LIGO:how it works and what it hopes to find

Rainer Weiss
MIT
on behalf of the LIGO Scientific Collaboration

May 24, 2004
Goddard Space Flight Center

LIGO Scientific Collaboration Member Institutions

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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
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697

SITZUNGSBERICHTE 1916.

XXXIII.

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN.

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

$$\gamma'_{\mu\nu} = \alpha_{\mu\nu} f(x_1 + i x_4) = \alpha_{\mu\nu} f(x - t). \qquad (15)$$

Dabei sind die $\alpha_{\mu\nu}$ Konstante; f ist eine Funktion des Arguments $x - t$. Ist der betrachtete Raum frei von Materie, d. h. verschwinden die $T_{\mu\nu}$, so sind die Gleichungen (6) durch diesen Ansatz erfüllt. Die Gleichungen (4) liefern zwischen den $\alpha_{\mu\nu}$ die Beziehungen

$$\left.\begin{aligned} \alpha_{11} + i\alpha_{14} &= 0 \\ \alpha_{12} + i\alpha_{24} &= 0 \\ \alpha_{13} + i\alpha_{34} &= 0 \\ \alpha_{14} + i\alpha_{44} &= 0 \end{aligned}\right\}. \qquad (16)$$

Von den 10 Konstanten $\alpha_{\mu\nu}$ sind daher nur 6 frei wählbar. Wir können die allgemeinste Welle der betrachteten Art daher aus Wellen von folgenden 6 Typen superponieren

$$\left.\begin{aligned} &\text{a)} \begin{cases} \alpha_{11} + i\alpha_{14} = 0 \\ \alpha_{14} + i\alpha_{44} = 0 \end{cases} \quad \text{b)}\ \alpha_{12} + i\alpha_{24} = 0 \quad \text{d)}\ \alpha_{22} \neq 0 \\ &\qquad\qquad\qquad\qquad\quad\ \text{c)}\ \alpha_{13} + i\alpha_{34} = 0 \quad \text{e)}\ \alpha_{23} \neq 0 \\ &\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad\ \text{f)}\ \alpha_{33} \neq 0 \end{aligned}\right\}. \qquad (17)$$

$$\text{d)}\quad \frac{1}{i} t_{22} = \frac{f'^2}{4\varkappa} \alpha_{22}^2 = \frac{1}{4\varkappa} \left(\frac{\partial \gamma'_{22}}{\partial t}\right)^2$$

$$\text{e)}\quad \frac{1}{i} t_{23} = \frac{f'^2}{4\varkappa} \alpha_{23}^2 = \frac{1}{4\varkappa} \left(\frac{\partial \gamma'_{23}}{\partial t}\right)^2$$

$$\text{f)}\quad \frac{1}{i} t_{33} = \frac{f'^2}{4\varkappa} \alpha_{33}^2 = \frac{1}{4\varkappa} \left(\frac{\partial \gamma'_{33}}{\partial t}\right)^2$$

Es ergibt sich also, daß nur die Wellen des letzten Typs Energie transportieren, und zwar ist der Energietransport einer beliebigen ebenen Welle gegeben durch

$$\mathfrak{I}_x = \frac{1}{i} t_{41} = \frac{1}{4\varkappa} \left[\left(\frac{\partial \gamma'_{22}}{\partial t}\right)^2 + 2\left(\frac{\partial \gamma'_{23}}{\partial t}\right)^2 + \left(\frac{\partial \gamma'_{33}}{\partial t}\right)^2\right]. \qquad (18)$$

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

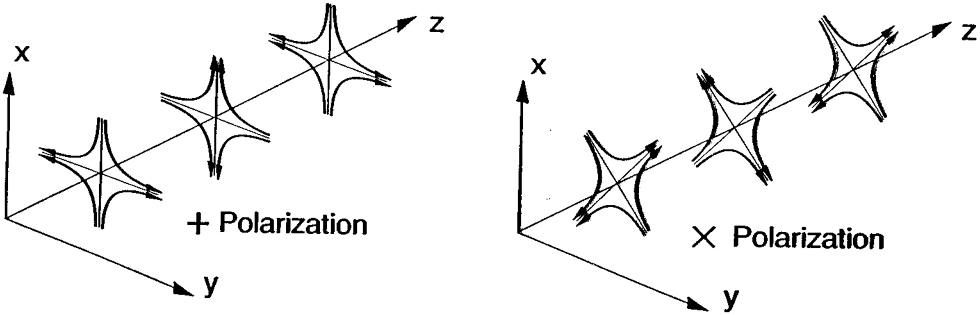
$$h_{ij} \;=\; \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \qquad \text{all } h_{ij} \ll 1$$

Plane Wave

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

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

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


x
z
y
+ Polarization
x
z
y
× Polarization

Die in (23), (23a) und (23b) auftretenden Integrale, welche nichts anderes sind als zeitlich variable Trägheitsmomente, nennen wir im folgenden zur Abkürzung J_{22}, J_{33}, J_{23}. Dann ergibt sich für die Intensität $\mathfrak{f}_x$ der Energiestrahlung aus (18)

$$\mathfrak{f}_x = \frac{\varkappa}{64\pi^2 R^2}\left[\left(\frac{\partial^3 J_{22}}{\partial t^3}\right)^2 + 2\left(\frac{\partial^3 J_{23}}{\partial t^3}\right)^2 + \left(\frac{\partial^3 J_{33}}{\partial t^3}\right)^2\right]. \qquad (20)$$

SPHERICALLY SYMMETRIC MOTION RADIATES GRAVITATIONAL WAVES

1918 VI. VII. VIII

SITZUNGSBERICHTE

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN

BERLIN 1918

VERLAG DER KÖNIGLICHEN AKADEMIE DER WISSENSCHAFTEN

IN KOMMISSION BEI GEORG REIMER

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

Sind die Bedingungen (15) erfüllt, so stellt (14) eine mögliche Gravitationswelle dar. Um deren physikalische Natur genauer zu durchschauen, berechnen wir deren Dichte des Energiestromes $\frac{t_{41}}{i}$. Durch Einsetzen der in (15) gegebenen $\gamma'_{\mu\nu}$ in Gleichung (9) erhält man

$$\frac{t_{41}}{i} = \frac{1}{4\varkappa} f'^2 \left[\left(\frac{\alpha_{22} - \alpha_{33}}{2} \right)^2 + \alpha_{23}^2 \right]. \tag{16}$$

$$\mathfrak{J}_{\mu\nu} = \int x_\mu x_\nu \rho \, dV_0 \tag{23}$$

gesetzt; $\mathfrak{J}_{\mu\nu}$ sind die Komponenten des (zeitlich variabeln) Trägheitsmomentes des materiellen Systems.

Auf analogem Wege erhält man

$$\int (T_{22} - T_{33}) \, dV_0 = \frac{1}{2} (\ddot{\mathfrak{J}}_{22} - \ddot{\mathfrak{J}}_{33}) . \tag{24}$$

Aus (7a) ergibt sich auf Grund von (22) und (24)

$$\gamma'_{23} = - \frac{\varkappa}{4 \pi R} \ddot{\mathfrak{J}}_{23} . \tag{25}$$

$$\frac{\gamma'_{22} - \gamma'_{33}}{2} = - \frac{\varkappa}{4 \pi R} \left(\frac{\ddot{\mathfrak{J}}_{22} - \ddot{\mathfrak{J}}_{33}}{2} \right) . \tag{26}$$

Die $\mathfrak{J}_{\mu\nu}$ sind nach (7a), (22), (24) für die Zeit $t - R$ zu nehmen, also Funktionen von $t - R$, oder bei großem R in der Nähe der x-Achse auch Funktionen von $t - x$. (25), (26) stellen also Gravitationswellen dar, deren Energiefluß längs der x-Achse gemäß (16) die Dichte

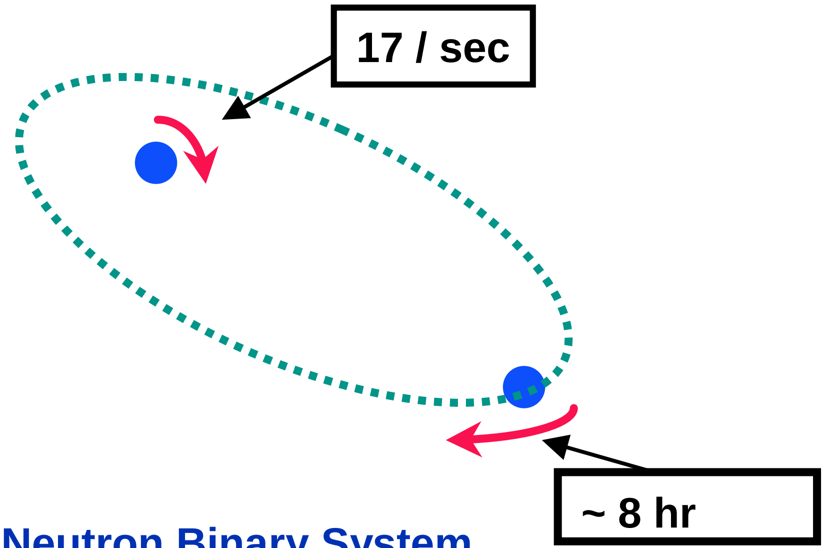
$$\frac{t_{41}}{i} = \frac{\varkappa}{64 \pi^2 R^2} \left[\left(\frac{\dddot{\mathfrak{J}}_{22} - \dddot{\mathfrak{J}}_{33}}{2} \right)^2 + \dddot{\mathfrak{J}}_{23}^{\,2} \right] \tag{27}$$

besitzt.

THE QUADRUPOLE FORMULA A FACTOR OF 2 TOO SMALL

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



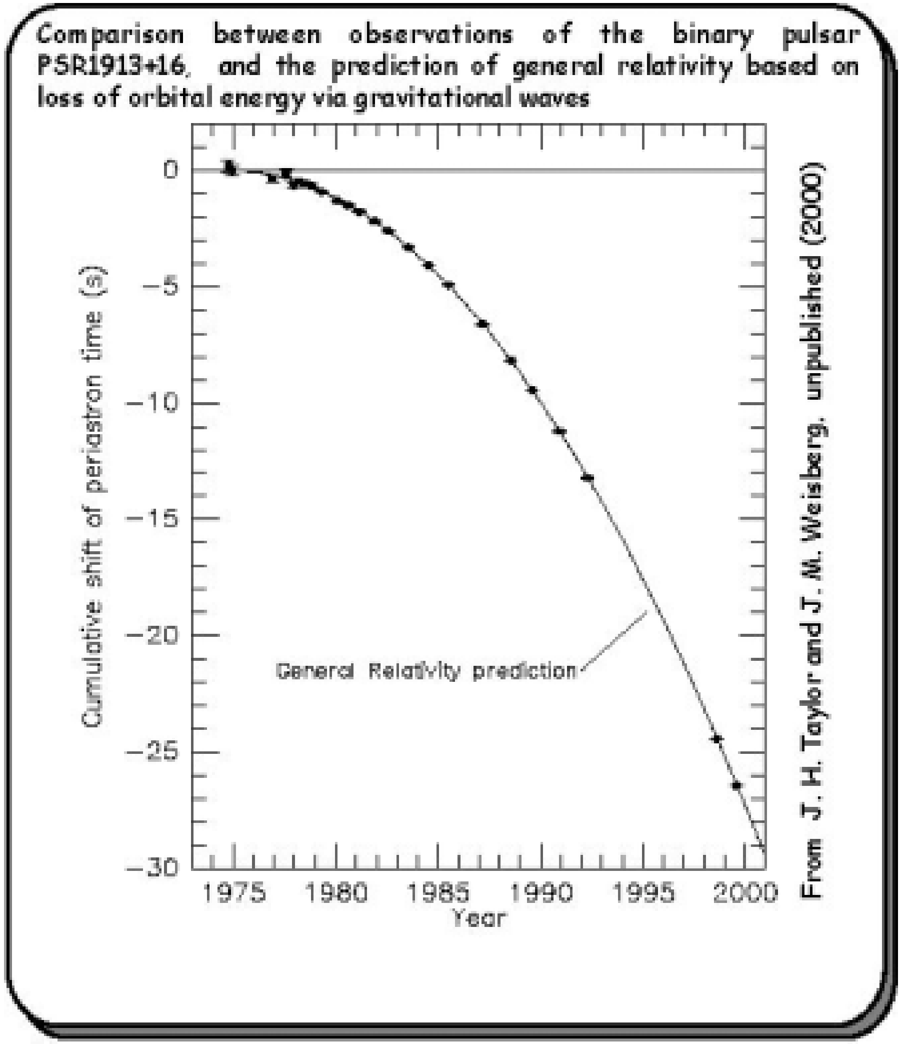
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves



Direct detection of gravitational waves from astrophysical sources

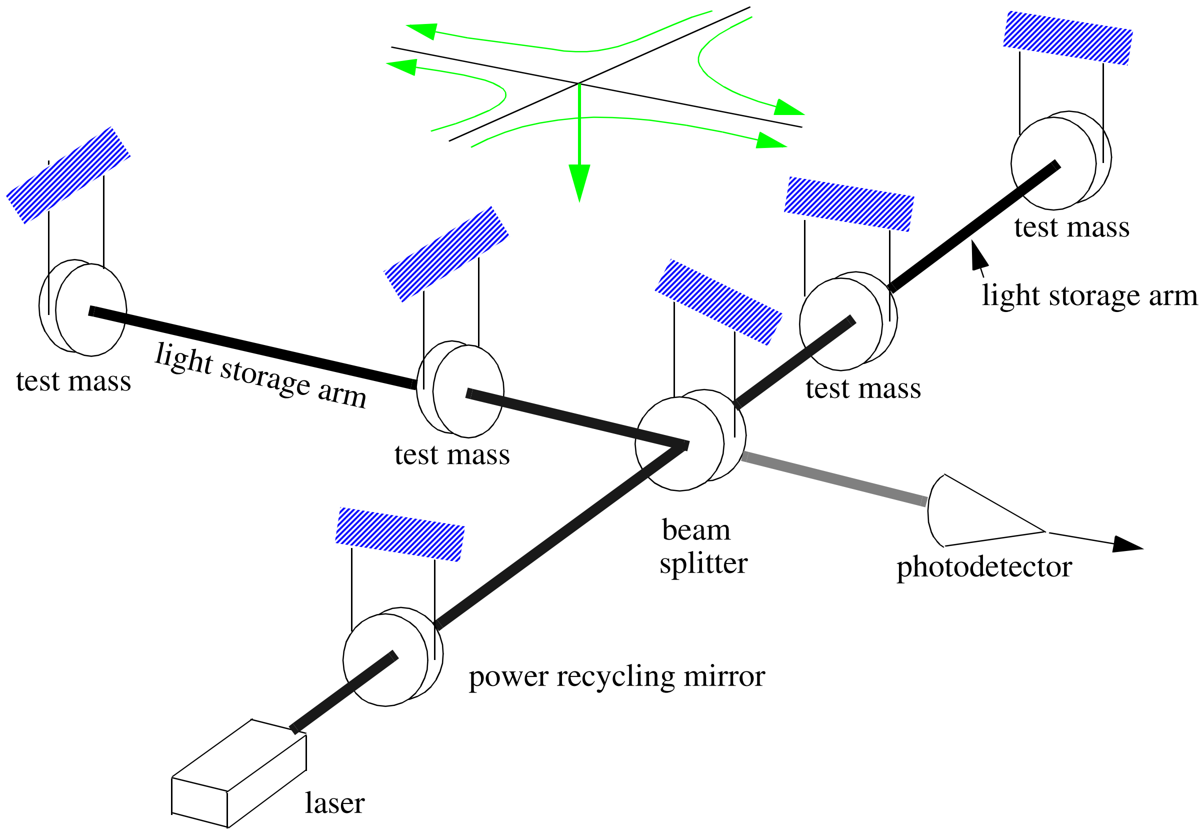
- Physics
  - Observations of gravitation in the strong field, high velocity limit
  - Determination of wave kinematics – polarization and propagation
  - Tests for alternative relativistic gravitational theories
- Astrophysics
  - Measurement of coherent inner dynamics – stellar collapse, pulsar formation….
  - 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

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
light storage arm
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

