The Status of LISA

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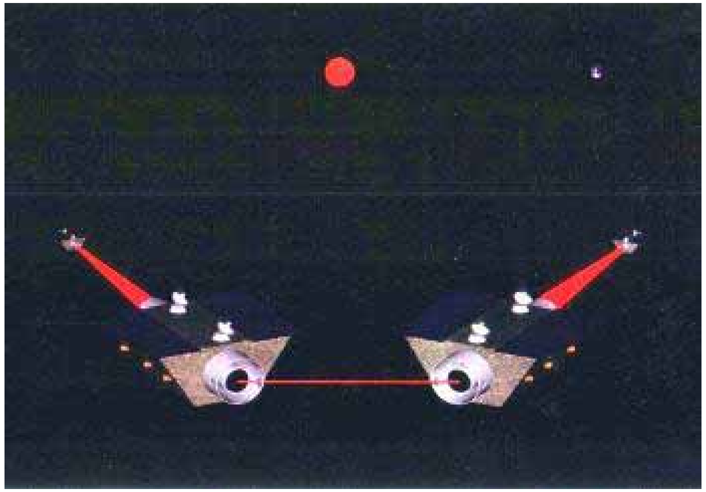
For the LISA Team

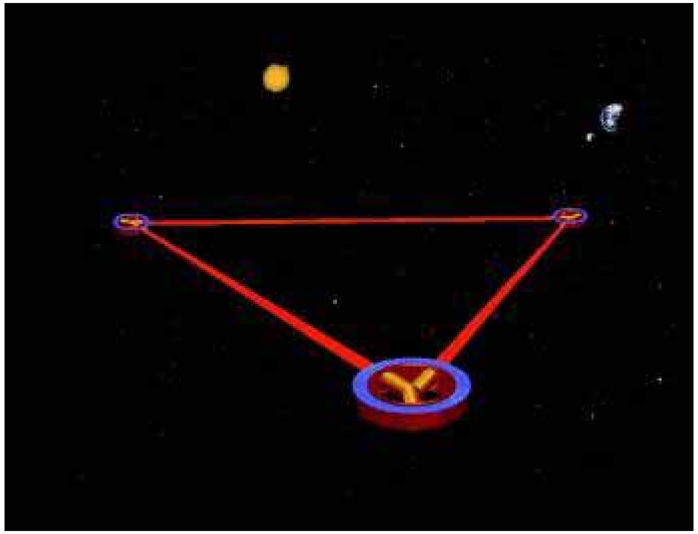
GWDAW, Potsdam

December 18, 2006

LISA: A Mature Concept

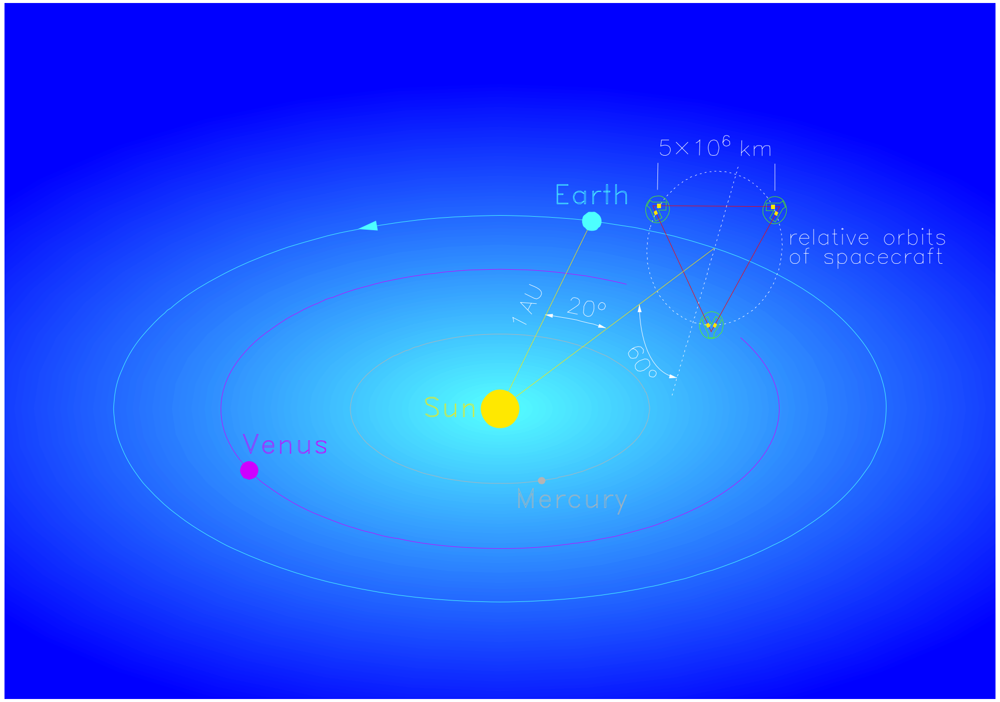
- *After first studies in 1980s, M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993*
- *LISA selected as ESA Cornerstone in 1995*
- *3 S/C NASA/ESA LISA appears in 1997*
- **Baseline concept unchanged ever since!**





A Collaborative NASA/ESA Mission

- *Cluster of 3 S/C in heliocentric orbit*
- *Laser interferometer measures distance changes between free flying test masses inside the S/C*
- *Equilateral triangle with 5 million km arms*
- *Trailing the Earth by 20 ° (50 million km)*
- *Inclined against ecliptic by 60 °*



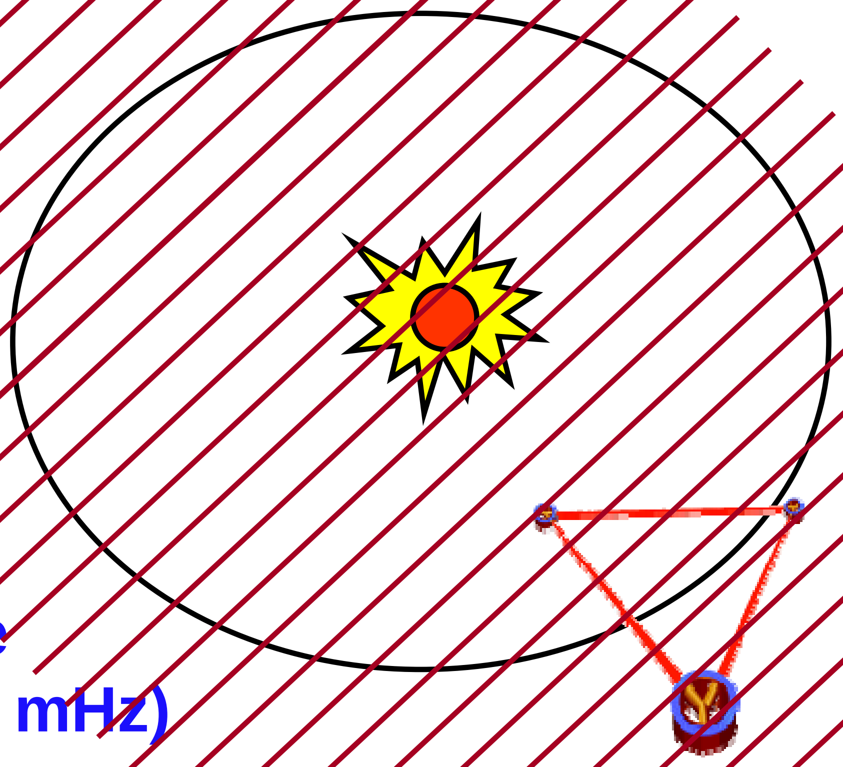
Angular Resolution with LISA

- *Amplitude and frequency modulation due to orbital motion equivalent to* ***Aperture Synthesis***
- *Diffraction limited angular precision*

$\Delta\theta = \lambda_{GW} / 1\ AU / SNR$

- ***For detected sources:***

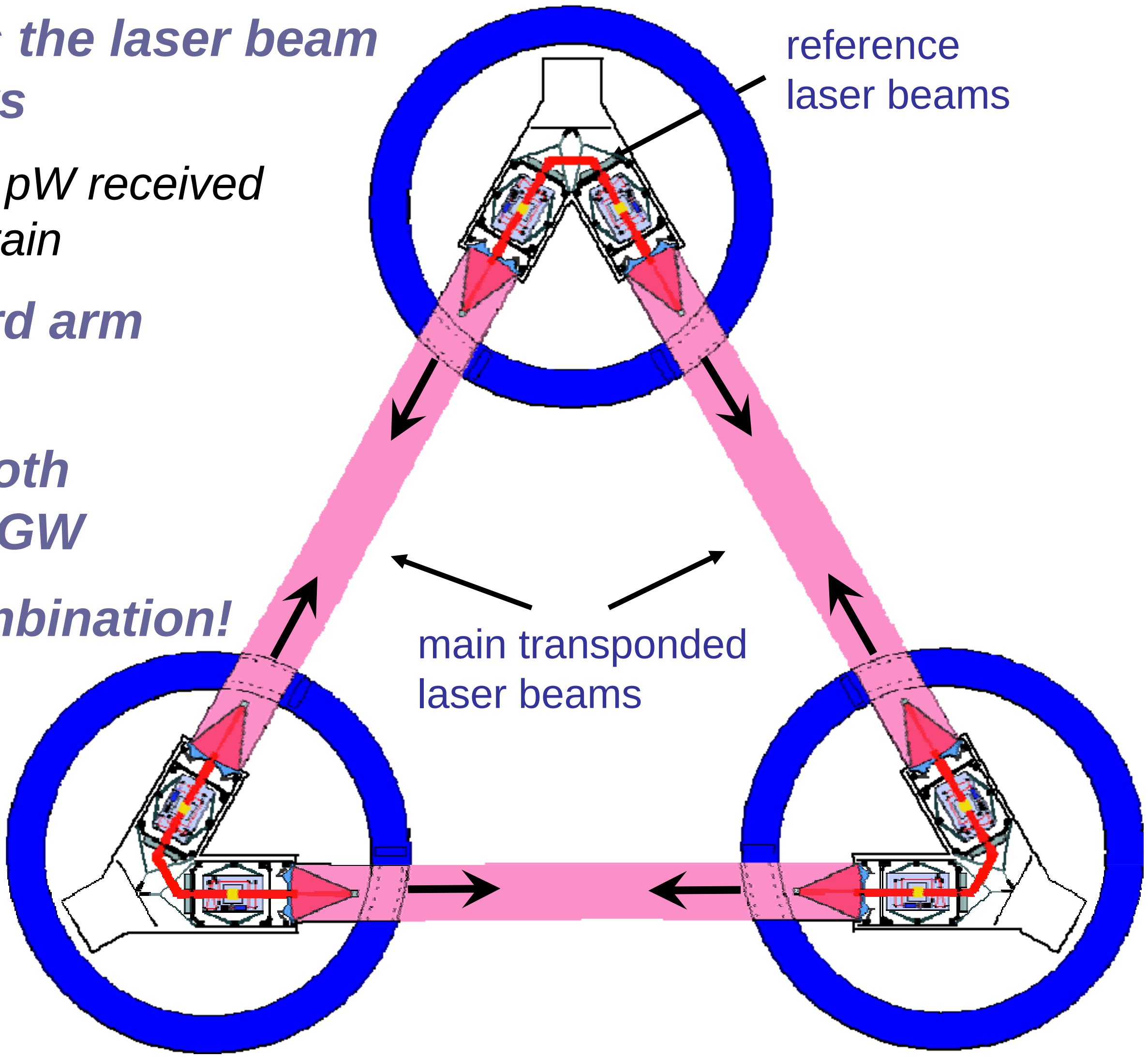
$- \Delta\theta \sim 1' - 1^o$



GWave
(*f* = 16 mHz)

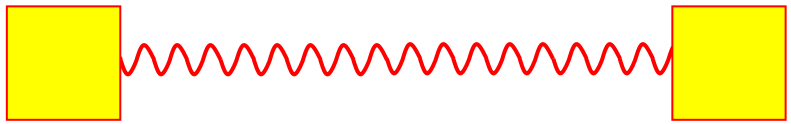
LISA layout

- *Laser transponder with 6 links, all transmitted to ground*
- *Diffraction widens the laser beam to many kilometers*
  - *1 W sent, still 100 pW received by 40 cm Cassegrain*
- *Michelson with 3rd arm and Sagnac mode*
- *Can distinguish both polarizations of a GW*
- *Can form Null combination!*



Gravitational wave action

Gravitational waves change the distance between test masses at rest in free-falling frame.



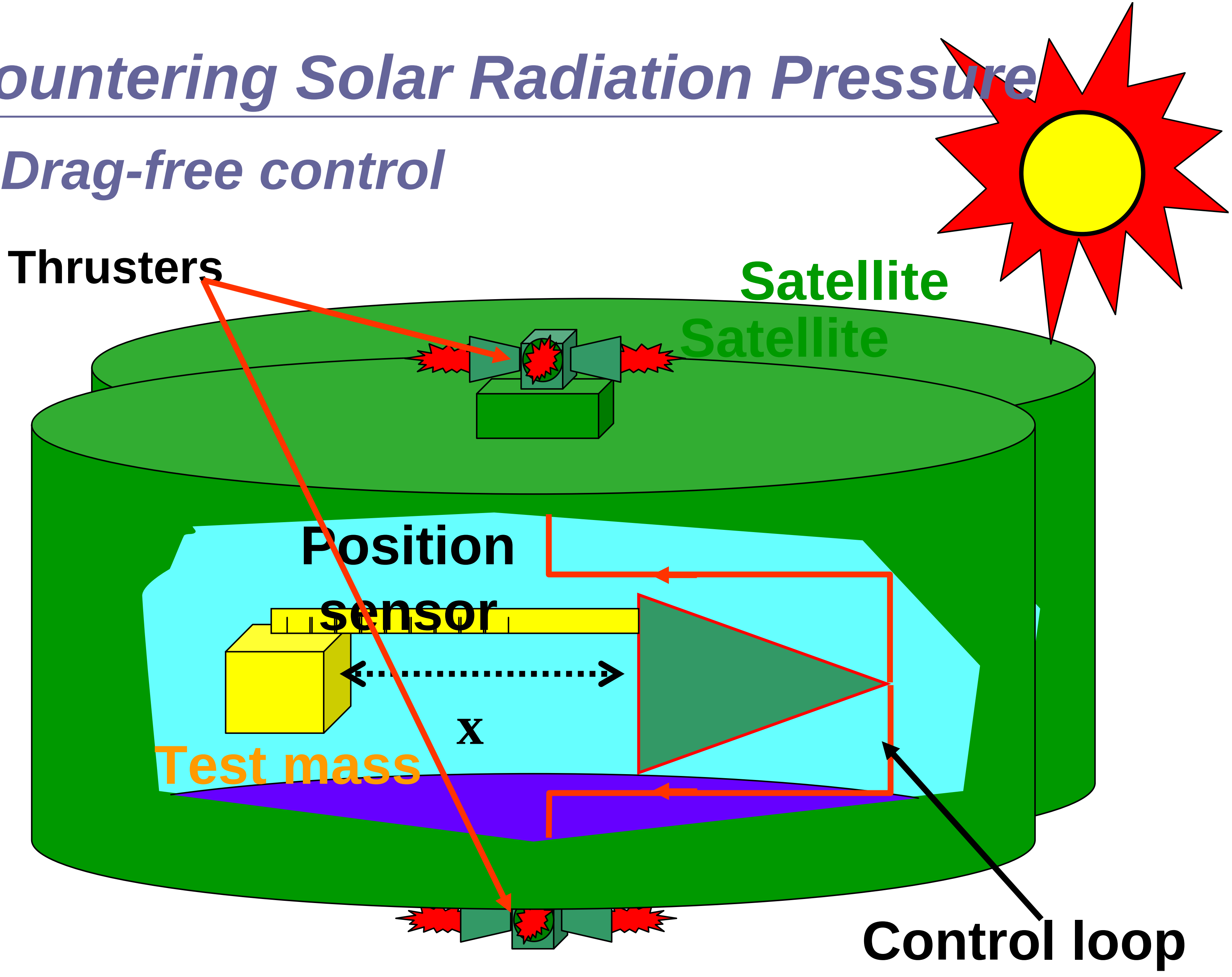
Spurious forces move masses as well!

We need the perfect free fall!

$\Rightarrow$ ***Drag-free control***

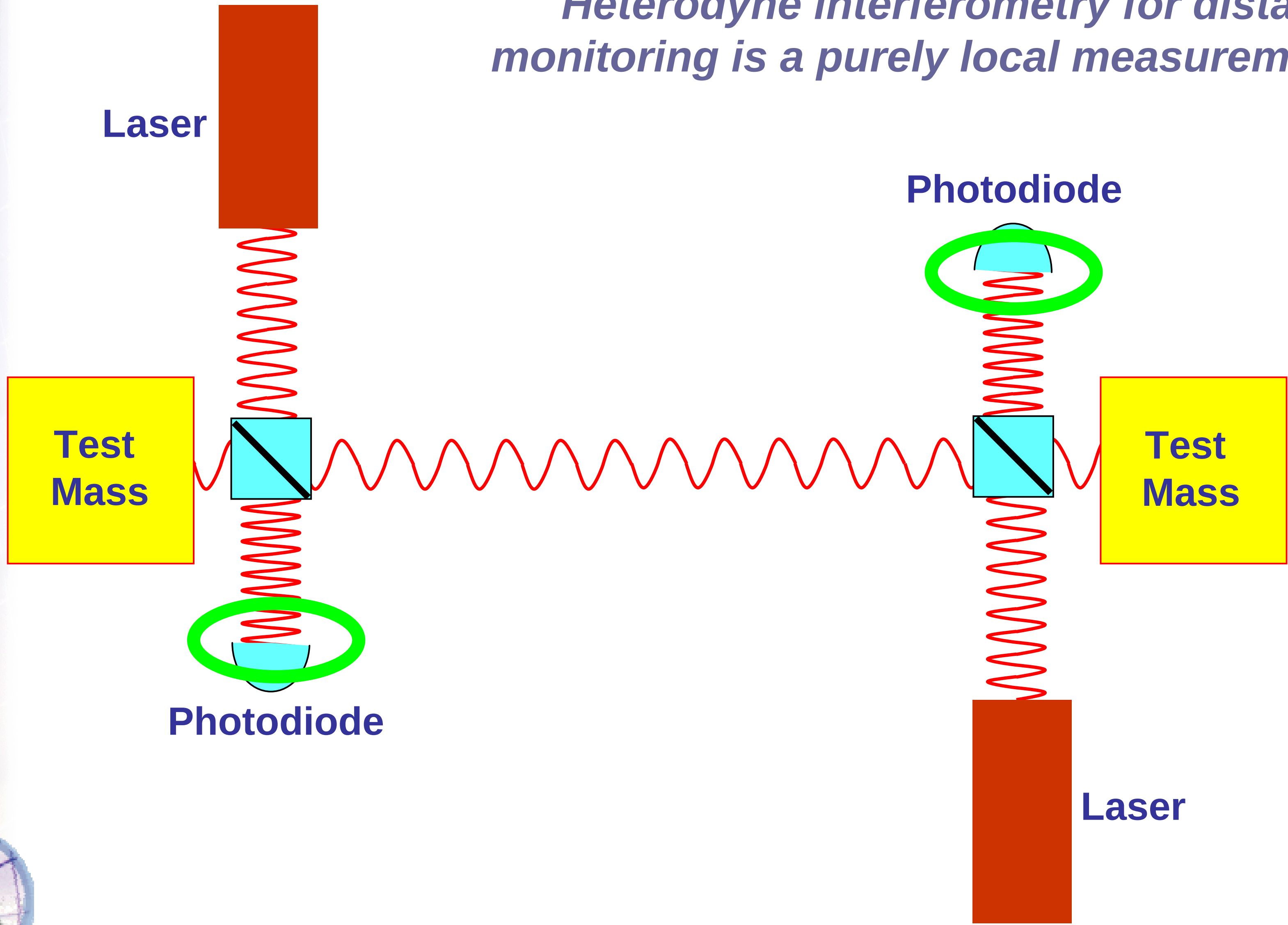
Countering Solar Radiation Pressure

- *Drag-free control*



Heterodyne Interferometry

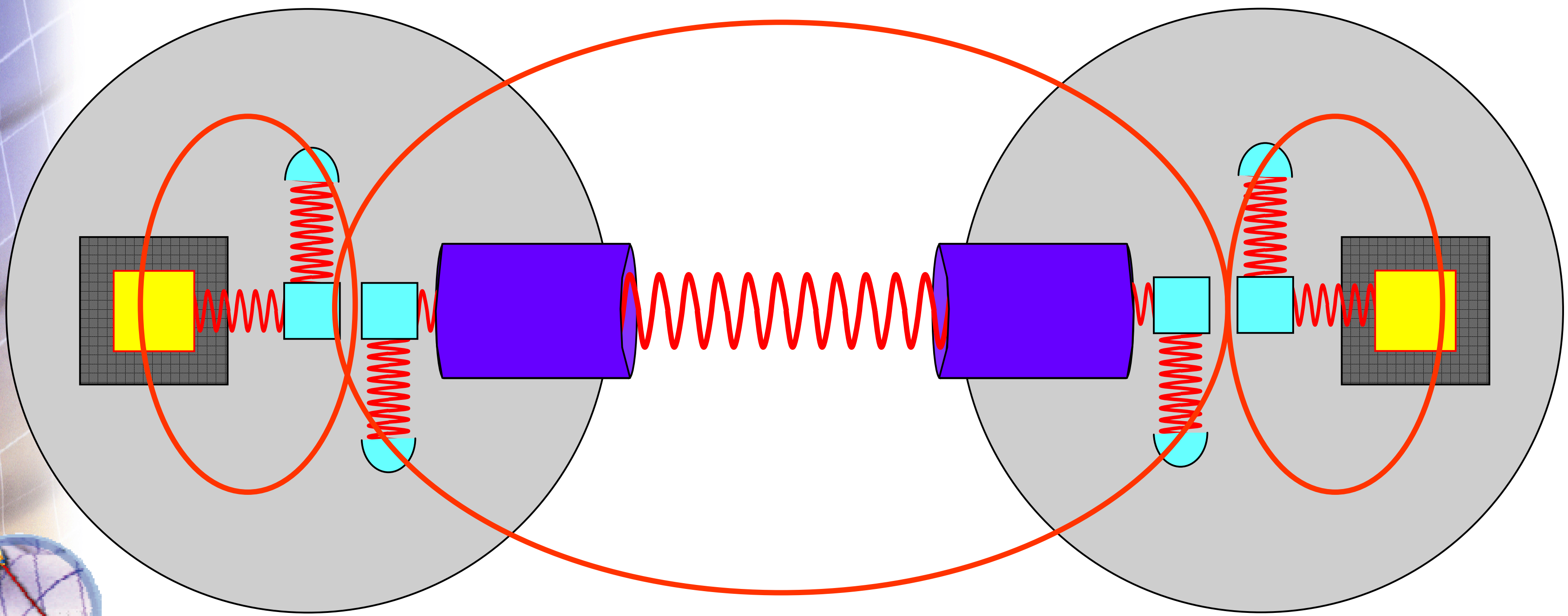
Heterodyne interferometry for distance monitoring is a purely local measurement!



