The Detection of Gravitational Waves

LIGO

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Kamiokande Seminar

Nov 15, 1996

LIGO-G960236-00-M

LIGO
Introduction

- Laser Interferometer Gravitational Wave Observatory
  - » **DIRECT** Detection of Gravitational Waves
- Joint Caltech/MIT Project funded by the National Science Foundation
- Under Construction
  - » Two Sites -- Louisiana and Washington

LIGO
The Project

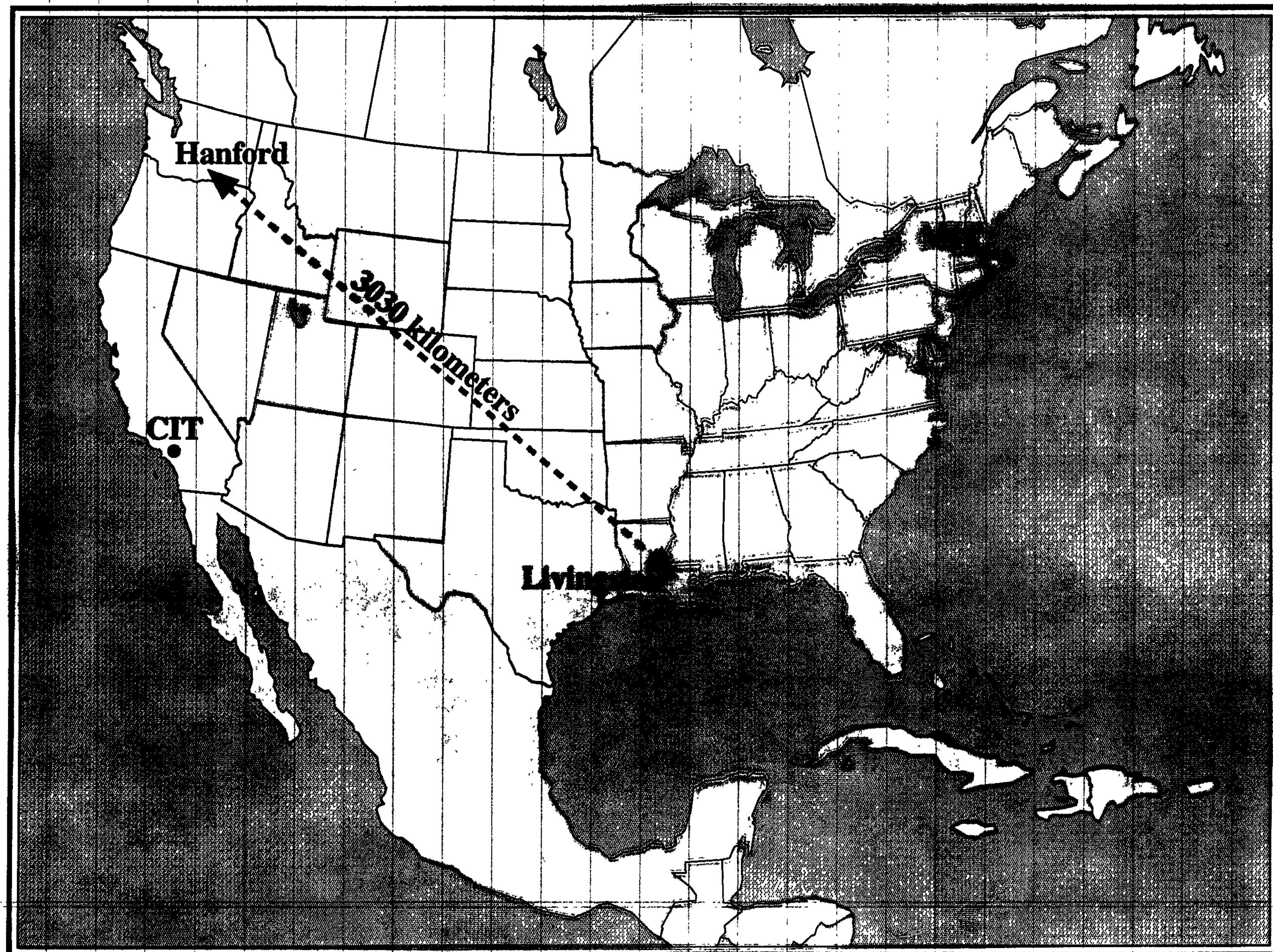
- National Science Foundation

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

- Commission Facility (1999-2001)
  - » Implement Initial Detectors
    - $h \sim 10^{-20}$ - Coincidence
      - Initial Search (end of 2000)
    - $h \sim 10^{-21}$ - Initial Design Sensitivity (end 2001)

- Full Operations (2002 + ...)
  - » Data Dating/Analysis
    - data collaboration with VIRGO
  - » Enhance Initial Detector
    - incorporate outside collaborations
  - » Advanced Detectors
    - Syracuse, Colorado, Stanford, etc
    - Caltech/MIT efforts

BB
AHM



Hanford
3030 kilometers
CIT

Gravitational vs E.M. Waves

	EM WAVES	GRAV. WAVES
Nature	Oscillation of EM Fields Propagating Through Spacetime	Oscillations of the "fabric" of spacetime
Emission Mechanism	Incoherent superposition of waves from molecules, atoms, particles	Coherent emission by bulk motion of energy
Interaction with Matter	Strong absorption and Scattering	Essentially None!
Frequency Band	$f > 10^7 Hz$	$f < 10^4 Hz$

- Implications
  - Most gravitational sources not seen as electromagnetic (and vice versa)
  - Potential for great surprises
  - Uncertainty in strengths of waves

