Introduction to LIGO

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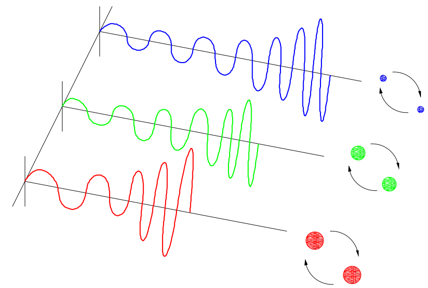
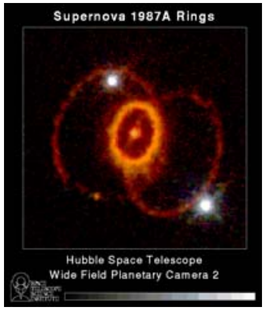
Astrophysical Sources of GWs

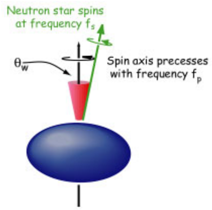
- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates



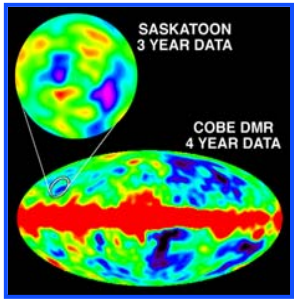
- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » prompt alarm (~ one hour) with neutrino detectors



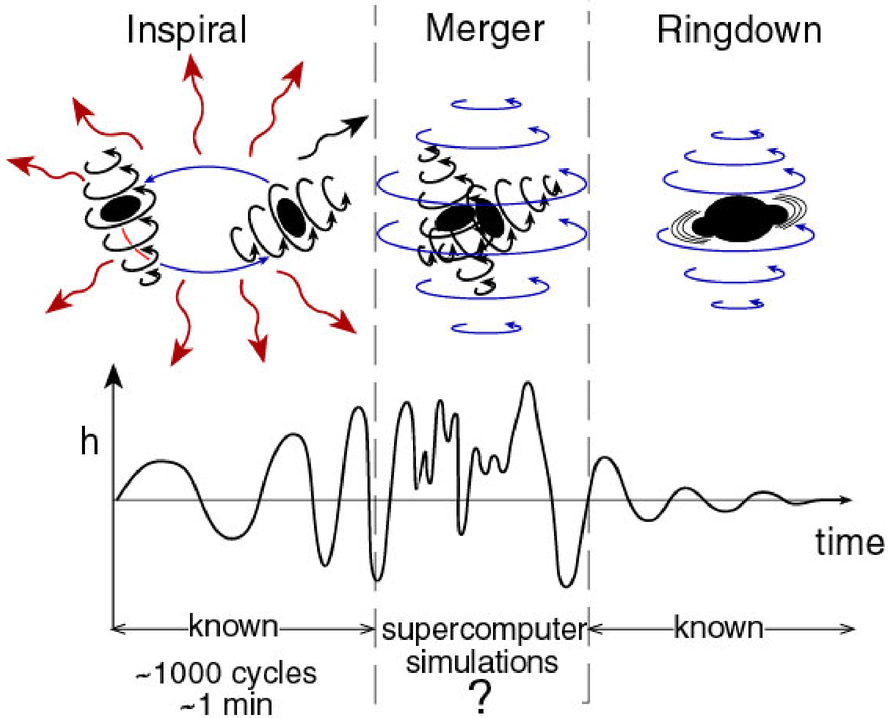
- Pulsars in our galaxy: *"periodic"*
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes



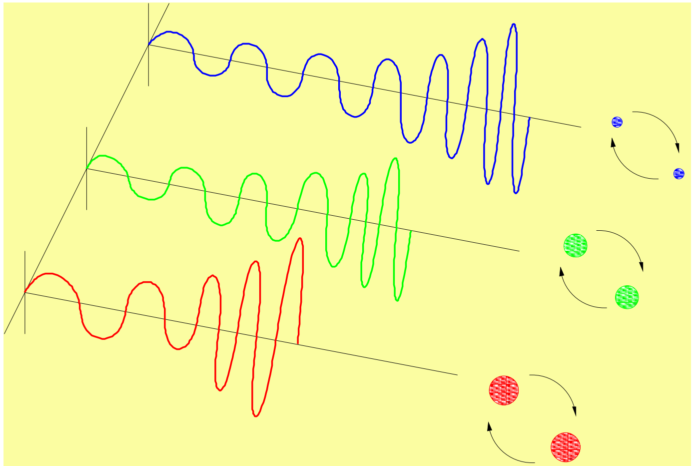
- Cosmological Signals *"stochastic background"*



Compact Binary Coalescence



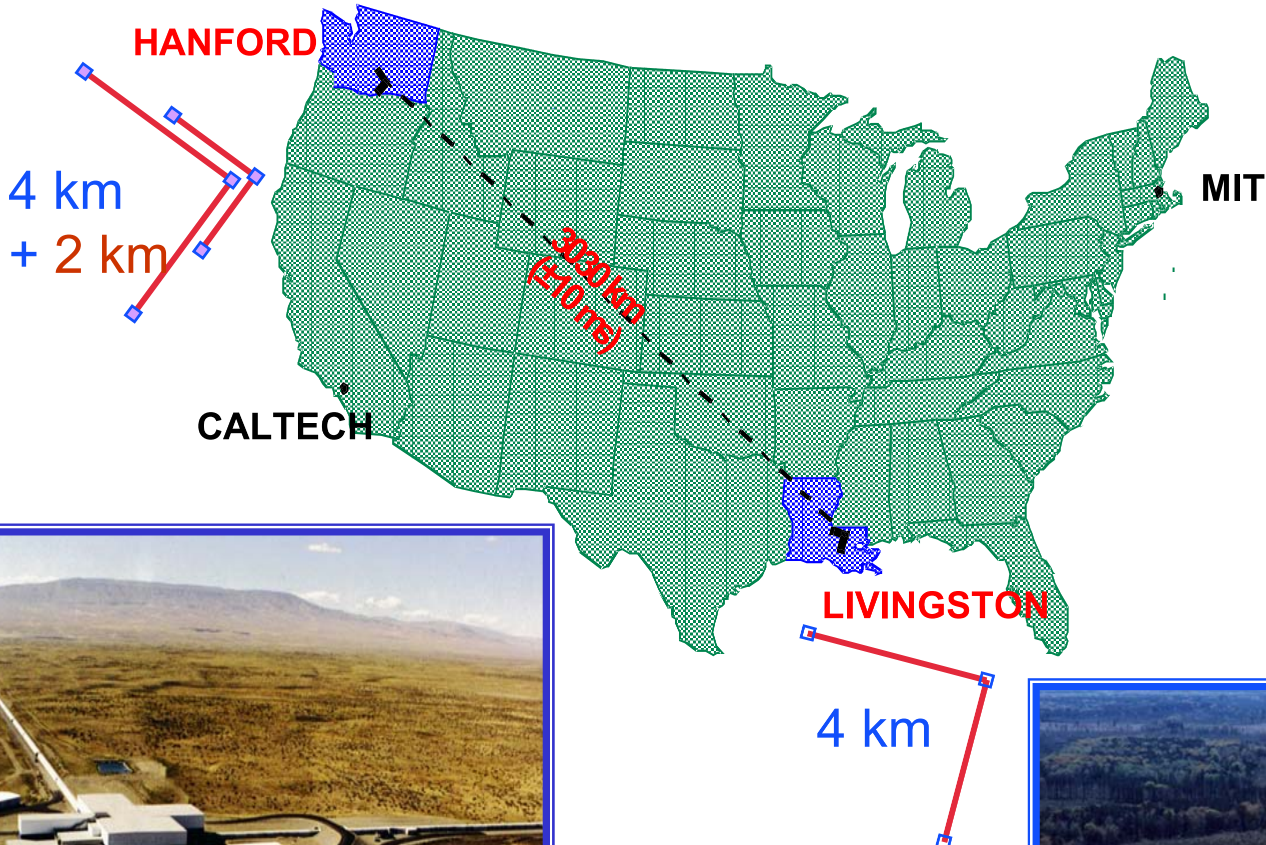
» Neutron Star – Neutron Star
  – **waveforms are well described**
» Black Hole – Black Hole
  – **need better waveforms**