Local measurements

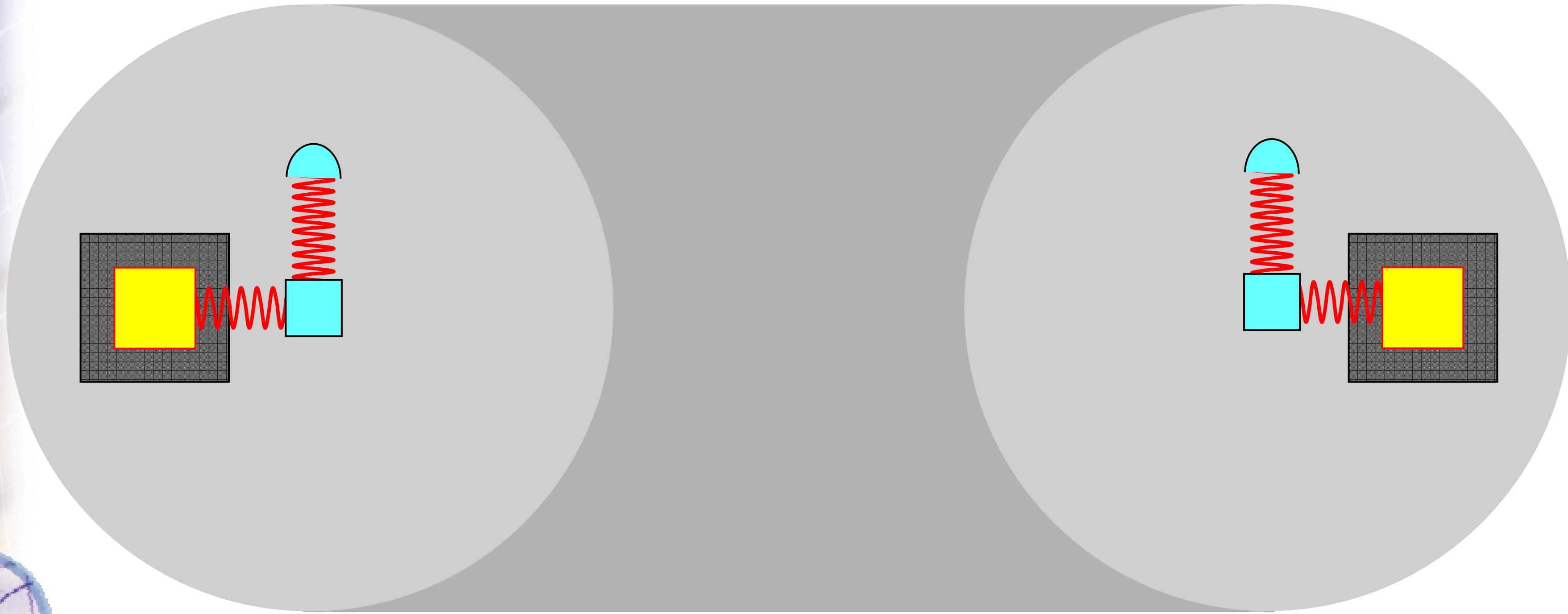
For convenience: Split measurement into 2 parts!

1. ***Spacecraft to test mass***
2. ***Spacecraft to spacecraft***



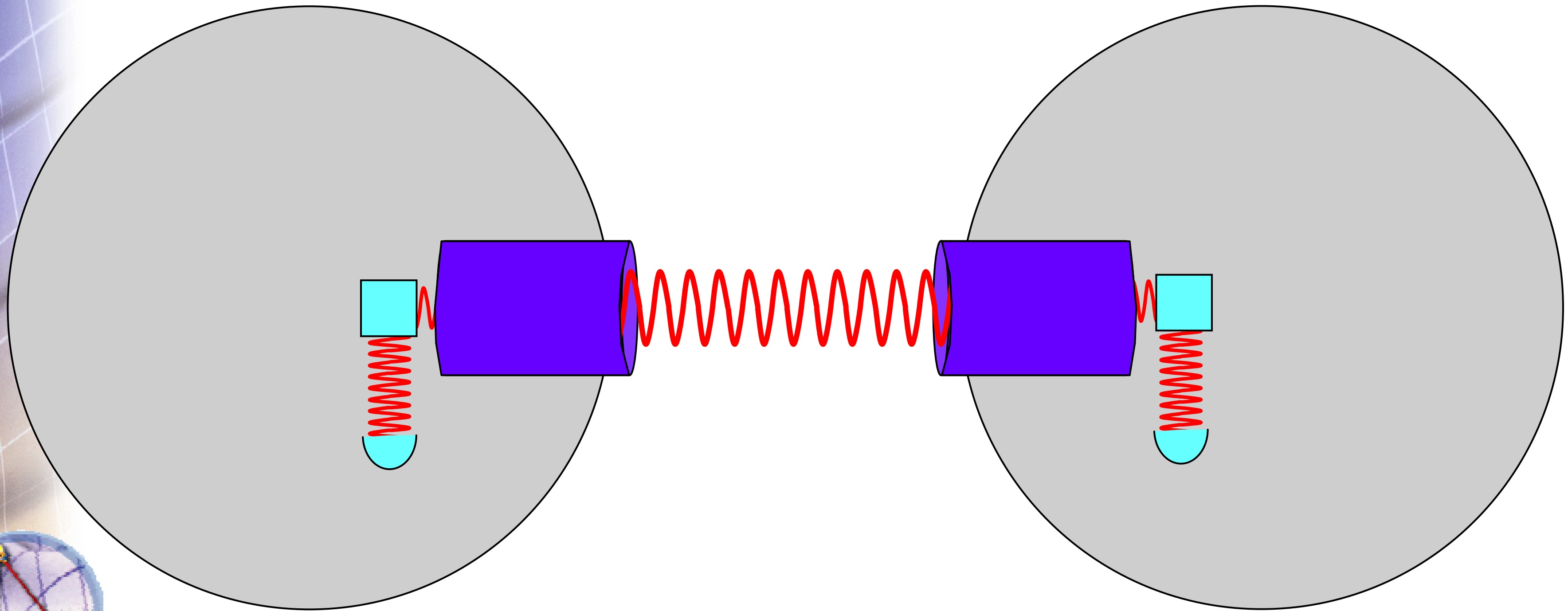
Measuring S/C to Test Mass

- Verification of measurement of SC to test mass on LISA Pathfinder
- Mission now in Implementation Phase
- Launch in 2009



Measuring S/C to S/C

- *S/C-to-S/C Measurement: Laboratory testing!*
- *Heritage from LISA Pathfinder and ground based interferometers*
- *Verification by similarity and analysis!*



ESA-NASA Coordination Meeting on LISA

11 August 2004, ESTEC, Noordwijk, NL

ESA-NASA Agreement on LISA!

"August agreement"

LISA PROJECT

Agreement
following the LISA meeting
11-12 August, 2004
Estec

Rick Howard – NASA HQ 8/12/04

Sergio Volonte – ESA HQ 12/08/04

NASA Formulation Phase on LISA began October 1, 2004

Formulation Authorization

The Beyond Einstein Program

A.V. Diaz
Associate Administrator for Science

Date 10/1/04

Formulation Authorization
The Beyond Einstein Program

PURPOSE

Beyond Einstein is a program within the Universe Division of NASA's Science Mission Directorate (SMD) that will address the following science goals, articulated in the 2003 Space Science Strategy:

Science Goals:

a. Discover what powered the Big Bang and the nature of the mysterious dark energy that is pulling the Universe apart.
b. Learn what happens to space, time, and matter at the edge of a black hole.
c. Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics.
d. Engage the public in shaping and sharing the experience of exploration and discovery.

Science Objectives:

This program will also address the following science objectives of the current applicable science roadmap, which is the Structure and Evolution of the Universe (SEU) Roadmap of January 2003:

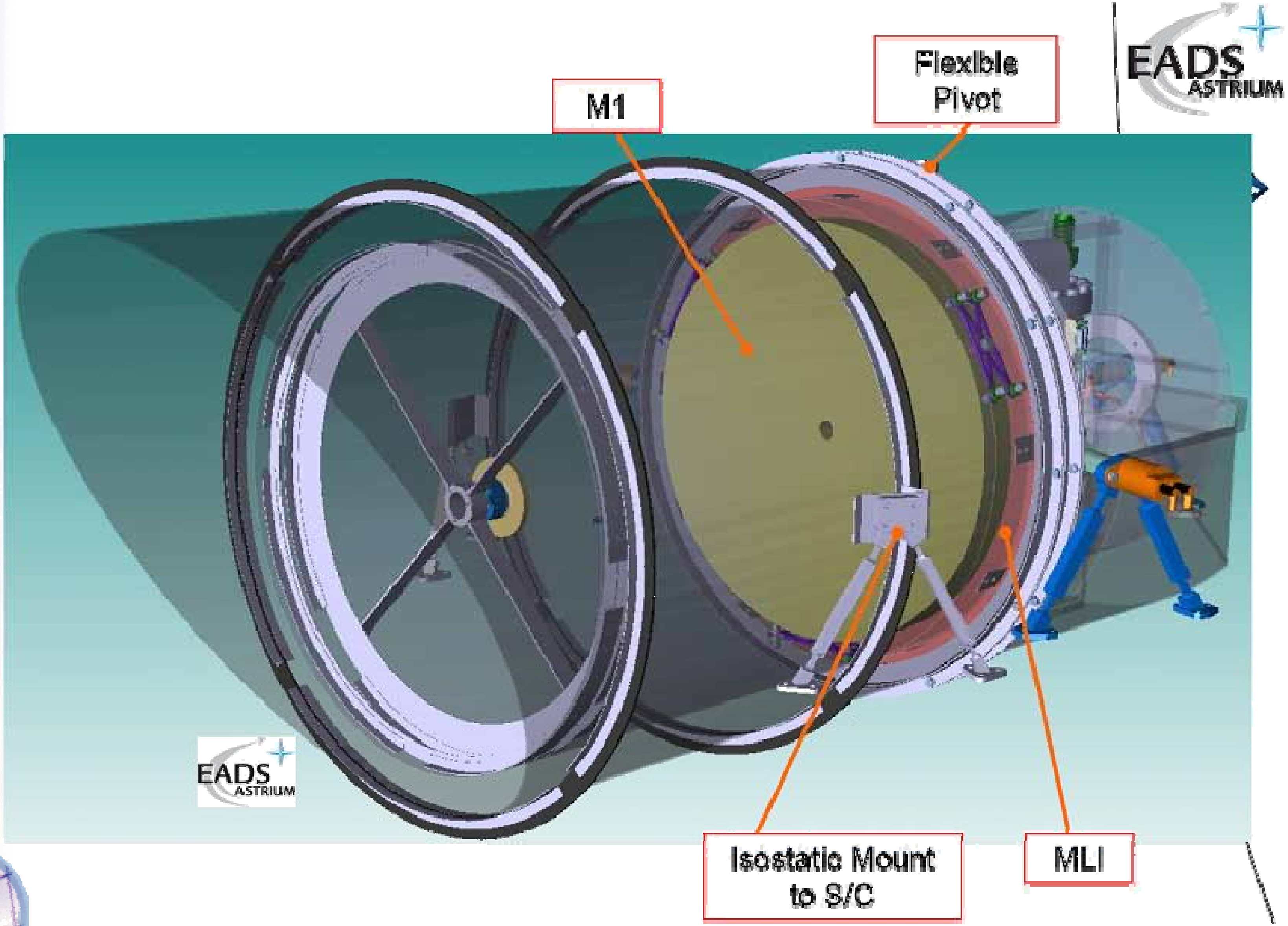
a. Find out what powered the Big Bang.
b. Observe how black holes manipulate space, time and matter.
c. Identify the mysterious dark energy pulling the Universe apart.

The Beyond Einstein Program will include missions, technology development and supporting activities. The missions that constitute the program include:

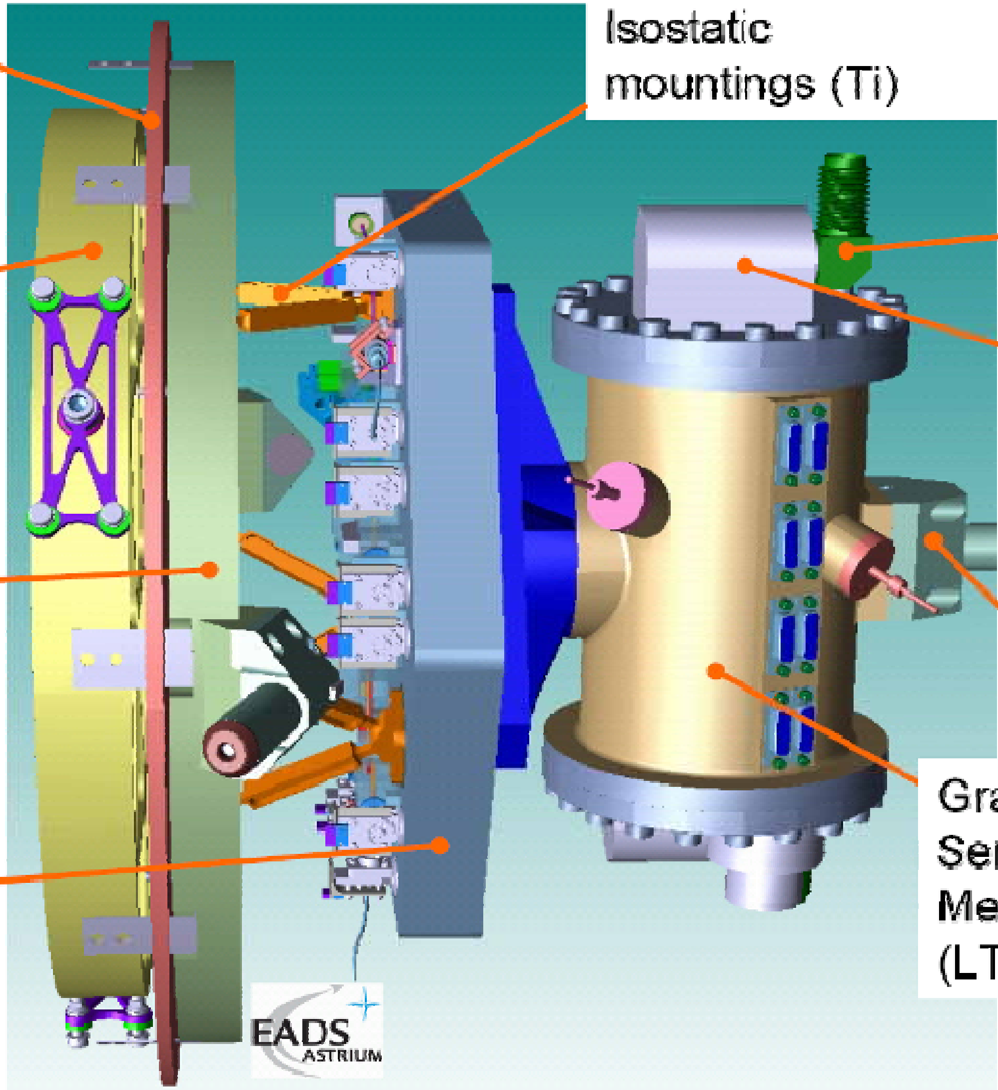
a. The Laser Interferometer Space Antenna (LISA) Mission. LISA will be the first space-based gravitational wave observatory and will aim to achieve the following key science goals: 1) Determine the crucial role of massive black holes (MBH) in galaxy evolution through the detection of MBH mergers, 2) Make precision tests of Einstein's theory of general relativity, 3) Determine the population of ultra-compact binaries in our galaxy, and 4) Search for gravitational wave emission from the early universe.
b. The Constellation-X (Con-X) Mission. Con-X will use high throughput, high resolution X-ray spectroscopy aimed at achieving the following key science goals: 1) Measure the effects of strong gravity near the event horizon of super-massive black holes, 2) Trace visible matter throughout the universe and constrain the nature of dark matter and dark energy, 3) Study the formation of super-massive black holes and trace their evolution with cosmic time, and 4) Study the life