Gravitational Wave

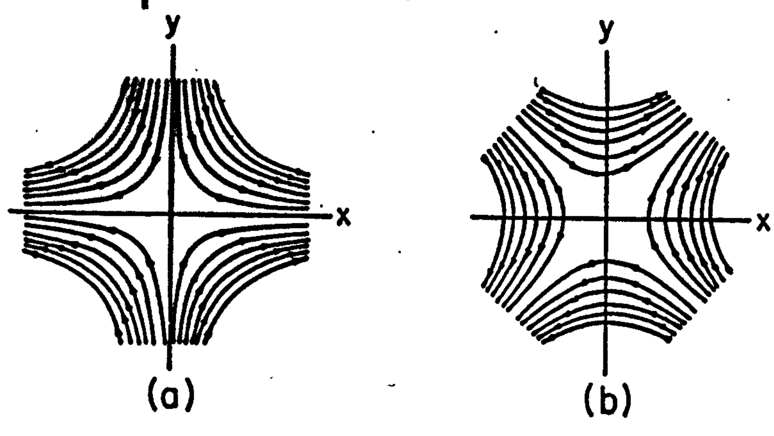
Forces

IF

- Detector Size << Wavelength
  (4 km) (300-30,000km)
  (10 kHz - 10 Hz LIGO)

THEN

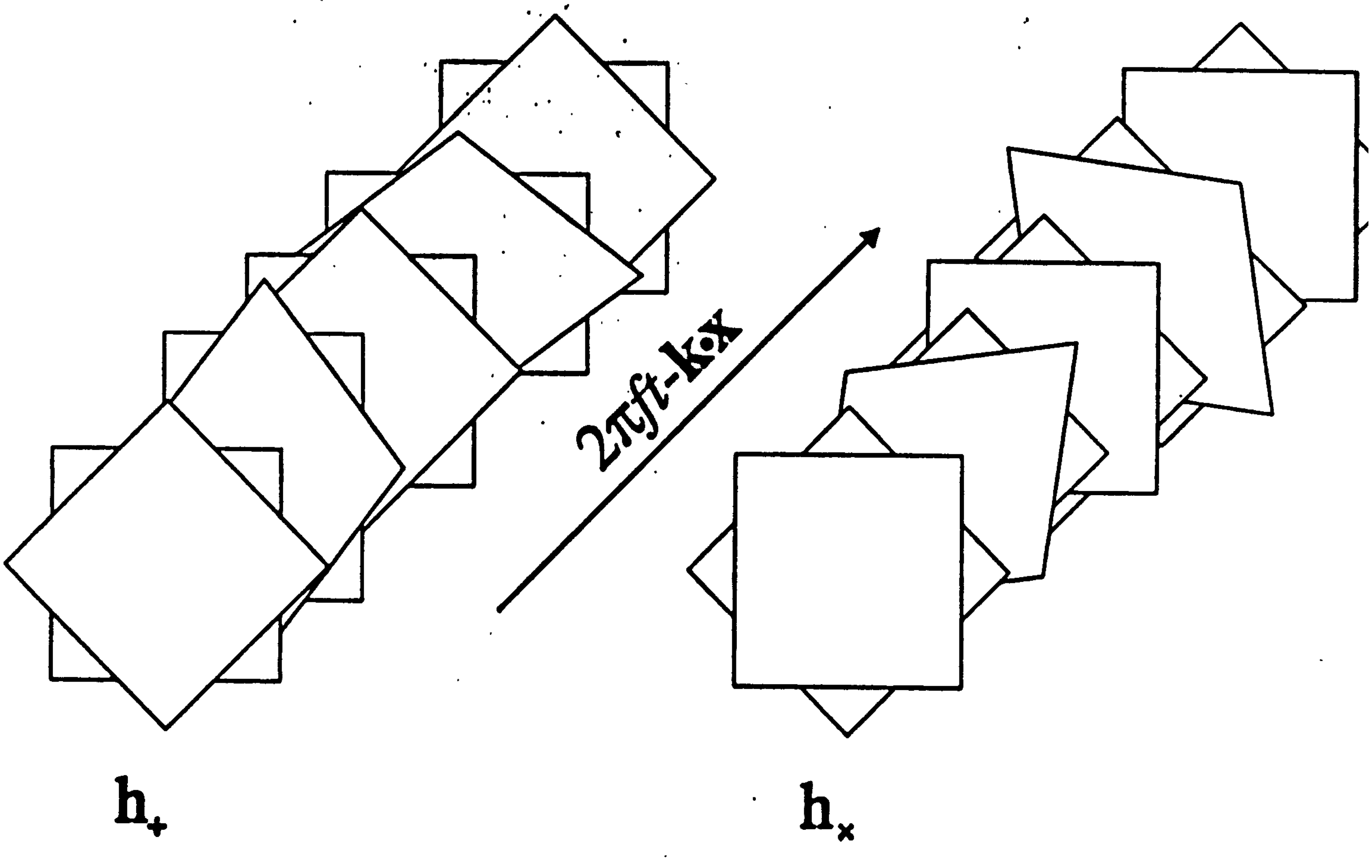
- Free Masses
- Quadrupolar Lines of Force