- Waveforms give information about:
  - Type of compact object (NS, BH)
  - Masses, distance, spin
  - Orbital parameters
  - Nuclear forces (Neutron star)
  - Nonlinear general relativity (BHs)

LIGO

LIGO Observatories



A Brief History -- 1

1960's	Weber reports first bar detector experiments with possible excess coincidences
1971-2	Independent inventions of GW interferometers Rai Weiss (MIT) performs first detailed noise analysis
1979	NSF funds interferometer development efforts at MIT and Caltech
1987	NSF panel endorses proceeding to full scale construction ("full authorization with phased construction and appropriate milestones")
1989	Construction proposal submitted (mature costing for facility
1990	NSB approval

Project Philosophy

- Strength of expected GW signals highly uncertain, typically by a factor of 10-100
- An approach emphasizing incremental technology demonstrations unlikely to attract and hold the required scientific team
- Problems for laboratory-scale and kilometer-scale interferometers substantially different
- Initial detectors would teach us what was important for future upgrades
- Facilities (big $) should be designed with more sensitive detectors in mind

A Brief History -- 2

1991	40 m interferometer at Caltech achieves required length sensitivity
	Congress approves first year “construction funding”
1992	Selection of Hanford and Livingston as sites
1993	NSF panel reviews and endorses technical status
	Vacuum system engineering design begins
1994	Ground-breaking at Hanford
1995	Ground-breaking at Livingston
1995-6	All major construction contracts signed

A Brief History - 3

1997	Laboratory interferometer at MIT demonstrates required optical phase sensitivity
	First interferometer components received for testing (laser, optics)
1998	Vacuum system complete at Hanford
	Interferometer installation begins
1999	Vacuum system complete at Livingston
	Interferometer installation begins
2000	Commissioning begins on Hanford 2 km
2002	First "science data" run, with GEO and TAMA
2003-4	Interleaved science runs with commissioning to improve detector sensitivity
	First results papers published in Phys Rev

Initial Detectors—Underlying Philosophy

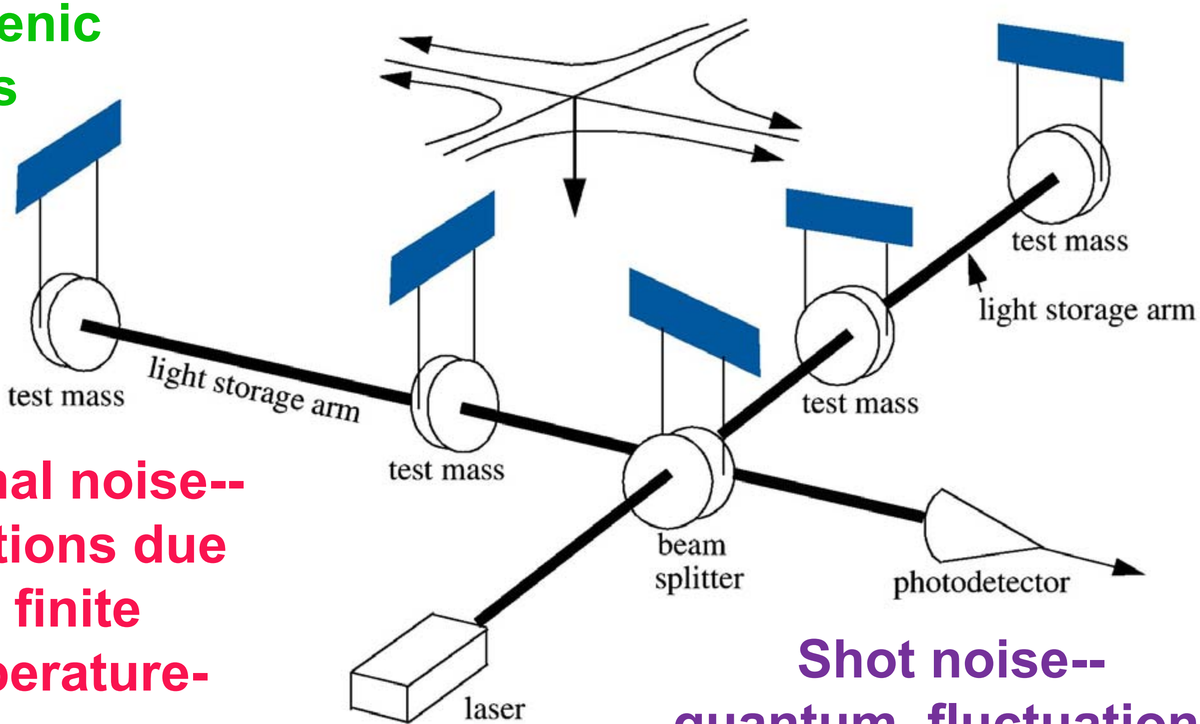
- Jump from laboratory scale prototypes to multi-kilometer detectors is already a BIG challenge
- Design should use relatively cautious extrapolations of existing technologies
  - » Reliability and ease of integration should be considered in addition to noise performance
    - – "The laser should be a light bulb, not a research project" Bob Byer, Stanford
  - » All major design decisions were in place by 1994
- Expected 100-1000 times improvement in sensitivity is enough to make the initial searches interesting even if they only set upper limits

