Listening to the Universe with Gravitational Waves: LISA and LISA Pathfinder

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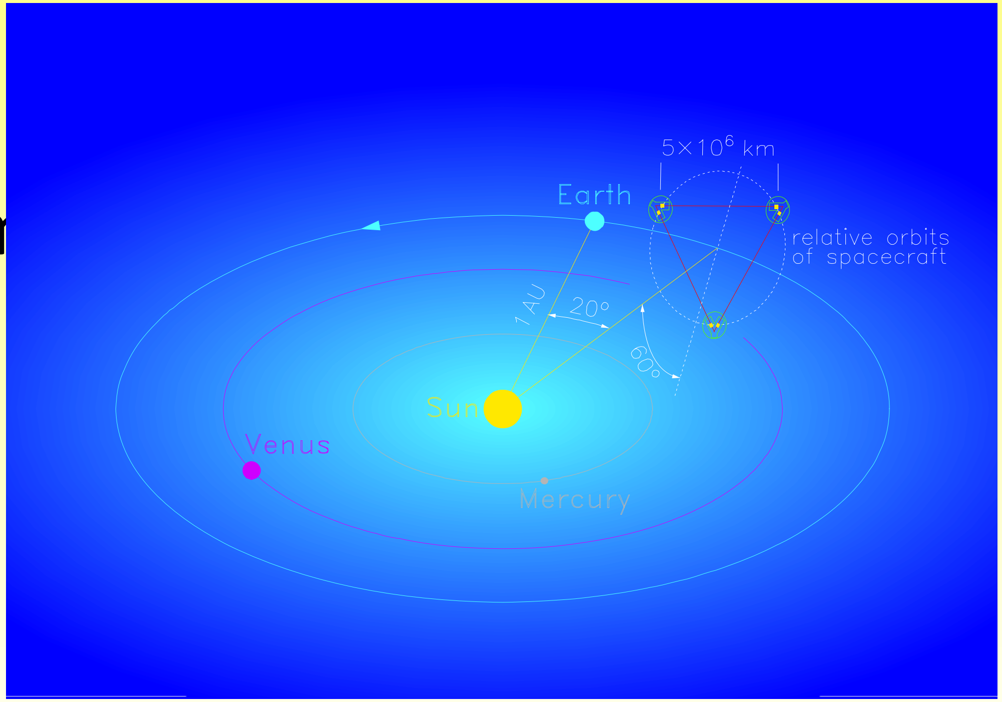
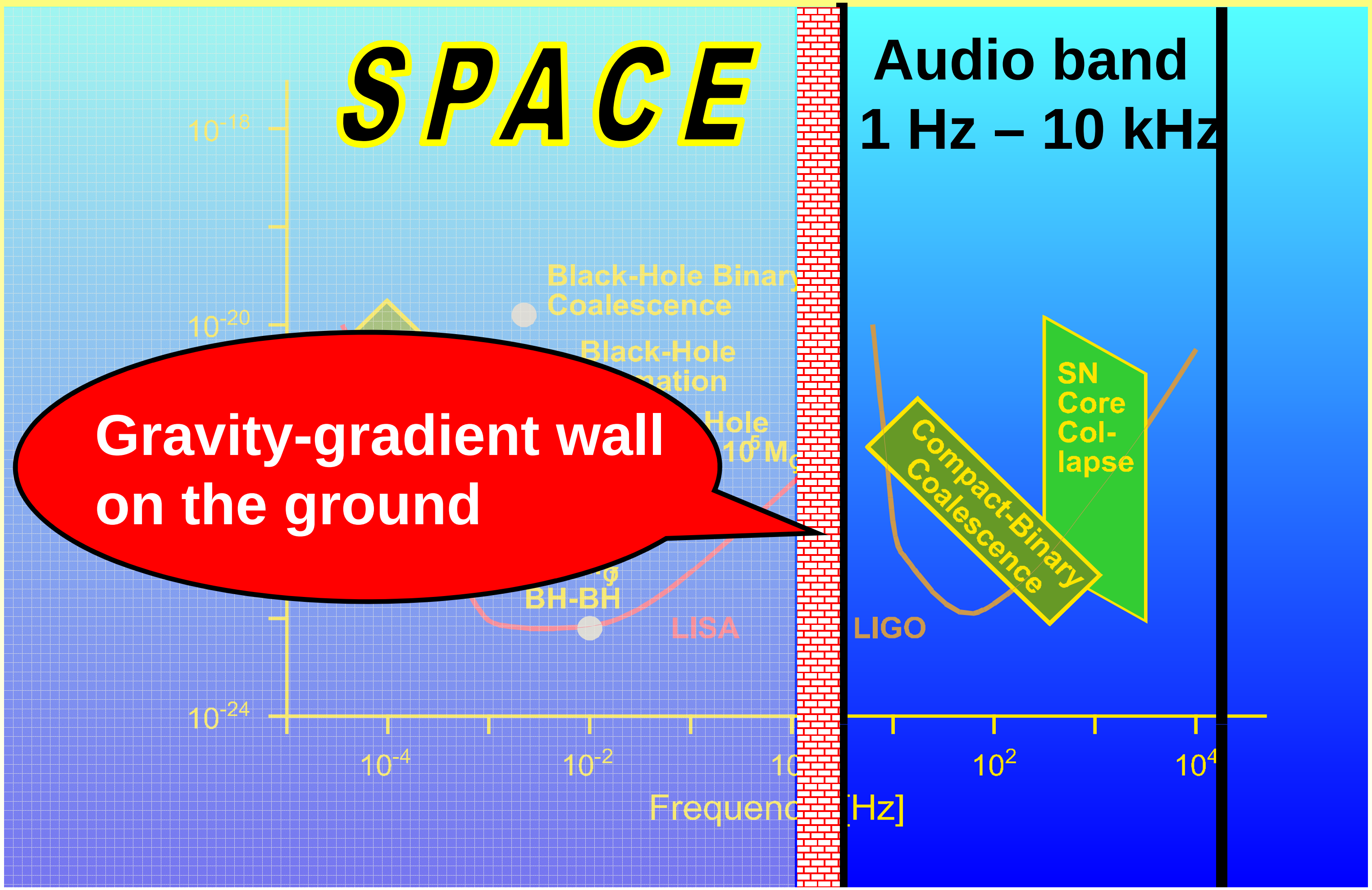
A Collaborative NASA/ESA Mission

- 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 arm
- Trailing the Earth by 20 ° (50 million km)
- Inclined against ecliptic by 60 °

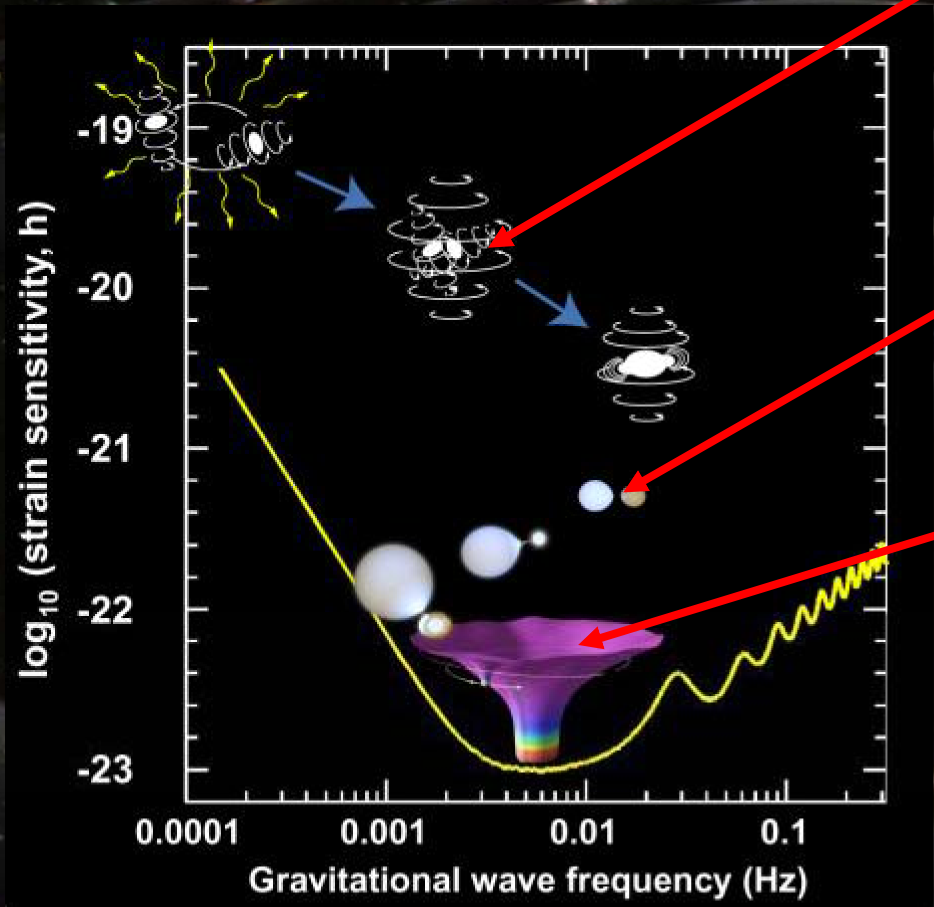


Gravitational Wave Sources

- **Ground-based detectors observe in the audio band**
  - **The analogue of optical astronomy**
- **Space detectors observe low frequencies**
  - **The analogue of radio astronomy**



LISA: A Universe Full of Strong GW Sources



Massive Black Hole Binary (BHB) inspiral and merger

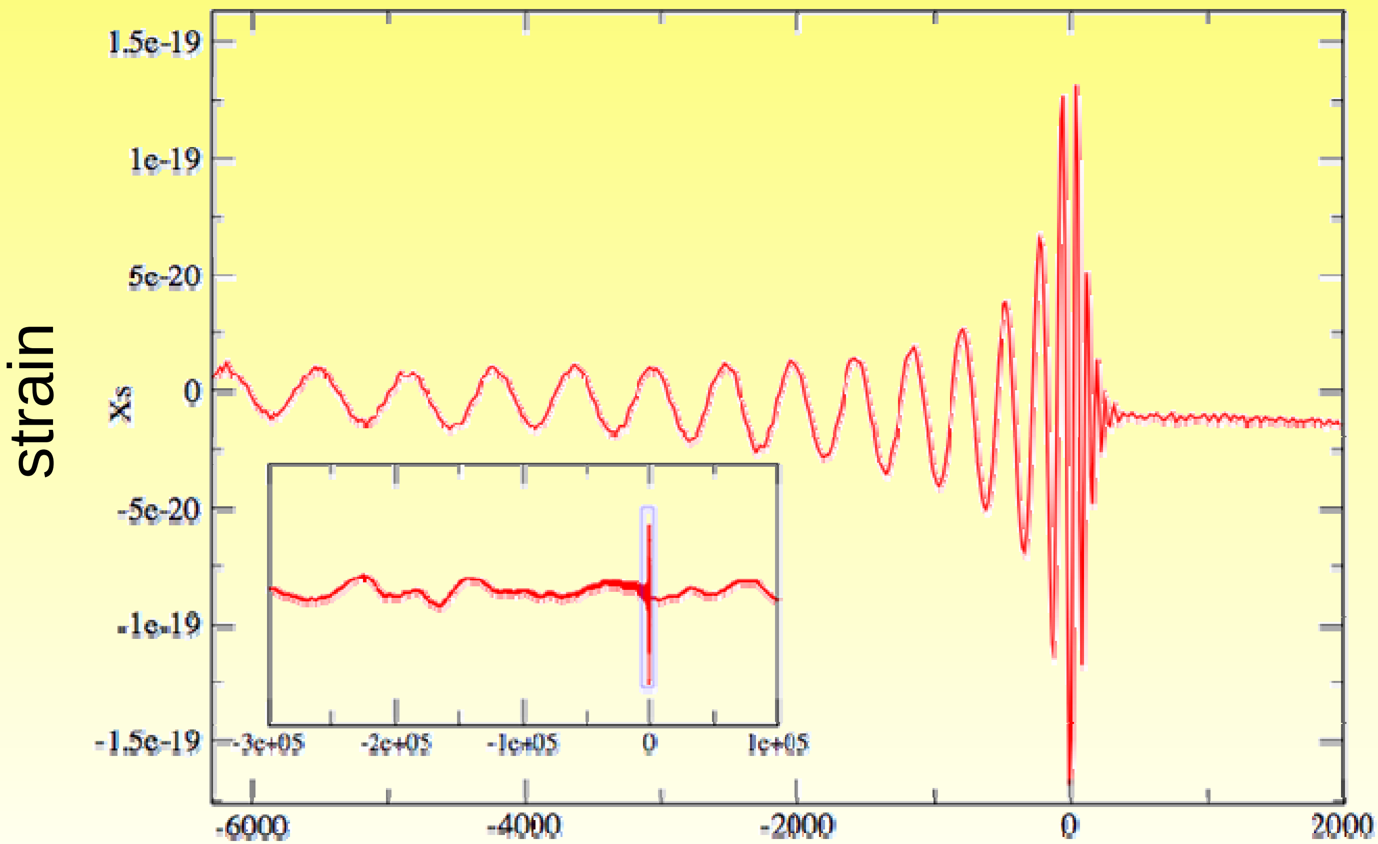
Ultra-compact binaries

Extreme Mass Ratio Inspiral (EMRI)

Cosmic backgrounds, superstring bursts?

