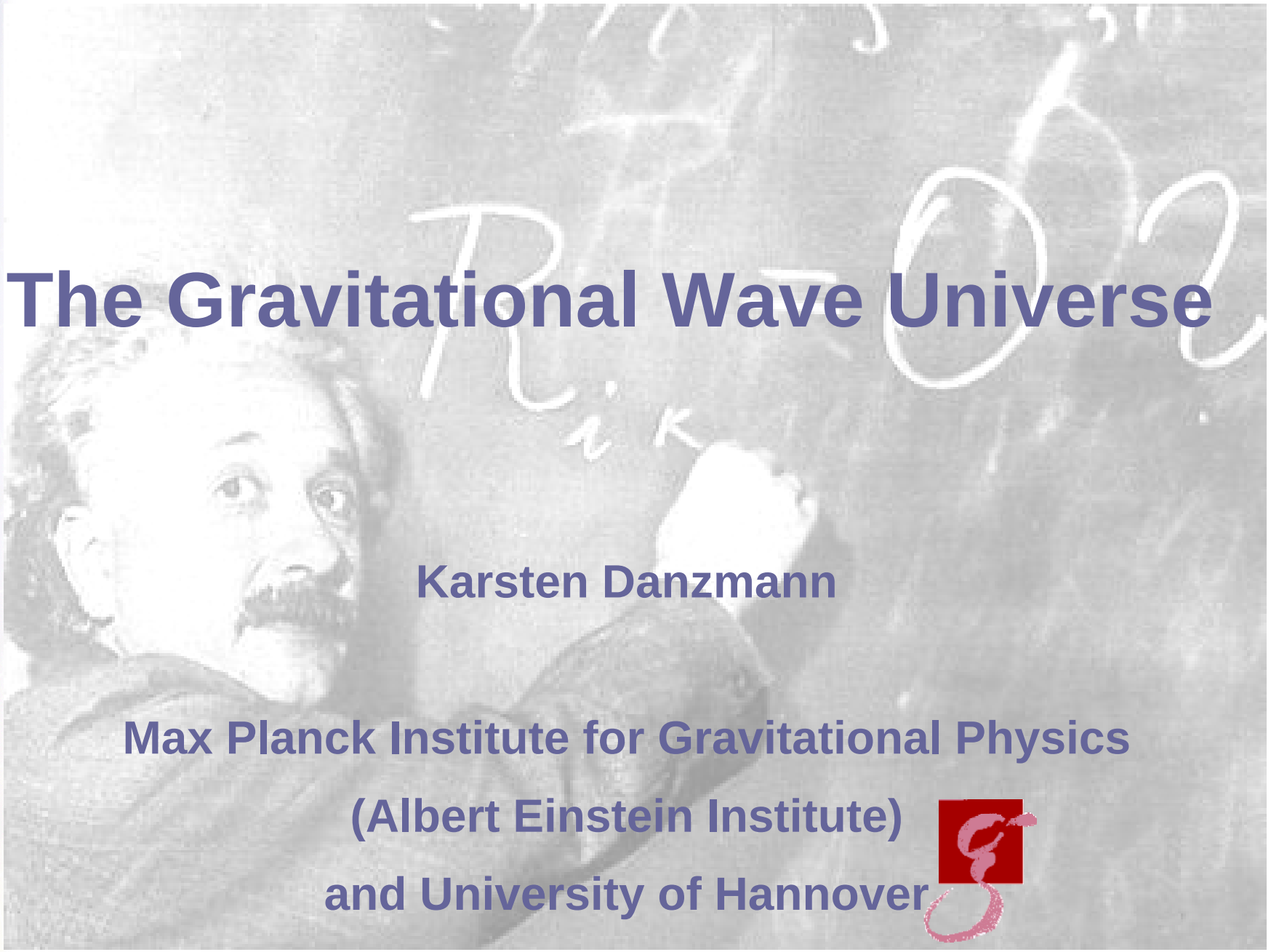
The Gravitational Wave Universe



Karsten Danzmann

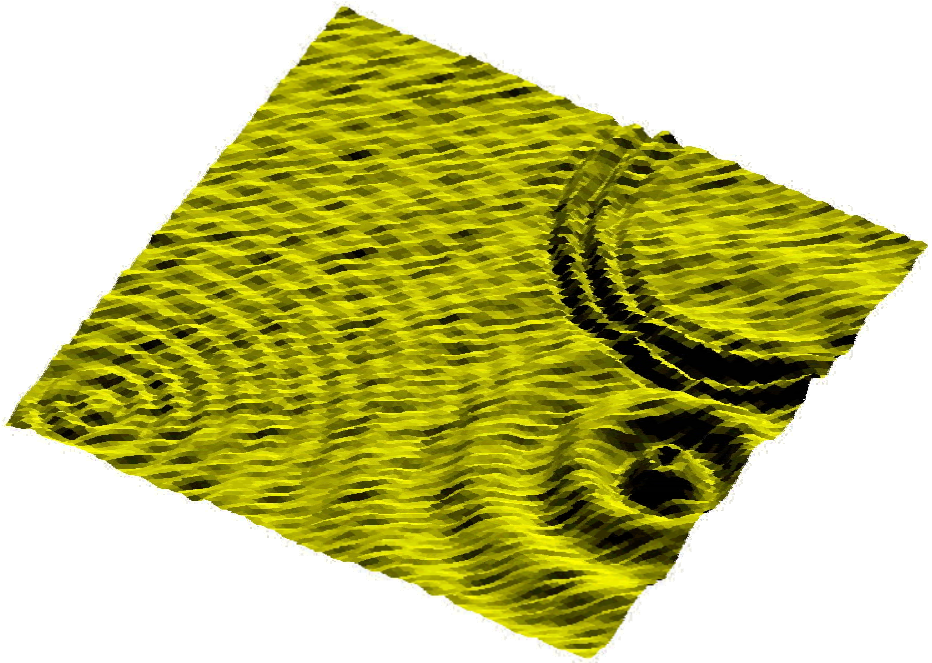
Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

and University of Hannover

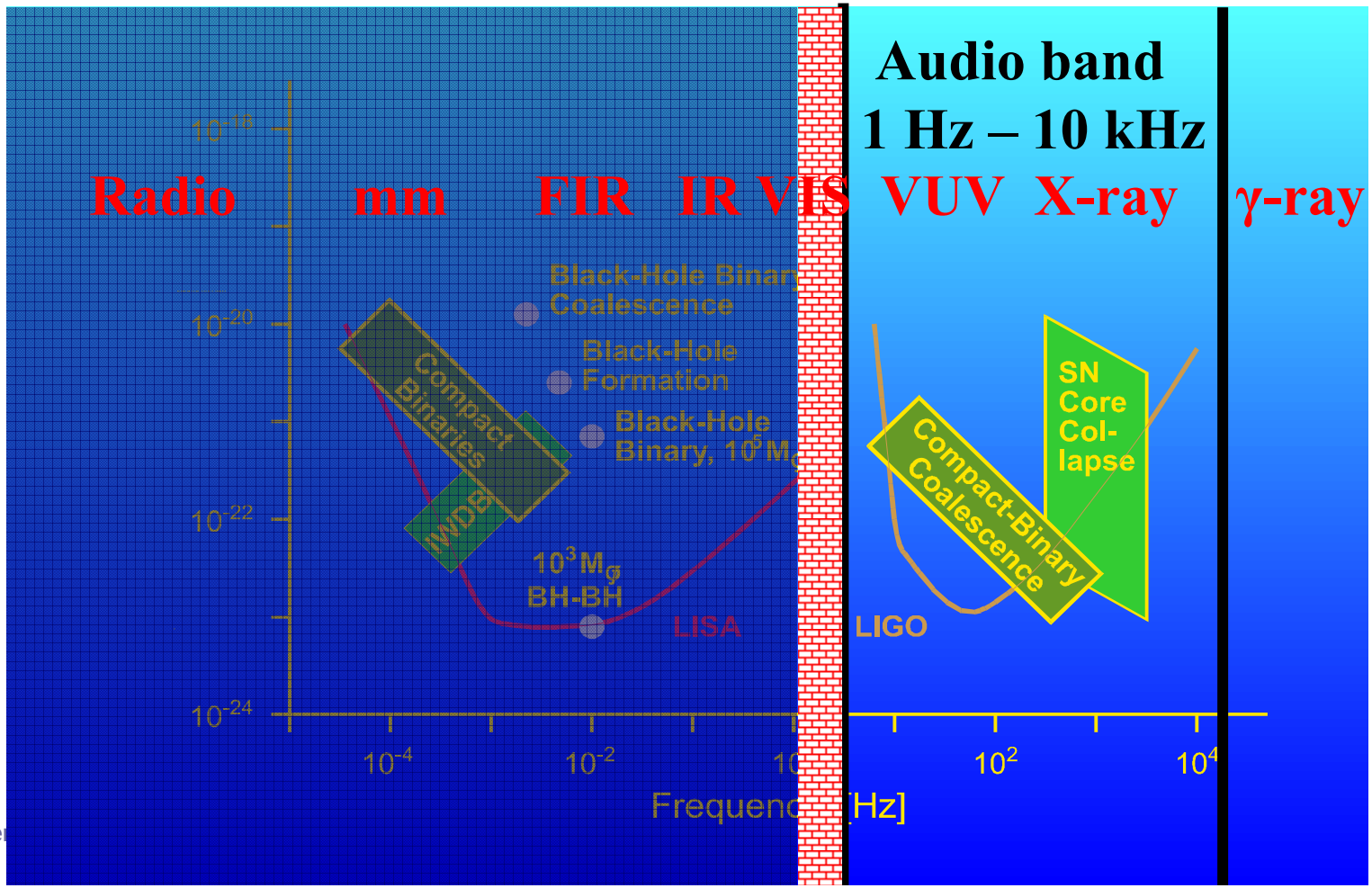
Gravitational Waves

- Predicted by Einstein more than 80 years ago
- No direct detection yet
- Indirect evidence through energy loss of binary pulsar PSR1913+16 (Hulse-Taylor)



Gravitational Wave Sources

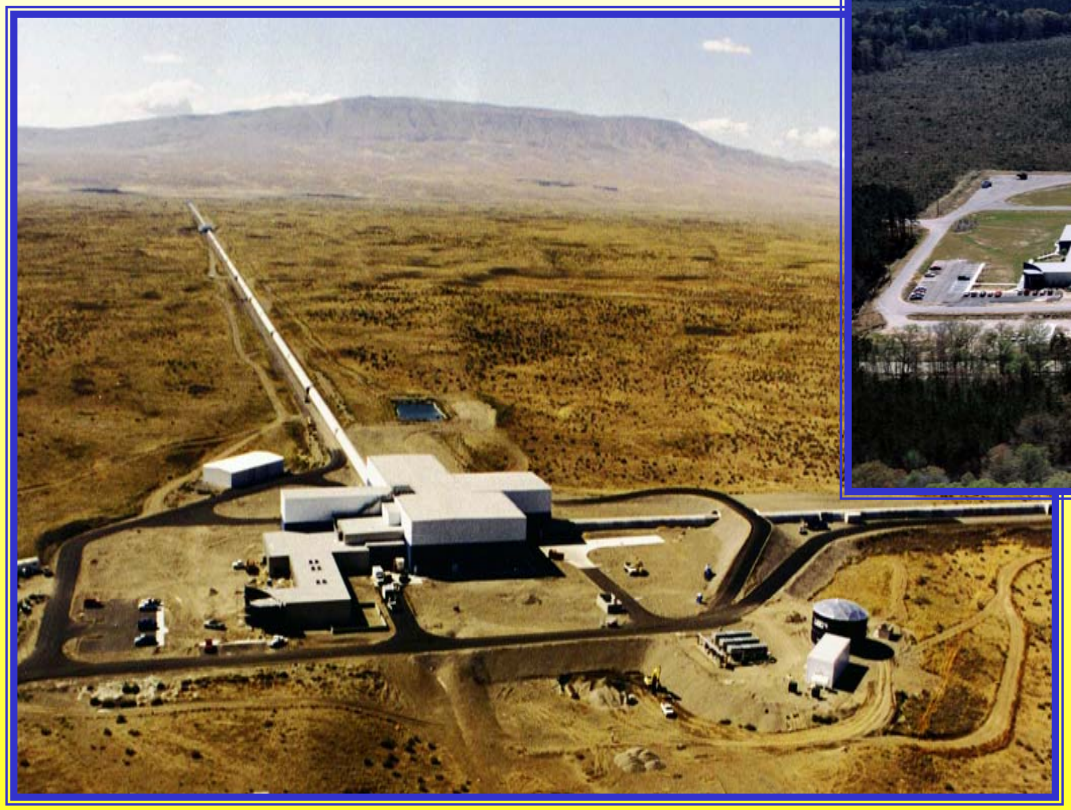
- **Ground-based detectors observe in the audio band**
  - The analogue of optical astronomy



LIGO : Two sites 3000 km apart

Laser interferometers with 4 km long arms!

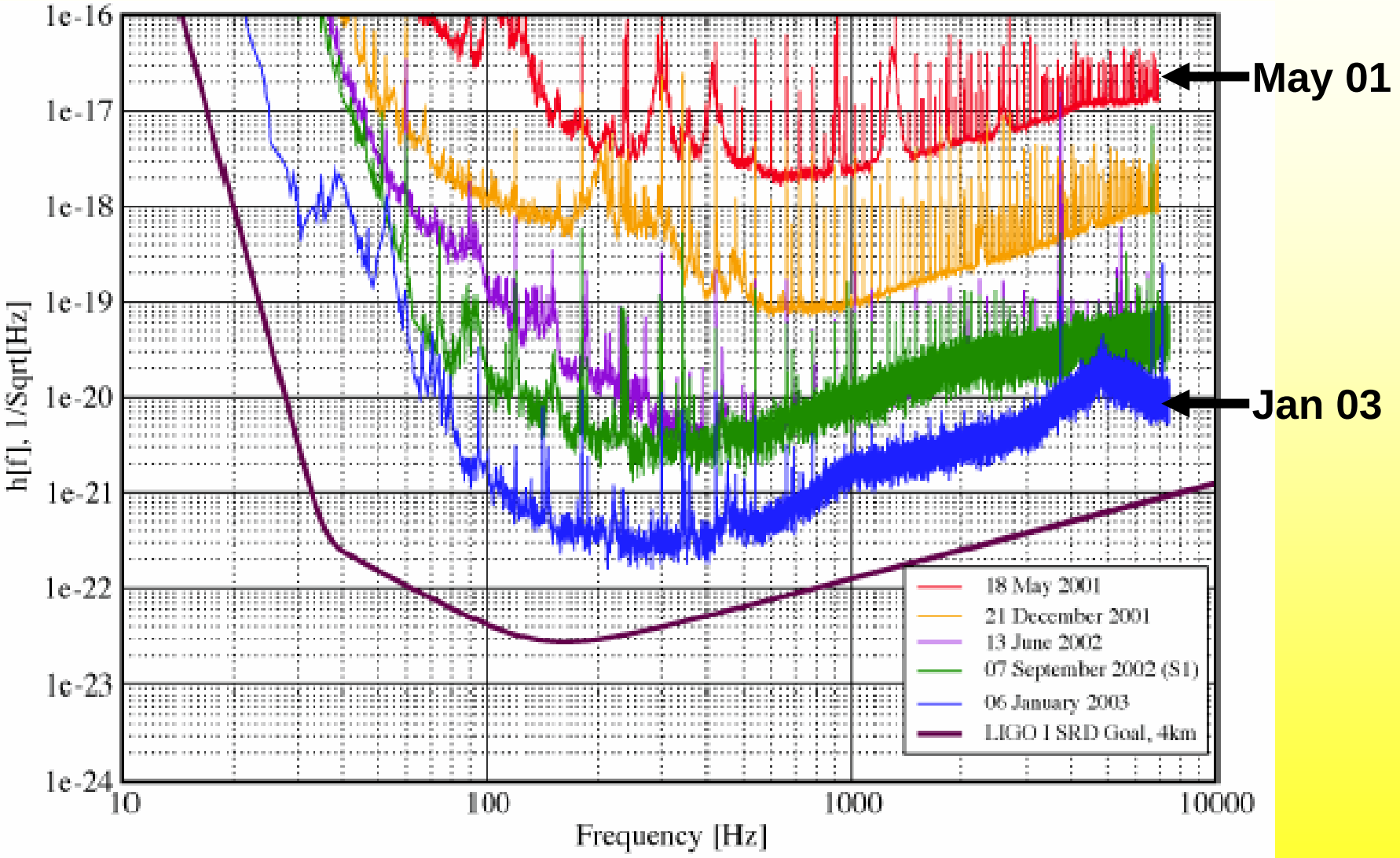
Hanford, Washington



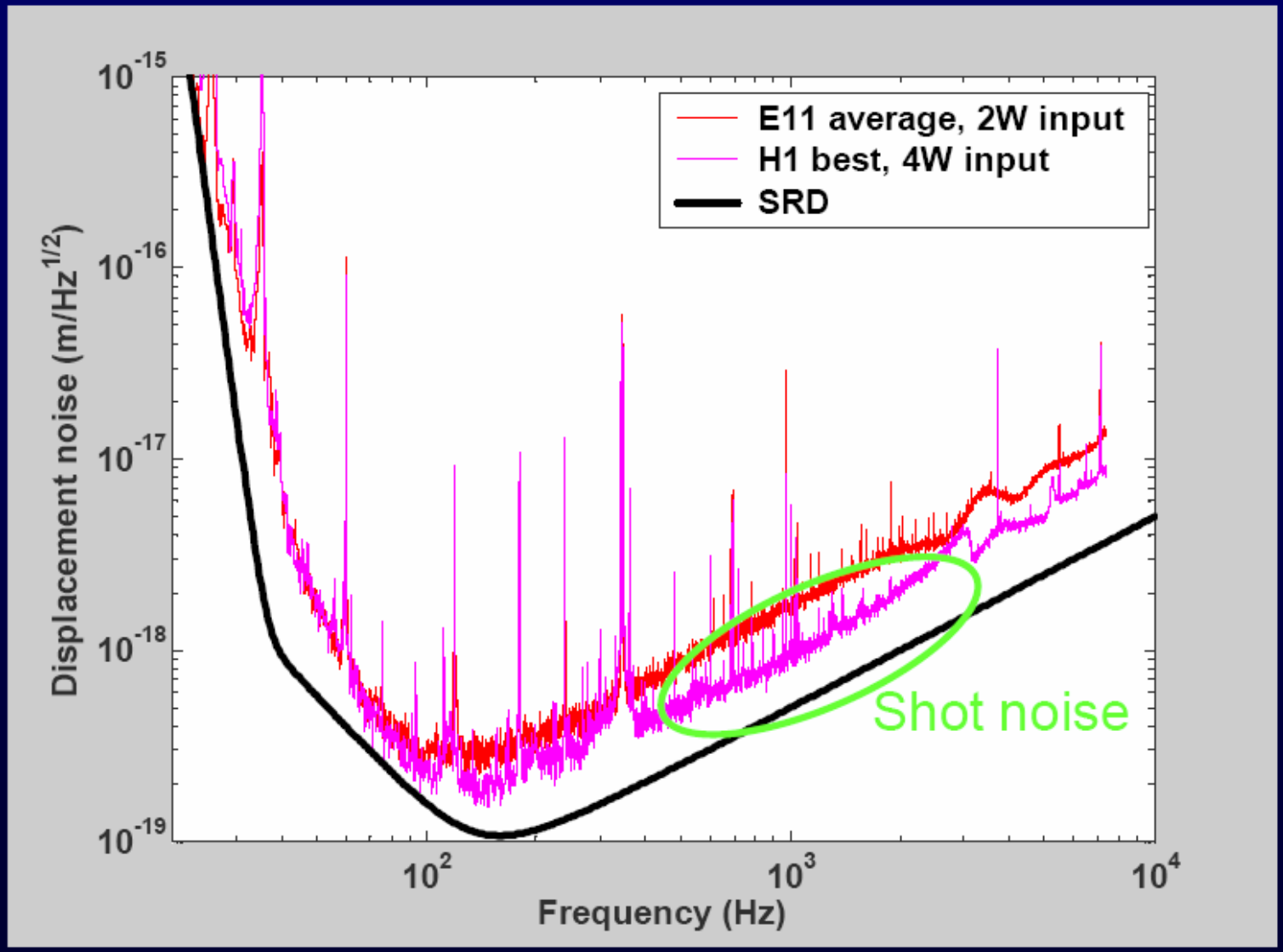
Livingston, Louisiana

LIGO Sensitivity

Livingston 4km Interferometer



H1 goal for next science run



VIRGO: The French-Italian Project
3 km armlength near Pisa

Great Progress in Commissioning!

