# LONG BASELINE GRAVITATIONAL WAVE DETECTION – THE STATUS OF THE LIGO PROJECT

IPAC@ MIT

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Rainer Weiss for the LIGO Scientific Collaboration

LIGO-G9900XX-00-M

# Direct detection of gravitational waves from astrophysical sources

- Physics
  - » Observations of gravitation in the strong field, high velocity limit
  - » Determination of wave kinematics – polarization and propagation
  - » Tests for alternative relativistic gravitational theories
- Astrophysics
  - » Measurement of coherent inner dynamics – stellar collapse, pulsar formation….
  - » Compact binary coalescence – neutron star/neutron star, black hole/black hole
  - » Neutron star equation of state
  - » Primeval cosmic spectrum of gravitational waves
- Gravitational wave survey of the universe

# LIGO Scientific Collaboration Member Institutions

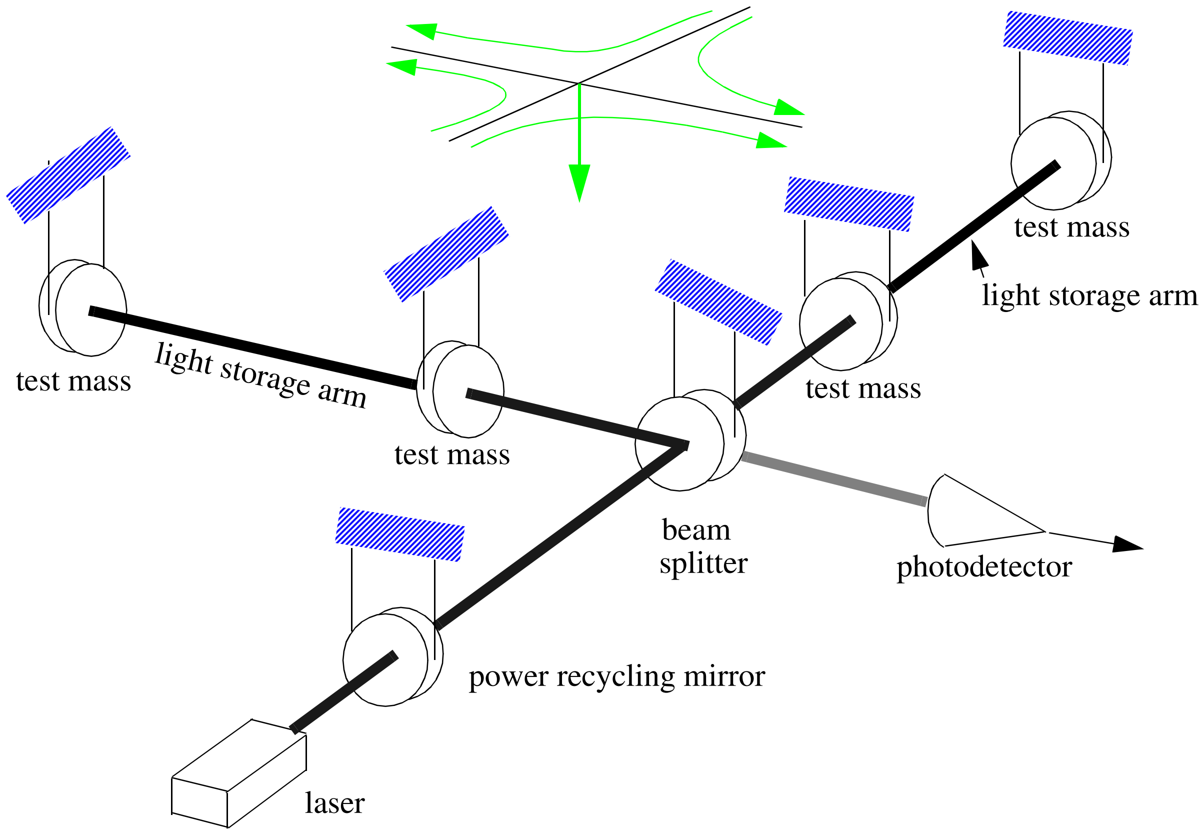
University of Adelaide ACIGA
Australian National University ACIGA
California State Dominquez Hills
Caltech LIGO
Caltech Experimental Gravitation CEGG
Caltech Theory CART
University of Cardiff GEO
Carleton College
Cornell University
Fermi National Laboratory
University of Florida @ Gainesville
Glasgow University GEO
Goddard Space Flight Center
University of Hannover GEO
India-IUCAA
IAP Nizhny Novgorod
Iowa State University
Joint Institute of Laboratory Astrophysics
LIGO Livingston LIGOLA
LIGO Hanford LIGOWA
Louisiana State University
Louisiana Tech University
MIT LIGO
Max Planck (Garching) GEO
Max Planck (Potsdam) GEO
University of Michigan
Moscow State University
NAOJ - TAMA
Northwestern University
University of Oregon
Pennsylvania State University
Salish Kootenai College
Southern University
Stanford University
Syracuse University
University of Texas @ Brownsville
University of Western Australia ACIGA
University of Wisconsin @ Milwaukee
Washington State University @ Pullman, WA

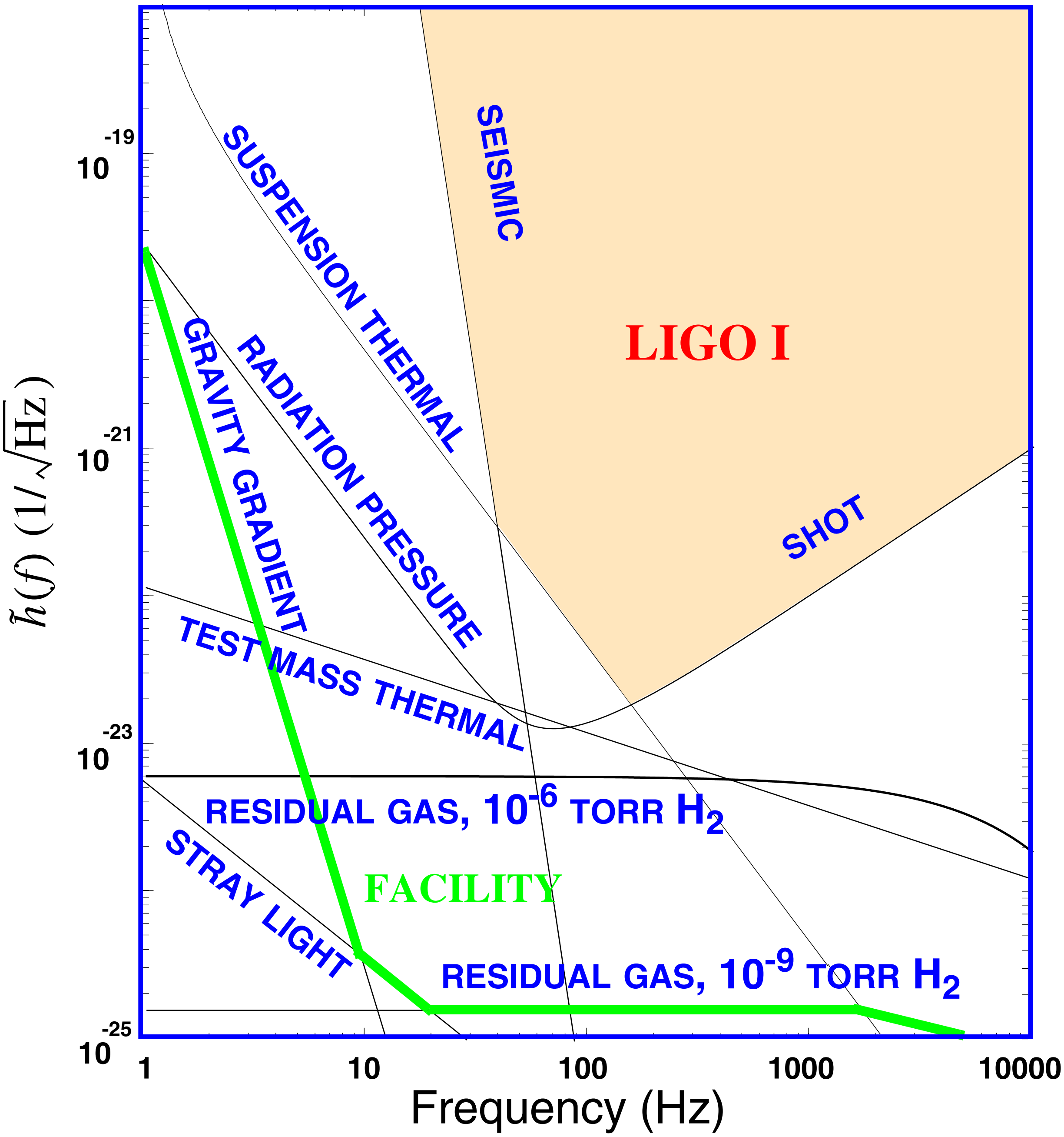
# Measurement challenge

- Needed technology development to measure:

$$h = \Delta L/L < 10^{-21}$$

$$\Delta L < 4 \times 10^{-18} \text{ meters}$$


test mass
light storage arm
test mass
test mass
test mass
light storage arm
beam
splitter
photodetector
power recycling mirror
laser



LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, $10^{-6}$ TORR $H_2$
STRAY LIGHT
FACILITY
RESIDUAL GAS, $10^{-9}$ TORR $H_2$
$10^{-19}$
$10^{-21}$
$10^{-23}$
$10^{-25}$
1
10
100
1000
10000
Frequency (Hz)
$\tilde{h}(f)$ $(1/\sqrt{\mathrm{Hz}})$