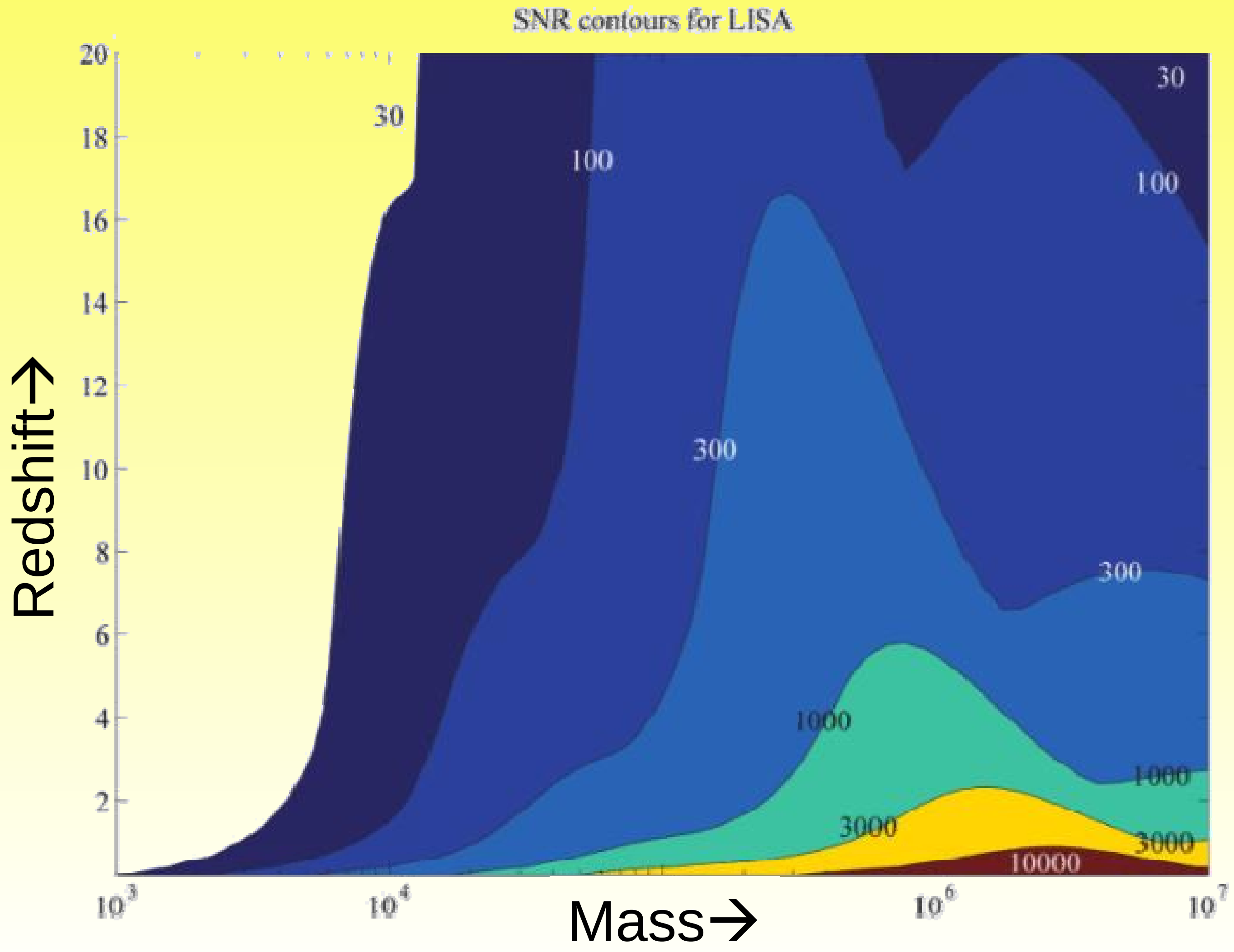
Merger Signals far above Noise!

- Simulated LISA datastream,
  - $10^5 M_\odot$ BH binary merger at z=5, including instrumental noise (SNR~500)



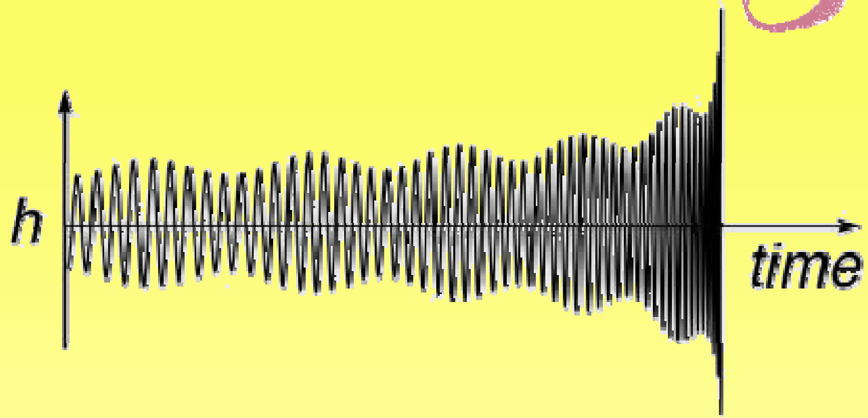
Massive Binary Black Holes at large Redshift!

Contours of SNR, equal mass merger (optimal)



Absolute Distances from Black Hole Binaries

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift



Absolute luminosity distances can be derived <u>*directly*</u> from

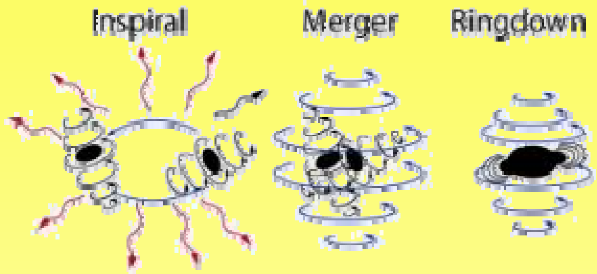
- amplitude
- orbital frequency
- chirp time

$$\text{Distance} \cong c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$

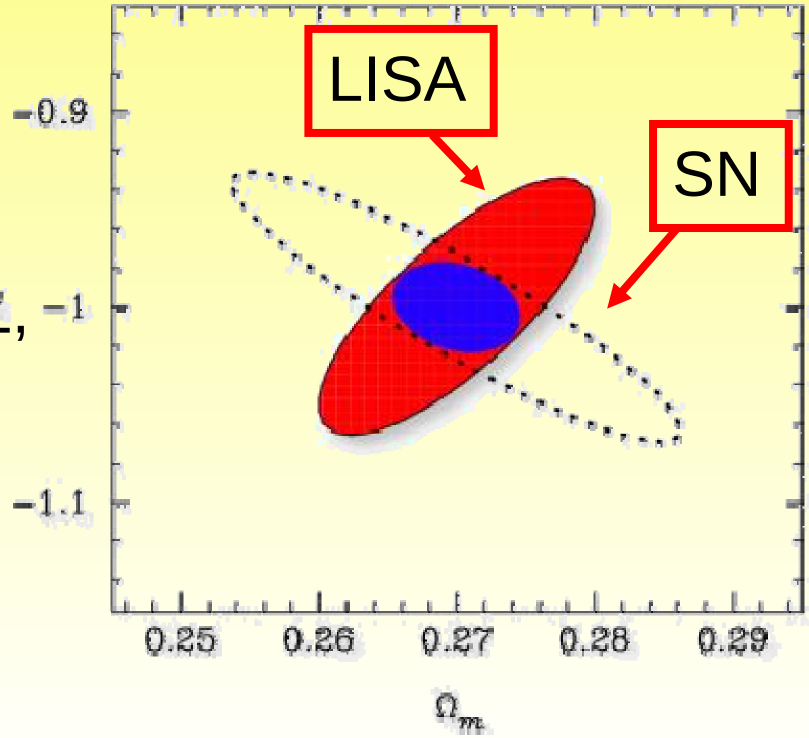
1. Distances accurate to 0.1% to 2% per event
2. Absolute, physical calibration using only gravitational physics

Absolute Distances from SMBH Mergers:

Hubble Constant and Dark Energy



- 100’s of events expected to z~3
- 10’s out to z~20
- Noise from weak lensing
- Comparable precision to CMB, WL, BAO, CL, SN techniques
- We need to identify the host to get the redshift!
- Optical counterparts?



100 BHB, 3000 SNIa (Dalal et al 0601275), includes lensing noise

LISA Error Ellipse shrinks from a few degrees

(only accessible to LSST)

to arcminutes in last day!

(accessible to most orbiting and large ground telescopes!)

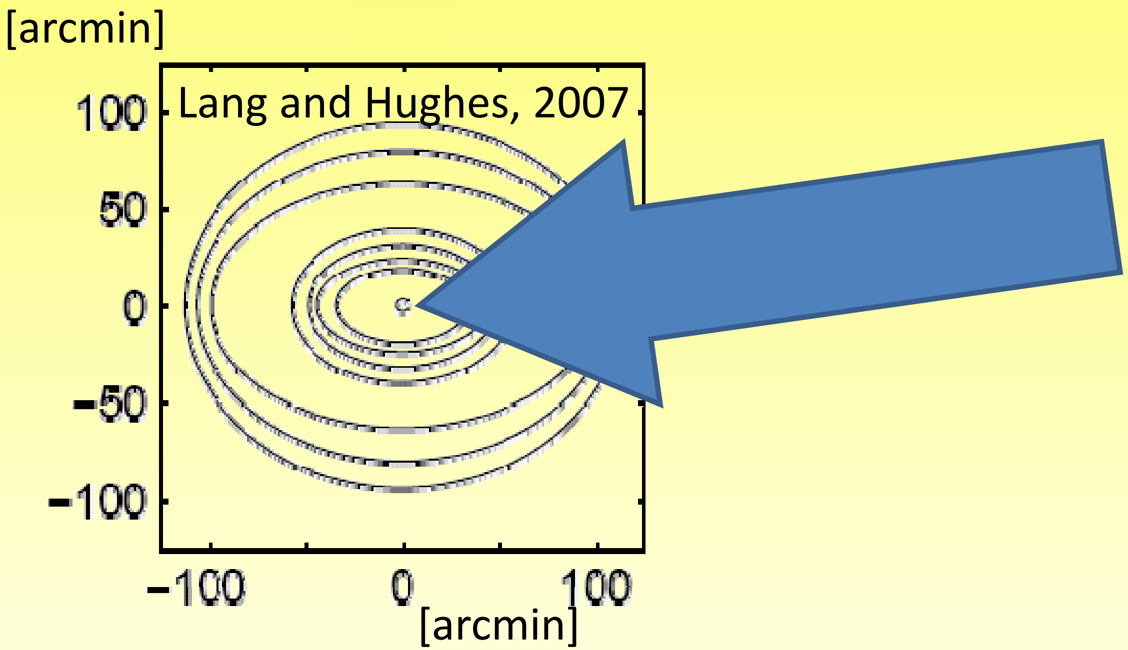
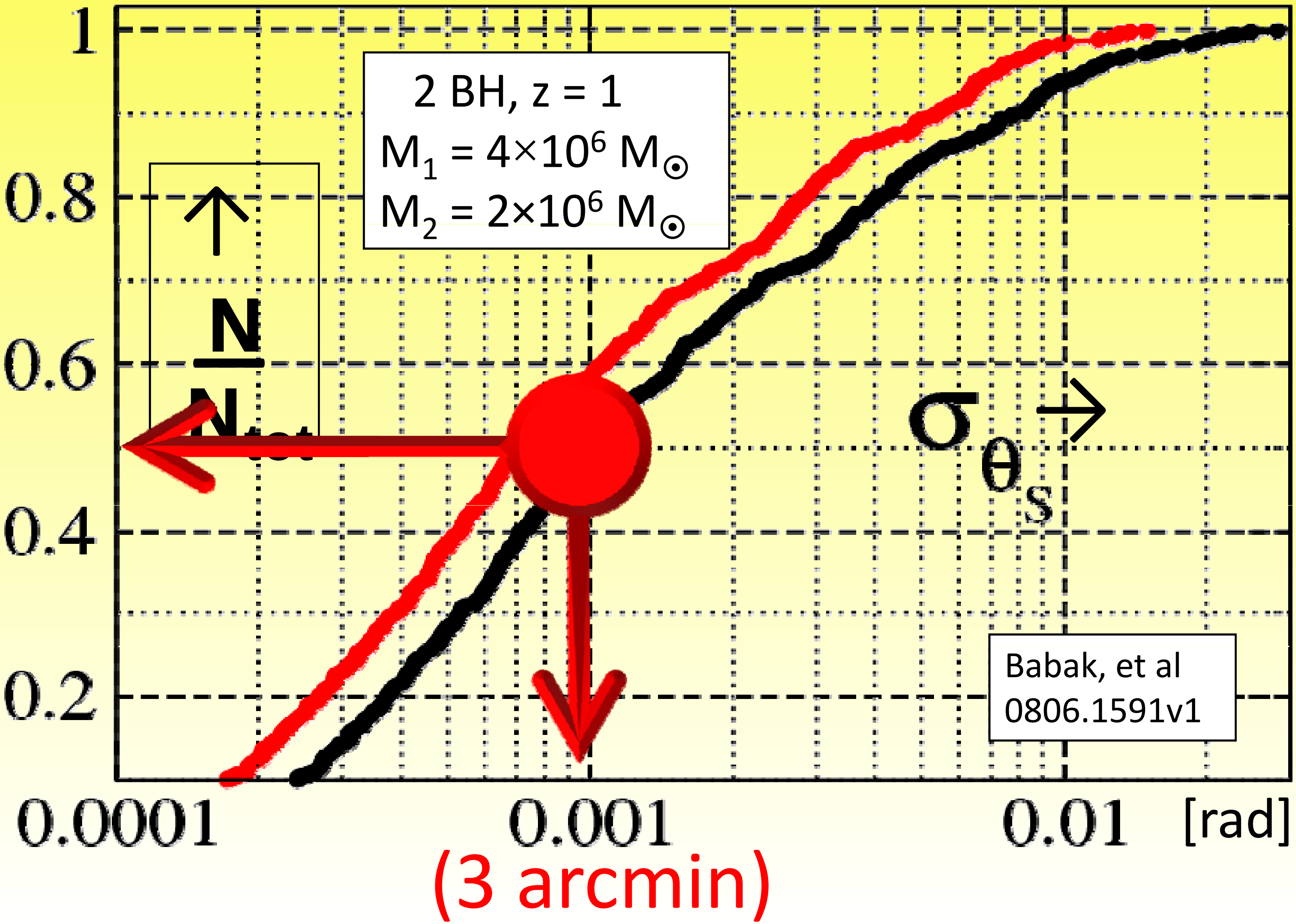


Fig. 2.— Evolution of the sky position error ellipse for nine individual binaries selected from a set of 10^4. All have $m_1 = 10^6 M_\odot$, $m_2 = 3 \times 10^5 M_\odot$, and $z = 1$. The ellipses are oriented so their major axes are parallel to the x-axis and their minor axes are parallel to the y-axis; the axes are labeled in arcminutes. From outside in, the ellipses are evaluated at 28, 21, 14, 7, 4, 2, 1, and 0 days before merger.

NumRel: Superb Angular Resolution!