The Detection Challenge

Seismic motion-- ground motion due to natural and anthropogenic sources

$$h = \Delta L / L$$

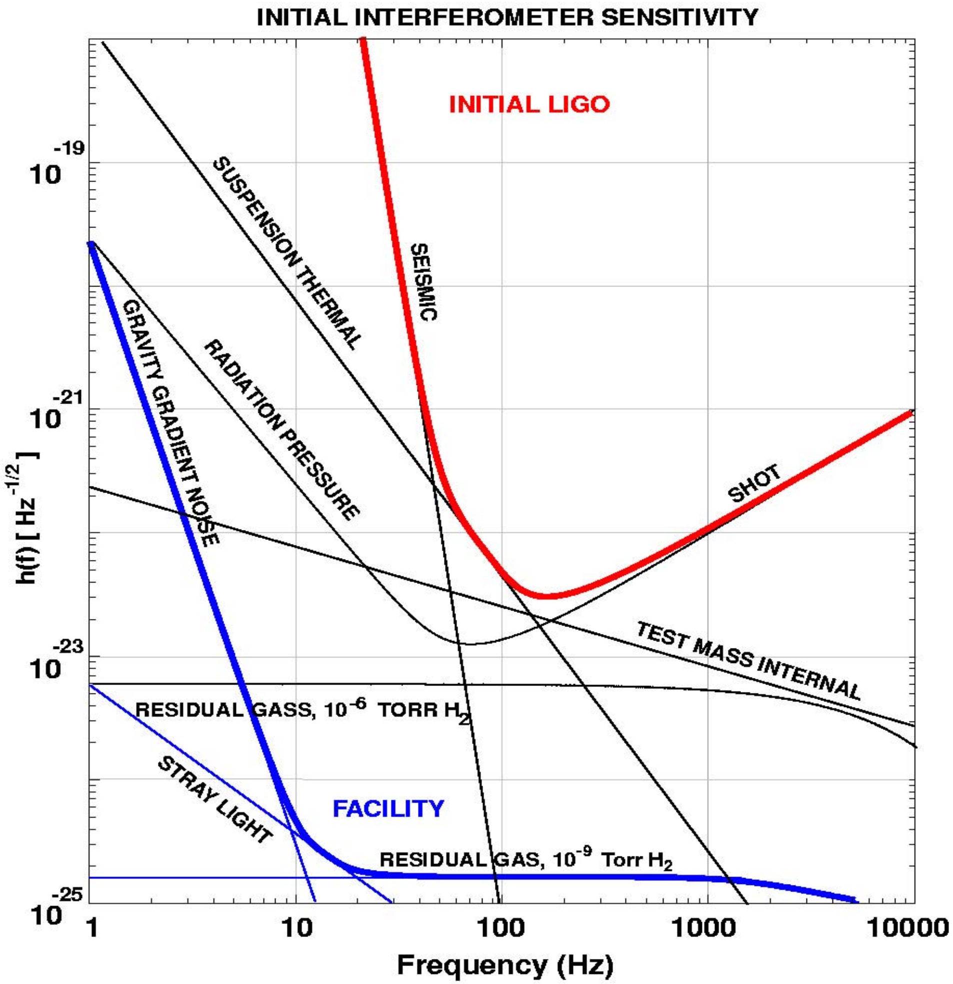
L ~ 4 km
For *h* ~ 10^{-21}
$\Delta L \sim 10^{-18}$ m