LISA Mission Formulation

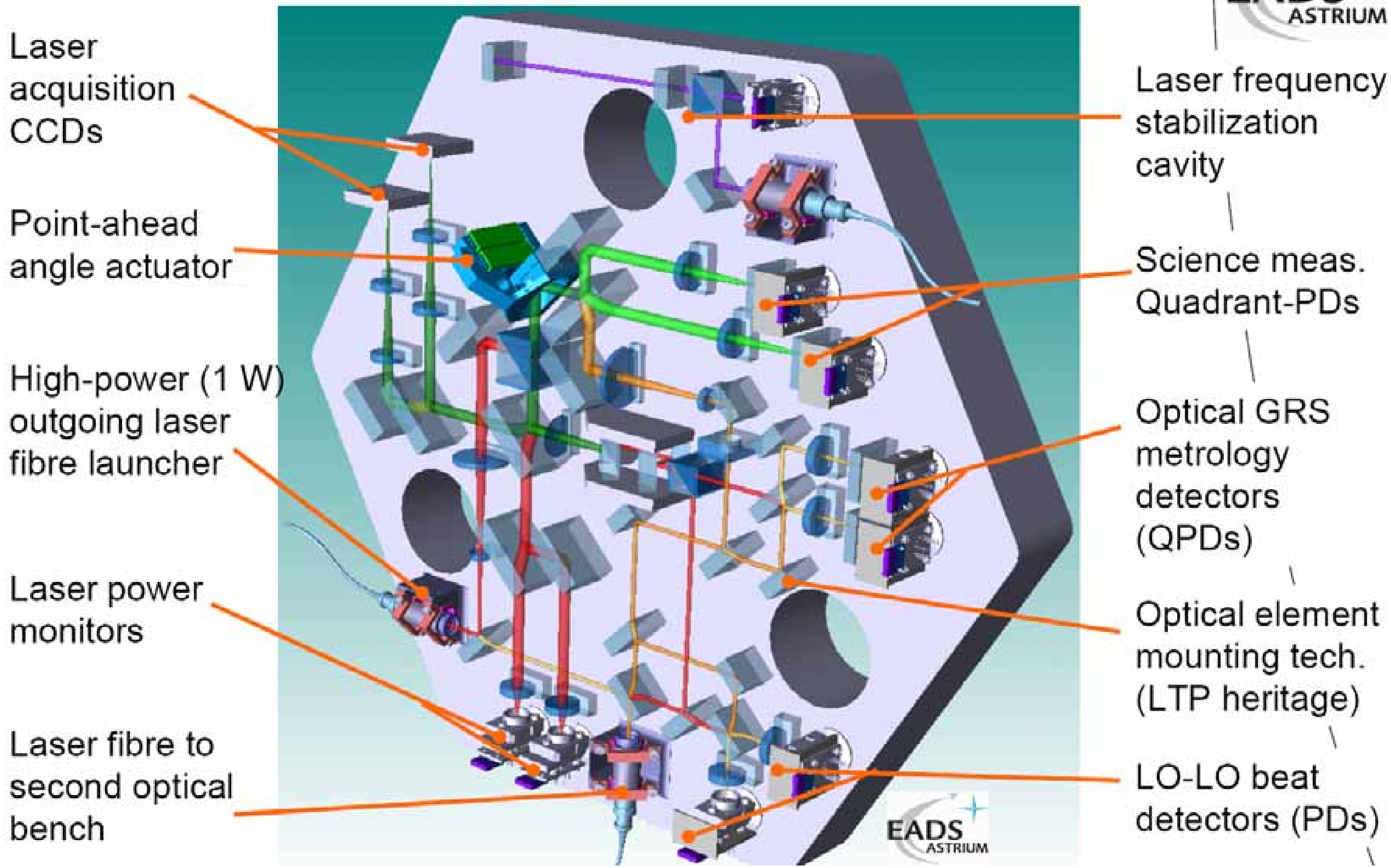
Payload – Current Design Status



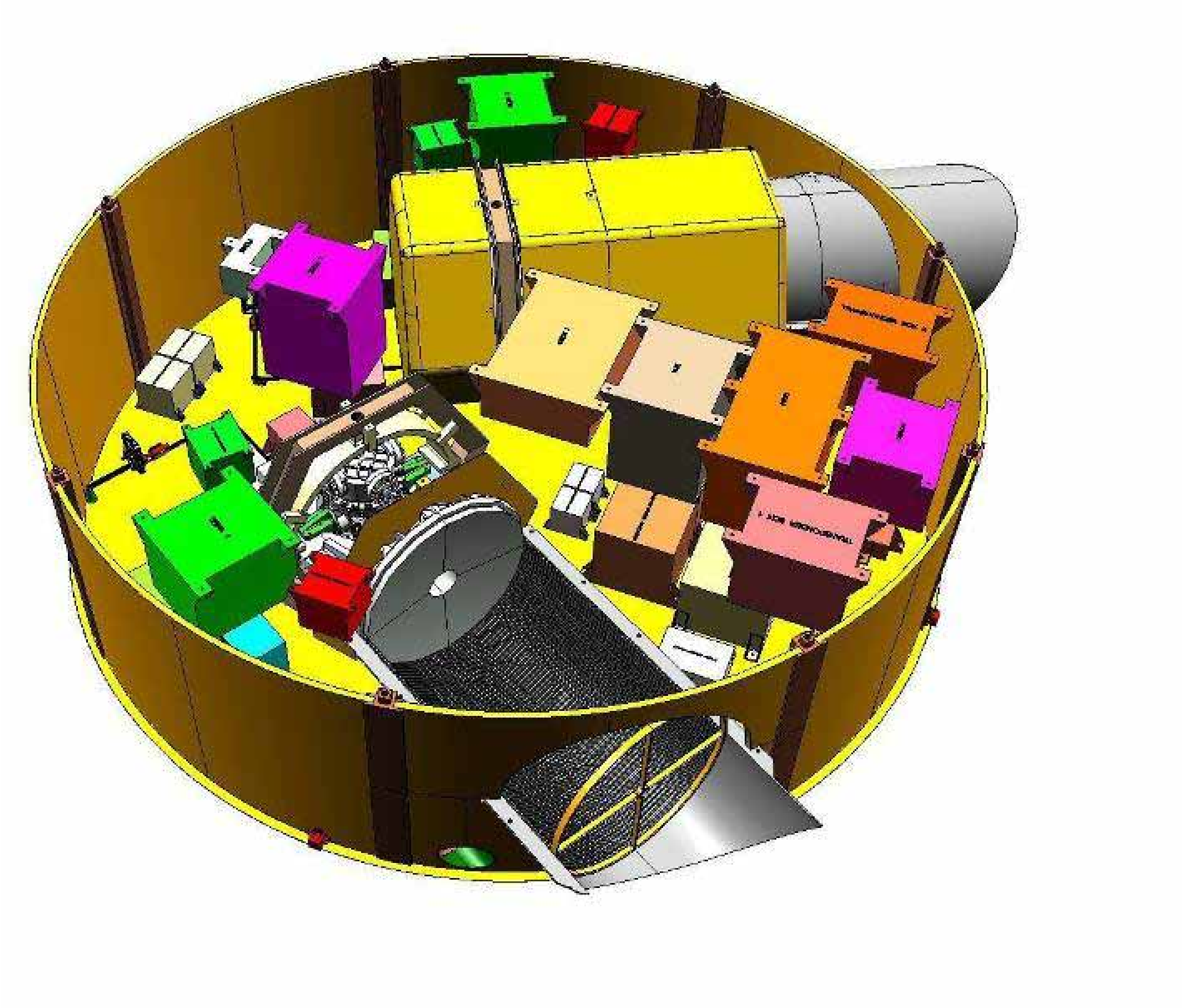
LISA Optical Assembly



LISA Optical Bench

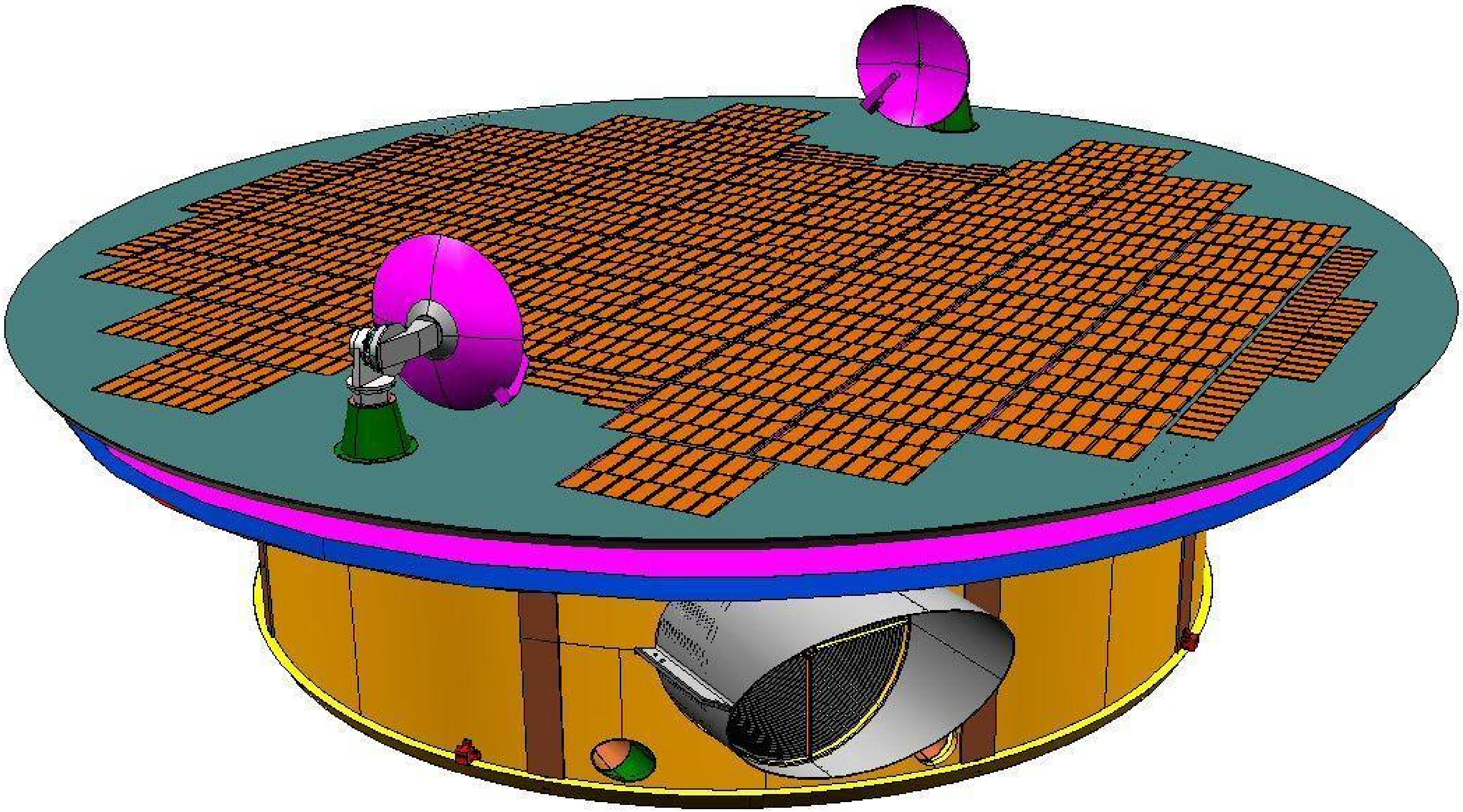


LISA Payload Accommodation



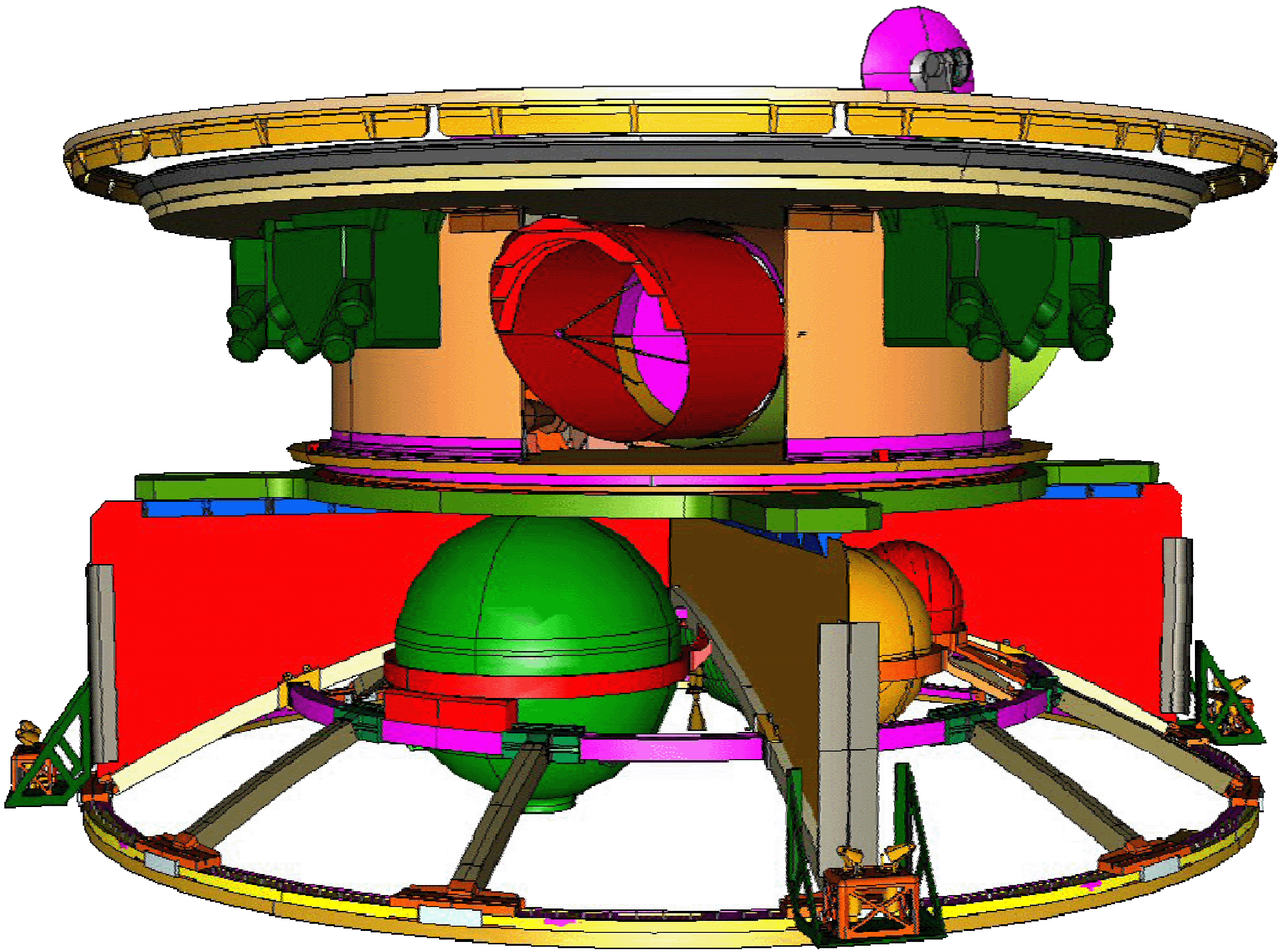
Sciencecraft

- ***Mass 517 kg***

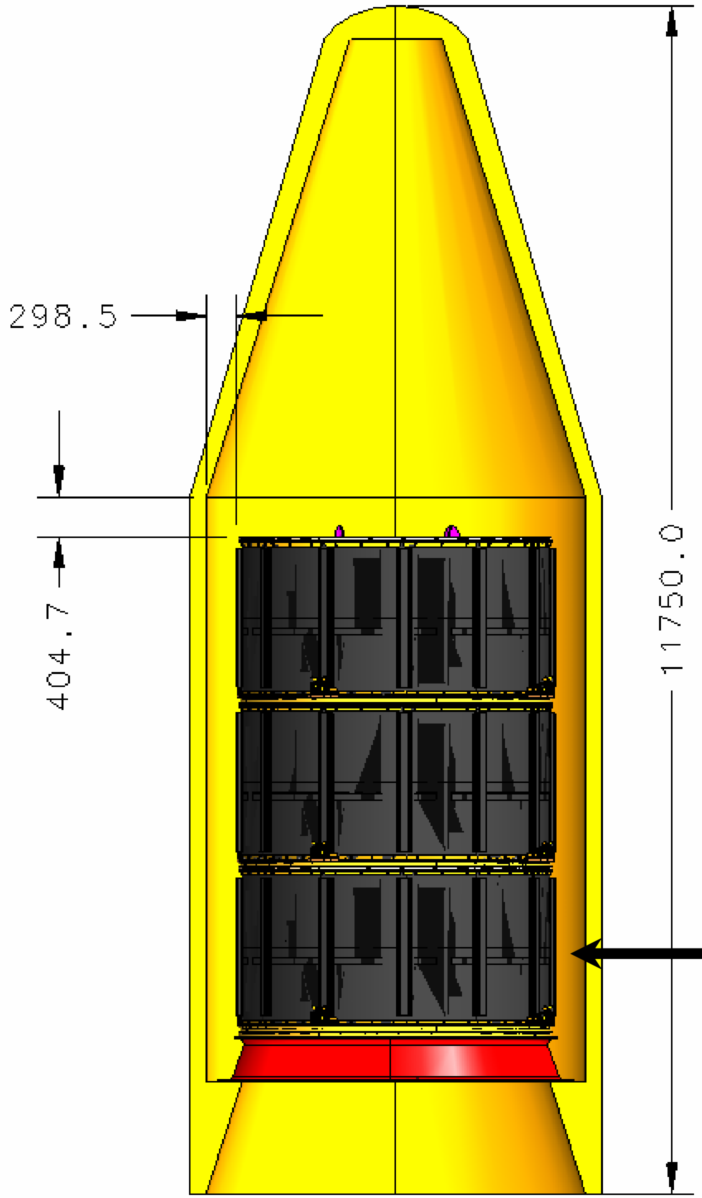


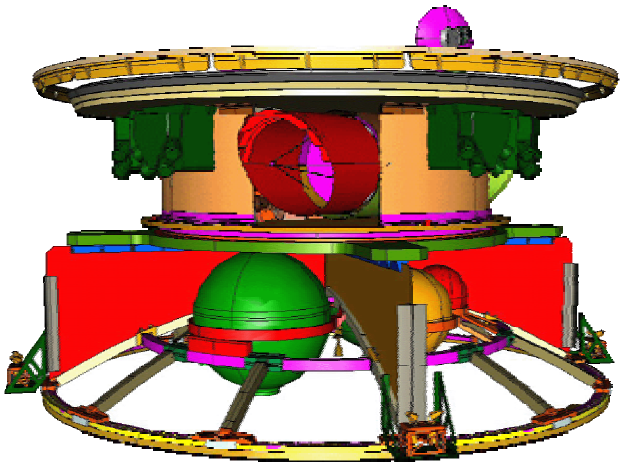
Propulsion Module

- *Mass 343 kg*   *Max Δv= 1130 m/s*



Launch Stack





Mission Design

Lifetime	1.5 yr cruise + 5 years science
Orbits	Heliocentric, 20° Earth trailing,equilateral triangle constellation with 5×10^6 km ± 1% armlength
Launch Vehicle	Atlas 531, C3=0.65, Lift capability 5185 kg
Communications	Ka-Band – HGA and Omnis, 90-180 kbps downlink, 2 kbps up, DSN, Inter-S/C comm
C&DH	Sciencecraft functions, science data processing on ground
GN&C	Star trackers, sun sensors
EPS	Fixed SA, triple junction GaAs, 820 W EOL @ 30° Sun Angle, 9Ah Li Ion battery, 60% DoD
Thermal	Passive design
Mechanical	Sciencecraft nests in Propulsion module (PM), PM carries launch loads
Propulsion Module	1100 m/s avg., 343 kg dry, 470 kg prop.
System Mass	Sciencecraft 517 kg, PM 343 kg, Prop 470 kg, wet 1330 kg, stack with 30% margin 4697 kg

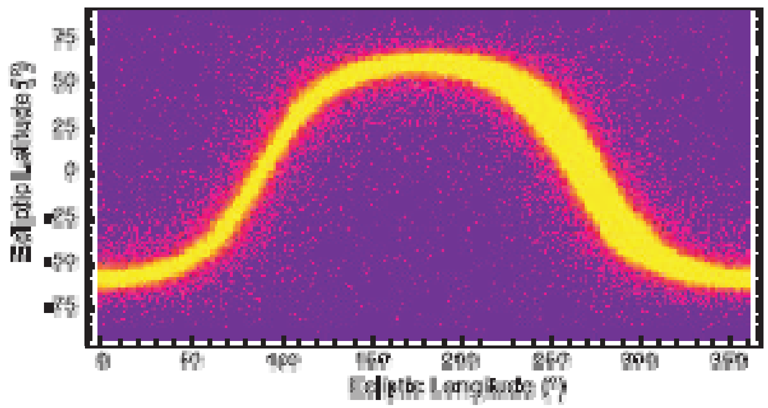
Expected Performance

Symbol	Frequency [mHz] 0.03	0.1	5	10	100	1000	Description (all values are contributions to the single link error given in pm Hz$^{-1.5}$)
T_a $\Delta x^* \Delta a$	231383.0	11981.4	5.1	1.1	0.0	0.0	Equivalent single link error due to proof mass acceleration
Δx_{ms}	7.5	7.5	7.5	7.5	7.5	7.5	Metrology Shot Noise
Δx_{uso}	276.3	82.9	1.7	1.0	1.0	1.4	Residual Noise from USO phase noise
Δx_{laser}	4330.2	389.7	3.9	3.9	3.9	3.9	Residual Noise from laser phase noise
Δx_{aser}	199.3	18.7	0.6	0.7	0.8	0.4	Geometrical path length error from spacecraft pointing
Δx_{mpmm}	4.0	1.9	1.3	1.6	2.3	0.1	Geometrical path length error from proof mass metrology
	43.7	14.0	1.6	1.5	1.4	1.4	Piston effect of PAA
Δx_{nthe}	249.3	74.8	1.5	0.7	0.1	0.0	Geometrical path length error from temperature variation (assessment not yet available allocation used)
Δx_{no}	0	0	0	0	0	0	Other effects
Δx_{mgt}	322.2	78.4	2.6	2.4	2.8	1.5	Total geometrical pathlength error
Δx	***231424.0***	***11988.2***	***10.4***	***8.9***	***8.9***	***8.7***	***Total expected equivalent single link error***
	327361.0	***49104.2***	***13.0***	***13.0***	***13.6***	***13.5***	***Requirement (incl 35% margin)***

Ample performance margin!

LISA Observing Modes

- ***Single science mode:***
  observes all the sky,
  all the sources,
  all the time!
  - *No pointing of the constellation,*
    no scheduling of detectors or observing slots necessary (or possible).
  - *No science processing on board.*
- ***Continuous Observing, normal interruptions only for***
  - *Antenna re-pointing (every 12 days)*
  - *Laser and sideband frequency adjustment (occasionally)*



From Constellation to Ground

- **Requirements**
  - All data on ground every 6 days
  - 1 day latency to science operations center before a merger
  - 90% net efficiency (gaps, outages, etc < 10%)

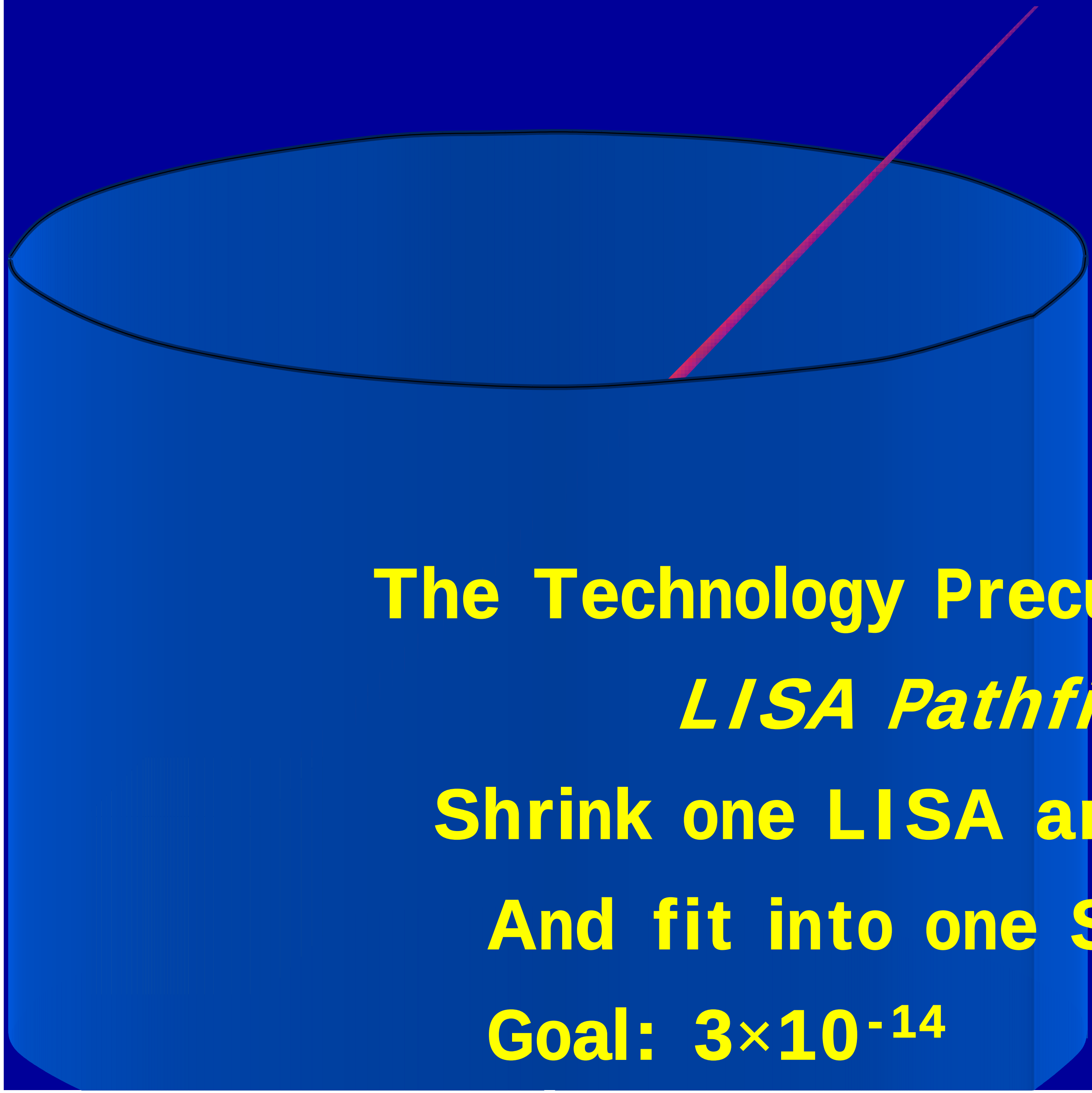
- **Baseline telemetry**
  - Ka-Band, 30 cm antenna, 25 W TWTA
  - 4.13 kbps continuous per S/C
    - 871 bps is main science data
    - Includes 15% coding overhead and 25% margin
  - 4 hr DSN (34m) contact every 48 hr
  - Total data volume per S/C
    - 1 day: 357 Mbits all data/ 78 Mbits science
    - 1 year: 130.4 Gbits all data/ 28.4 Gbits science
    - 5 year mission: 652 Gbits all data / 142 Gbits science

Data archive

LISA Independent Technology Review

Chartered by
NASA/Goddard Space Flight Center Director

7 December 2005



The Technology Precursor Mission:

LISA Pathfinder!

