Interferometric Detection of Gravitational Waves – status of the LIGO

University of Illinois@ Urbana-Champaign

November 14, 2002

Rainer Weiss (MIT) for the LIGO Scientific Collaboration

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
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

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

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

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

Gravity Wave Propagating in the x_1 Direction

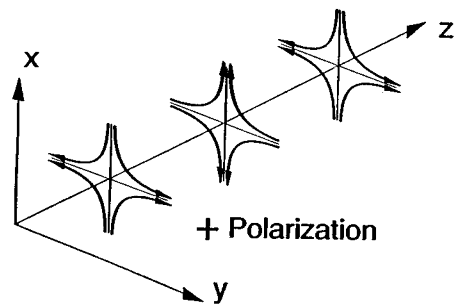
$$h_{ij} \;=\; \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \qquad \text{all } h_{ij} \ll 1$$

Plane Wave

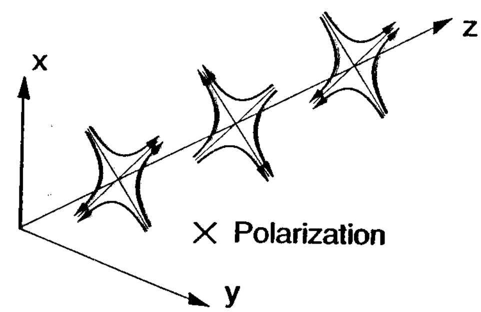
$\mathbf{h_{22}} \;=\; -\mathbf{h_{33}}$ $\qquad$ $\mathbf{h_{23}} \;=\; \mathbf{h_{32}}$

$+$ **polarization** $\qquad$ $\times$**polarization**

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



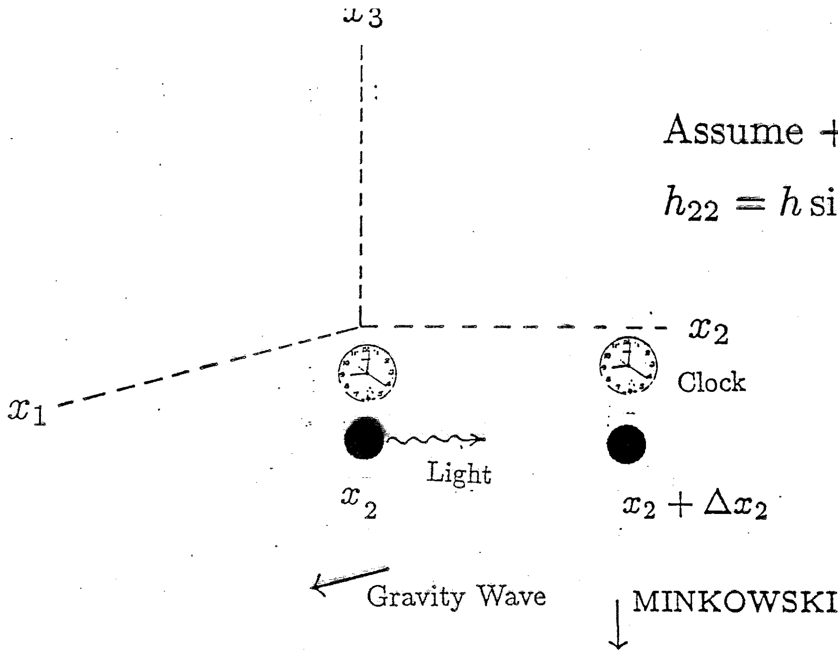
x
z
y
+ Polarization



x
z
y
× Polarization

Assume + Polarization

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



$$\Delta s^2 = 0 = c^2 \Delta t^2 - \Big(1 + h \sin(kx_1 - \omega t)\Big) \Delta x_2^2$$

LIGHT RAY

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

$$c \Delta t \cong \Big(1 + \frac{h}{2} \sin(kx_1 - \omega t)\Big) \Delta x_2$$

↖ *INFERRED DISTANCE BETWEEN POINTS*

$$\frac{\delta(c \Delta t)}{\Delta x_2} = \frac{h}{2} \sin(kx_1 - \omega t)$$

Time Dependent **Strain**

$$\frac{\Delta l}{l} = \frac{h}{2}$$

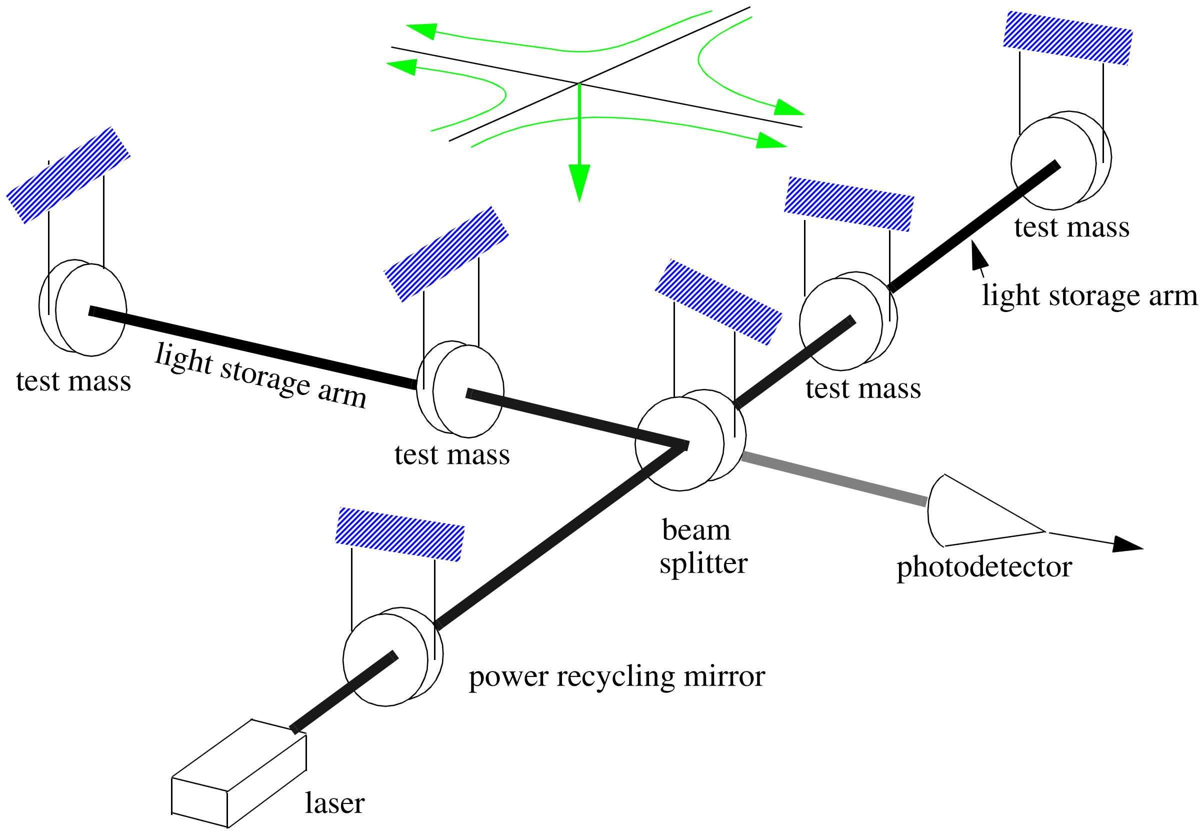
The Measurable Quantity

Measurement challenge

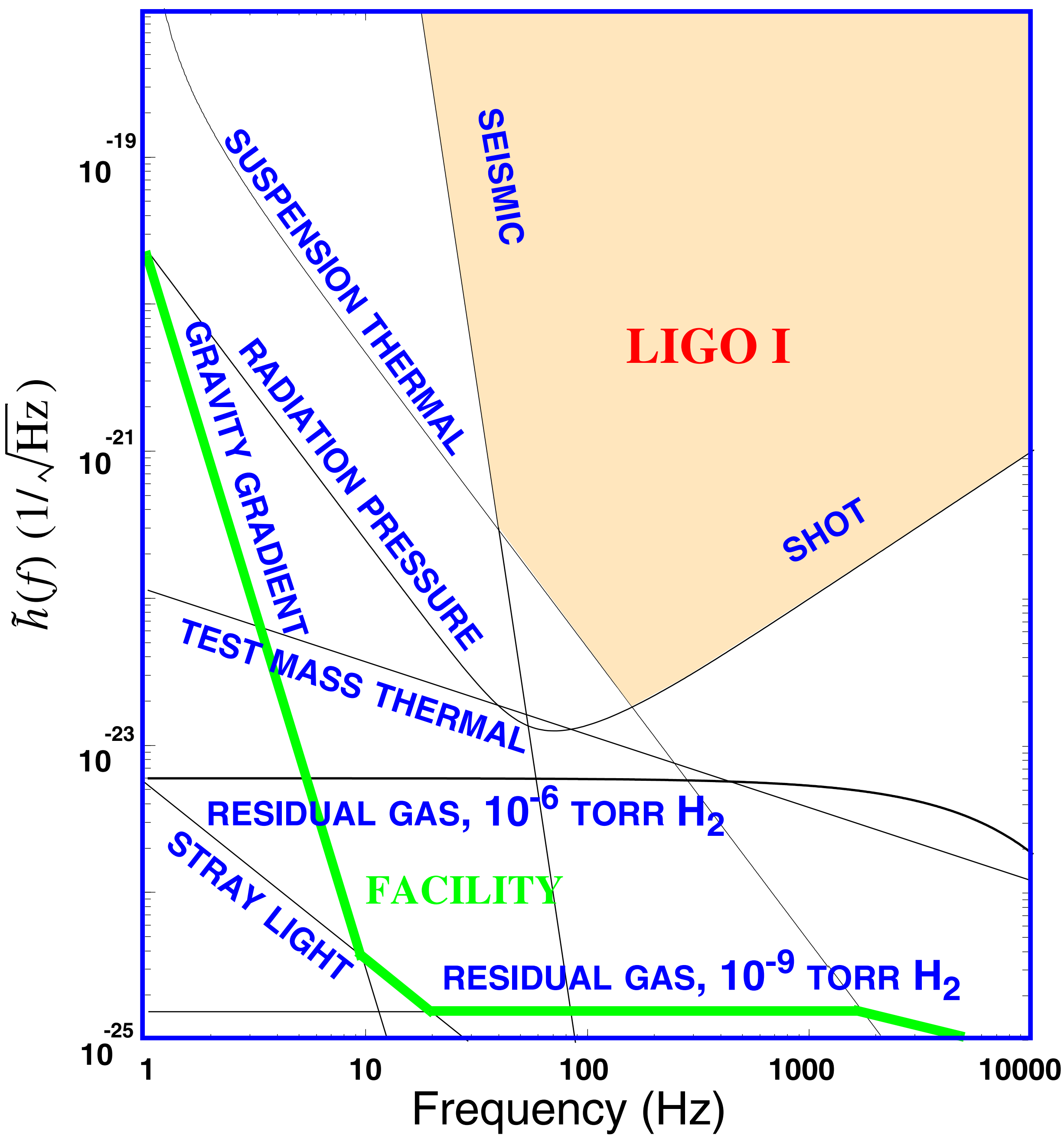
- Needed technology development to measure:

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

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



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



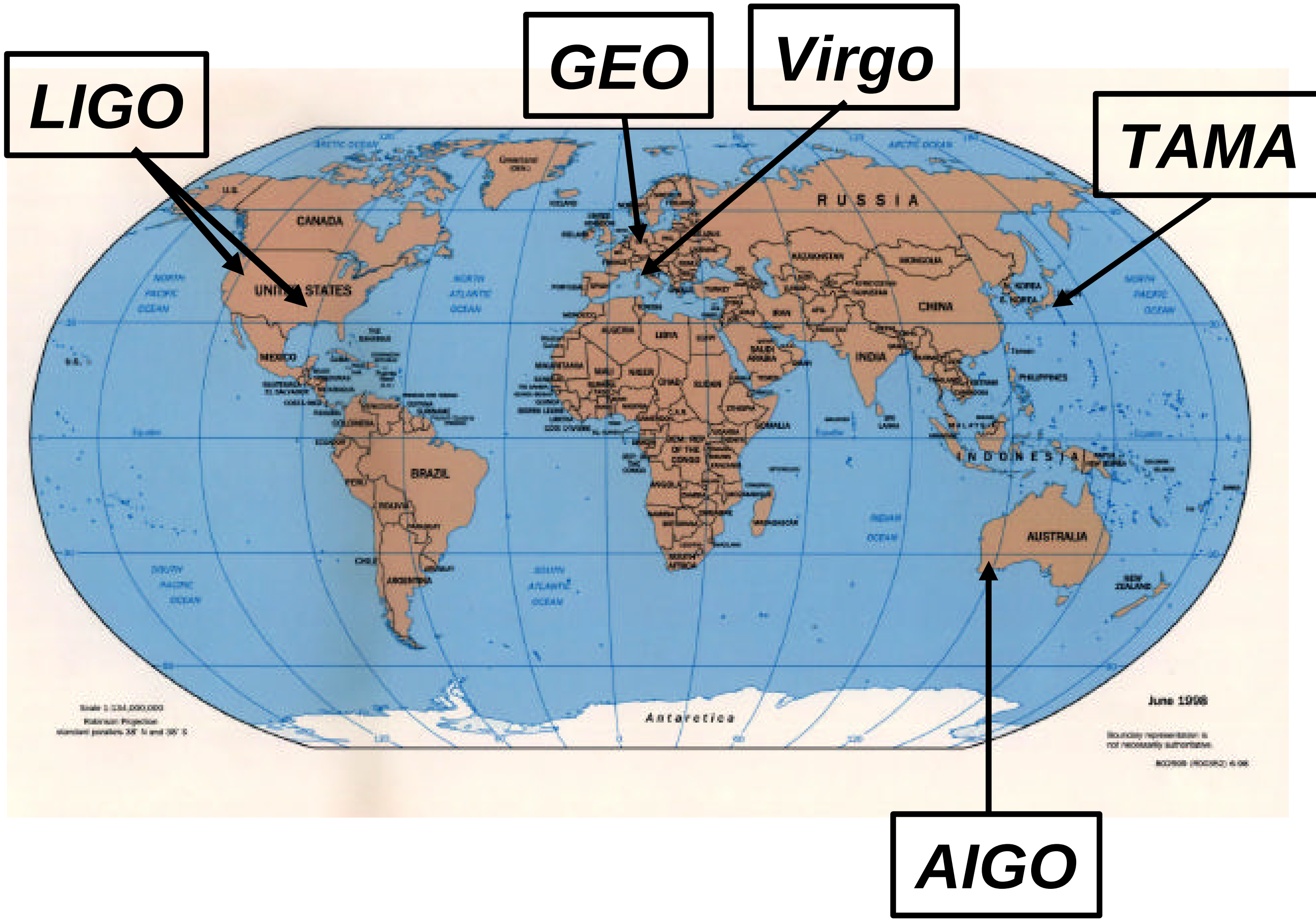
SUSPENSION THERMAL
SEISMIC
LIGO I
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^{-9} TORR H_2
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)
$\tilde{h}(f)\ (1/\sqrt{\mathrm{Hz}})$

Table 1: Initial detector parameters

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

Interferometers
international network

Simultaneously detect signal (within msec)



