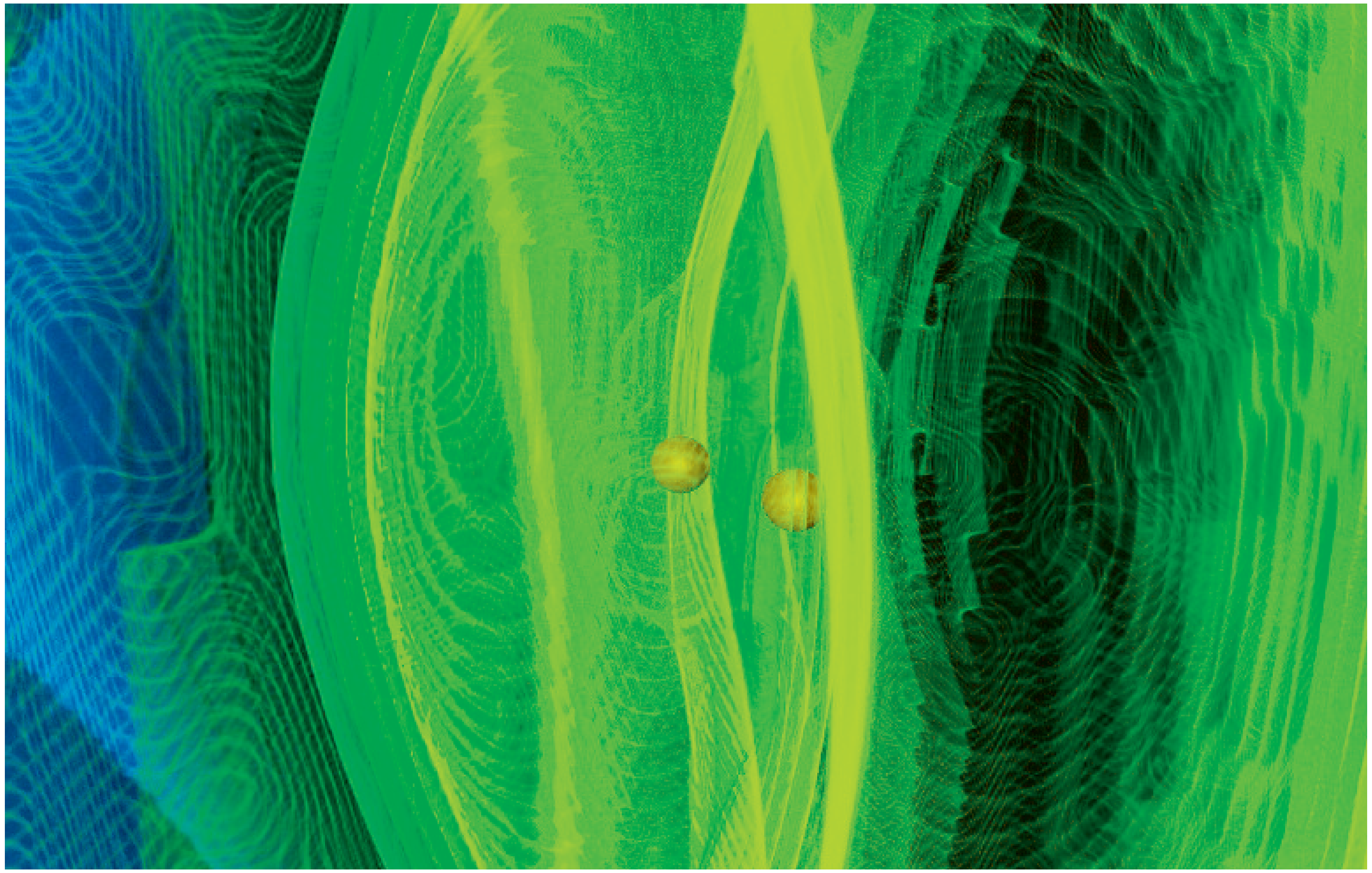
# Gravitational Waves



Ed Daw
The University of Sheffield

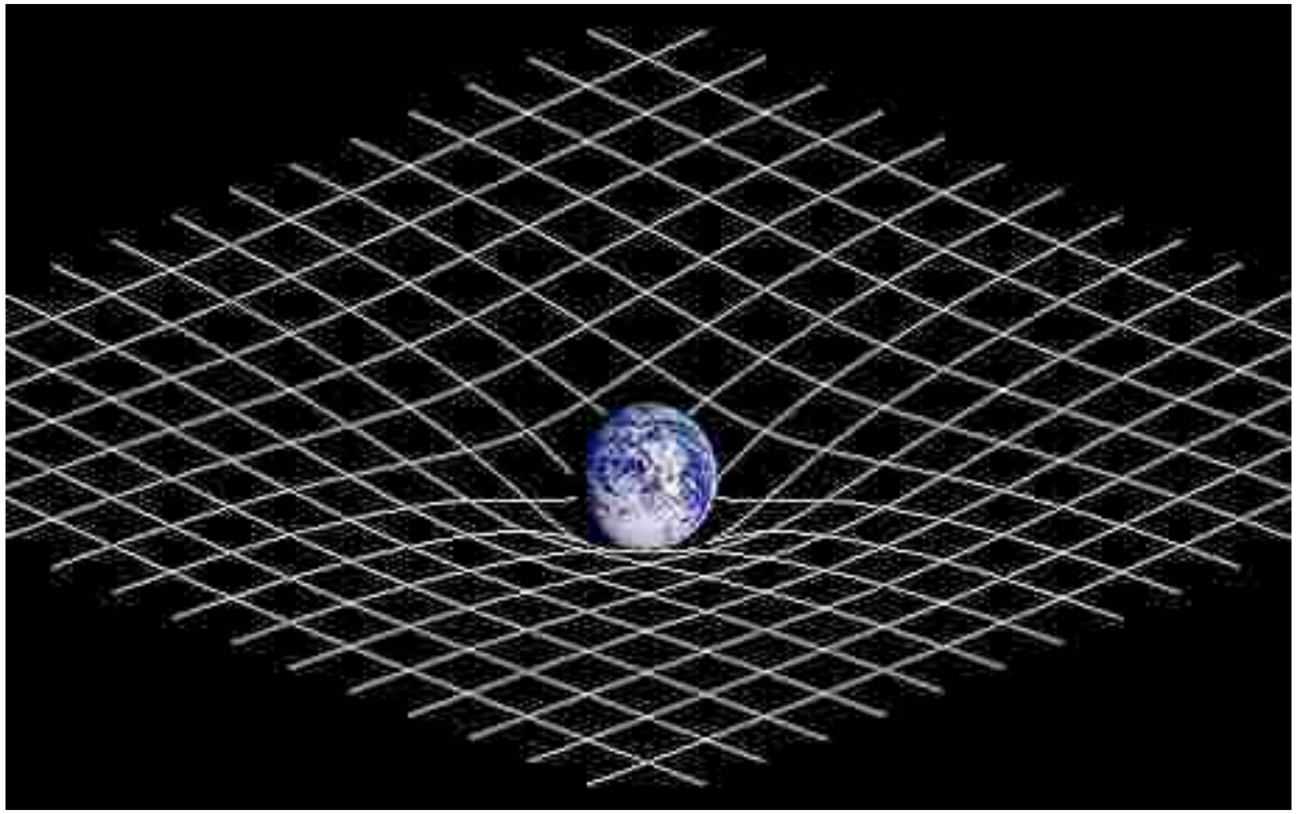
# What are Gravitational Waves ?

Newtonian Gravity $\Rightarrow F = \frac{-GMm}{r^2} \Rightarrow$ Action at a distance.

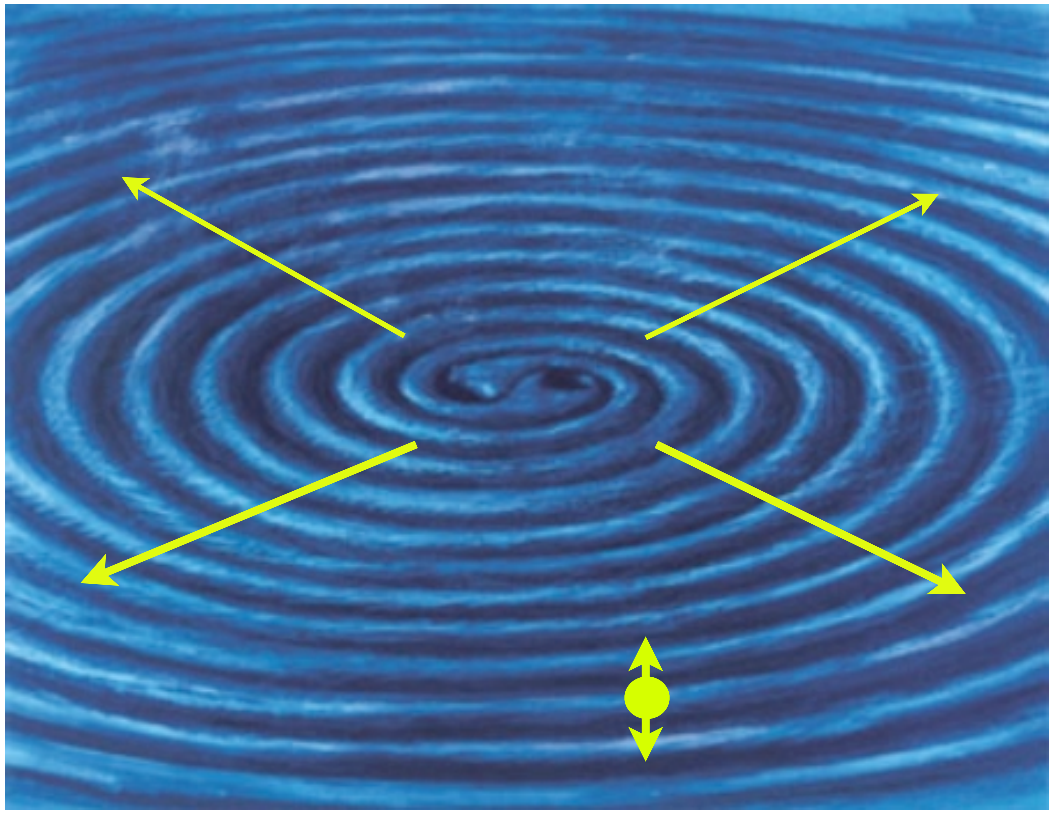
Special Relativity $\Rightarrow$ Limiting, finite speed of propagation for information

In General Relativity, information about sources of gravity is carried at the speed of light by gravitational waves.

A RUBBER SHEET ANALOGY



RUBBER SHEET POTENTIAL MODEL OF A STATIC GRAVITATIONAL FIELD DUE TO A BODY AT REST



RUBBER SHEET POTENTIAL MODEL OF THE GRAVITATIONAL FIELD OF A BINARY SYSTEM

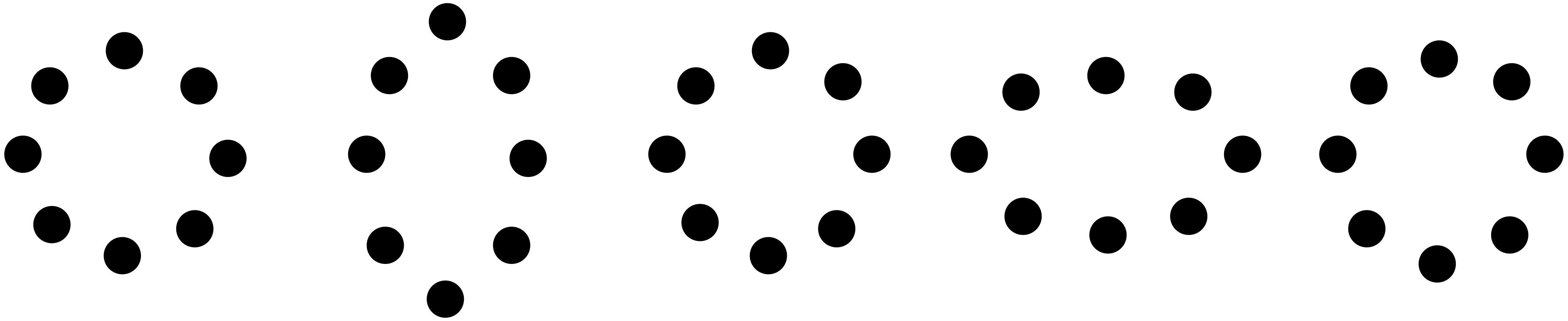
# Sensing gravitational waves

The rubber sheet analogy is imperfect. In fact, gravitational waves cause components of the metric tensor to oscillate. For example:

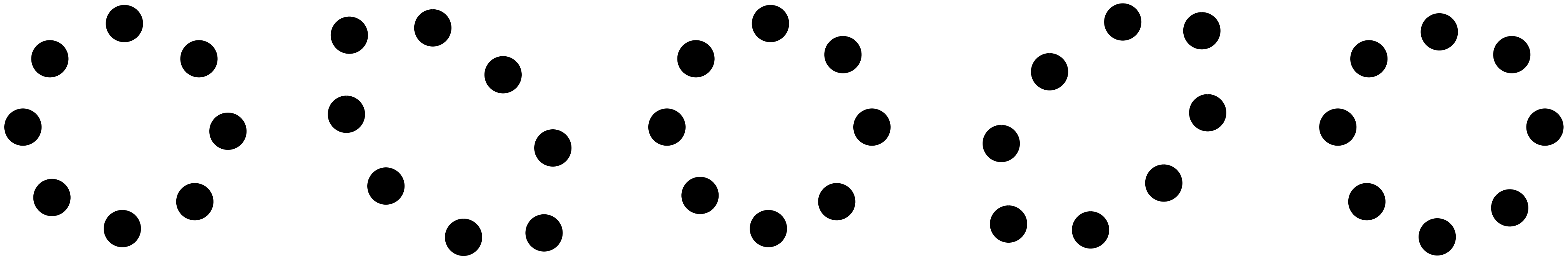
$$(g_{\mu\nu}(z,t)) = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 + h_+ \cos(kz - \omega t) & 0 & 0 \\ 0 & 0 & 1 - h_+ \cos(kz - \omega t) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

These oscillations cause massive objects in free fall to oscillate

For the waves above (+ polarized), a ring of test masses would do this:

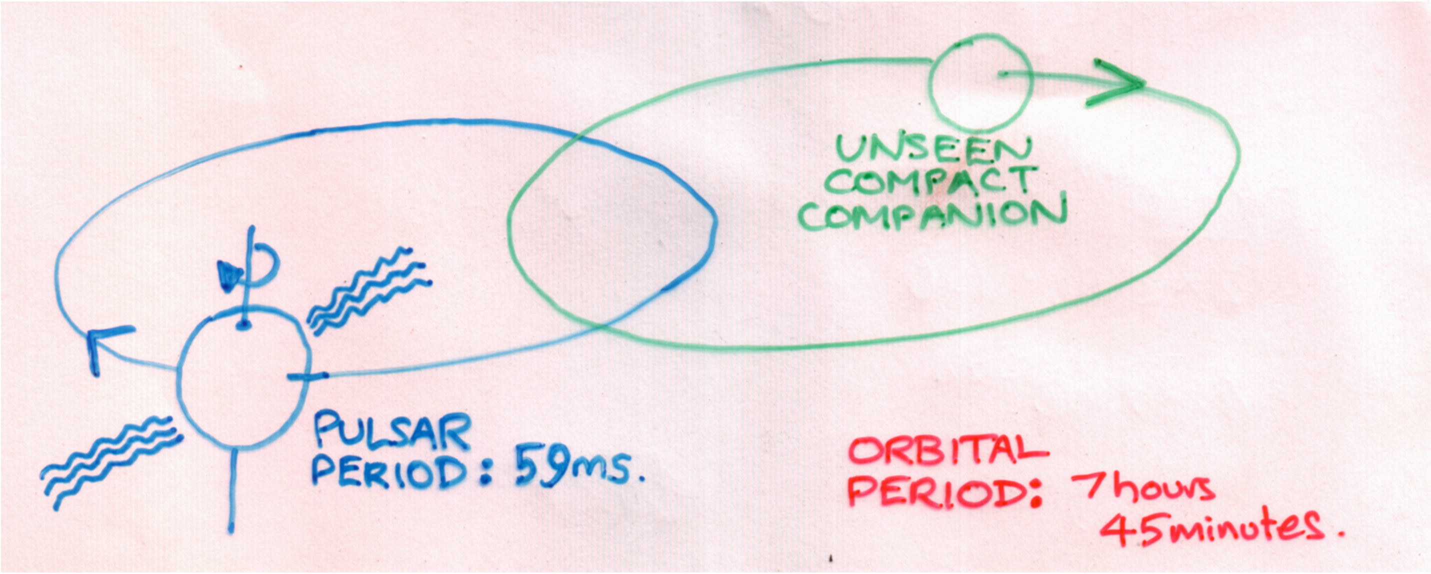


For a second, orthogonal (x) polarization:



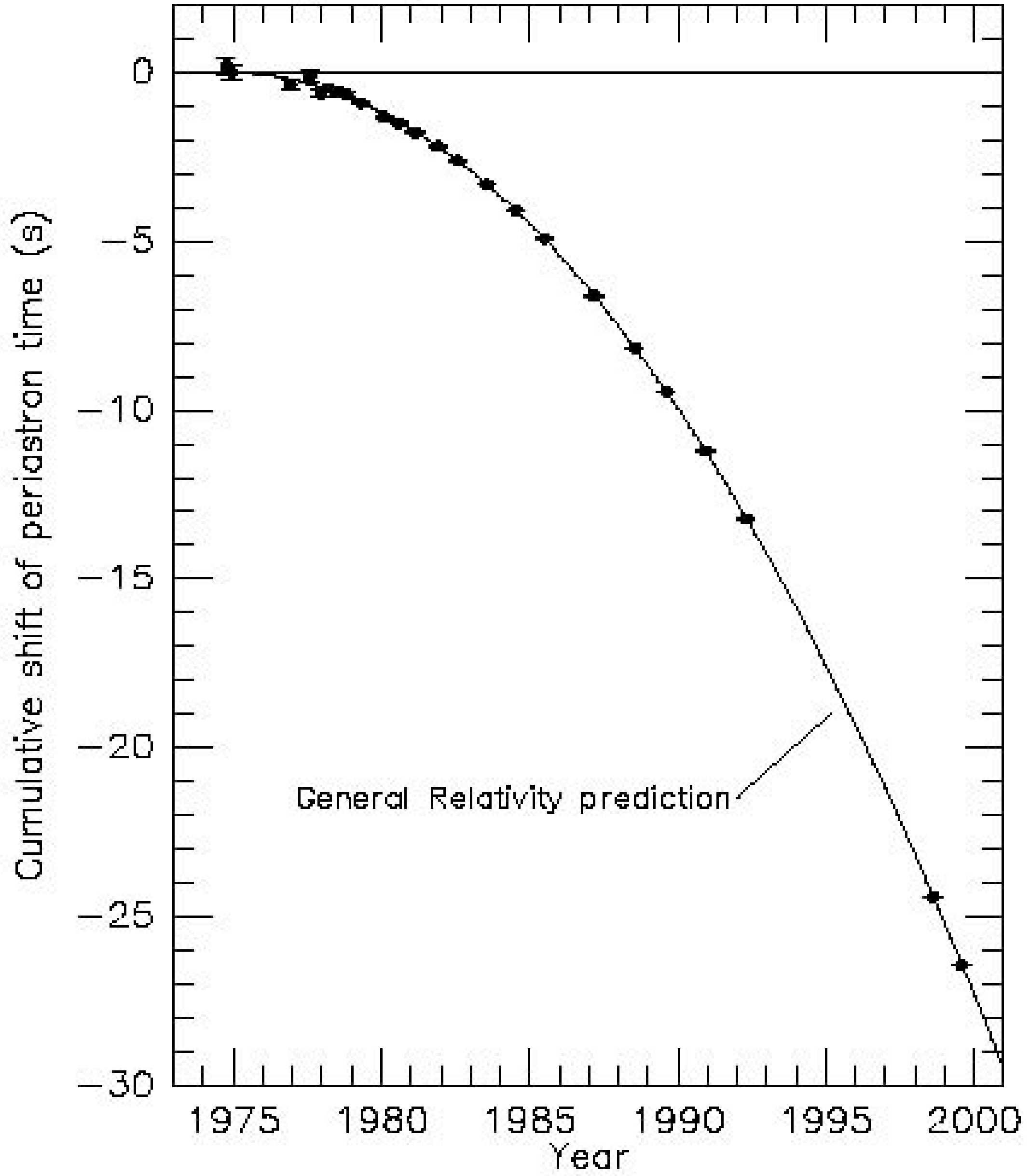
# Indirect Evidence for Gravitational Waves

Binary pulsar PSR1913+16, Hulse and Taylor, 1976



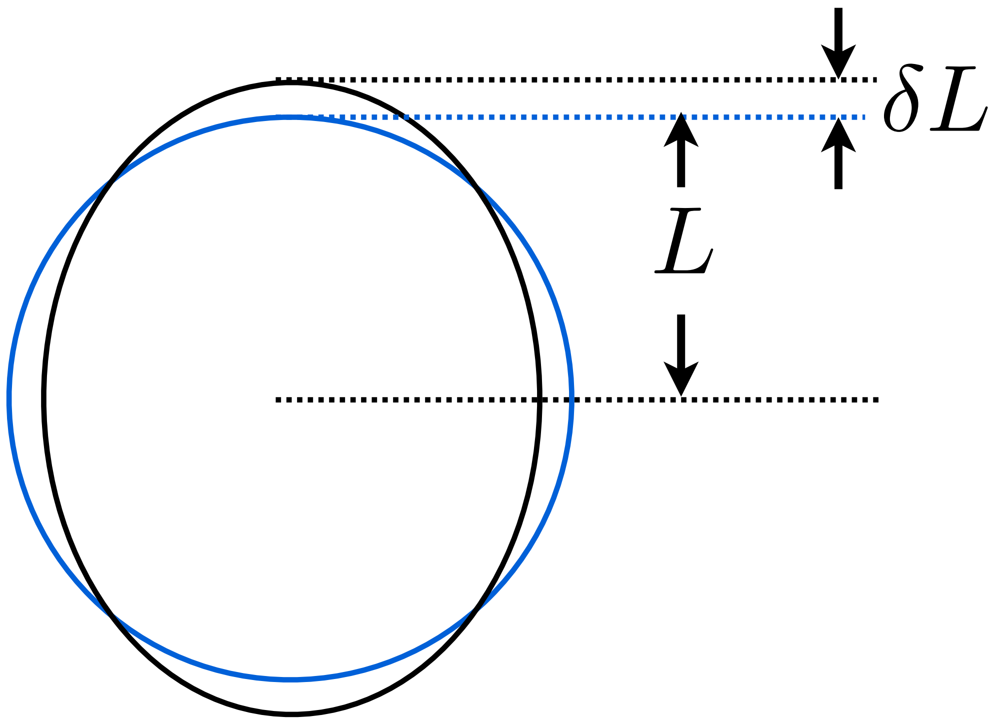
Doppler shift of millisecond pulses gives a measure of the orbital period. Orbital period decreases with time as system radiates energy in gravitational waves.

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



From J. H. Taylor and J. M. Weisberg (2000), unpublished

# Anticipated Signal Strength



For an optimistic source, like a neutron star pair inspiral in the Virgo cluster, 20 Mpc from here,

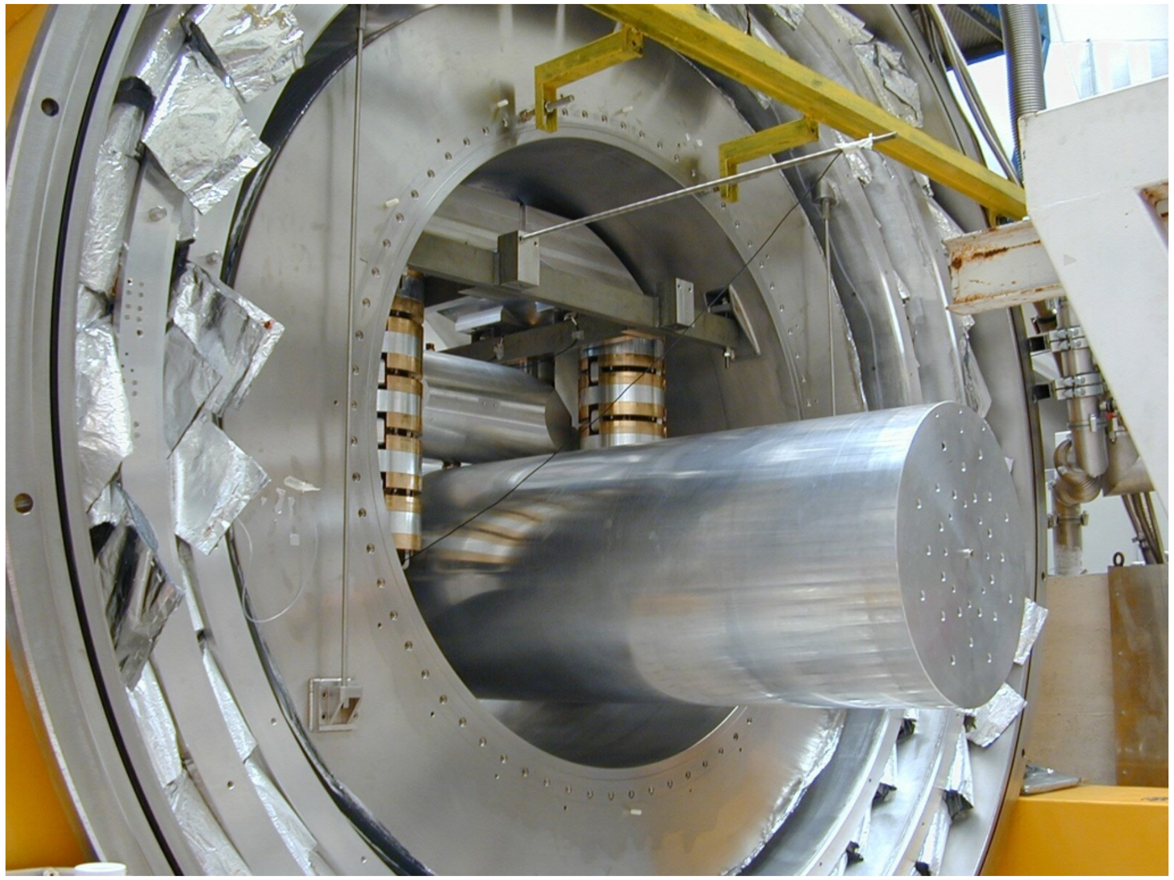
$$\frac{\delta L}{L} \sim 10^{-21}$$

Two free masses separated by 4km have their separation distorted by about 1/250 of a proton diameter !

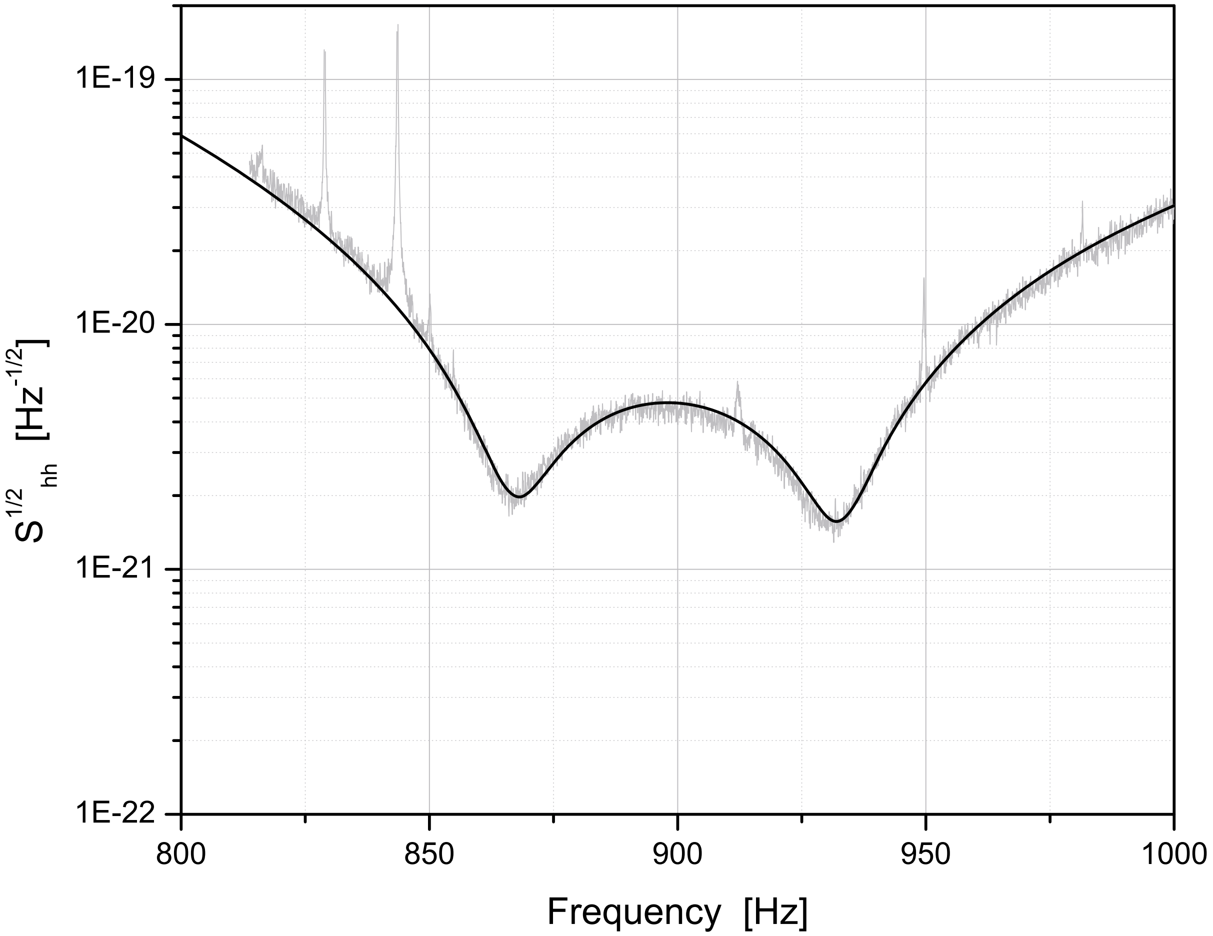
# Detection methods

| METHOD | FREQUENCY/SOURCE z |
|---|---|
| Resonant Detectors | narrow band, few×100 Hz–few kHz. |
| Ground based interferometers | $\sim 10\,\mathrm{Hz} \to \sim 8\,\mathrm{kHz}$ |
| Space based interferometers | $\sim 10^{-4}\,\mathrm{Hz} \to \sim 1\,\mathrm{Hz}$ |
| Pulsar timing measurements | $\sim 10^{-9}\,\mathrm{Hz} \to \sim 10^{-7}\mathrm{Hz}$ |
| CMBR polarisation | $z = 1100,\ z = 10$ |