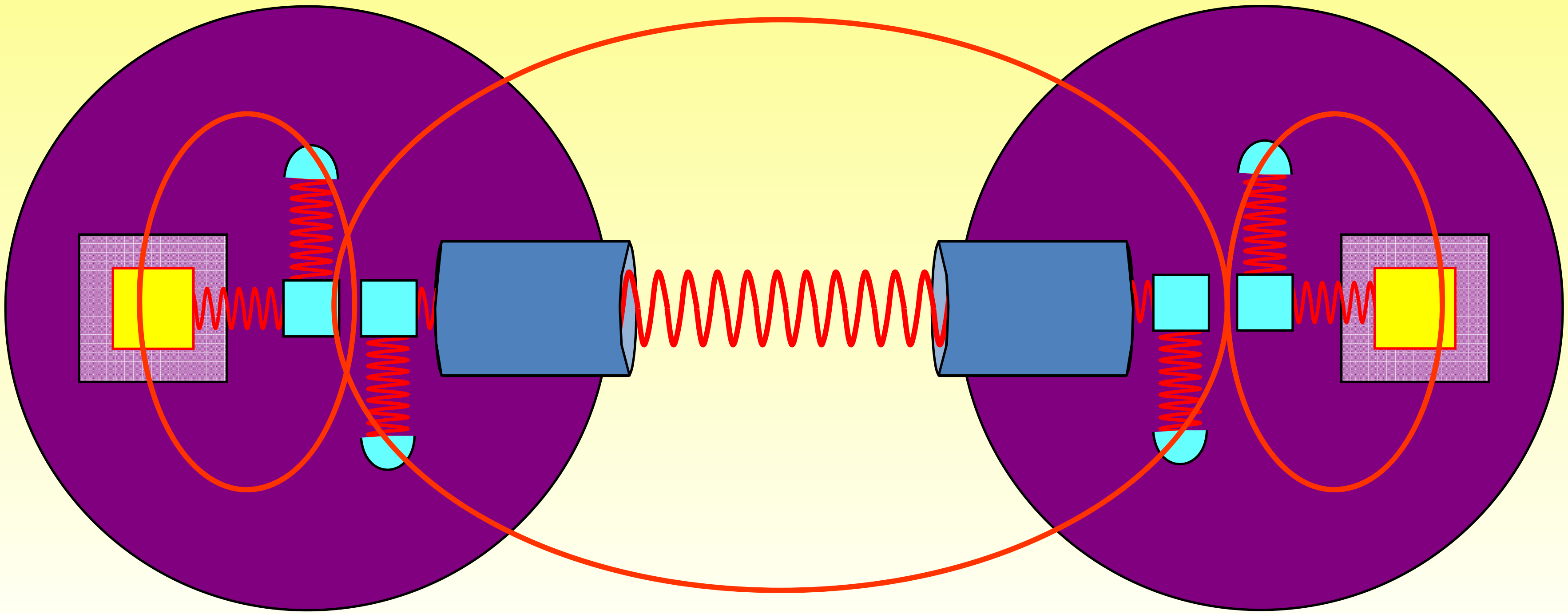
- 50 % under 3 arcmin at z=1



Local measurements

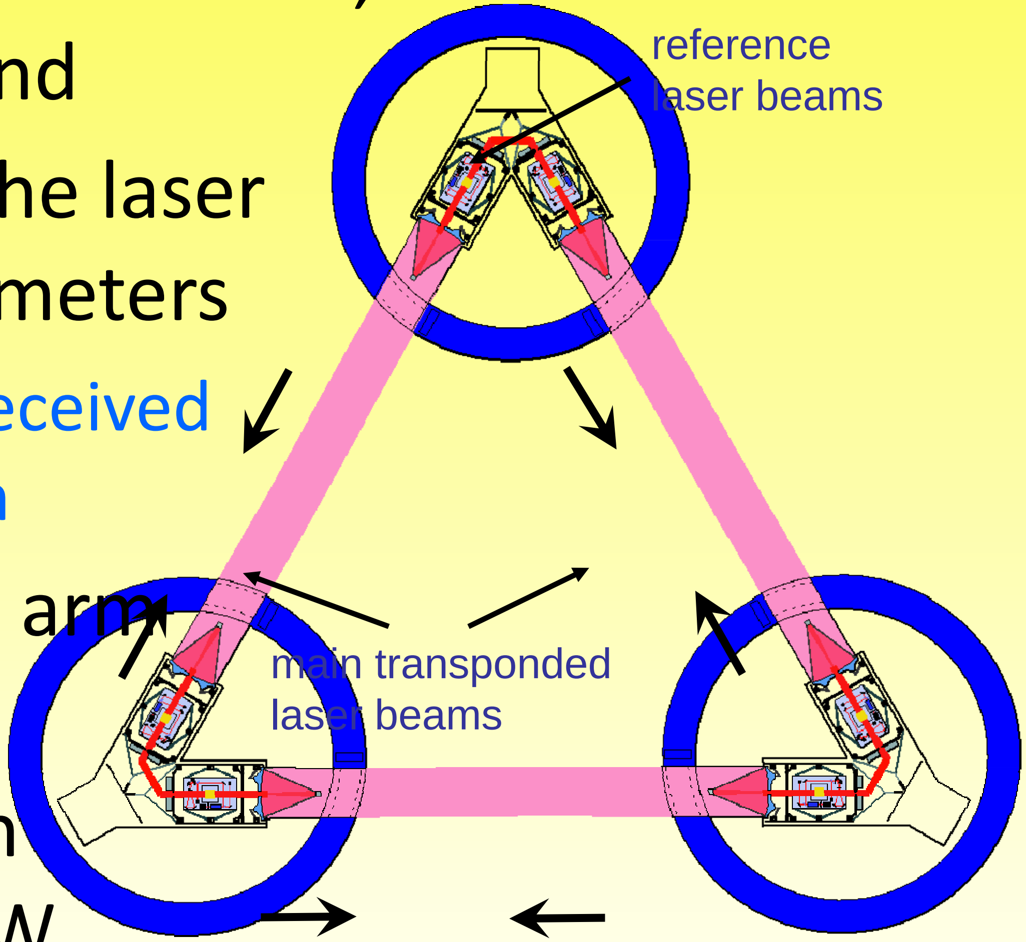
For convenience: Split measurement into 2 parts!

1. Spacecraft to test mass
2. Spacecraft to spacecraft



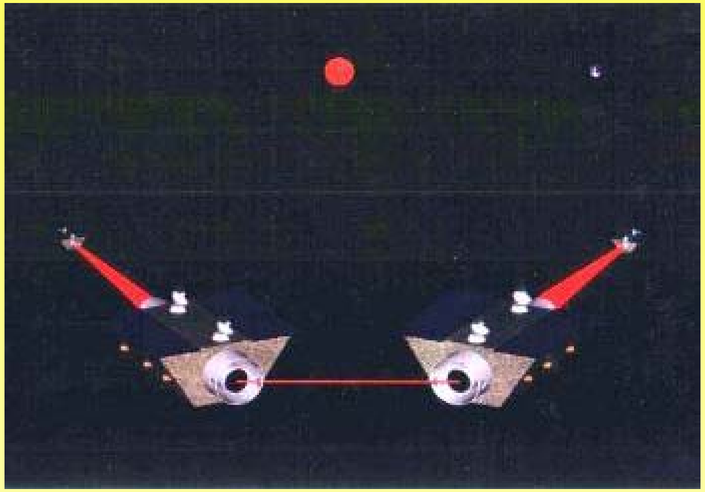
LISA Layout

- Laser transponder with 6 links, all transmitted to ground
- Diffraction widens the laser beams to many kilometers
  - 1 W sent, 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!

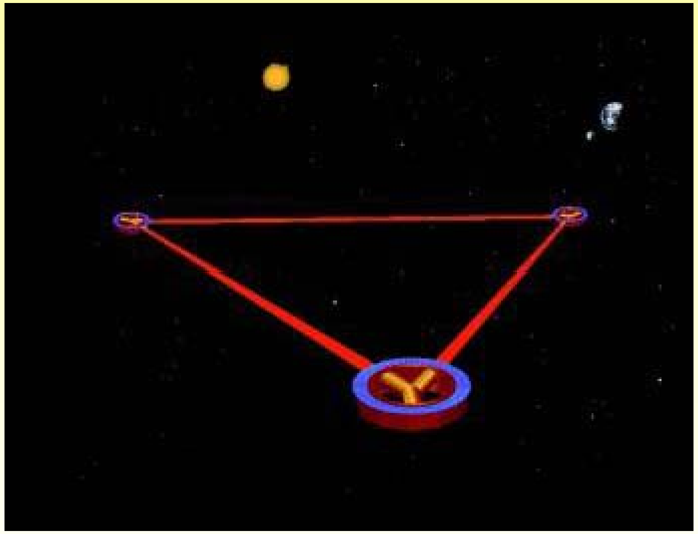


LISA: A Mature Concept

- *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!

ESA-NASA Coordination Meeting on LISA

11 August 2004, ESTEC, Noordwijk, NL

ESA-NASA

Agreement on LISA!

