LIGO and the Search for Gravitational Waves

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LIGO-G980082-00-m

LIGO

SLAC - May 14, 1998

General Theory of Relativity

- Newtonian Gravity has instantaneous action at a distance

- Einstein showed fluctuating fields give gravitational waves
  - transverse, like radio waves
  - propagate at speed of light
  - two polarizations are at 45°

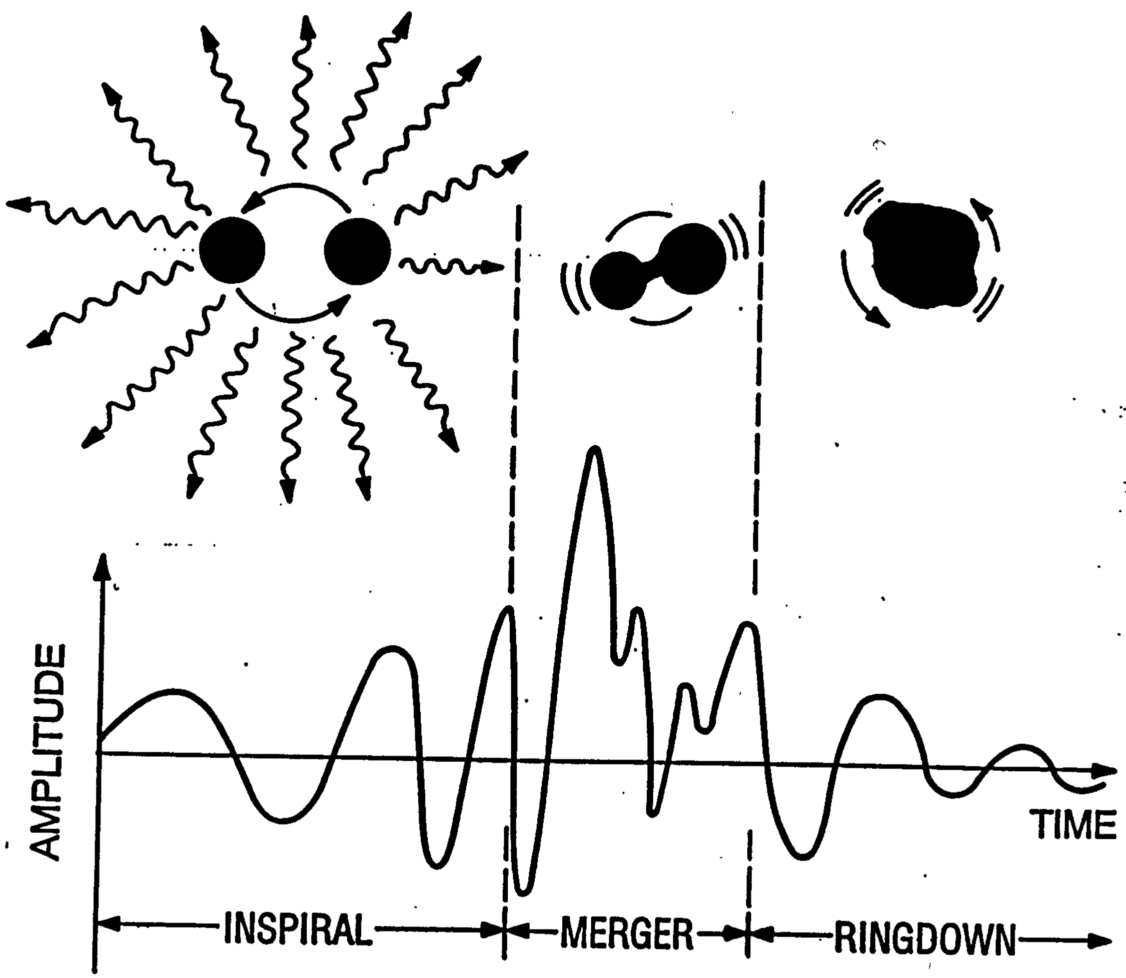
- Lowest order radiation term: quadrupole
  - field proportional to $\ddot{Q}$,
  - second derivative of non-spherical part of kinetic energy
  - dimensional analysis leads to $h \approx \frac{G}{c^4}\frac{\ddot{Q}}{r}$

- passing GW leads to change in proper distance

  $\delta l \approx \left(\frac{1}{2}h(t)\right)L$ between points separated by L

Binary Sources

Inspiral and Coalescence



LIGO

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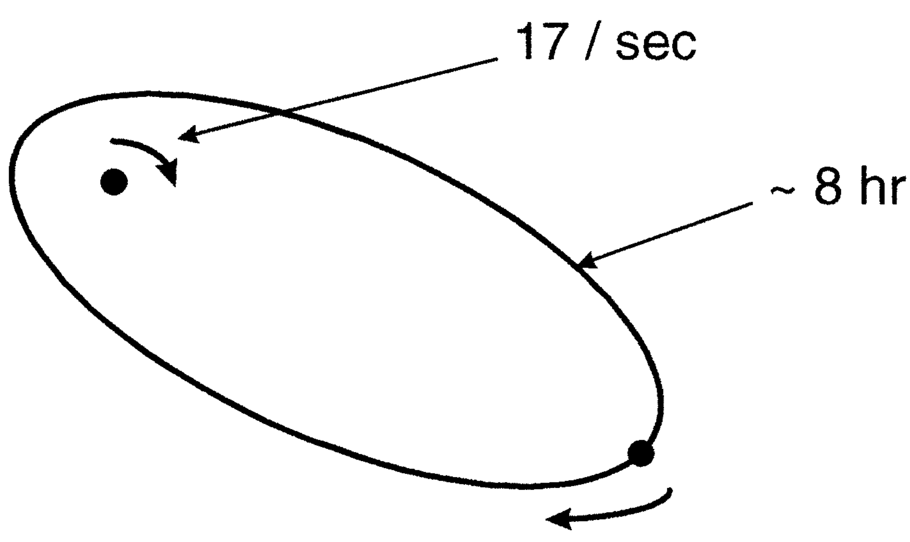
Gravitational Waves
Evidence

- **Russell Hulse and Joseph Taylor**

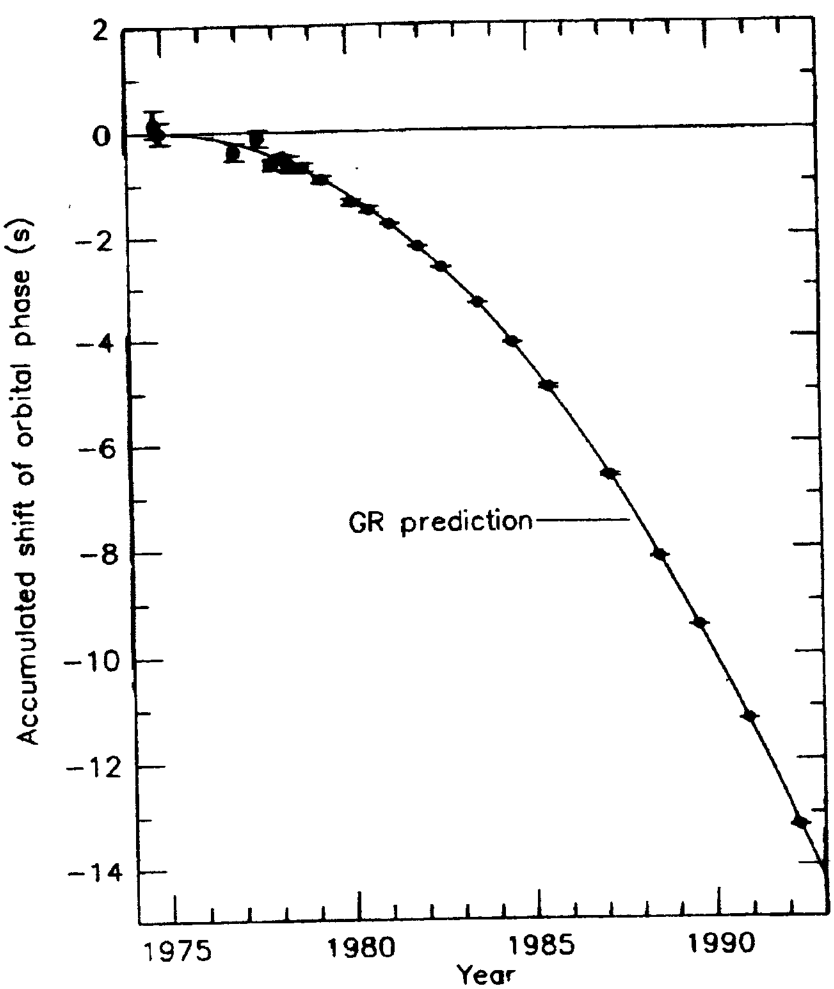
- Neutron Binary System
  - » PSR 1913 + 16 -- Timing of Pulsars
  - » separated by 10^6 miles
  - » m_1=1.4m_0; m_2=1.36m_o; $\varepsilon = 0.617$

- Predictions from general relativity
  - » spiral in by 3 mm/orbit
  - » rate of change orbital period



Hulse and Taylor
timing of the orbital period

- period speeds up of 14 sec from 1975-94
  - » measured to ~50 μsec accuracy
- deviation grows quadratically with time
- due to loss of orbital energy, from the emission of gravitational waves



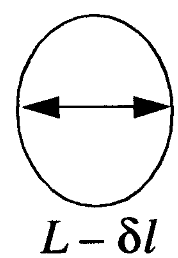
Coalescing Compact Binaries

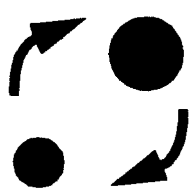
Standard candle: Binary stars

- Taylor-Hulse Binary 1913+16 shows clear spin-up
- almost certainly due to GW radiation at present 8h period
- later in life (10^8 yr.), period shortens to audio frequencies
- spends ~1 minute in frequency range from ~30 Hz-1 kHz
- our detector will target this frequency range.

for most of life, waveform well known if masses known

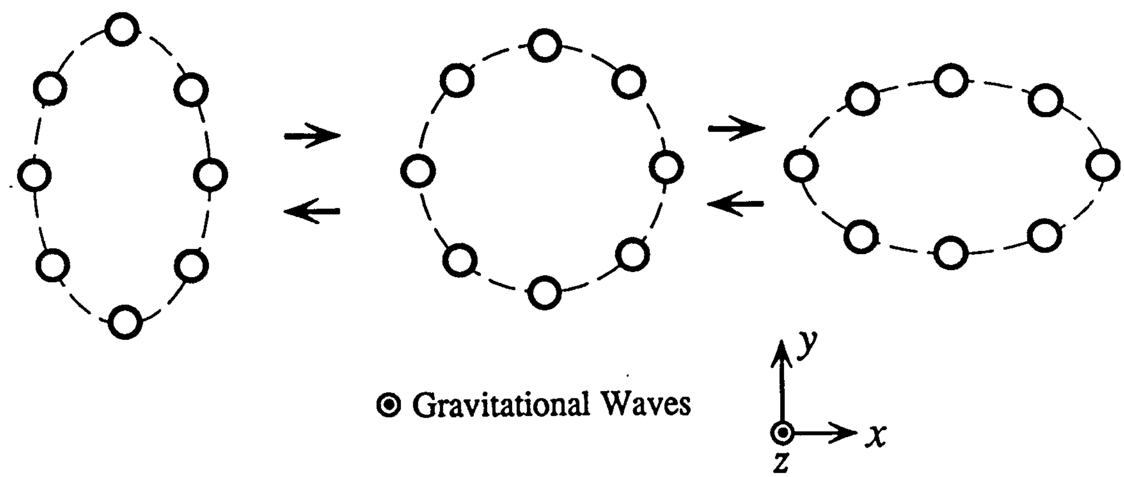
- allows calculation of signal amplitudes, optimal filters
- end of life (coalescence) yet to be calculated (measure first?)
- typical number: $h \approx 10^{-21}$ for 1.4 M_o, 200 Mpc, ~3 events/yr.
- since $h = \delta l / L$, expect $\delta l = 10^{-21}$ m for $L = 1$ m



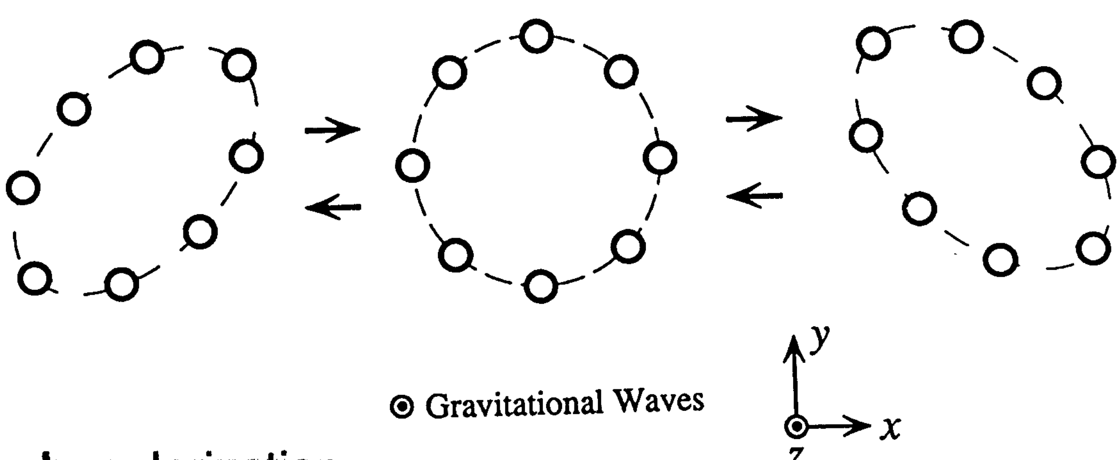


Gravitational Waves
Effects

- Displacement of free particles



  - » h_+ polarization

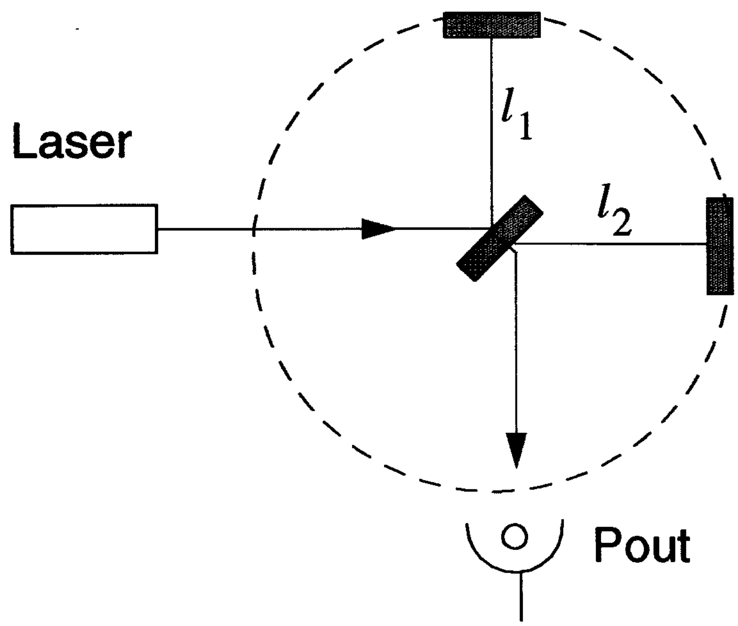


  - » h_x polarization

Basic principle of detection

Laser Interferometry

- basic sensing mechanism: a Michelson Interferometer



- GW strain induces differential length changes in arms
  - proportional to arm length, up to fraction of GW wavelength
- lengths are measured using light beams and 'free masses'

Realistic interferometer not so simple

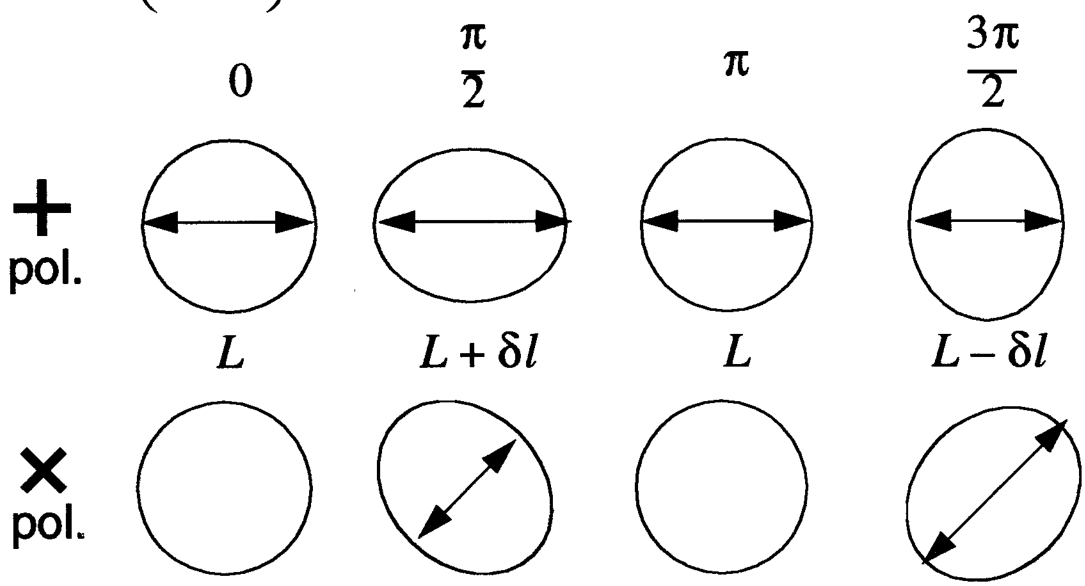
- will explore limitations to understand initial LIGO design

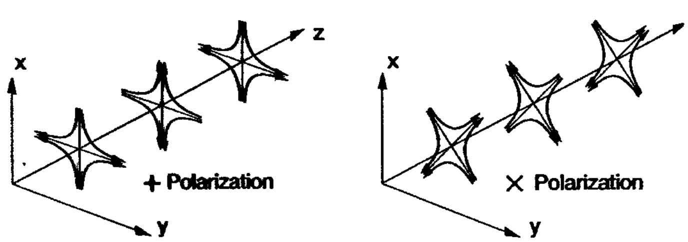
Basis of the detection

Assume General Relativity

- wave is transverse, like radio waves
- propagates at speed of light
- two polarizations are at 45°
- passing GW leads to change in proper distance

$\delta l \approx \left(\frac{1}{2}h(t)\right)L$ between points of initial separation L





This is the key for the detection of GWs.

