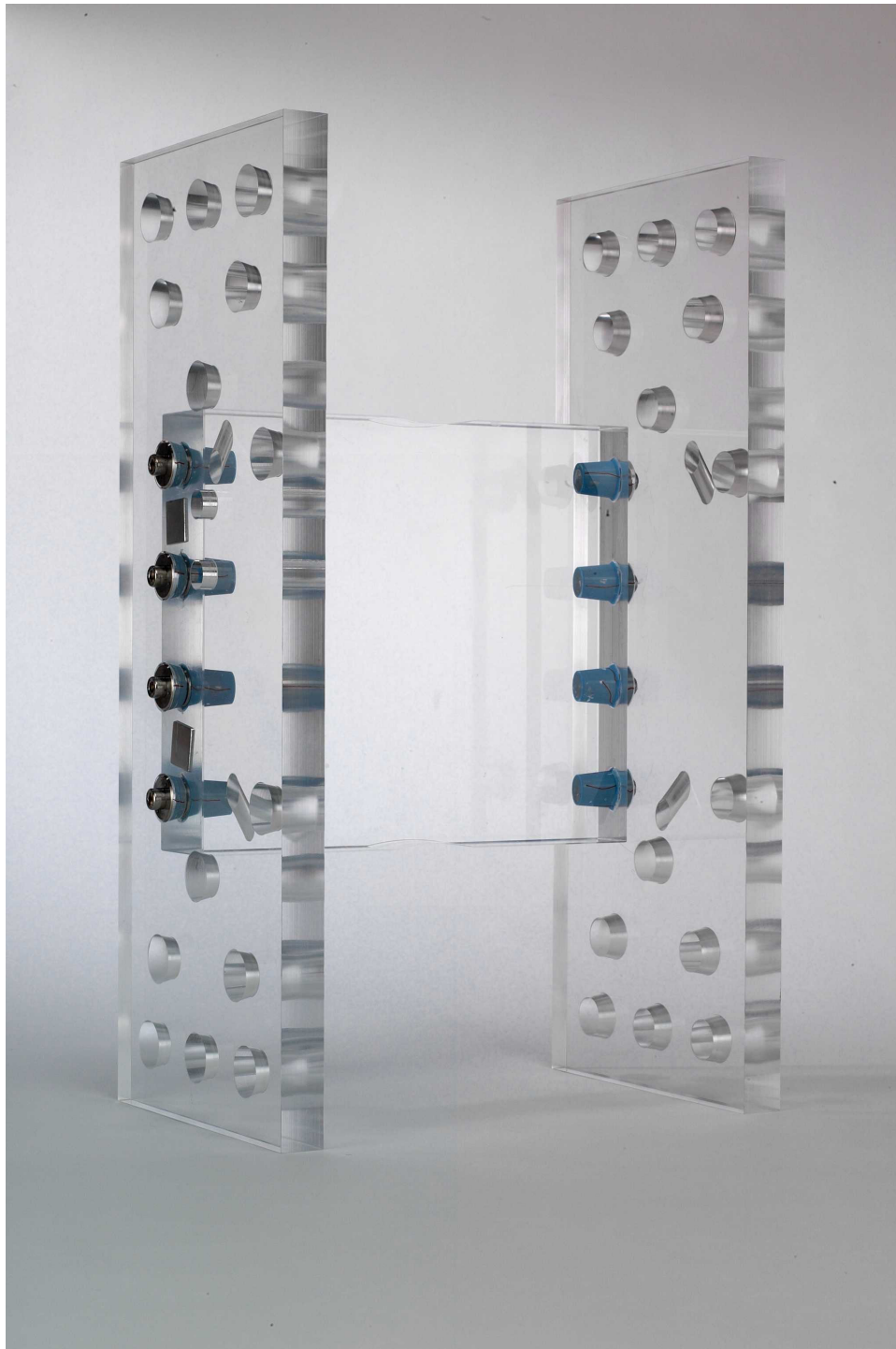


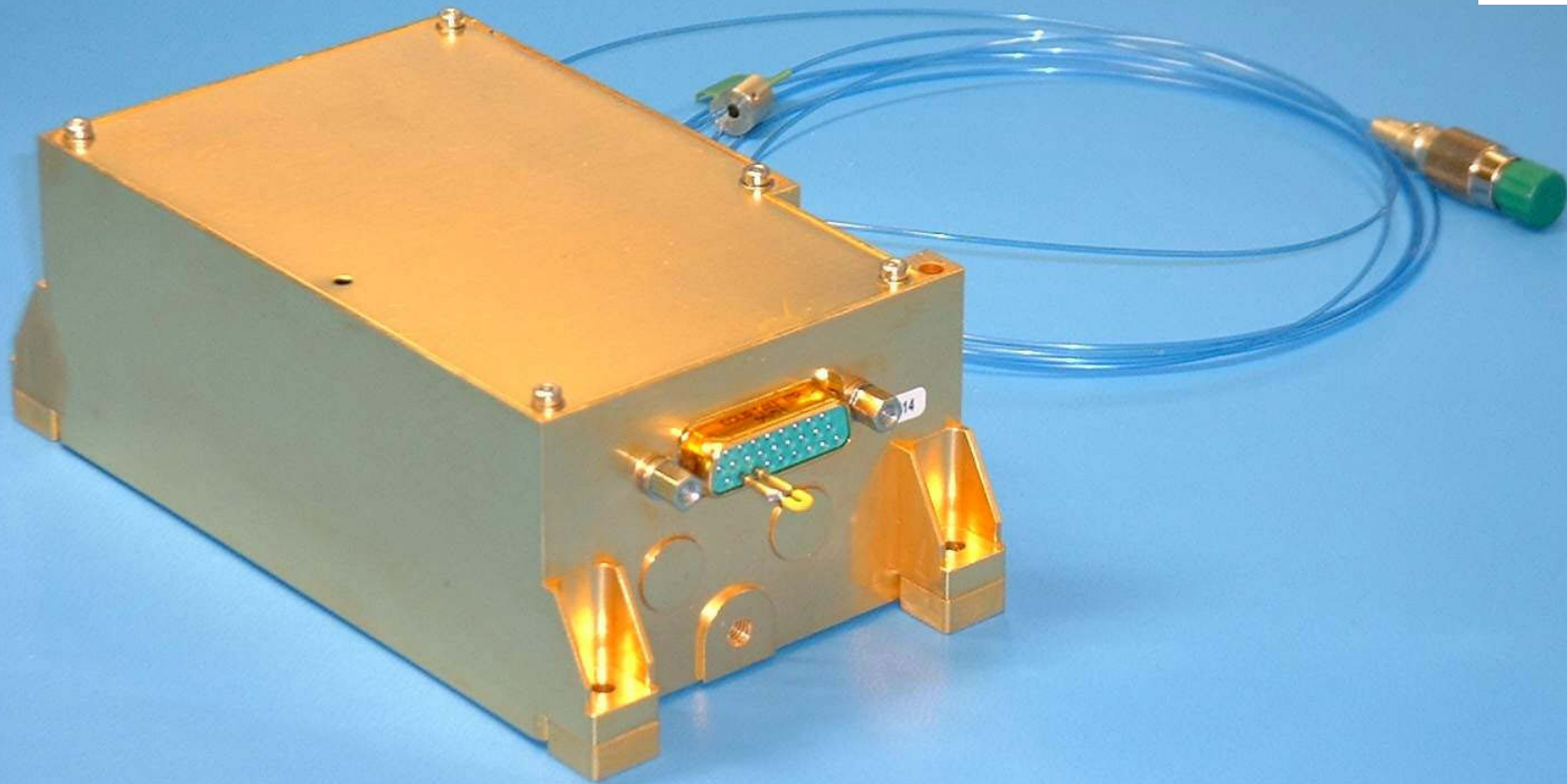
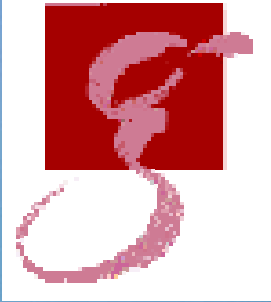


Trieste-25-09-03

S. Vitale

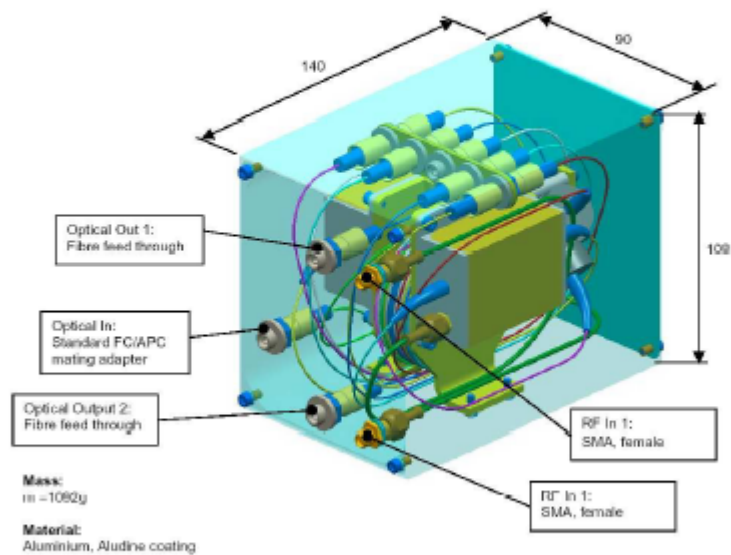






Laser

AOM Prototype (Contraves)



3D-plot of the mechanical layout of the Modulation Bench

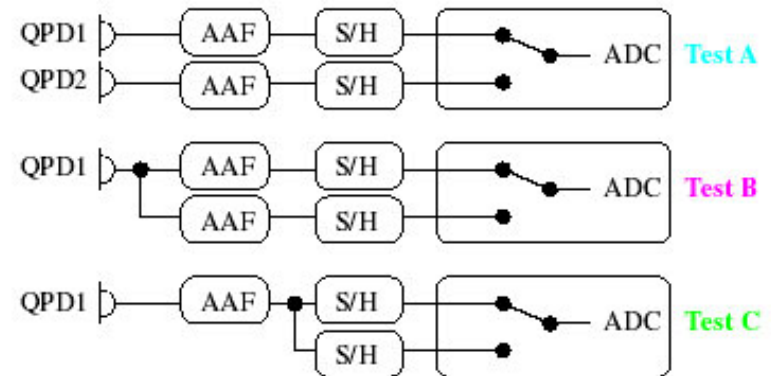
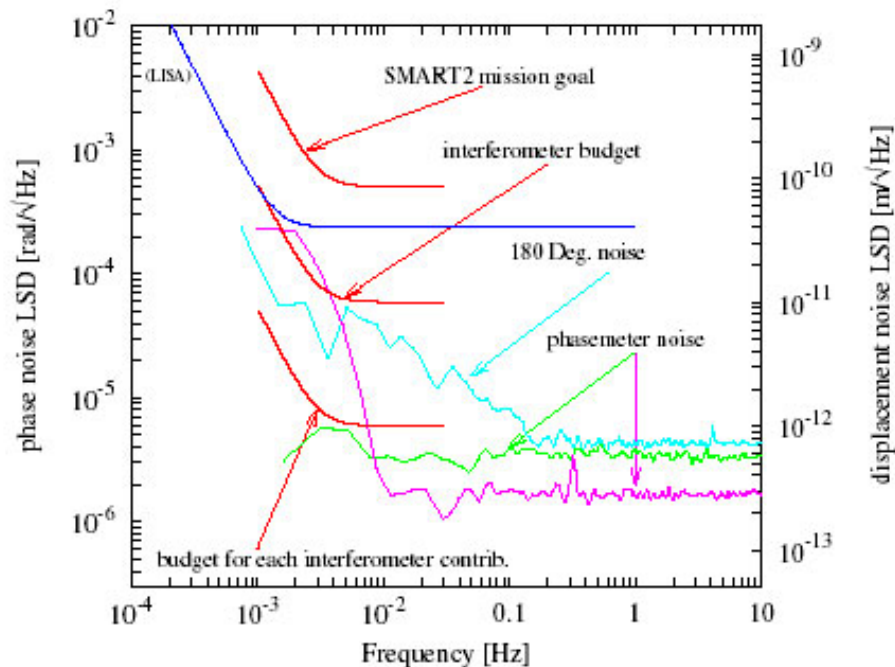
Note: The figure shows FC/APC mating adapters for the outputs; To avoid losses these are substituted by fibre feed throughs.



