LIGO – Laser Interferometer Gravitational-wave Observatory—status of the detector

Jim and Dave Fest

Princeton University

March 15, 2003

Rainer Weiss (MIT) for the LIGO Scientific Collaboration

Dave did have his hand in it

Physics through the 1990s (Brinkman Physics Survey)

Gravitation, Cosmology and Cosmic-Ray Physics

"…..The National Science Foundation (NSF) has played an important role in fostering this work and is currently considering a major initiative – a Long-Baseline Gravitational-Wave Facility. We have studied this idea and enthusiastically endorse it, assuming that other ongoing work of high quality will not be adversely affected. We recommend that the NSF enhance its leadership in gravitation research by funding the Long-Baseline Facility, while continuing to support a vigorous program to search for gravitational waves with resonant bar detectors…"

David T. Wilkinson, Chairman NAS Press 1986

LIGO Scientific Collaboration Member Institutions

University of Adelaide ACIGA
Australian National University ACIGA
Balearic Islands University
California State Dominquez Hills
Caltech CACR
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
NASA-Goddard Spaceflight Center
University of Hannover GEO
Hobart – Williams University
India-IUCAA
IAP Nizhny Novgorod
Iowa State University
Joint Institute of Laboratory Astrophysics
Salish Kootenai College

LIGO Livingston LIGOLA
LIGO Hanford LIGOWA
Loyola New Orleans
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
Southeastern Louisiana University
Southern University
Stanford University
Syracuse University
University of Texas@Brownsville
Washington State University@ Pullman
University of Western Australia ACIGA
University of Wisconsin@Milwaukee

THE RADIATION FIELD

Transverse Plane Wave Solutions with “Electric” and “Magnetic” Terms

Geometric Interpretation

$$d\,s^2 \;=\; g_{ij} dx^i\, dx^j$$

$$g_{ij} \;=\; \eta_{ij} \;+\; h_{ij} \qquad \text{weak field}$$

$$\eta_{ij} \;=\; \begin{pmatrix} 1 & & & 0 \\ & -1 & & \\ 0 & & -1 & \\ & & & -1 \end{pmatrix} \quad \text{Minkowski Metric of Special Relativity}$$

Gravity Wave Propagating in the x_1 Direction

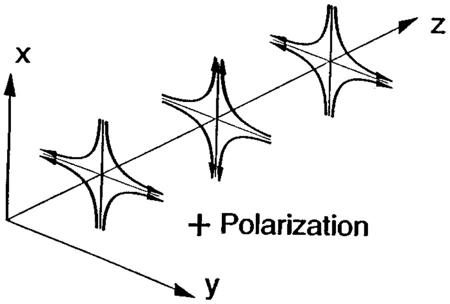
$$h_{ij} \;=\; \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \quad \text{all } h_{ij} \ll 1$$

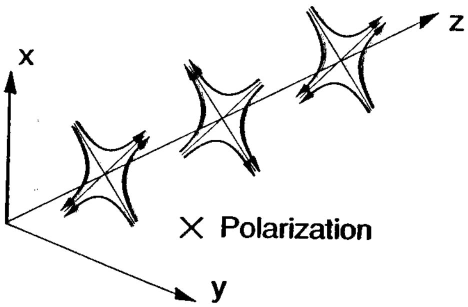
Plane Wave

$\mathbf{h_{22} \;=\; -h_{33}}$ $\qquad$ $\mathbf{h_{23} \;=\; h_{32}}$

+ polarization $\qquad$ **×polarization**

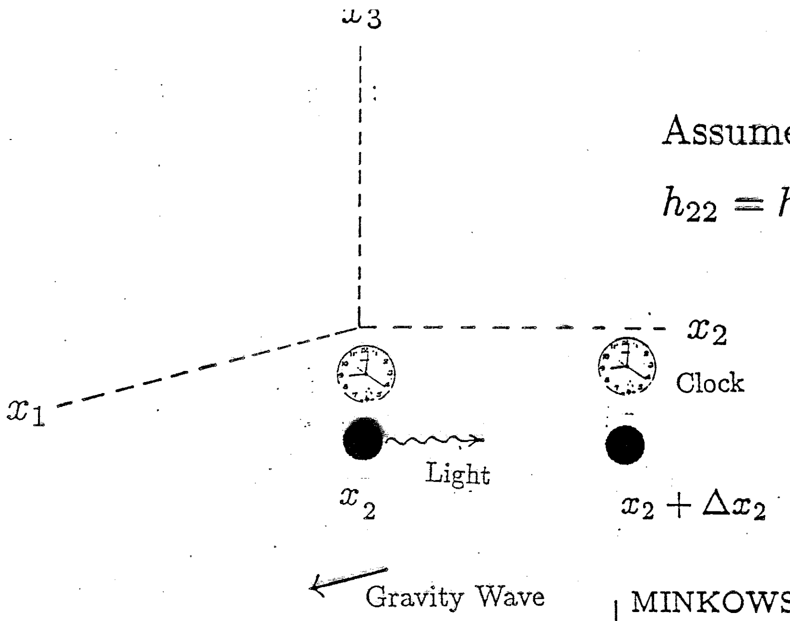
And All Only Function of $x_1 \;-\; ct$


x
z
y
+ Polarization


x
z
y
× Polarization

Assume + Polarization

$$h_{22} = h\sin(kx_1 - \omega t)$$



$$\underset{\text{LIGHT RAY}}{\Delta s^2 = 0} = c^2 \Delta t^2 - \overset{\text{MINKOWSKI}}{\overset{\downarrow}{\Big(1 + h\sin(kx_1 - \omega t)\Big)}}\,\Delta x_2^2$$

Let $\Delta t \ll \dfrac{1}{\omega}$ $\quad h \ll 1$

$$\underset{\nwarrow\ \text{INFERRED DISTANCE BETWEEN POINTS}}{c\Delta t} \cong \left(1 + \frac{h}{2}\sin(kx_1 - \omega t)\right)\Delta x_2$$

$$\frac{\delta(c\,\Delta t)}{\Delta x_2} = \frac{h}{2}\sin(kx_1 - \omega t)$$ Time Dependent **Strain**

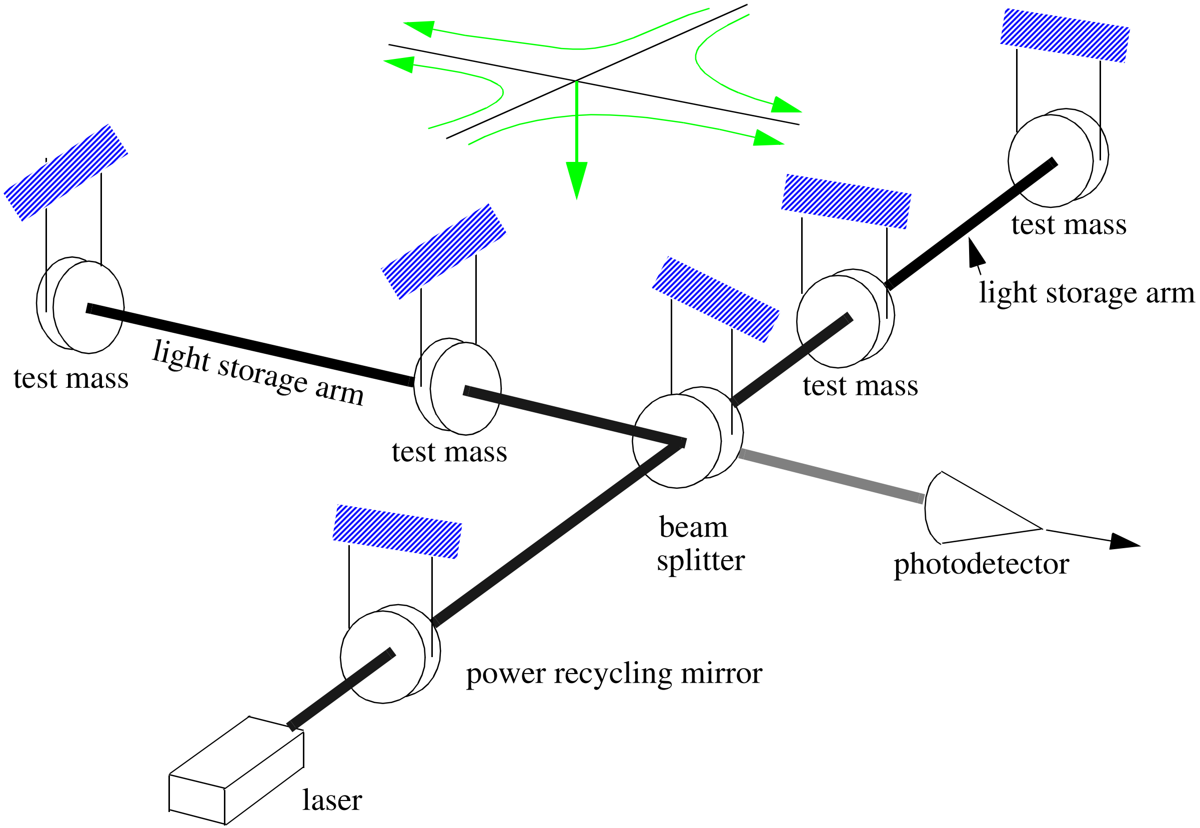
$$\frac{\Delta l}{l} = \frac{h}{2}$$ The Measurable Quantity

