LIGO – Laser Interferometer Gravitational-wave Observatory—Status of the detector and initial observations

University of New Hampshire

March 24, 2003

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

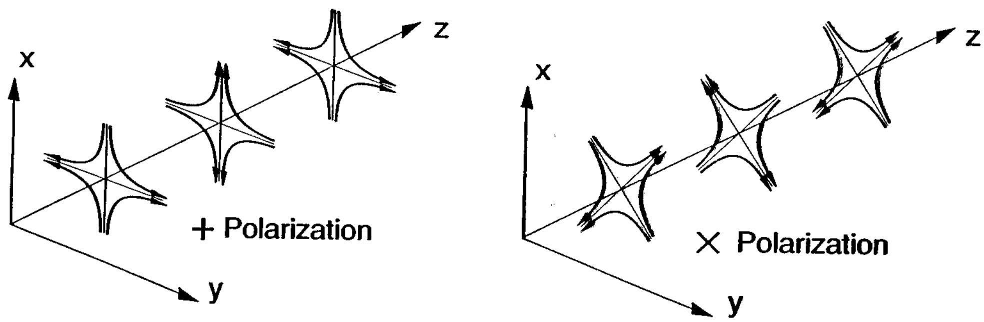
$$h_{ij} \;=\; \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \qquad \text{all } h_{ij} \ll 1$$

Plane Wave

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

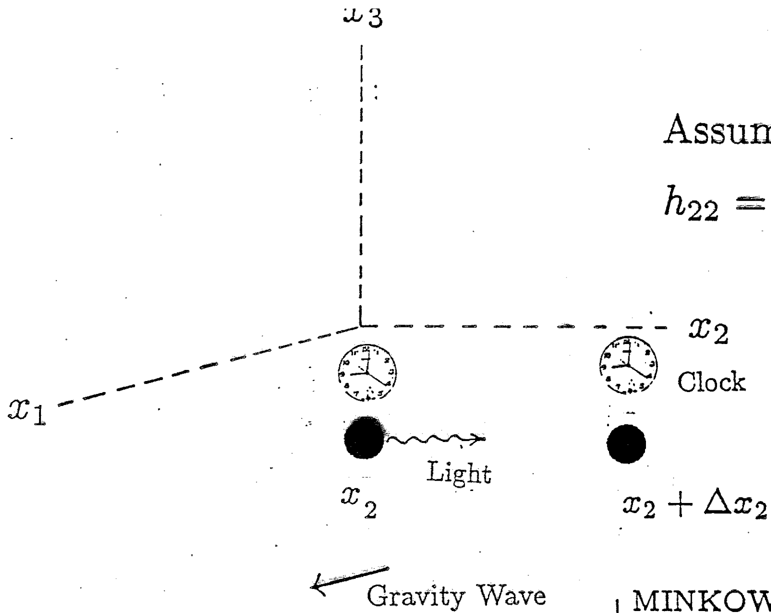
$+$ **polarization** $\qquad$ $\times$**polarization**

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


x
z
y
+ Polarization
x
z
y
× Polarization

Assume + Polarization

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



MINKOWSKI

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

LIGHT RAY

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

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

INFERRED DISTANCE BETWEEN POINTS

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

Time Dependent **Strain**

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

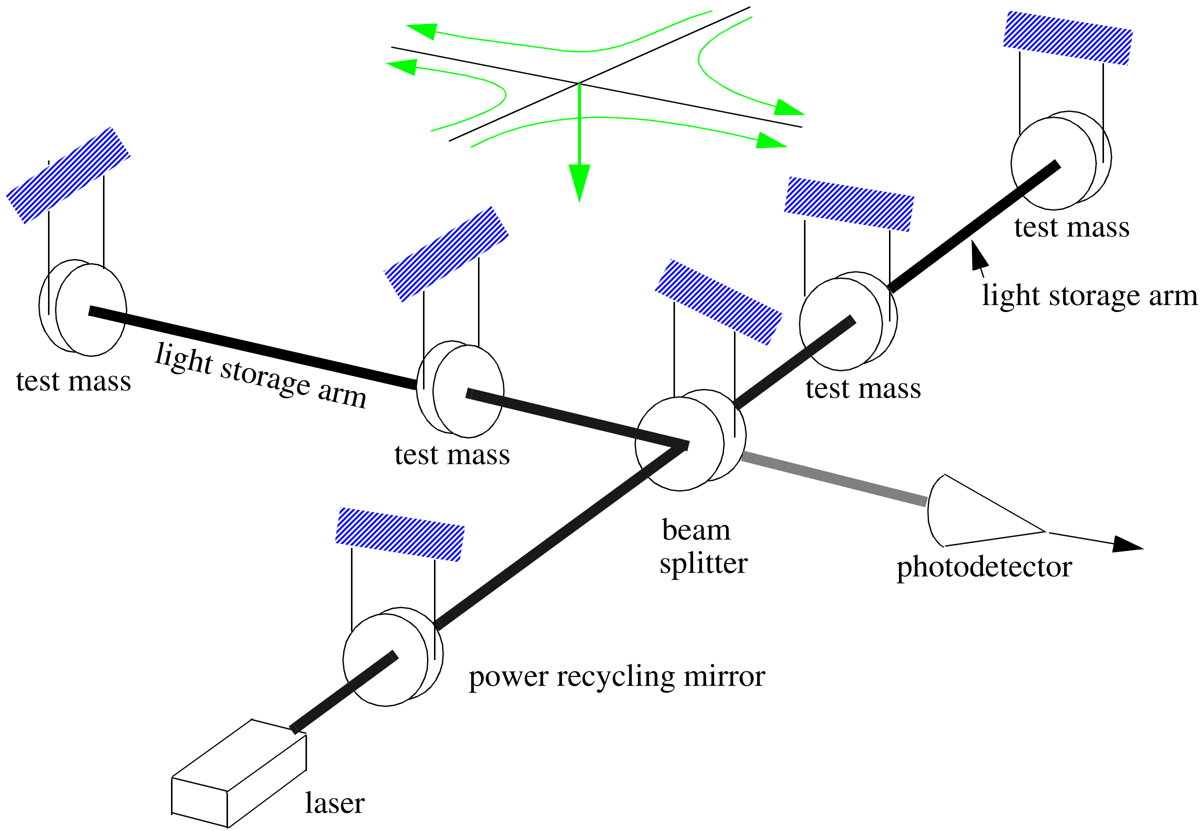
The Measurable Quantity

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

FRINGE SENSING

wavelength 1×10^{-6} m

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

arm length = 4000 m

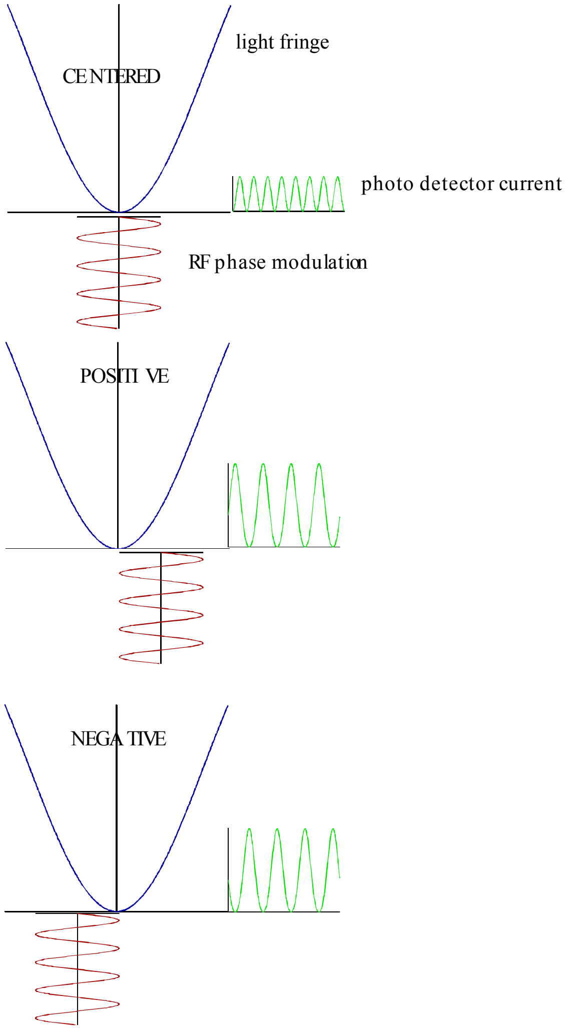
integration time

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



LIGO

PENDULUM THERMAL NOISE

Pendulum Brownian motion

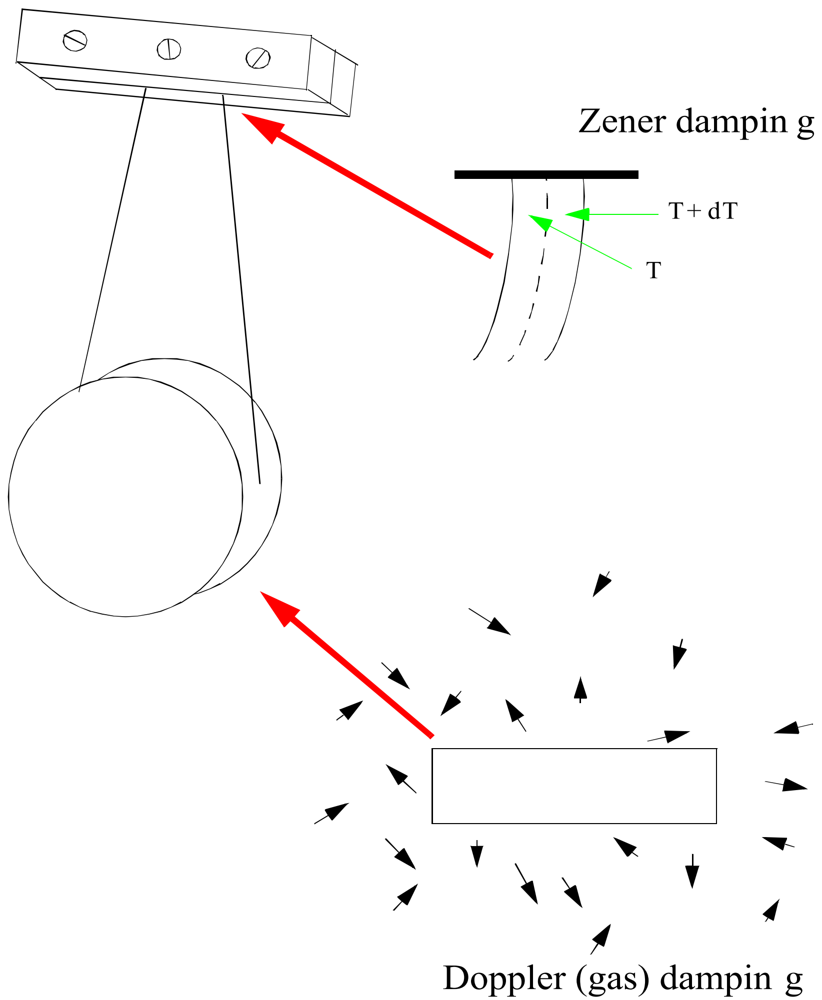
Dissipation leads to fluctuations

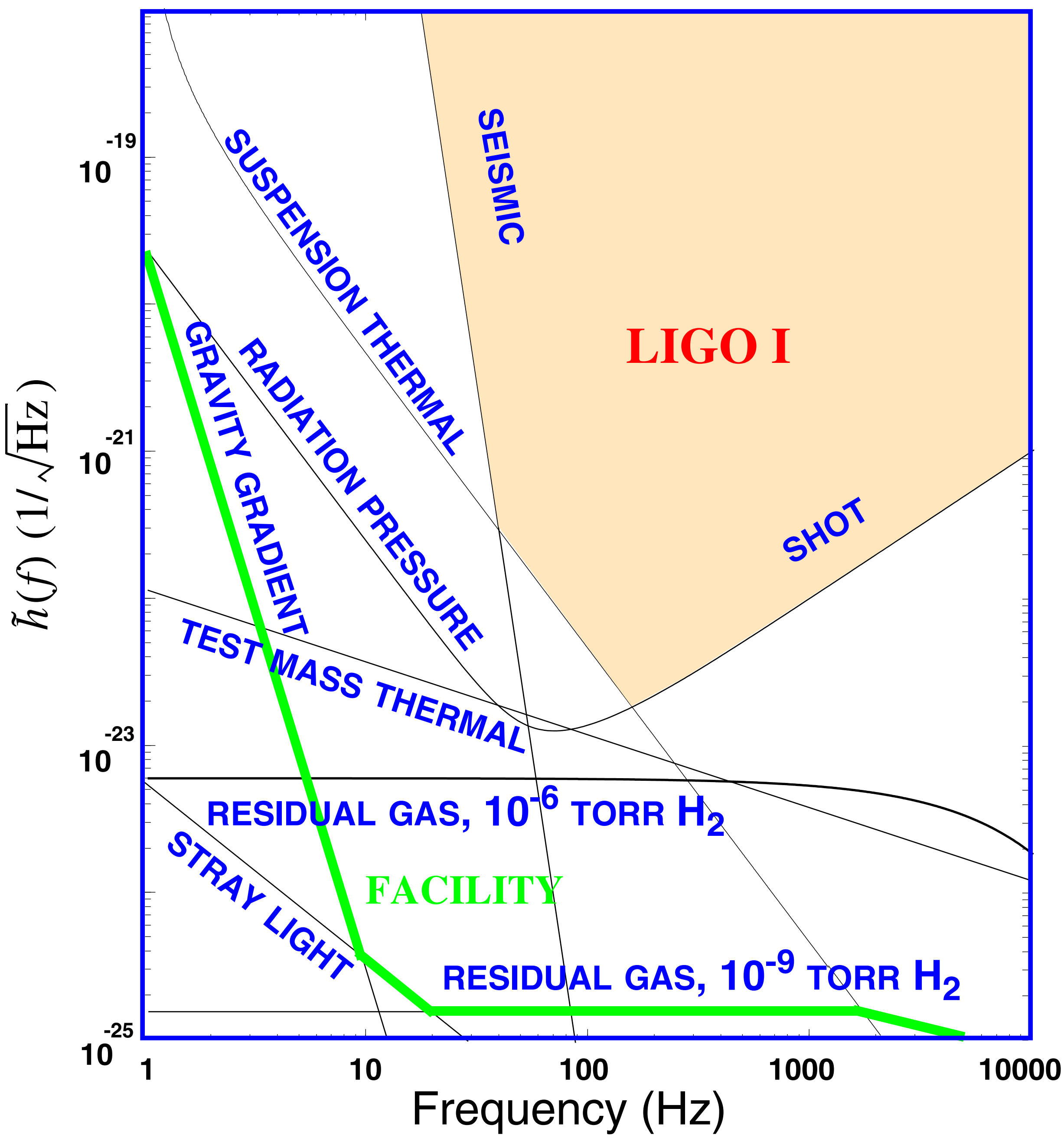
Tc = coherence or damping time
= Q x period of oscillator

Exchange with surroundings:

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

Large Tc => smaller fluctuations





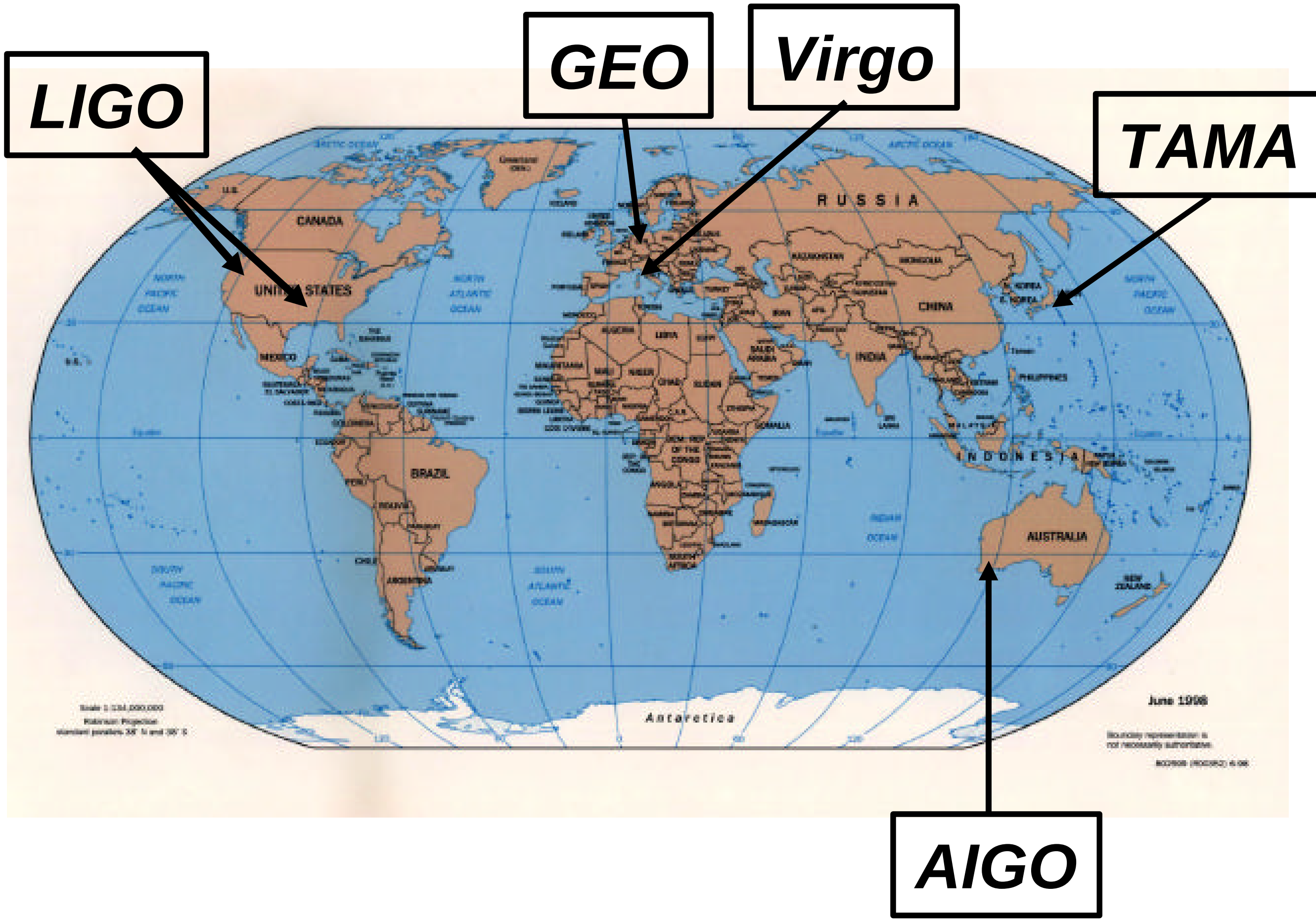
LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^{-9} TORR H_2
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)
$\tilde{h}(f)\ (1/\sqrt{\mathrm{Hz}})$

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	$< 3 \times 10^{-3}$
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)

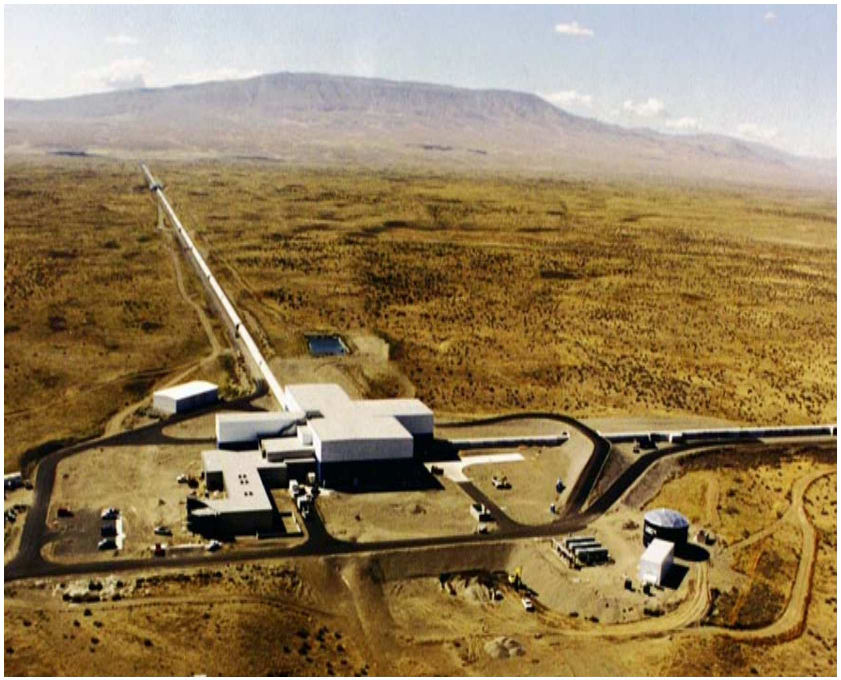


detection confidence

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

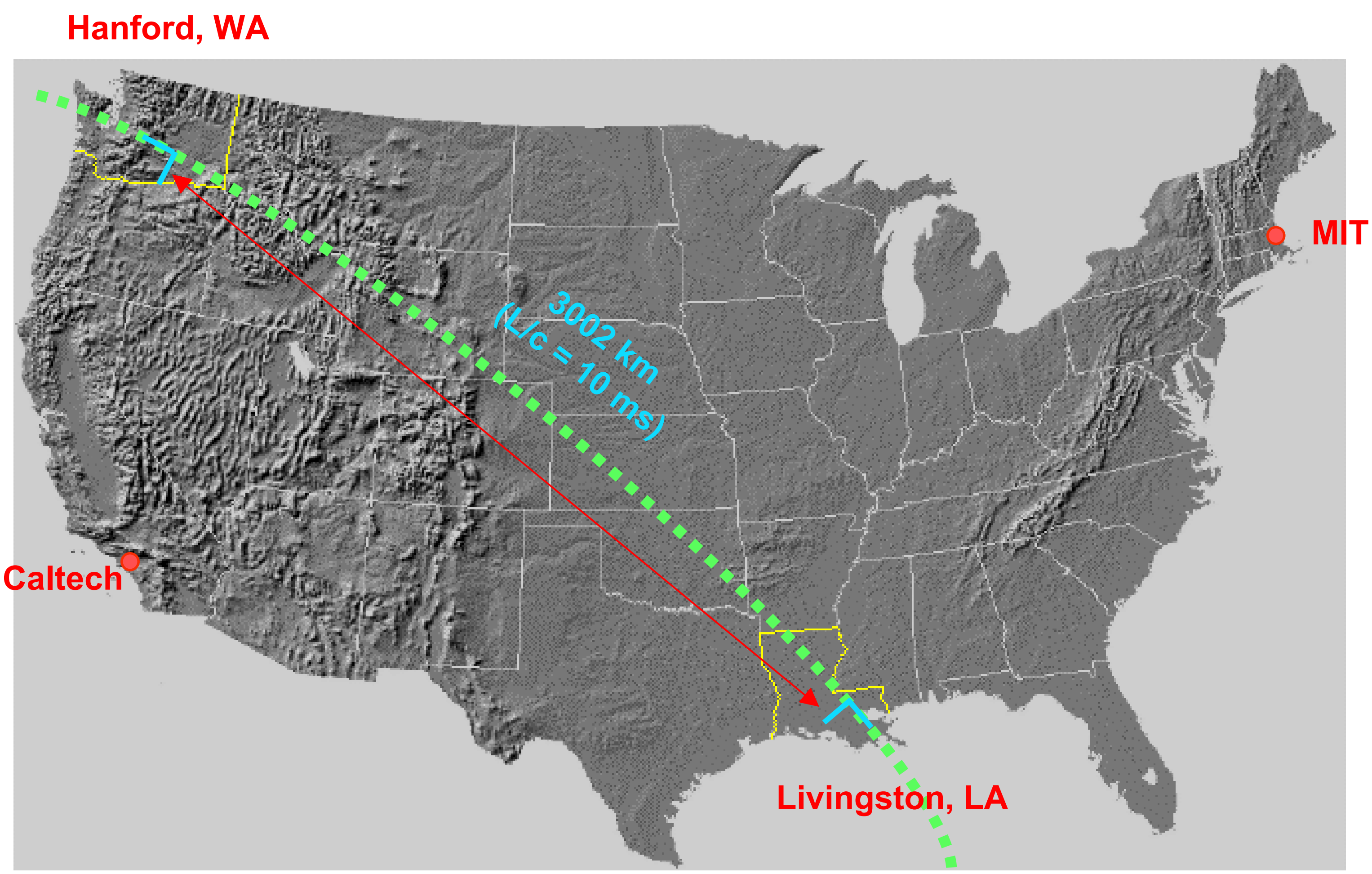
LIGO Livingston Observatory [LLO]

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

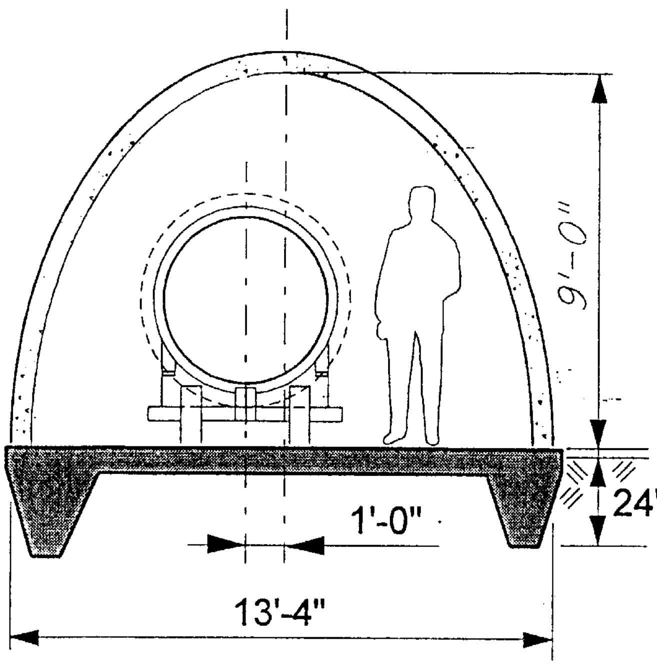
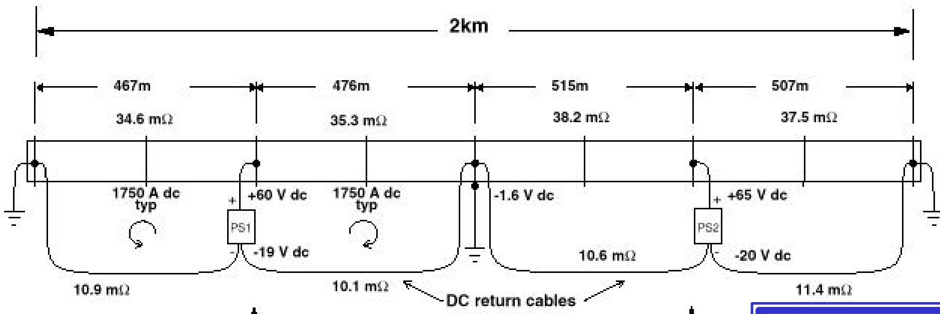


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

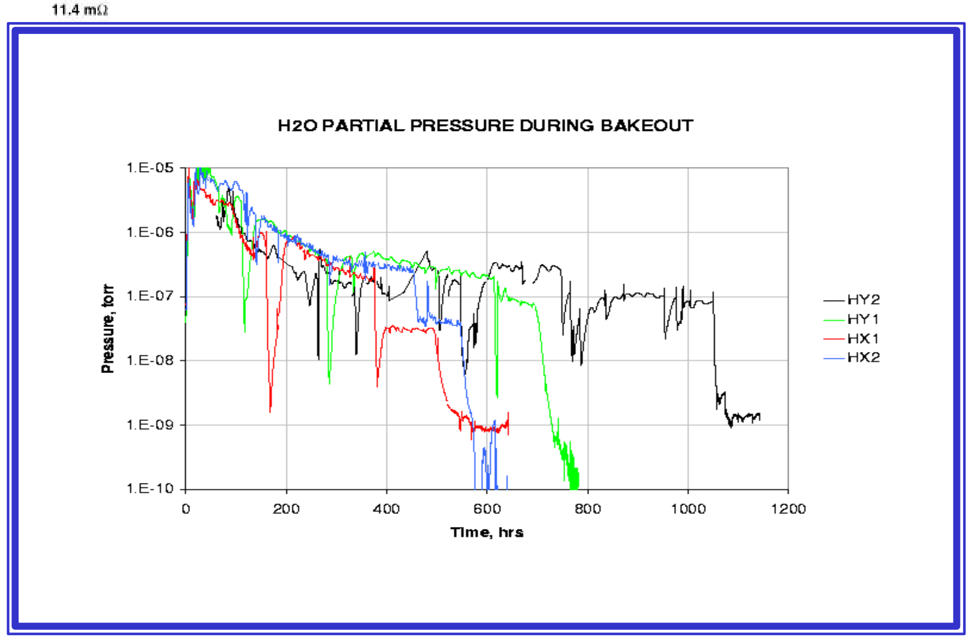
- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **In situ 160 C bakeout**
  - **20,000 m^3 @ 10^{-8} to 10^{-9} torr**