# Resonant Detectors



AURIGA



Mion et al., A&A 504, 673-679 (2009)

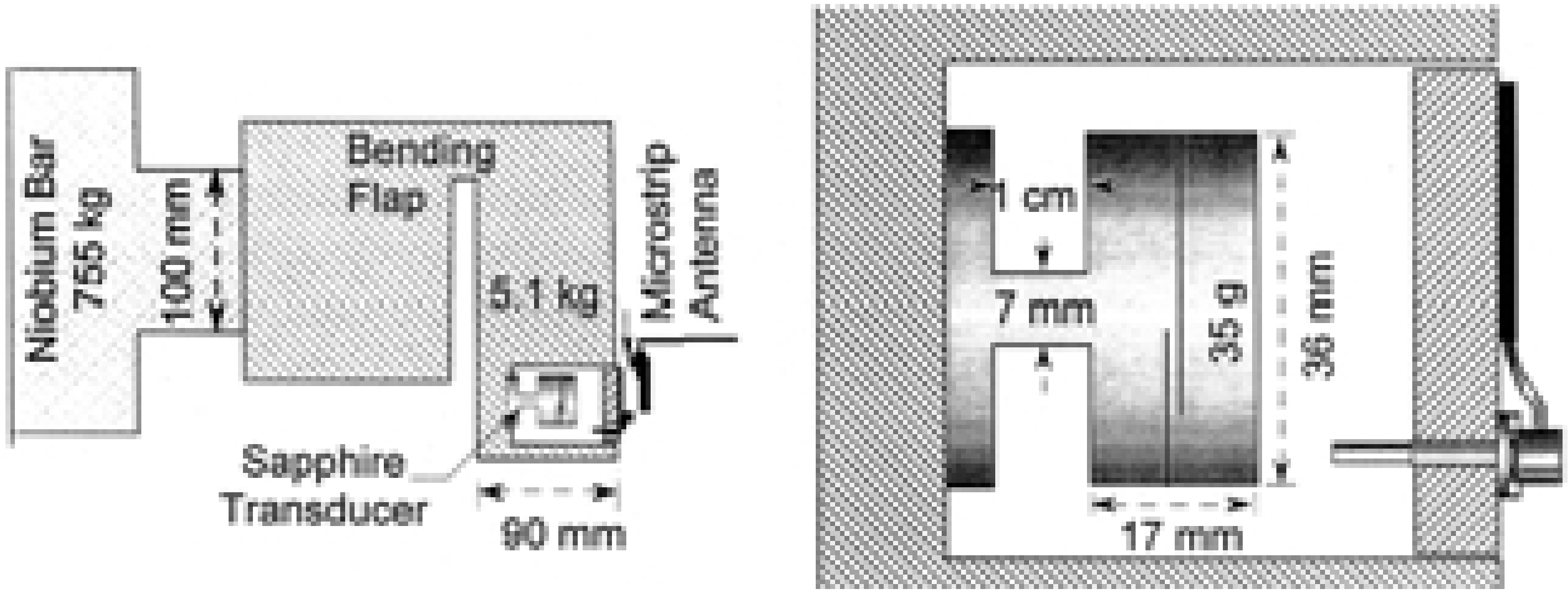
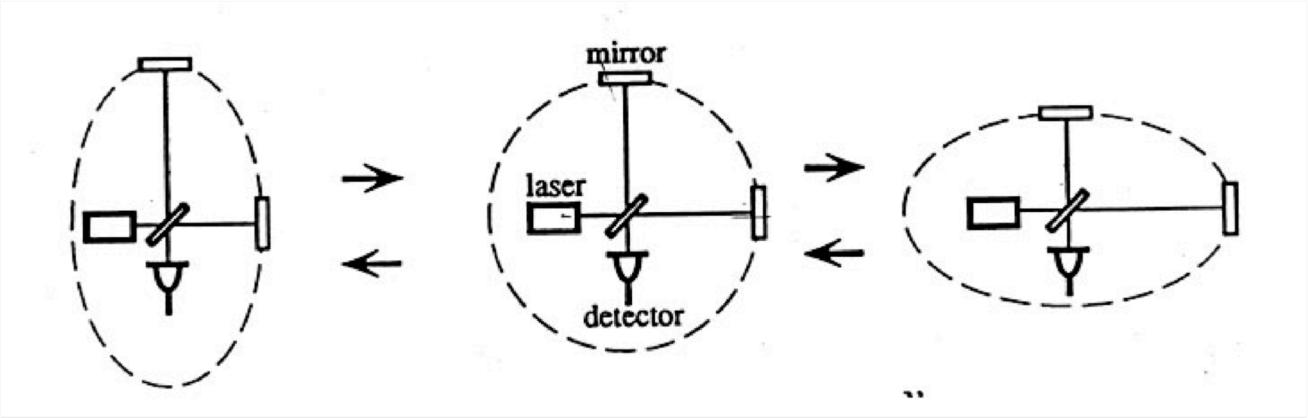


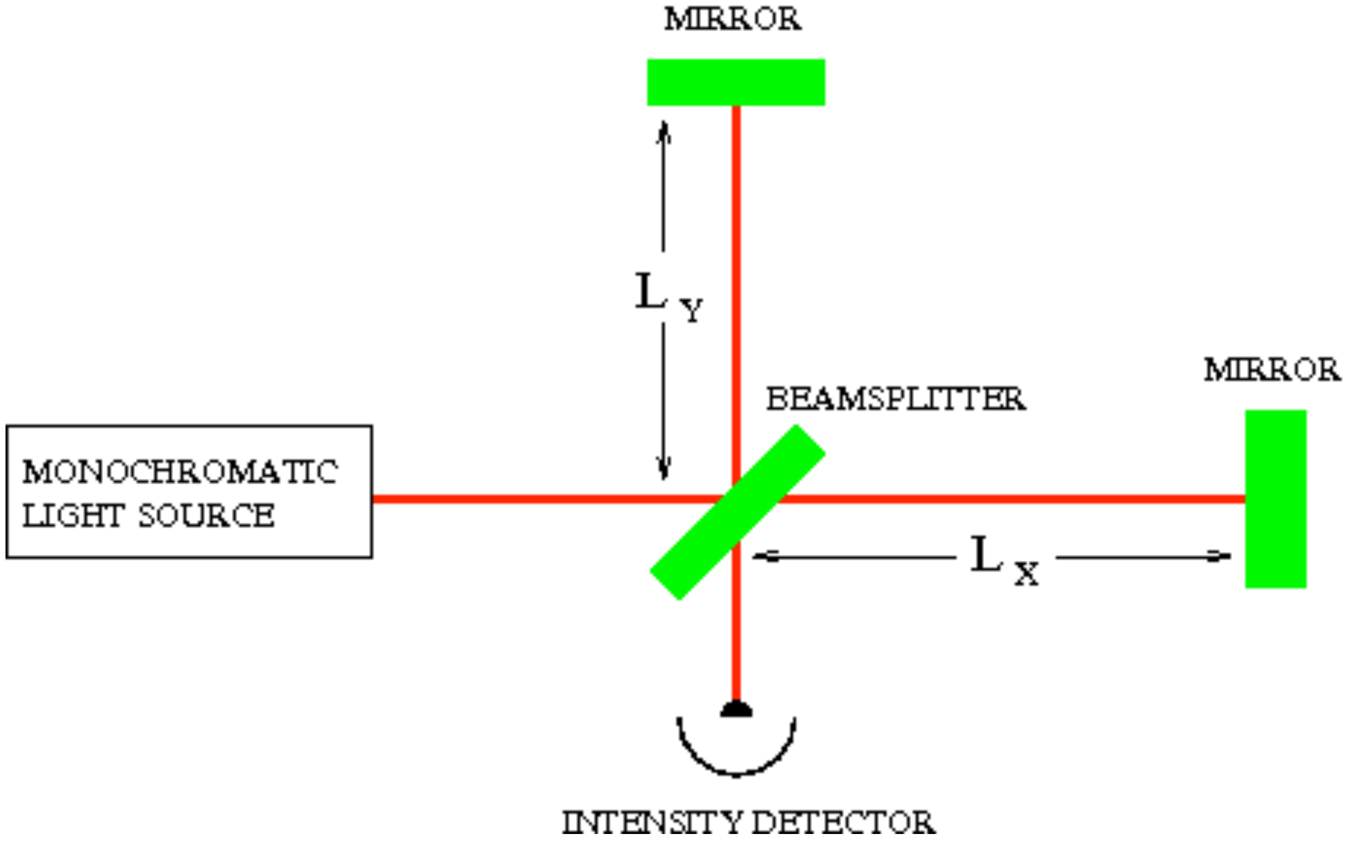
**Figure 3.** Left: Schematic of the resonant sapphire transducer configuration for Niobe as a 3-mode detector. Right: Close up of the resonant sapphire transducer, the fundamental clapping mode of the slotted sapphire can be tuned to the main resonant detector (Niobe or Sphere) near 700 to 800 Hz.

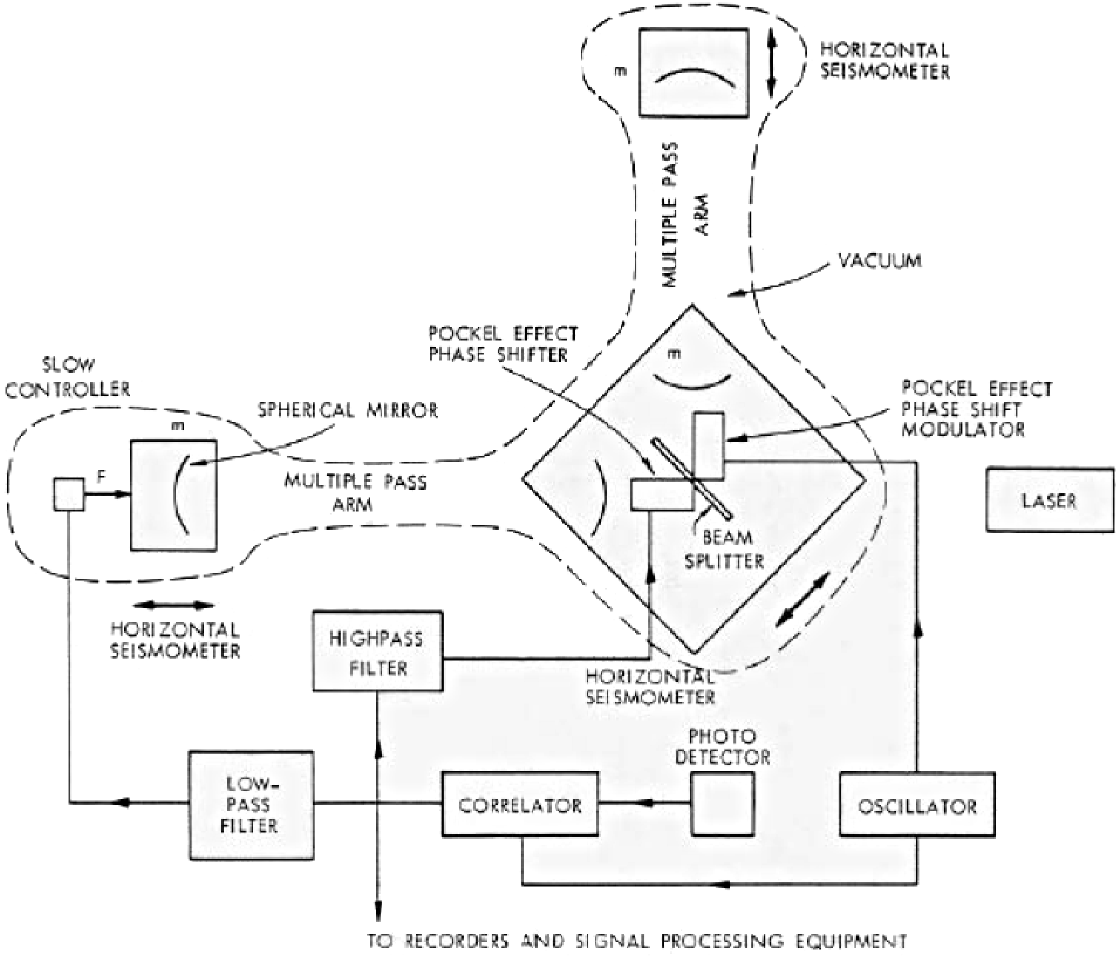
M. Tobar, E. Ivanov, D. Blair,
General Relativity and Gravitation
Vol. 32, No. 9, 2000

# Ground Based Interferometers



http://www.ligo.caltech.edu/docs/P/P720002-01/P720002-01.pdf





# Small strains necessitate big interferometers


LIGO Livingston Observatory, Louisiana, U.S.A.


GEO 600 - Hopfenberg, near Hannover, DE

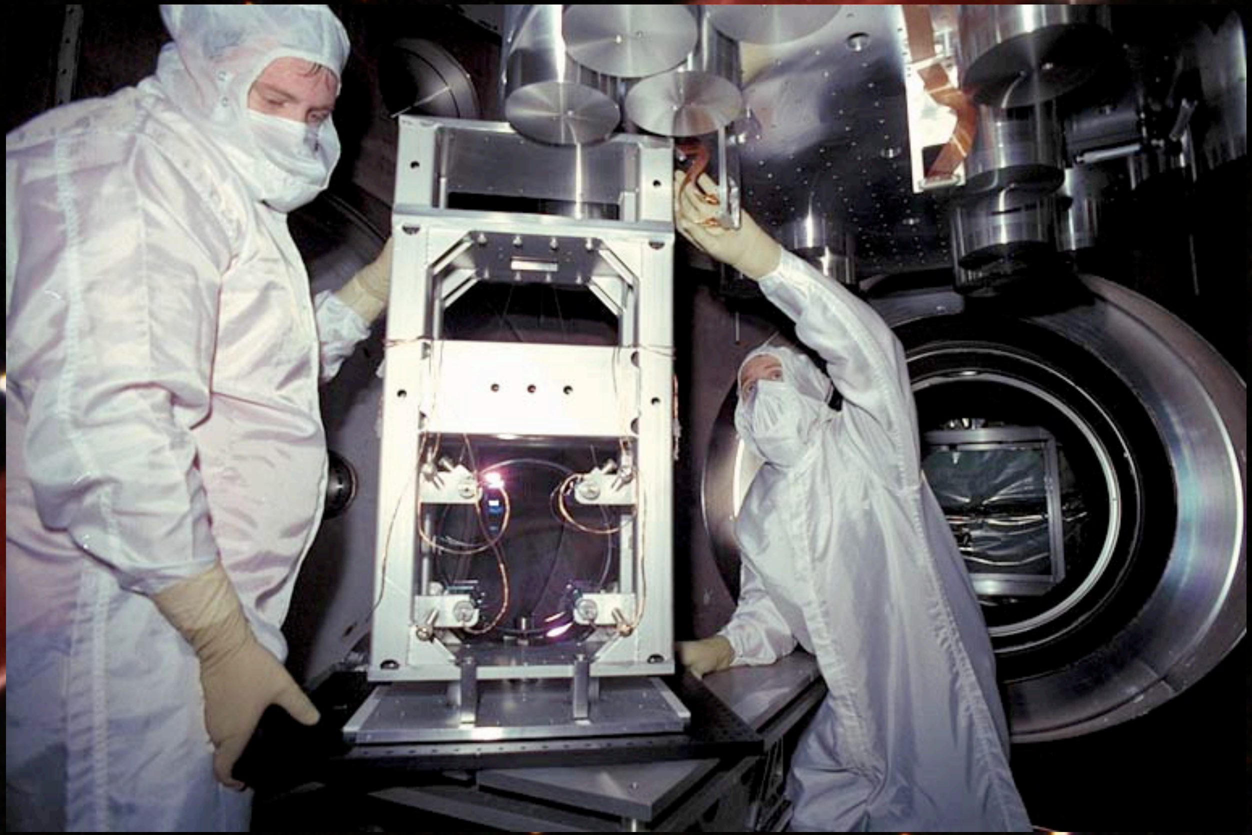

LIGO Hanford Observatory, Washington State, U.S.A.