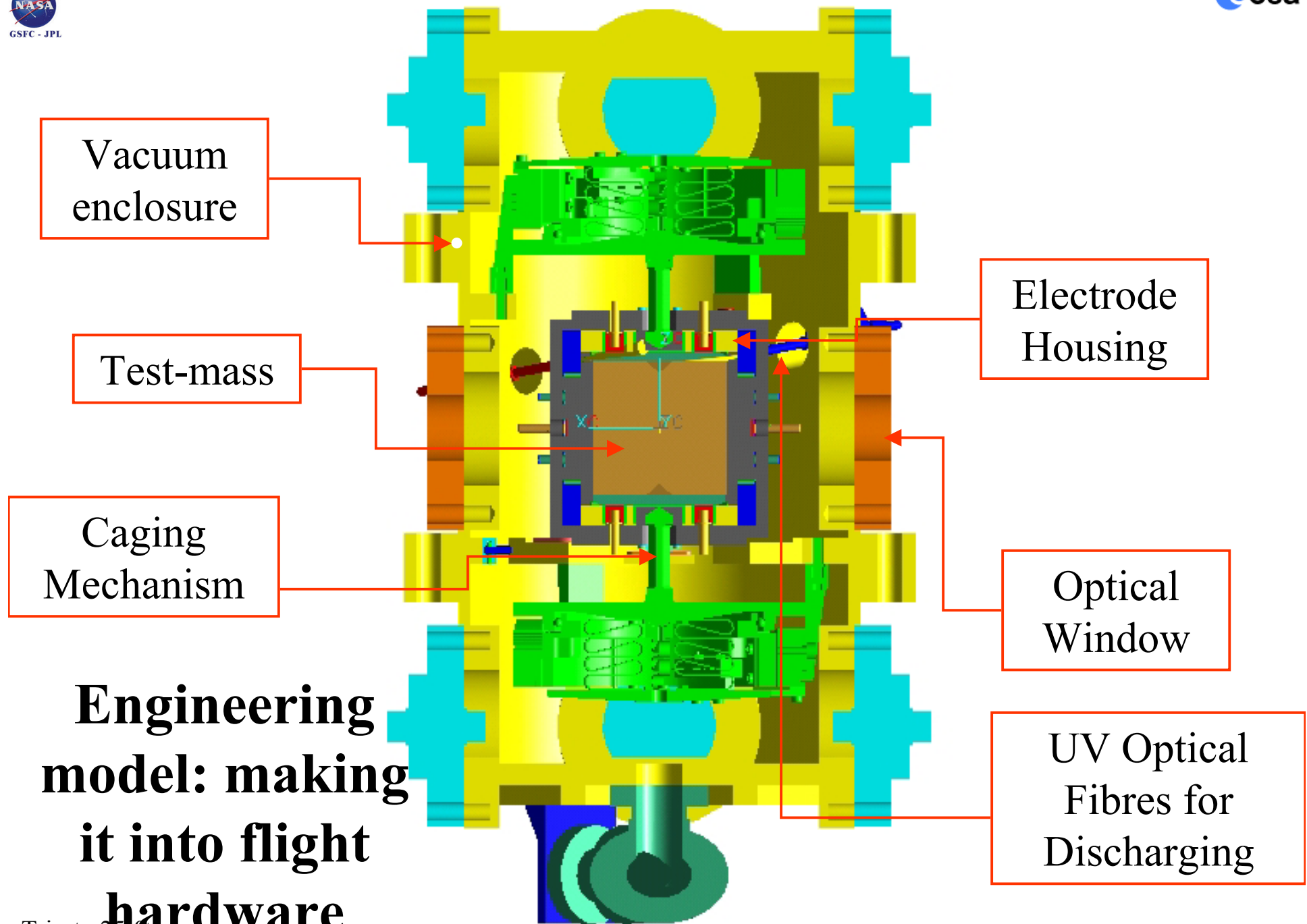
BreadBoard Testing

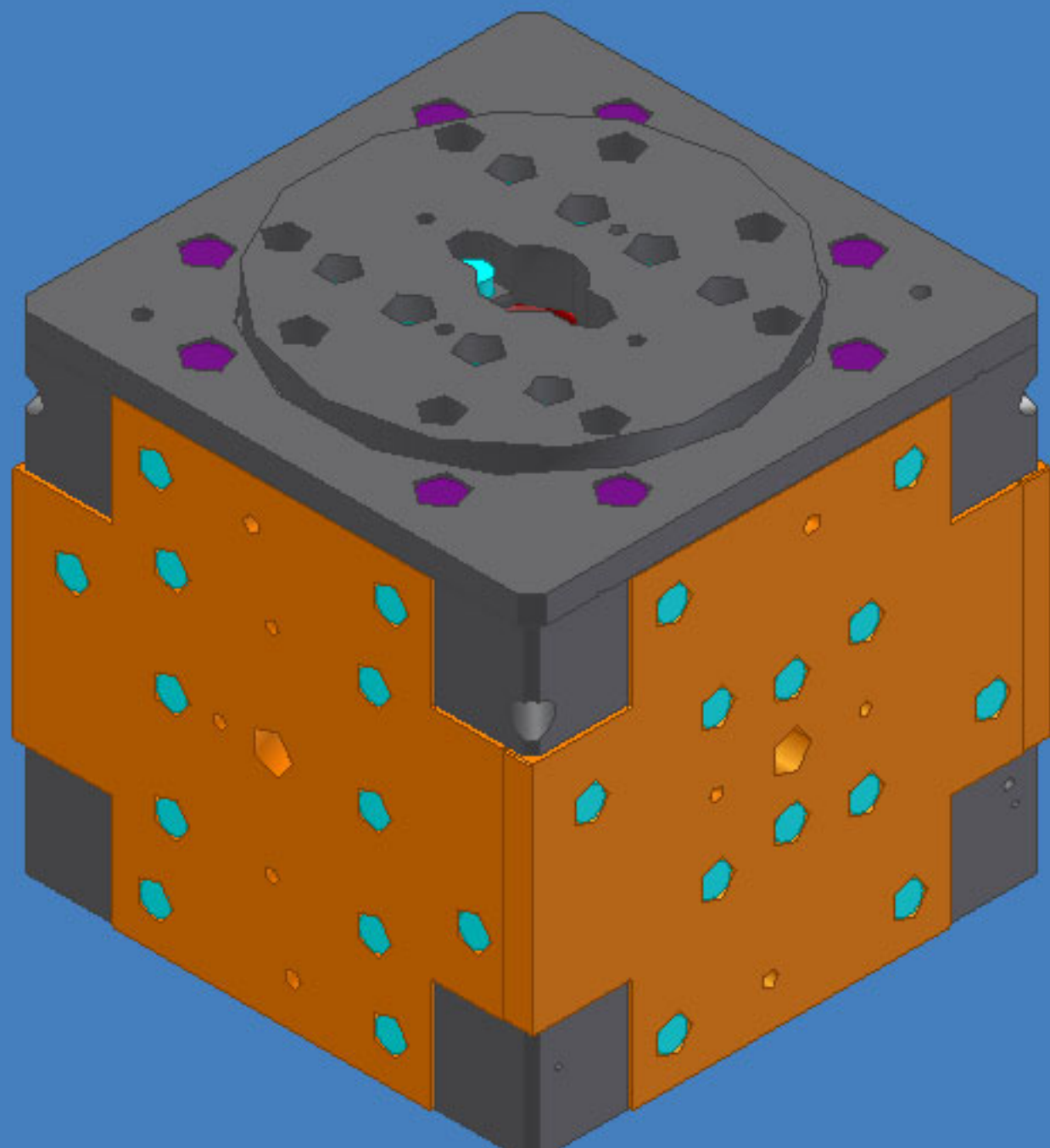


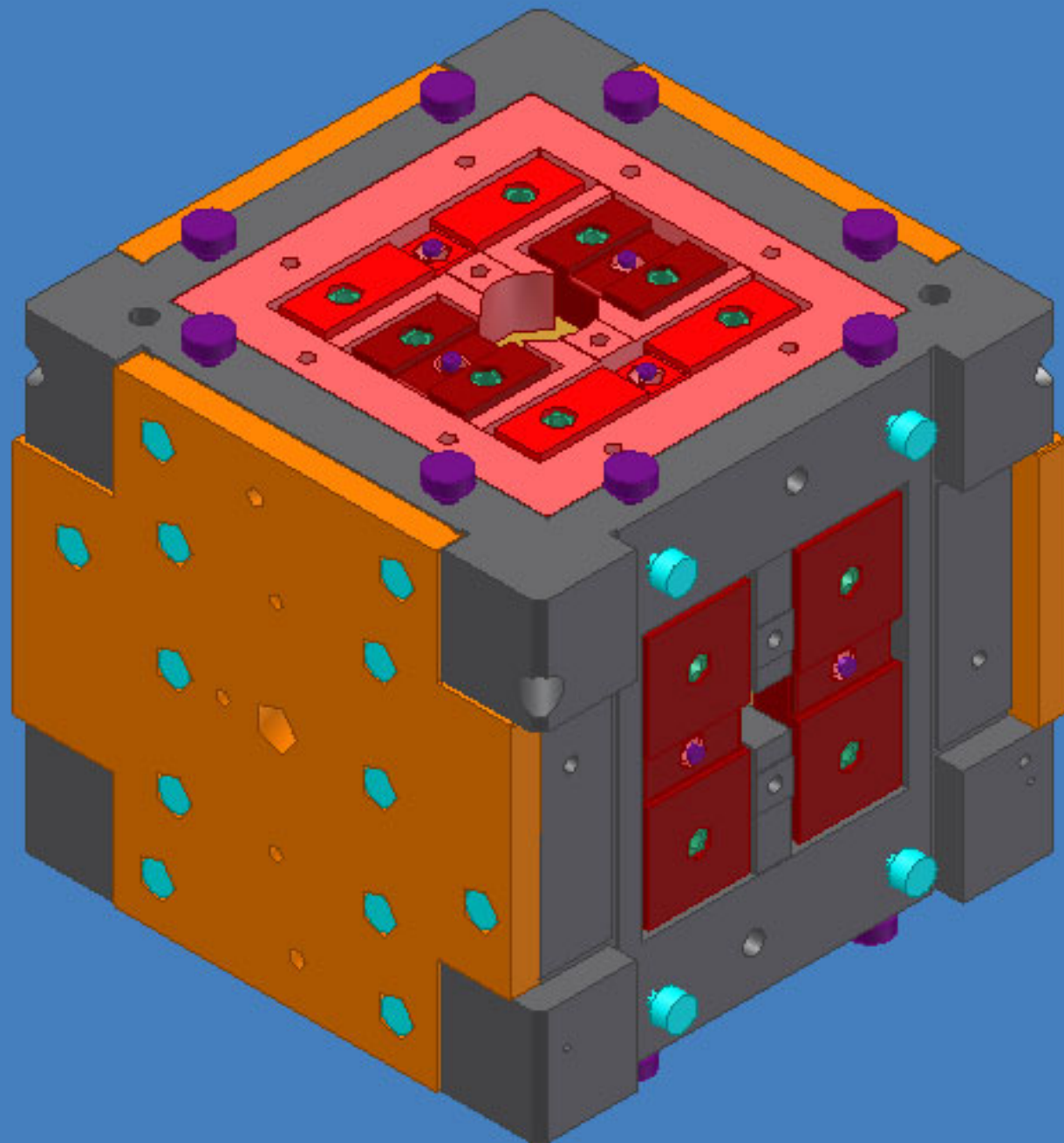
Phasemeter noise and interferometer noise

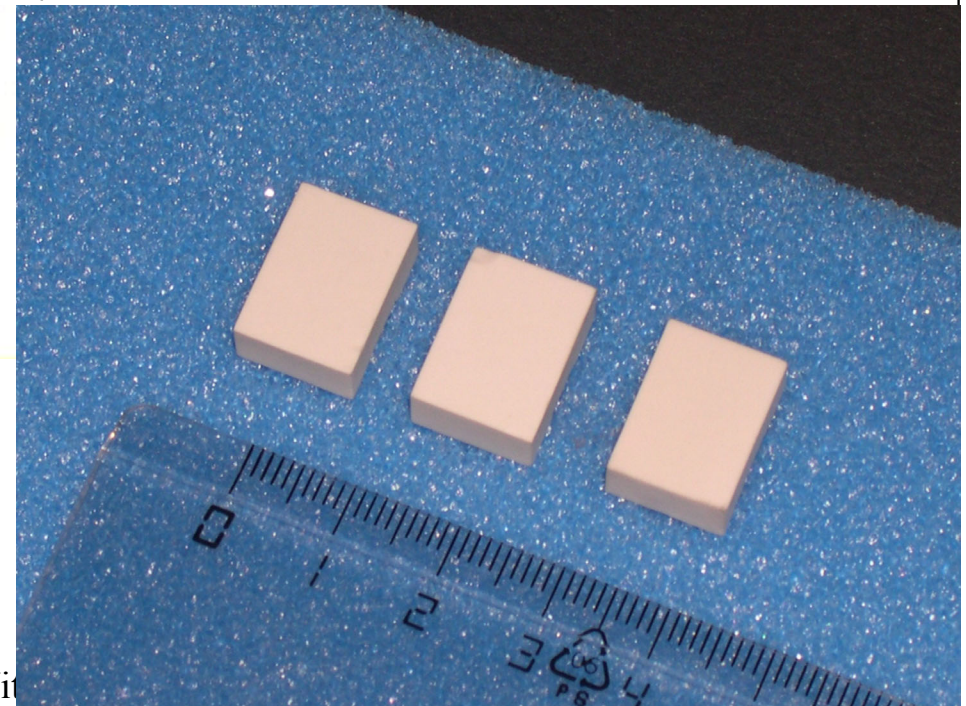
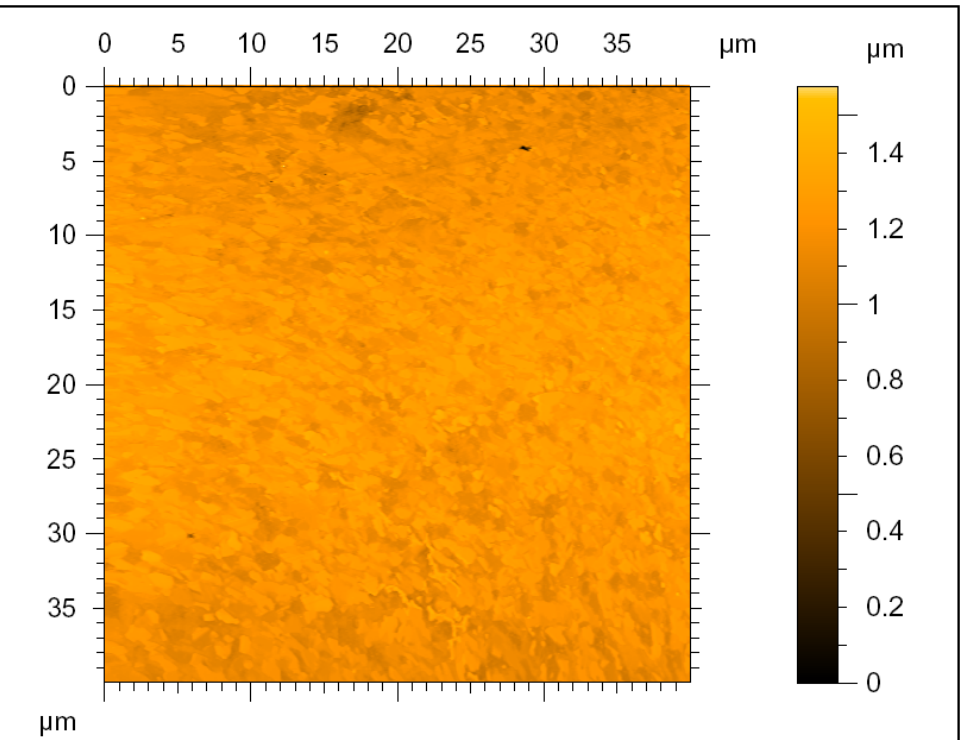
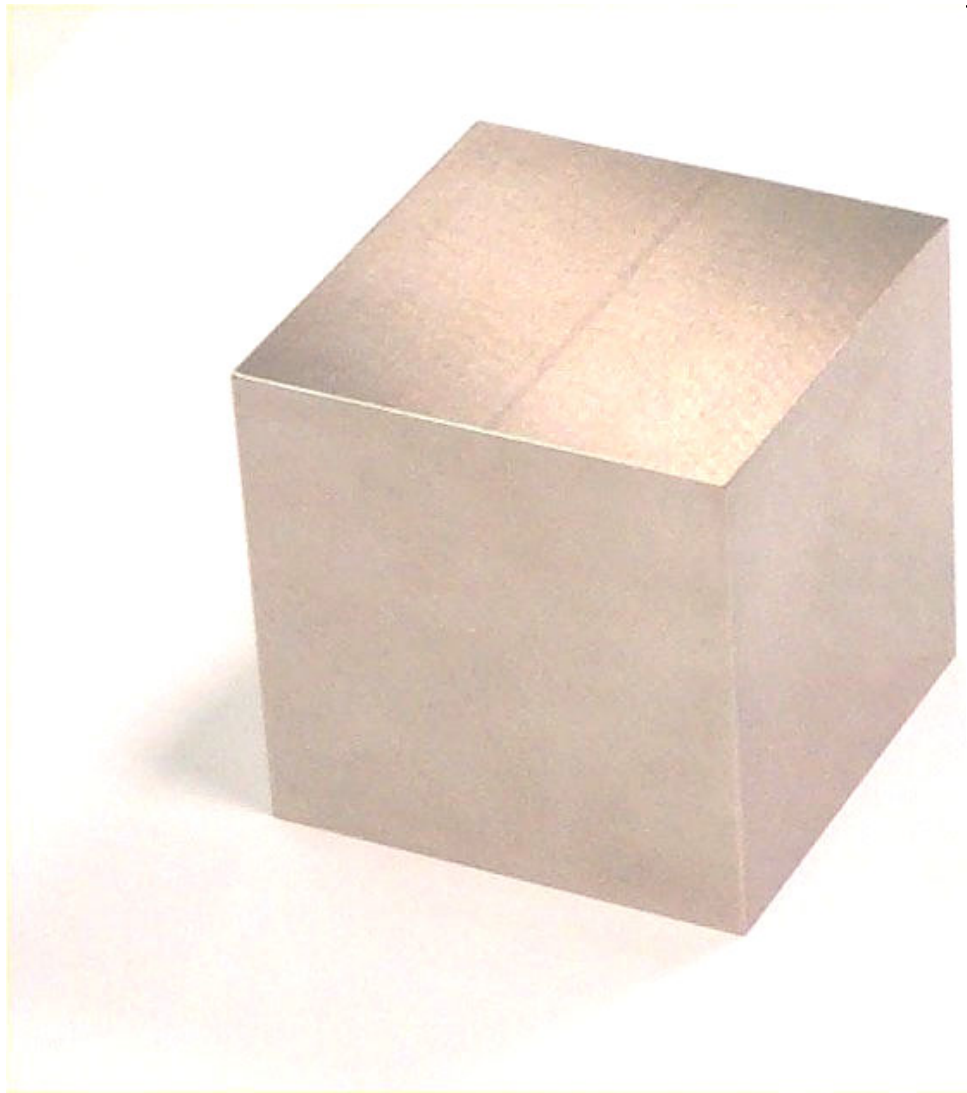


The phasemeter noise is already good enough. It is near the theoretical A/D converter noise (LTC1604 at 15 bit / 25 kHz). The interferometer noise at low frequencies is under investigation.