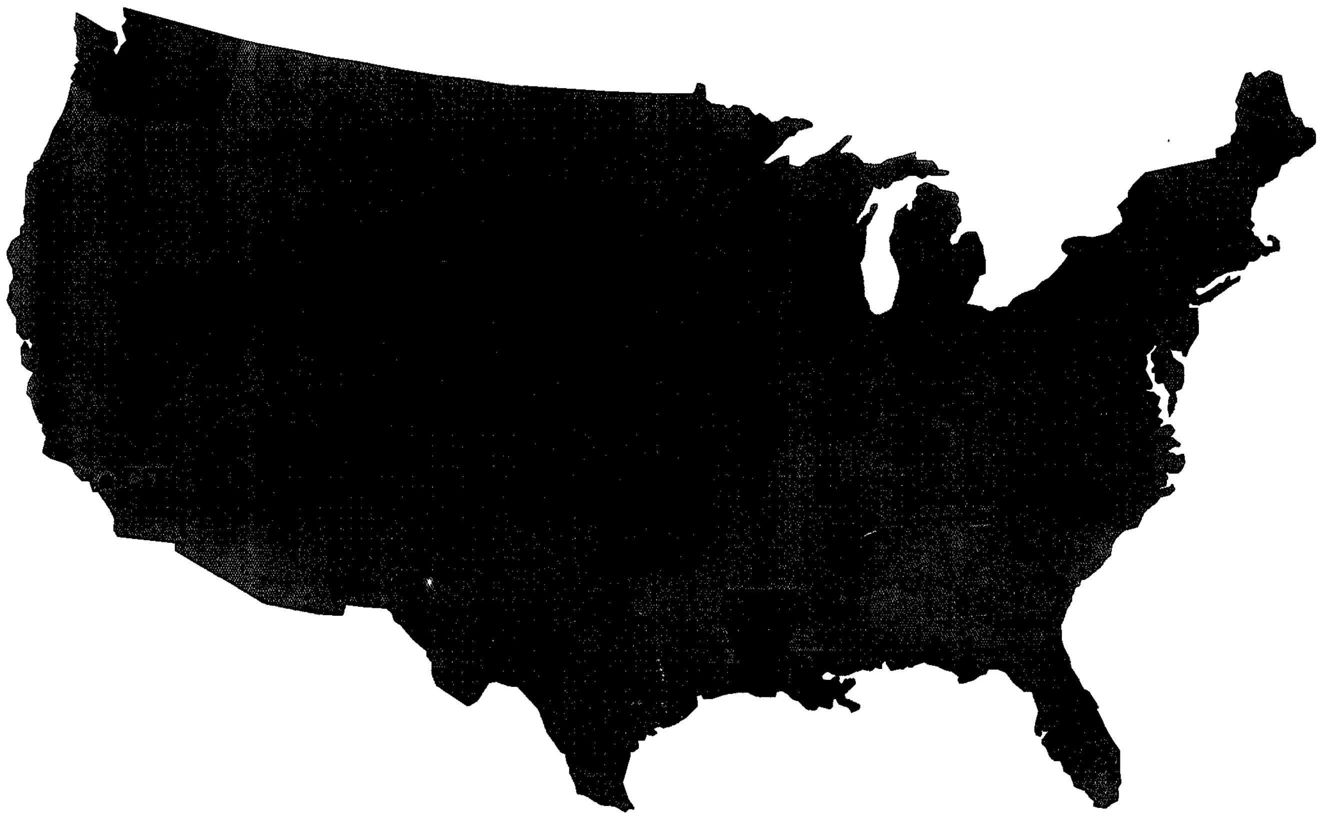
Gravitational Waves
ground based effort

- Techniques
  - » Resonant Bar Detectors (LSU, Rome, etc)
    - – narrow band (~ few Hz)
  - » Large Scale Interferometers
    - – broad band (~ 10Hz -> 10KHz)

- International Interferometer Effort
  - » U.S. -- LIGO (two sites)
    - – Caltech & MIT (Wash and Louisiana)
  - » Europe -- VIRGO (One Site)
    - – French and Italian (near Pisa)
  - » Smaller efforts
    - – Germany, Japan, Australia

- Time Scale (Interferometers)
  - » Approximately year 2000 +

Two LIGO Observatory Sites



Detection Strategy

Coincidences

- Two Sites - Three Interferometers
  - » Single Interferometer ~50/hr
    - – non-gaussian level
  - » Hanford (Doubles) ~1/day
    - – correlated rate (x1000)
  - » Hanford + Livingston <0.1/yr
    - – uncorrelated (x5000)
- Signal Extraction
  - » signal from noise (vetoes, noise analysis)
  - » templates, wavelets, etc
- Data Recording (time series)
  - » graviational wave signal (0.2 MB/sec)
  - » total data (16 MB/s)
  - » on-line filters, diagnostics, data compression
  - » off line data analysis, archive etc

LIGO

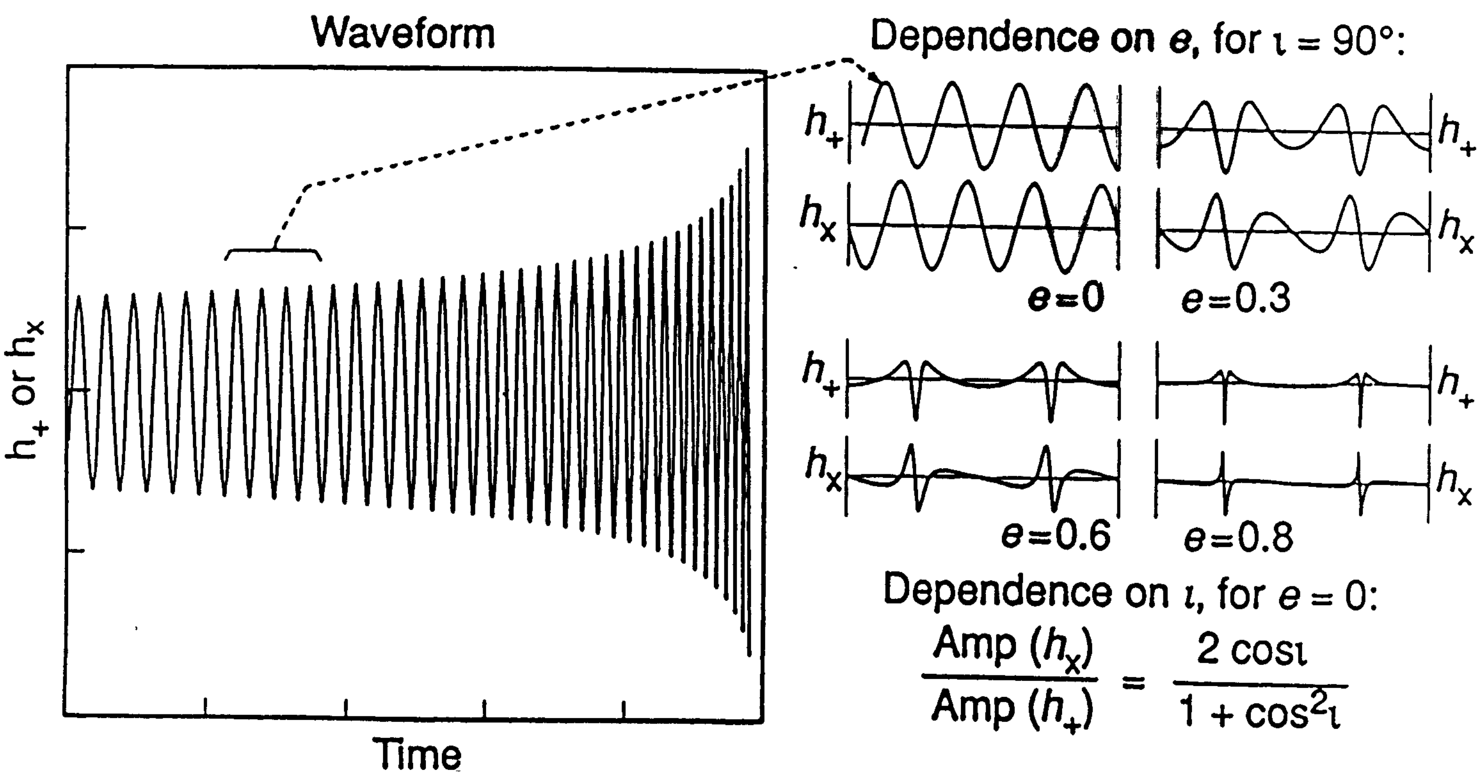
Long Range Goals

- Inspiral of Compact Binary ***[chirps]***
  - » Neutron Star/Neutron Star Inspiral
    - – Design Benchmark: last 15 min
20,000 cycles
600 MLyr
  - » Black-hole/Black-hole Inspiral and Coalescence
  - » Black-hole/Neutron Star Inspiral
- Supernovae ***[bursts]***
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr
- Pulsars ***[periodic]***
  - » rotating non-axisymmetric neutron stars
- Early Universe ***[stochastic]***
  - » Vibrating Cosmic Strings
  - » Vacuum Phase Transitions
  - » Vacuum Fluctuations from Planck Era
- Unknown Sources ***[??]***

Gravitational Waveforms

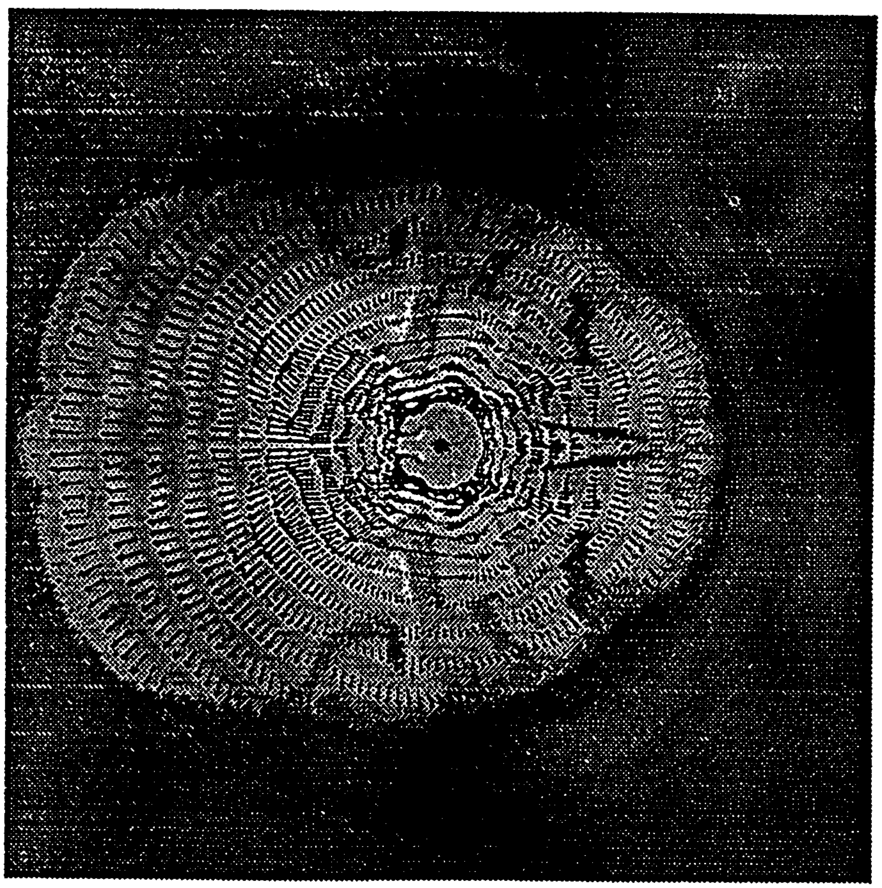
binary inspiral

- can determine
  - » distance from the earth r
  - » masses of the two bodies
  - » orbital eccentricity e and orbital inclination i



Supernovae
simulation

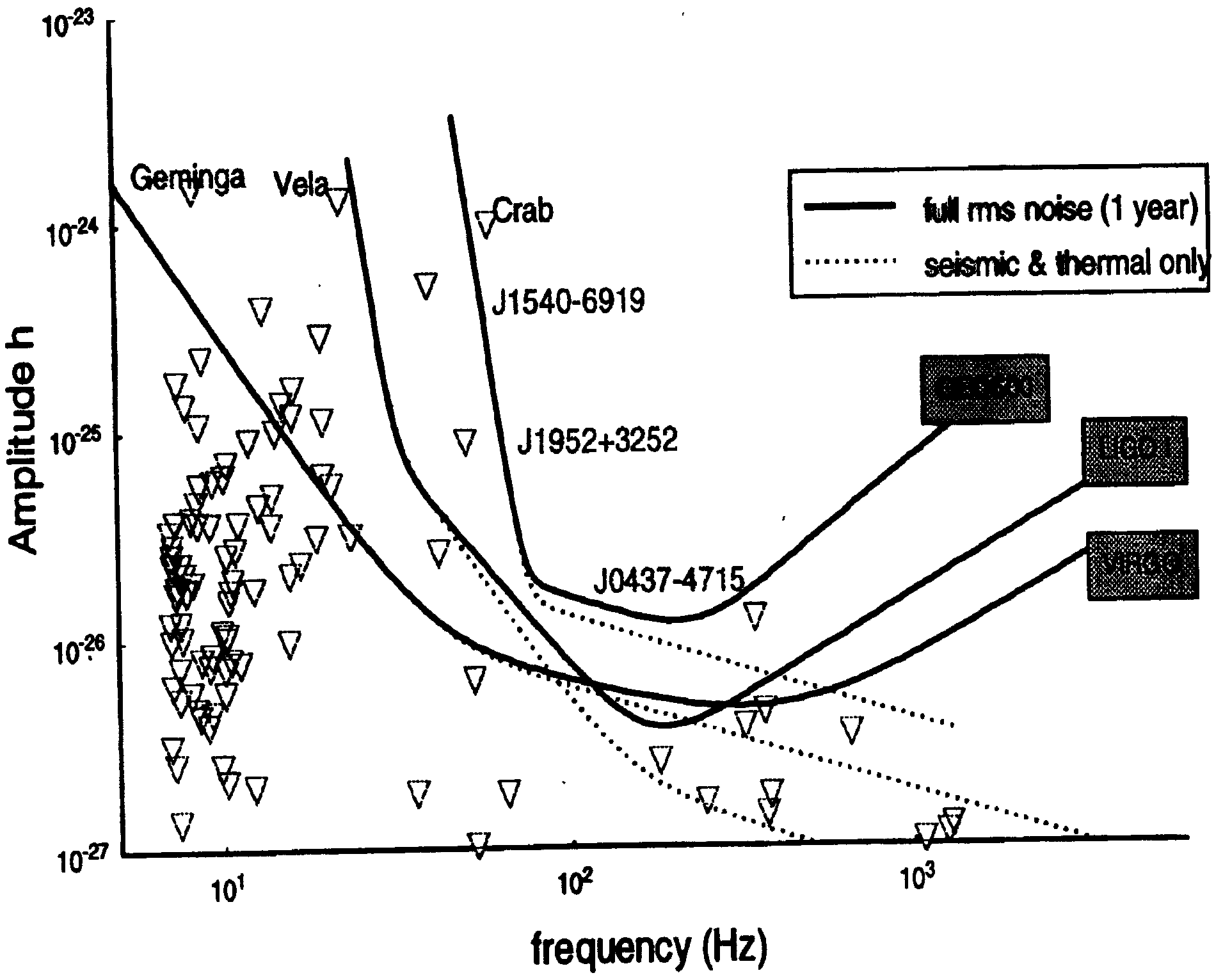
- A. Burrows
  - » 2 - dim model
  - » 50 msec into the explosion