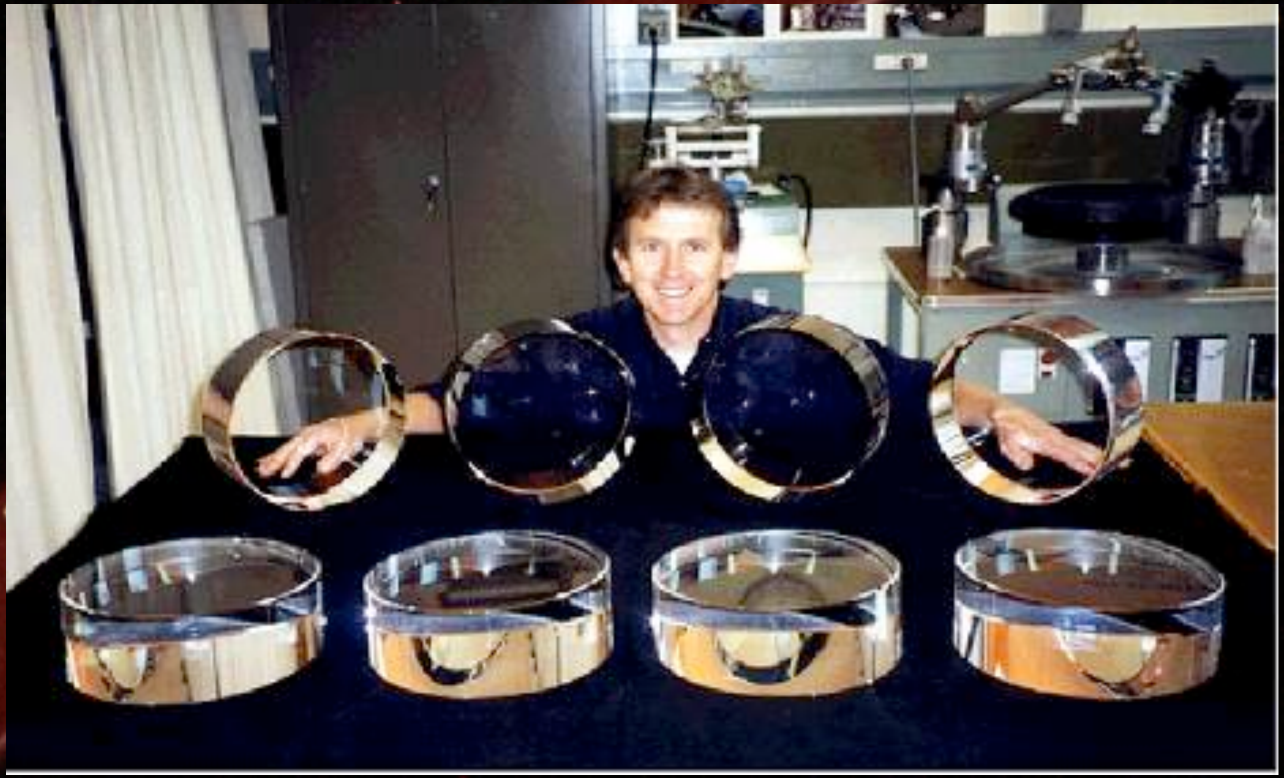

Virgo - EGO laboratory, Cascina, near Pisa, Italy.

# Some LIGO Technology

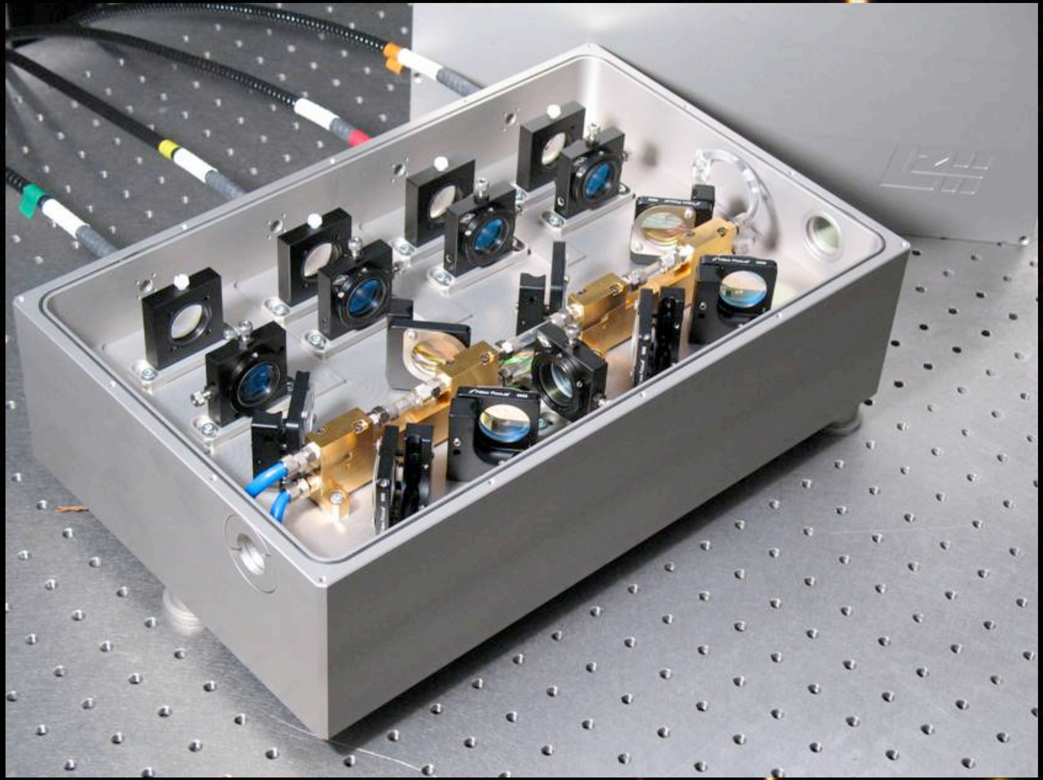
Vacuum system inside the corner station at Livingston

Livingston beam splitter installation





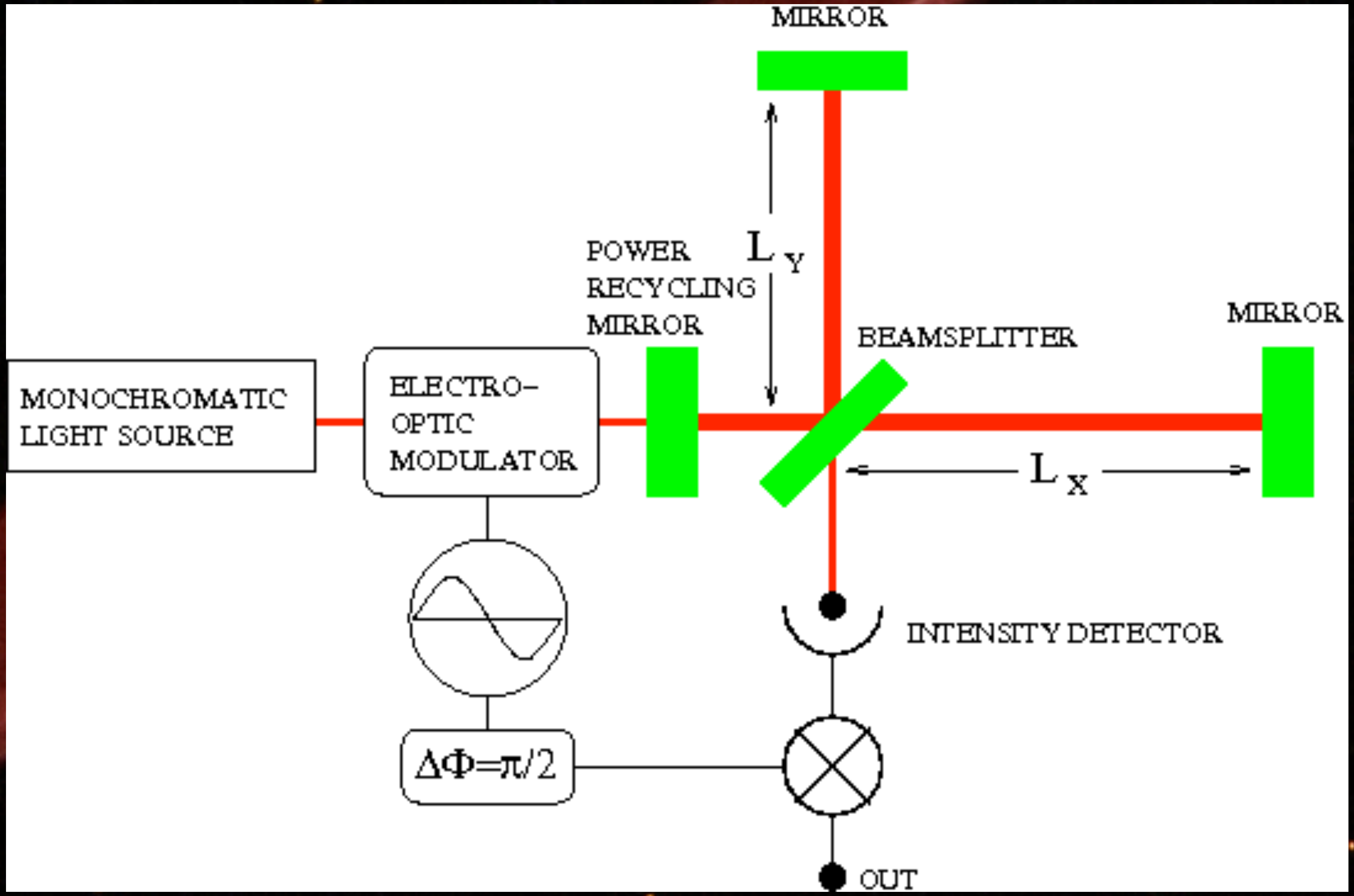
Initial LIGO fused silica optics



35W CW output 1.06um laser amplifier (Enhanced LIGO)

# Power Recycling

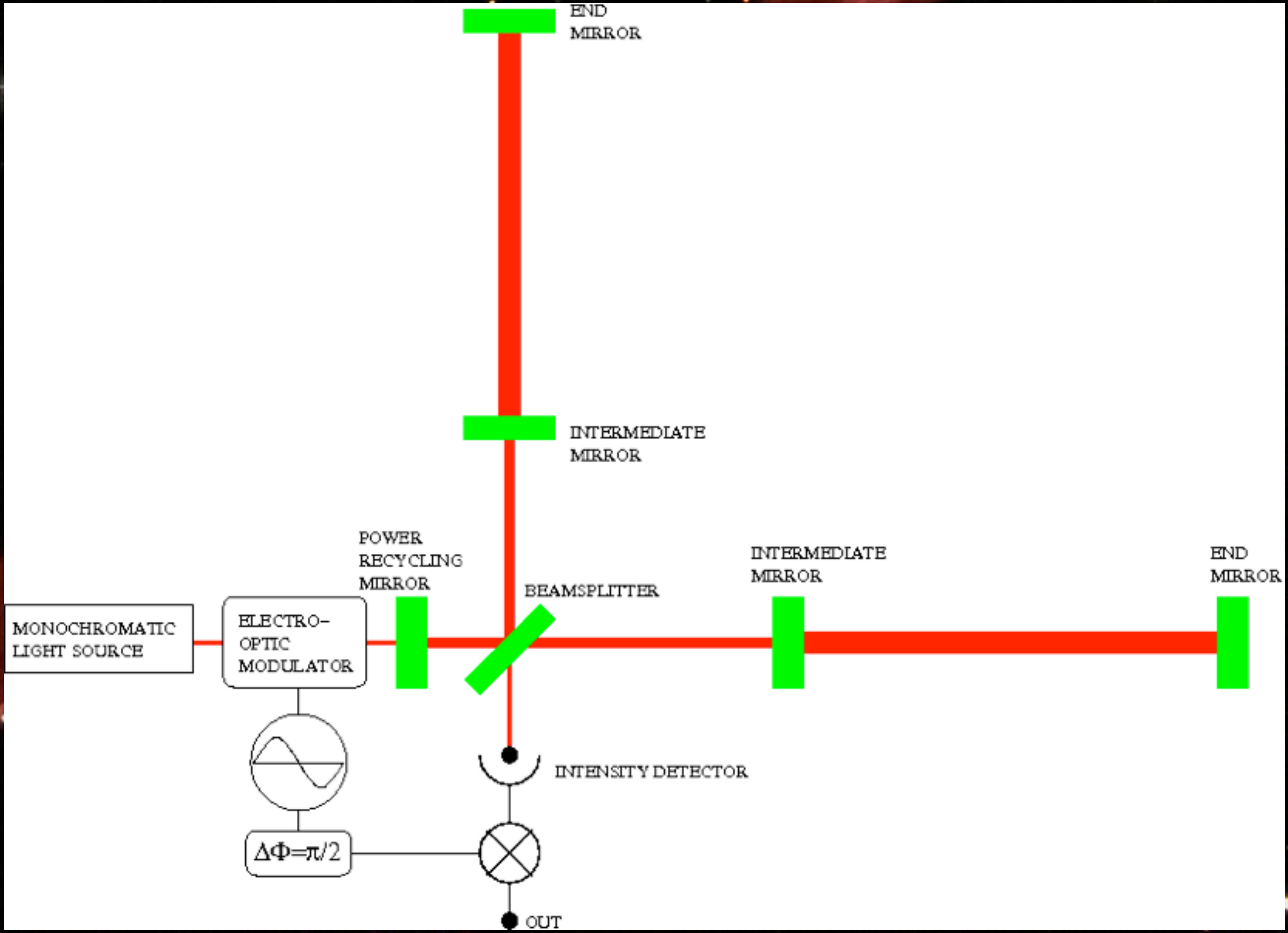
Normally the interferometer is operated on a dark fringe, with differential length signals being read out using a phase modulation scheme on the laser light. This yields a signal that is linear in the gravitational wave amplitude.