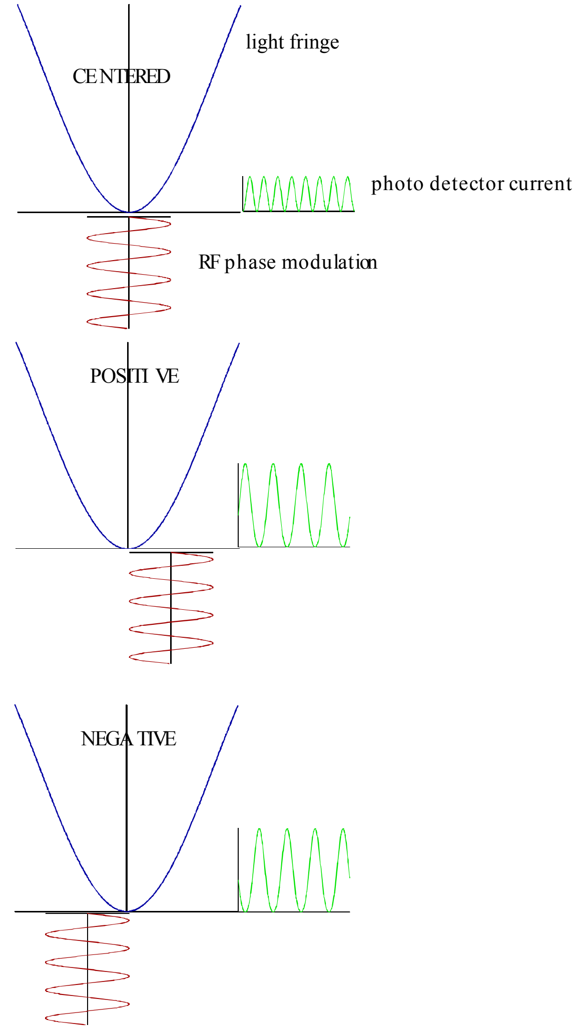
equivalent # of passes = 100

number of quanta/second at the beam splitter

integration time

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

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



PENDULUM THERMAL NOISE

Pendulum Brownian motion

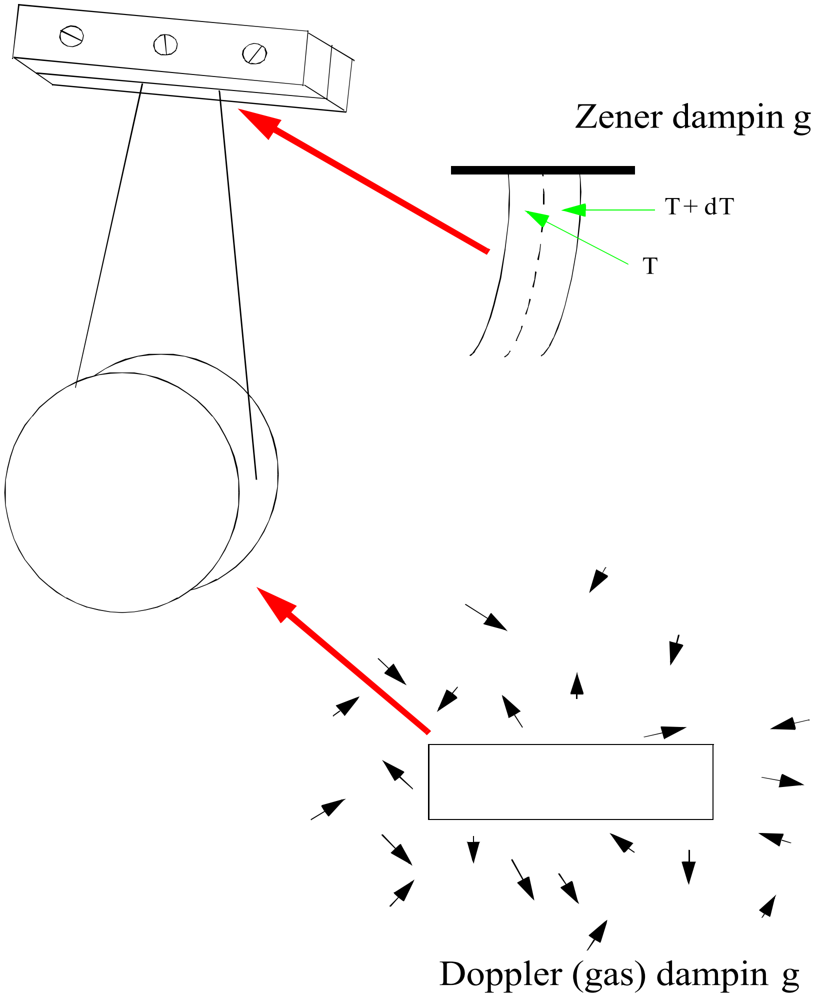
Dissipation leads to fluctuations

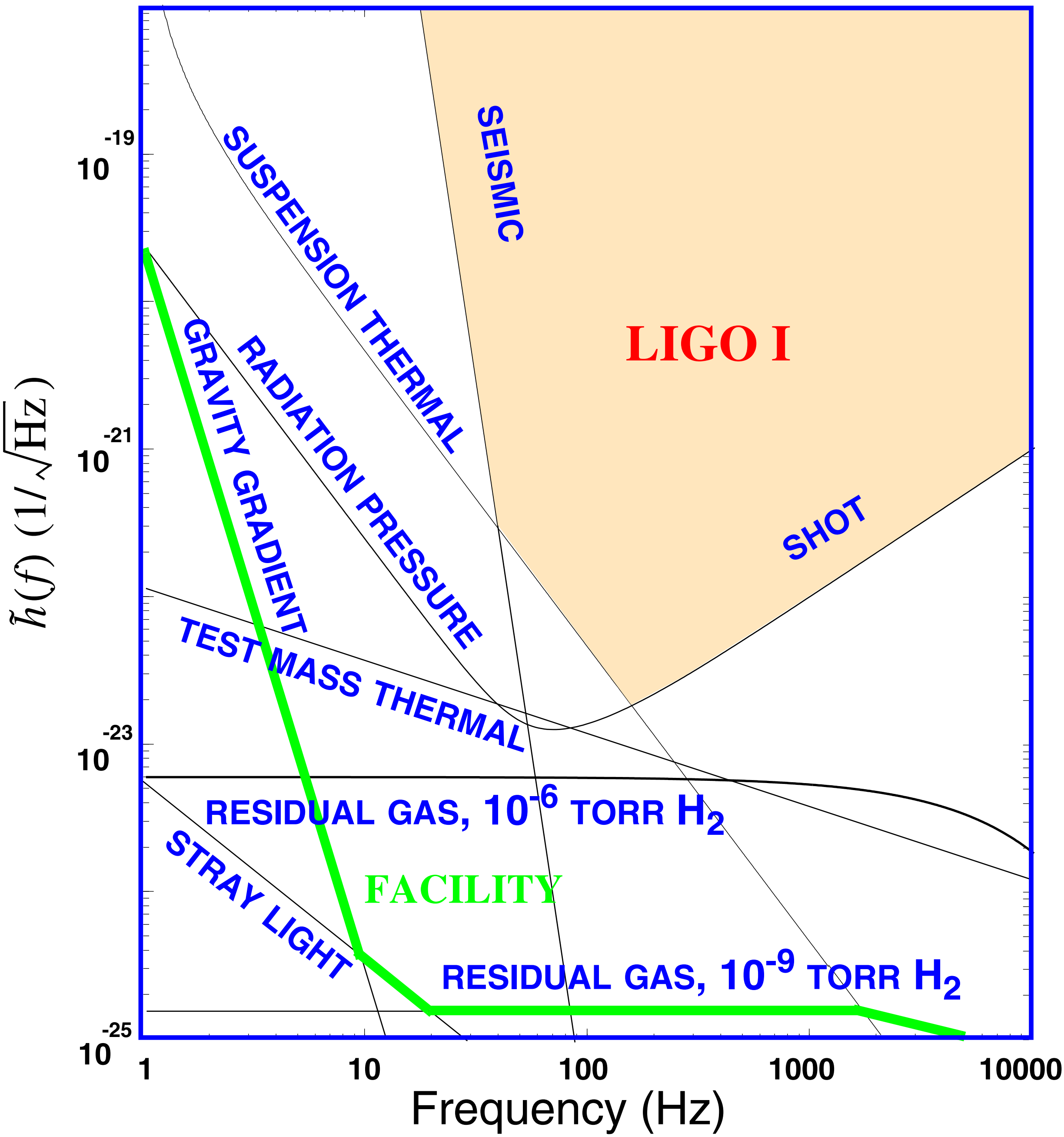
Tc = coherence or damping time
= Q x period of oscillator

Exchange with surroundings:

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

Large Tc => smaller fluctuations

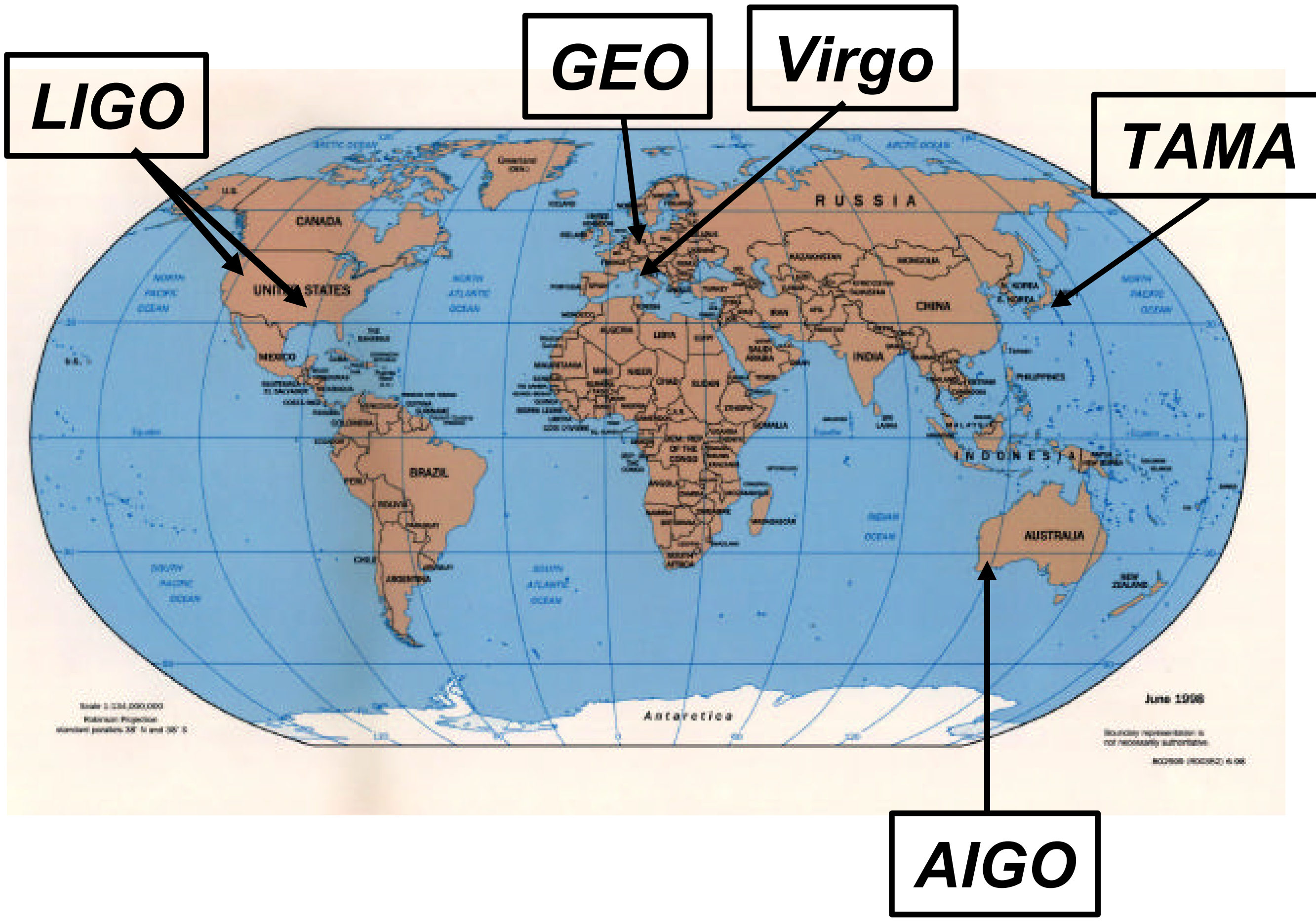




LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^{-9} TORR H_2
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)
$\tilde{h}(f)$ $(1/\sqrt{\mathrm{Hz}})$

Interferometers
international network

Simultaneously detect signal (within msec)

