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# Building LIGO: A Big Science Project

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SURF-REU Undergraduate Seminar

California Institute of Technology

August 23, 1996

# Microsoft Bookshelf 95

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**gravitational wave**

**gravitational wave** *noun*

*Physics.*

A hypothetical wave that is held to propagate the force of gravity and to travel at the speed of light. Also called *gravity wave*.

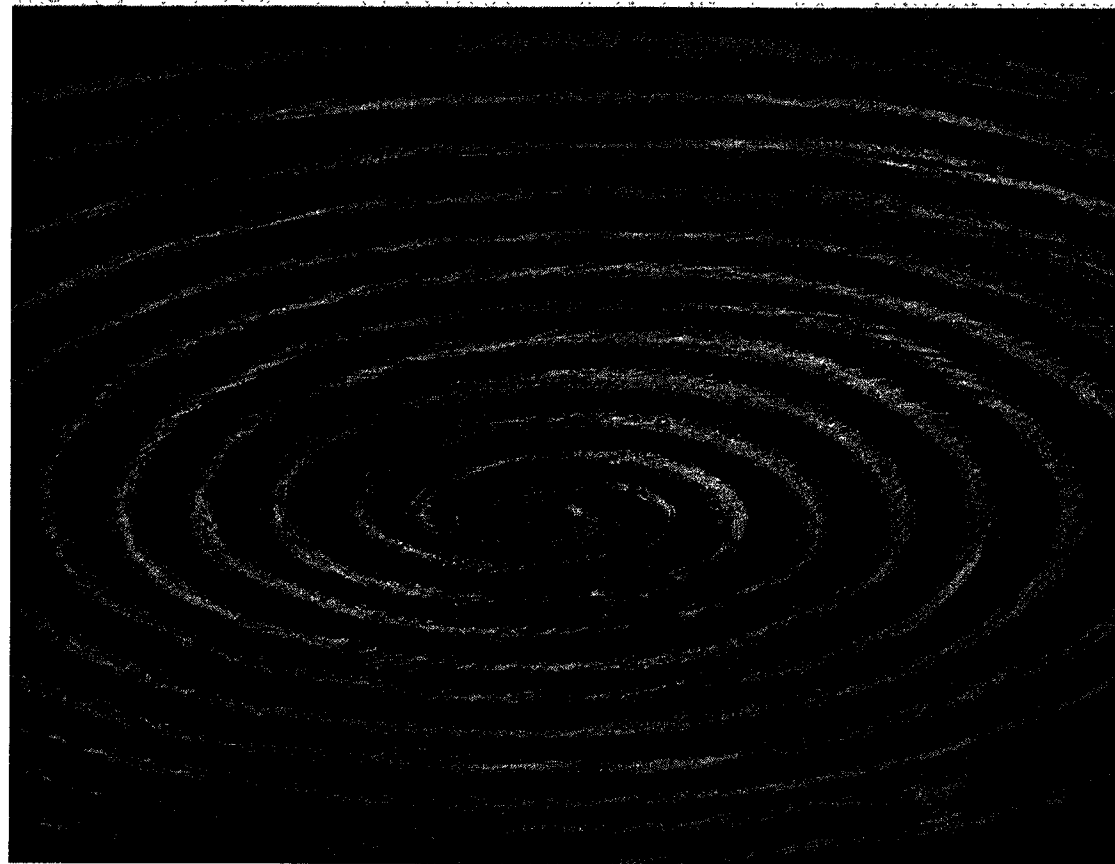
# This Talk

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- Science and Human Vision
- Recapitulation of the main points in the talks this summer
- Big Science
- Big Project
  - » Managing a Project
- A Travelogue Through LIGO Construction

# Neutron Star Inspiral Embedding Diagram

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# Science and Human Vision

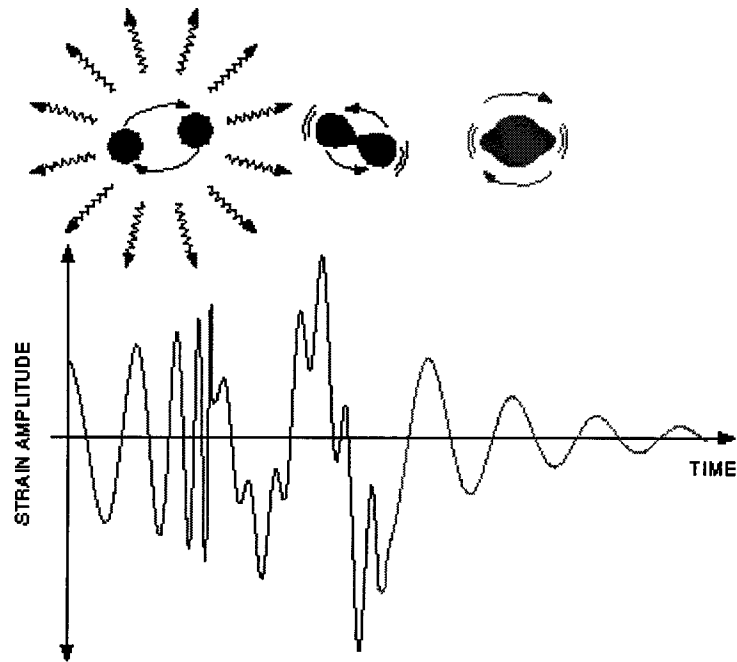
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- Science is a creative human activity
- Newton
- Einstein from 1905-1915  
(read “Subtle is the Lord...” - Pais)
- Einstein’s thought underpins all of the important elements of LIGO
  - » gravitational radiation
  - » photons as quanta
  - » thermal physics - Brownian motion
  - » even “Big Science”



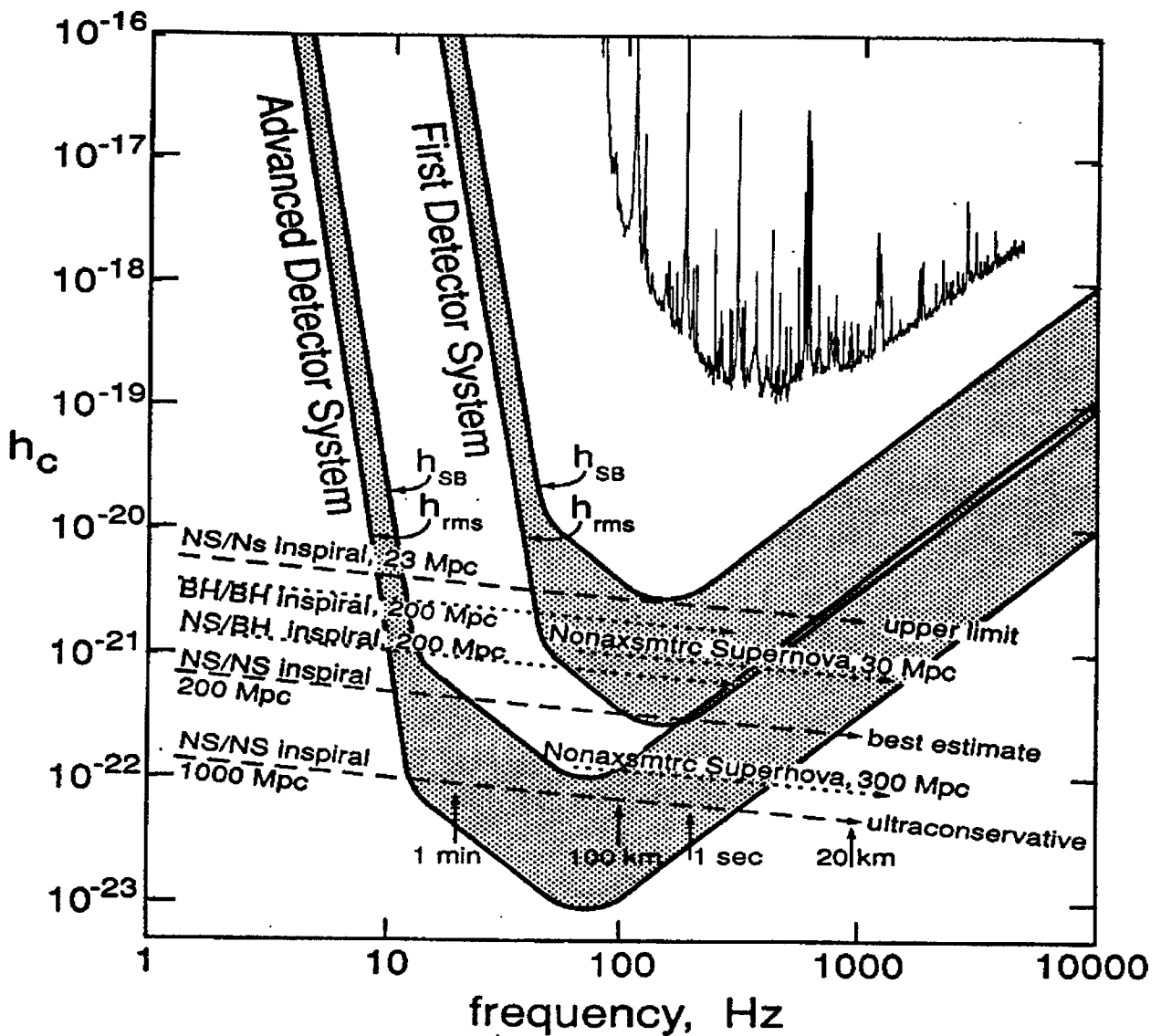
# A Gravitational Wave Signal

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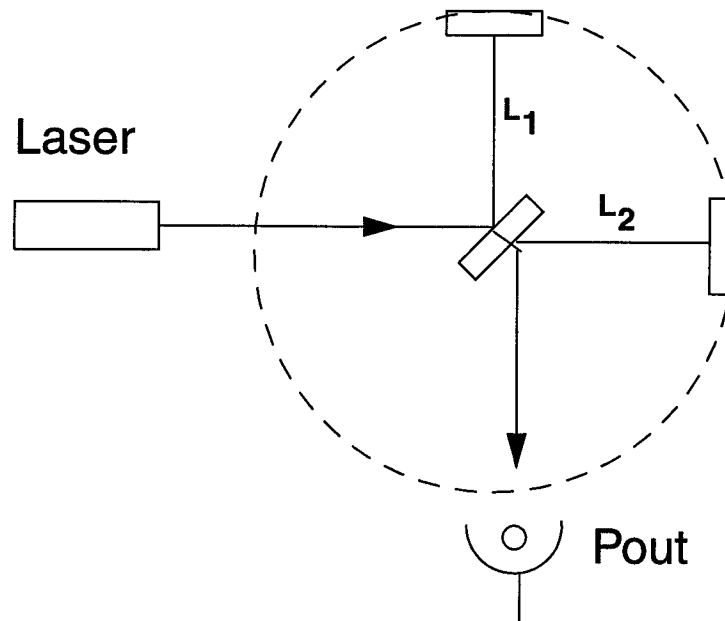
Signal from a neutron star - neutron star binary inspiral/coalescence

# LIGO DETECTOR SPECTRAL NOISE DENSITY



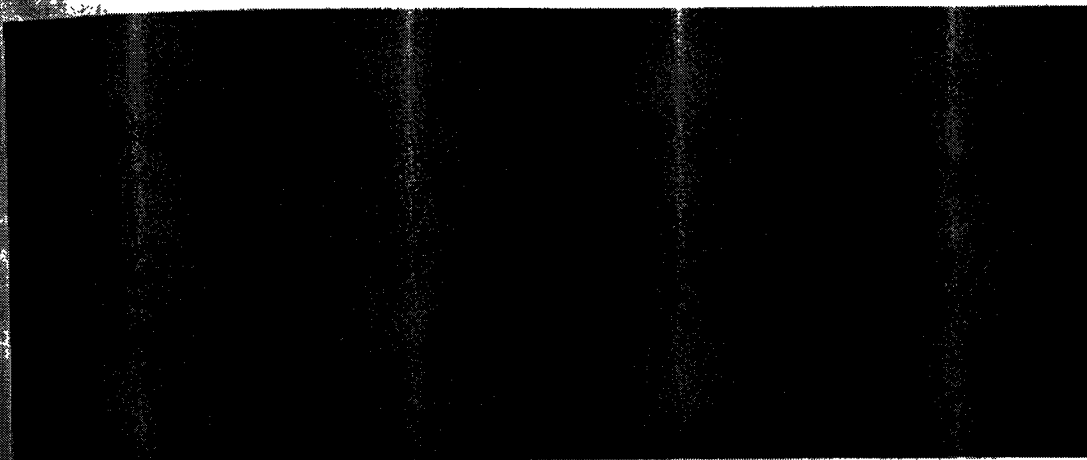
# MICHELSON INTERFEROMETER

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The Michelson-Morley Experiment

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# FABRY-PEROT INTERFEROMETER