+ Polarization   x Polarization

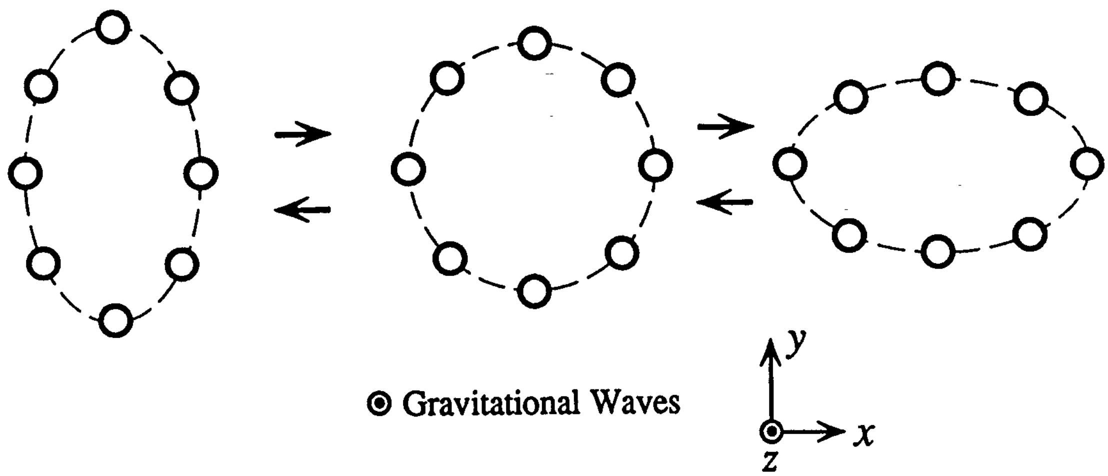
Gravitational Waves

Two Polarizations

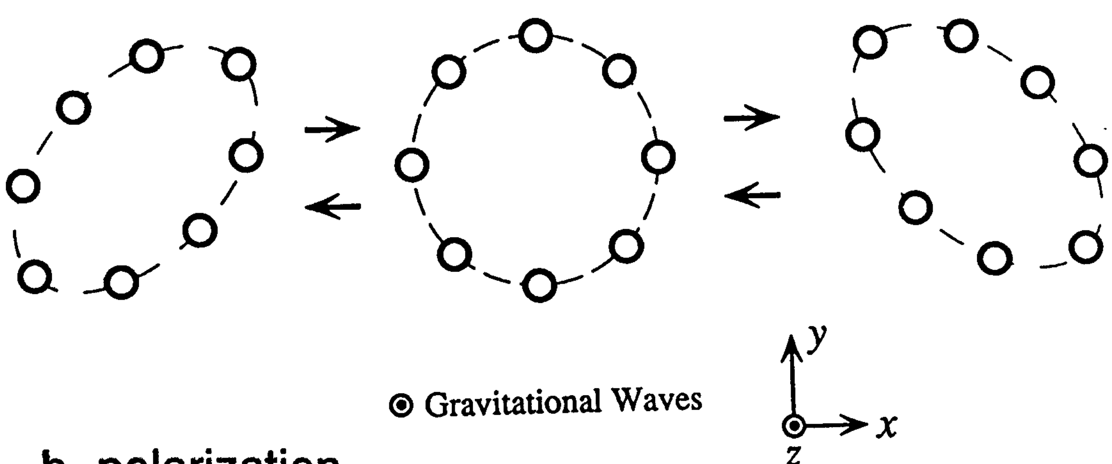


Gravitational Waves
Effects

- Displacement of free particles

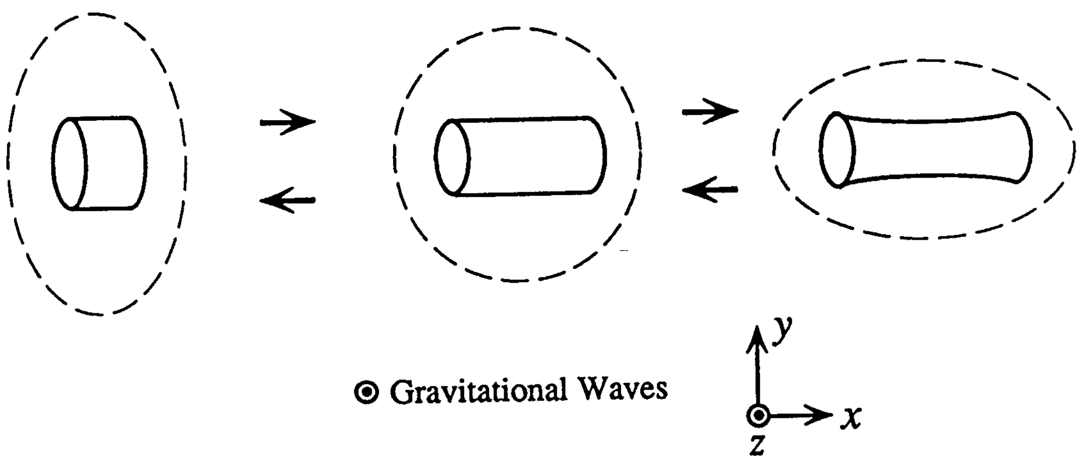


» h_+ polarization

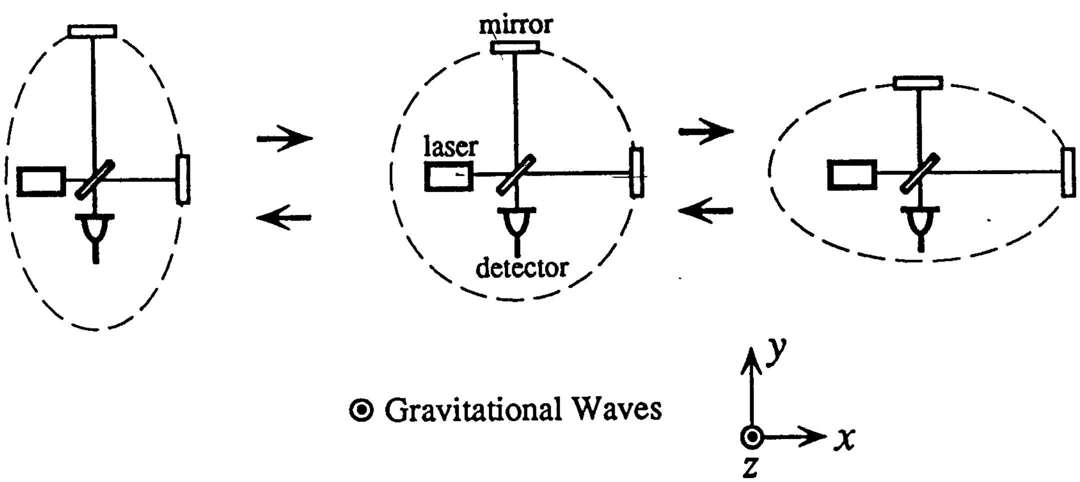