Pulsar Searches

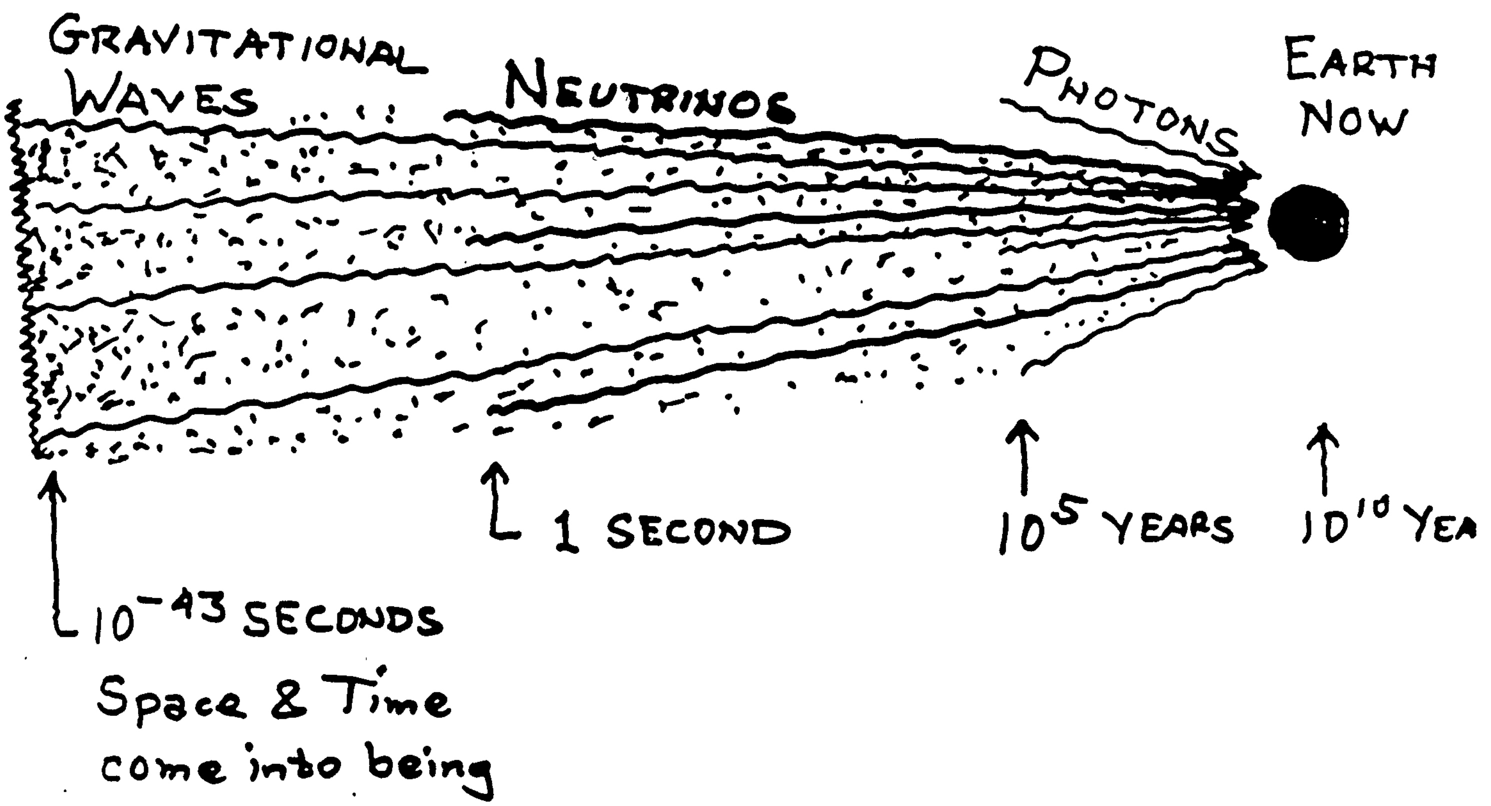
first generation sensitivity

- assumes all spindown accounted for by emission of gravitational wave energy



The Early Universe
Stochastic Background

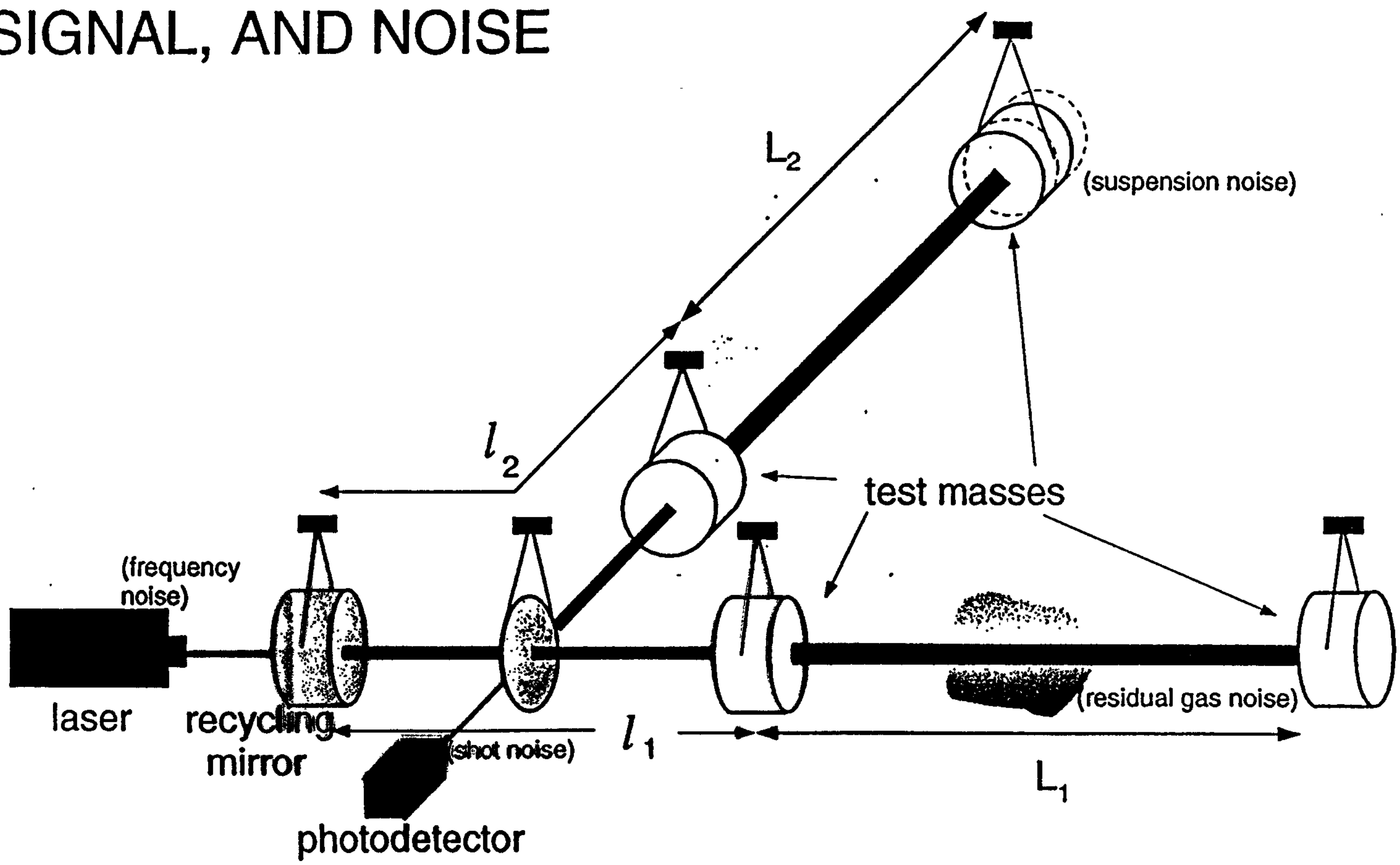
- The Big Bang Singularity



- LIGO
  - » time ~10^{-22} sec
  - » temp ~ 10^6 GeV
  - » graviton ~ 10 MeV

Interferometer
Noise Limitations

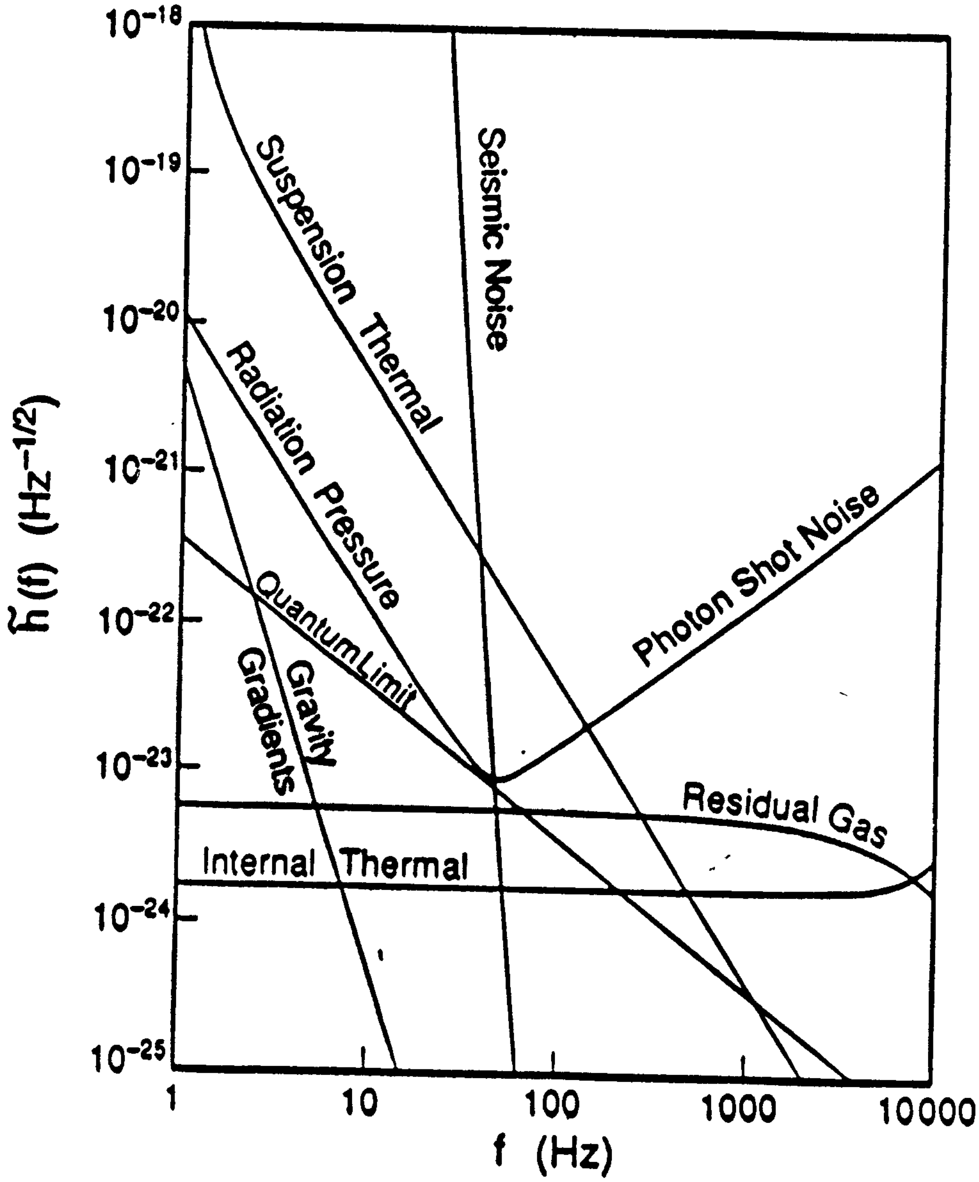
INTERFEROMETER, SIGNAL, AND NOISE



SIGNAL = L_1 - L_2

Noise Budget For First LIGO Detectors

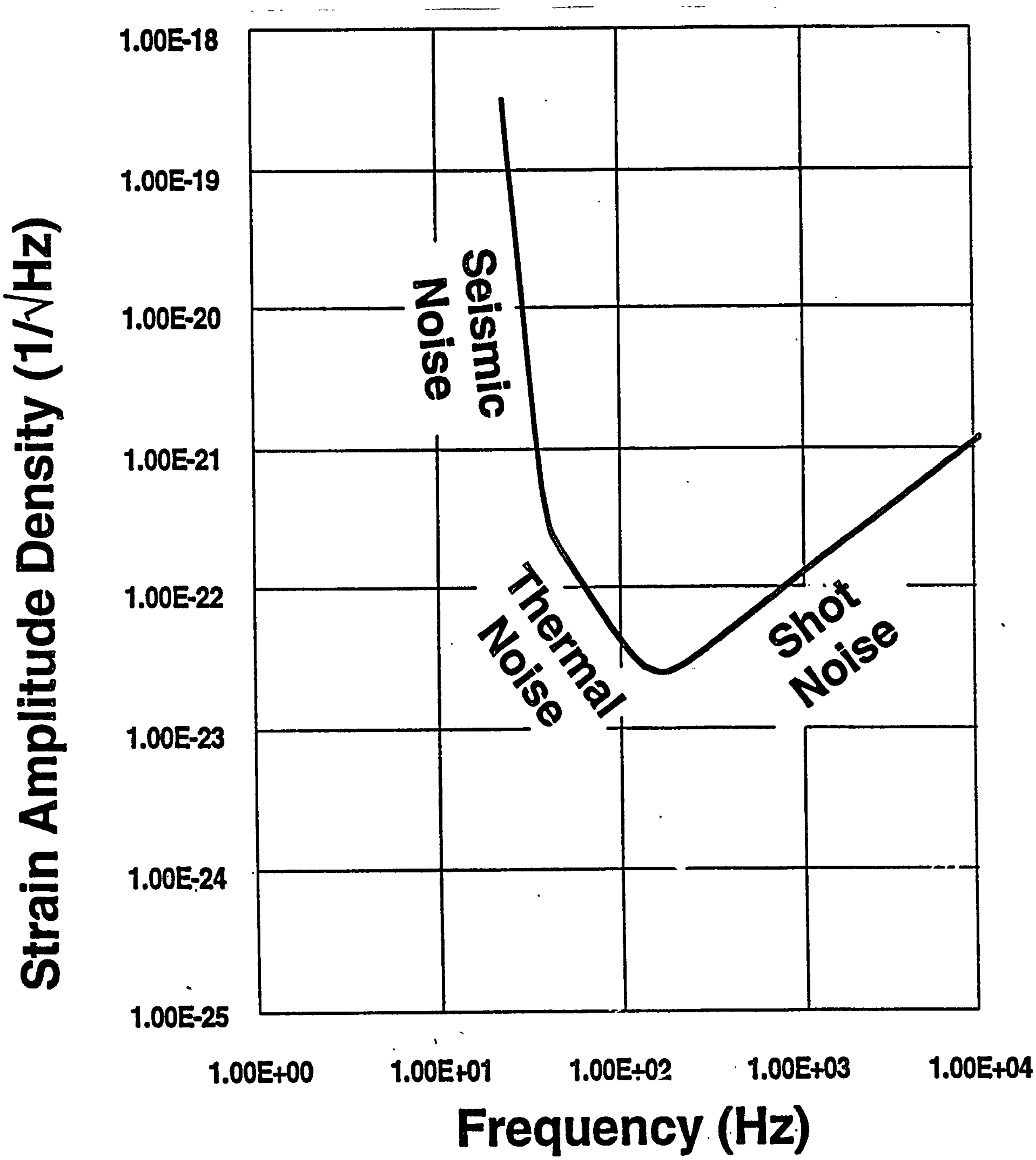
- **5 Watt Laser**
- **Mirror Losses 50 ppm**
- **Recycling Factor of 30**
- **10 kg Test Masses**
- **Suspension Q=10^7**