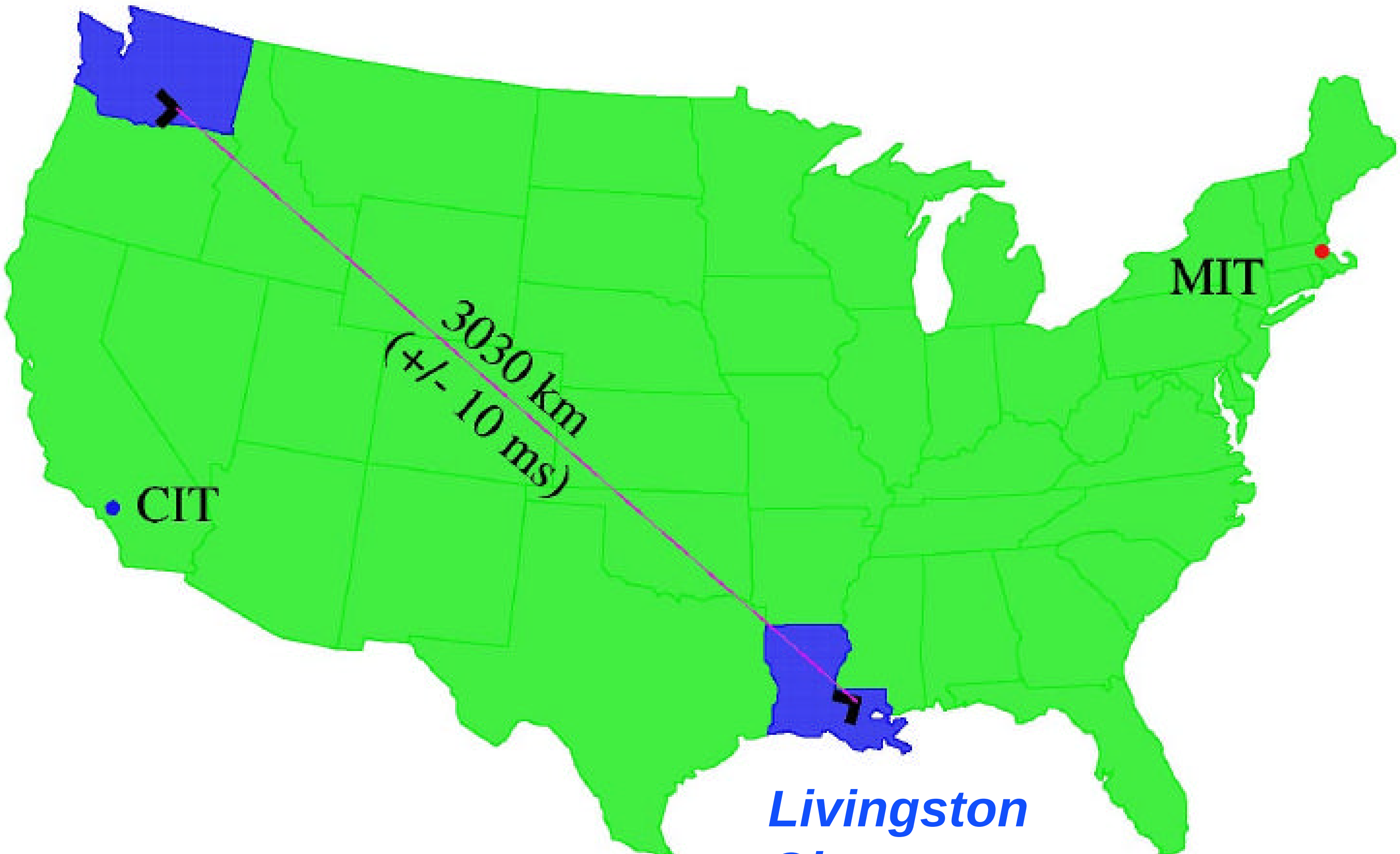
detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Sites

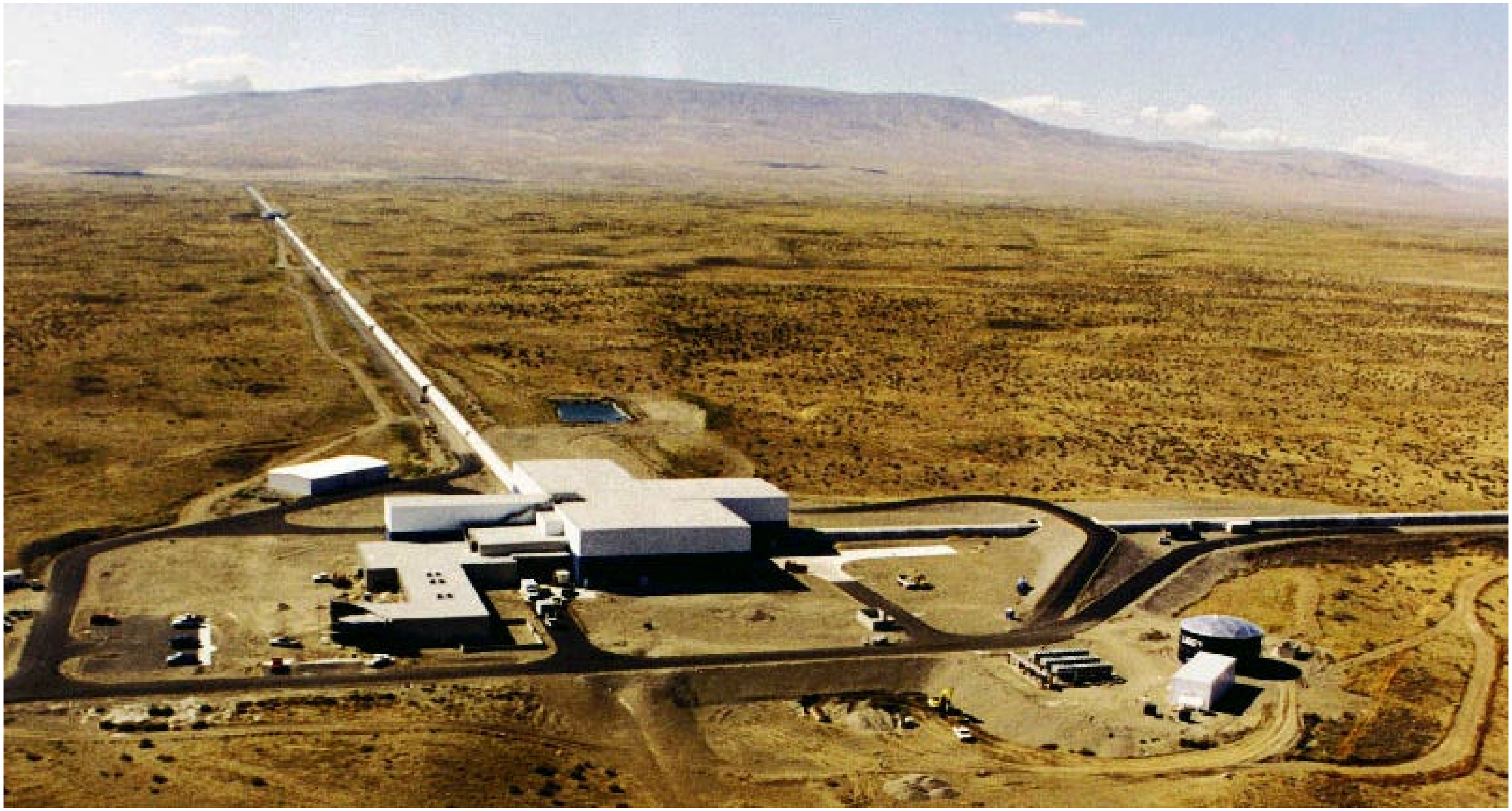
Hanford Observatory



Livingston Observatory

LIGO
Livingston Observatory

LIGO
Hanford Observatory



LIGO

Beam Tube

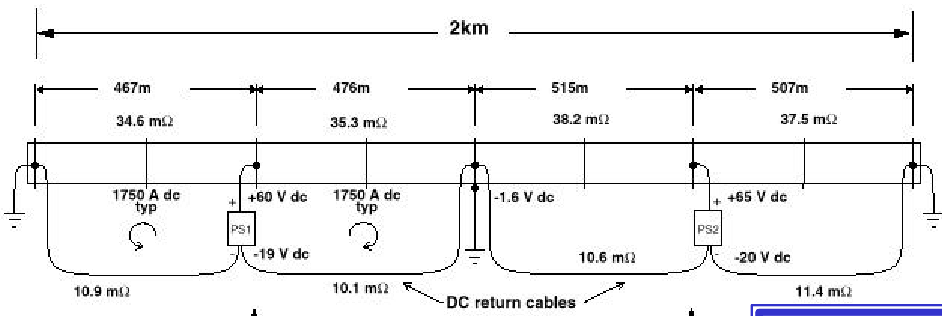
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

Beam Tube

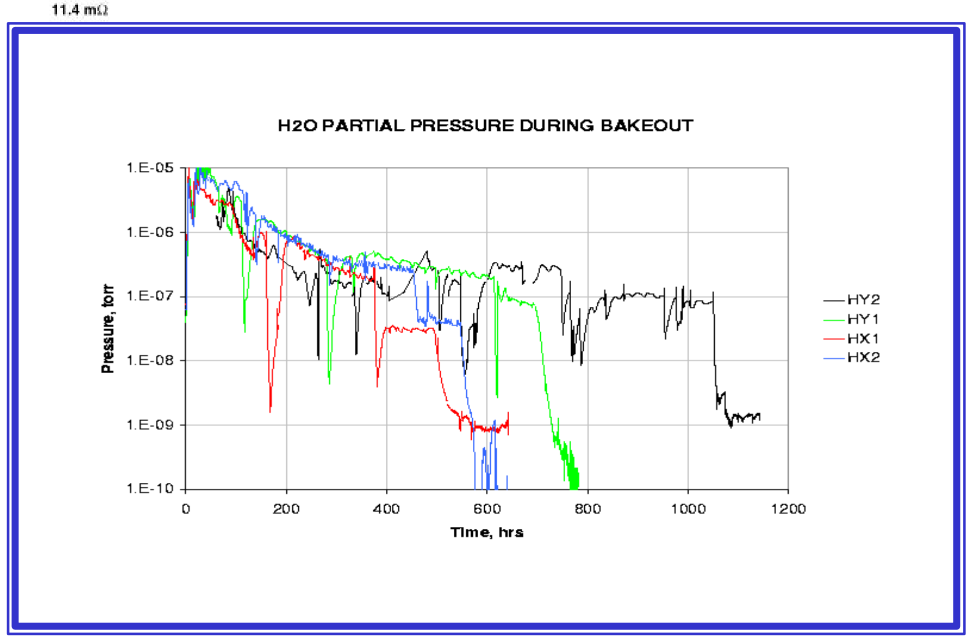
bakeout



- I = 2000 amps for ~ 1 week

- no leaks !!

- final vacuum at level where not limiting noise, even for future detectors



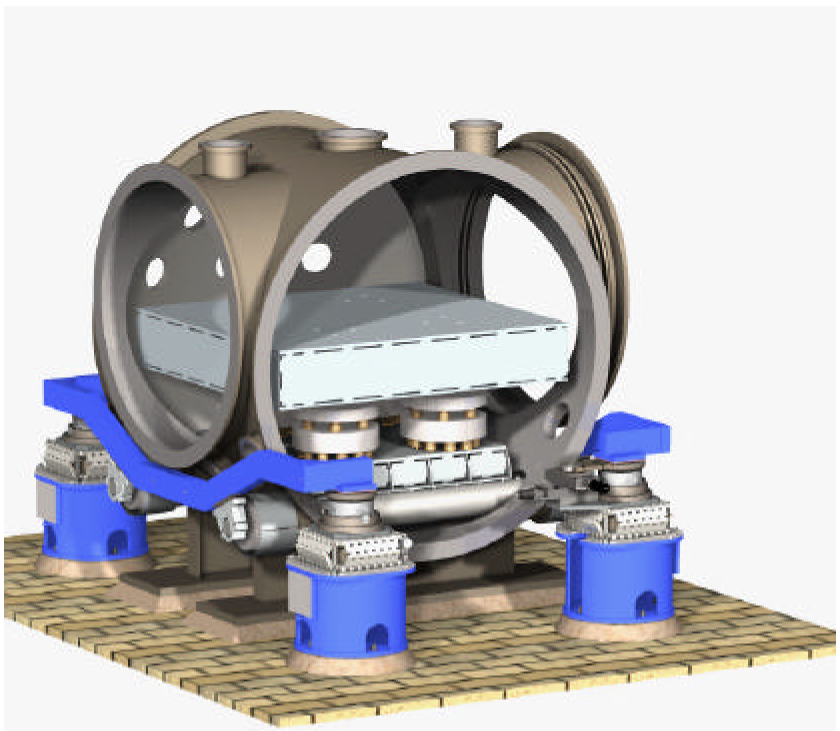
LIGO

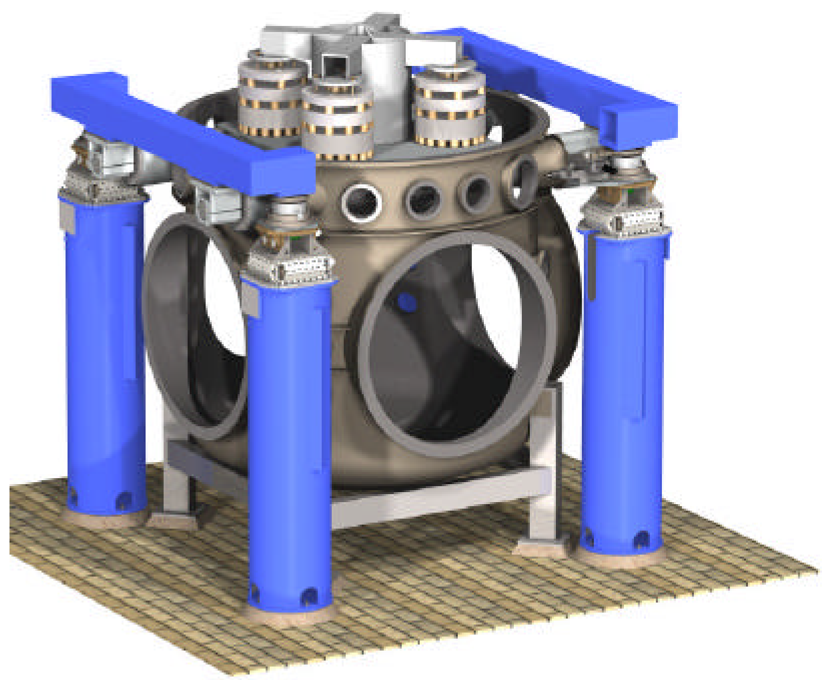
vacuum equipment

Vacuum Chambers

Vibration Isolation Systems

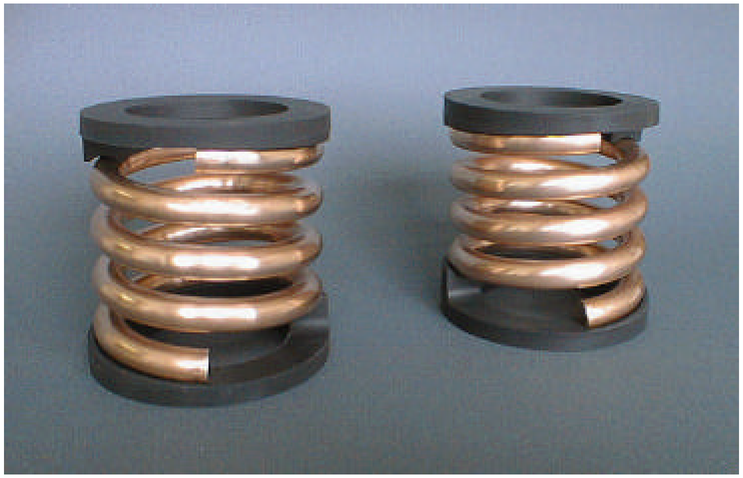
- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Compensate for microseism at 0.15 Hz by a factor of ten
- Compensate (partially) for Earth tides