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

FRINGE SENSING

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{L b \sqrt{\dot{N} \tau}}$$

arm length = 4000 m

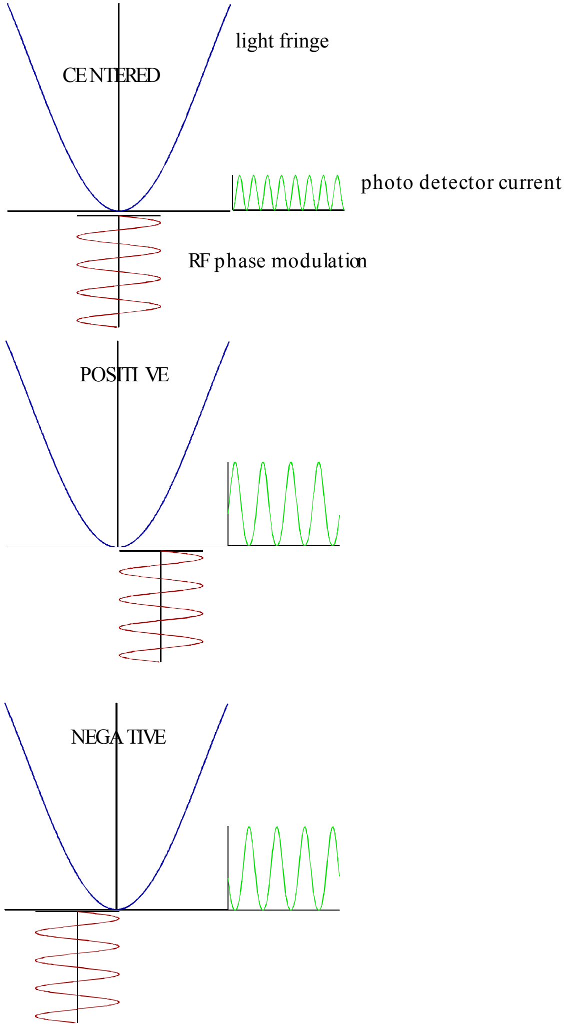
integration time

equivalent # of passes = 100

number of quanta/second at the beam splitter

300 watts at beam splitter = 10^{21} identical photons/sec

$h = 6 \times 10^{-22}$ integration time 10^{-2} sec



ττ=

PENDULUM THERMAL NOISE

Pendulum Brownian motion

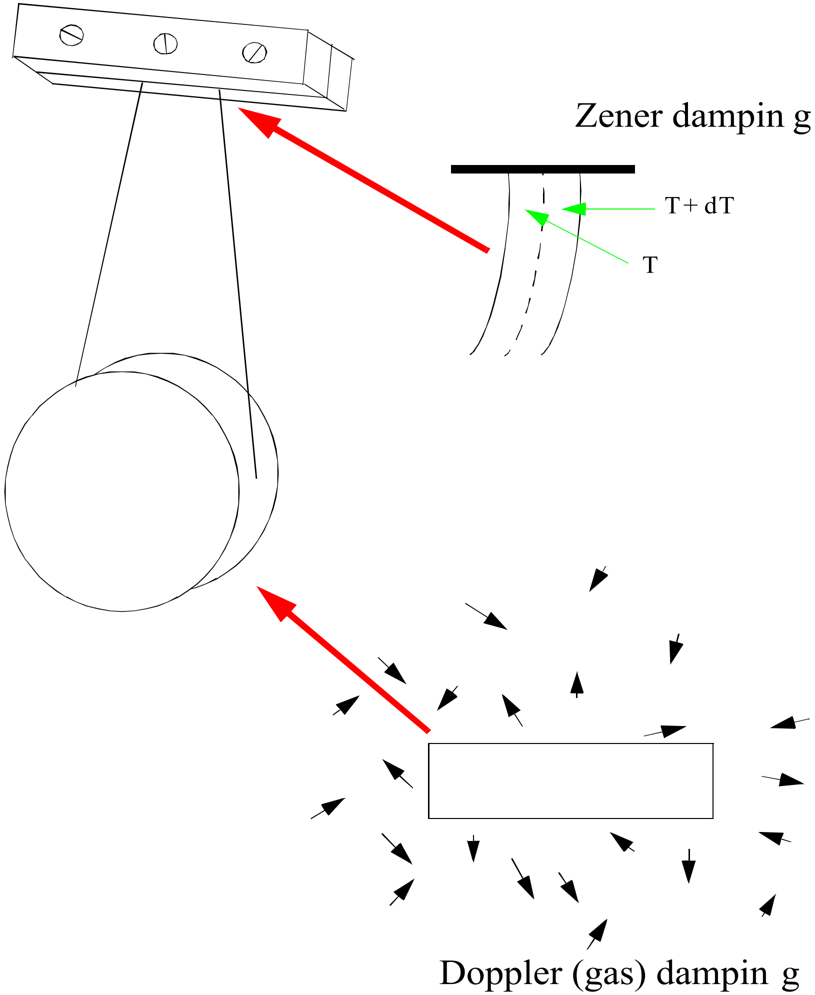
Dissipation leads to fluctuations

Tc = coherence or damping time
= Q x period of oscillator

Exchange with surroundings:

$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

Large Tc => smaller fluctuations



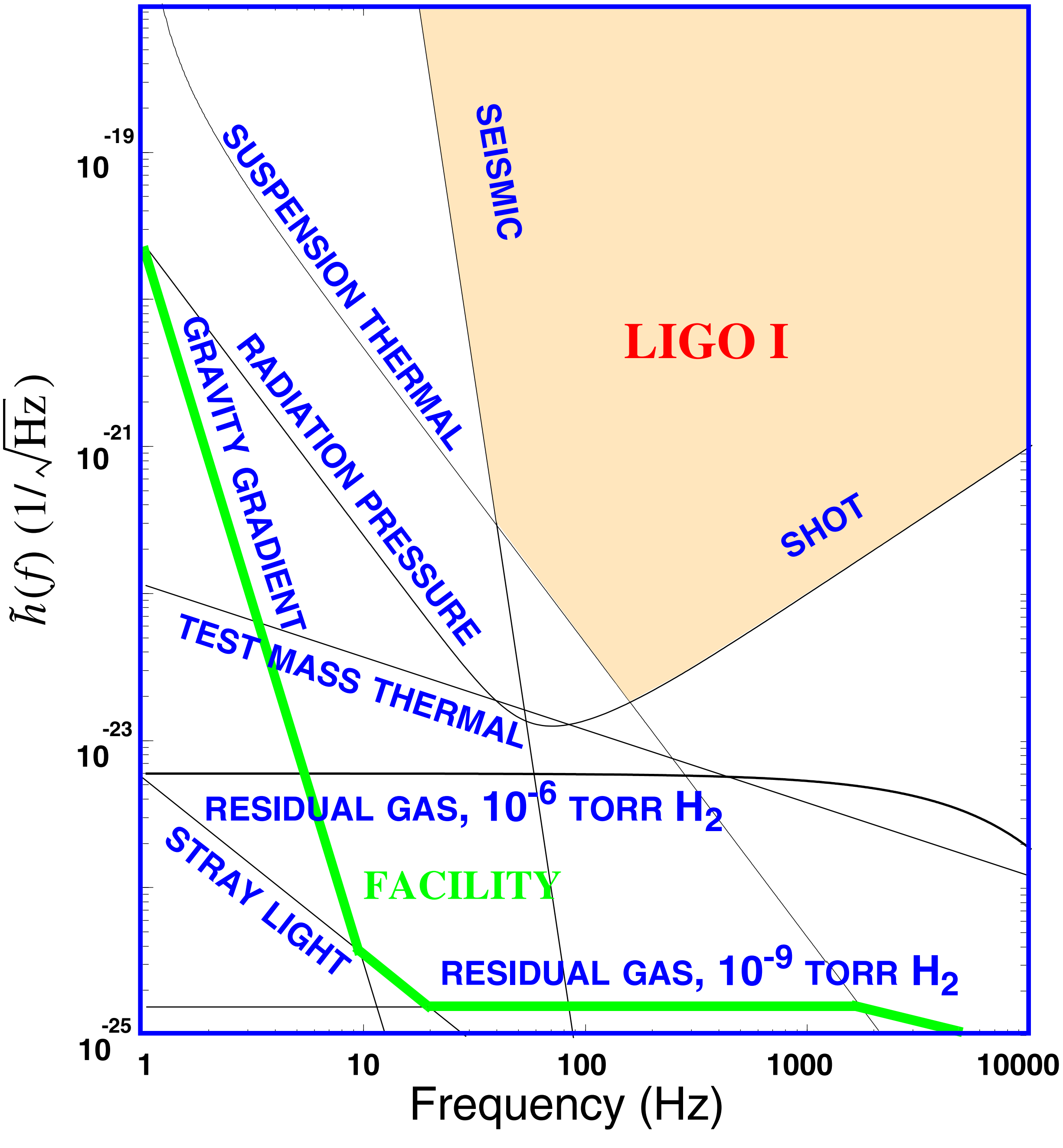
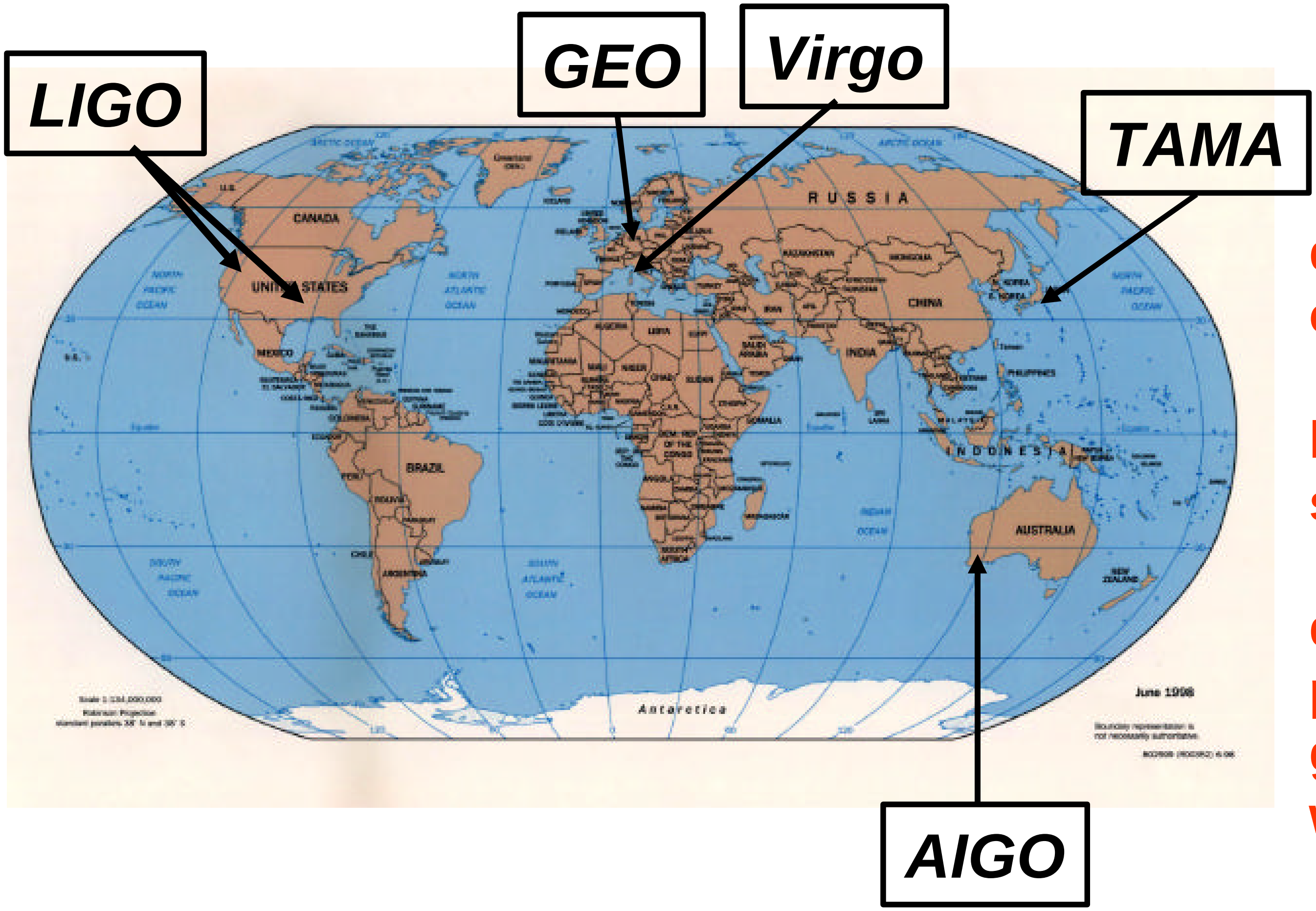

LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
FACILITY
STRAY LIGHT
RESIDUAL GAS, 10^{-9} TORR H_2
10^{-19}
10^{-21}
10^{-23}
10^{-25}
$\tilde{h}(f)\ (1/\sqrt{\mathrm{Hz}})$
1
10
100
1000
10000
Frequency (Hz)

Table 1: Initial detector parameters

Parameter	*Nominal Initial Interferometer*
Arm length	4000 m
Laser type @wavelength	Nd:YAG λ = 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 μ sec
Cavity input mirror transmission	3×10^{-2}
Mirror mass	10.7 kg
Mirror diameter	25 cm
Mirror internal Q	1×10^{6}
Pendulum Q (structure damping)	1×10^{5}
Pendulum period (single)	1 sec
Seismic isolation system	T(100Hz) = -110dB

Interferometers
international network

Simultaneously detect signal (within msec)

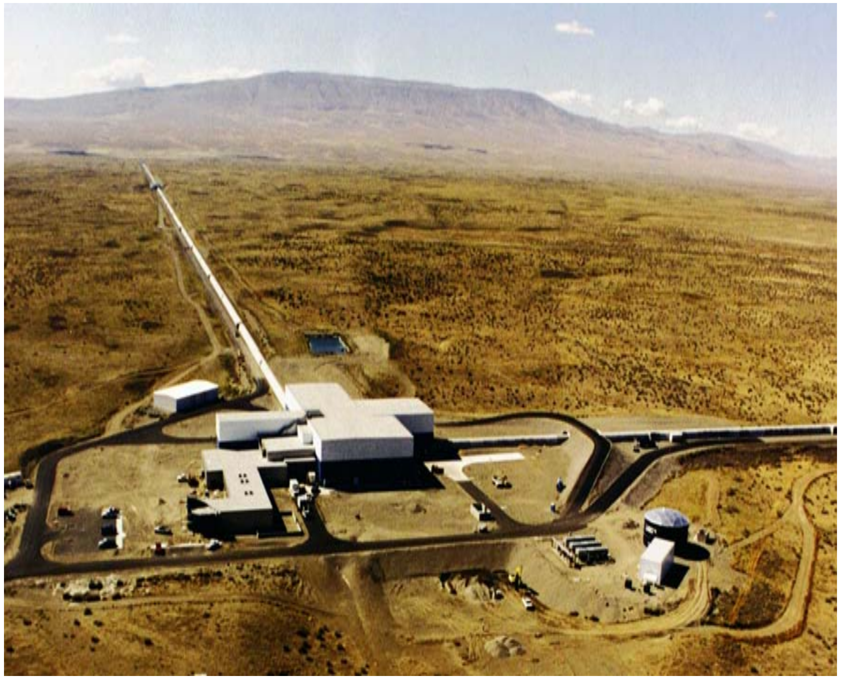


detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

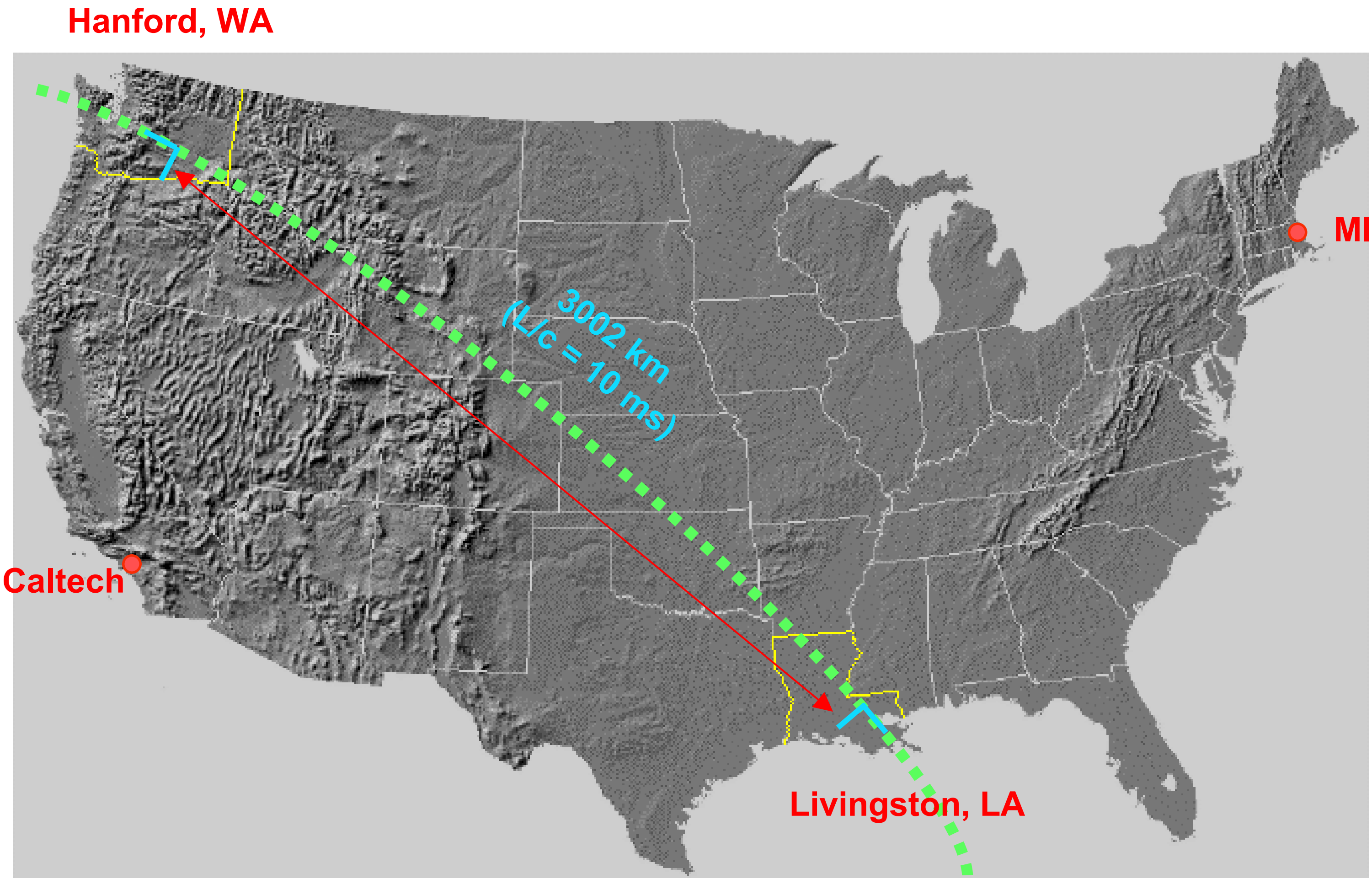
LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites



Beam Tubes and Enclosures

Precast concrete enclosure

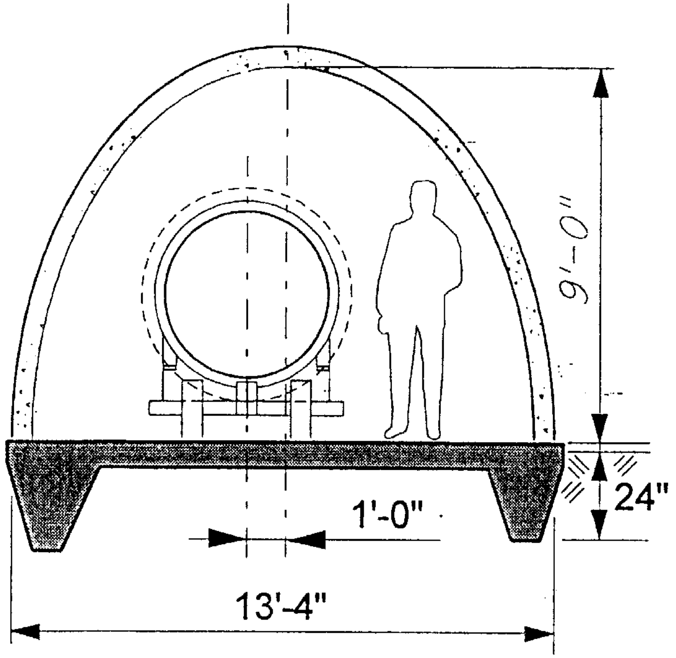
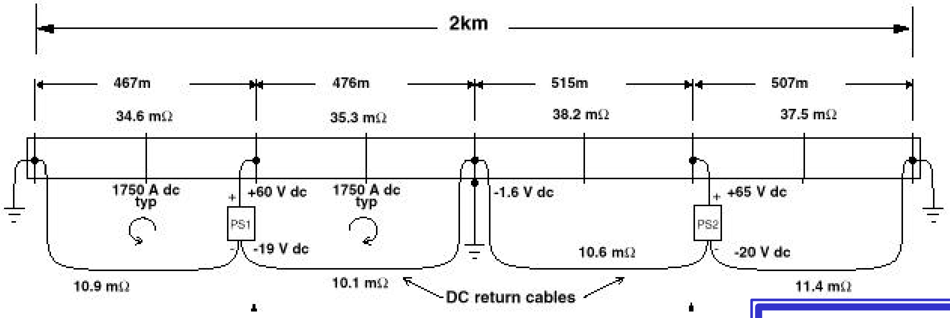