LISA Mission Formulation

EADS ASTRIUM

LISA Mission Formulation
Negotiation/Kick-Off Meeting

Meeting Date: January 17, 2005

Meeting Place: ESTEC

Page 1 LISA MF, Kick-Off, January 17, 2005, ESTEC

LISA Mission Formulation Study

Mission Design Review Agenda

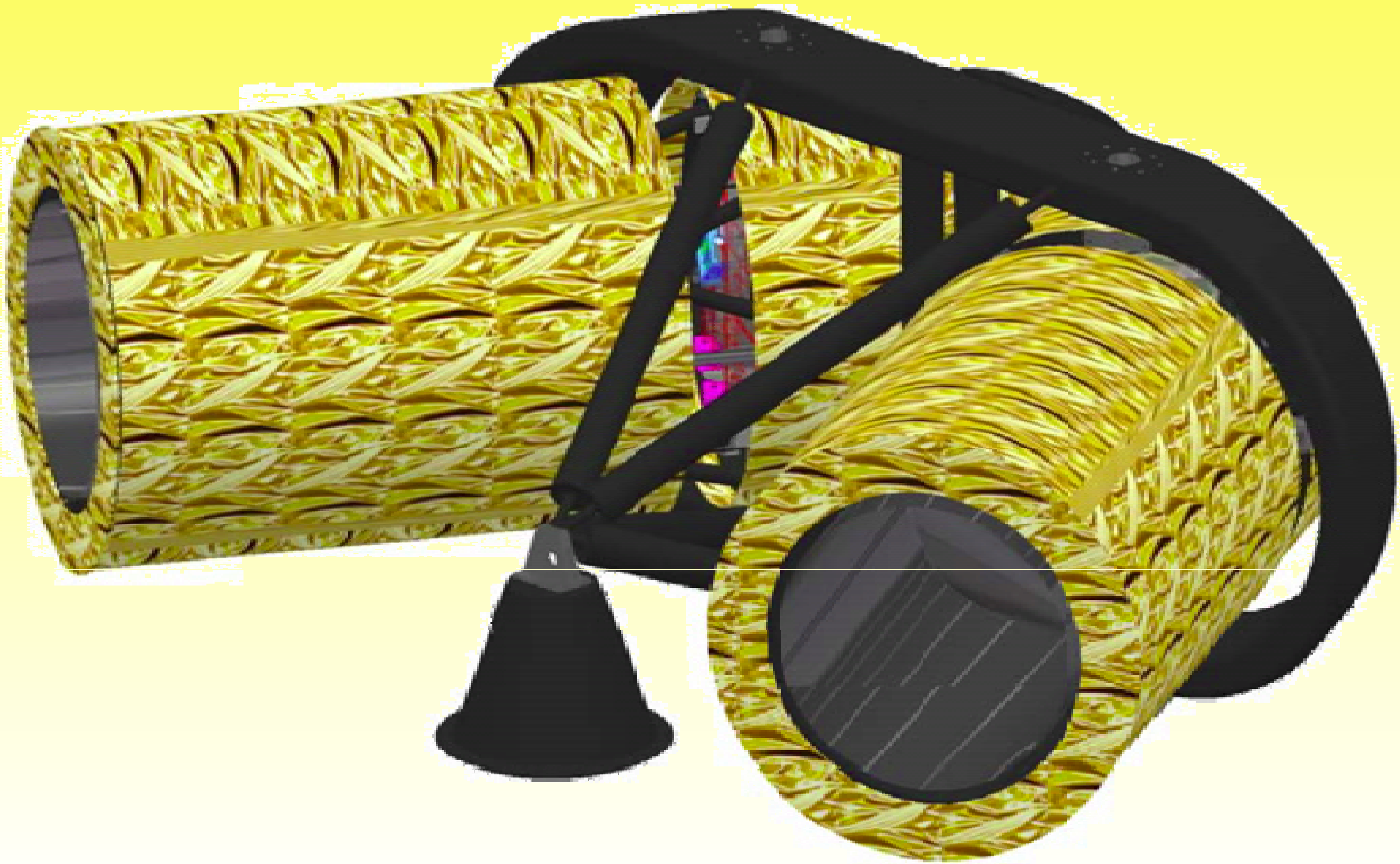
10./11.-June-2008

All the space you need

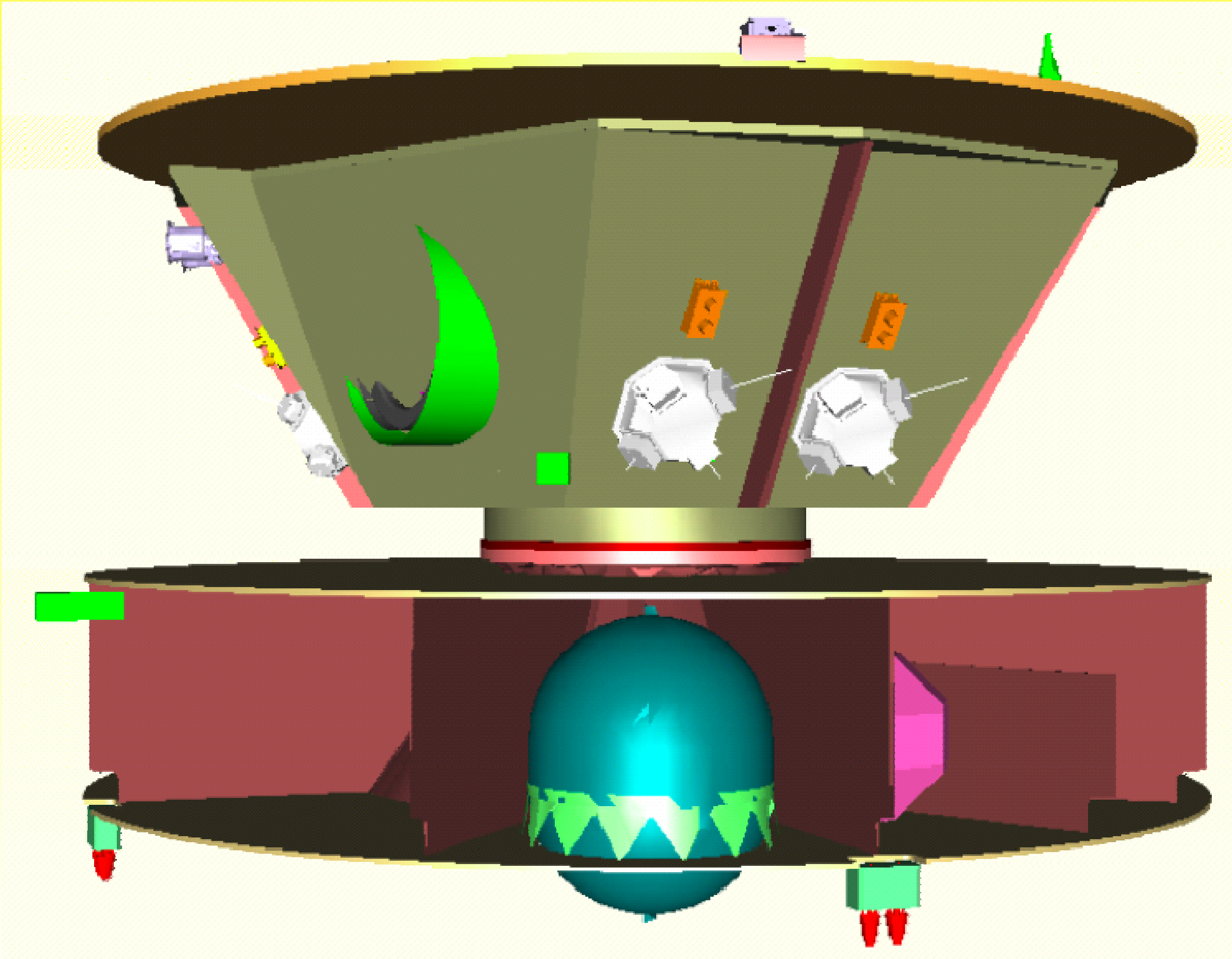
esa

EADS astrium

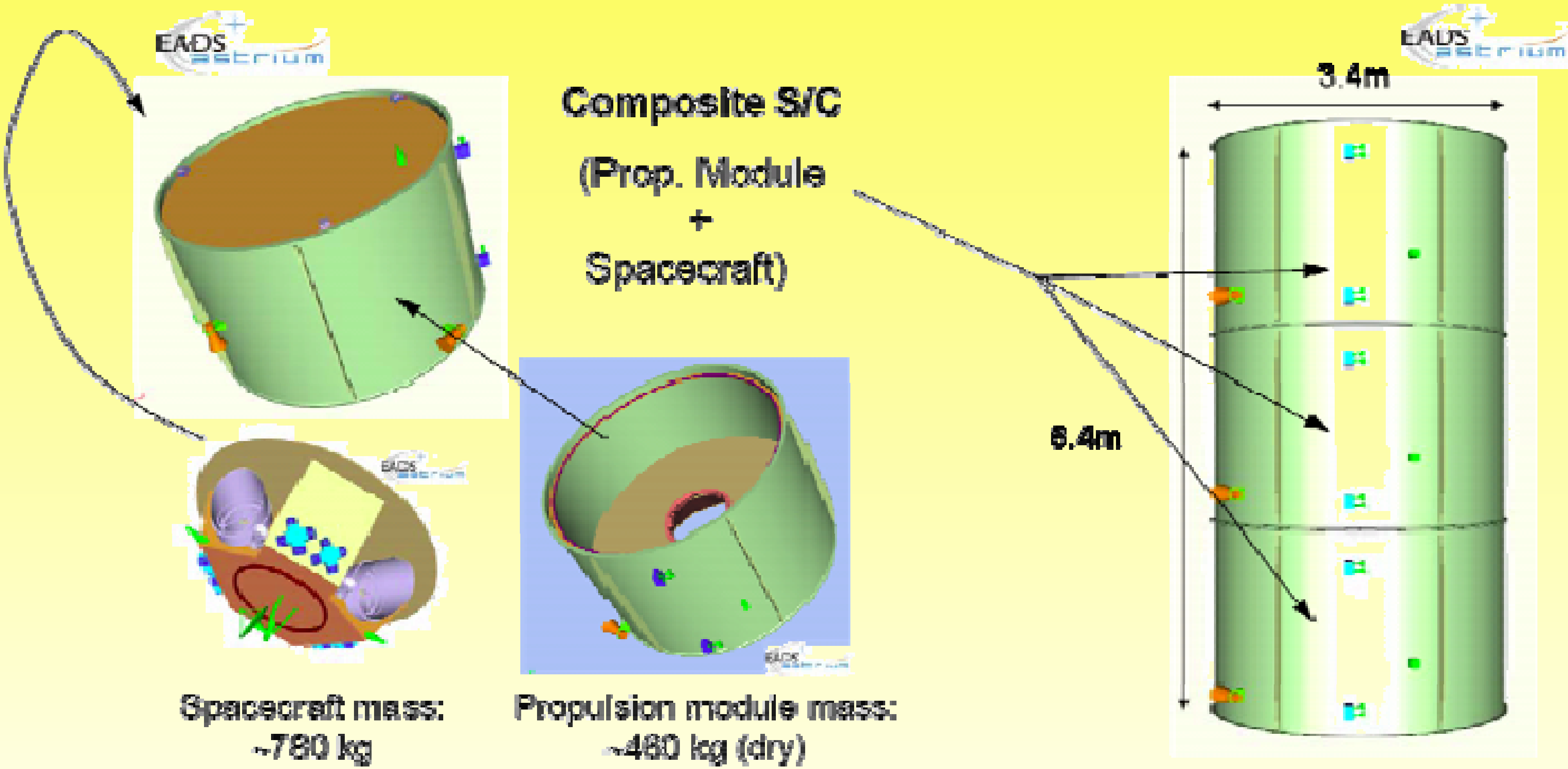
Thermal Insulation



Satellite and Propulsion Module



Launch Stack



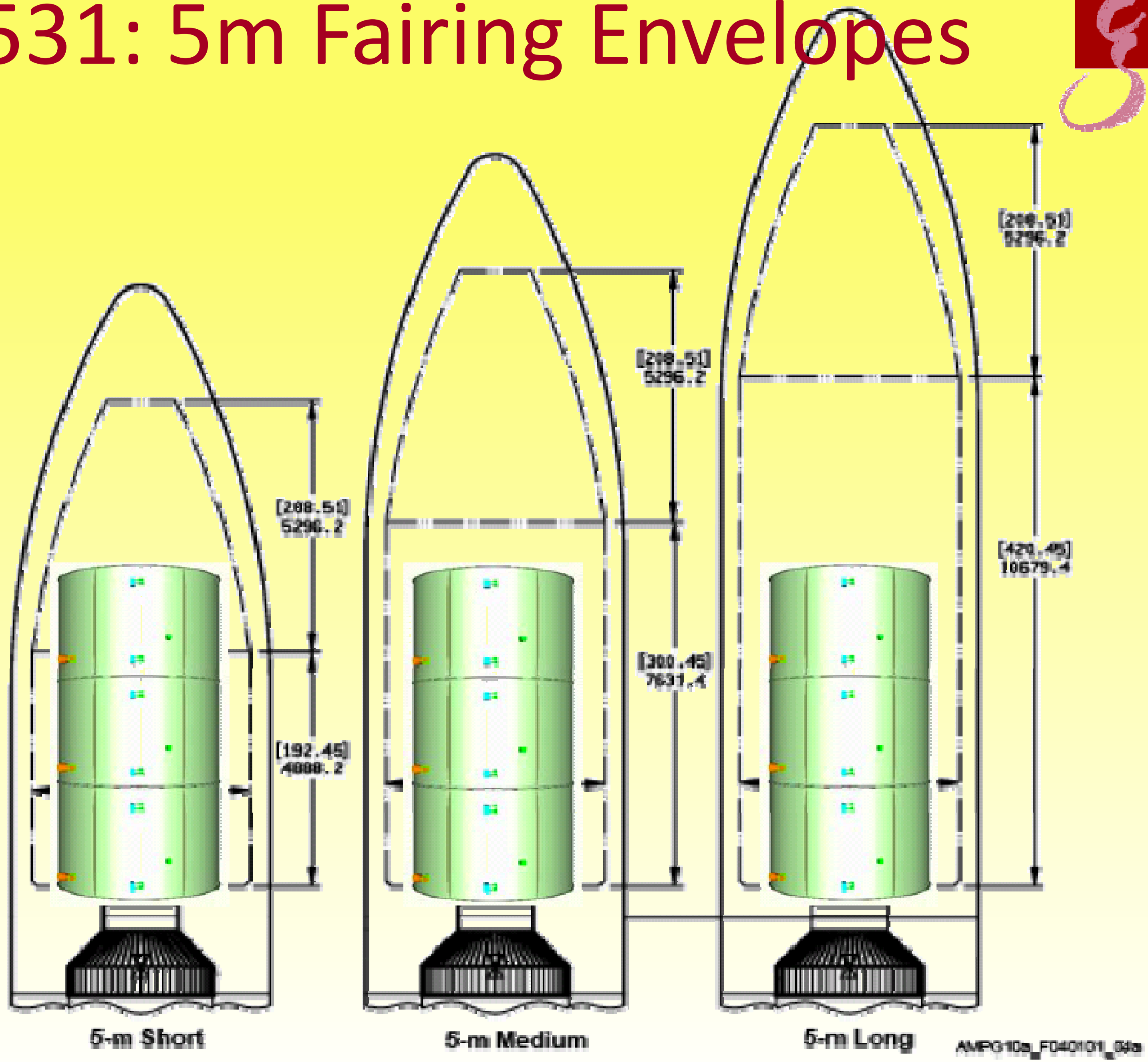
Spacecraft mass:
~780 kg
(Incl. payload)

Propulsion module mass:
~460 kg (dry)

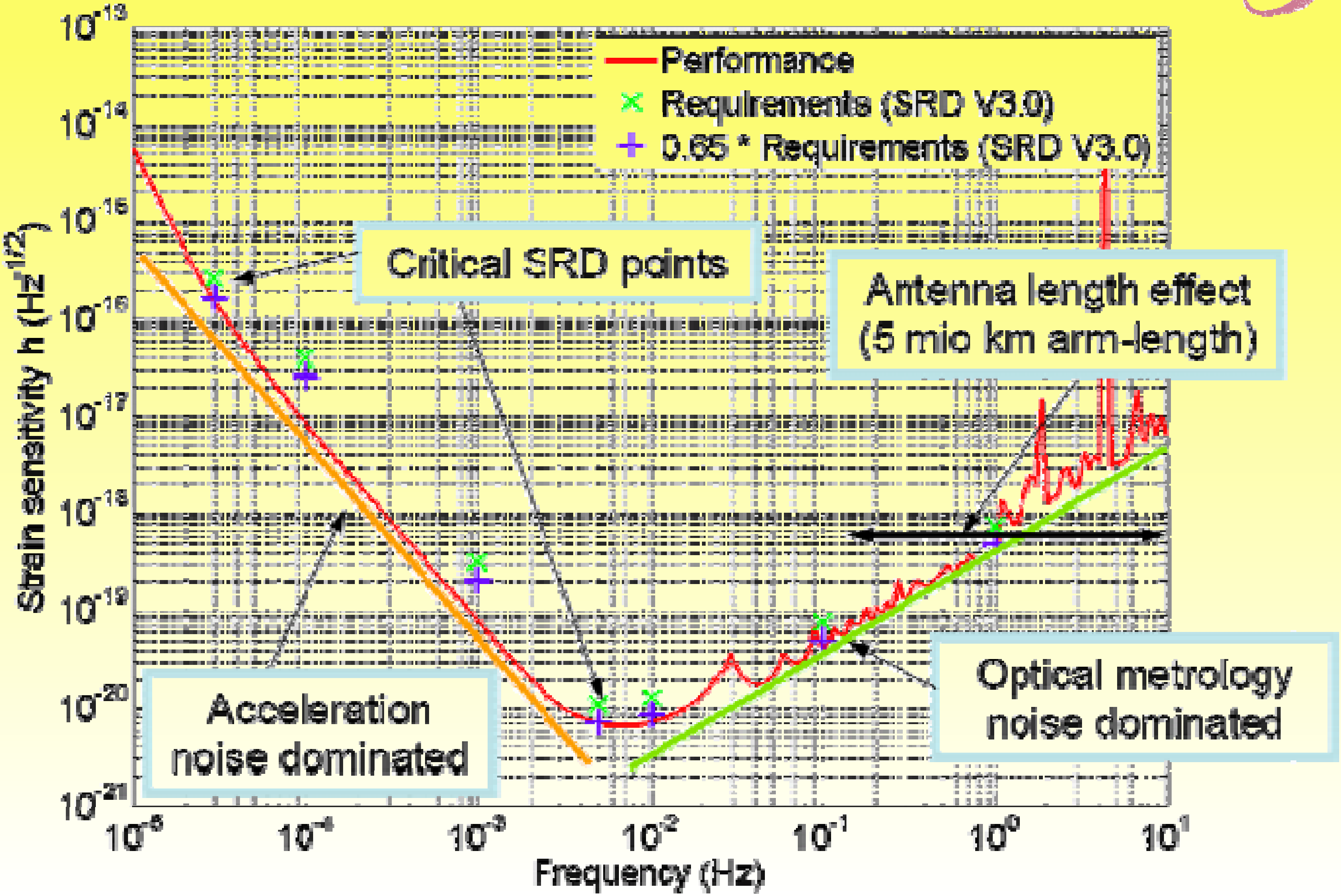
Max. total ΔV: 1130 m/s

Launch Stack (e.g. Atlas V)

Atlas 531: 5m Fairing Envelopes



LISA Performance

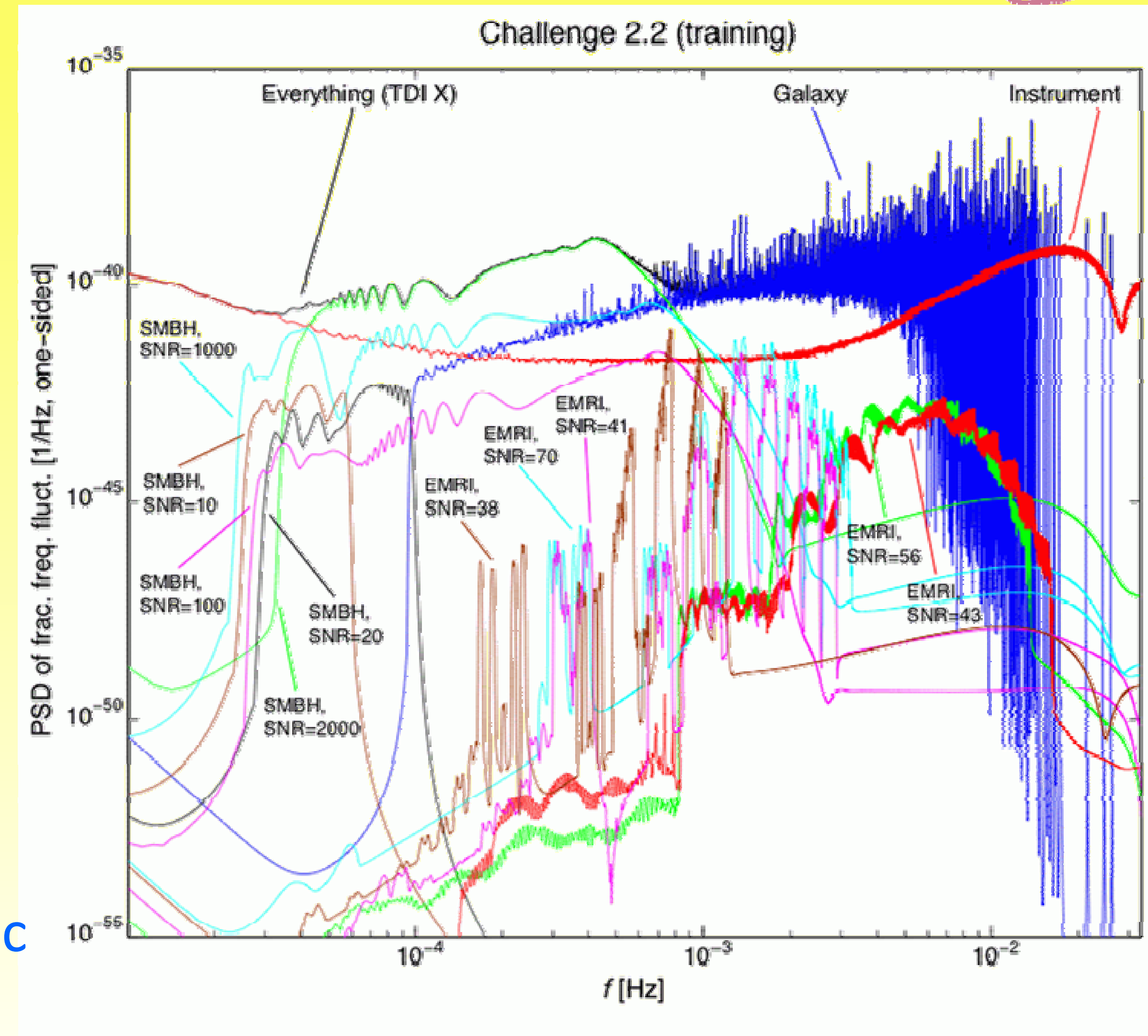


From Constellation to Ground

- Requirements
  - All data on ground every 6 days
  - 1 day latency to science operation 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**