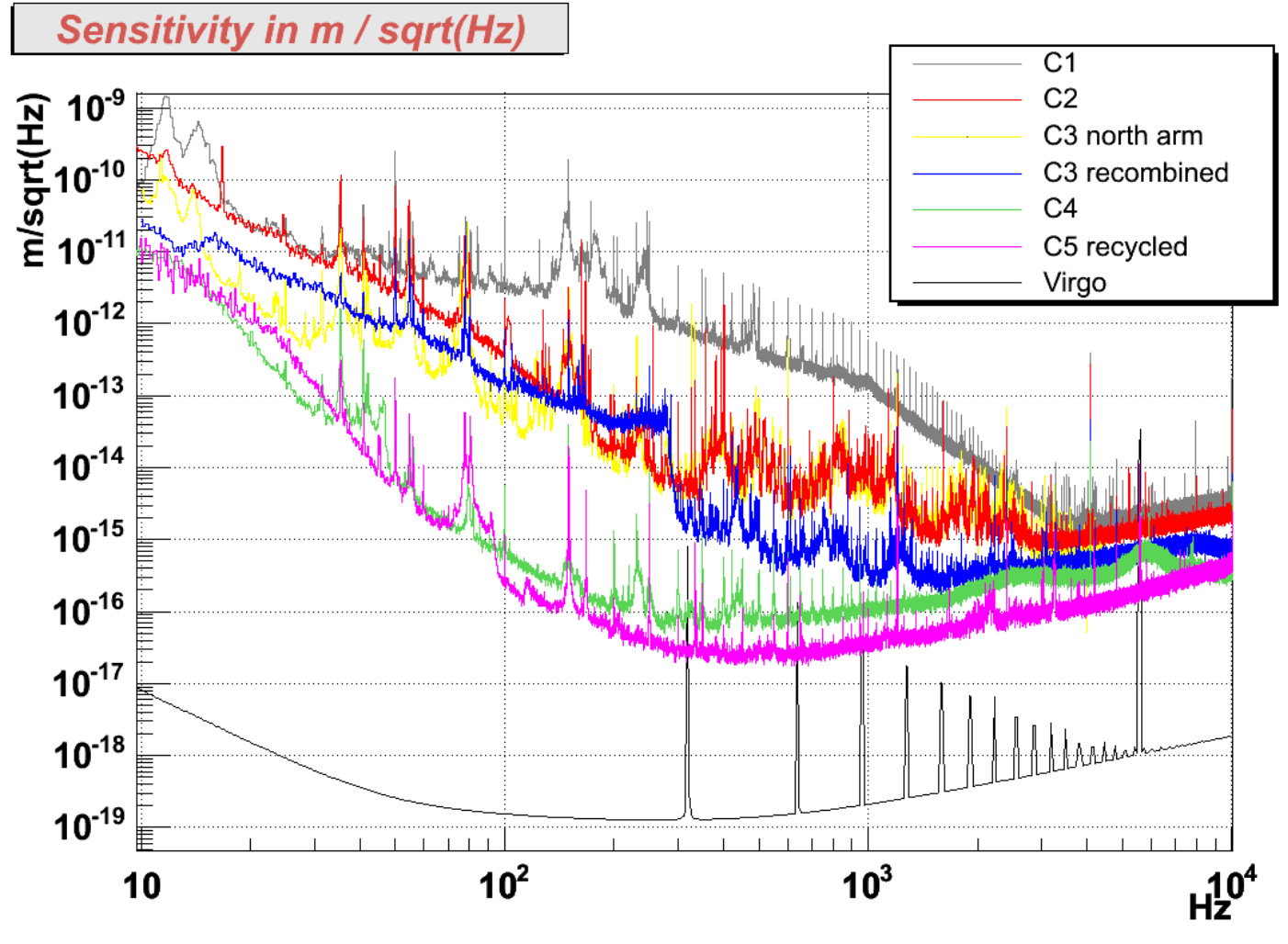
- 1,5 years of commissioning

28th Oct 2003

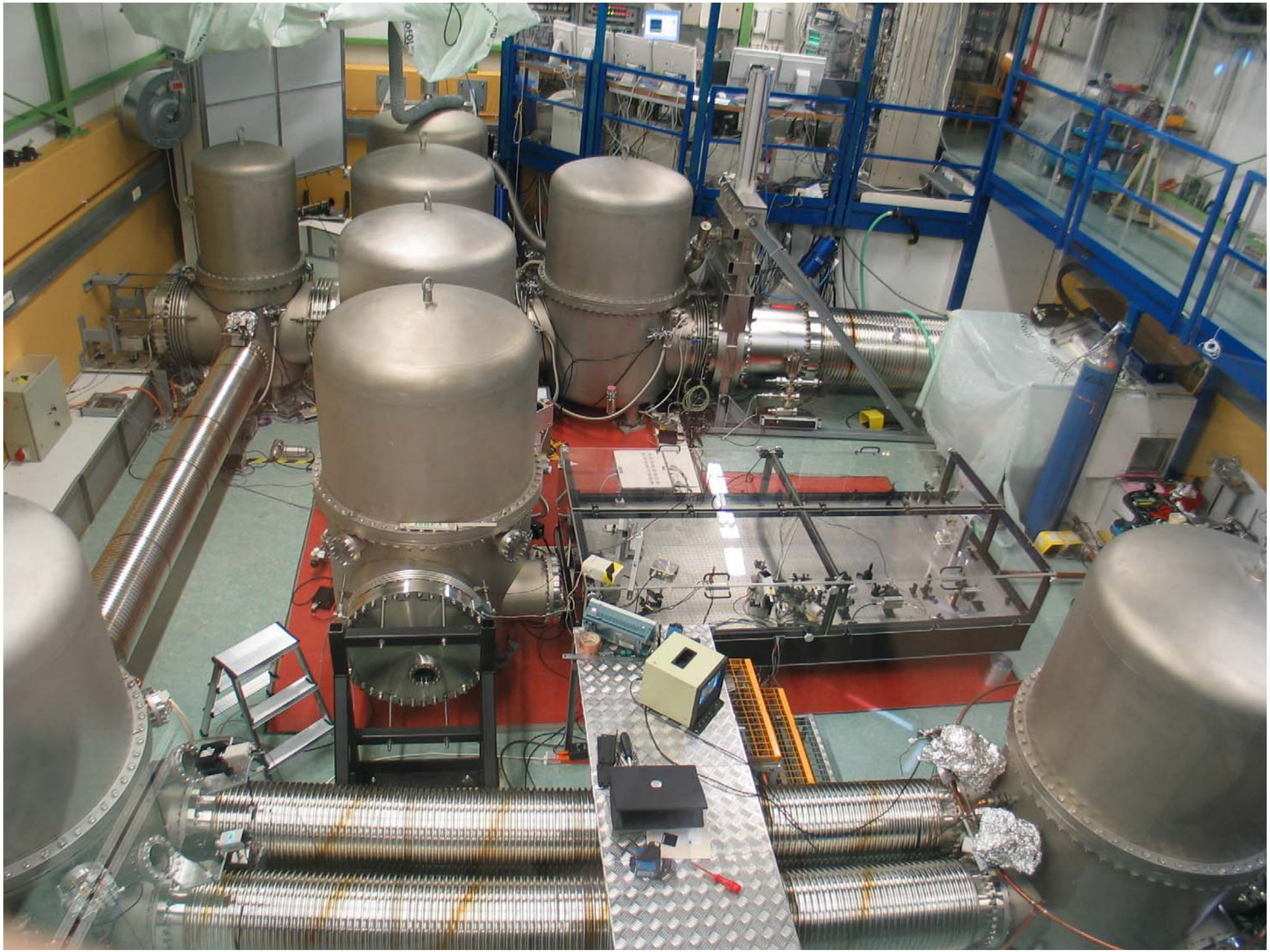
First lock of the north cavity

26th Oct 2004

First lock of the recycled ITF

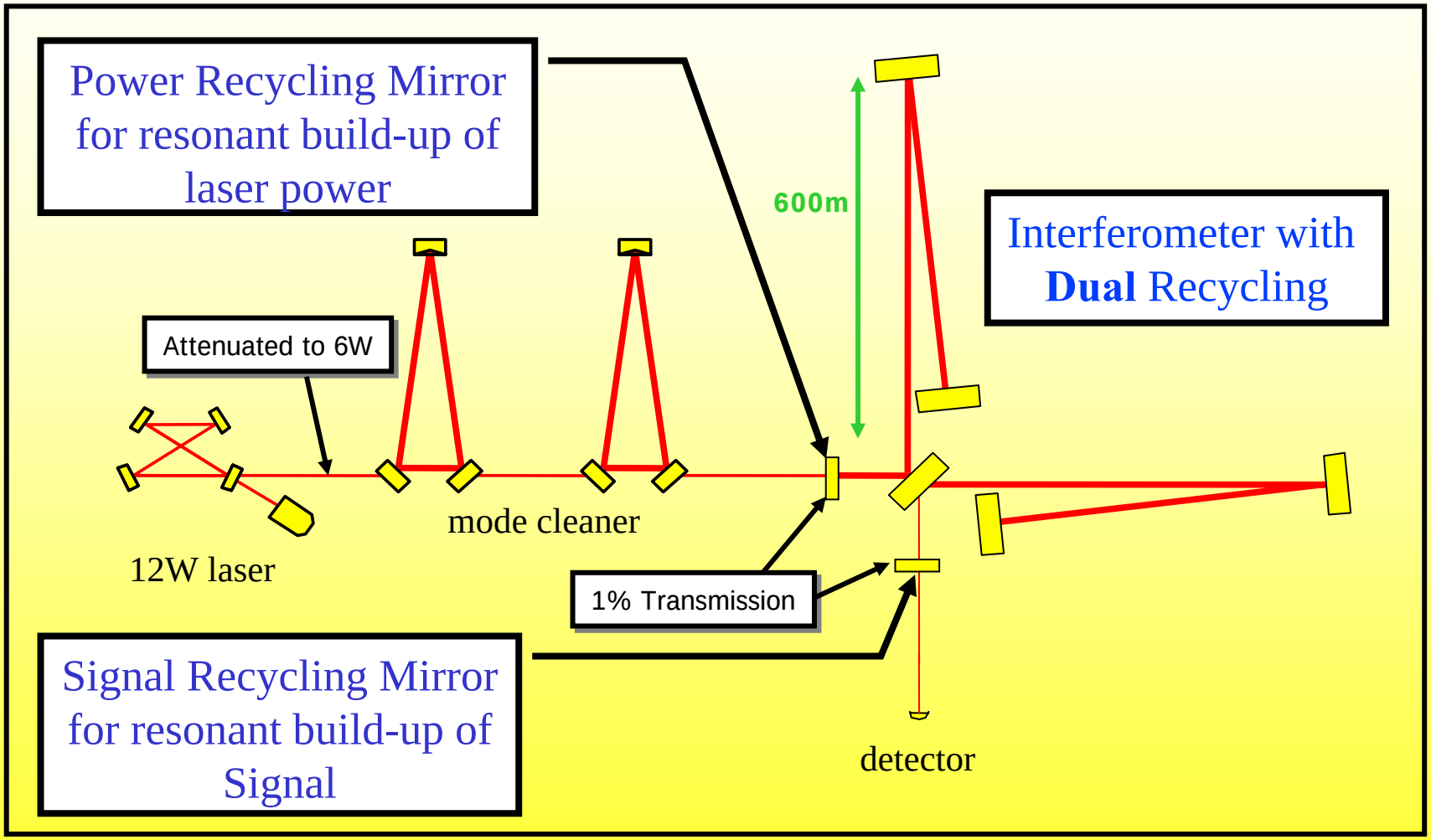



The GEO600 Project
- German-British collaboration, location Hannover / Germany
- Michelson Interferometer with power- and signal-recycling (folded 600m long arms, no armcavities)
G e O 6 0 0
MPQ
U Birmingham
U Mallorca
CARDIFF UNIVERSITY
IGR



GEO600 Optical Layout Jan 2005

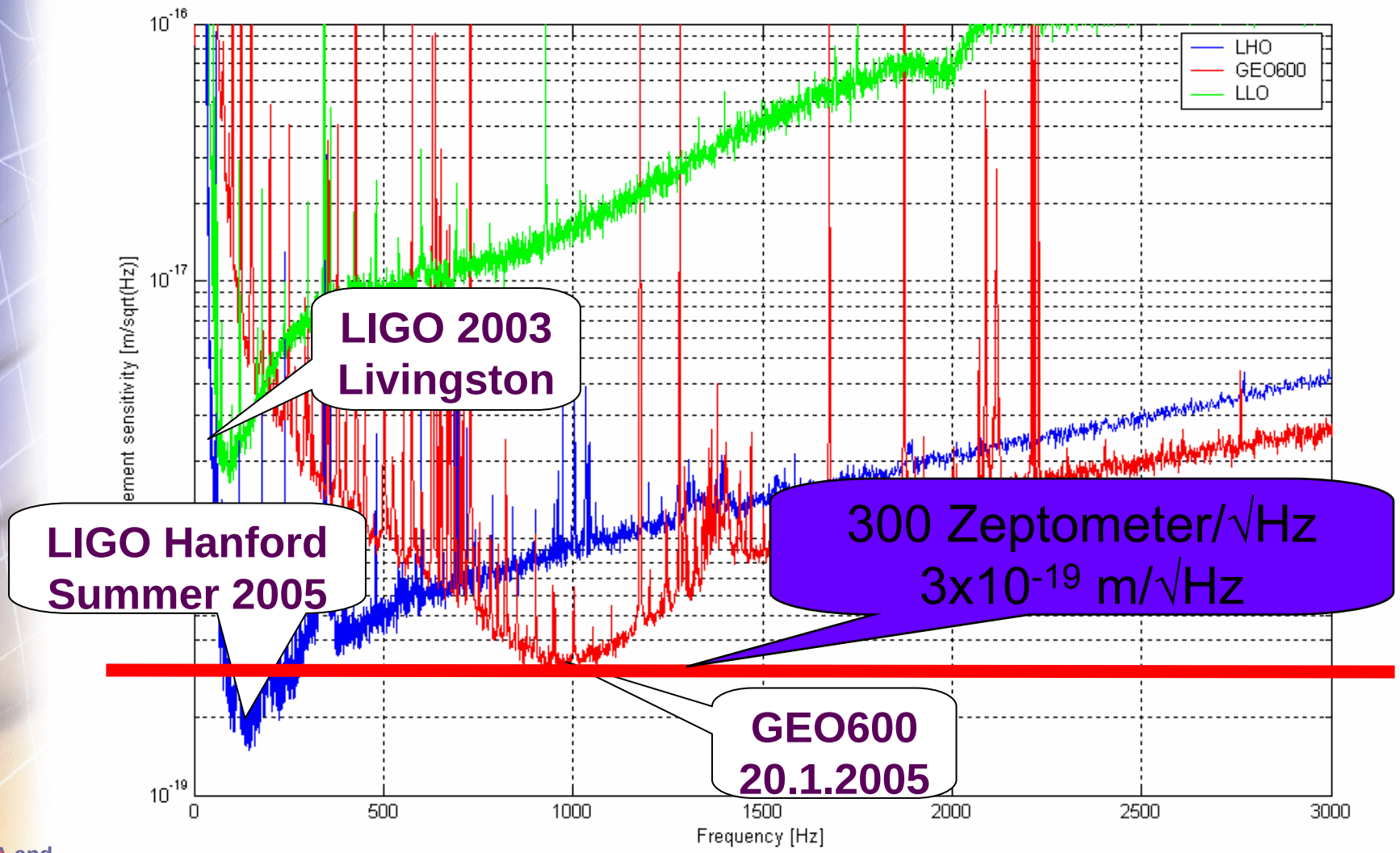
- Not final: Laser still attenuated, low recycling factors in PR and SR, expect factor 10 improvement



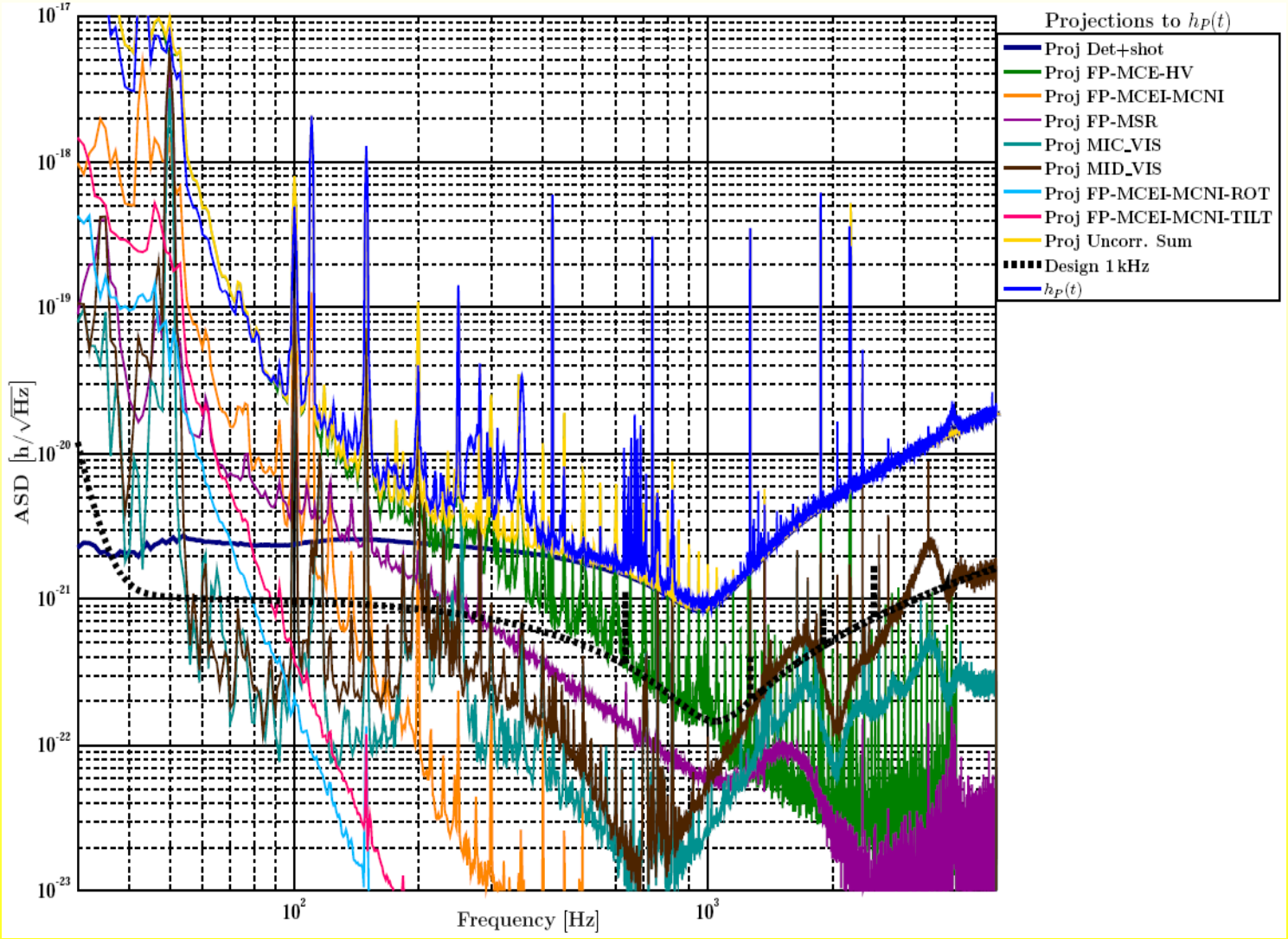
S4 Science Run with LIGO

- Feb 22nd – March 23rd, 708 hours
- Two manned shifts/day (5-21 UTC),
  1 „Expert-On-Duty“ 8-8UTC
- Fully automated overnight shifts;
  SMS alarms to ‚E-O-D‘
- Instrumental duty cycle 97.5%, 72%>10h
- Longest lock 52h

Displacement Sensitivity of Ground-Based Laser Interferometers



Noise hunting:
on the way to design sensitivity!