LIGO

Initial Interferometers

Noise Floor



LIGO

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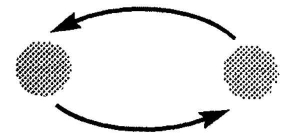
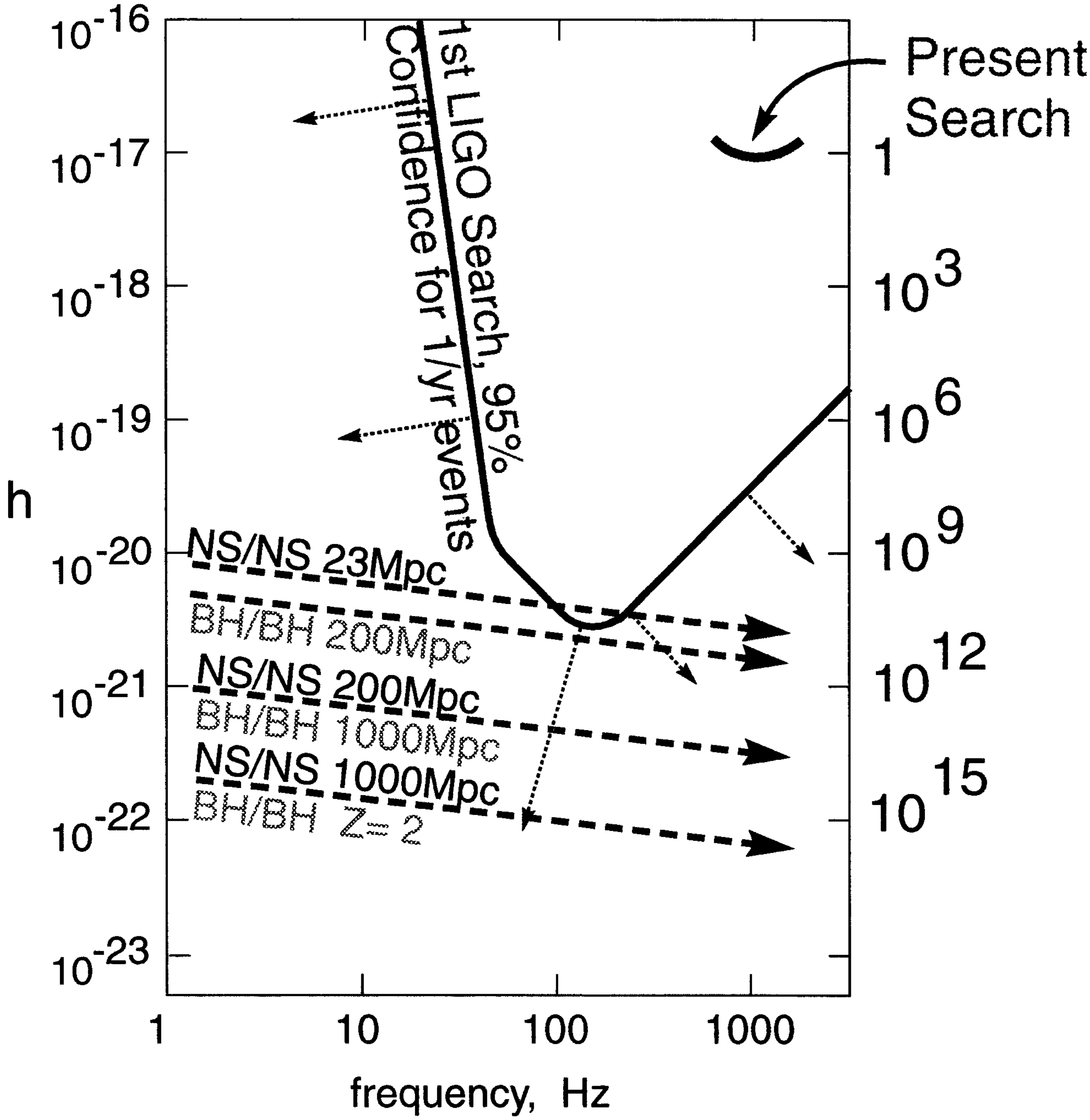
NEUTRON STAR BINARIES 

["Near-Guaranteed" source]



- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

LIGO
the facility

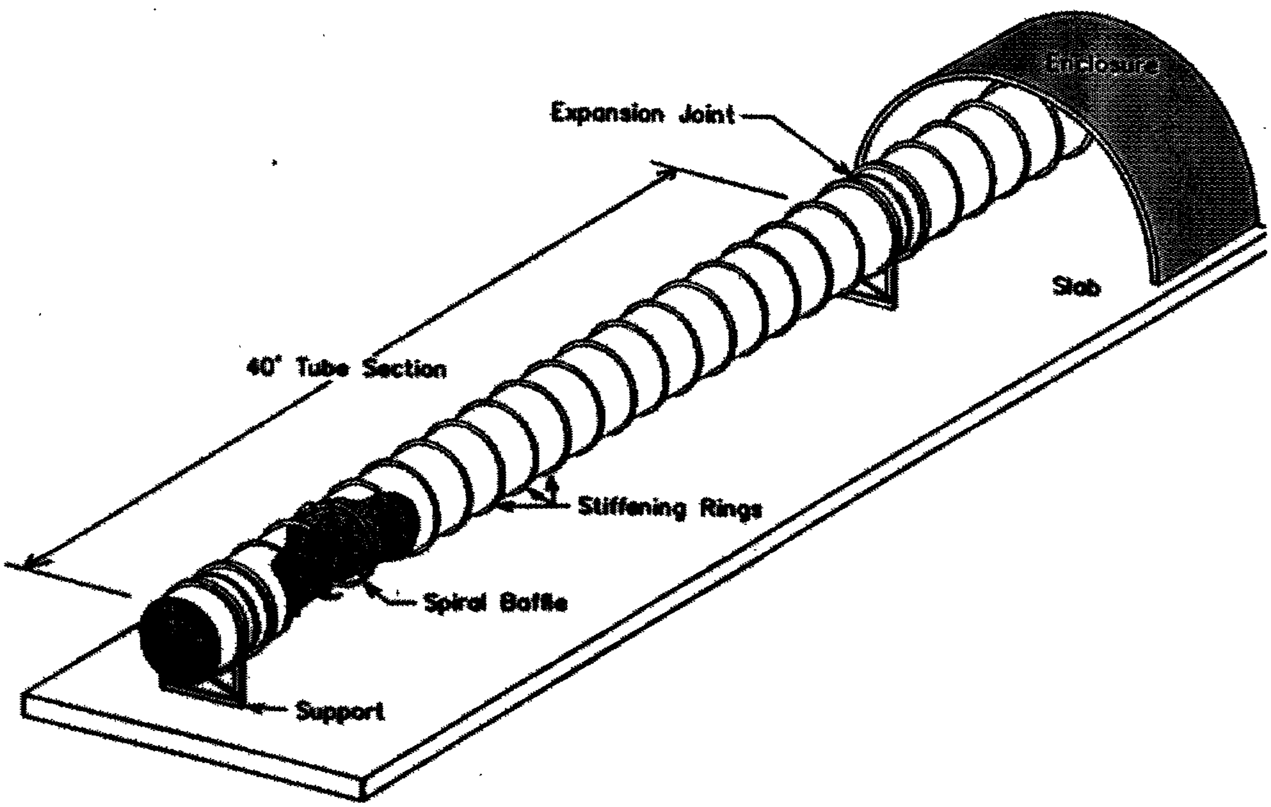
- National Science Foundation

- Construction Project (1995-1999)
  - » Facilities and Initial Detector

- Commission Facility (1999-2001)
  - » Implement Initial Detectors
    - – $h \sim 10^{-20}$ - Coincidence (Hanford/Livingston)
      - Engineering run (end of 2000)
    - – $h \sim 10^{-21}$ - Initial Design Sensitivity (end 2001)

- Full Operations (2002 + ...)
  - » Data Taking/Analysis
    - – LIGO I (2 year run @ $h \sim 10^{-21}$)
  - » Enhance Initial Detector
    - – improved subsystems (lasers, test masses, etc)
  - » Advanced Detectors
    - – new interferometer configurations

Beam Tube



Enclosure
Expansion Joint
Slab
40' Tube Section
Stiffening Rings
Spiral Baffle
Support

LIGO Facilities

Beam Tube Enclosure

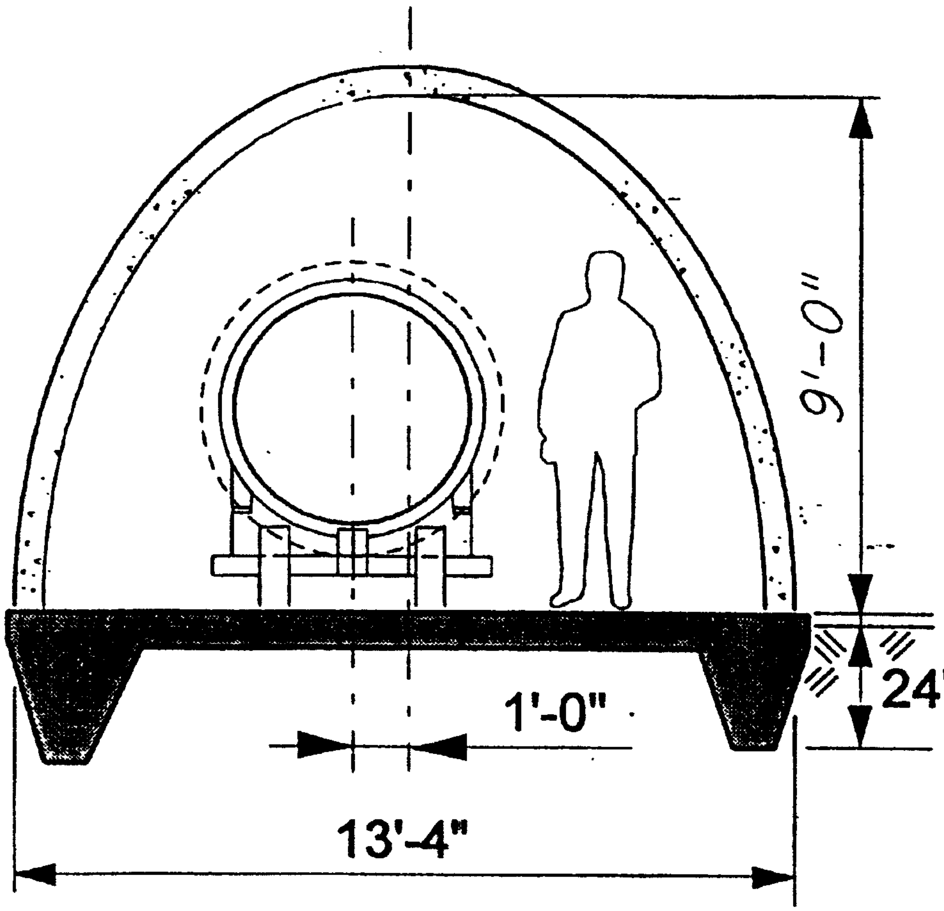
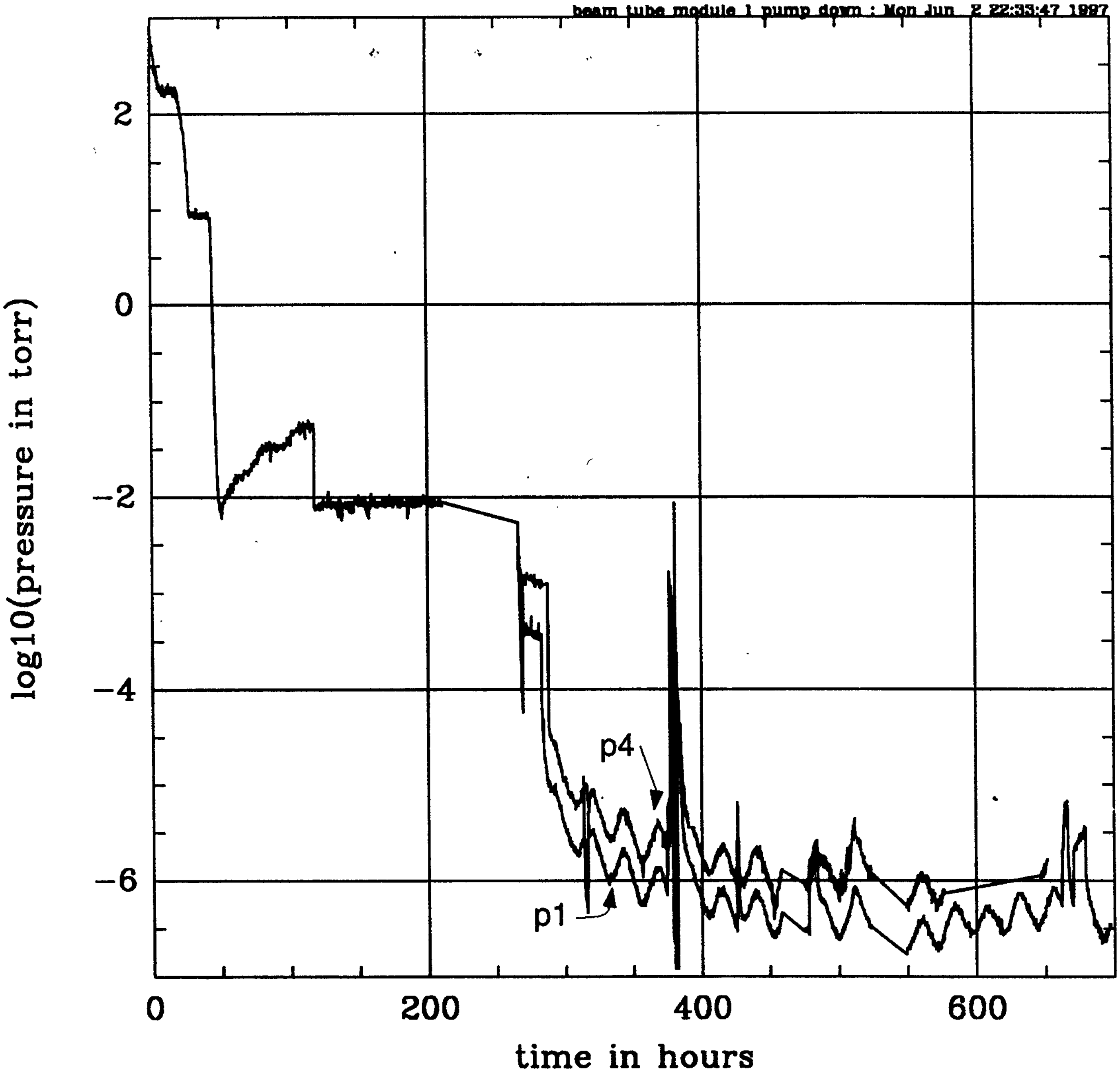


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford



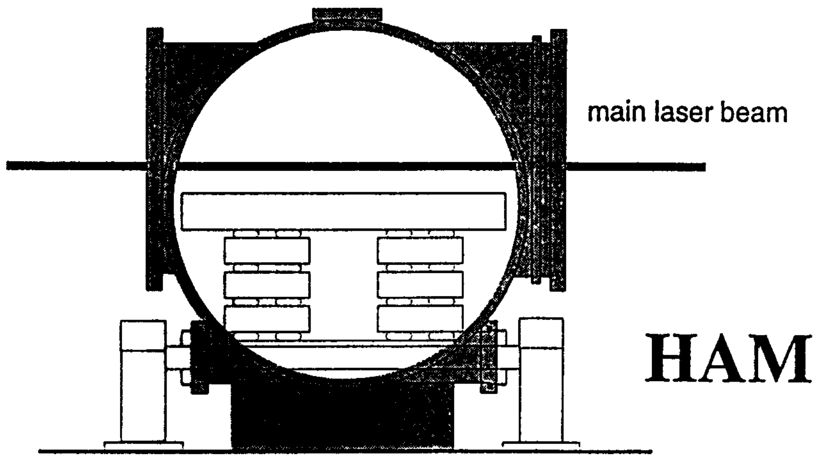
beam tube module 1 pump down : Mon Jun 2 22:35:47 1997
log10(pressure in torr)
2
0
−2
−4
−6
p4
p1
0
200
400
600
time in hours