Shrink one LISA arm to 38 cm

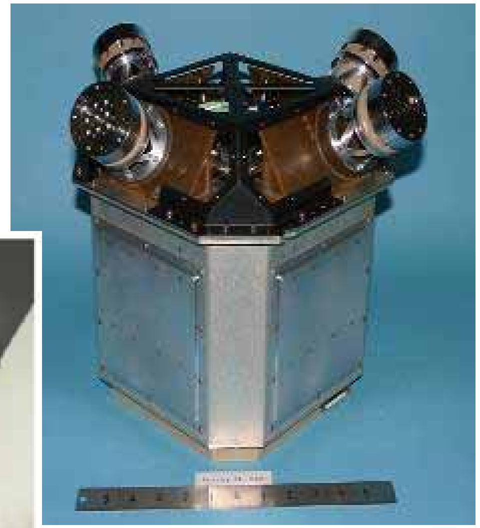
And fit into one Spacecraft

Goal: 3×10^{-14} f > 1mHz

Graphics: Stefano Vitale

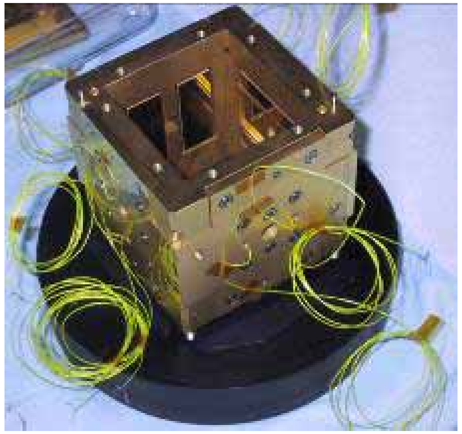
Microthrusters

- *Thruster technologies developed and verified on ground.*
- *Ground testing shows better than required thrust noise!*
- *Pathfinder demonstrates two microthruster technologies in flight.*
- *FEEPs and colloidal thrusters with 10s of µN thrust*

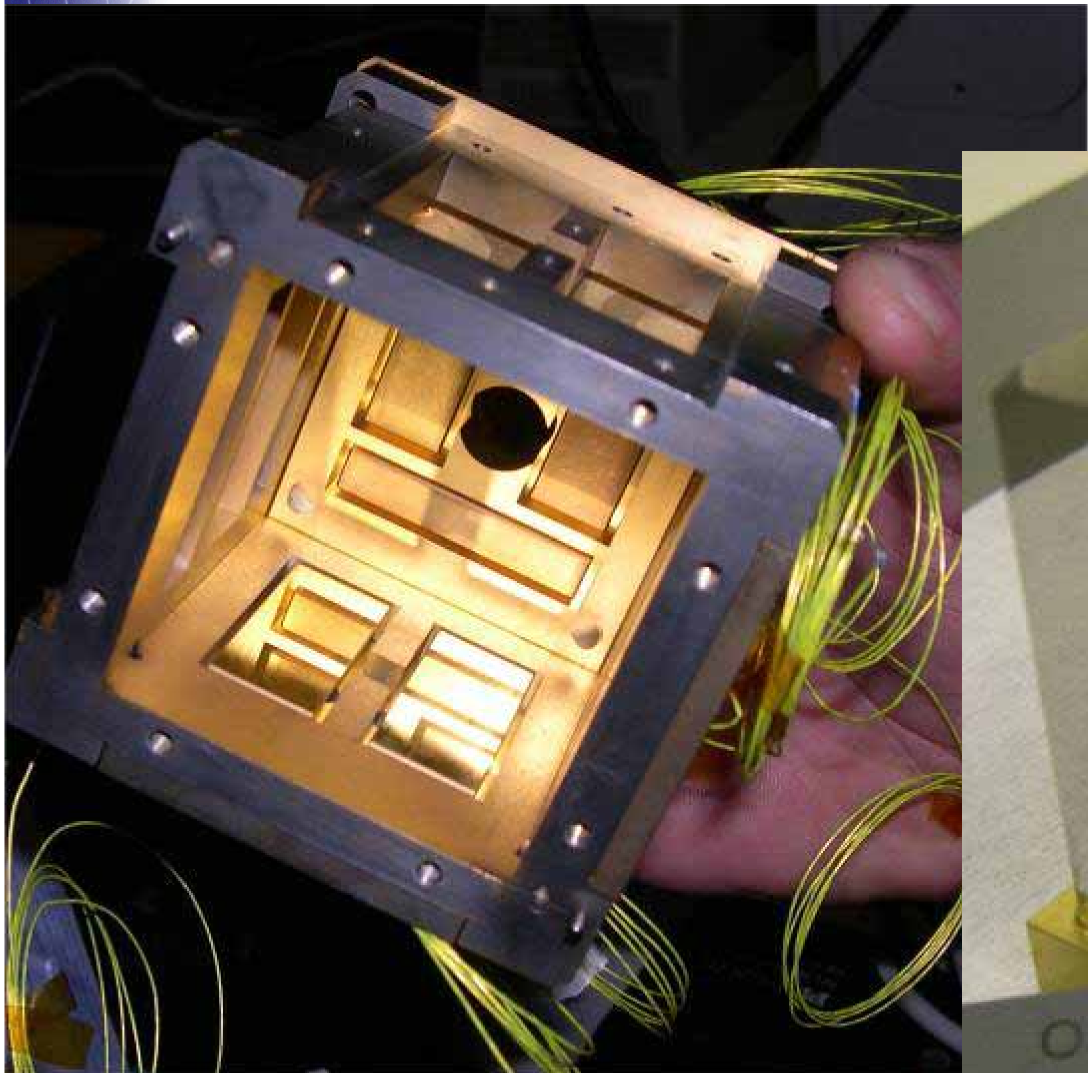


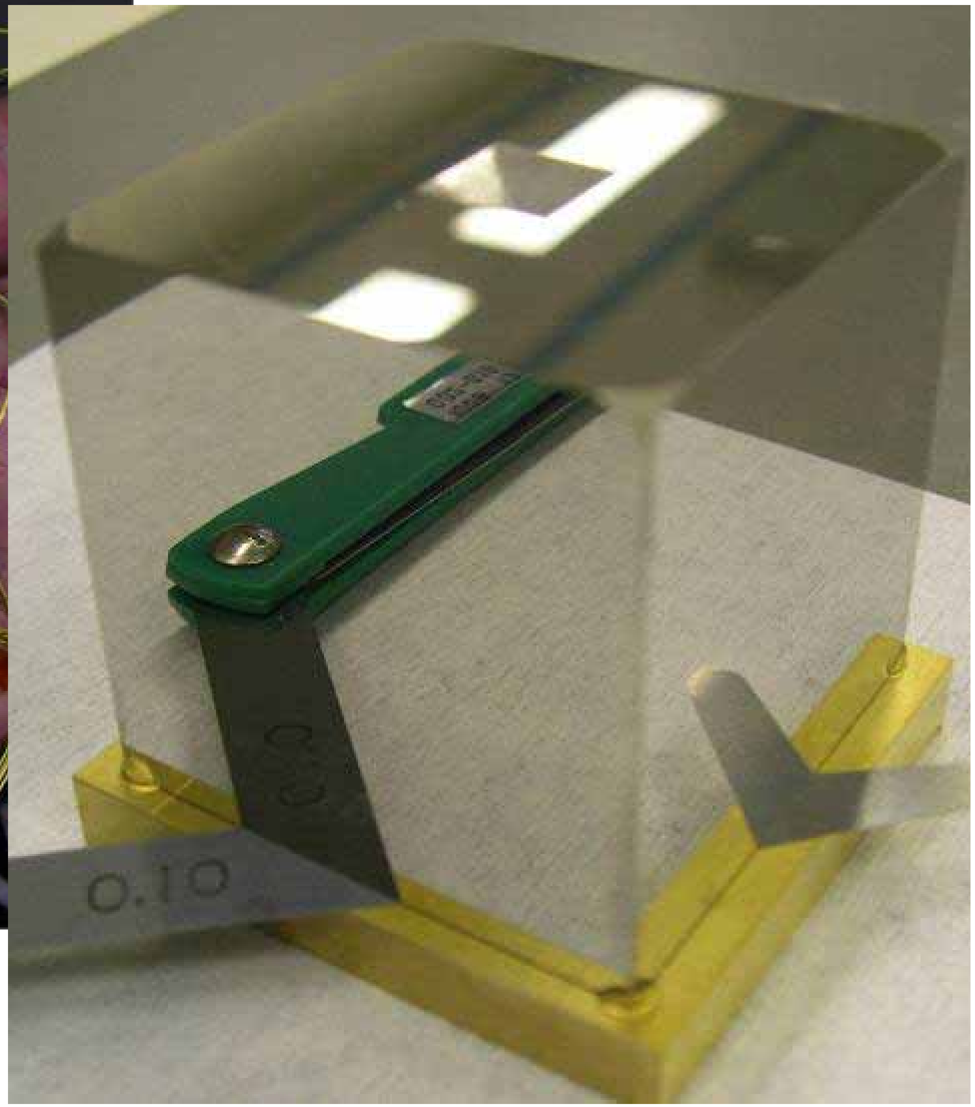
Gravitational Reference Sensor

- *The Pathfinder GRS is the LISA GRS.*
- *Technology fully developed and verified on ground.*
- *Pathfinder validates the GRS on orbit.*
- *Additional ground testing needed at low frequency for LISA.*

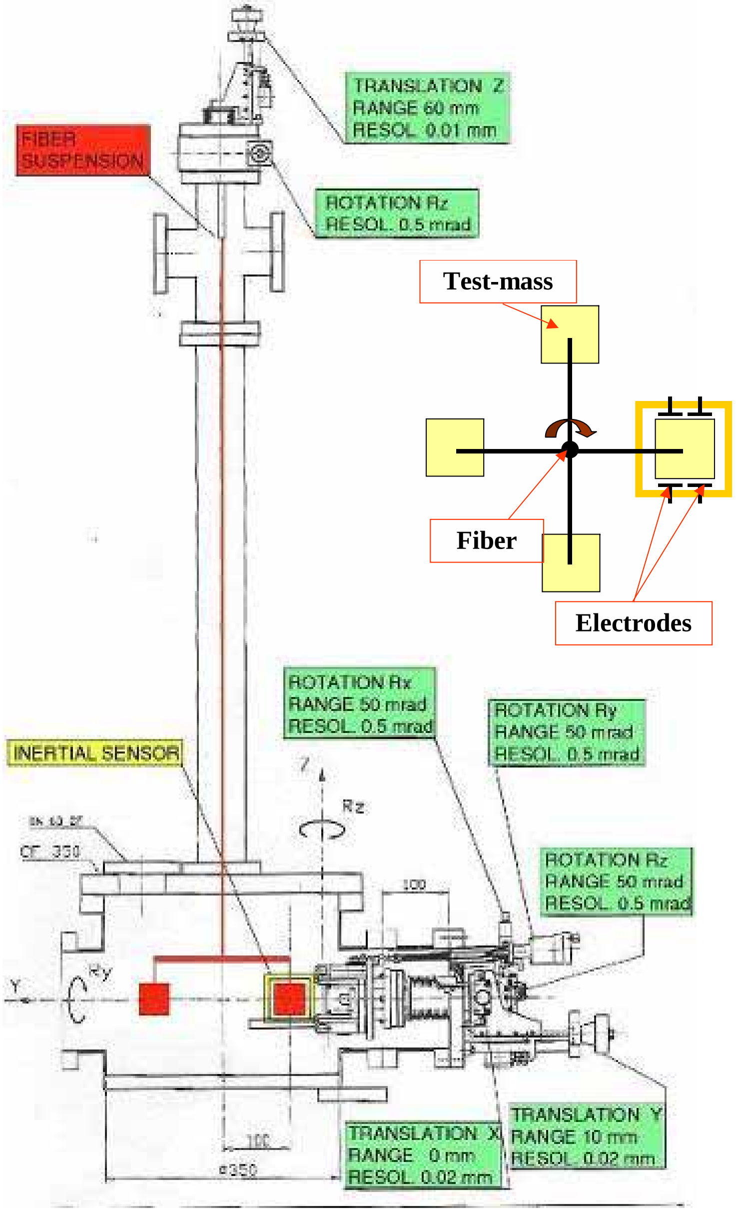



GRS and Test Mass

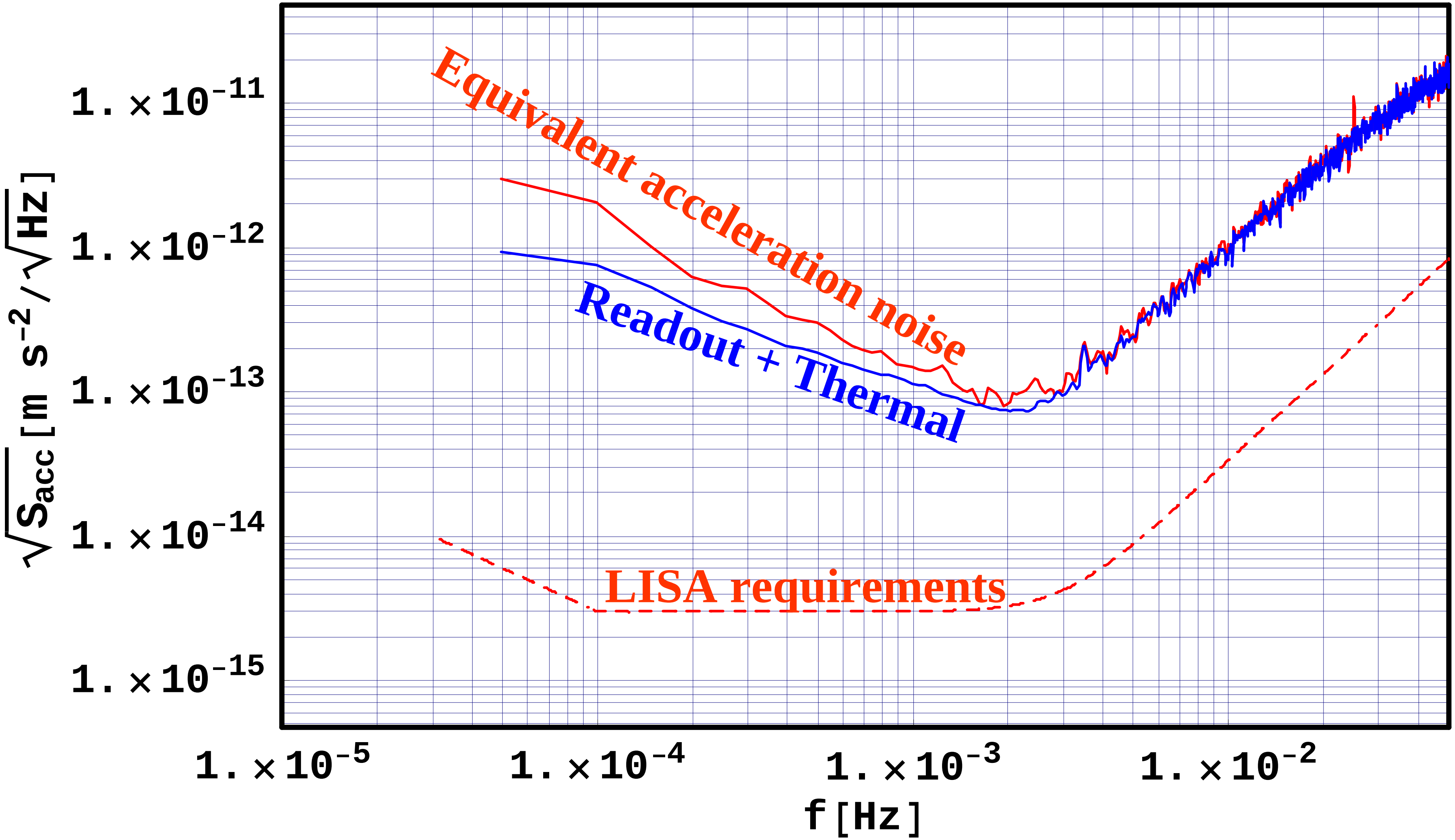




Ground testing – Torsion pendulum

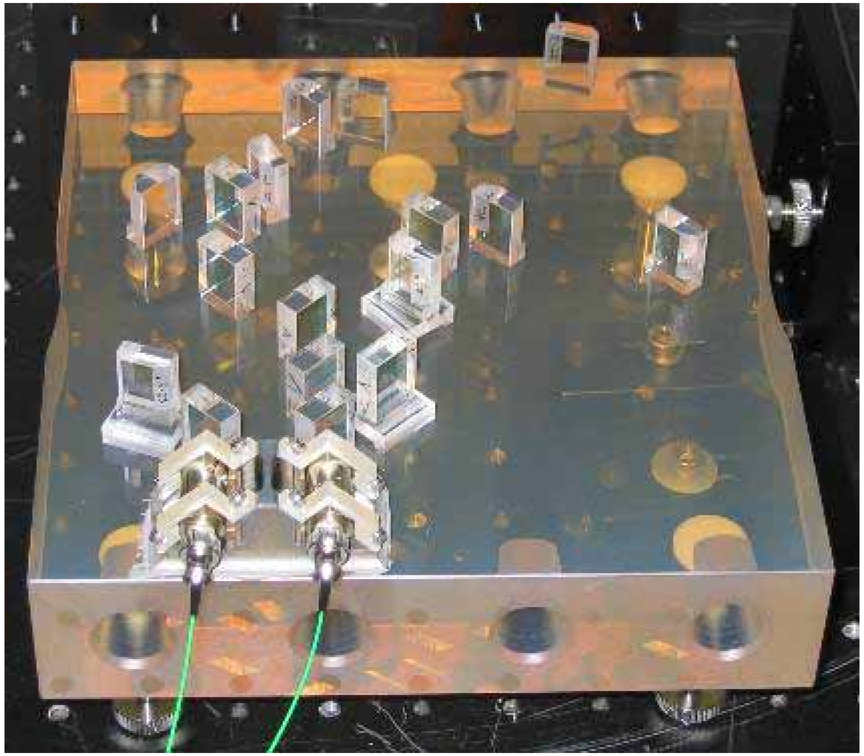


GRS Sensor Ground Testing

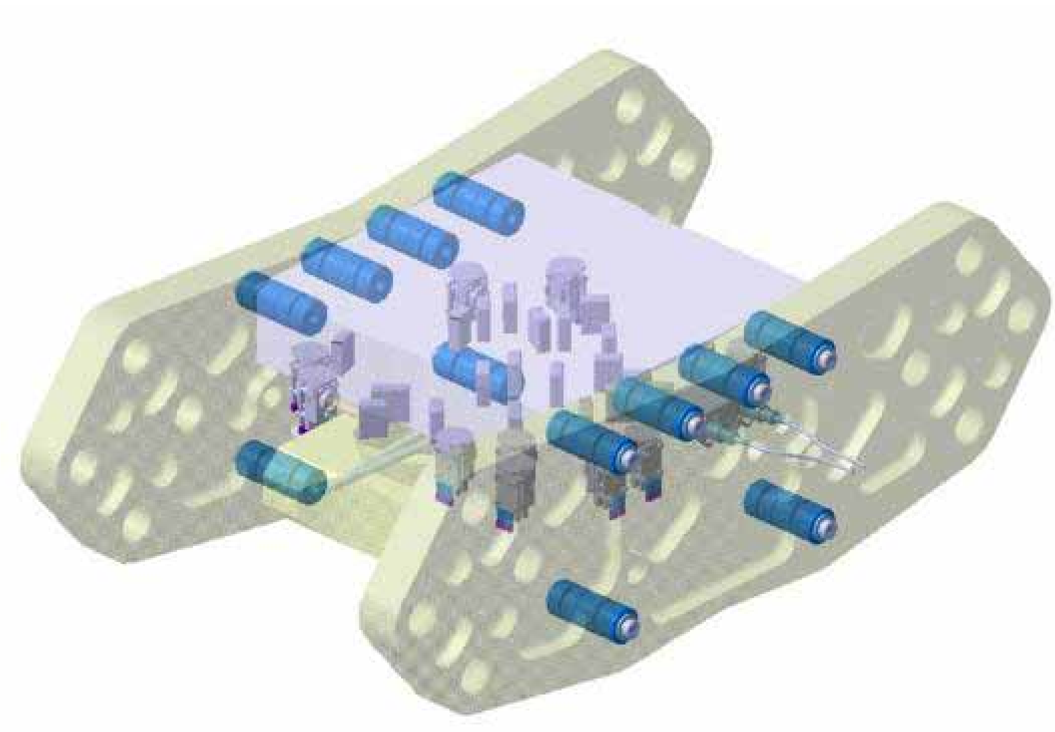


LISA Optical Bench

- *No new technology required!*
- *Hydroxide Catalysis bonding with space heritage from GP/B*
- *Passed environmental and performance testing!*
- *Technology validated in space on LISA Pathfinder!*