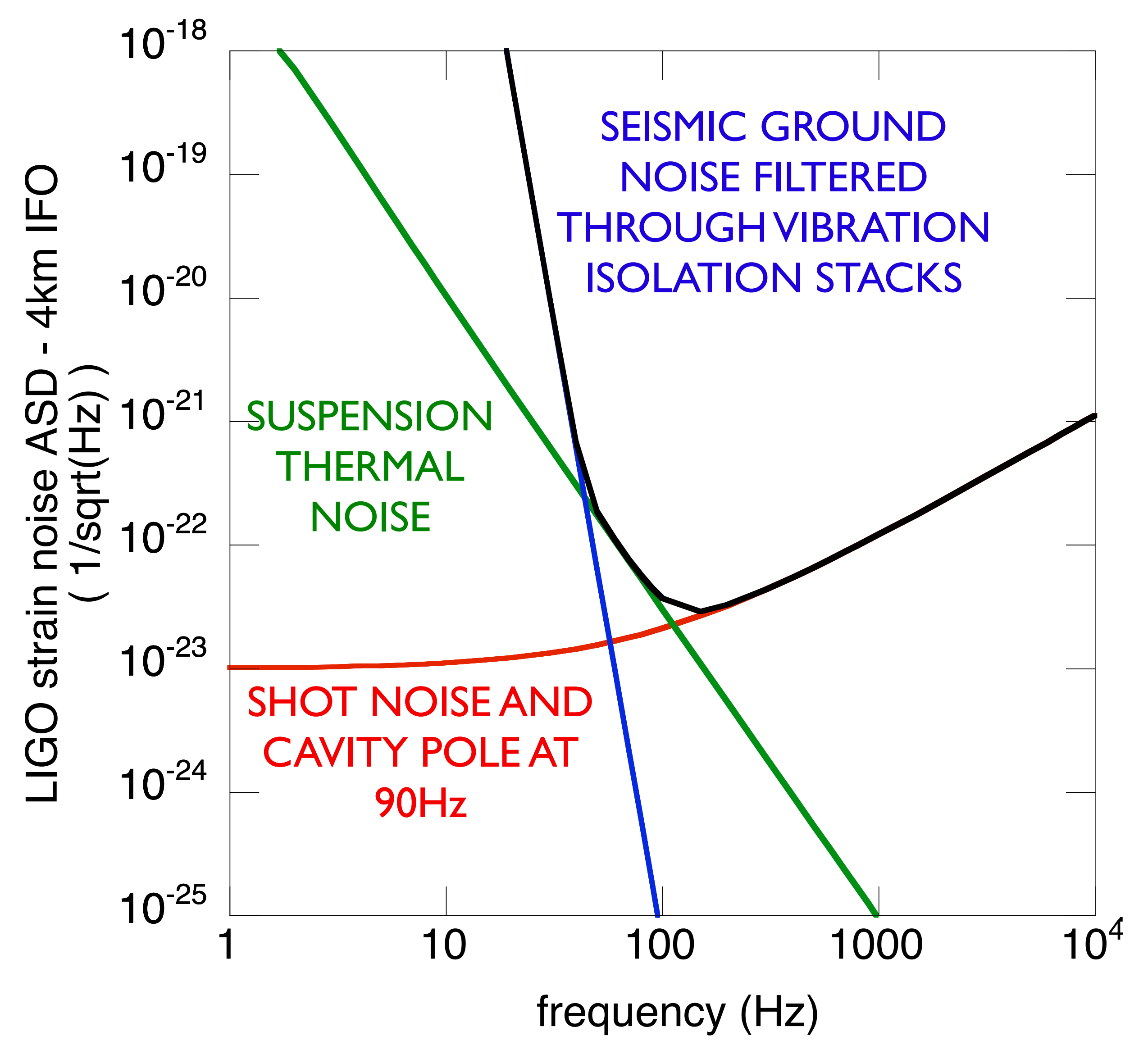
If we are on a dark fringe, where does the laser light go? Back towards the laser. To maximise power at the beam splitter, a mirror is placed between the light source and the interferometer is operated as a resonator.

# Making the interferometer arms longer

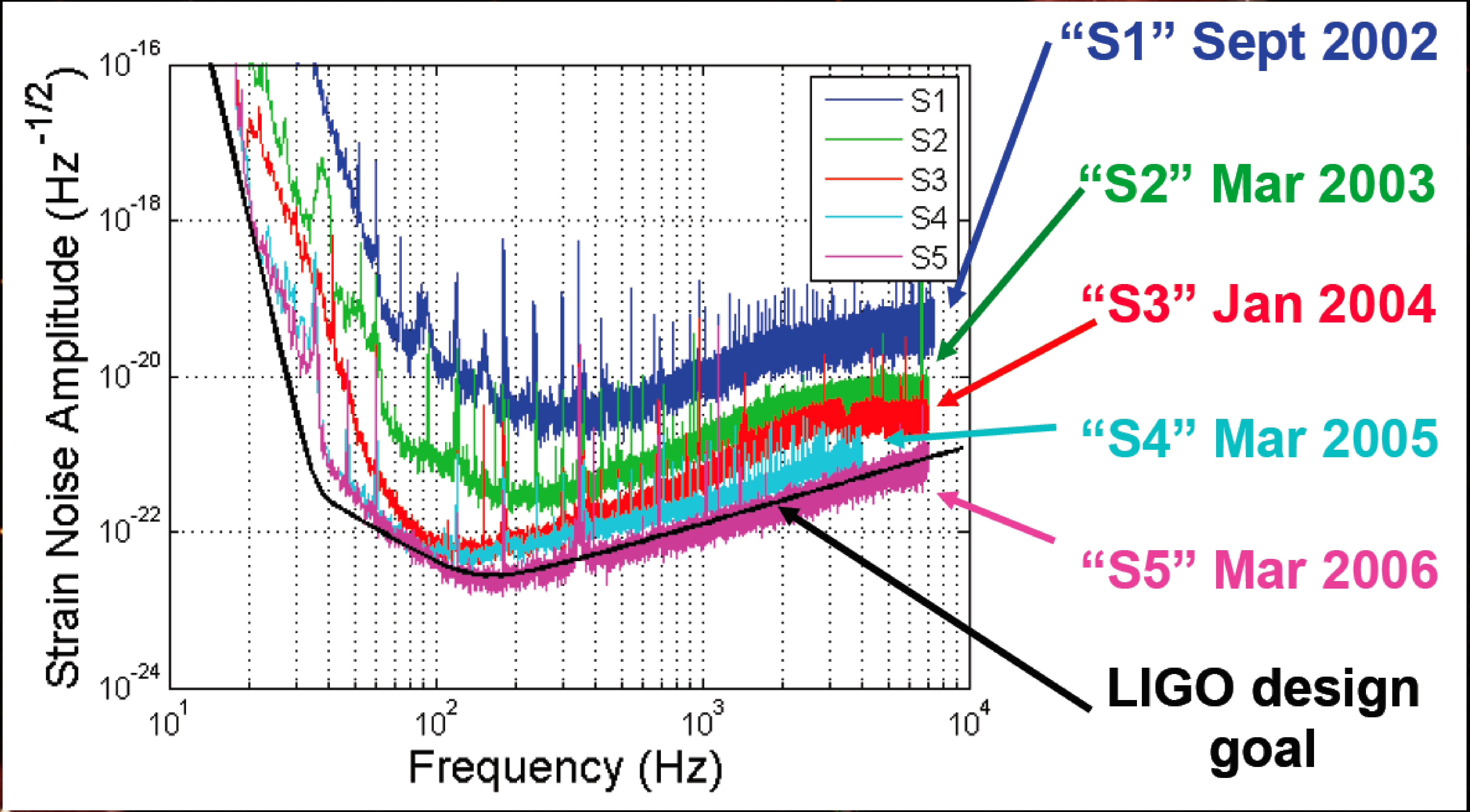
Finally, the signal detected is proportional to the phase shift of photons entering the arms. So make the arms as long as possible, but also make the arms into resonators, so that each photon makes multiple trips (around 100) down the arms before returning to the beam splitter.



# The initial LIGO noise floor



# Initial LIGO Hanford strain sensitivity



**“S1” Sept 2002**

**“S2” Mar 2003**

**“S3” Jan 2004**

**“S4” Mar 2005**

**“S5” Mar 2006**

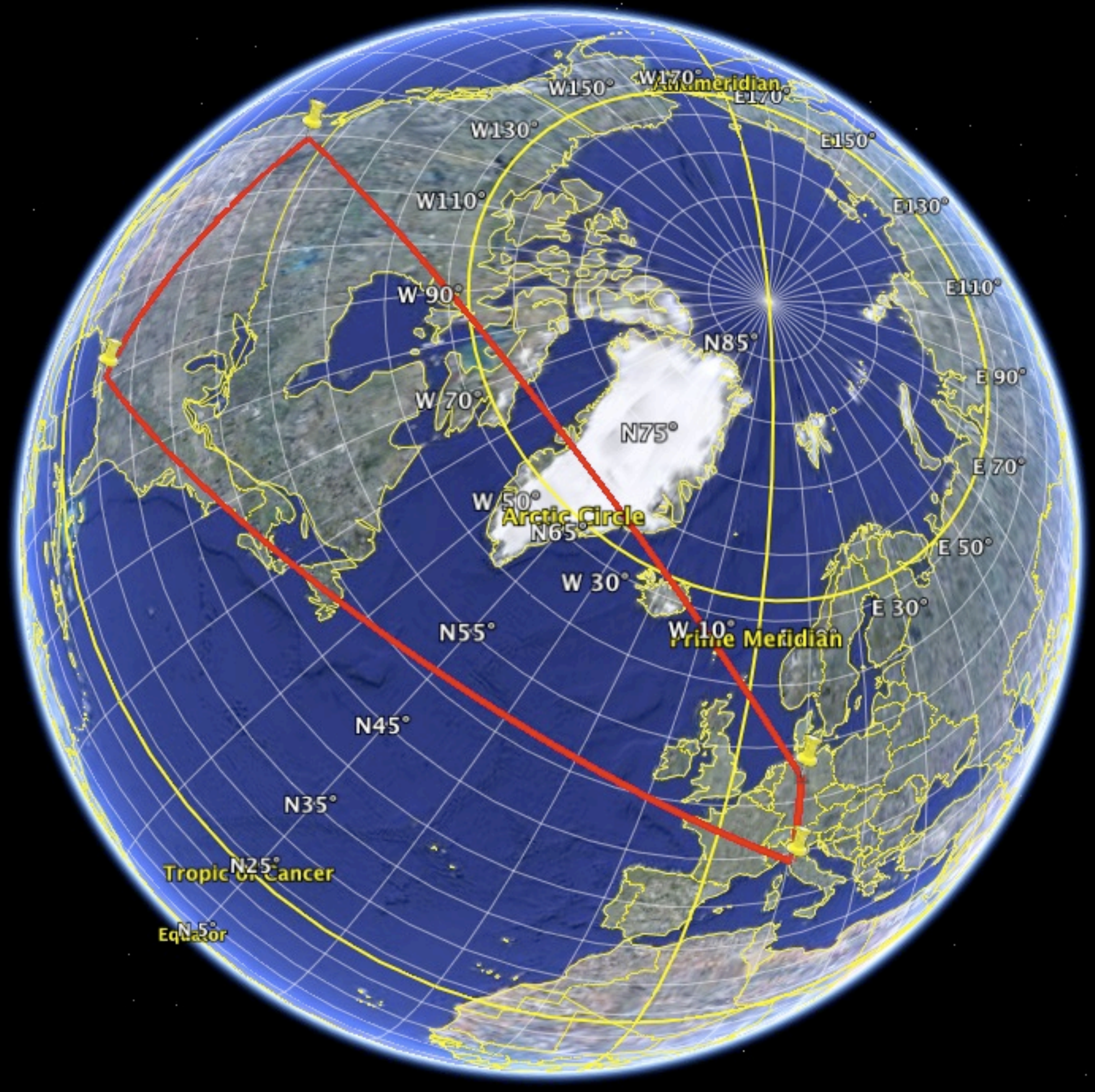
**LIGO design goal**

Narrow line features removed by characterization and subtraction

Some excess noise above initial LIGO design remains below 100Hz.

# Gravitational Wave Interferometer Array, 2010

Longest baseline is approximately $10^7$ m



© 2008 MapLink/Tele Atlas
Image NASA
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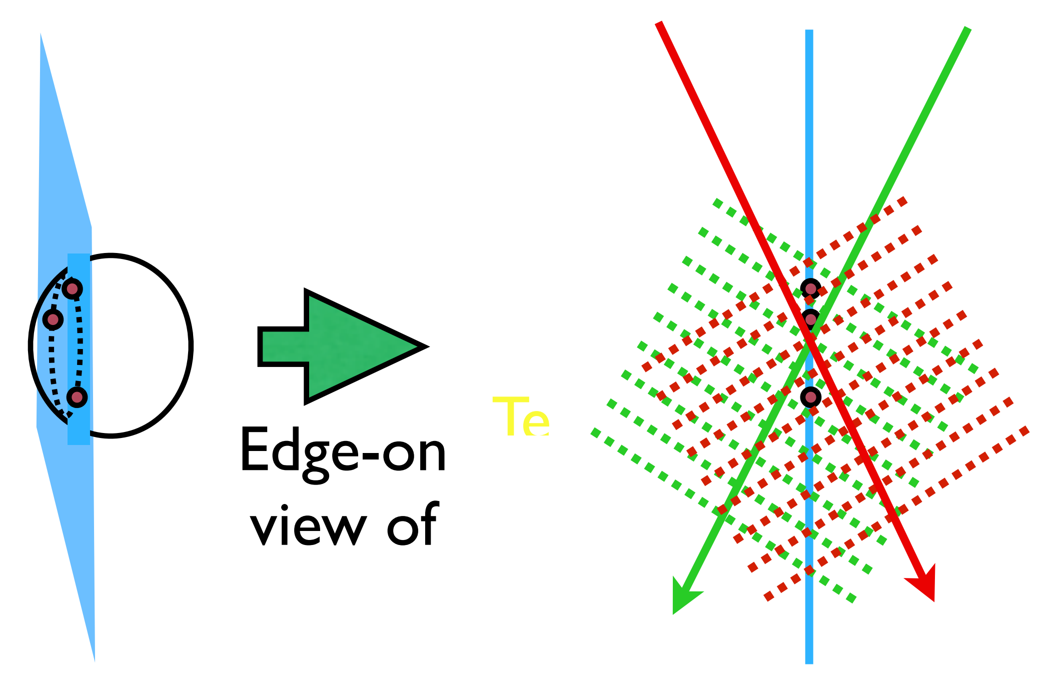
©2008 Google™

63°44'02.98" N 40°09'27.14" W

Eye alt 10642.04 km



# Advanced LIGO Upgrade

## Aim: A factor of 10 reduction in noise floor compared to initial LIGO

Enhancements:

Active seismic isolation
Reduced thermal noise suspensions
Higher laser power
More sensitive and flexible optical layout.