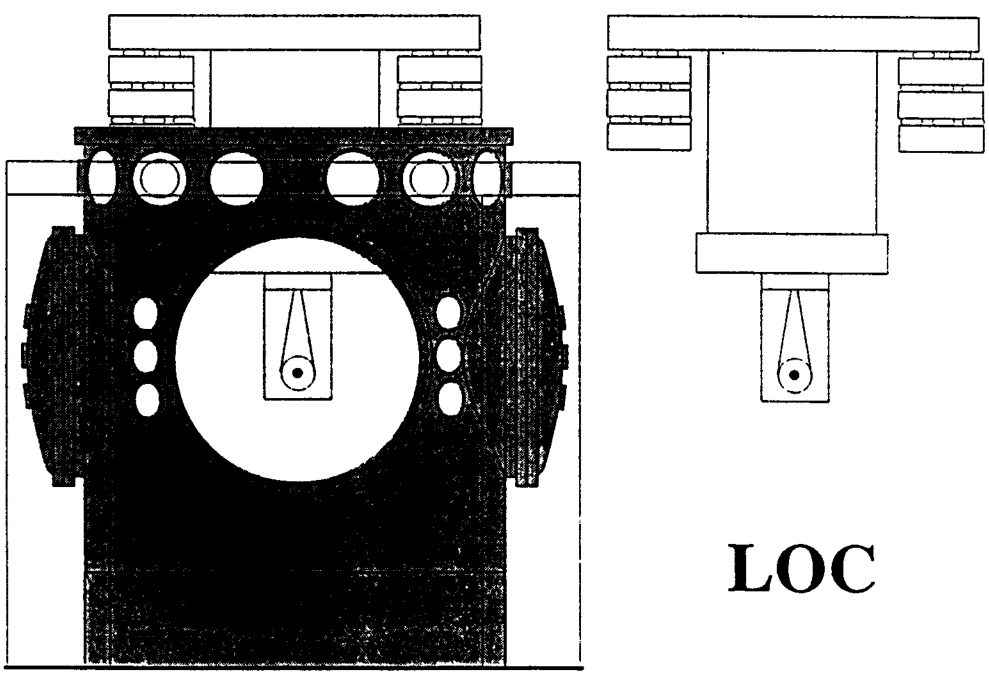
Outgassing Result From First 2 km Module

Table 1: Prebake Outgassing Rates (torr liters/sec cm²)

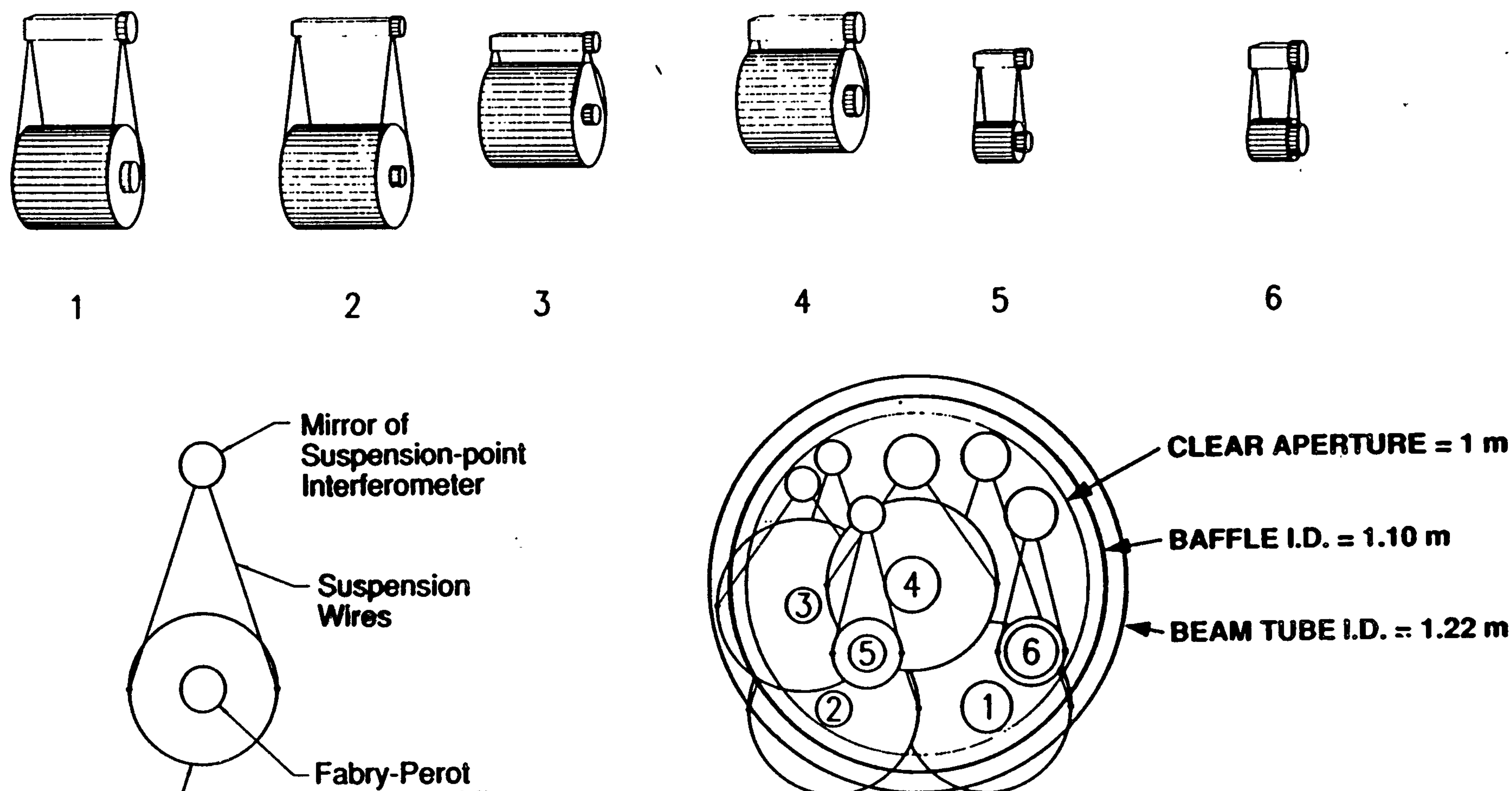
gas	measured at 1100 hrs	assumed 1/t	comments
H_2	**< 7.4×10^{-14}**		larger than QT by 2 max correction for ordinary 304 SS 2.7×10^5 cm² at $J(H_2) = 1 \times 10^{-11}$ $J_{equiv}(H_2) < 3.5 \times 10^{-14}$
CO	6.9×10^{-15}	7.6×10^{-12} / t(hr)	smaller than QT by 10
CO_2	1.9×10^{-14}	2.1×10^{-11} / t(hr)	smaller than QT by 2
CH_4	5.2×10^{-16}	5.6×10^{-13} / t(hr)	larger than QT by 4
H_2O		8.0×10^{-9} / t(hr)	*see table 7 and 8* smaller than QT by 2
Hydrocarbons $\sum$ 41, 43, 55, 57		$8 \times 10^{-3} * J(H_2O)$	larger than QT by 2

SEI Configuration



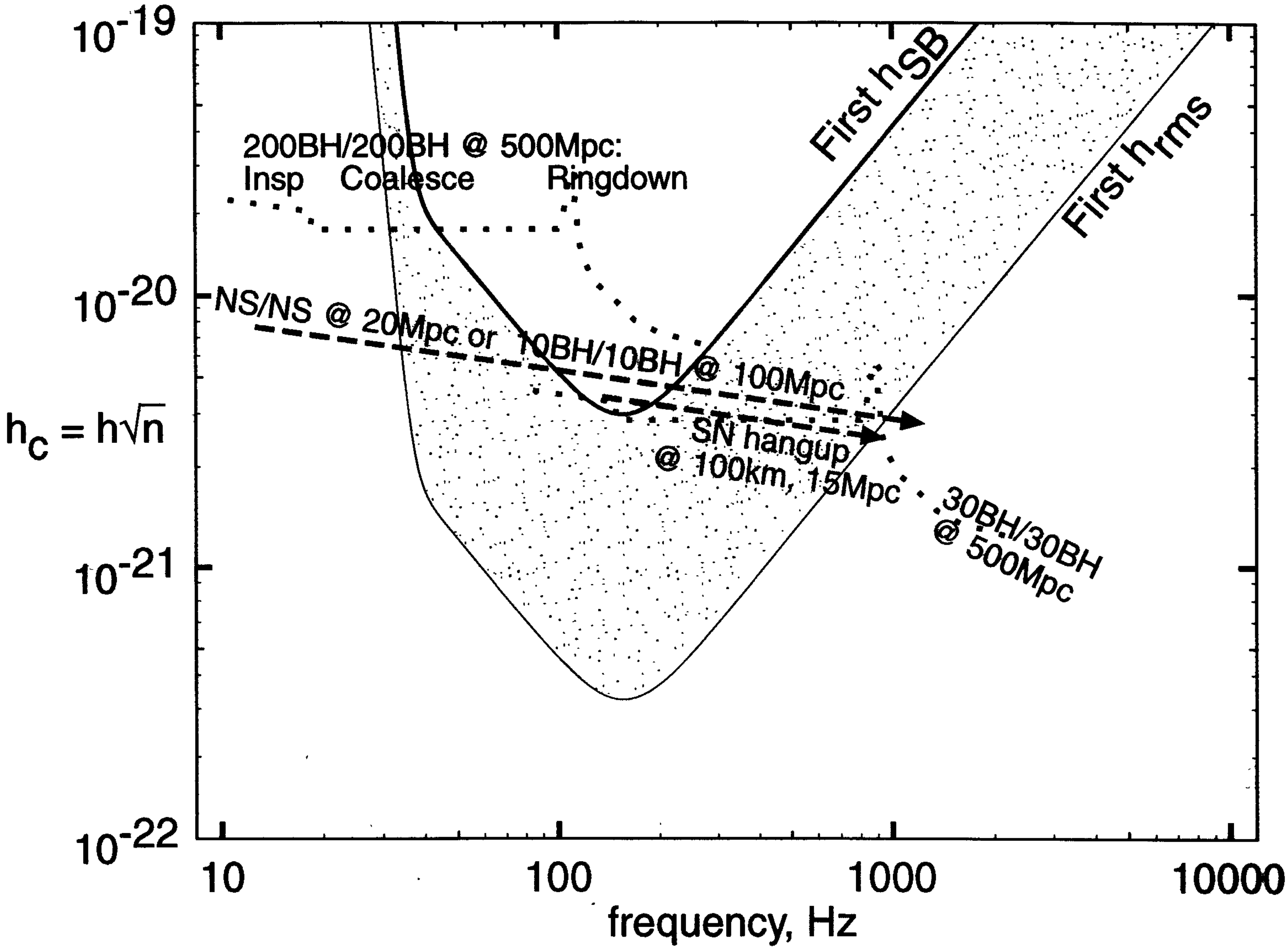


LIGO


1
2
3
4
5
6
Mirror of Suspension-point Interferometer
Suspension Wires
Test Mass
Fabry-Perot Test Mass Mirror
CLEAR APERTURE = 1 m
BAFFLE I.D. = 1.10 m
BEAM TUBE I.D. = 1.22 m
1
2
3
4
5
6

CAPABILITIES OF THE INITIAL LIGO INTERFEROMETERS

2002



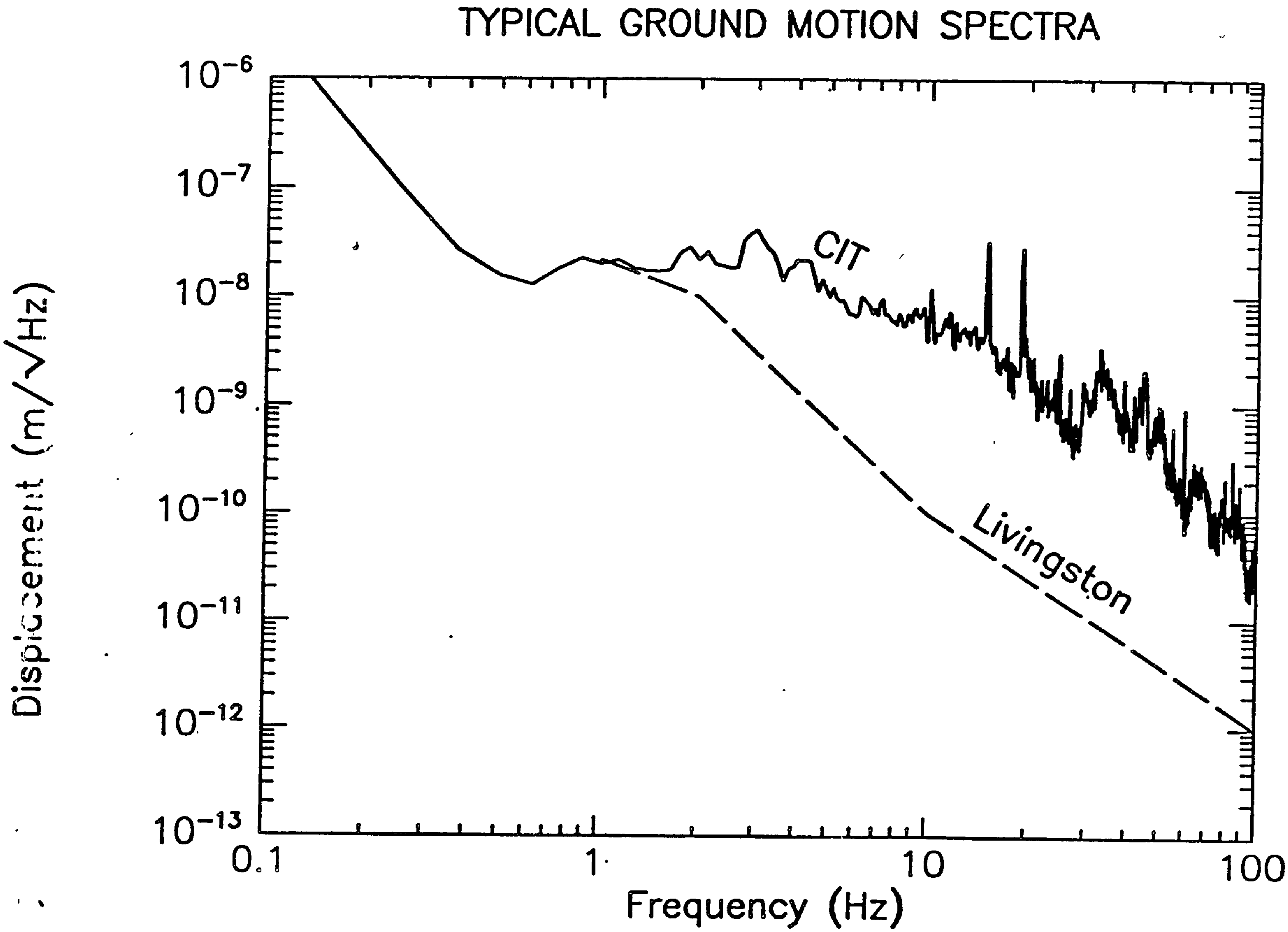
Seismic Noise

Motion of the earth

- driven by ocean tides, wind, volcanic/seismic activity, humans
- for LIGO sites, characterized by $10^{-7}/f^2\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
- requires e.g., roughly 10^9 attenuation at 100 Hz