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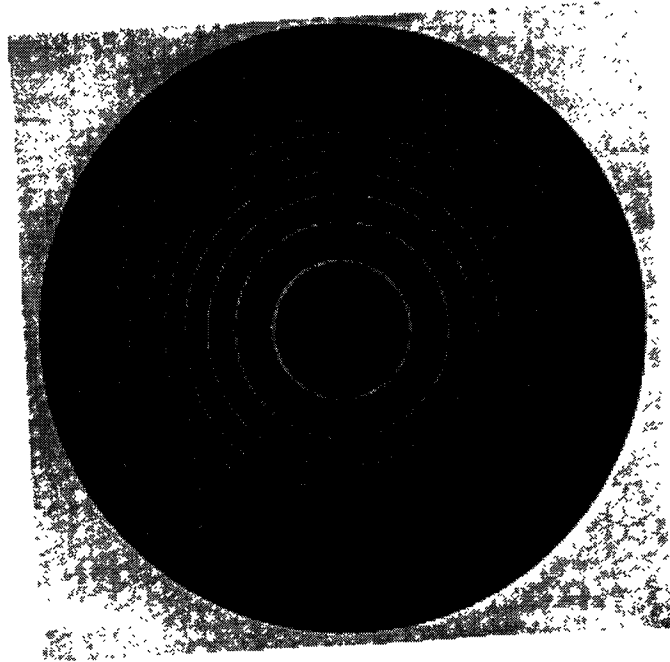
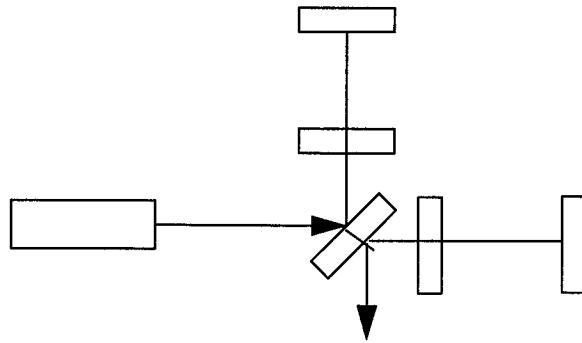
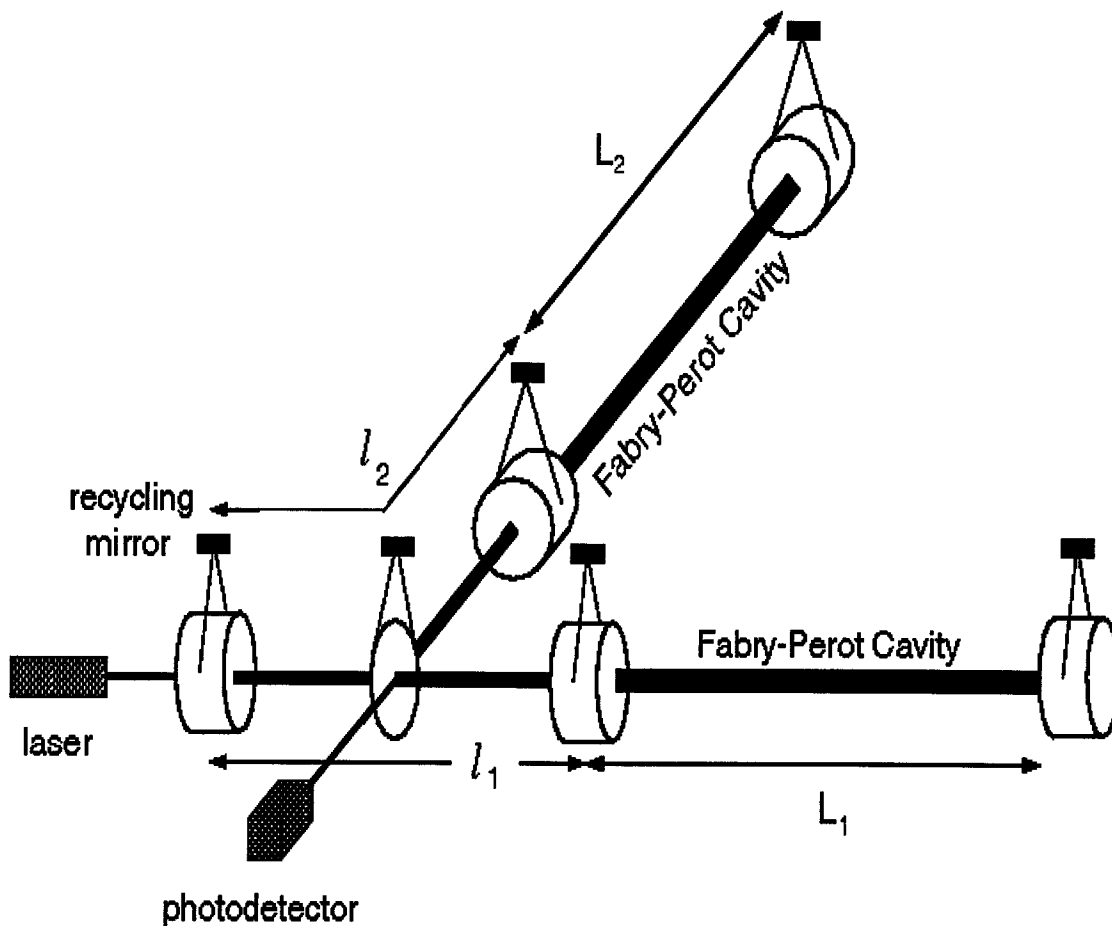


Fig. 7.60. FABRY-PEROT fringes.

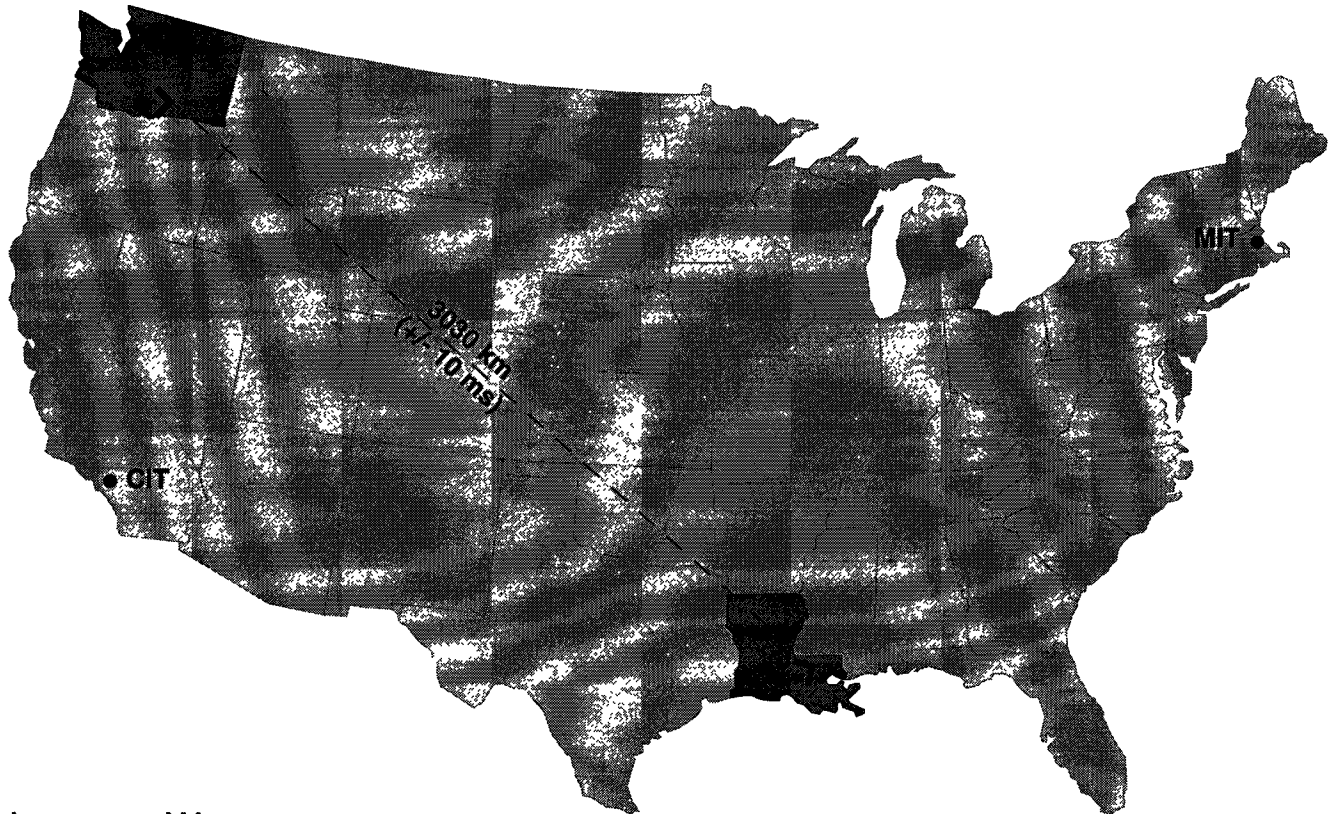
# LIGO INTERFEROMETER CONFIGURATION

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# LIGO SITES

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## HANFORD, WASHINGTON

- LOCATED ON U.S. DOE RESERVATION
- TREELESS, SEMI-ARID HIGH DESERT
- APPROX. 25 KM FROM RICHLAND, WA (POPULATION :140,000)
- **TWO INTERFEROMETERS (4 KM, 2KM) LOCATED AT THIS SITE**

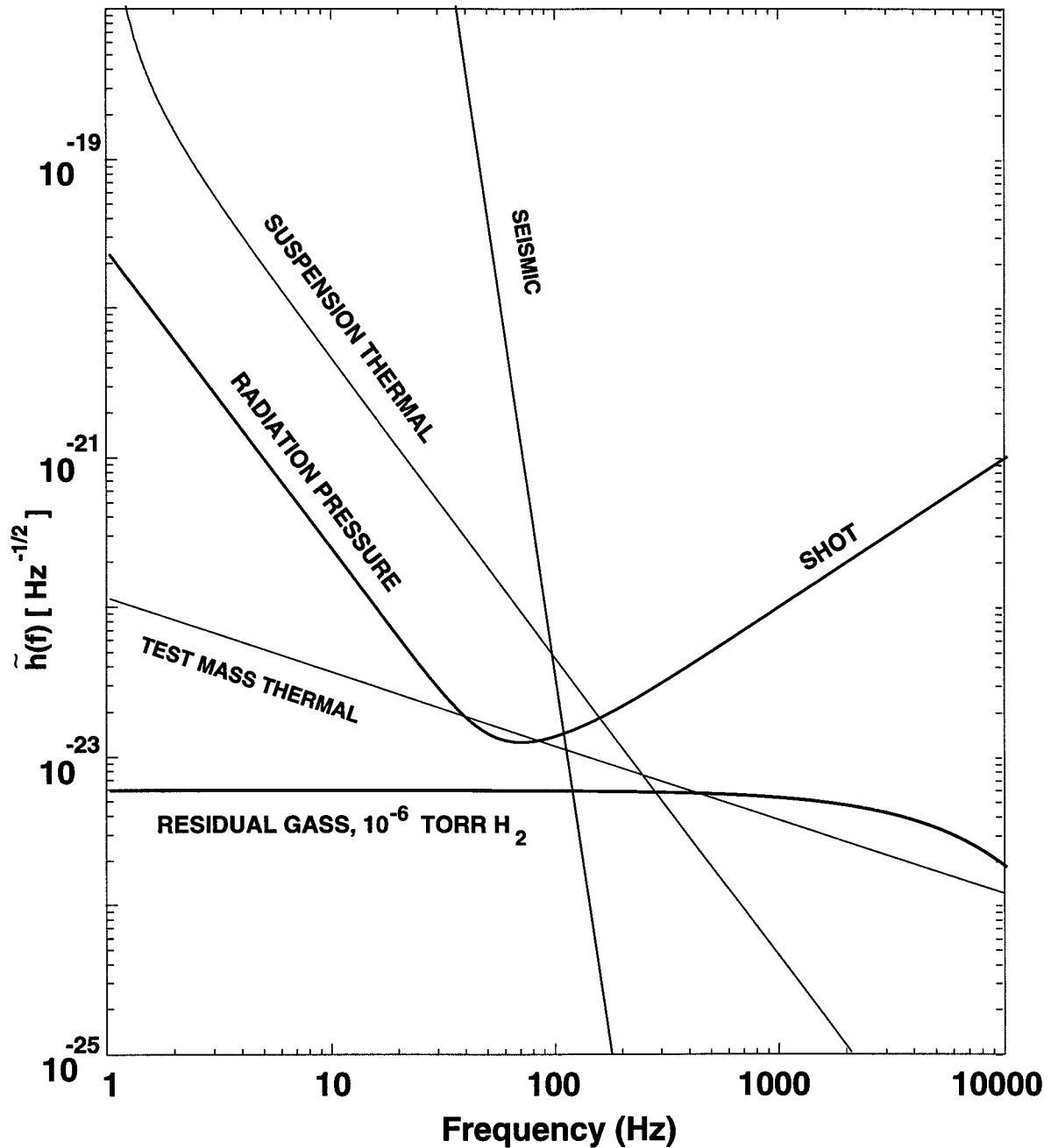
## LIVINGSTON, LOUISIANA

- LOCATED IN FORESTED RURAL AREA
- MIXED FOREST; LOW-LYING; POOR DRAINAGE
- APPROX. 50 KM FROM BATON ROUGE, LA (POPULATION :450,000)
- **ONE 4 KM INTERFEROMETER LOCATED AT THIS SITE**