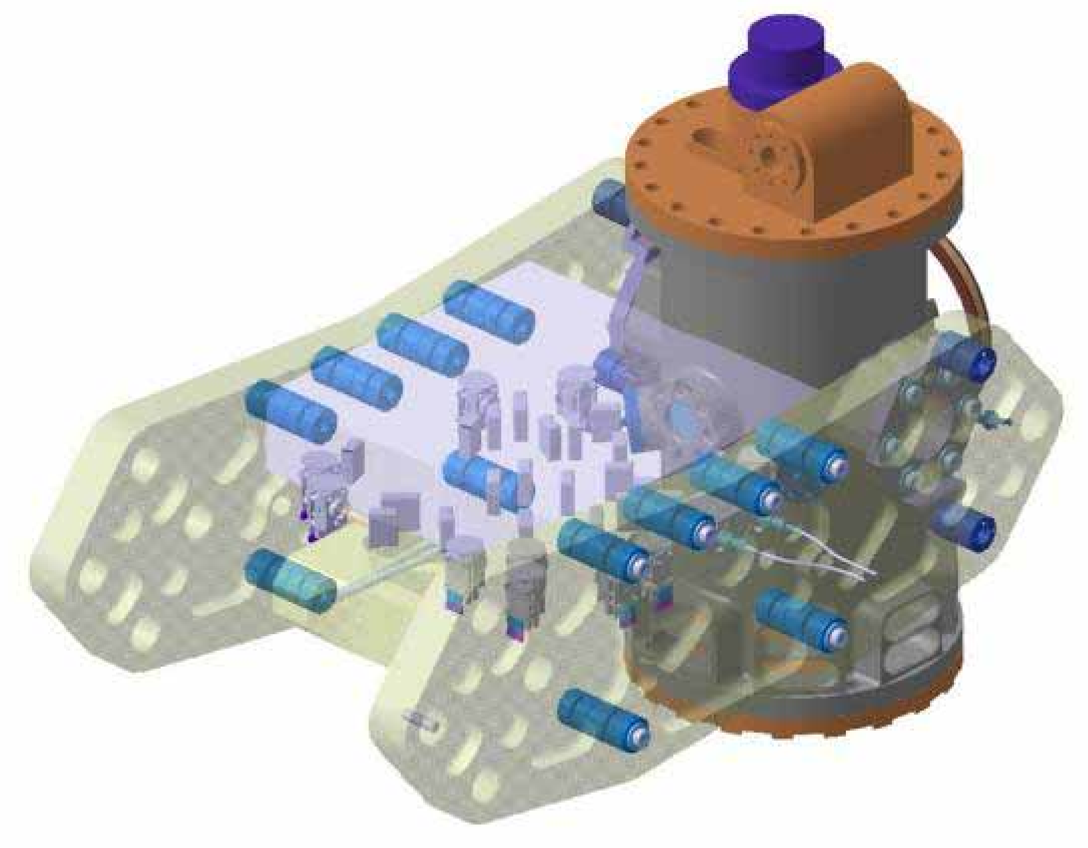


LTP Core Assembly

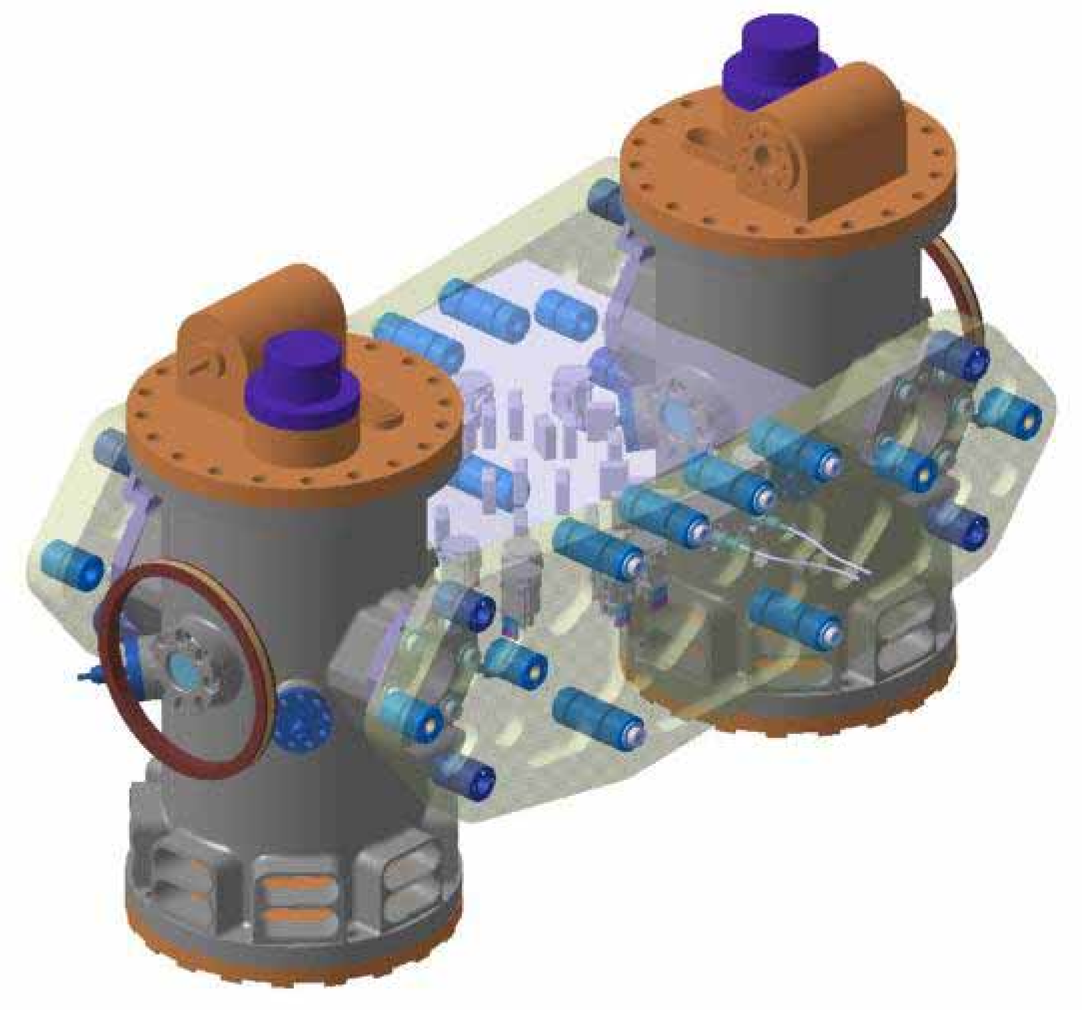


Vacuum housing for GRS

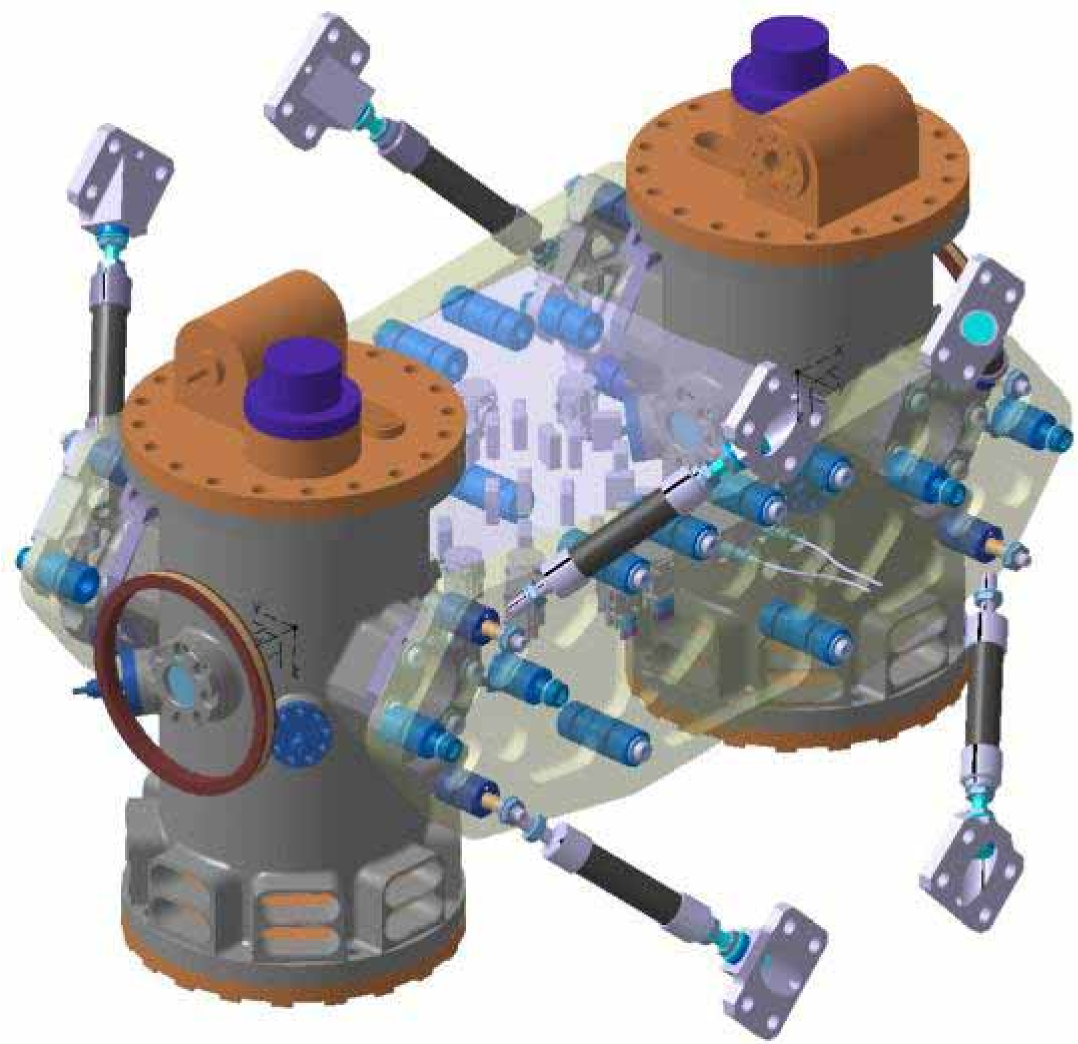
LTP Core Assembly



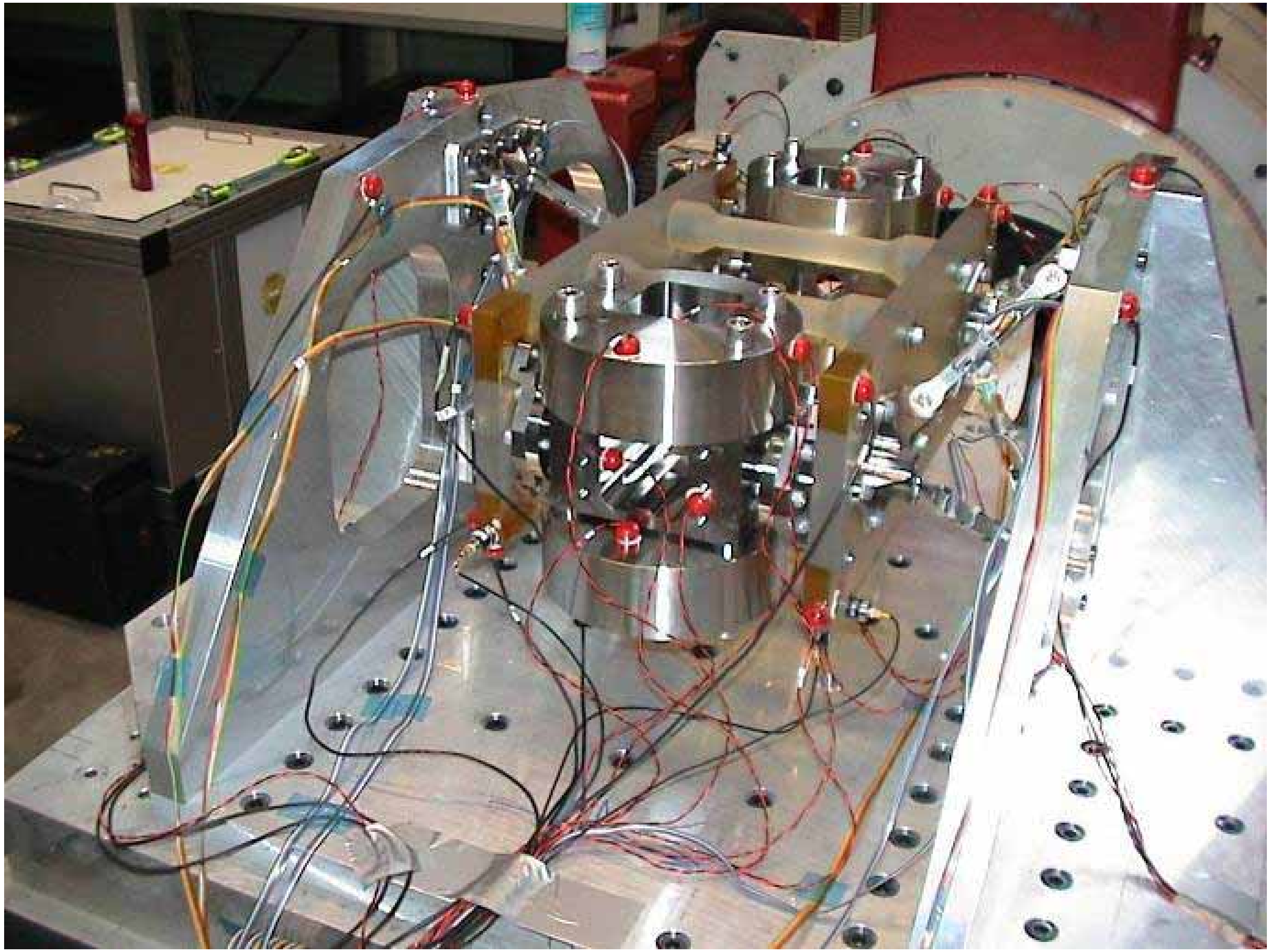
LTP Core Assembly

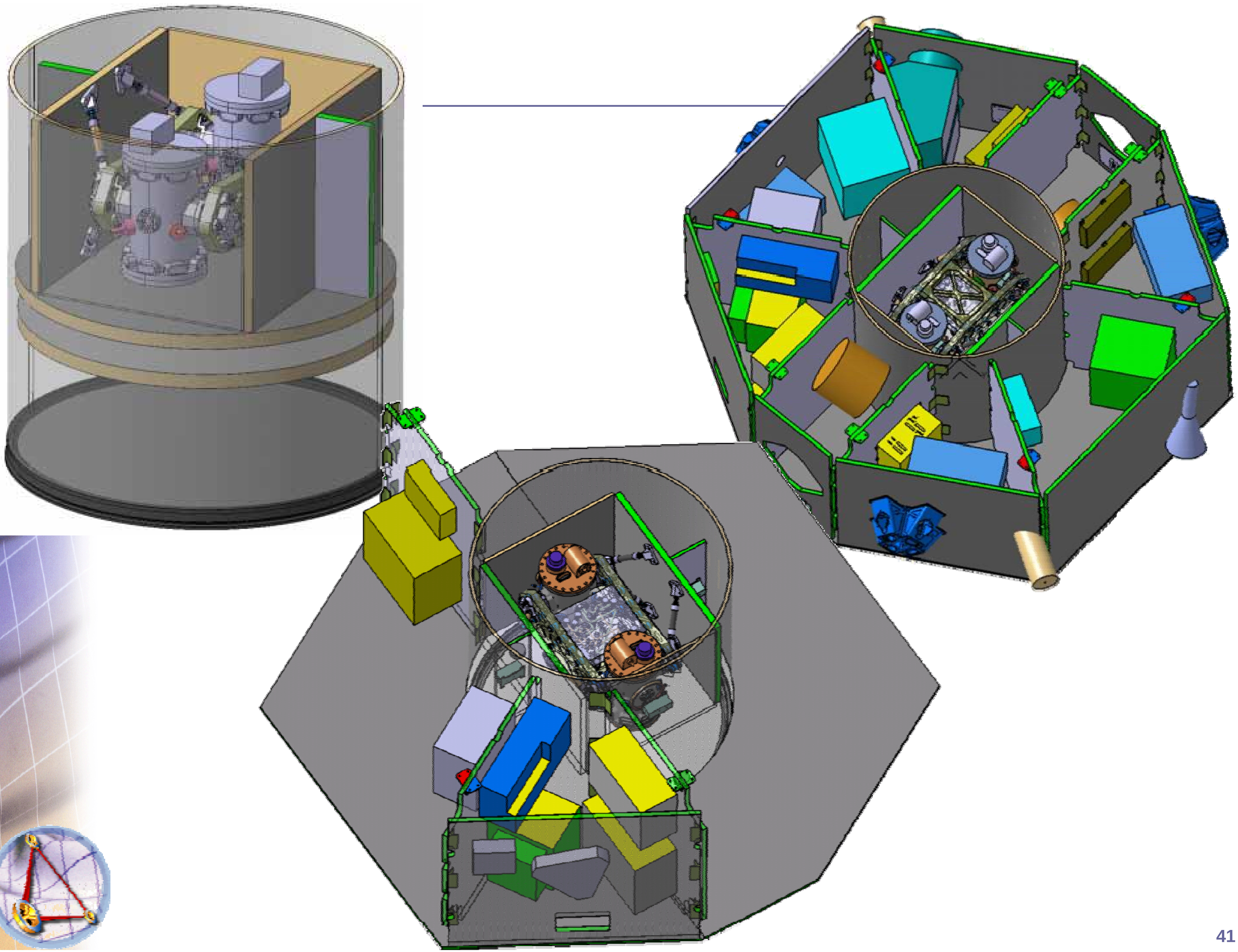


LTP Core Assembly



Vibration Test LTP Optical Bench





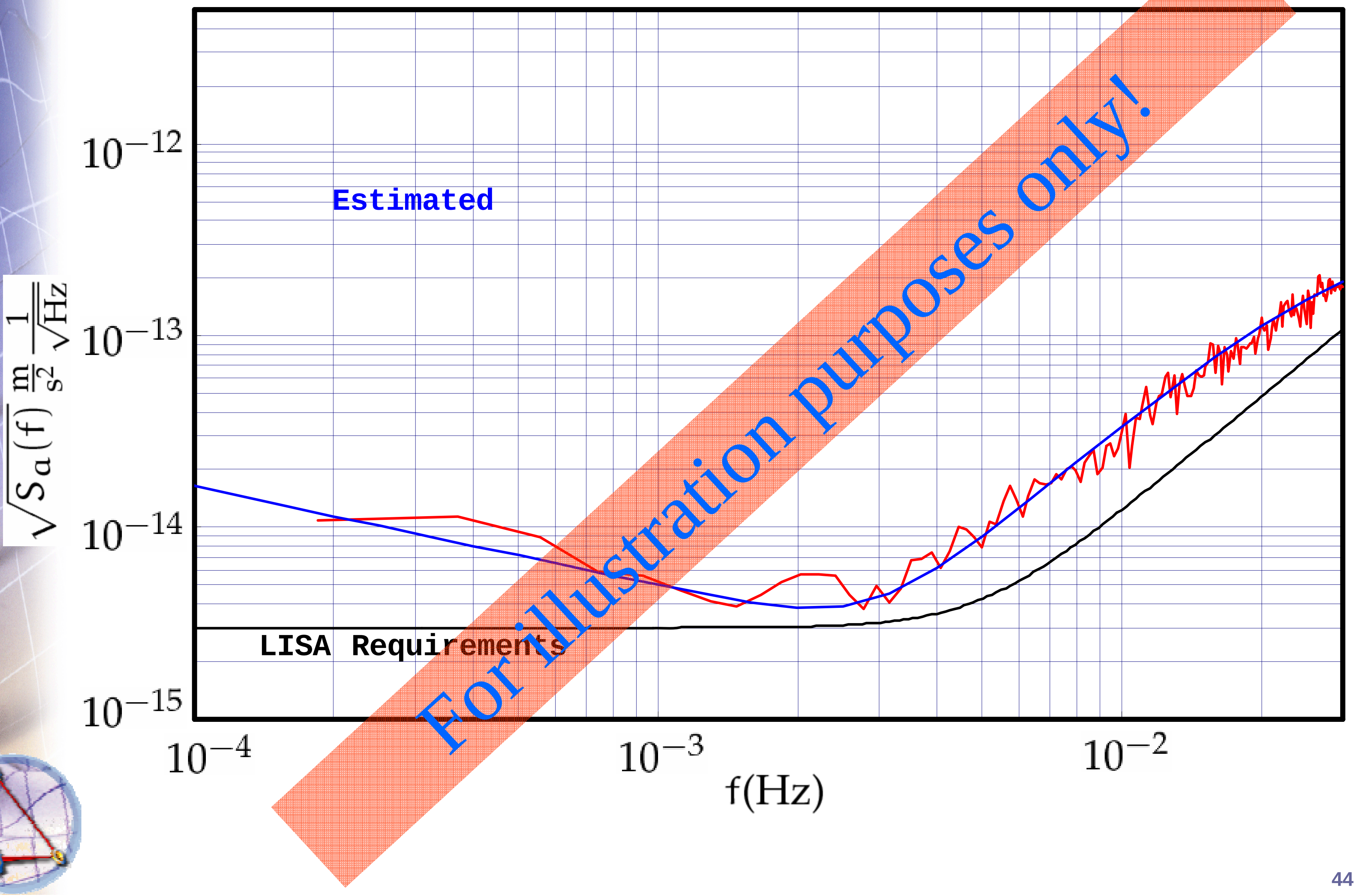
LPF Main Goals

- ***Demonstrate that total acceleration noise in realistic conditions is not larger than goals***
- ***March toward LISA:***
  - *Identify and subtract largest contributions to total noise*
  - *Verify LISA noise model*
  - *Identify excess noise*