Approaches to limiting seismic noise

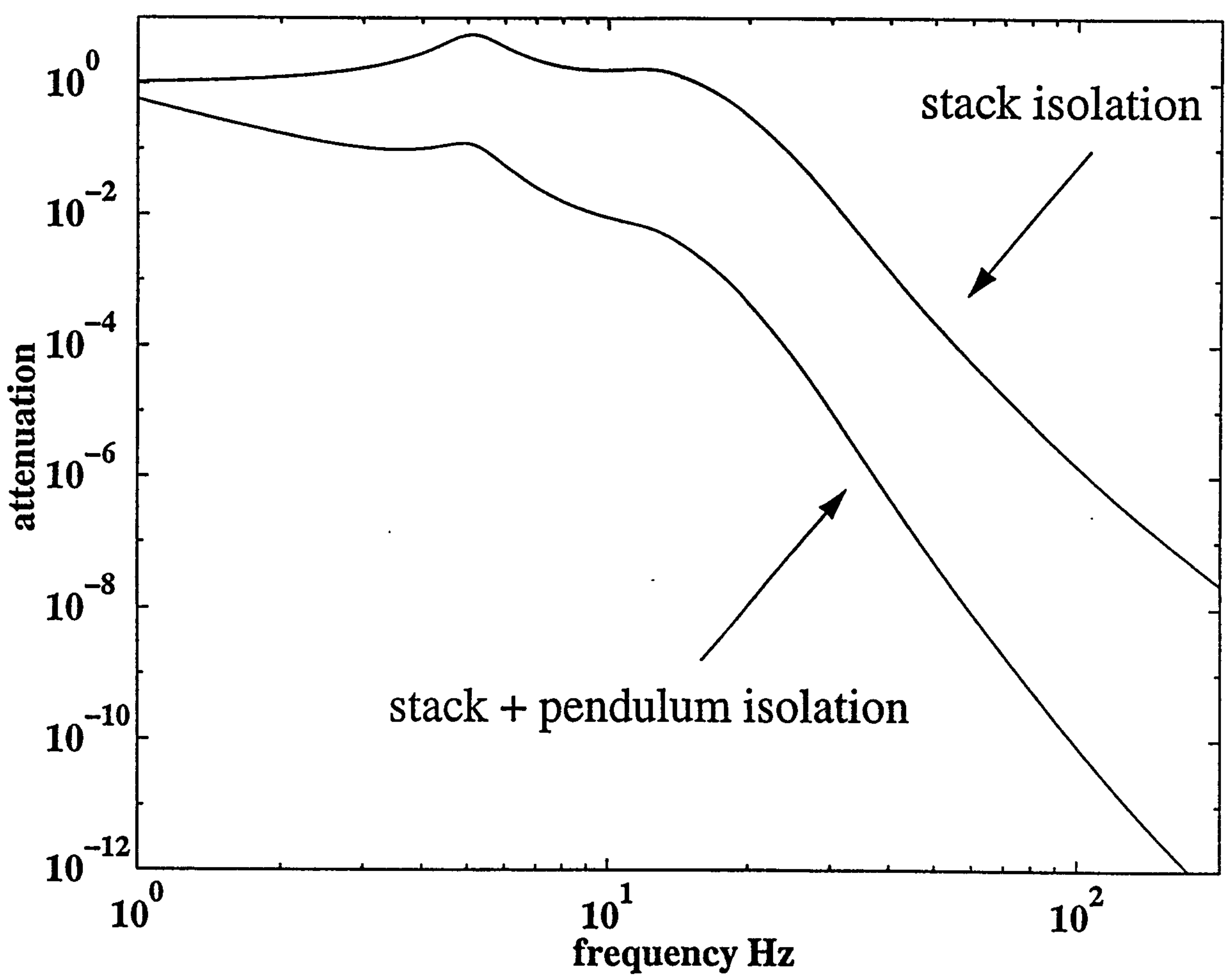
- careful site selection
  - far from ocean, significant human activity, seismic activity
- careful building design
  - low air velocities in HVAC, put refrigeration at a distance
- simple damped harmonic oscillators in series
  - LIGO: 'stacks', using lossy Viton springs and SS masses
  - alternatively, constrained layer damped spring
- one or more low-loss pendulums for final suspension
  - gives $1/f^2$ for each pendulum



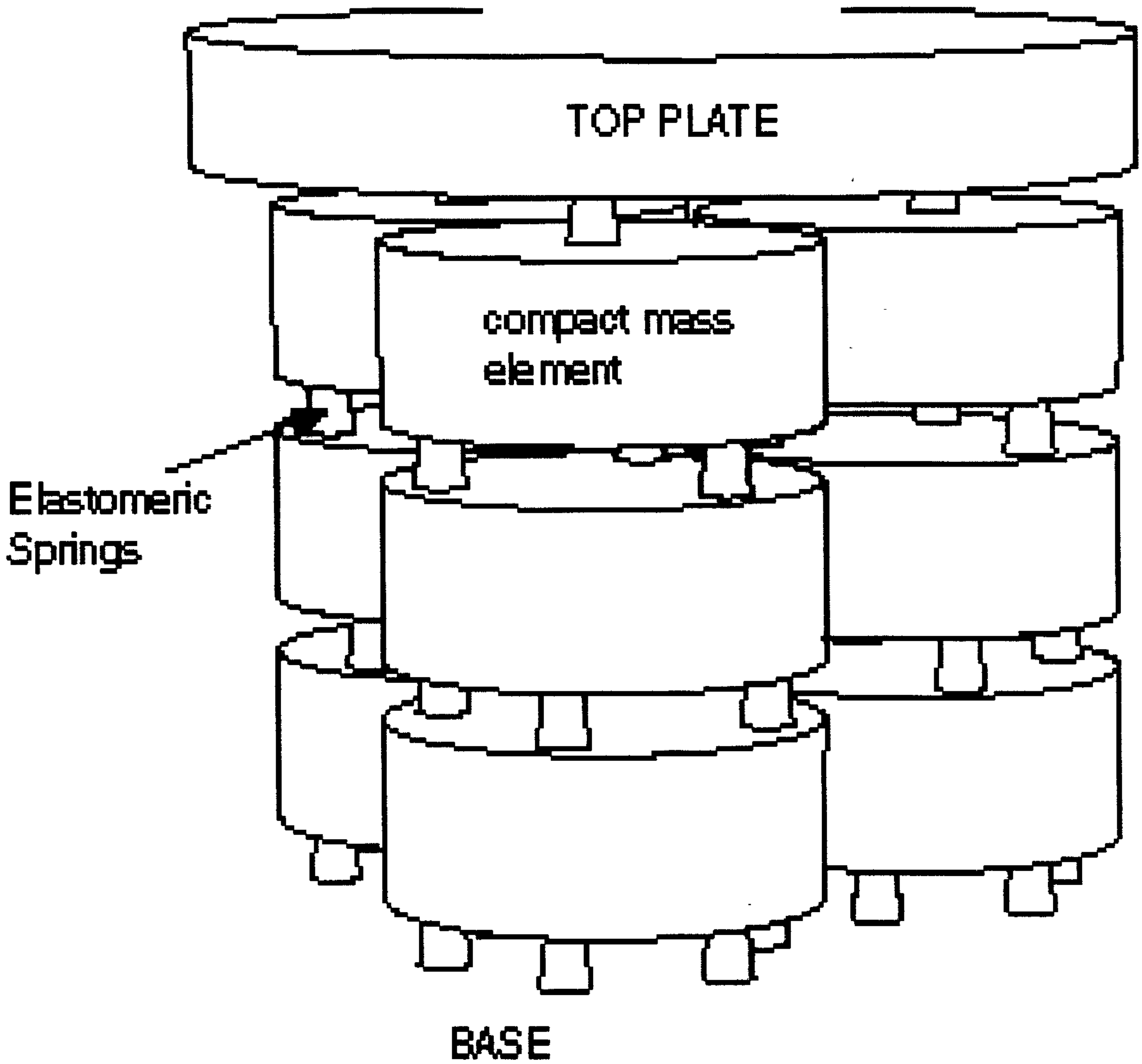
TYPICAL GROUND MOTION SPECTRA
Displacement (m/√Hz)
10−6
10−7
10−8
10−9
10−10
10−11
10−12
10−13
0.1
1
10
100
Frequency (Hz)
CIT
Livingston

7B

Baseline Isolation Performance



- Displacement noise 10^{-21} m/rHz @ 100 Hz



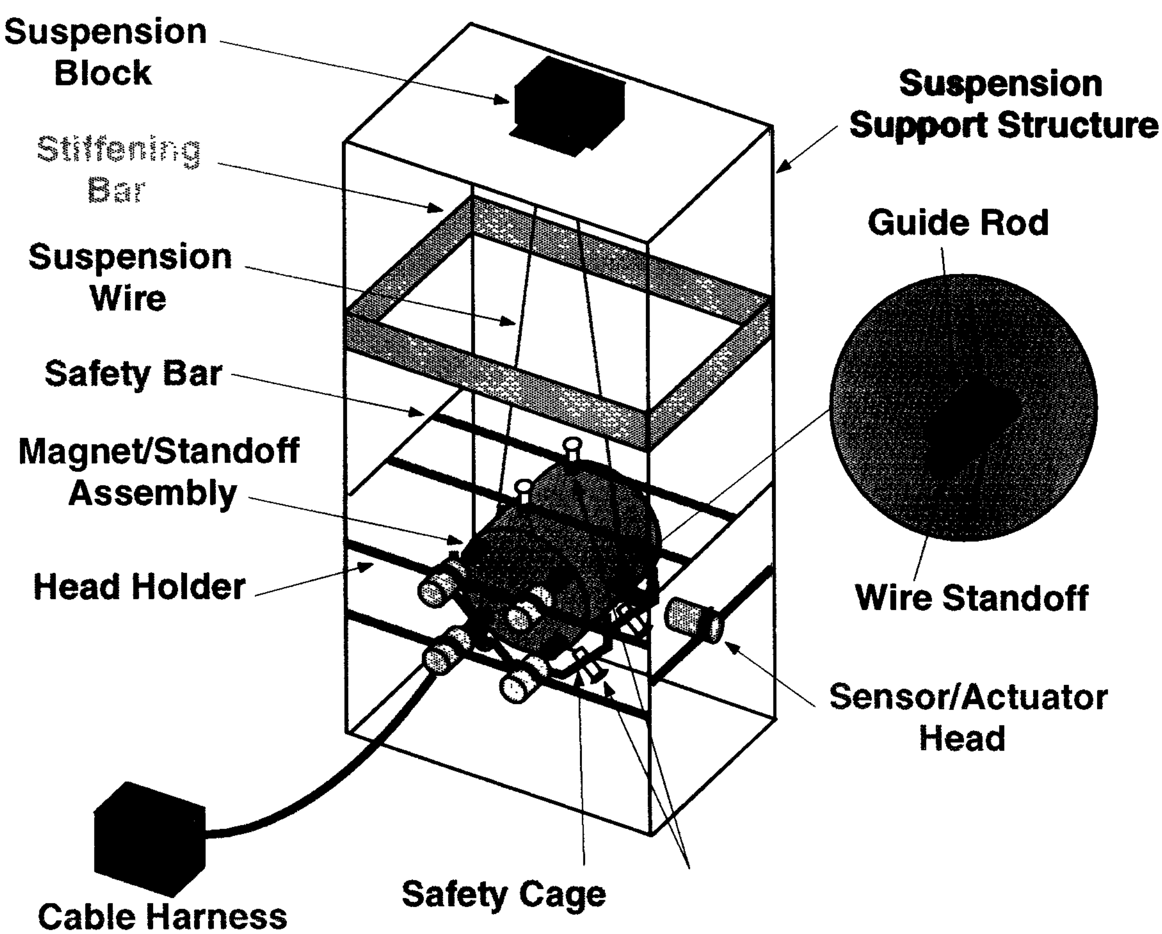
PROTOTYPE ISOLATION STACK

R&D: Suspension Research

Pendulum suspension serves several purposes

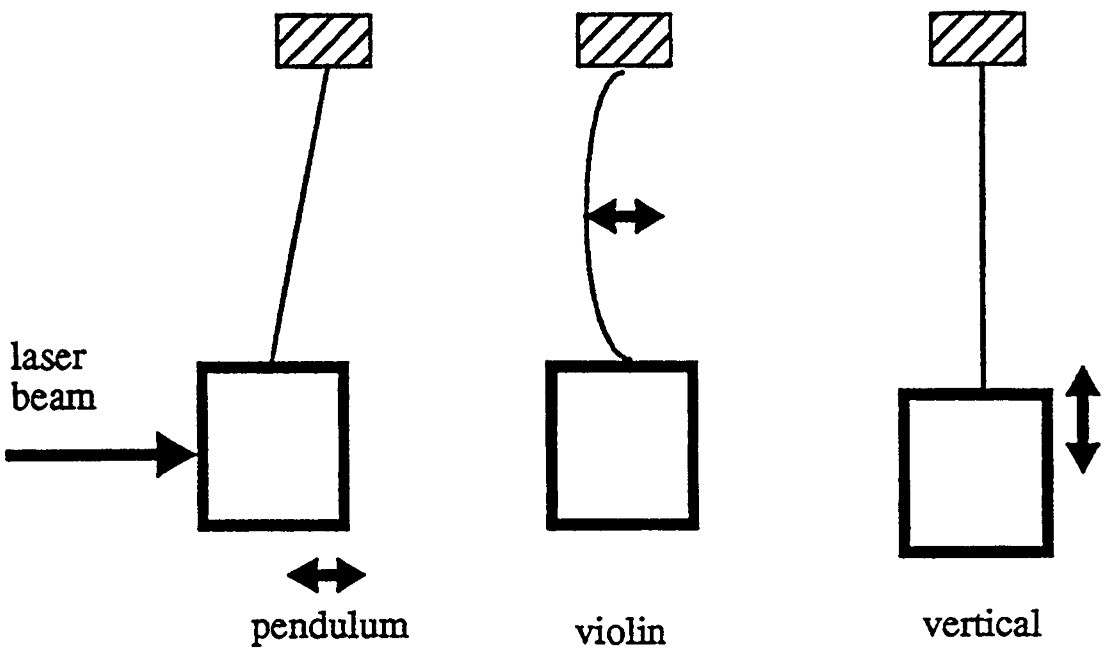
- minimizes thermal noise generated by test mass suspension
  - high-Q pendulum
- provides seismic isolation, $\sim f^{-2}$ above resonance
- allows translation and orientation forces to be applied

Prototypes tested separately, and in, interferometers



Interferometers

Mechanical Thermal Noise

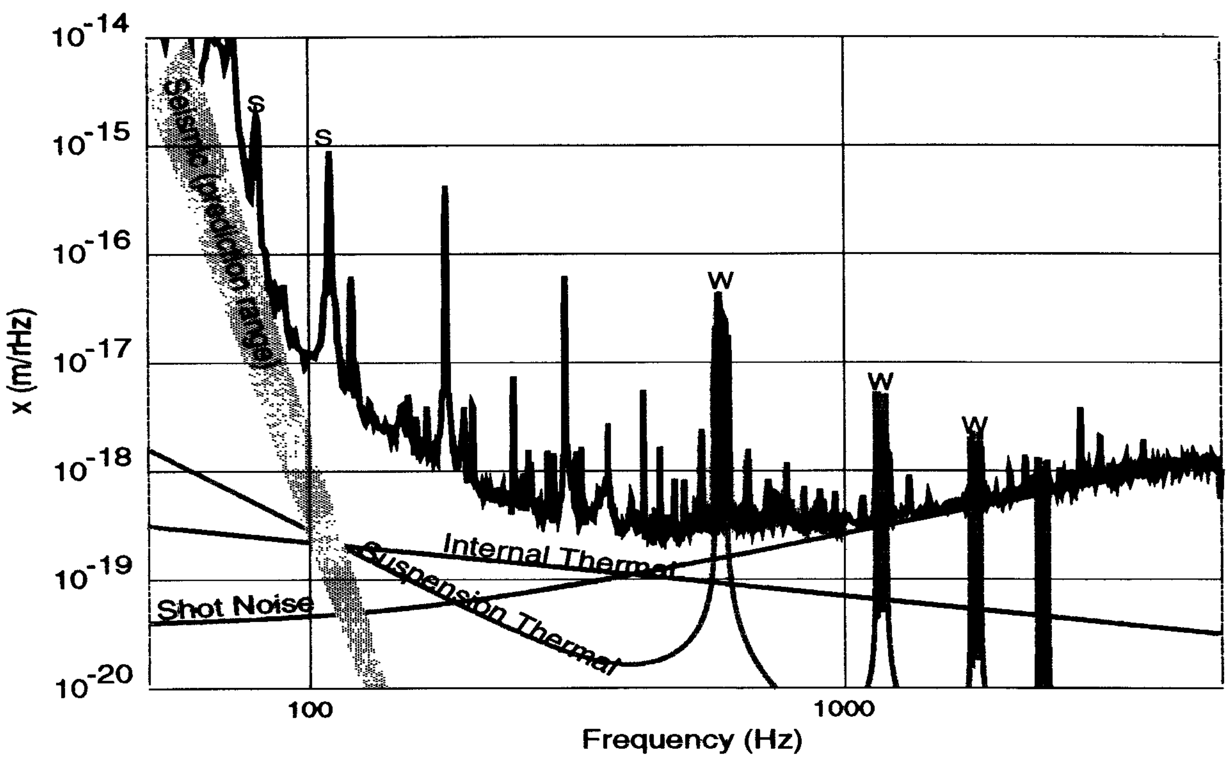


- pendulum noise
  - » $x_{rms} \sim 10^{-11}$ m, $f_0 \sim 1$ Hz
- violin mode
  - » $x_{rms} \sim 5\ 10^{-17}$m; $f_{0n} \sim 600n$ Hz
- test mass vibrational mode
  - » $x_{rms} \sim 5\ 10^{-16}$m, $f_0 > 10$ kHz