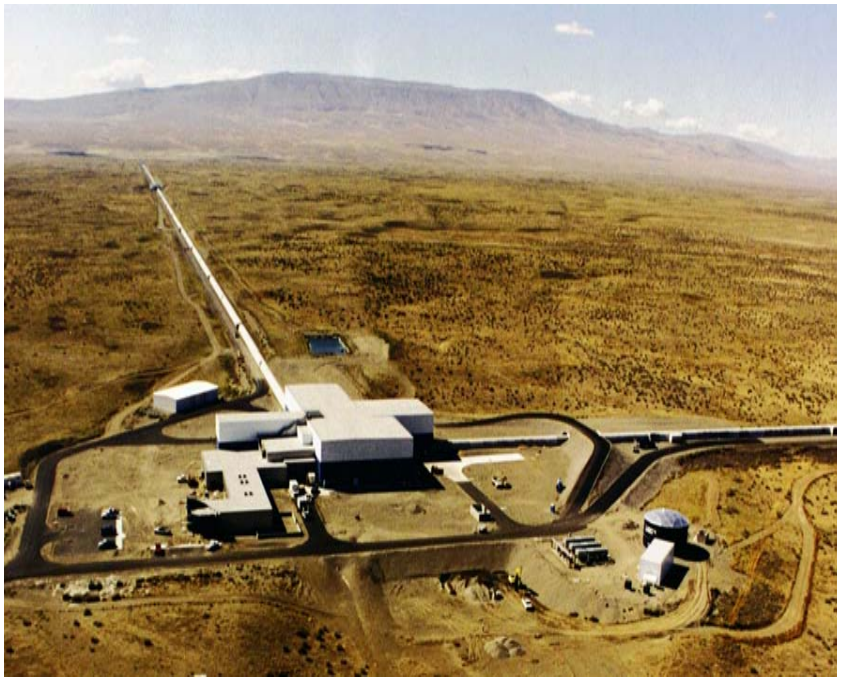


detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

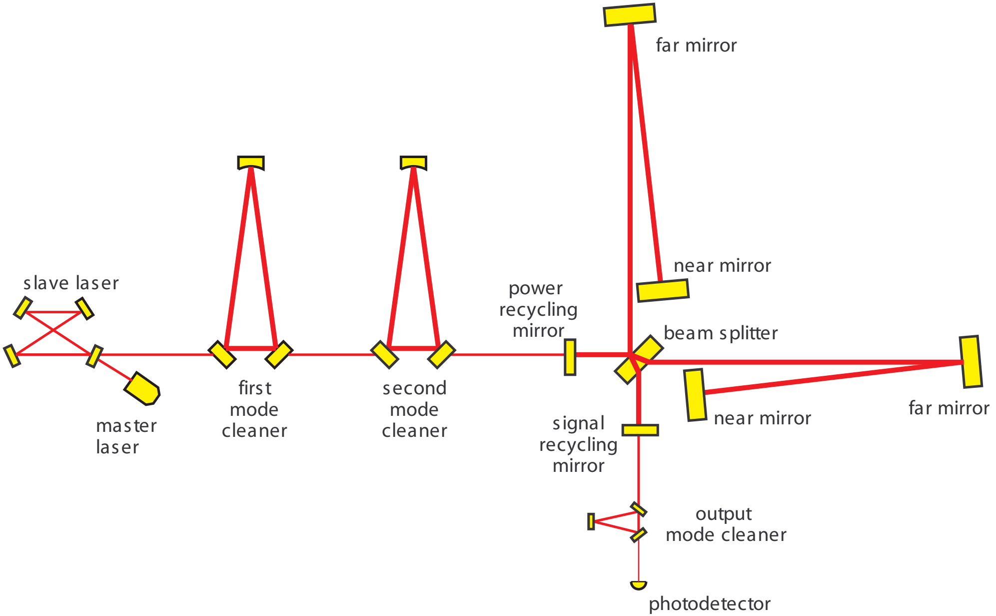
26 km north of Richland, WA

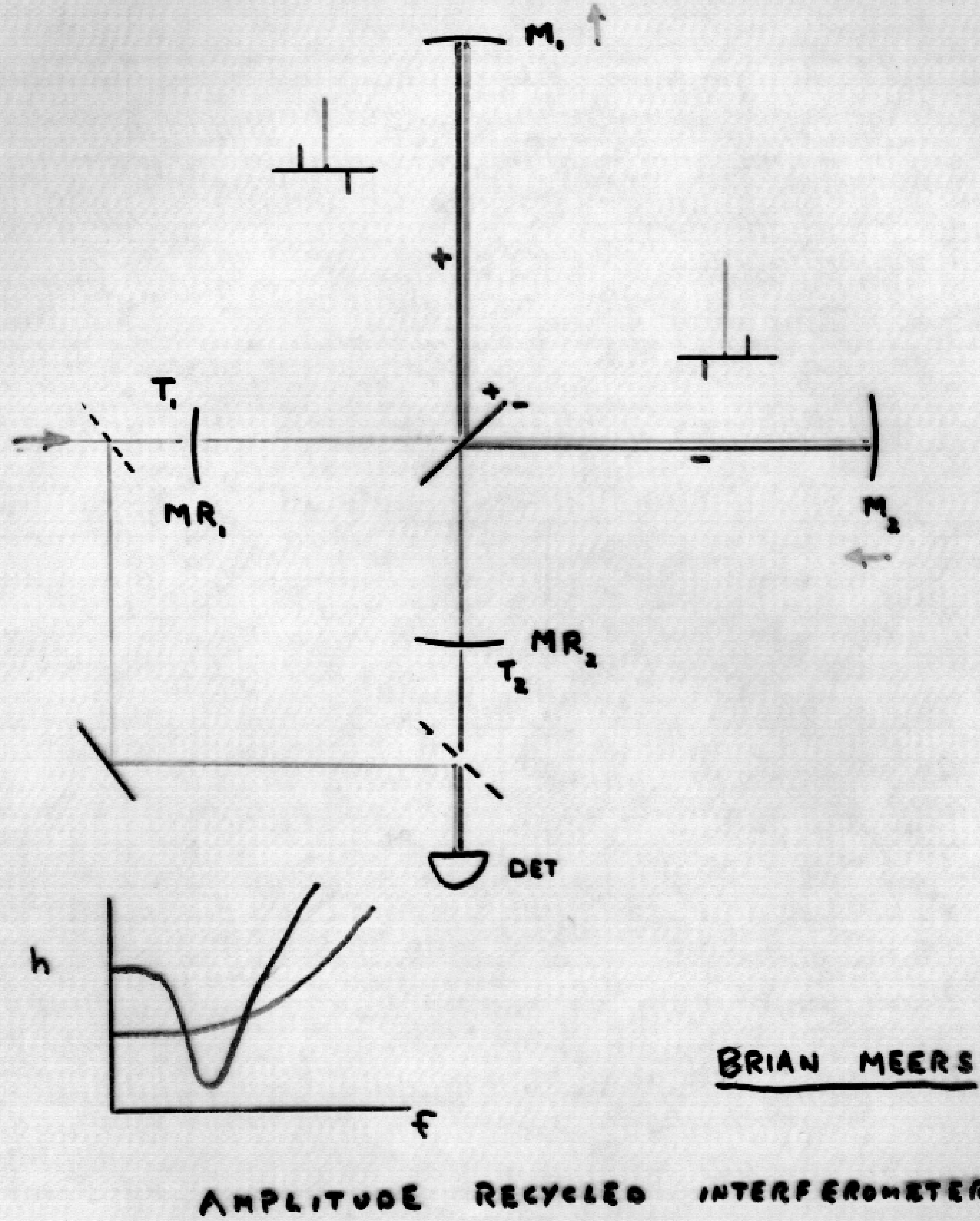
2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

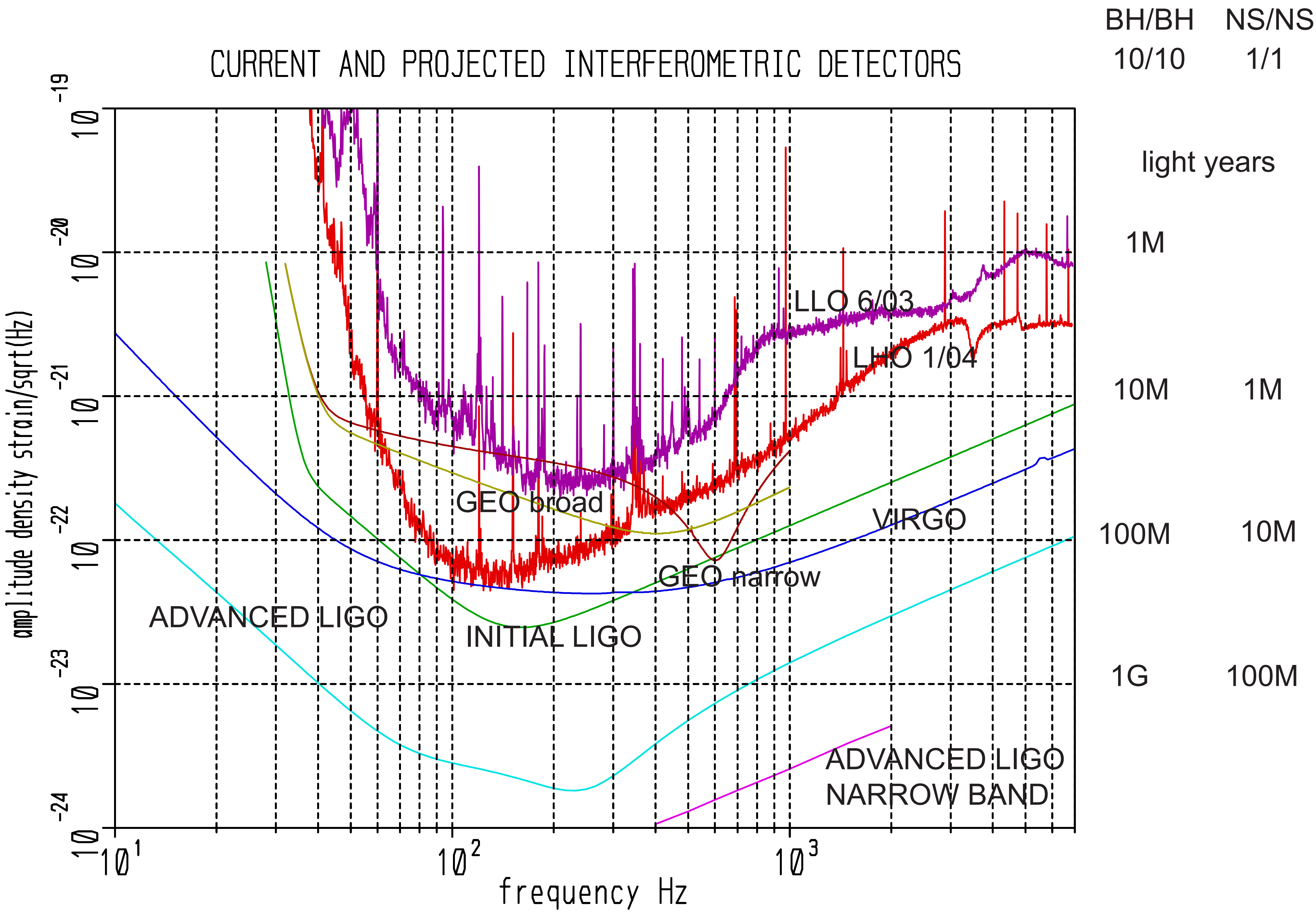
42 km east of Baton Rouge, LA

Single 4 km interferometer


far mirror
near mirror
slave laser
power
recycling
mirror
beam splitter
first
mode
cleaner
second
mode
cleaner
far mirror
near mirror
master
laser
signal
recycling
mirror
output
mode cleaner
photodetector



AMPLITUDE RECYCLED INTERFEROMETER



CURRENT AND PROJECTED INTERFEROMETRIC DETECTORS
BH/BH
NS/NS
10/10
1/1
light years
1M
10M
1M
100M
10M
1G
100M
LLO 6/03
LHO 1/04
GEO broad
VIRGO
GEO narrow
ADVANCED LIGO
INITIAL LIGO
ADVANCED LIGO
NARROW BAND
amplitude density strain/sqrt(Hz)
frequency Hz

LIGO
Beam Tube

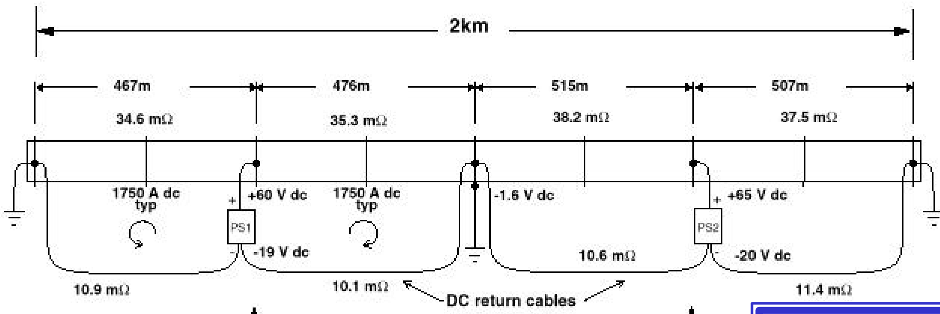
1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

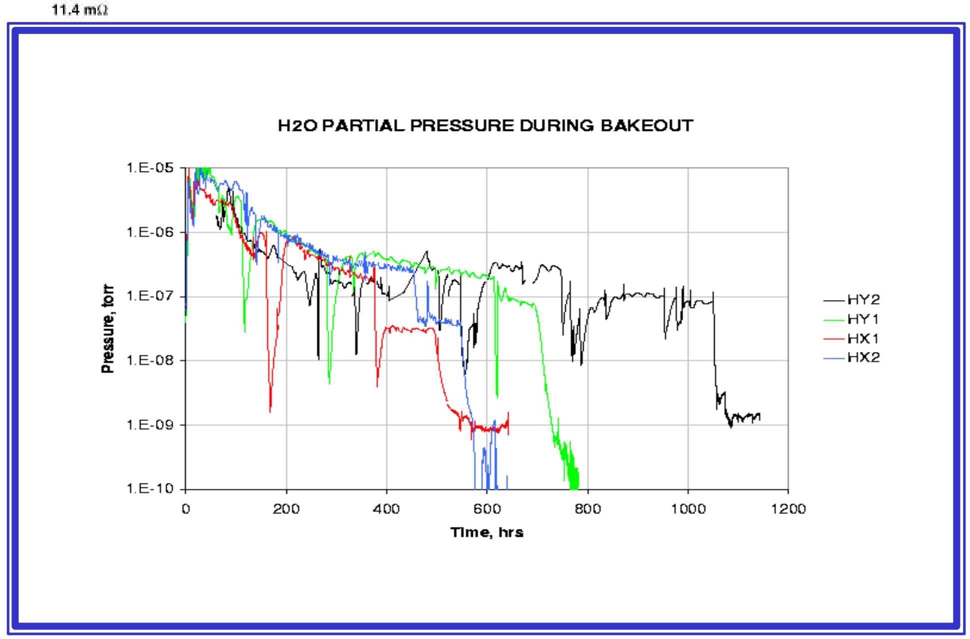
- **LIGO beam tube under construction in January 1998**
- **65 ft spiral welded sections**
- **girth welded in portable clean room in the field**

Beam Tube

bakeout



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



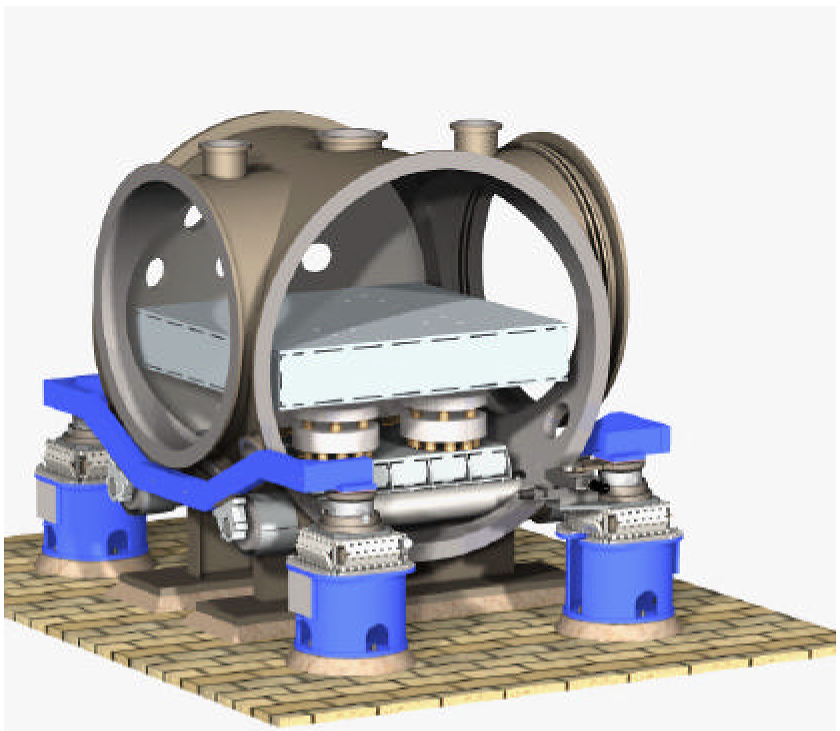
LIGO

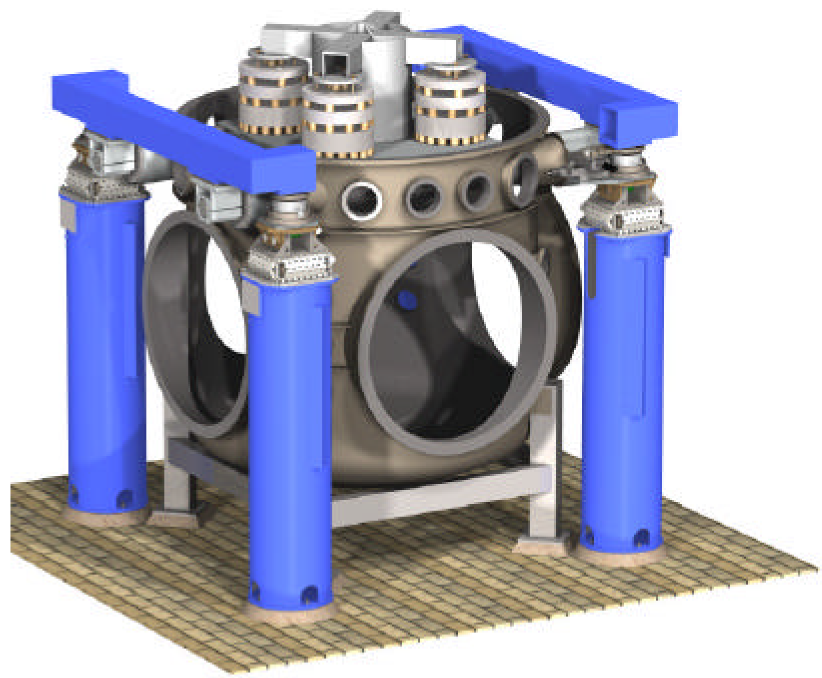
vacuum equipment

Vacuum Chambers

Vibration Isolation Systems

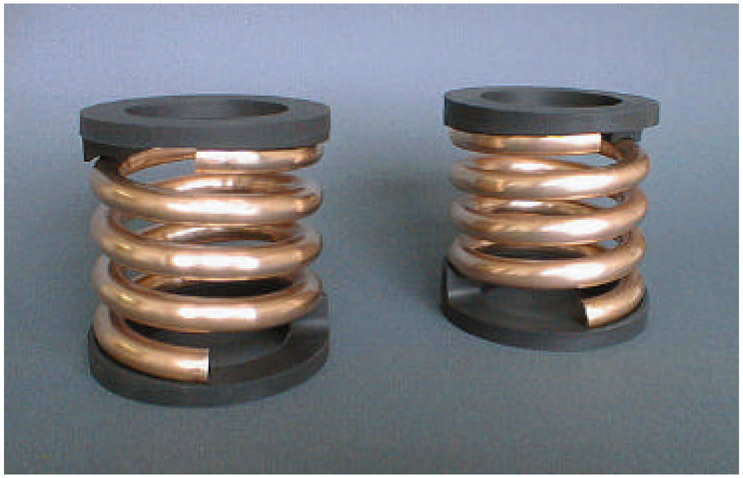
- » Reduce in-band seismic motion by 4 - 6 orders of magnitude
- » Compensate for microseism at 0.15 Hz by a factor of ten
- » Compensate (partially) for Earth tides