Beam Tube

bakeout



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



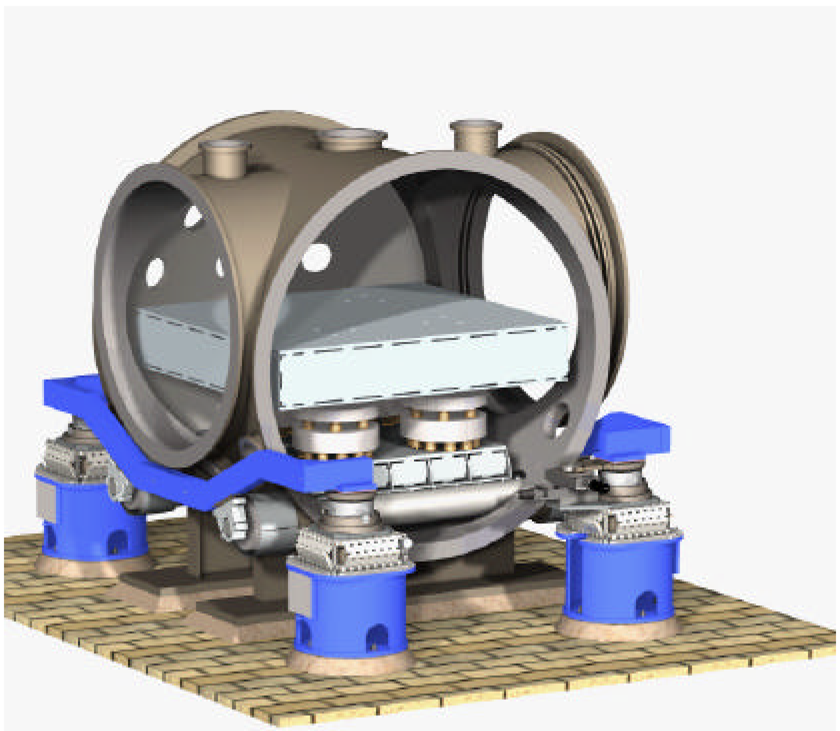
LIGO

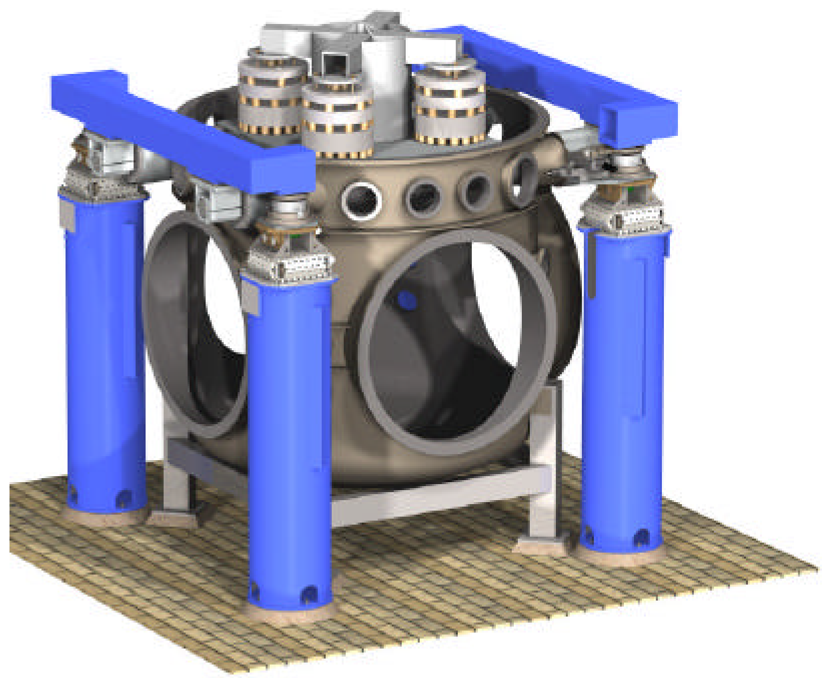
vacuum equipment

Vacuum Chambers

Vibration Isolation Systems

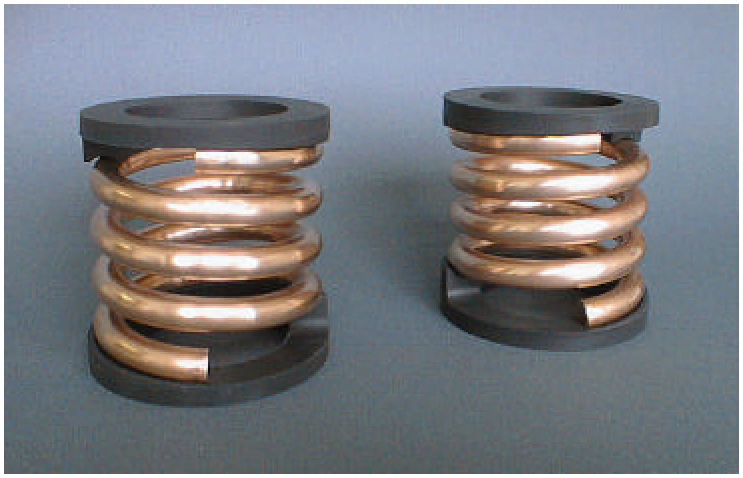
- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Compensate for microseism at 0.15 Hz by a factor of ten
- Compensate (partially) for Earth tides

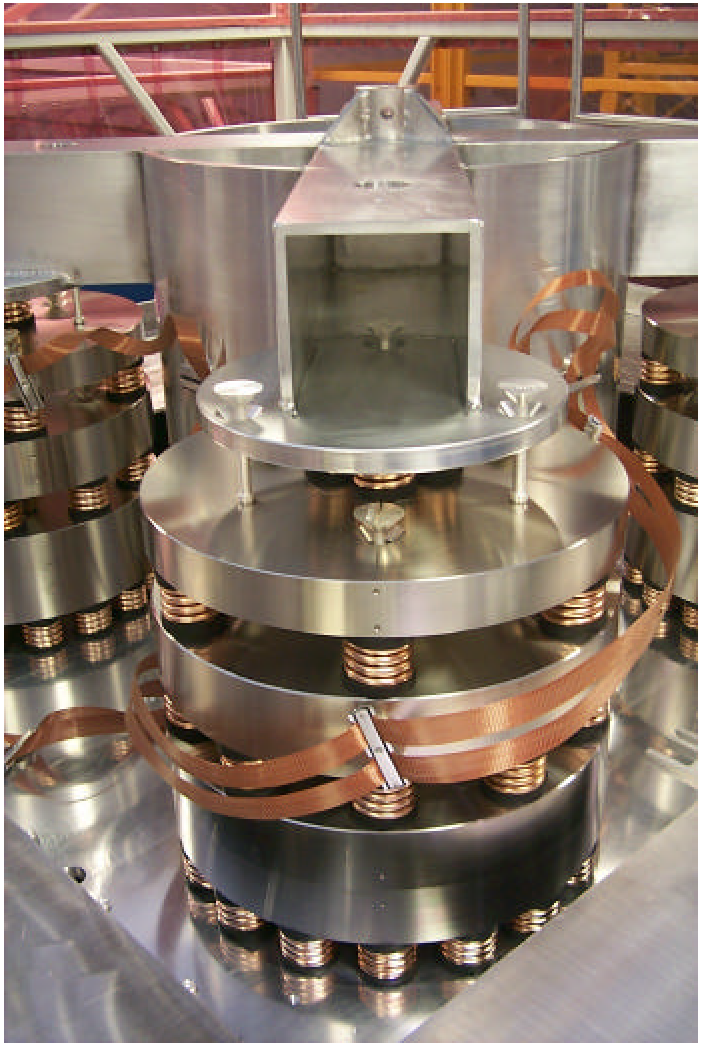




Seismic Isolation

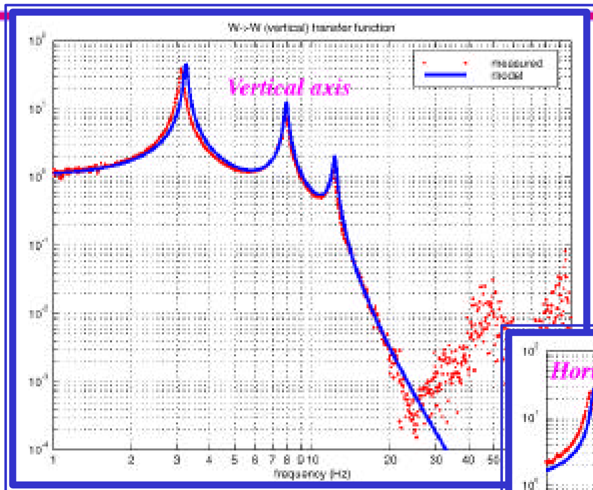
Springs and Masses

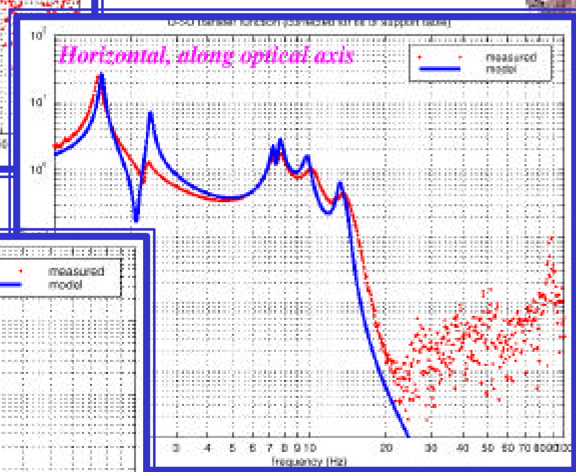


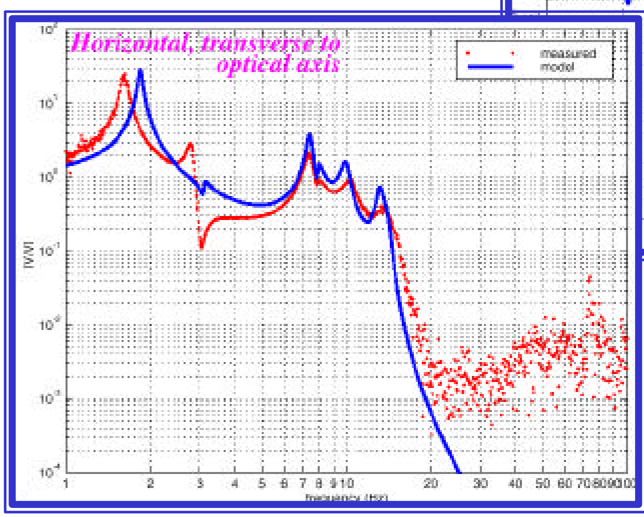


Seismic Isolation

performance

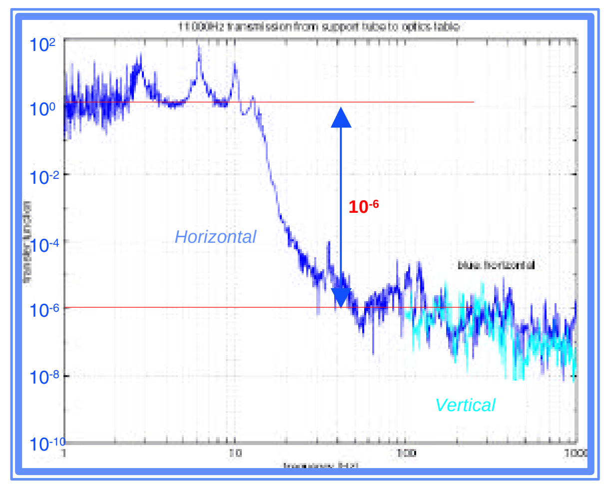




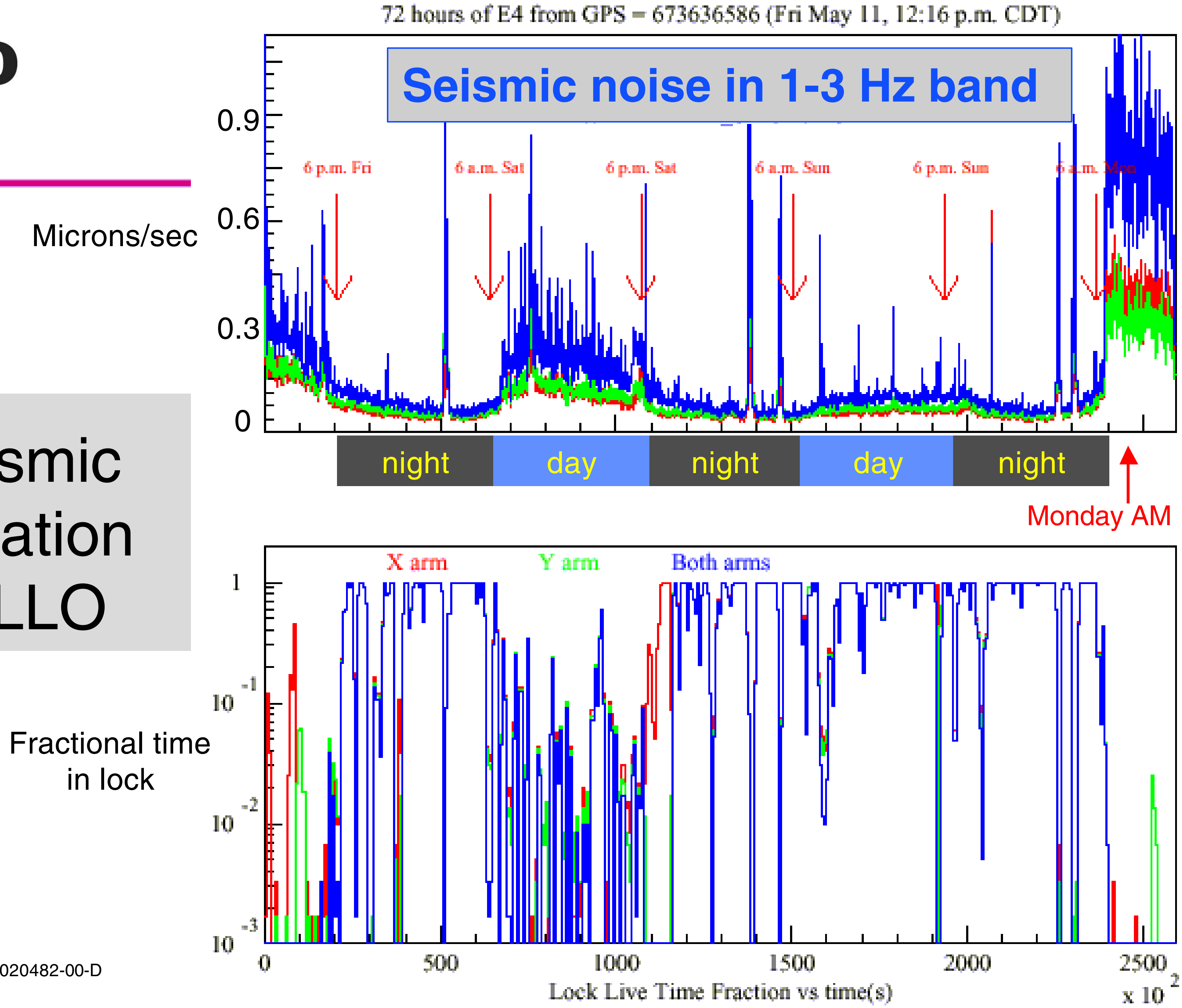


HAM stack in air

BSC stack in vacuum

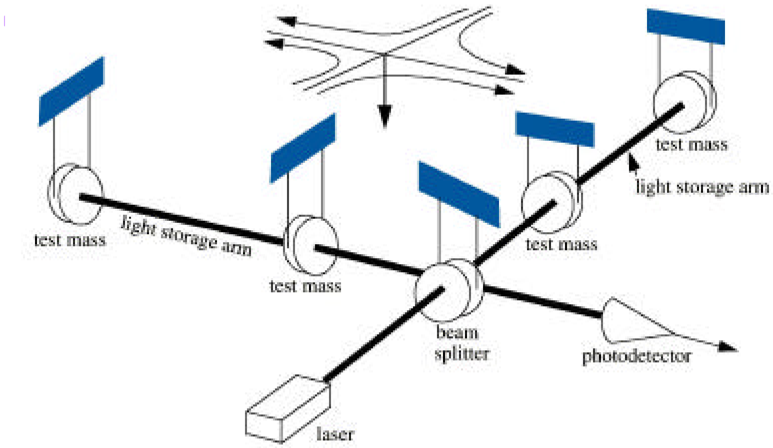


Seismic Situation at LLO



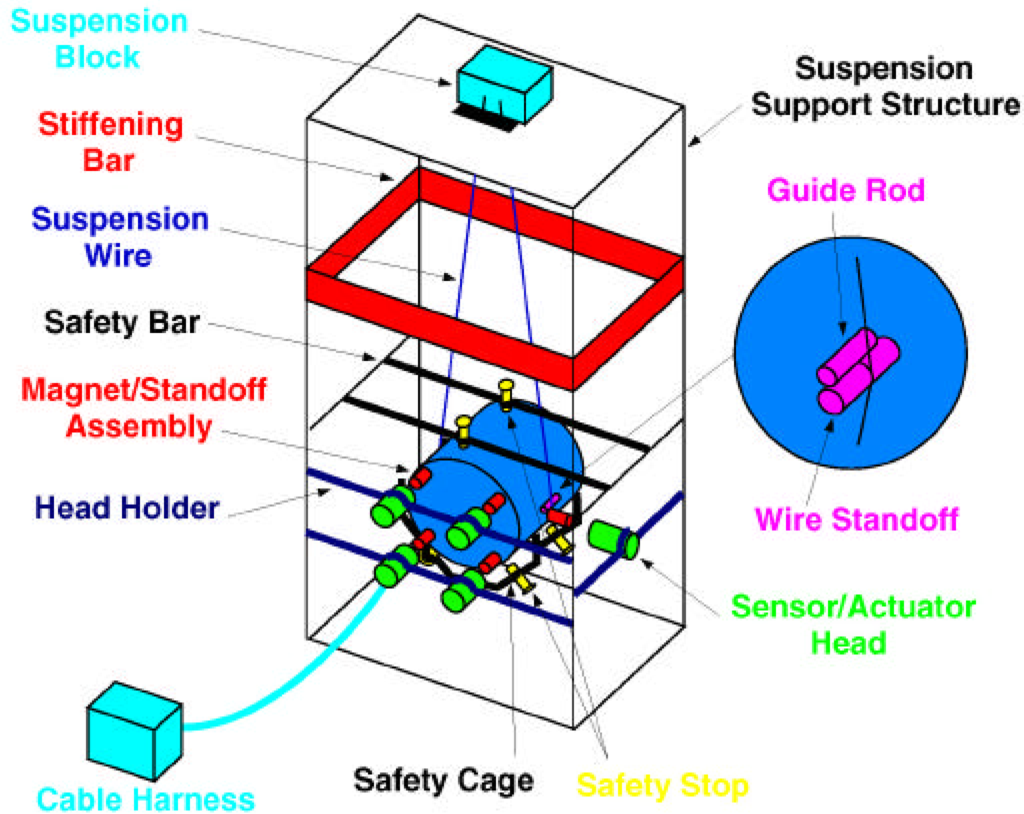
Seismic Isolation

suspension system



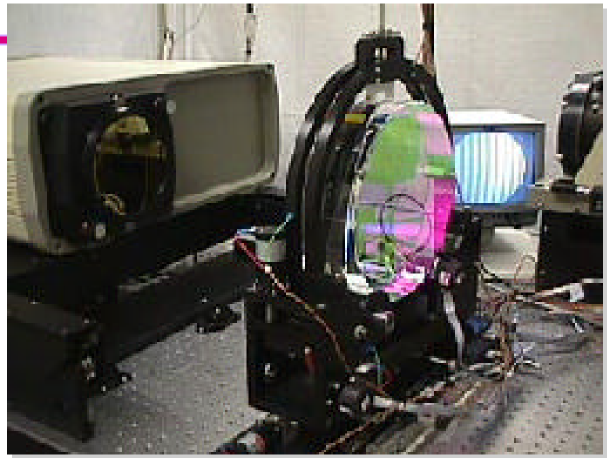
- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