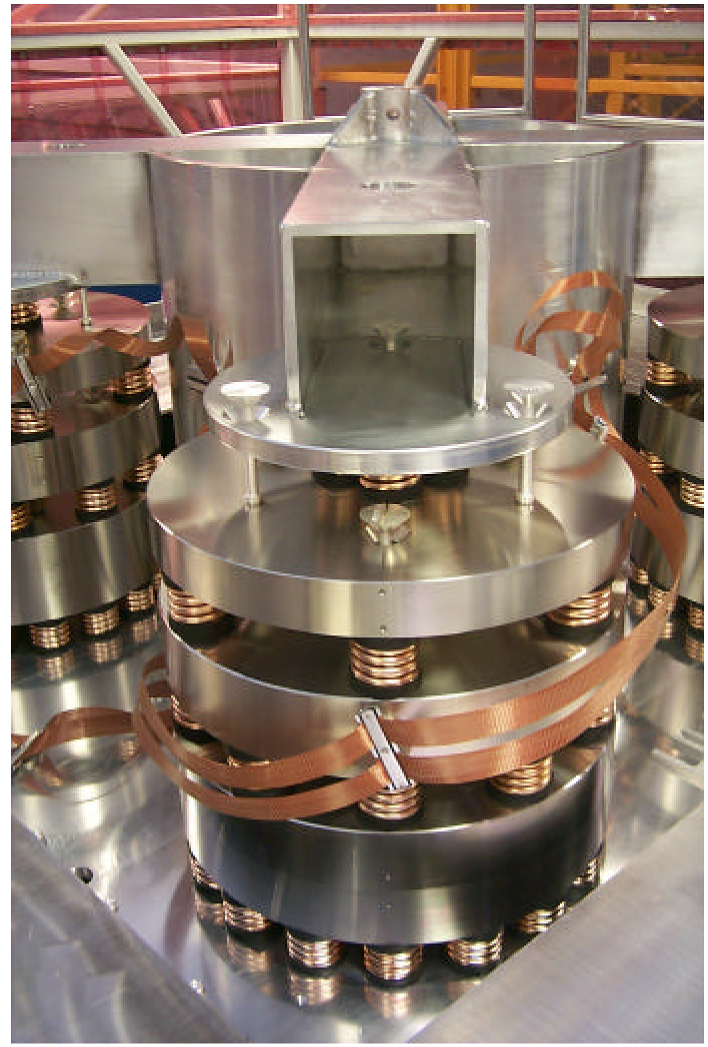


Seismic Isolation

Springs and Masses

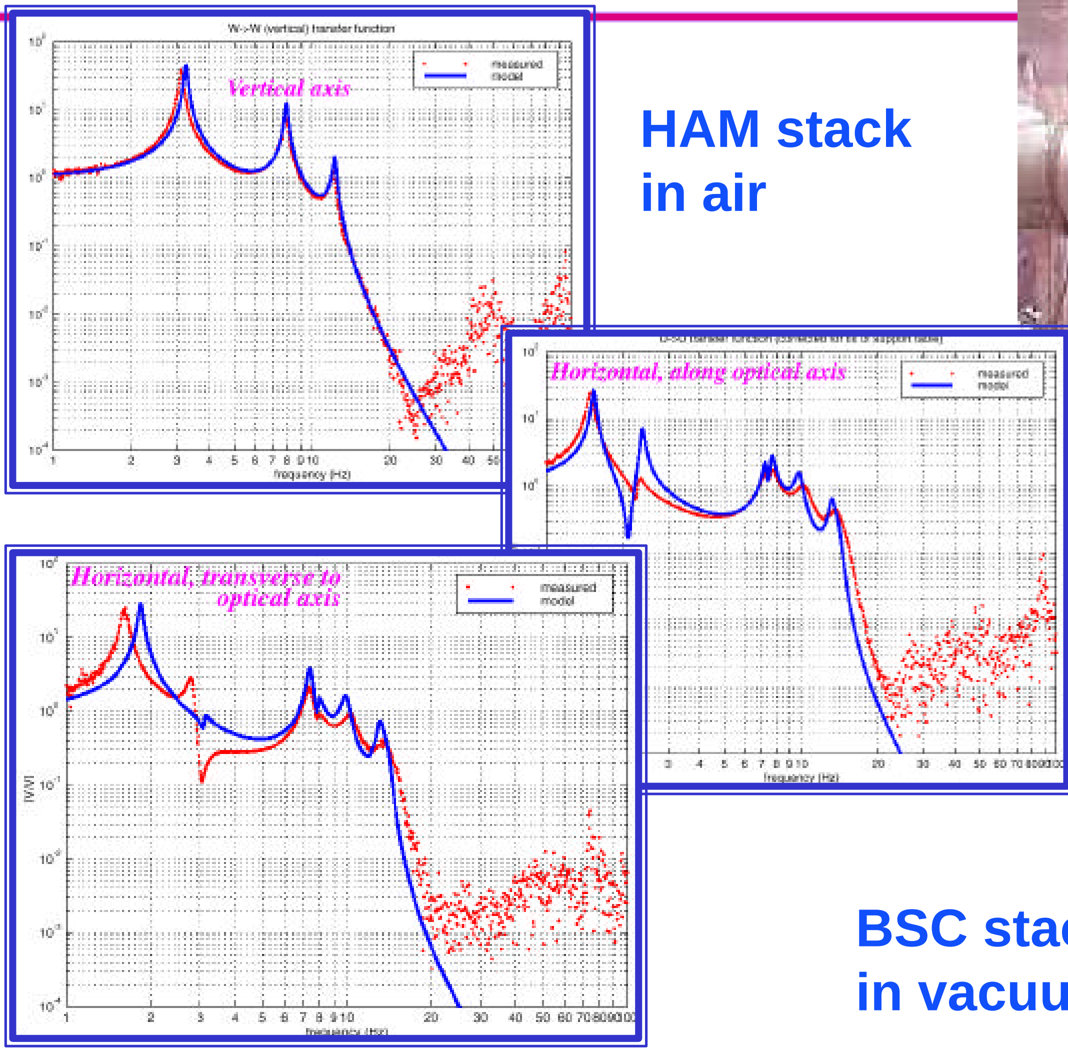


damped spring
cross section

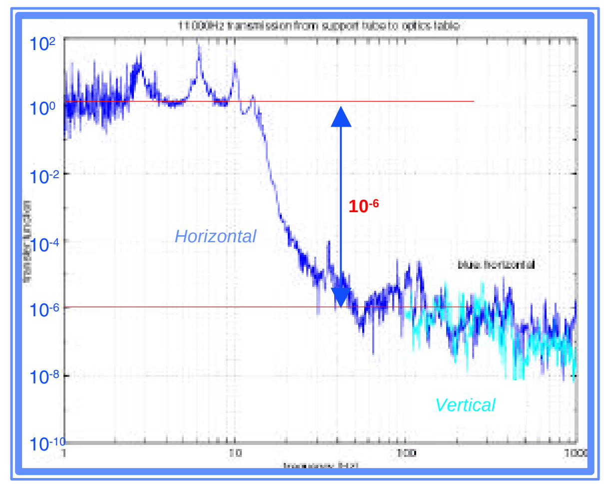


Seismic Isolation

performance



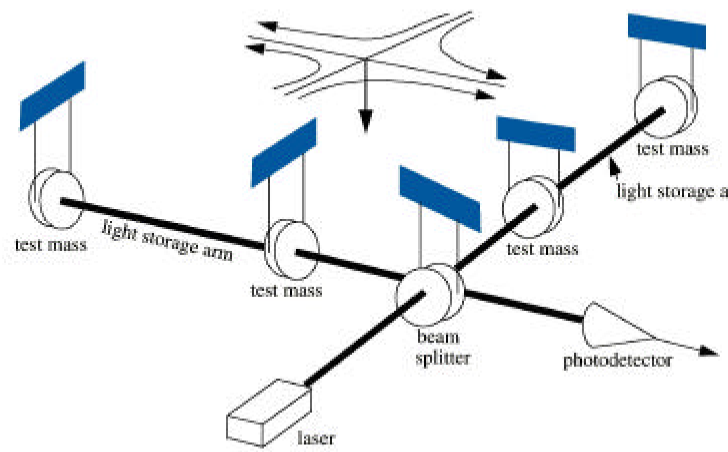
HAM stack in air



BSC stack in vacuum

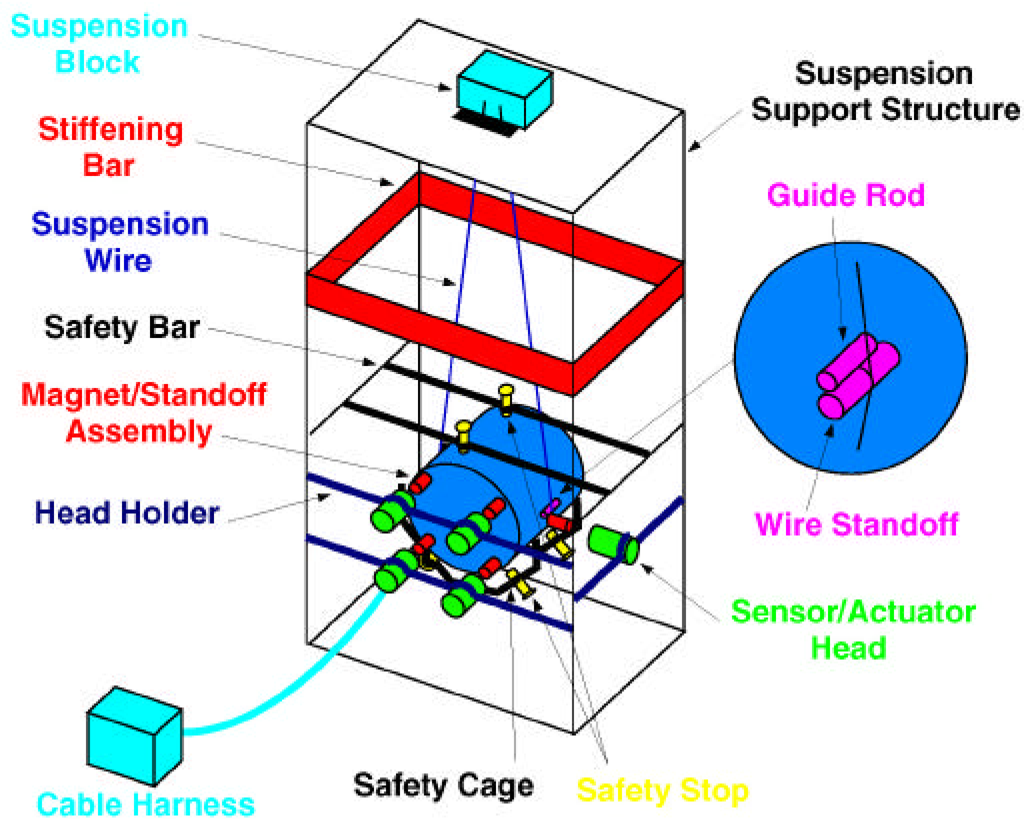
Seismic Isolation

suspension system



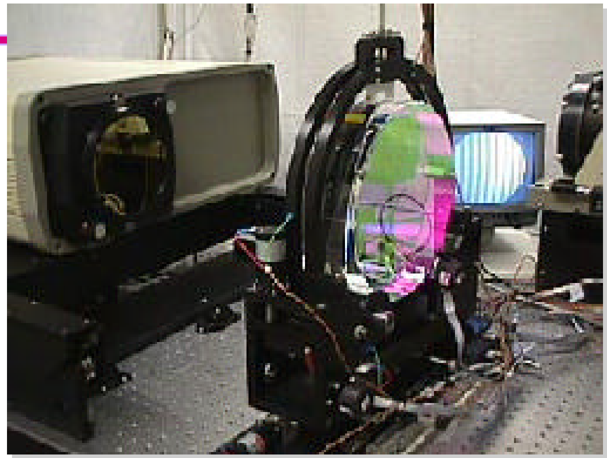
- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