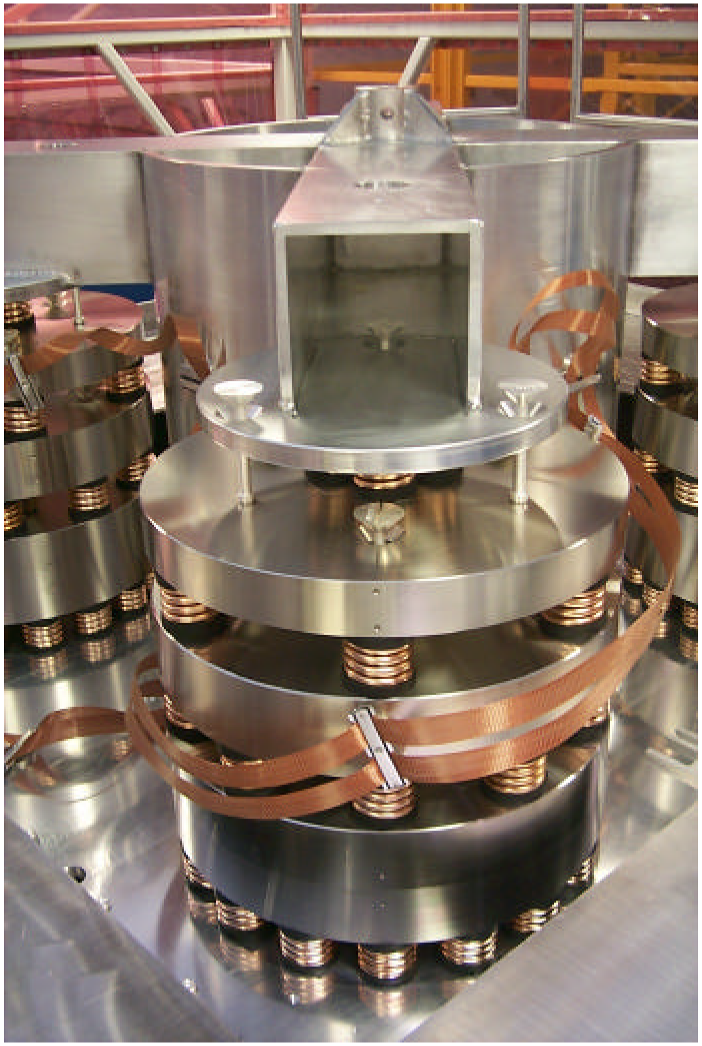




Seismic Isolation

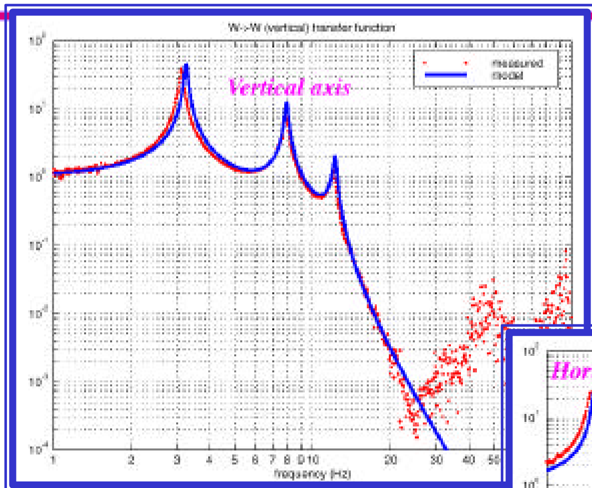
Springs and Masses

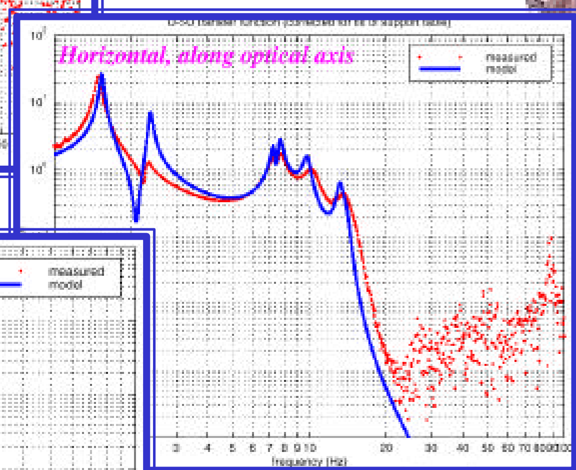


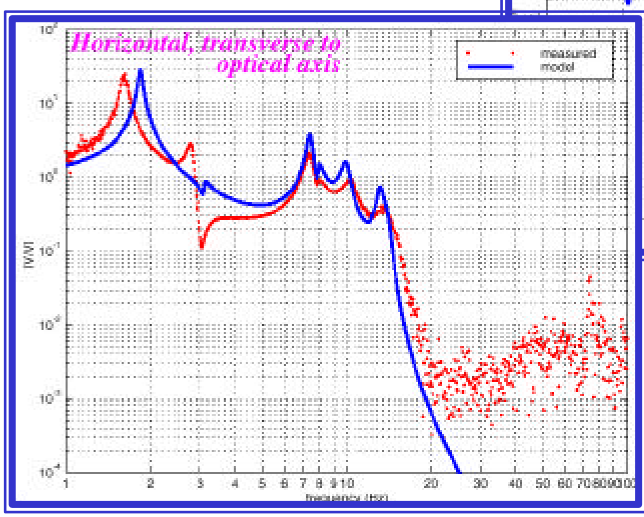


Seismic Isolation

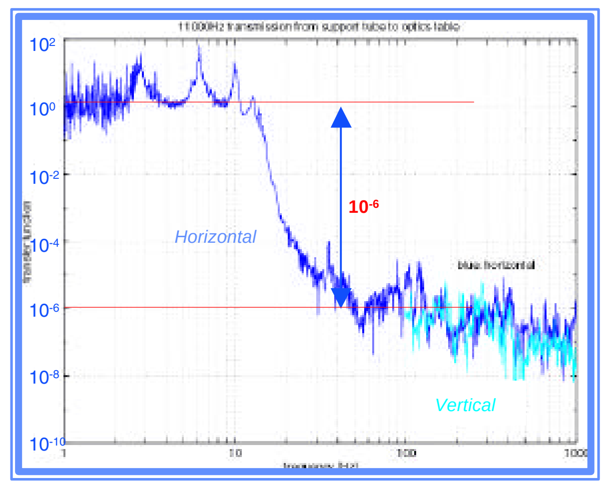
performance







HAM stack in air

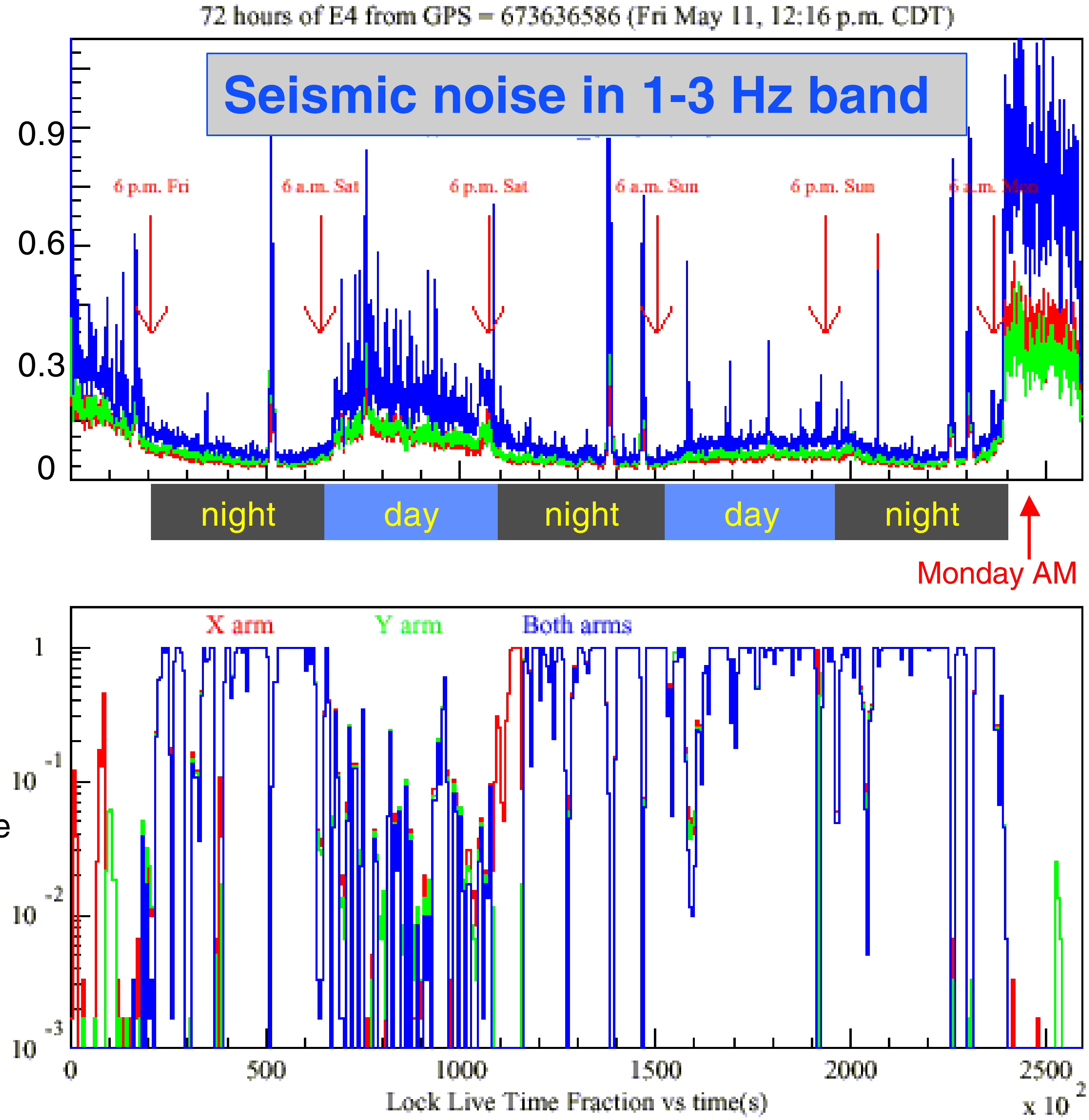


BSC stack in vacuum

LIGO-G000306-00-M

Seismic Situation at LLO

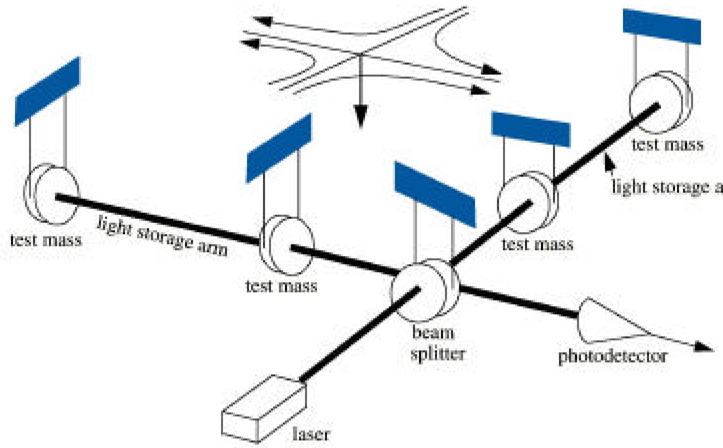
Microns/sec



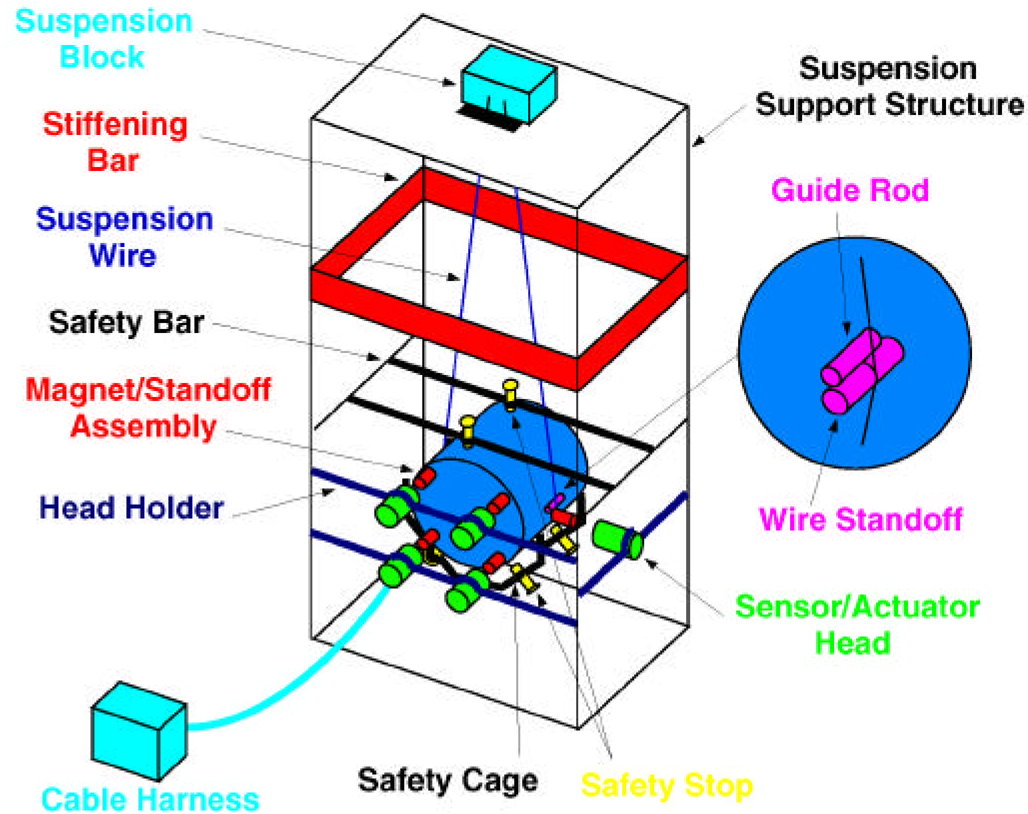
Fractional time in lock

Seismic Isolation

suspension system



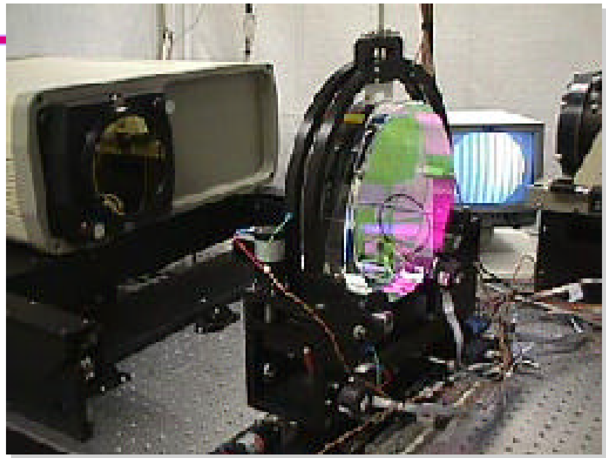
suspension assembly for a core optic



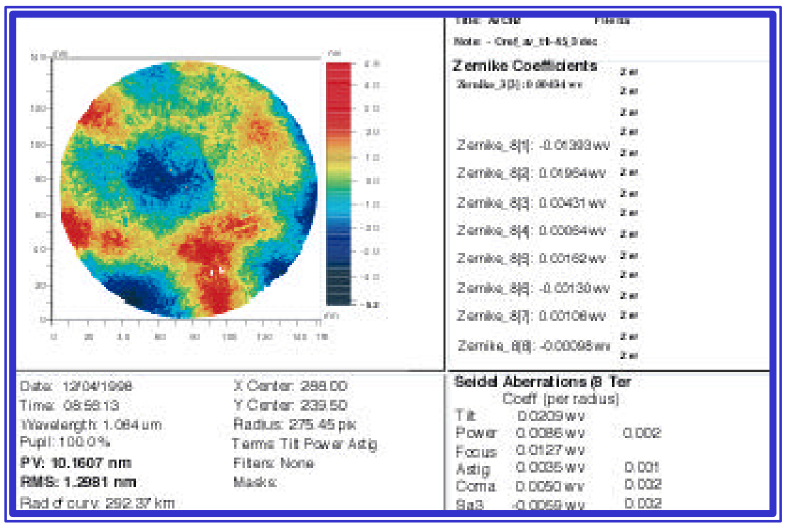
- **support structure is welded tubular stainless steel**
- **suspension wire is 0.31 mm diameter steel music wire**
- **fundamental violin mode frequency of 340 Hz**