Noise hunting:
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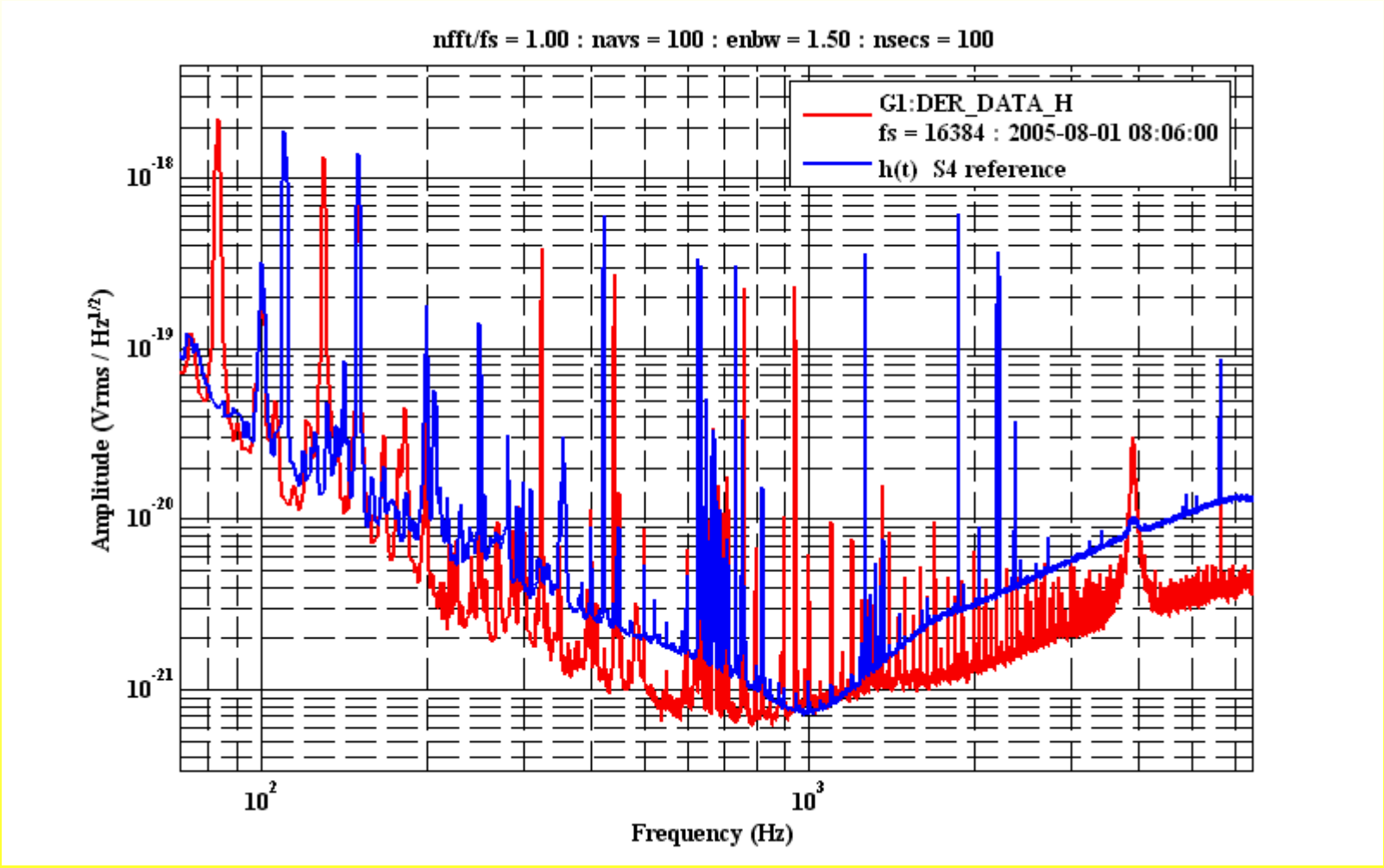
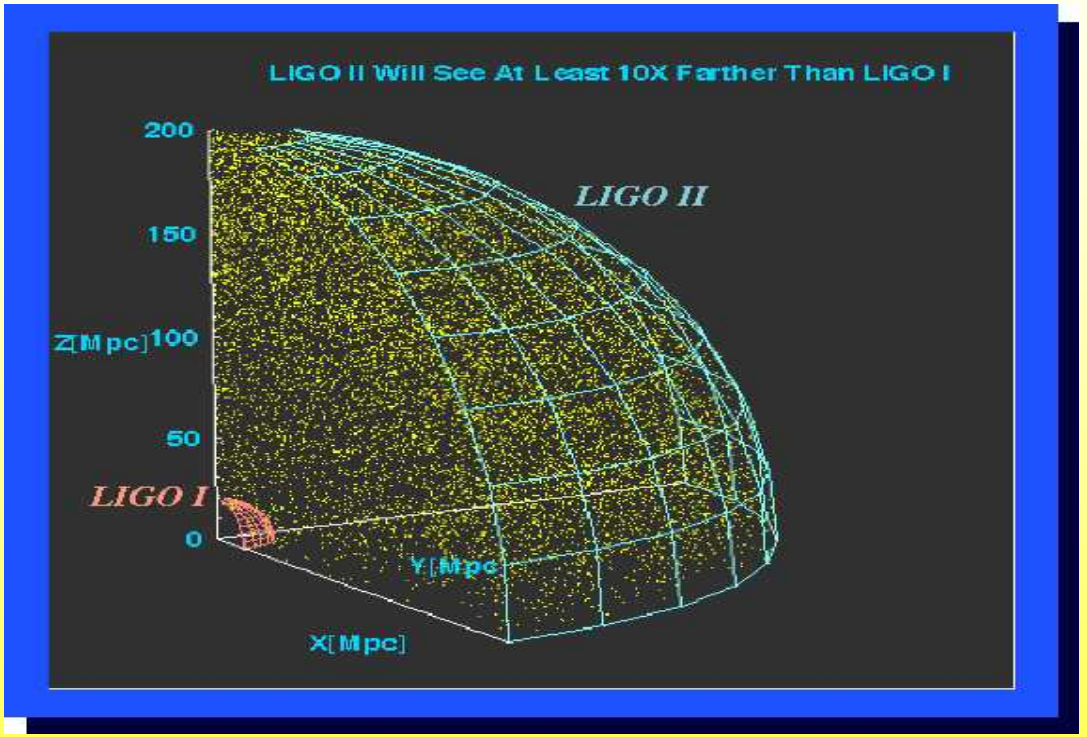


LIGO – Future Plans : Advanced LIGO

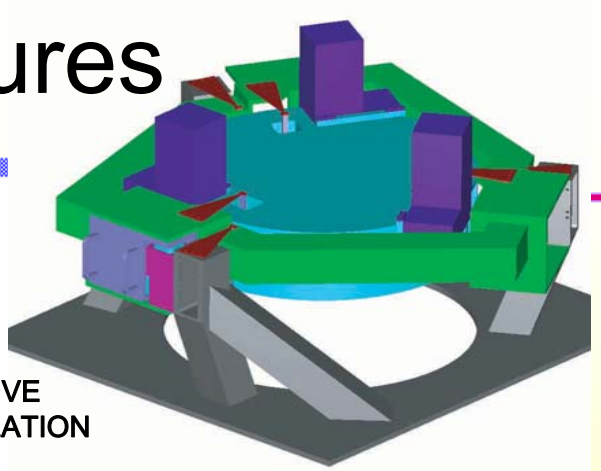
- Observable volume several thousand times LIGO
- Start 2008
- Installation 2010-13
- New main suspensions
- New Optics
- 200 W lasers



- Signal Recycling – Resonant Sideband Extraction

LIGO AdLIGO Design features

GEO600 Innovations!



0 KG SAPPHIRE
EST MASSES

INPUT MODE
CLEANER

ACTIVE
THERMAL
CORRECTION

QUAD SILICA
SUSPENSION

180 W LASER,
MODULATION SYSTEM

LASER

MOD.

T=0.5%

125W

PRM
T~6%

BS

ITM

ETM

SRM

T=5%

OUTPUT MODE
CLEANER

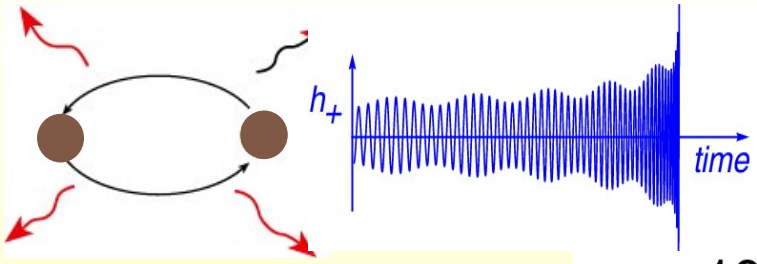
PD

GW READOUT

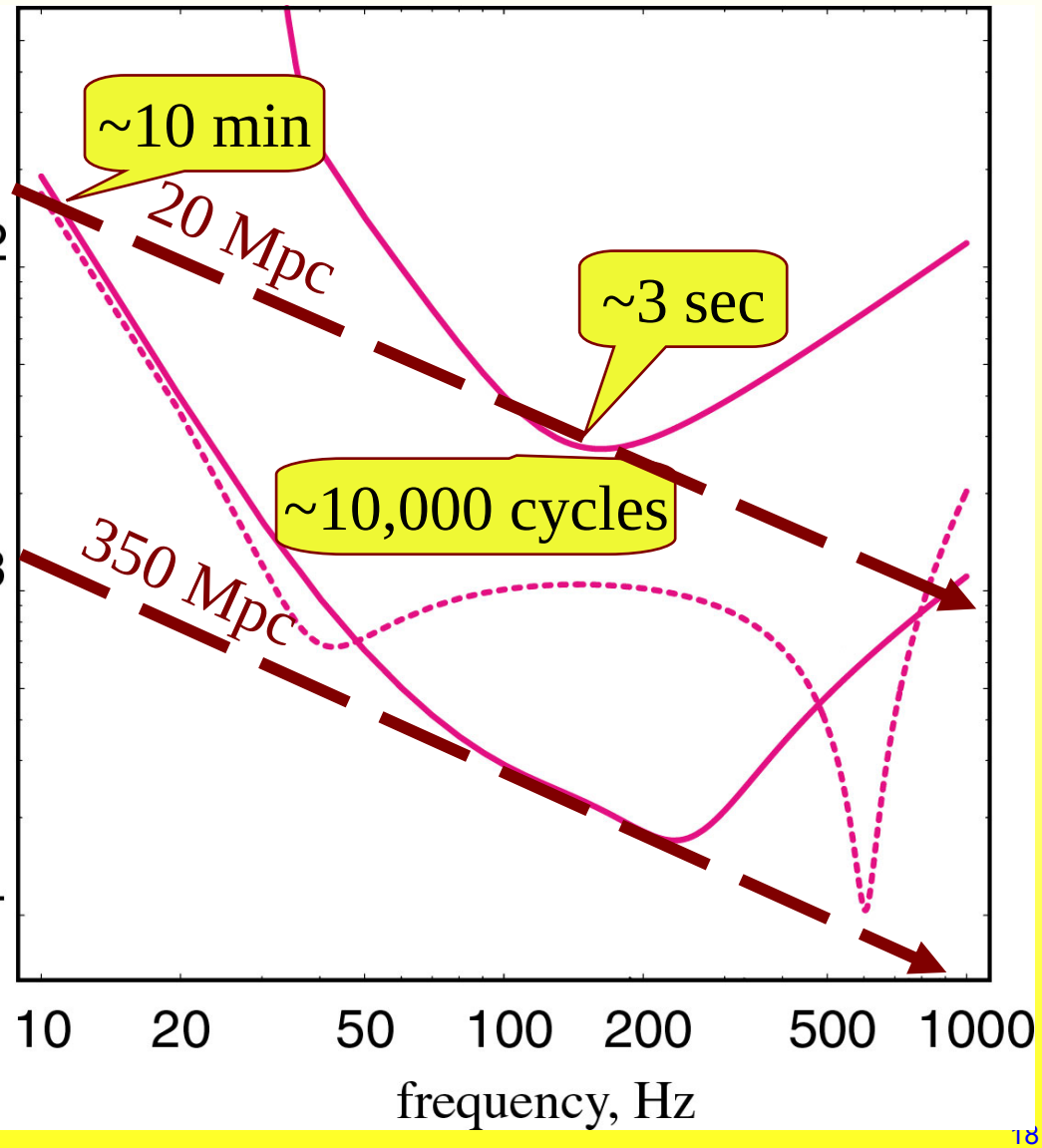
PRM Power Recycling Mirror
BS Beam Splitter
ITM Input Test Mass
ETM End Test Mass
SRM Signal Recycling Mirror
PD Photodiode

Neutron Star / Neutron Star Inspiral

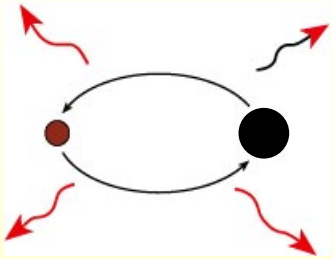
(our most reliably understood source)

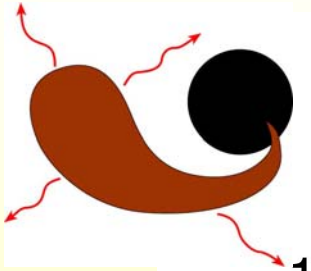


- 1.4 Msun / 1.4 Msun NS/NS Binaries
- Event rates
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor astro-ph/0012038; …
- Initial IFOs
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 3yrs**
- Advanced IFOs -
  - » Range: 350Mpc
  - » **3 / yr to 4 / day**

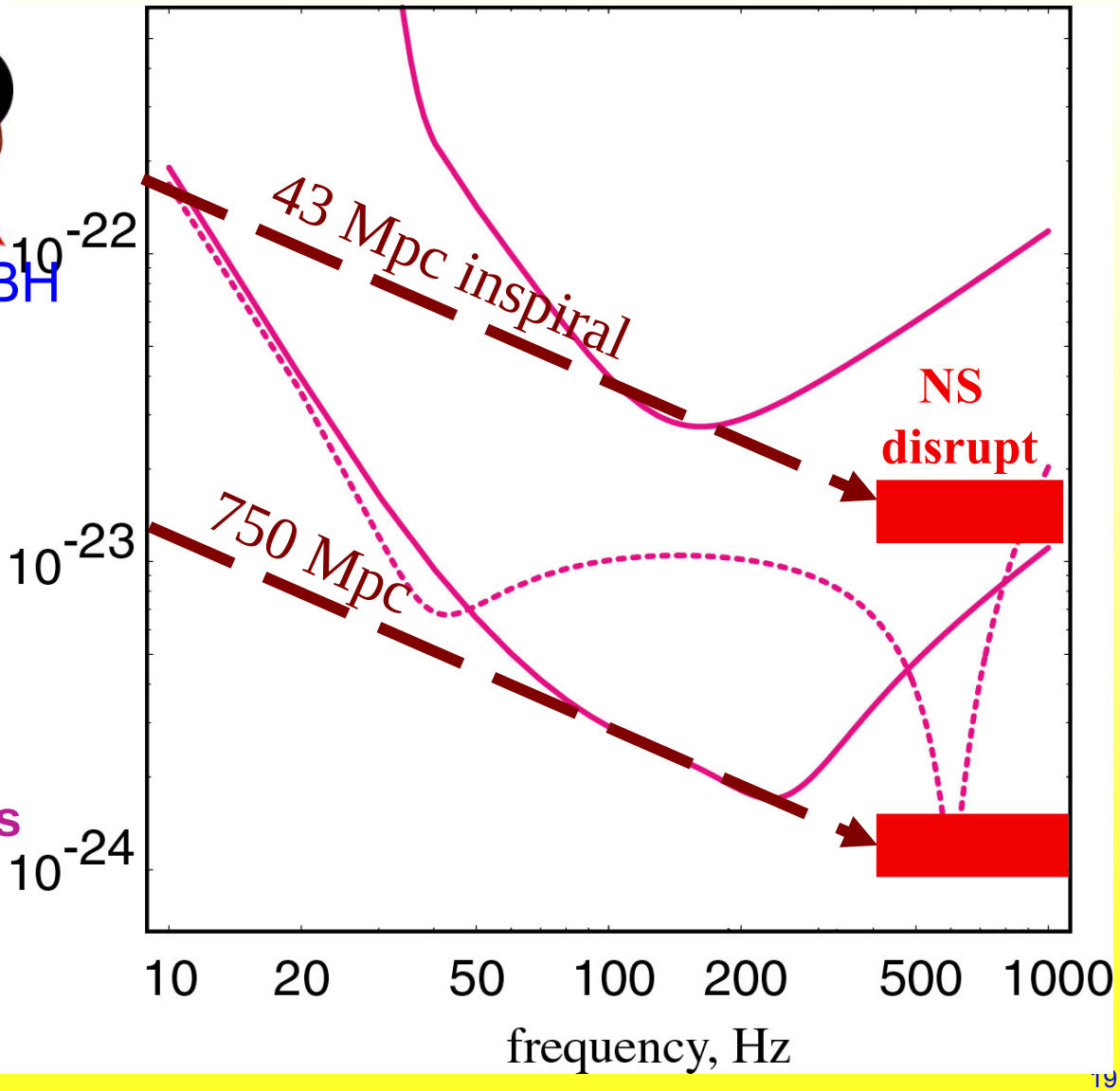


Neutron Star / Black Hole Inspiral and NS Tidal Disruption



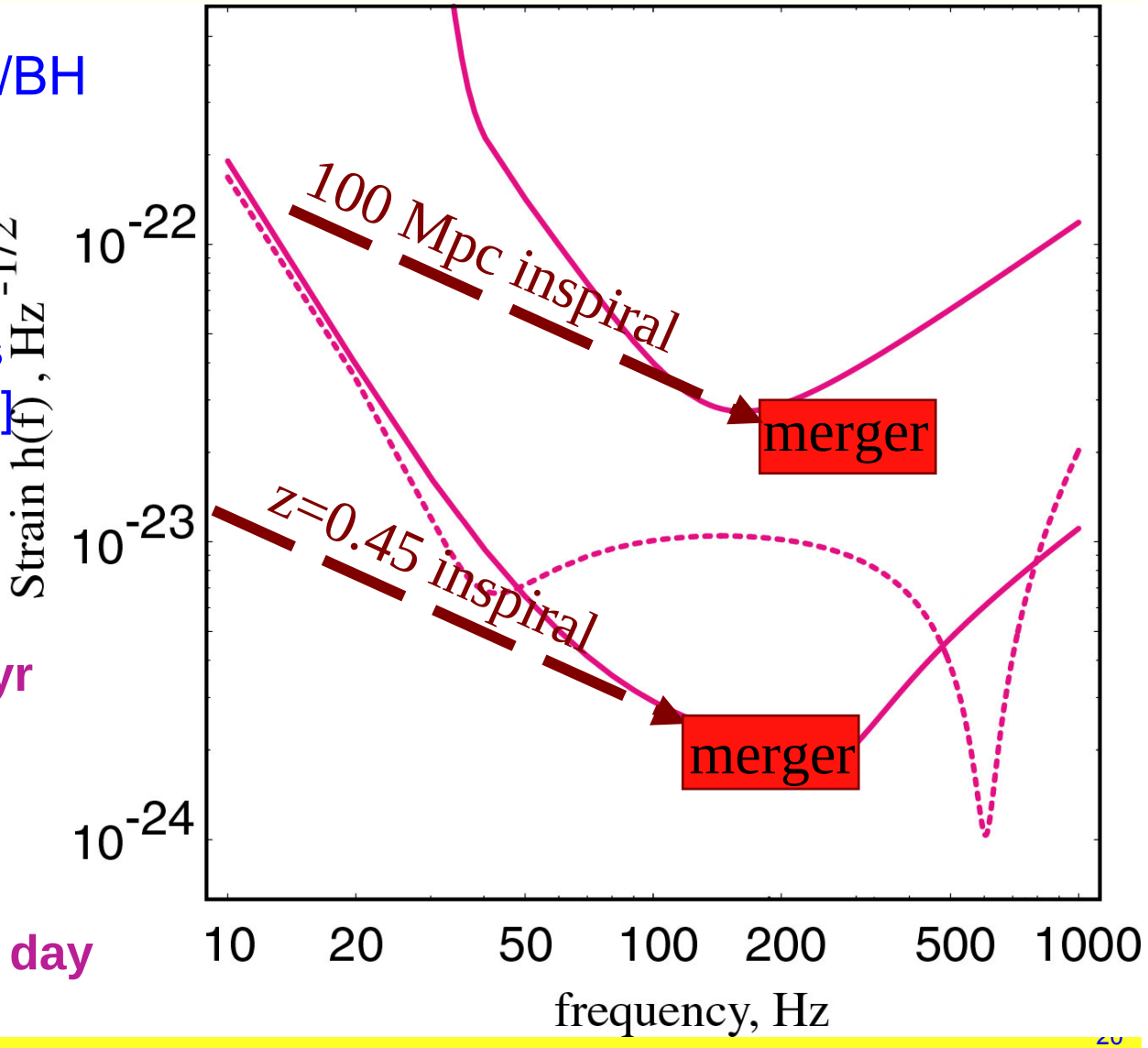


- 1.4Msun / 10 Msun NS/BH Binaries
- Event rates
  - » Population Synthesis [Kalogera's summary]
- Initial IFOs
  - » Range: 43 Mpc
  - » 1 / 2500 yrs to **1 / 2yrs**
- Advanced IFOs
  - » Range: 750 Mpc
  - » **1 / yr to 6 / day**