» h_x polarization

Gravitational Waves
Detection



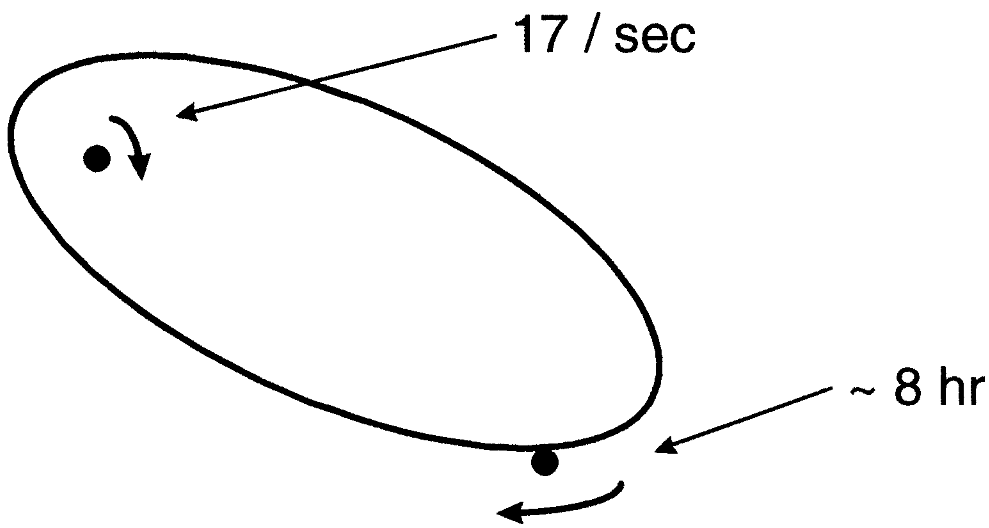
- Bar detector



- Interferometer detector

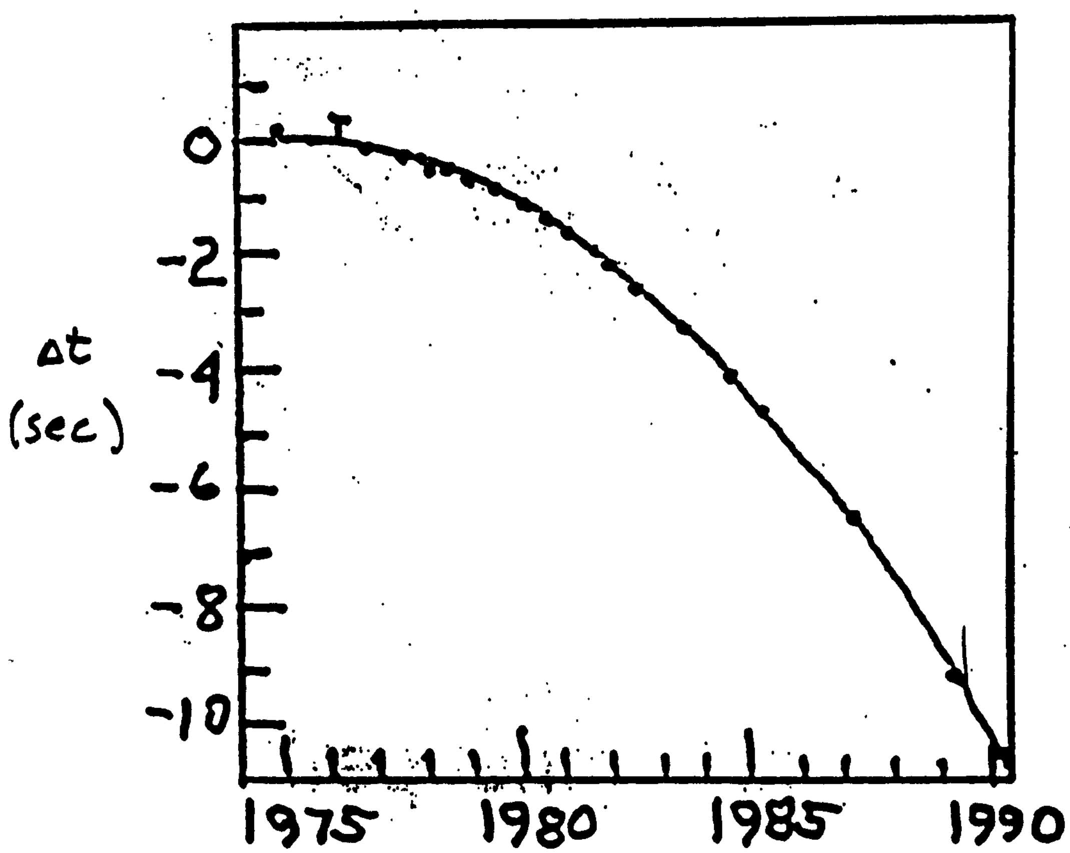
Gravitational Waves
Evidence

- **Russell Hulse and Joseph Taylor**
- Neutron Binary System
  - » PSR 1913 + 16 -- Timing of Pulsars