suspension assembly for a core optic

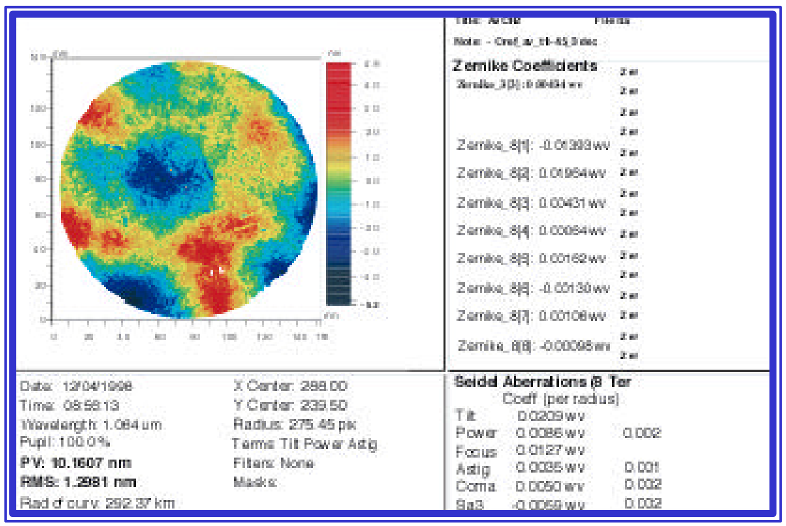


Core Optics

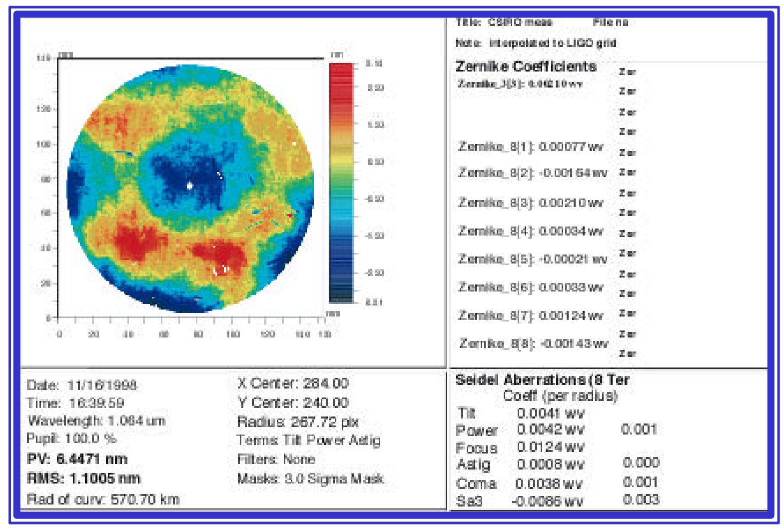
fused silica



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



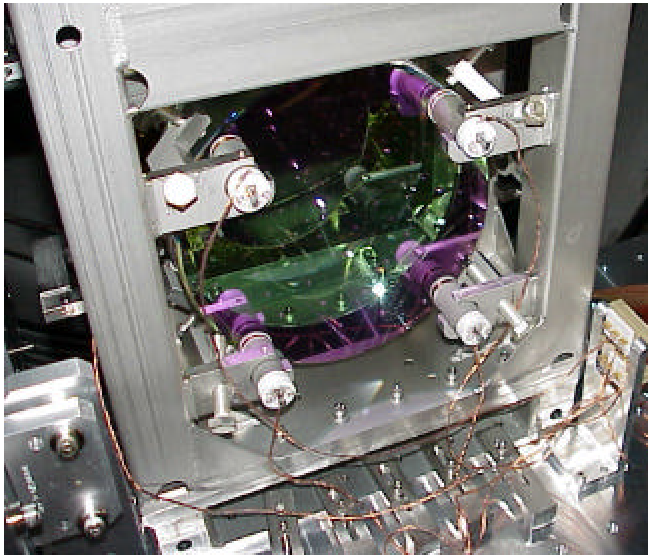
Caltech data

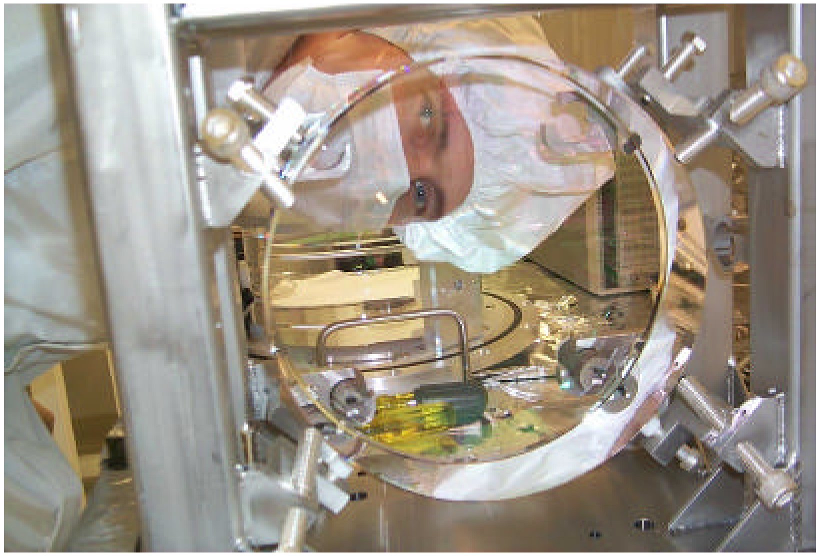


CSIRO data

Core Optics

Suspension

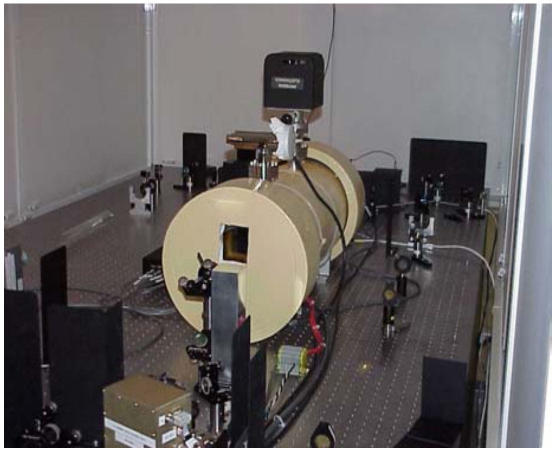


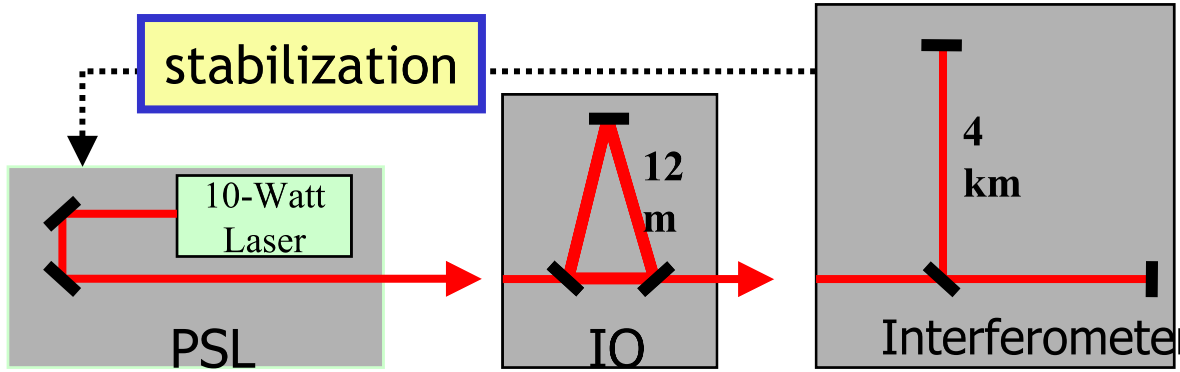


Core Optics

Installation and Alignment

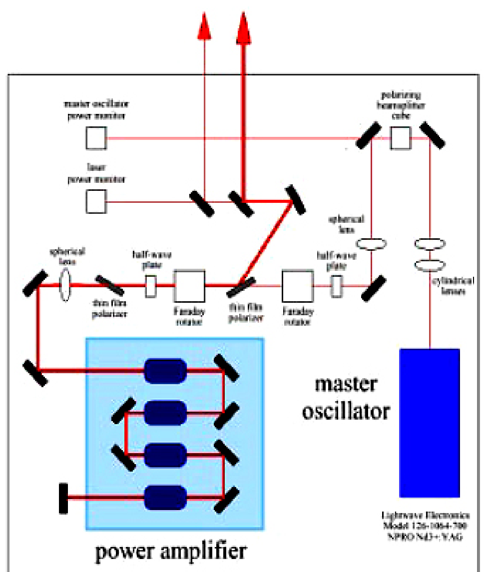
LIGO Prestabilized Laser



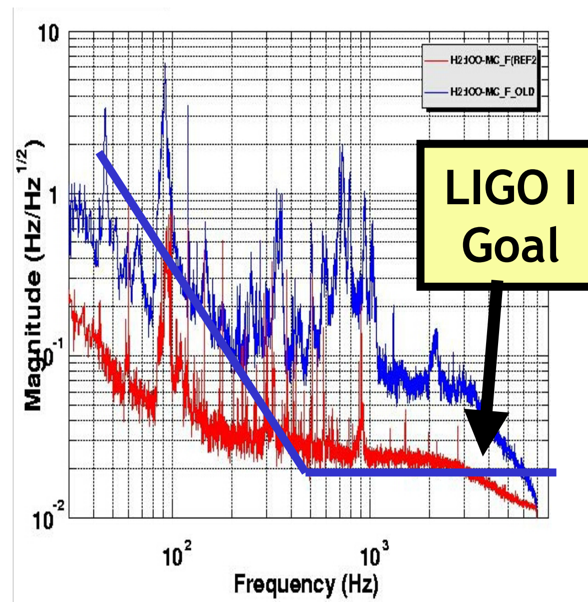


10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/Hz$^{1/2}$ 10^{-7} Hz/Hz$^{1/2}$