suspension assembly for a core optic

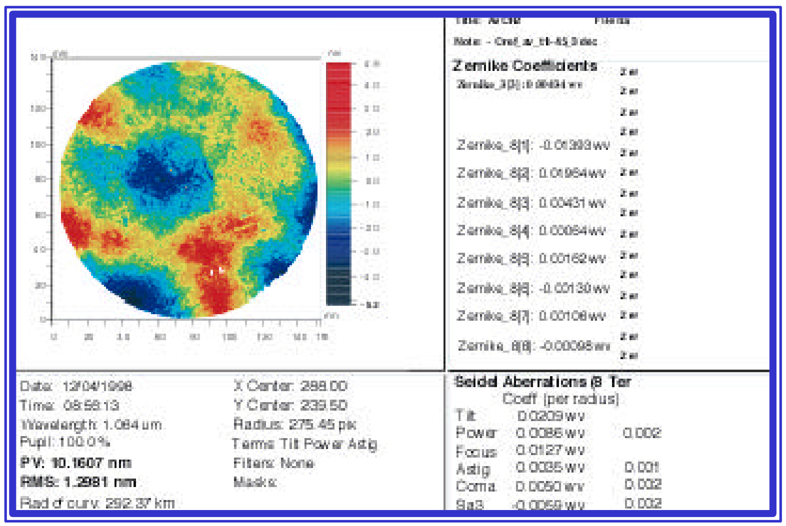


Core Optics

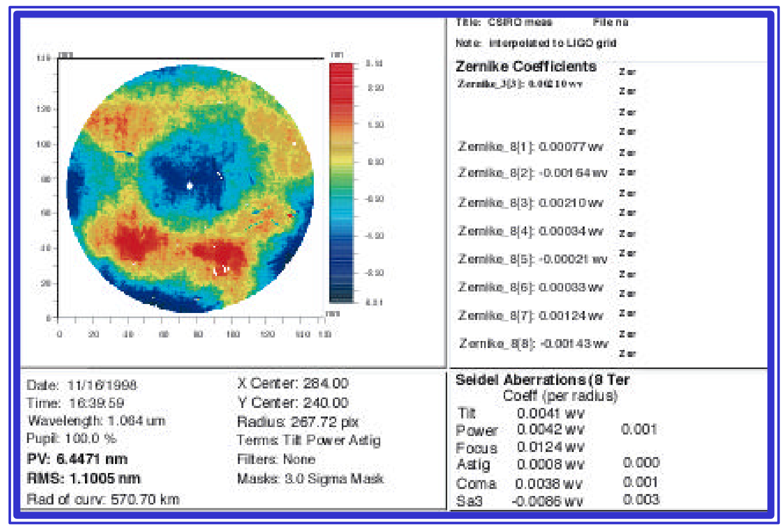
fused silica



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



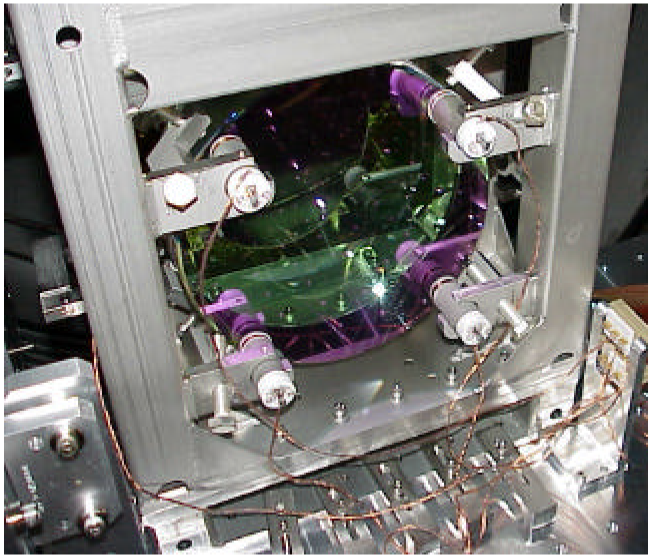
Caltech data

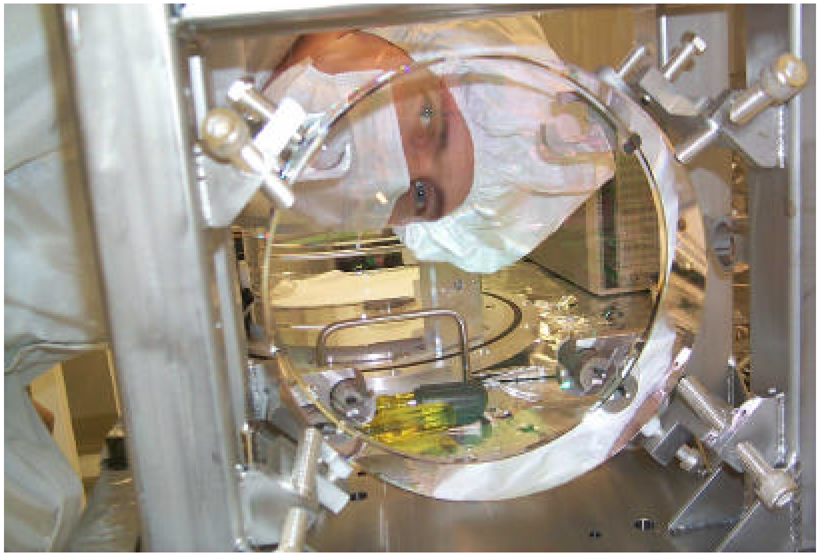


CSIRO data

Core Optics

Suspension





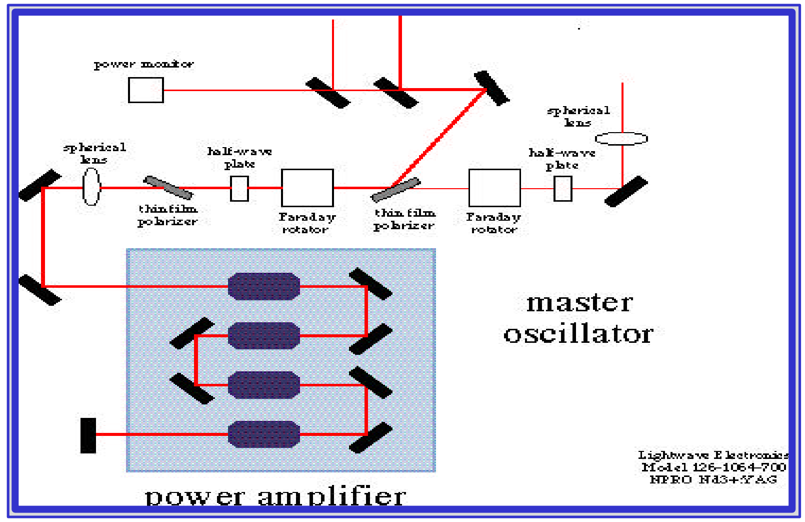
Core Optics

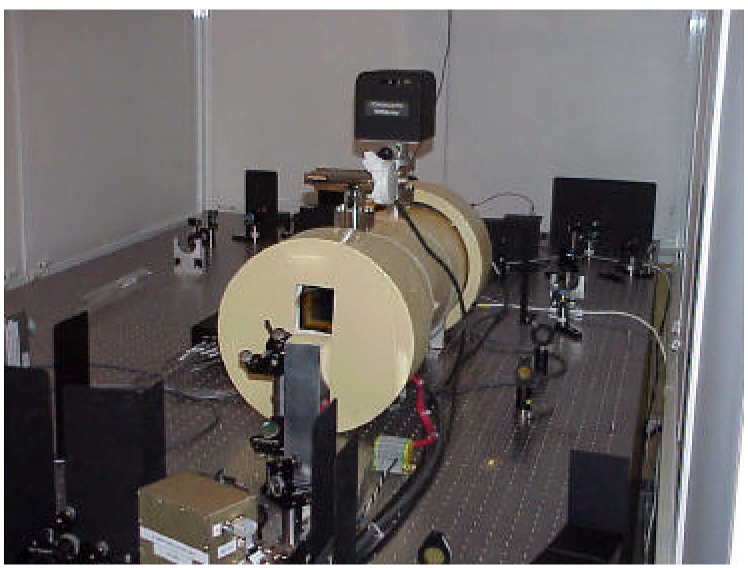
Installation and Alignment

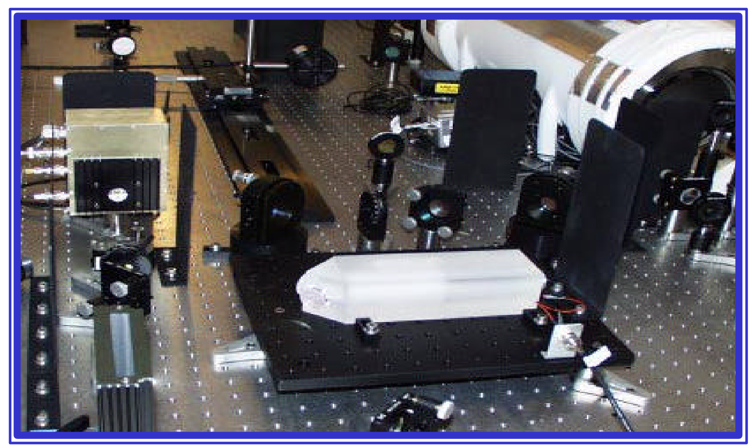
LIGO

Laser

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



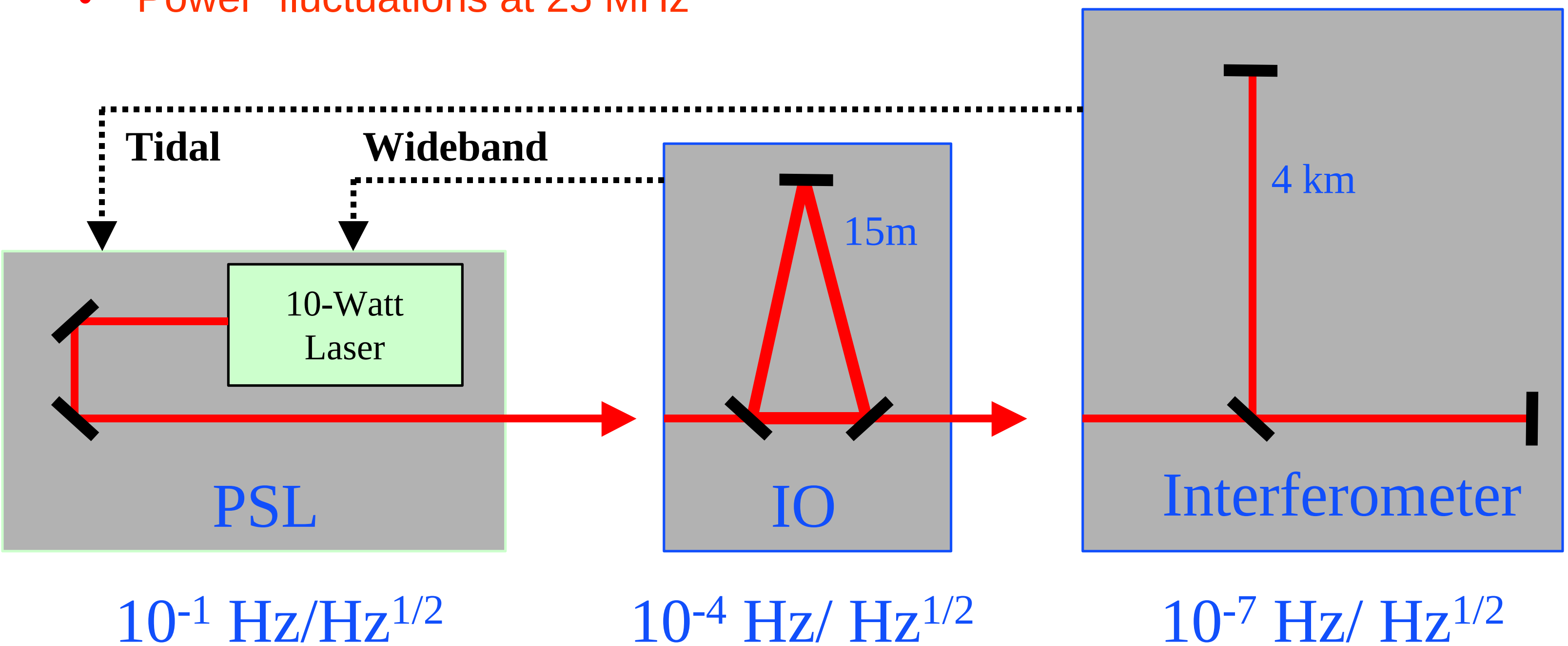




Laser

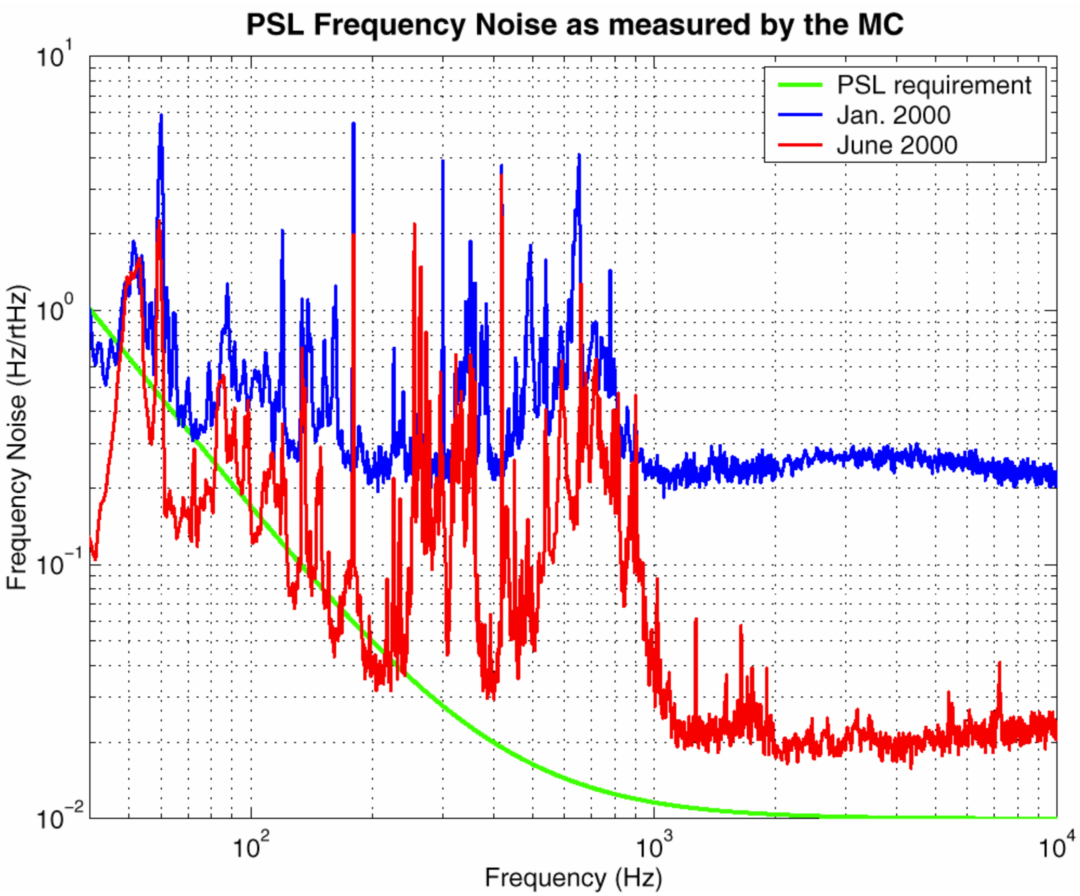
stabilization

