Listening to the Universe with Gravitational Waves!

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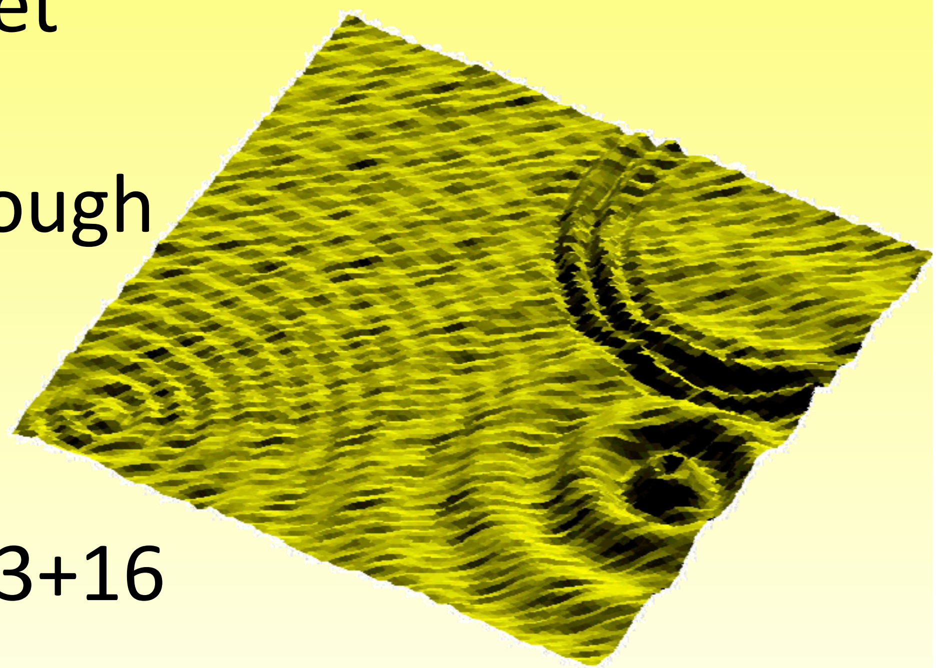
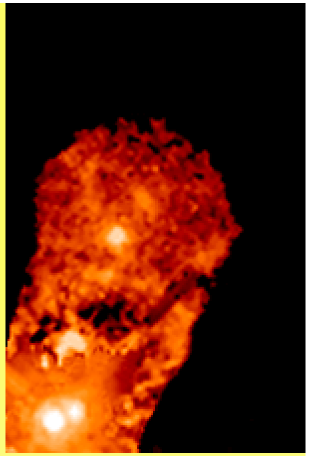
Gravitational Waves

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

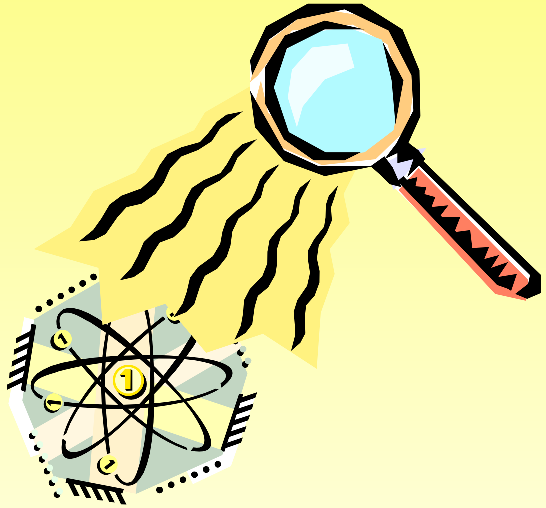


The Effect is small!



- Supernova in local group of galaxies

$\Rightarrow$ Squeezing of space by 10^{-21}

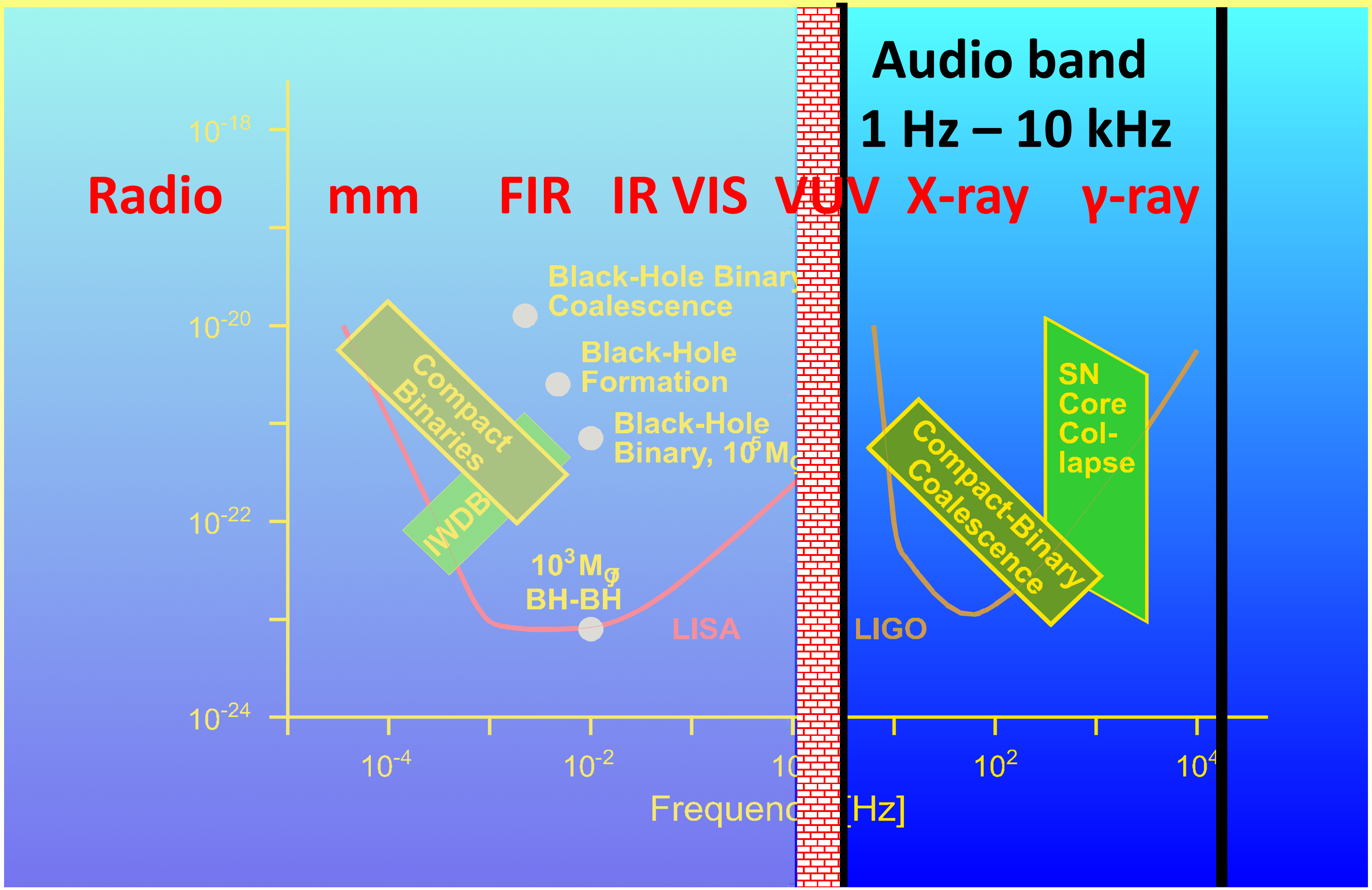


$\Rightarrow$ 1 km baseline changes by 1/1000 of a Proton diameter (10^{-18} m = 1 Attometer)!

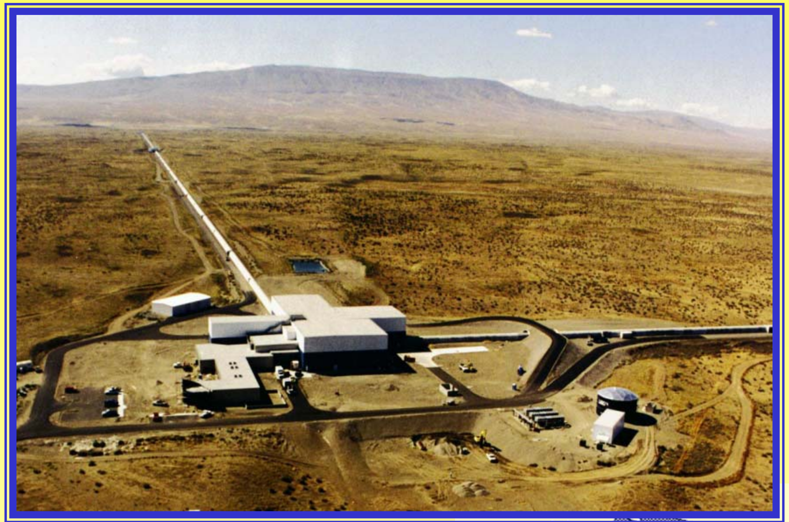
$\Rightarrow$ For a few milliseconds!