Hulse and Taylor
Timing of Orbit

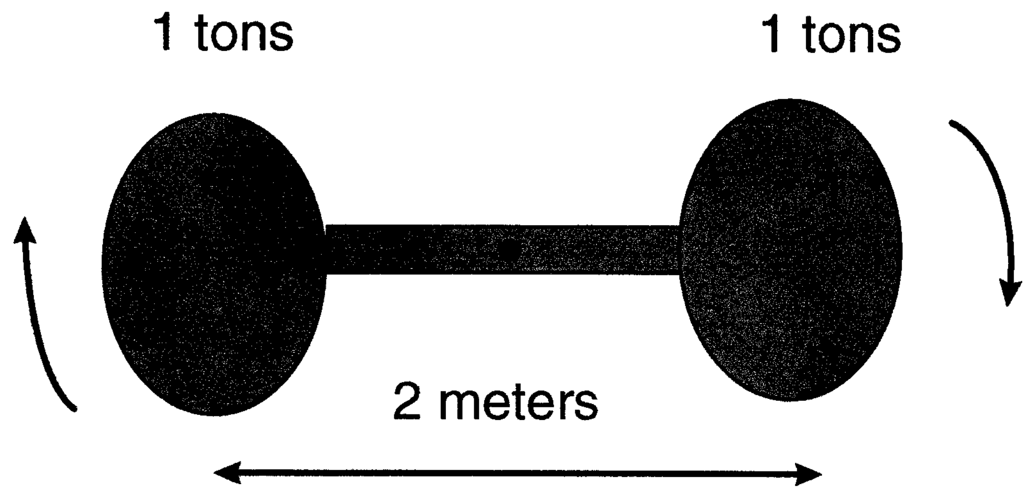
- Speed up 10 sec in 15 years
  - » measured to ~50 μsec accuracy
- Deviation grows quadratically in time



- Due to loss of orbital energy, from emission of gravitational waves

Laboratory Experiment
(a la Hertz)

Laboratory Dumbbell System



f_{rot} = 1 kHz

h_{lab} = 2.6 10^{-33} m x 1/R

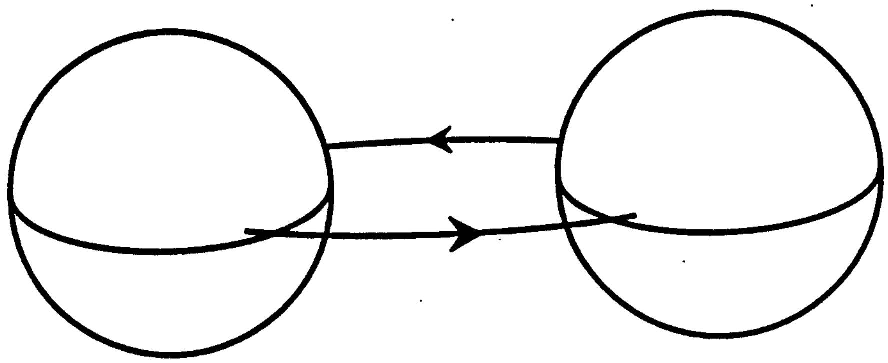
R = detector distance (> 1 wavelength) = 300 km

$\mathbf{h_{lab} = 9\ 10^{-39}}$

This is too weak by about 16 orders of magnitude!

Gravitational Waves

Sources and Detection



- binary star system

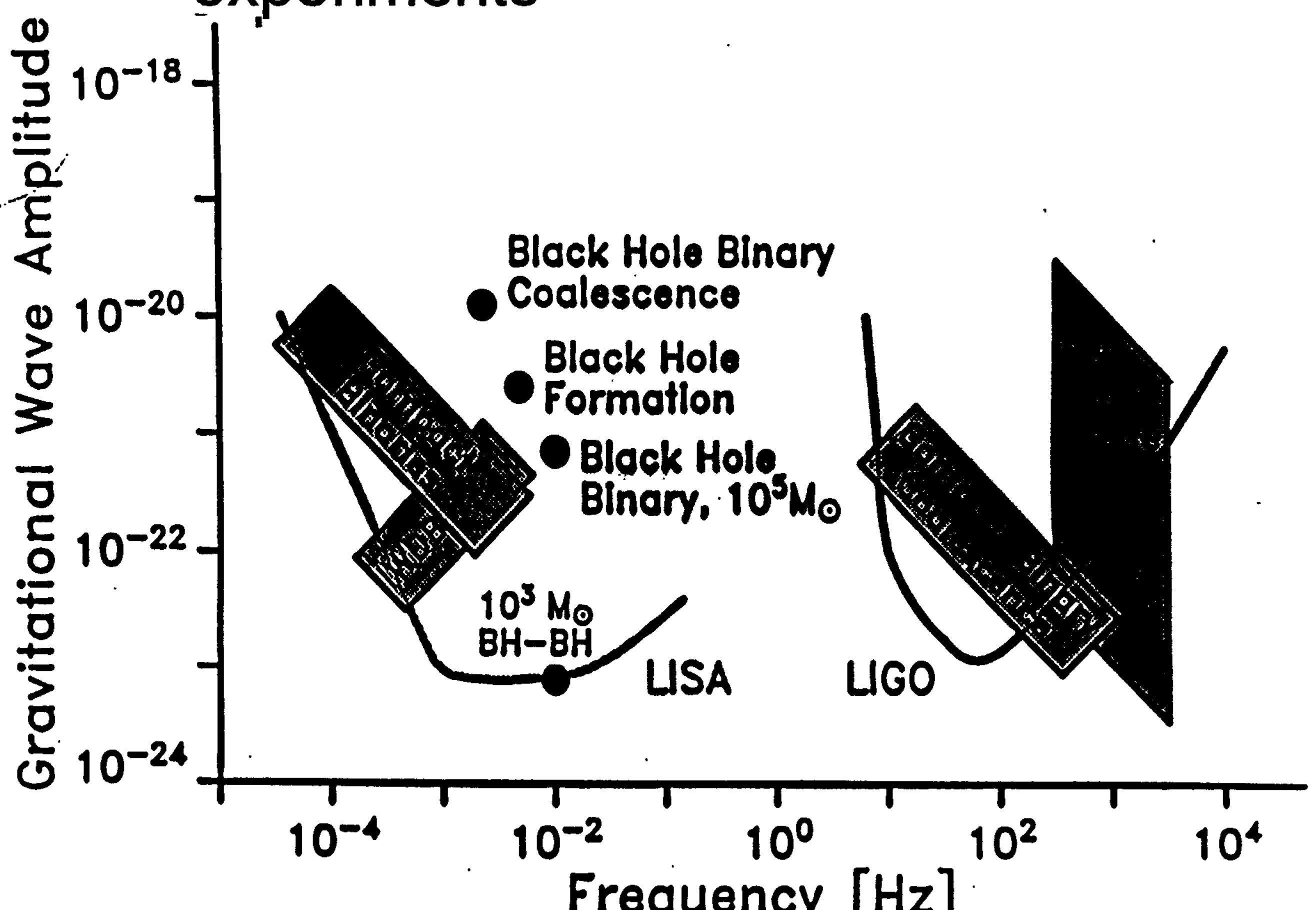
Sources	Frequency	h	Event Rate	Detection
Coalescing Binary Neutron Stars (200 Mpc)	10∼1000 Hz	10^{-22}	∼3/year	Interferometer +Template
Supernovae (in our Galaxy)	∼1 kHz	10^{-18}	∼3/century	Interferometer, Resonant
Supernovae (in Virgo)	∼1 kHz	10^{-21}	several/year	Interferometer
Generation of Large Black Holes	∼1 mHz	10^{-17}	1/year	Interferometer in Space
Pulsars	10∼1000 Hz	10^{-25}	periodic	Interferometer, Resonant
Cosmic Strings	10^{-7} Hz	10^{-15}	stochastic	Pulsar Timing