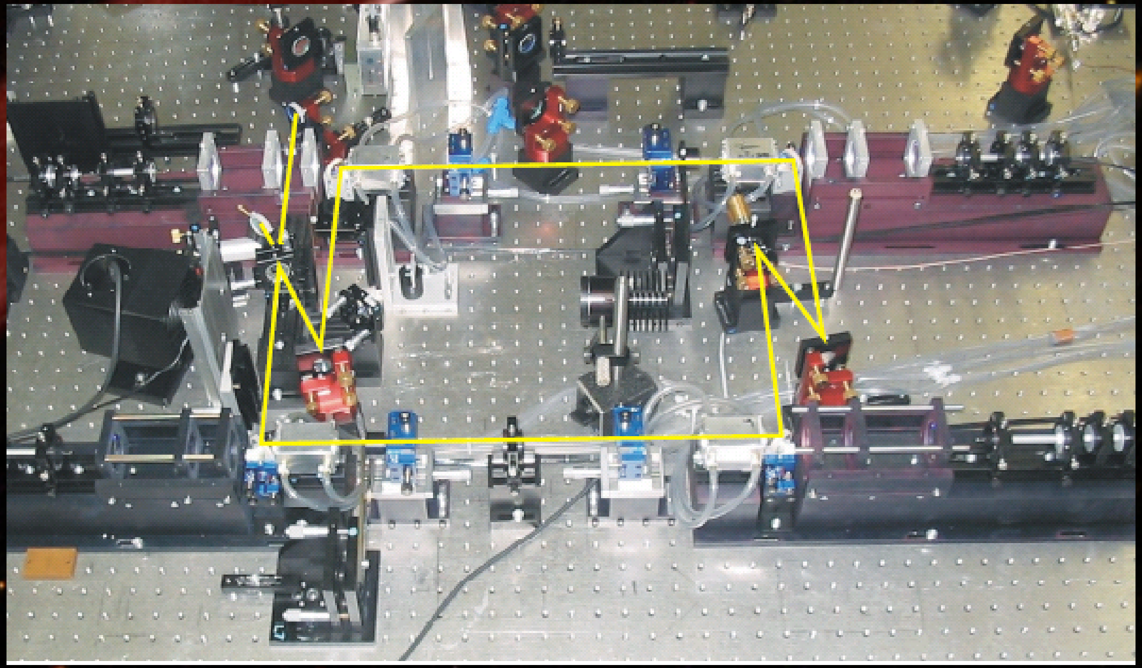
Current status:

Advanced LIGO has started.
U.S. (NSF), U.K. (STFC), and German funding.
Turn-on scheduled for 2014.

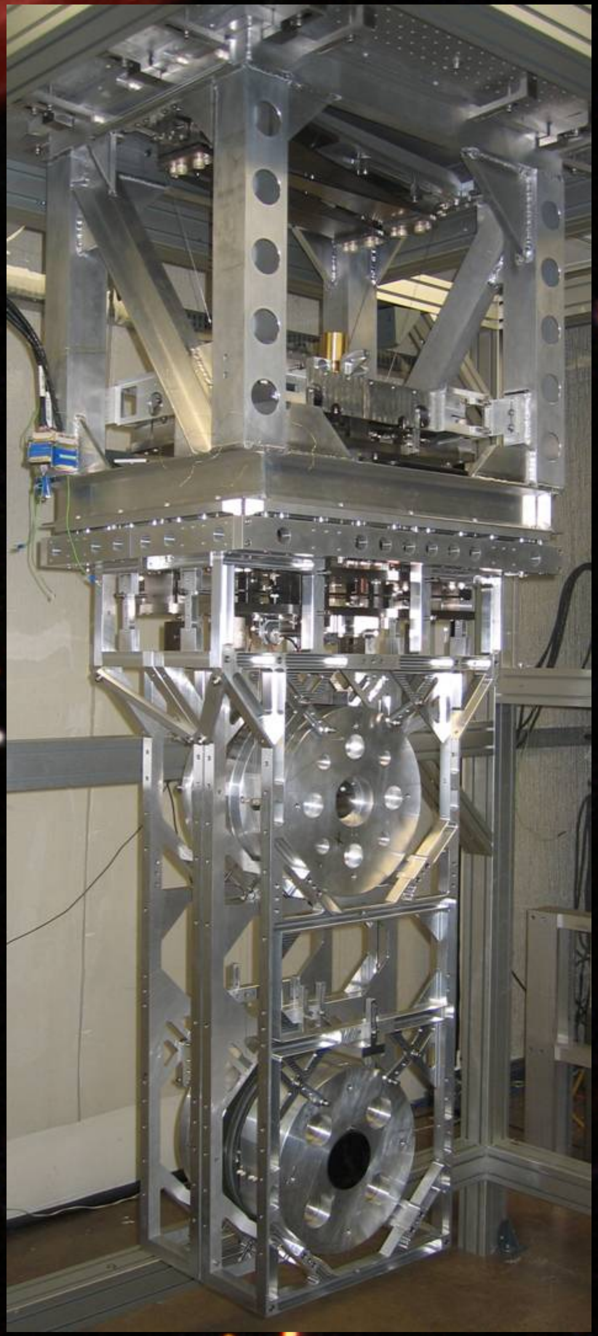
# Advanced LIGO Hardware

- 180W laser power
- HEPI active vibration isolation at both sites
- High Q compound pendulum suspensions
- 40kg optics to reduce radiation pressure noise
- Signal recycling mirror for narrowbanding
- Parallel comparable upgrades to Virgo

HEPI hydraulic actuator

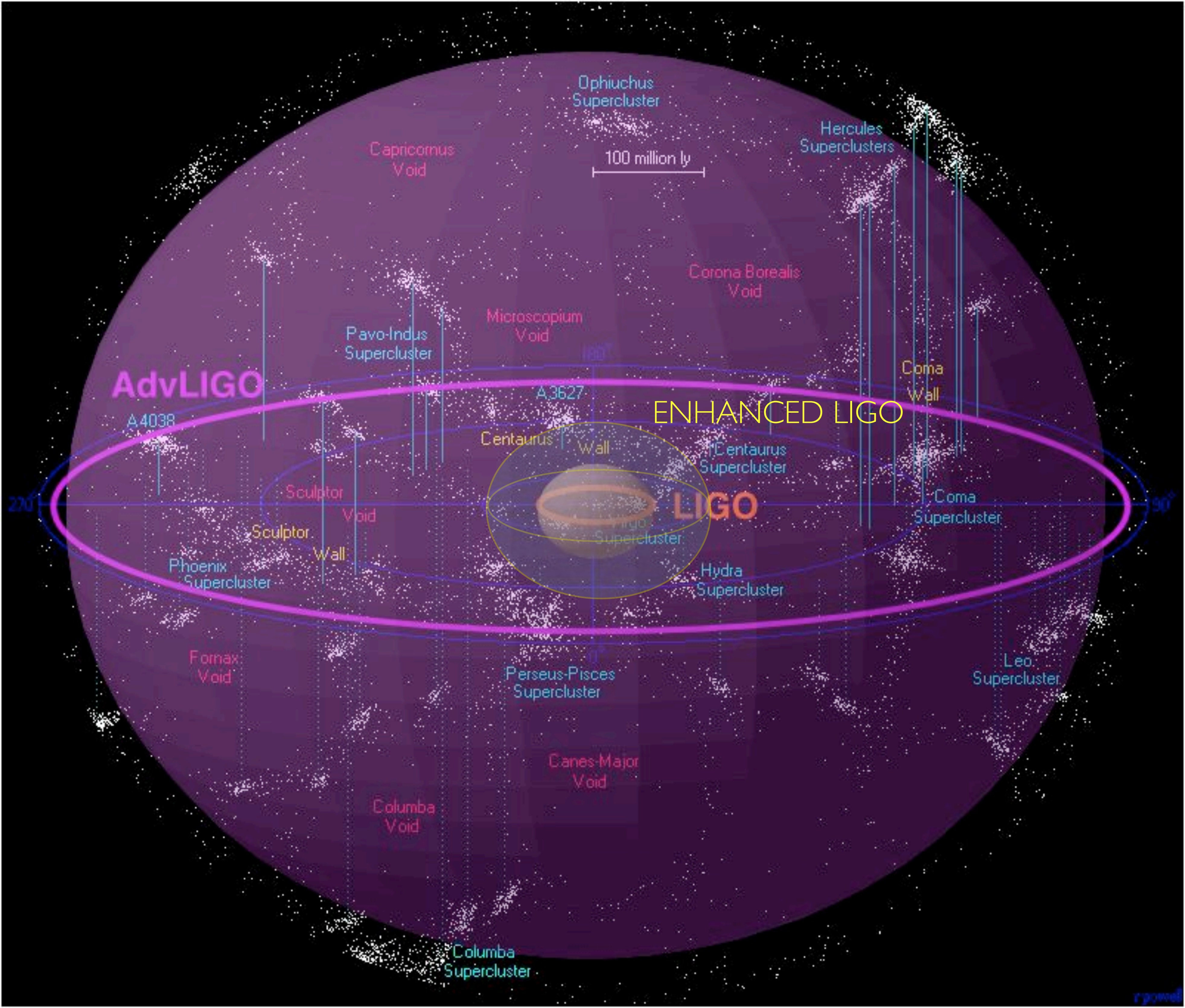


180W laser amplifier prototype (Germany)

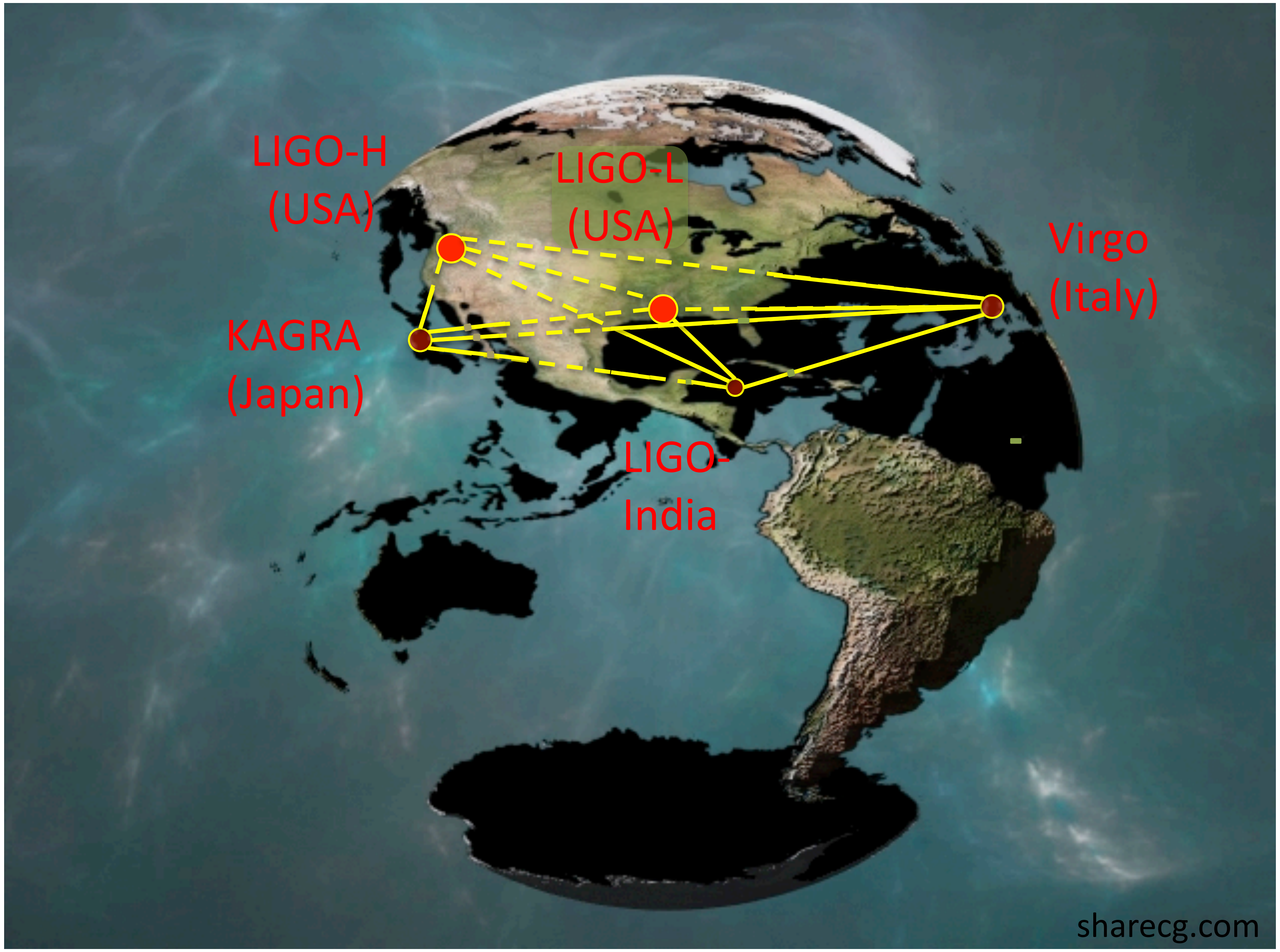


Quad suspension prototype
(U.K.- Glasgow, RAL)

# Reach of Initial, Enhanced and Advanced LIGO



# FUTURE Gravitational Wave Interferometer Network



# Interferometry in Space

The seismic wall between 10 and 100Hz precludes observations below 10Hz using ground based instruments

Space based instruments can be used to look at lower f

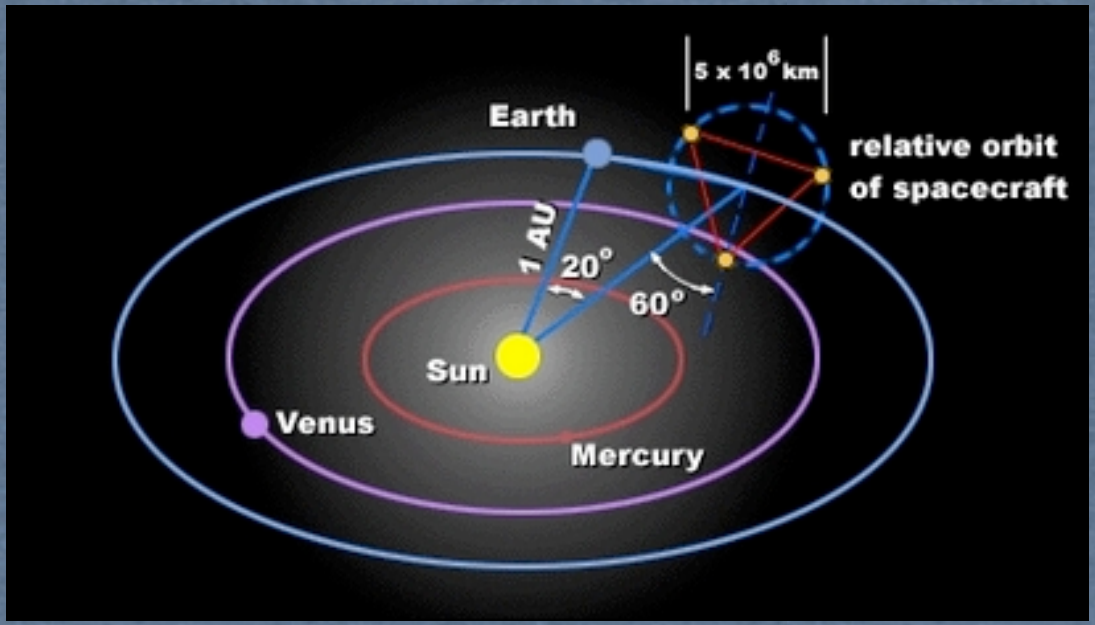
These instruments have their own difficulties

- They are expensive.
- They must work first time in space.
- They must survive launch.
- They must not rely on resonance between spacecraft.
- The test masses must be freely floating.