Gravitational Wave Sources

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



LIGO: Two Sites, Three Ifos

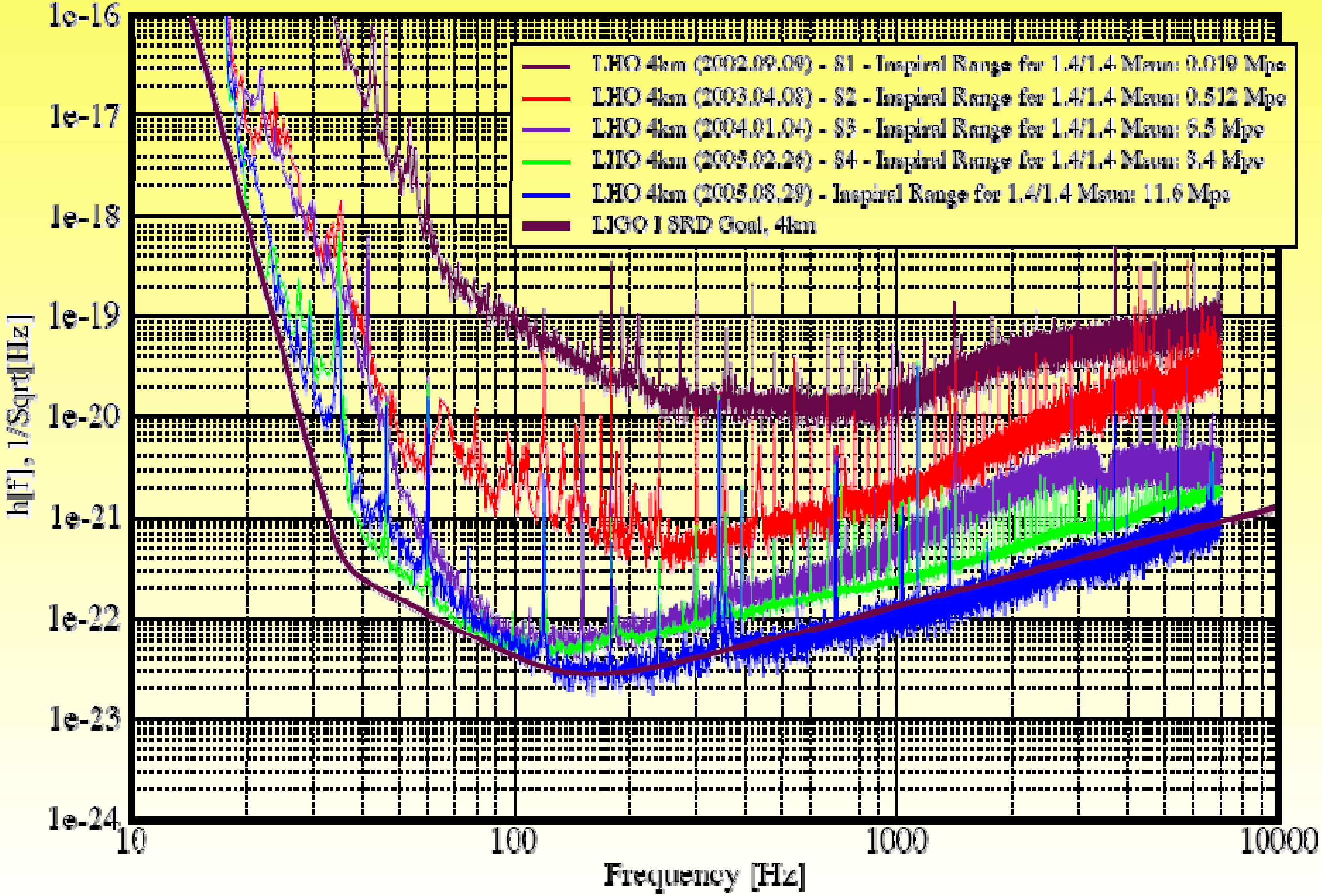


One interferometer with 4 km Arms, one with 2 km Arms

One interferometer with 4 km Arms

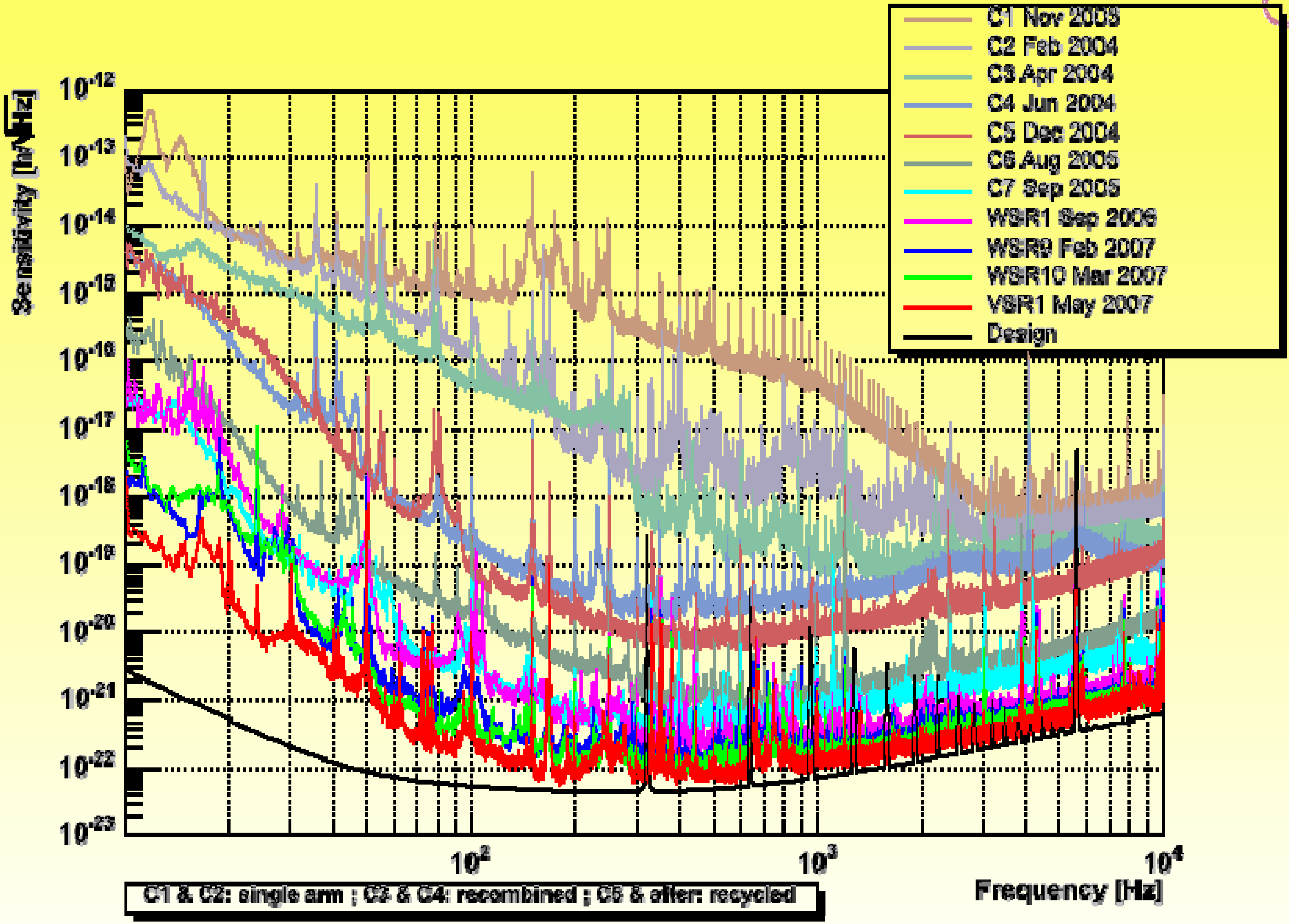
LIGO Sensitivity History

Science Runs S1 to S5



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

Progress of Virgo Sensitivity

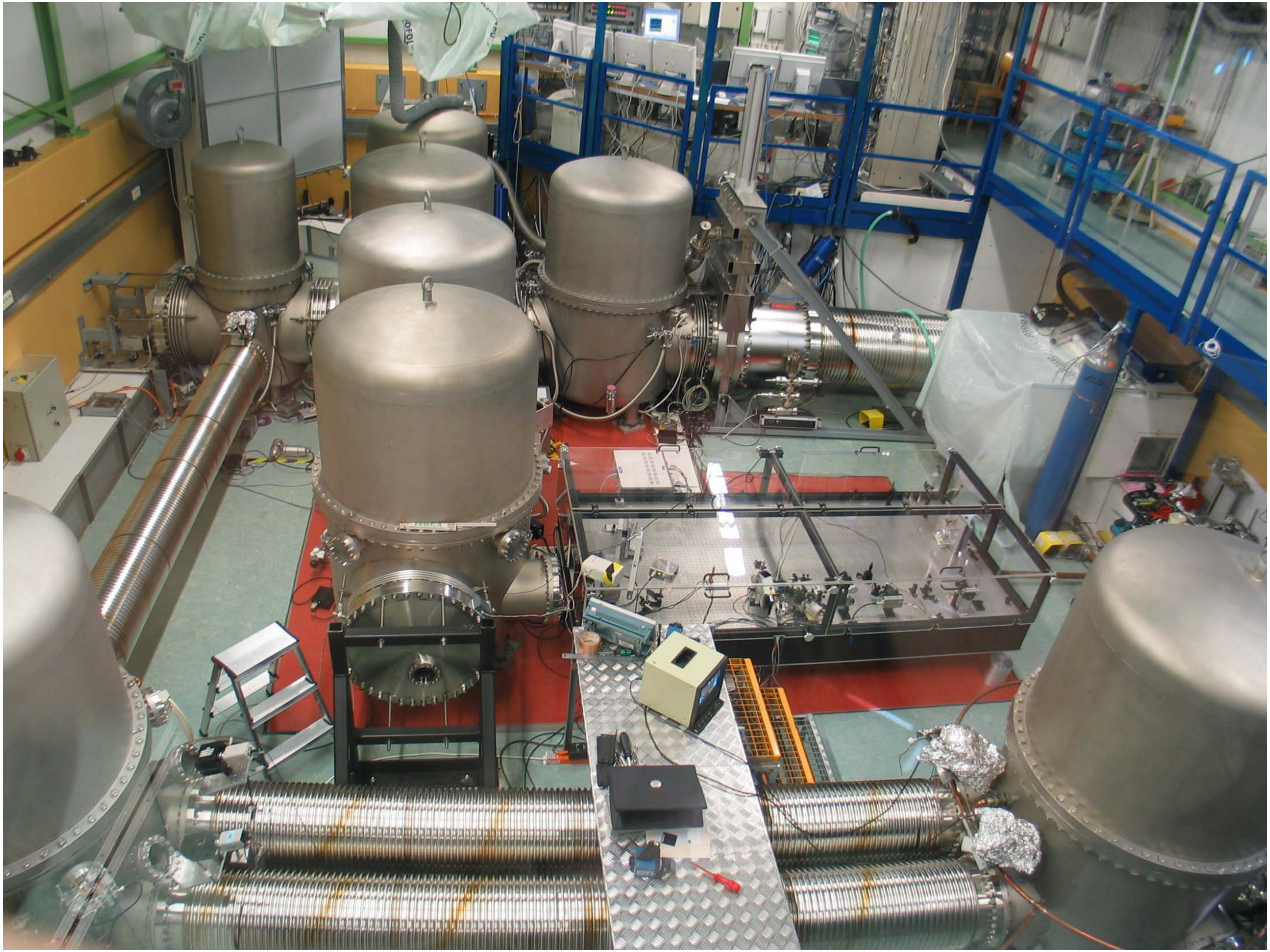


The GEO600 Project

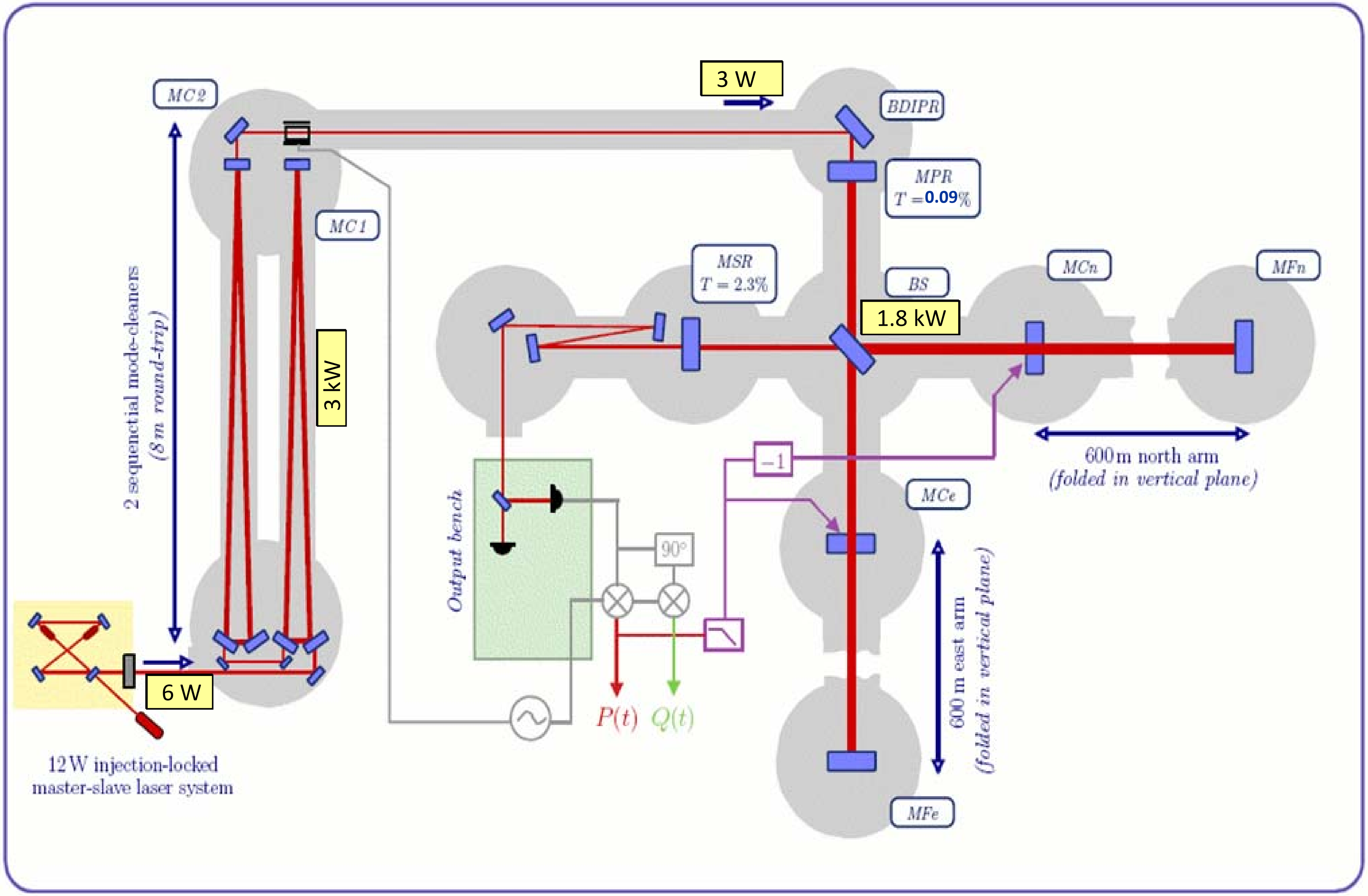
- German-British collaboration, location Hannover / Germany
- Michelson Interferometer with power- and signal-recycling (folded 600m long arms, no armcavities)

U Birmingham
U Mallorca

Glasgow

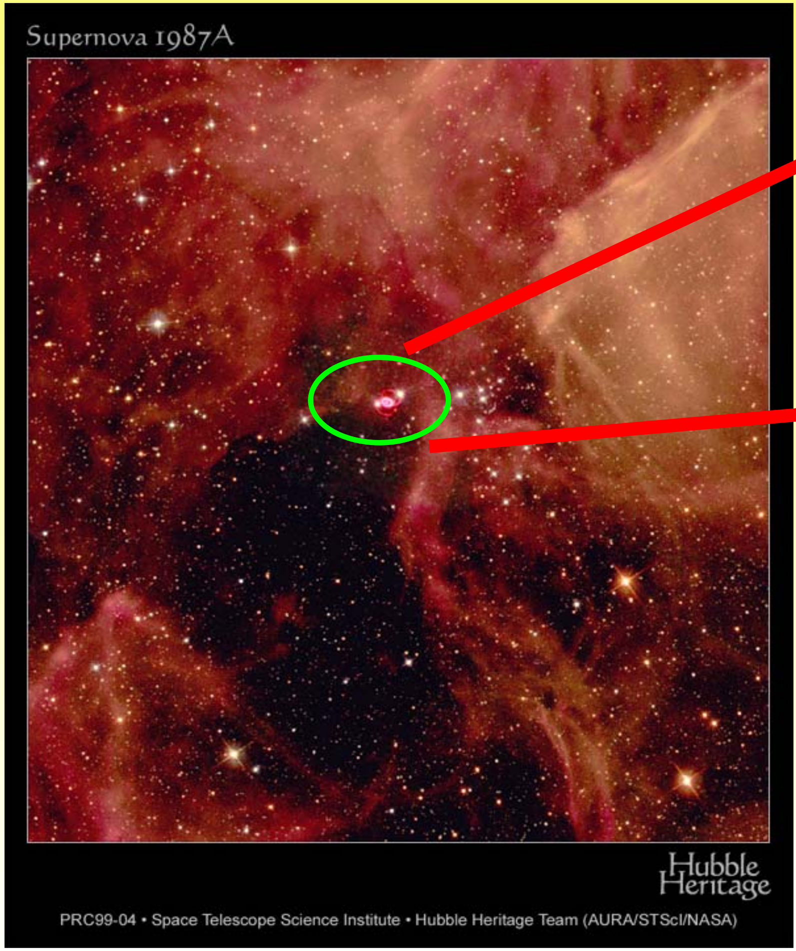


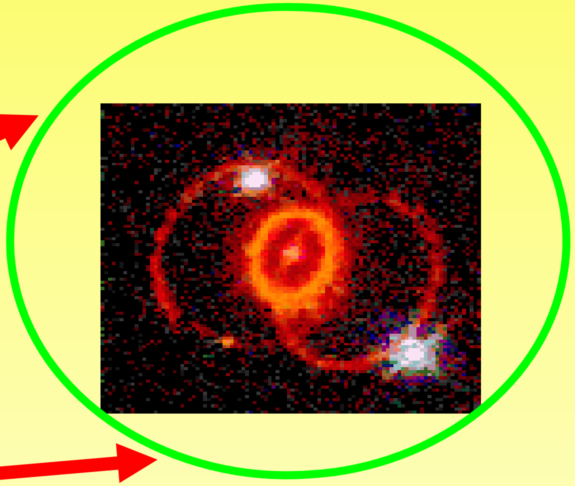
GEO600 Speciality: Signal Recycling

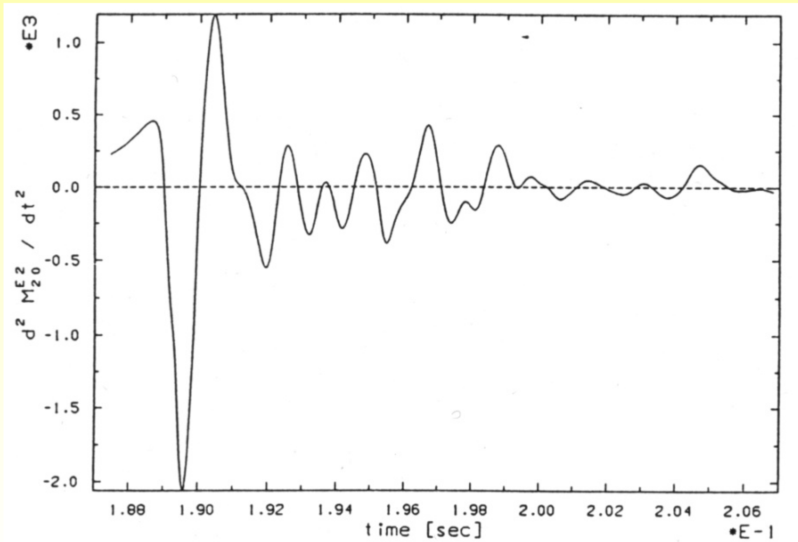


Sources for Ground-Based Detectors

- Supernovae

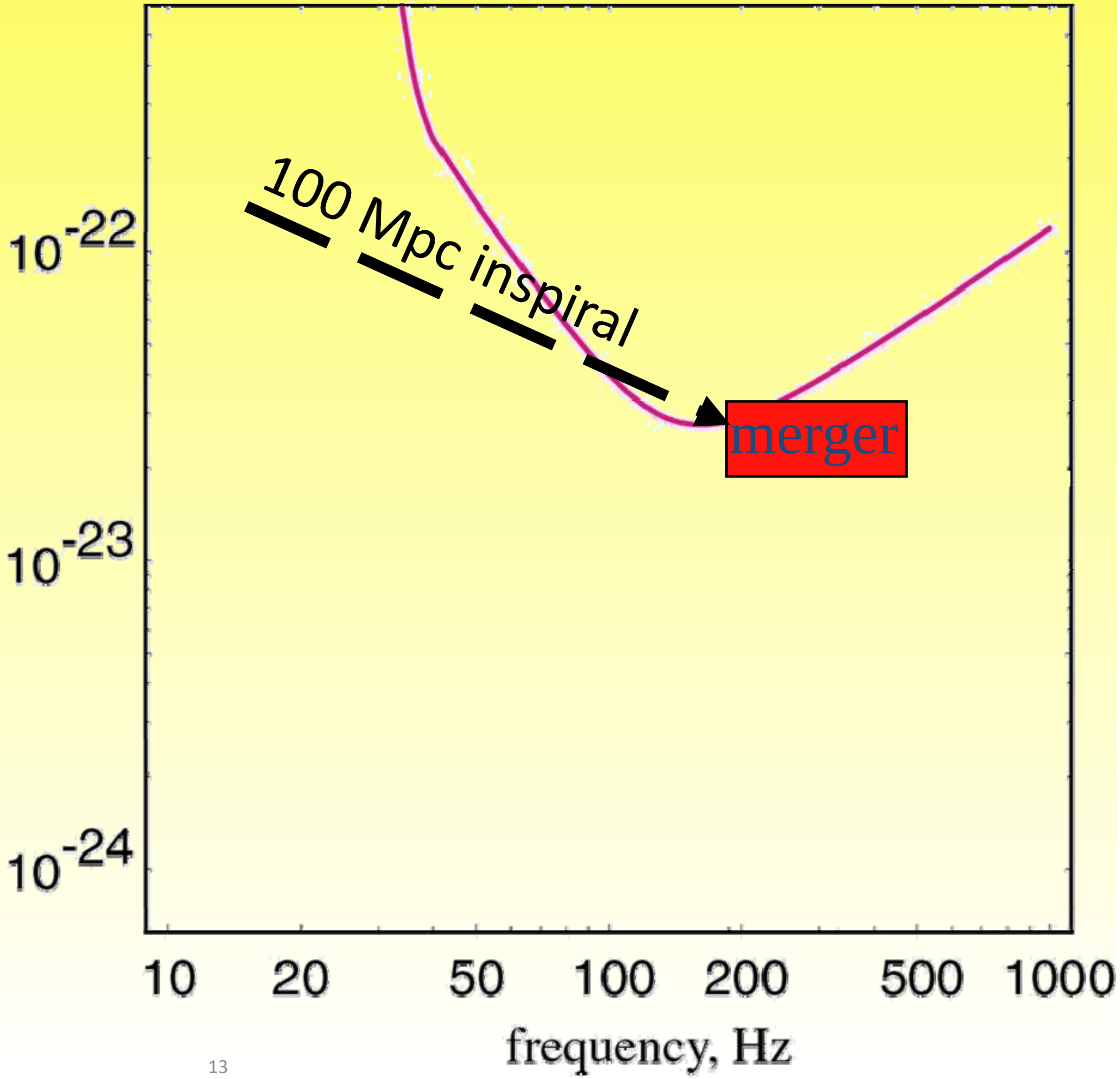






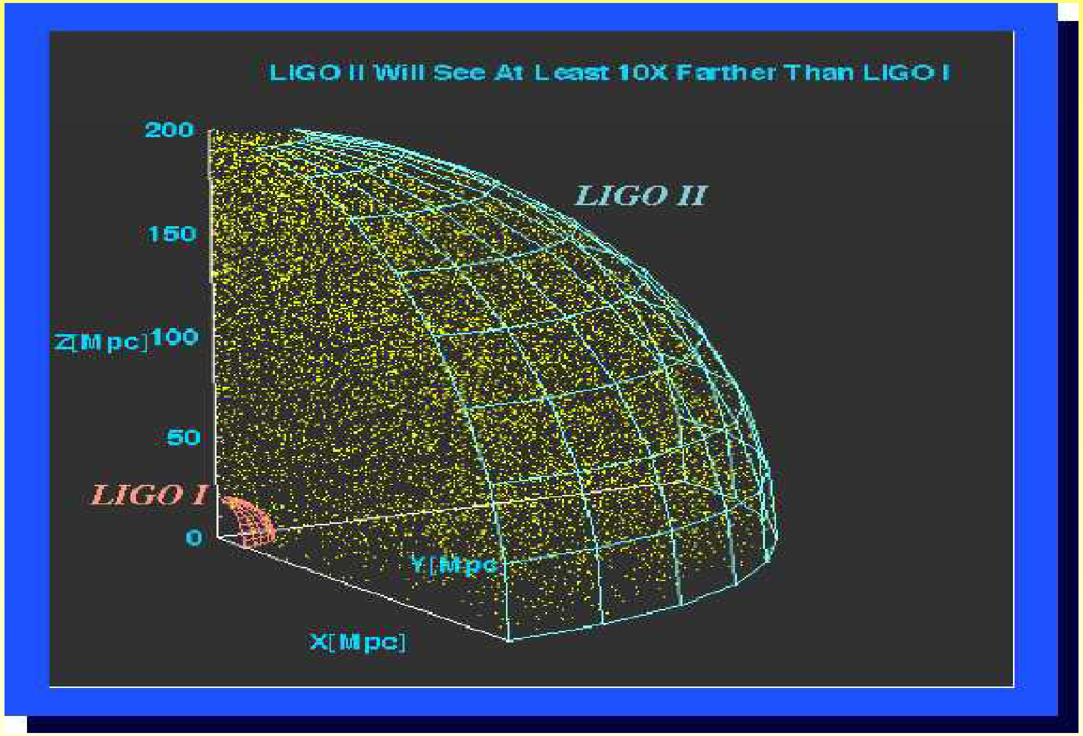
Present Sensitivity (S5)

- 10 M_{sun} - 10 M_{sun} BH - BH binaries
- Event rates
  - Based on population synthesis [Kalogera's summary of literature]
- Initial IFO event rates
  - Range: 100 Mpc
  - 1 / 600yrs to **~3/yr**