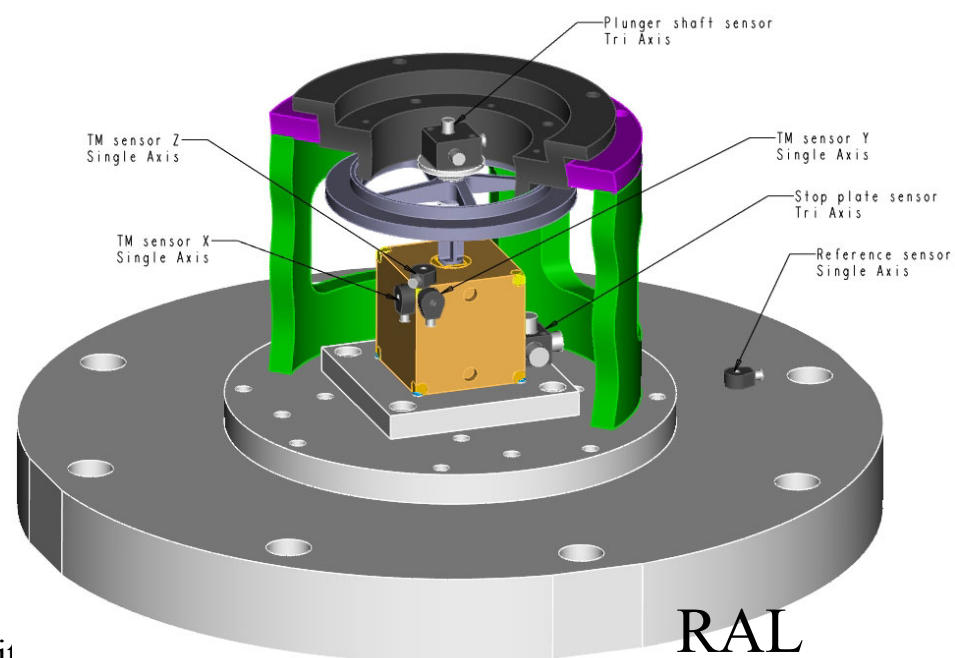
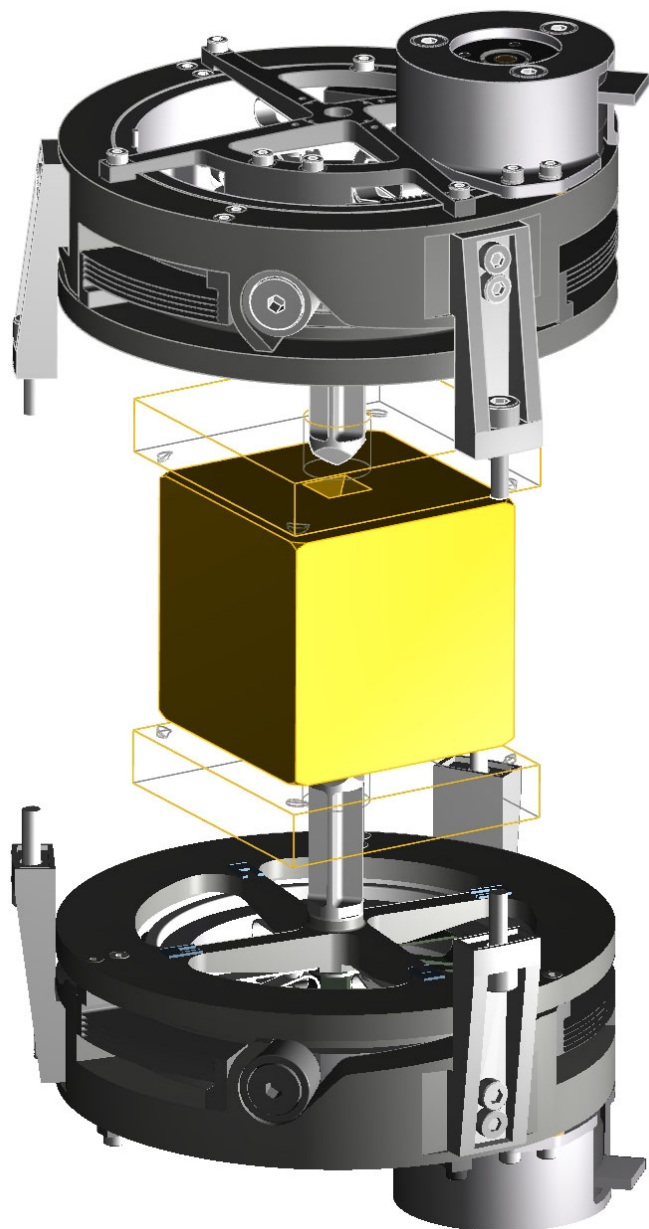






Caging

Adhesion/damage test completed



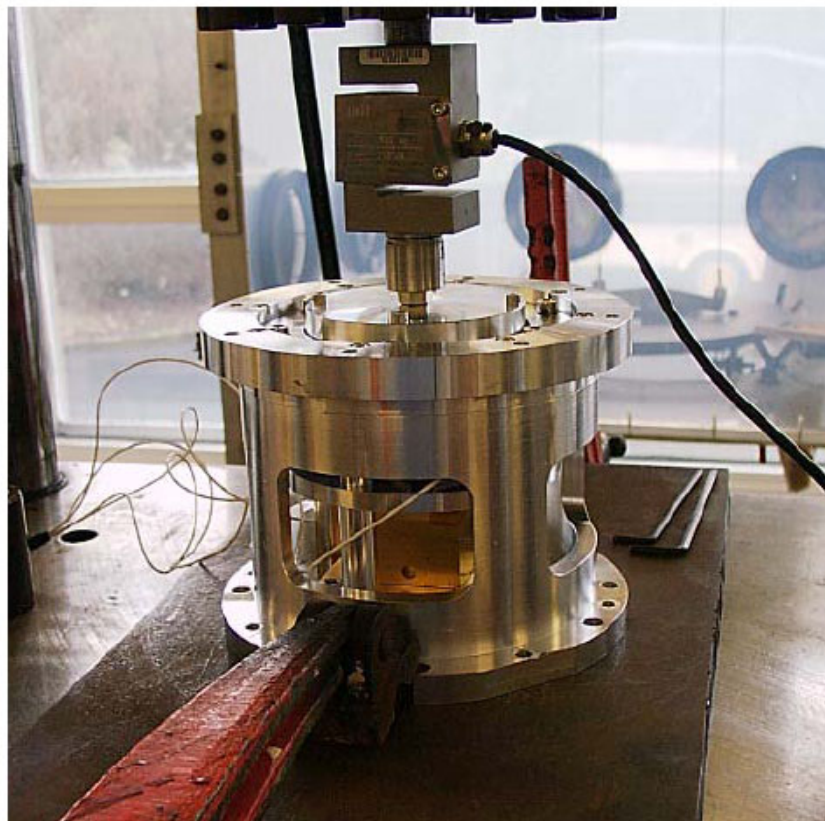


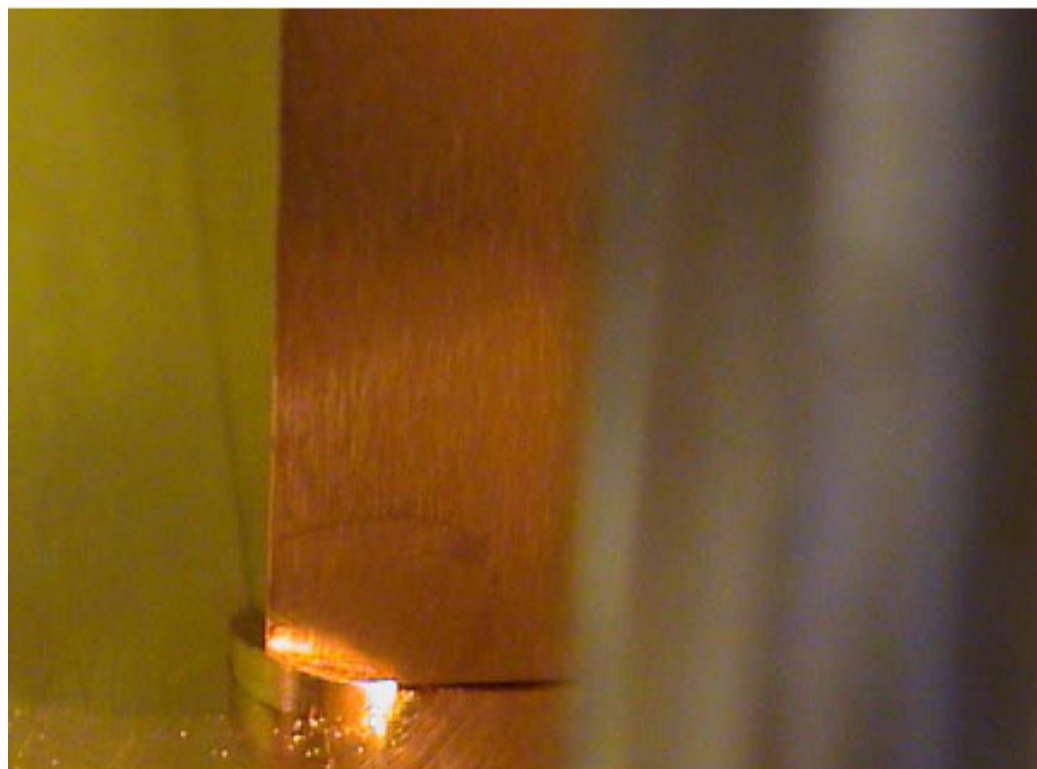
Figure 4-1 Plunger/TM Separation

No damage detected at stops

Pre-load 2500 N

Residual adhesion 50 N

Requirement <2000 N



Charge management

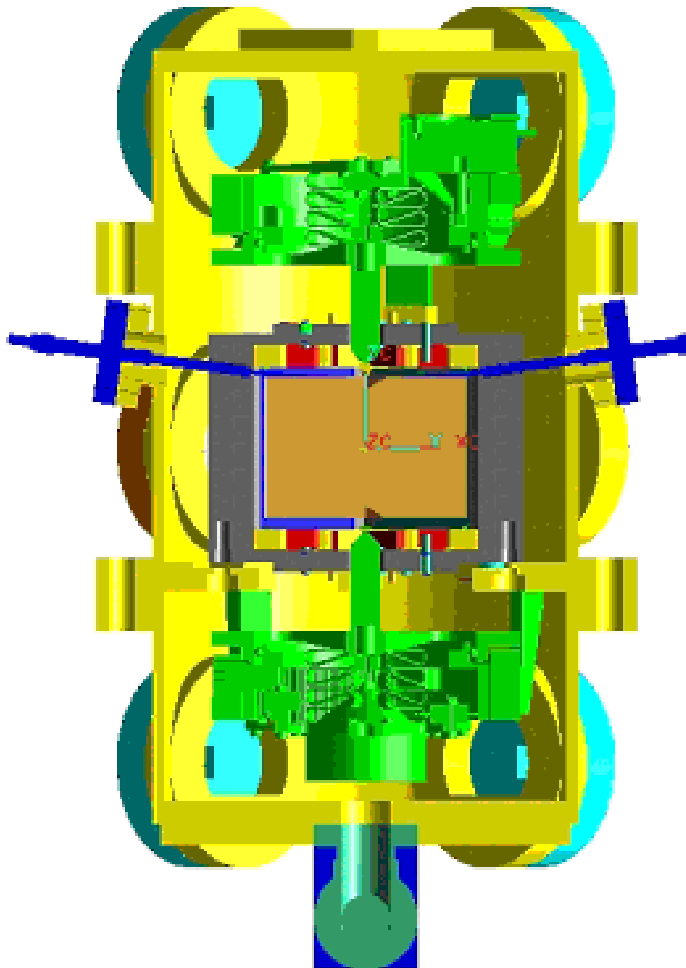
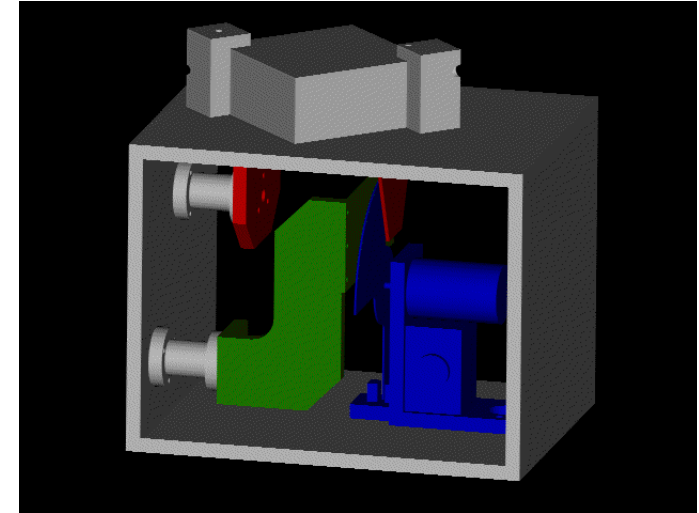
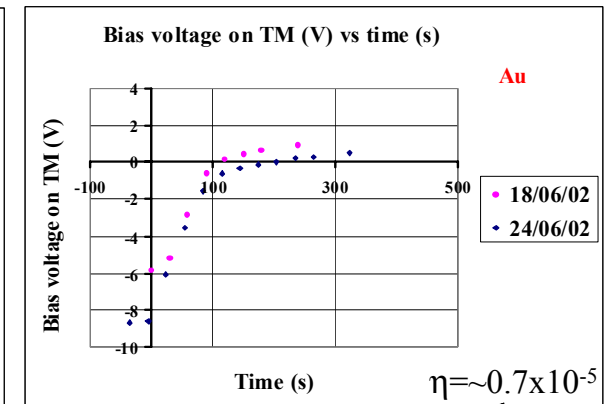
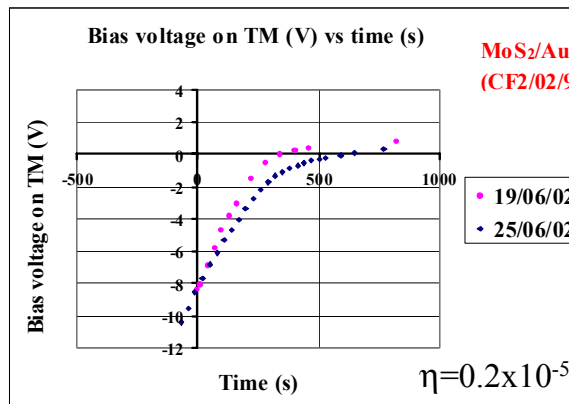
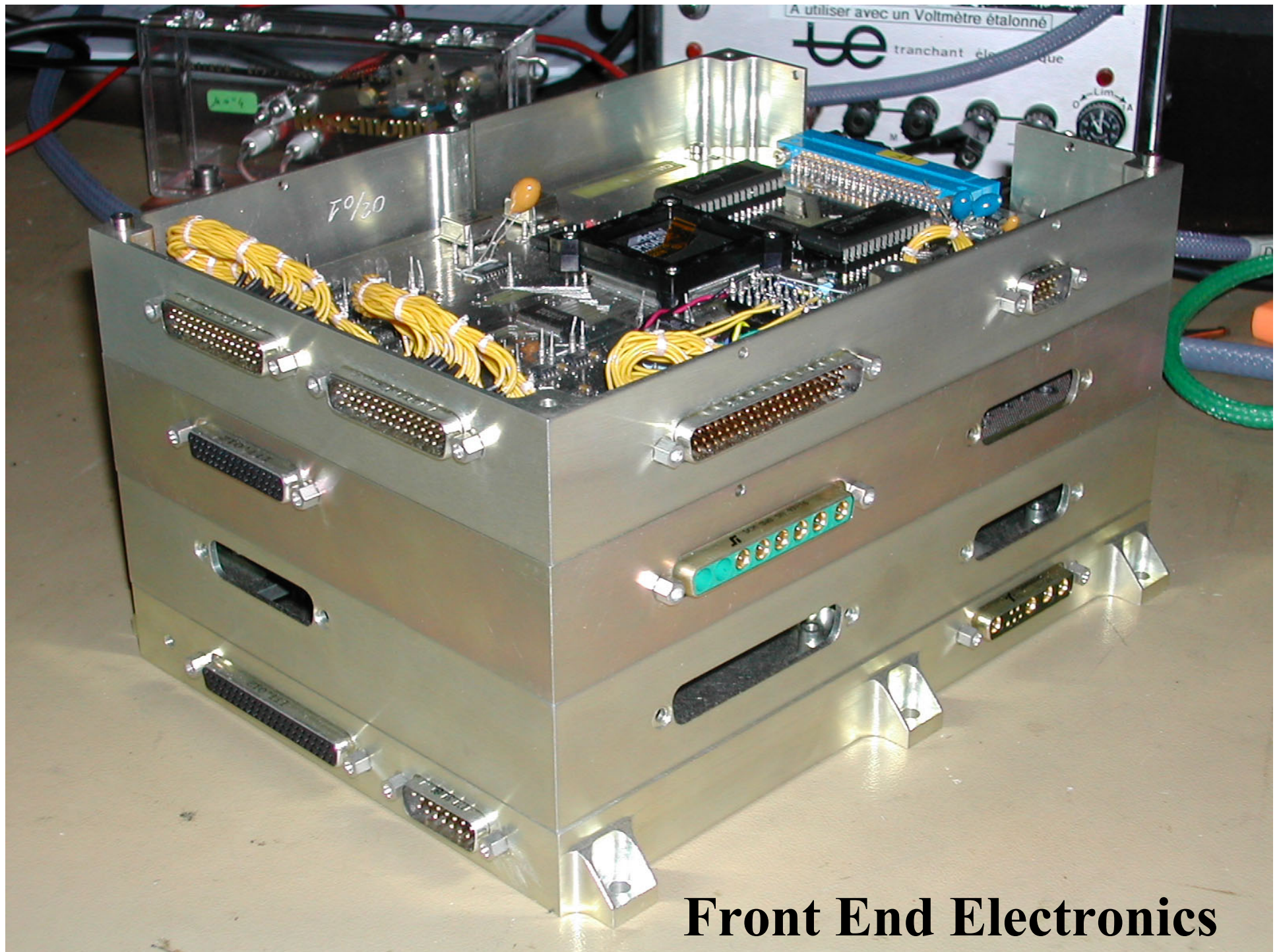