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



Lightwave Electronics MOPA

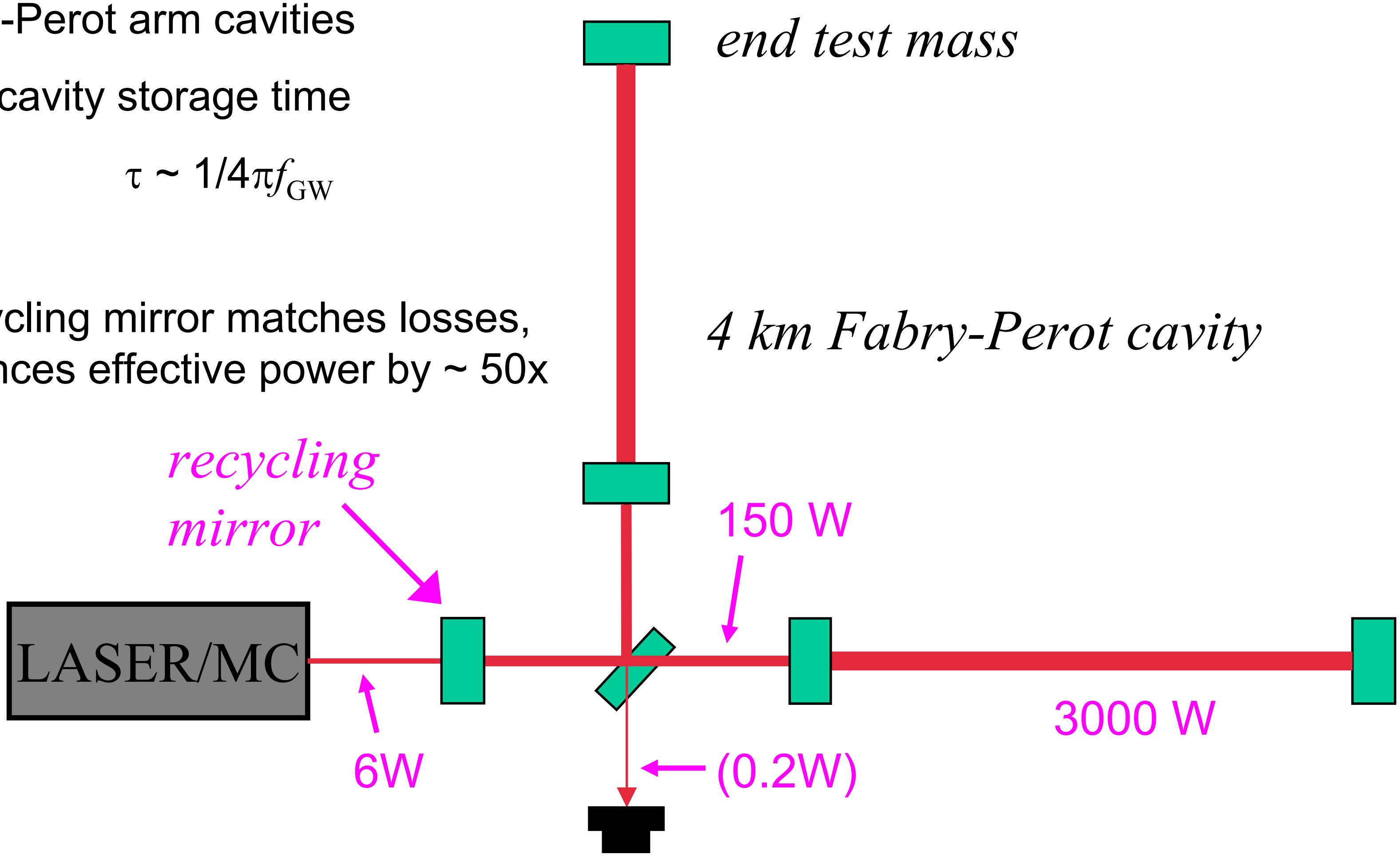


LIGO Interferometer Optical Scheme

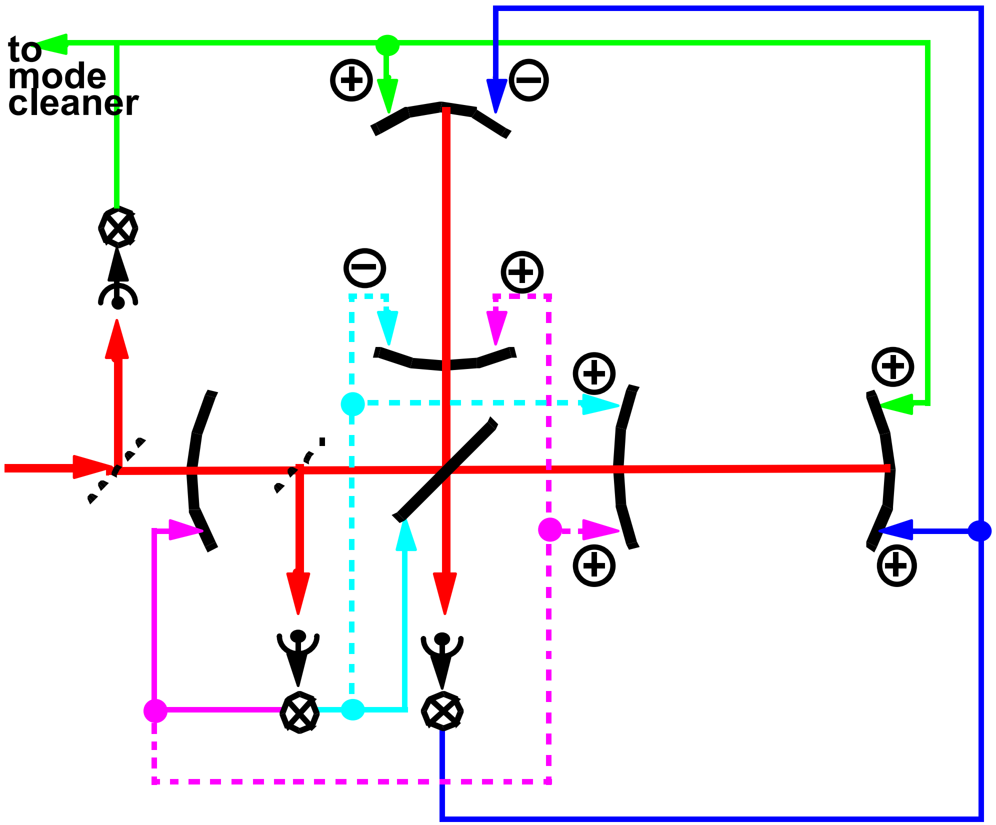
- Michelson interferometer with Fabry-Perot arm cavities
- Arm cavity storage time

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

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

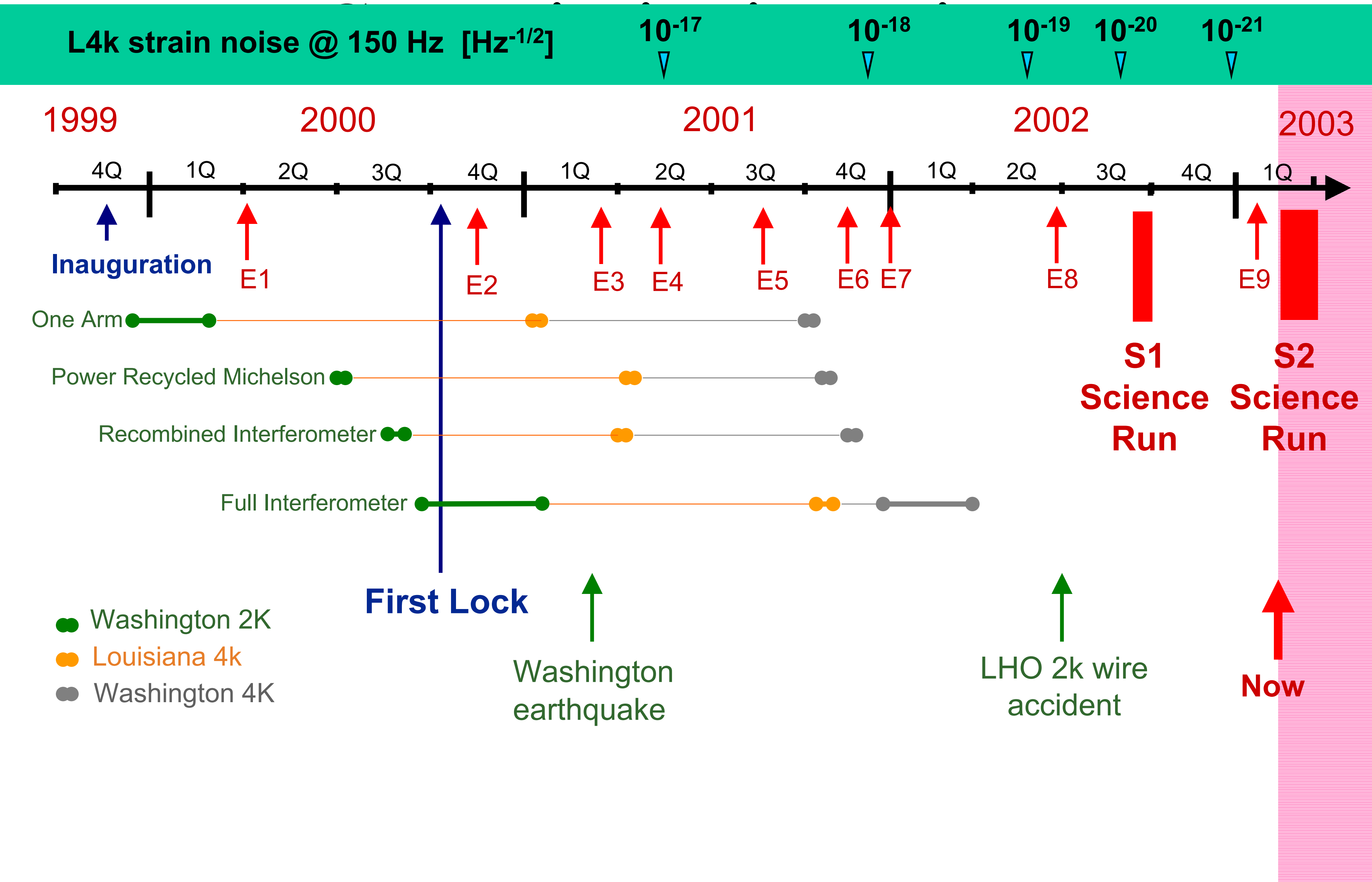


Feedback Control Systems



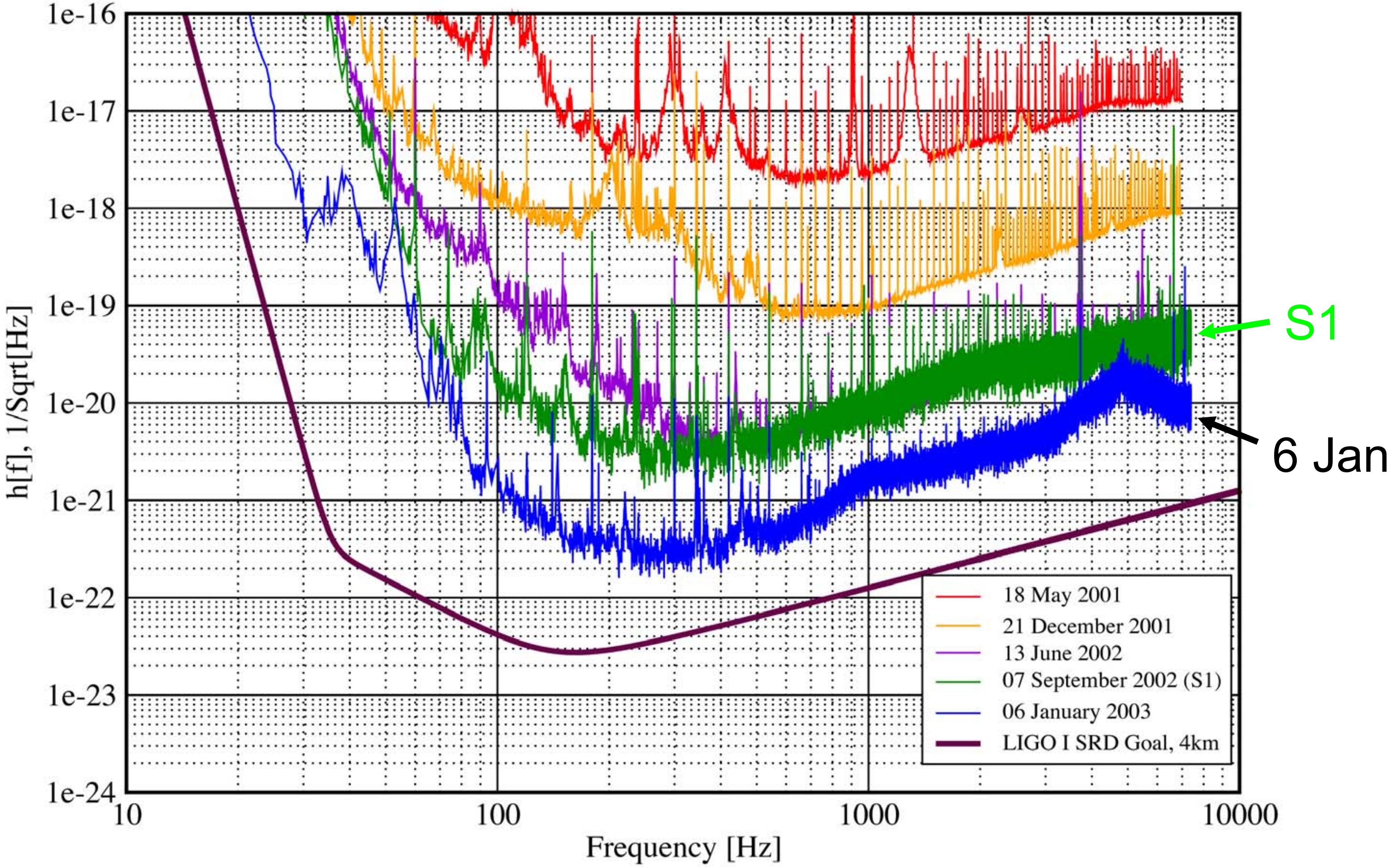
example: cavity length sensing & control topology

- 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 [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
S1 Science Run
S2 Science Run
One Arm
Power Recycled Michelson
Recombined Interferometer
Full Interferometer
First Lock
Washington earthquake
LHO 2k wire accident
Now
Washington 2K
Louisiana 4k
Washington 4K

Strain Sensitivity for the LLO 4km Interferometer

31 January 2003 LIGO-G030014-00-E



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

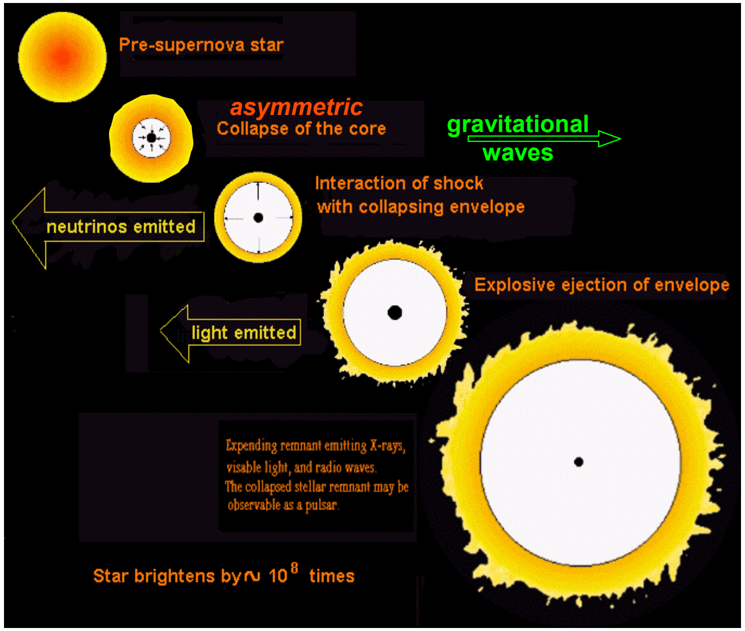
Burst Group membership

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

LIGO Gravitational wave burst searches

Burst Working Group

- Target: gravitational wave bursts of transient nature
  - **No waveform model**
  - Bound on *rate vs. strength*
- Methods used to look for events:
  1. *"TFCLUSTERS":* adaptively identifies clusters of excess power in time-frequency space
  2. *"SLOPE":* identifies rapid increases in amplitude of a filtered time series
- Determine detection efficiency via simulation
- *Require coincidence between 3 interferometers*



SN Rate
1/50 yr - Milky Way
3/yr - out to Virgo cluster

Upper Bound $\propto$ N / (ε(h) T)

- N: number observed events
- ε(h): detection efficiency for amplitude h
- T: observation time -- *livetime*
- Proportionality constant depends on confidence level (CL) ~ 1 for 90%

Data processing flow

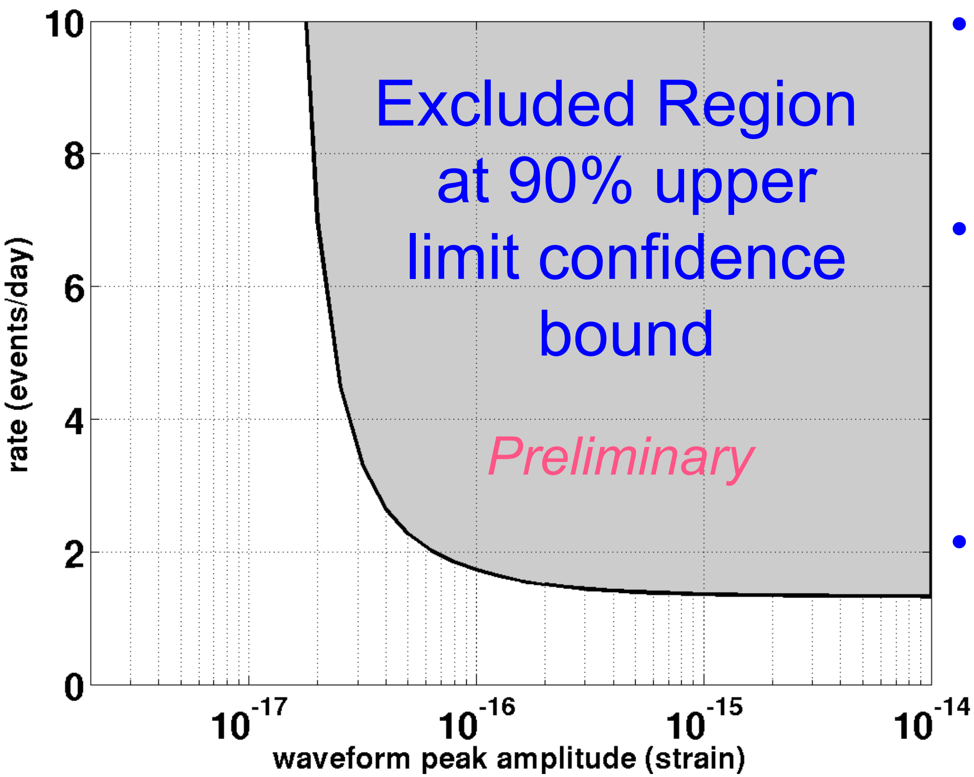
Burst Working Group

- Prototypical for other event-based searches -

1. Event Trigger -> candidate gravitational wave event
2. Diagnostic Triggers -> indicator of instrumental or environmental artifacts
3. Interferometer Trigger-> Event Triggers *not vetoed* by Diagnostic Triggers
   - Vetoes eliminate particularly noisy data
4. Coincident Events: Require "simultaneous" events in all interferometers
   - Time window: require same time for event within experimental bounds
     - Greater of light travel time between detectors (+/- 10 ms) or filter time resolution
   - Frequency window: require same characteristic frequency from filter output
     - For TFCLUSTERS filter