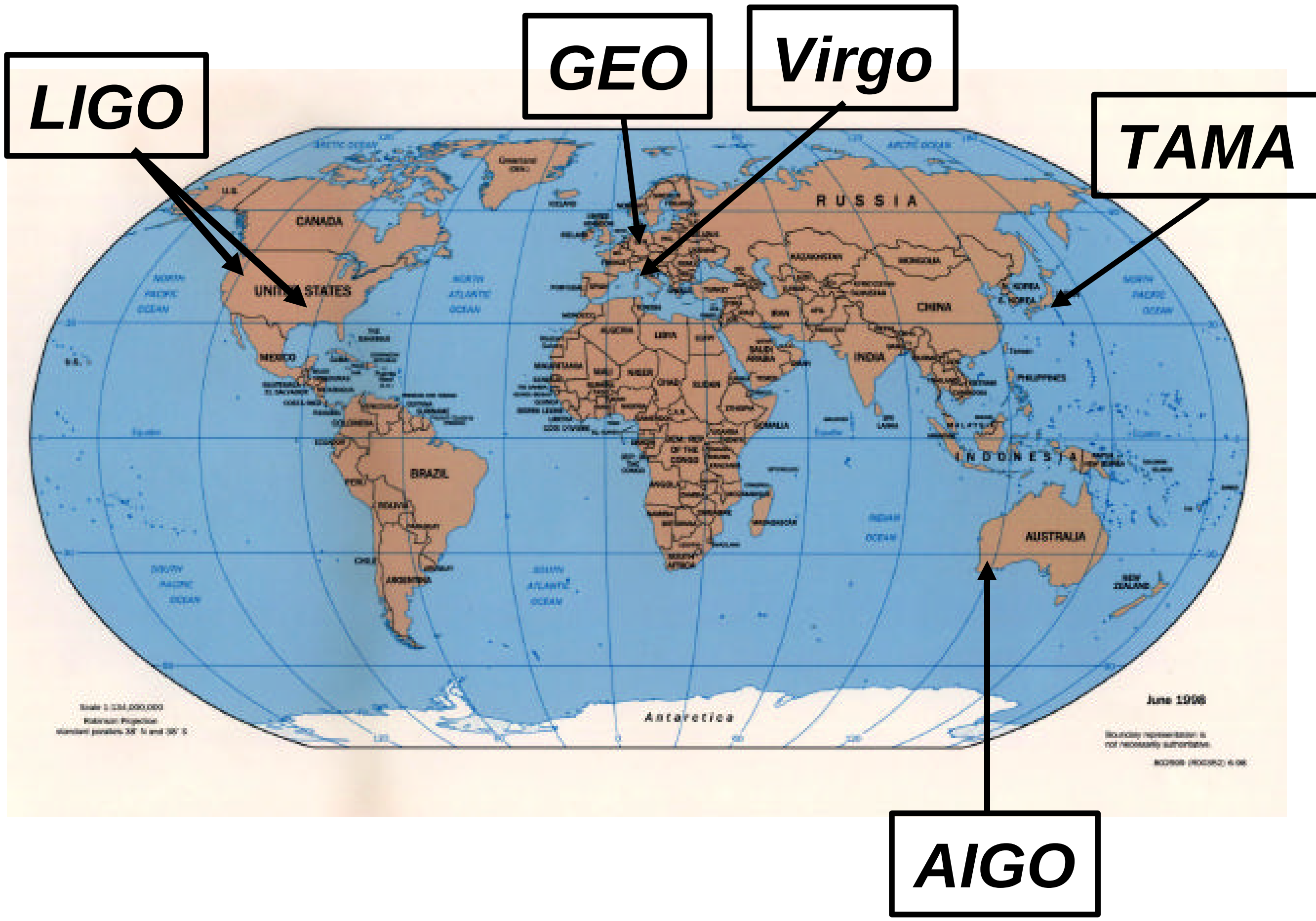
## Table 1: Initial detector parameters

| *Parameter* | *Nominal Initial Interferometer* |
|---|---|
| Arm length | 4000 m |
| Laser type @wavelength | Nd:YAG $\lambda$ = 1064 nm |
| Input power at recycling cavity | 6 W |
| Contrast defect 1-c | $< 3 \times 10^{-3}$ |
| Mirror loss | $< 1 \times 10^{-4}$ |
| Power recycling gain | 30 |
| Arm cavity storage time | 880 $\mu$ sec |
| Cavity input mirror transmission | $3 \times 10^{-2}$ |
| Mirror mass | 10.7 kg |
| Mirror diameter | 25 cm |
| Mirror internal Q | $1 \times 10^{6}$ |
| Pendulum Q (structure damping) | $1 \times 10^{5}$ |
| Pendulum period (single) | 1 sec |
| Seismic isolation system | T(100Hz) = -110dB |