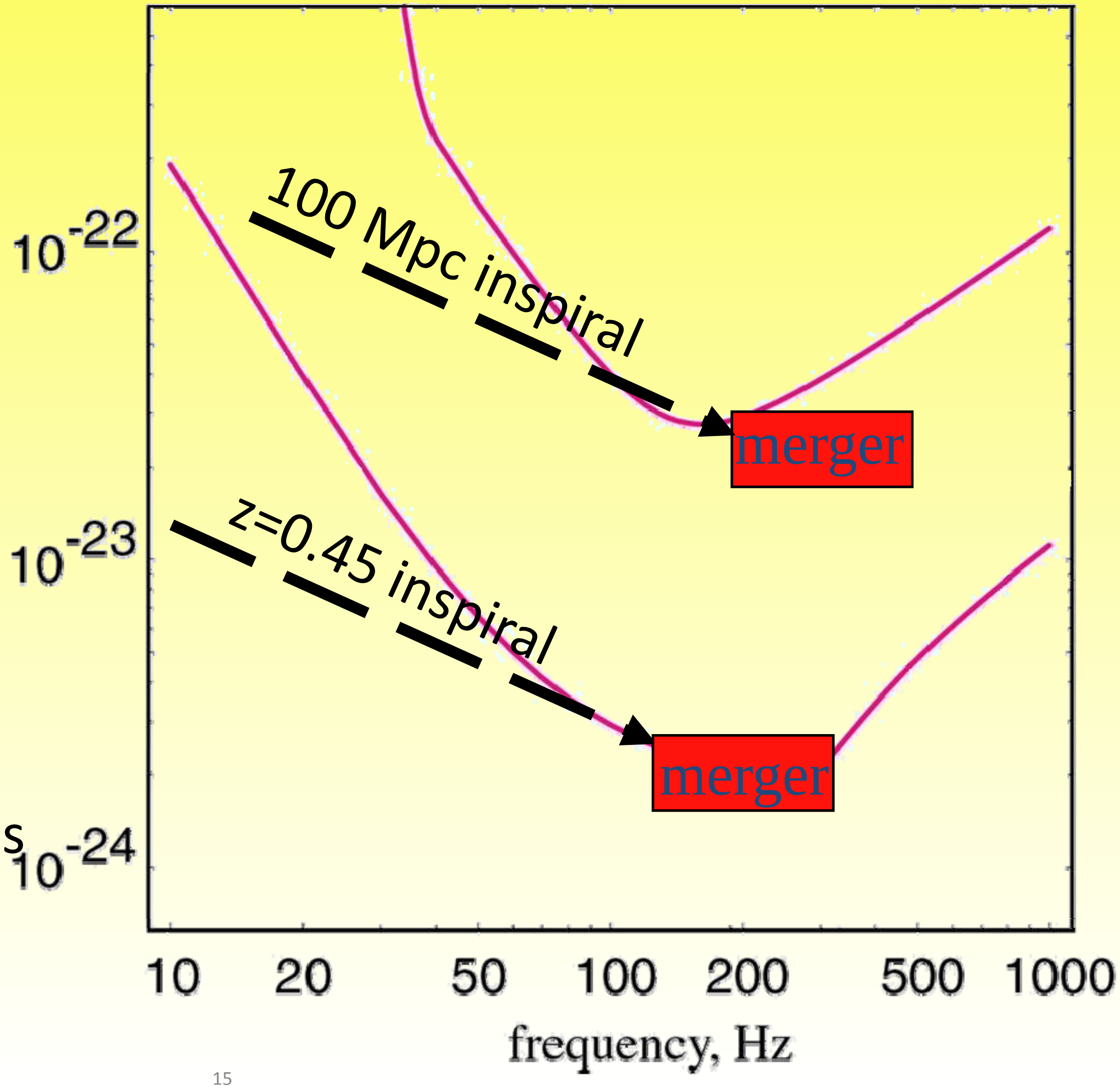
Future Plans : Advanced LIGO with Technology from GEO!

- Observable volume several thousand times LIGO!
- Installation 2010-13
- GEO contributions:
- New suspensions
- New Optics
- 200 W lasers
- Signal Recycling – Resonant Sideband Extraction

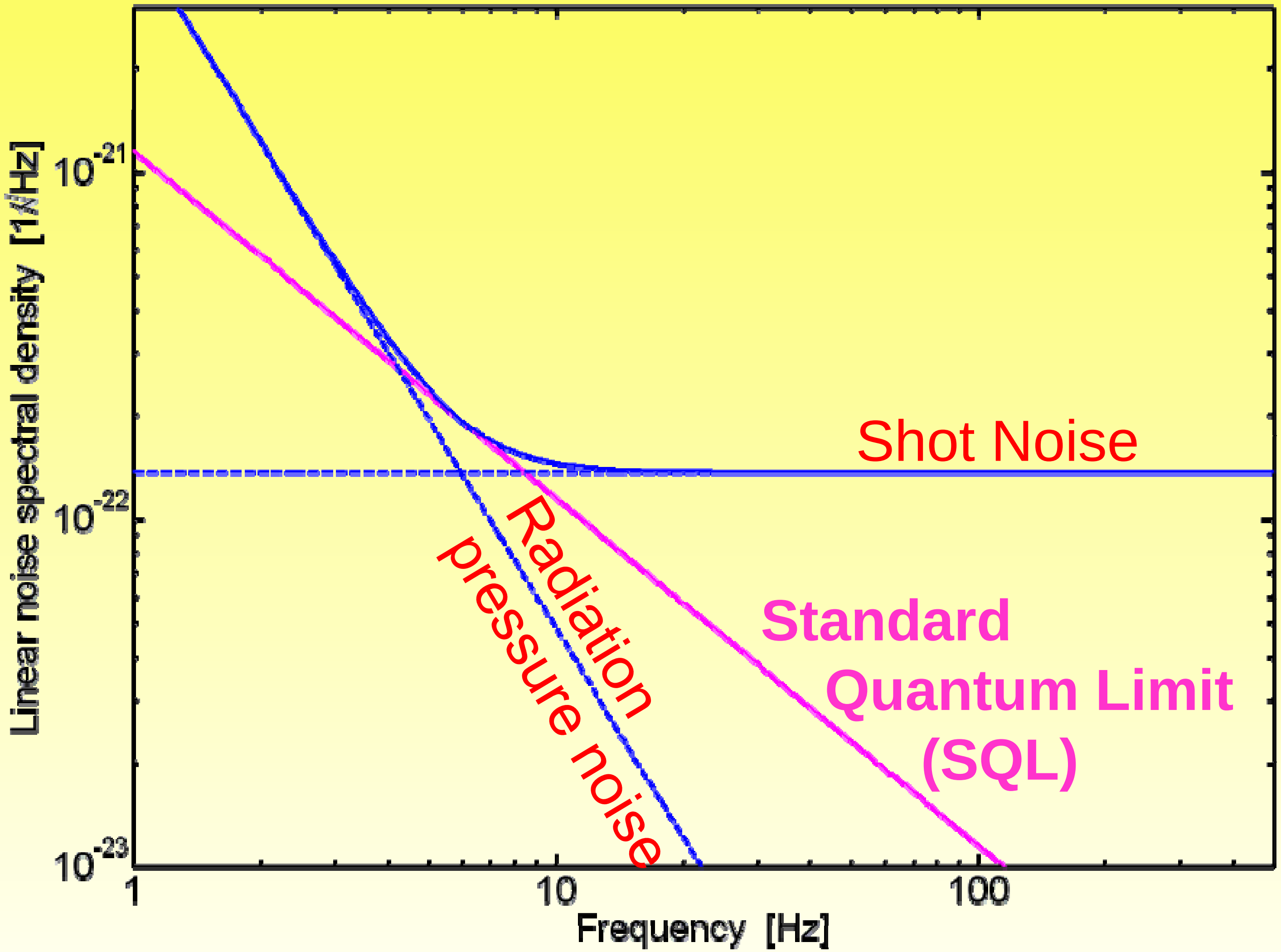


Advanced LIGO and AdVirgo

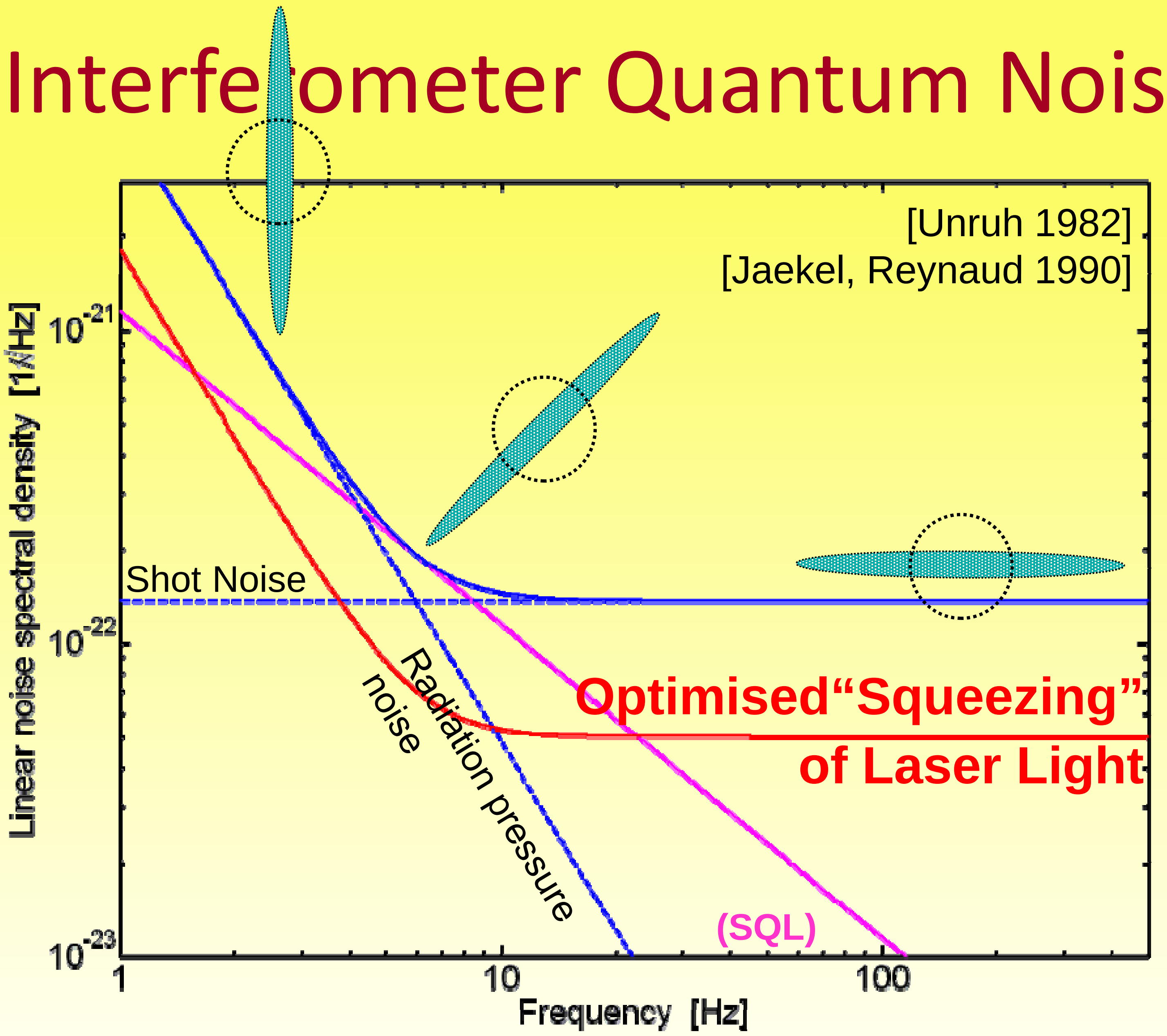
- 10 M_{sun} - 10 M_{sun} BH - BH binaries
- Event rates
  - Based on population synthesis [Kalogera's summary of literature]
- Initial IFO event rates
  - Range: 100 Mpc
  - 1 / 600yrs to **~3/yr**
- Advanced IFO event rates
  - Range: z = 0.45
  - **1 / mo to ~30/day**