Burst Searches -- Preliminary Results

Burst Working Group



Work in progress:

- Correlations with gamma ray bursts
- Observed Type II SNe

- *Able to exclude gravitational wave bursts* of peak strength *h* above rate *r*
- Burst model --
  - » 1 ms width Gaussian pulse
  - » Linear polarization with random orientation
  - » Arriving from random directions
- *Upper limit in <u>strain sensitivity</u> with regard to prior (cryogenic bar) observations:*
  - » *Within 5X of IGEC 2000[1] results*
    - – *ICEG observation time was much longer than S1 - 90 days (triple bars)*
  - » *Within 25X of Astone[2] et al. 2001 sensitivity*

[1]*Int.J.Mod.Phys. D9 (2000) 237*
[2]*Class.Quant.Grav. 19 (2002) 5449*

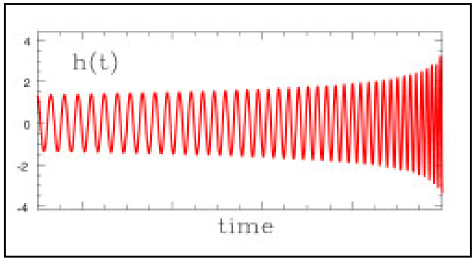
Inspiral Group Membership

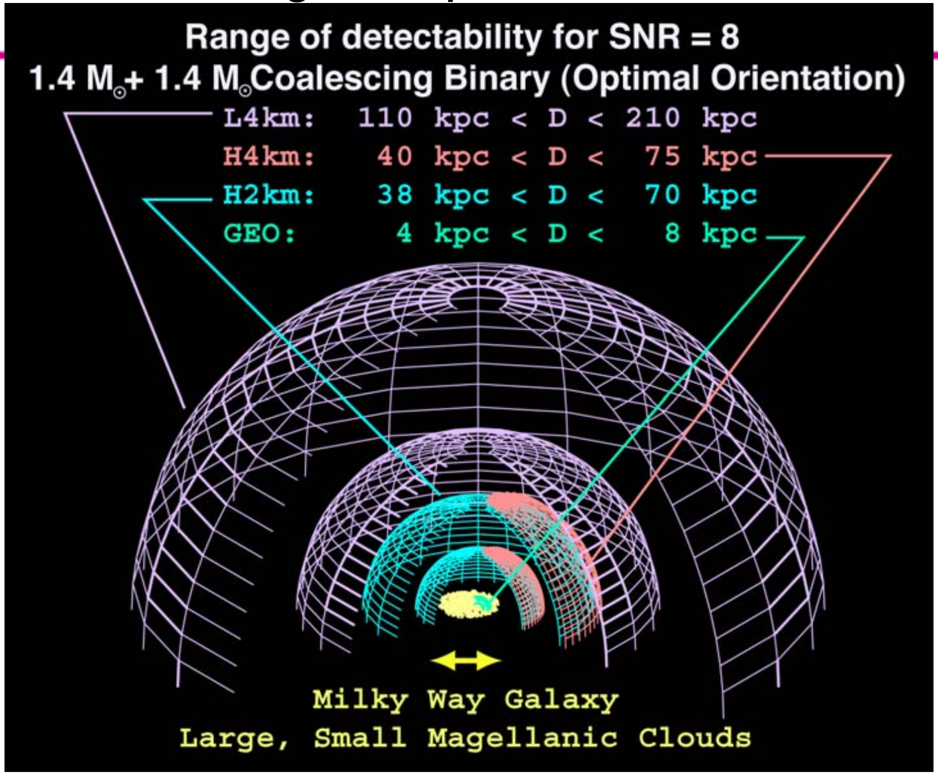
- Bruce Allen, Russ Bainer, Kent Blackburn, Sukant Bose, *Patrick Brady*, Duncan Brown, Jordan Camp, Vijay Chickarmane, Nelsen Christensen, David Churches, Jolien Creighton, Teviet Creighton, S.V. Dhurander, Carl Ebeling, *Gabriela Gonzalez*, Andr M. Gretarsson, Gregg Harry, Vicky Kalogera, Joe Kovalik, 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.

Coalescing Binaries

Inspiral Sources Working Group

- Three targets:
  - » Neutron star binaries (1-3 M_{sun})
  - » Black hole binaries (> 3 M_{sun})
  - » MACHO binaries (0.5-1 M_{sun})
- Search method
  - » template based matched filtering





- Status
  - ✓ Neutron star search complete
  - » MACHO search under way
  - » Black hole search will be done in next science run, S2

- Limit on binary neutron star coalescence rate:
  - » $R_{90\%}$ *(Milky Way) < 2.3 / (0.35 x 295.3 hr) = 170 /yr*
- Use triggers from H 4km and L 4km interferometers: *T = 295.3 hours*
  - » Monte Carlo simulation efficiency: ε *= 35%*
  - » 90% confidence limit = *2.3 / (ε T)*
- *26X lower than best published observational limit -- 40m prototype at Caltech[1]:*
  - » $R_{90\%}$ *(Milky Way) < 4400 /yr*

[1] 1994 data, Allen et al., *Phys.Rev.Lett. 83 (1999) 1498*

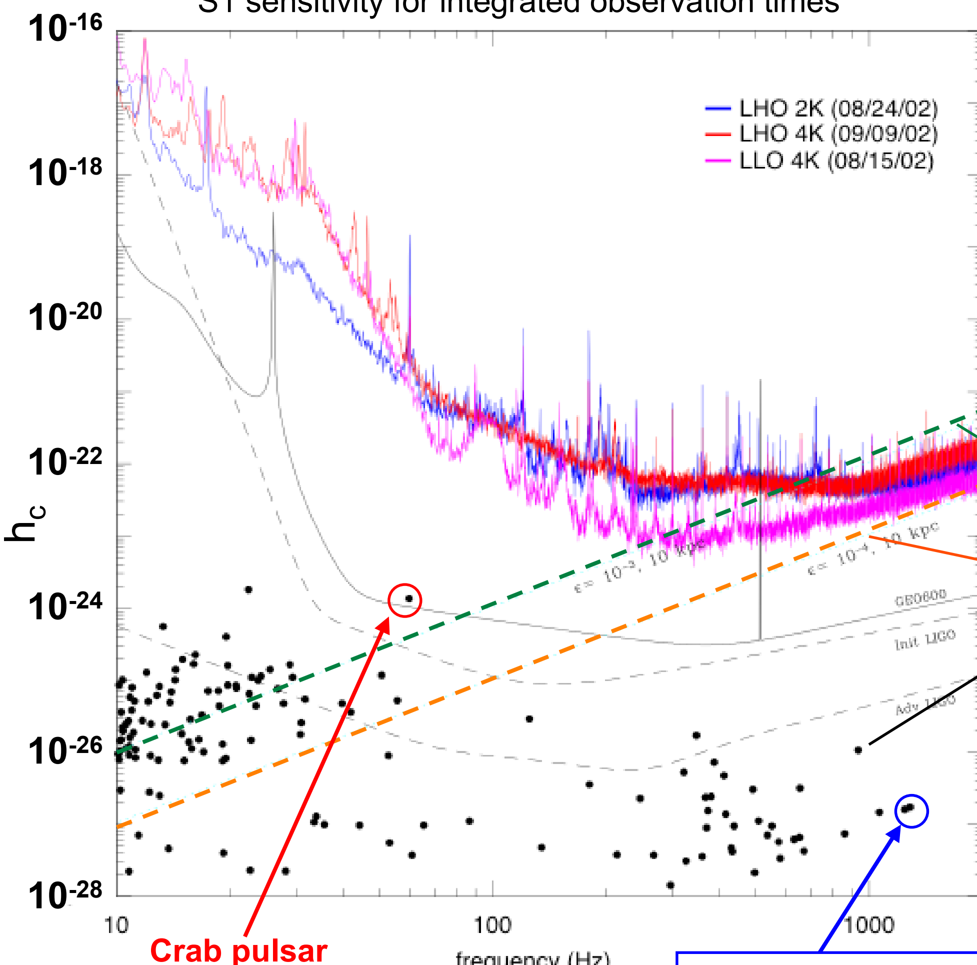
Continuous Waves Searches ULs

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

Establishing limits on gravitational waves radiated by periodic sources

Periodic Sources Working Group



Crab pulsar

PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1051.9 10^{-7} s/s
D = 3.6 kpc

- h_c: Amplitude detectable with 99% confidence during observation time T:

$$h_c = 4.2\,[S_h(f)/T]^{1/2}$$

- *Limit of detectability for rotating NS with prolate ellipticity, $\varepsilon = \delta I/I_{zz}$:*

10^{-3} @ 10 kpc

10^{-4} @ 10 kpc

- *Values of h_c consistent with measured spin-down **known** EM pulsars*
  - *IF spin-down were entirely attributable to GW emissions*
  - *Rigorous astrophysical upper limit from energy conservation arguments*

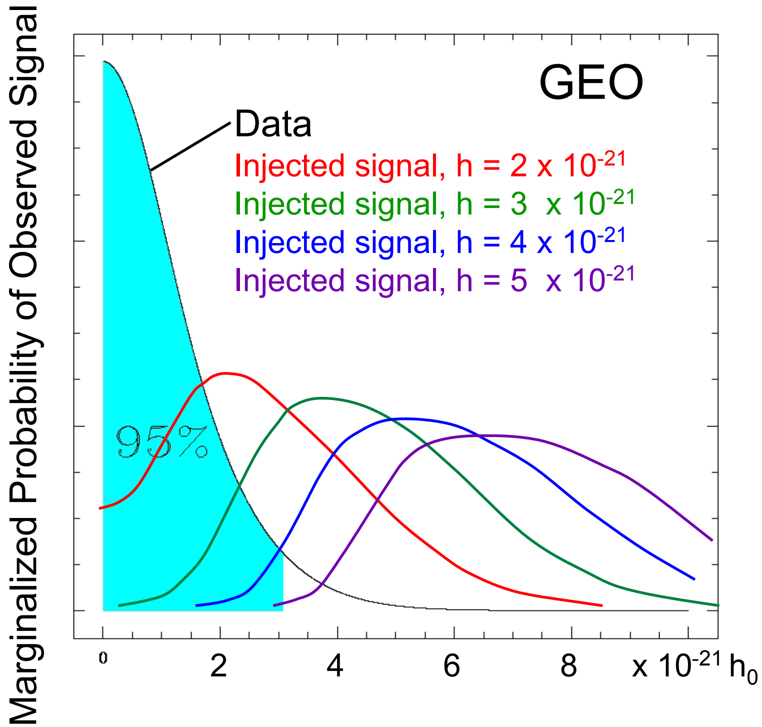
Graphic by R. Dupuis, Glasgow

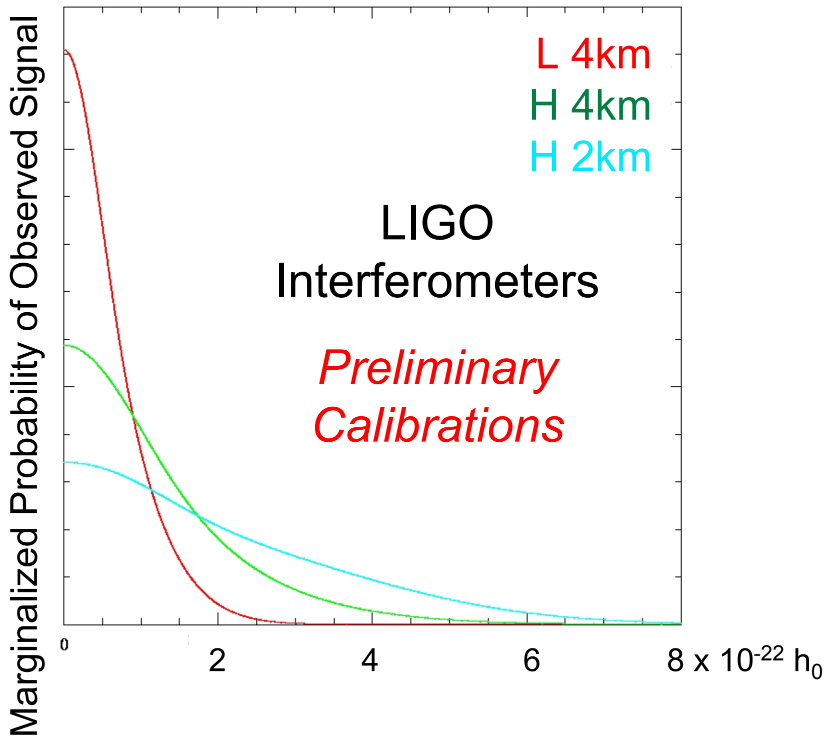
Two complementary analysis approaches

Periodic Sources Working Group

- Time-domain search -- process signal to remove frequency variations due to Earth's motion around Sun
  - Targeted searches
  - Handles missing data
  - Adaptable to complicated phase evolutions.
  - Upper limit interpretation straightforward
    - Compare result to what would be expected from noise without signal
- Frequency domain search -- permits searches over large parameters space when signal characteristics uncertain
  - Standard matched filtering technique
    - Cross-correlation of signal with template, look for correlated power
  - *Analysis still progress*

Preliminary results -- (EM pulsar) PSR J1939
Periodic Sources Working Group





- No evidence of signal from PSR J1939 at f = 1283.86 Hz
- 95% of the probability lies below:
  - GEO: $h_{max} < 3 \times 10^{-21}$
  - H 2km: $h_{max} < 5 \times 10^{-22}$
  - H 4km: $h_{max} < 3 \times 10^{-22}$
  - ***L 4km:*** $\boldsymbol{h_{max} < 2 \times 10^{-22}}$ ***(*** $\boldsymbol{\varepsilon < 7 \times 10^{-5}}$ ***@ 3.6 kpc)***