Thermal noise-- vibrations due to finite temperature-

Shot noise-- quantum fluctuations in the number of photons detected

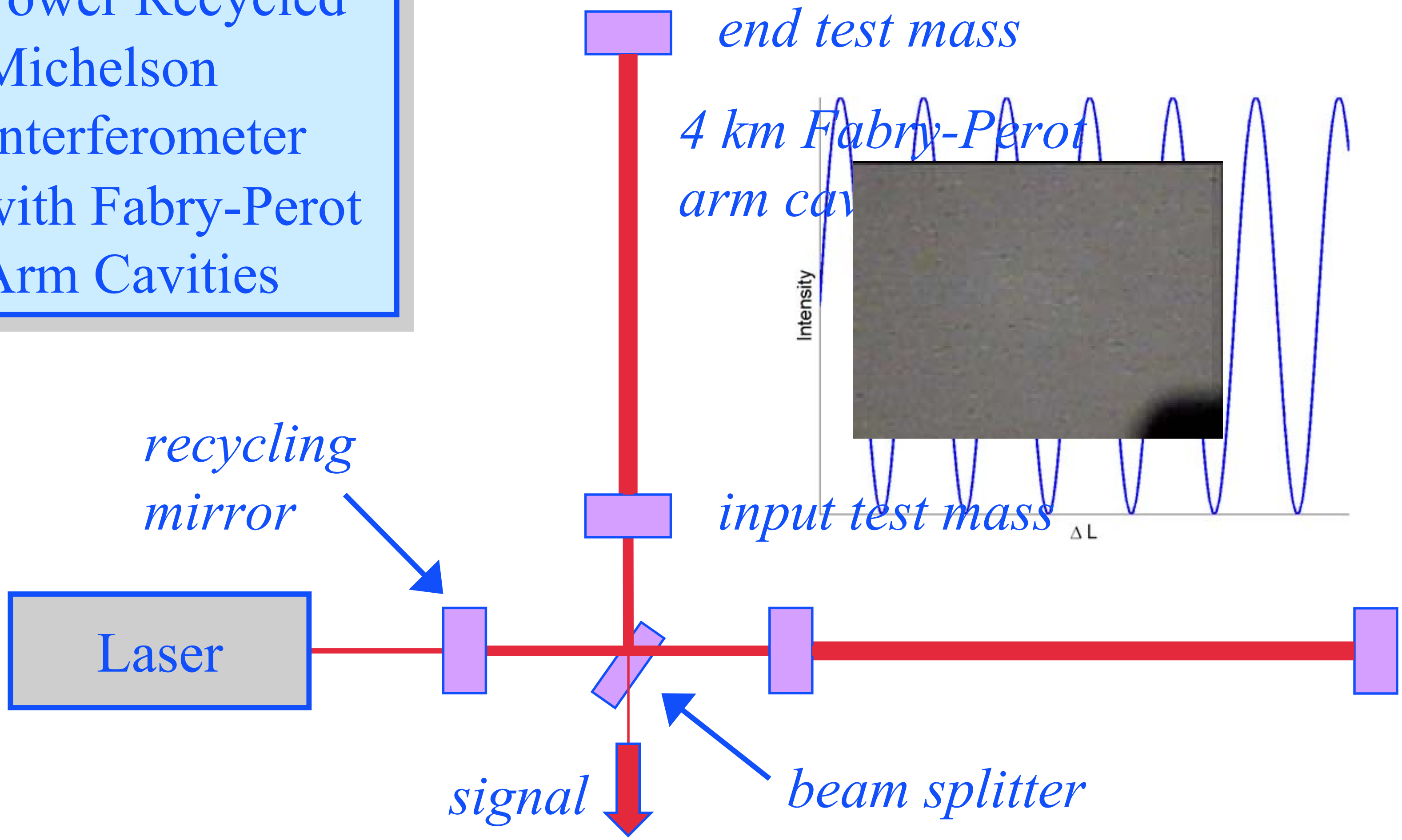
Initial LIGO Sensitivity Goal



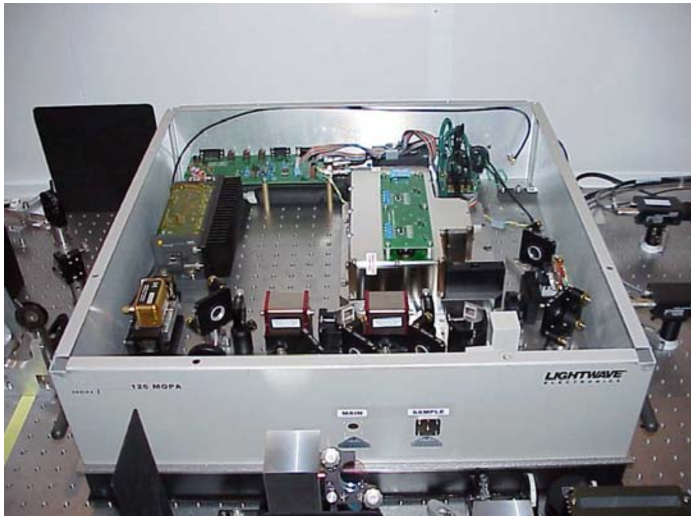
- Strain sensitivity $<3 \times 10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

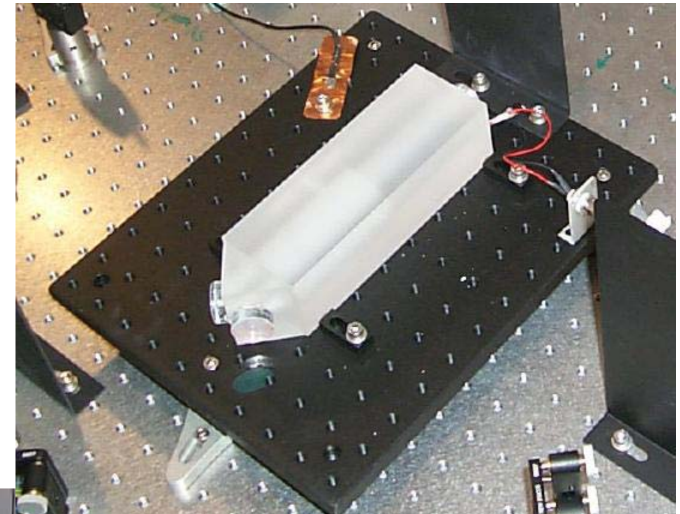
Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



Stabilized Laser





Custom-built
10 W Nd:YAG
laser—
Now a commercial
product

Stabilization cavities
for laser beam—
Widely used for
precision optical
applications

$$\frac{\delta f}{f} \approx 10^{-21}$$

LIGO Optics

Substrates: SiO_2

High purity, low absorption

Polishing

Accuracy < 1 nm (~10 atomic diameters)

Micro-roughness < 0.1 nm (1 atom)

Coating

Scatter < 50 ppm

Absorption < 0.5 ppm

Uniformity $<10^{-3}$ (~1 atom/layer)

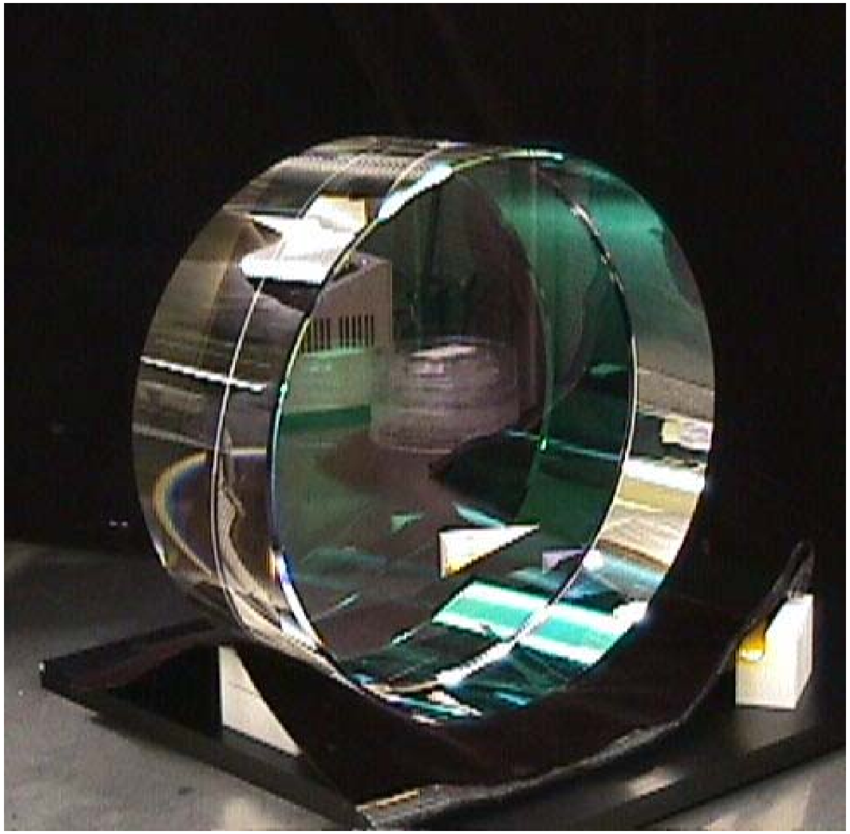
Worked with industry to develop required technologies

2 manufacturers of fused silica

4 polishers

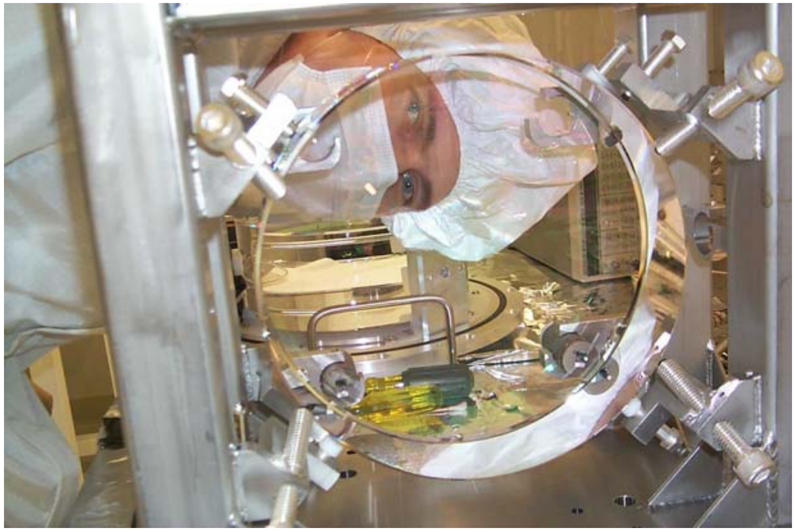
5 metrology companies/labs

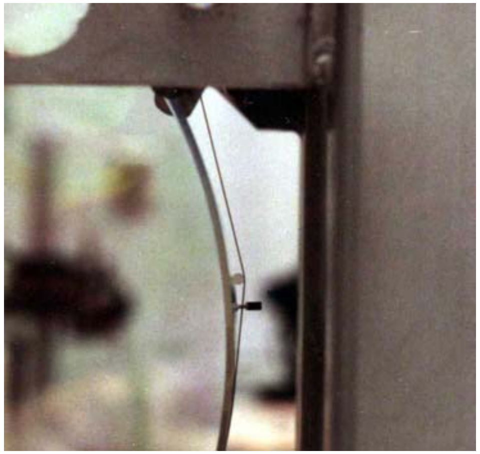
1 optical coating company



Optics Suspension and Control

- Suspension is the key to controlling thermal noise
- Magnets and coils to control position and angle of mirrors