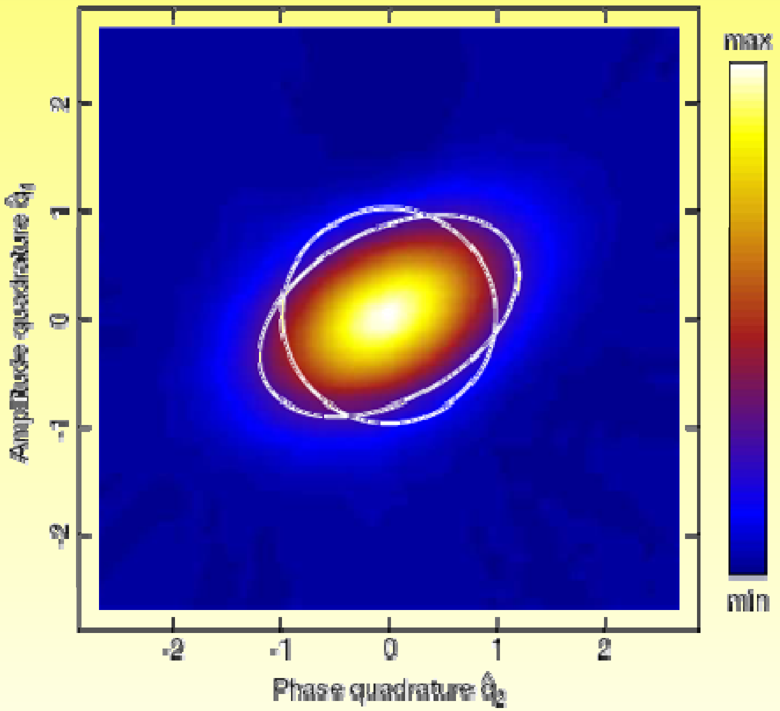
Interferometer Quantum Noise

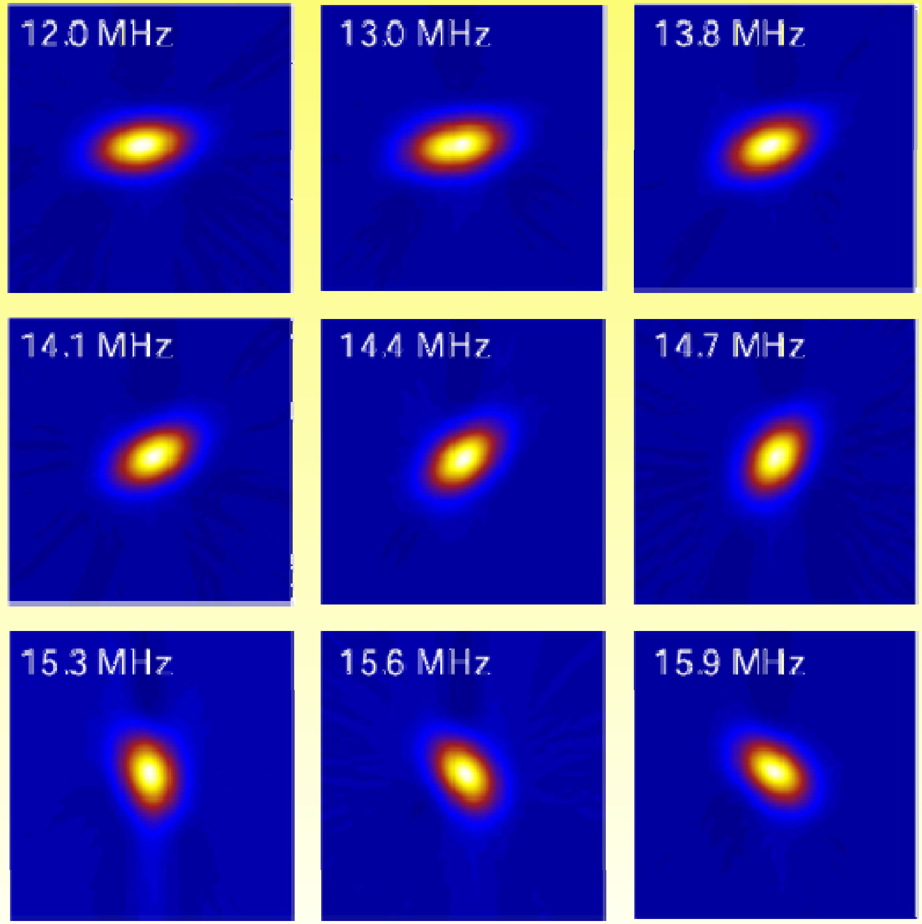


Interferometer Quantum Noise

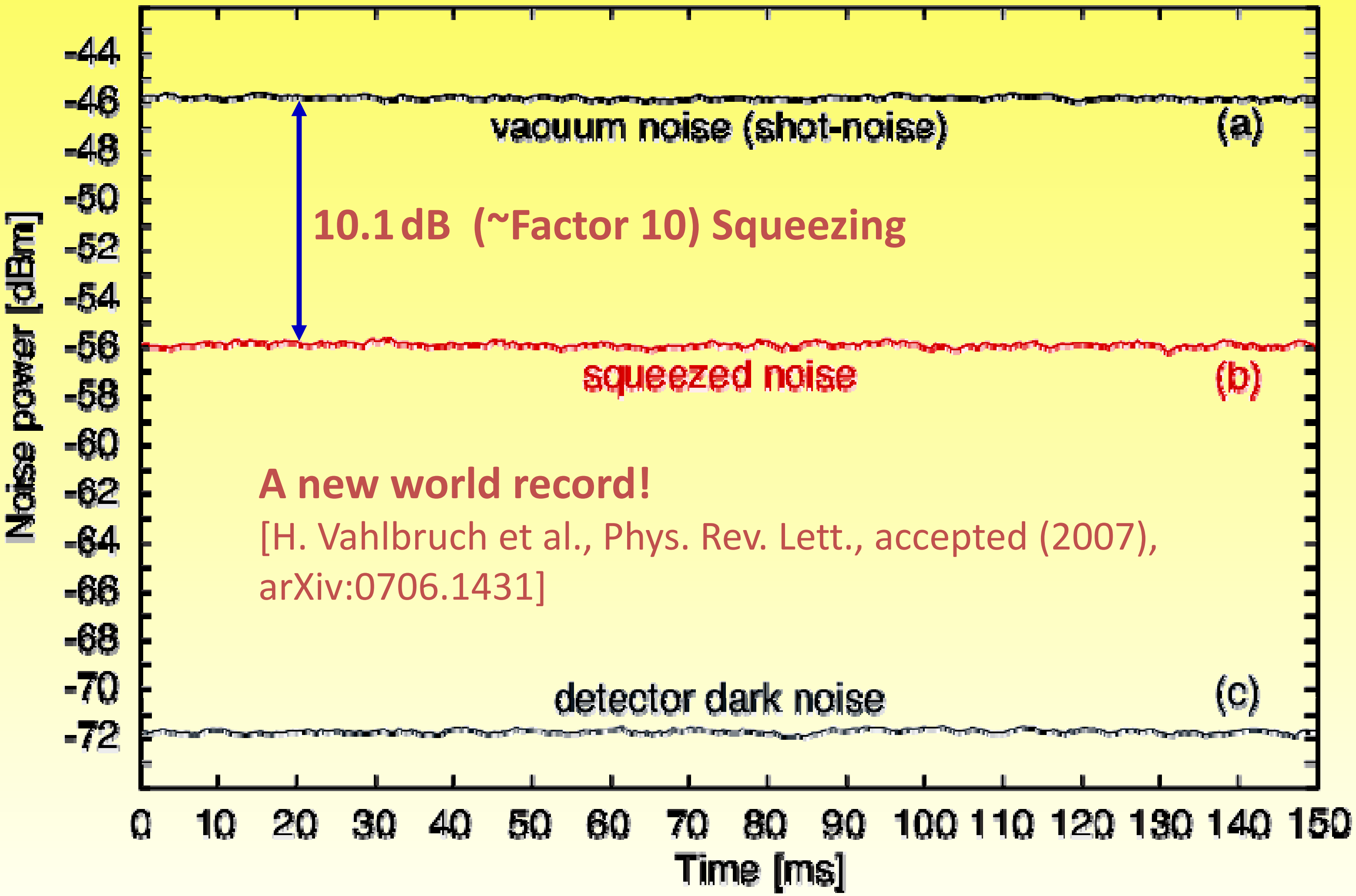


Squeezed Light in Hannover





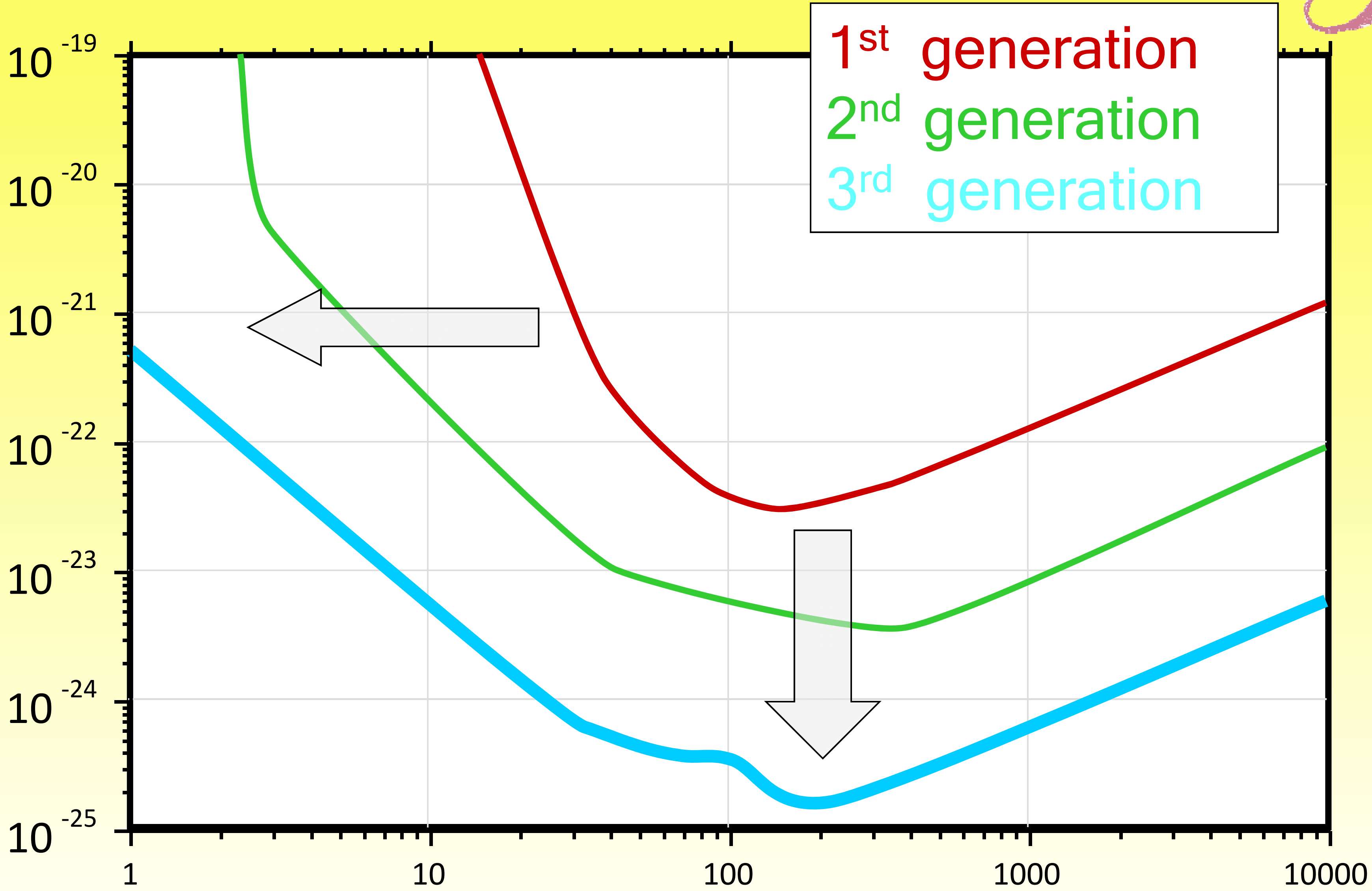
Observation of 10dB squeezing



Our Goal: The Third Generation
The Einstein Gravitational Telescope
E.T.

- Overall beam tube length ~ 30km
- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic
- Squeezing
- QND Readout

The Goal: one order beyond AdLIGO



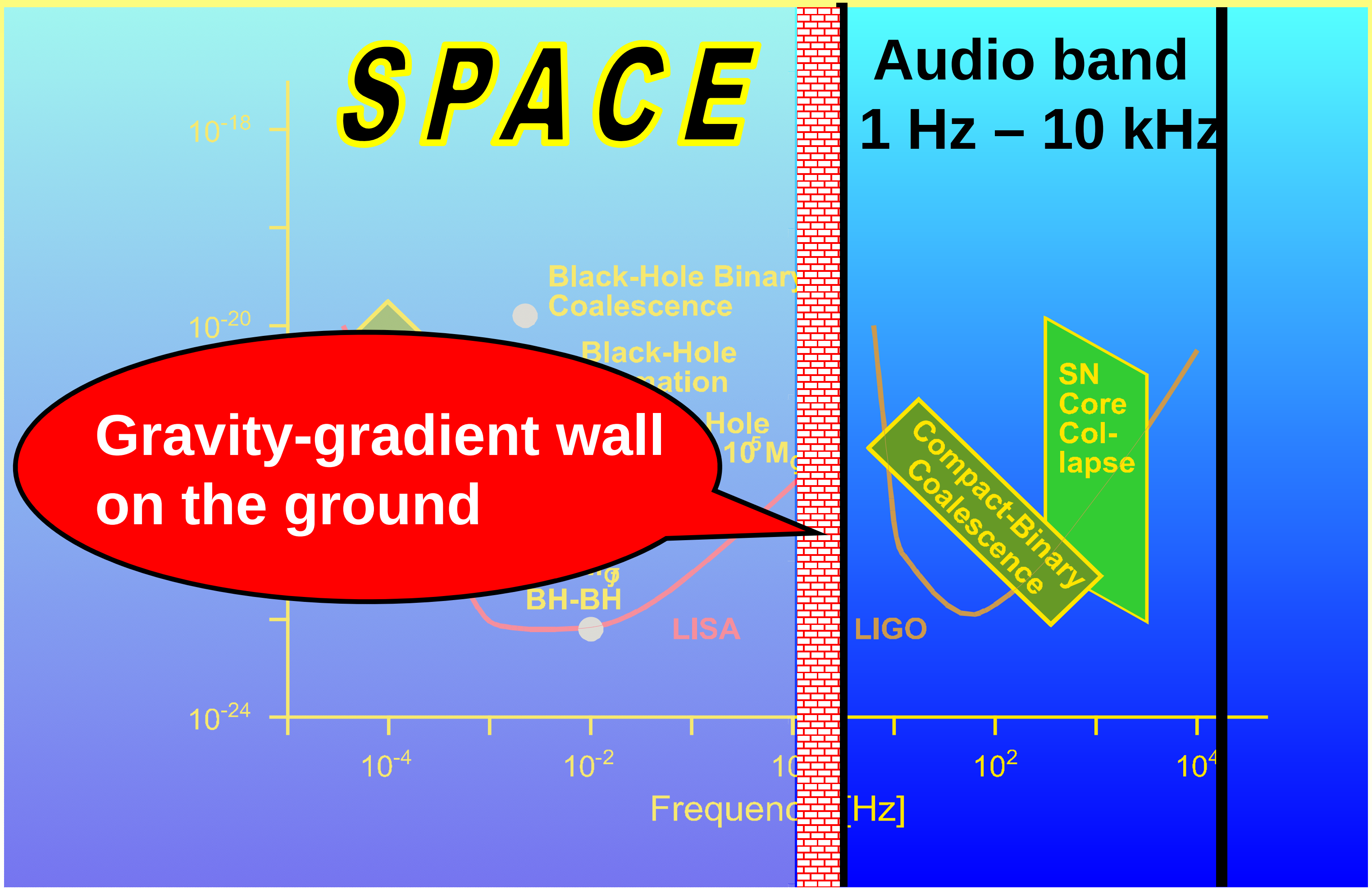
Conceptual Design Study in European Union FP7 Program

- Kick-Off May 2008
- Work Packages:
  1. Site and infrastructure
  2. Thermal noise of mirrors, suspensions / cryogenics
  3. Optical configuration
  4. Astrophysics issues
  5. Management

SEVENTH FRAMEWORK PROGRAMME

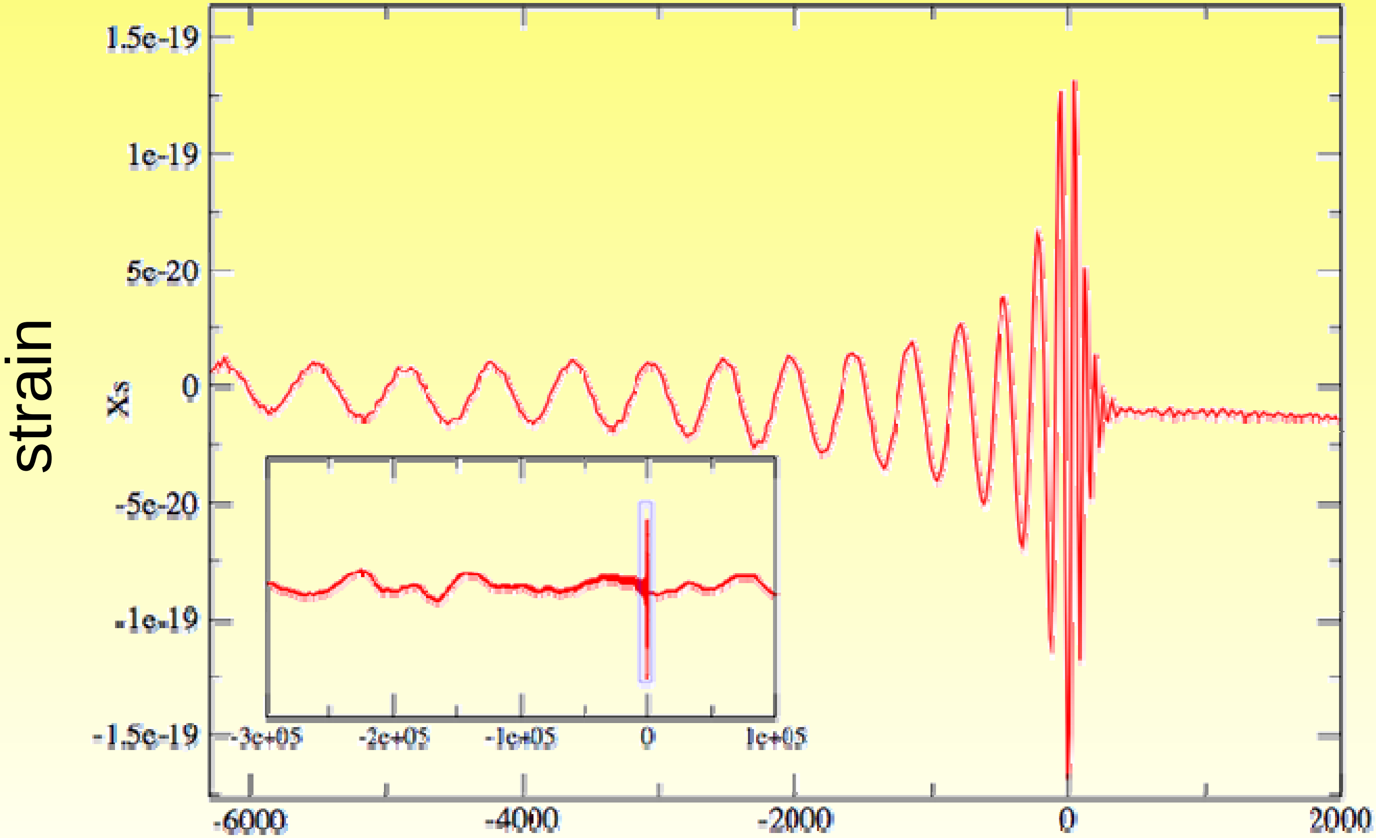
Gravitational Wave Sources

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



Merger Signals far above Noise!

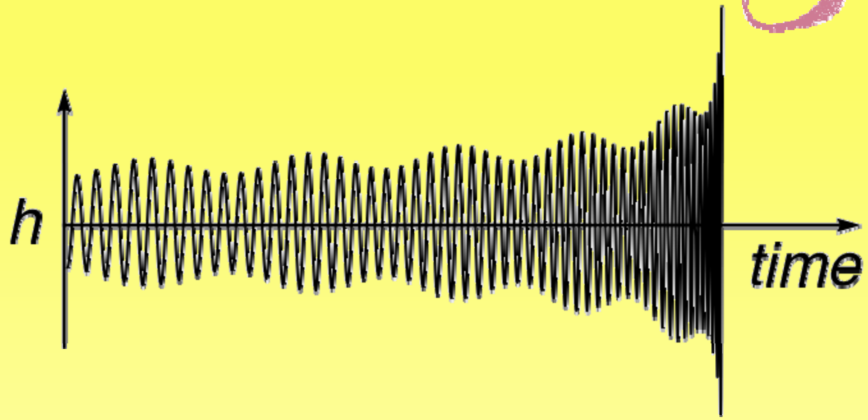
- Simulated LISA data stream,
  - $10^5 M_{\odot}$ BH binary merger at z=5, including instrumental noise (SNR~500)



Baker et al. 2006

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 *directly* from

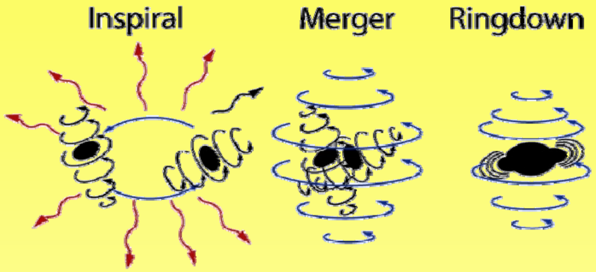
- amplitude
- orbital frequency
- chirp time

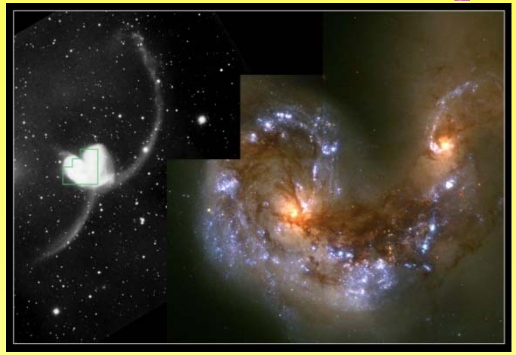
$$\text{Distance} \cong c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$

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

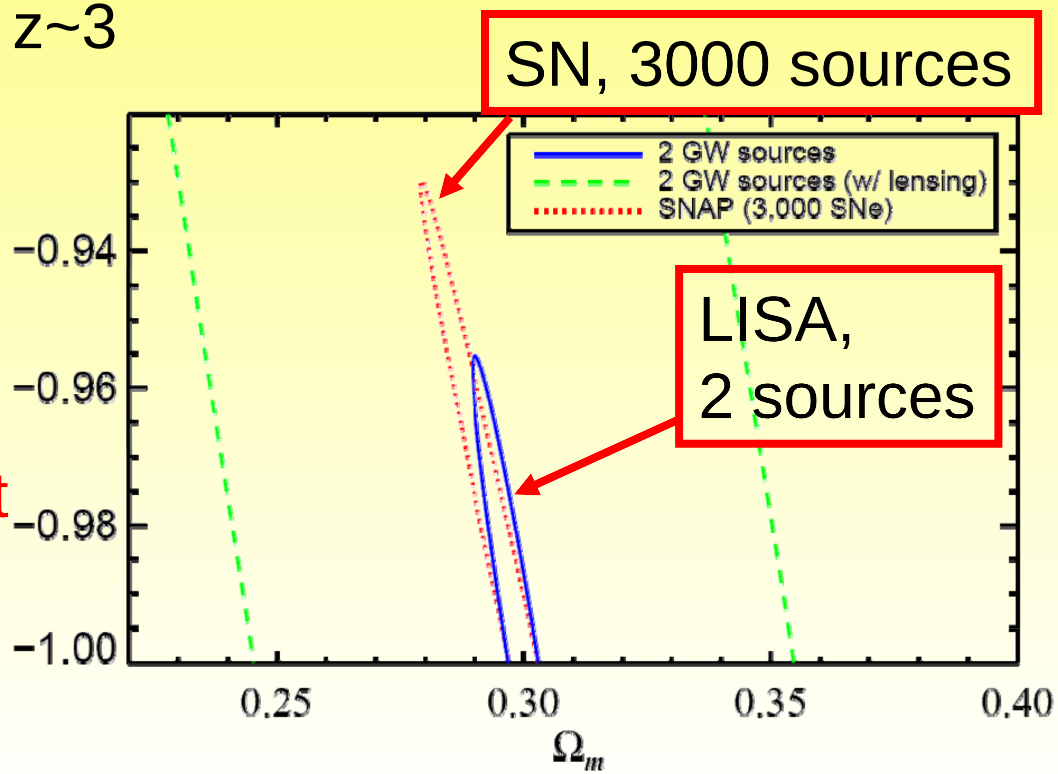
Absolute Distances from SMBH Mergers:

Hubble Constant and Dark Energy



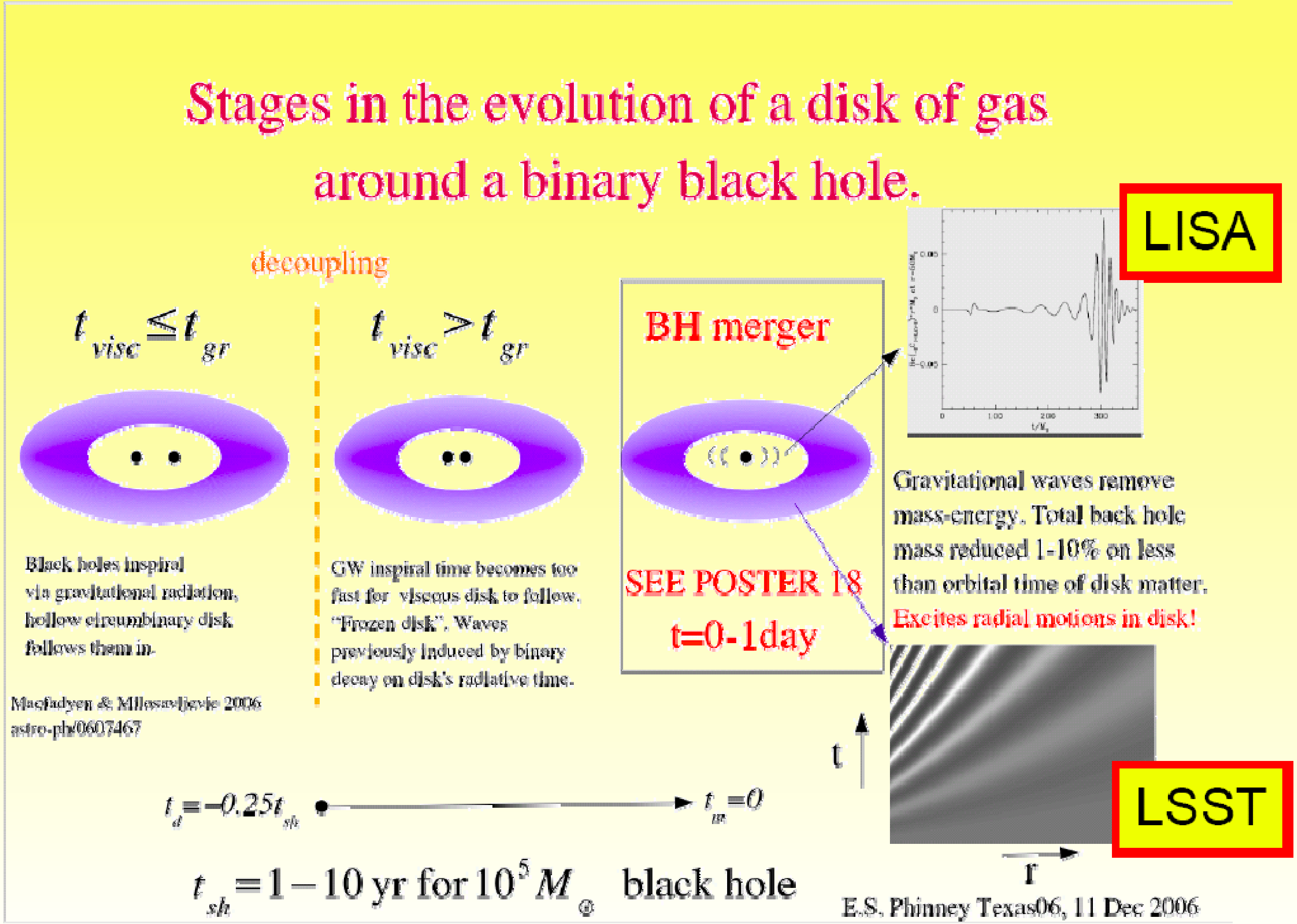


- 100’s of events expected to z~3
- 10’s out to z~20
- Noise from weak lensing
- Comparable precision to CMB, WL, BAO, CL, SN
- We need to identify the host to get the redshift!
- Optical counterparts?



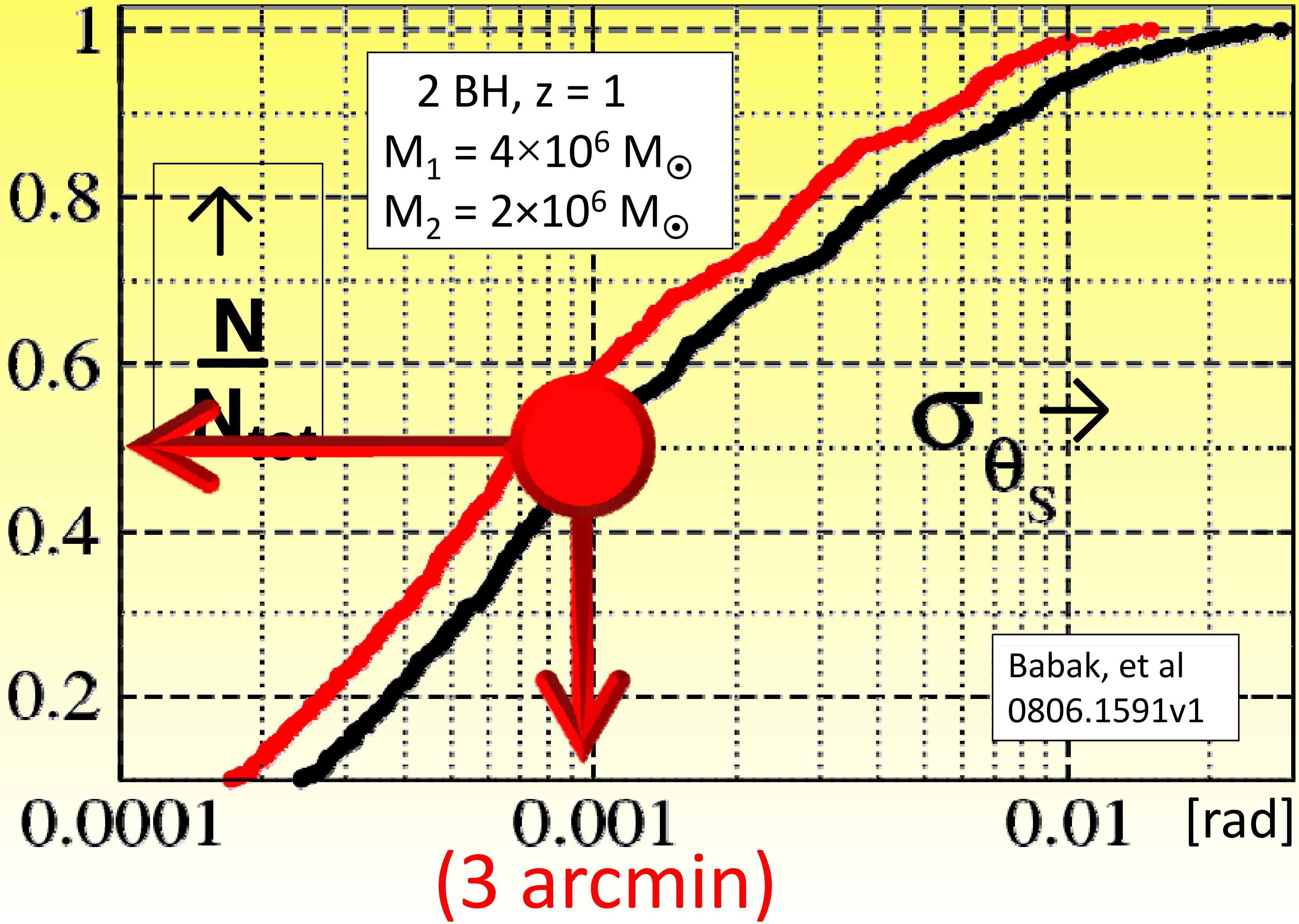
Holz and Hughes, astro-ph/0504616

Accretion Disk Variability



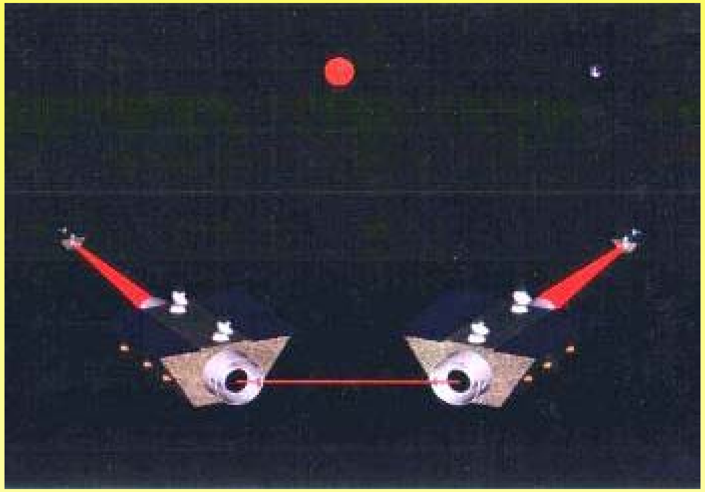
NumRel: Superb Angular Resolution!

- 50 % under 3 arcmin at z=1 (preliminary)

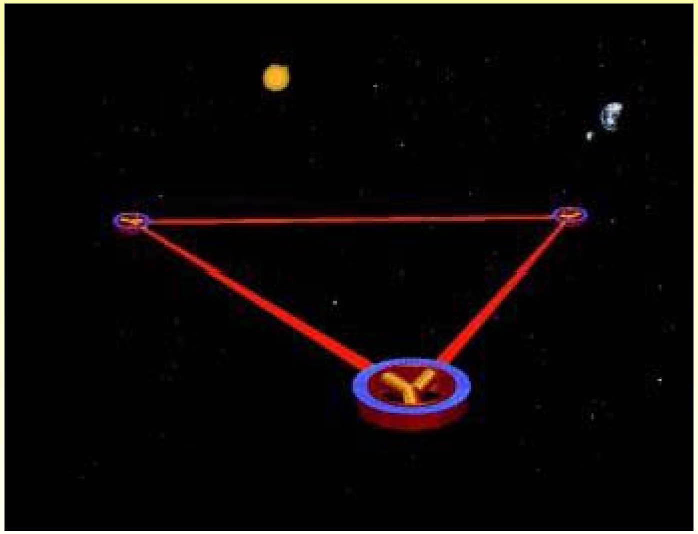


LISA: A Mature Concept

- After first studies in 1980s, M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993

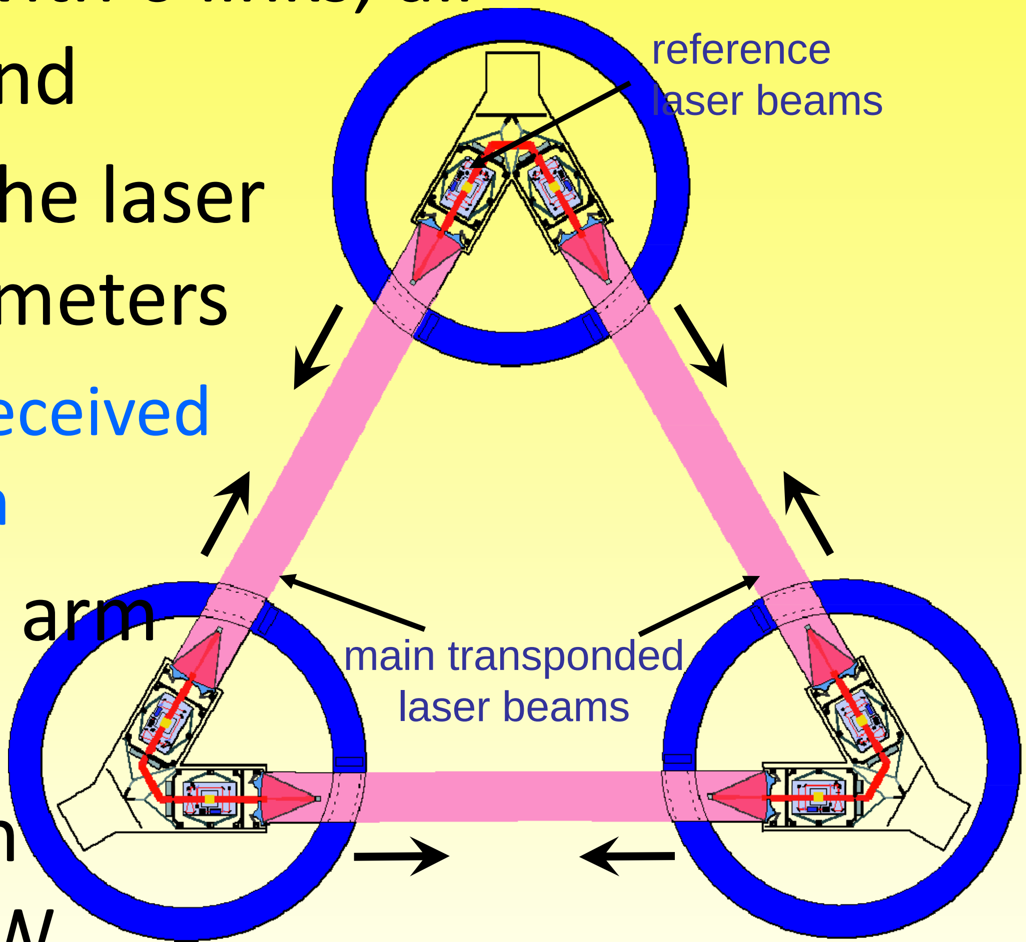


- LISA selected as ESA Cornerstone in 1995
- *3 S/C NASA/ESA LISA appears in 1997*
- **Baseline concept unchanged ever since!**