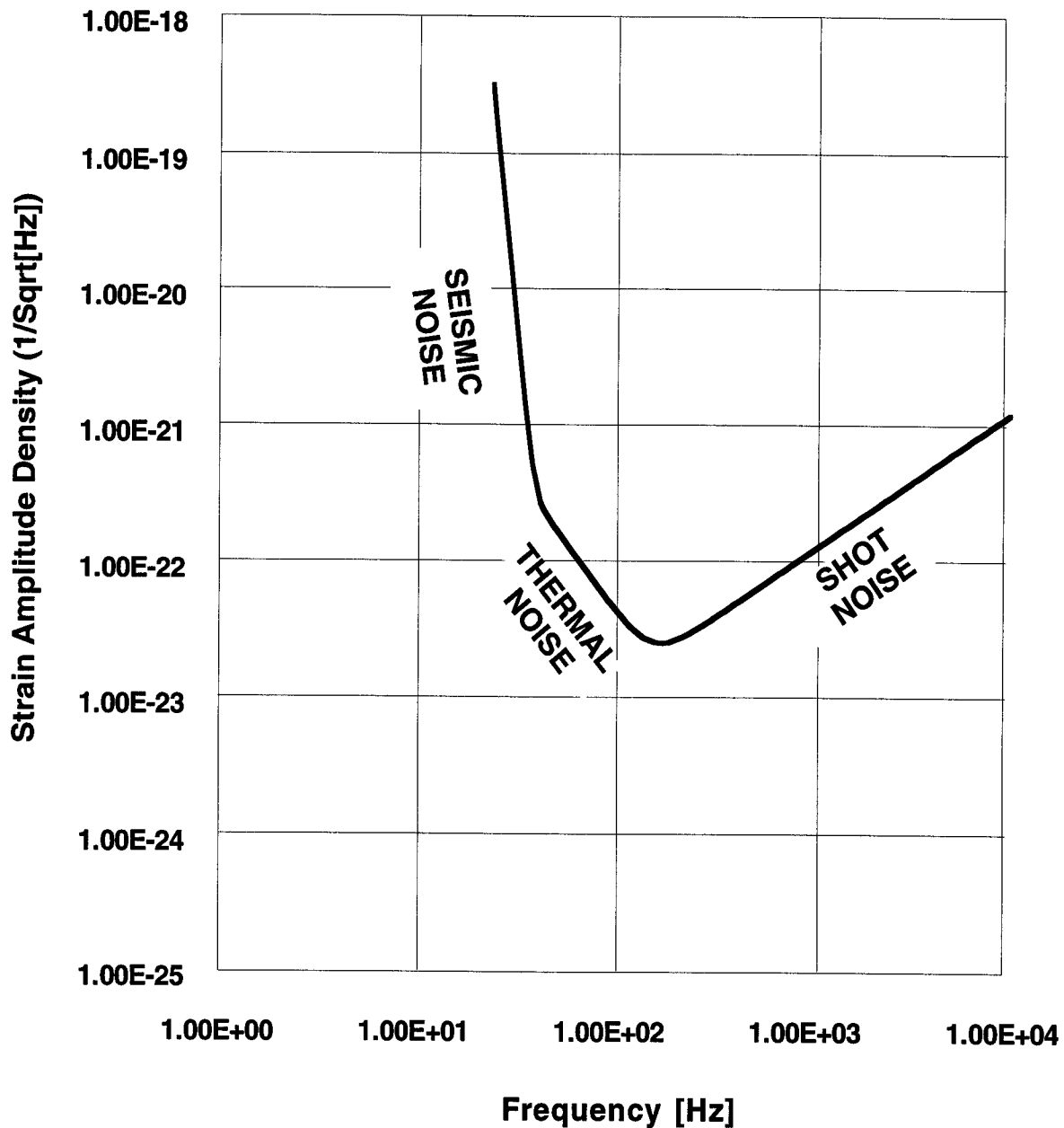
# INITIAL DESIGN PERFORMANCE GOAL

INITIAL INTERFEROMETER SENSITIVITY

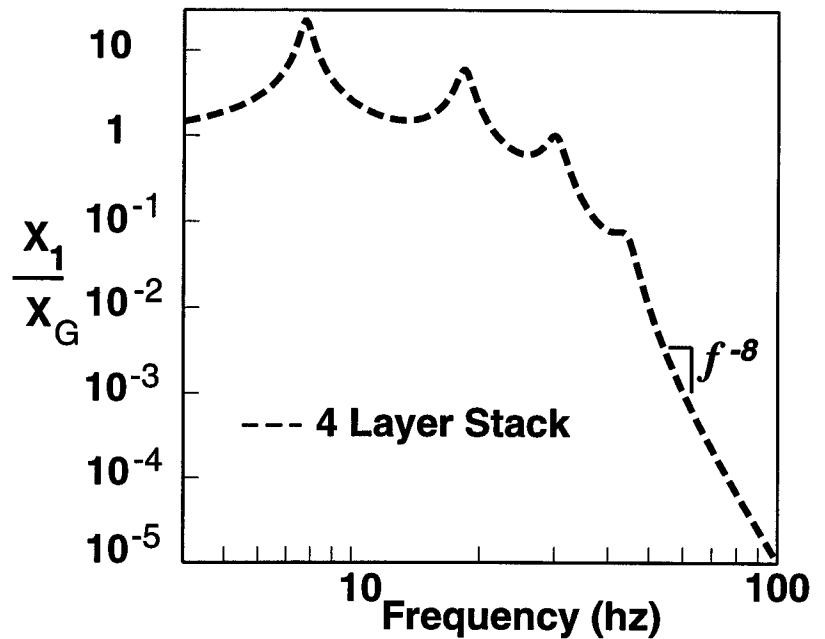
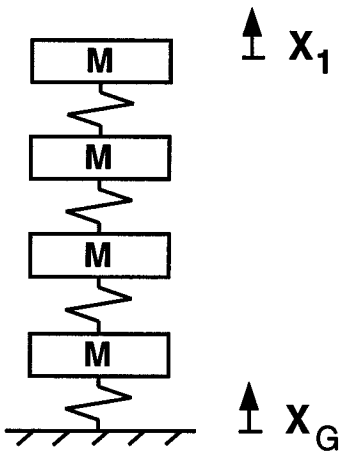
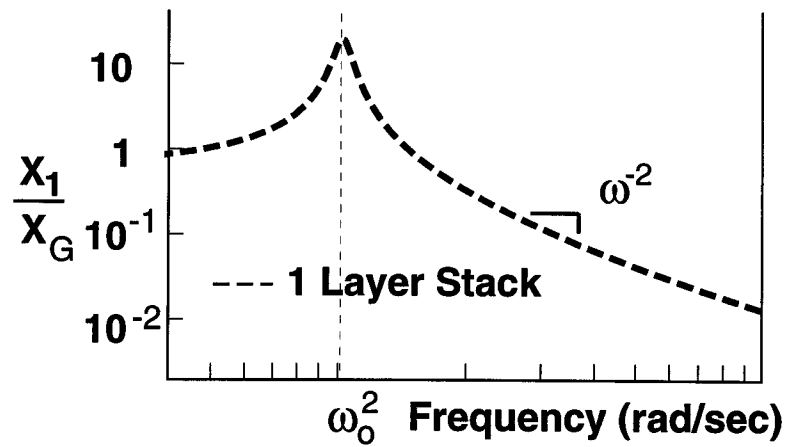
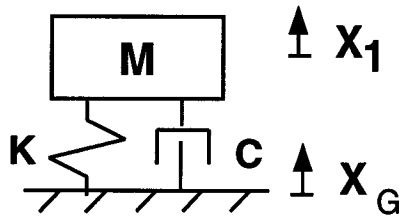


# INITIAL DESIGN PERFORMANCE GOAL

## LIGO Initial Interferometer Noise Equivalent Strain

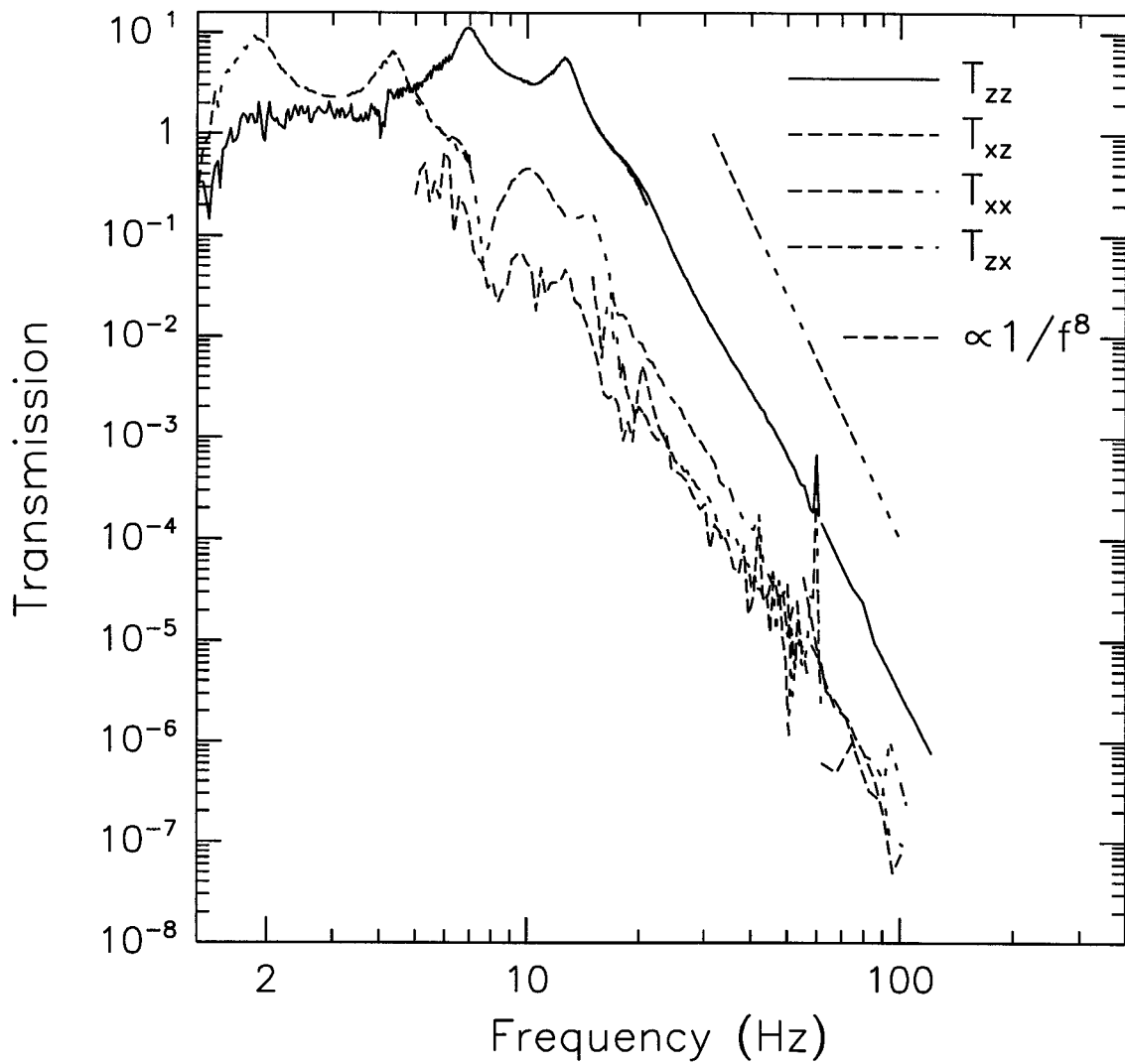


# SEISMIC ISOLATION



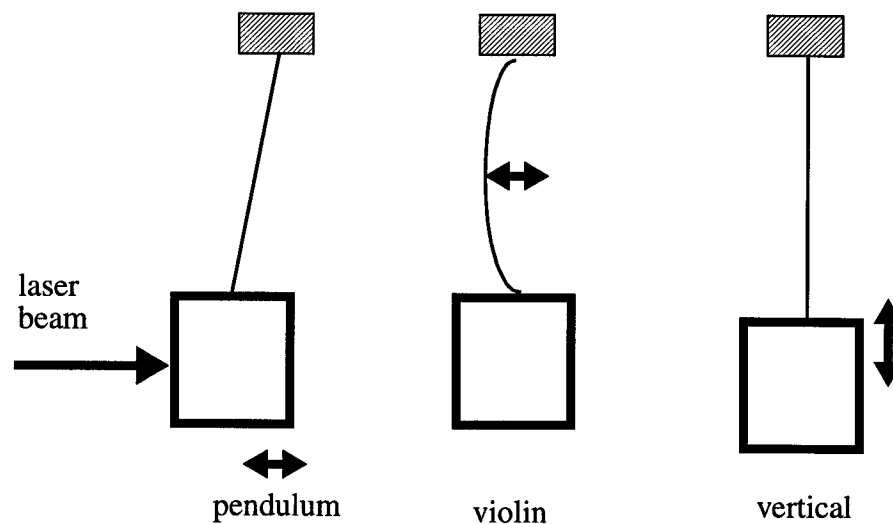
Simple Model of Mark 2 Stack Isolation (vertical)