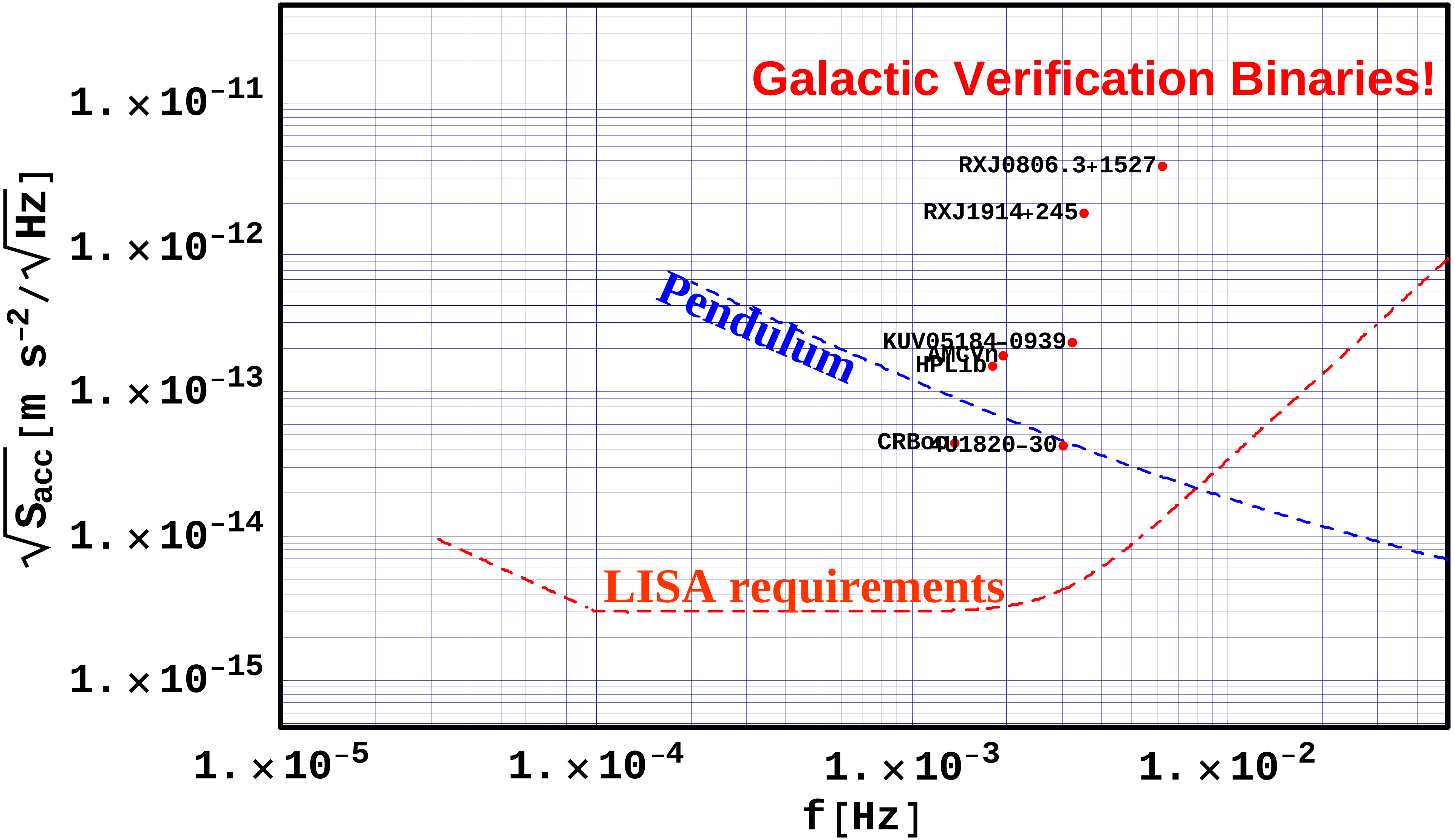
LPF noise sources

Source	Formula	Value $\frac{m}{s^2}\frac{1}{\sqrt{Hz}}$
Correlated readout noise	$f_{corr} = \sqrt{2}\sqrt{f^2_{trip} + f^2_{ampip} + f^2_{act100}}$	6.36×10^{-18}
Uncorrelated noise sources	$f_{unc} = \sqrt{2}\sqrt{f^2_{act0} + f^2_{actth}}$	8.81×10^{-18}
Thermal effects	$f_{thermal} = 2(f_{rad} + f_{radpr} + f_{og} + f_{th} + f_{gravIS})$	4.97×10^{-15}
Brownian noise	$f_{Brownian} = \sqrt{2}\sqrt{f^2_{diel} + f^2_{gas} + f^2_{magdmp} + f^2_{magimp}}$	9.36×10^{-16}
Magnetics S/C	$f_{magnSC} = \sqrt{2}(f_B + f_{\Delta B} + f_{Bac})$	8.9×10^{-15}
Magnetics Interplanetary	$f_{magnIP} = \sqrt{2}(f_{Bi} + f_{Lz})$	3.25×10^{-16}
Charging and voltage	$f_{charge} = \sqrt{2}\sqrt{f^2_q + f^2_{vs}}$	3.61×10^{-15}
Miscellanea	$f_{misc} = \sqrt{2}\sqrt{f^2_{VAC} + f^2_{laser} + f^2_{grav}}$	6.04×10^{-15}
Cross-talk	$f_{cross\text{-}talk} = 1.01 \times 10^{-14}$	
Readout noise	$f_{readout} = \sqrt{f^2_{corr} + f^2_{unc}}$	1.09×10^{-17}
Drag-free	$f_{dragfree} = \lvert\Delta\omega^2_x\rvert x_{tot}$	1.57×10^{-15}
Total	$f^2_{total} = f^2_{dragfree} + f^2_{corr} + f^2_{unc} + f^2_{readout} + f^2_{thermal} + f^2_{Brownian} + f^2_{cross\text{-}talk} + f^2_{magnSC} + f^2_{magnIP} + f^2_{charge} + f^2_{misc}$	1.61×10^{-14}
Measurement Noise	$f_{meas} = \sqrt{f^2_{act} + f^2_{bl} + f^2_{OM}}$	5.06×10^{-15}
Grand Total	$f_{gtotal} = \sqrt{f^2_{total} + ^2_{meas}}$	1.68×10^{-14}

PF Expected Noise Model Validation

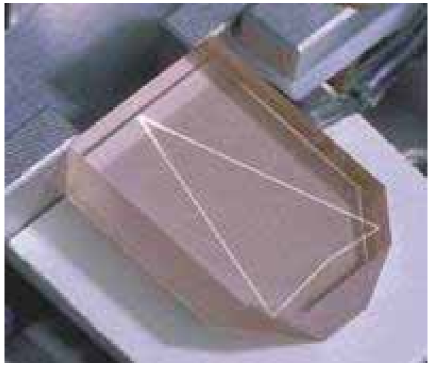


Excess Noise Limits on Ground



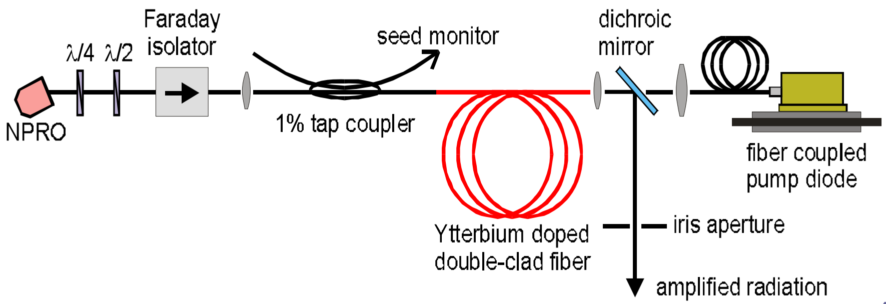
Which Laser Source for LISA?

- **Diode-pumped Nd:YAG non-planar ring lasers (NPROs)**
  - *High efficiency*
  - *High intrinsic stability*
  - *Output power up to 2 W*



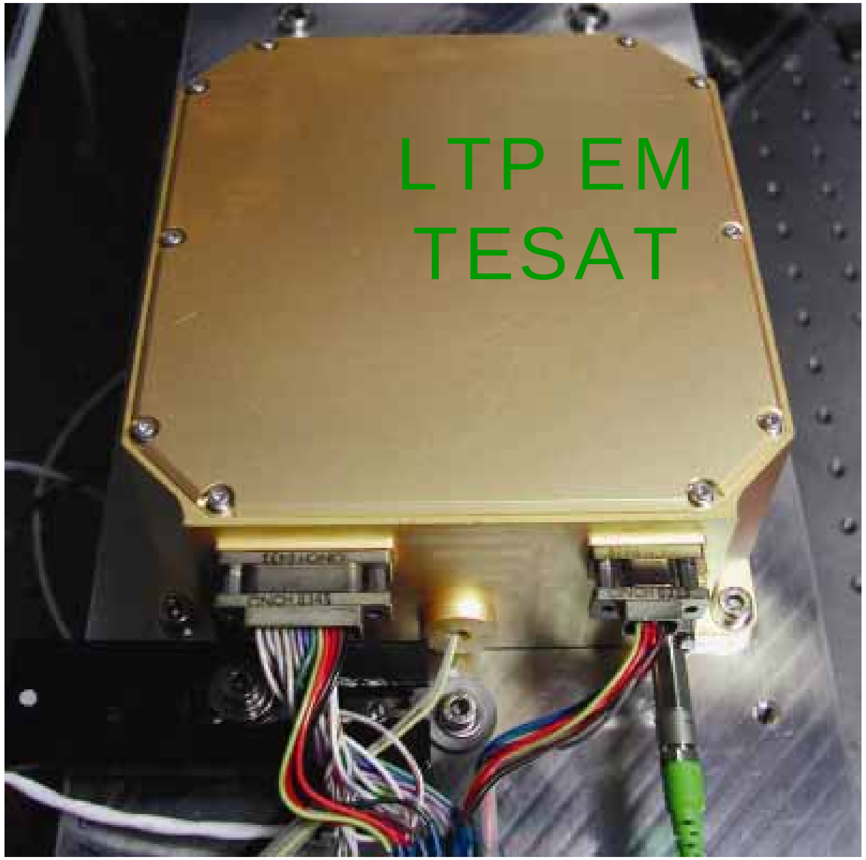
- **Single stage high-power NPRO (Off-ramp)**
  - *demonstrated on breadboard level (ESA)*

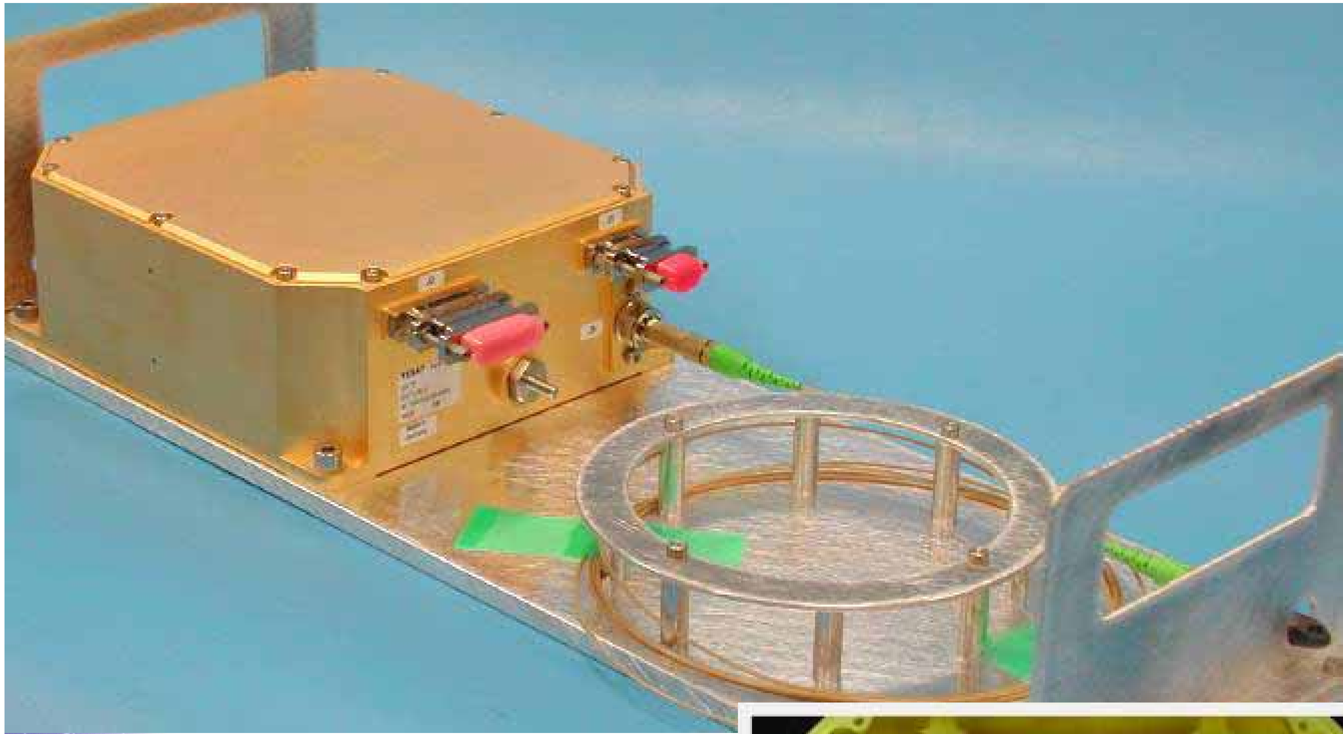
- **Two stage oscillator-fiber amplifier (Baseline)**
  - *Space qualified master and slave available (TESAT)*
  - *Master to fly on LISA Pathfinder*
  - *Delta-development needed for amplifier power*

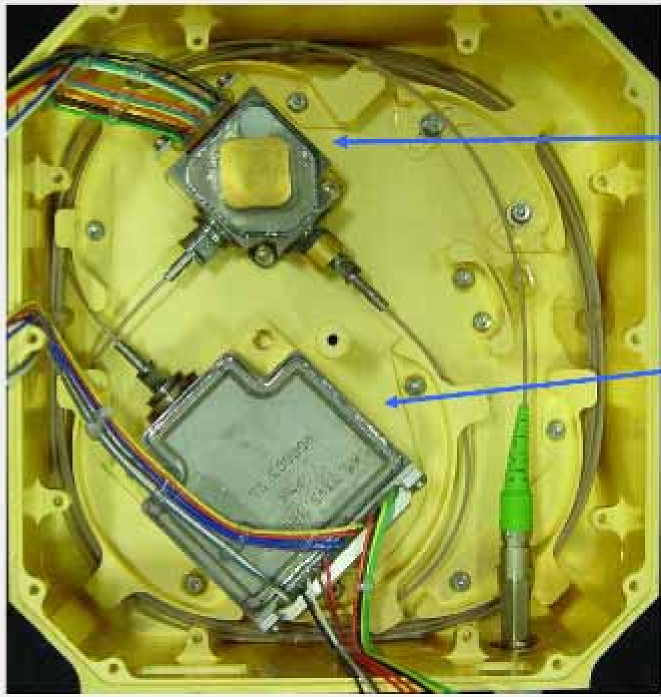


Flight Tests of LISA Master Laser

- ***Non-Planar Ring Oscillator (NPRO) laser developed for TESS (NASA)***
- ***LPF-like NPRO developed for EO3-GIFTS (NASA)***
- ***Identical NPRO will fly on LTP (ESA), now in CDR!***
  - *Volume 1 liter, Mass 1 kg,*
  - *10 W electrical power*
  - *25 mW single mode optical output power into polarization maintaining single mode fiber output*
  - *Free running stability 100 MHz for 24 h and 1-2 MHz for 5 s*







Laserhead
Nd:YAG 1064nm

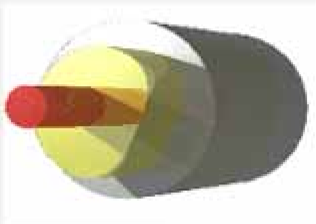
Pumpmodule
bragg-stabilized 808nm
with redundant bench

all optical units in direct
thermal contact with
RLU housing

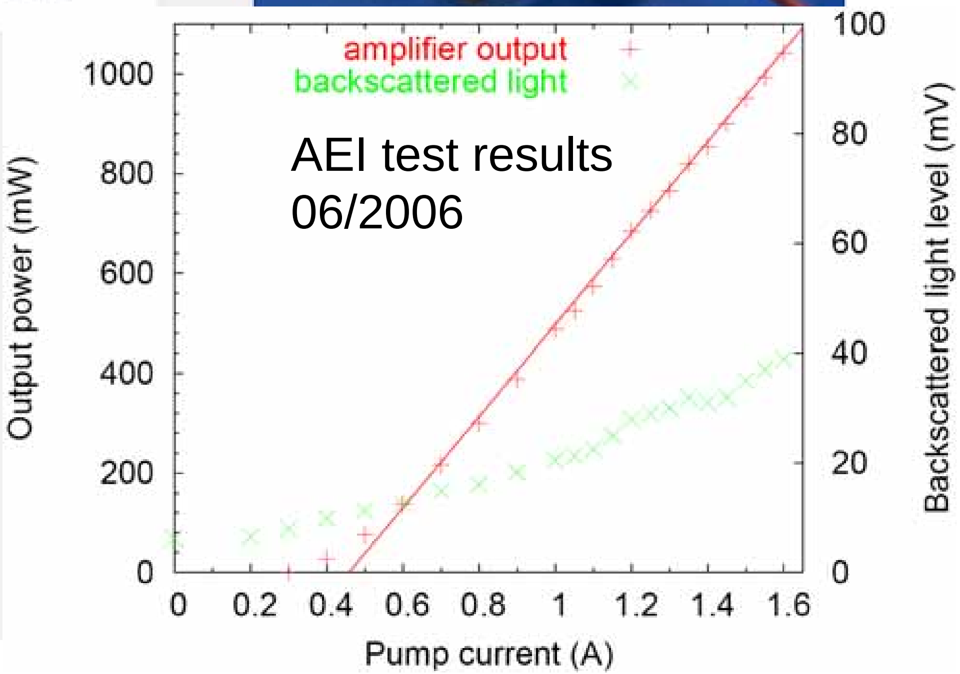
LISA Laser Fiber Amplifier

- ***To be launched on TerraSAR in 2006/7!***

Polarisation Maintaining Optical Fiber Amplifier



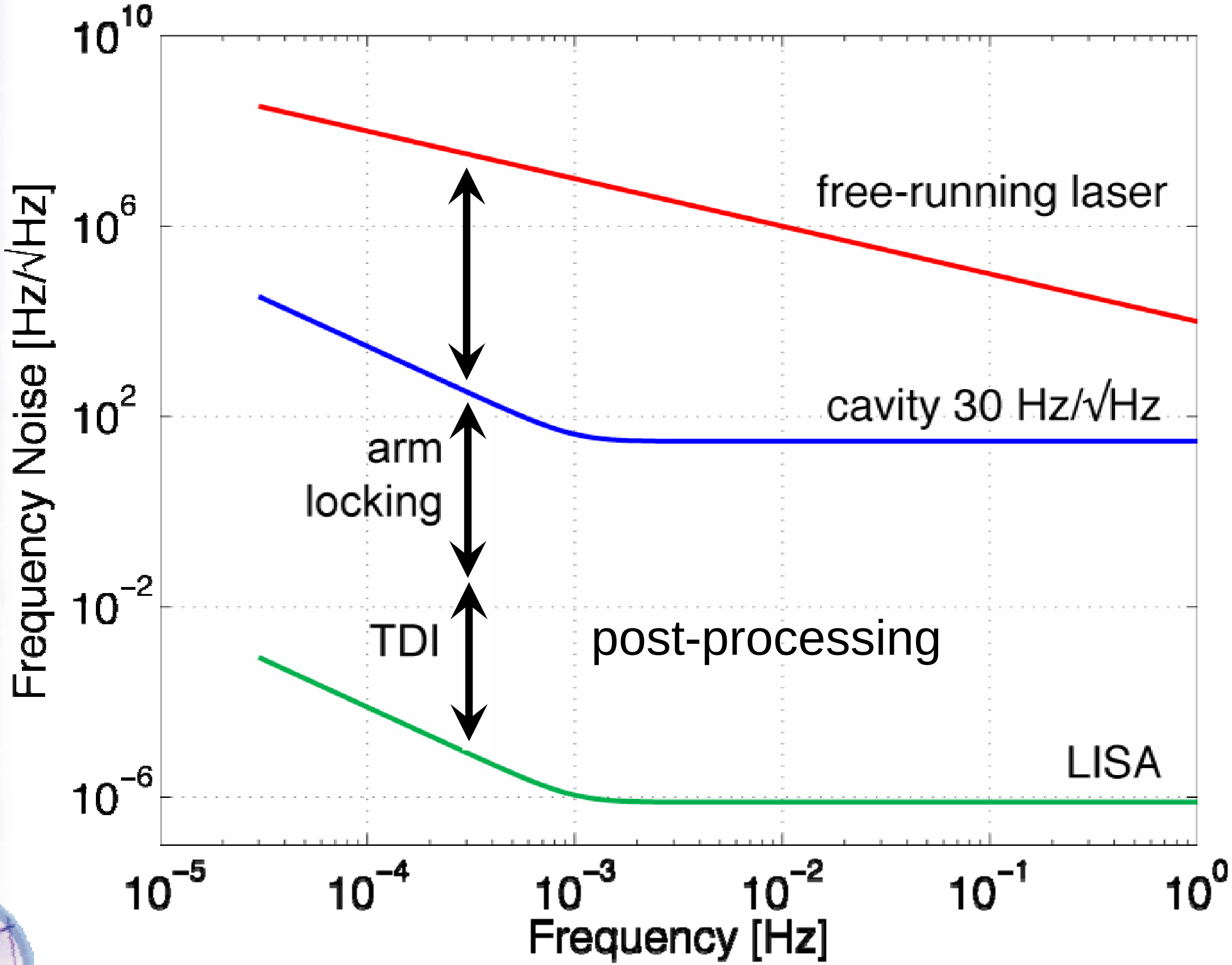
- Polarized single frequency output power of 2 W
- Low input power (10mW)
- More than 95% of initial performance after 100 krad gamma irradiation
- Temperature independent operation between -20°C and + 40°C