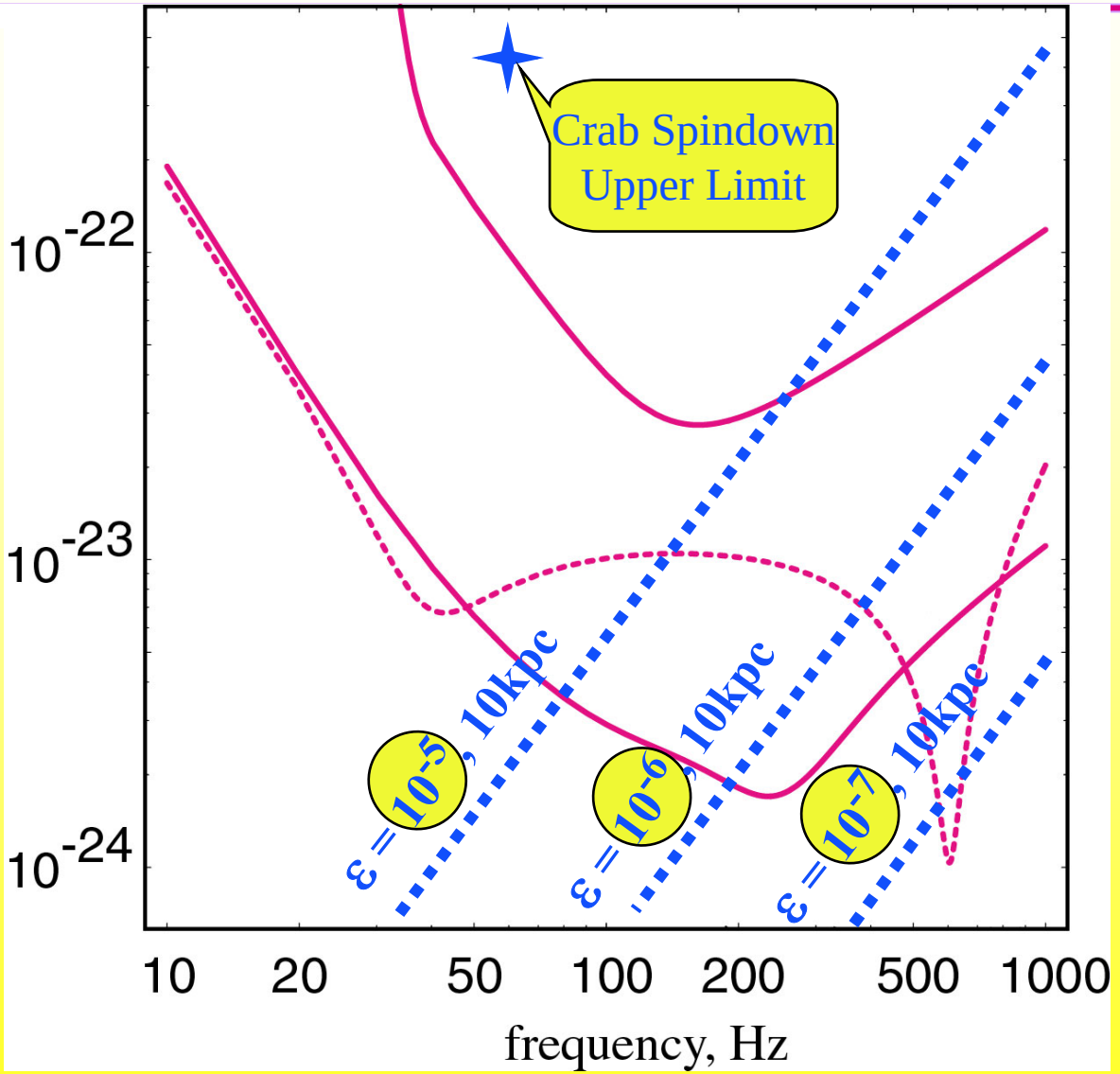
Black Hole / Black Hole Inspiral and Merger

- 10Msun / 10 Msun BH/BH Binaries
- Event rates
  - » Based on population synthesis [Kalogera's summary of literature]
- Initial IFOs
  - » Range: 100 Mpc
  - » ≲ 1 / 600yrs to **~3 / yr**
- Advanced IFOs -
  - » Range: z=0.45
  - » ≲ **1/ month to ~30 / day**



Spinning NS's: Pulsars

- NS Ellipticity:
  - » Crust strength $\varepsilon \lesssim 10^{-5}$
- Known Pulsars:
  - » First Interferometers: $\varepsilon \gtrsim 3\times10^{-6}$ (1000Hz/f) x (distance/10kpc)
  - » Narrowband Advanced $\varepsilon \gtrsim 2\times10^{-8}$ (1000Hz/f)^2 x (distance/10kpc)
- Unknown NS's - All sky search:
  - » Sensitivity ~5 to 15 worse

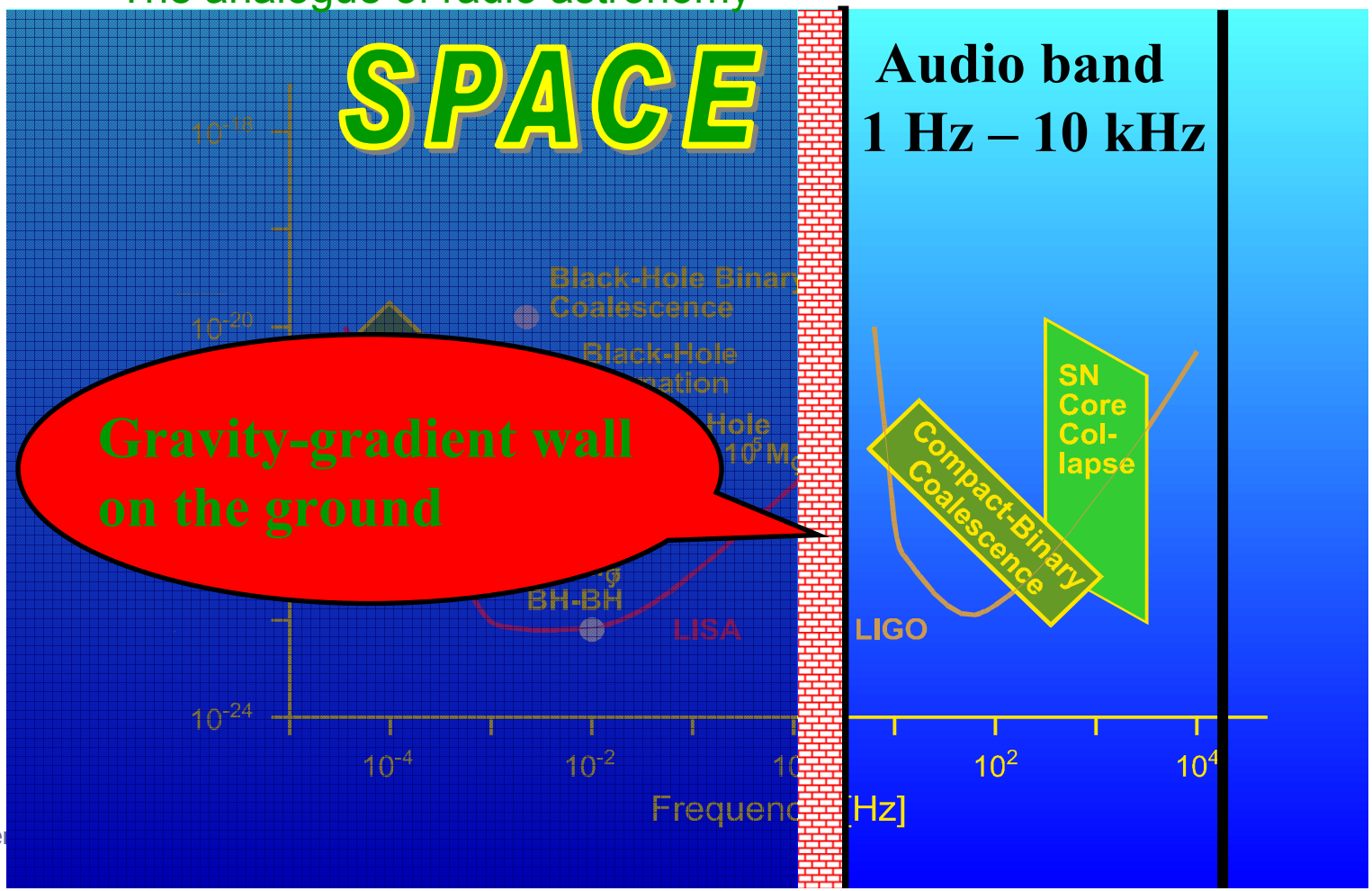


Advanced LIGO

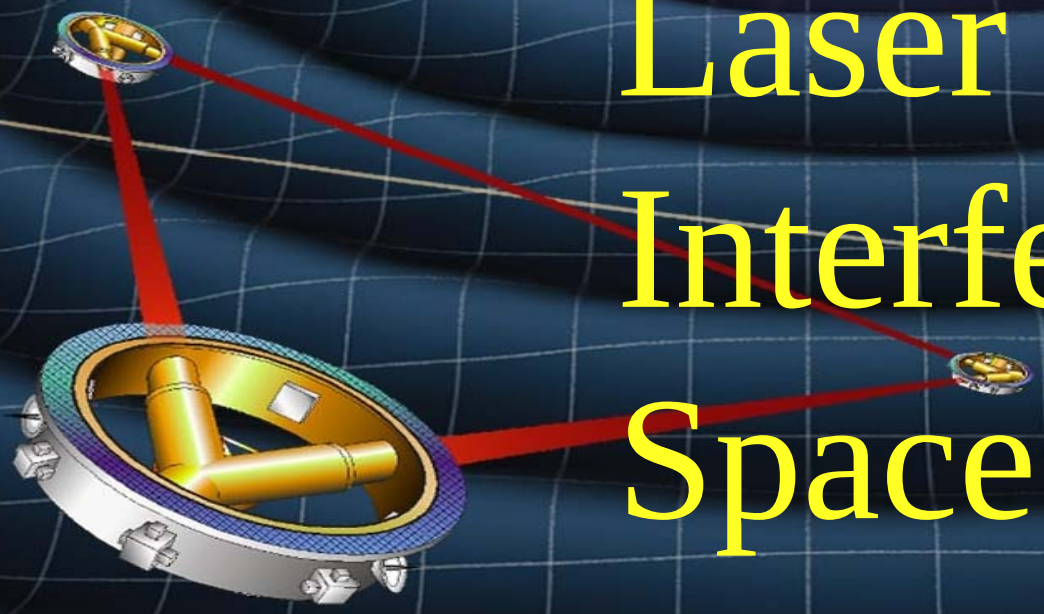
- **Advanced LIGO approved by the US National Science Board in Fall 2004**
  - » It is in the President's budget to Congress!
    - – Hubble servicing mission and Fermilab BTeV B-Factory did not make it!
  - » It will be built!
  - » Start 2008, LIGO down for refurbishing 2010, Advanced LIGO data taking 2013
  - » MPG contribution approved!
  - » Gravitational Waves not in Verbundforschung
    - – No way for universities in Germany to participate in GEO or LIGO!

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



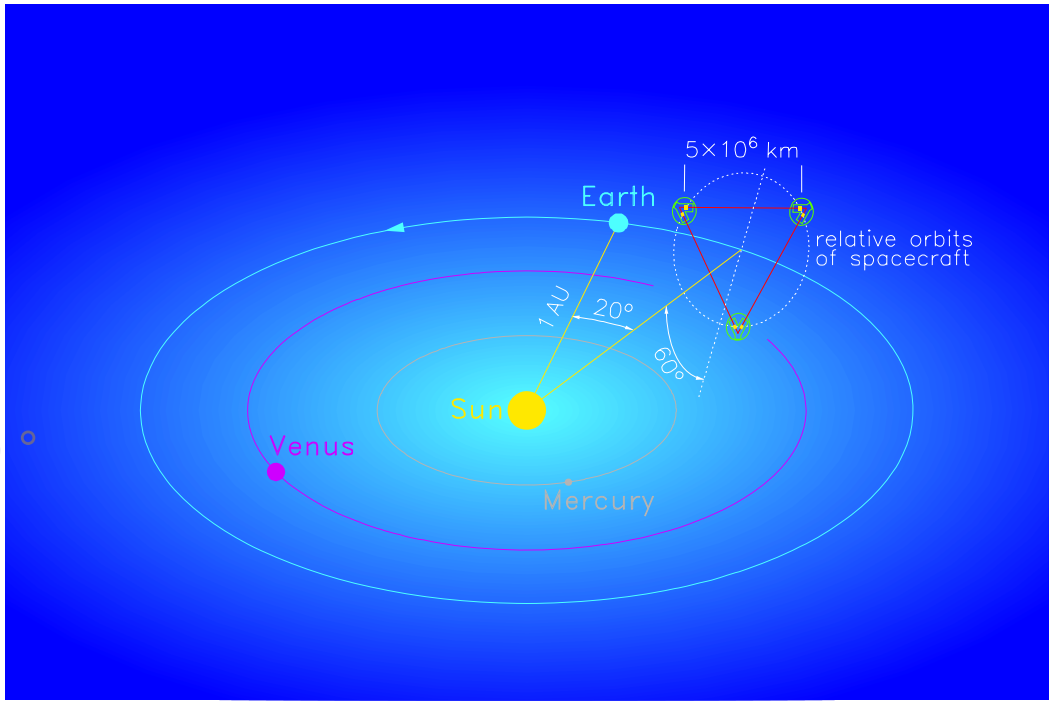
LISA



Laser
Interferometer
Space Antenna

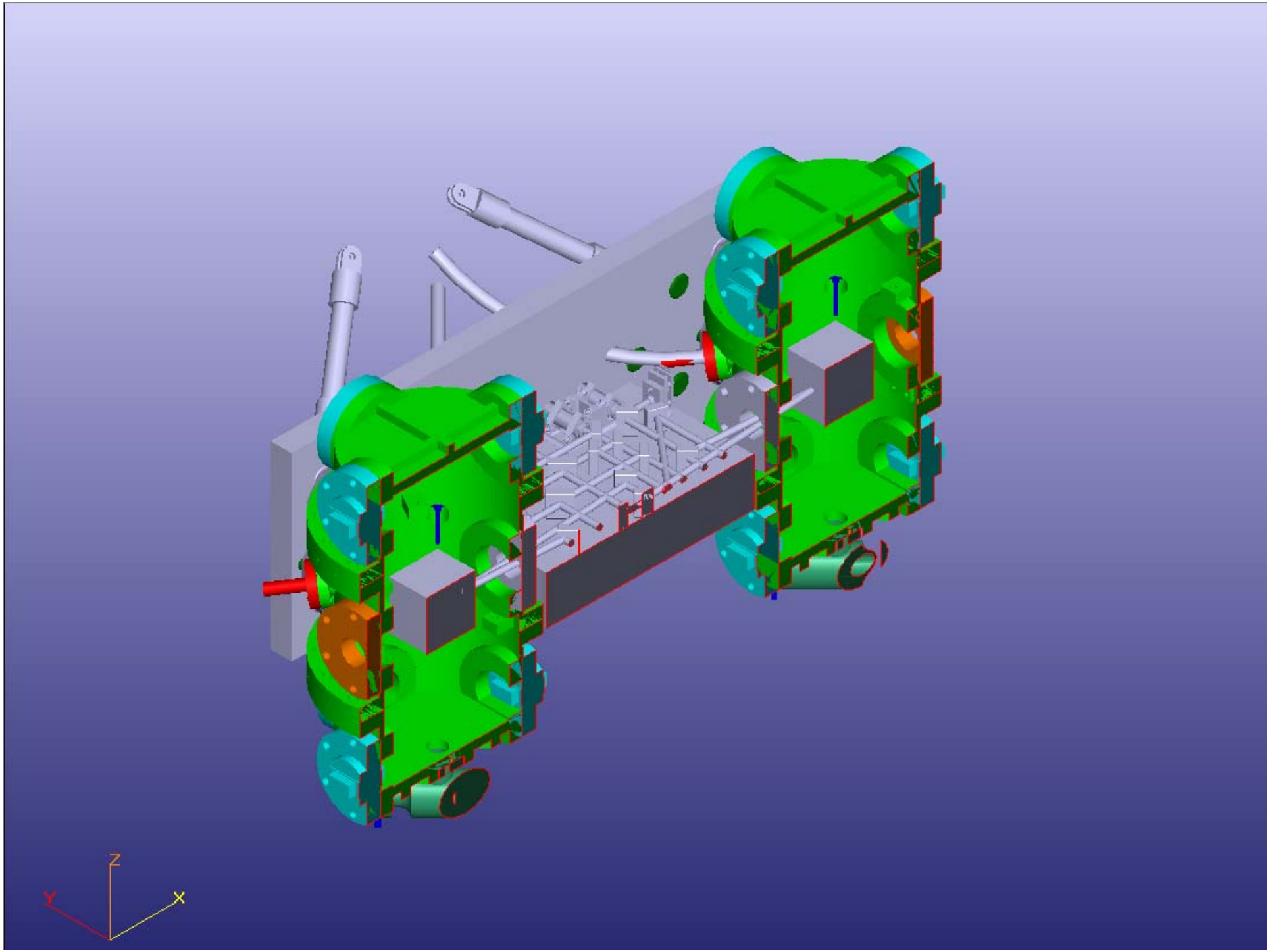
LISA: A Collaborative ESA/NASA Mission

- Cluster of 3 S/C in heliocentric orbit
- Free flying test masses shielded inside the S/C
- Trailing the earth by 20 ° (50 Mio km)
- Equilateral triangle with 5 Mio km arms
- Inclined against ecliptic by 60 °