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

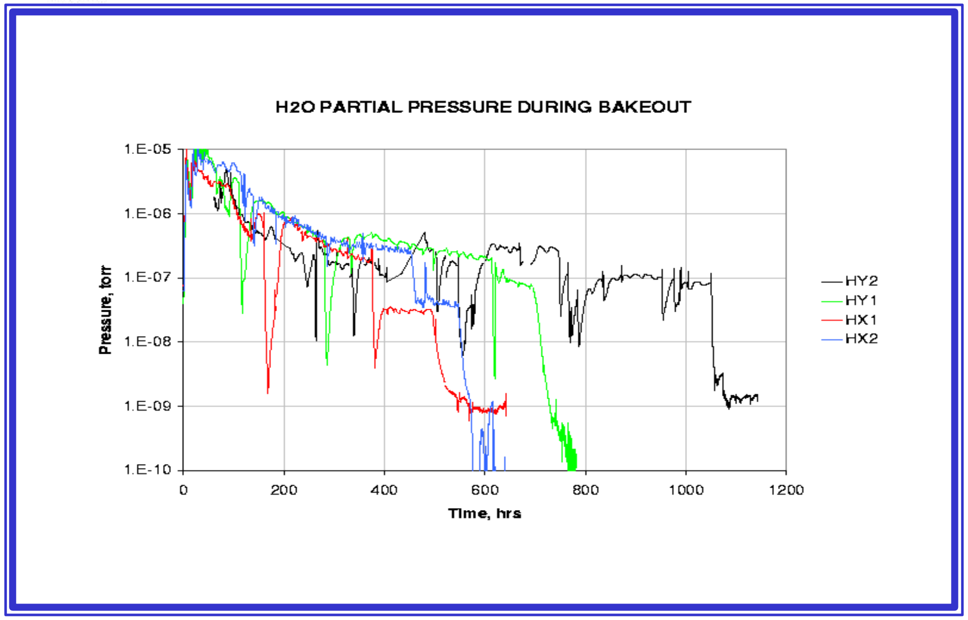
- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **In situ 160 C bakeout**
  - **20,000 m^3 @ 10^{-8} to 10^{-9} torr**