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 Mission Formulation Study

Mission Design Review Agenda

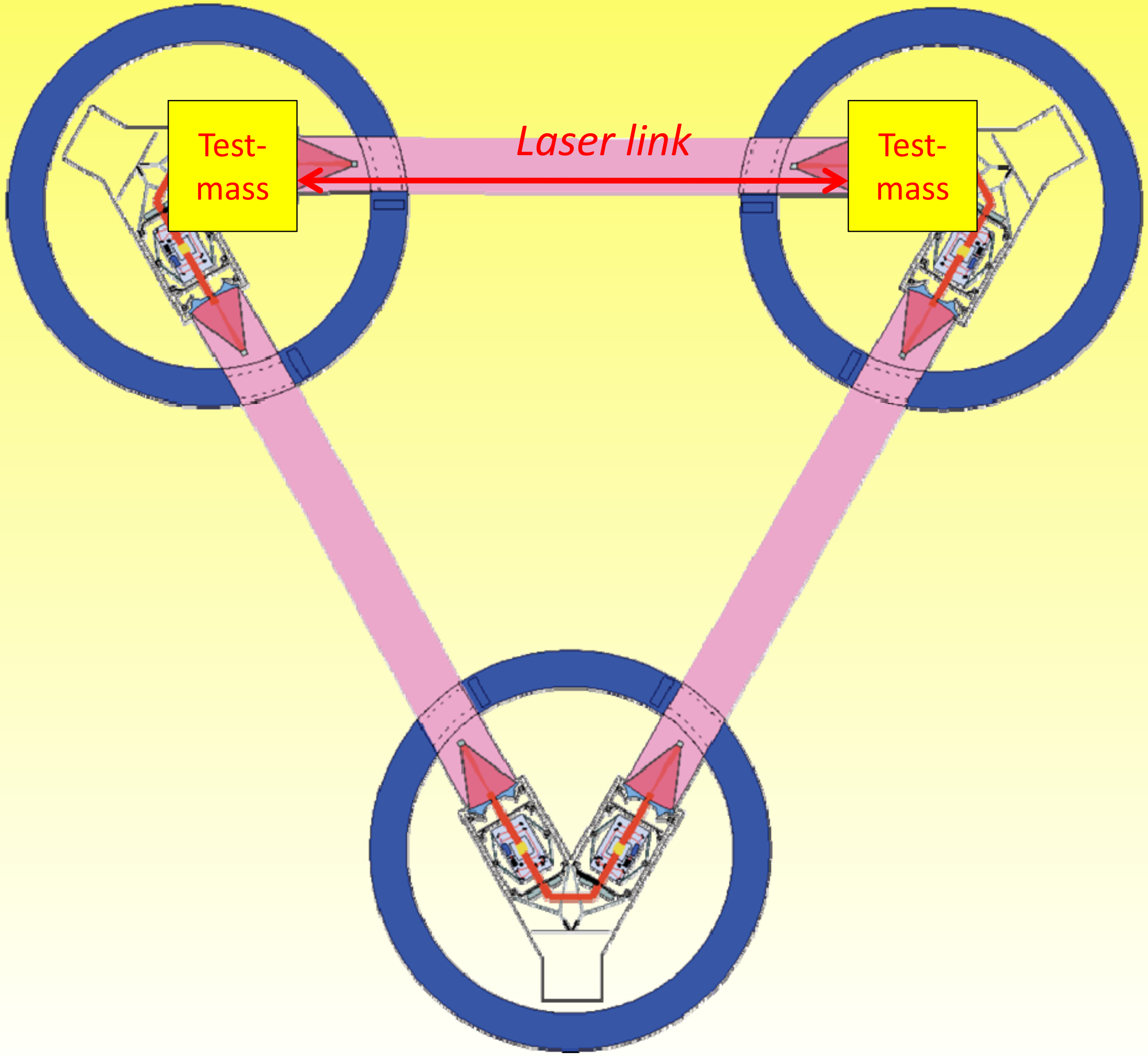
10./11.-June-2008

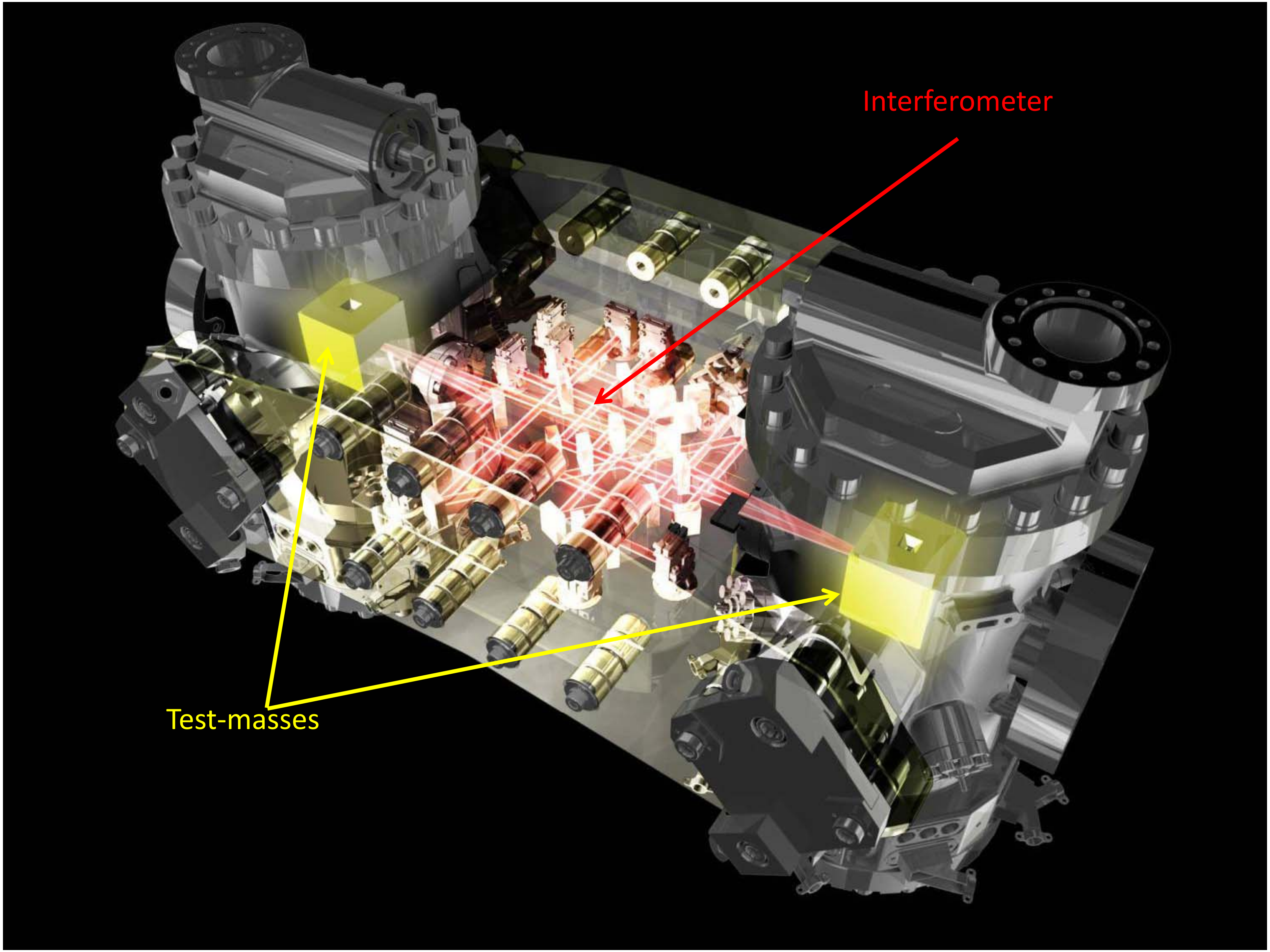
All the space you need

LISA Pathfinder

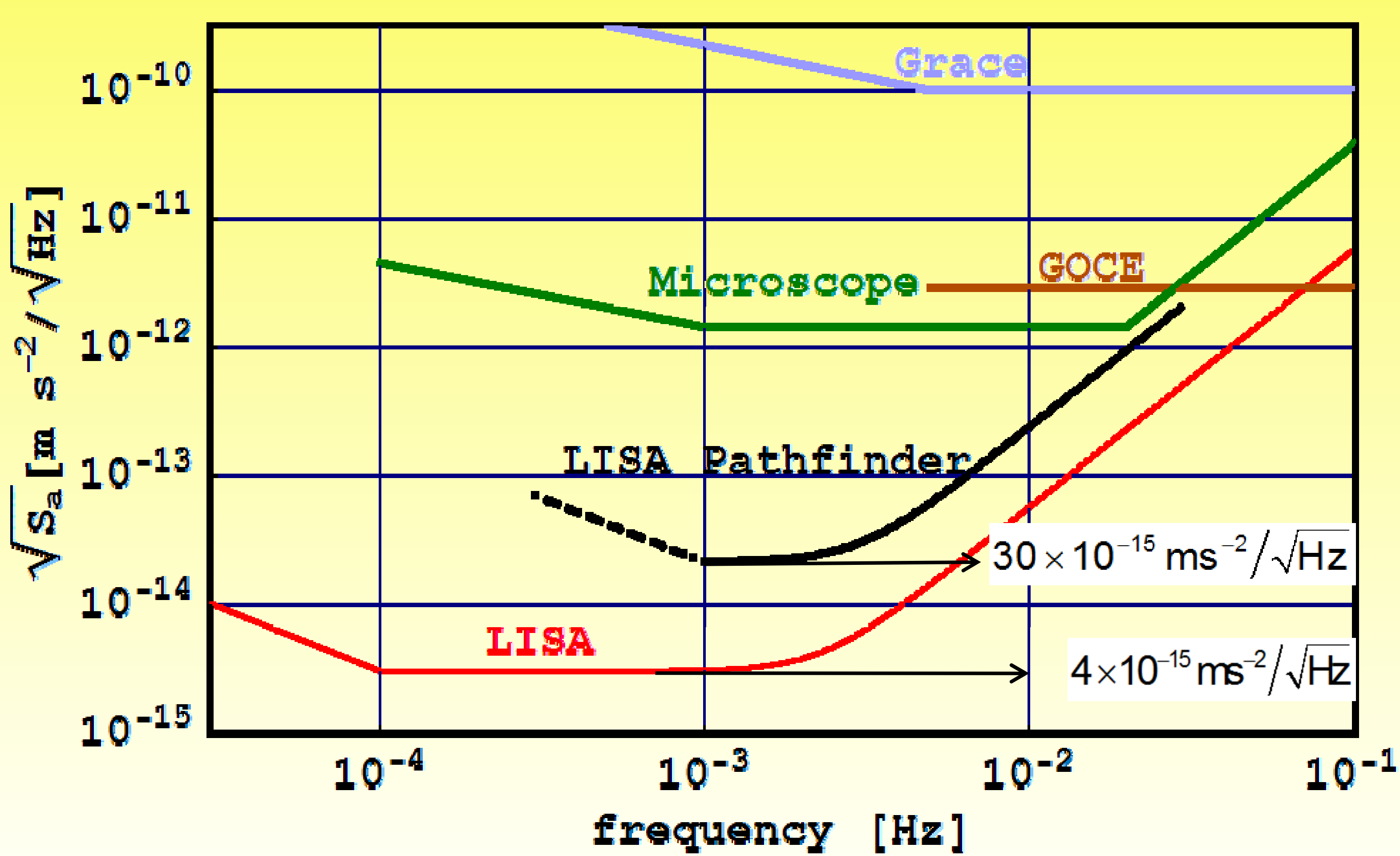
Parts from Decadal Survey Presentation by Stefano Vitale

The Basic Element of one LISA Arm: the Test Mass to Test Mass Link

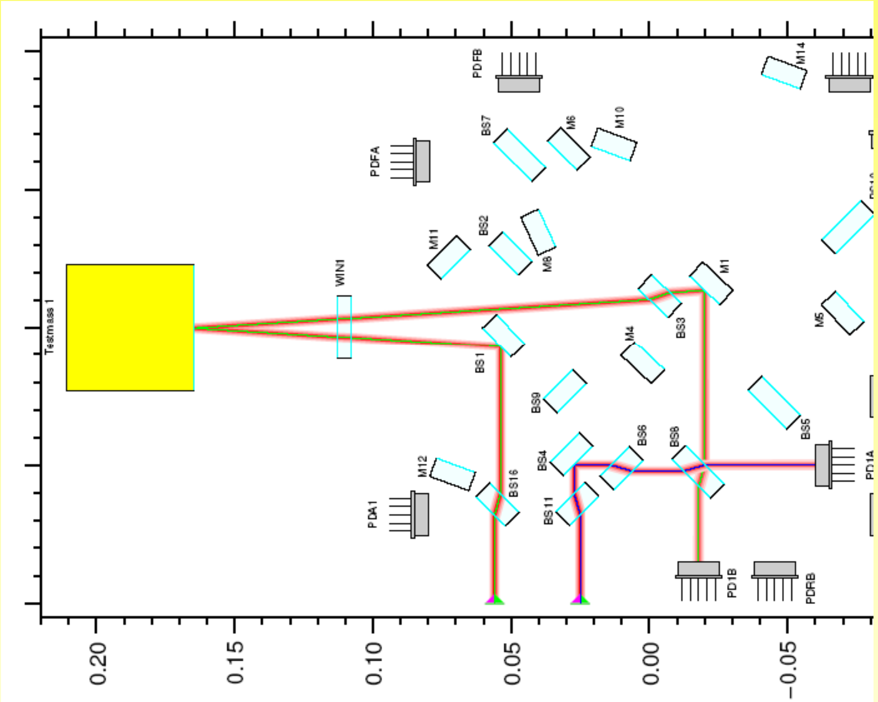


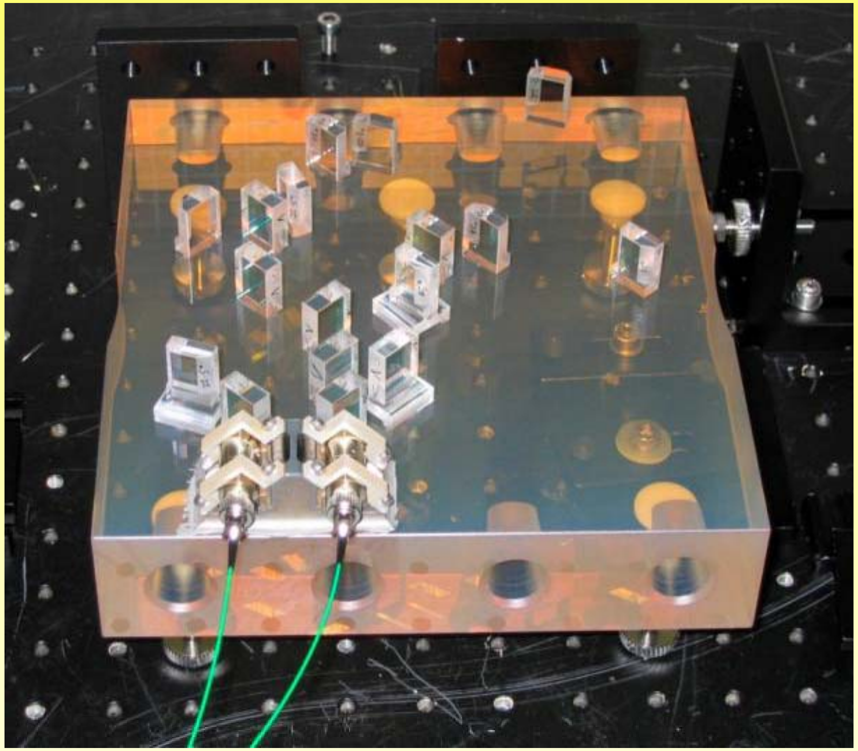

Interferometer
Test-masses

LISA and LPF requirements



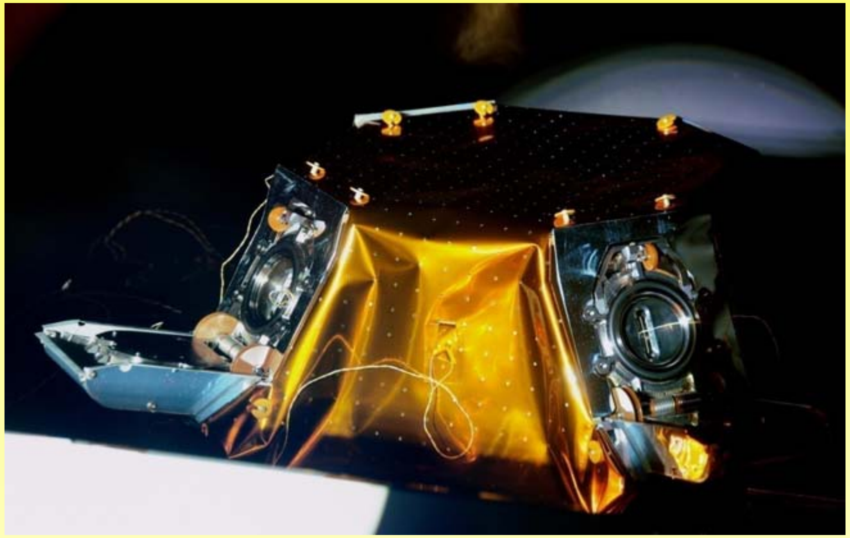
The Local Interferometer: Test Mass to Spacecraft Motion Readout

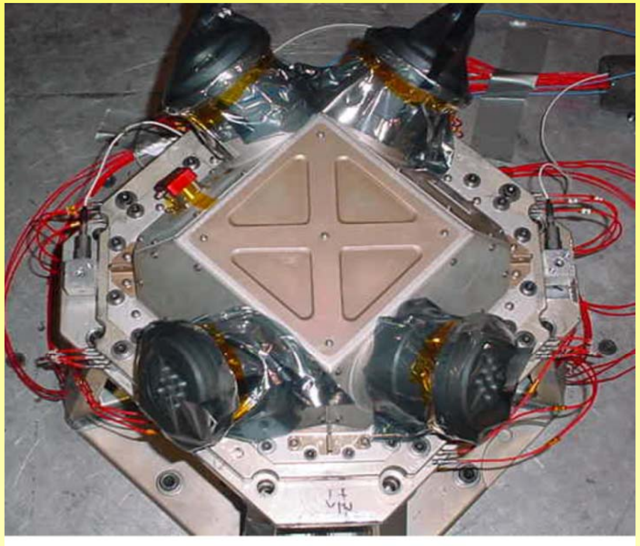




- LPF local interferometer has full required LISA performance.