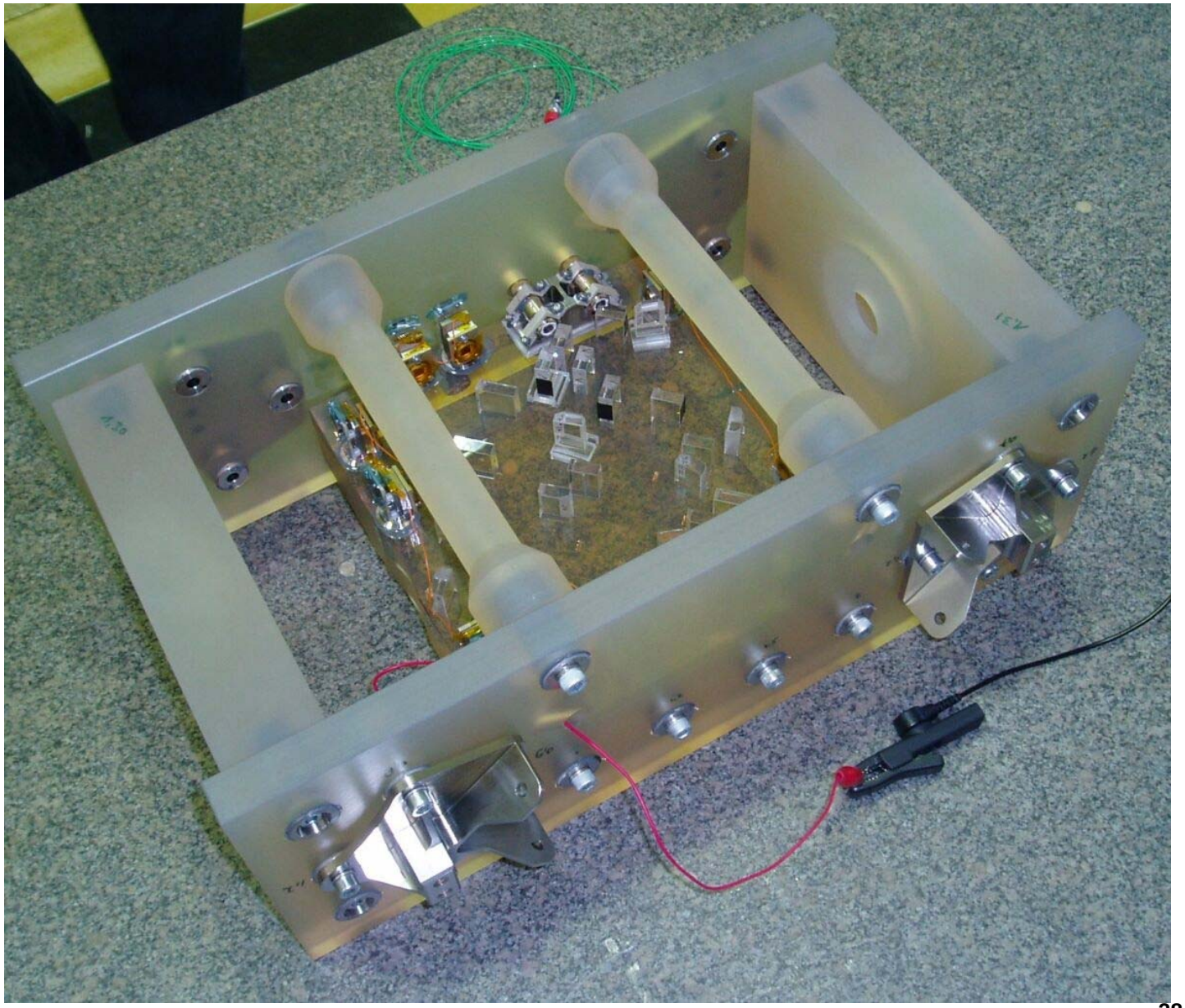


Testing Technology in Space: LISA Pathfinder (SMART-2) Mission

- One LISA arm shrunk to 30 cm
- Technology demonstration for LISA Technology Package (LTP)
- Launch in 2008/9 for LPF and 2013/4 for LISA
- Implementation Phase has begun Feb. 2005!
- Astrium Friedrichshafen LTP Prime under contract from AEI with grant from DLR