Photo-emissive surfaces

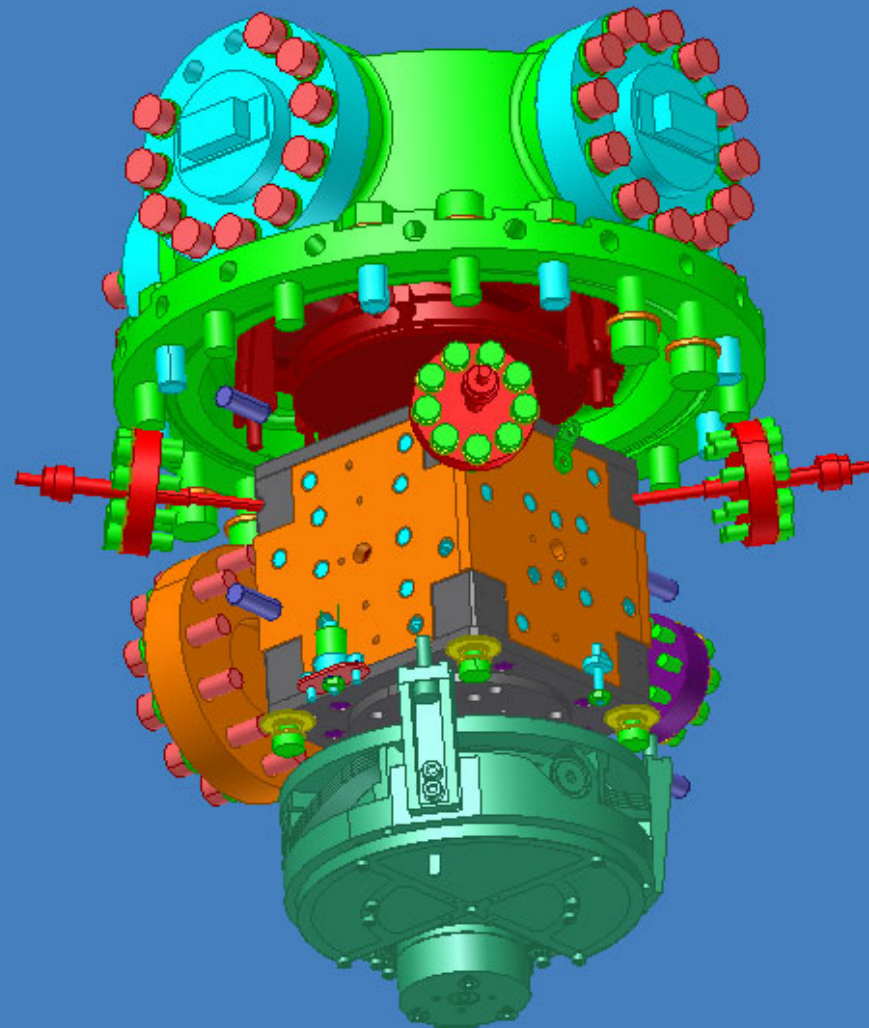
- Tests have been done on sample surfaces made of Au and Au/MoS₂ within LTP development programme.