- **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**



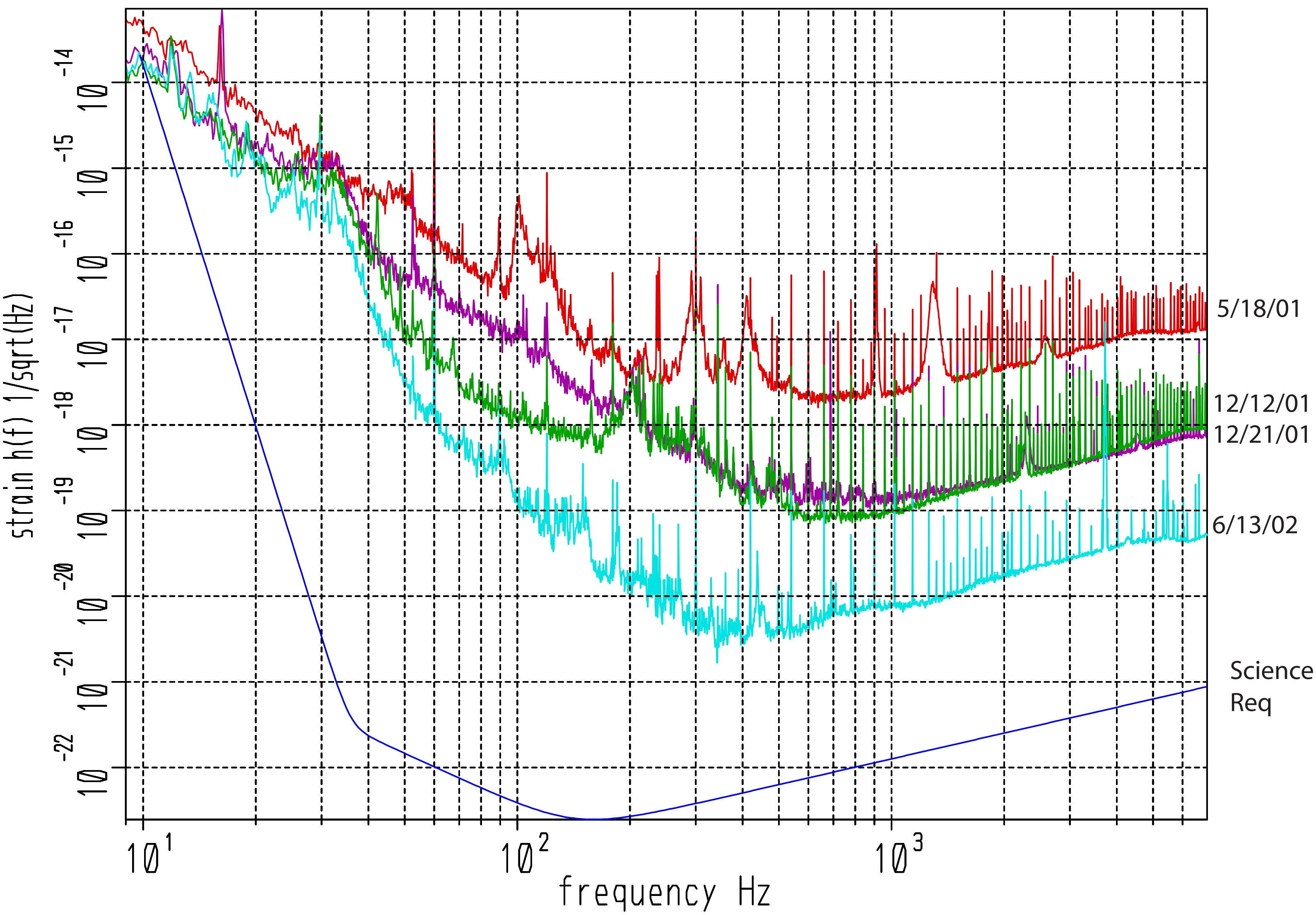
Prestabalized Laser

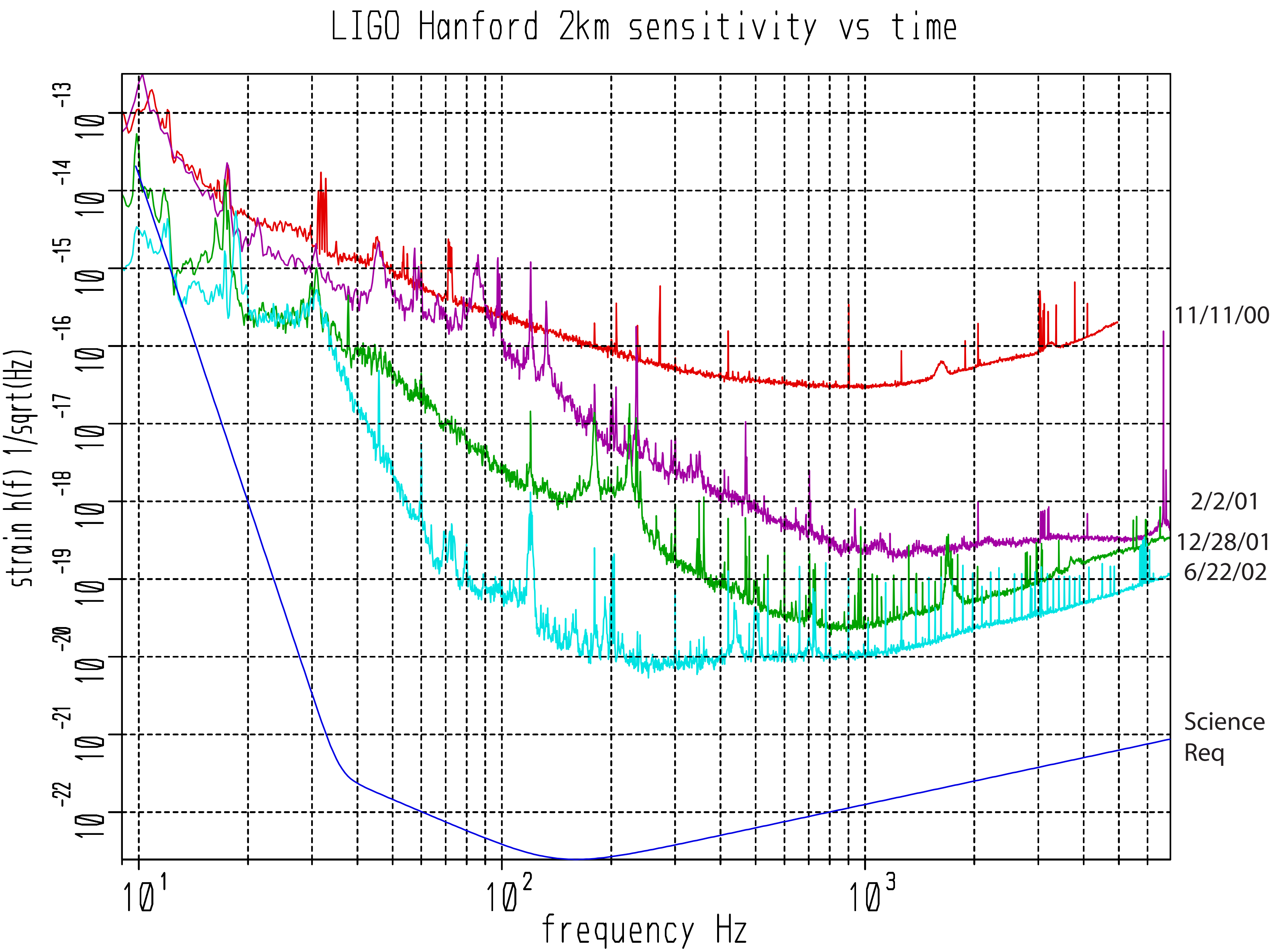
performance

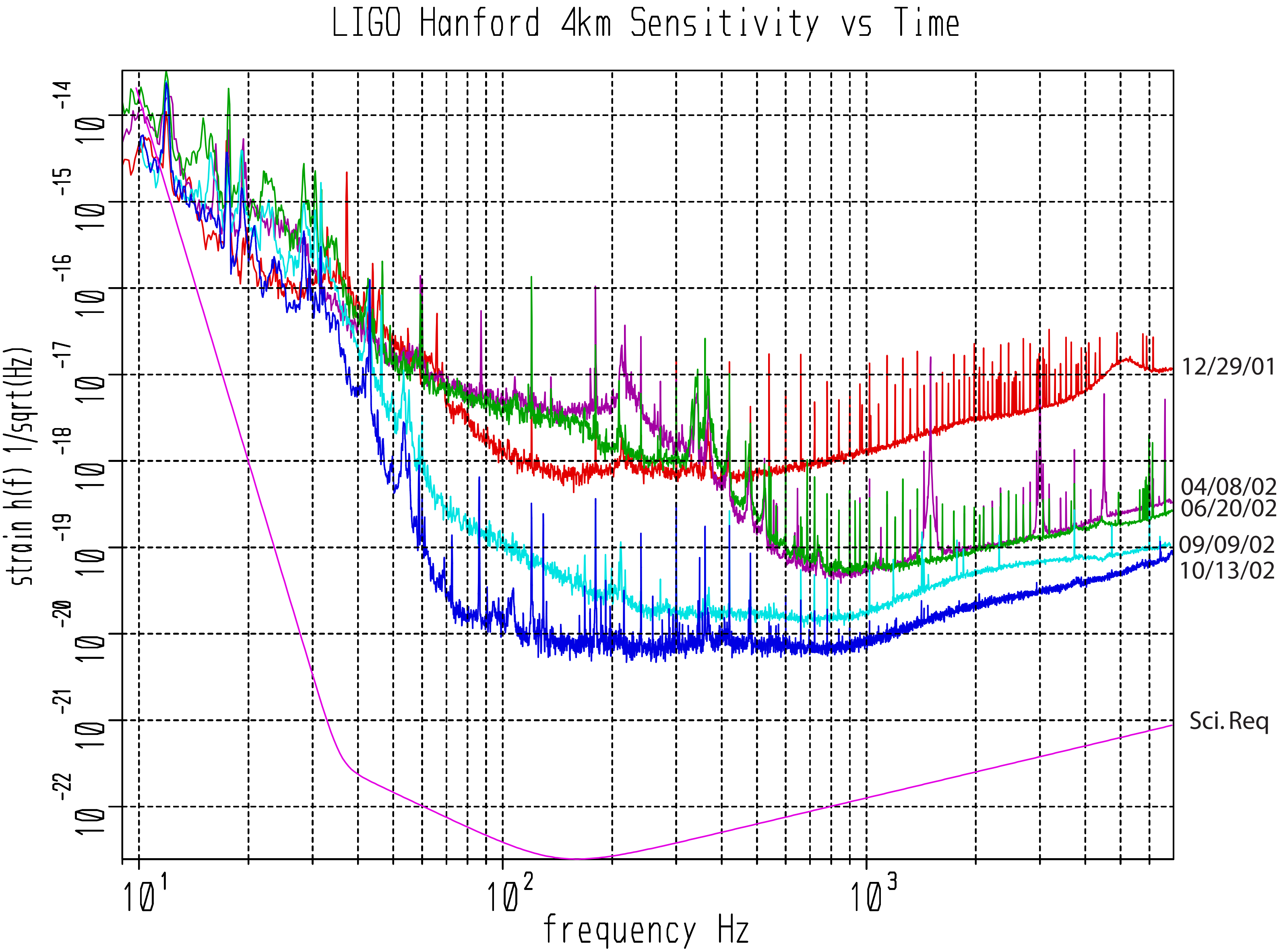


- > 18,000 hours continuous operation
- Frequency and lock very robust
- TEM_{00} power > 8 watts
- Non-TEM_{00} power < 10%

LIGO Livingston 4km sensitivity vs time

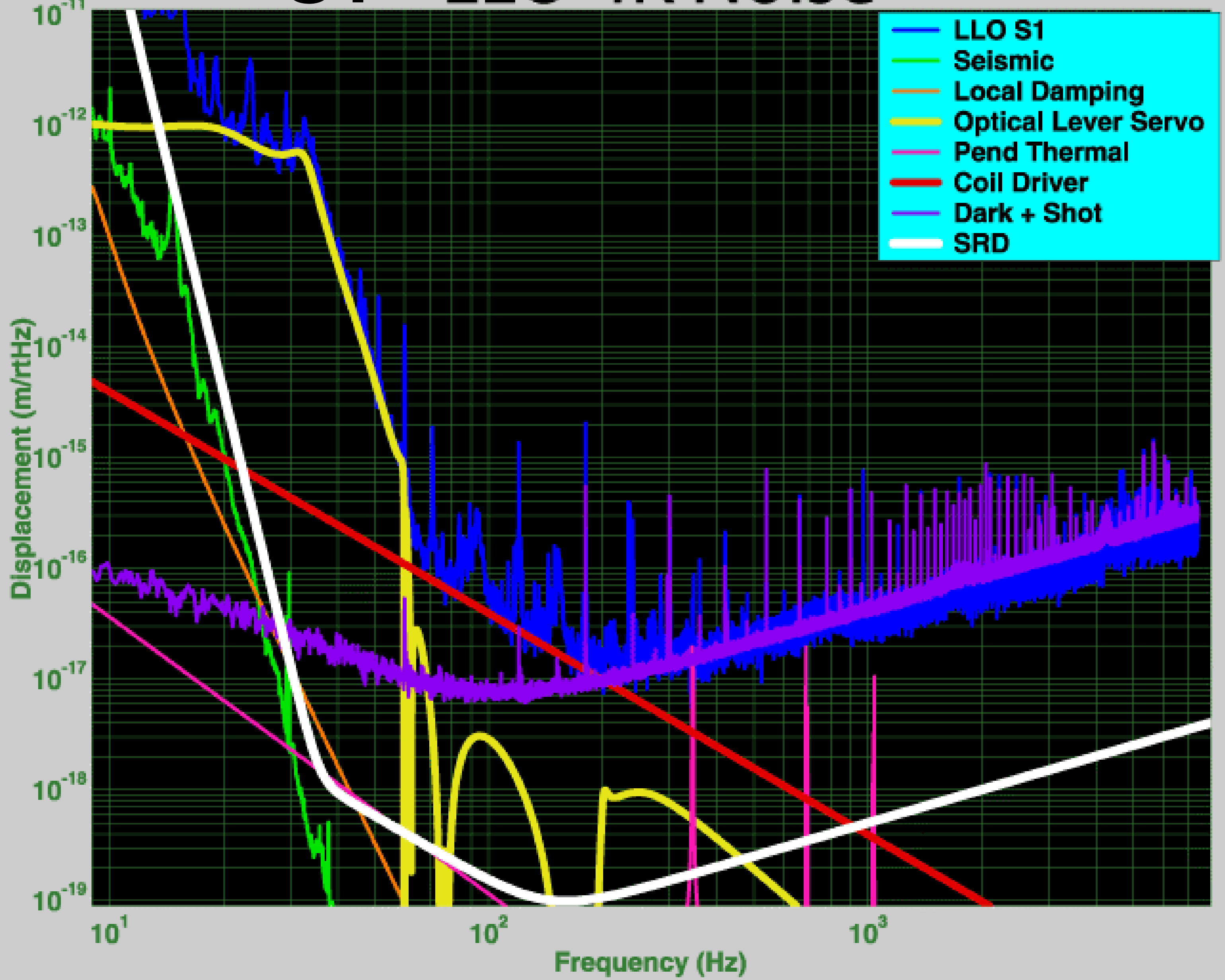



LIGO Hanford 2km sensitivity vs time
strain h(f) 1/sqrt(Hz)
frequency Hz
11/11/00
2/2/01
12/28/01
6/22/02
Science
Req

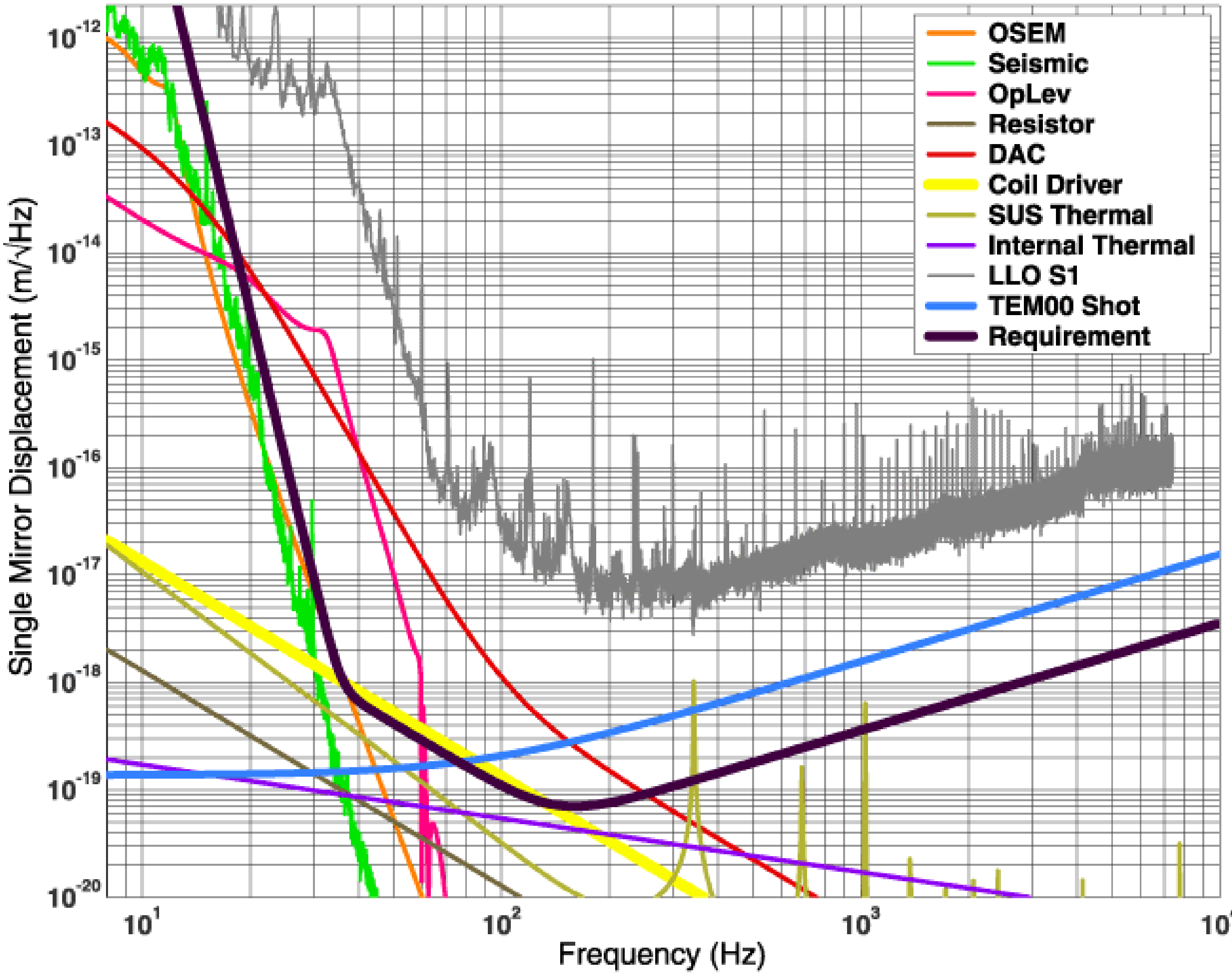


LIGO Hanford 4km Sensitivity vs Time
strain h(f) 1/sqrt(Hz)
frequency Hz
12/29/01
04/08/02
06/20/02
09/09/02
10/13/02
Sci. Req