Beam Tube

bakeout



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



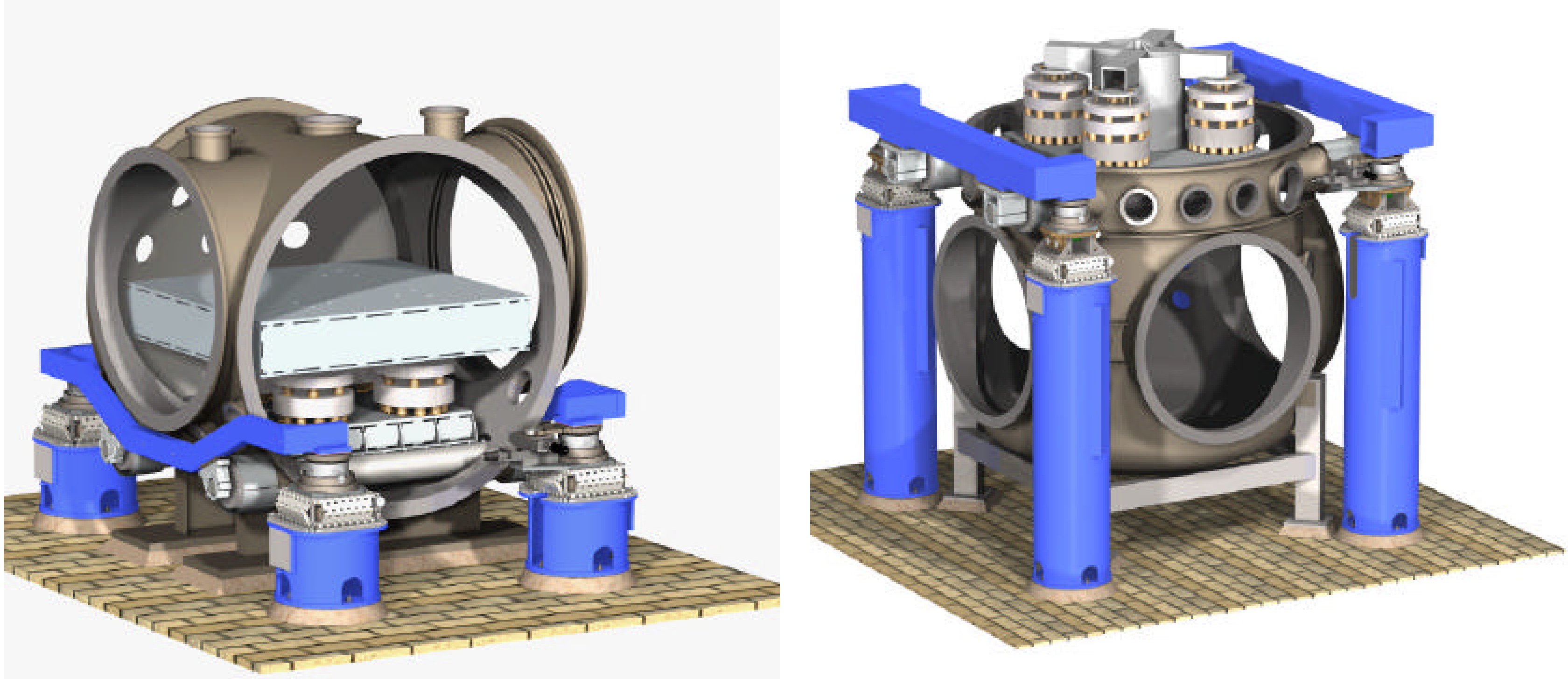
LIGO

vacuum equipment

Vacuum Chambers

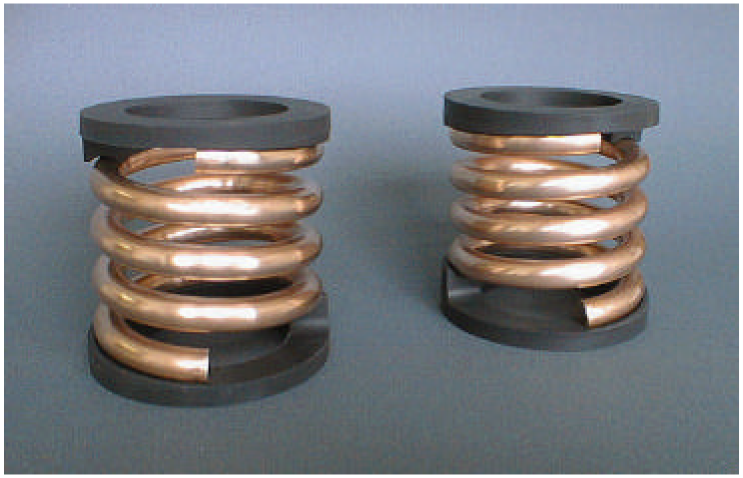
Vibration Isolation Systems

- 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

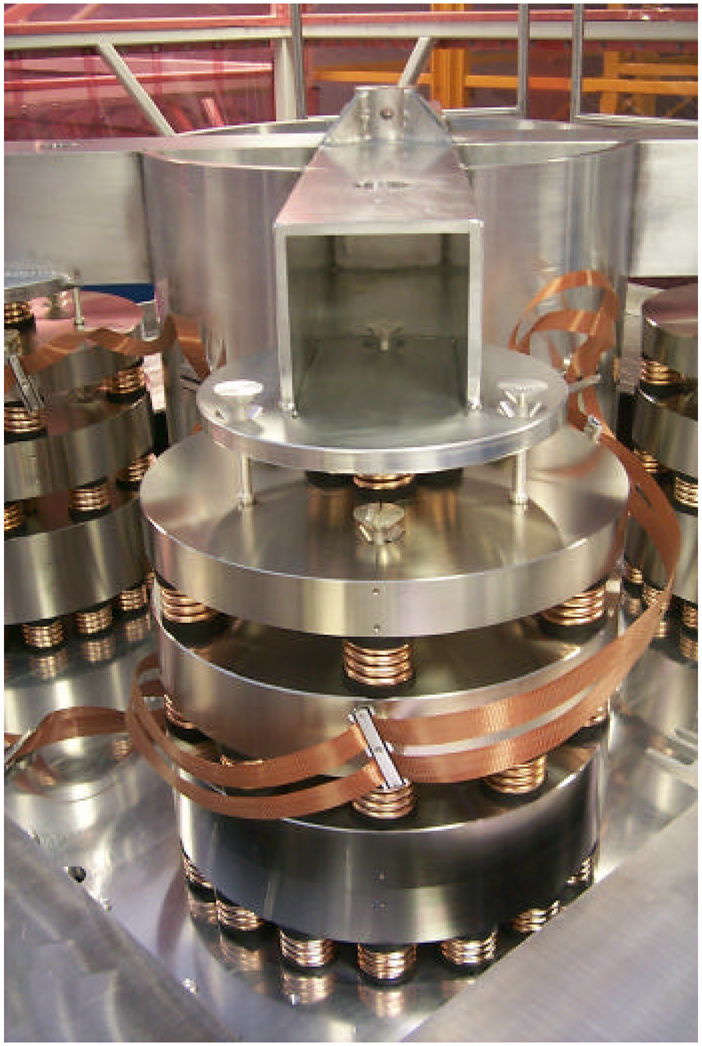


Seismic Isolation

Springs and Masses

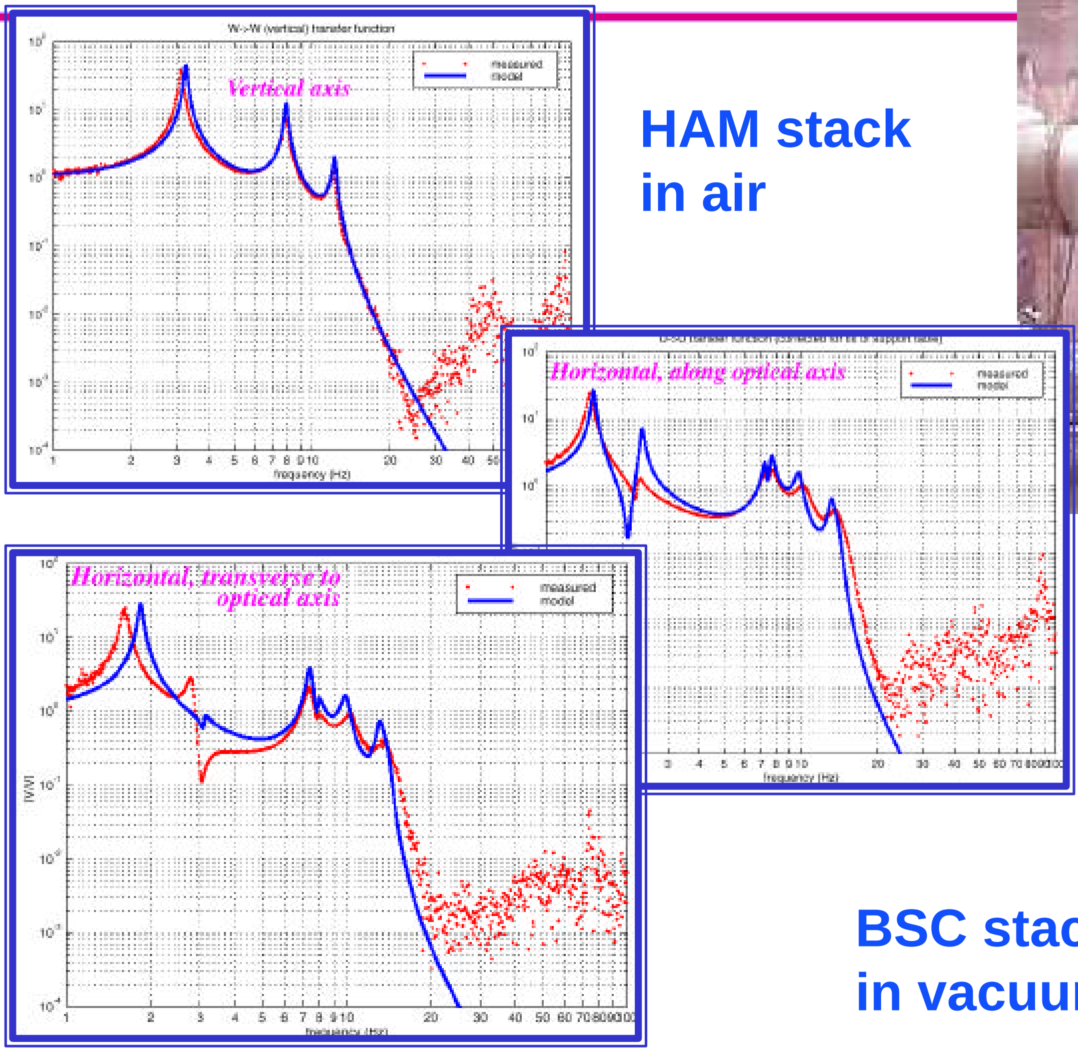


damped spring
cross section



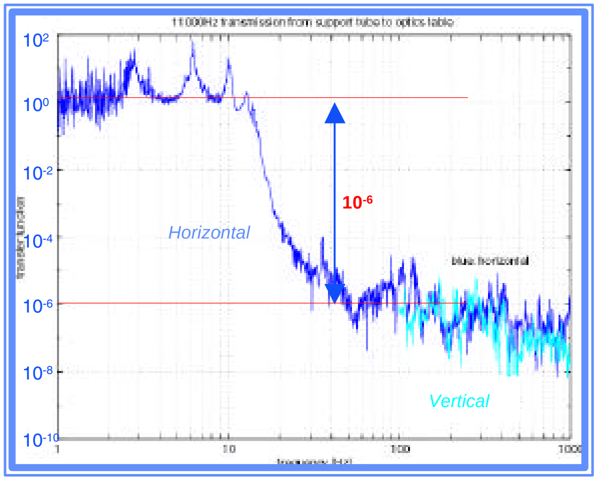
Seismic Isolation

performance

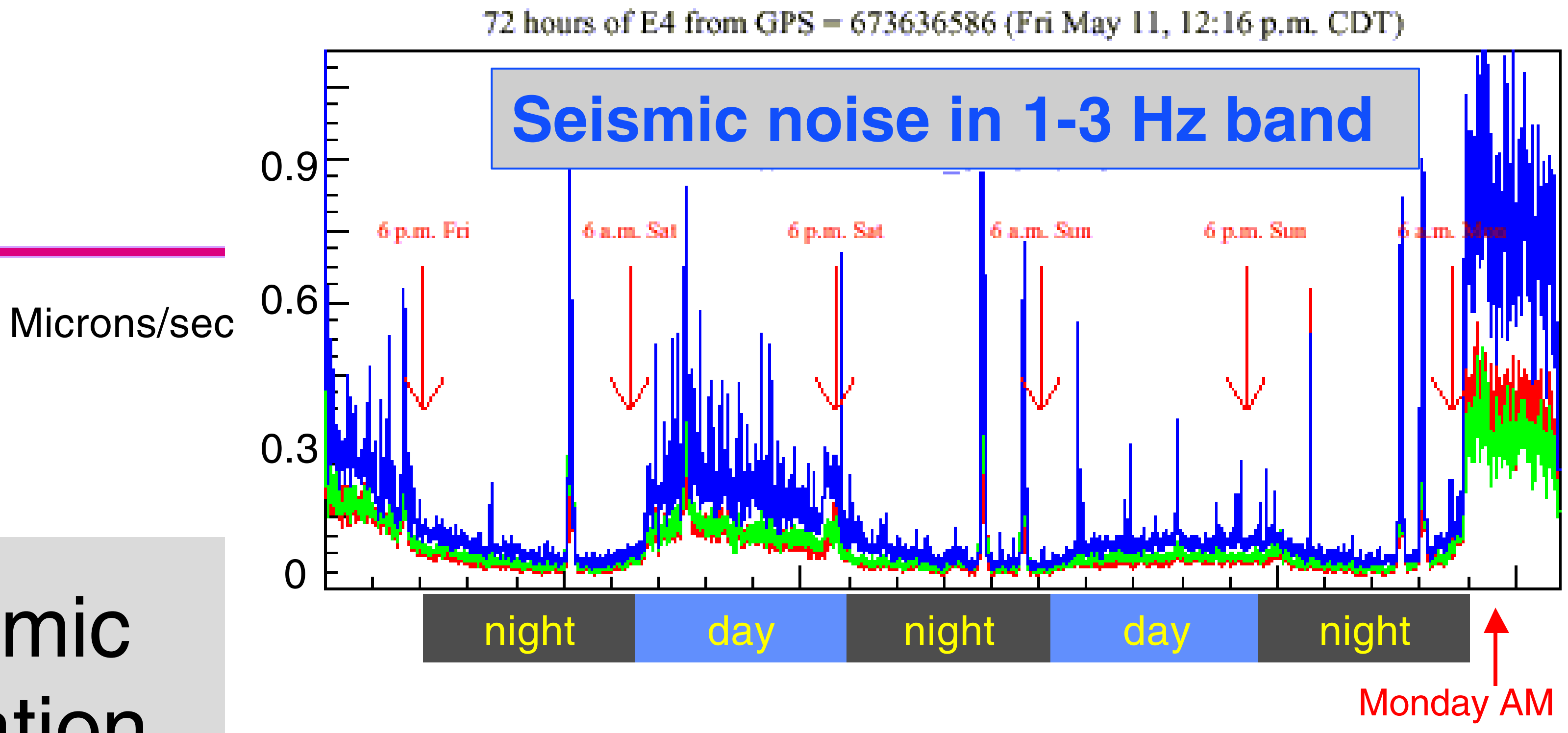


HAM stack in air

BSC stack in vacuum

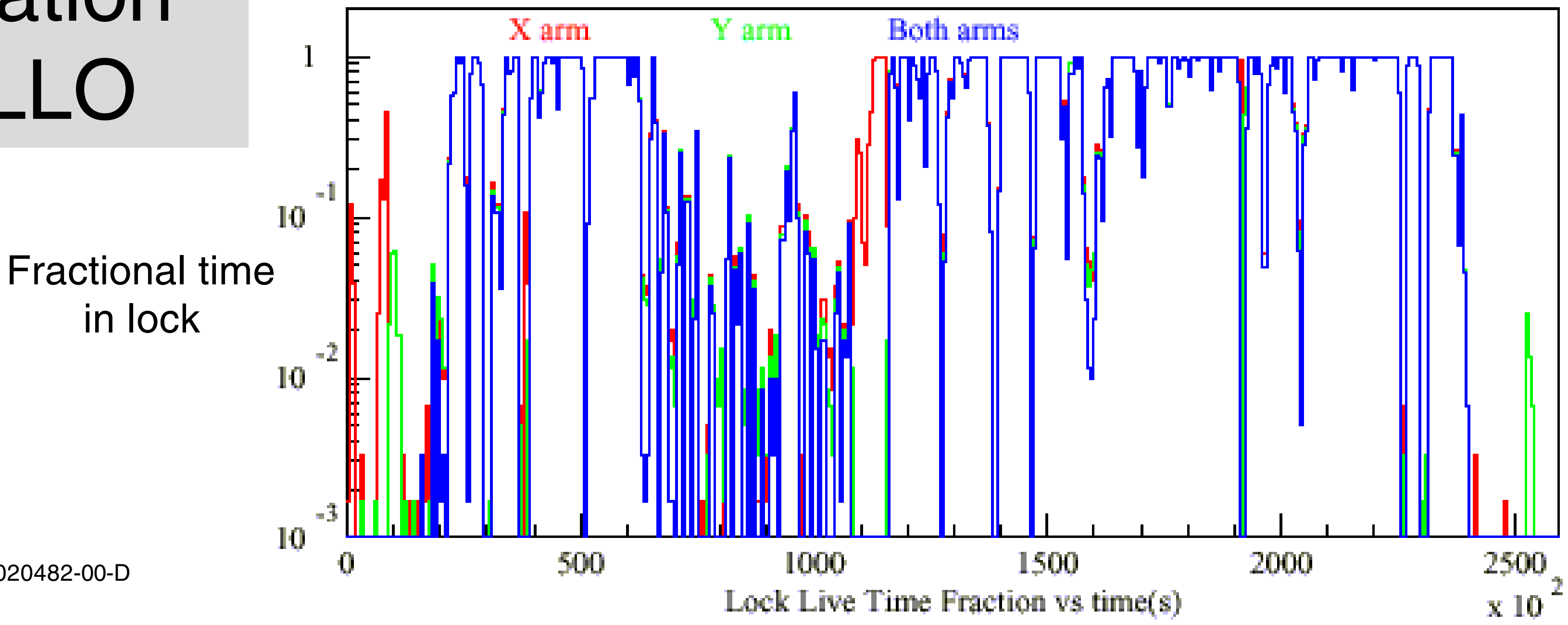


Seismic Situation at LLO



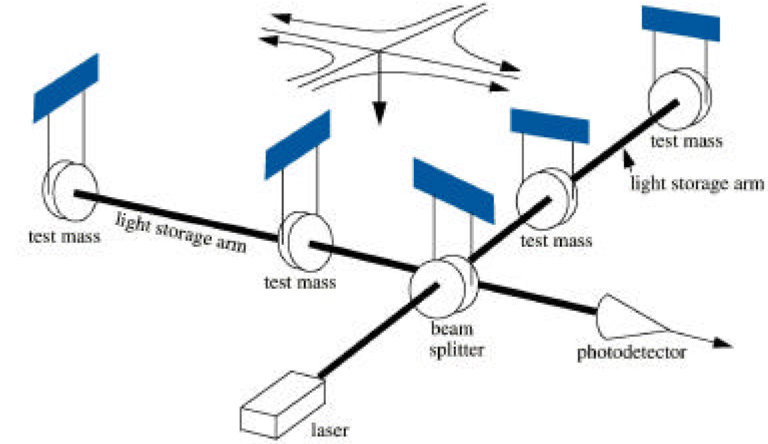
Seismic noise in 1-3 Hz band

Monday AM



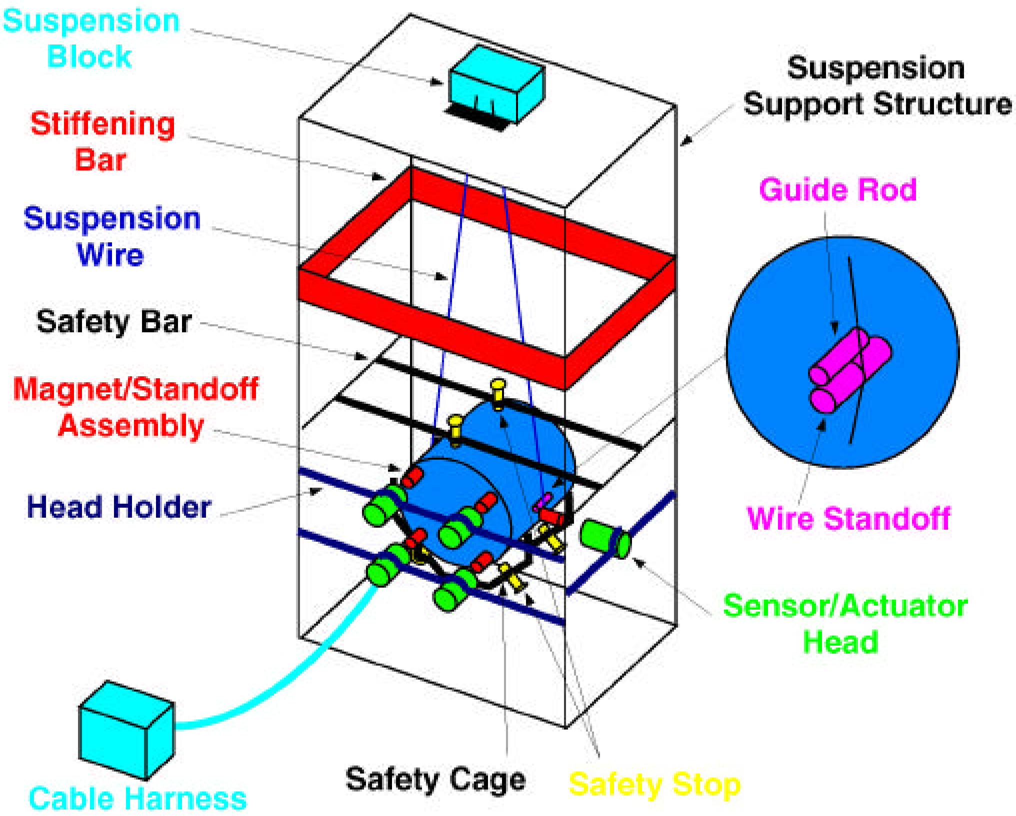
Seismic Isolation

suspension system



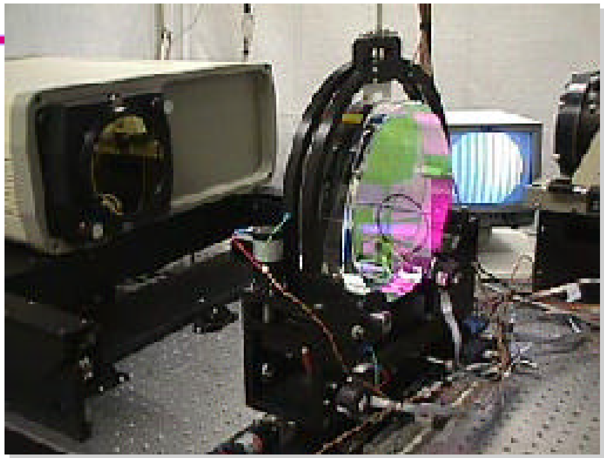
- **support structure is welded tubular stainless steel**
- **suspension wire is 0.31 mm diameter steel music wire**
- **fundamental violin mode frequency of 340 Hz**

suspension assembly for a core optic

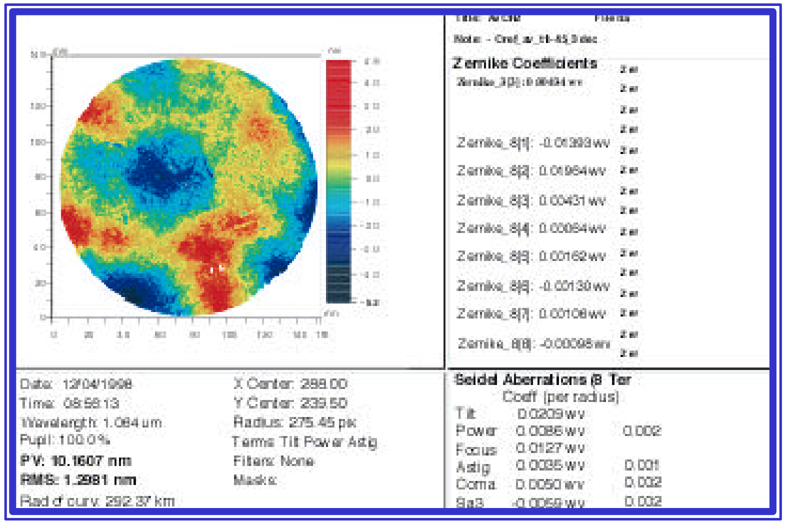


Core Optics

fused silica



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



Zernike Coefficients

Zernike_8[1]: -0.01393 wv
Zernike_8[2]: 0.01964 wv
Zernike_8[3]: 0.00431 wv