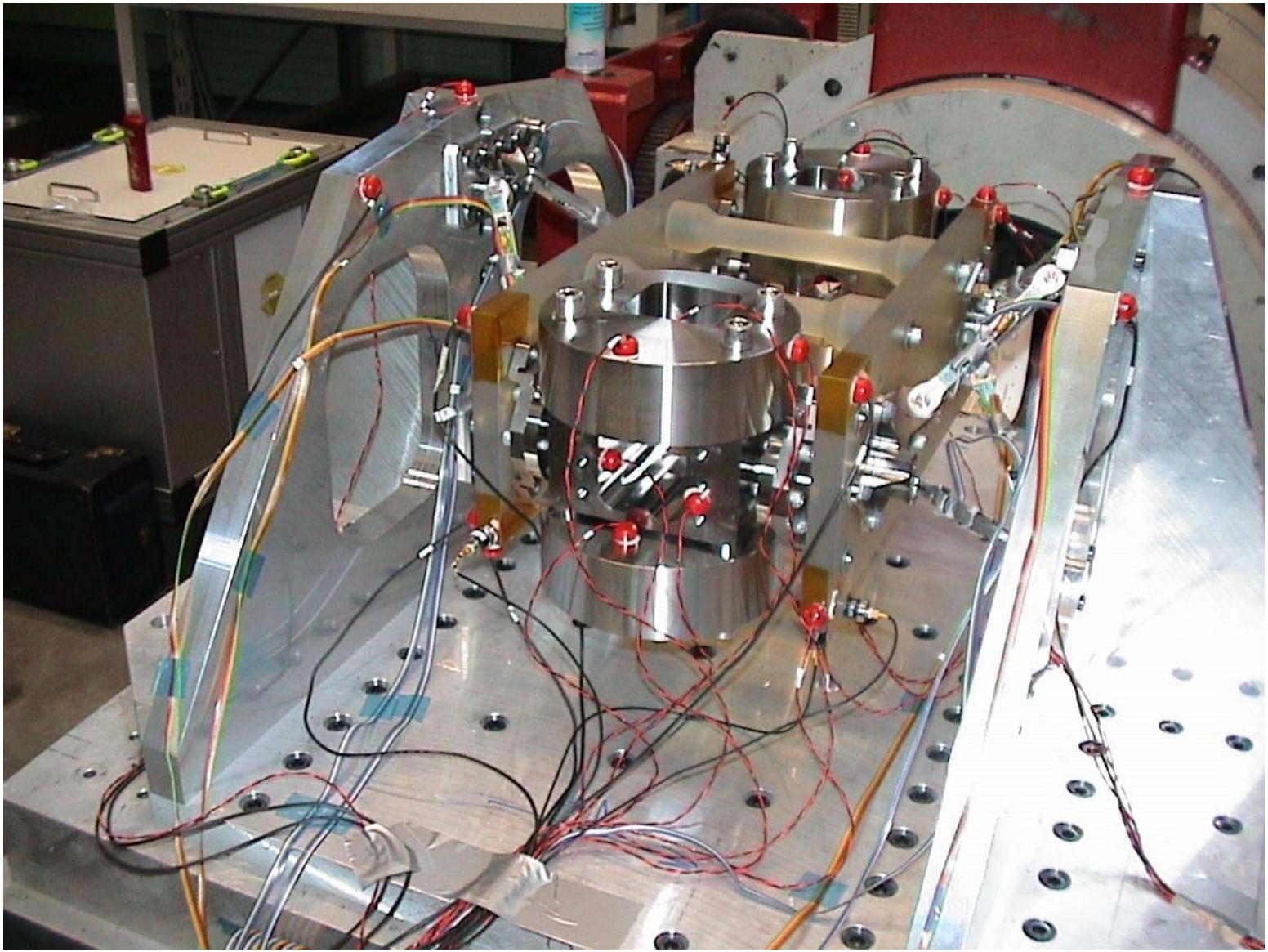

Z
Y
X

LISA Pathfinder OB Engineering Model

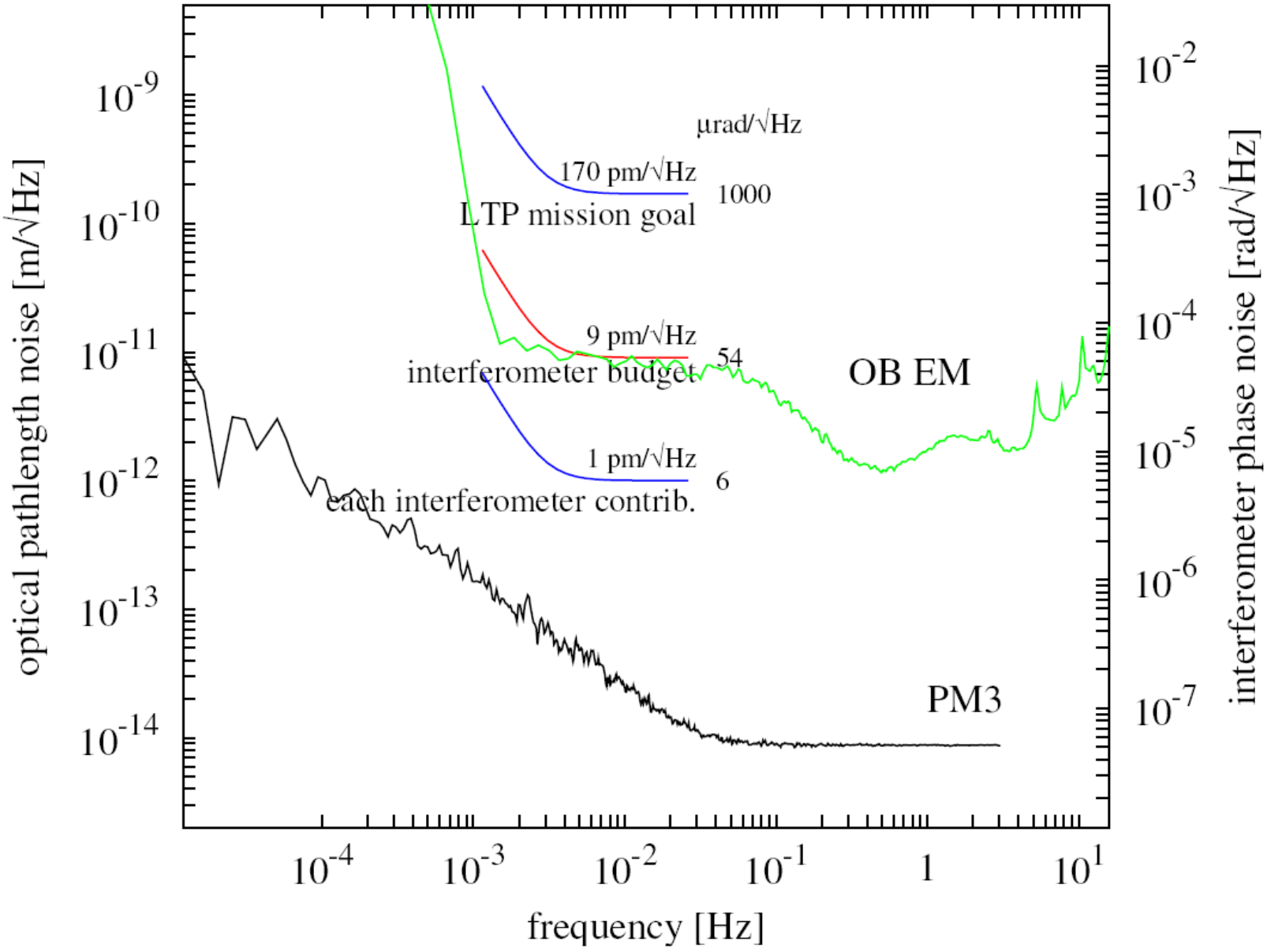


Assembly in Friedrichshafen

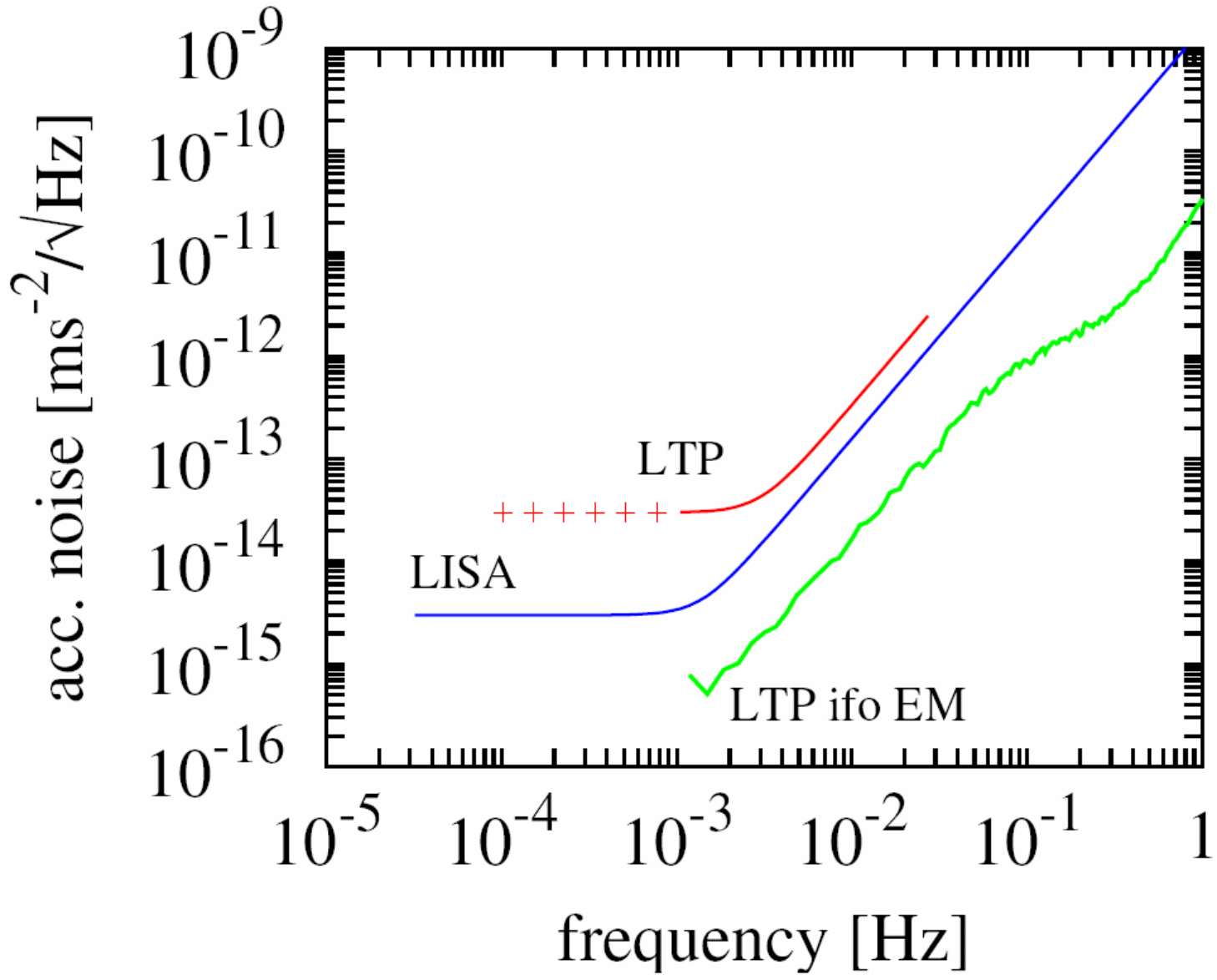
Vibration test of Optical Bench

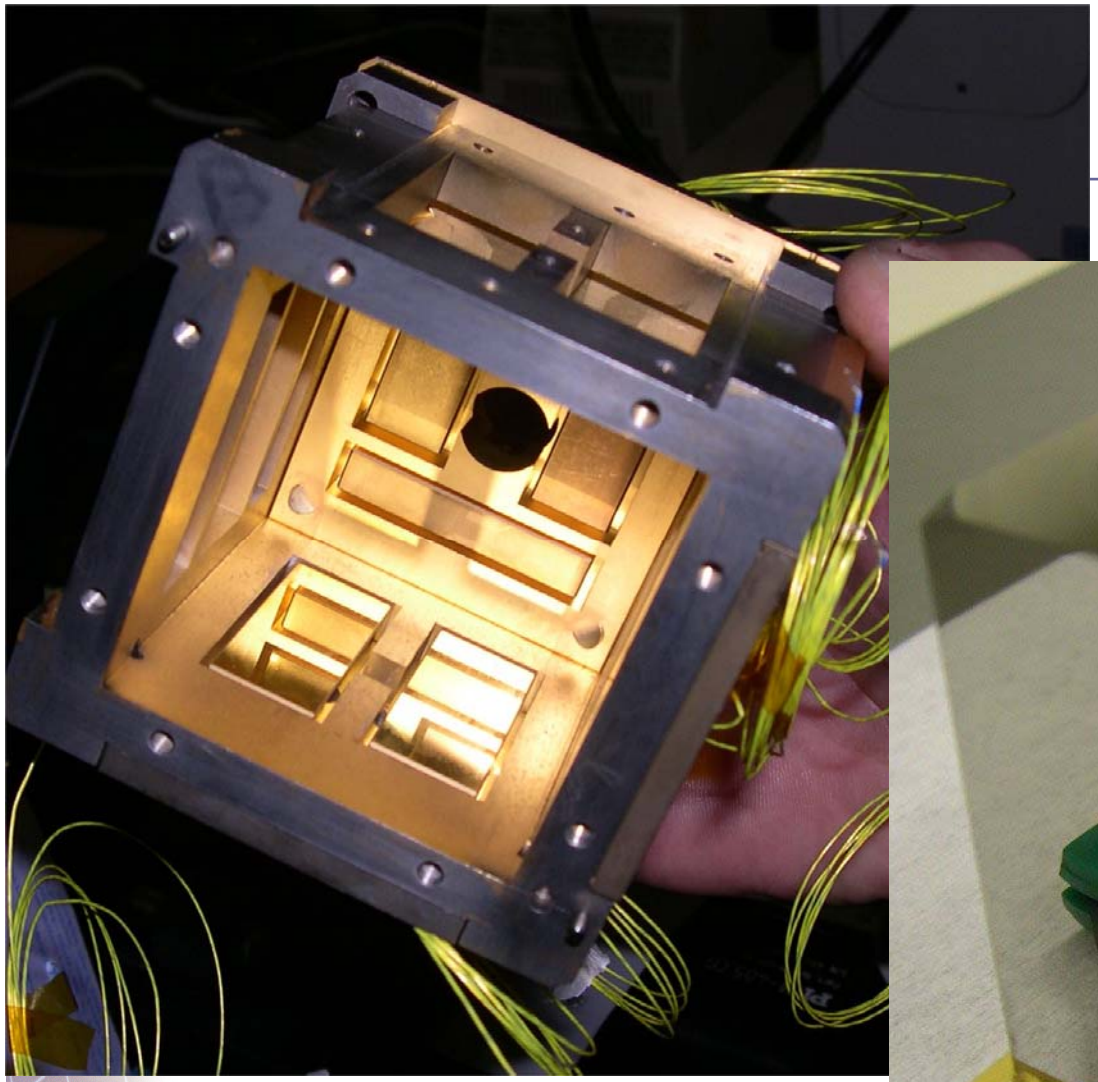


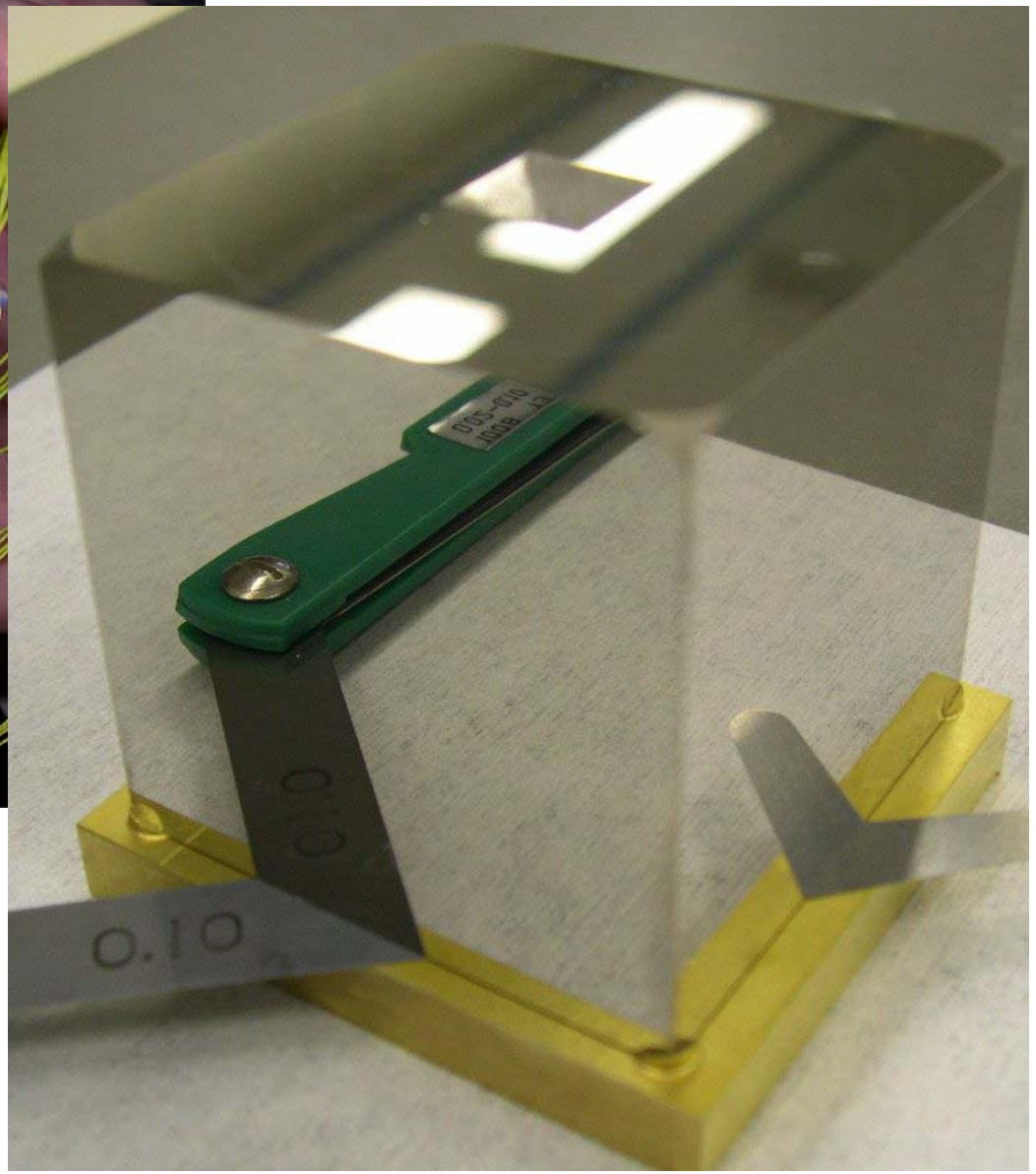
Optical Bench EM Performance



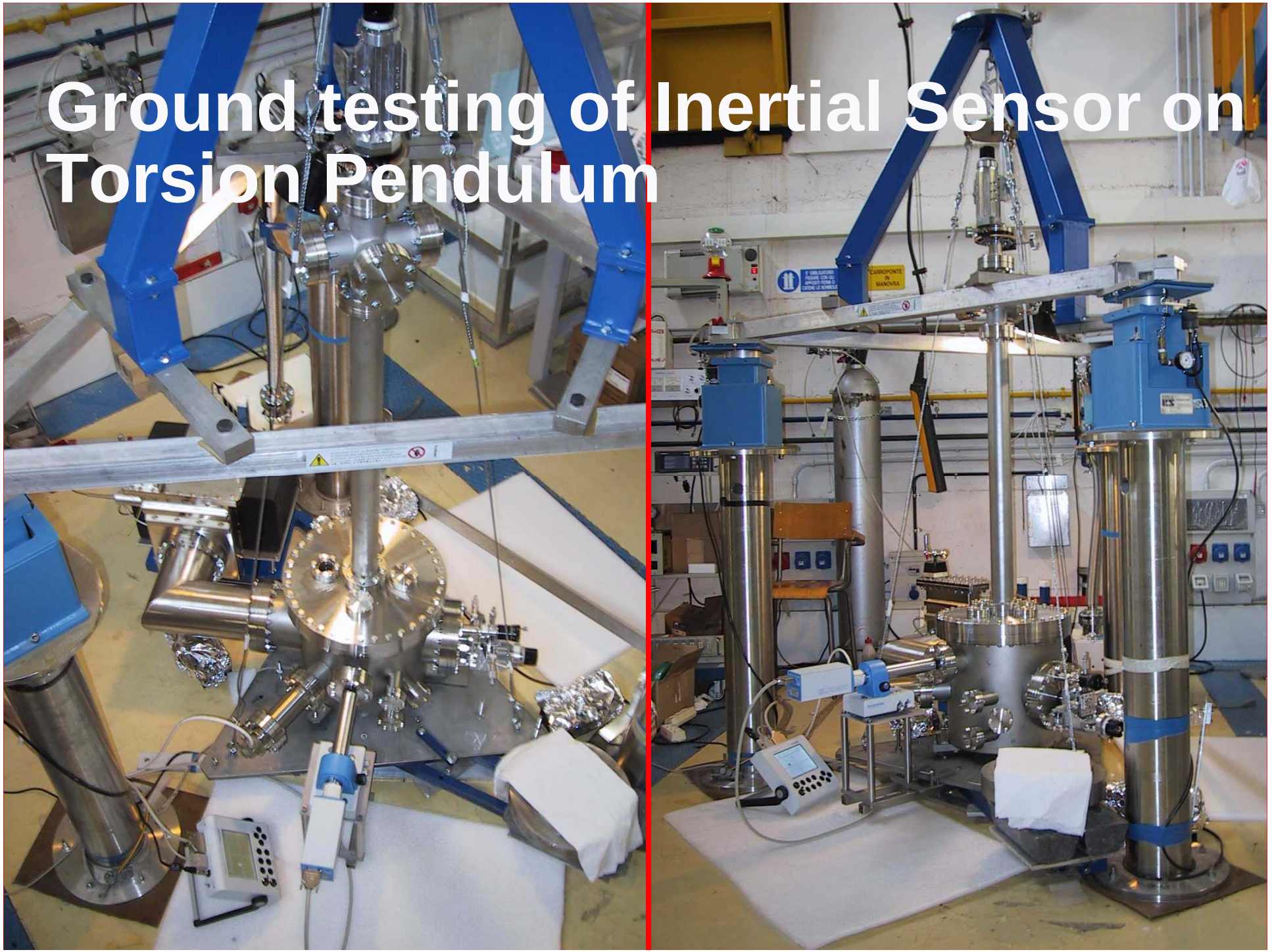
Optical Bench EM Performance

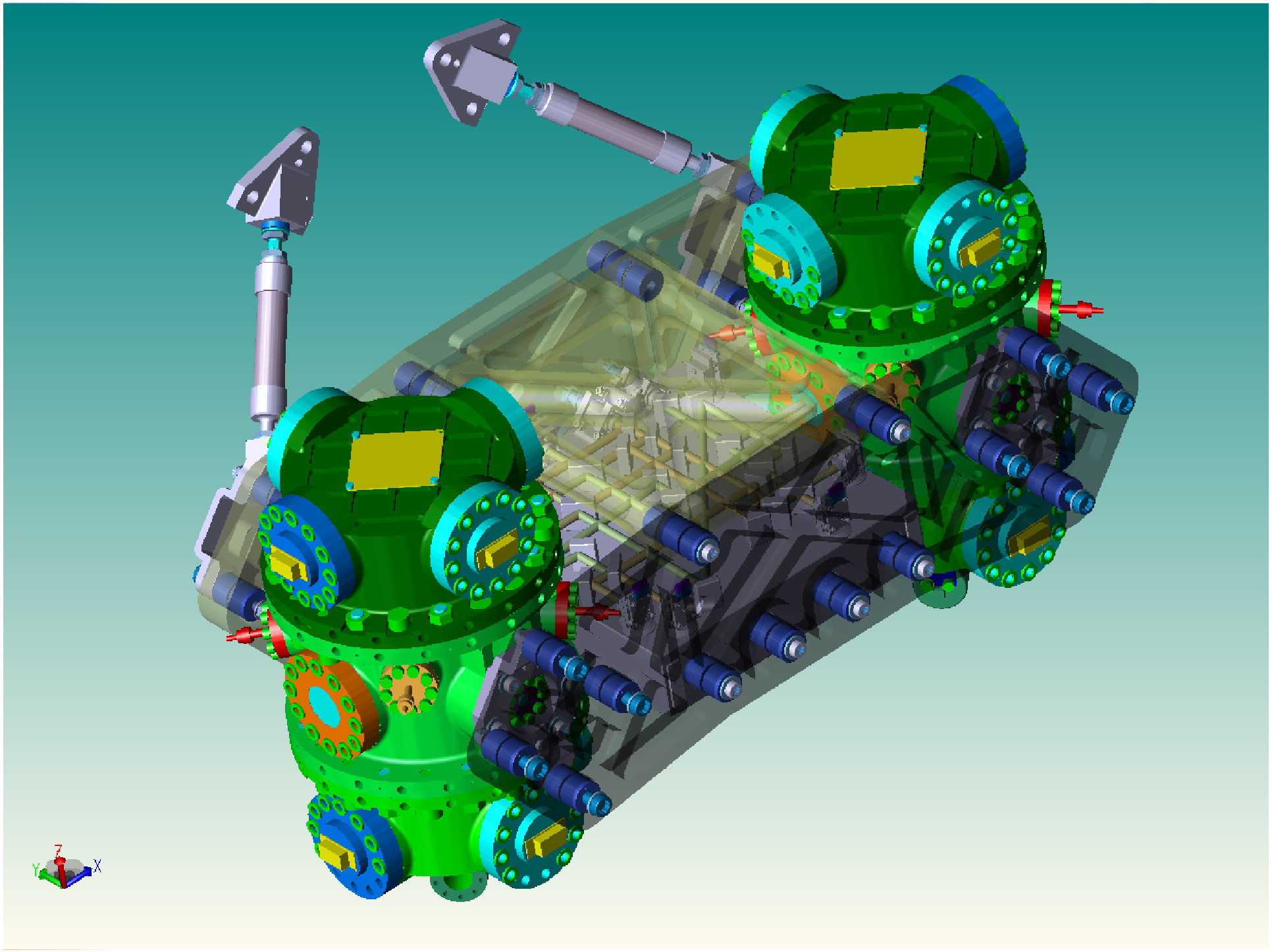


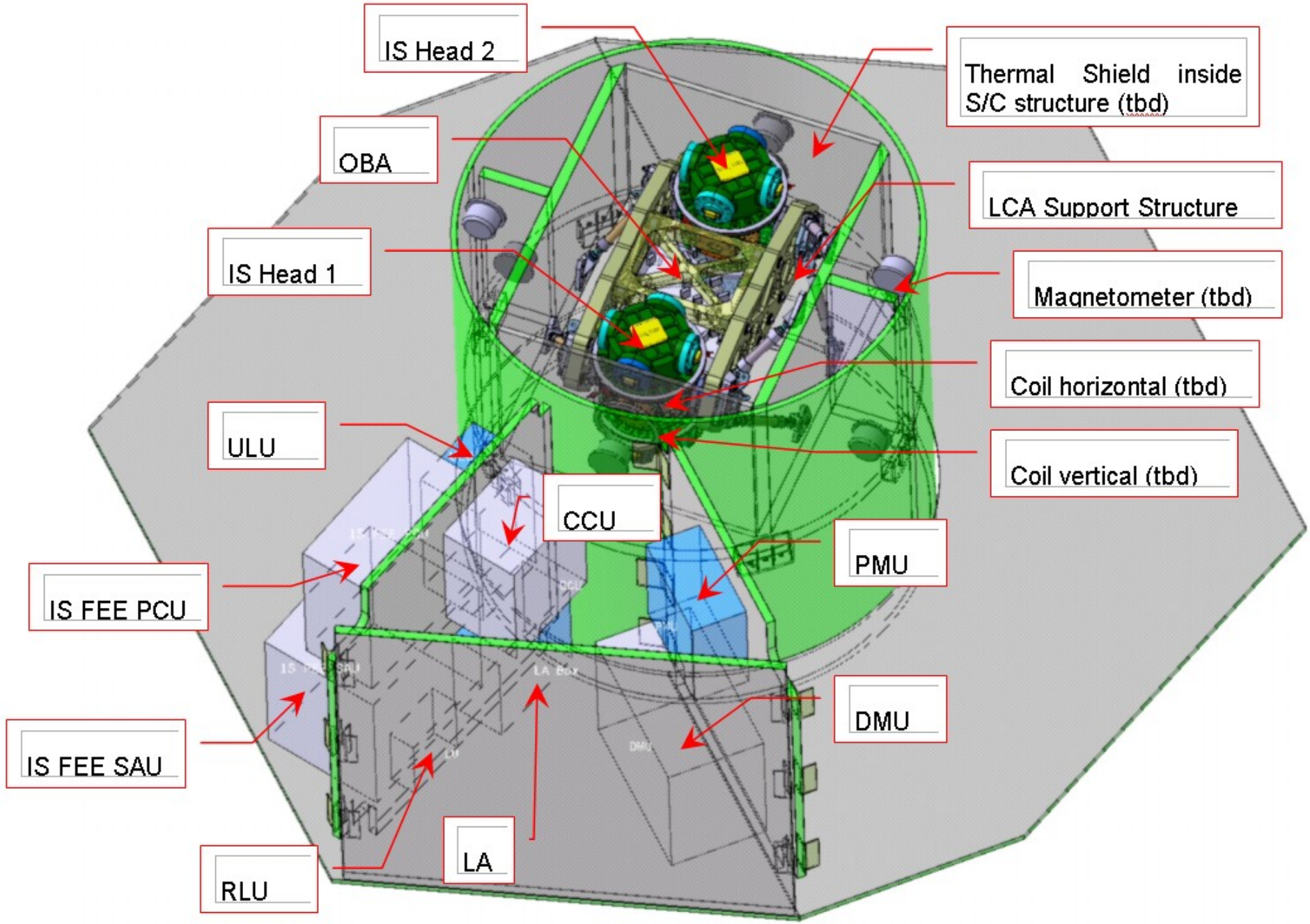



0.10

Ground testing of Inertial Sensor on Torsion Pendulum




Z
Y
X

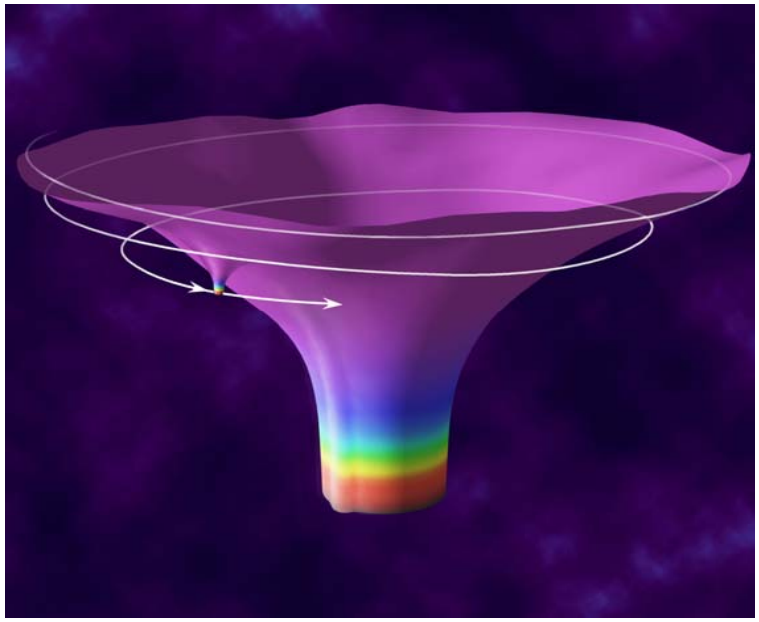


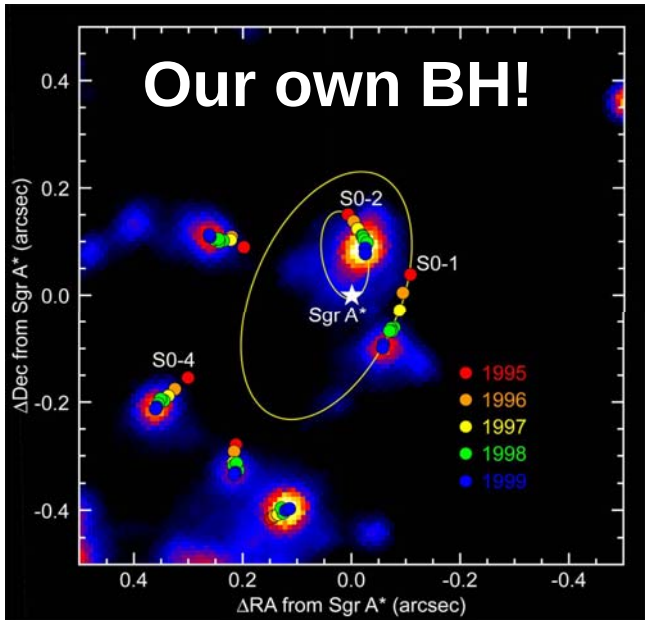
LCA inside S/C with preliminary box accommodation

Operational Orbit: Lagrange Point 1

At the Edge of a Black Hole

- **Capture by Massive Black Holes**
  - Compact object inspiral into massive black hole (MBH),
  - GW map space-time geometry with superb precision
  - Allows tests of many predictions of General Relativity including the “no hair” theorem



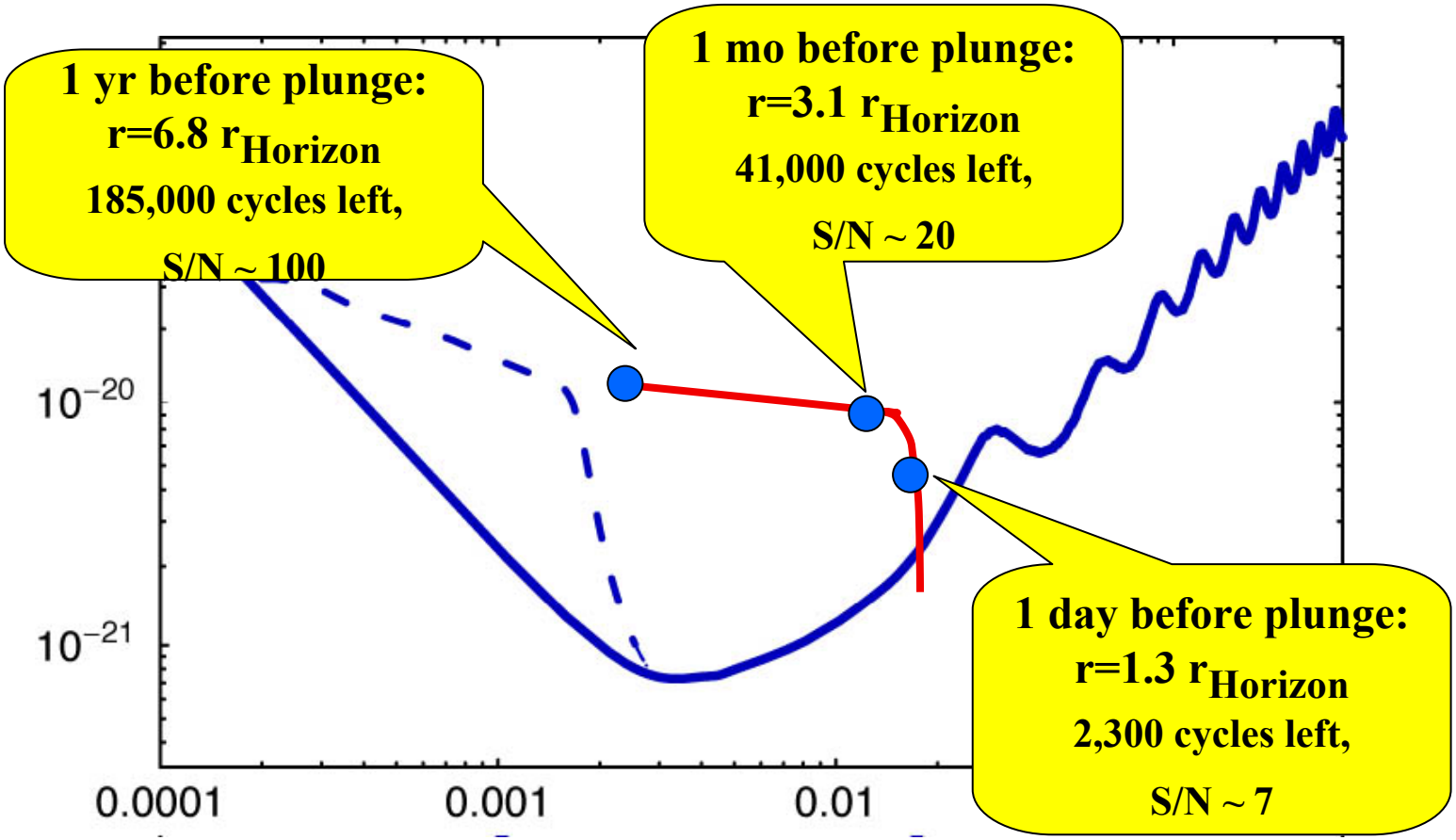


Ghez et al. 1998 ApJ 509, 678, Eckart et al. 2002 MNRAS 331, 917

Precision Bothrodesy (BH Science) with GWs

(Ancient Greek: Bothrod = sacrificial pit, well)