# SEISMIC ISOLATION



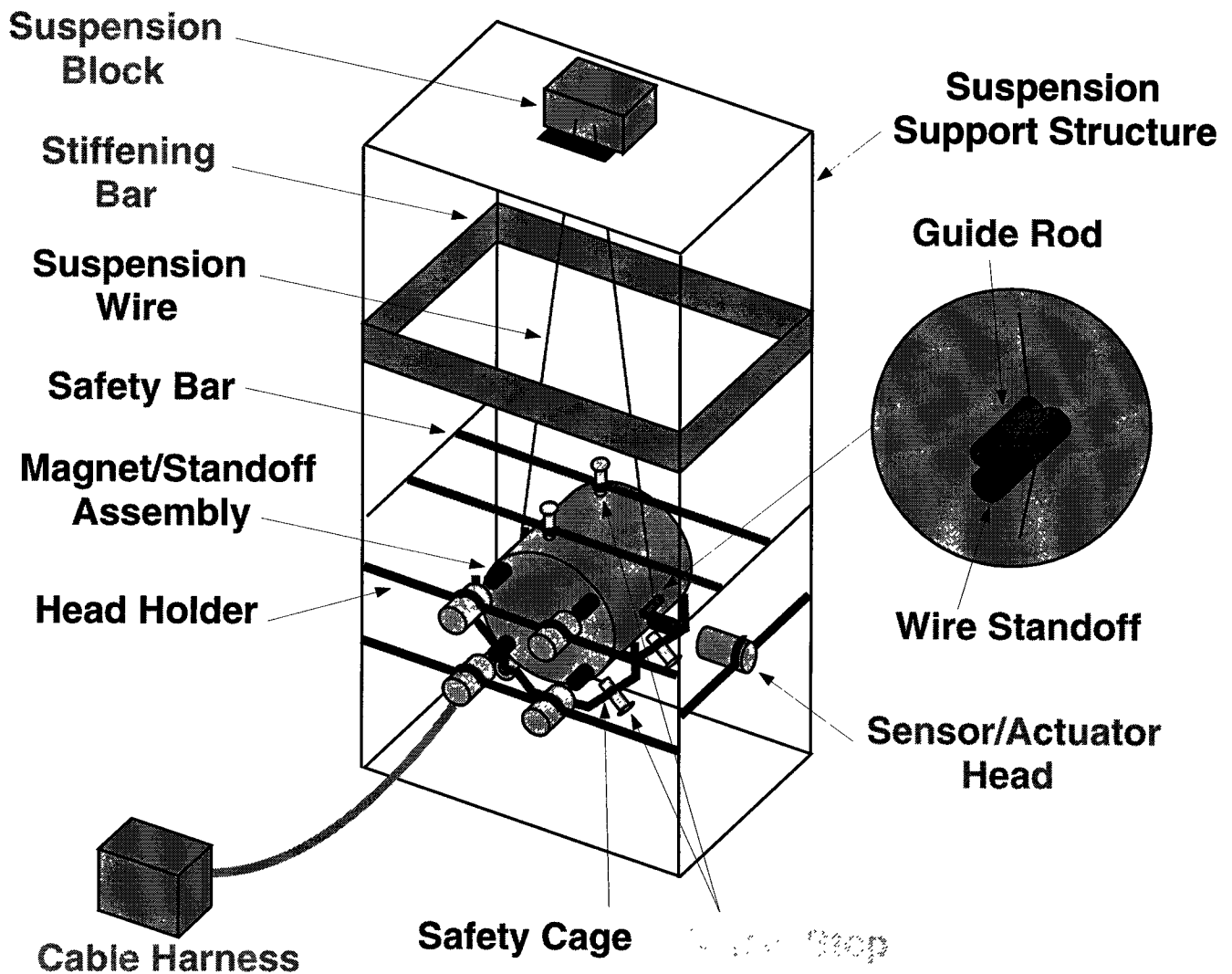
# SUSPENSION THERMAL NOISE

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# TEST MASS SUSPENSION



# “EXCESS” SUSPENSION THERMAL NOISE

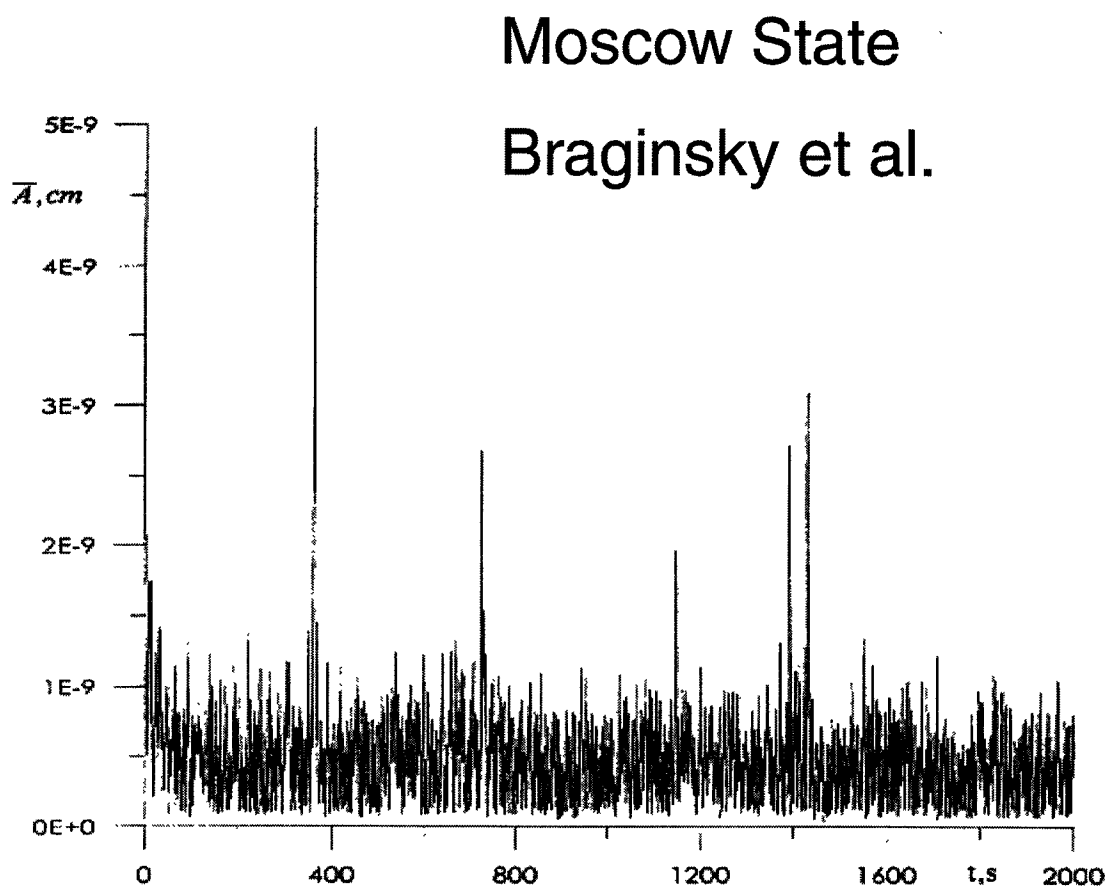
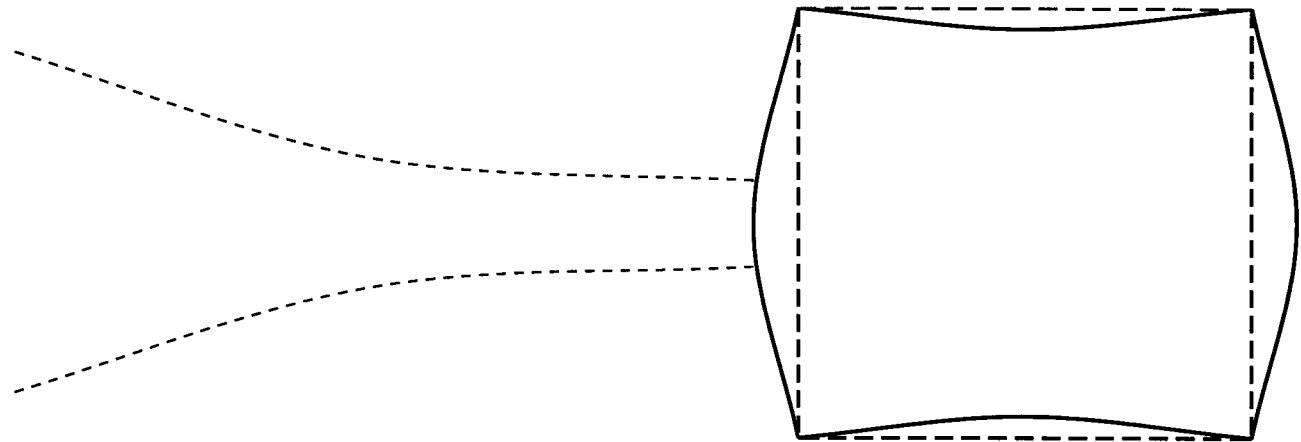


Fig. 5. Fragment of the record of noise oscillation of tungsten wire

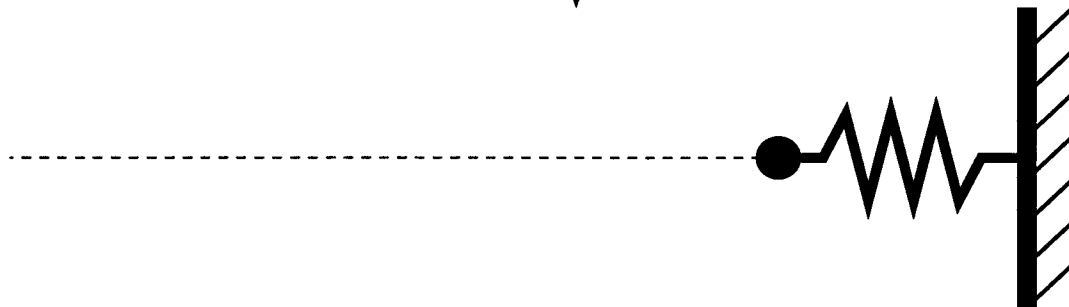
# TEST MASS INTERNAL THERMAL NOISE

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optical mode:  $\psi(\rho, \theta, z)$   
wave vector:  $\vec{k}$