Zernike_8[4]: 0.00064 wv
Zernike_8[5]: 0.00162 wv
Zernike_8[6]: -0.00130 wv
Zernike_8[7]: 0.00108 wv
Zernike_8[8]: -0.00098 wv

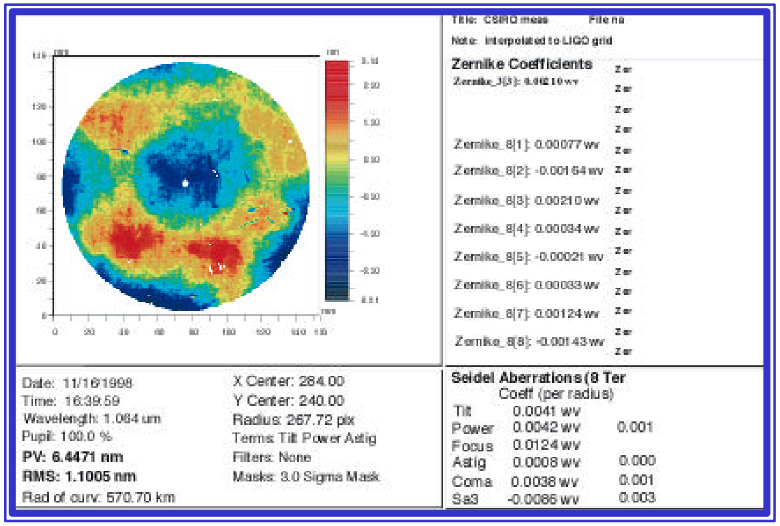
Date: 12/04/1998
Time: 08:58:13
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 10.1607 nm
RMS: 1.2981 nm
Rad of curv: 292.37 km

X Center: 288.00
Y Center: 239.50
Radius: 275.45 pix
Terms: Tilt Power Astig
Filters: None
Masks:

Seidel Aberrations (8 Ter

	Coeff (per radius)	
Tilt	0.0209 wv	
Power	0.0086 wv	0.002
Focus	0.0127 wv	
Astig	0.0035 wv	0.001
Coma	0.0050 wv	0.002
Sa3	-0.0059 wv	0.002

Caltech data



Title: CSIRO meas File na
Note: interpolated to LIGO grid

Zernike Coefficients

Zernike_8[1]: 0.00077 wv
Zernike_8[2]: -0.00164 wv
Zernike_8[3]: 0.00210 wv
Zernike_8[4]: 0.00034 wv
Zernike_8[5]: -0.00021 wv
Zernike_8[6]: 0.00033 wv
Zernike_8[7]: 0.00124 wv
Zernike_8[8]: -0.00143 wv

Date: 11/16/1998
Time: 16:39:59
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 6.4471 nm
RMS: 1.1005 nm
Rad of curv: 570.70 km

X Center: 284.00
Y Center: 240.00
Radius: 267.72 pix
Terms: Tilt Power Astig
Filters: None
Masks: 3.0 Sigma Mask

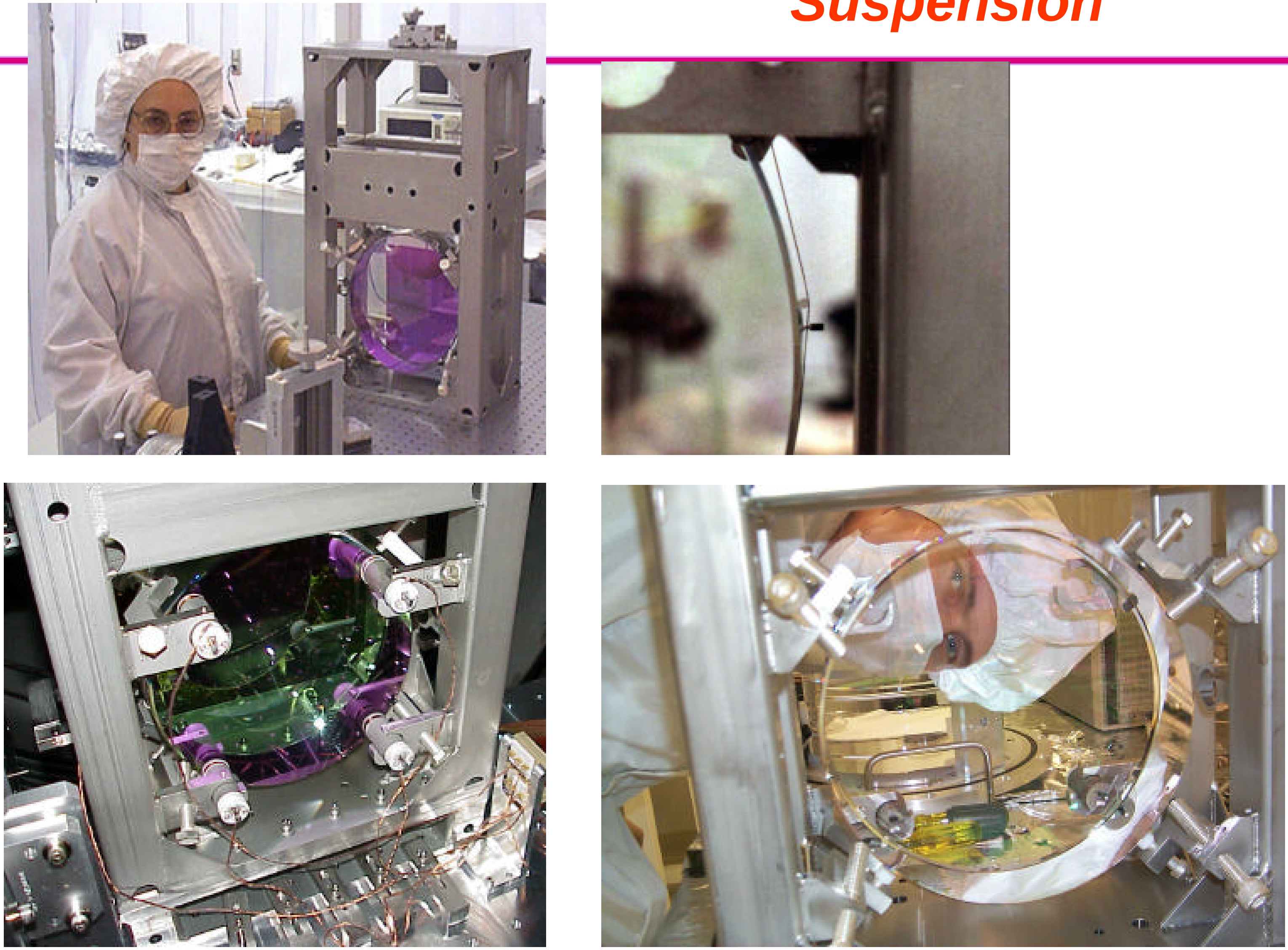
Seidel Aberrations (8 Ter

	Coeff (per radius)	
Tilt	0.0041 wv	
Power	0.0042 wv	0.001
Focus	0.0124 wv	
Astig	0.0008 wv	0.000
Coma	0.0038 wv	0.001
Sa3	-0.0086 wv	0.003