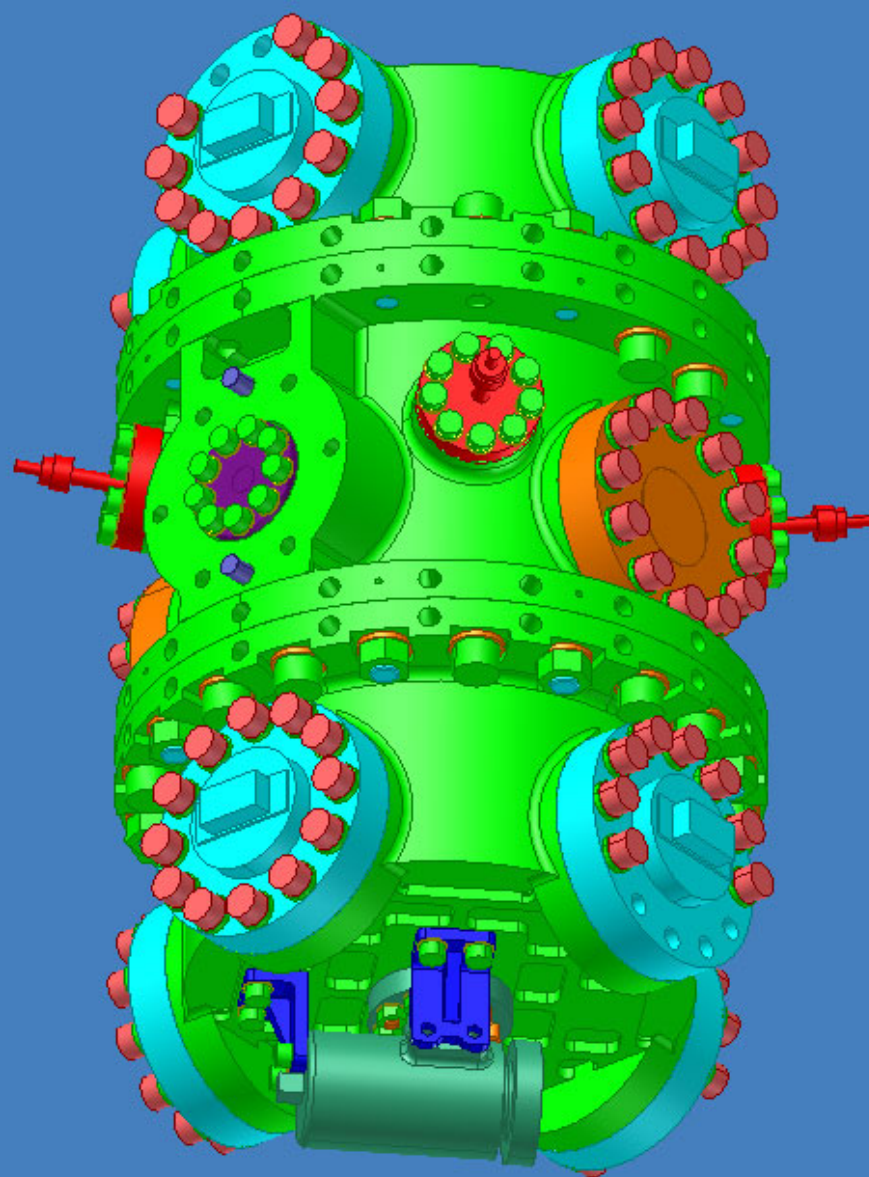


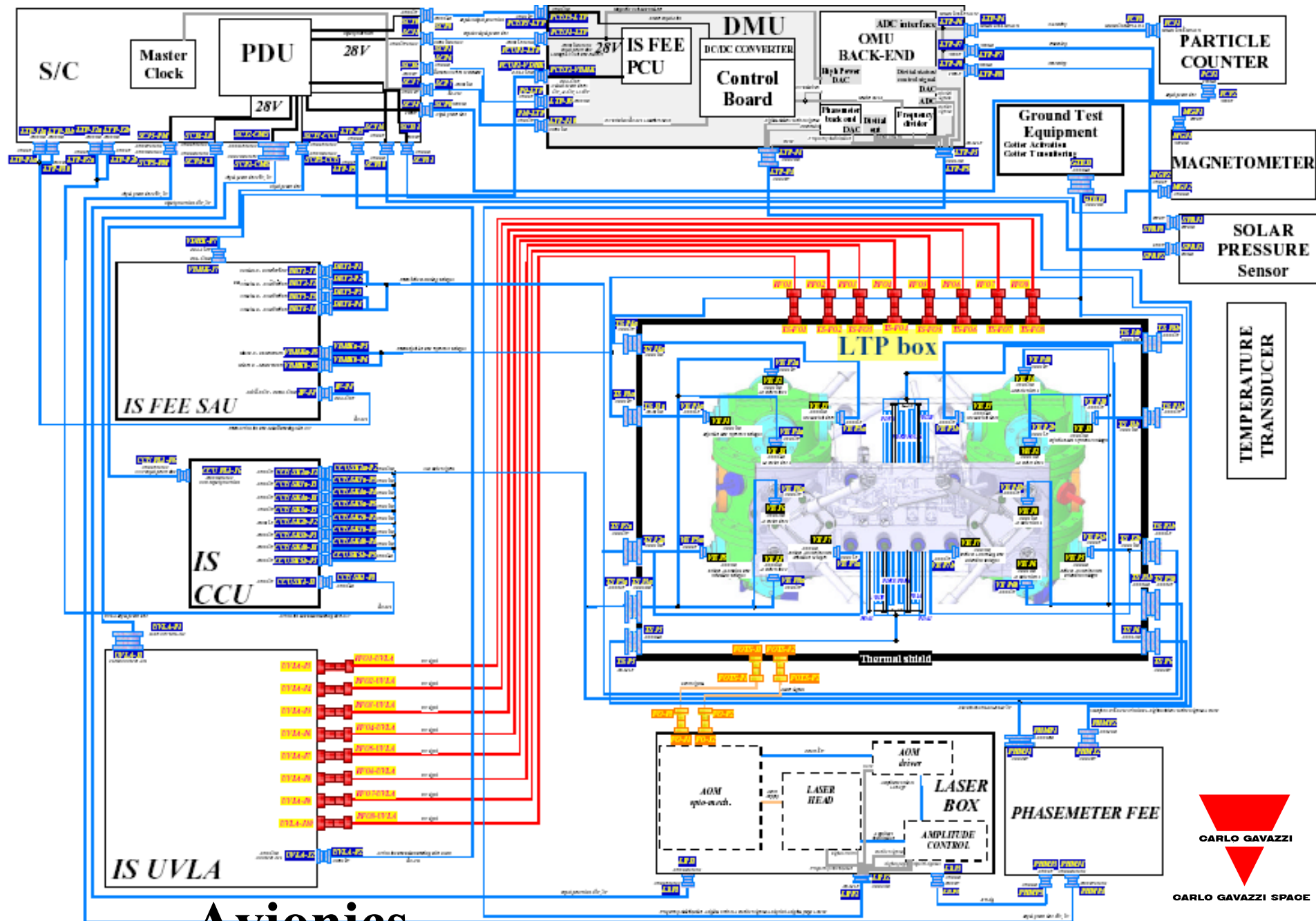
**LISA discharge in
100secs!!**



Front End Electronics

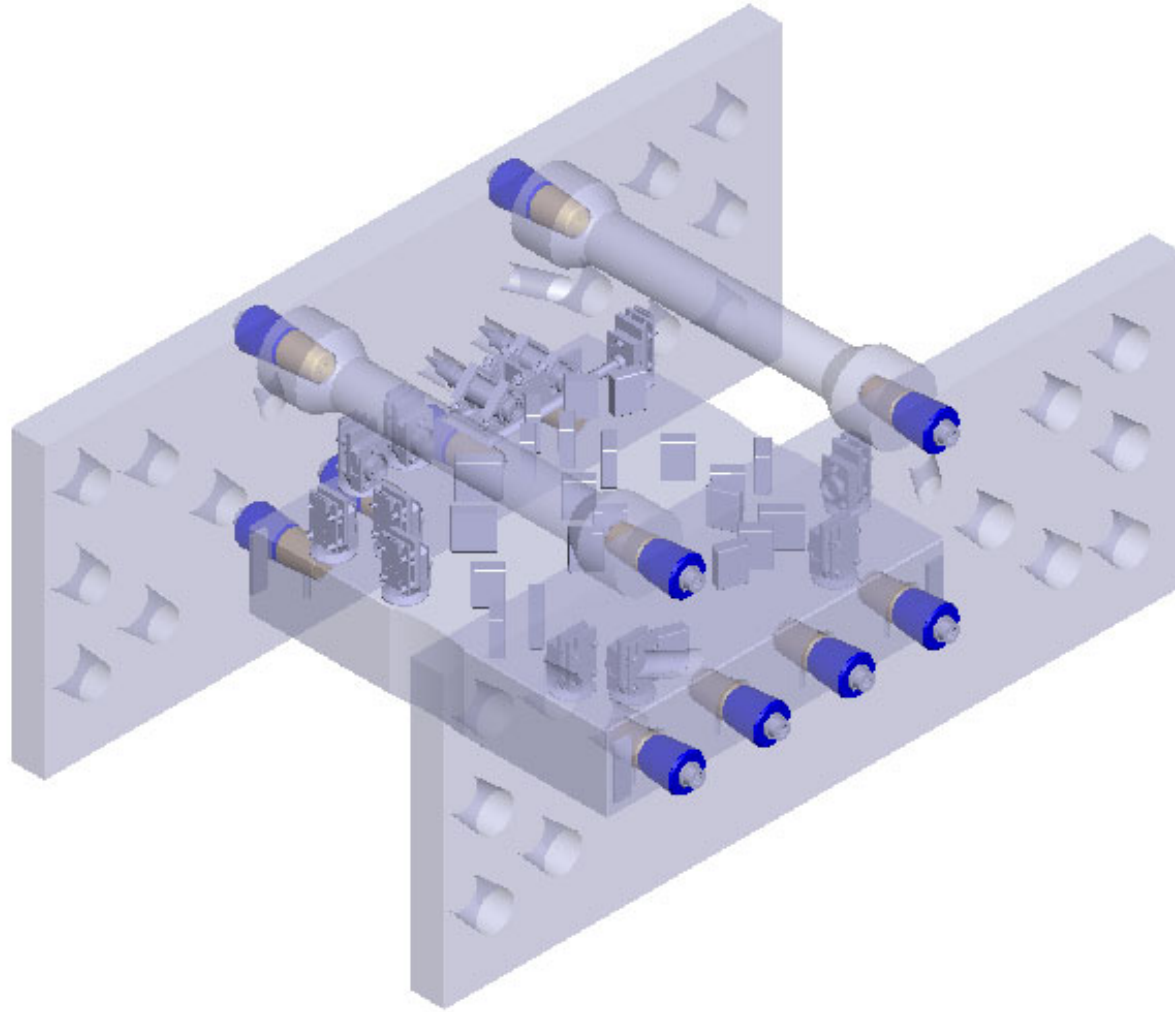


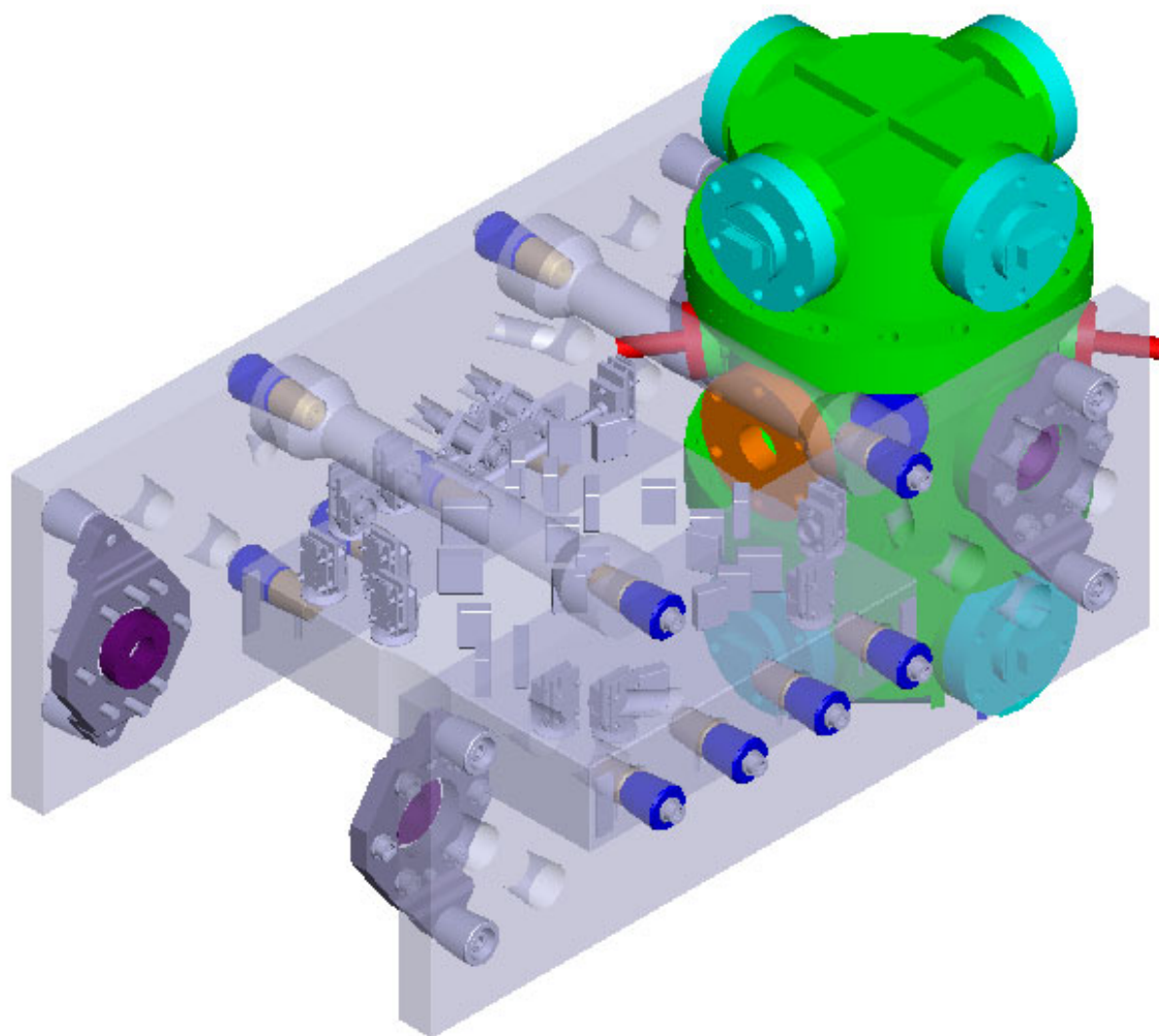


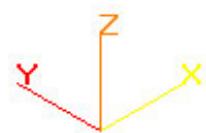
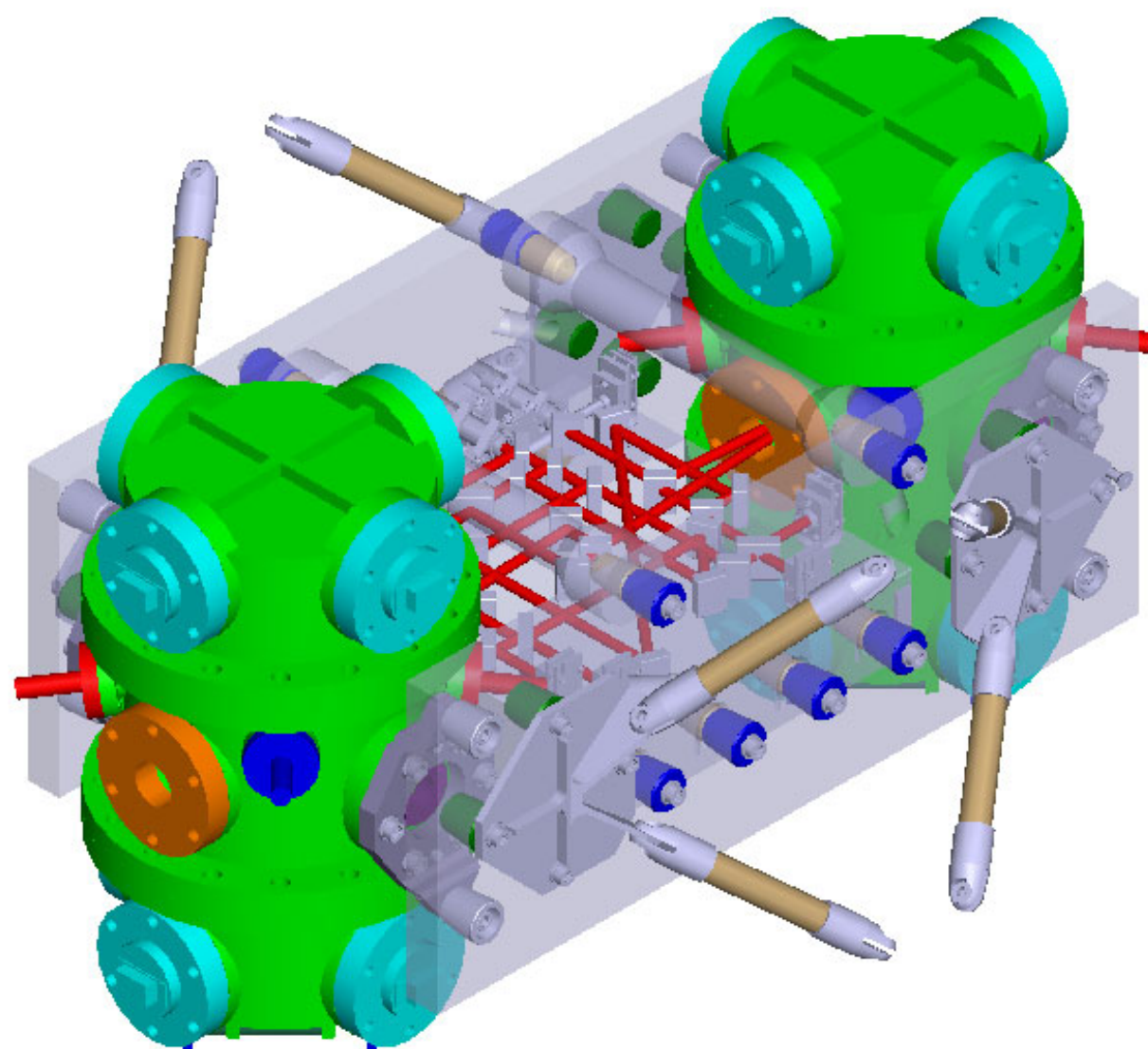