# Interferometers

## *international network*

**Simultaneously detect signal (within msec)**



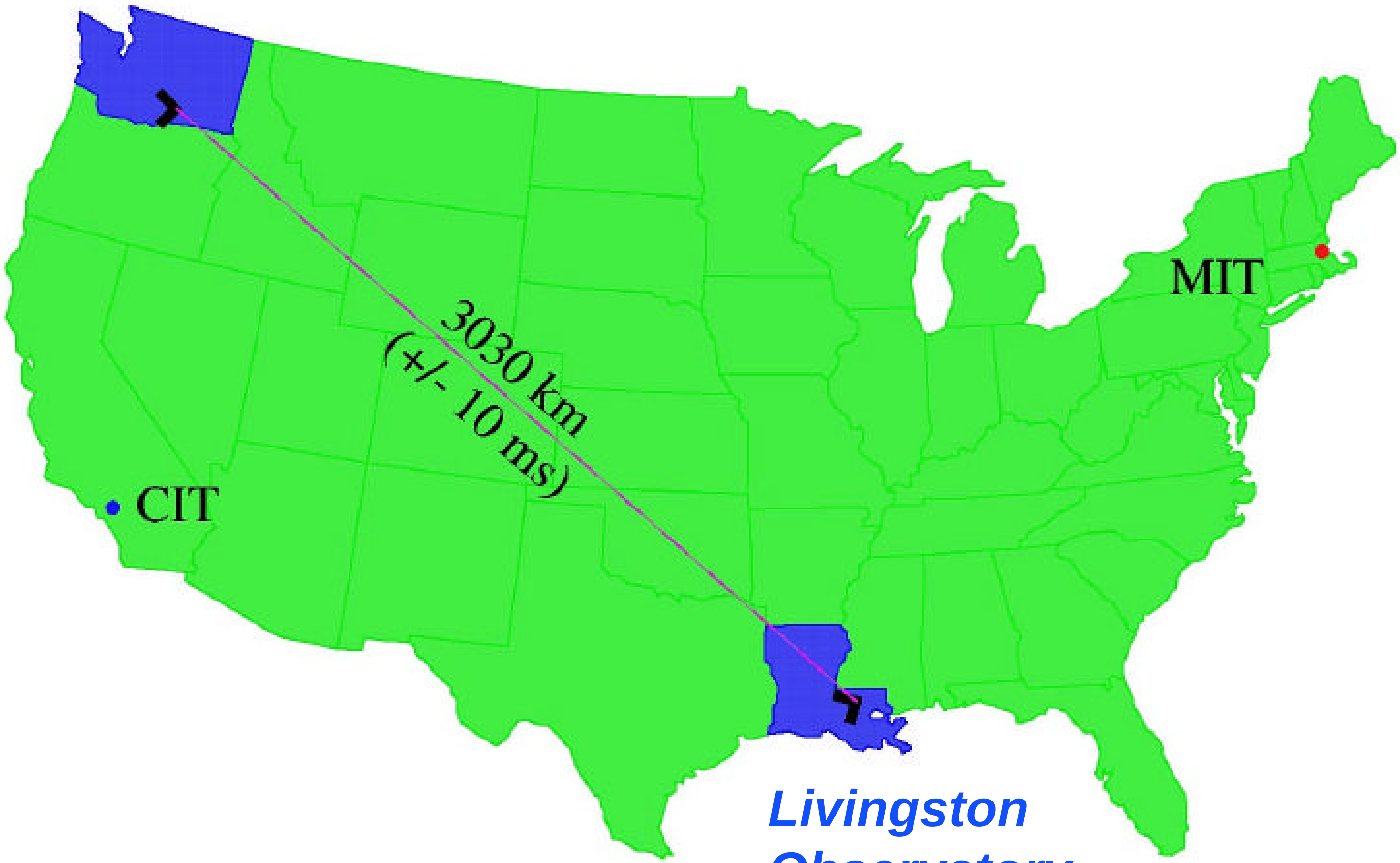

**detection confidence**

**locate the sources**

**decompose the polarization of gravitational waves**

# LIGO Sites

*Hanford Observatory*

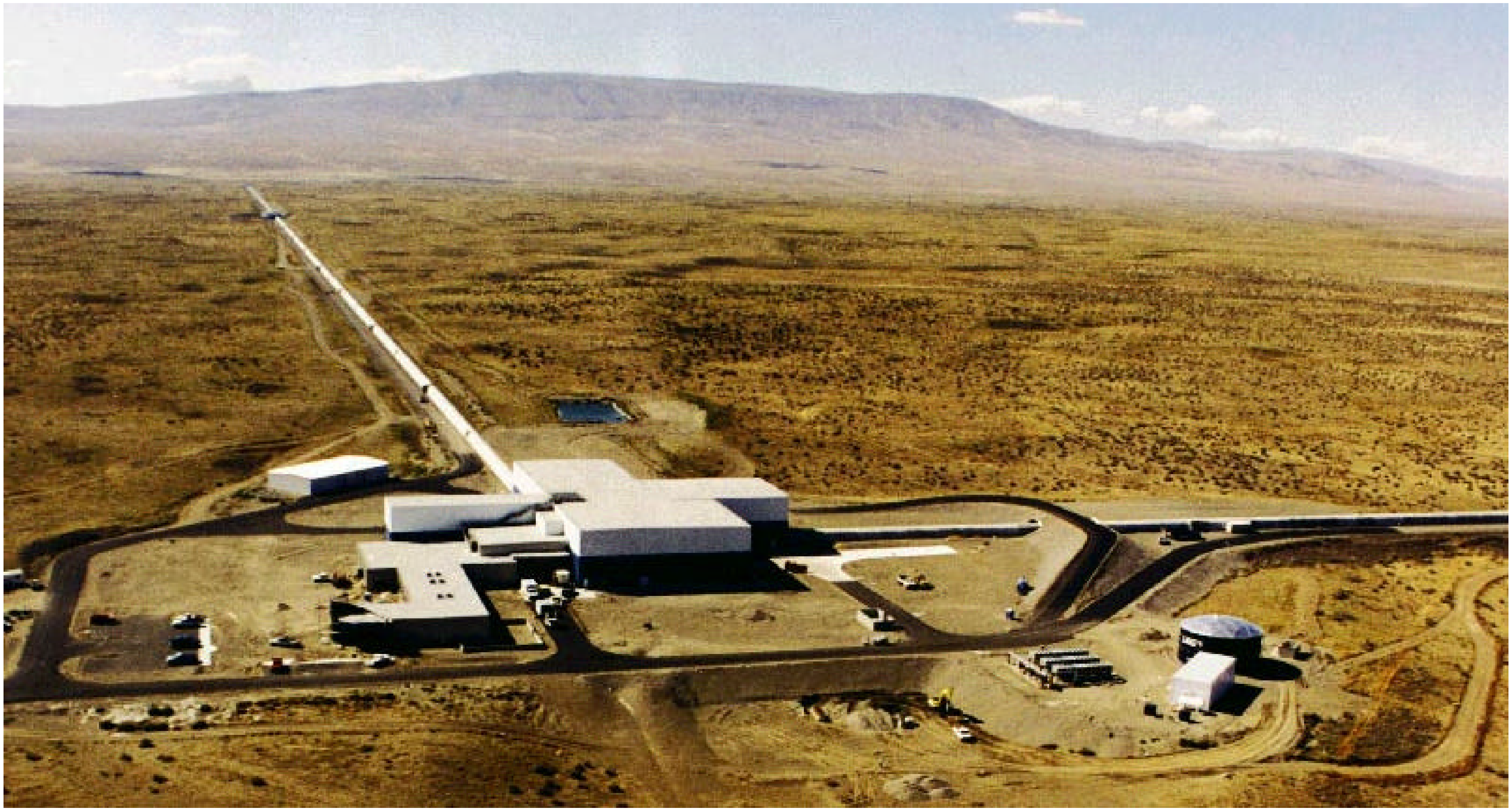



*Livingston Observatory*

# LIGO
## *Livingston Observatory*

# LIGO

## *Hanford Observatory*



# LIGO

## *Beam Tube*

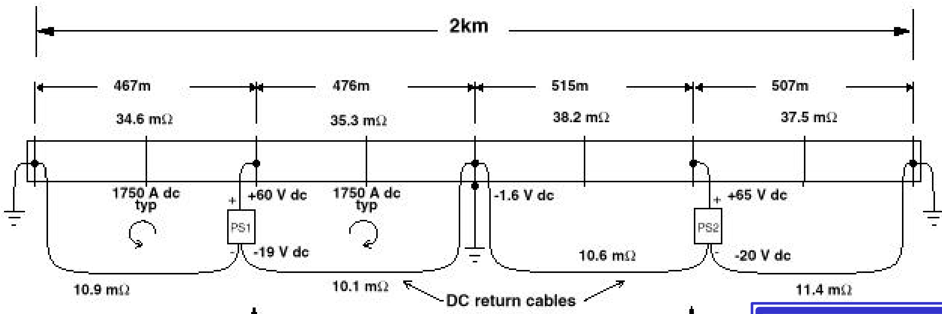
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

**1.2 m diameter - 3mm stainless**
**50 km of weld**

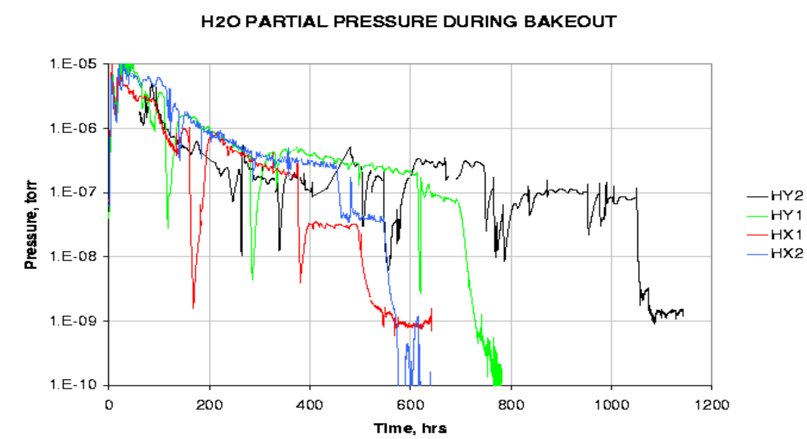
**NO LEAKS !!**

# Beam Tube

## *bakeout*




- I = 2000 amps for ~ 1 week
- no leaks !!
- final vacuum at level where not limiting noise, even for future detectors



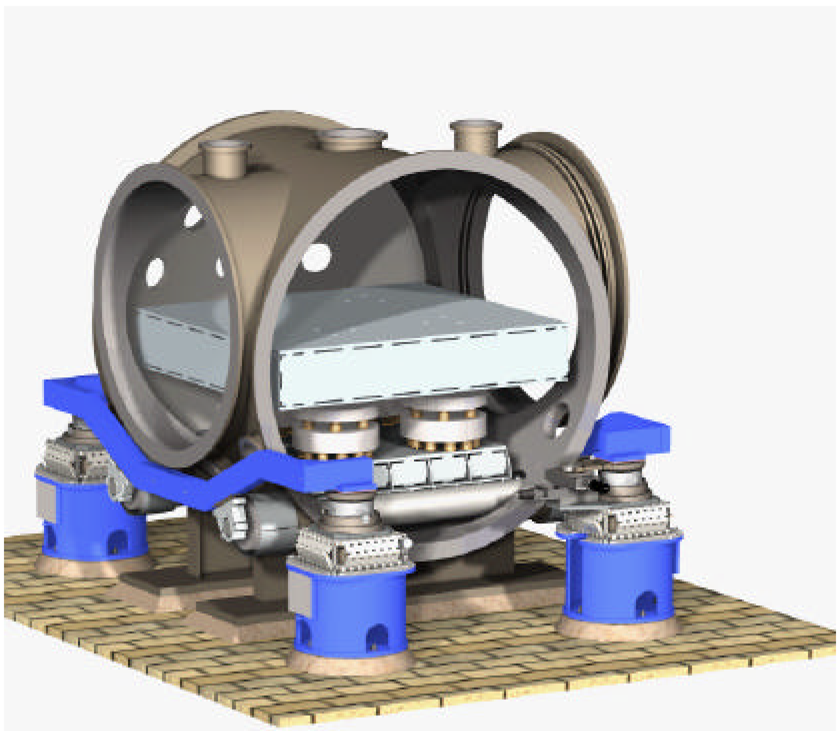
# LIGO

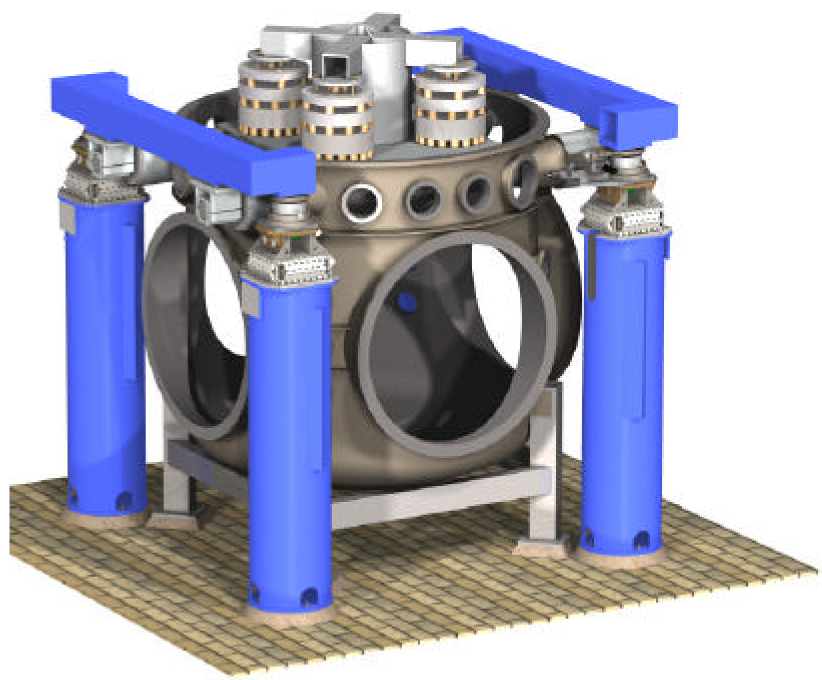
## *vacuum equipment*

# Vacuum Chambers

## *Vibration Isolation Systems*

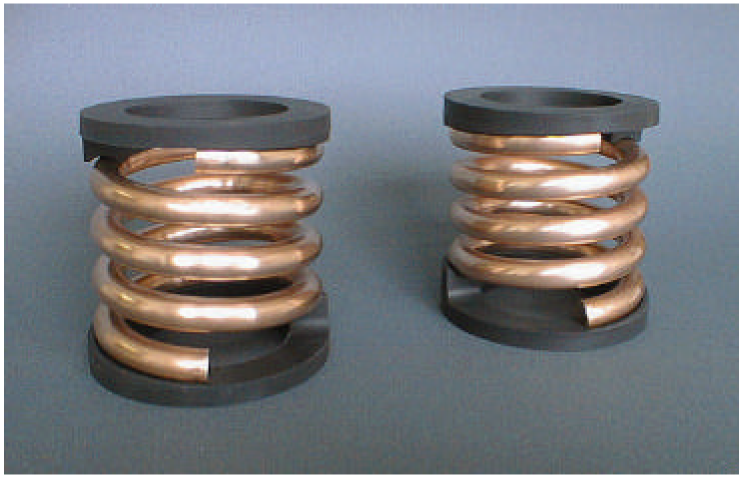
- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Compensate for microseism at 0.15 Hz by a factor of ten
- Compensate (partially) for Earth tides