mirror mode:  $\vec{u}(\rho, \theta, z)$   
frequency:  $\omega_n$

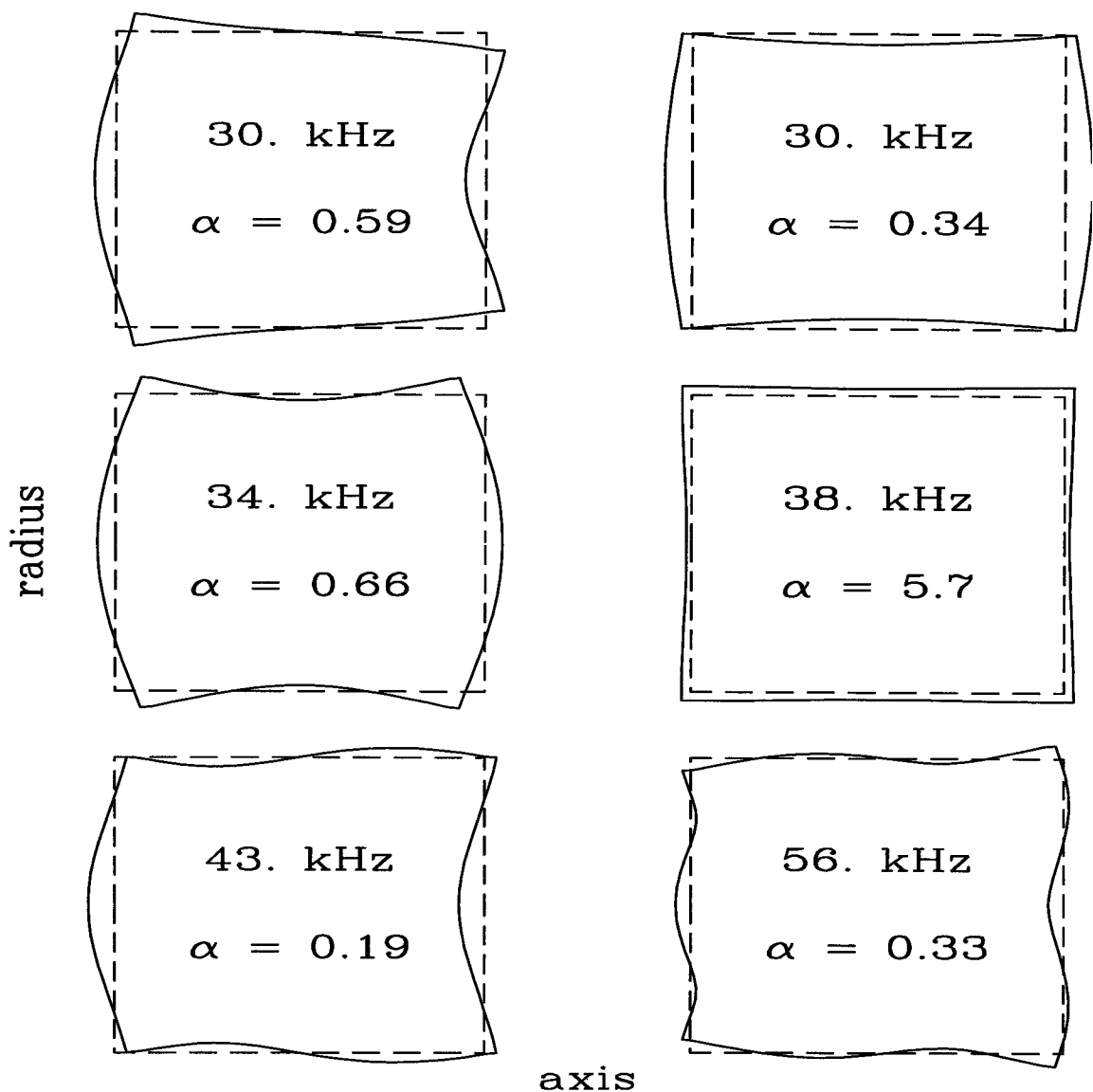


one-dimensional  
laser beam  
wave vector:  $\vec{k}$

point mass on spring  
mass:  $\alpha_n m$   
frequency:  $\omega_n$

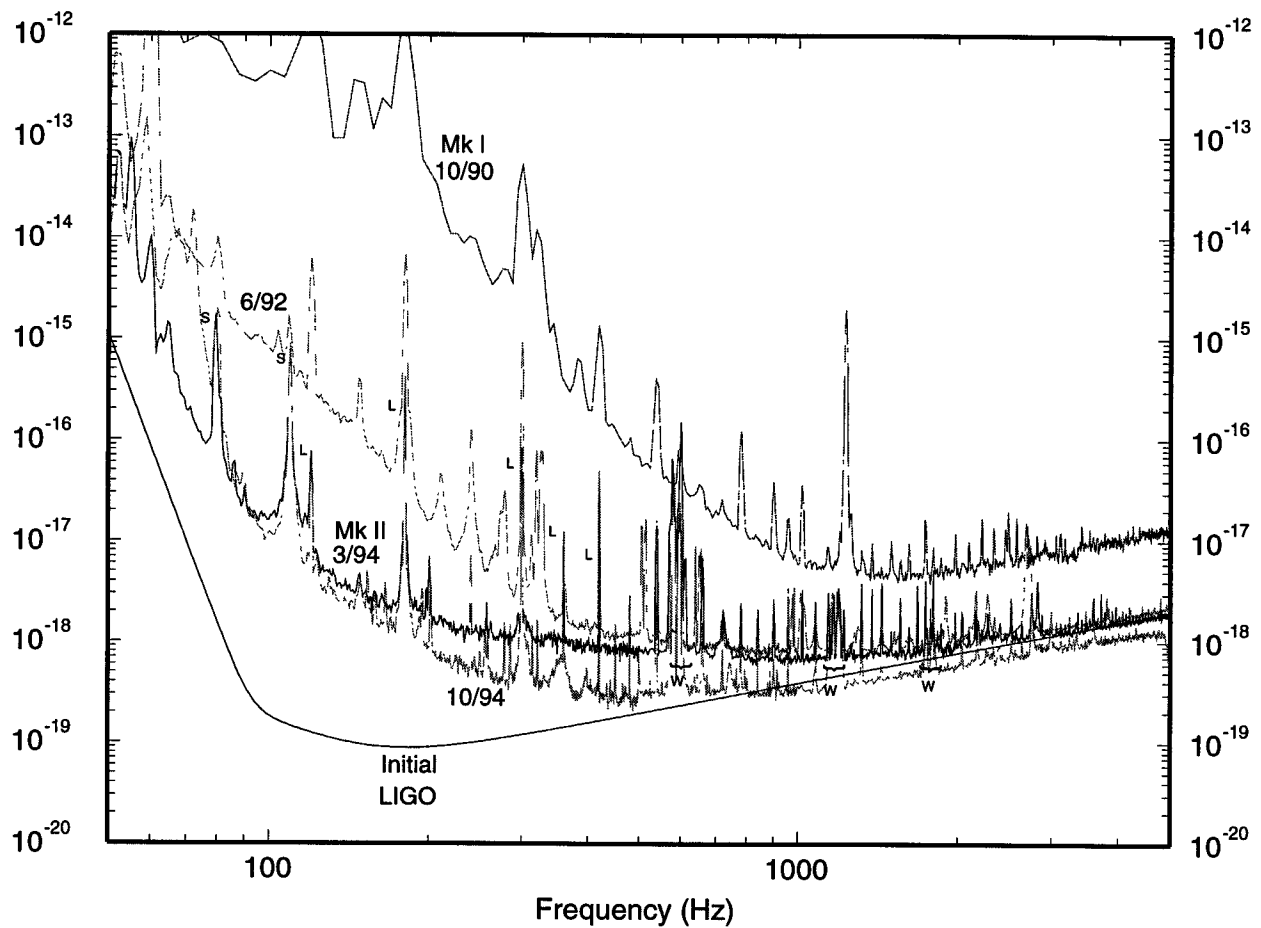
# TEST MASS INTERNAL THERMAL NOISE

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# PROGRESS IN 40 METER DISPLACEMENT NOISE R&D

Displacement Sensitivity of Caltech 40 m Interferometer



# “Big Science”

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- This phrase is not generally used to describe scientific research with a “big” consequence or a “big” challenge
- “Big Science” refers to large scientific projects requiring great resources, considerable planning, large numbers of scientists and collaborating technical staff, and a high level of management in the execution of the project.
  - » CERN LEP and LHC, SSC, Hubble, ...
- Big Science is not generally found on university campuses, and is often treated with disdain

# “Big Science”

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- Ancient big projects
  - » pyramids, Hadrian’s palace, Panama Canal, the Pentagon
- Early Big Science
  - » Mt. Wilson, Palomar observatories
    - read “The Perfect Machine”
- First Big Science (not really science projects)
  - » Manhattan Project
    - based on mass-energy equivalence and initiated by Einstein’s letter to Roosevelt
    - led by Oppenheimer and Gen. Groves (Project Manager of the Pentagon)
  - » NASA space program
- Legacy of relationship between science and defense

# The Goal of the Project Manager

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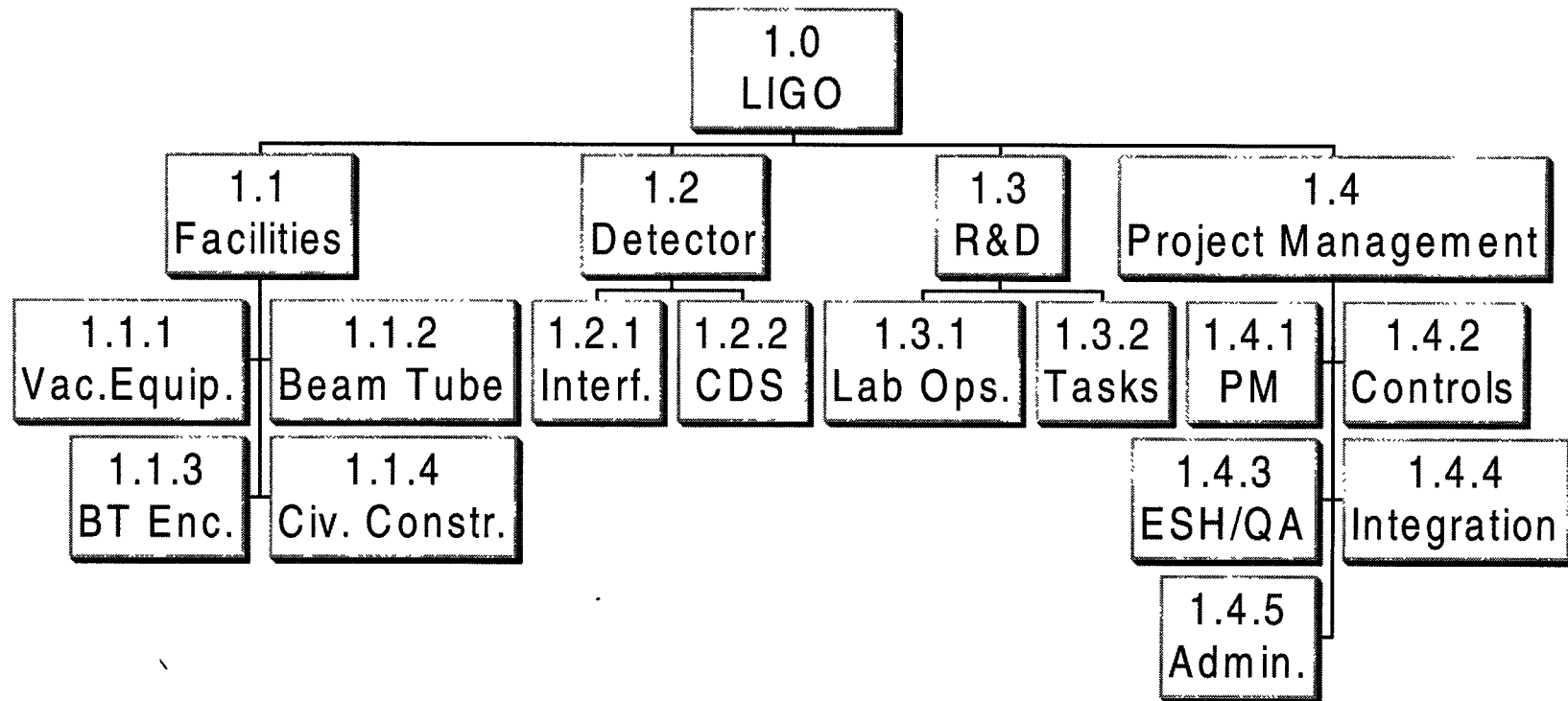
"See first that the design is wise and just: that ascertained, pursue it resolutely; do not for one repulse forego the purpose that you resolved to effect."

*William Shakespeare*

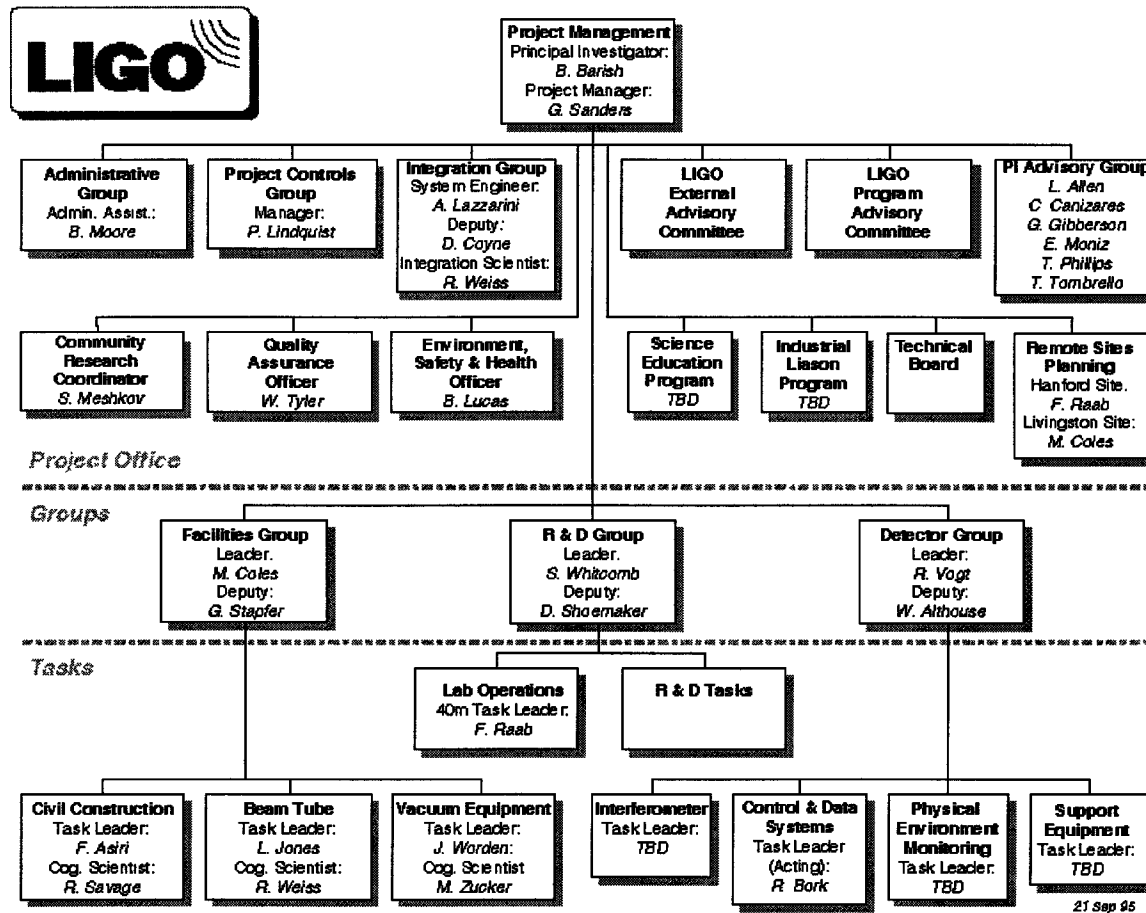


# LIGO Work Breakdown Structure

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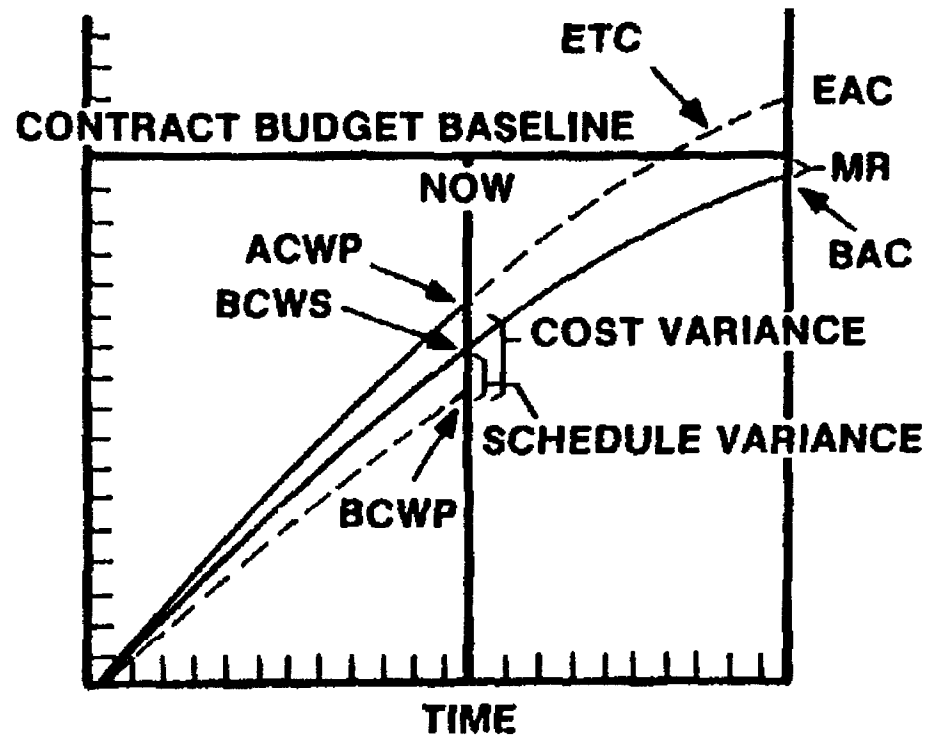