- sources and detection

Astrophysical Sources

Frequency Range

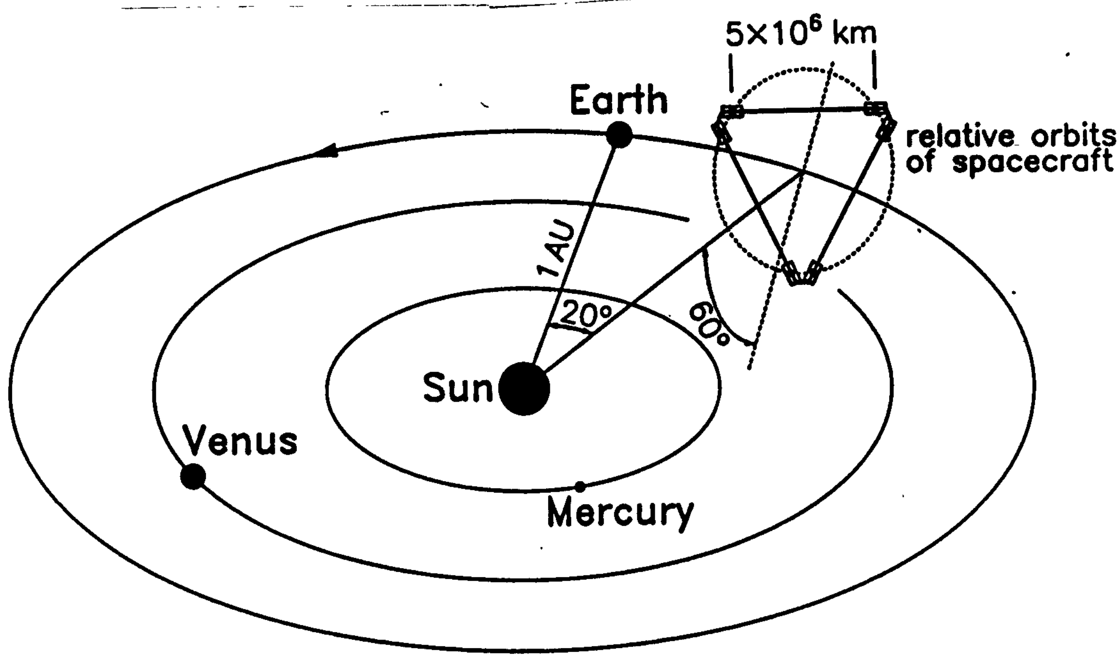
- Electromagnetic Waves - ~ 20 orders of magnnitude (ULF radio -> HE γ rays)
- Gravitational Waves - ~ 10 orders of magnitude
- Combination of terrestrial and space experiments



Gravitational Waves

Space Experiment

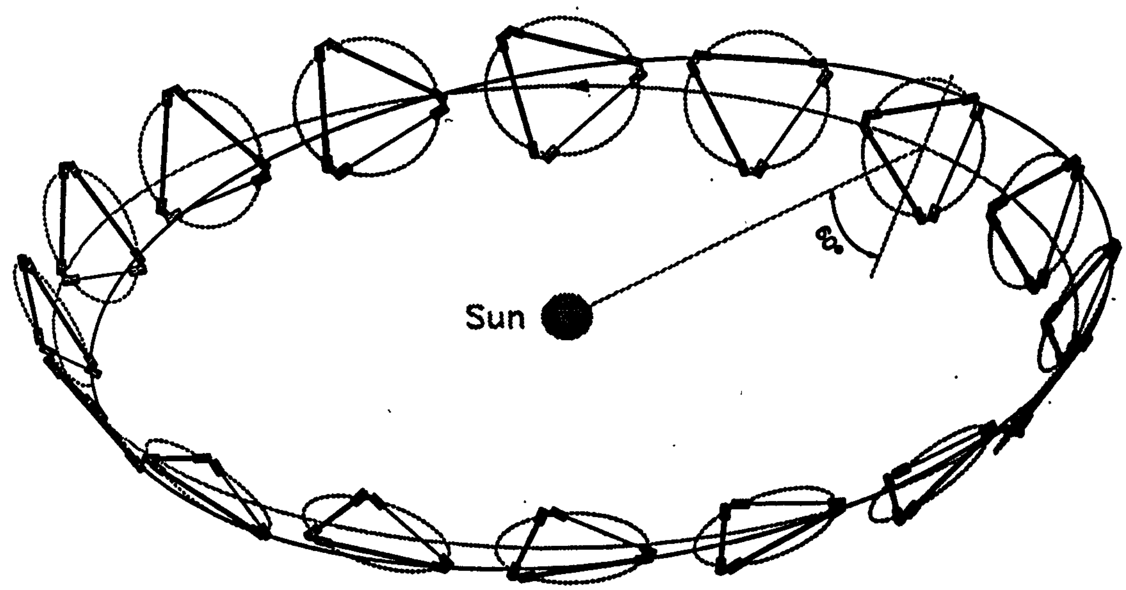
- LISA - Laser Interferometer Space Antenna
  - » six spacecraft in triangle (four needed)
  - » pair at each vertex