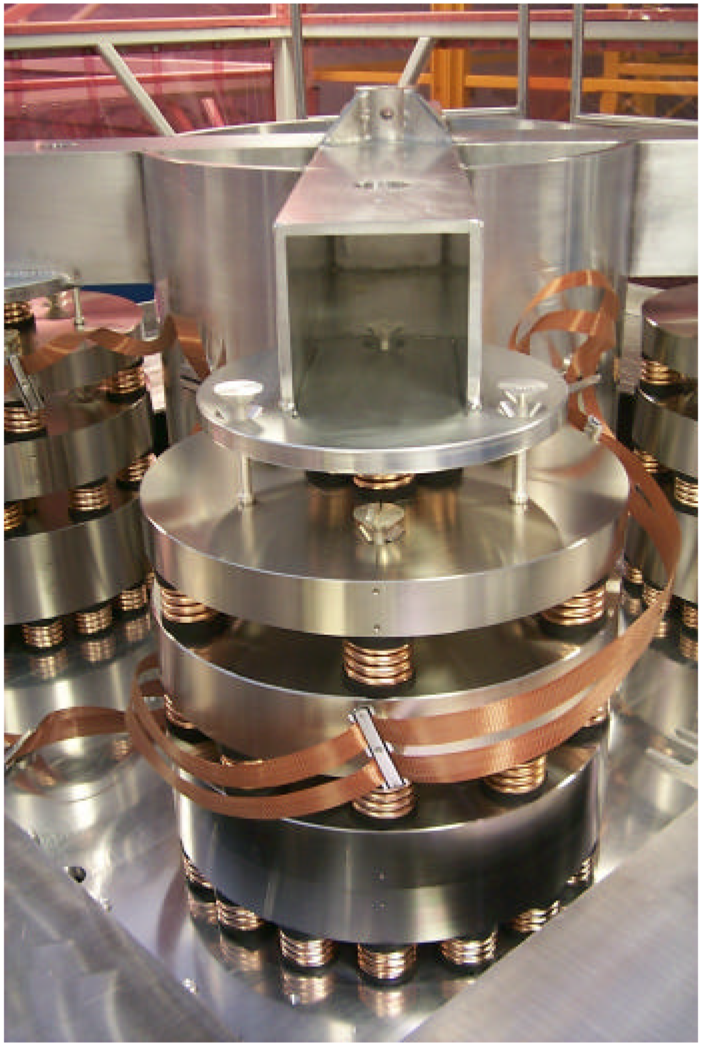


# Seismic Isolation

## *Springs and Masses*

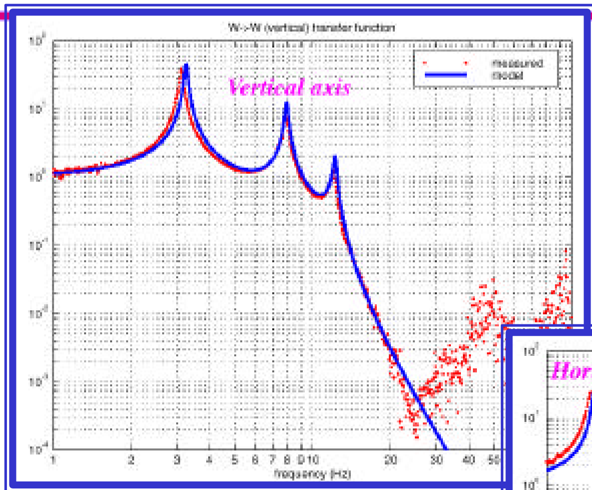


damped spring
cross section

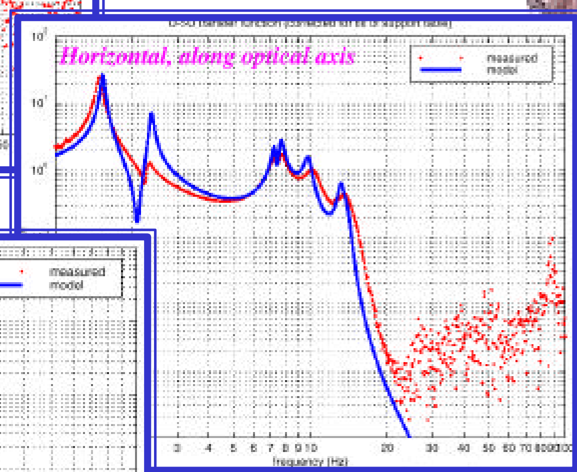


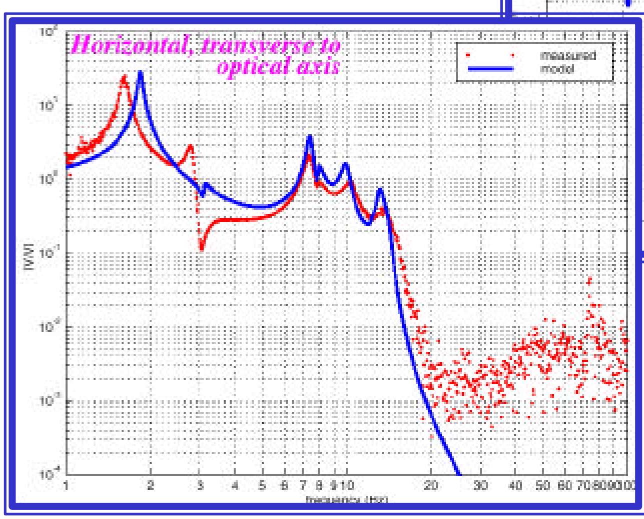
# Seismic Isolation

## *performance*

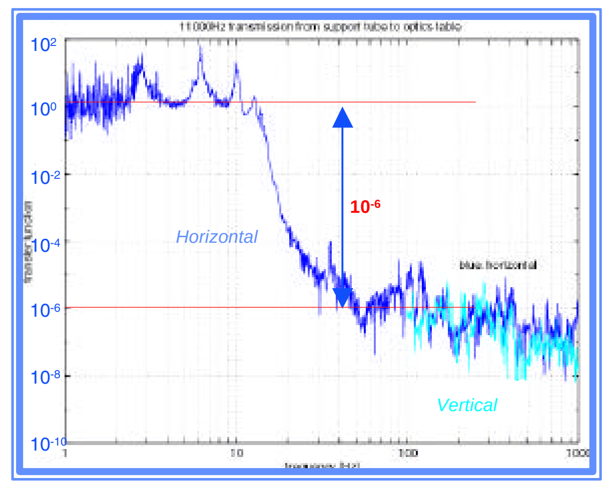



**HAM stack in air**



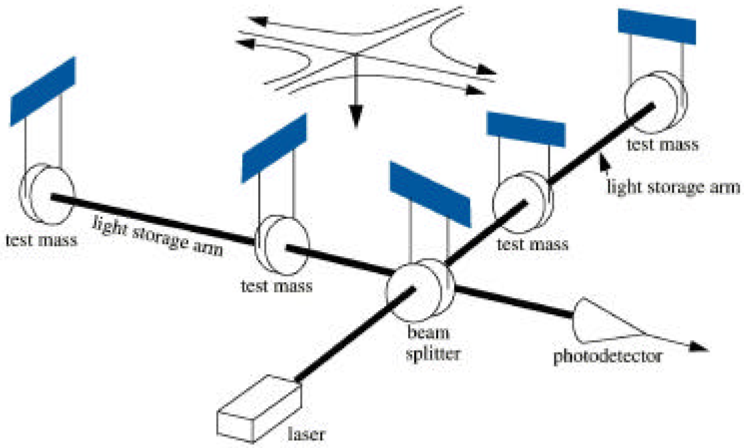




**BSC stack in vacuum**



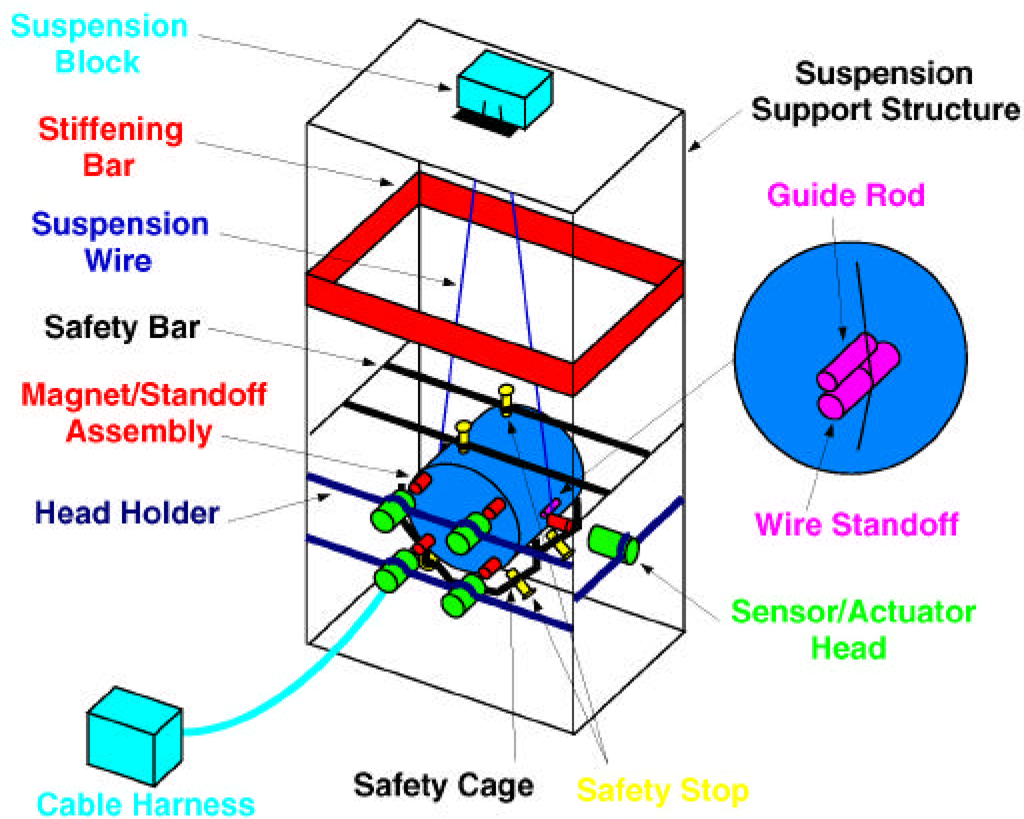
# Seismic Isolation

*suspension system*



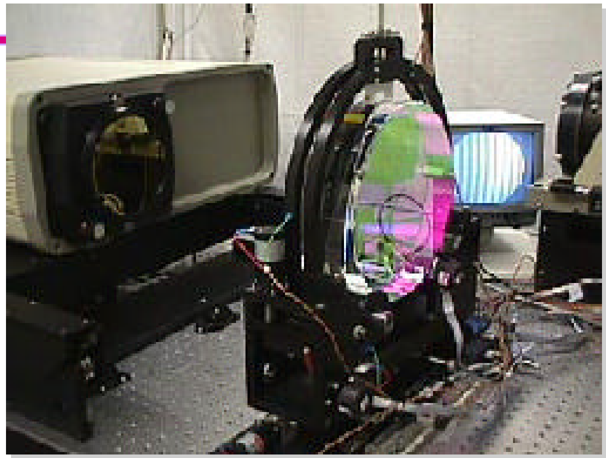

- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

**suspension assembly for a core optic**

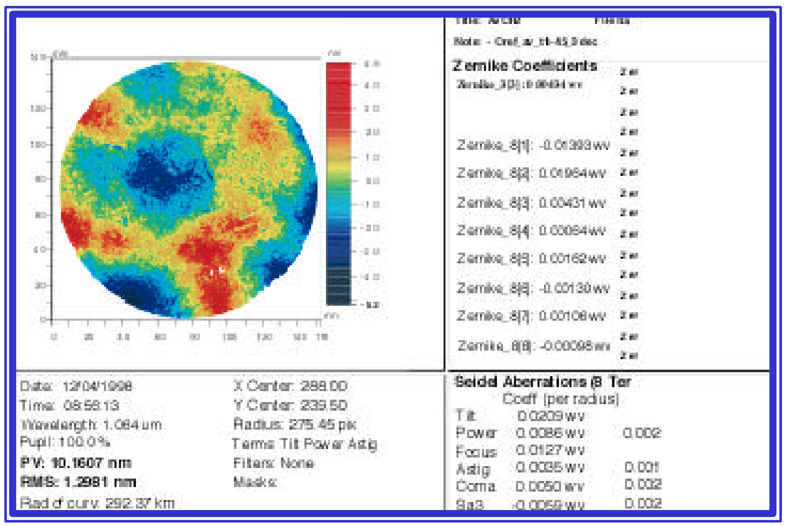


# Core Optics

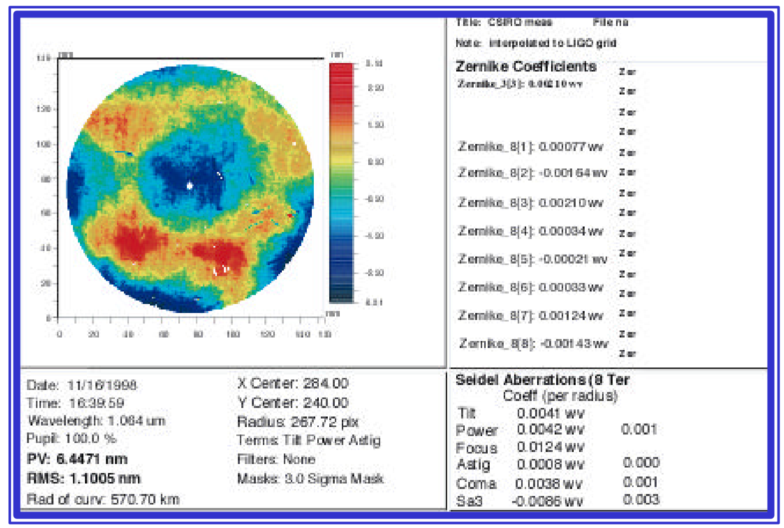
## *fused silica*



- **Surface uniformity < 1 nm rms**
- **Scatter < 50 ppm**
- **Absorption <  2 ppm**
- **ROC matched < 3%**
- **Internal mode Q's > 2 x $10^6$**