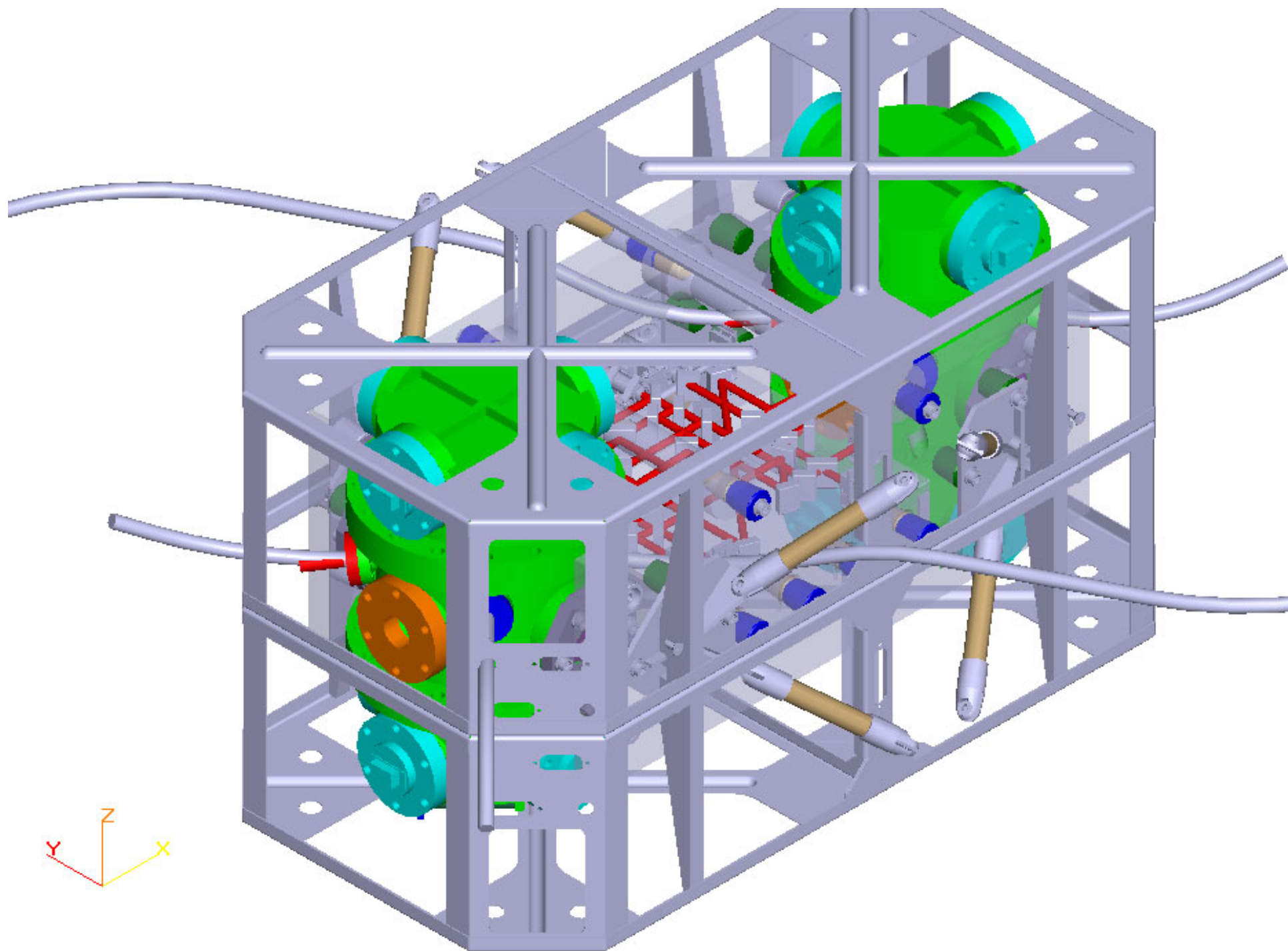
Avionics

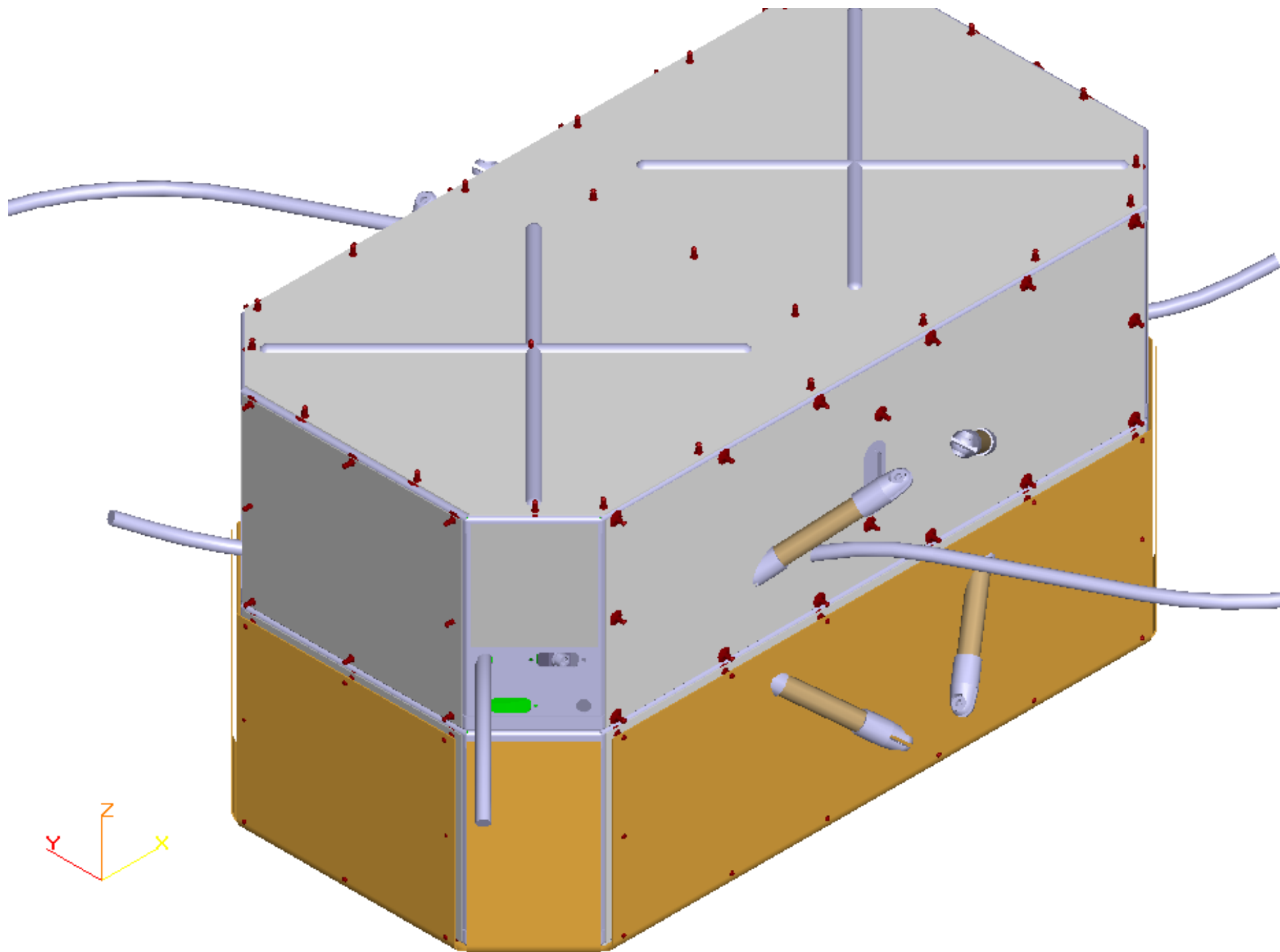


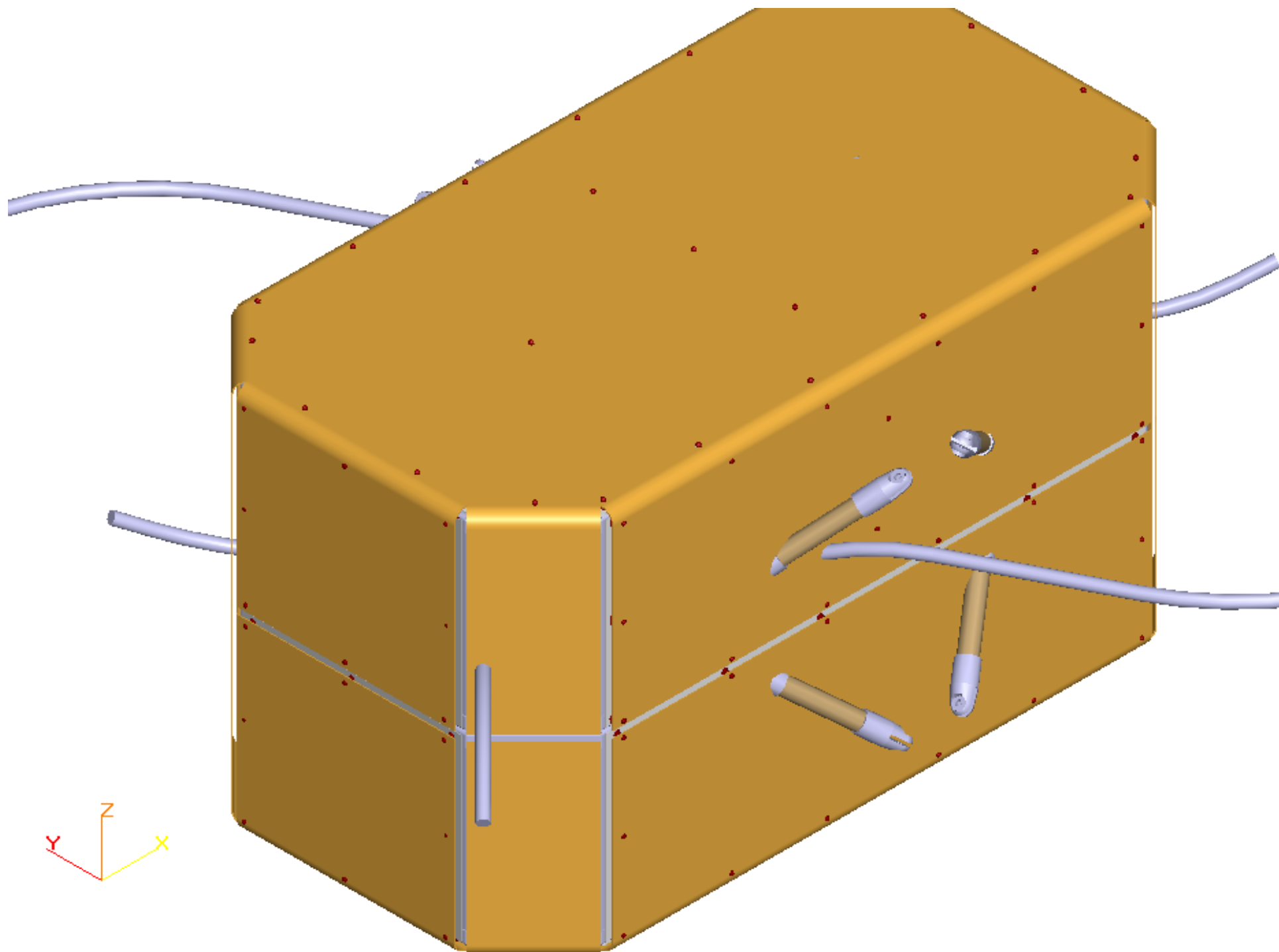


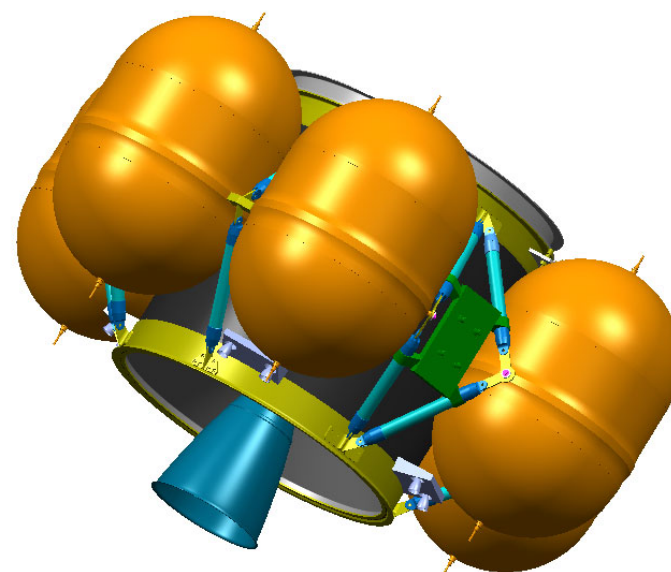
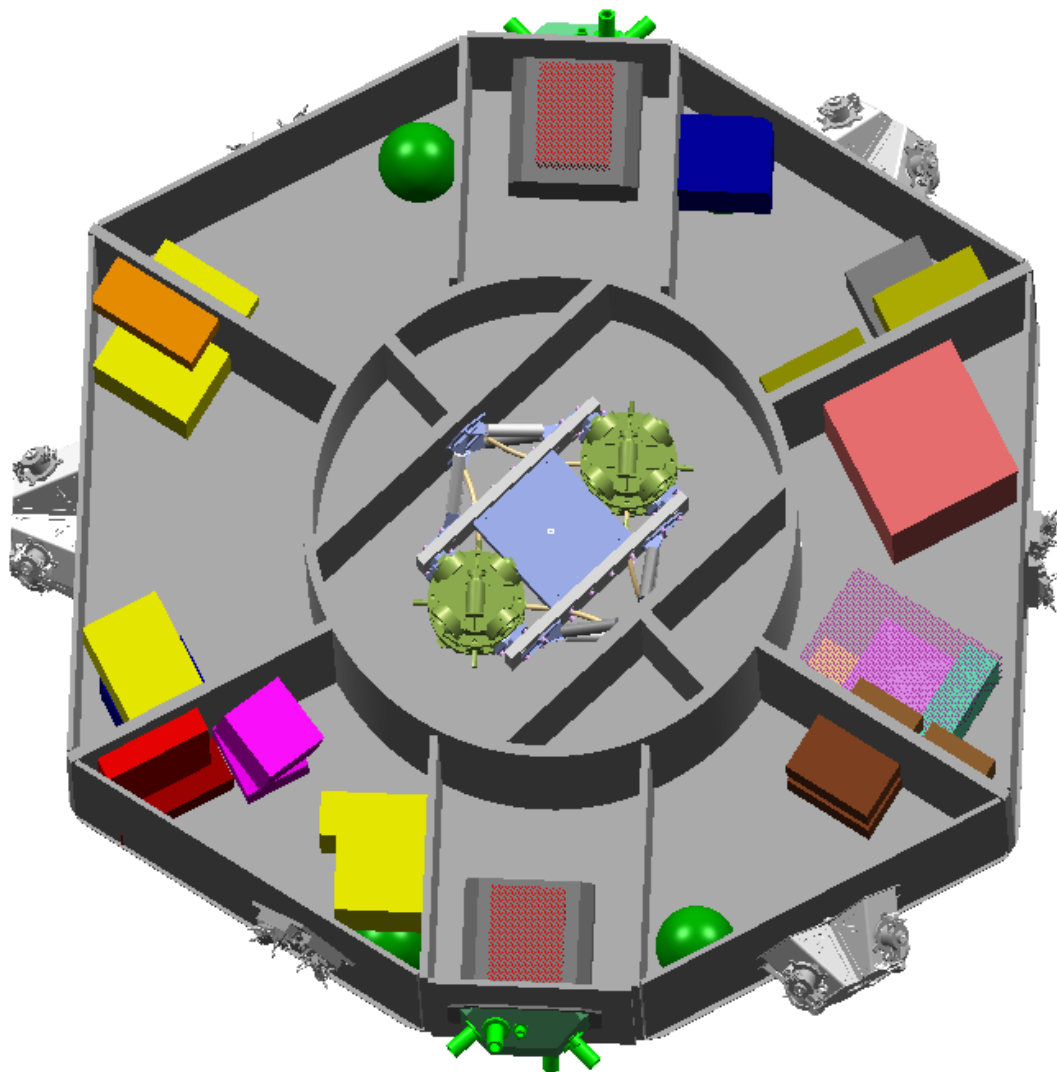