Core Optics Installation and Alignment

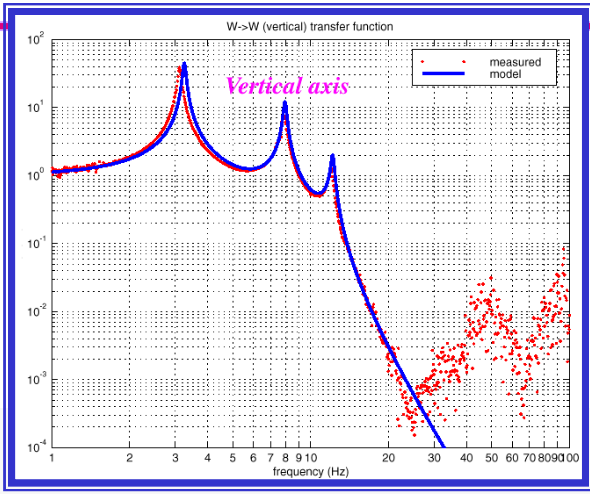
- Cleanliness of paramount importance

Seismic Isolation

- Cascaded stages of masses on springs (same principle as car suspension)

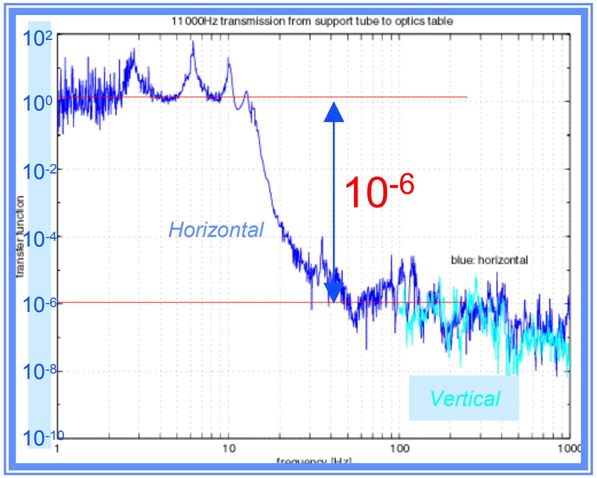
damped spring cross section

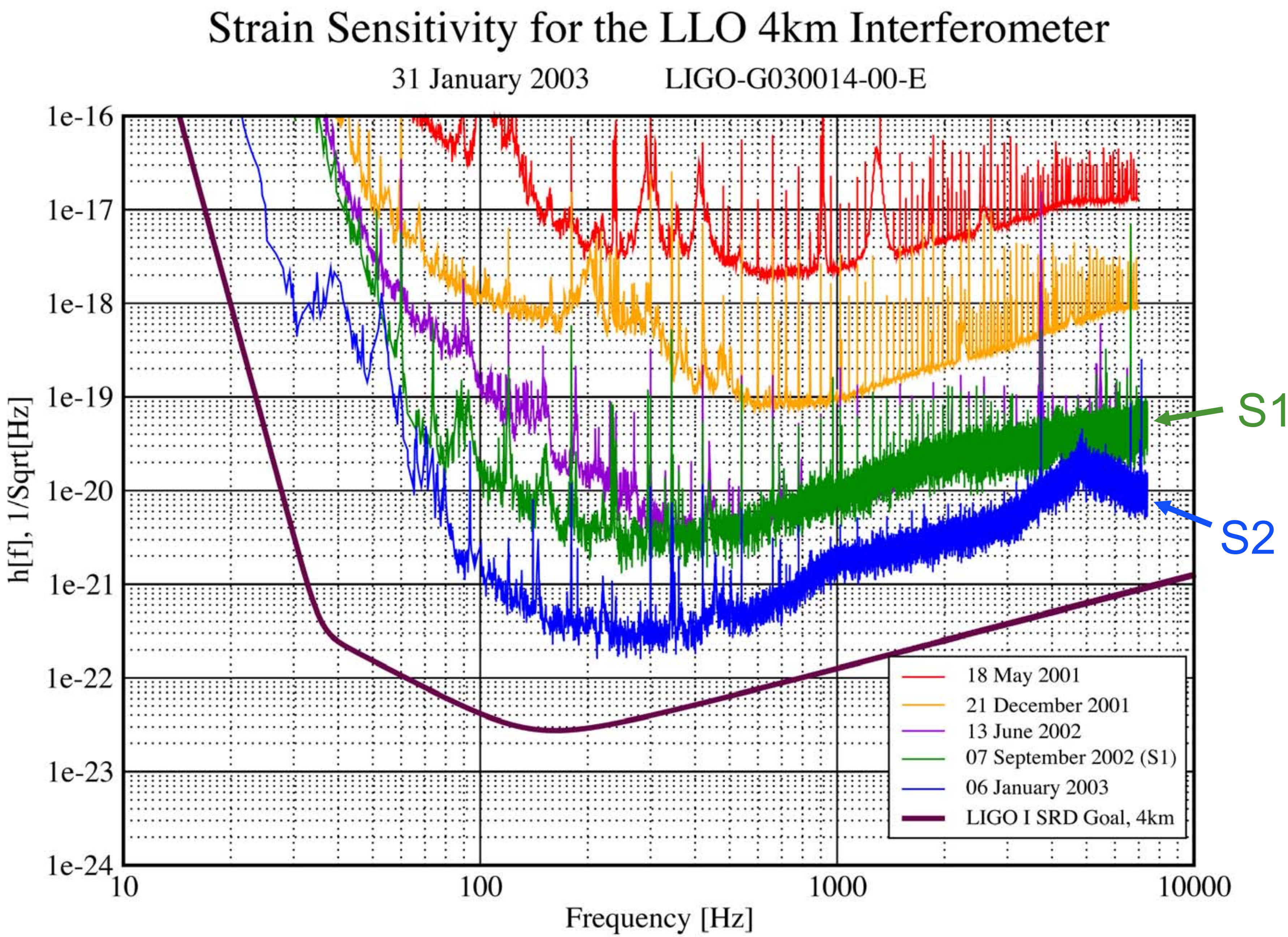
Seismic Isolation



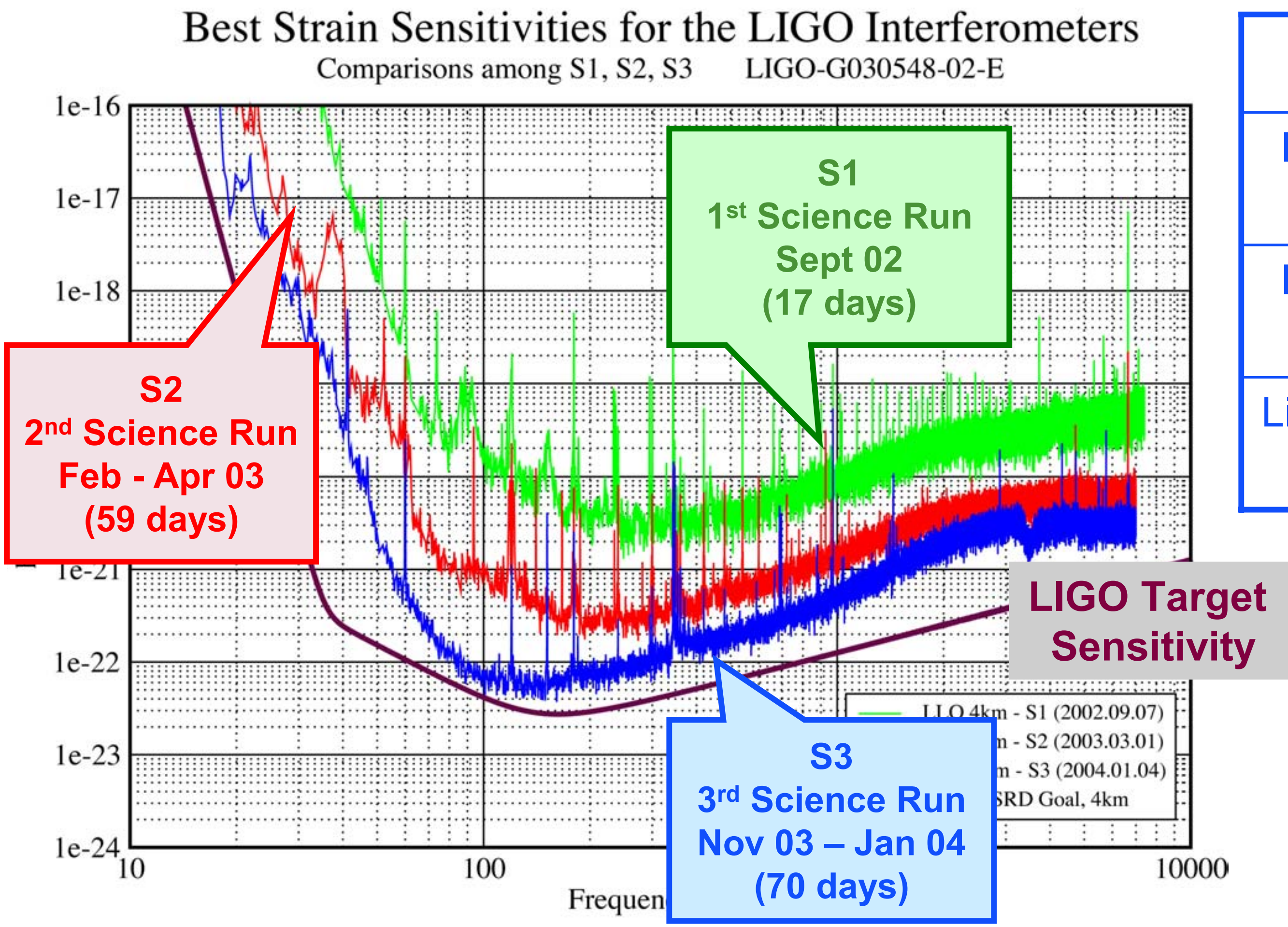
In air

In vacuum