LISA

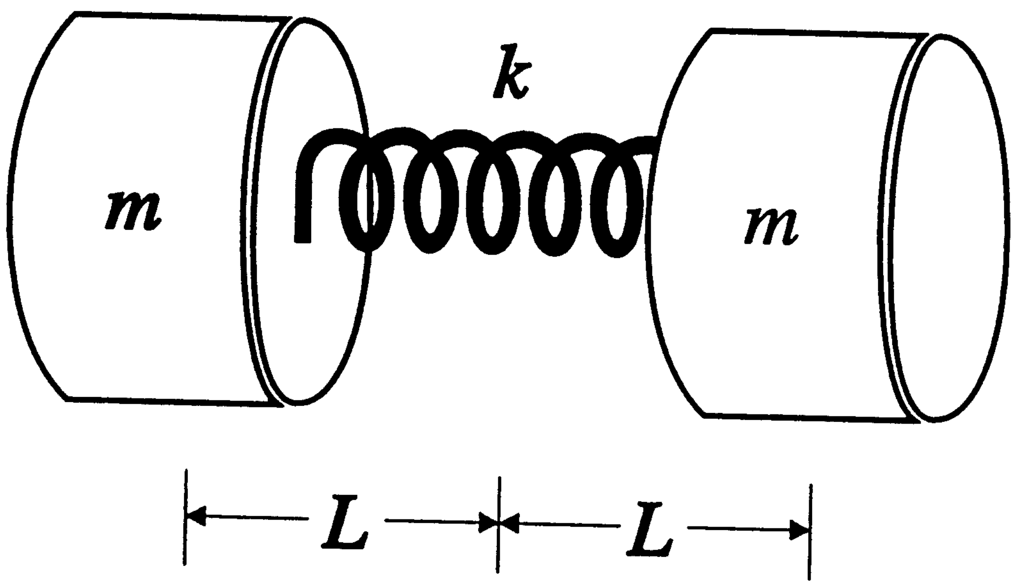
Annual Revolution

- 60 degree half opening angle
- 'tumbling' allows determination of position of source and polarization of wave

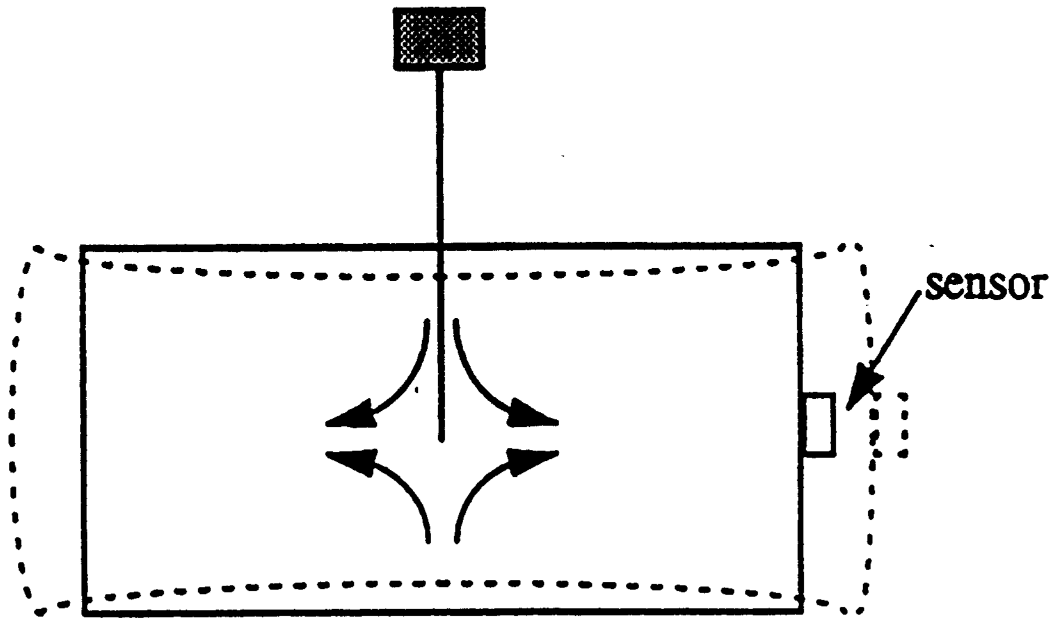


Gravitational Waves
Resonant Bar Detector

- Schematic Version



Gravitational Waves
Resonant Bar Detection



- Bar detector

Group	Antenna	Transducer	Sensitivity (h)
CERN/Rome	Al5056, 2.3ton, 2.6K	Capacitive+SQUID	7×10^{-19}
CERN	Al5056, 2.3ton, 0.1K	Capacitive+SQUID	2×10^{-18}
LSU(USA)	Al5056, 1.1ton, 4.2K	Inductive+SQUID	7×10^{-19}
Stanford	Al6061, 4.8ton, 4.2K	Inductive+SQUID	10^{-18}
UWA(Australia)	Nb, 1.5ton, 5K	RF cavity	9×10^{-19}
ICRR(Japan)	Al5056, 1.7ton, 300K	Laser Transducer	–
KEK(Japan)	Al5056, 1.2ton, 4.2K	Capacitive+FET	4×10^{-22} (60Hz)