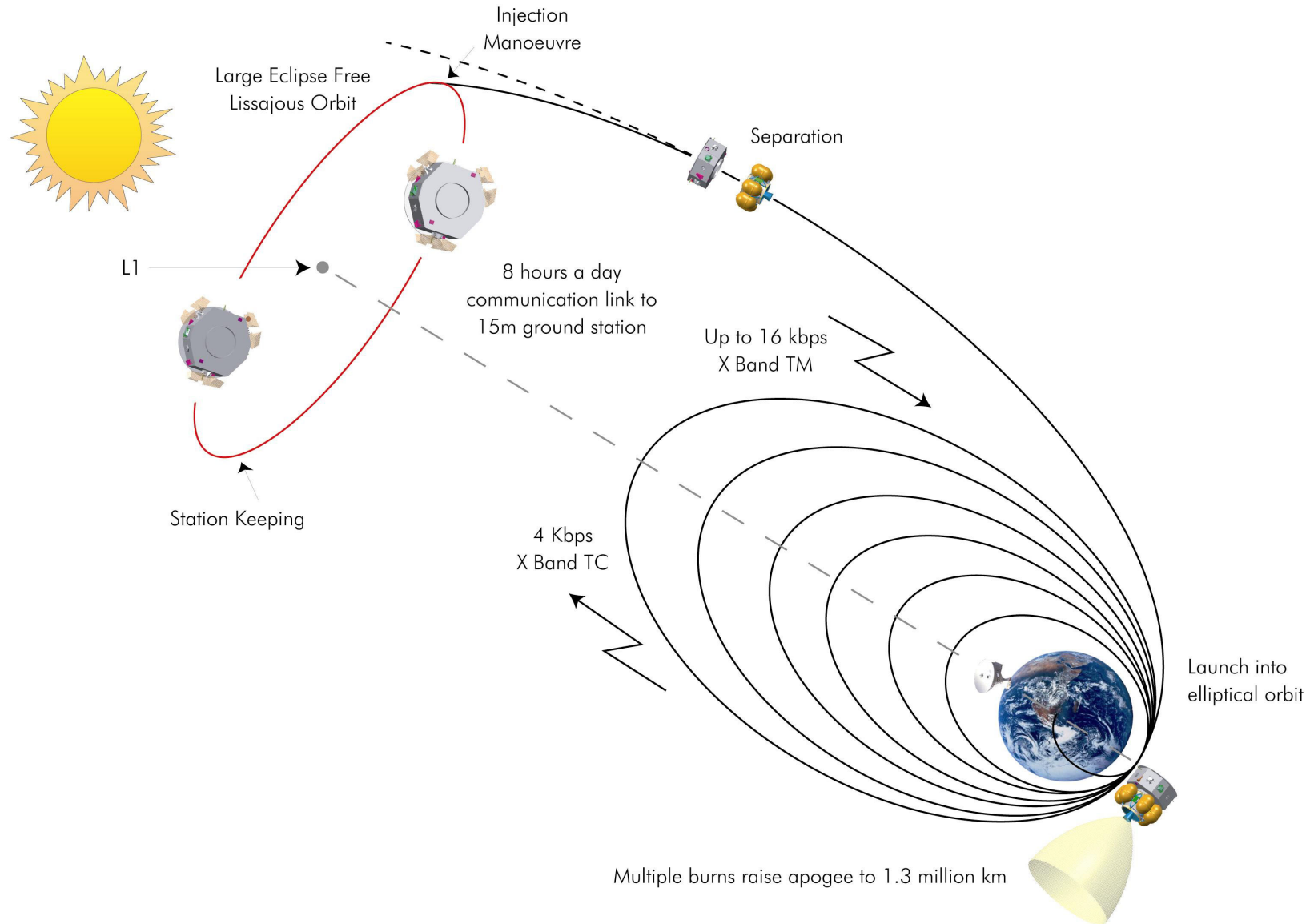






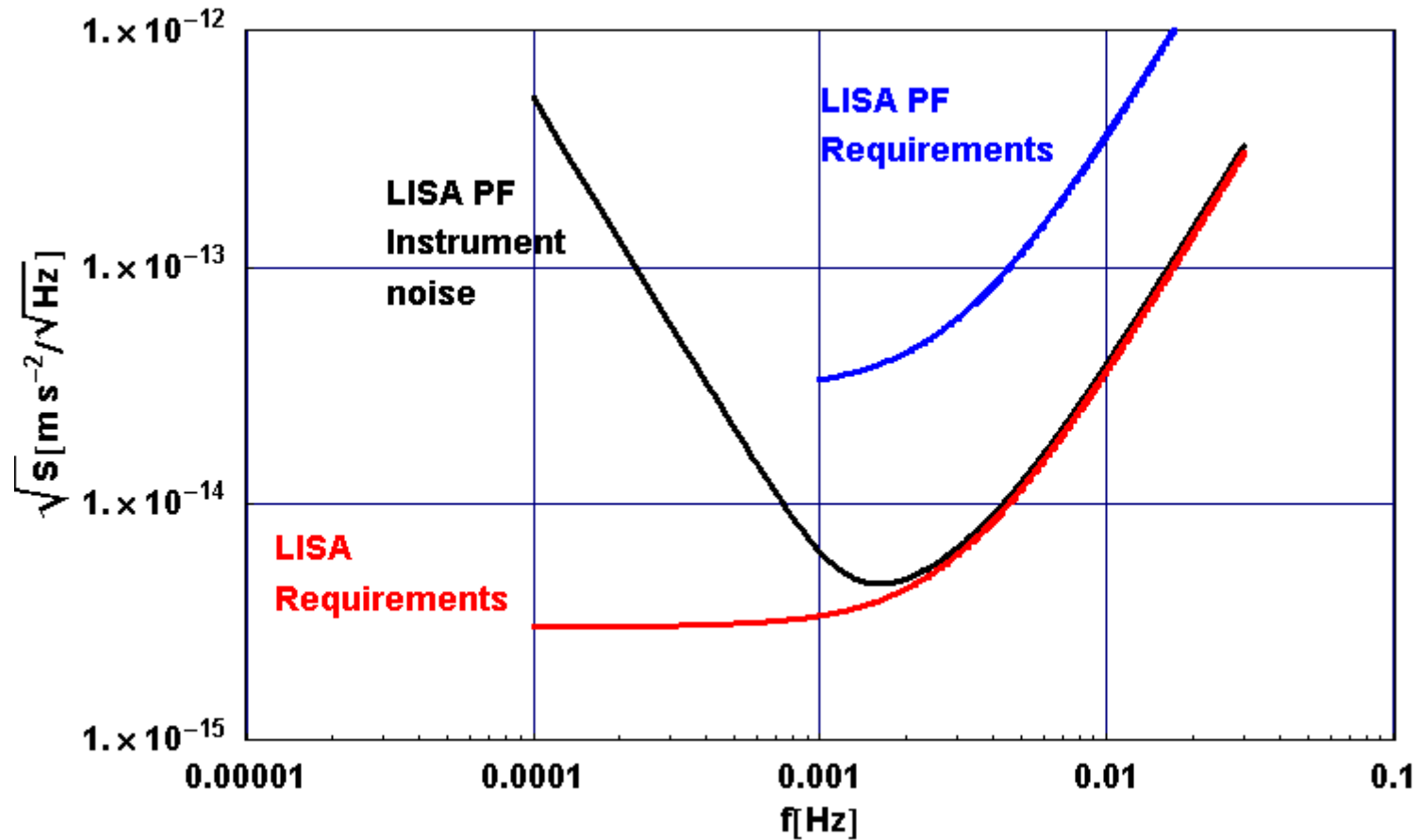




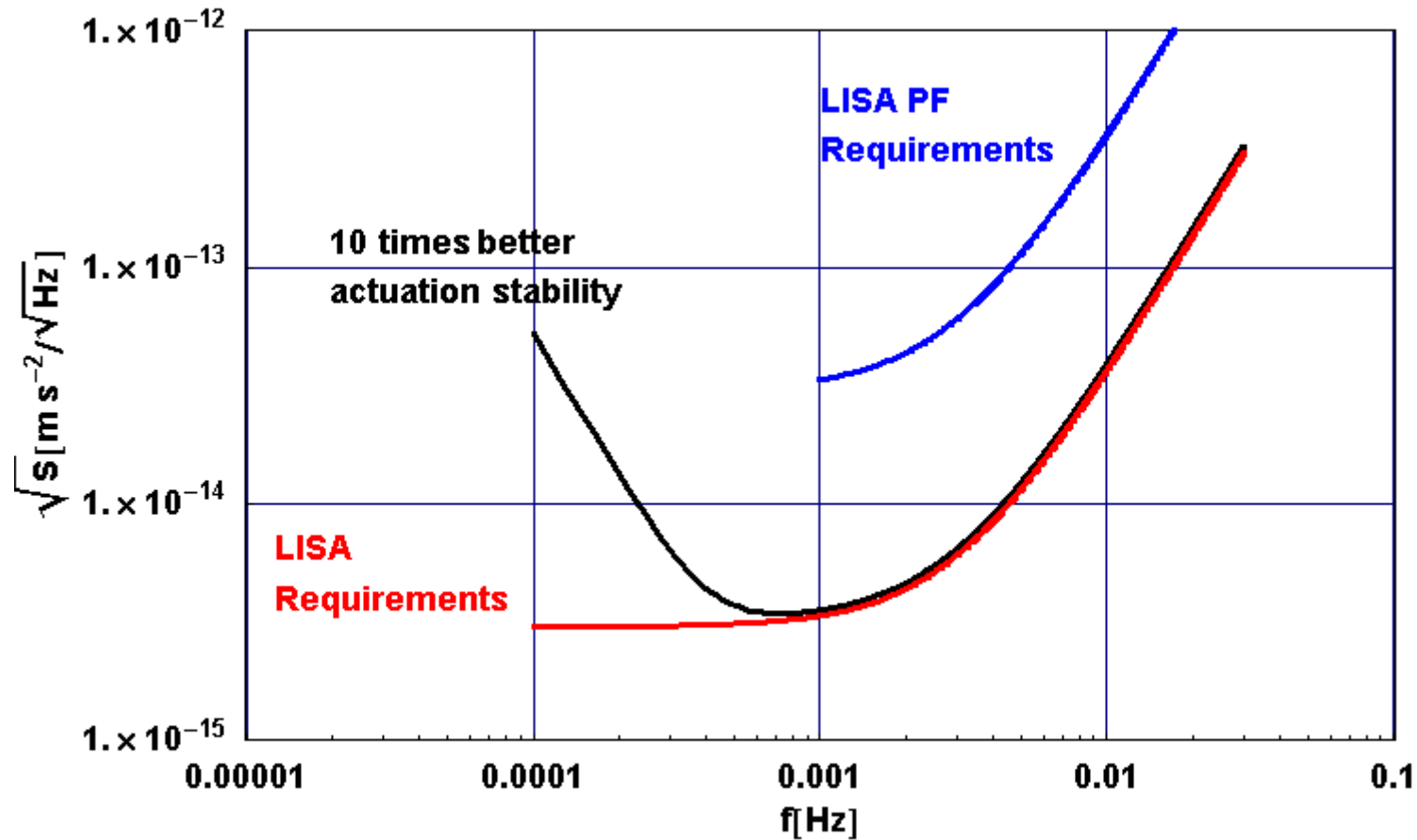


LISA Technology Package Architect

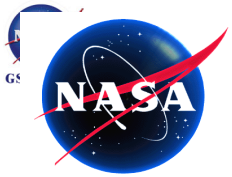
5.3	Test requirements	22
5.3.1	List of required tests.....	23
5.3.1.1	<i>Run 1 Measurement of total acceleration</i>	<i>23</i>
5.3.1.2	<i>Run 1.1 Measurement of acceleration noise in M3.....</i>	<i>24</i>
5.3.1.3	<i>Run 2 Measurement of internal forces</i>	<i>24</i>
5.3.1.4	<i>Run 3 Stiffness calibration and thrust noise determination</i>	<i>25</i>
5.3.1.5	<i>Run4 Measurement of cross talk.....</i>	<i>25</i>
5.3.1.6	<i>Run 5 Test of continuous charge measurement</i>	<i>25</i>
5.3.1.7	<i>Run 6 Test of continuous discharge</i>	<i>25</i>
5.3.1.8	<i>Run 7 Drift mode.....</i>	<i>26</i>
5.3.1.9	<i>Run8 Acceleration noise at different working points.....</i>	<i>26</i>
5.3.1.10	<i>Run 9 <1 mHz acceleration noise measurement.....</i>	<i>26</i>
5.3.1.11	<i>Run 10 Sensitivity to magnetic field and thermal gradients, and estimate of the parasitic dc potential.</i>	<i>26</i>
5.3.2	Joint operation with Disturbance Reduction System.....	27
5.3.2.1	<i>2-axes 2-test-mass control with full functionality for both packages and one axis controlled by DRS.....</i>	<i>27</i>



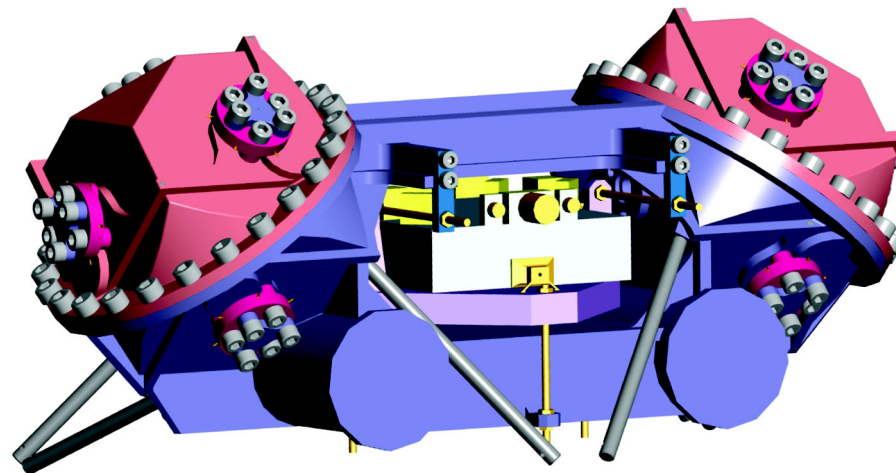
Instrument noise: laser + actuation



Instrument noise: laser + actuation



ST7+LTP A combined experiment



JPL

Trieste-25-09-03

S. Vitale

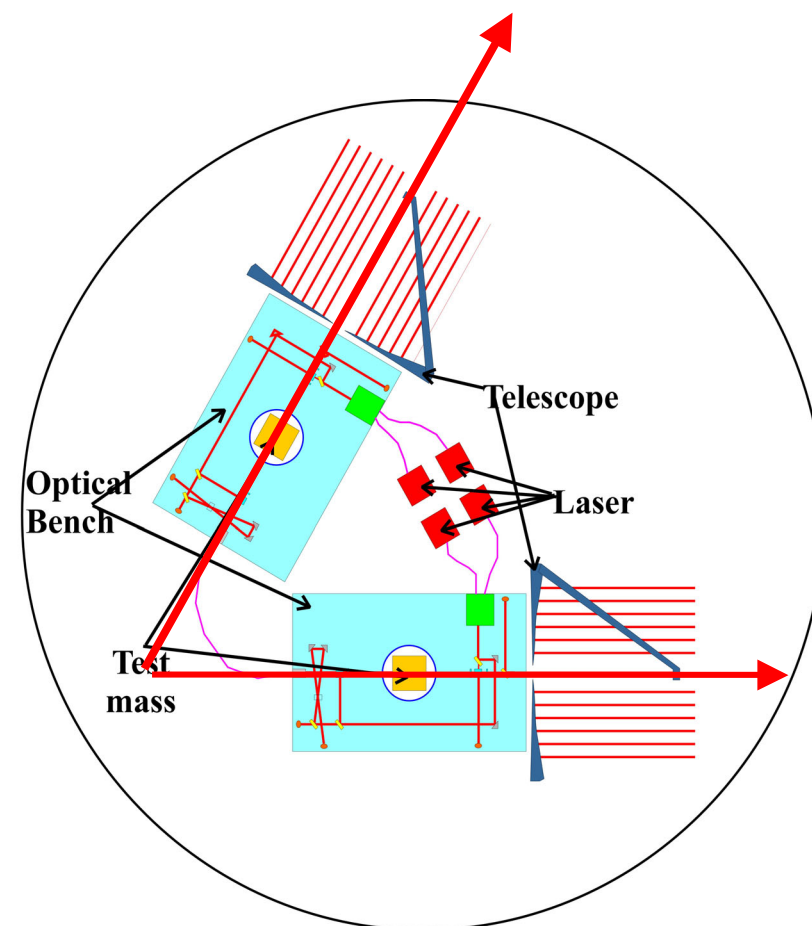
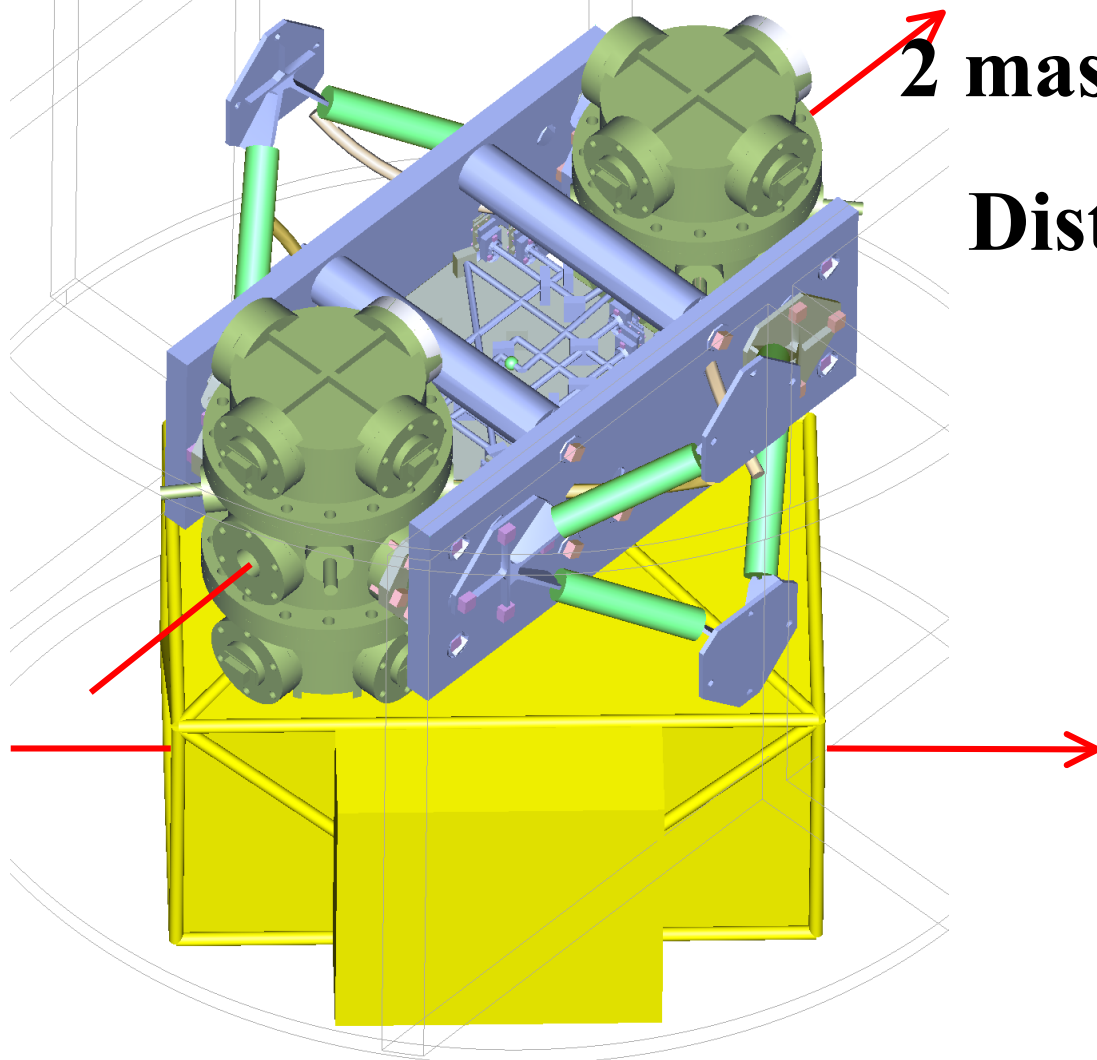


154

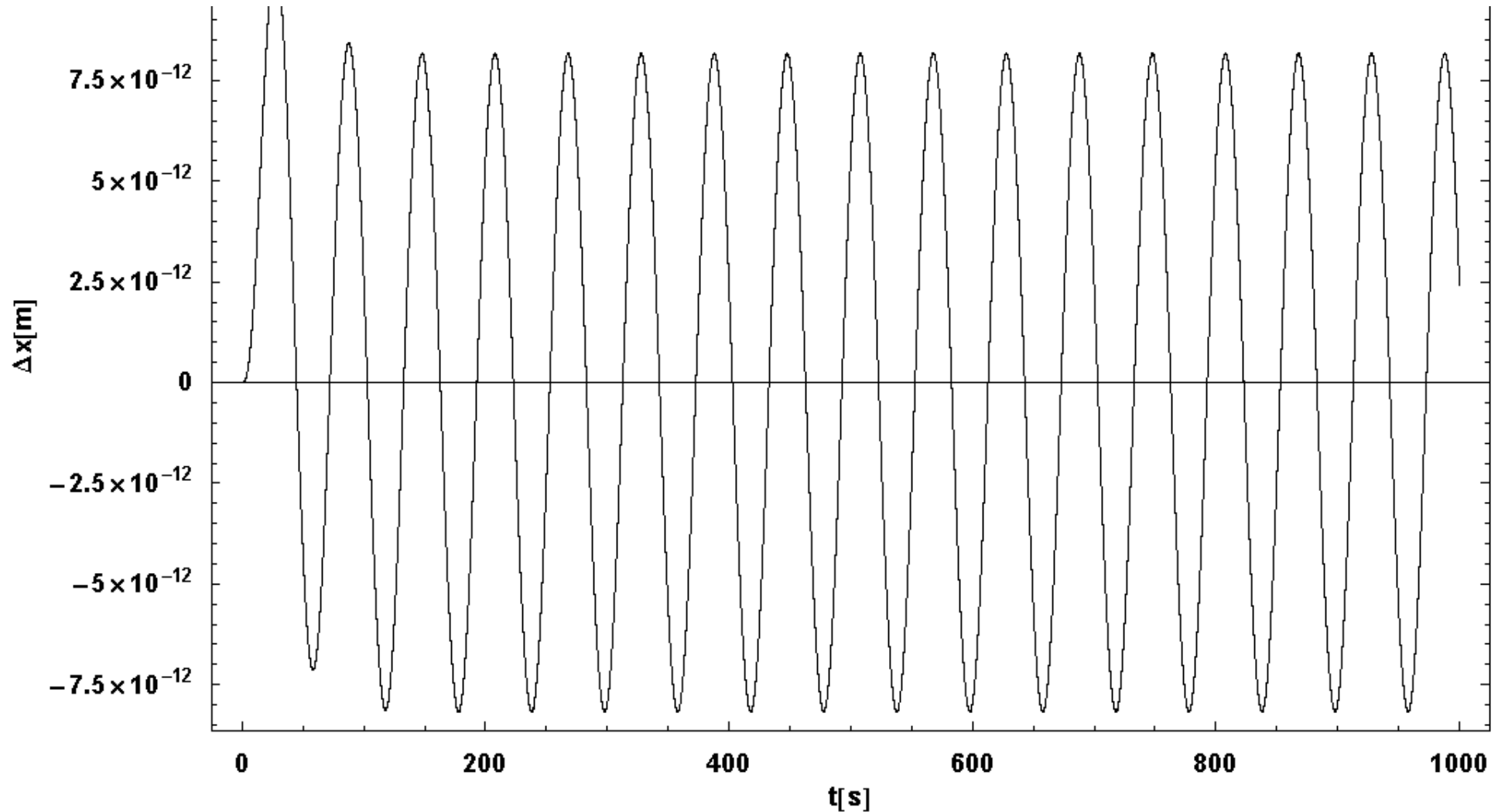
LTP/ST-7 joint operation

2 masses control as in LISA

Disturbance correlation



Gravitational calibration (big G at 1 mo km?)