S1 LLO 4K Noise

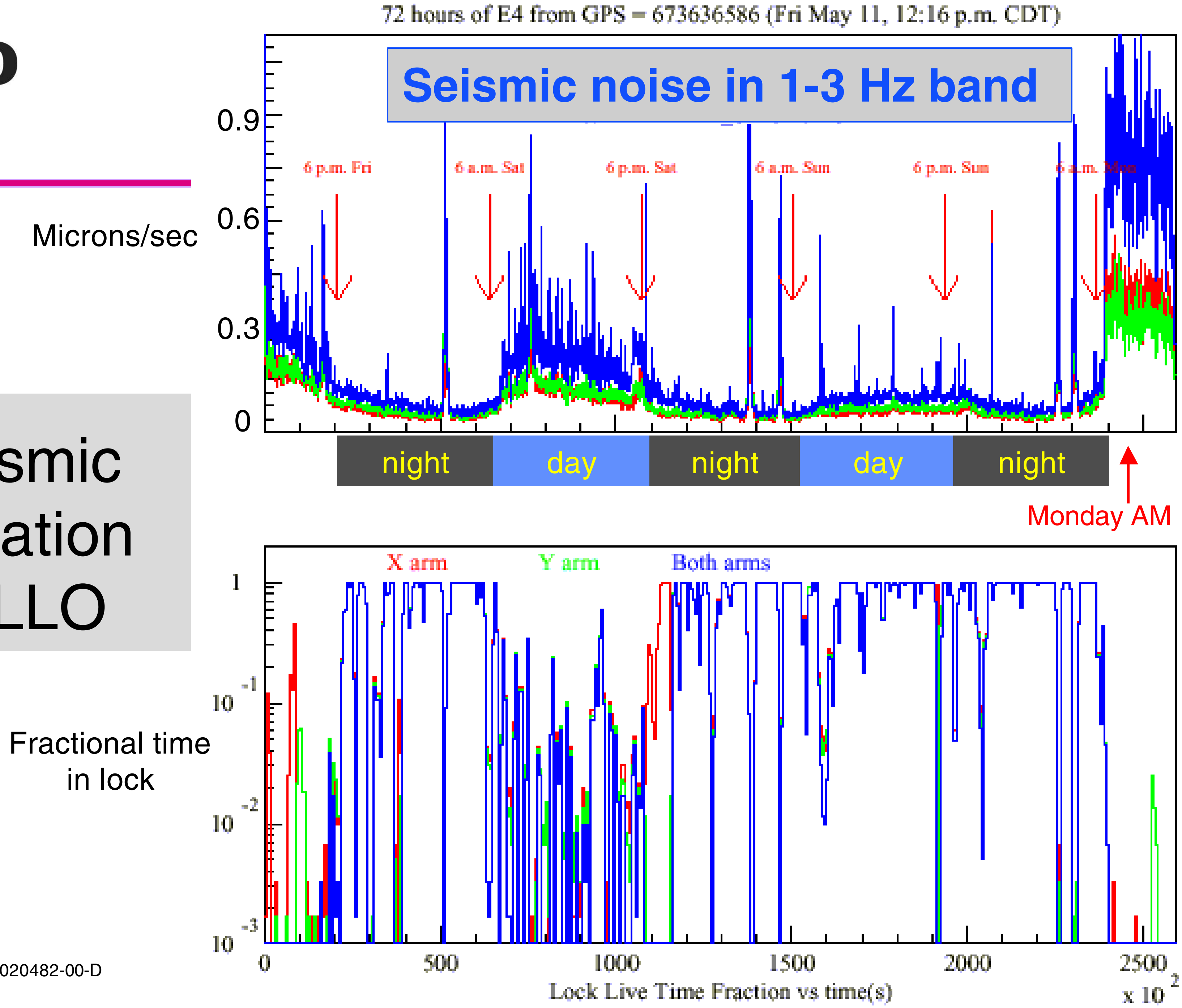


Estimated Noise limits for S2



LIGO

Seismic Situation at LLO



Astrophysical source upper limit groups

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

Purpose:

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

Groups: (Data Analysis)

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

Inspiral sources: Pat Brady, Univ of Wisconsin, Gabriela Gonzalez, LSU

Periodic sources: Maria A Papa , AEI , Michael Landry, LIGO Hanford

Stochastic background: Joe Romano, UT Brownsville, Peter Fritschel, MIT

Burst Group membership

Rana Adhikari, Warren Anderson, Stefan Ballmer, Barry Barish, Biplab Bhawal, Jim Brau, Kent Blackburn, Laura Cadonati, Joan Centrella, Ed Daw, Ron Drever, *Sam Finn*, Ray Frey, Ken Ganezer, Joe Giaime, Gabriela Gonzalez, Bill Hamilton, Ik Siong Heng, Masahiro Ito, Warren Johnson, Erik Katsavounidis, Sergei Klimenko, Albert Lazzarini, Isabel Leonor, Szabi Marka, Soumya Mohanty, Benoit Mours, Soma Mukherjee, David Ottoway, Fred Raab, Rauha Rahkola, *Peter Saulson*, Robert Schofield, Peter Shawhan, David Shoemaker, Daniel Sigg, Amber Stuver, Tiffany Summerscales, Patrick Sutton, Julien Sylvestre, Alan Weinstein, Mike Zucker, John Zweizig

Inspiral Group Membership

- Bruce Allen, Russ Bainer, Kent Blackburn, Sukant Bose, *Patrick Brady*, Duncan Brown, Jordan Camp, Vijay Chickarmane, Nelsen Christensen, David Churches, Jolien Creighton, Teviet Creighton, S.V. Dhurander, Carl Ebeling, *Gabriela Gonzalez*, Andr M. Gretarsson, Gregg Harry, Vicky Kalogera, Joe Kovalik, Nergis Mavalvala, Brian O Reilly, Valera, Adrian Ottewill, Ben Owen, Tom Prince, David Reitze, Anthony Rizzi, David Robertson, B.S. Sathyaprakash, Peter Shawhan, Julien Sylvestre, Massimo Tinto, Linqing Wen, Benn Wilk , Alan Wiseman, Natalia Zotov.

Continuous Waves Searches ULs

B. Allen, S.Anderson, S.Berukoff, P.Brady, D.Chin,
R.Coldwell, T.Creighton, C.Cutler, R.Drever, R.Dupuis,
S.Finn, D.Gustafson, J.Hough,M.Landry, G. Mendell,
C.Messenger, S.Mohanty, S.Mukherjee, M.A. Papa, B.Owen,
K.Riles, B.Schutz, X. Siemens, A.Sintes, A.Vecchio, H.Ward,
A. Wiseman, G.Woan, M. Zucker

www.lsc-group.phys.uwm.edu/pulgroup

Stochastic UL Group: Prospects for S1

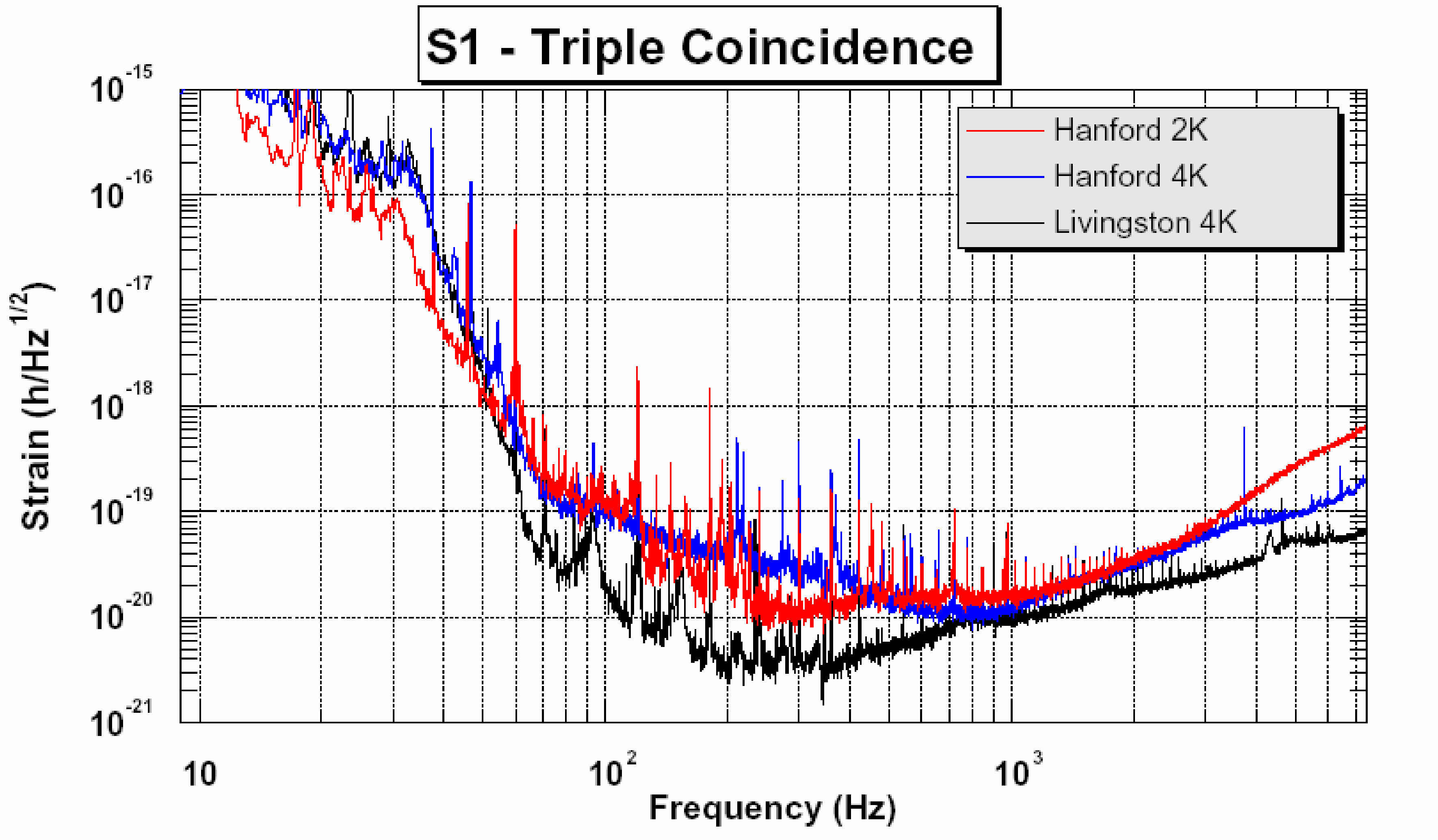
LSC Stochastic Sources Upper Limit Group

LIGO-G020411-00-Z

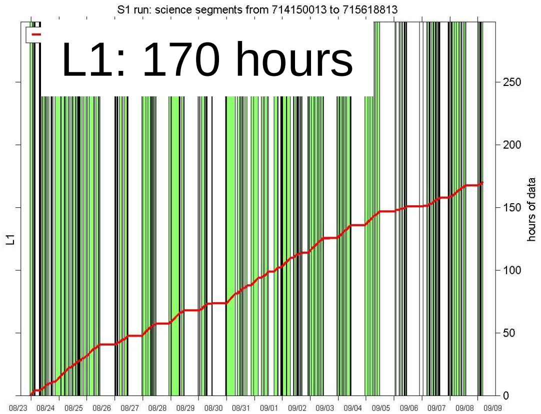
September 20, 2002

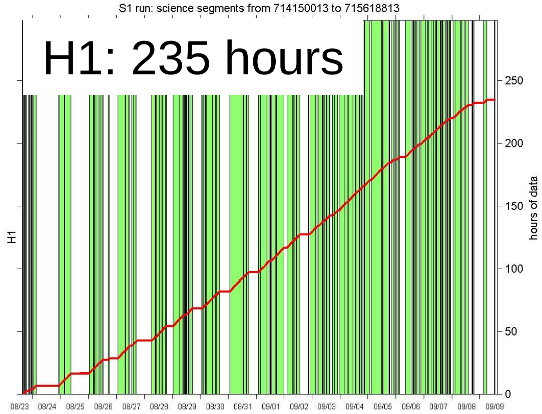
B. Allen, W. Anderson, S. Bose, N. Christensen, E. Daw, M. Diaz, R. Drever, S. Finn, P. Fritschel, J. Giaime, B. Hamilton, S. Heng, R. Ingley, W. Johnson, B. Johnston, E. Katsavounidis, S. Klimenko, M. Landry, A. Lazzarini, M. McHugh, T. Nash, A. Ottewill, P. Perez, T. Regimbau, J. Rollins, J. Romano, B. Schutz, A. Searle, P. Shawhan, A. Sintes, C. Torres, C. Ungarelli, E. Vallarino, A. Vecchio, R. Weiss, J. Whelan, B. Whiting