The Micro-Newton Thrusters

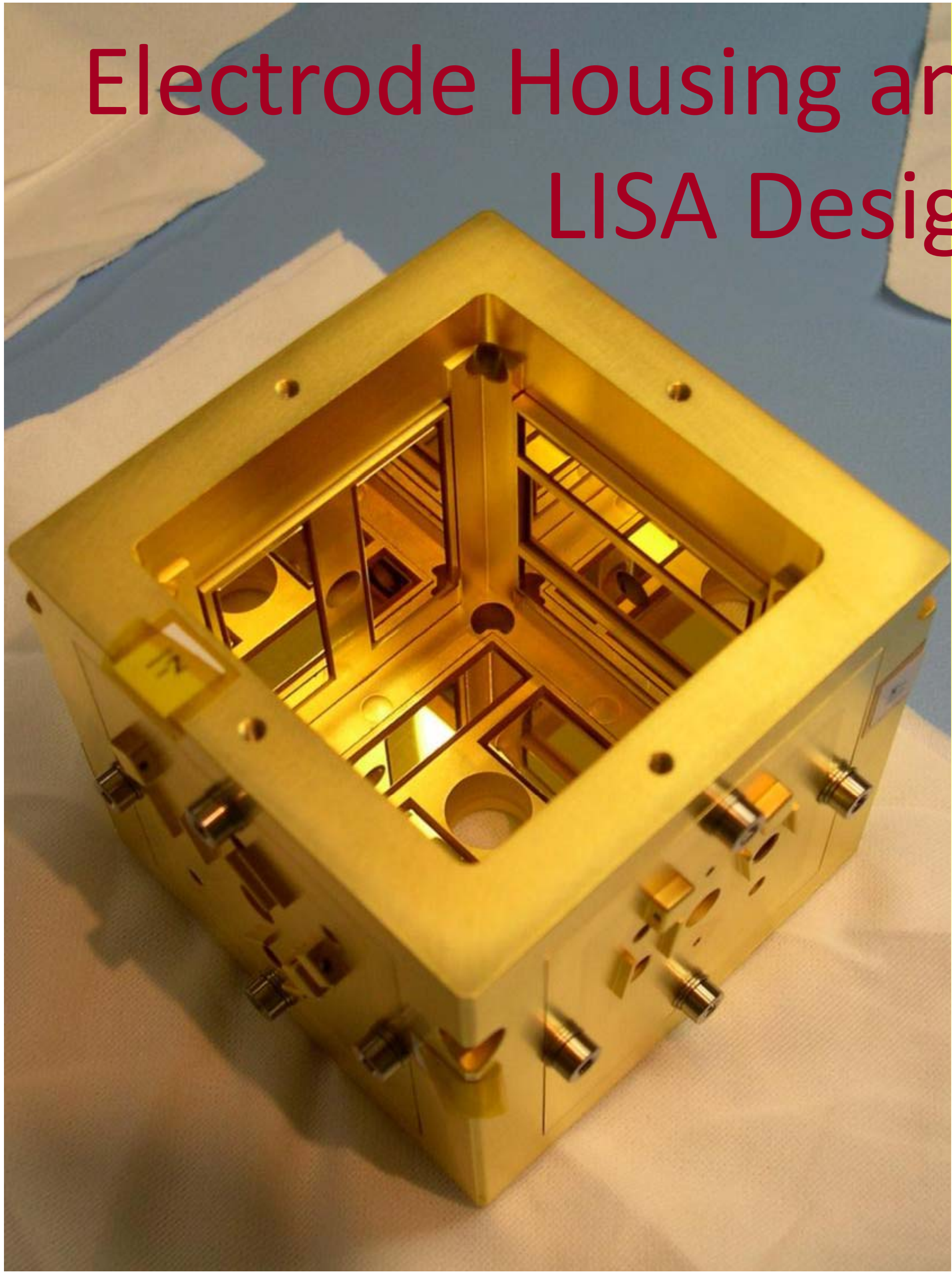




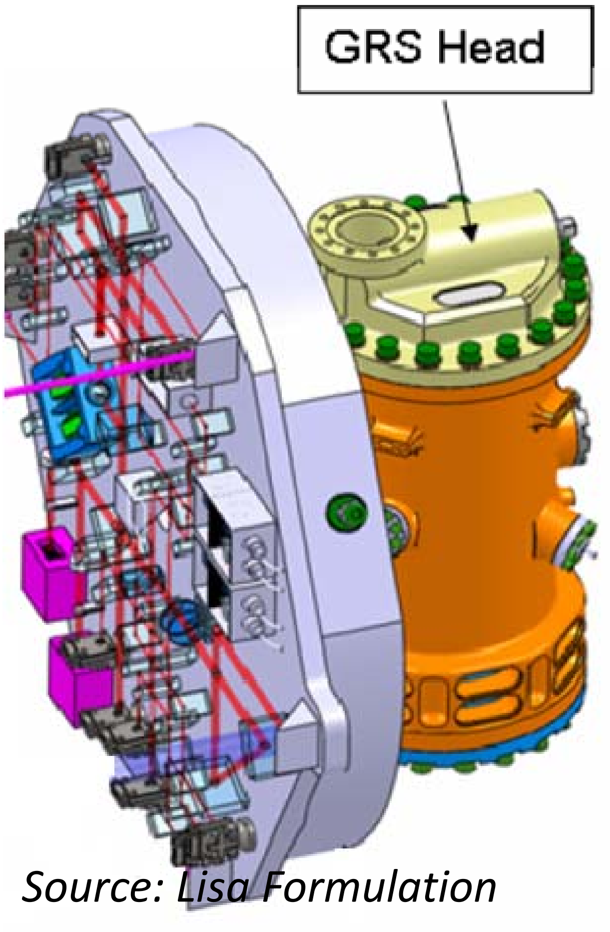
•FEEP: Field Emission Electric Propulsion

•Nominal LISA design

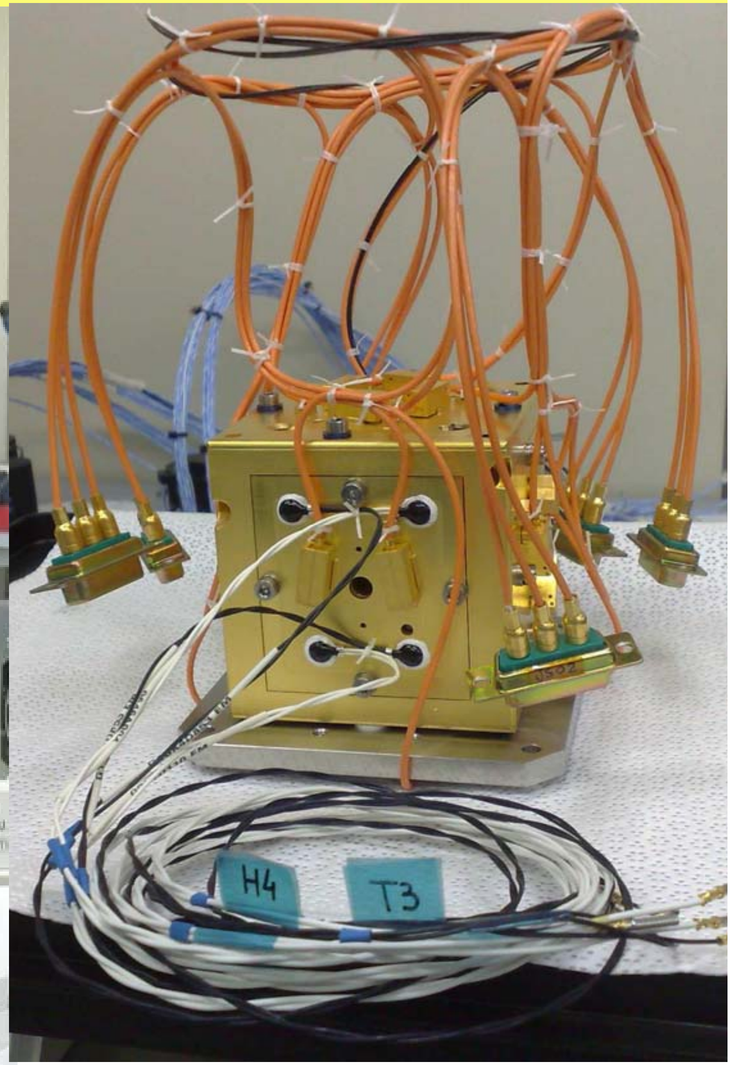
Electrode Housing and Test Mass: LISA Design



The GRS Head and Integration: LISA Design

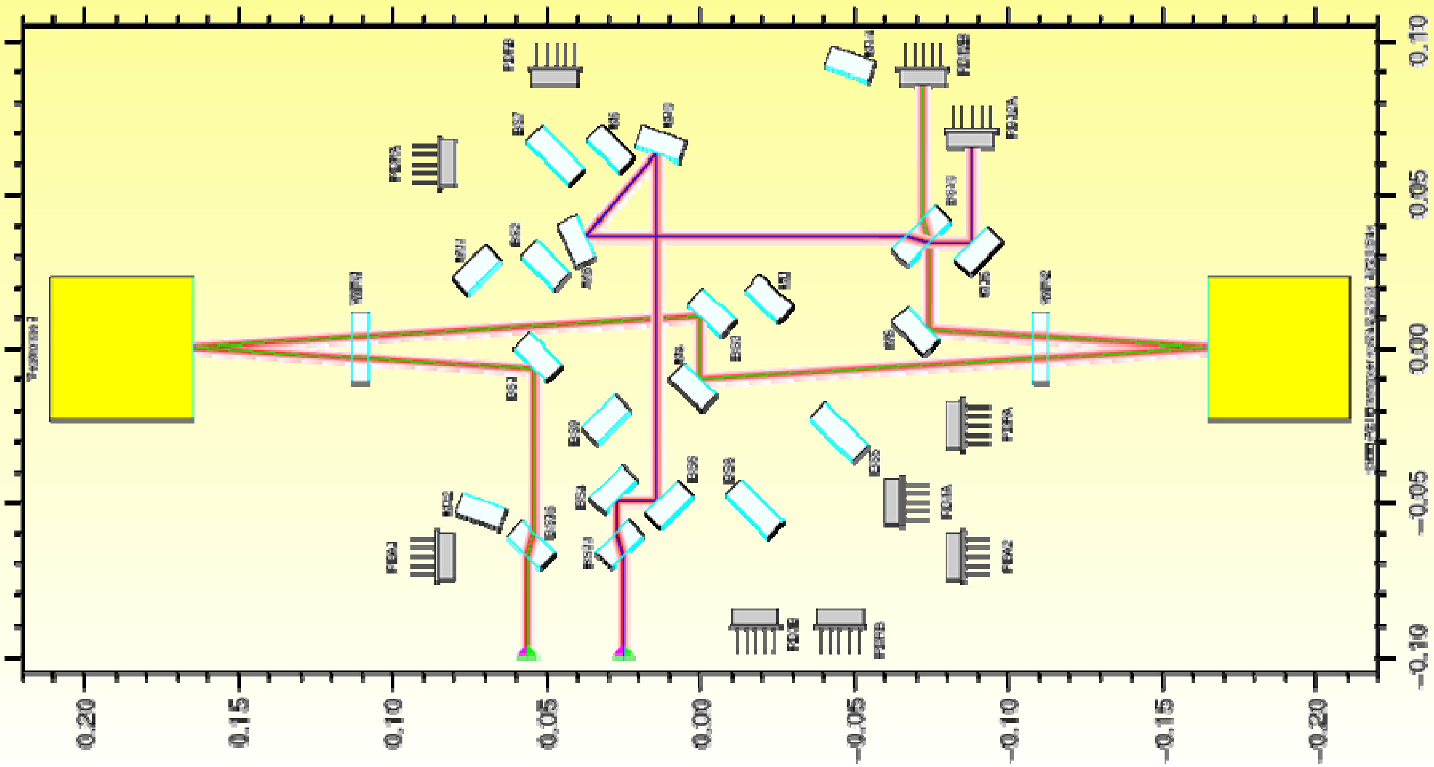


Source: Lisa Formulation



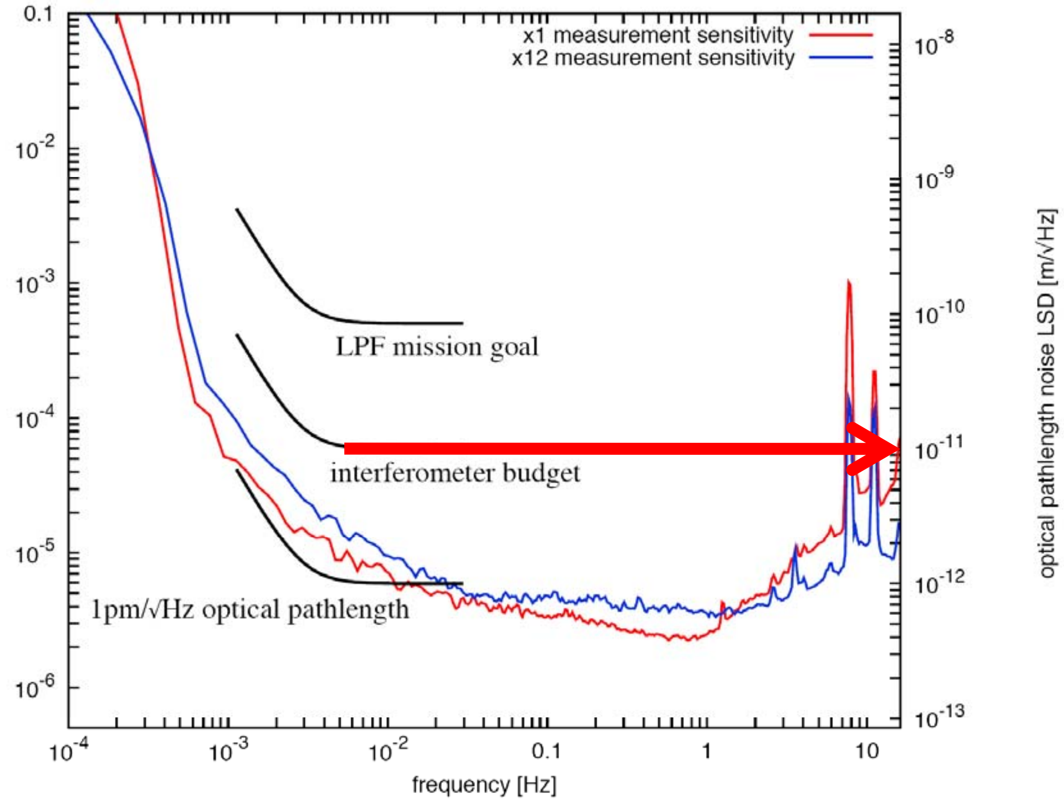
Test Mass ↔ (Spacecraft)↔ Test Mass Link <10 pm/√Hz

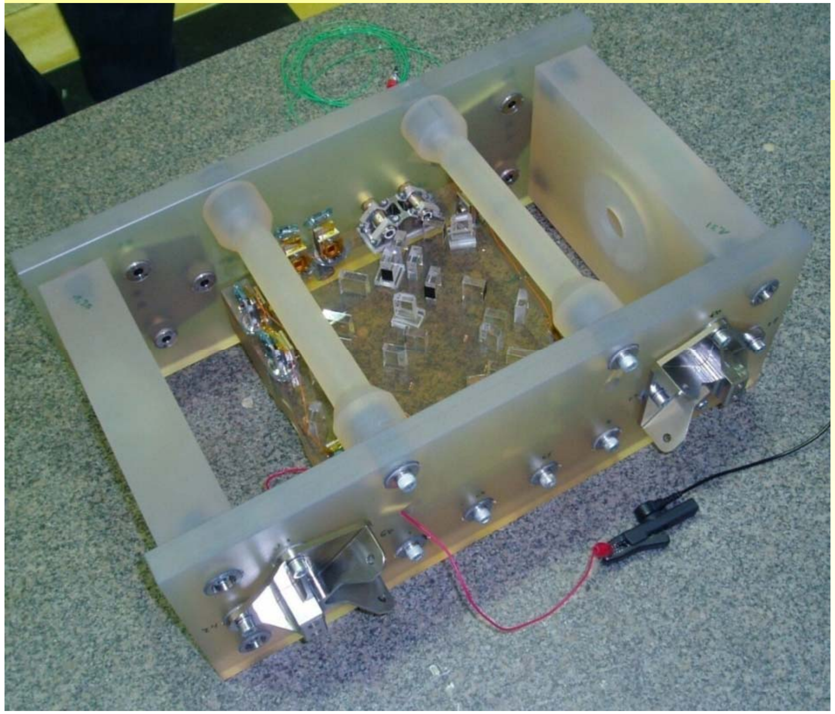
- A measurement of relative acceleration of free-flying test masses due to parasitic forces
- Cross coupling due to misalignment relevant for LISA tested as well



Demonstrated Performance

LISA's 10 pm/√Hz

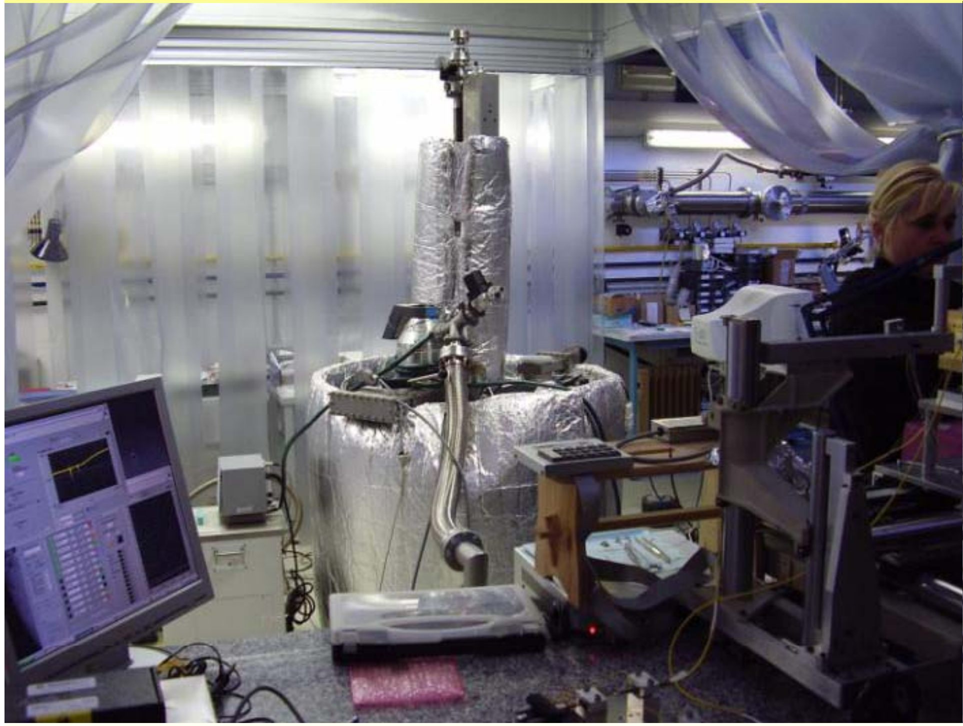


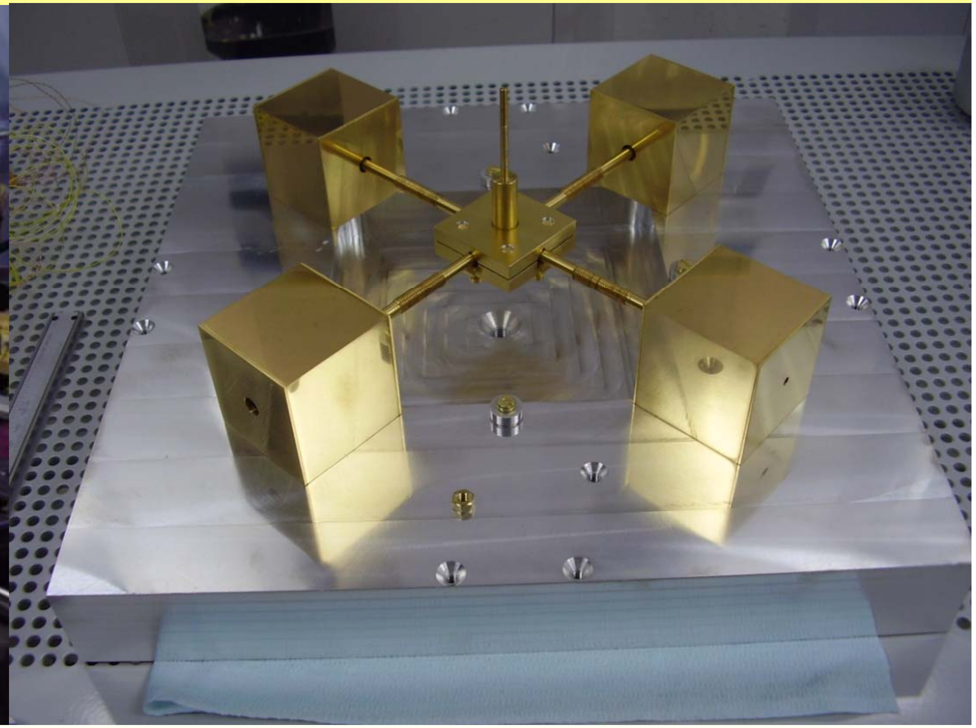


- Engineering model of the full interferometer system of LISA Pathfinder:
  - Local test mass to spacecraft interferometer
  - Test mass to test mass interferometer