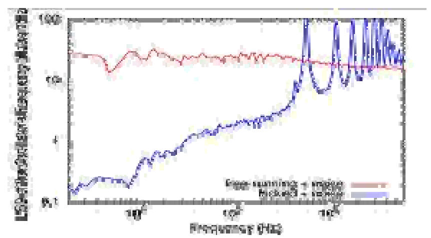


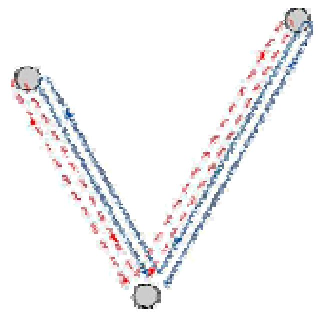
Frequency Stabilization

- ***A perfect equal-arm Michelson is immune to frequency noise!***
- ***But for unequal arm interferometer $\delta L = \Delta L \bullet \delta\nu/\nu$***
  - *For ΔL= 10 000 km want $\delta\nu$=10 µHz*
- ***Free-running miniature Nd-YAG laser***
  - *$\delta\nu$ ~ 10 kHz/√Hz•[1Hz/f]*
- ***Need to suppress $\delta\nu$ by many orders of magnitude!***
- ***Combination of***
  - *pre-stabilization,*
  - *stabilization on armlength, and*
  - *post-correction in data analysis!*

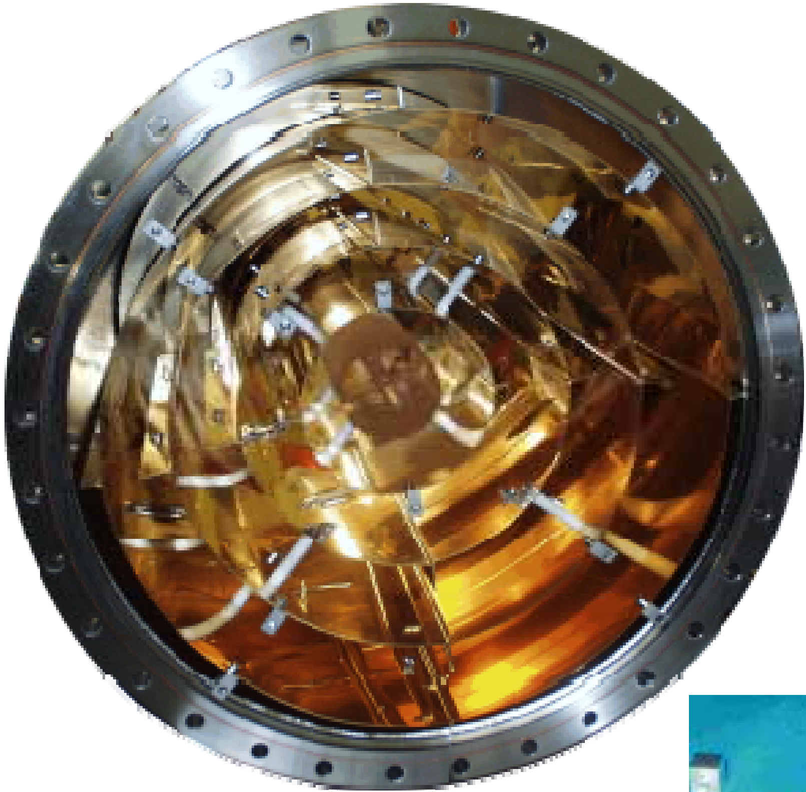
3-Stage Frequency Stabilization

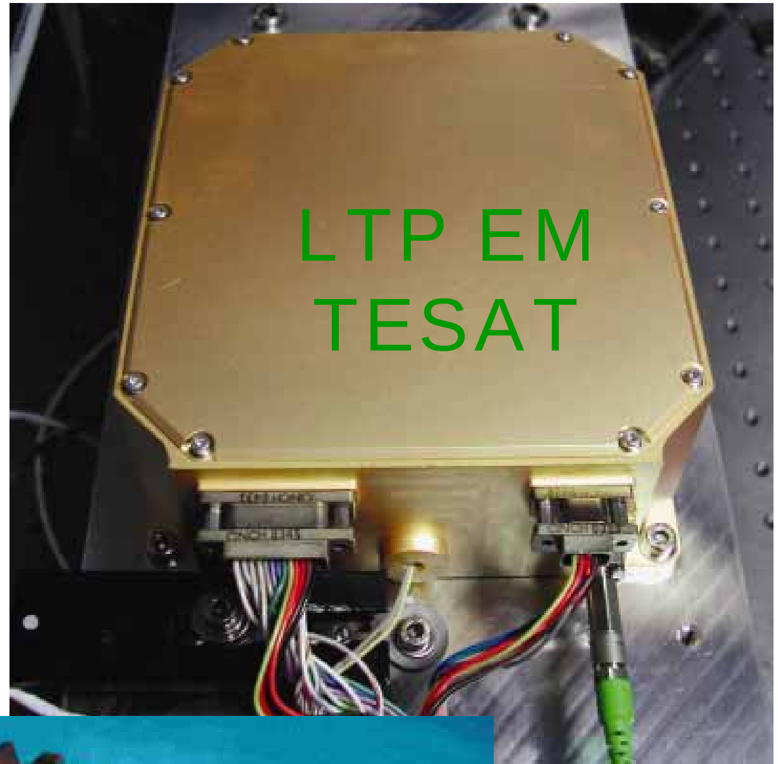


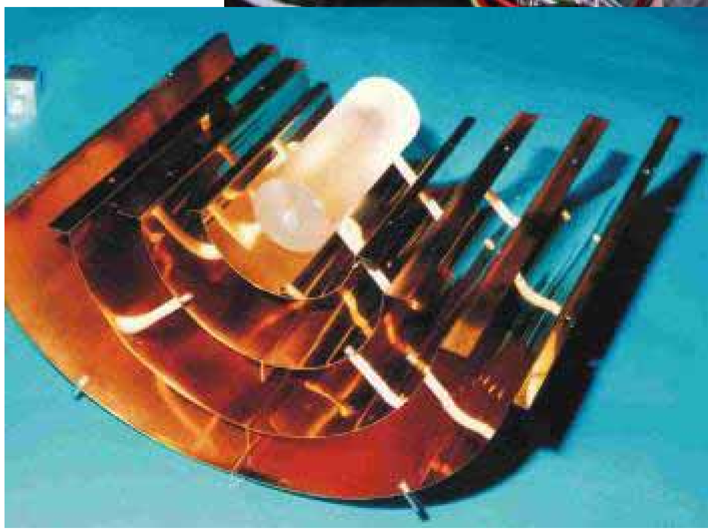




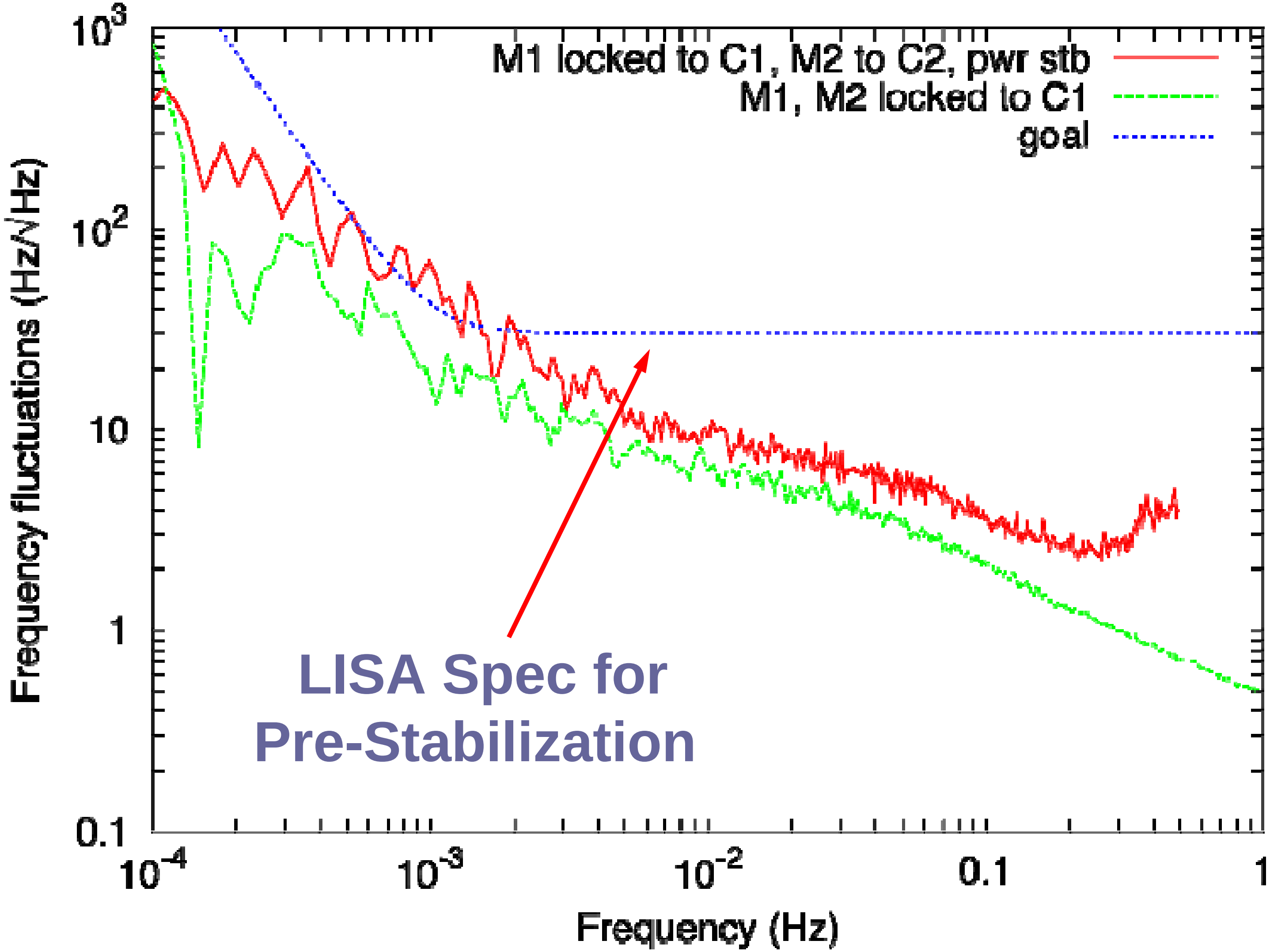
Cavity Pre-Stabilization in Lab







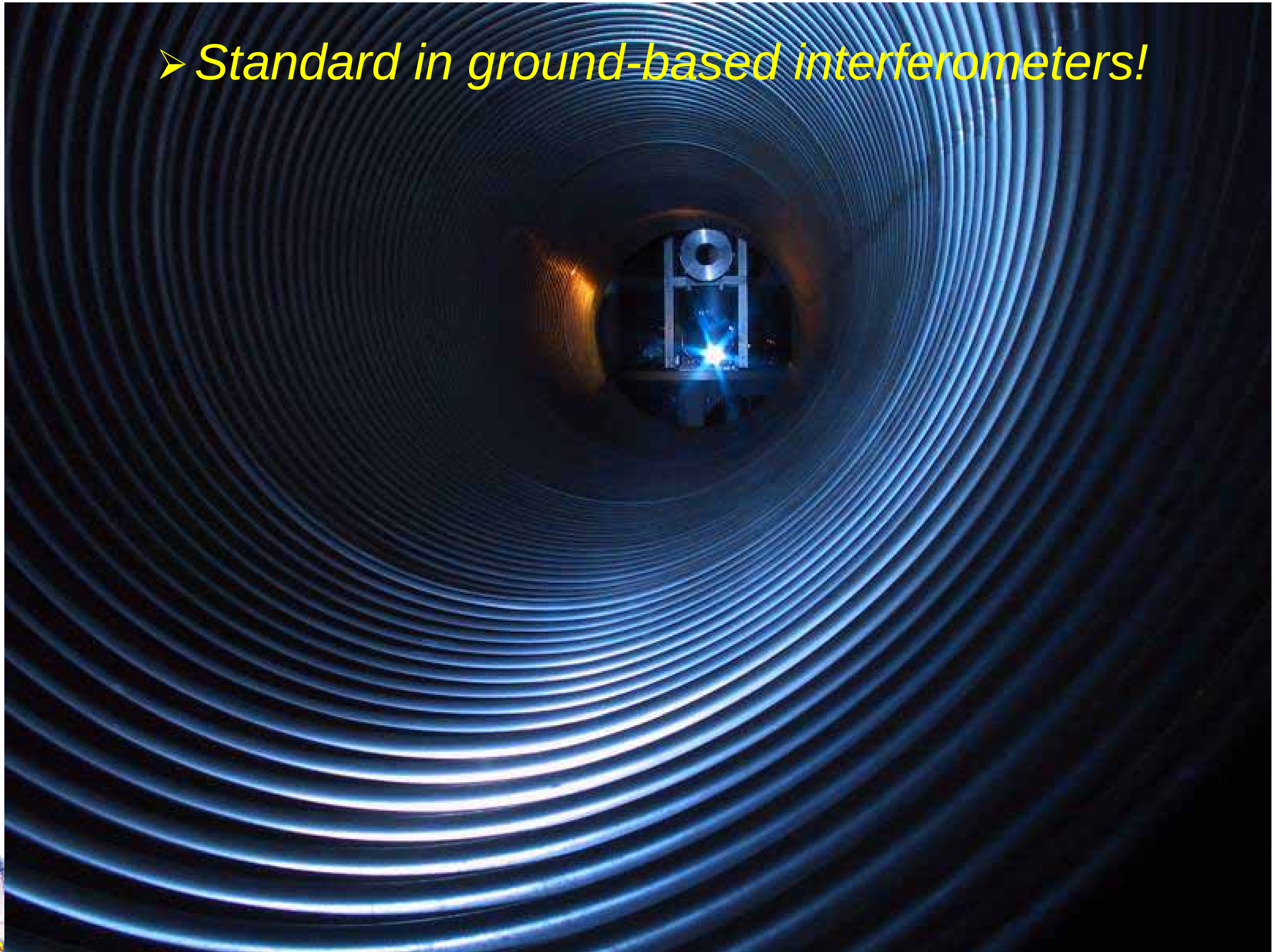
Laser Cavity Stabilization



2 independent systems, out of loop

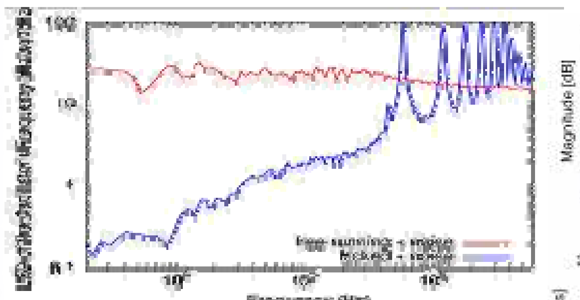
Arm Locking of Laser Frequency

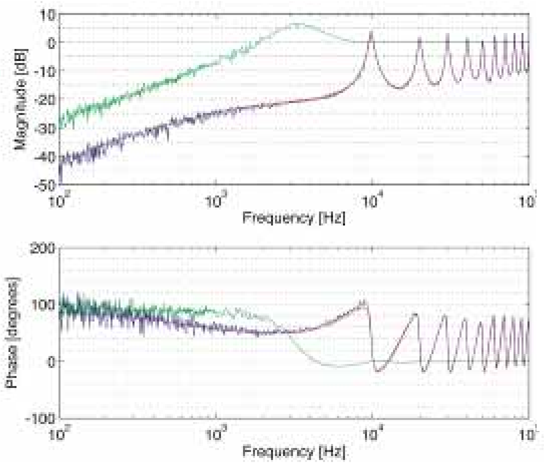
- *Standard in ground-based interferometers!*

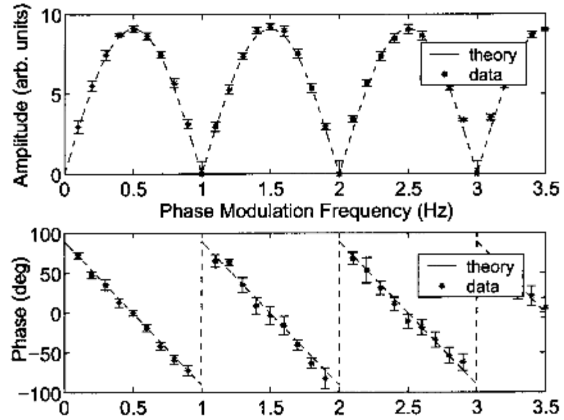


Arm locking demonstrations

- ***Several experimental verifications***
  - *Electrical measurements using 300 m cable.*
  - *Optical measurements using 10 km optical fiber.*
  - *Optical measurements with up to 30 s electronic delay.*







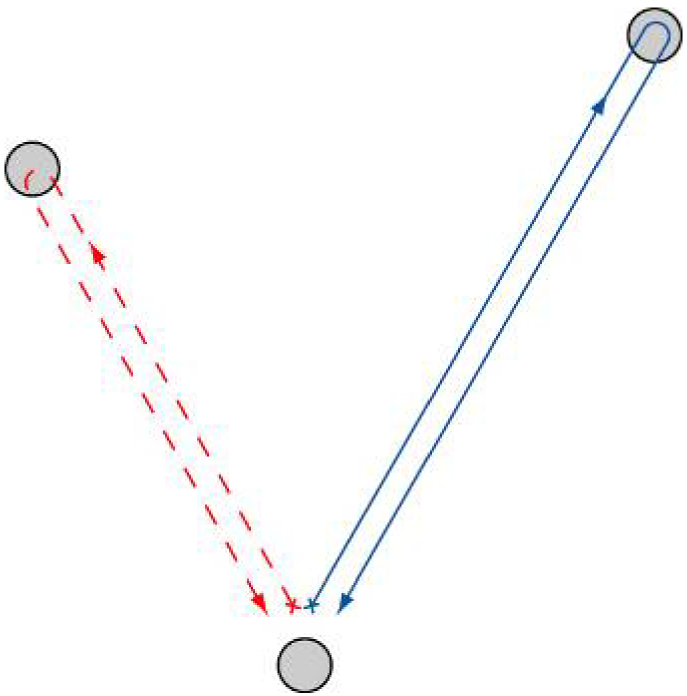
- ***All experiments verify analytical studies.***

Time-Delay Interferometry

Post-processing technique to synthesize equal-arm interferometer!

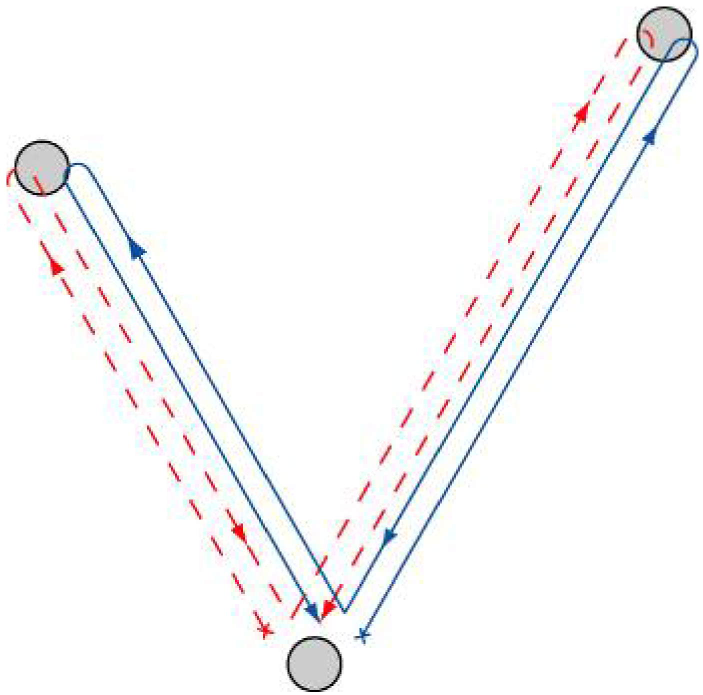
Replace the 100 m armlength <u>difference</u> requirement

by a 100 m armlength <u>knowledge</u> requirement!



Unequal-arm interferometer.