Core Optics

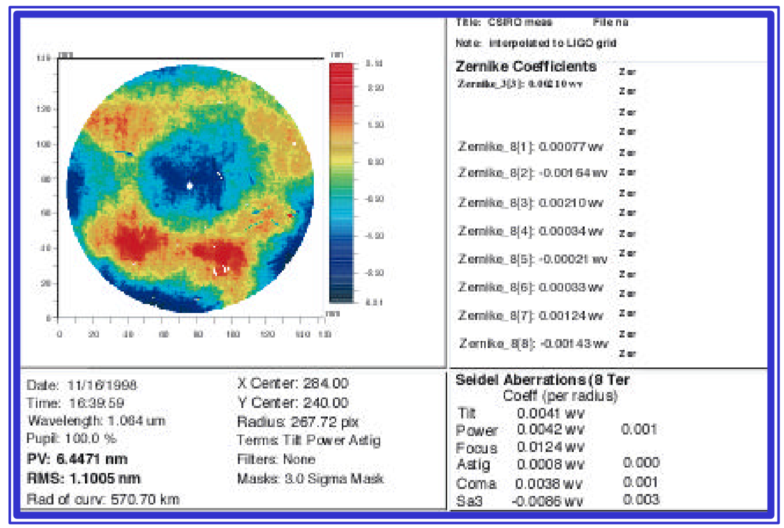
fused silica



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



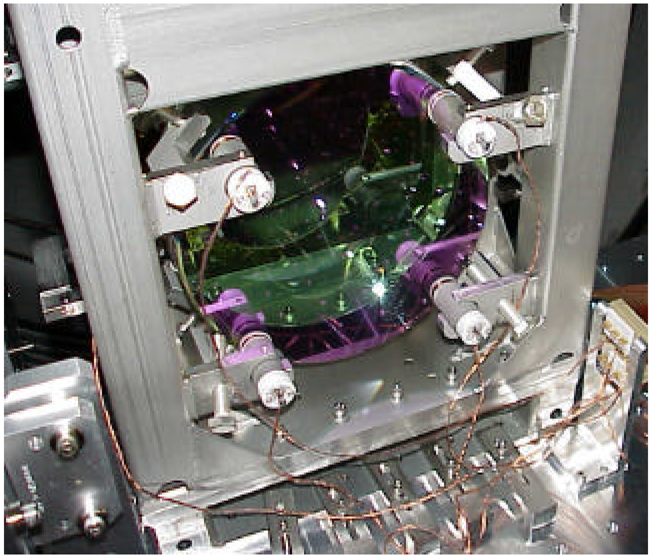
Caltech data

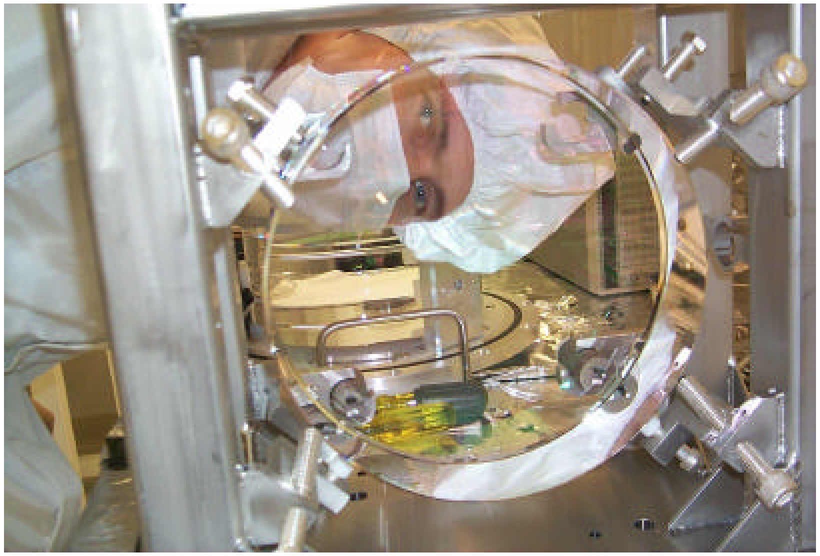


CSIRO data

Core Optics

Suspension

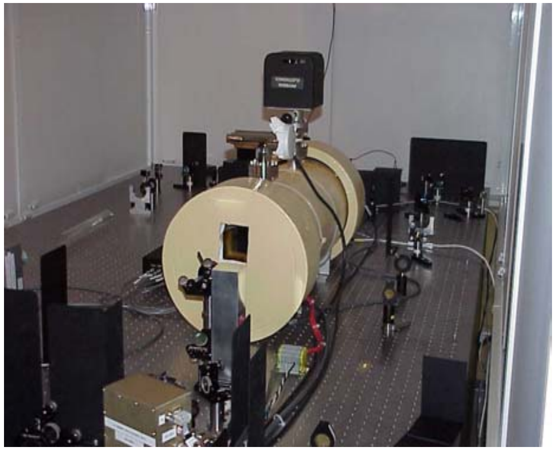


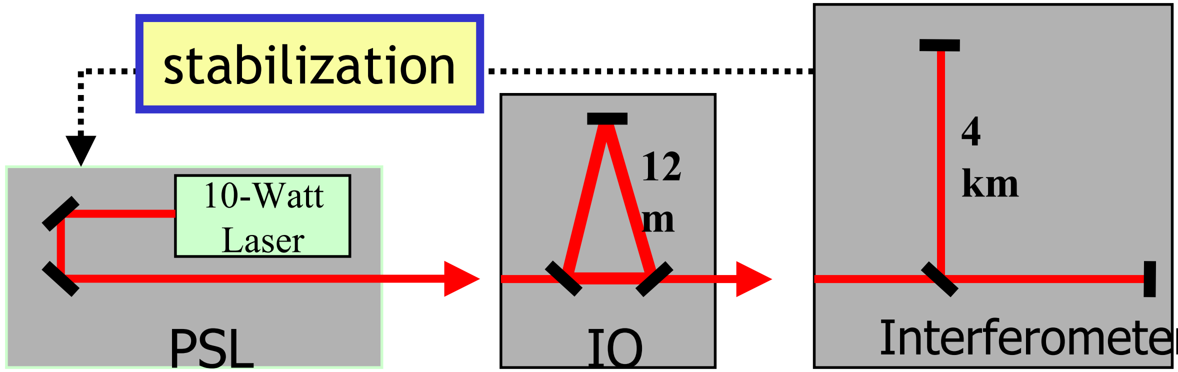


Core Optics

Installation and Alignment

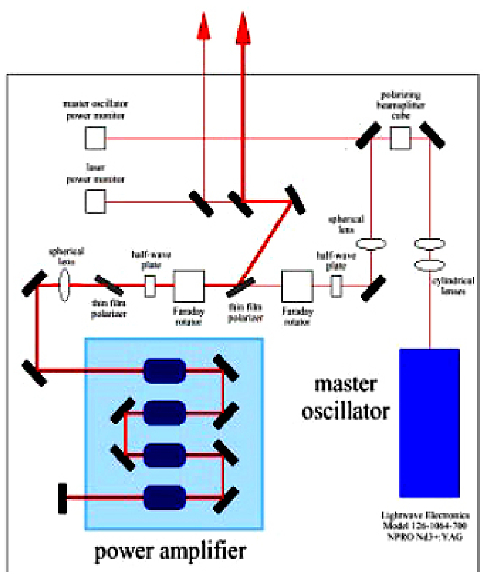
LIGO Prestabilized Laser



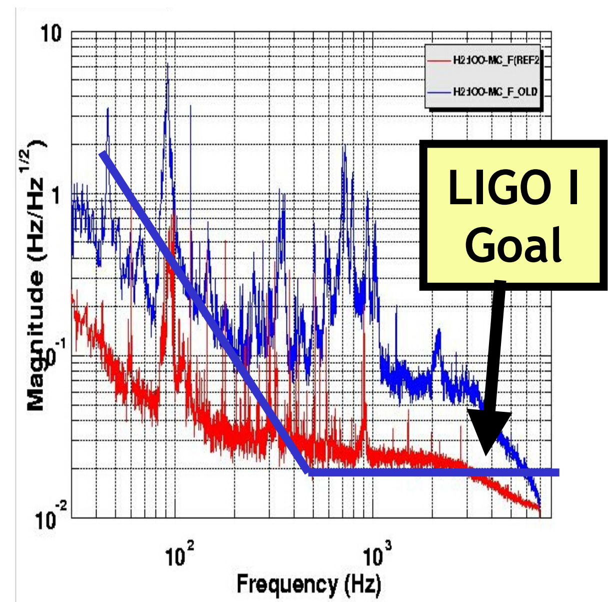


10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/Hz$^{1/2}$ 10^{-7} Hz/Hz$^{1/2}$

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



Lightwave Electronics MOPA

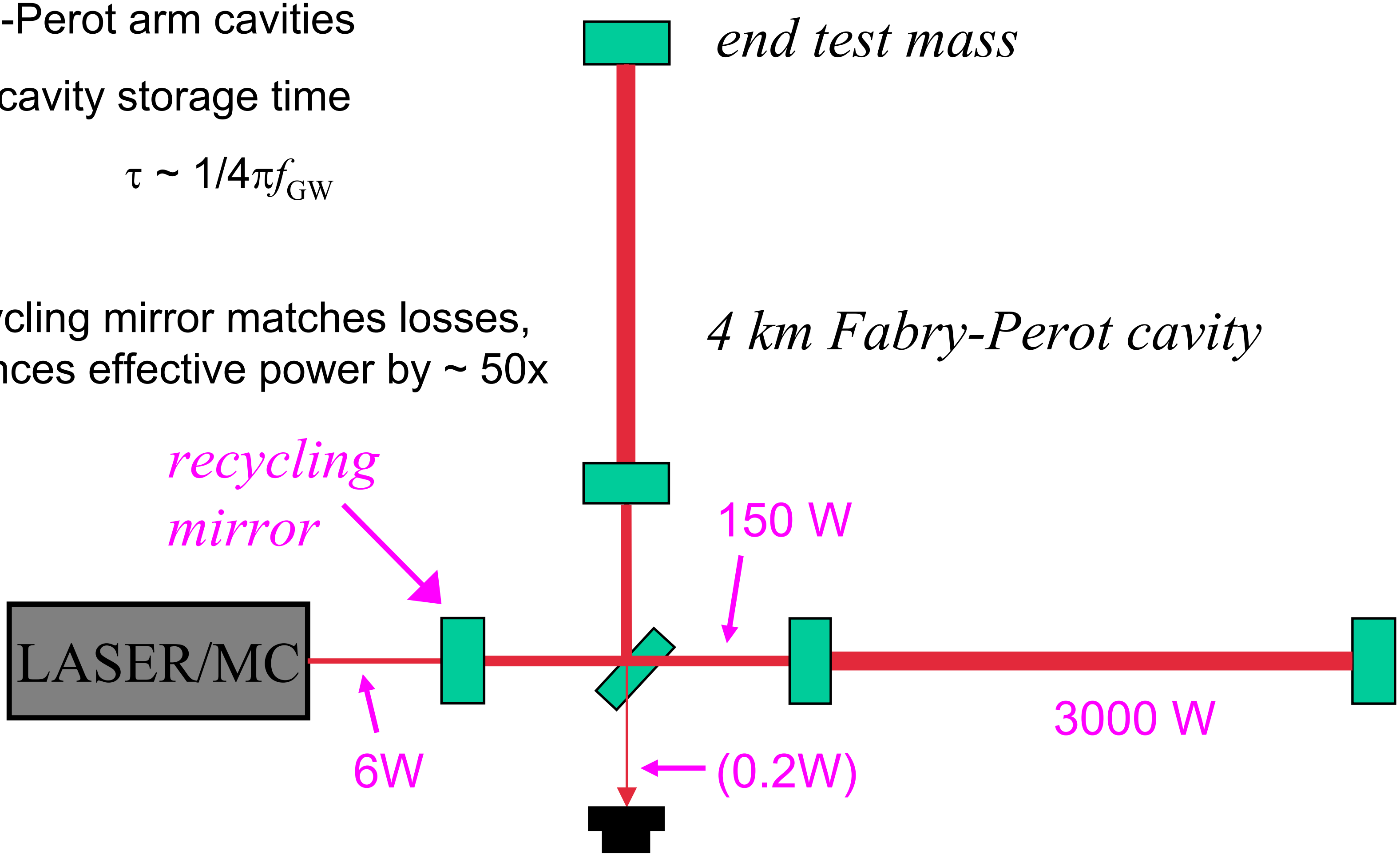


LIGO Interferometer Optical Scheme

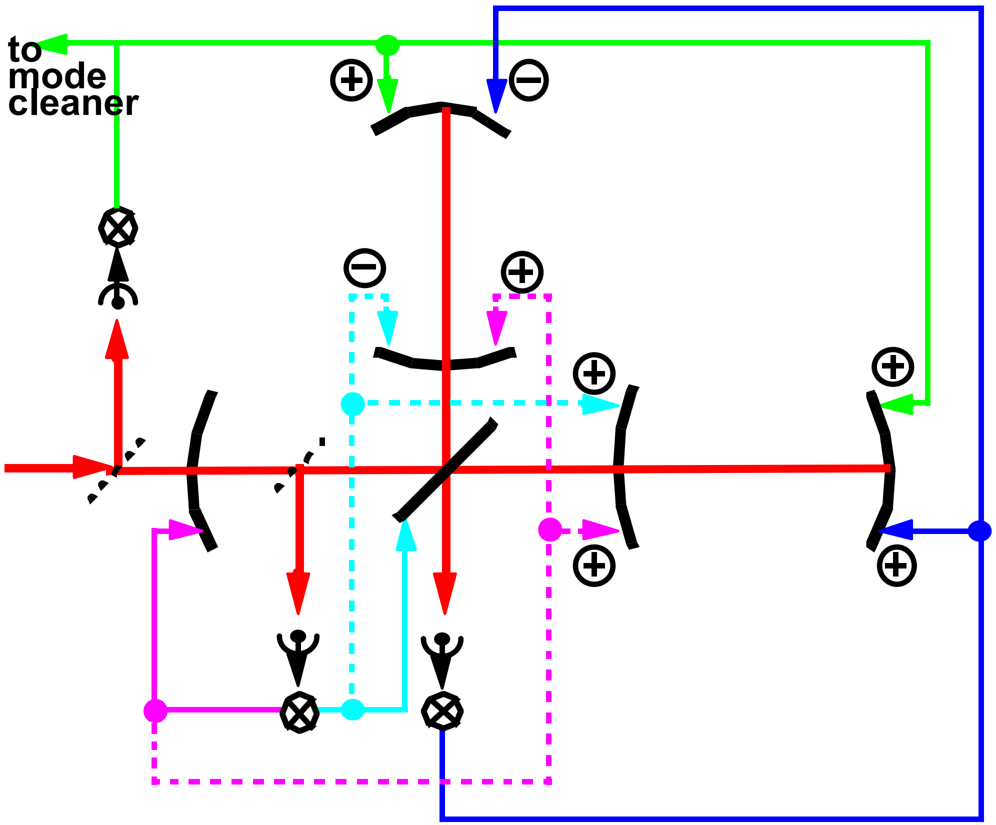
- Michelson interferometer with Fabry-Perot arm cavities
- Arm cavity storage time