R&D: Thermal Noise research

Models, independent measurements, 40m tests

- thermal noise of substrate, pendulum significant for LIGO
  - previously no direct experimental observations to verify models
  - opportunity to observe in 40m by changing test masses
- thermal noise in compound test masses carefully calculated
  - measurements on 40m in good agreement
- new monolithic masses studied separately
  - coupling of control/sensing magnets/fins, suspension wires...
- installed in 40m; spectrum consistent with thermal noise model
- scaled thermal noise for LIGO meets initial curve



Shot Noise

$$\delta h(f) \approx \frac{1}{L} \left(\frac{\partial \phi}{\partial x}(f) \right)^{-1} \delta \phi(f)$$

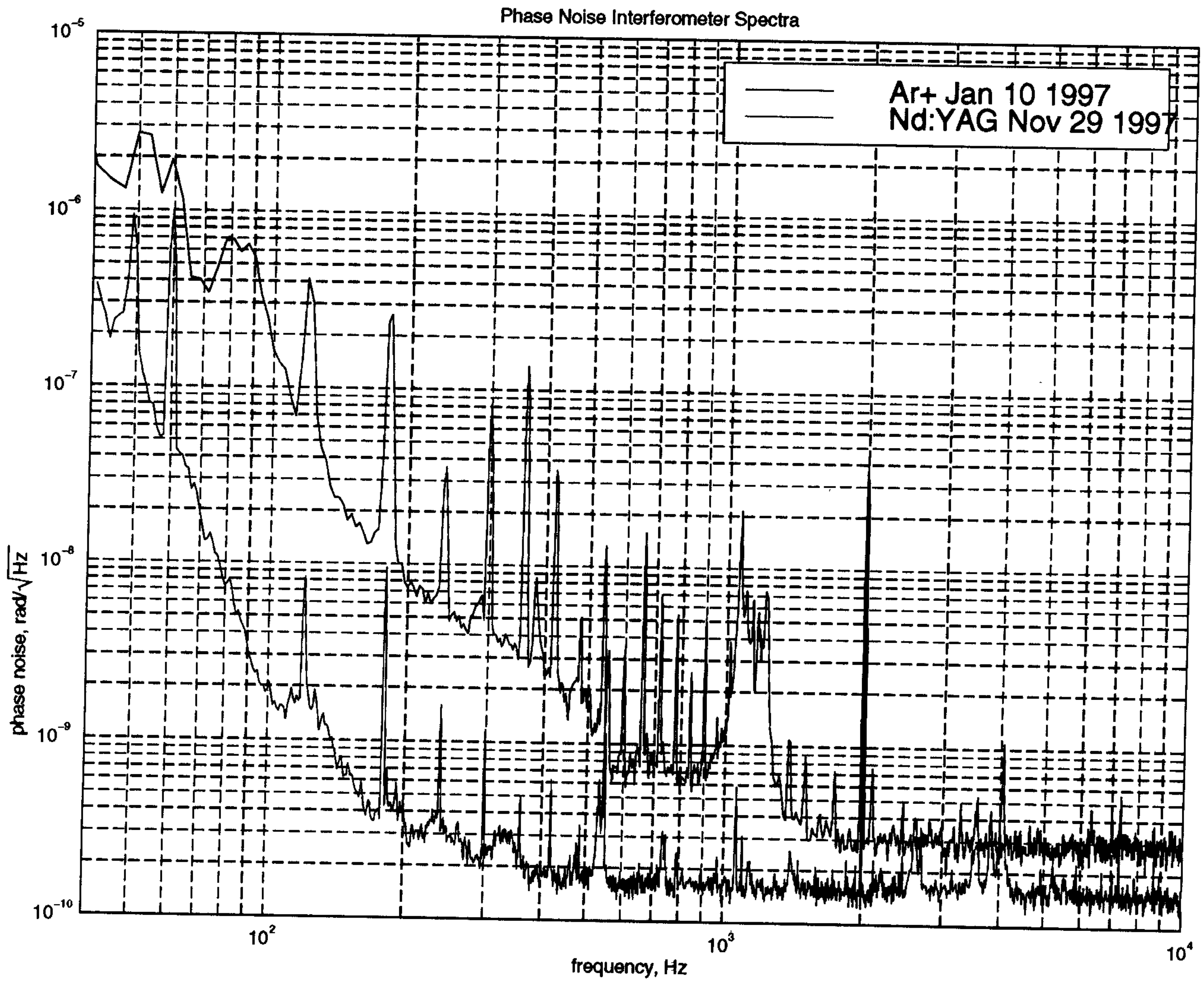
PROPERTY OF INTERFEROMETER OPTICAL CONFIGURATION (MIRROR R'S, ETC.)

DETERMINED PRIMARILY BY EFFECTIVE OPTICAL POWER

- **Achieving Shot-Noise Limited Phase Sensitivity Requires Understanding and Control of All Other Optical Sources of Noise**
  - **Laser Noise**
  - **Photodiode Uniformity**
  - **Modulator-Induced Noise**
  - **Scattered Light**

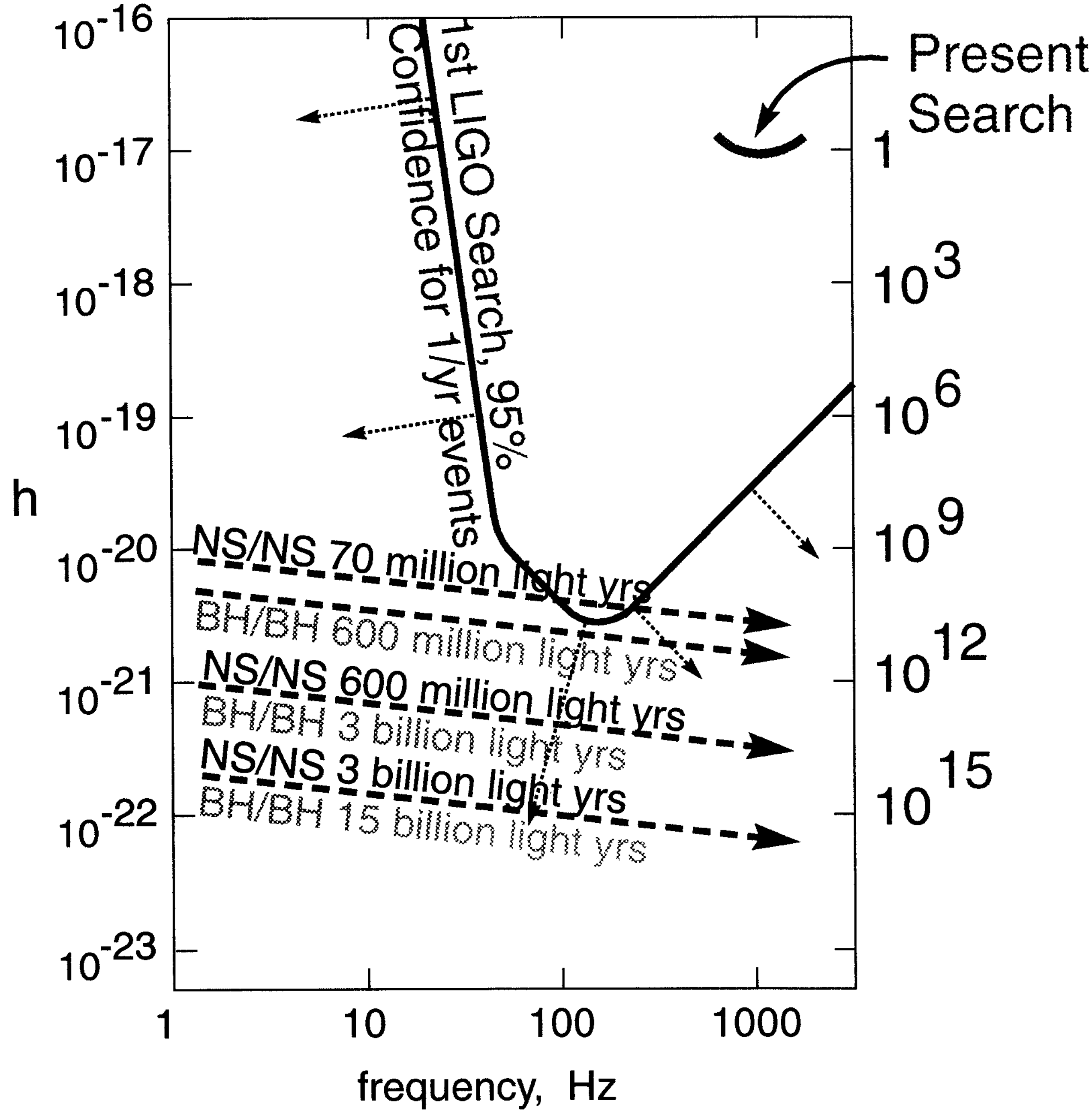
LIGO Requirement	10^{-10} rad/$\sqrt{\text{Hz}}$
Current 40-m Interferometer	10^{-8} rad/$\sqrt{\text{Hz}}$
MPQ Garching	10^{-9} rad/$\sqrt{\text{Hz}}$

PNI Spectrum

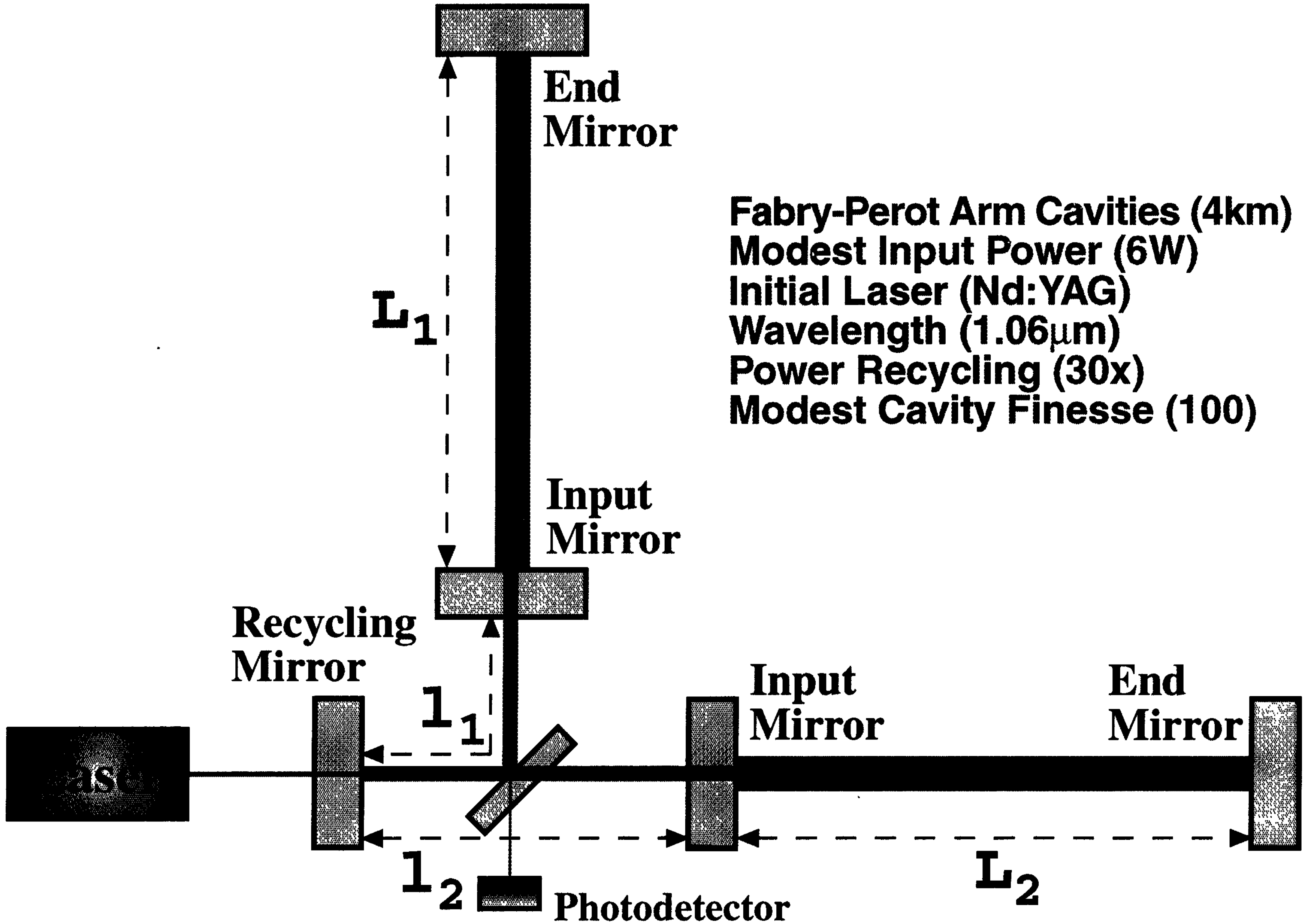


NEUTRON STAR BINARIES

["Near-Guaranteed" source]

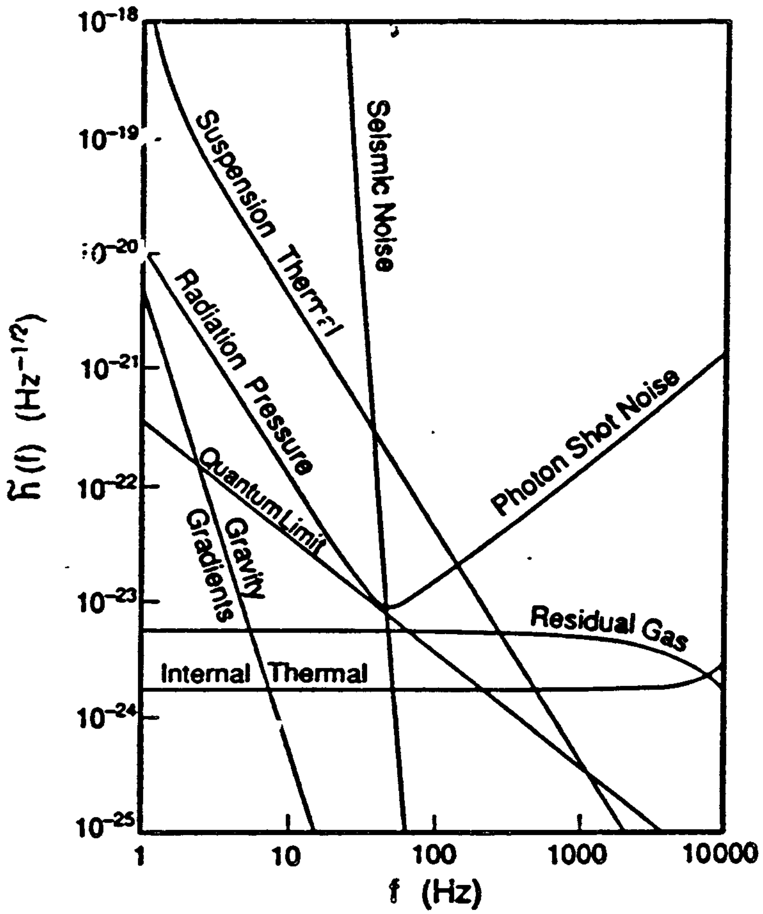


- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

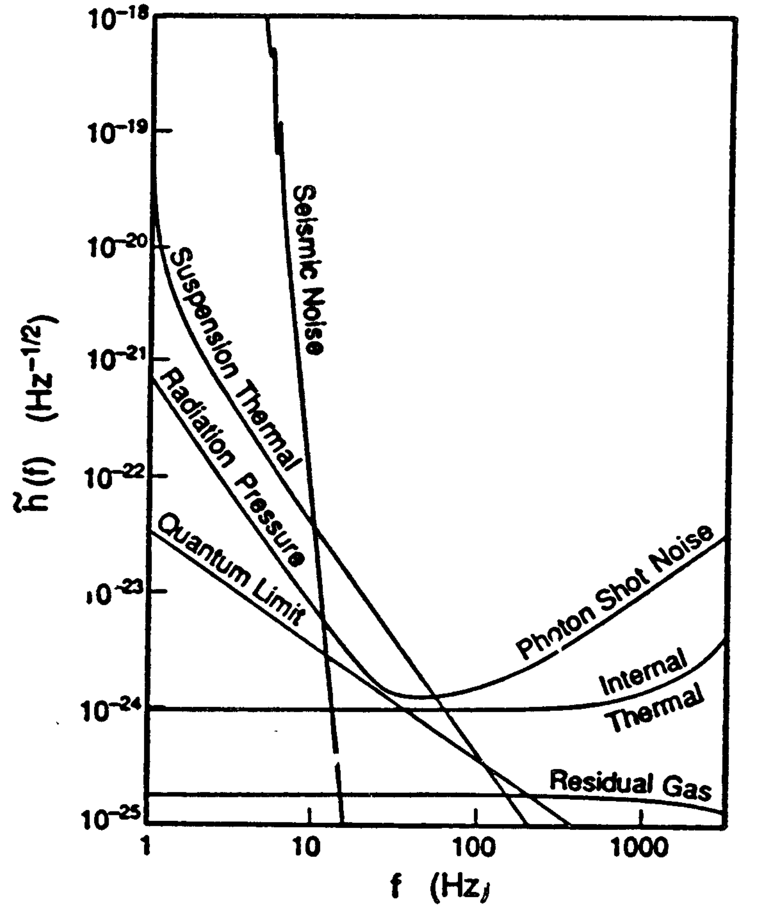

End
Mirror
Fabry-Perot Arm Cavities (4km)
Modest Input Power (6W)
Initial Laser (Nd:YAG)
Wavelength (1.06μm)
Power Recycling (30x)
Modest Cavity Finesse (100)
L1
Input
Mirror
Recycling
Mirror
l1
Input
Mirror
End
Mirror
l2
L2
Photodetector