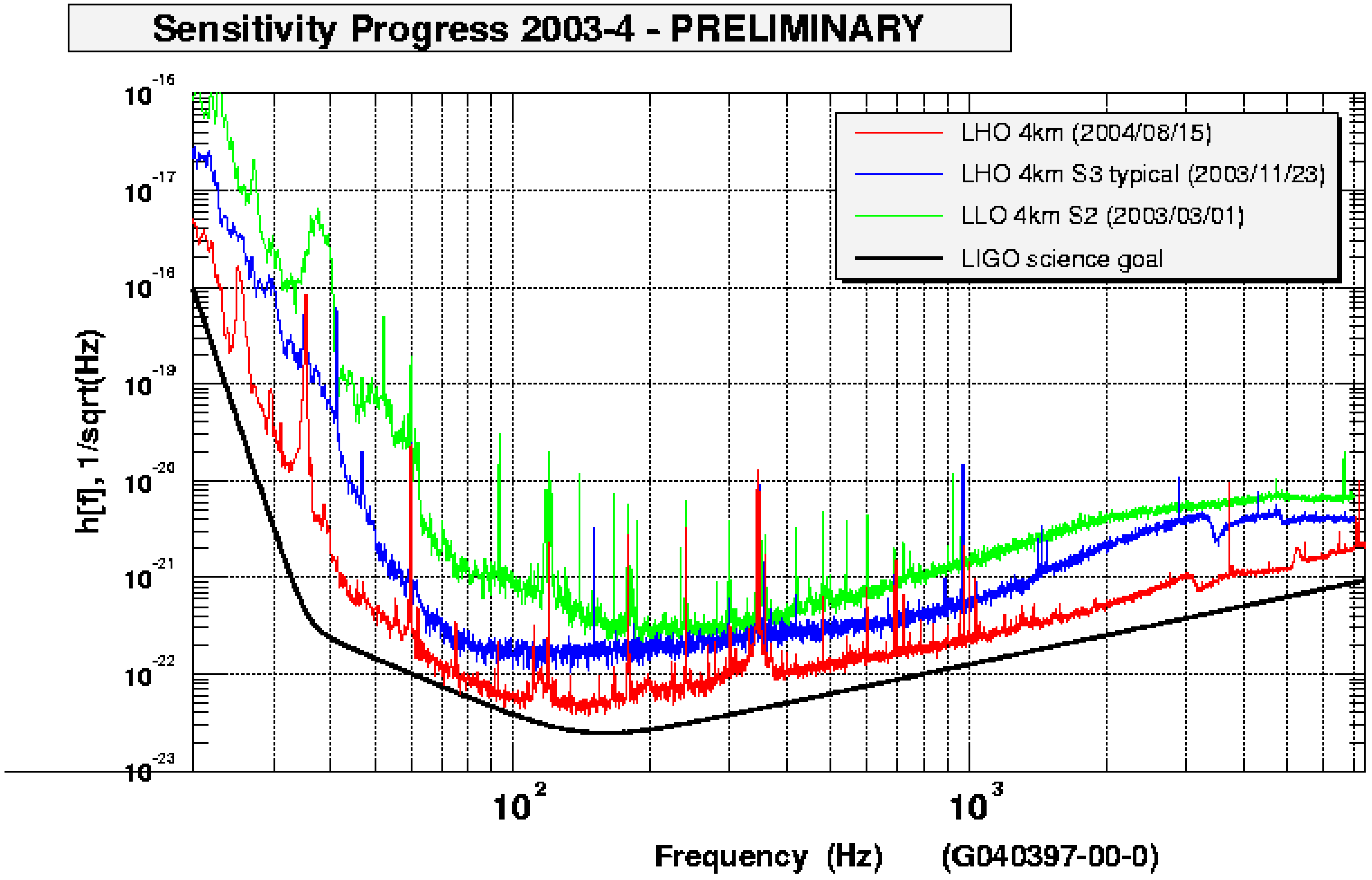

Strain Sensitivity for the LLO 4km Interferometer
31 January 2003
LIGO-G030014-00-E
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
18 May 2001
21 December 2001
13 June 2002
07 September 2002 (S1)
06 January 2003
LIGO I SRD Goal, 4km
S1
S2

LIGO Science Runs



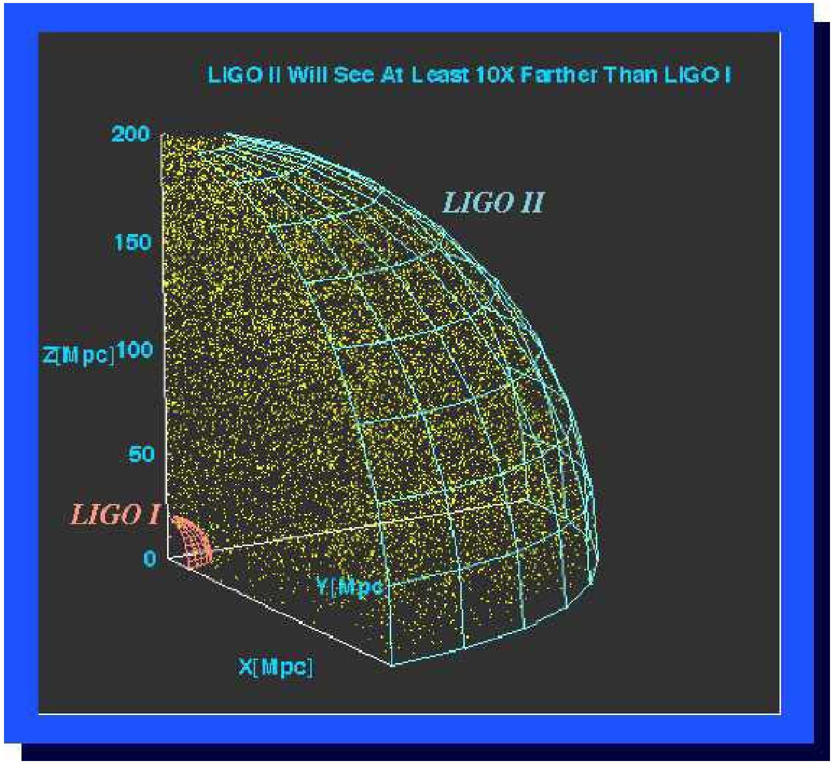
S3 Duty Cycle	
Hanford 4km	69%
Hanford 2km	63%