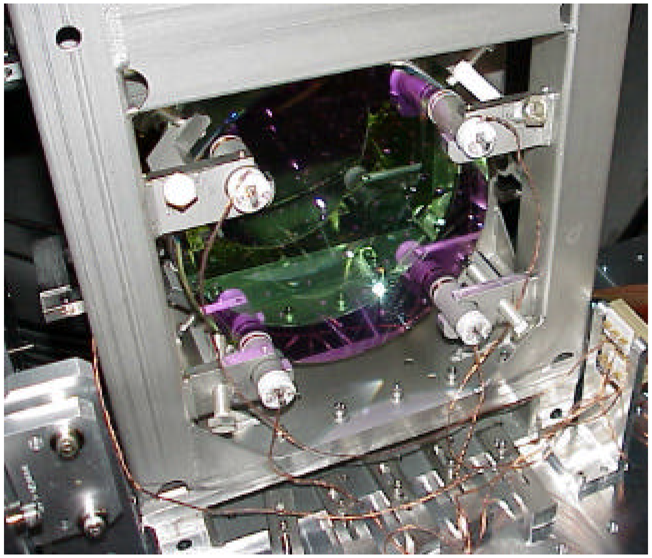

Caltech data

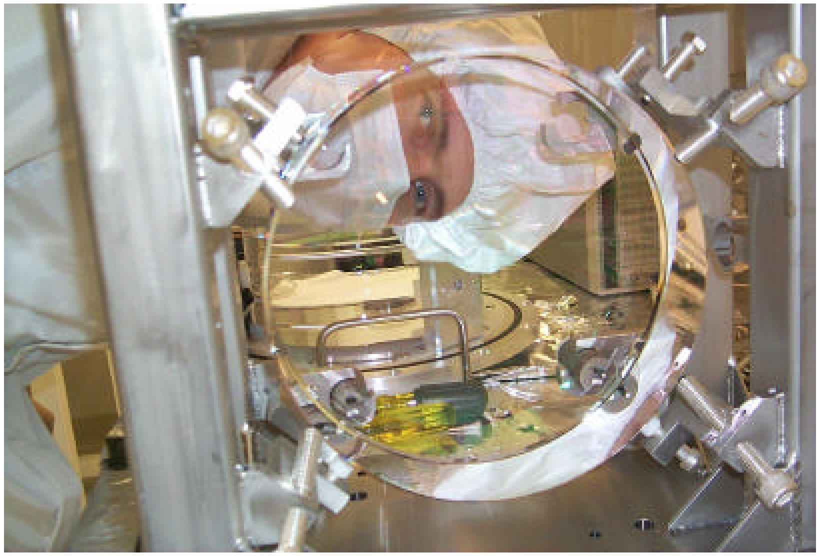



CSIRO data

# Core Optics

## *Suspension*





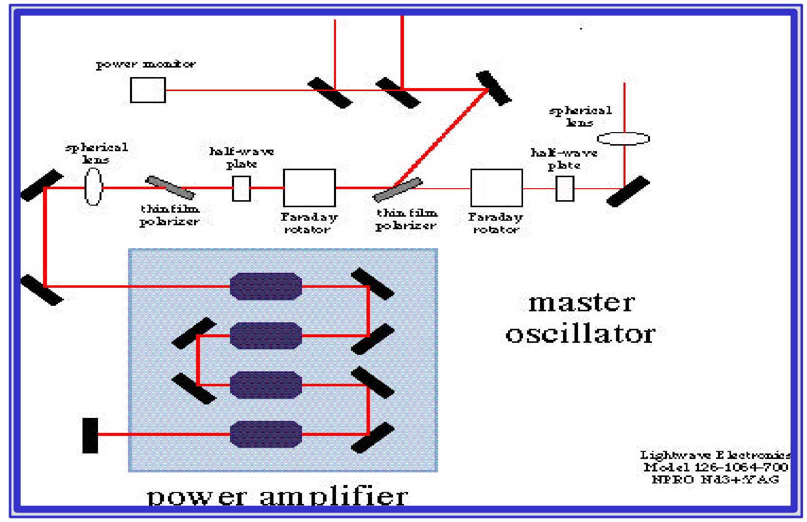
# Core Optics

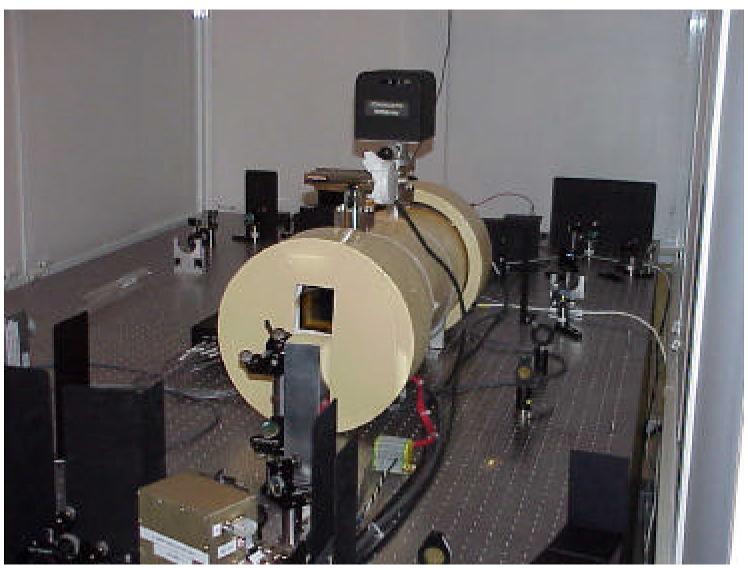
## *Installation and Alignment*

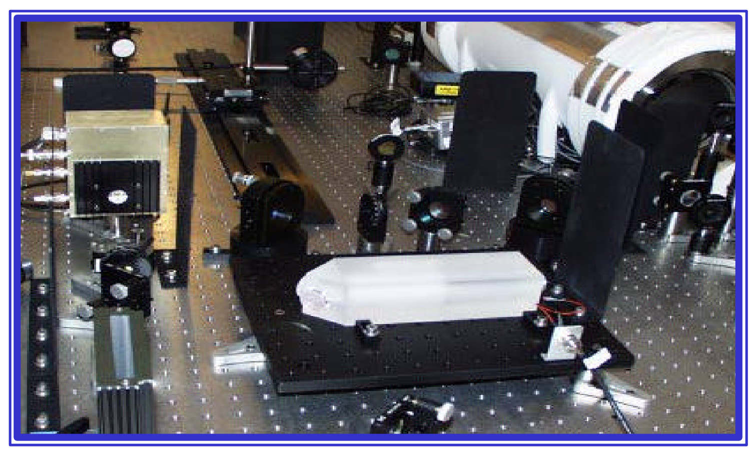
# LIGO

## *Laser*

- **Nd:YAG**
- **1.064 μm**
- **Output power > 8W in TEM00 mode**

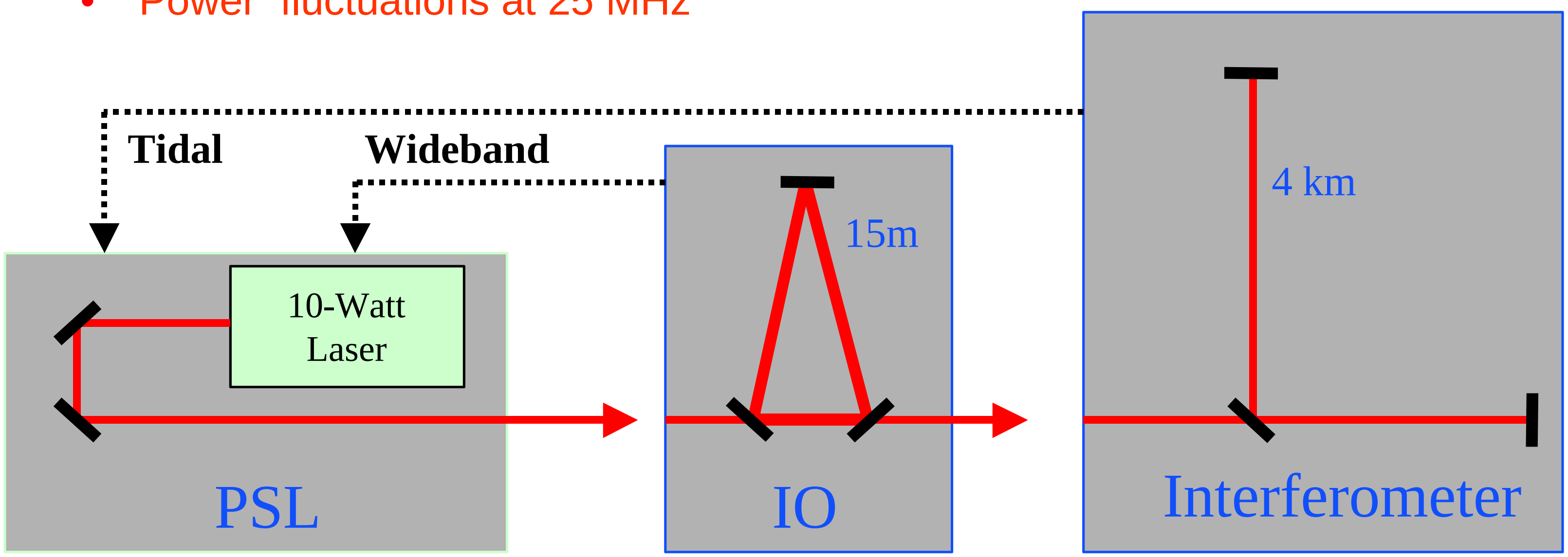




# Laser
## *stabilization*

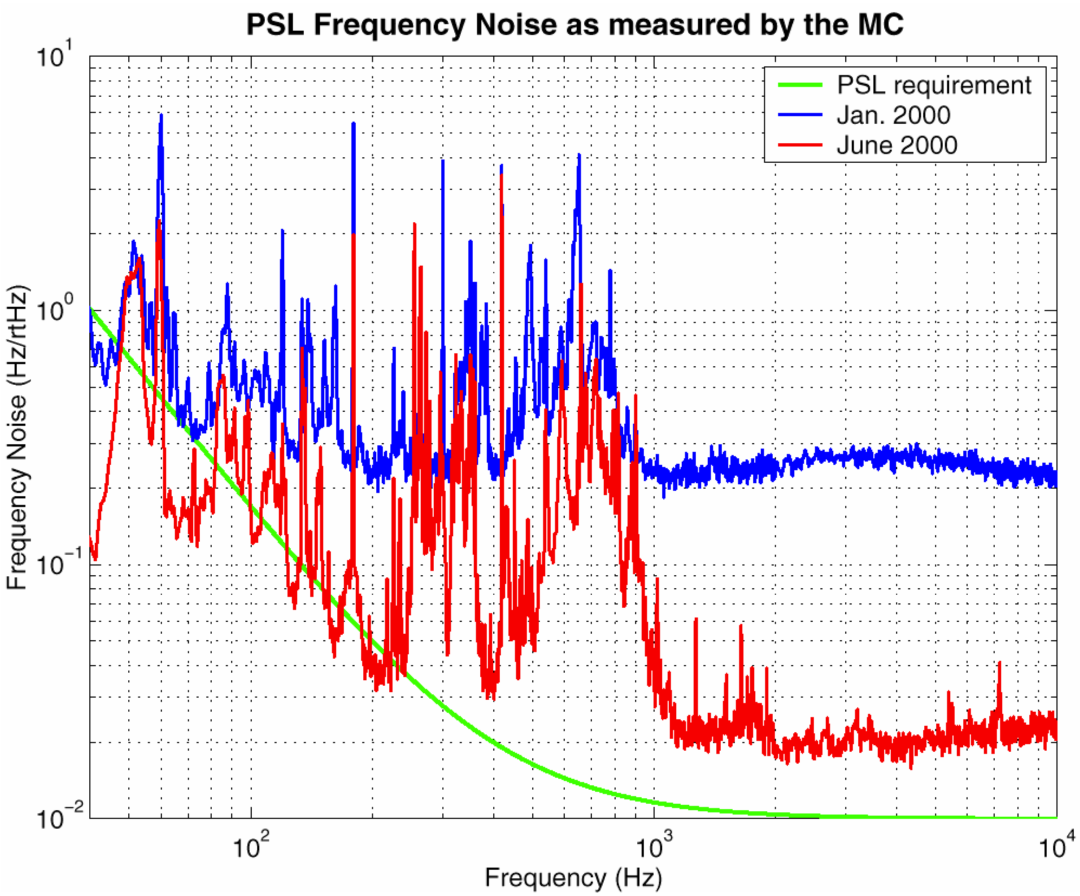
- **Deliver pre-stabilized laser light to the 15-m mode cleaner**
  - Frequency fluctuations
  - In-band power fluctuations
  - Power  fluctuations at 25 MHz
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**