# LIGO Organization



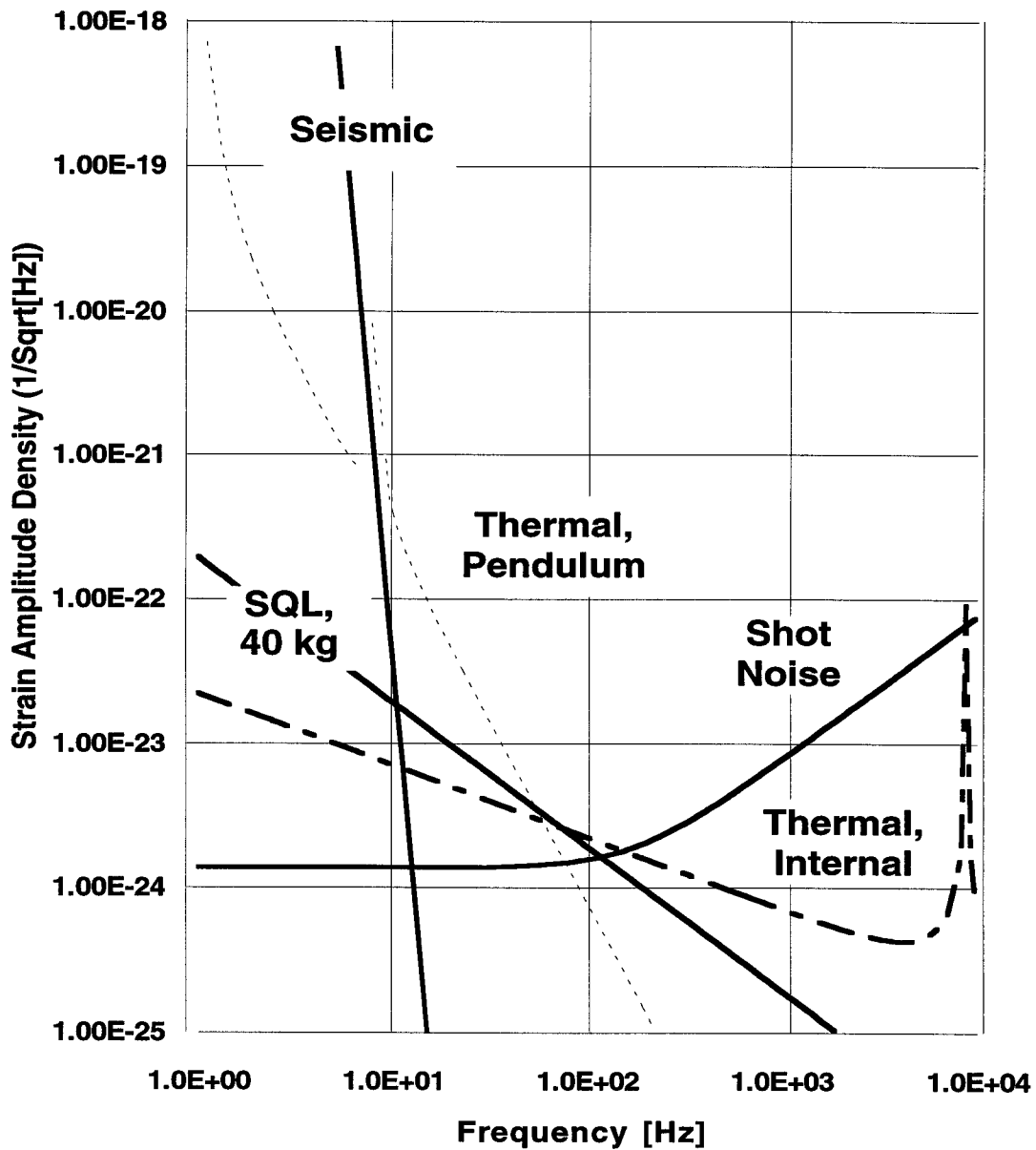
# Performance Measurement Display

## PERFORMANCE MEASUREMENT DATA



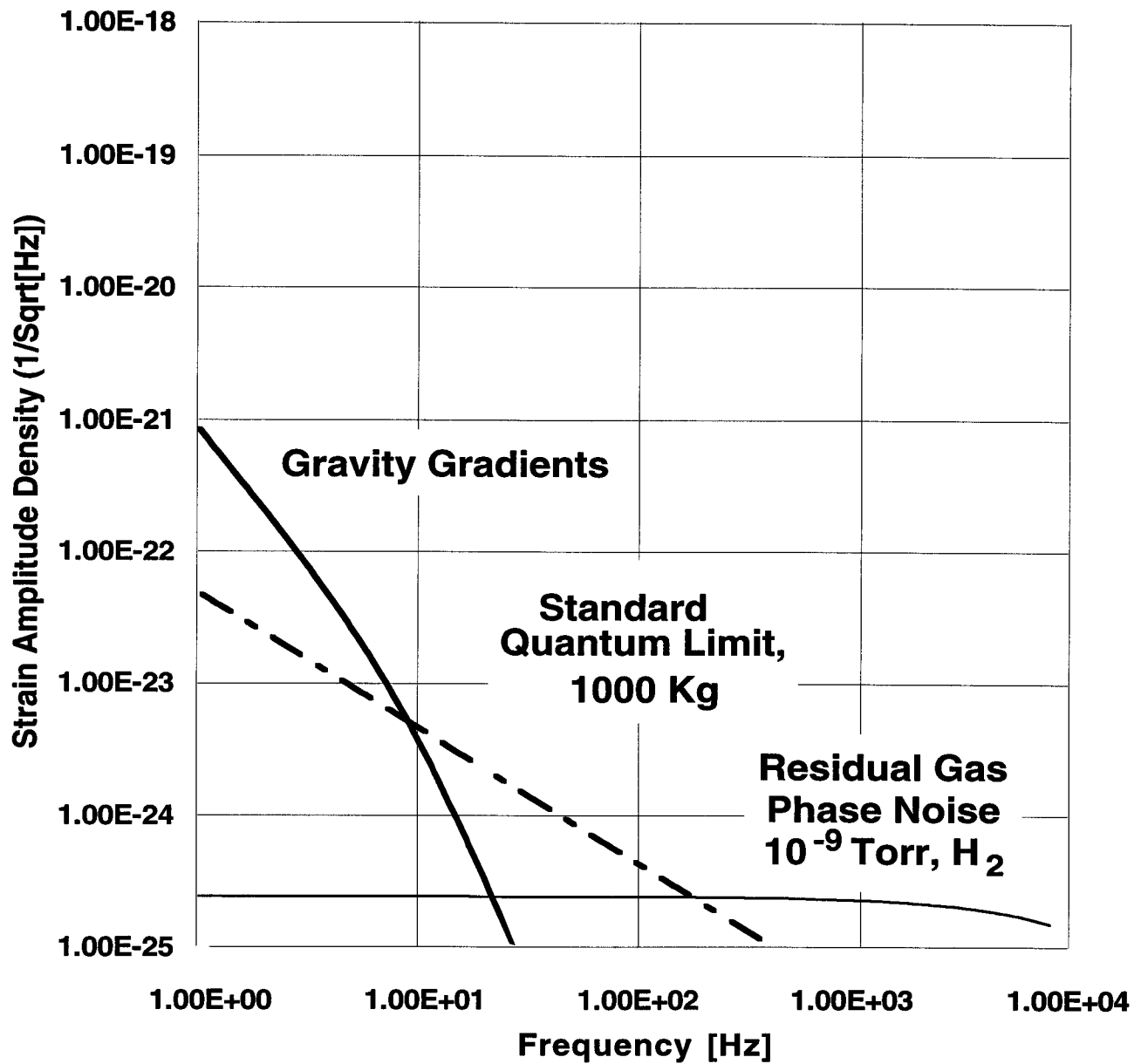
# ADVANCED DESIGN PERFORMANCE GOAL

Enhanced LIGO Interferometer Noise Budget



# LIMITING PERFORMANCE DUE TO FACILITIES

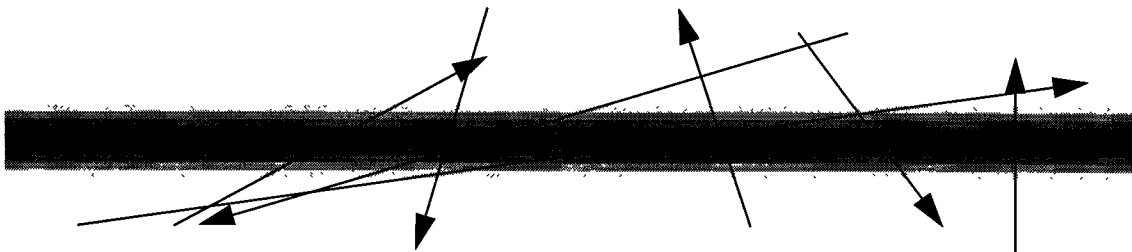
LIGO Facilities Limiting Noise Equivalent Strain



# VACUUM SYSTEM REQUIREMENTS

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**Light must travel 4 km without attenuation or degradation**



- index fluctuations in gas cause variations in optical path
  - › pressure, polarizability, molecular speed of various species
  - › light beam intensity distribution, coherence of effect

$$h(f) \approx 4\pi\alpha \left( \frac{2\rho}{v_0 w_0 l} \right)^{\frac{1}{2}}$$

- requirement for quality of vacuum in 4 km tubes from this
  - › H<sub>2</sub> of 10<sup>-6</sup> torr initial, 10<sup>-9</sup> torr ultimate
  - › H<sub>2</sub>O of 10<sup>-7</sup> torr initial, 10<sup>-10</sup> ultimate
- vacuum system, 1.22 m diameter, ~10,000 cubic meters