Mock LISA Data Challenge

- Blind international challenge
- Rund 1 completed
  - Report published *
- Round 2
- Full LISA data stream
  - Instrumental noise
  - 4 MBH events
  - 5 EMRI events
  - 26.1 million Galactic binaries

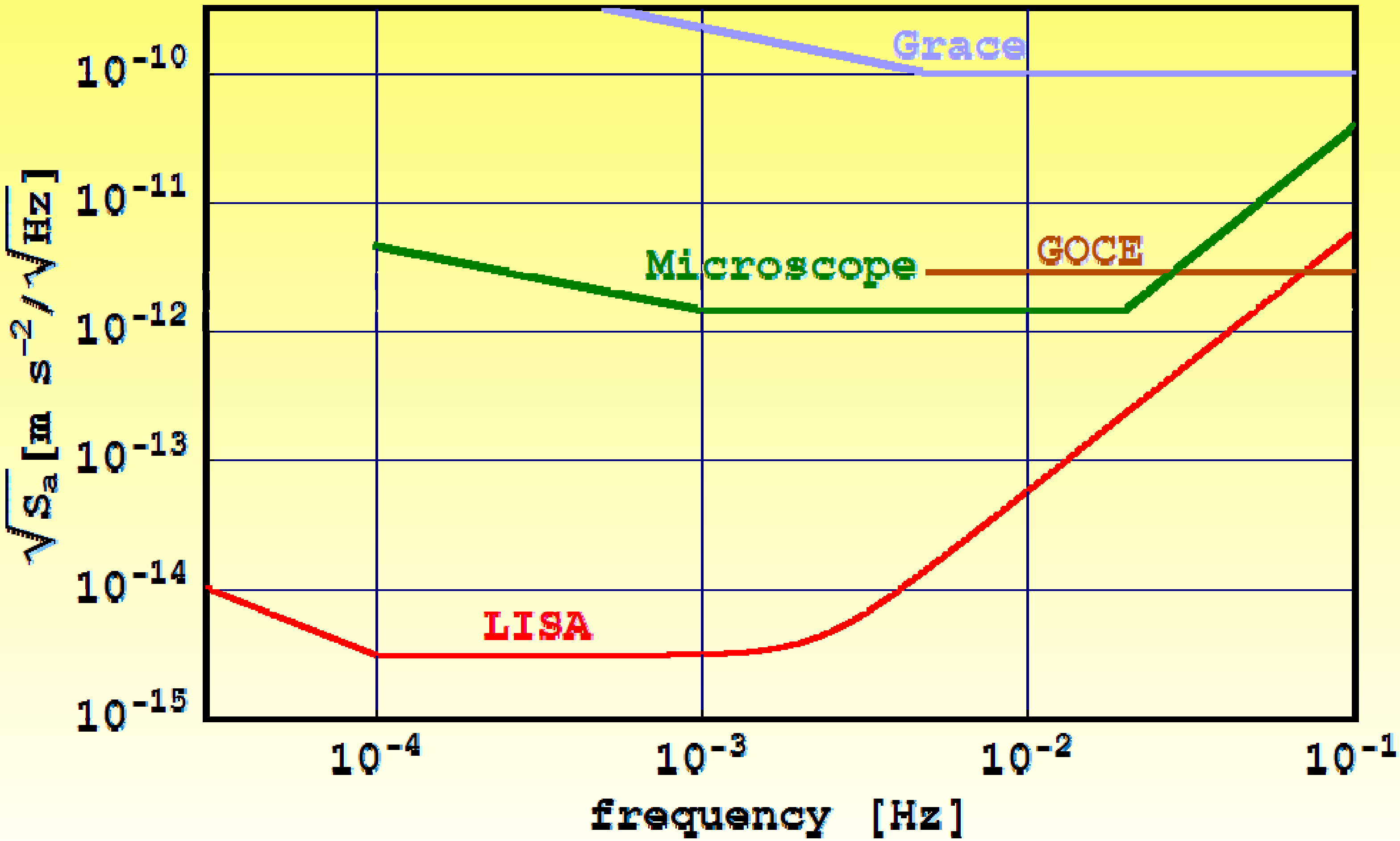


http://www.tapir.caltech.edu/dowiki/listwg1b:home

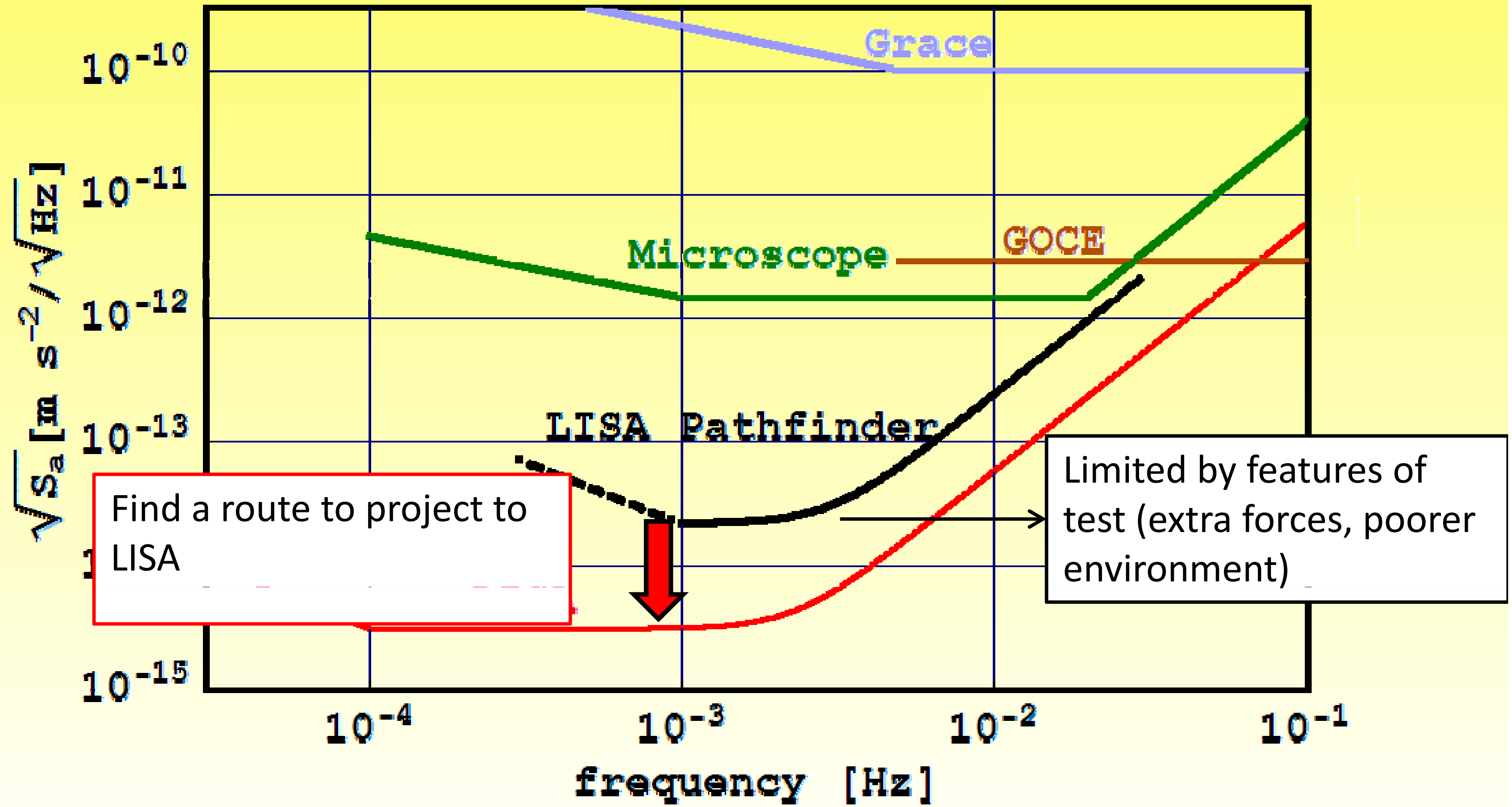
http://astrogravs.nasa.gov/docs/mldc

The Technology Demonstration Mission: LISA Pathfinder

Implement LISA Geodesic Link within a factor 10

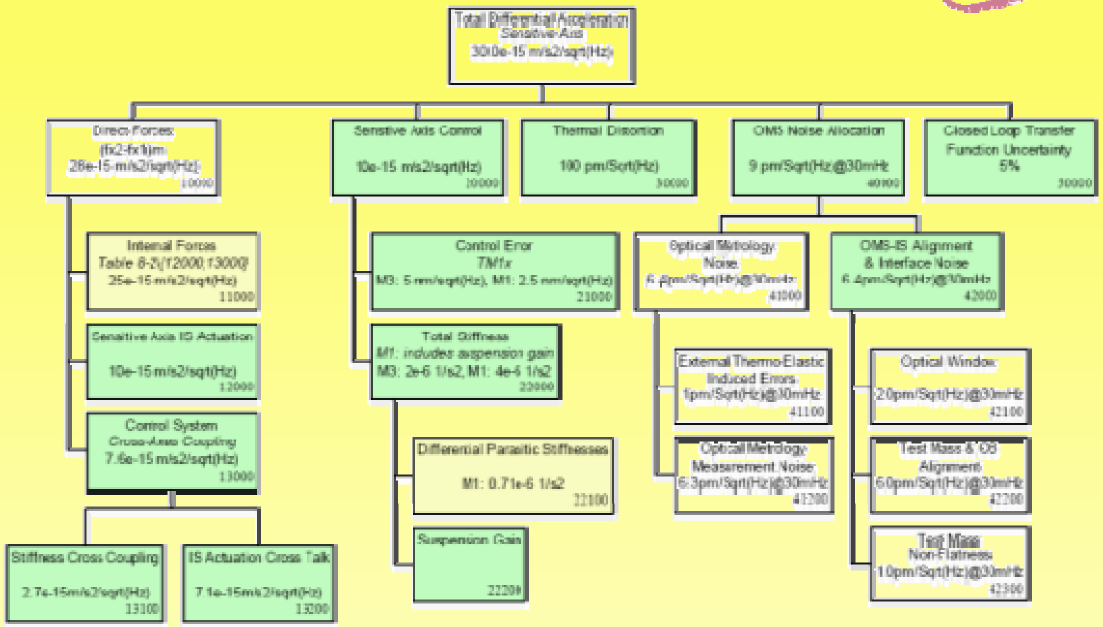


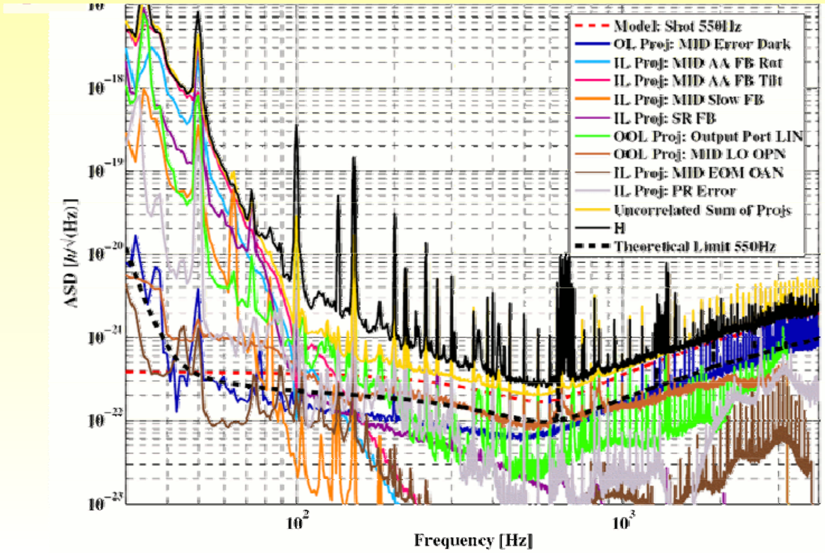
Implement LISA Geodesic Link within a factor 10



Pathfinder → LISA

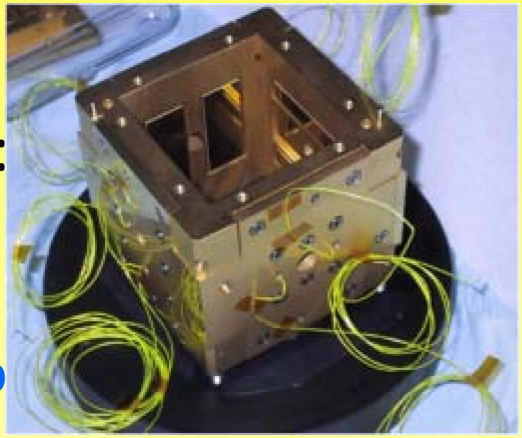
- Identify quantitatively leading sources of noise:
  - Physical model allows extrapolation to LISA
  - Will allow accurate understanding of LISA data
- Demonstrated by ground-based interferometers