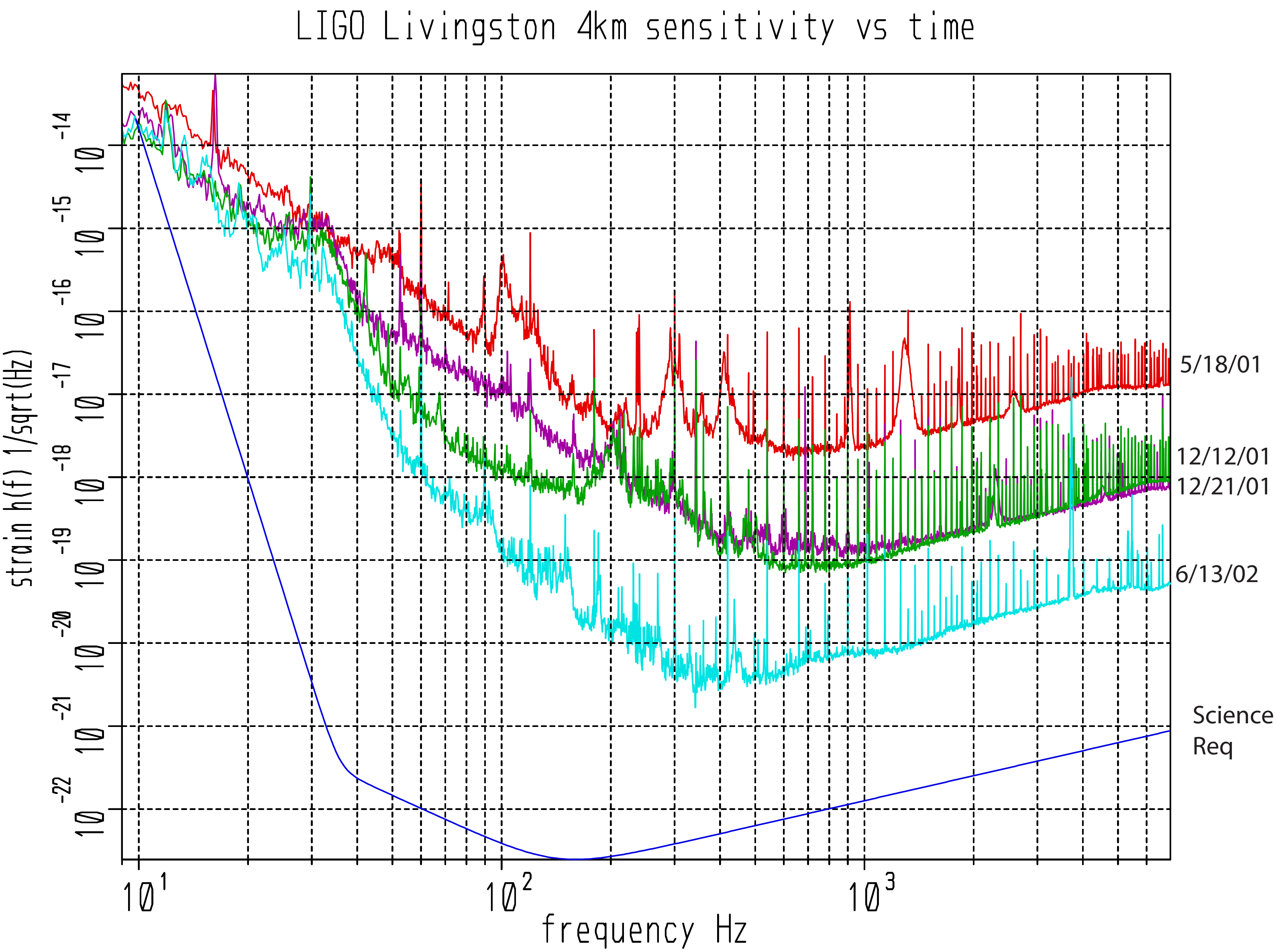

$10^{-1}$ Hz/Hz$^{1/2}$  $10^{-4}$ Hz/ Hz$^{1/2}$  $10^{-7}$ Hz/ Hz$^{1/2}$

# Prestabalized Laser

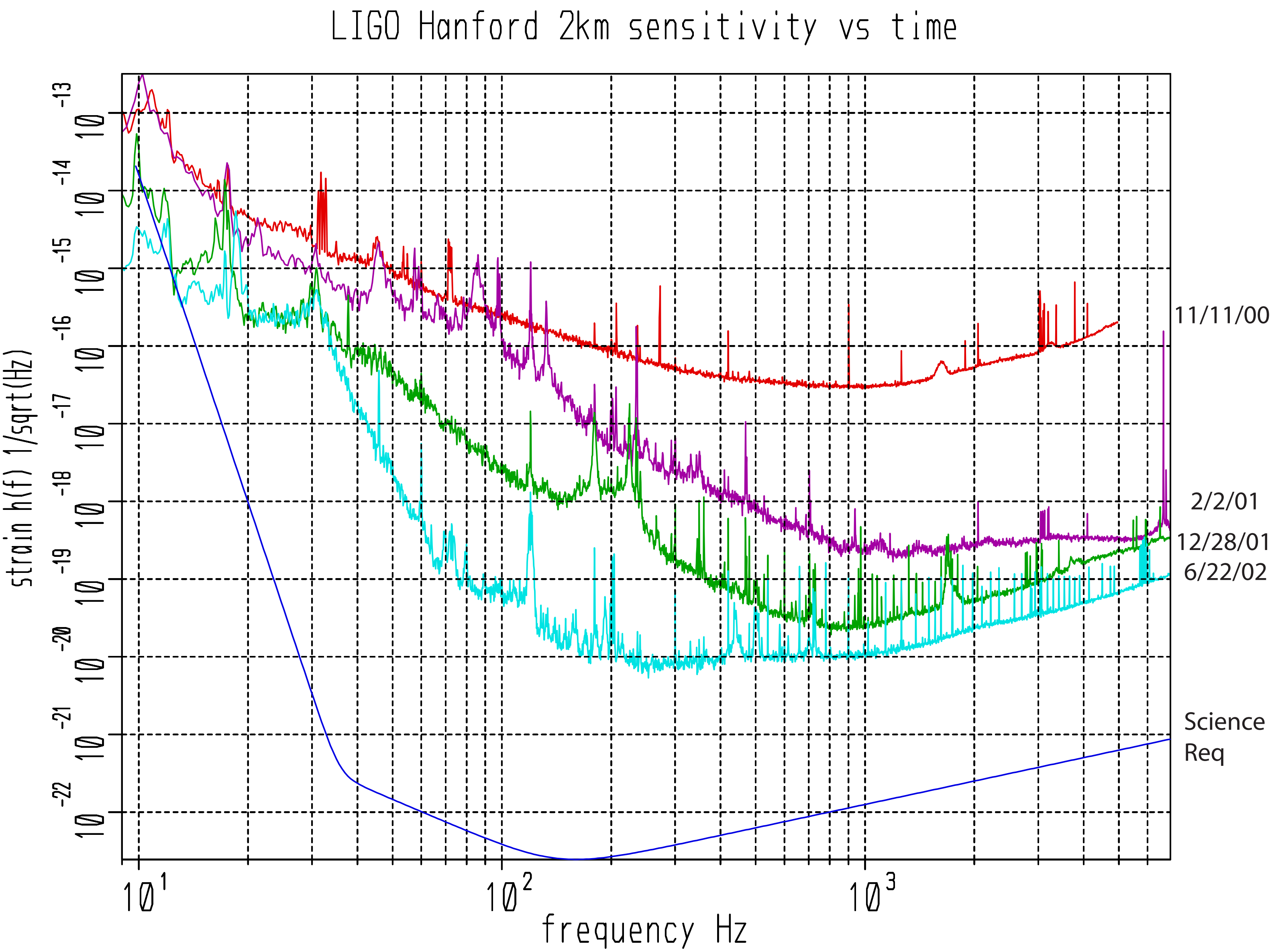
## *performance*



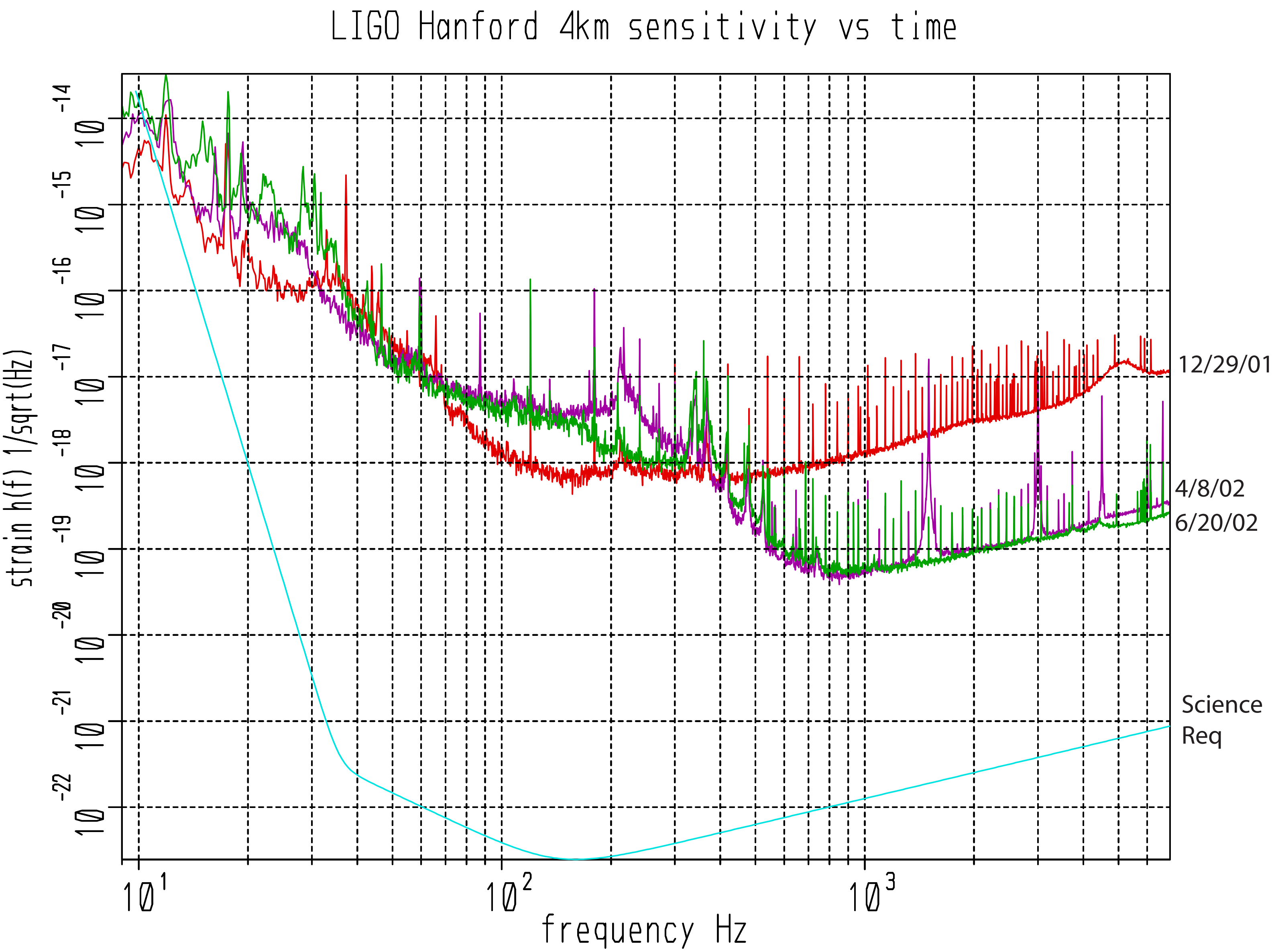

- > 18,000 hours continuous operation
- Frequency and lock very robust
- $TEM_{00}$ power > 8 watts
- Non-$TEM_{00}$ power < 10%



LIGO Livingston 4km sensitivity vs time
strain h(f) 1/sqrt(Hz)
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^1
10^2
10^3
frequency Hz
5/18/01
12/12/01
12/21/01
6/13/02
Science Req



LIGO Hanford 2km sensitivity vs time
strain h(f) 1/sqrt(Hz)