# LIGO Vacuum System

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# LIGO VACUUM EQUIPMENT

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LIGO-G960182-00-M



Chamber  
and  
BT photos

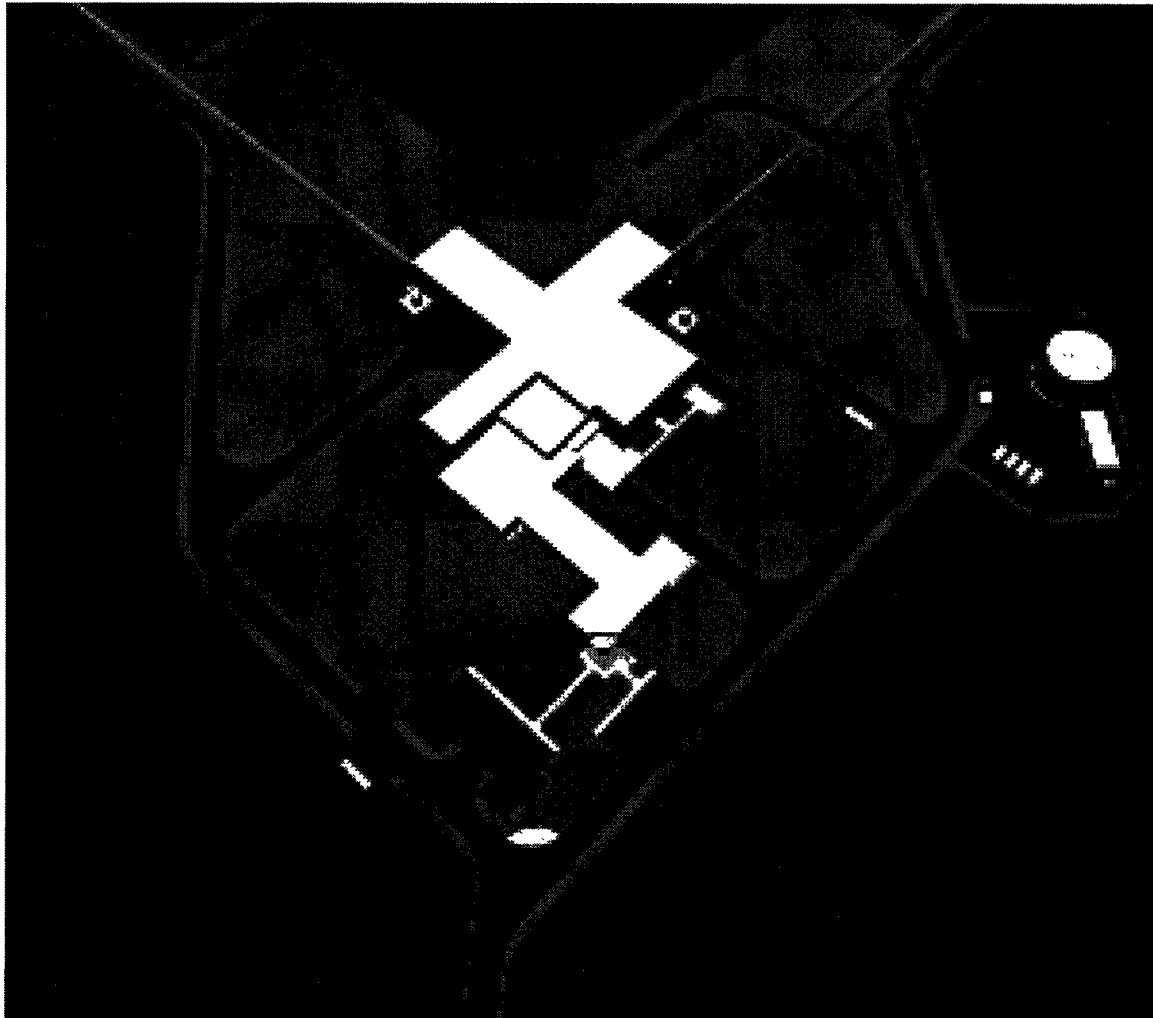
# LIGO Beam Tube

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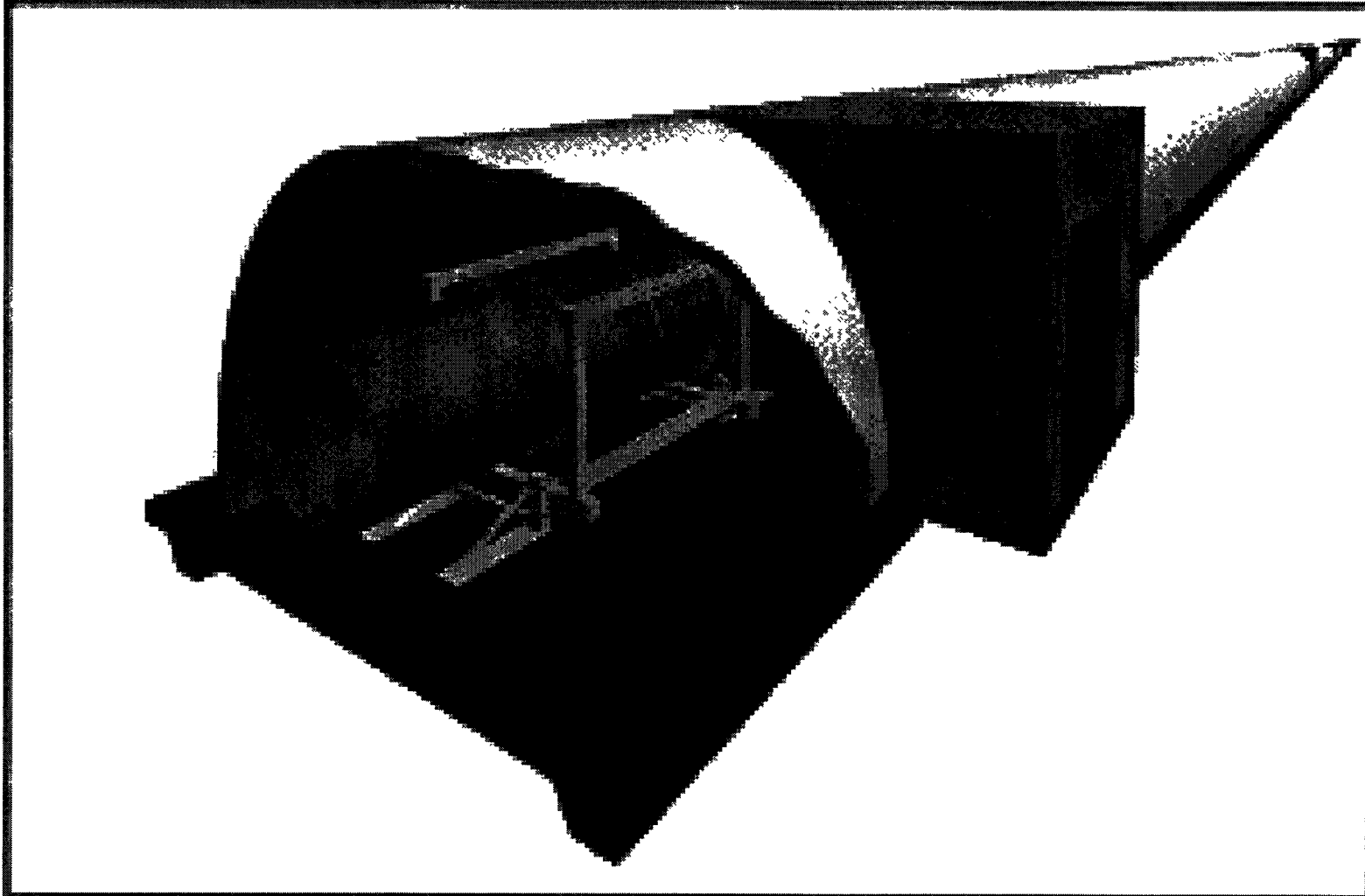


# LIGO Conventional Facilities

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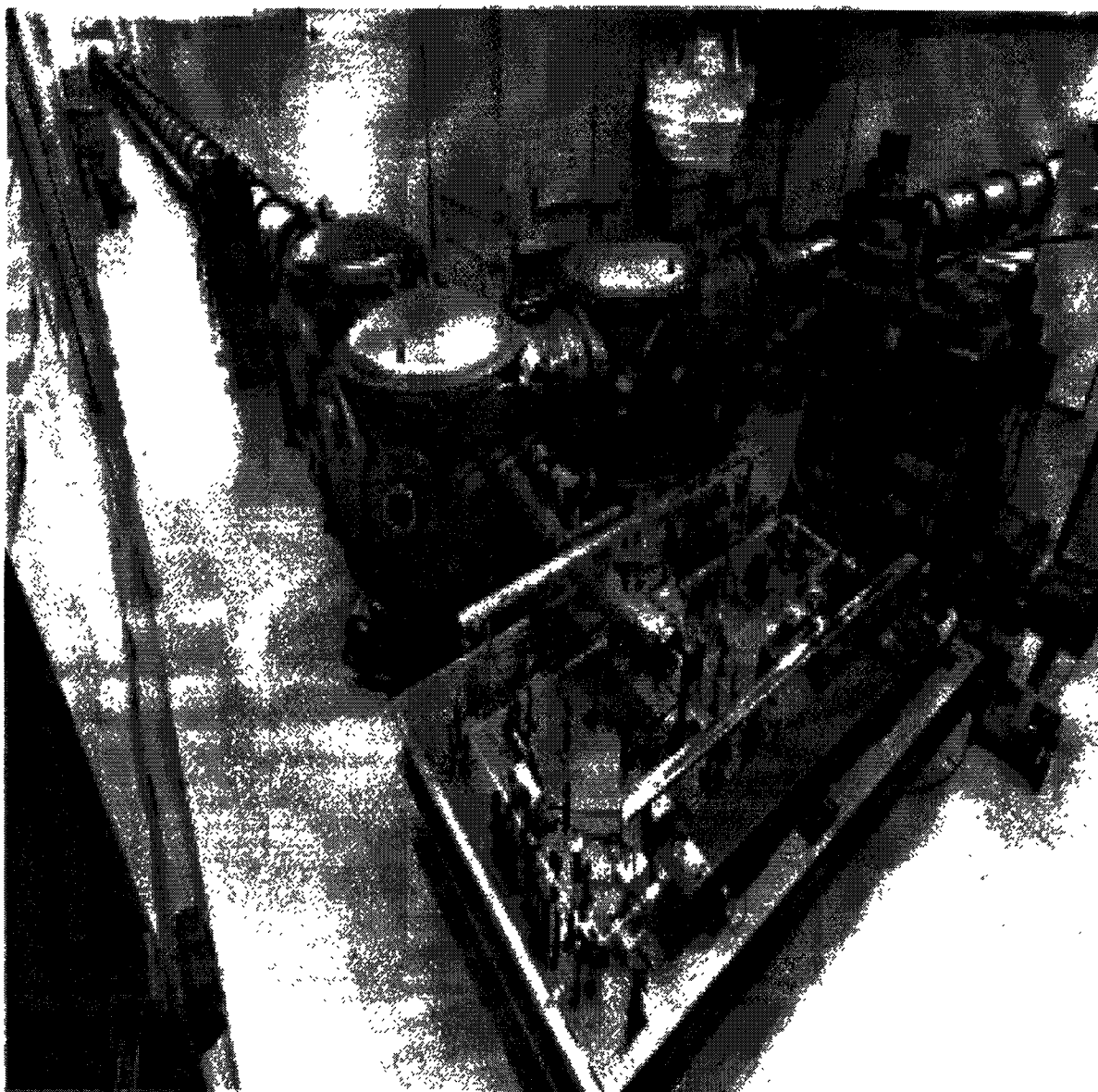


# LIGO Beam Tube Enclosure



# 40 METER INTERFEROMETER

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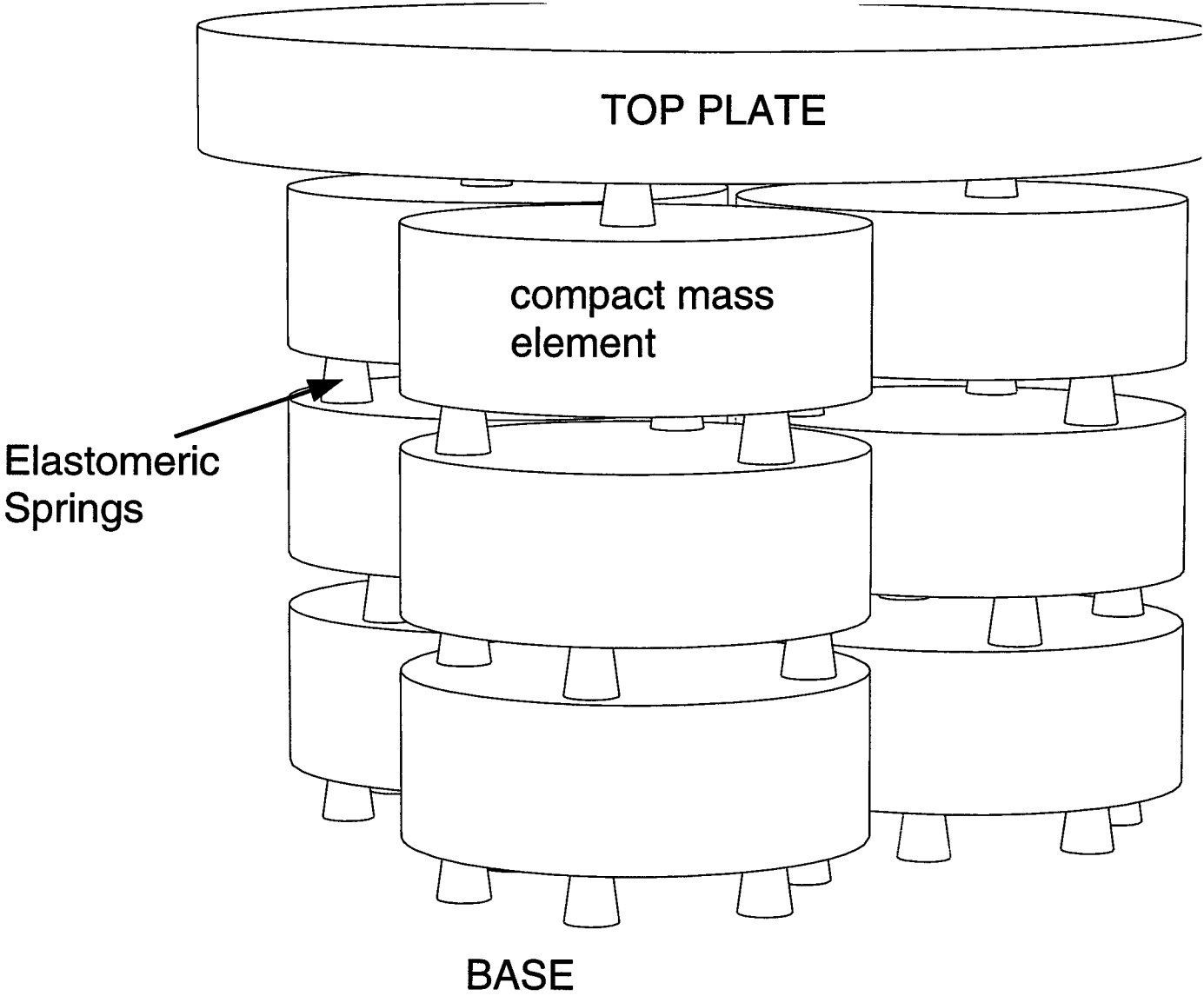


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# SEISMIC ISOLATION

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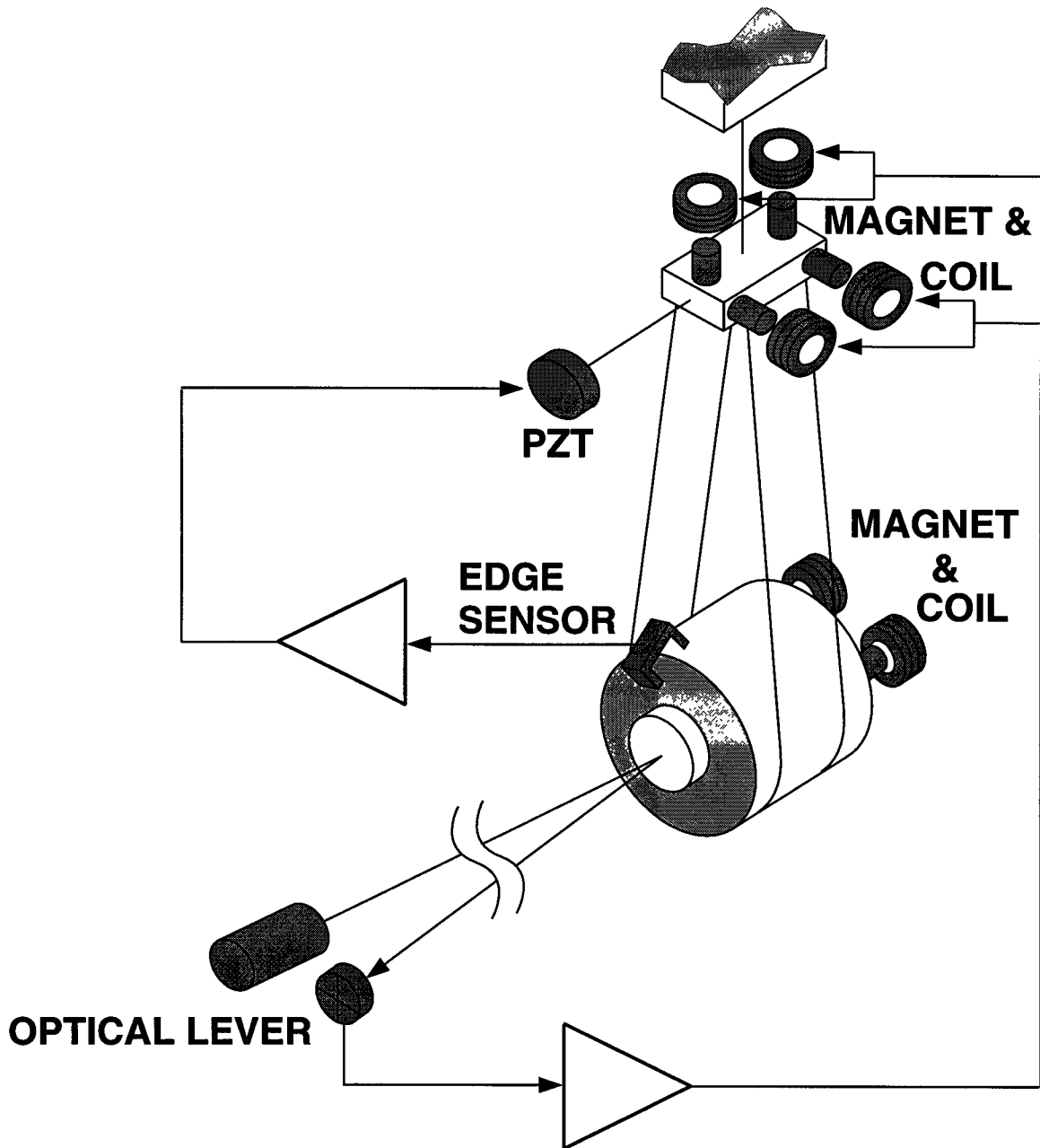