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

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



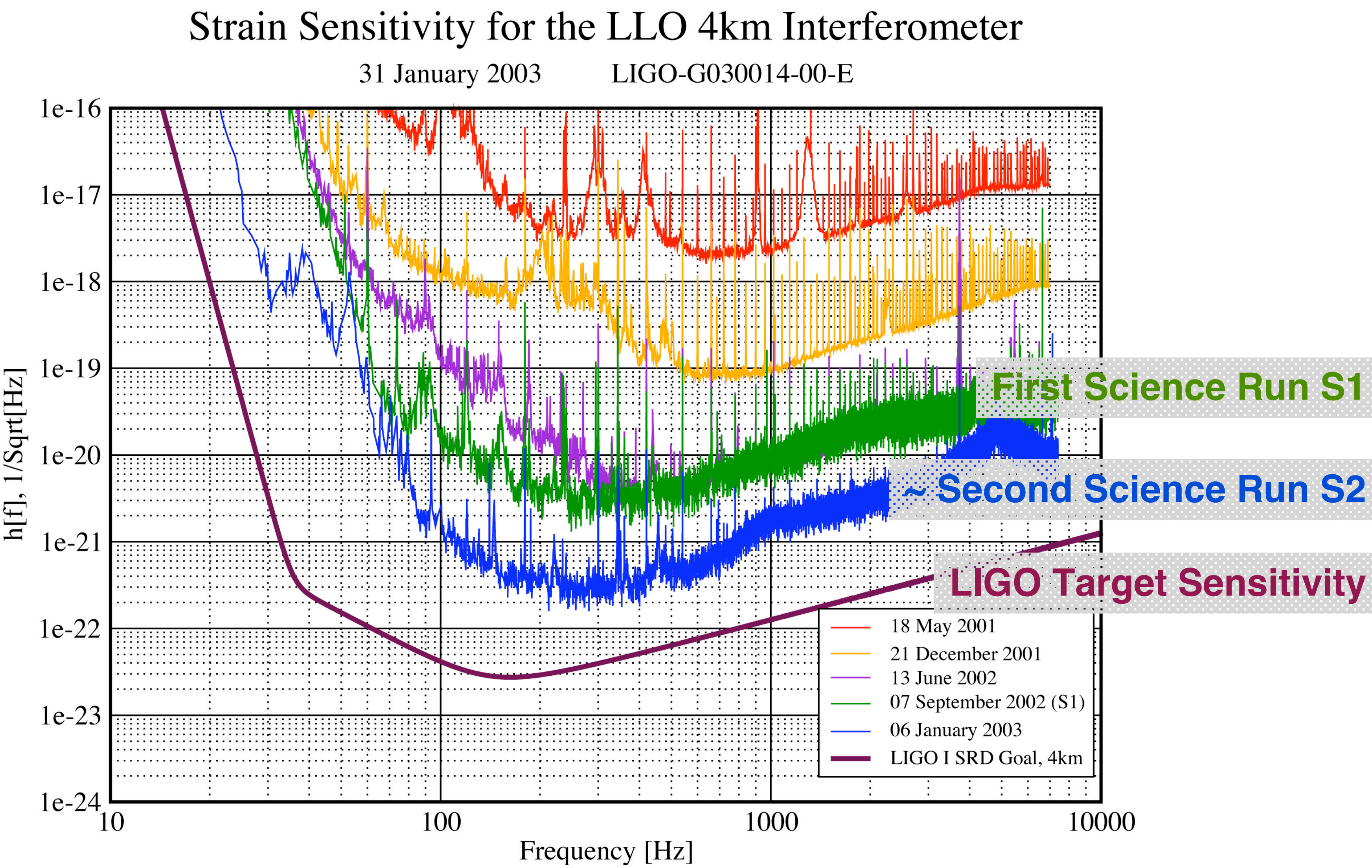
Feedback Control Systems



example: cavity length sensing & control topology

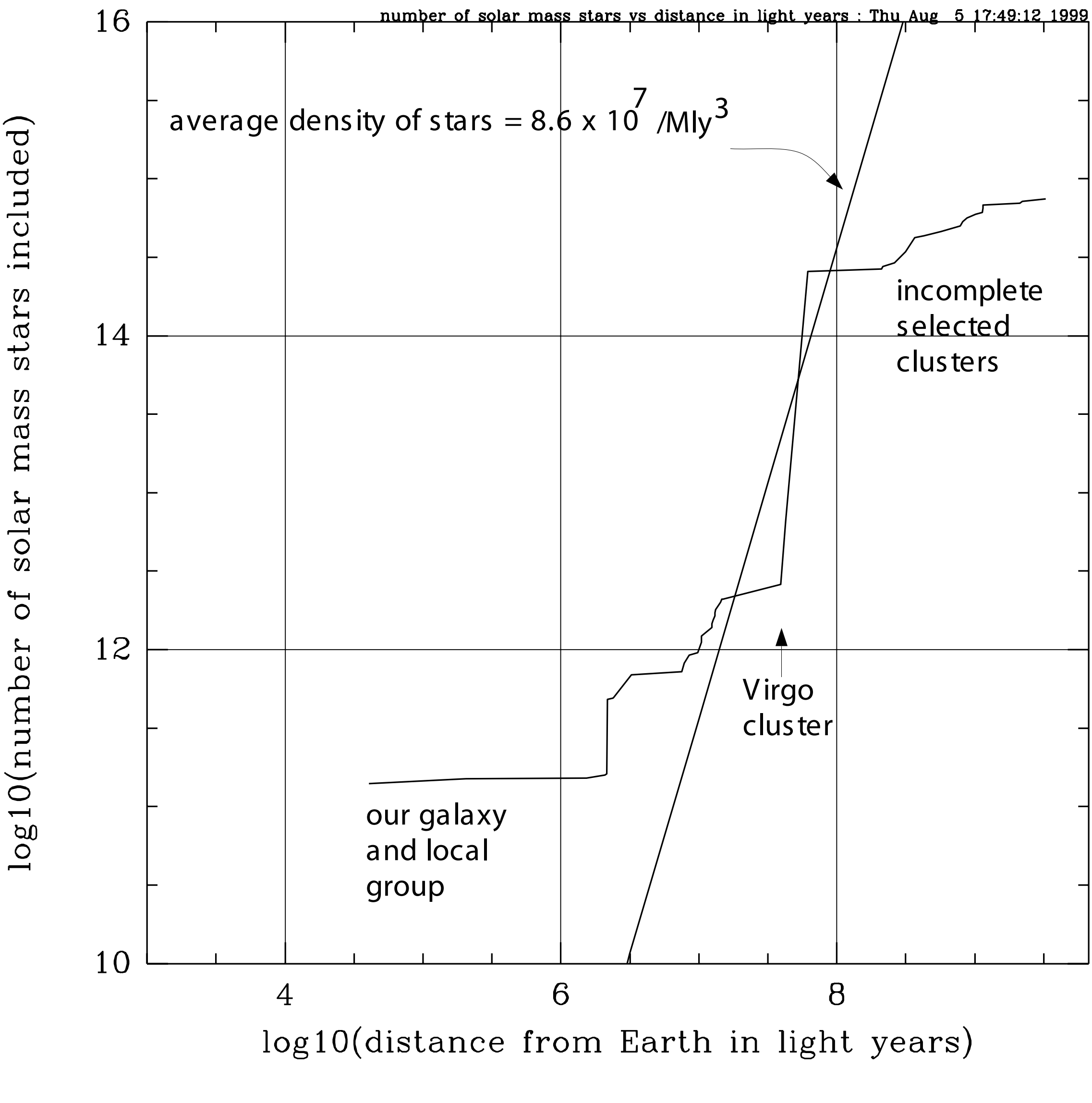
- •Array of sensors detects mirror separations, angles
- •Signal processing derives stabilizing forces for each mirror, filters noise
- •5 main length loops shown; total ~ 25 degrees of freedom
- •Operating points held to about 0.001 Å, .01 µrad RMS
- •Typ. loop bandwidths from ~ few Hz (angles) to >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

Gravitational Radiation and Detectors:
LIGO Sensitivity Improvements



Data Analysis According to Source Characteristics

- Deterministic signals -- ***Binary coalescences, Periodic sources***
  - »Amplitude and frequency evolution parametrized
  - »Set of templates covering parameter space matched to data
- Statistical signals -- ***Stochastic gravitational wave background***
  - »Cross-correlation of detector pairs, look for correlations above statistical variation
- Unmodeled signals- ***Supernovae, Gamma Ray Bursts, …***
  - »Non-parametric techniques
    - Excess power in frequency-time domain
    - Excess amplitude change, rise-time in time domain
- *In all cases: coincident observations among multiple detectors*



DATA: Cosmology of the Local Group G.Lake
Astrophysical Quantities C.W. Allen

Binary Coalescence Sources & Science:
Binary Neutron Stars: S1 Range

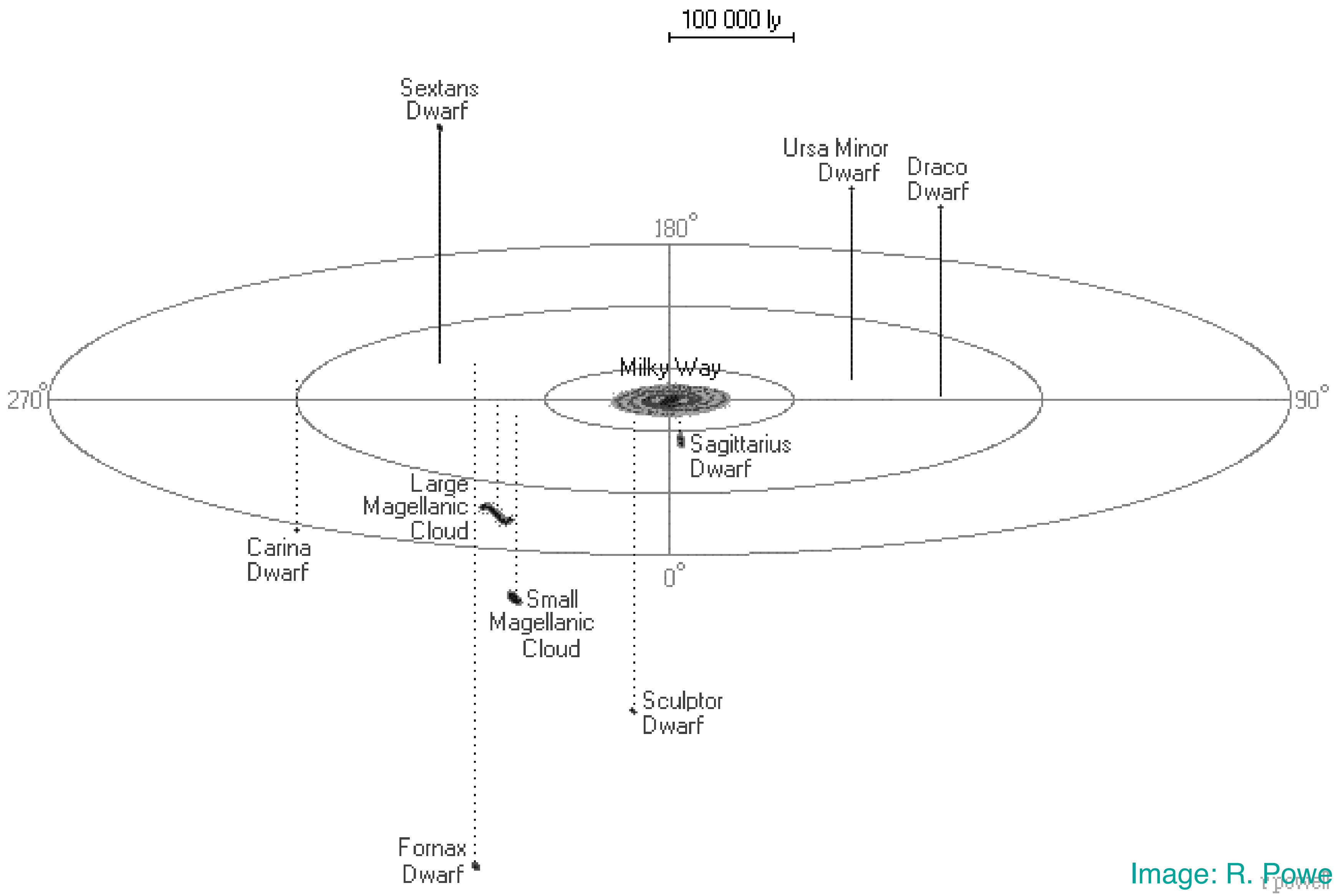


Image: R. Powell

LIGO

Binary Coalescence Sources & Science:

Binary Neutron Stars: S2 Range

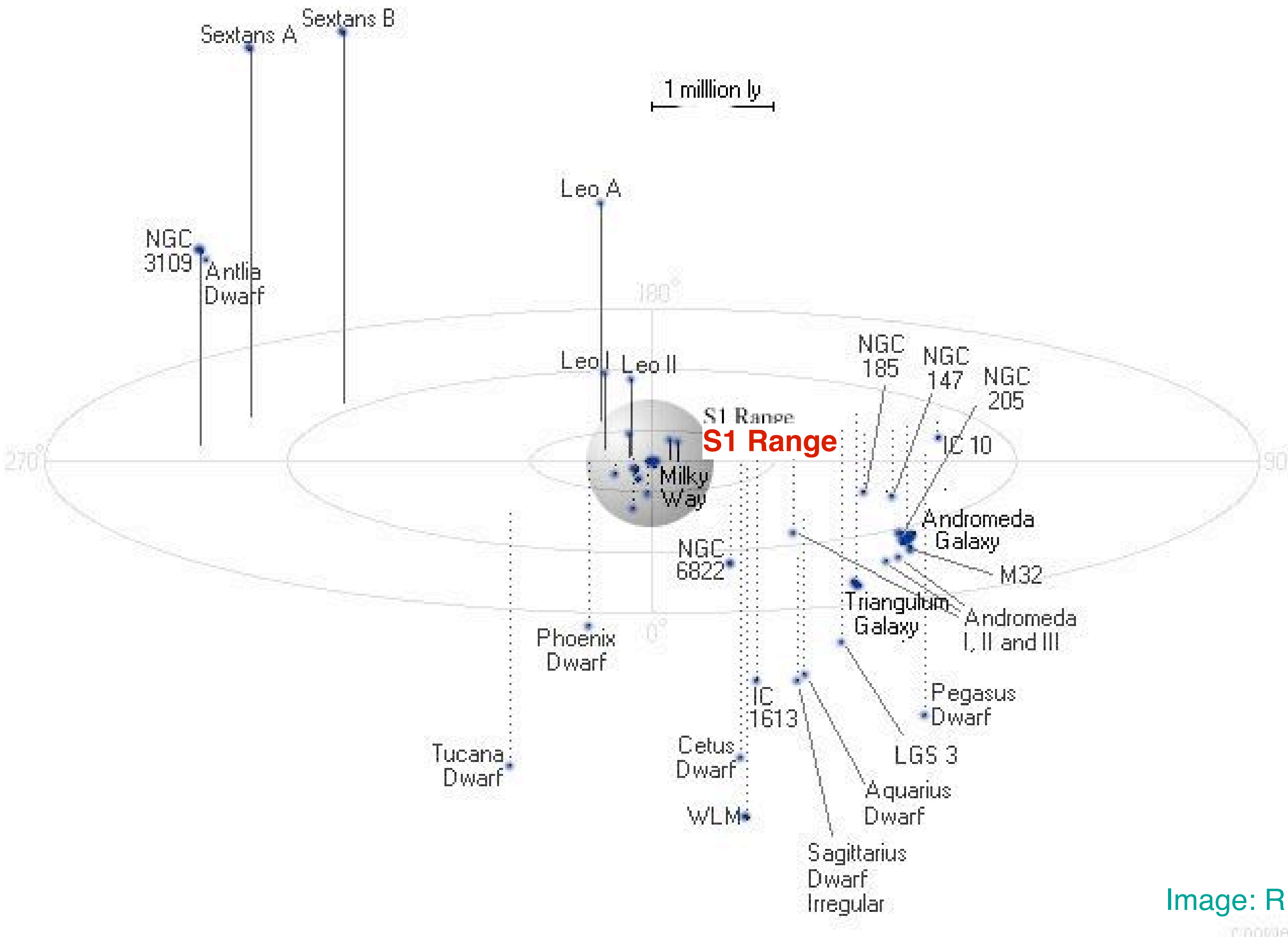


Image: R. Powell

Binary Coalescence Sources & Science:
Binary Neutron Stars: LIGO Range

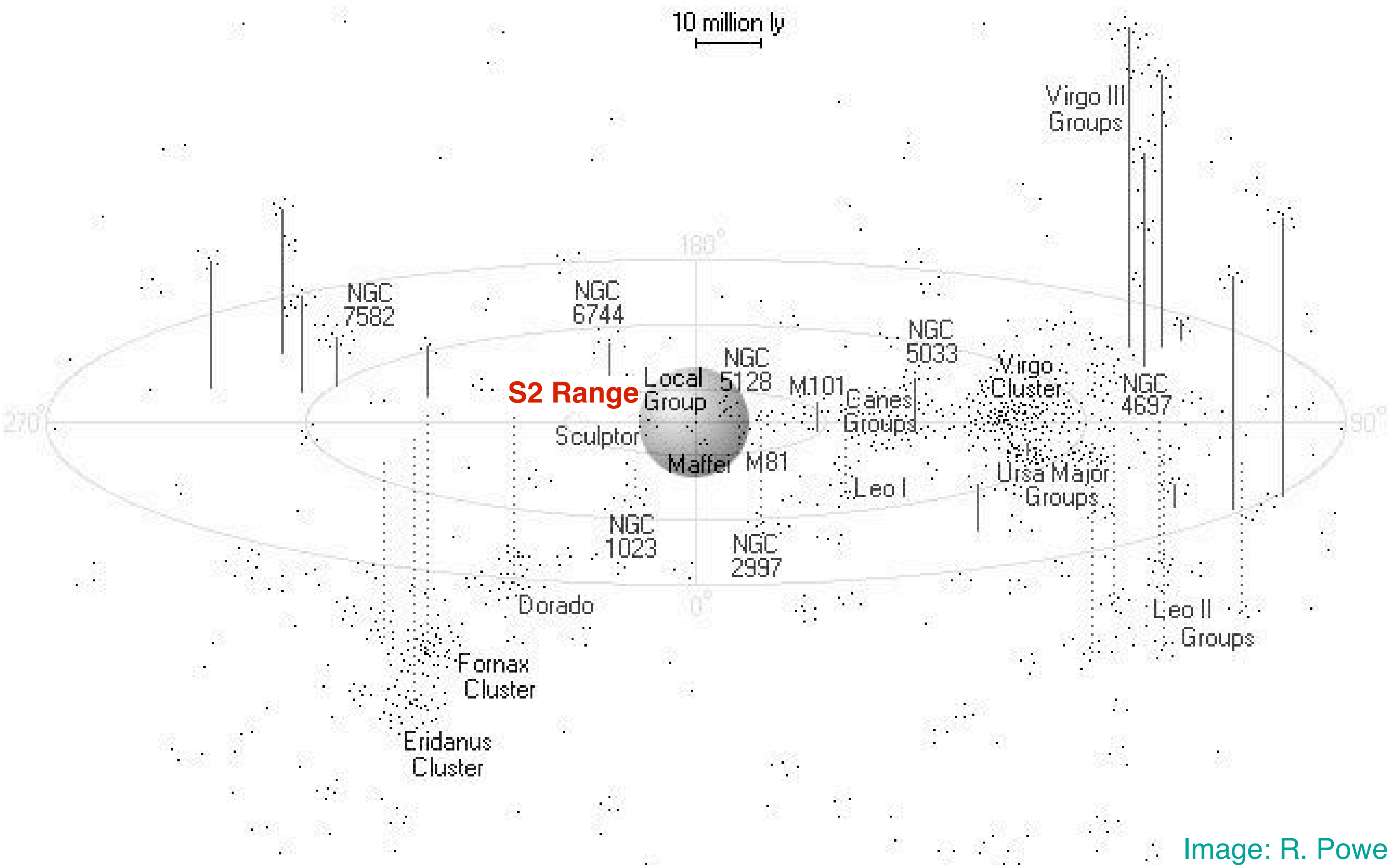


Image: R. Powell

Binary Coalescence Sources & Science:
Binary Neutron Stars: AdLIGO Range

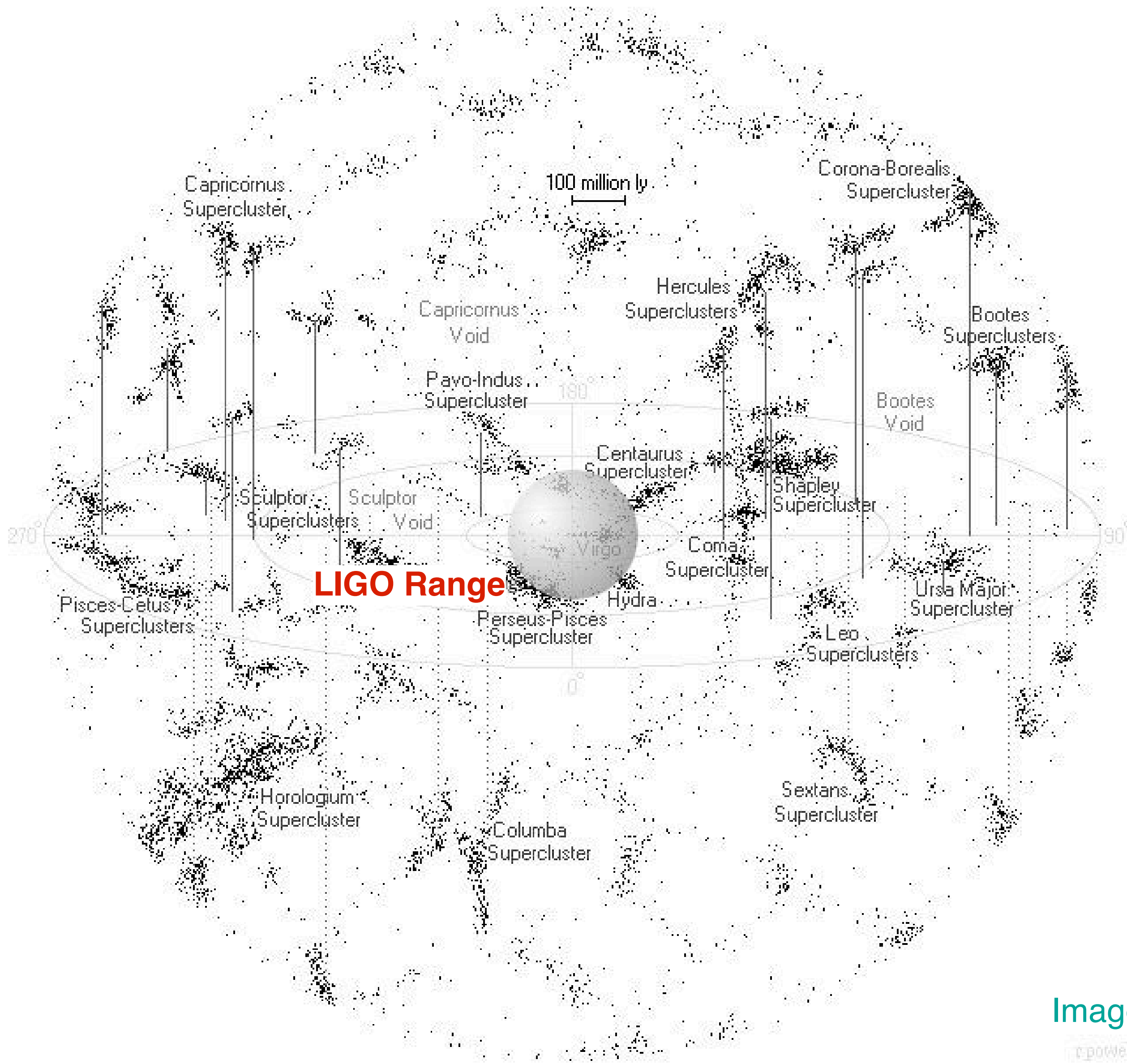
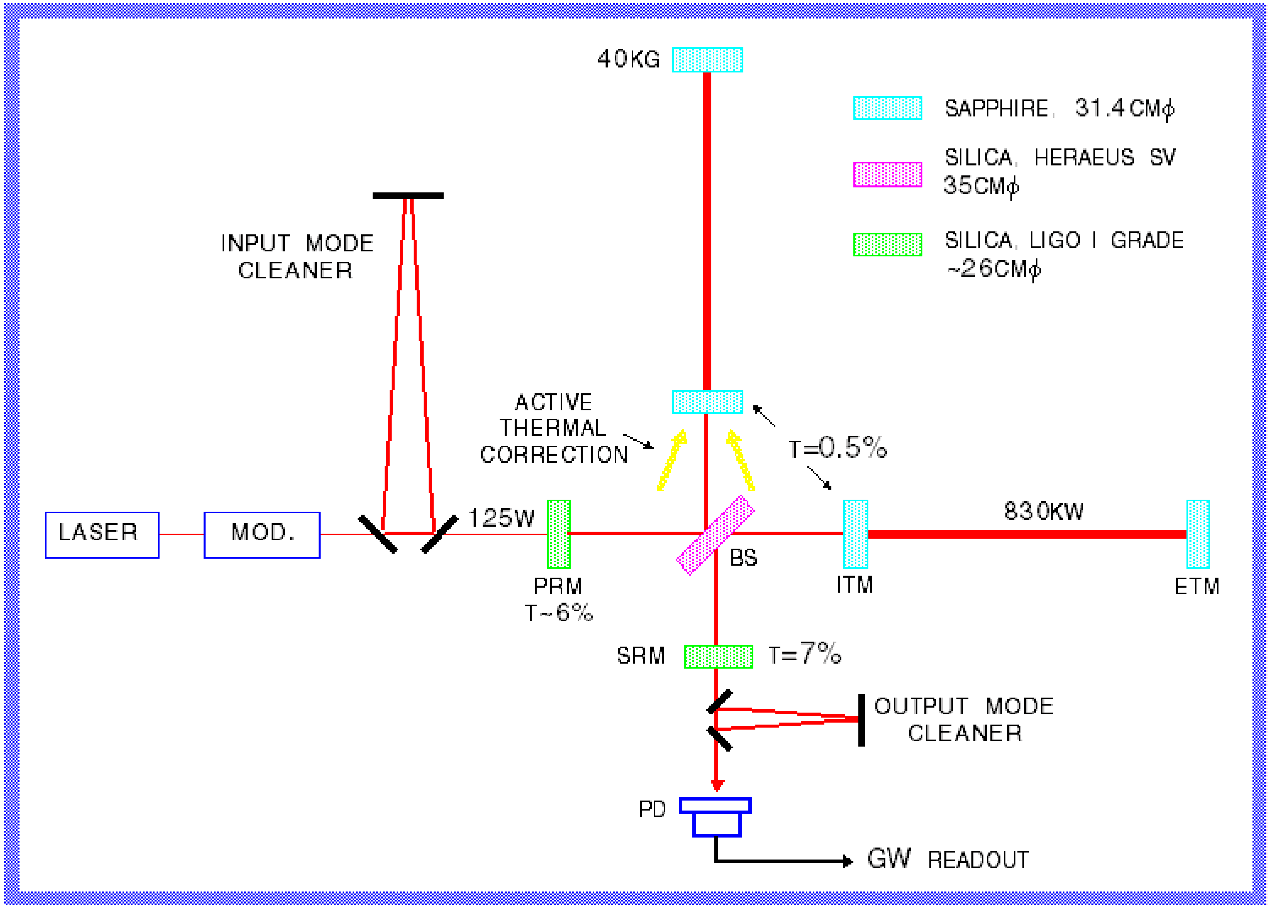