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^1
10^2
10^3
frequency Hz
11/11/00
2/2/01
12/28/01
6/22/02
Science
Req


LIGO Hanford 4km sensitivity vs time
strain h(f) 1/sqrt(Hz)
frequency Hz
12/29/01
4/8/02
6/20/02
Science
Req

# Astrophysical source upper limit groups

- Combined groups of experimenters and theorists
- Develop data analysis proposals

*Purpose:*

- Test the LIGO Data Analysis System
- Set upper limits using engineering data and first science run
- Publish first astrophysically interesting results from LIGO

*Groups:*

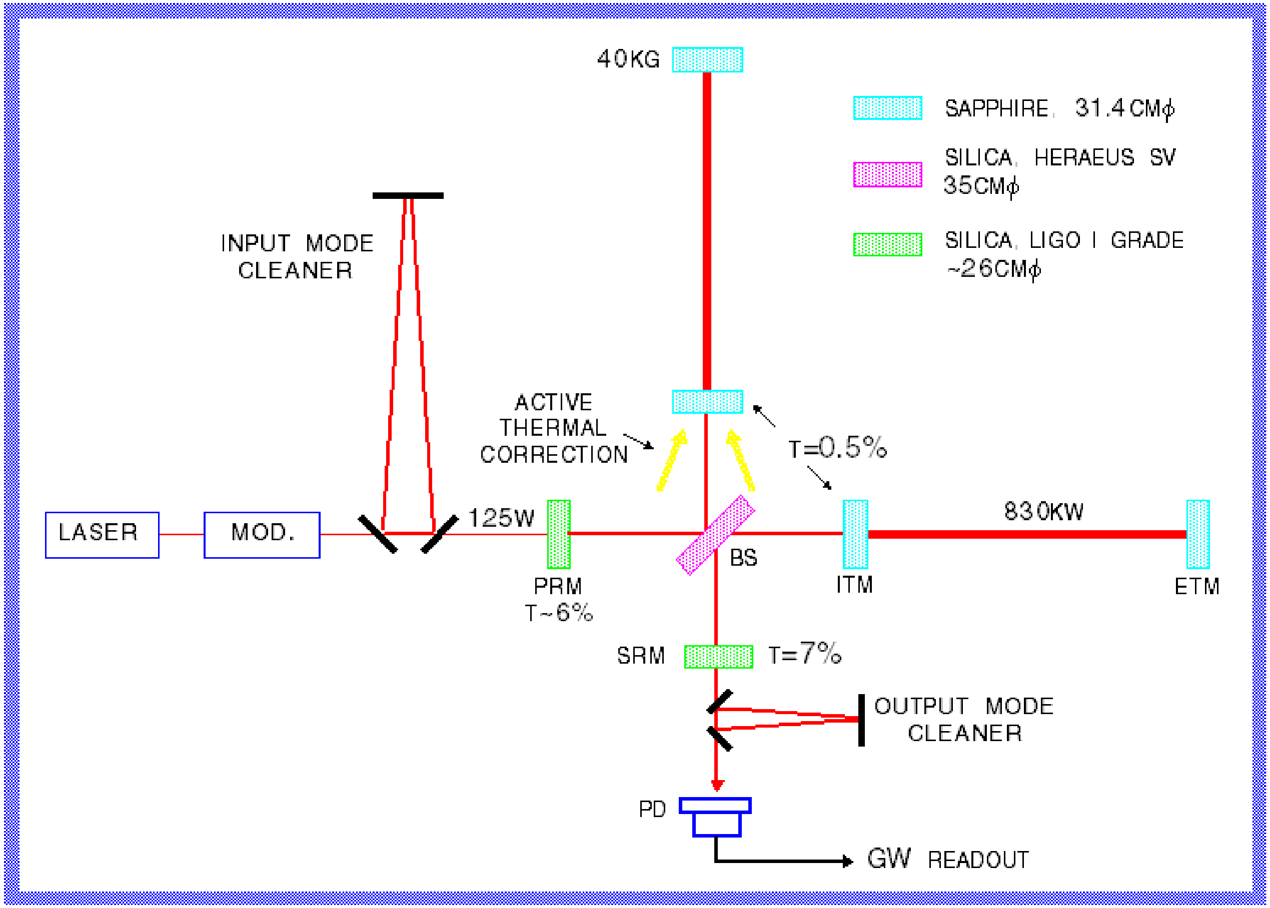
**Burst sources** : Sam Finn Penn State, Peter Saulson Syracuse