CSIRO data

Core Optics

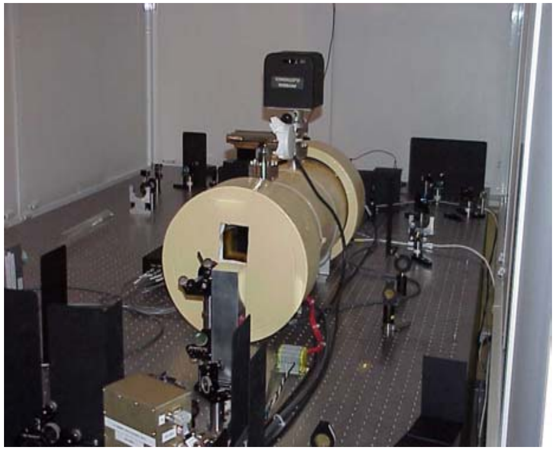
Suspension

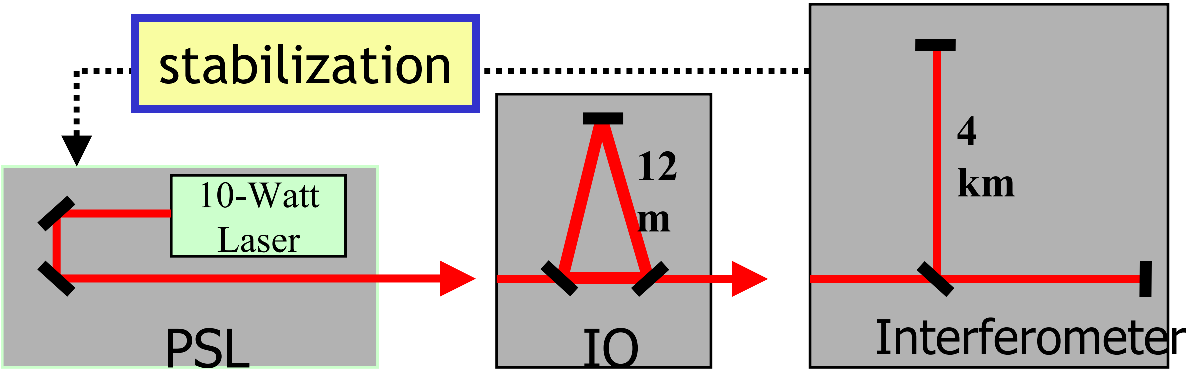


Core Optics

Installation and Alignment

LIGO Prestabilized Laser



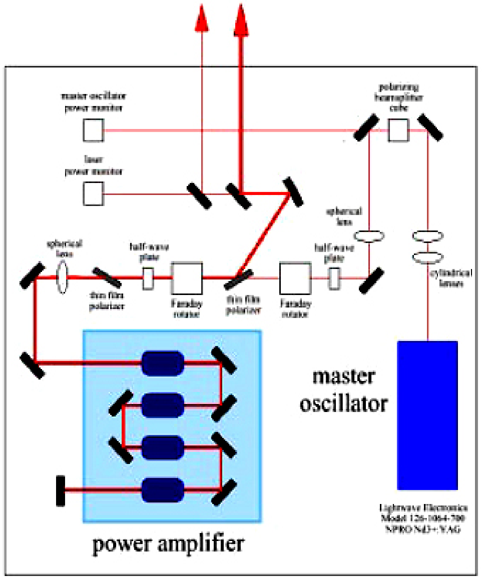


10^{-1} Hz/Hz$^{1/2}$

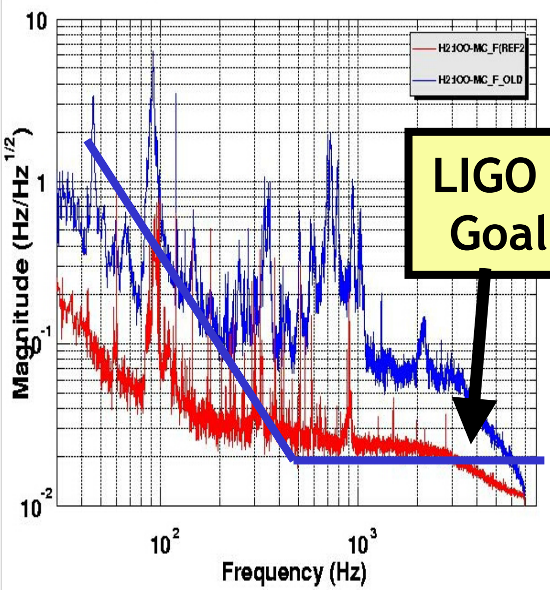
10^{-4} Hz/Hz$^{1/2}$

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

- •Nd:YAG 1064 nm
- •P > 8 W TEM_{00}
- •Cascaded multi-loop frequency stabilization



Lightwave Electronics MOPA

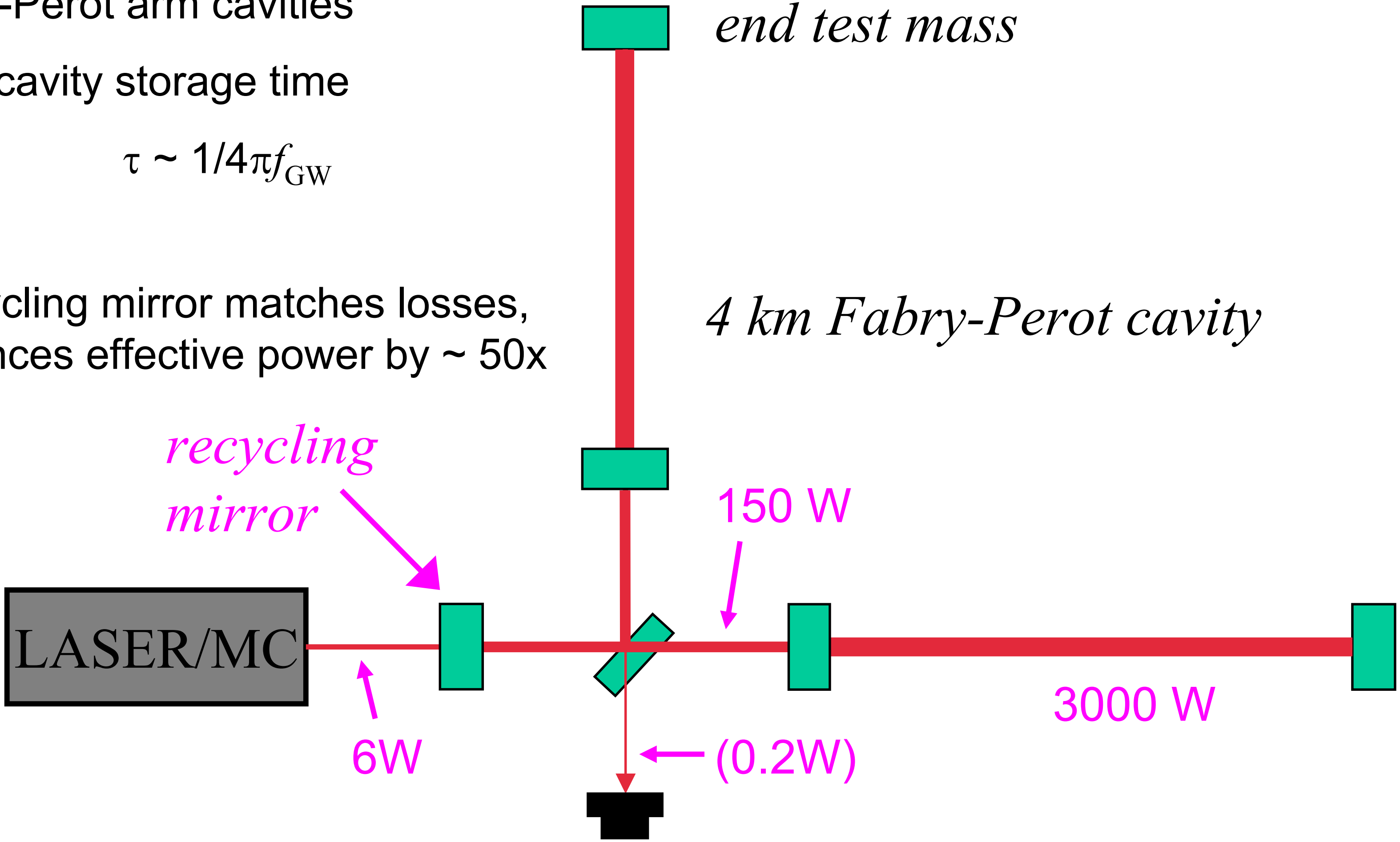


LIGO Interferometer Optical Scheme

- Michelson interferometer with Fabry-Perot arm cavities
- Arm cavity storage time