# SEISMIC ISOLATION

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# TEST MASS SUSPENSION





# COMPOSITE AND MONOLITHIC TEST MASSES

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# 40 METER AND LIGO TEST MASSES

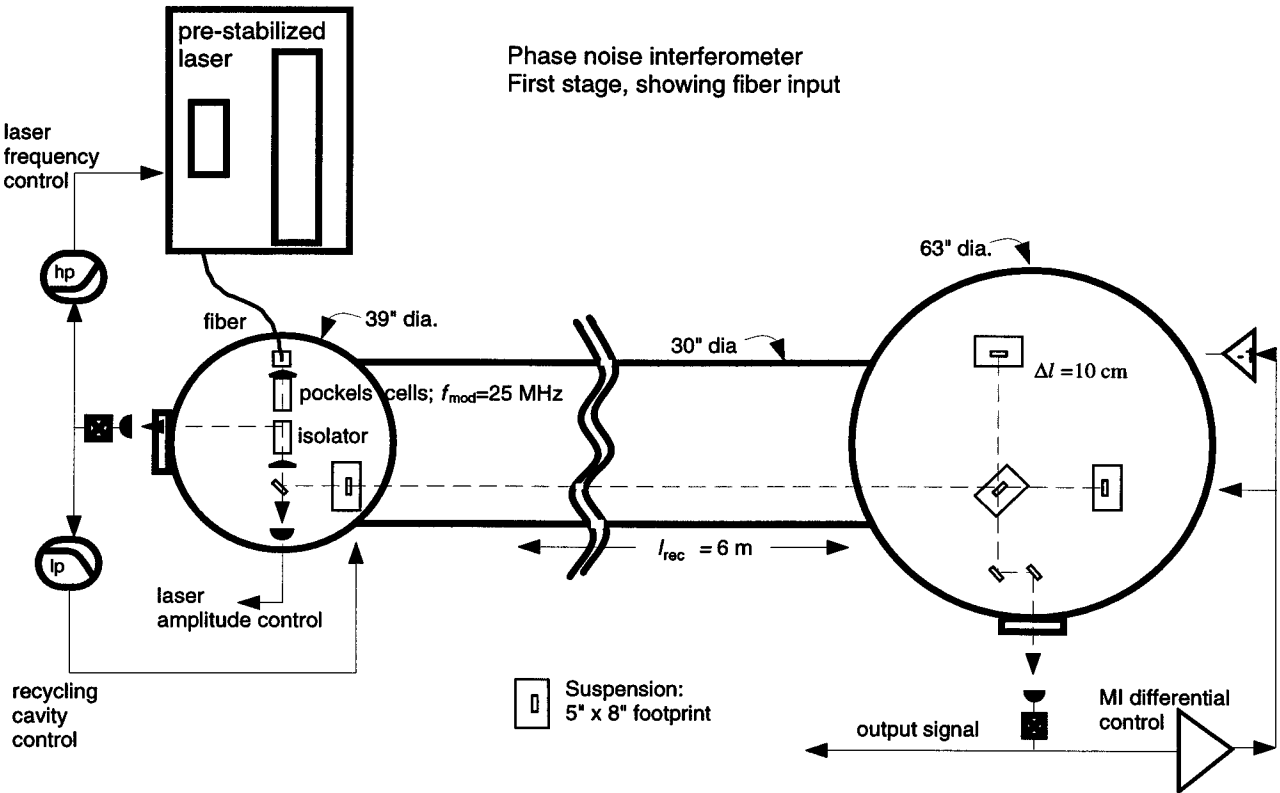
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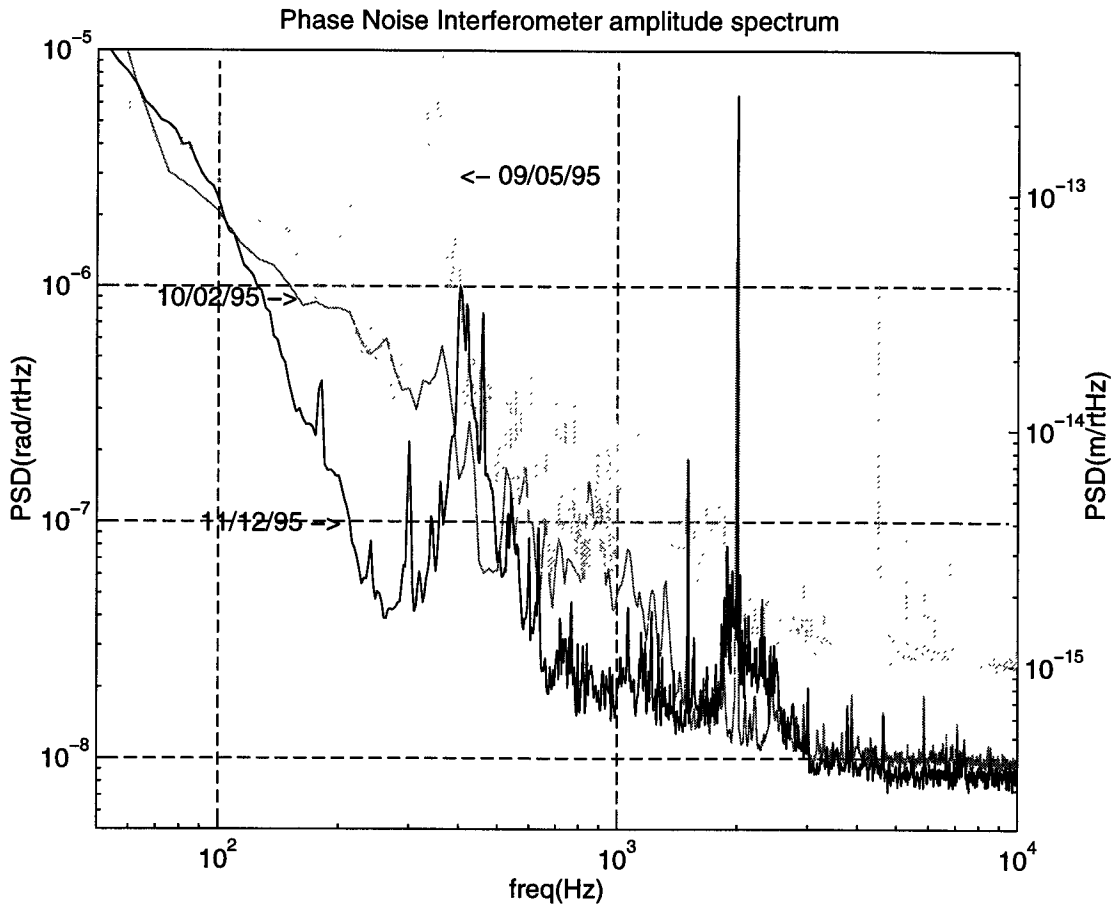
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LIGO-G960182-00-M

# PHASE NOISE - MIT PHASE NOISE INTERFEROMETER



# PHASE NOISE RESULTS TO DATE



# LIGO INFORMATION ON INTERNET

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*<http://www.ligo.caltech.edu>*

The LIGO logo consists of the word "LIGO" in a bold, sans-serif font, followed by three curved lines representing gravitational waves.



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LIGO-G960182-00-M

# LIGO SCHEDULE

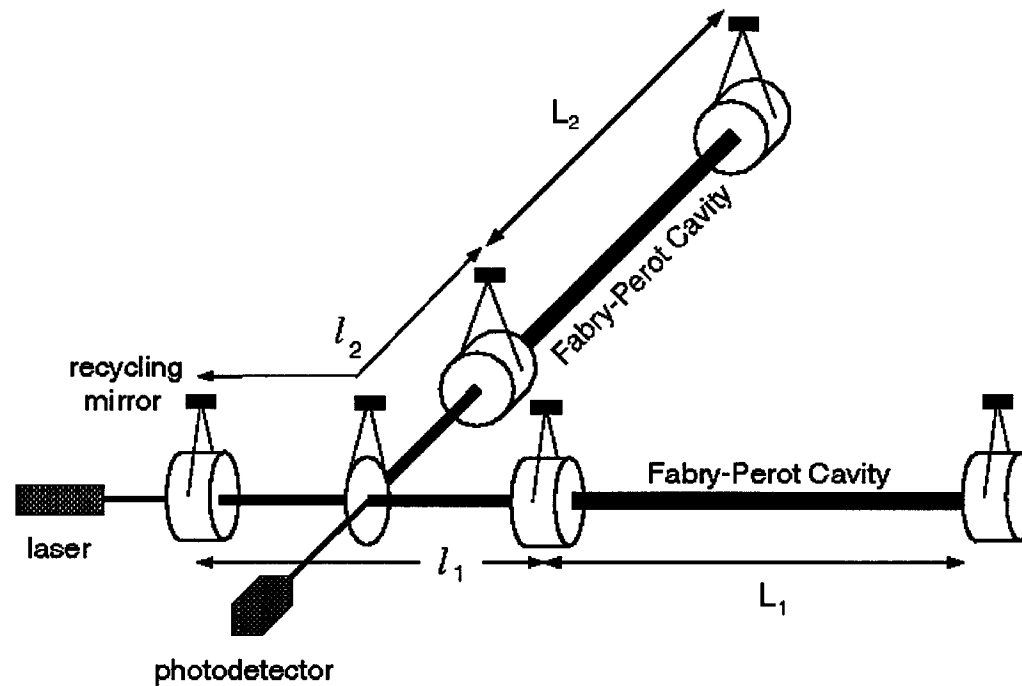
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- Strain sensitivity of  $10^{-20}$  on July 4, 2000 with three operating interferometers at the two sites
- Strain sensitivity reaches  $10^{-21}$  by December, 2001
- Enhancements and advanced interferometers after 2001



# A LIGO Interferometer

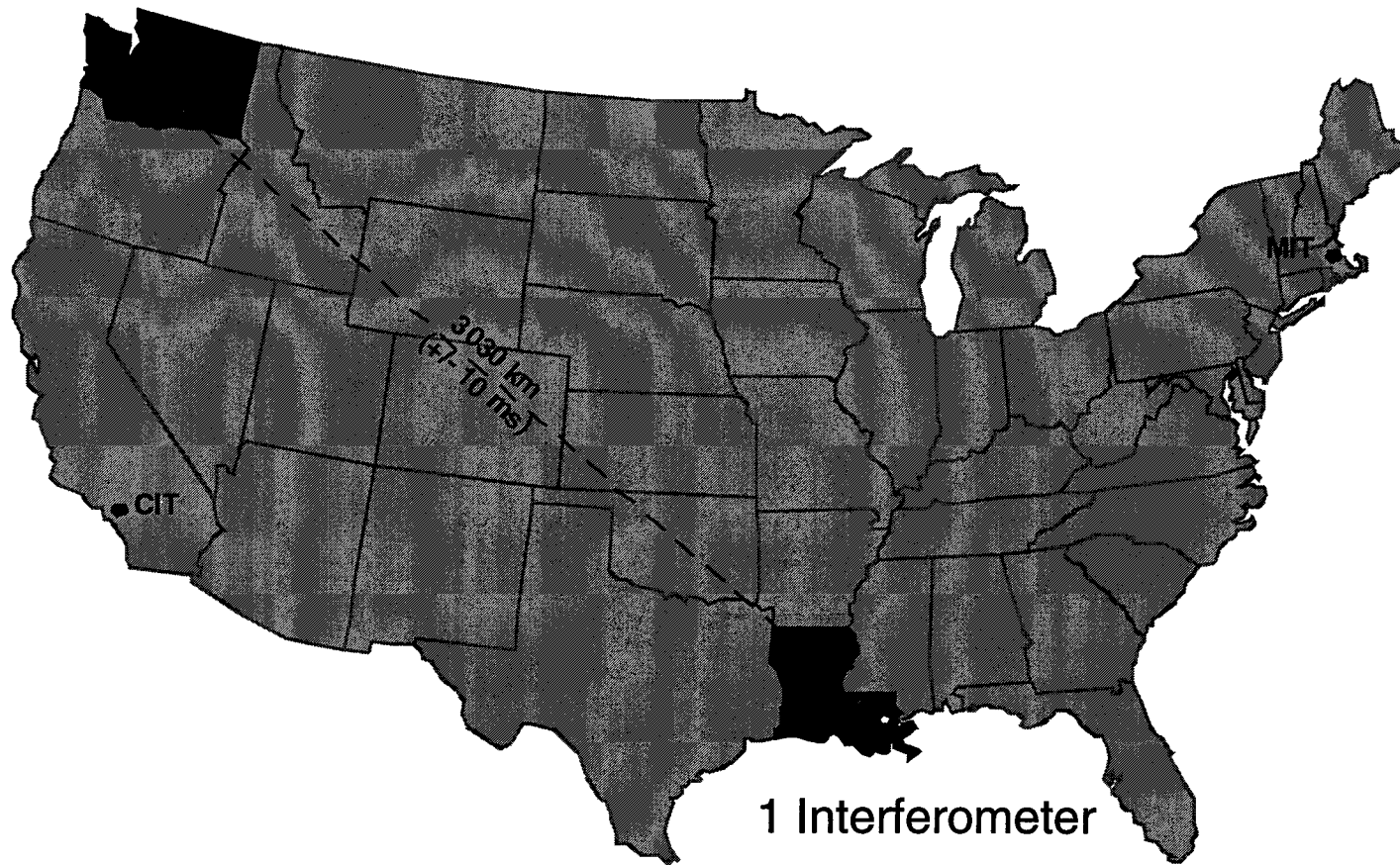
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# Two Sites - Three Interferometers

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2 Interferometers



1 Interferometer



# Aerial Concept of LIGO

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# Aerial View of LIGO - Hanford

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# Aerial View of LIGO - Louisiana

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