Image: R. Powell

Advanced Interferometer Concept



» Signal recycling

» 180-watt laser

» 40 kg Sapphire test masses

» Larger beam size

» Quadruple suspensions

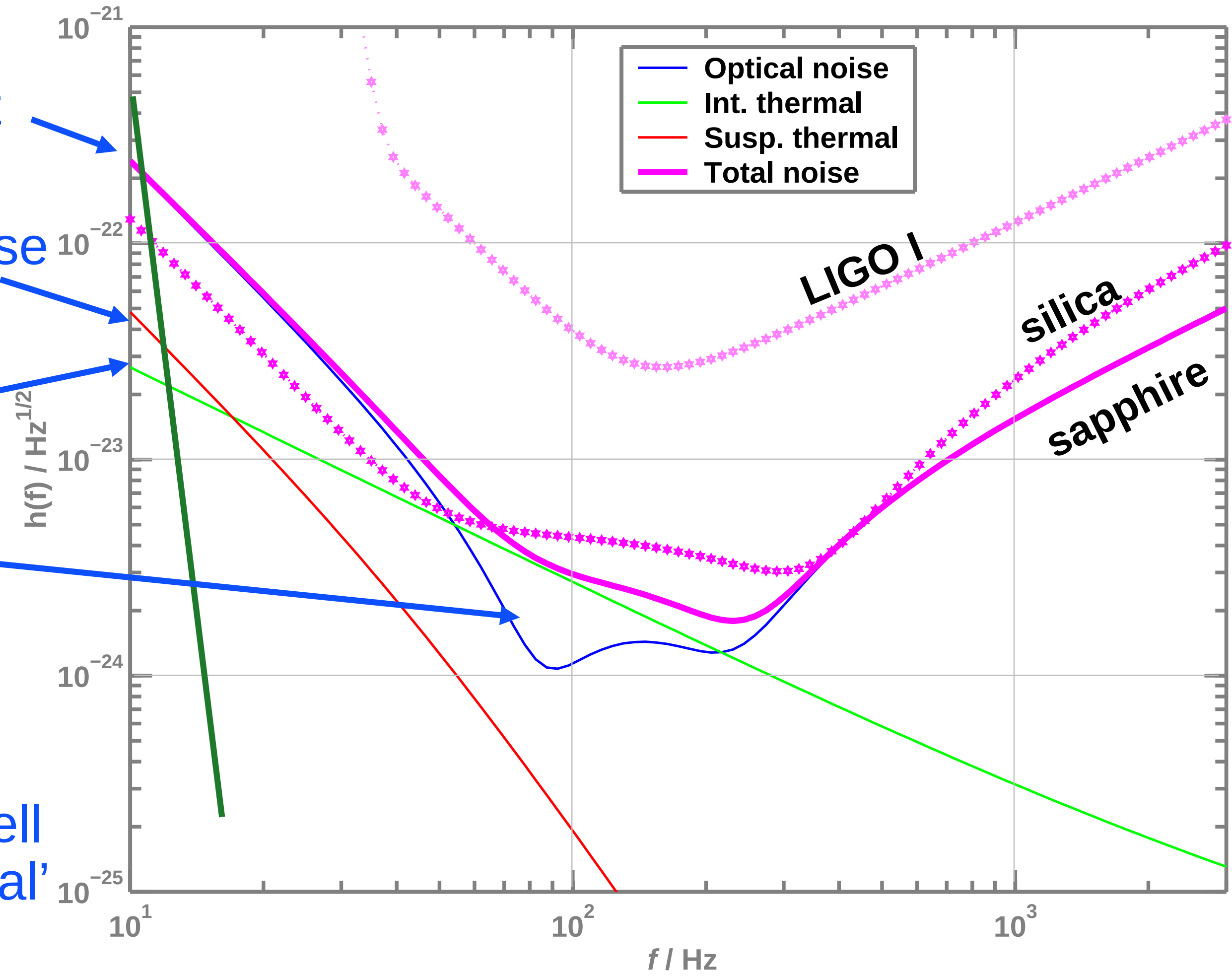
» Active seismic isolation

» Active thermal correction

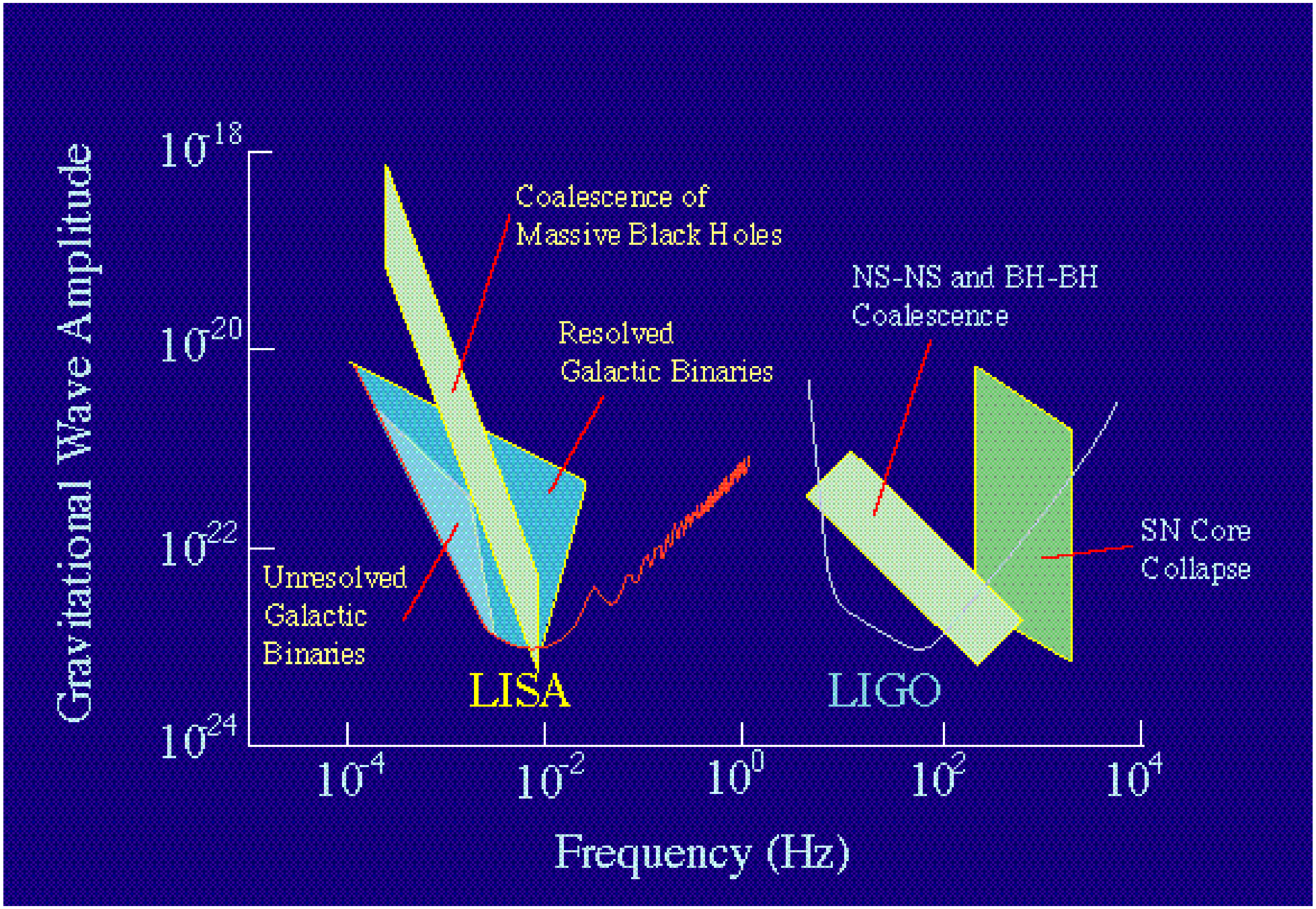
» Output mode cleaner

Projected Performance

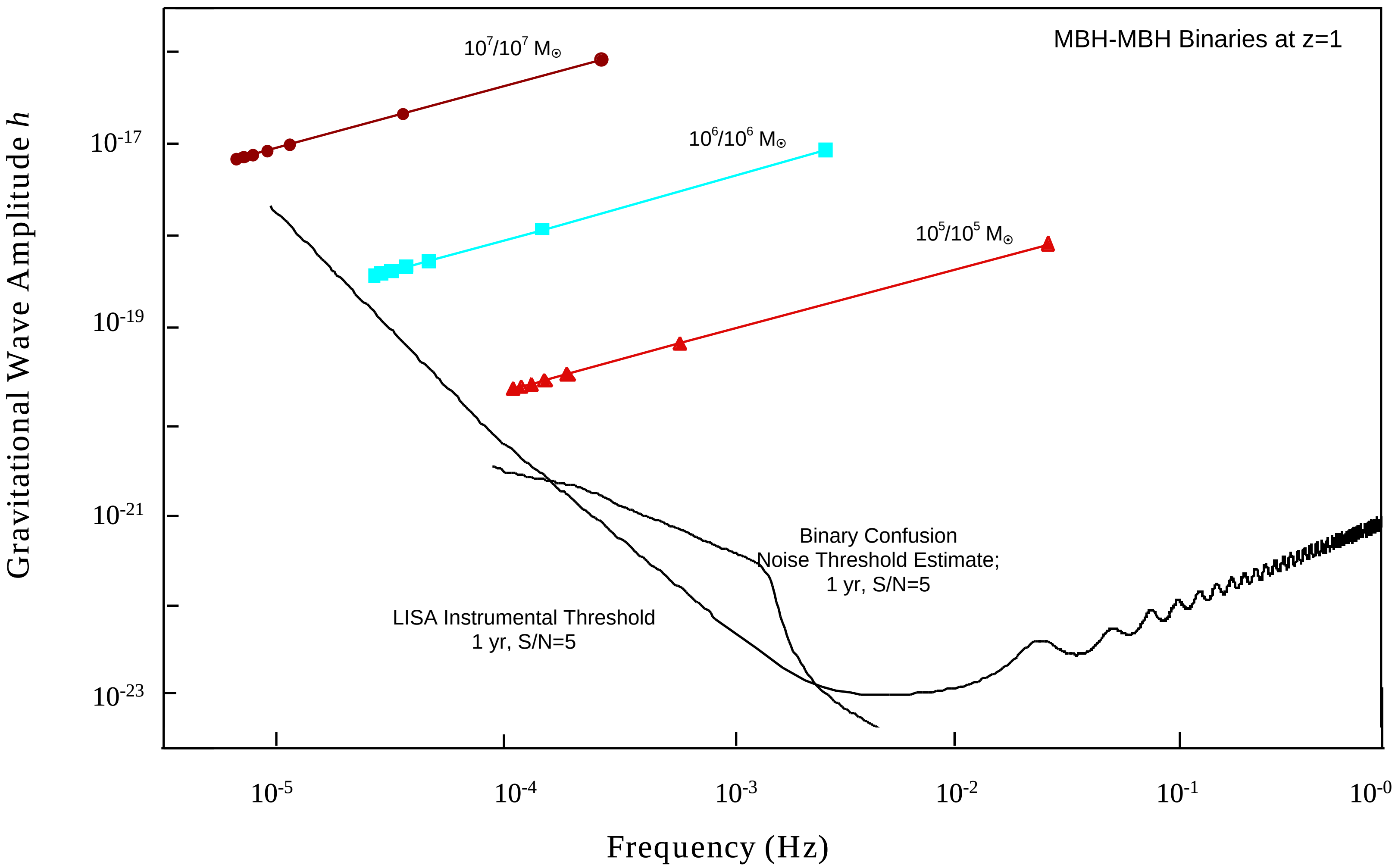
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises



The Gravitational-Wave Spectrum



Massive Black Holes in Merging Galaxies



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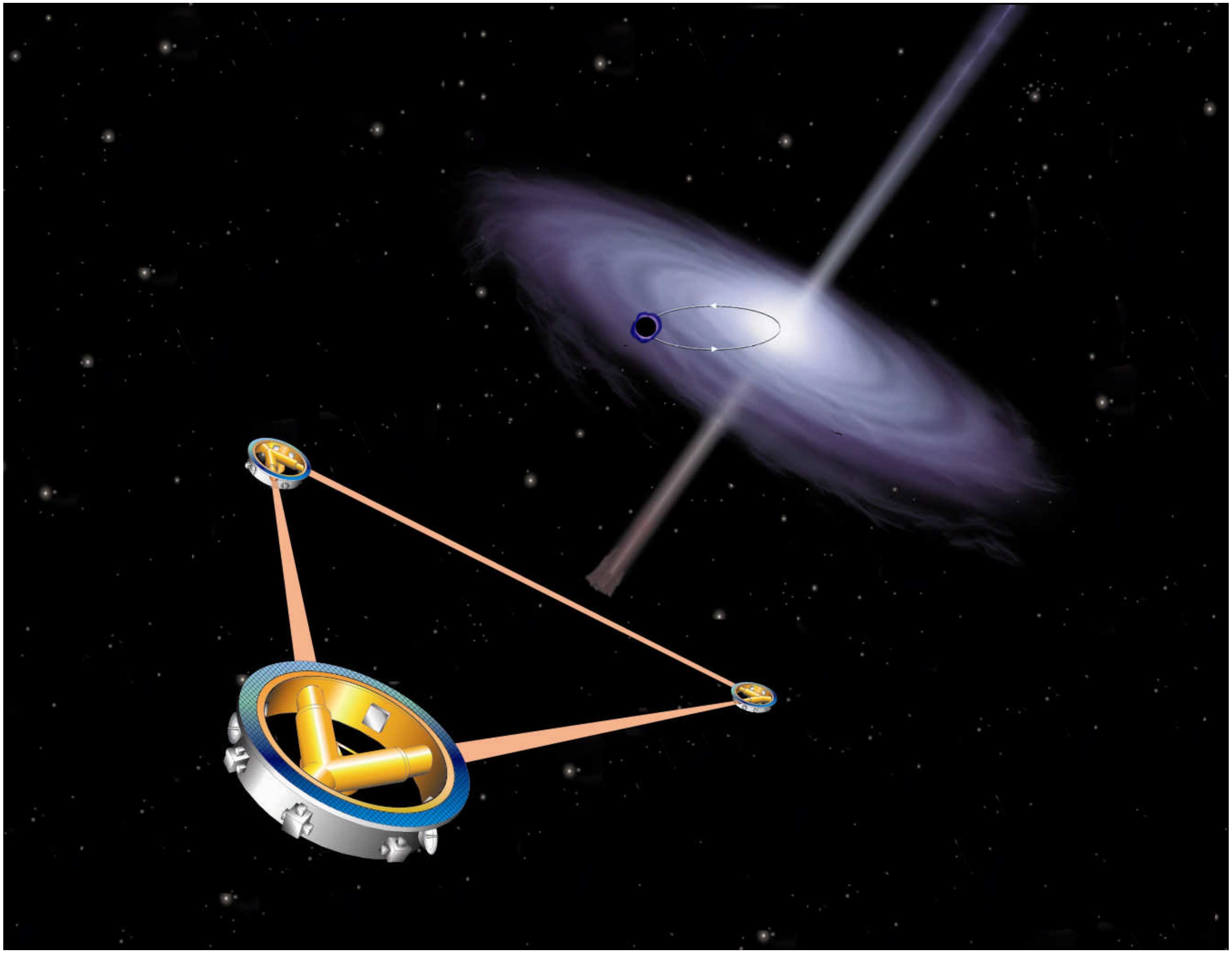
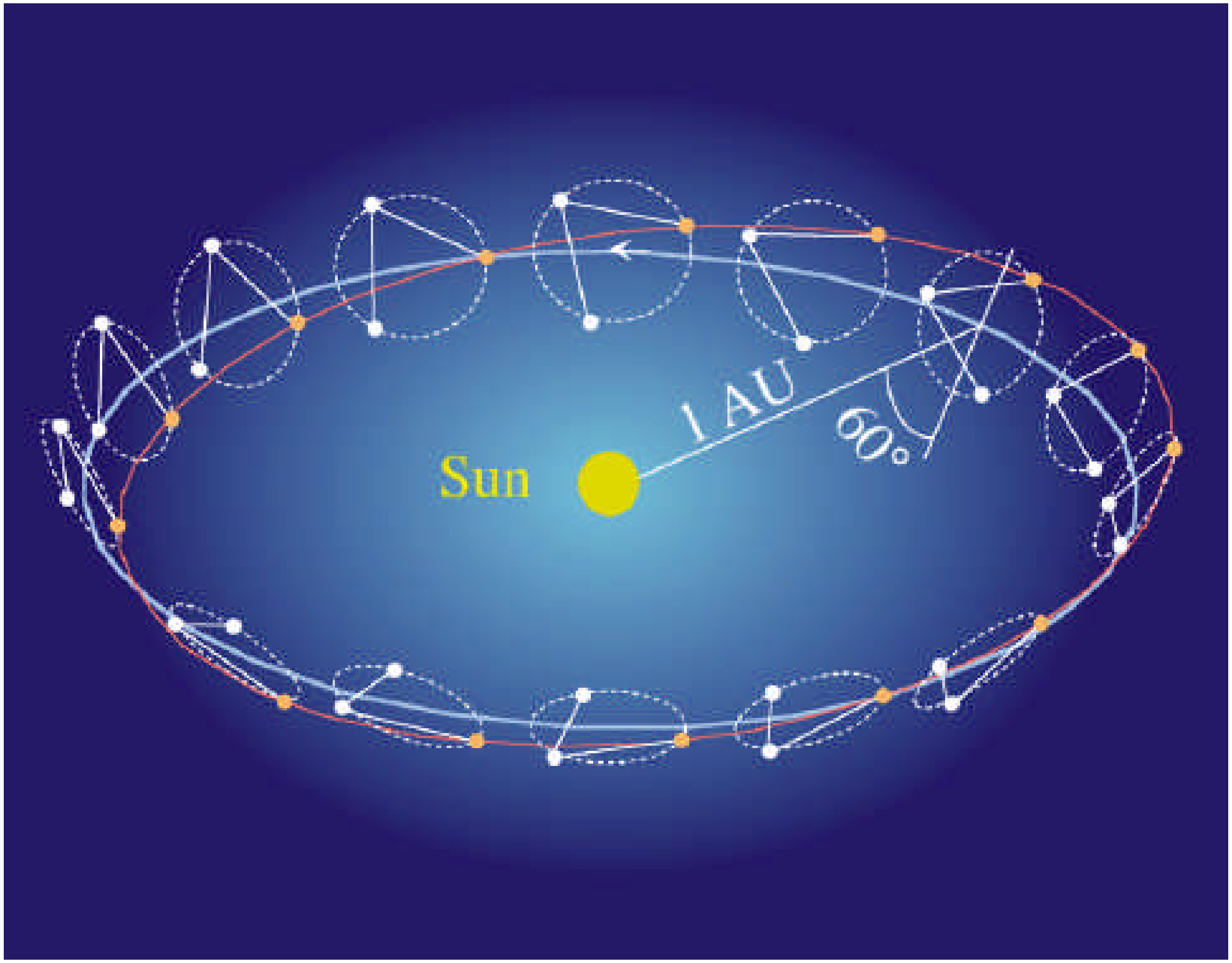
Mission Concept

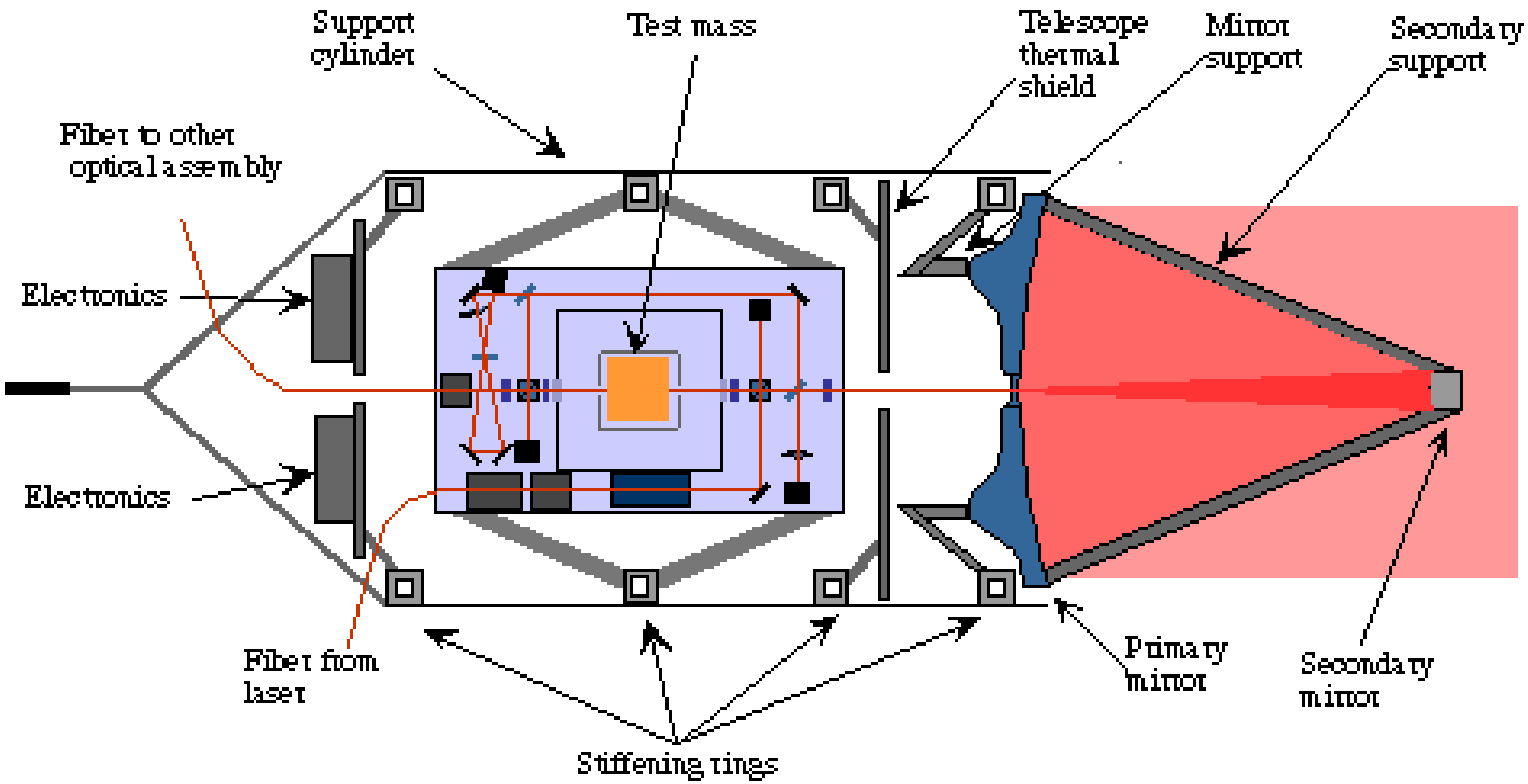


Spacecraft Orbits

- Spacecraft orbits evolve under gravitational forces only
- Spacecraft fly “drag-free” to shield proof masses from non-gravitational forces



Optical System



LISA