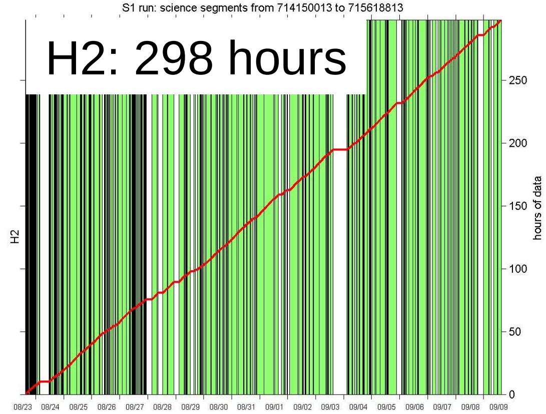
S1 run: Aug 23-Sept 9

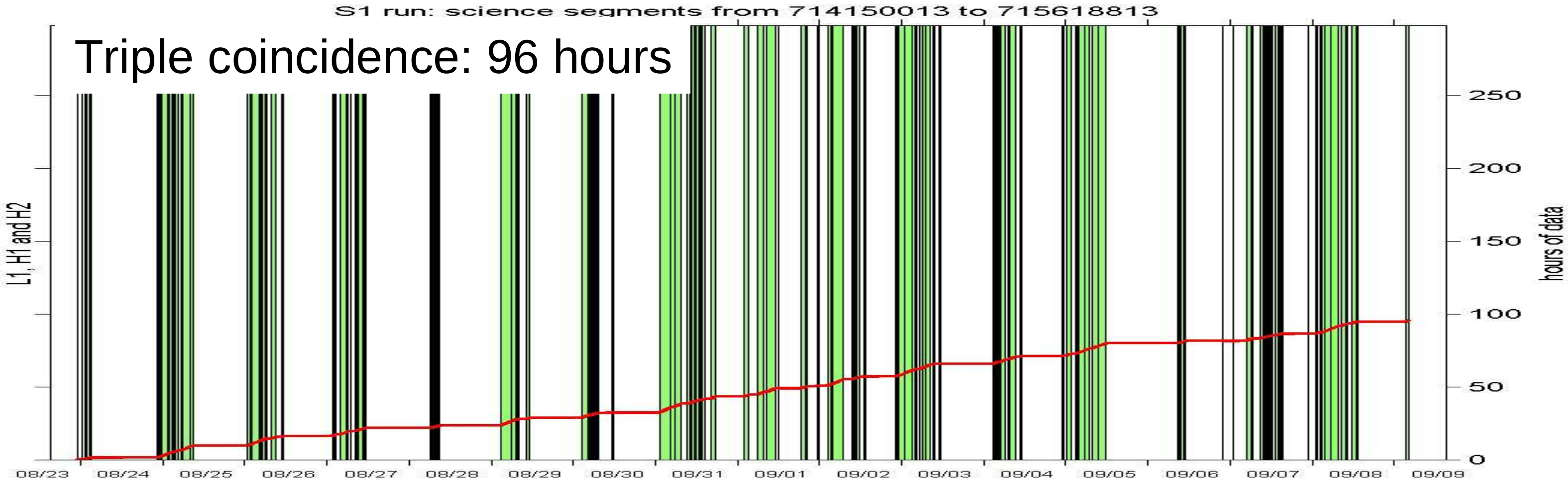


Lots of data…



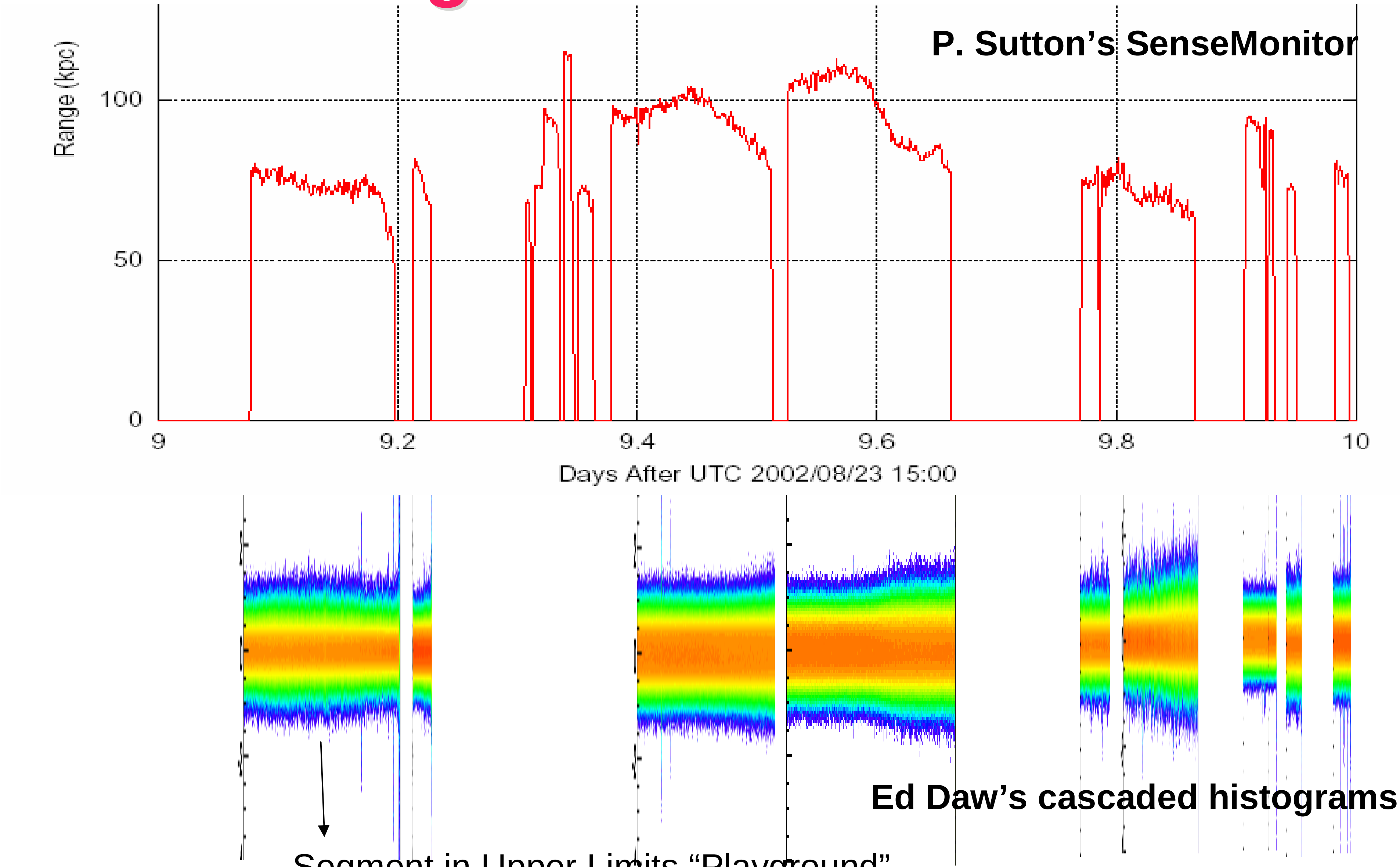




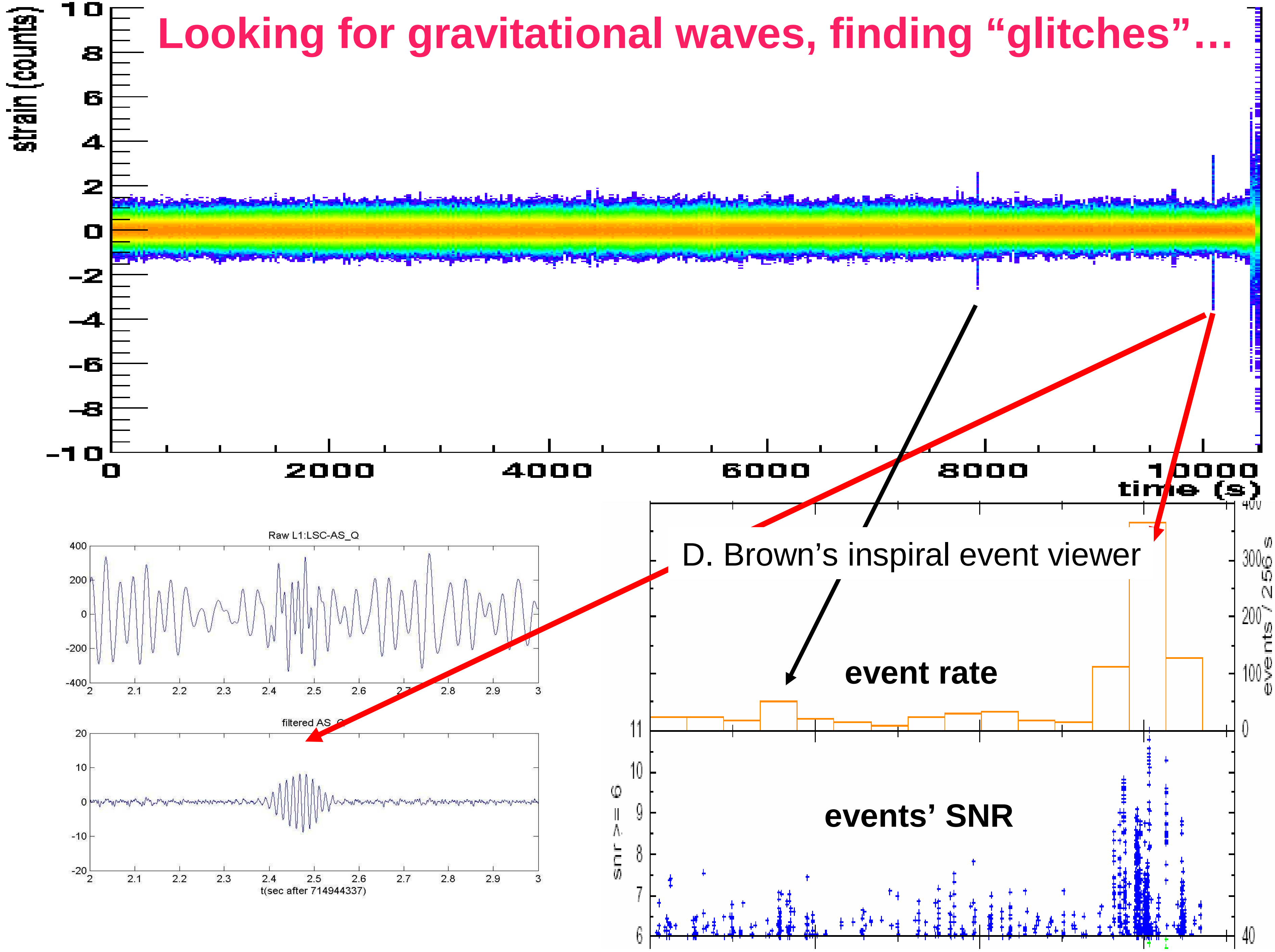


http://www.phys.lsu.edu/faculty/gonzalez/S1LockStats/

Looking farther than ever before

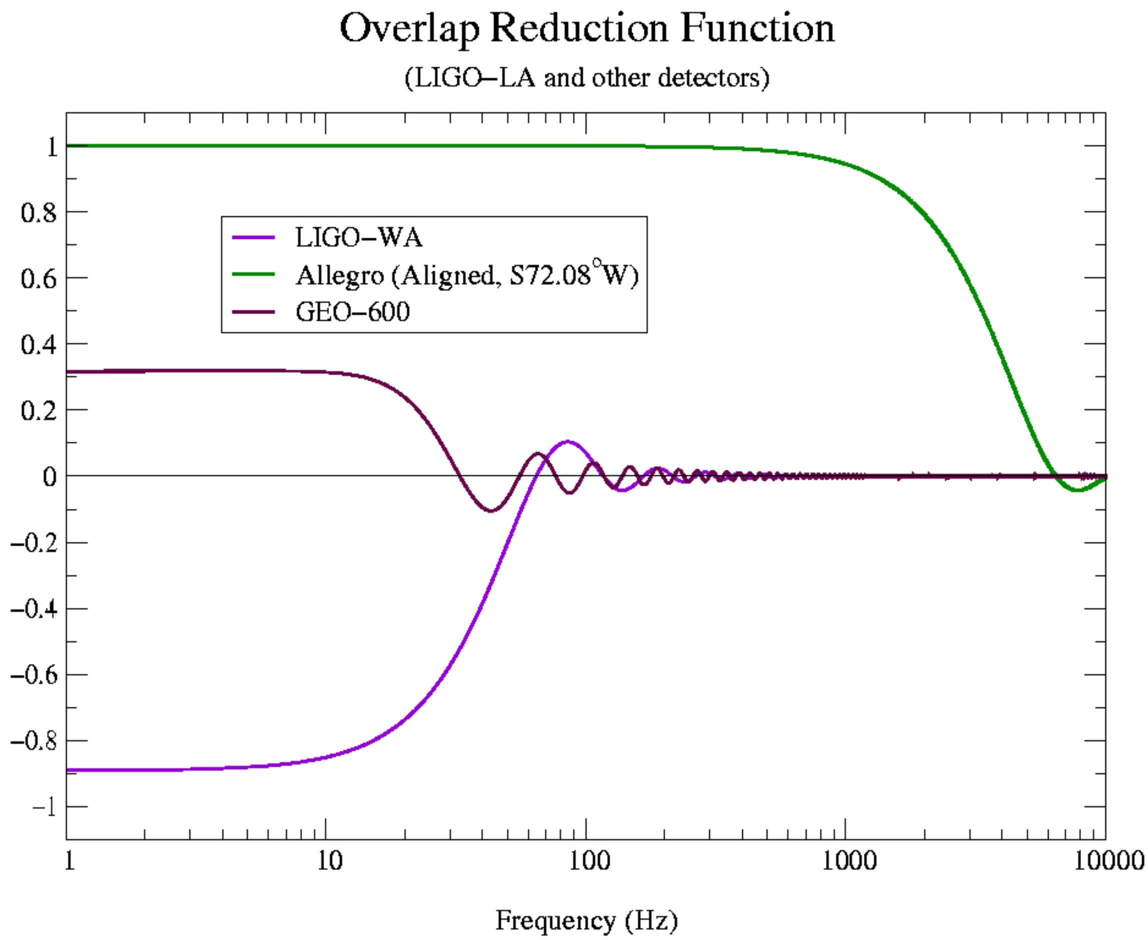


Looking for gravitational waves, finding “glitches”…

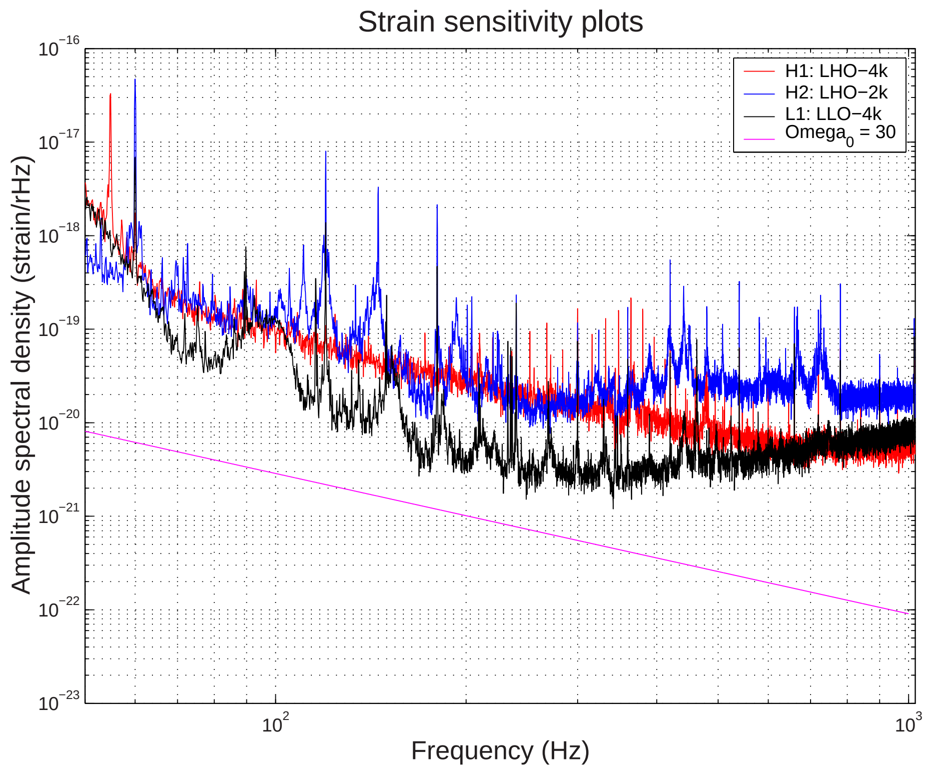


Overlap reduction function

Specifies the reduction in sensitivity due to the separation and orientation of the two detectors:



Expected upper limit for S1

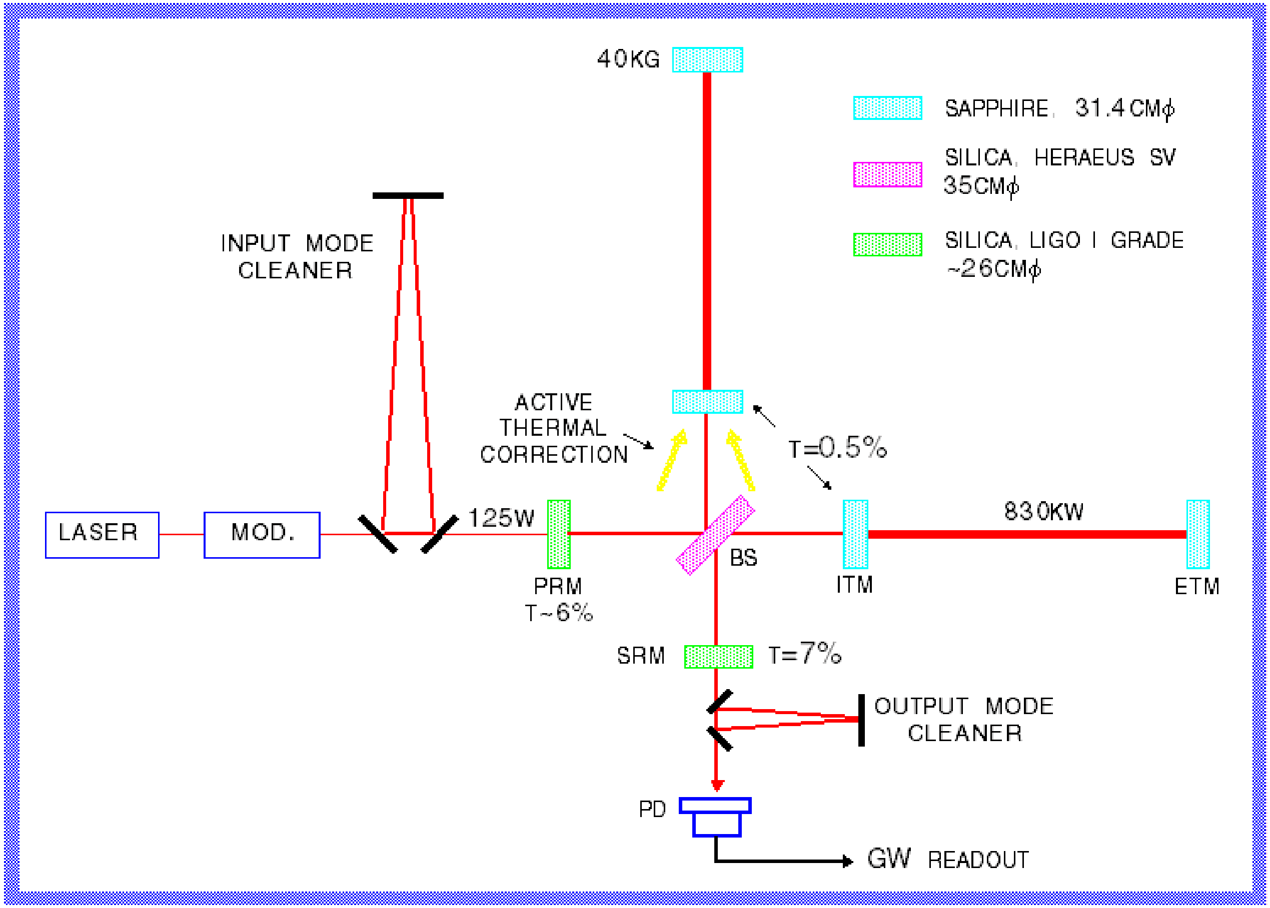


Upper limit: (90% CL, 70 hrs H2-L1 data)

$$\Omega_0 \leq 30 \quad \text{for} \quad 40\text{ Hz} < f < 215\text{ Hz}$$

NOTE: Factor of 2×10^3 improvement over E7.