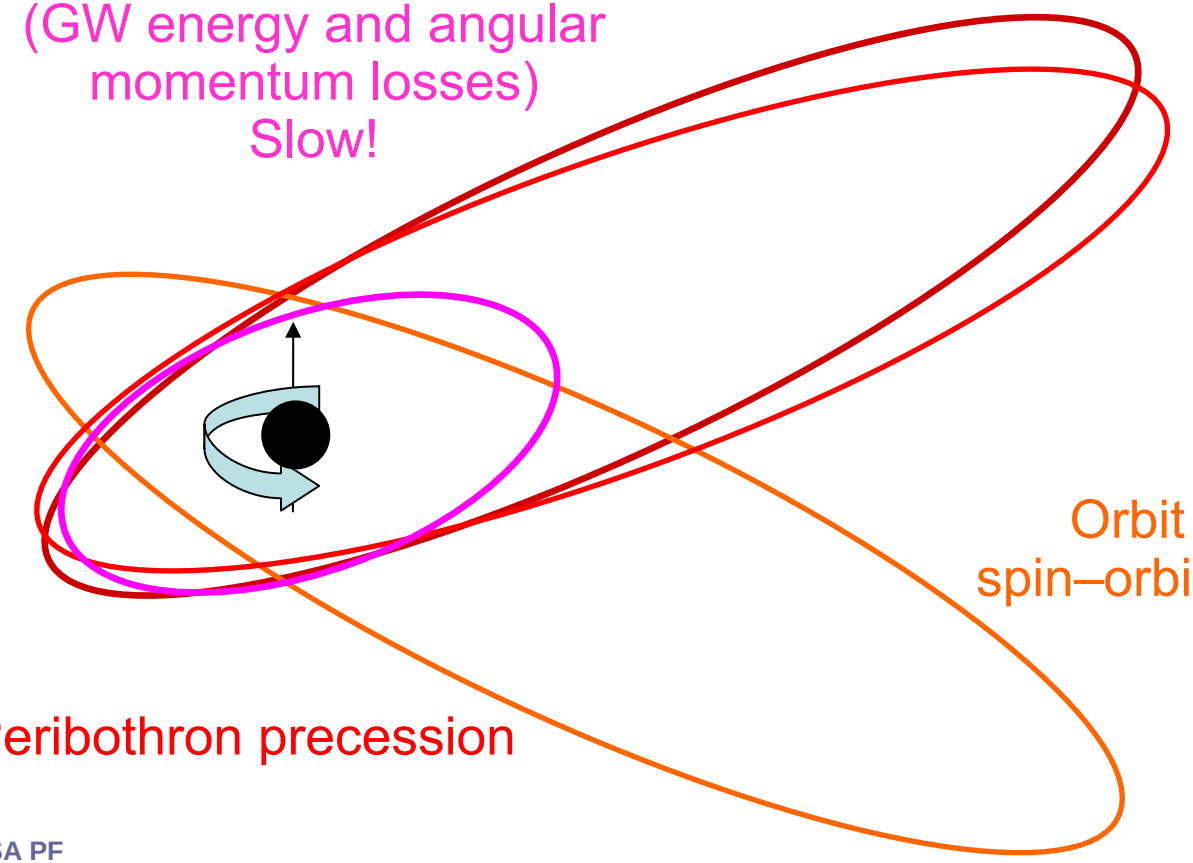
Here: 10 $M_\odot$ BH into 10^6 $M_\odot$ BH; large spin [Phinney,Finn&Thorne]



Orbits and spiral-in of small bodies around spinning Black Holes

(Extreme Mass Ratio Inspirals, EMRIs)

Spiral-in and Circularization
(GW energy and angular momentum losses)
Slow!



Orbit plane precession
spin–orbit; L-T(Lense-Thirring)

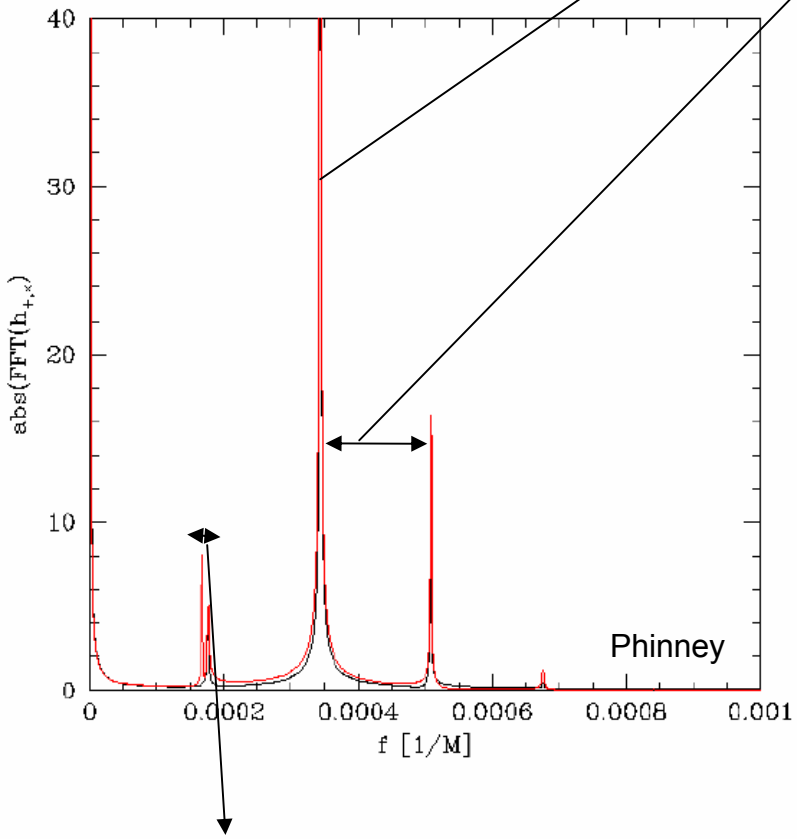
Peribothron precession

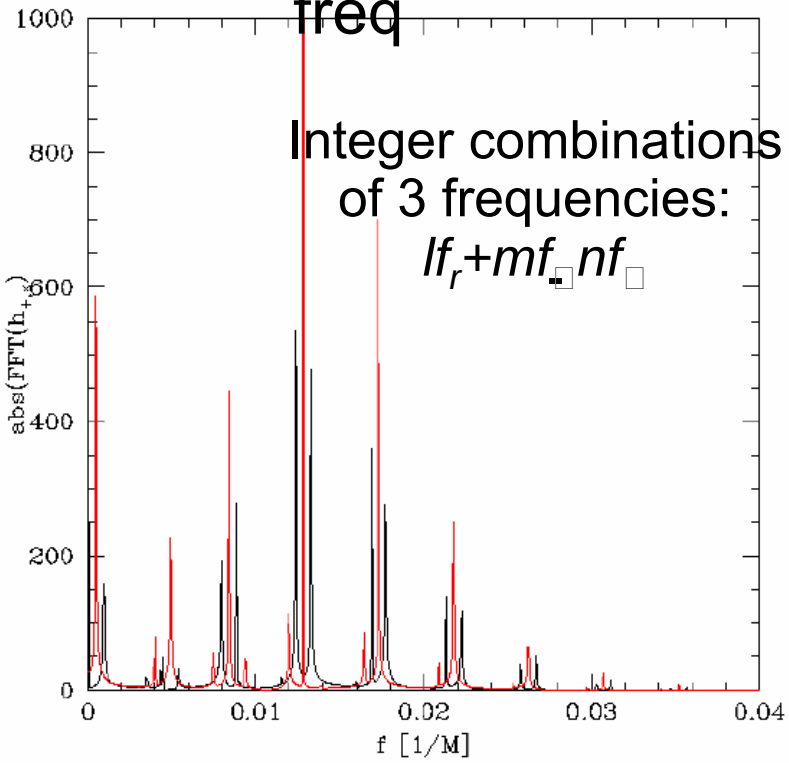
Signal from EMRIs

a=100M, e=0.05, i=45

2x orbital freq

Peribothron precession freq



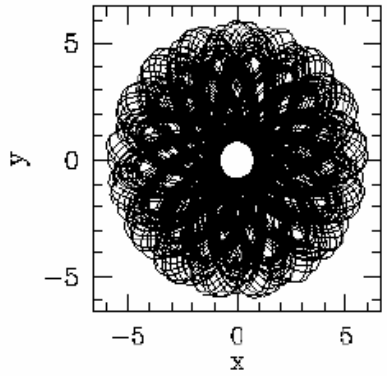


Integer combinations of 3 frequencies: $lf_r+mf_{\square}nf_{\square}$

a=10M, e=0.2, i=45

L-T orbit plane precession freq

Signal from



Frequencies s
and shift slowl
compact objec
mapping spac
the horizon.

⇒ *Like a Geoc*

⇒ *GRACE for*

esa

D/SCI/SV/val/20105

Paris, 4 May 2005

Letter of Intent to participate in the LISA data processing study

Dear Colleagues,

LISA (Laser Interferometer Space Antenna) is a collaborative ESA/NASA mission to detect and observe gravitational waves with a launch currently foreseen in the timeframe of 2012/2013. LISA will interferometrically measure the changes in distance between free-falling proof masses that are due to gravitational waves. More details of the LISA mission can be found on http://lisa.esa.int.

To extract the astrophysical parameters of the sources, a substantial effort in data analysis is necessary. Therefore, ESA intends to carry out a study of the data analysis requirements and planning in support of the ongoing Mission Formulation phase for LISA. The objectives of the study include the following tasks:

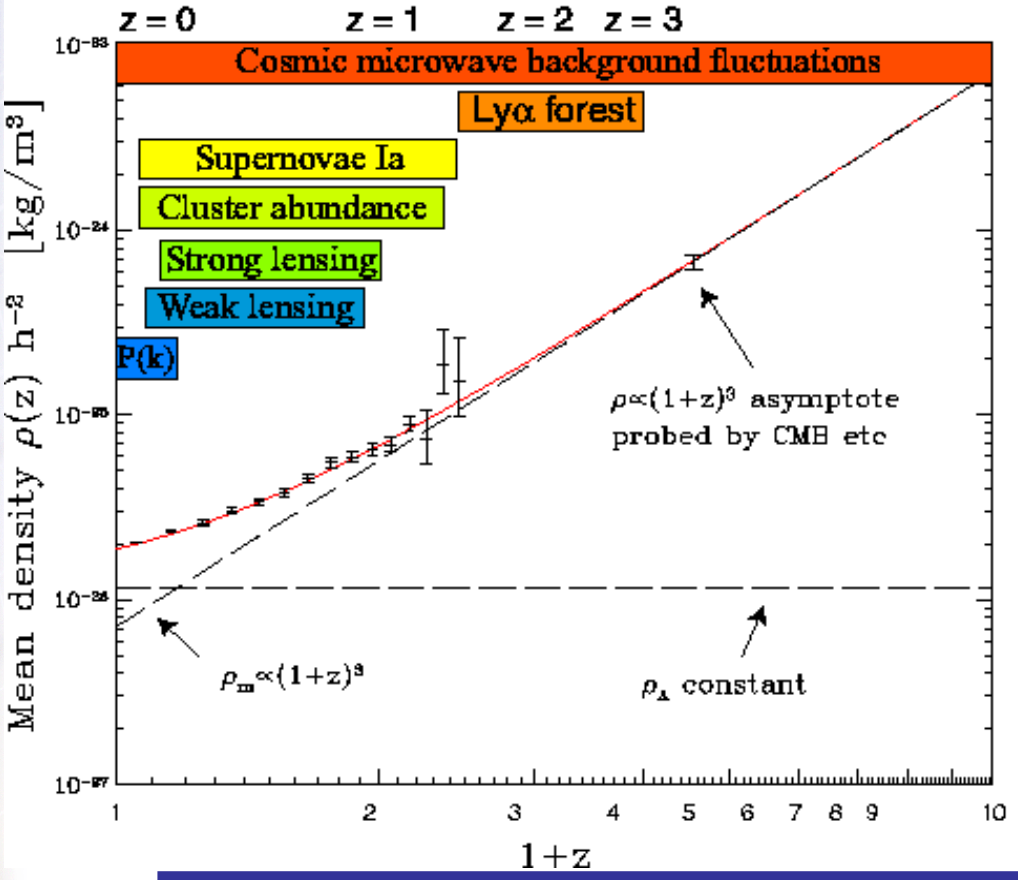
- To identify and prioritize the areas of data analysis, astrophysics, and physics that still require investment in research.
- To formulate requirements on the data that will be returned from the spacecraft, including types of data, data rates, and continuity.
- To assess the viability of existing algorithms for data analysis.
- To develop algorithms able to meet the core science goals and formulate a plan for further software development.
- To issue data format specifications.
- To define the architecture of the data analysis hardware and software. This includes an assessment of hard- and software necessary as well as studying the implications on hardware location and the infrastructure.

Extreme Mass Ratio Inspiral (EMRI)

- **Fundamental Physics Science Goals**
  - Relativity
    - Precision Bothrodesy: Map the central SMBH's spacetime geometry, i.e. measure its multipole moments
      - Do Black Holes really have no hair?
    - Search for massive central bodies that are not BH's
      - Are there soliton stars or naked singularities?
    - Measure response of central body (SMBH?) to tidal gravity of orbiting object
      - How does dynamic strong field gravity work?

Dark Energy

Measuring the expansion history of the Universe:



Effect of dark energy becomes apparent at late times

Expansion passes from decelerating to accelerating at z ~ 1

Effective density asymptotes to vacuum contribution

Dark Energy is apparent at z < 3

Binary Black Hole Coalescences can be used as Standard Candles to complement the Ia Supernova distance scale!

Mergers of Massive Black Holes

- Coalescing Supermassive Binary Black Holes at z=1 give amplitude signal-to-noise of 1000 or more
- Standard Candles at cosmological distances
- Provide precision distance scale independent of electromagnetic observations

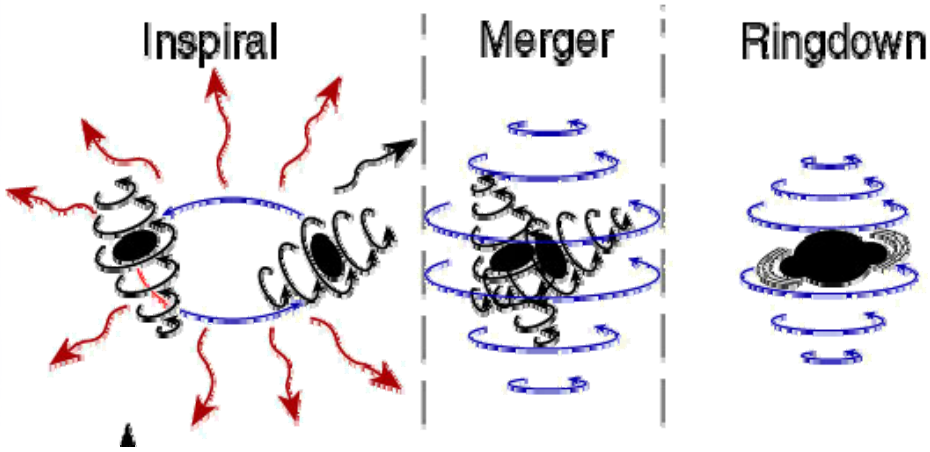
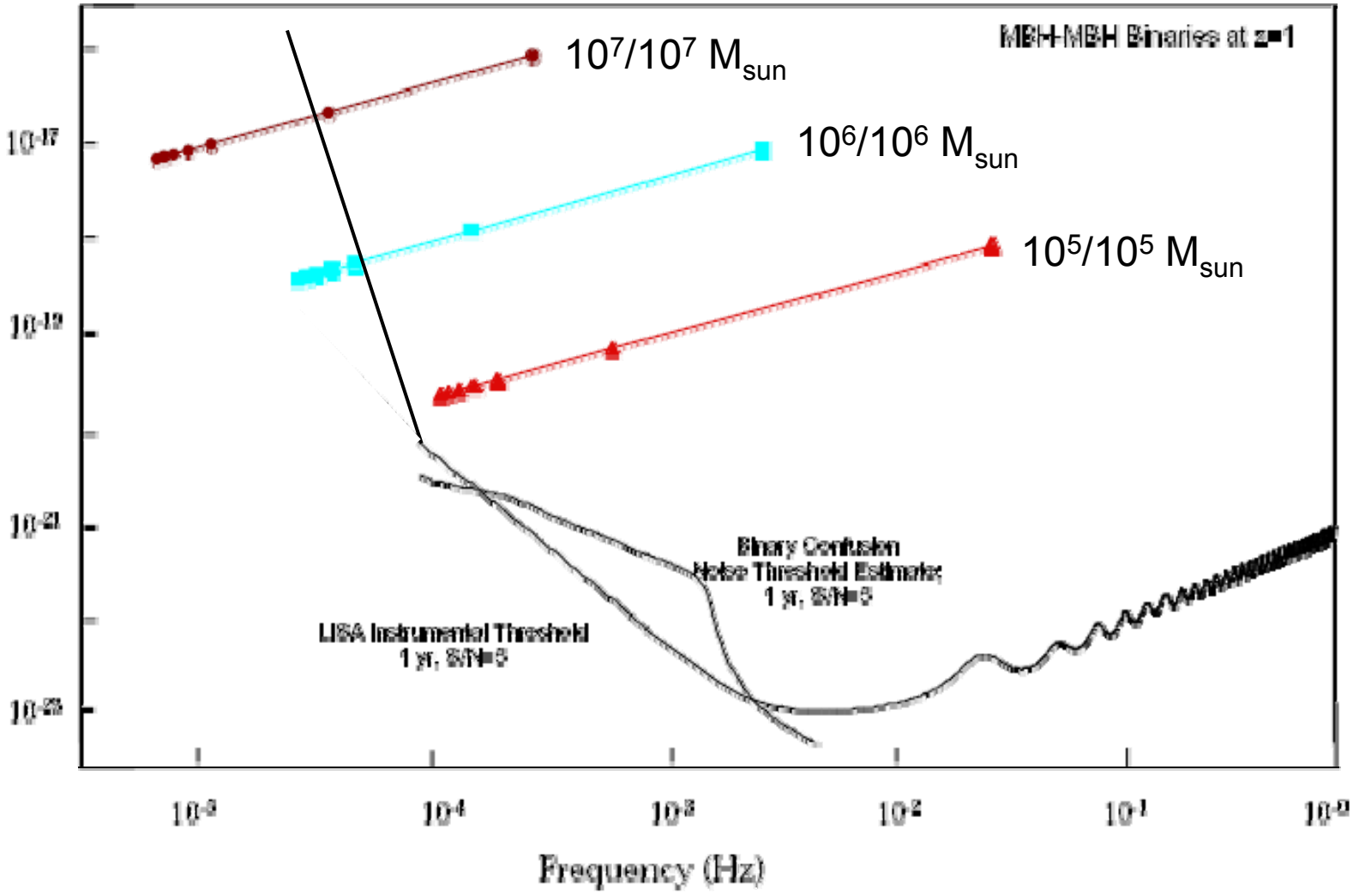
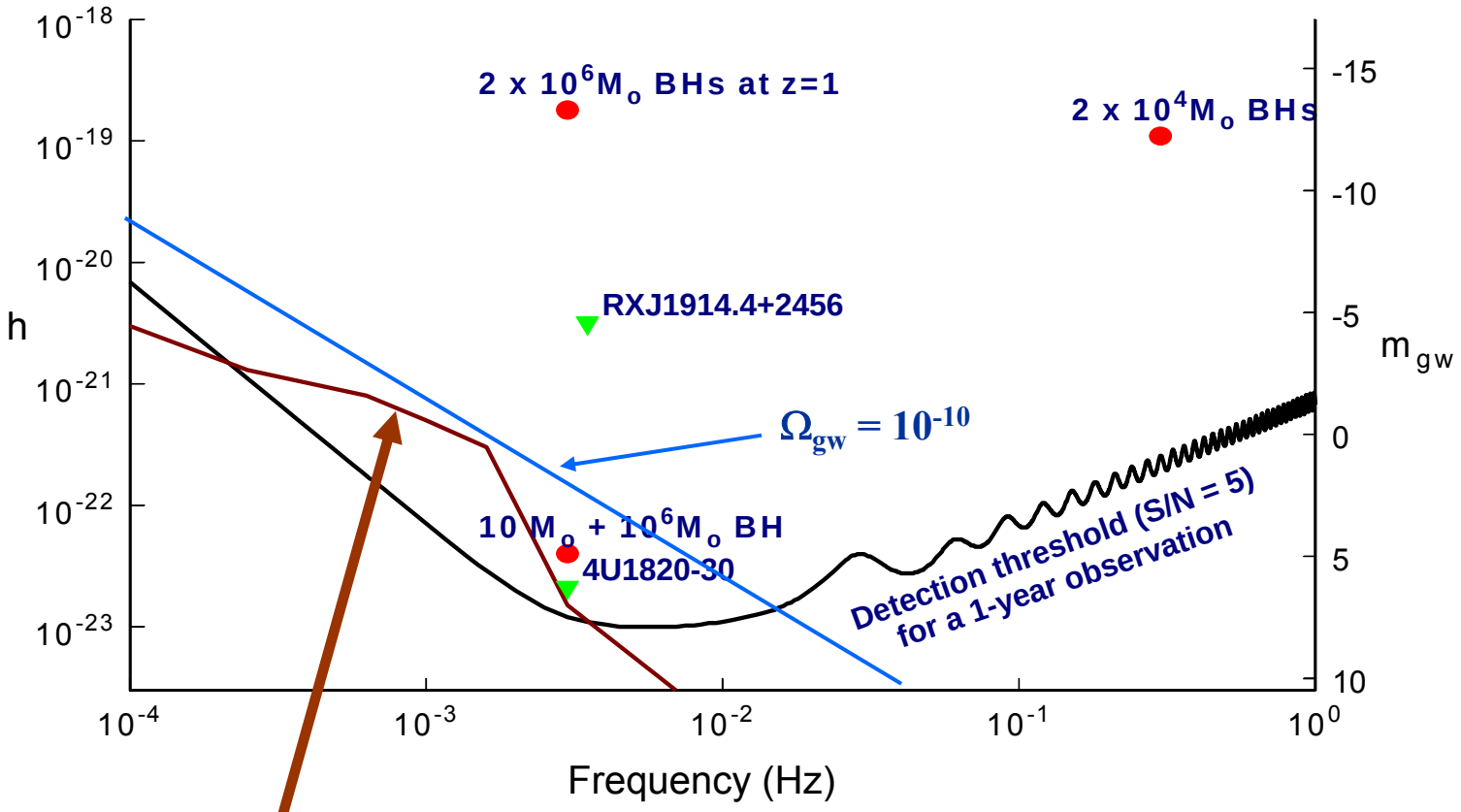