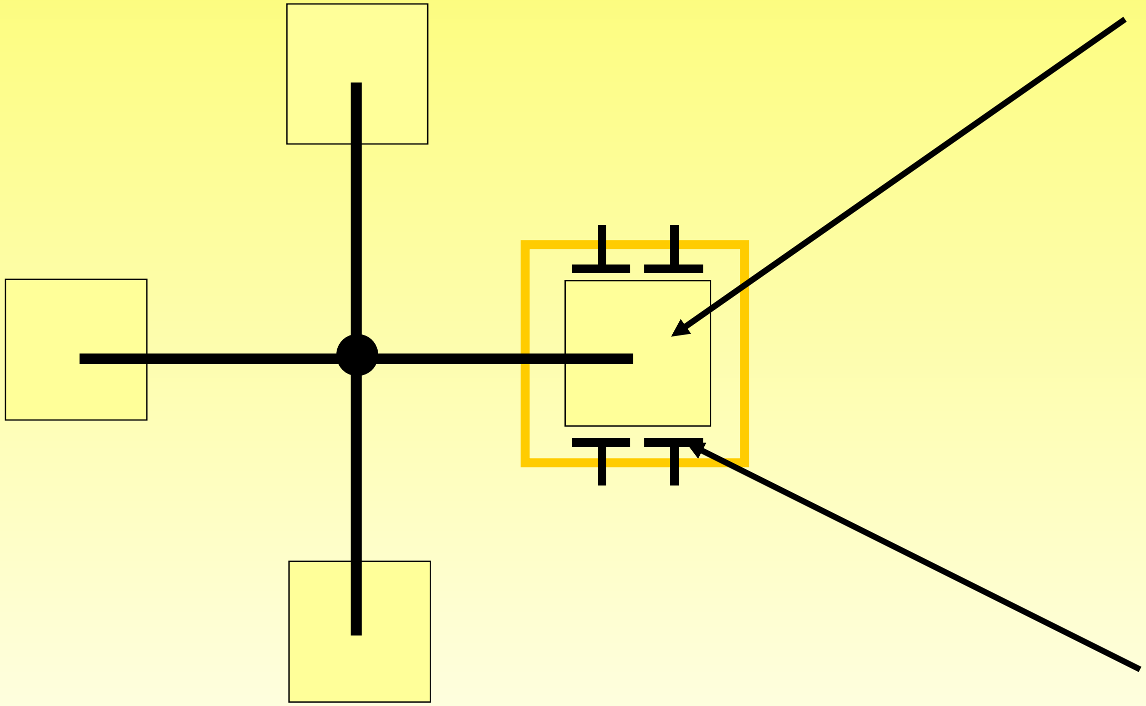
Unexpected Disturbance Sources?

- Unlikely due to extensive ground testing on torsion pendulum

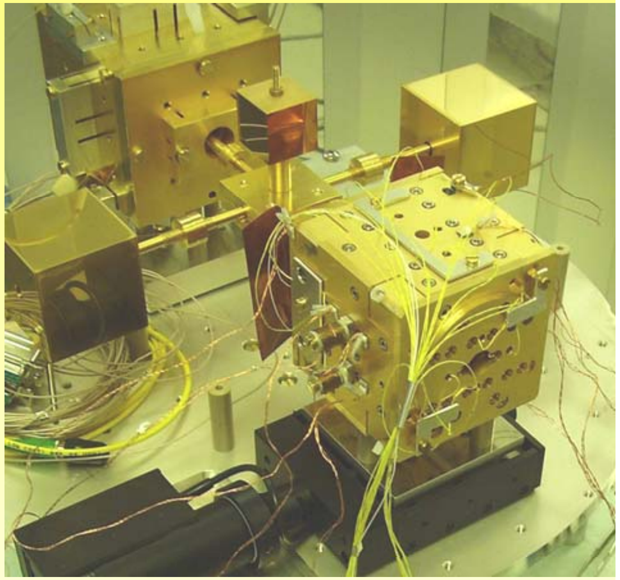




Chasing Forces on Ground: Torsion Pendulum

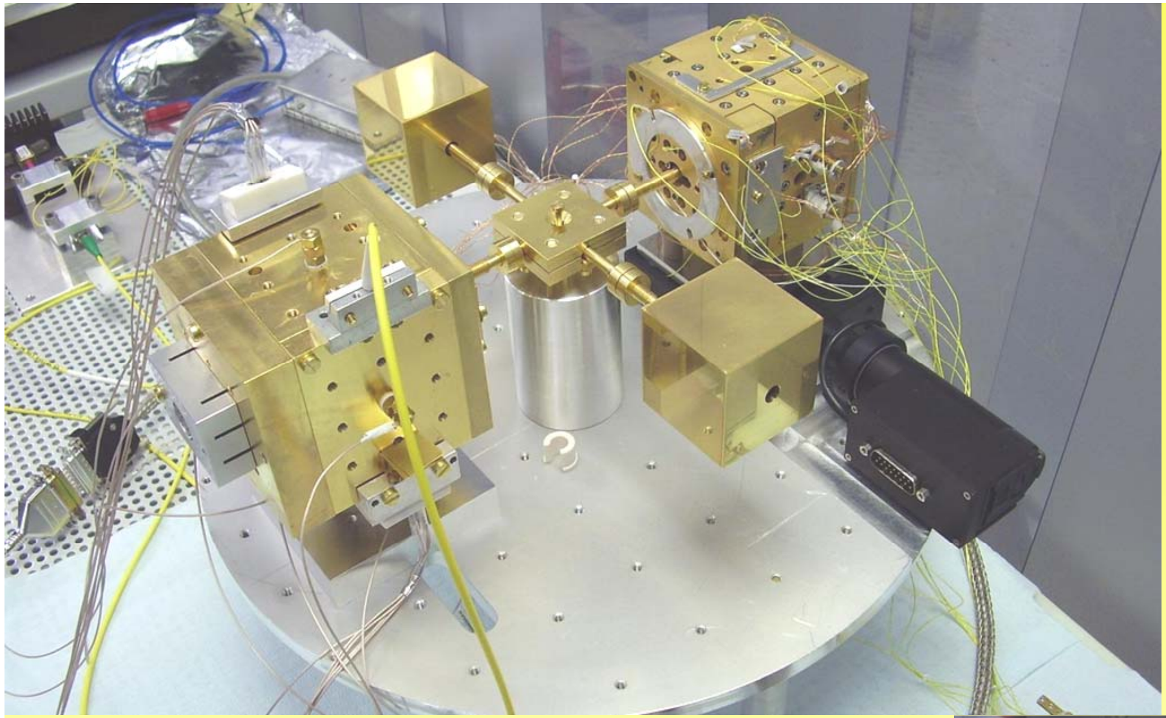


Test-mass (hollow)



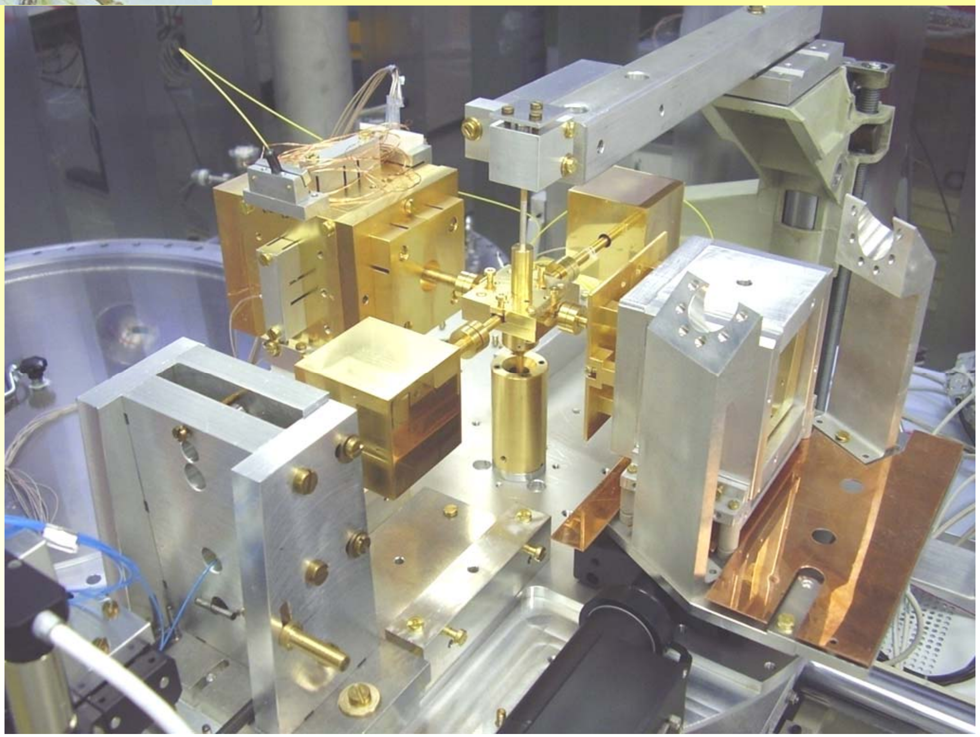
Disturbing surroundings (GRS)

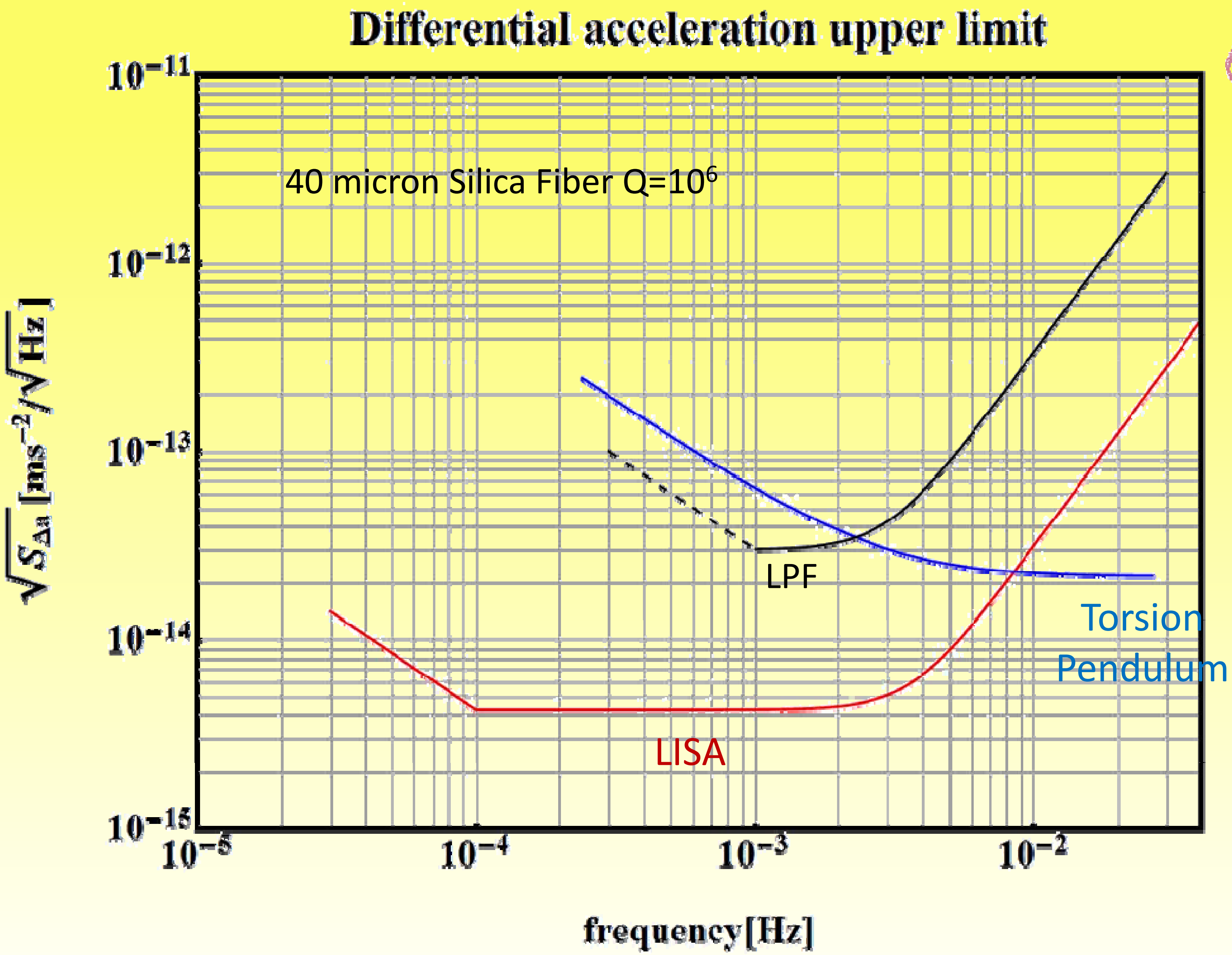
Torsion Pendulum Campaigns



Elegant breadboard of GRS at Uni Trento

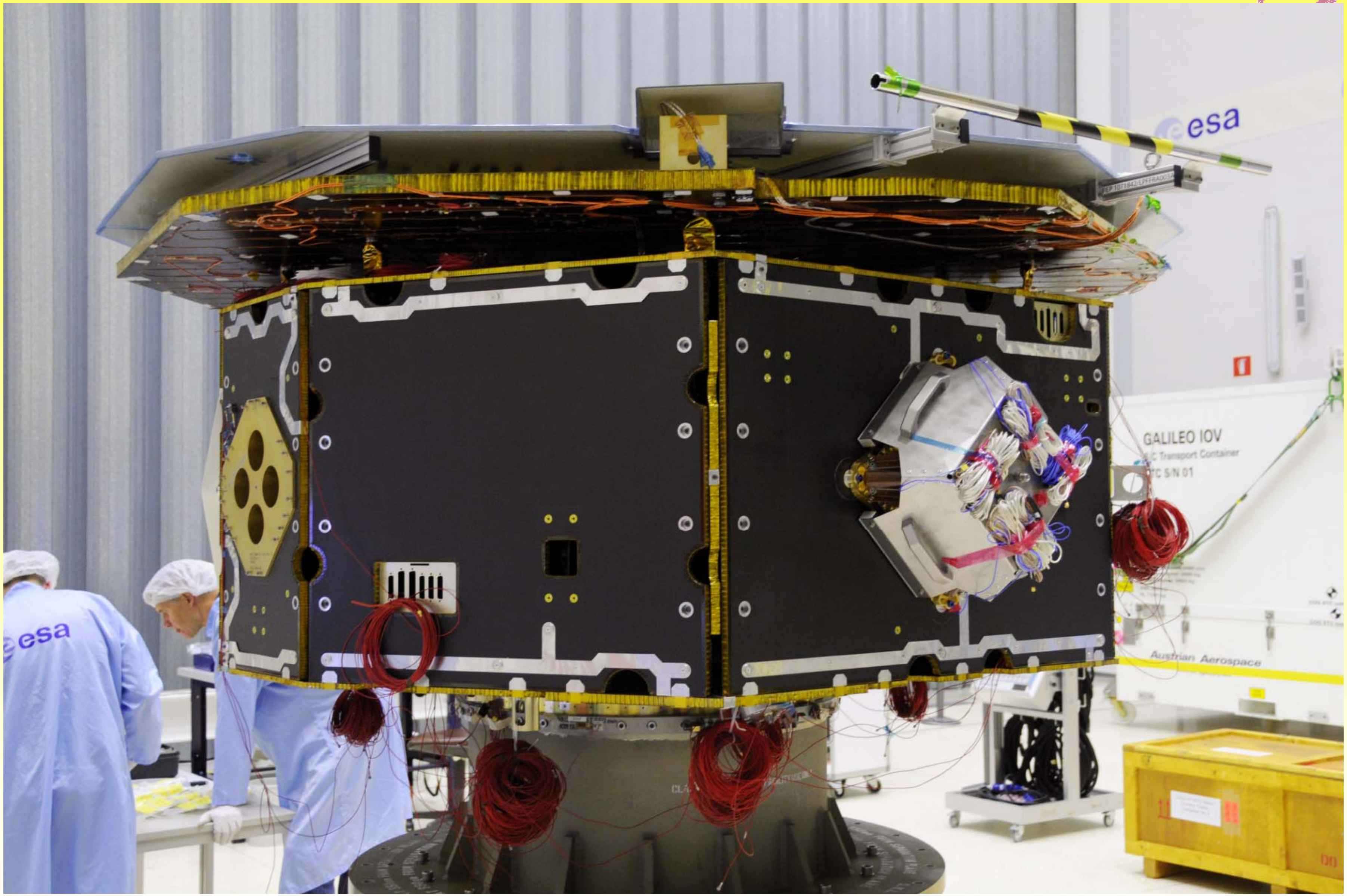
During installation of flight spare model





Differential acceleration upper limit
40 micron Silica Fiber Q=10^6
$\sqrt{S_{\Delta a}}$ [$ms^{-2}/\sqrt{Hz}$]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
LPF
Torsion Pendulum
LISA
10^{-5}
10^{-4}
10^{-3}
10^{-2}
frequency[Hz]

LPF Spacecraft




Waiting for the Launch in 2011!

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 Status

- Mission Formulation Study began in Jan 2005
- Precursor LISA Pathfinder in Phase C/D
  - Launch in 2011
- ESA:
  - LISA L1 candidate, launch in 2018-20, subject to budget constraints!
- NASA:
  - LISA flagship mission in Beyond Einstein Review!
  - Beyond Einstein Program doesn’t exist any more!
  - Now in Decadal Survey in 2009, first presentation took place 2 weeks ago in Pasadena! We are doing well!