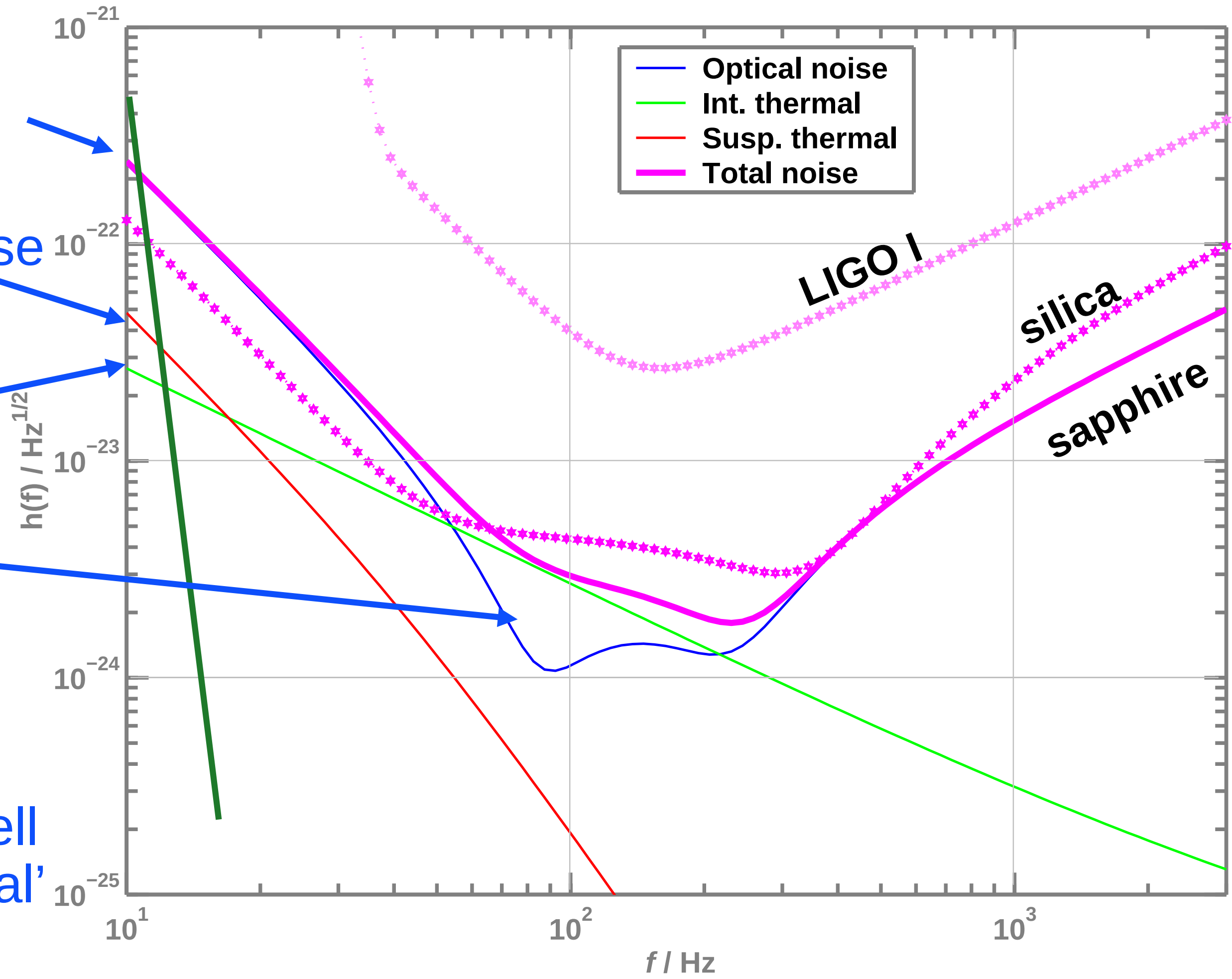
Advanced Interferometer Concept



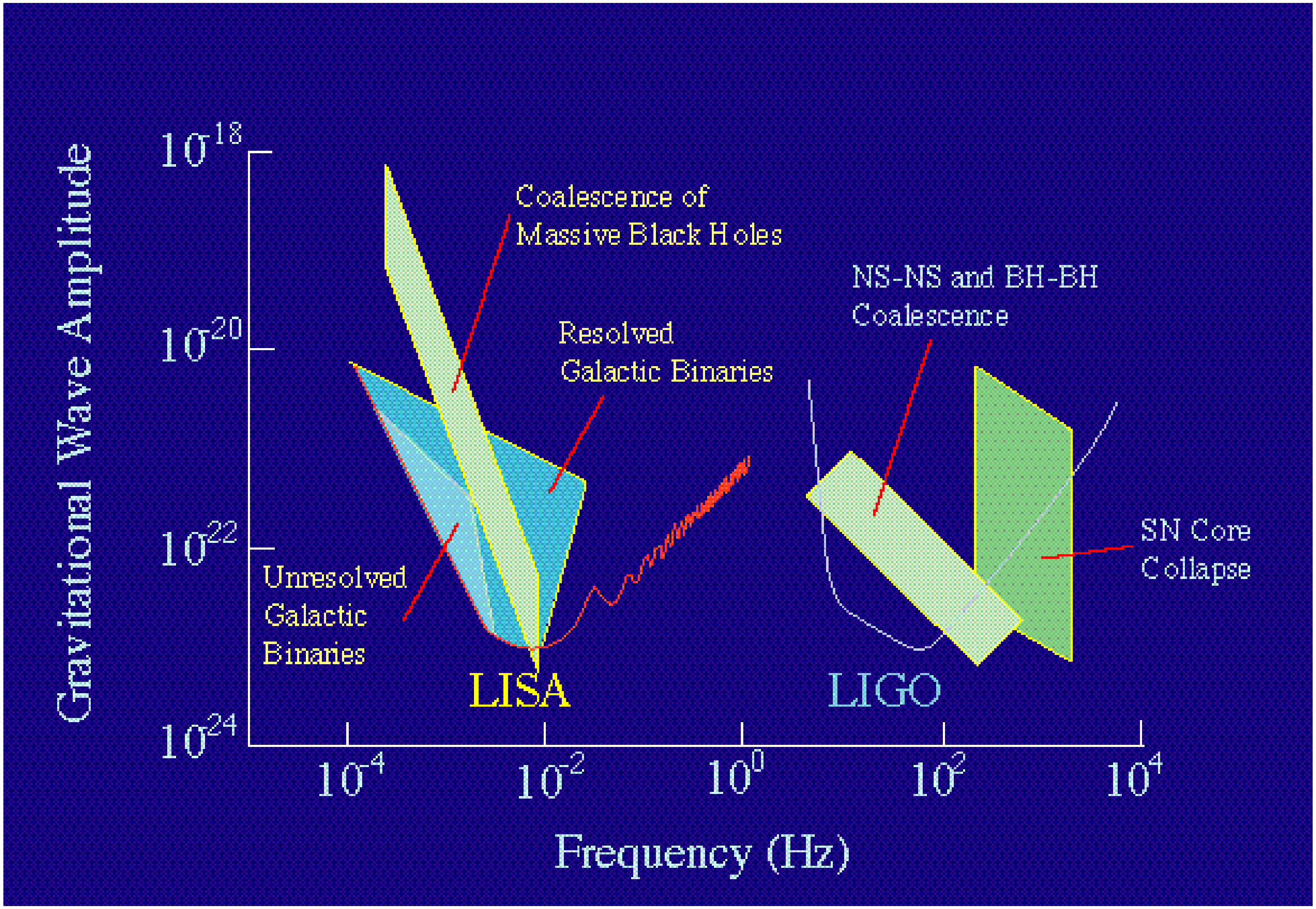
- » Signal recycling
- » 180-watt laser
- » 40 kg Sapphire test masses
- » Larger beam size
- » Quadruple suspensions
- » Active seismic isolation
- » Active thermal correction
- » Output mode cleaner

Projected Performance

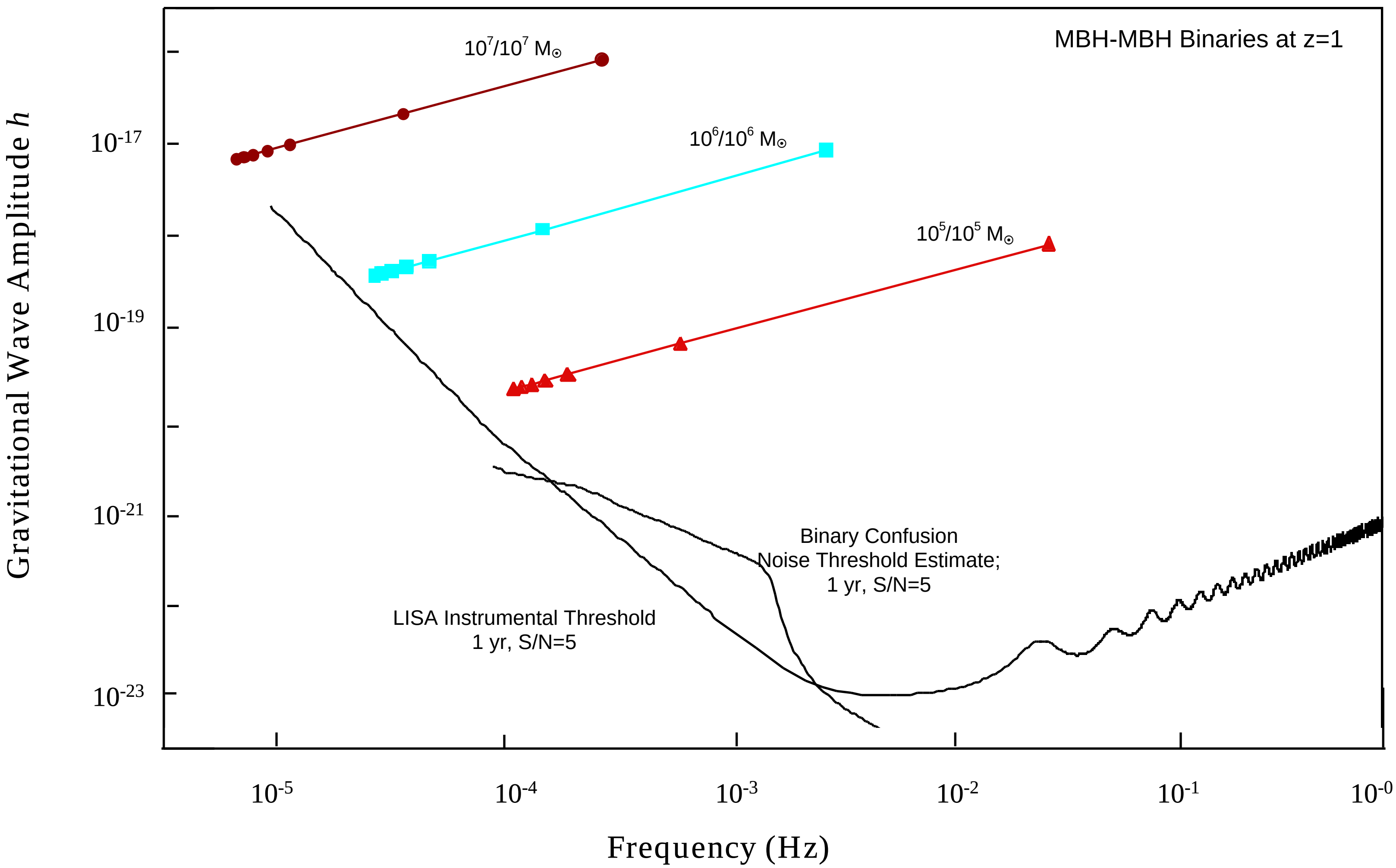
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held in general well below these 'fundamental' noises



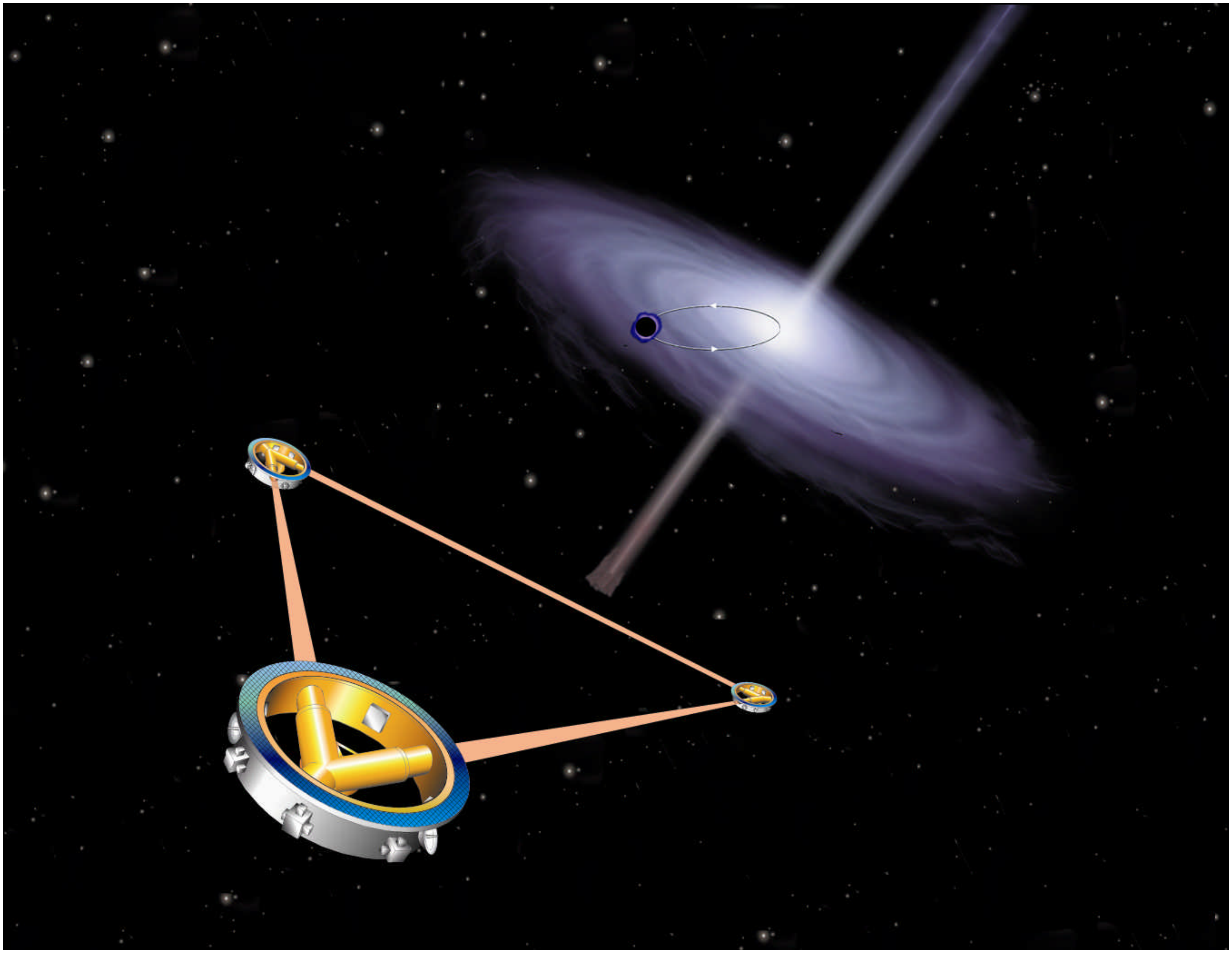
The Gravitational-Wave Spectrum



Massive Black Holes in Merging Galaxies



Mission Concept



Optical System