200 μm p-p displacement of ST-7 test-mass: signal at LTP output. SNR>1000 in a few hours



Site Map

structure and evolution of the universe

BEYOND EINSTEIN

FROM THE BIG BANG TO BLACK HOLES

The Science

The Program

The Program

- o Great Observatories
- o Probes
- o Vision Missions

The *Beyond Einstein* program has three linked elements which advance science and technology towards two visions: to detect directly gravitational wave signals from the earliest possible moments of the [Big Bang](#), and to image the event horizon of a [black hole](#). The central element is a pair of [Einstein Great Observatories](#), [Constellation-X](#) and [LISA](#). These powerful facilities will blaze new paths to the questions about black holes, the Big Bang, and [dark energy](#). They will also address other central goals of contemporary astrophysics (discussed in Part II of the [2003 Roadmap](#)). The second element is a series of competitively selected [Einstein probes](#), each focused on one of the science questions. The third element is a program of [technology development](#), theoretical studies, and [education](#), to support the [Probes](#) and the [vision missions](#): the [Big Bang Observer](#) and the [Black Hole Imager](#). The program offers competitive opportunities for mission leadership, technology development, and groundbreaking scientific research, with goals that excite the public.

What's New

Press Room

2003 Roadmap

The Technology

Education

Life Cycles of Matter and Energy

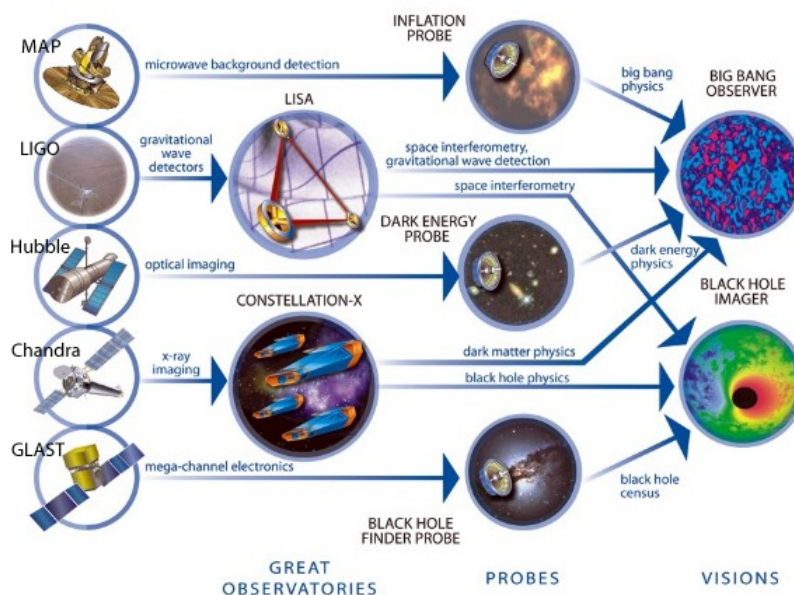
Resources

People

Contact Us

[Home](#)

Beyond Einstein Program







Technical Readiness, Implementation and Planning



TRIP Site Visit

Beyond
Einstein:
From the
Big Bang
to
Black
Holes

Agenda

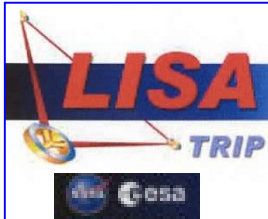
- 8:00** *Welcome & Introductions* L. Simmons / C. Elachi / A. Diaz
B. Cramer / A. Gianolio
S. Volonte / J. Hrastar
- 8:30** *A - Briefing Introduction* B. Cramer
- 8:40** *B - Science Requirements & Mission Science Performance* T. Prince
T. Stebbins
- 9:35** *C - Mission Implementation Plan (Part 1)* C. McGraw
- 10:00** **BREAK**
- 10:15** *C - Mission Implementation Plan (Part 2)* O. Jennrich / K. Danzmann
C. McGraw
- 11:30** *D - Technology Roadmap and Program Formulation (Part 1)* S. Merkowitz
- 12:00** **LUNCH**
- 1:00** *Board Executive Session*
- 1:30** *D - Technology Roadmap and Program Formulation (Part 2)* S. Vitale
B. Folkner
- 3:00** **BREAK**
- 3:15** *D - Technology Roadmap and Program Formulation (Part 3)* K. Danzmann
- 3:45** *E - Management, Schedule, and Budget* G. Man / B. Cramer
- 4:10** *Contingency Period (Questions & Discussion)*
- 4:40** *F - Briefing Summary* A. Gianolio
- 4:50** *G - Introduction to Tour* A. Abramovici
- 5:00** *Guided Tour*
- 6:00** *Adjourn*



GSFC - JPL

ii





LISA-TRIP

SUMMARY

Assessment of Risk

Achieving technology roadmap: Medium

Formulation in addition to technology development: Medium

Implementation: Medium

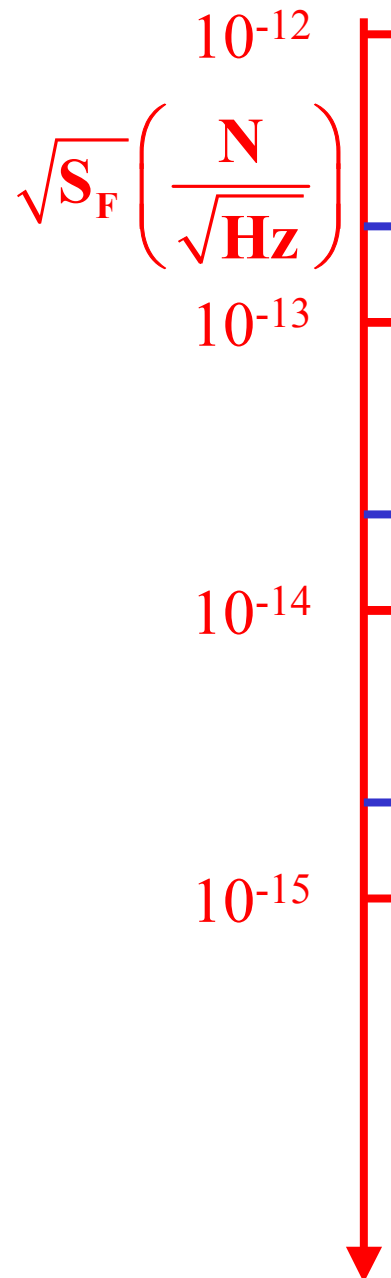
April 22, 2003

26

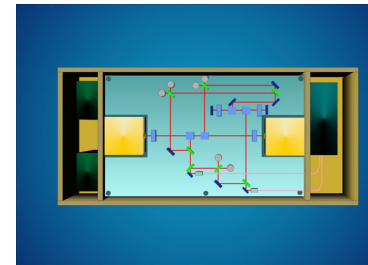
Beyond Einstein: From the Big Bang to Black Holes



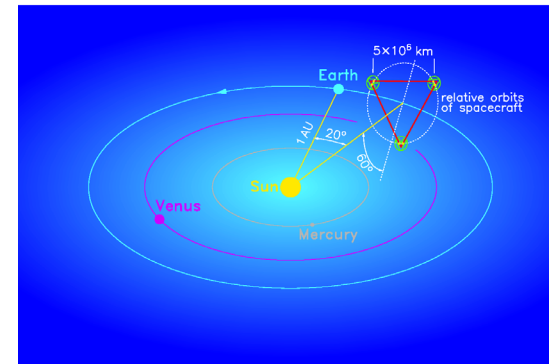
Testing quality of free fall



Torsion pendulum
(surface disturbances)



LISA PF



LISA

The plan:

**LISA PF/LTP-ST7, ESA/NASA technology
demonstration mission 2007**

**LISA NASA/ESA $\approx$ 50/50 collaborative mission
2012**

2013: enjoy listening to black-holes

The Big Bang Observer:

Direct detection of gravitational waves from the birth of the Universe
to the present

P.I.: E. S. Phinney

US Co-Is: Peter Bender, Saps Buchman, Robert Byer, Neil Cornish, Peter Fritschel, William Folkner, Stephen Merkowitz

Foreign Co-P/Is: Karsten Danzmann, Luciano DiFiore, Seiji Kawamura, Bernard Schutz, Alberto Vecchio, Stefano Vitale

Collaborators: John Armstrong, Fabrizio Barone, Charles Bennett, Jordan Camp, Joan Centrella, David Chernoff, Adrian Cruise, Curt Cutler, Frank Estabrook, Jens Gundlach, Gerhard Heinzl, Ronald Hellings, Craig Hogan, James Hough, Scott Hughes, Andrew Jaffe, Barry Kent, William Kinney, Alberto Lobo, Nergis Mavalvala, Thomas Prince, Michael Sandford, Bangalore Sathyaprakash, David

I. Introduction: Primary and Secondary Science Objectives

NASA's 2002 SEU Roadmap *Beyond Einstein* highlights three major unanswered questions raised by Einstein's general theory of relativity:

1. *What powered the Big Bang?*
2. *What happens to space, time and matter at the edge of a black hole?*
3. *What is the mysterious dark energy pulling the Universe apart?*

The prime scientific objective of the Big Bang Observer (BBO) mission is the direct detection of relic gravitational waves from inflation. When combined with cosmic microwave background inferences about gravitational waves 17 orders of magnitude lower in frequency, the BBO measurements will enable quantitative testing of the theory of inflation (§II.1), addressing the first question above (SEU Objective 1 and RFAs 1a).

Gravitational waves from inflation have been propagating essentially unchanged (Weinberg 2003) since the universe was $\lesssim 10^{-35}$ s old, with temperature $kT \sim 10^{14}$ GeV. At

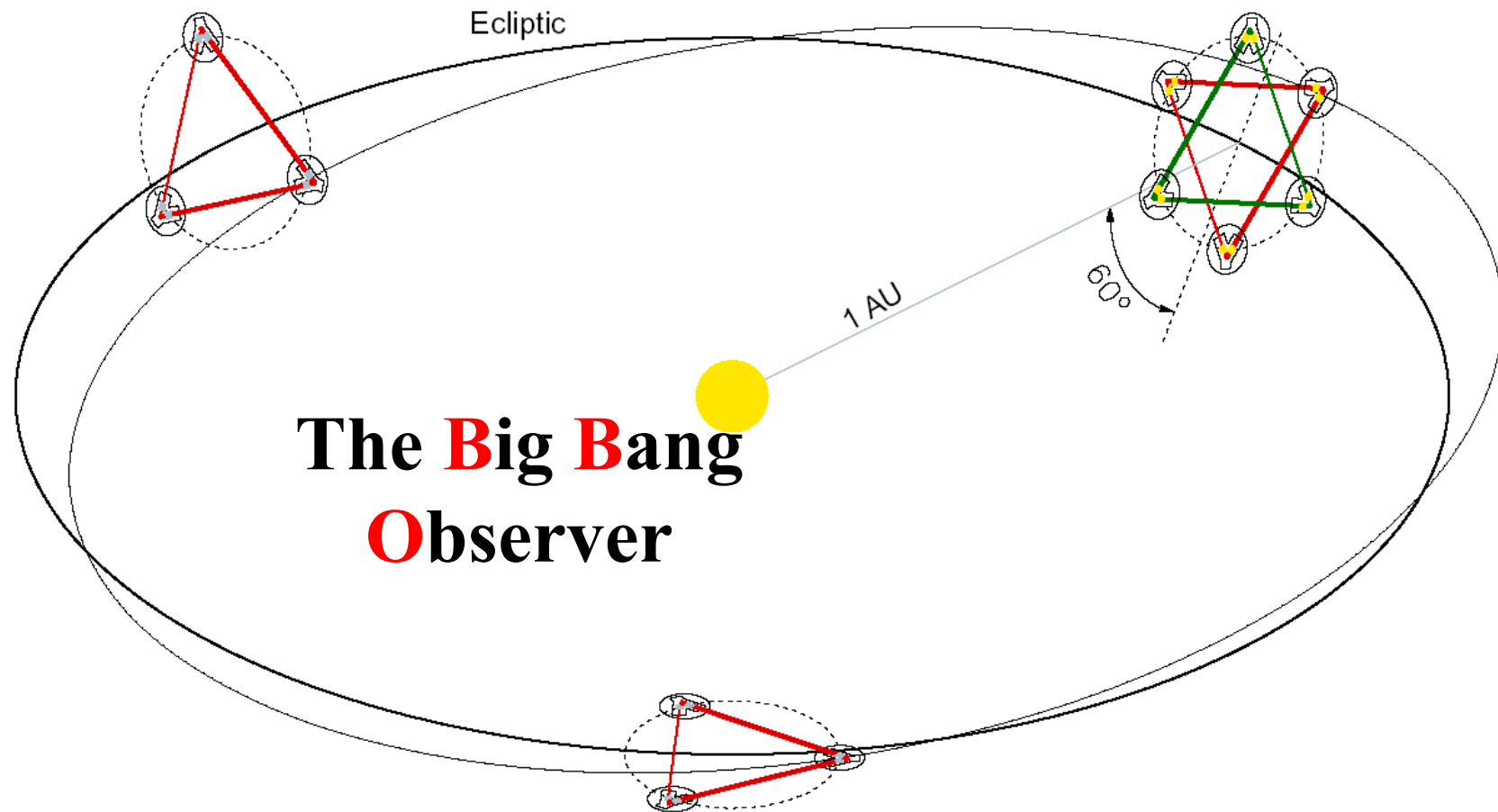


Table 1: Possible BBO Configurations

name	Laser power W	Laser λ μm	opt eff	arm length km	mirror dia m	Acc noise vs LISA
BBO-lite	100	1.06	0.3	2×10^4	3	0.1
BBO	300	0.5	0.3	5×10^4	3.5	0.01
BBO-grand	500	0.5	0.5	2×10^4	4	0.001