Stochastic UL Group: Prospects for S1

LSC Stochastic Sources Upper Limit Group

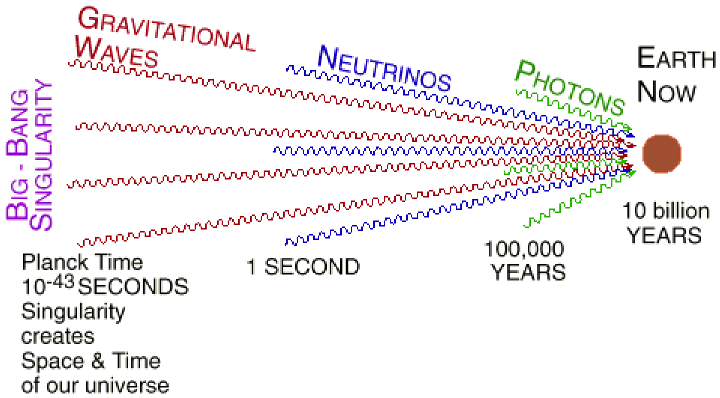
LIGO-G020411-00-Z

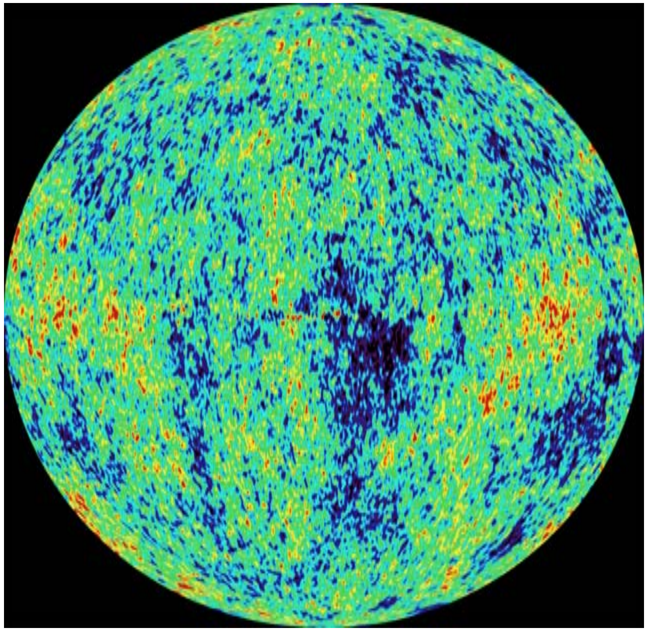
September 20, 2002

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

Stochastic Background Sources

Stochastic Background Sources Working Group





Analog from cosmic microwave background -- WMAP 2003

Stochastic Gravitational Wave Background

- Detect by
  - » cross-correlating interferometer outputs
    - »H 4km + L 4km
    - »H 2km + H 4km
  - » Good sensitivity requires:
  - » (GW wavelength) <u>></u> **2X** (detector baseline)
    - »f <u><</u> 40 Hz for L-H pair
- Initial LIGO sensitivity:
  - » $\Omega < 10^{-5}$
- Advanced LIGO sensitivity:
  - » **$\Omega < 5\times10^{-9}$**

$$\int_0^\infty d(\ln f)\ \Omega_{GW}(f) = \frac{\rho_{GW}}{\rho_{critical}}$$

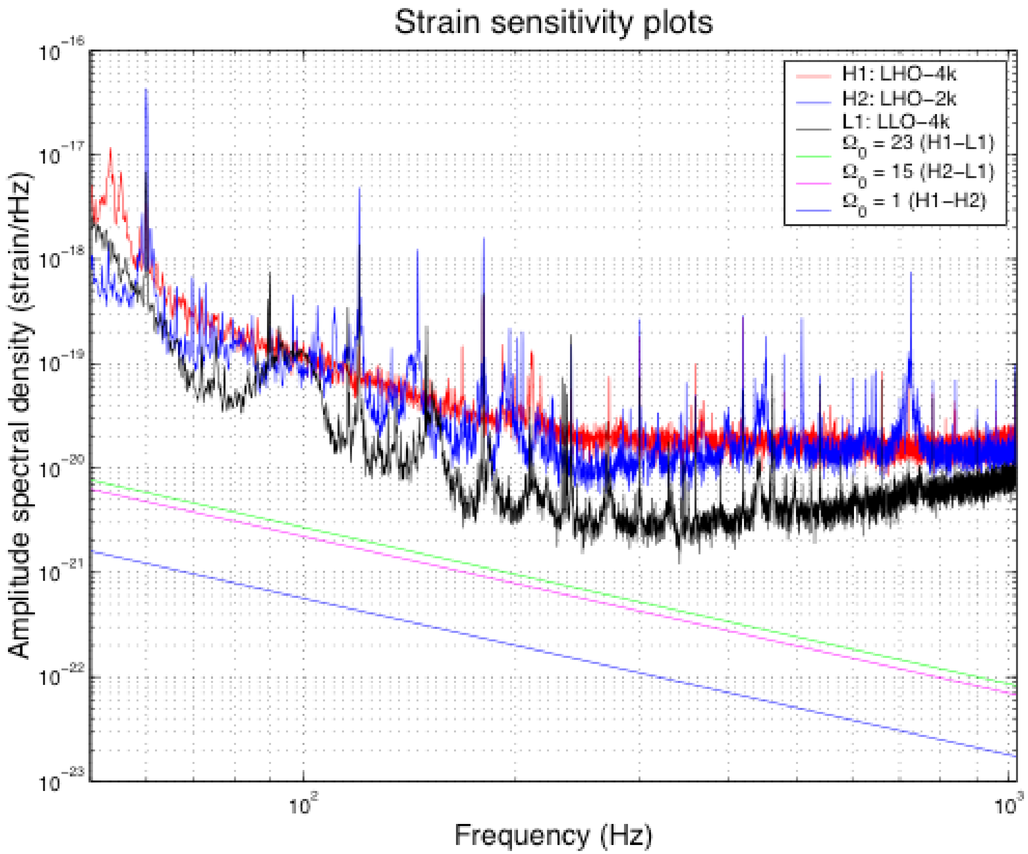
The integral of $[1/f \cdot \Omega_{GW}(f)]$ over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

Stochastic Gravitational Wave Background

Stochastic Background Sources Working Group

- Current best upper limits:
  - » Inferred: From Big Bang nucleosynthesis: (Kolb et al., 1990) $\int \Omega_{GW}(f)\ d\ln f < 1\times 10^{-5}$
  - » *Measured:* Garching-Glasgow interferometers (Compton et al. 1994): $\Omega_{GW}(f) < 3\times 10^{5}$
  - » *Measured*: EXPLORER-NAUTILUS (cryogenic bars -- Astone et al., 1999) $\Omega_{GW}(907Hz) < 60$

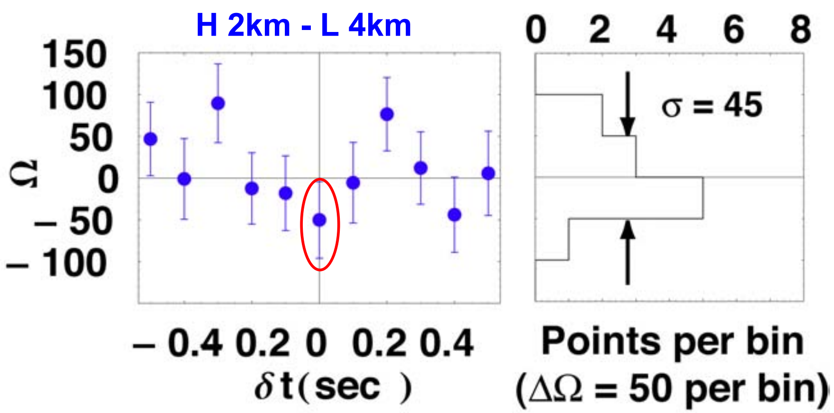
Cross-correlation technique enables one to “dig” signal below individual interferometer noise floors

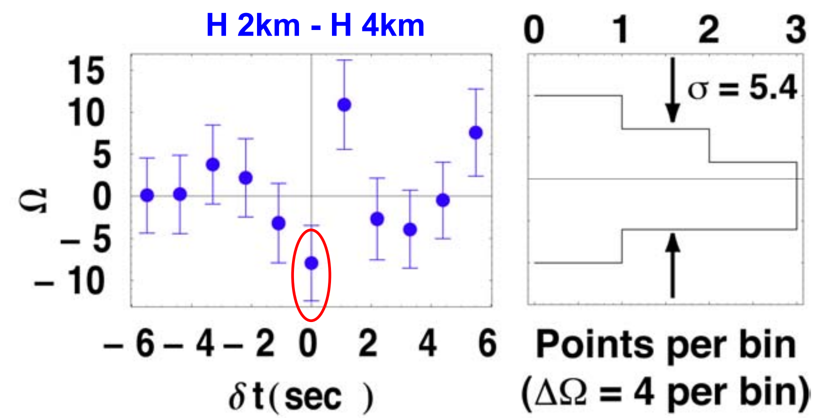


Stochastic Gravitational Wave Background

Stochastic Background Sources Working Group

- Preliminary results from 7.5 hr of data -



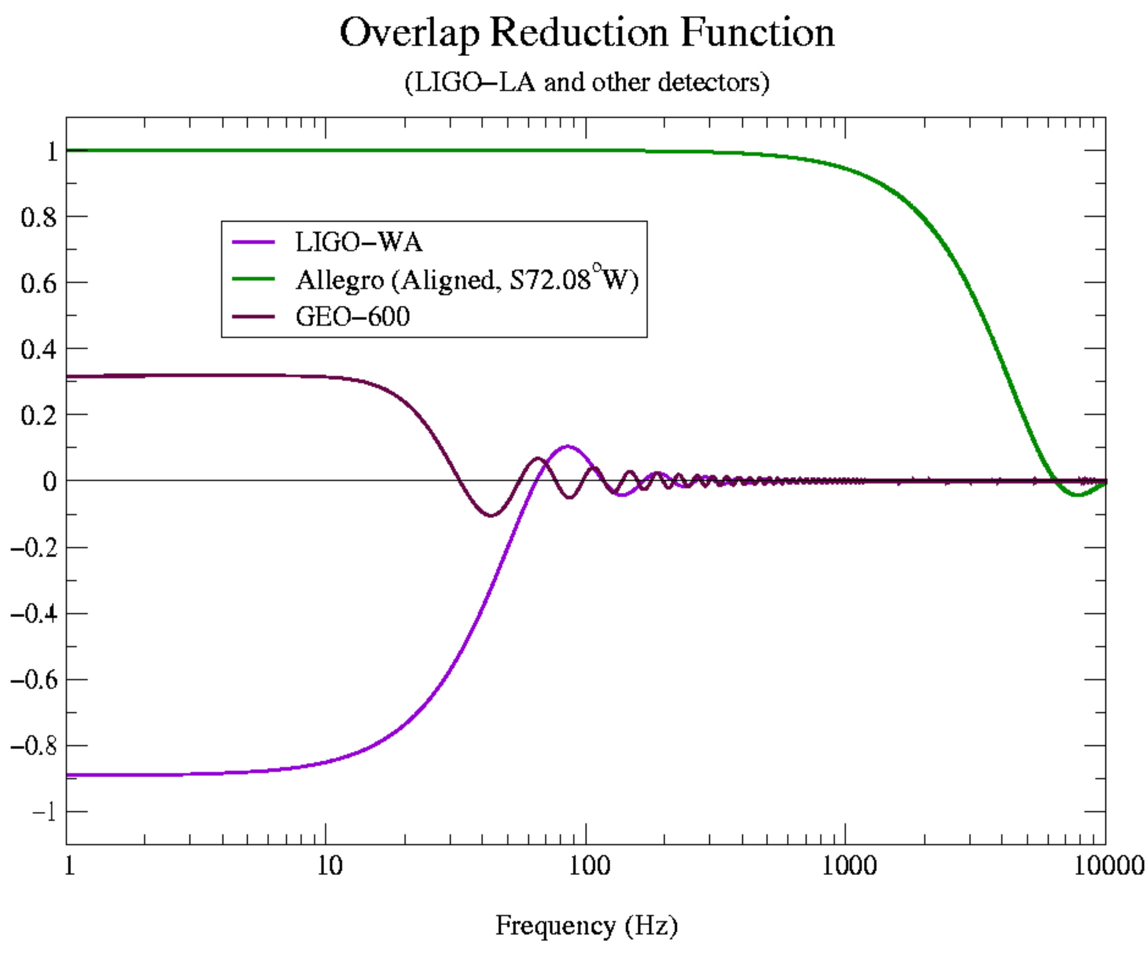


- Introduce non-astrophysical time lags (>20ms) to determine backgrounds *(off-source)*
  - *δt = 0 sec (on-source)* measurements consistent with *off-source* backgrounds
- Extrapolated S1 H 2km - H 4km result covers **240 Hz bandwidth, is ~10X better** than best published result for *direct measurement* of Ω_{GW} (Astone et al., 1999, cryogenic bar, 907 Hz).
- Ultimate sensitivity for LIGO I: ~ 1 x 10^{-5} for T_{obs} = 4 months

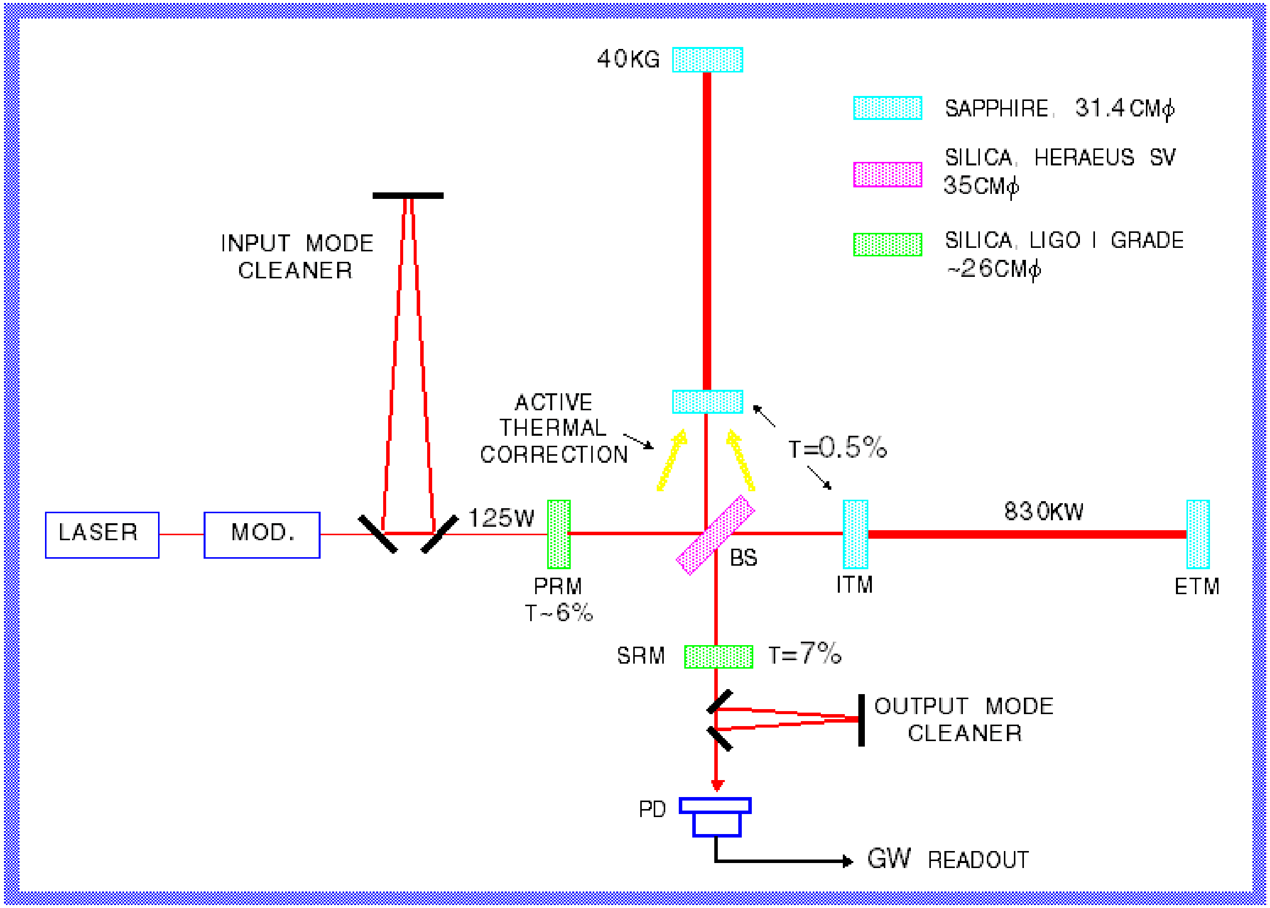
Interferometer Pair	Measurement Bandwidth	**Extrapolated Upper Limit for S1 (by scaling 7.5 hrs to 150 or 100 hrs)**	**T_{obs}**
H 2km - H 4km	40 Hz < f < 300 Hz	**Ω_{GW} < 5 (90% C.L.)**	**150 hr**
H 4km - L 4km	40 Hz < f < 314 Hz	**Ω_{GW} < 70 (90% C.L.)**	**100 hr**
H 2km - L 4km	40 Hz < f < 314 Hz	**Ω_{GW} < 50 (90% C.L.)**	**100 hr**