# The LISA satellite constellation

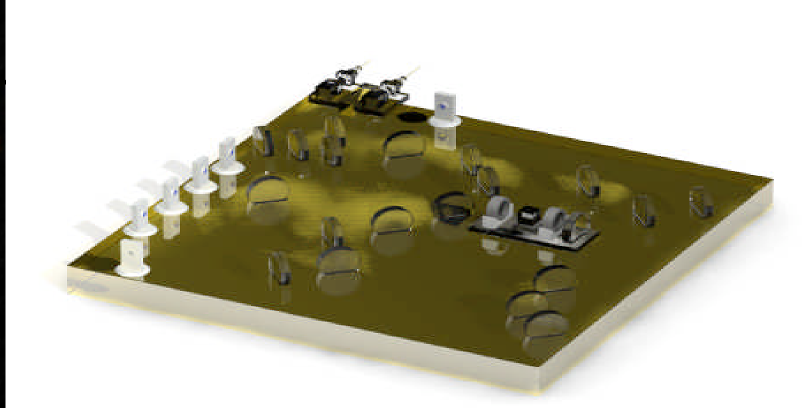
Baseline set by storage time of photons order of period of highest frequency gravitational waves in search.

$$L = c\Delta t = \frac{c}{f}$$ for f=0.1Hz, $$L = \frac{c}{0.1} = 3 \times 10^6\,\mathrm{km}$$



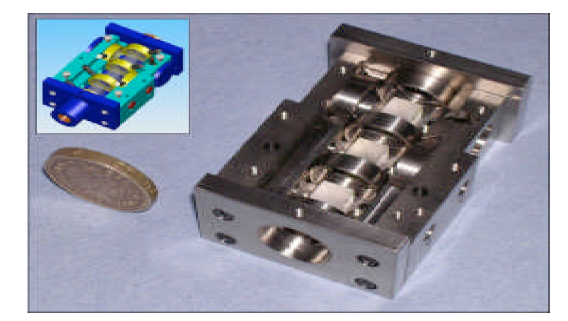
3 LISA satellites in solar orbit

# Some LISA technology



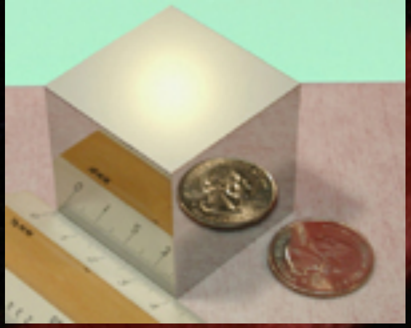
Laser power: 1W.

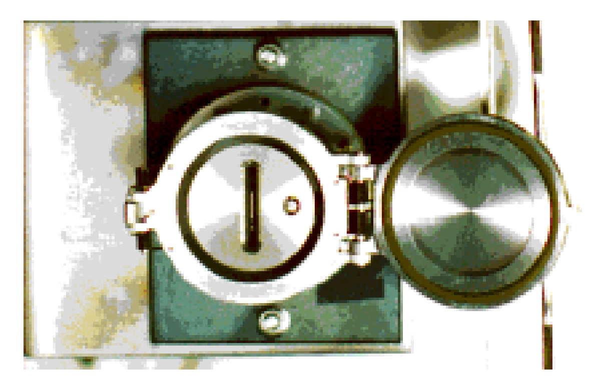
All except 100pW lost in transmission between satellites.

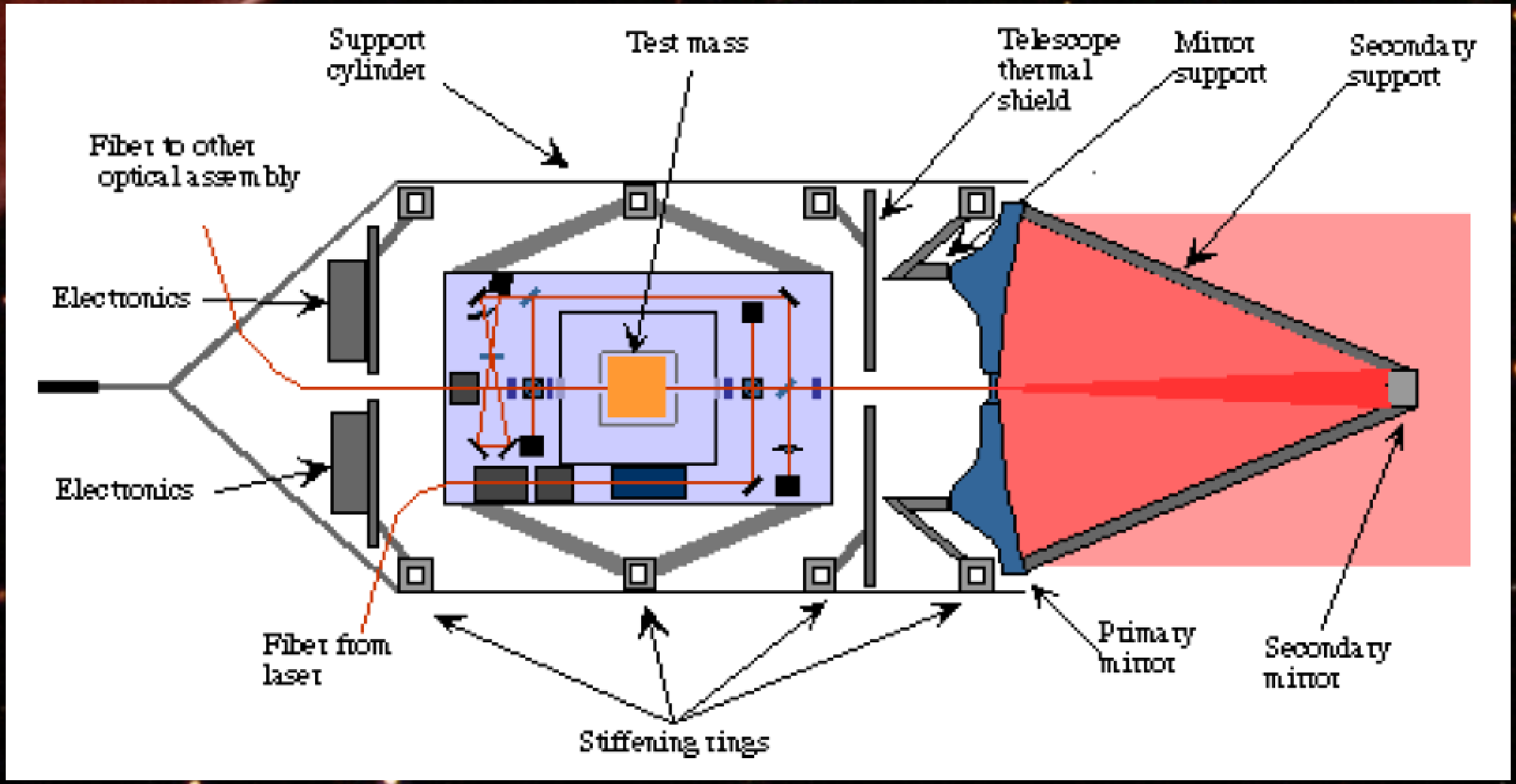


Problem - satellite subject to non-gravitational forces. It is not itself a suitable test mass.

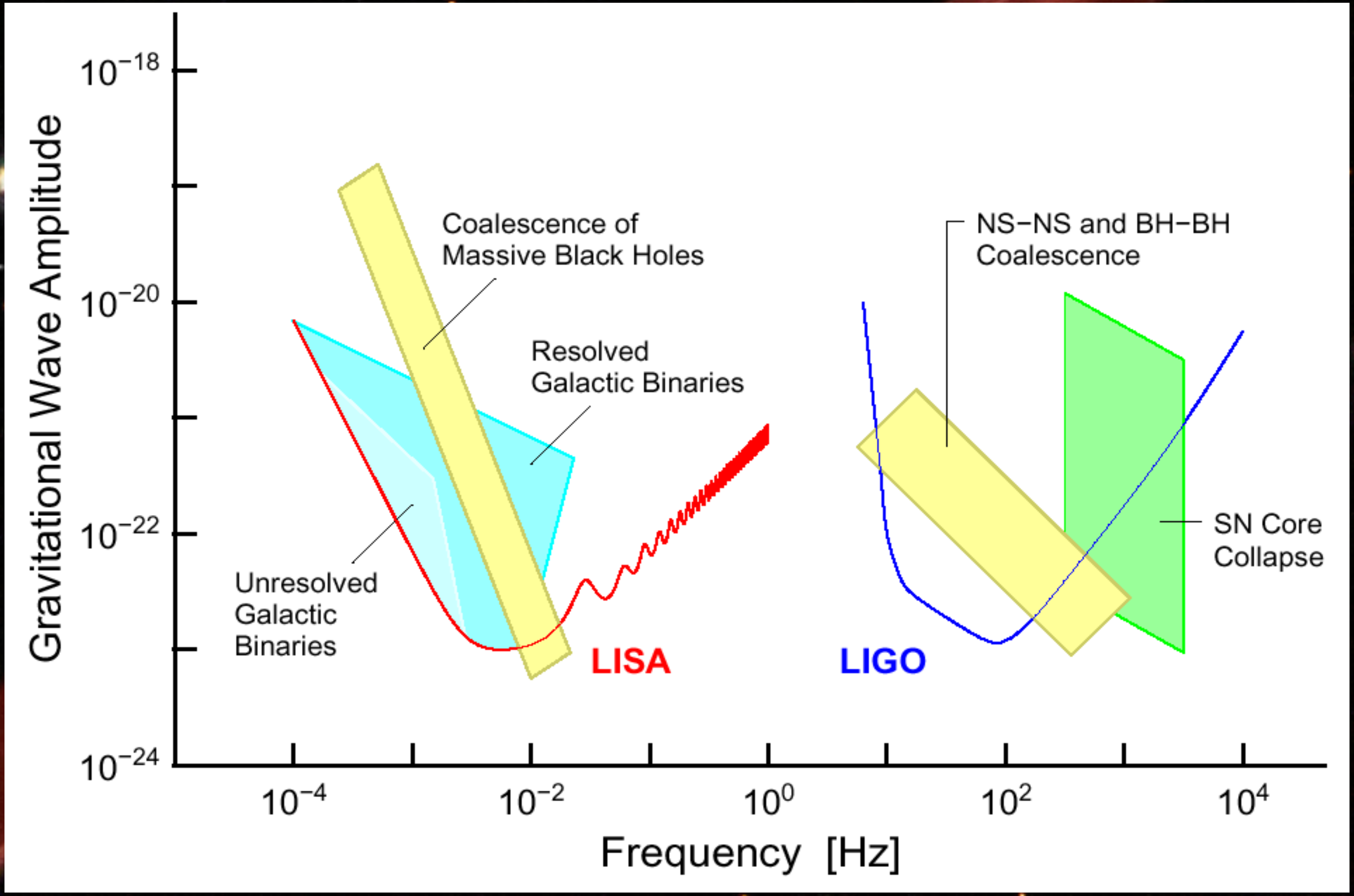
LISA concept - the satellite body encloses test masses, and moves to track their motions,





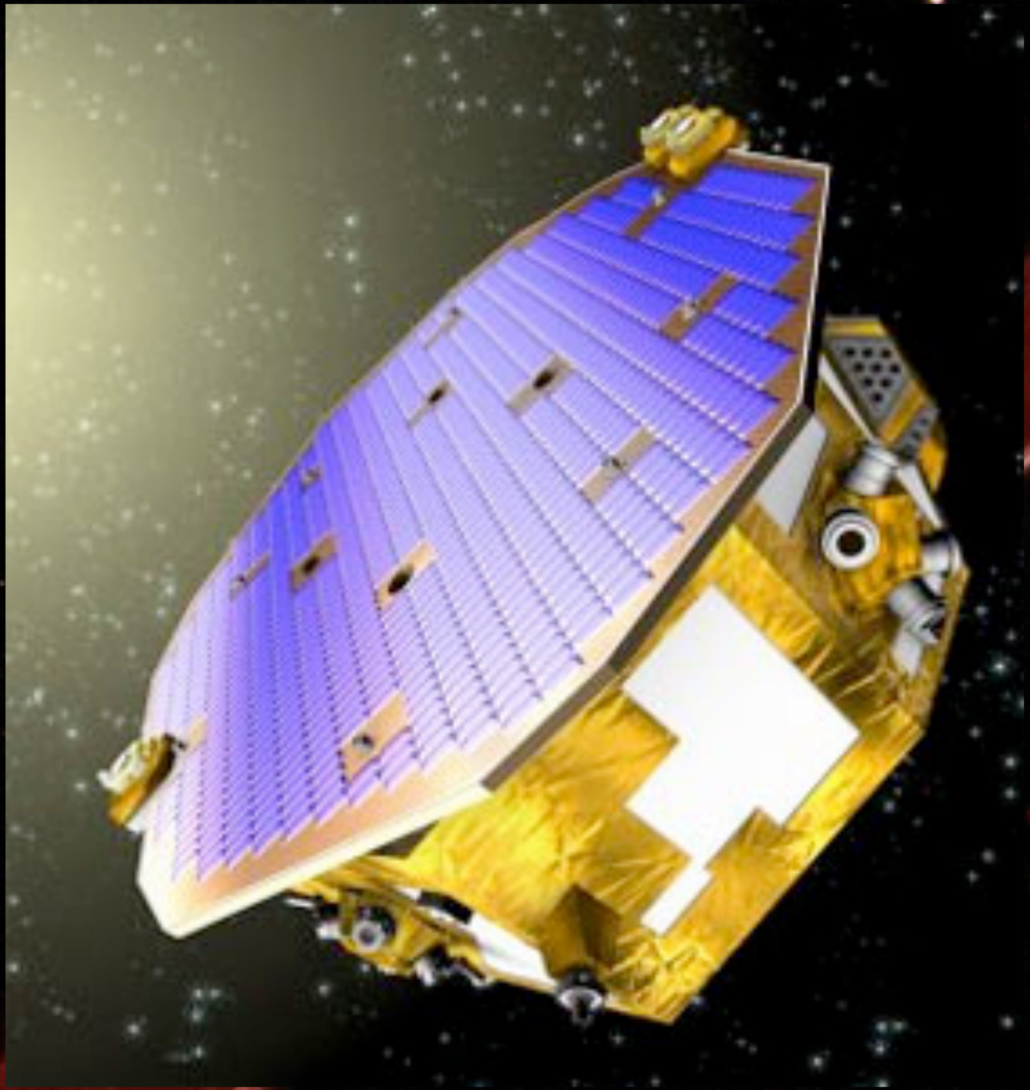


# LISA and LIGO Noise Floors



# LISA Pathfinder Mission

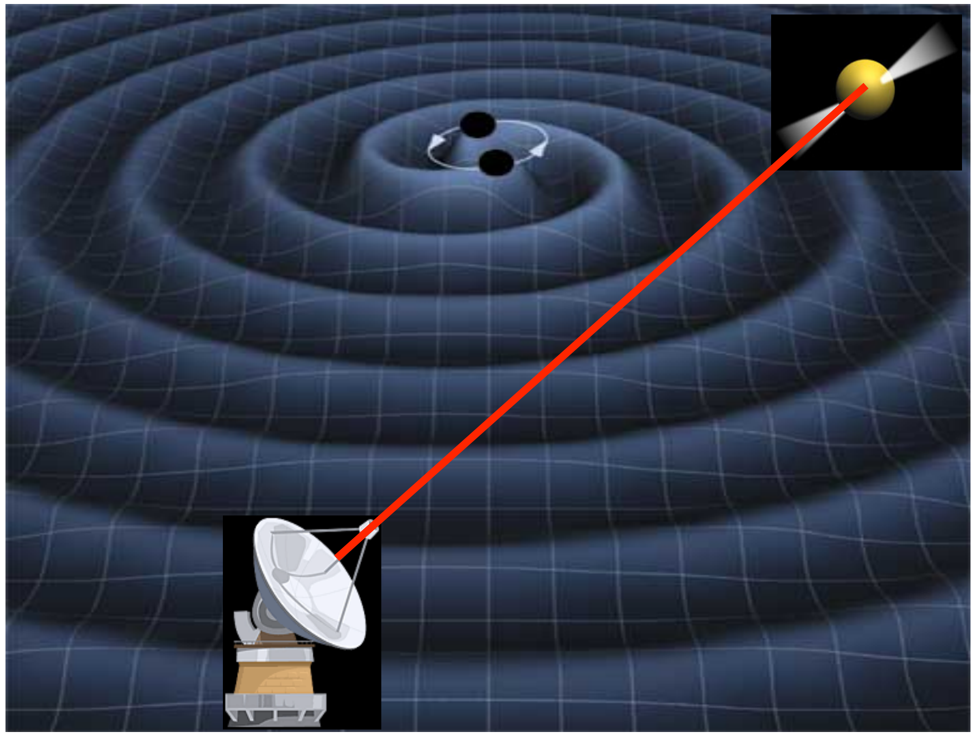
A single satellite for Earth orbit housing two test masses to test and verify technology for LISA. For example:



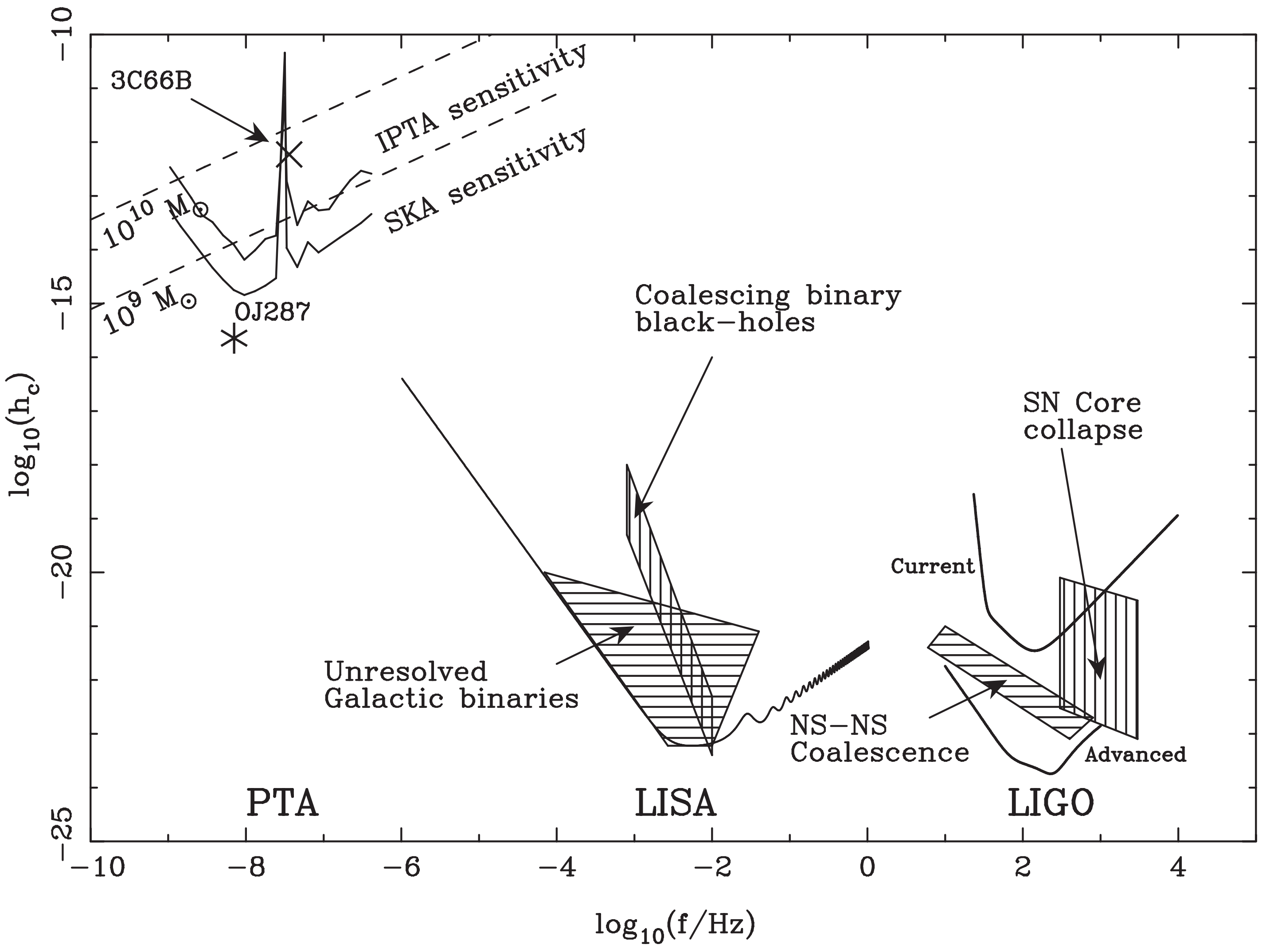
- Micronewton thrusters
- Drag free control
- Test mass charge mitigation
- Optical interferometery
- On board data processing

Scheduled for 2014 launch

# Pulsar Timing



## International pulsar timing array project



G Hobbs *et al* 2010 *Class. Quantum Grav.* **27** 084013

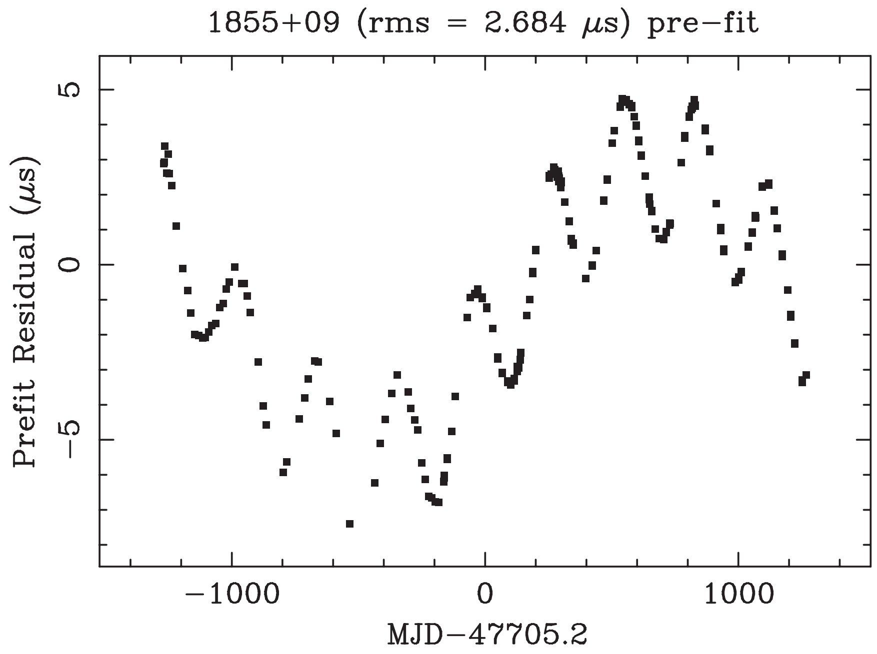
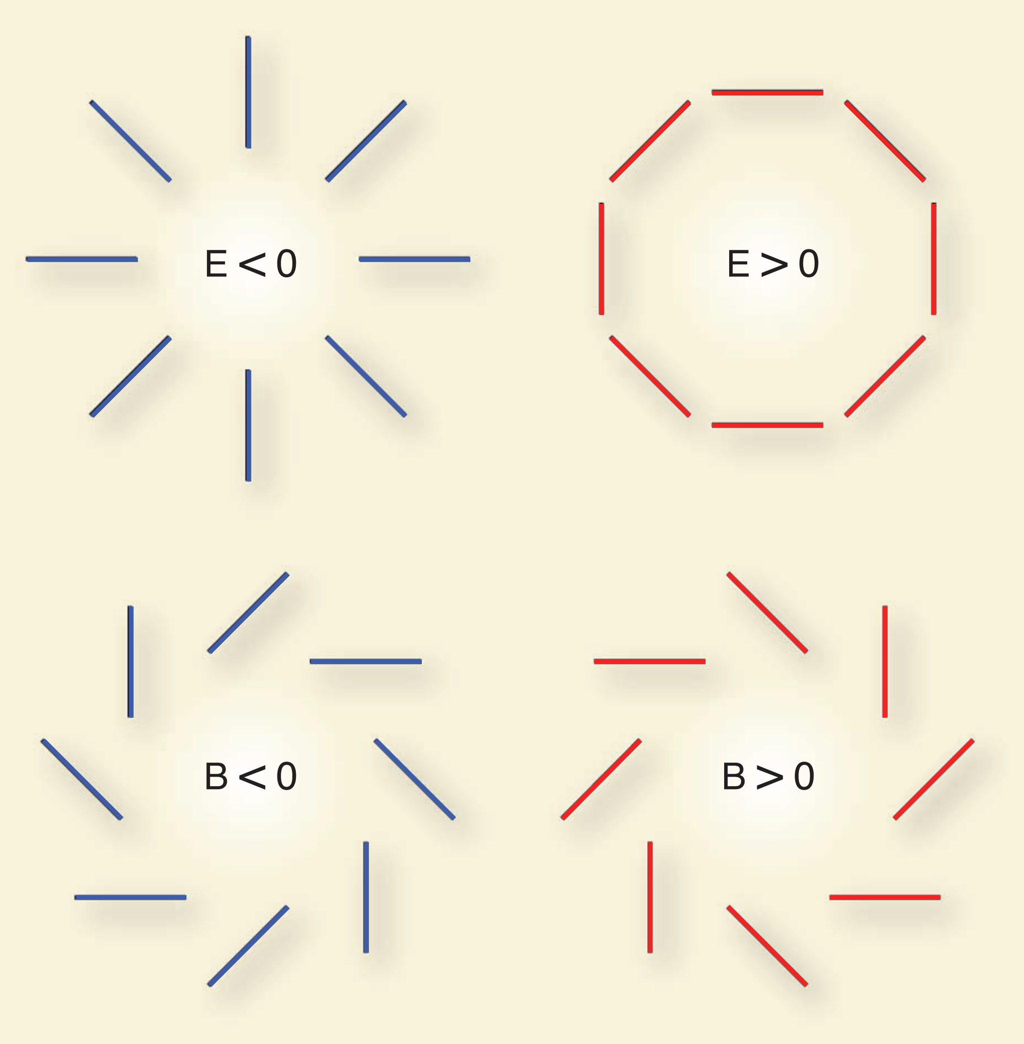
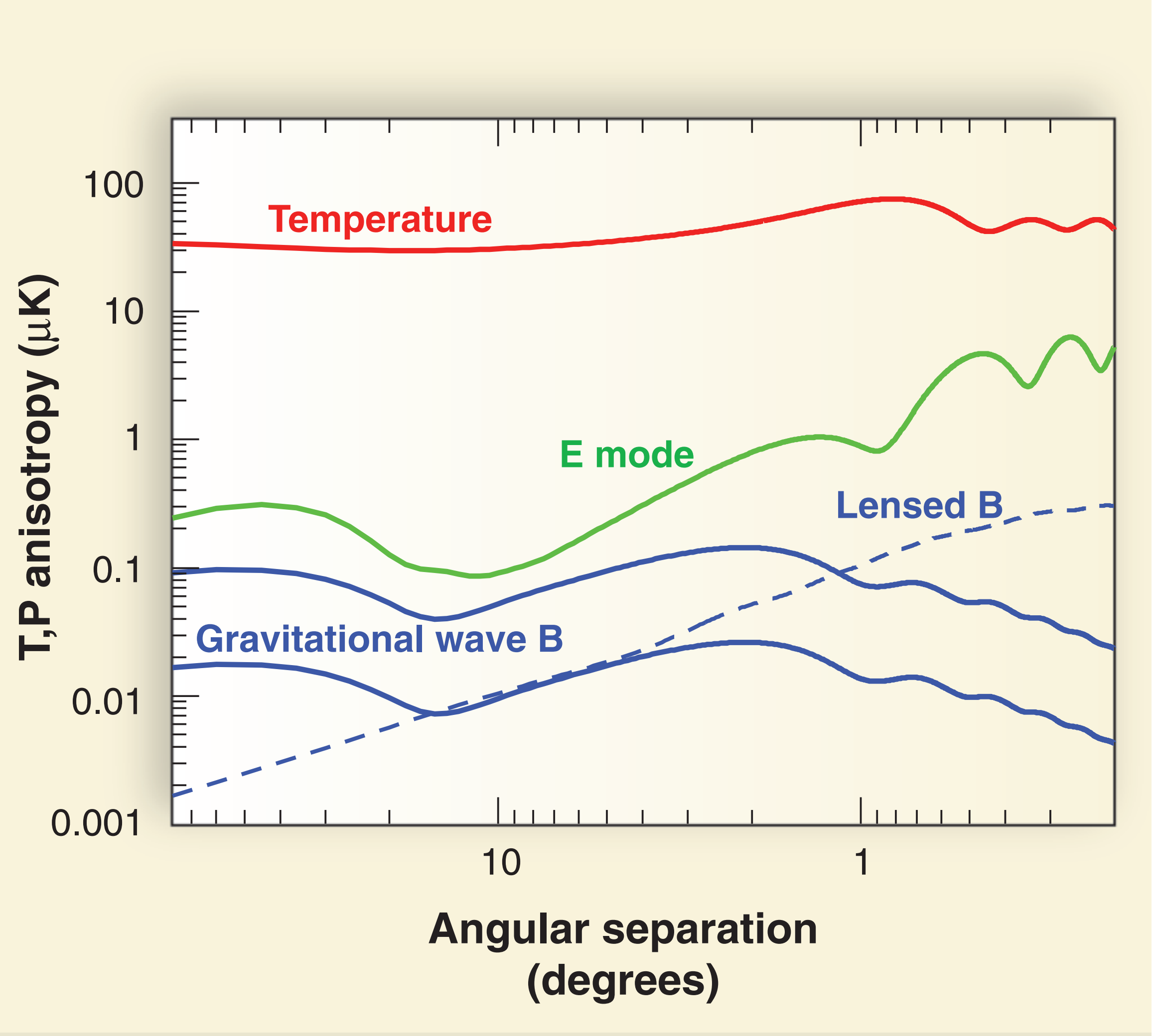


**Figure 2.** Simulation of the induced timing residuals for PSR B1855+09 caused by a postulated supermassive binary black-hole system in the radio galaxy 3C66B.

# CMBR polarization measurements

- The polarization spectrum of the microwave background is sensitive to primordial gravitational waves from the inflationary era.





H. Krauss, S. Dodelson, S. Meyer, SCIENCE 328, 21 May 2010

# Conclusions

- Gravitational wave searches are a source of a great deal of scientific activity
- Ground based interferometry with LIGO, Virgo, GEO and Tama is now very mature.
- Detector upgrades make detection of some sources very likely, 2014-2020.
- Space-based LISA detector strongly supported by ESA.
- Low frequency searches with pulsar timing and/or CMBR polarisation results may detect too!
- It's an exciting time to be working in this field.