Image by B. Whitmore (STSci), F. Schweizer (DTM), NASA

Evolution of SMBH binaries



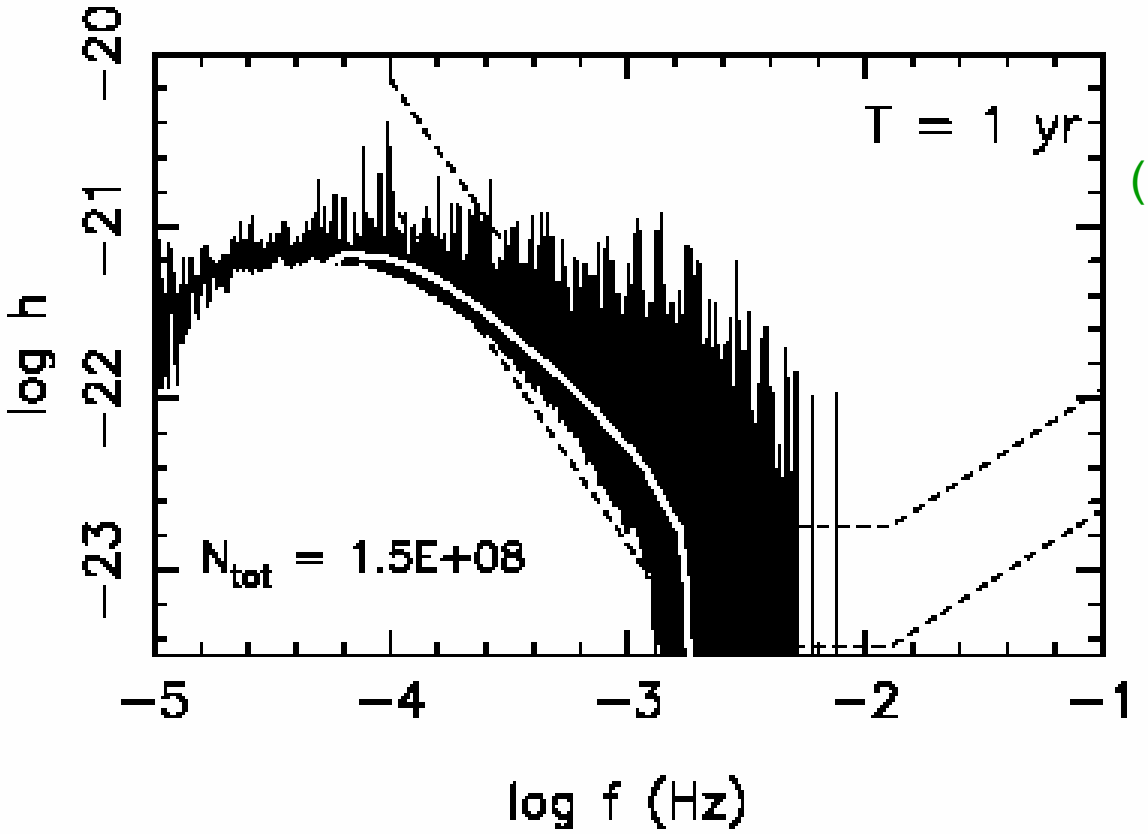
LISA Sensitivity and Primordial GWs



WD Binary confusion limit

(from Schutz)

Binary Confusion Limit



(Nelemans et al, 2001)

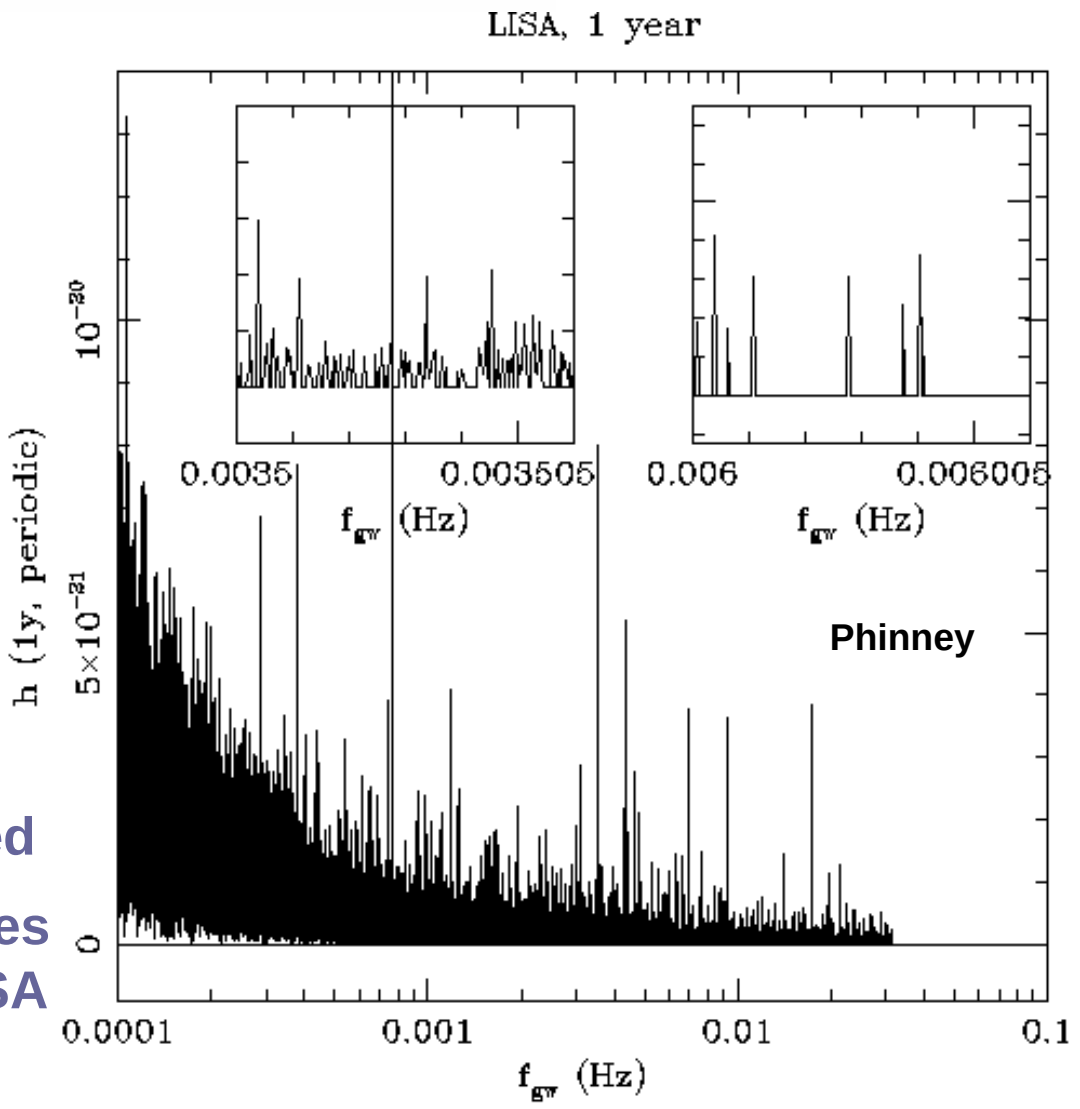
- LISA is expected to provide the largest observational sample of white dwarfs (WDs)
- Very large number in frequency space

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

Galactic WD (/NS) binaries

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

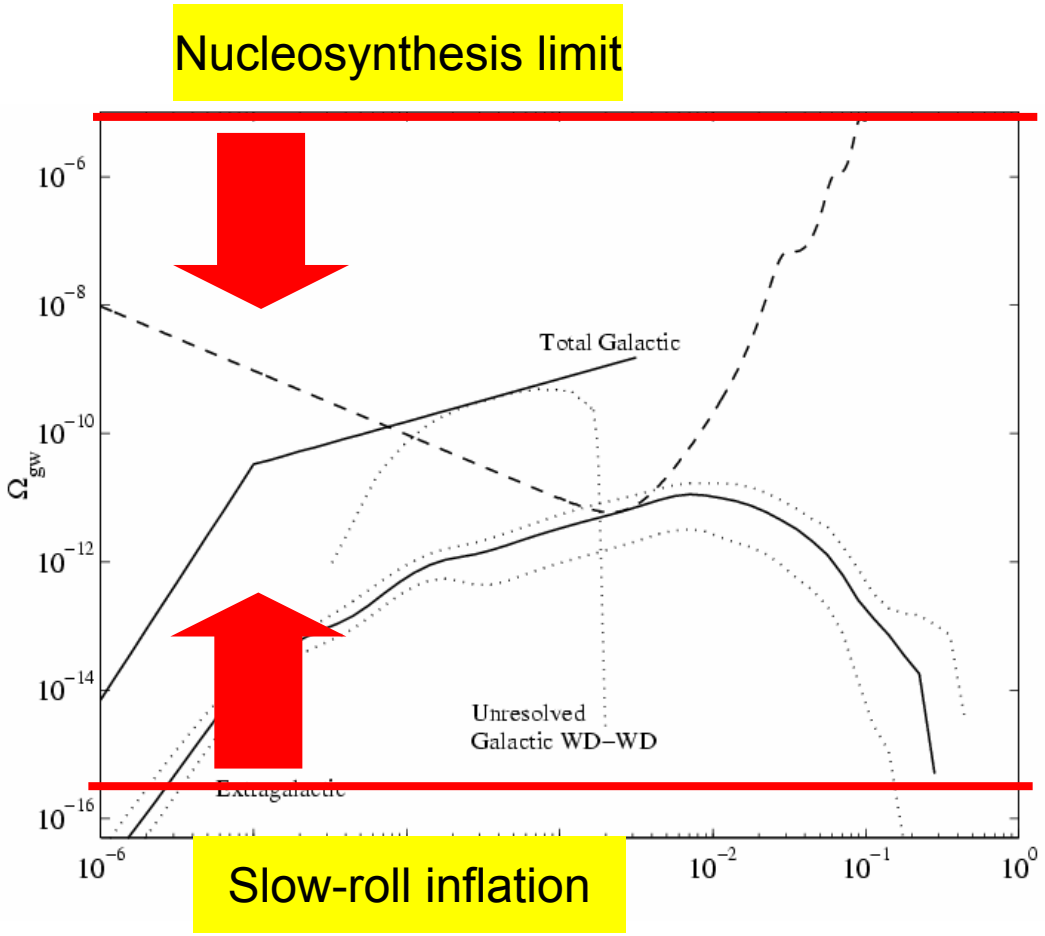
(Nelemans et al, 2001, 2002)



- **Above 3 mHz individual WD binaries are resolved**
- **Below 3 mHz WD binaries give background for LISA**

Primordial GW Background

- Slow-roll inflation probably not detectable by LISA
  - The sky is too bright
    - Ungarelli and Vecchio, 2001
- Speculative models, but exciting
  - First-order phase transitions $\Omega \sim 10^{-11}$
    - Apreda et al, 2001
  - Extra-dimensions, may be up to $\Omega \sim 10^{-7}$
    - Hogan, 2000
  - Kinks/Cusps in cosmic strings, $\Omega \sim 10^{-10}$
    - Damour and Vilenkin, 2000



Primordial Gravitational Waves

- **Production: Fundamental Physics in early Universe**
  - Inflation, phase transitions, topological defects, brane-worlds, strings
- **Non-thermal spectrum gives energies and masses**
- **GW density expressed as fraction of closure density**
- **Poorly constrained** $10^{-14} \approx \Omega_{gw} < 10^{-5}$

Simple Inflation (max.)

Nucleosynthesis Bound

LISA sees $\Omega_{gw} > 10^{-11}$

Covers 6 out of 9 orders of magnitude!

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Critical decisions on Cosmic Vision

7 November 2003

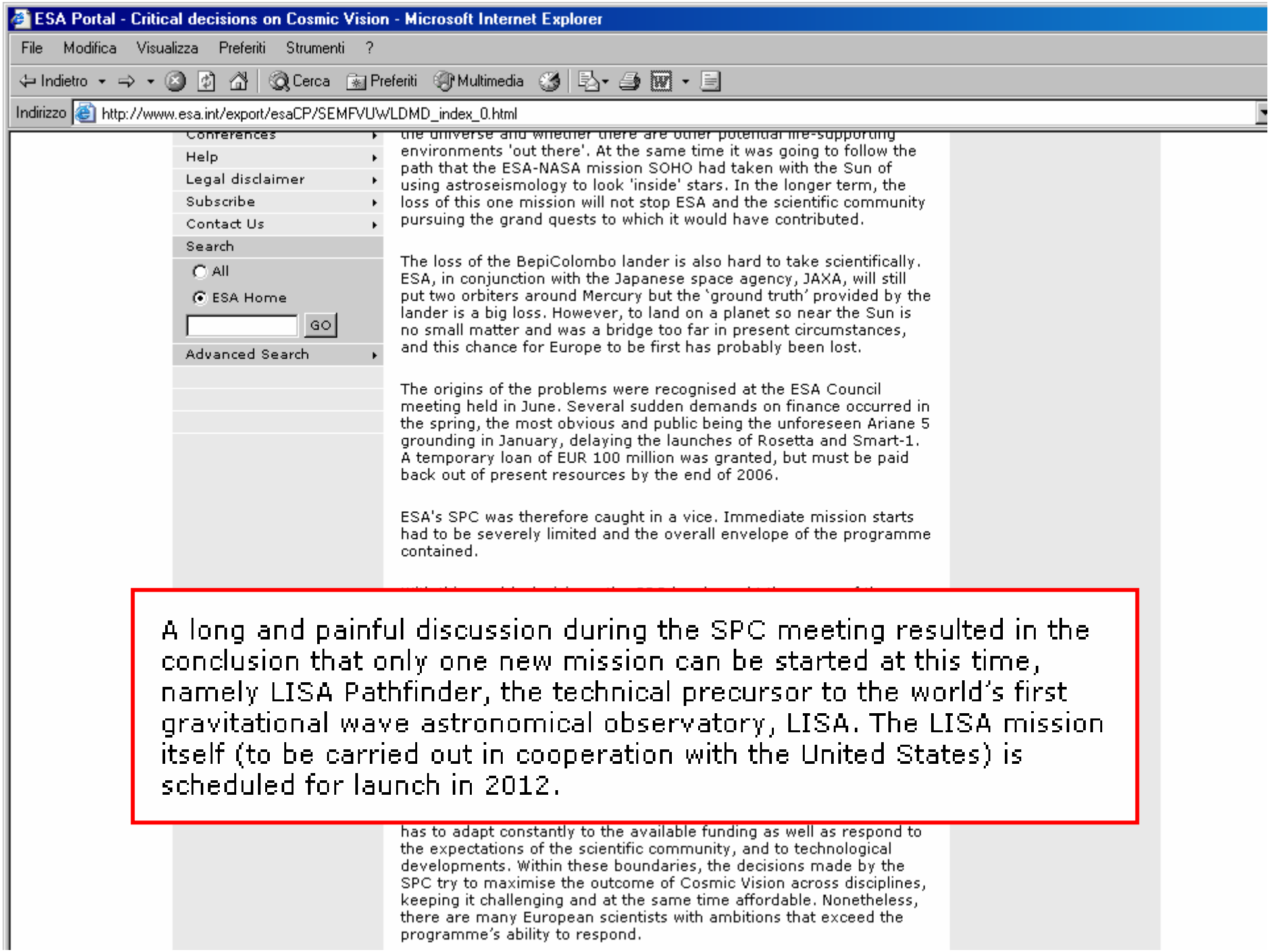
ESA PR 75-2003. At its 105th meeting, on 5/6 November, ESA's Science Programme Committee (SPC) made important decisions concerning the Cosmic Vision programme. Due to the current financial exigencies and an outlook with no budget increase or other relief, the SPC was forced to cancel the Eddington mission and rescope the BepiColombo mission.

Eddington had two aims, both remarkable and very pertinent to front-line astronomical interests. The first was to look for Earth-like planets outside our solar system - one of the key goals in the search to understand how life came to be, how it is that we live where we do in the universe and whether there are other potential life-supporting environments 'out there'. At the same time it was going to follow the path that the ESA-NASA mission SOHO had taken with the Sun of using astroseismology to look 'inside' stars. In the longer term, the loss of this one mission will not stop ESA and the scientific community pursuing the grand quests to which it would have contributed.

The loss of the BepiColombo lander is also hard to take scientifically. ESA, in conjunction with the Japanese space agency, JAXA, will still put two orbiters around Mercury but the 'ground truth' provided by the lander is a big loss. However, to land on a planet so near the Sun is no small matter and was a bridge too far in present circumstances, and this chance for Europe to be first has probably been lost.

The origins of the problems were recognised at the ESA Council meeting held in June. Several sudden demands on finance occurred in the spring, the most obvious and public being the unforeseen Ariane 5 grounding in January, delaying the launches of Rosetta and Smart-1. A temporary loan of EUR 100 million was granted, but must be paid back out of present resources by the end of 2006.

Related links
- ESA Science
- Eddington overview
- Bepicolombo overview
- LISA overview


ESA Portal - Critical decisions on Cosmic Vision - Microsoft Internet Explorer
File Modifica Visualizza Preferiti Strumenti ?
Indietro Cerca Preferiti Multimedia
Indirizzo http://www.esa.int/export/esaCP/SEMFVUWLDMD_index_0.html
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ESA's SPC was therefore caught in a vice. Immediate mission starts had to be severely limited and the overall envelope of the programme contained.
A long and painful discussion during the SPC meeting resulted in the conclusion that only one new mission can be started at this time, namely LISA Pathfinder, the technical precursor to the world's first gravitational wave astronomical observatory, LISA. The LISA mission itself (to be carried out in cooperation with the United States) is scheduled for launch in 2012.
has to adapt constantly to the available funding as well as respond to the expectations of the scientific community, and to technological developments. Within these boundaries, the decisions made by the SPC try to maximise the outcome of Cosmic Vision across disciplines, keeping it challenging and at the same time affordable. Nonetheless, there are many European scientists with ambitions that exceed the programme's ability to respond.