**Inspiral sources**: Pat Brady Univ of Wisc., Gabi Gonzalez LSU

**Periodic sources**: Stuart Anderson Caltech, Michael Zucker MIT

**Stochastic backgrd.**: Joe Romano, UT Brownsville, Peter Fritschel MIT

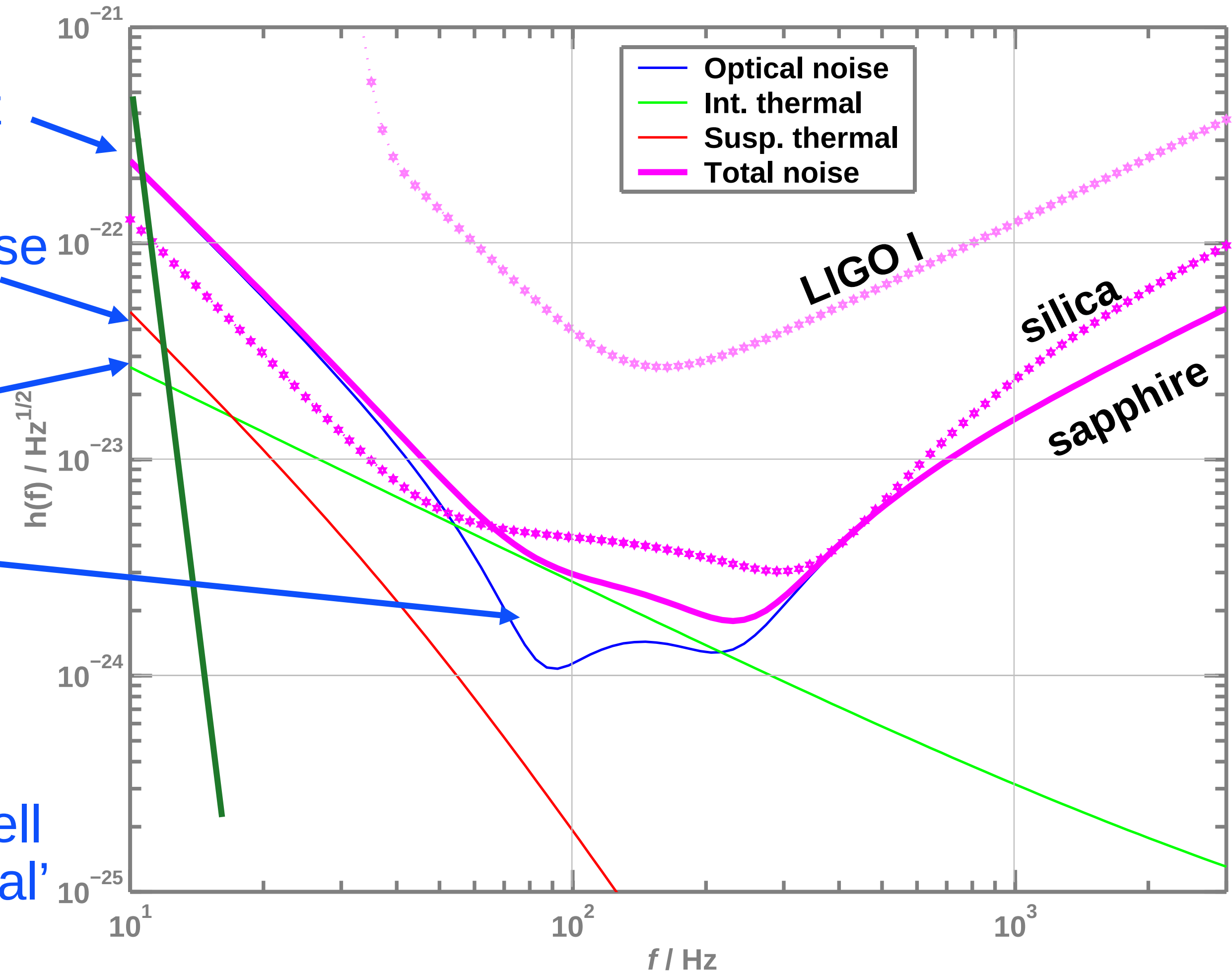
# Advanced Interferometer Concept



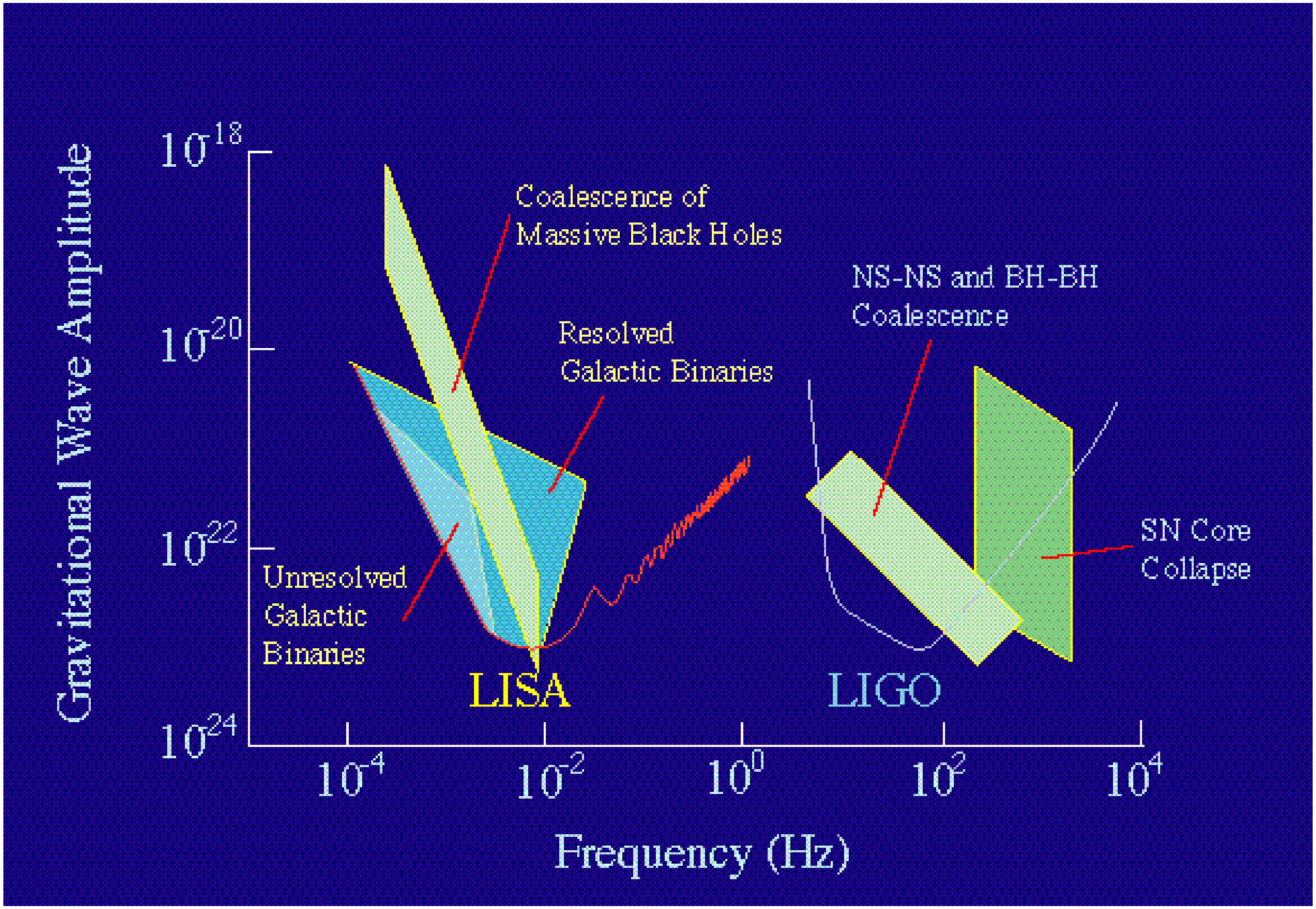

- » Signal recycling
- » 180-watt laser
- » 40 kg Sapphire test masses
- » Larger beam size
- » Quadruple suspensions
- » Active seismic isolation
- » Active thermal correction
- » Output mode cleaner

# Projected Performance

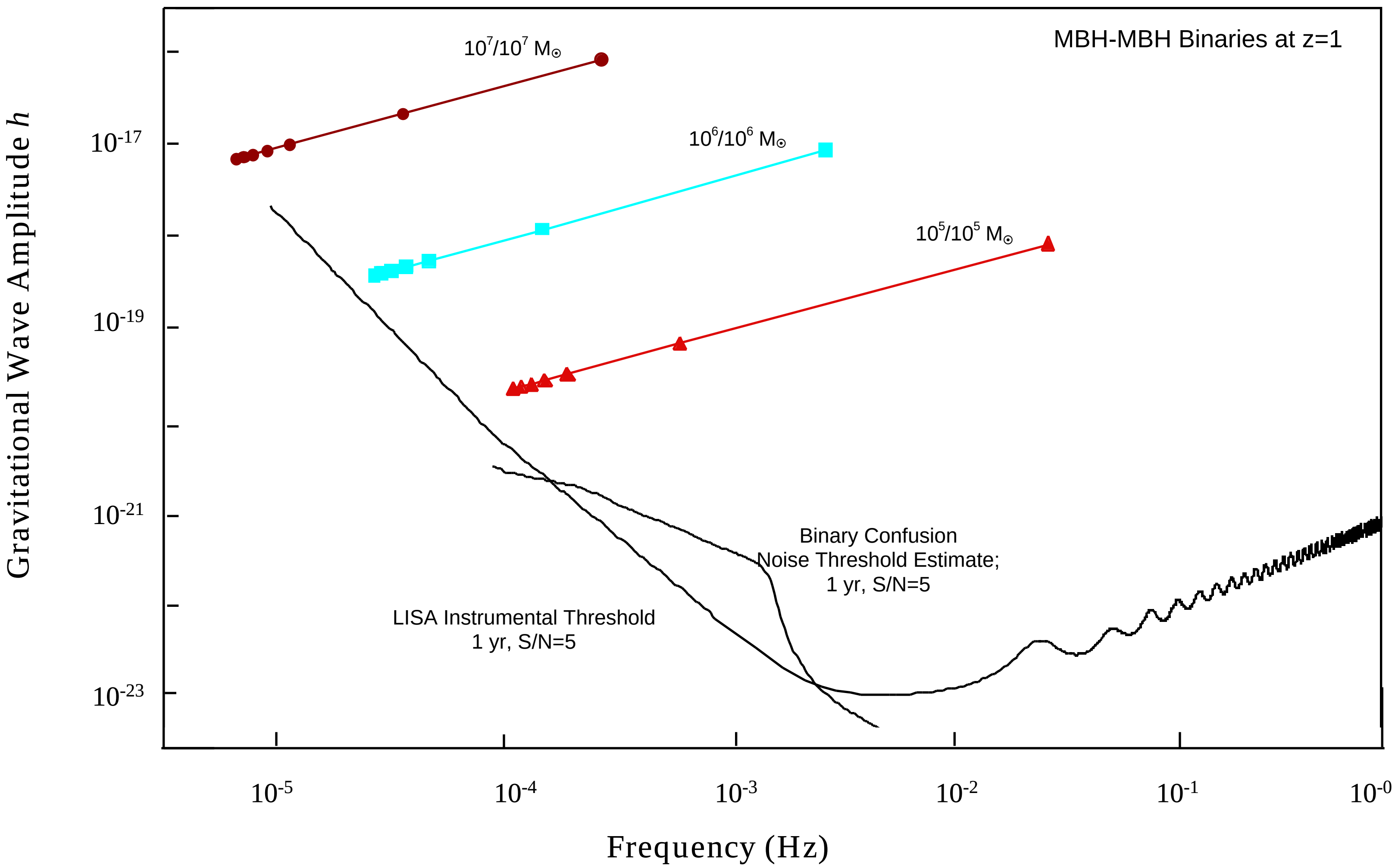
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held in general well below these 'fundamental' noises



# The Gravitational-Wave Spectrum



# Massive Black Holes in Merging Galaxies






LISA

# Mission Concept