Livingston 4 km	22%*

Continued Noise Improvements

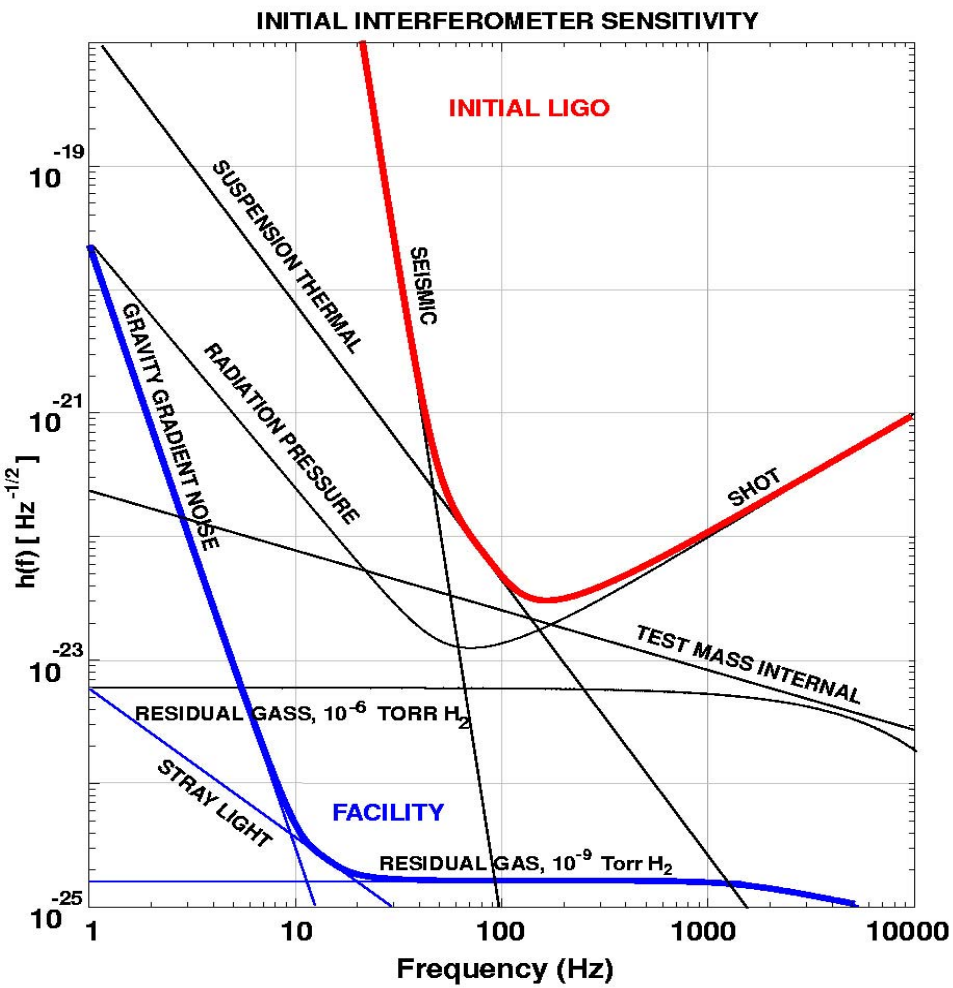


Advanced LIGO

- Now being designed by the LIGO Scientific Collaboration
- Goal:
  - » Quantum-noise-limited interferometer
  - » Factor of ten increase in sensitivity
  - » Factor of 1000 in event rate. One day > entire 2-year initial data run
- Schedule:
  - » Begin installation: 2009?
  - » Begin data run: 2012?