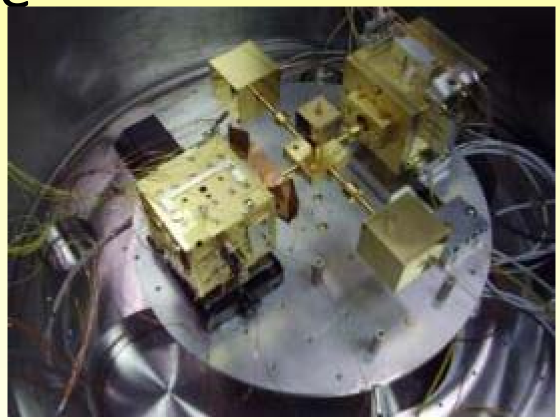


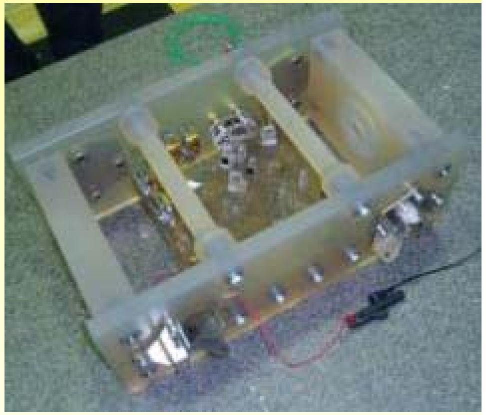
Pathfinder → LISA

- Fly nominal LISA hardware on Pathfinder:
  - Maximize returns of the test
  - Shortens time to develop LISA



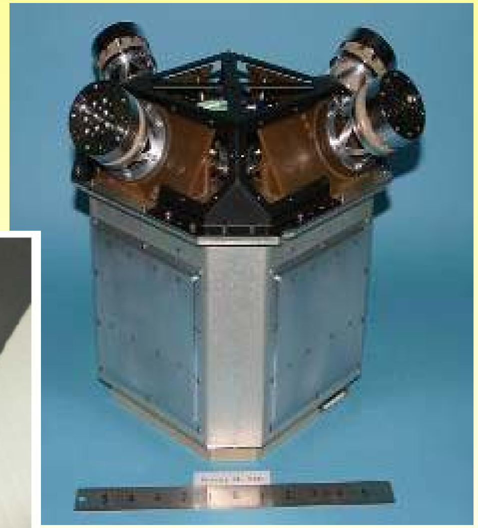
- Consolidate in the lab the physical model of disturbances:
  - Reduces Pathfinder risk
  - Maximizes Pathfinder return





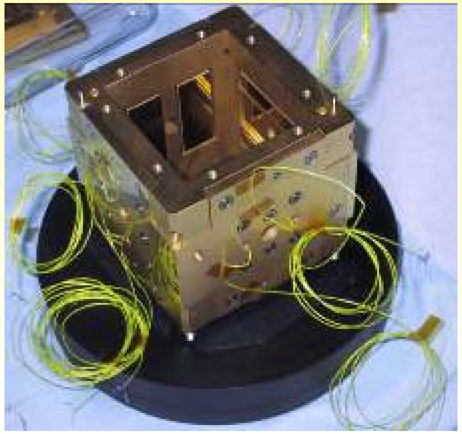
Microthrusters

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

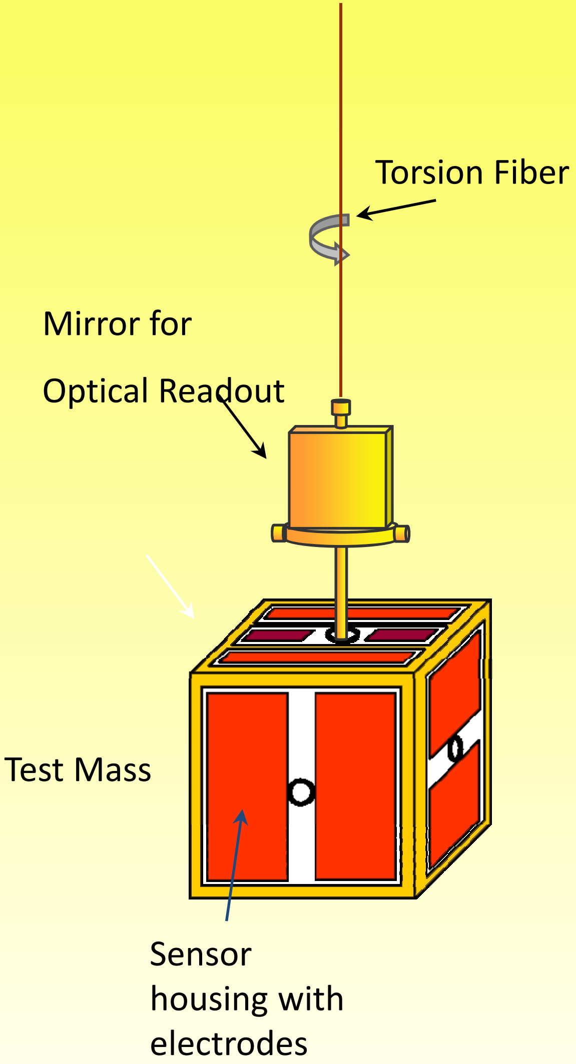


Gravitational Reference Sensor

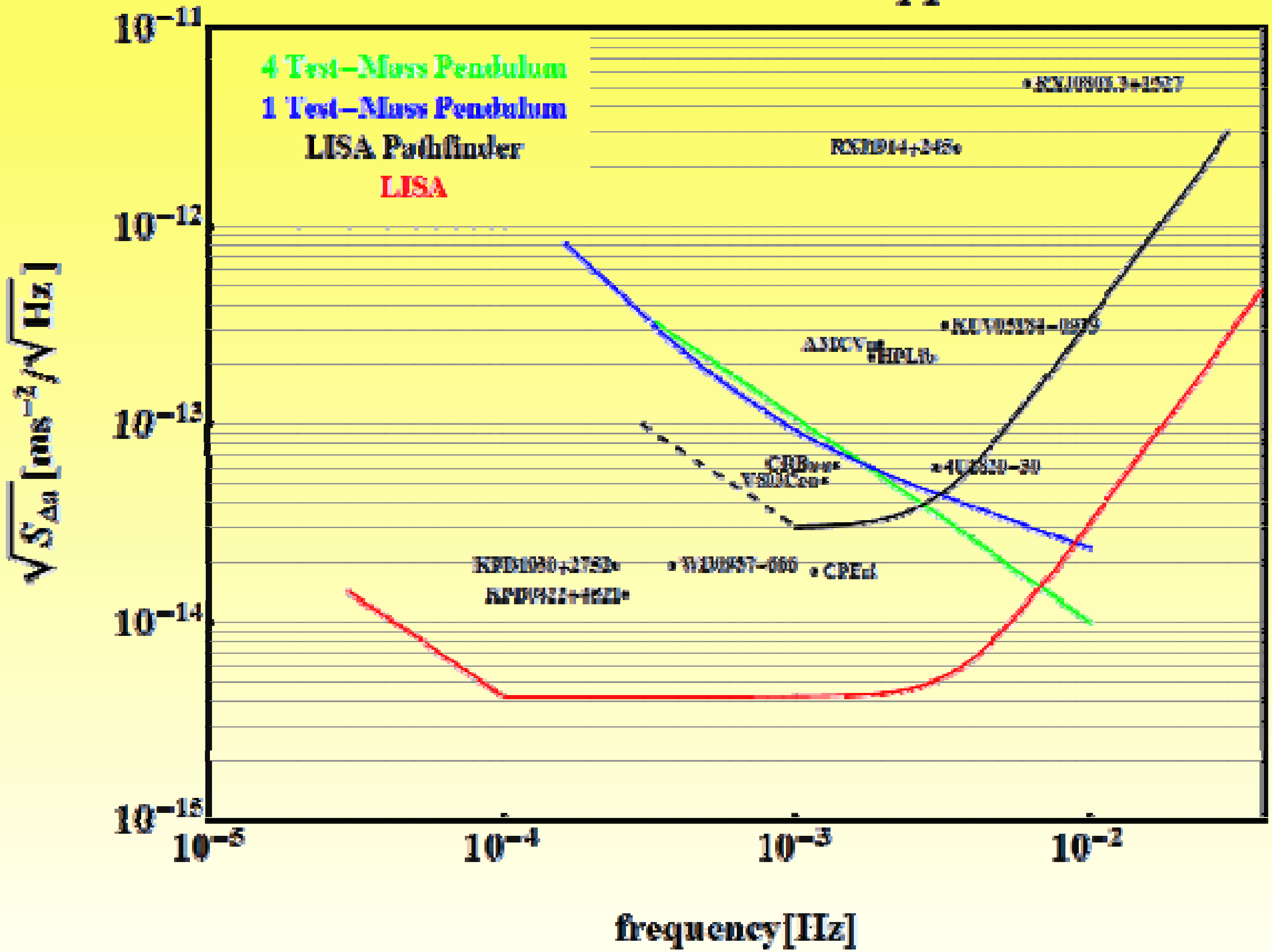
- Sensing free fall of test mass.
- The Pathfinder GRS is the LISA GRS.
- Technology developed and verified on ground.
- Pathfinder validates the GRS on orbit.

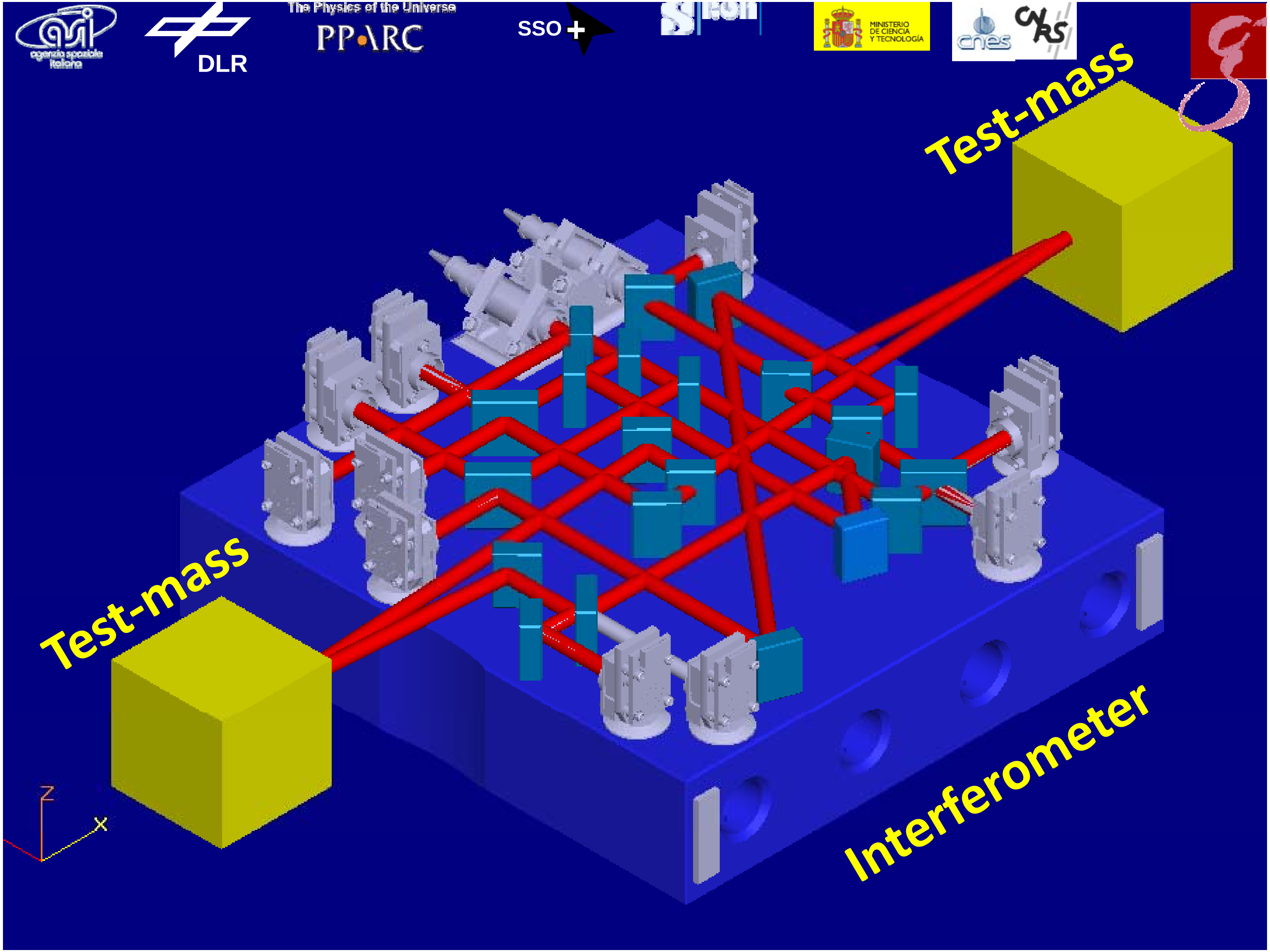



Ground testing – Torsion pendulum



Differential acceleration upper limit

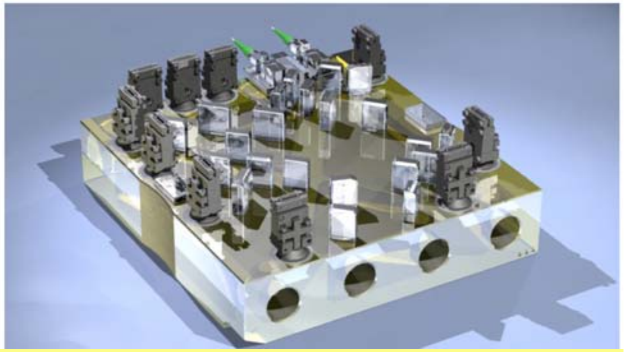


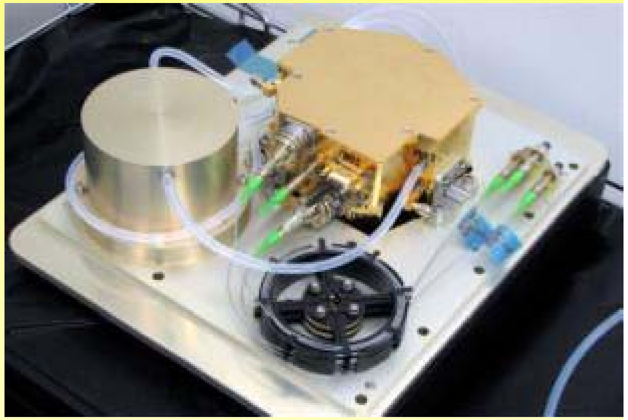


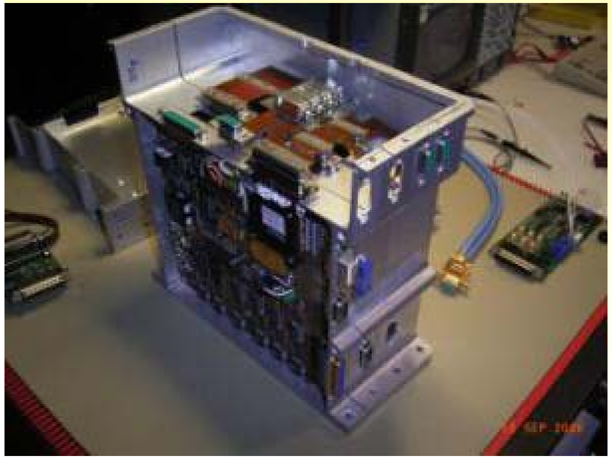
The Physics of the Universe
PPARC
DLR
SSO
MINISTERIO DE CIENCIA Y TECNOLOGÍA
cnes
Test-mass
Test-mass
Interferometer
Z
X