$$\tau \sim 1/4\pi f_{\mathrm{GW}}$$

- Recycling mirror matches losses, enhances effective power by ~ 50x



end test mass

4 km Fabry-Perot cavity

recycling mirror

LASER/MC

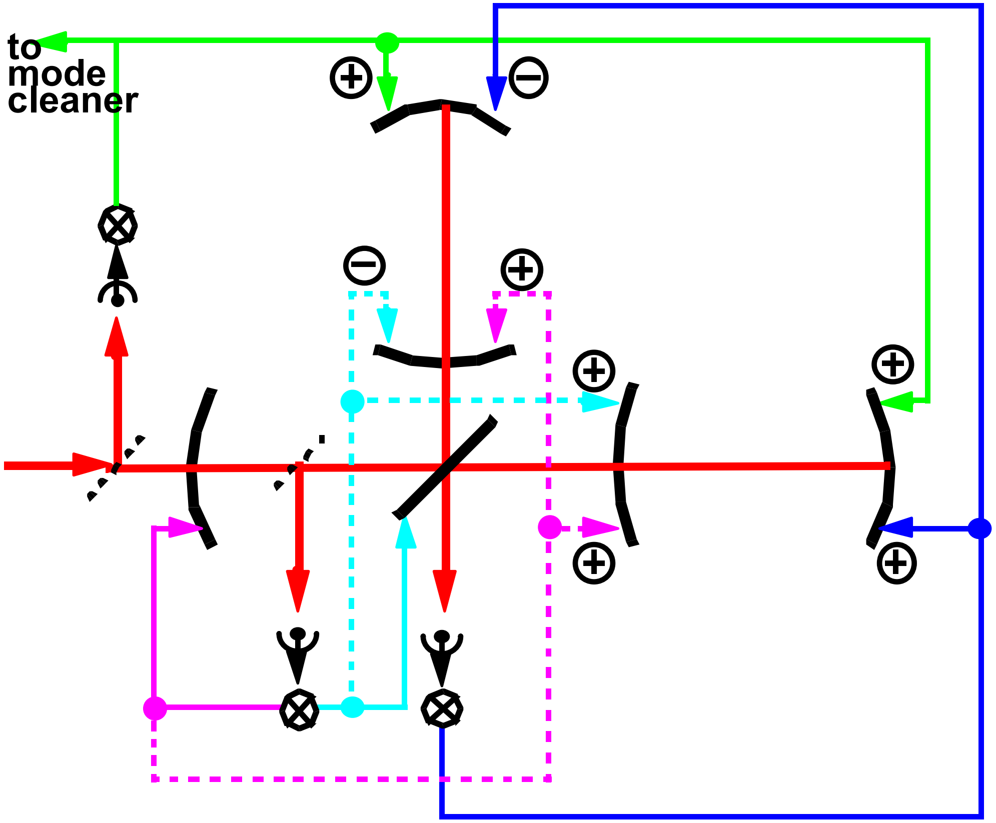
150 W

6W

(0.2W)

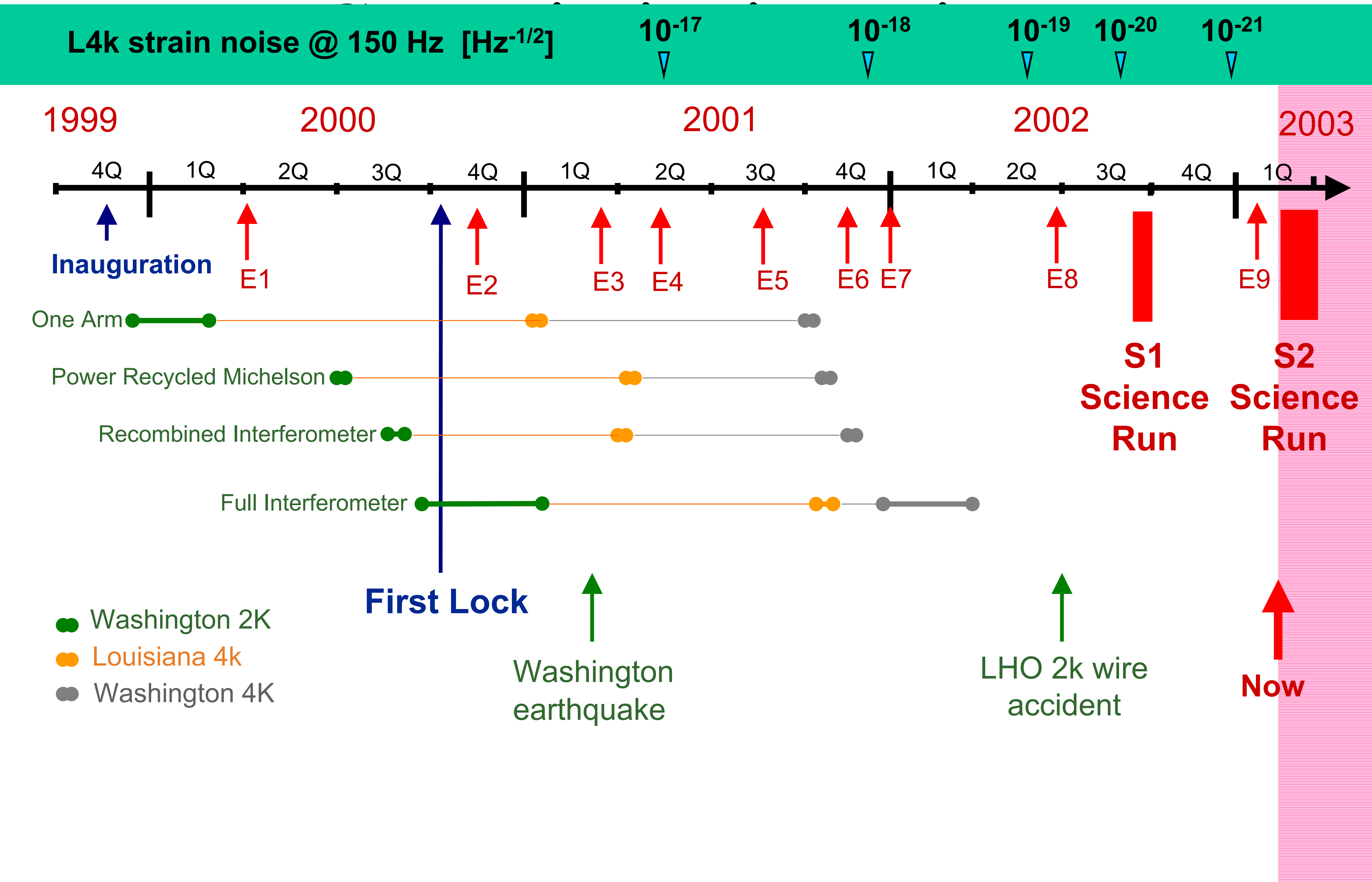
3000 W

Feedback Control Systems



example: cavity length sensing & control topology

- Array of sensors detects mirror separations, angles
- Signal processing derives stabilizing forces for each mirror, filters noise
- 5 main length loops shown; total ~ 25 degrees of freedom
- Operating points held to about 0.001 Å, .01 µrad RMS
- Typ. loop bandwidths from ~ few Hz (angles) to > 10 kHz (laser wavelength)



L4k strain noise @ 150 Hz [$\mathrm{Hz}^{-1/2}$]

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21}

1999 2000 2001 2002 2003

4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q

Inauguration

E1 E2 E3 E4 E5 E6 E7 E8 E9

One Arm

Power Recycled Michelson

Recombined Interferometer

Full Interferometer

First Lock

Washington earthquake

LHO 2k wire accident

S1 Science Run

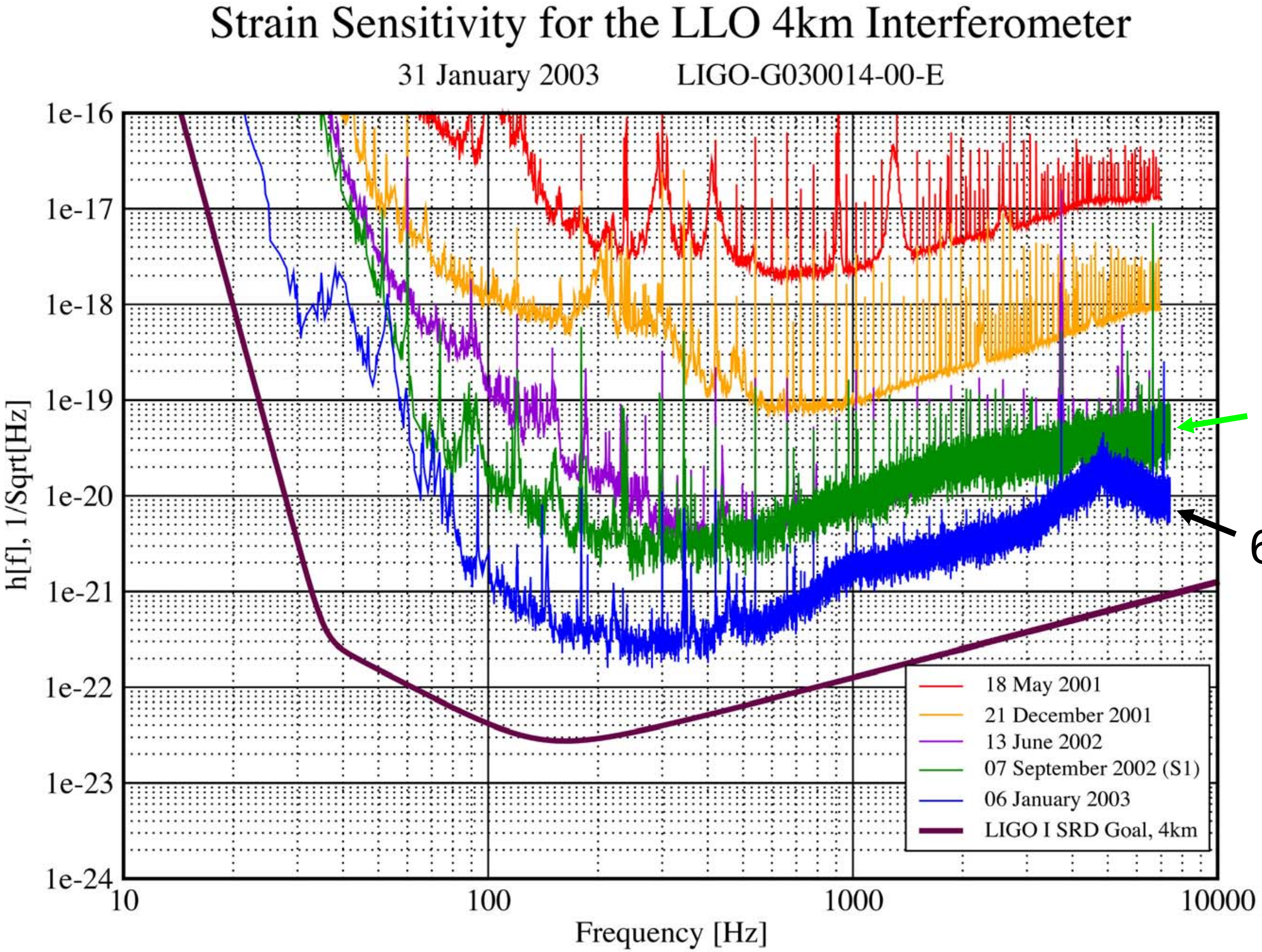
S2 Science Run

Now

● Washington 2K

● Louisiana 4k

● Washington 4K


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

6 Jan