Overlap reduction function

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



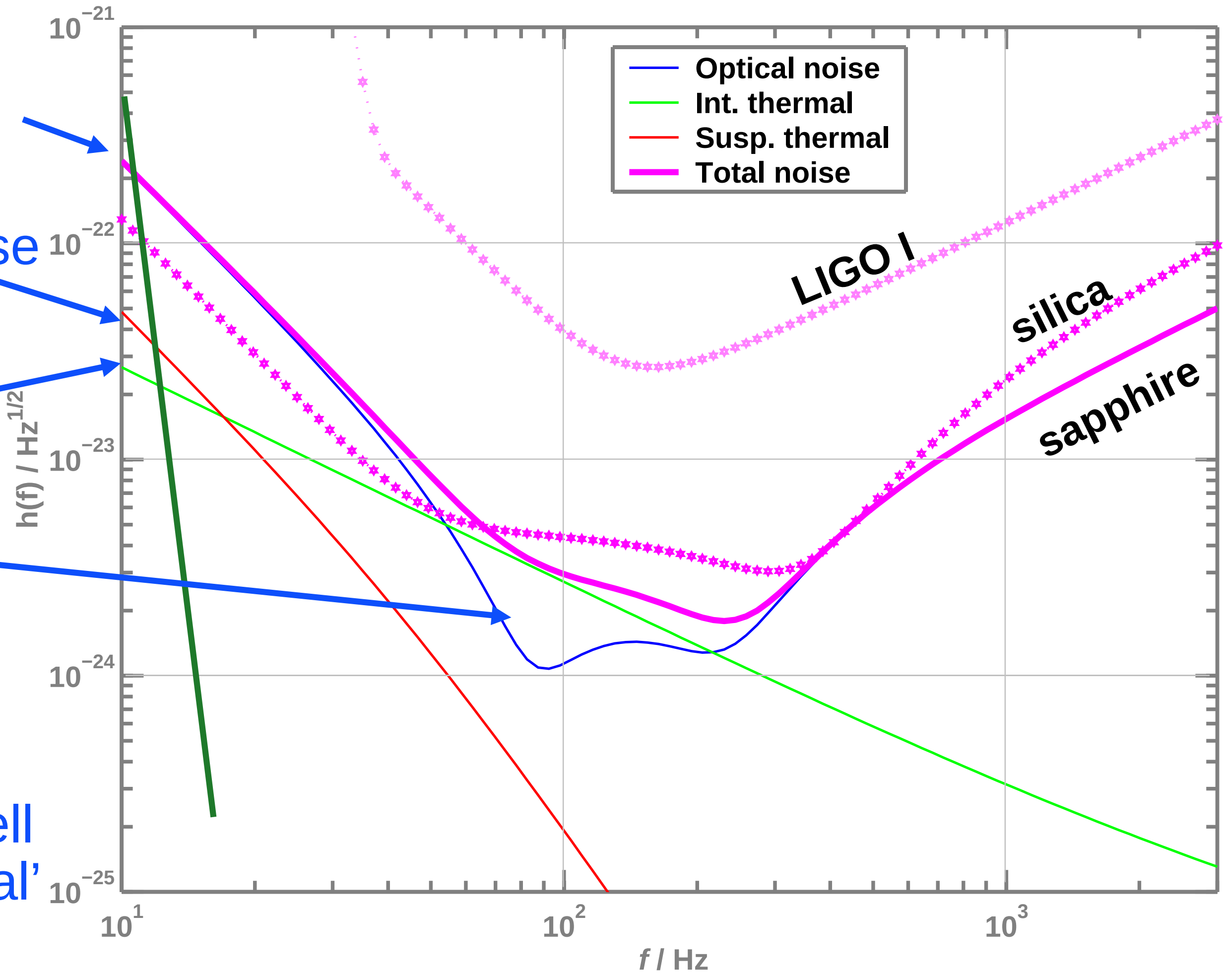
Advanced Interferometer Concept



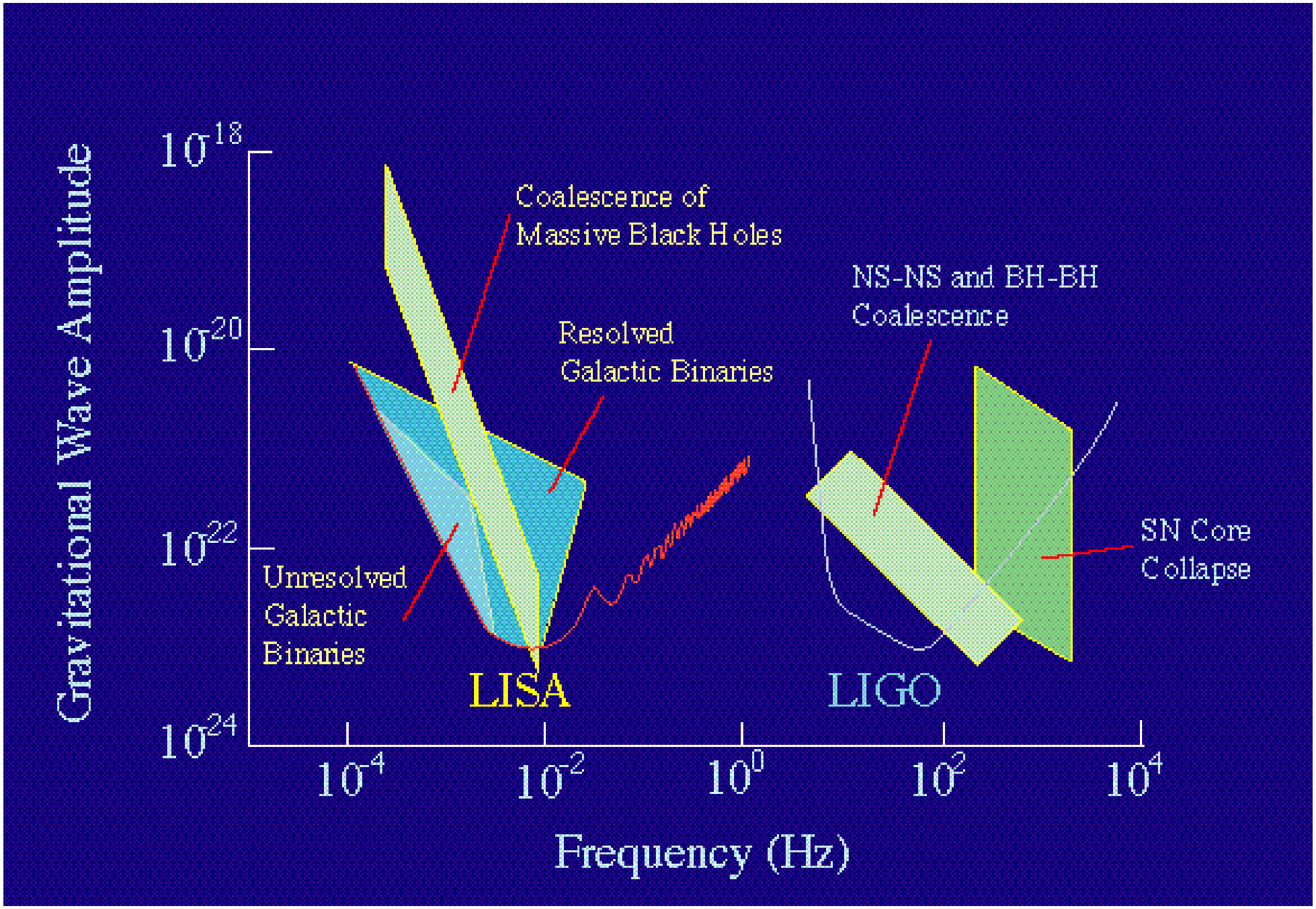
- » Signal recycling
- » 180-watt laser
- » 40 kg Sapphire test masses
- » Larger beam size
- » Quadruple suspensions
- » Active seismic isolation
- » Active thermal correction
- » Output mode cleaner

Projected Performance

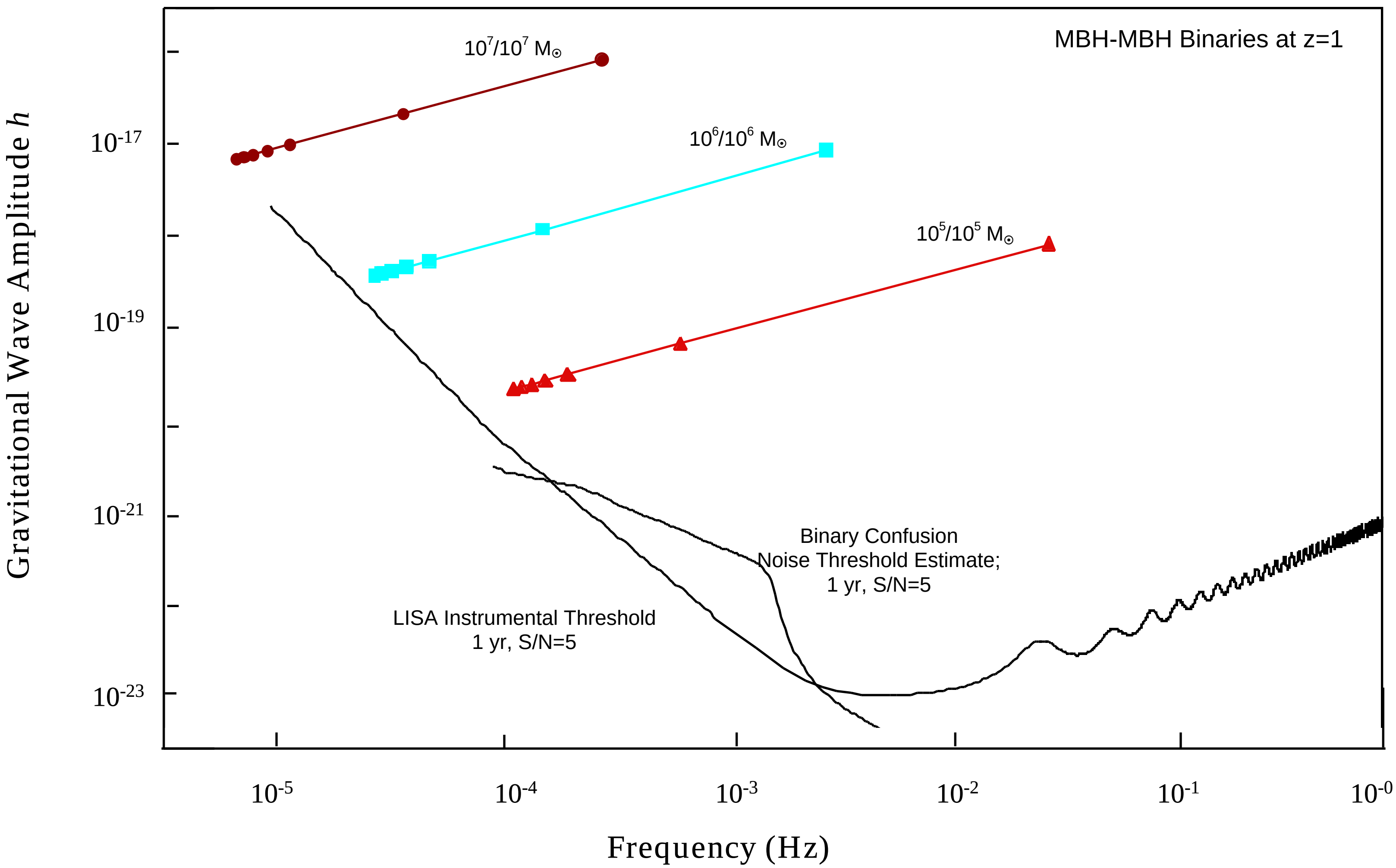
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises



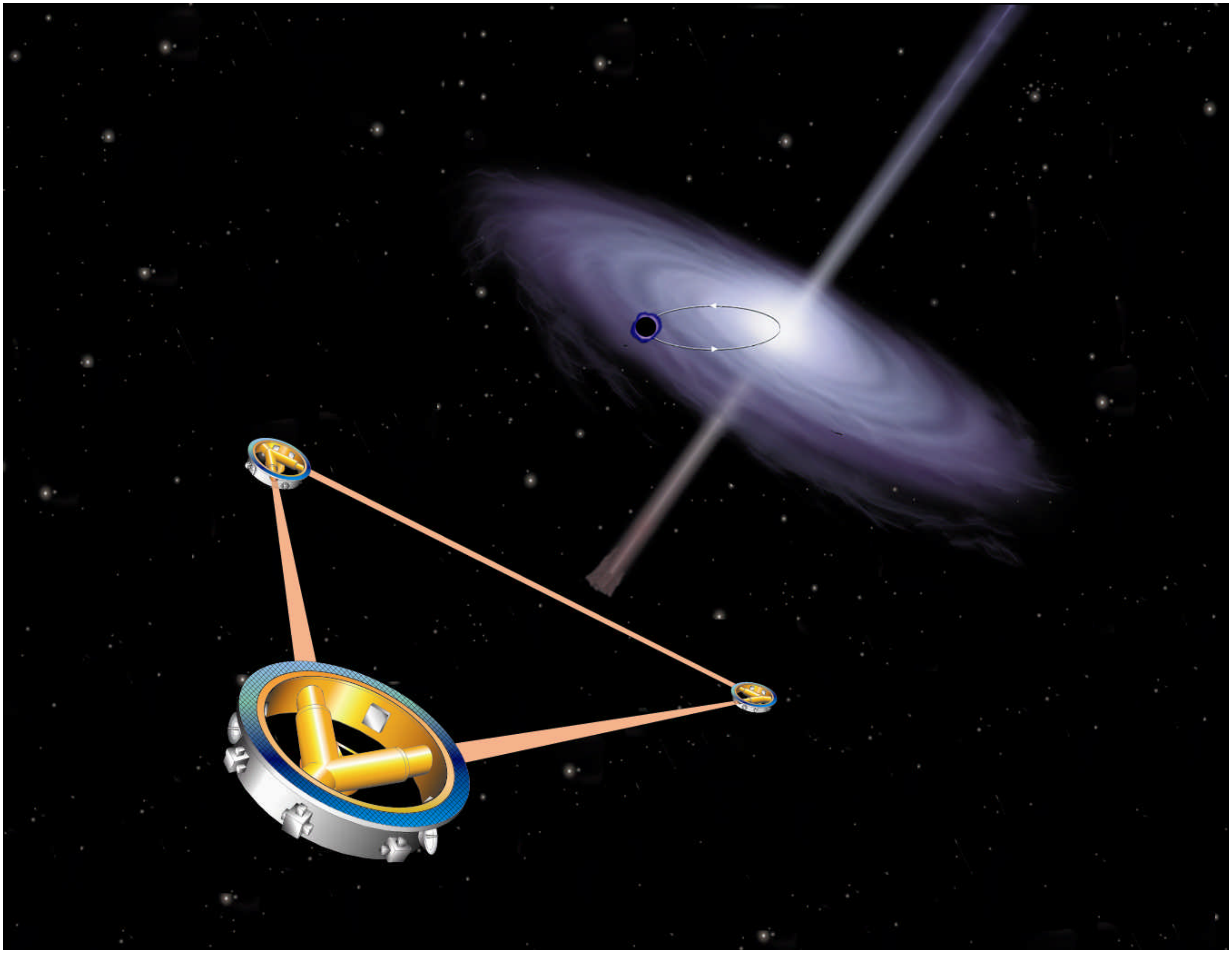
The Gravitational-Wave Spectrum



Massive Black Holes in Merging Galaxies



Mission Concept



Optical System