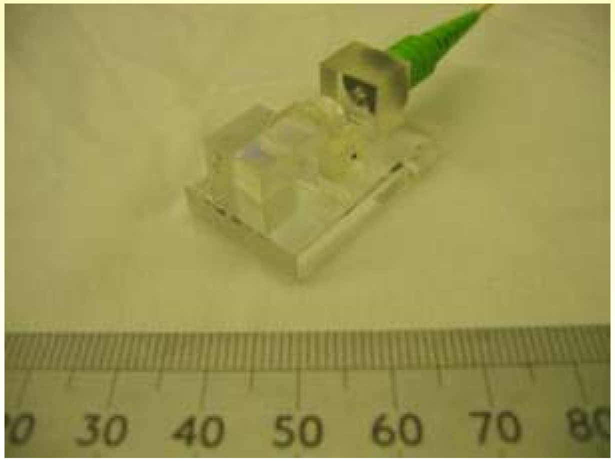
Optical Metrology System

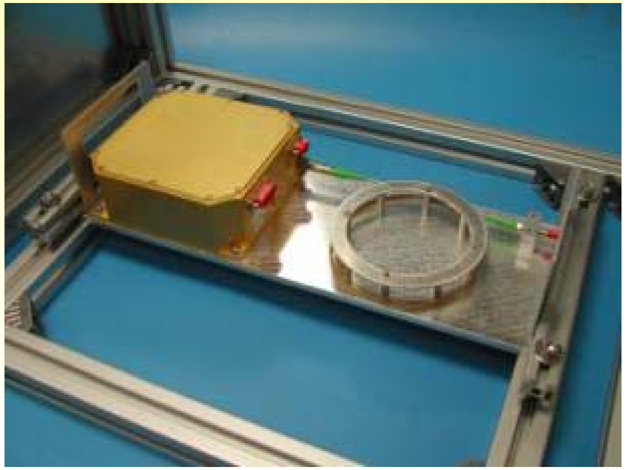
- Design review in March 07
- EM's manufactured
- Good progress for Flight Model