Facility Limits to Sensitivity



- Facility limits leave lots of room for future improvements

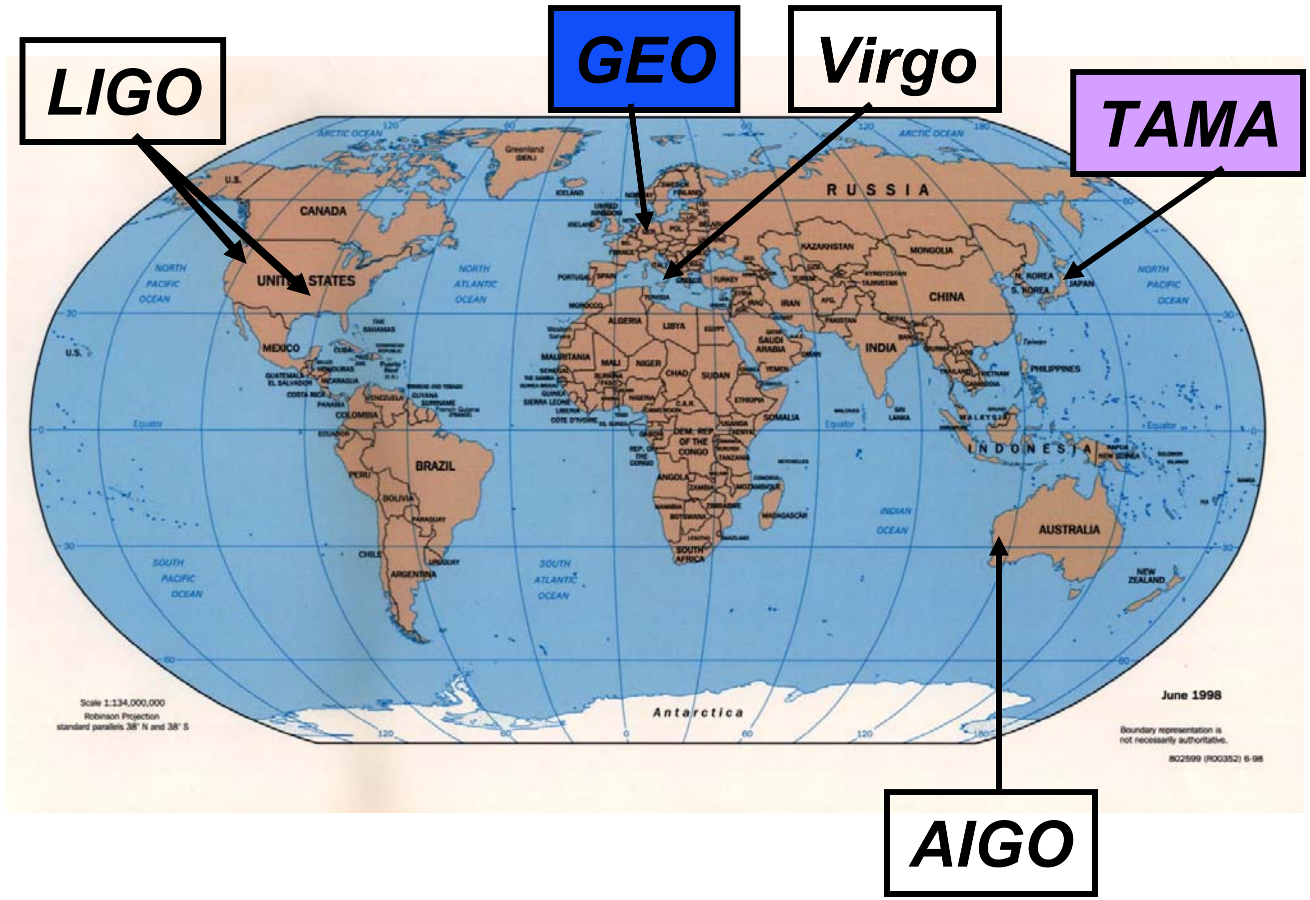
LIGO Anchors an International Network of Interferometers

Rare events require *coincident* detections.

LIGO's three interferometers were designed to emphasize obtaining good coincidences.

This makes LIGO the anchor of the worldwide network of interferometers

GEO and LIGO have a special link: all GEO members are also members of the LSC. Joint data analysis is routine.

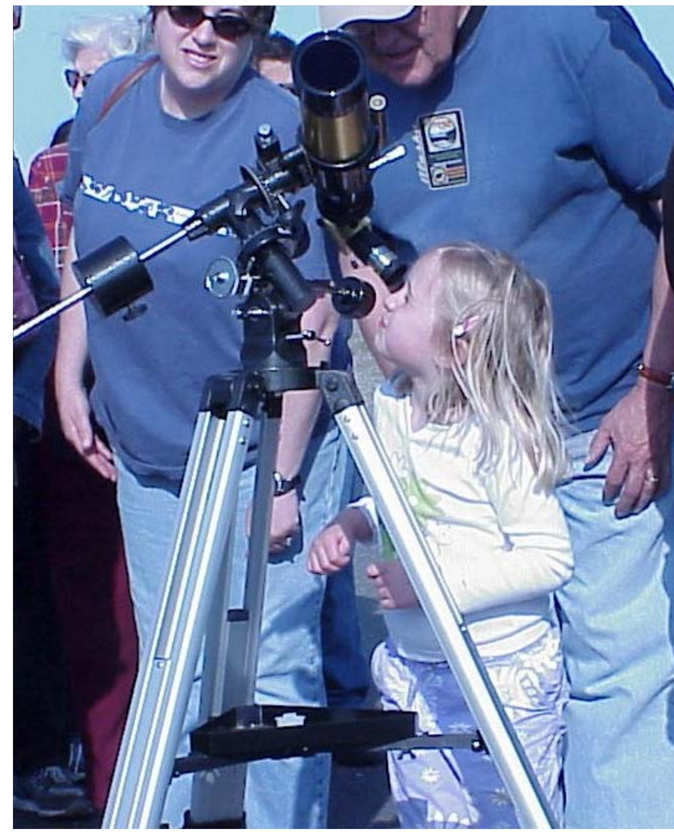


LIGO Outreach Activities

- New outreach coordinators at both observatories
  - » Dale Ingram at LHO
  - » John Thacker at LLO

School Group Tour at LLO

National Astronomy Day at LHO



The LIGO Scientific Collaboration

The LSC is the group of scientists that sets the scientific program of LIGO and carries it out.

It has ~500 members. They come from the LIGO Lab and from 35 other institutions (including 19 single-investigator groups.)

~75 members are postdocs, ~100 are grad students. More than 20 are undergrads.

Most are from the U.S., but we have GEO members from the U.K. and Germany, and from Australia, India, Japan, Russia and Spain.