Output sensitive to laser noise

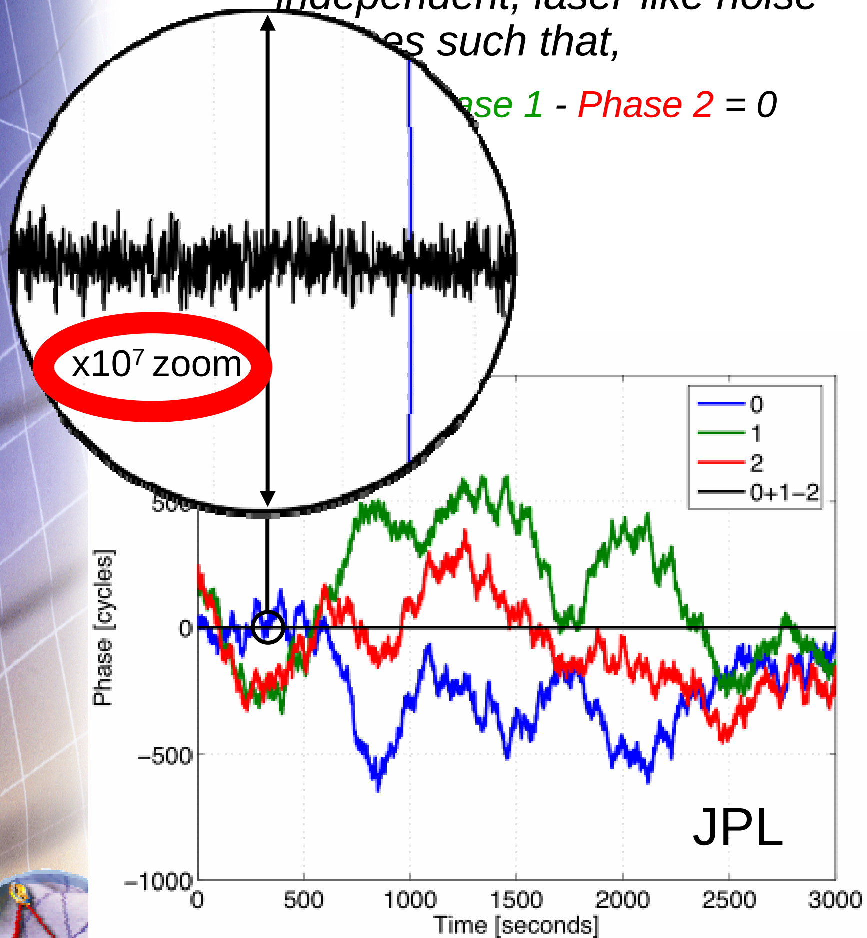


Synthesized equal-arm interferometer

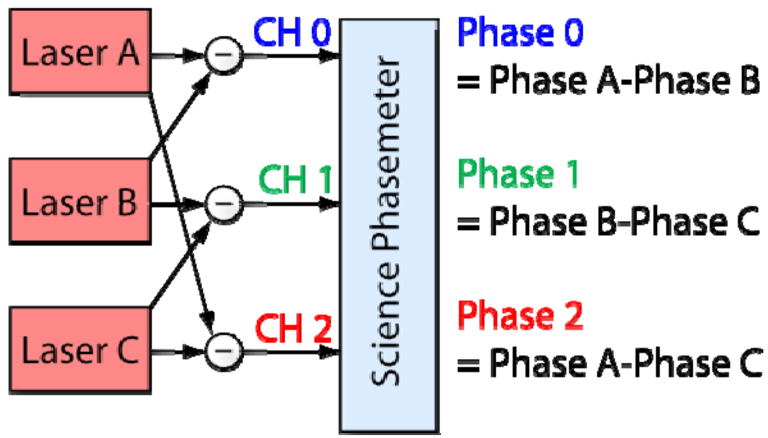
Output immune to laser noise

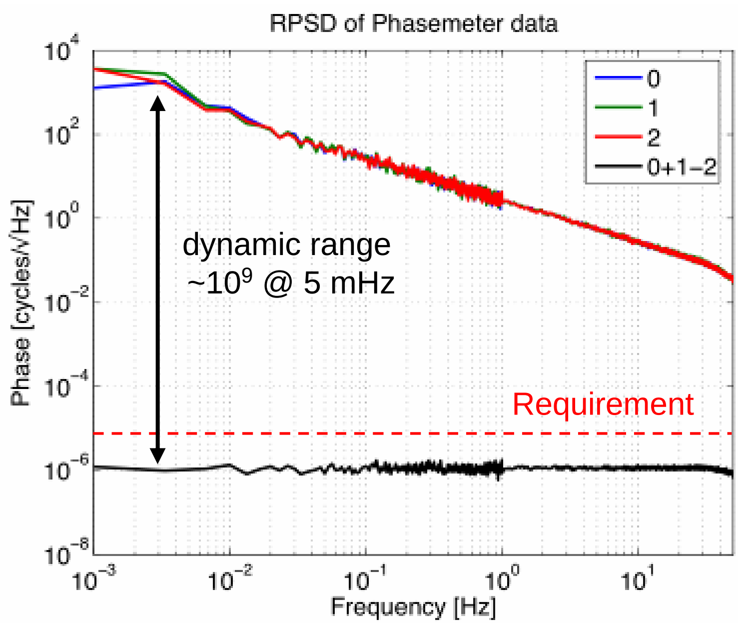
Science phasemeter testing

- ***Digitally tested dynamic range requirement.***
  - *Digitally generated 3 independent, laser-like noise ...es such that,*
  - *...ase 1 - Phase 2 = 0*

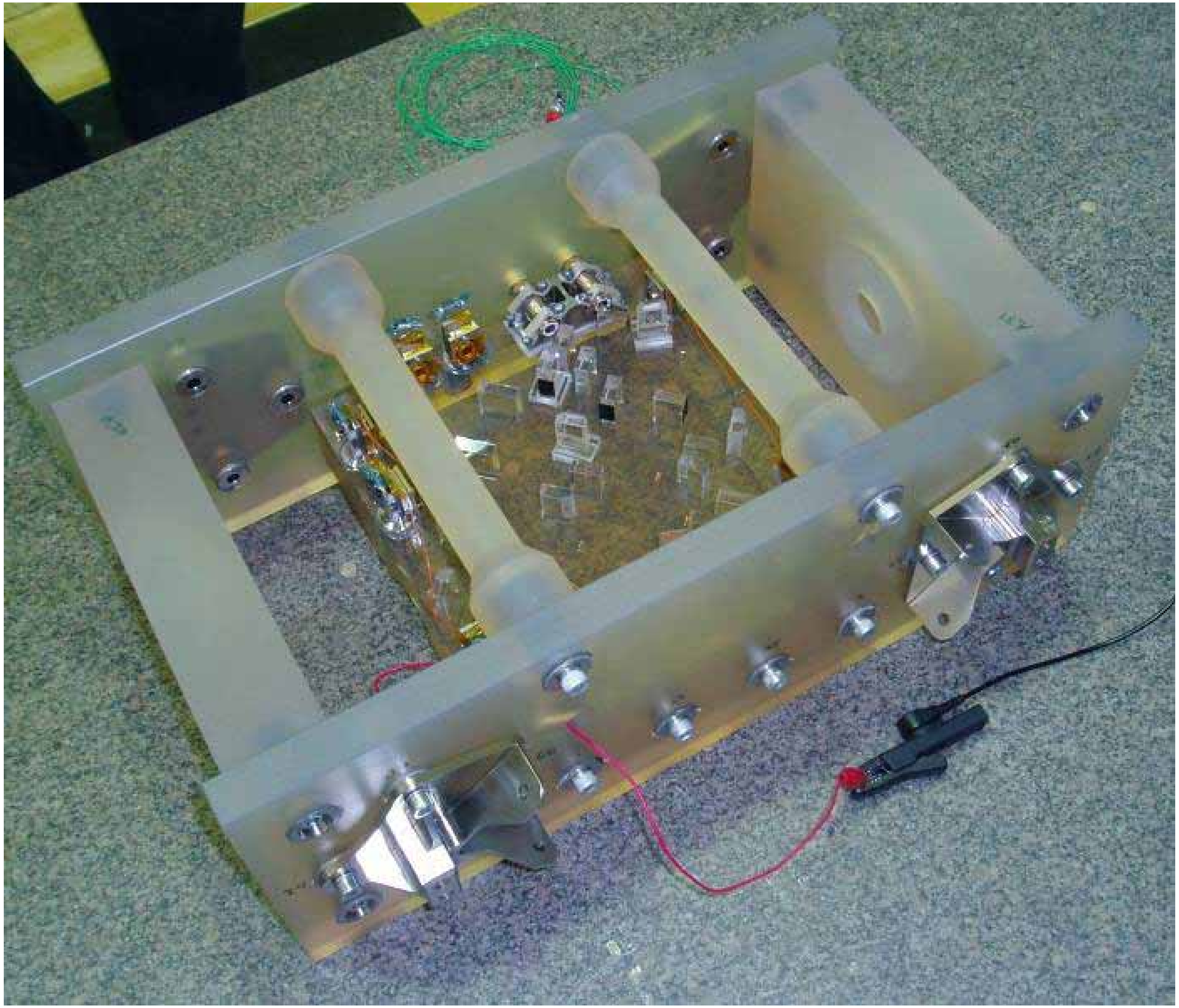


Equivalent Optical Setup

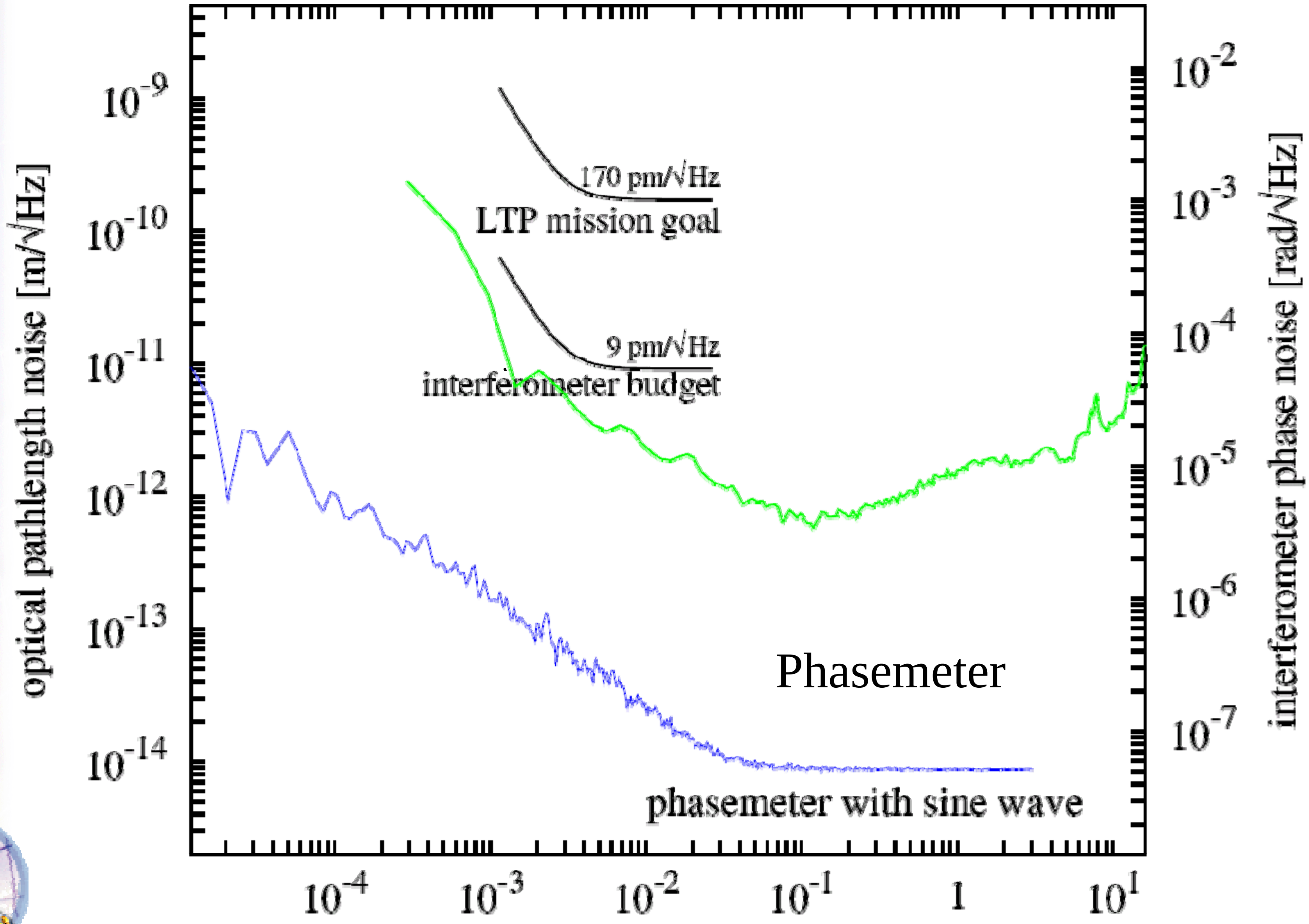




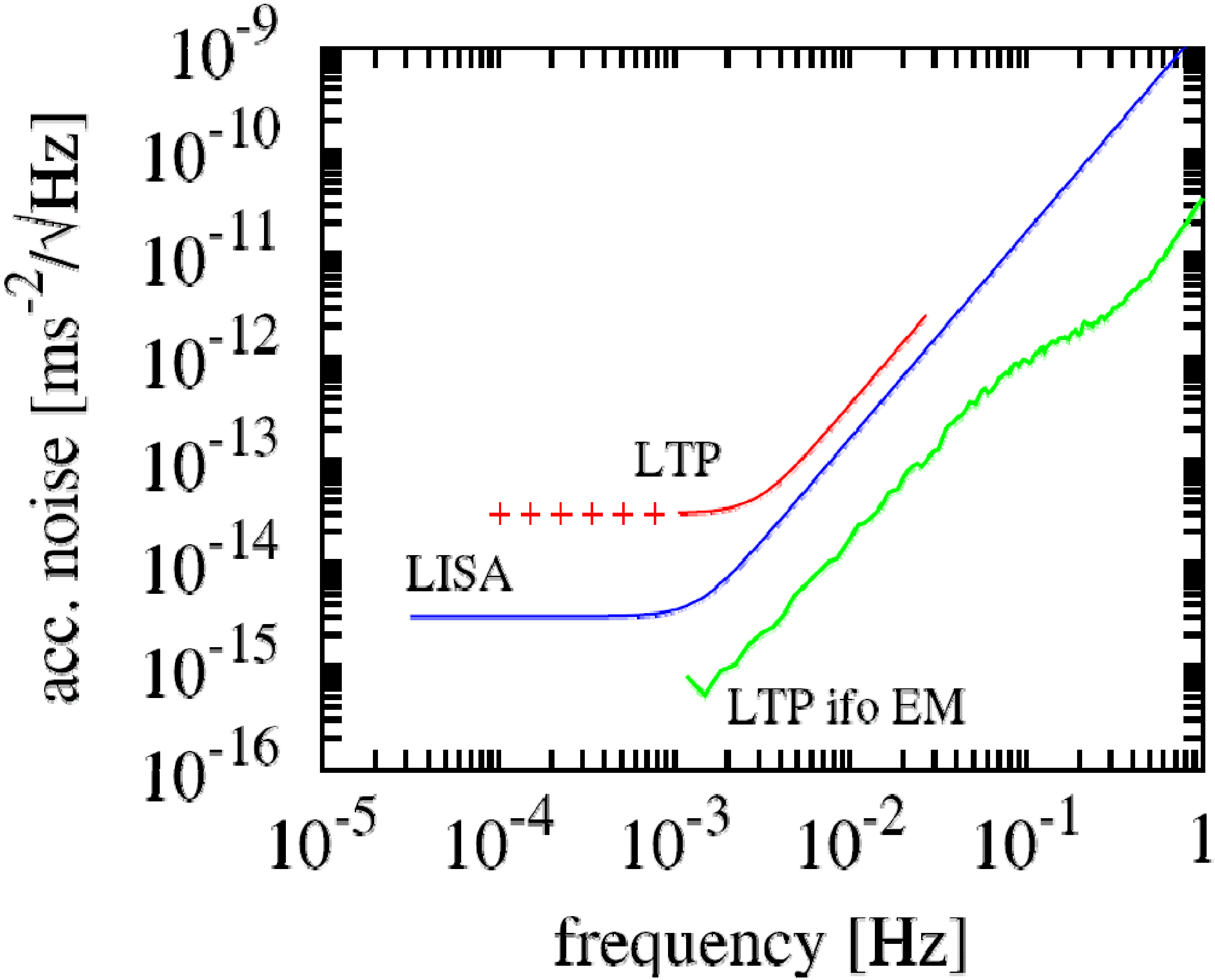
S/C-to-Test Mass Ifo Test on LPF EM



Optical Bench EM Performance

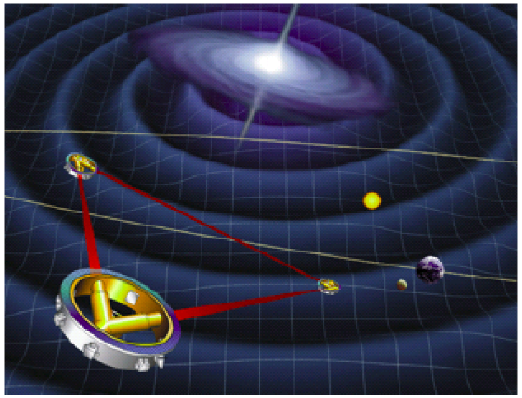


Optical Bench EM Performance



Independent Technology Review

Laser Interferometer Space Antenna (LISA)
Technology Assessment



Prepared for Dr. Edward Weiler
Center Director
Goddard Space Flight Center
January 20, 2006

Independent Technology Review

Final Report

III. <u>Technology Assessment Summary and TRL Table</u>

The project developed a LISA Technology Readiness and Implementation Plan (TRIP) that was extensively reviewed in March 2003 by an independent team of experts. The findings of the TRIP review were considered as a baseline for this technology assessment, with the same critical technology areas reviewed.

Based on detailed assessments of the LISA critical technology areas, there has been

LISA Review Team has determined that the technology requirements for this mission are well understood and the plans for completing development of each of the critical technologies are sound and compatible with the LISA Project schedule.

The following is a summary of the critical technology areas and current technology readiness levels. Each critical technology area is reviewed and assessed in detail as part of this report.

LISA Status

- ***ESA-NASA collaboration agreement since August 2004***
  - *Joint Management Structure working well!*
- ***Mission Formulation Study began in January 2005***
  - *ESA prime contractor EADS Astrium Friedrichshafen*
  - *NASA GSFC and JPL fully integrated*
- ***LISA Technology Assessment Review at GSFC***
  - *Passed with flying colors in December 2005!*
- ***Technology precursor LISA Pathfinder in Phase C/D***
  - *Launch in 2009*
- ***LISA technically well on track for launch in 2015!***
  - *Launch date is determined by budget*

Technology-paced Schedule

▪ Formulation Phase Kick-Off:	January 2005
▪ Definition Phase Start:	January 2008
▪ LISA Pathfinder Launch:	October 2009
▪ LISA Phase B/C/D Start:	January 2010
▪ LPF final results available:	July 2010
▪ LISA Launch:	August 2015
▪ Reach Science Orbit:	September 2016
▪ Science Operations Start:	October 2016
▪ End of nominal mission:	October 2021

Project schedule calls for 2016 launch based on funding profile.

LISA

NRC Beyond Einstein Review

November 6-8, 2006
Washington

Scott Hughes
Craig Hogan
Karsten Danzmann

Committee Roster

To view biographies of committee members, visit this site.

Charles F. Kennel, co-chair
Scripps Institution of Oceanography

Joseph H. Rothenberg, co-chair
Universal Space Network

Eric G. Adelberger
University of Washington

Bill Adkins
Adkins Strategies, LLC

Thomas Appelquist
Yale University

David A. Bearden
The Aerospace Corporation

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Futron Corporation

Karl Gebhardt
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William C. Gibson
Southwest Research Institute

Fiona A. Harrison
California Institute of Technology

Andrew Lankford
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Joel R. Primack
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University of California Los Angeles

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Note: Presentations are in PDF format; Beyond Einstein Program Assessment Committee is referred to as BEPAC.

November 6, 2007

Purpose of the Study

Rick Howard, NASA HQ	NASA Presentation to the NRC BEPAC
Rob Dimeo, OSTP	OSTP Perspective: 1; OSTP Perspective: 2

Beyond Einstein Science

Michael Turner, Univ. of Chicago	From Quarks to the Cosmos to the BEPAC
Joseph Lykken, FNAL	What is the Nature of Dark Energy
Marc Kamionkowski, Caltech	The Cosmic Microwave Background and the Dawn of Time
Scott Hughes, MIT	Did Einstein Have the Last Word on Gravity?
Chris Reynolds, Univ. of Maryland	Did Einstein Have the Las Word on Gravity?

November 7, 2006

Beyond Einstein Programs

Tom Prince, Caltech (LISA)	The Laser Interferometer Space Antenna
Harvey Tananbaum, Harvard (CON-X)	The Constellation X-ray
Josh Grindlay, Harvard (EXIST)	EXIST Concept for BHFP
Mark McConnell, UNH (CASTER)	The Coded Aperture Survey Telescope for Energetic Radiation
Michael Levi, LBL (SNAP)	The SNAP Experiment
Tod Lauer, NOAO (DESTINY)	Dark Energy Space Telescope
Charles Bennett, JHU (ADEPT)	JDEM: An ADEPT Approach
Peter Timbie, Univ. of Wisconsin (EPIC)	The Einstein Polarization Interferometer for Cosmology
James Bock, JPL (EPIC)	Experimental Probe of Inflationary Cosmology
Gary Hinshaw, GSFC (CMBPol)	Probing Inflation with CMBPol
Gary Melnick, SAO (CIP)	Cosmic Inflation Probe

If you want to see a presentation, click

- http://www7.nationalacademies.org/ssb/BE_November_2006_mtg_DC.html

- LISA came across extremely well!

LISA

Summary

- **LISA science is spectacular and unique!**
  - Black Holes
  - Cosmology
  - Galaxy growth
  - Galactic Binaries
  - Terascale Physics
  - The truly unknown
- **The mission concept is mature, stable and well-developed!**
  - Requirements flowed down and well-understood
  - Architecture stable since a decade
- **The technology is well advanced, no breakthroughs required!**
  - Comprehensive development plan
  - Ground-based technology demonstrations complete
  - LISA Pathfinder carries most technologies into space
- **LISA is ready to go!**
  - Technology is ready
  - Strong NASA – ESA partnership
  - Science community is large, growing and vigorous
- **LISA is truly new!**