Improvement Toward Advanced Interferometers

Initial Interferometer



Advanced Interferometer



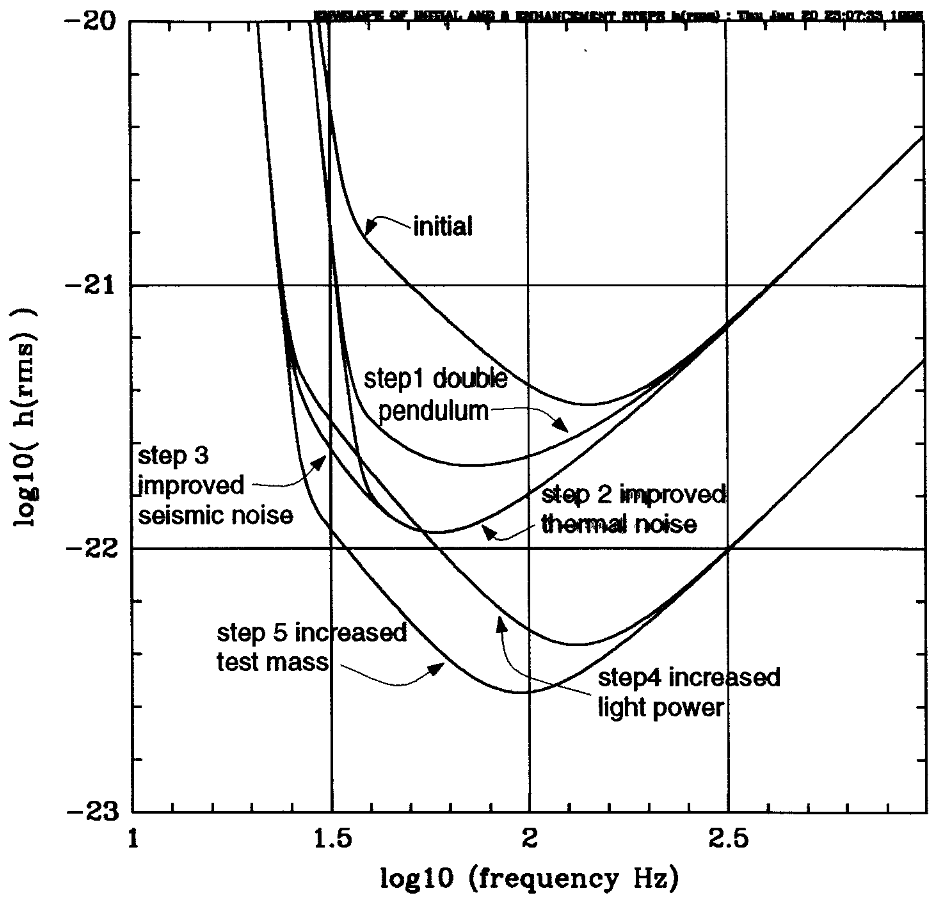
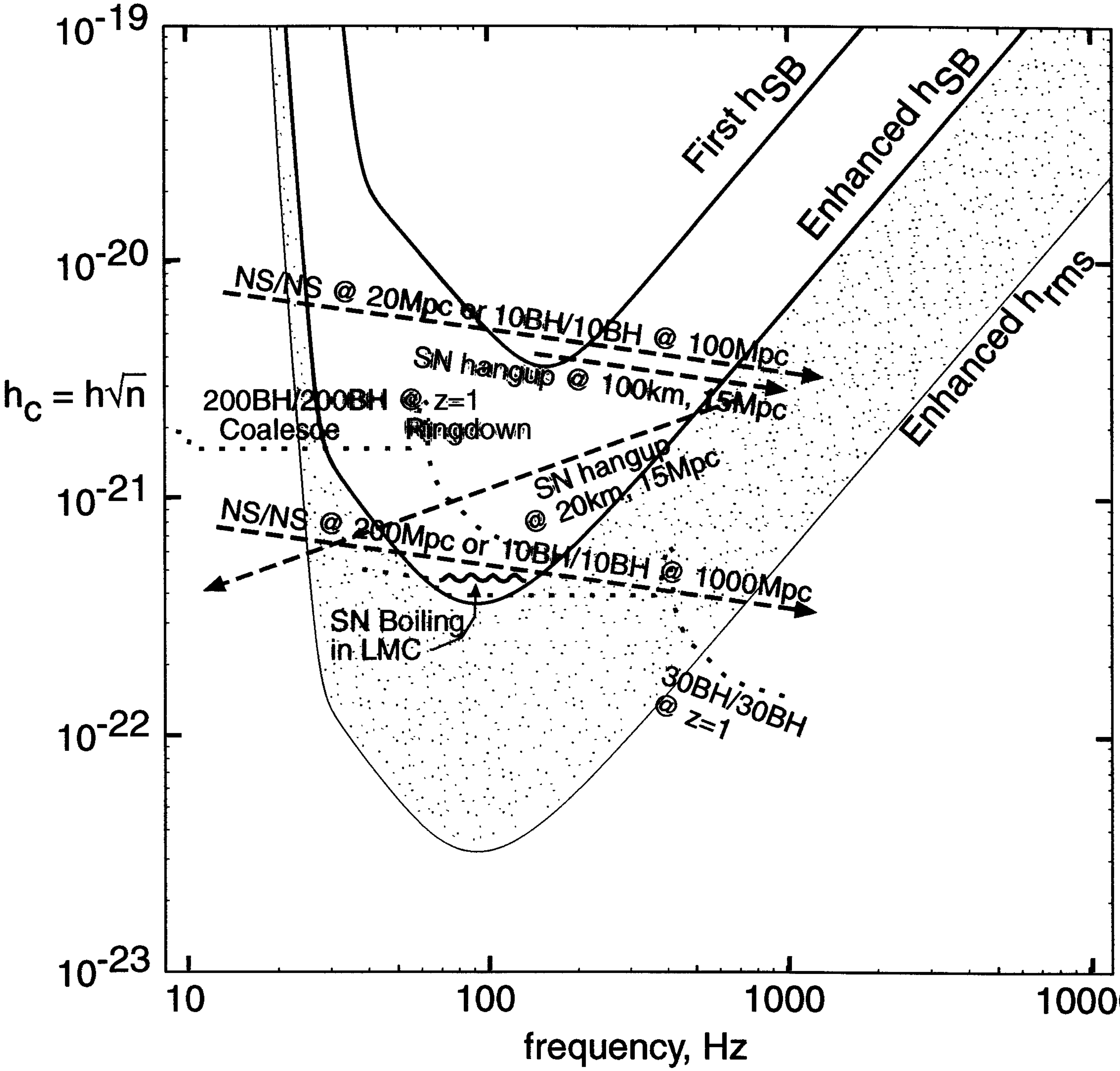


Figure 4:

The improvements in h_{rms} associated with the steps outlined in the proposed program and resulting in the parameters given in Table 2. The logic of the steps is determined by the assumption that compact binary coalescences are the most likely source to be detected, hence the importance of improving the sensitivity near 100 Hz. The improvements associated with the do

CAPABILITIES OF ENHANCED LIGO INTERFEROMETERS

~2007

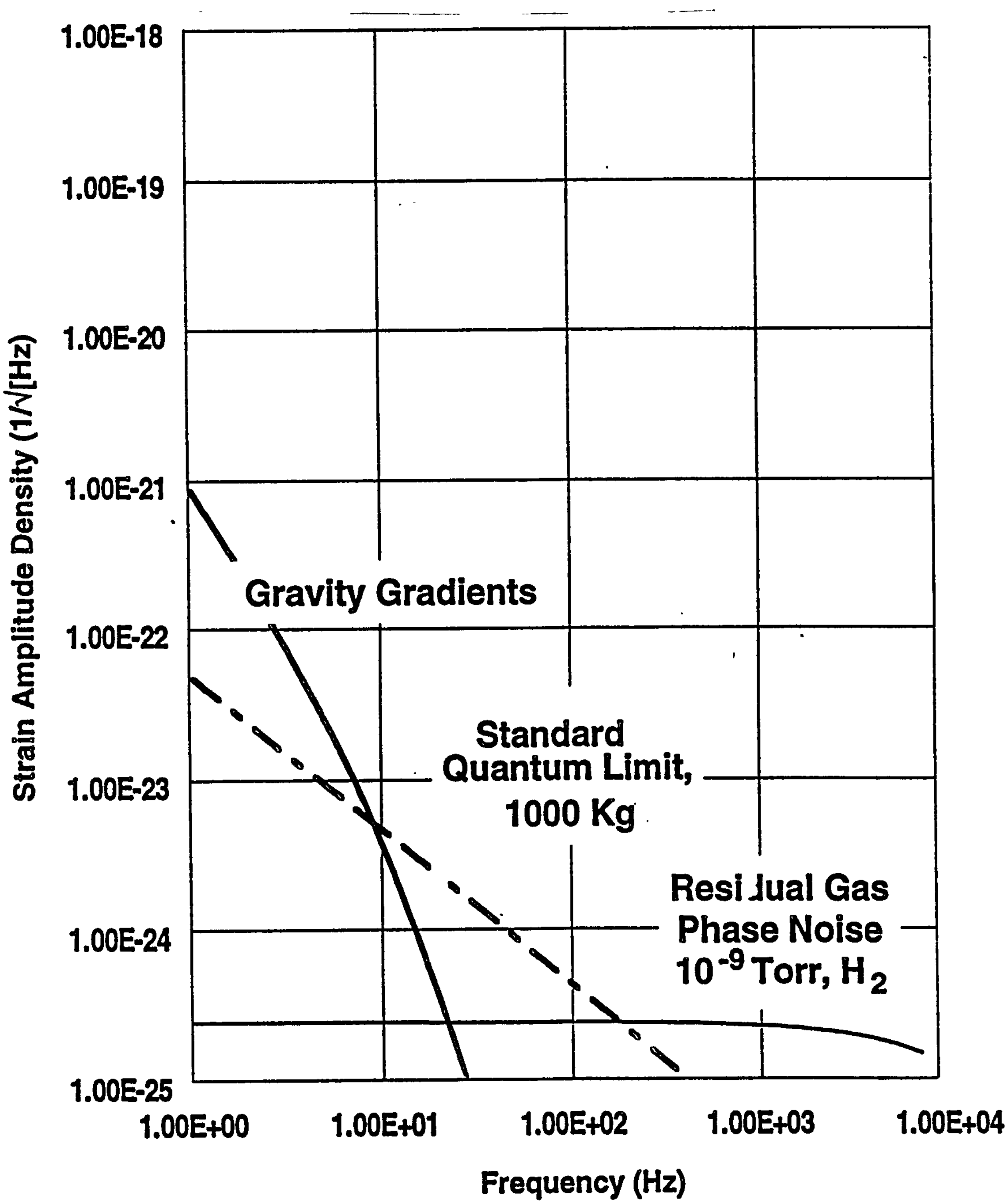


CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO-G960140-00-E
June 21, 1996 9:07 am

LIGO Facilities

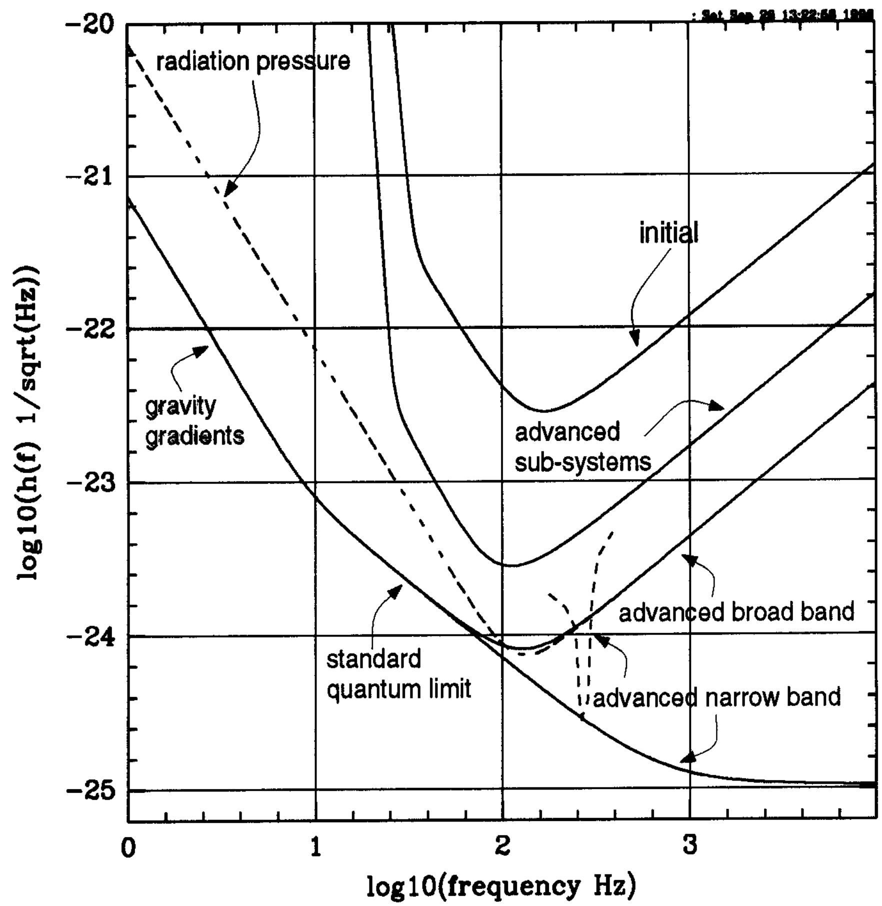
Limiting Noise Floor



LIGO

LIGO-G960108-00-M

Amplitude Spectral Strain Noise Expressed as an Equivalent h(f)



LIGO-G960209-00-M

LIGO Operations
physics/enhancements

- First Physics Run (~2002-2004)
  - » **LIGO I** Development Group
  - » Initial LIGO design sensitivity h ~ 10^{-21}
  - » one year integrated data (~ 2 year run)
  - » data reserved for LIGO I group for two years from collection
- Enhancements/Data Taking (~2004- ?)
  - » Advanced R&D to reach h ~ 10^{-22}
  - » incremental improvements - **LIGO II**
  - » implemented from 2004, mixed with data taking
- Advanced Detector Configurations
  - » development work begins now
  - » implementation within 10 years (eg. 2008)?