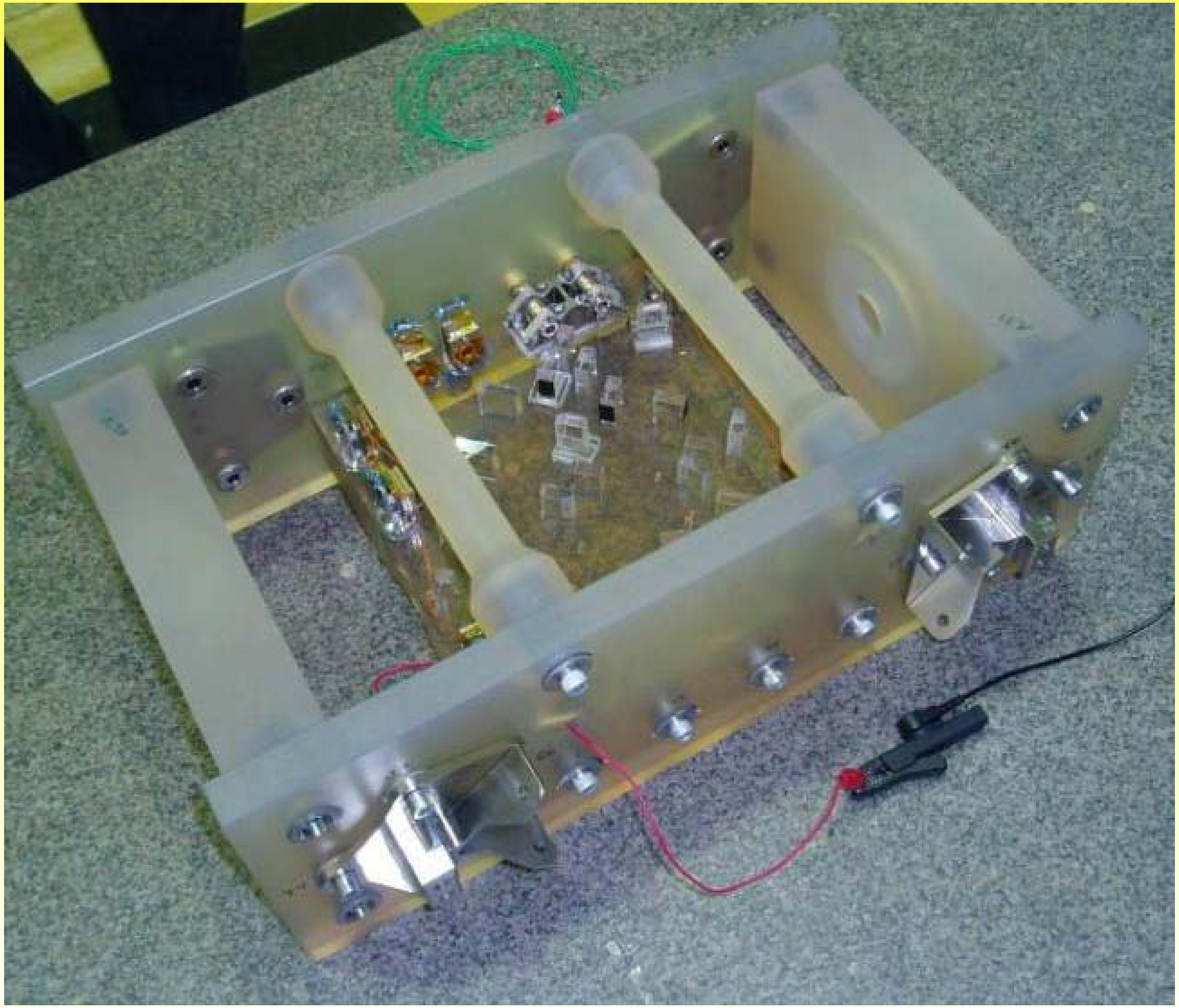




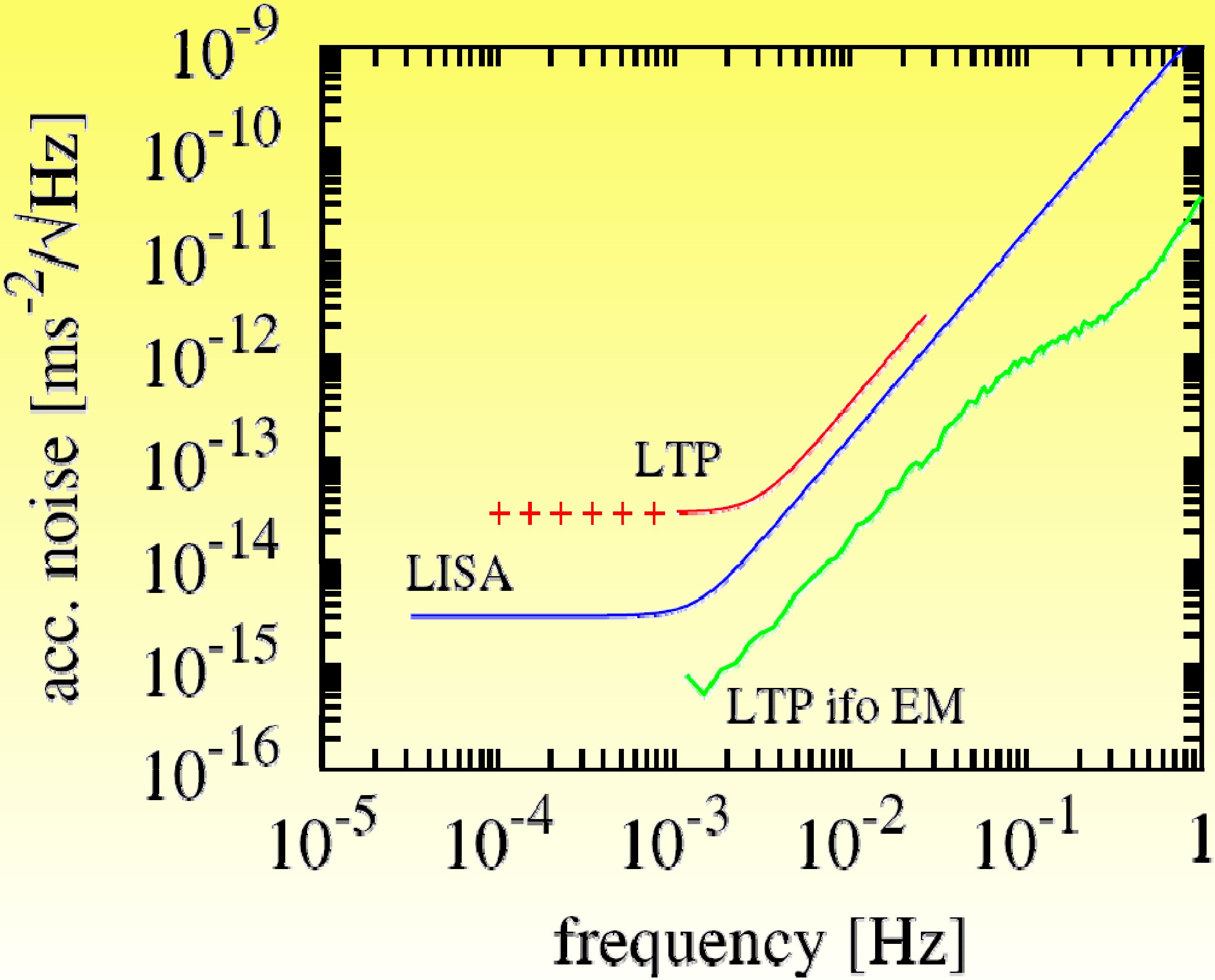




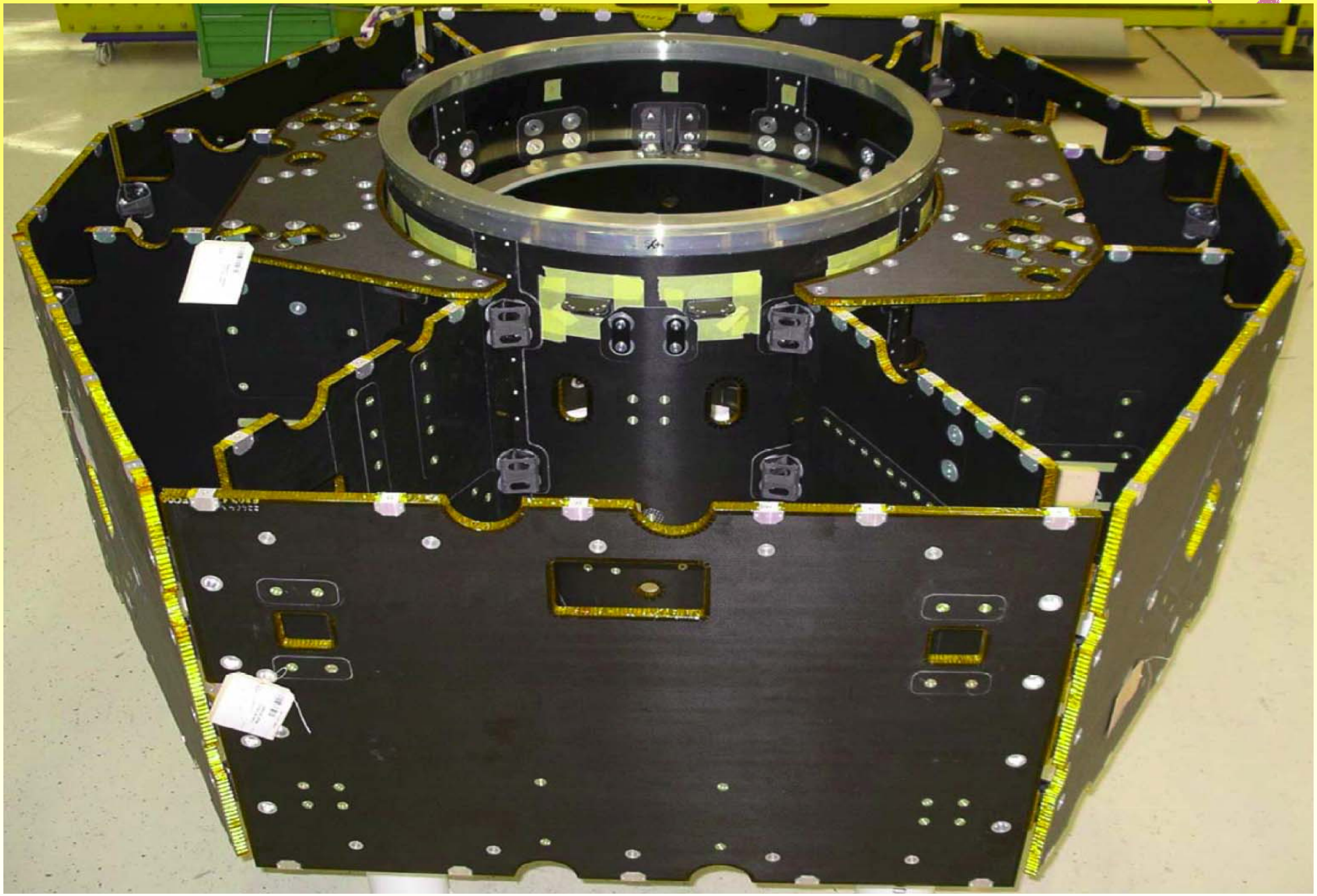
Interferometer Test on LPF EM

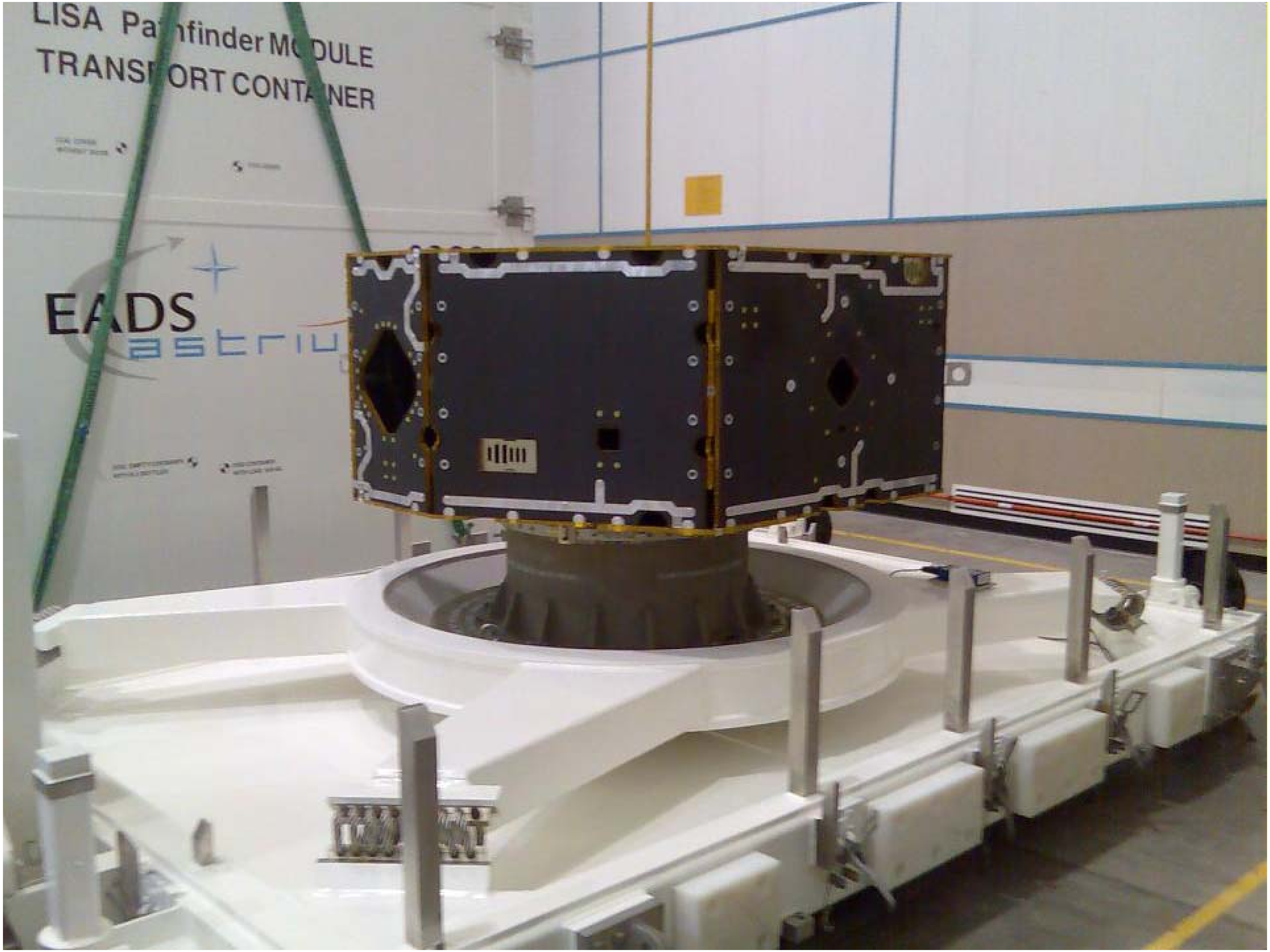


Optical Bench EM Performance



LPF Primary Structure Flight Model

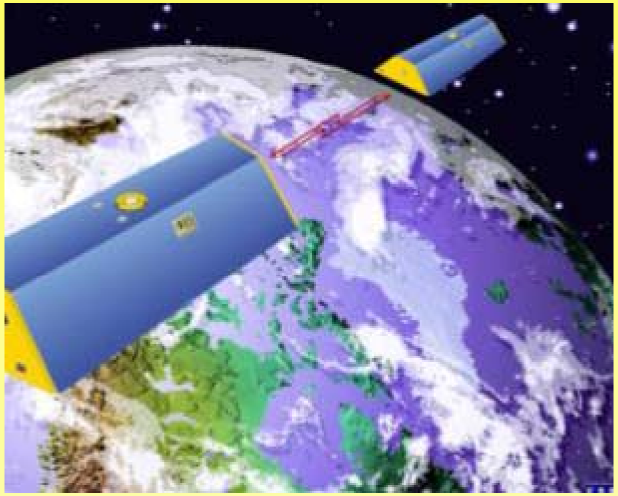



LISA
EADS

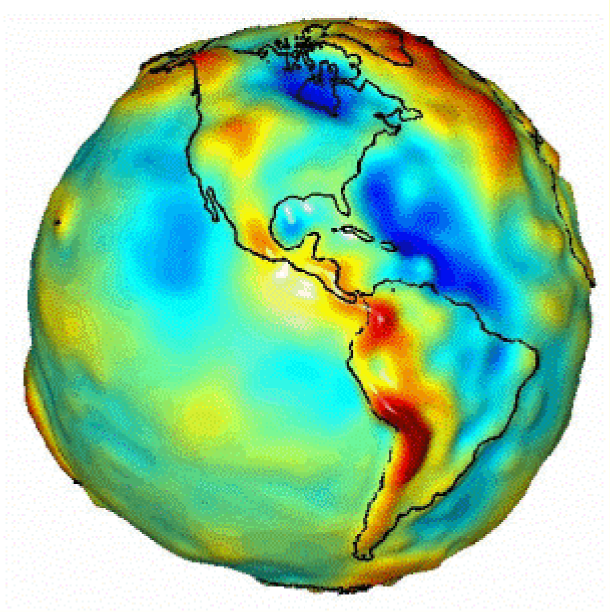
LISA Pathfinder Orbit

Launch in 2010 for an orbit around L1

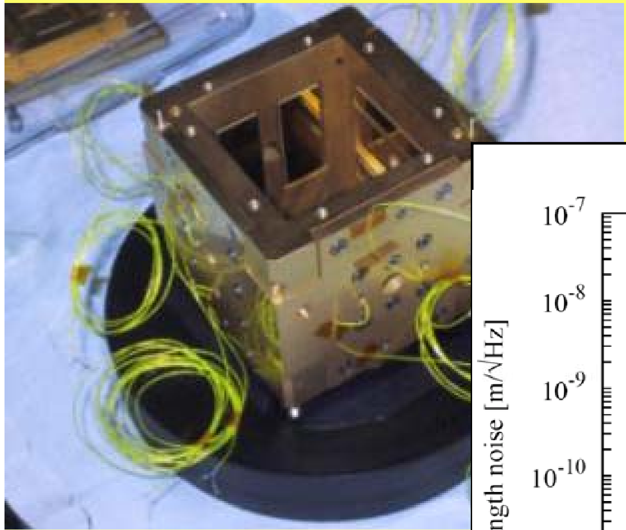
Geodesy Missions: Observation of Earth Gravitational Field

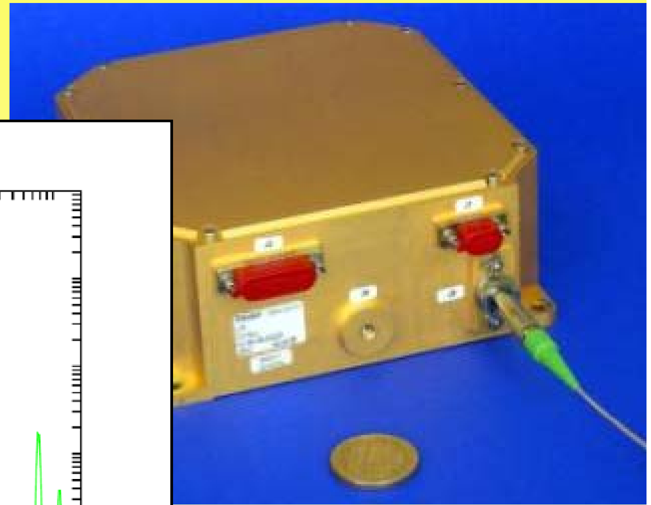


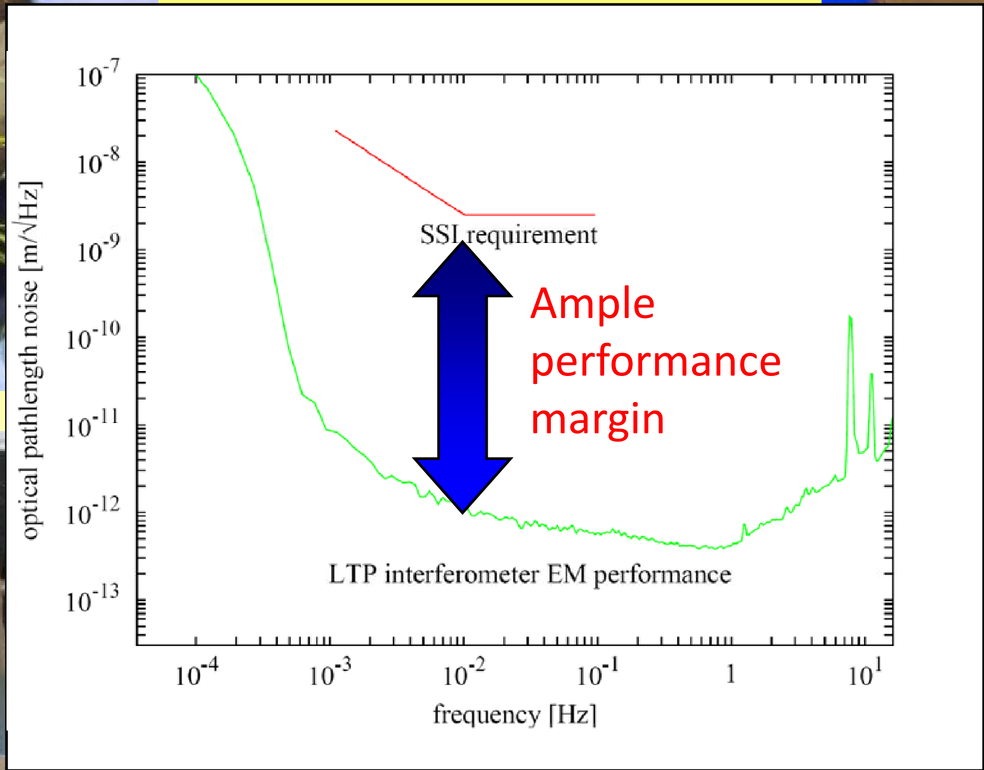
- GRACE (Launched 2002)
- GOCE (Launch 2008)

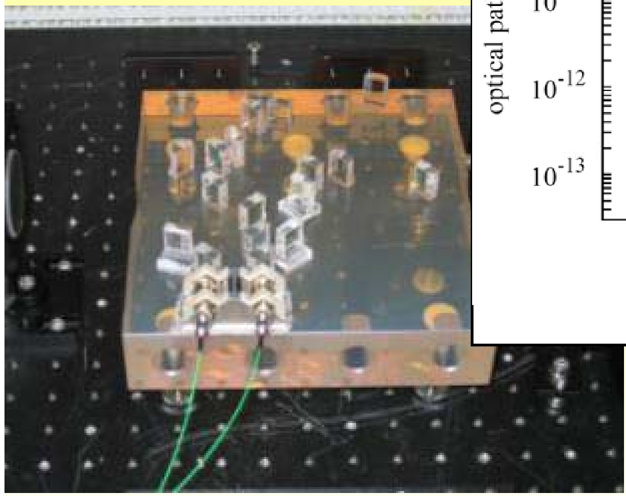


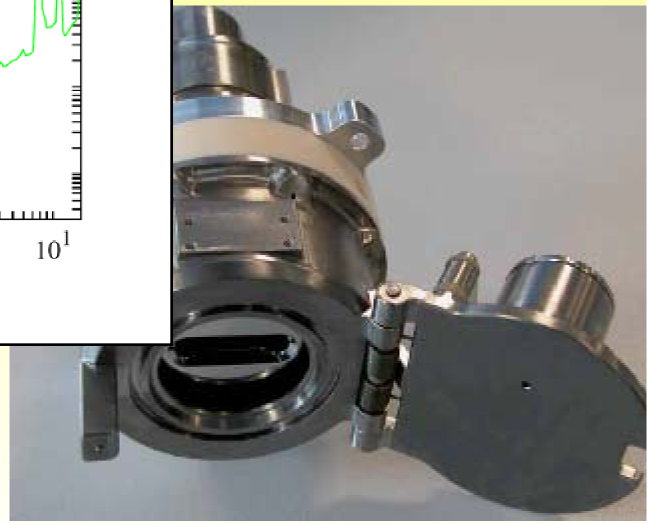
LISA Pathfinder Technology for Next Generation Geodesy Mission











LISA Status

- ESA-NASA collaboration agreement since August 2004
  - Joint Management Structure working well!
  - Mission Formulation Study began in January 2005
- Technology precursor LISA Pathfinder in Phase C/D
  - Launch in 2010
- ESA SPC Meeting 22 Feb 2007: LISA L1 launch in 2018!
- NASA Beyond Einstein Review: Report released September 6, 2007
  - LISA is Flagship mission! Schedule compatible with ESA!

Back to LISA:

NASA Beyond Einstein Program Review

November 2006 – September 2007

National Research Council
The National Academies, Washington, DC

BEPAC Recommendations for LISA:

- "On purely scientific grounds LISA is the mission that is most promising and least scientifically risky. Even with pessimistic assumptions about event rates, it should provide unambiguous and clean tests of the theory of general relativity in the strong field dynamical regime and be able to make detailed maps of space time near black holes. **Thus, the committee gave LISA its highest scientific ranking."**
- " LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways**. LISA, in the committee's view, should be the flagship mission** of a long-term program addressing Beyond Einstein goals."
- **"NASA should invest additional Beyond Einstein funds in LISA technology** development and risk reduction, to help ensure that the Agency is in a position to proceed in partnership with ESA to a new start after the LISA Pathfinder results are understood."
- "LISA was recommended second in implementation because of money and programmatics. But even assuming an unnecessarily pessimistic financial contribution from ESA, and being second in Beyond Einstein, the assumed **launch date of LISA as ESA Cosmic Vision Mission L1 in 2018 is still feasible and the committee strongly recommends that."**

LISA in new SPC Document

EUROPEAN SPACE AGENCY

ESA/SPC(2007)36
Paris, 29 October 2007

SCIENCE PROGRAMME COMMITTEE

Cosmic Vision Call cycle1: Selection of mission proposals for assessment/technology studies

Summary

This document describes the selection for assessment/technology studies of mission proposals resulting from the first planning cycle of the Cosmic Vision 2015-2025 long term plan.

With the L class mission candidates currently assessed as incompatible with the launch window planned in 2018, at this stage, LISA remains the only candidate at present for the L1 launch slot.