- Status of bar detectors

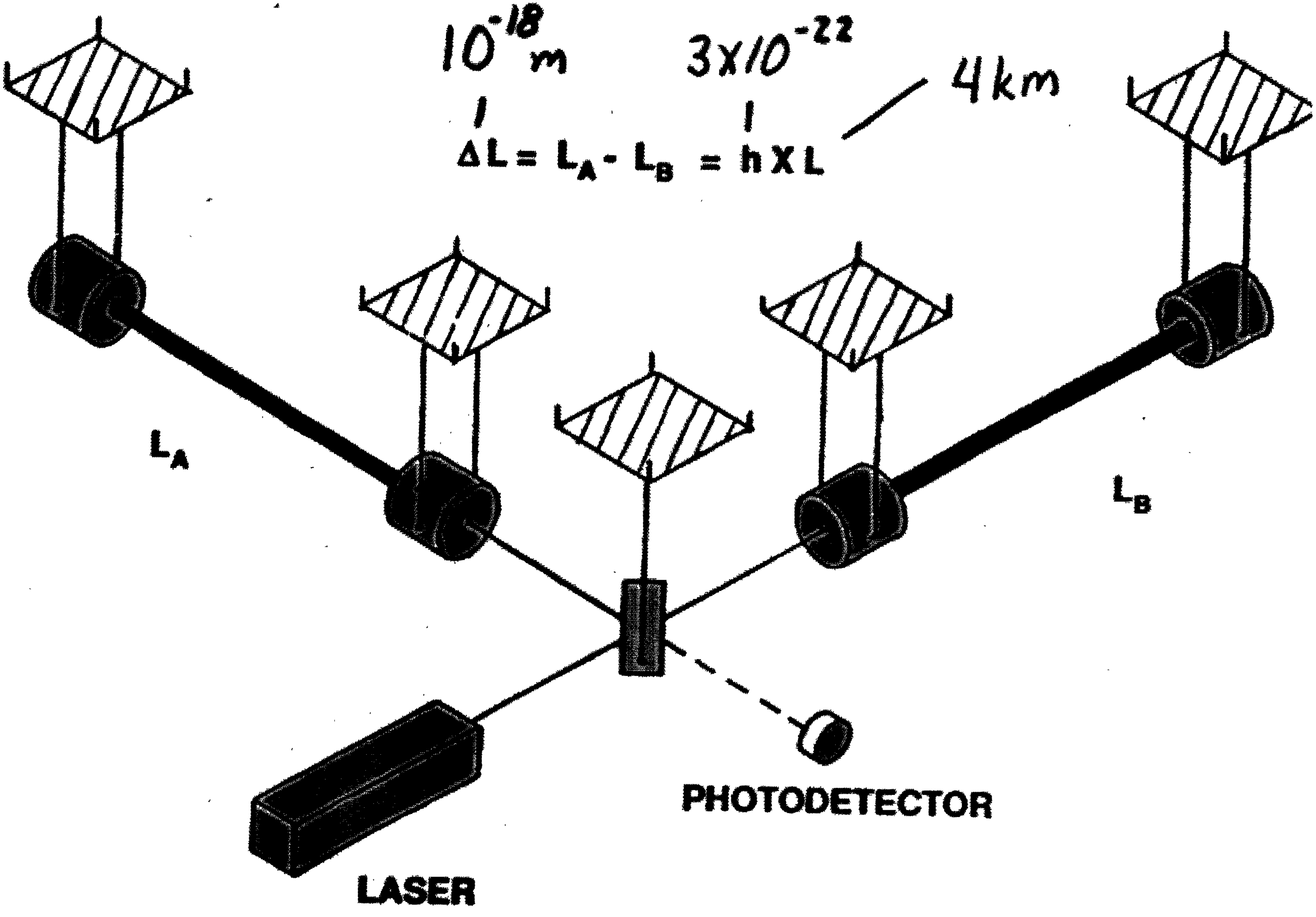
Gravitational Waves
International Effort

- Techniques
  - » Resonant Bar Detectors (LSU, Rome, etc)
    - – narrow band
  - » Large Scale Interferometers
    - – broad band

- 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

SCHEMATIC INTERFEROMETRIC DETECTOR



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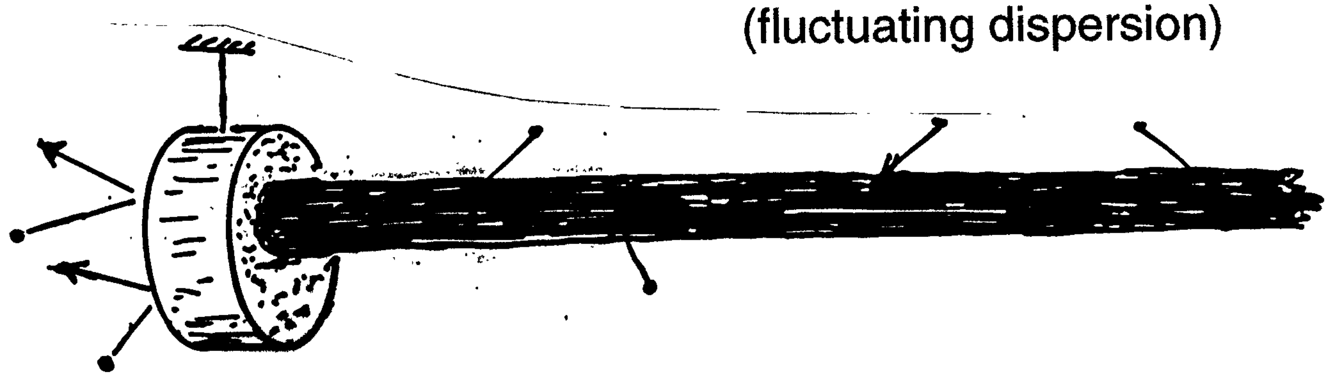
LIGO

Achieving 10^{-18} m Sensitivity

How is it possible????

- Air molecules:



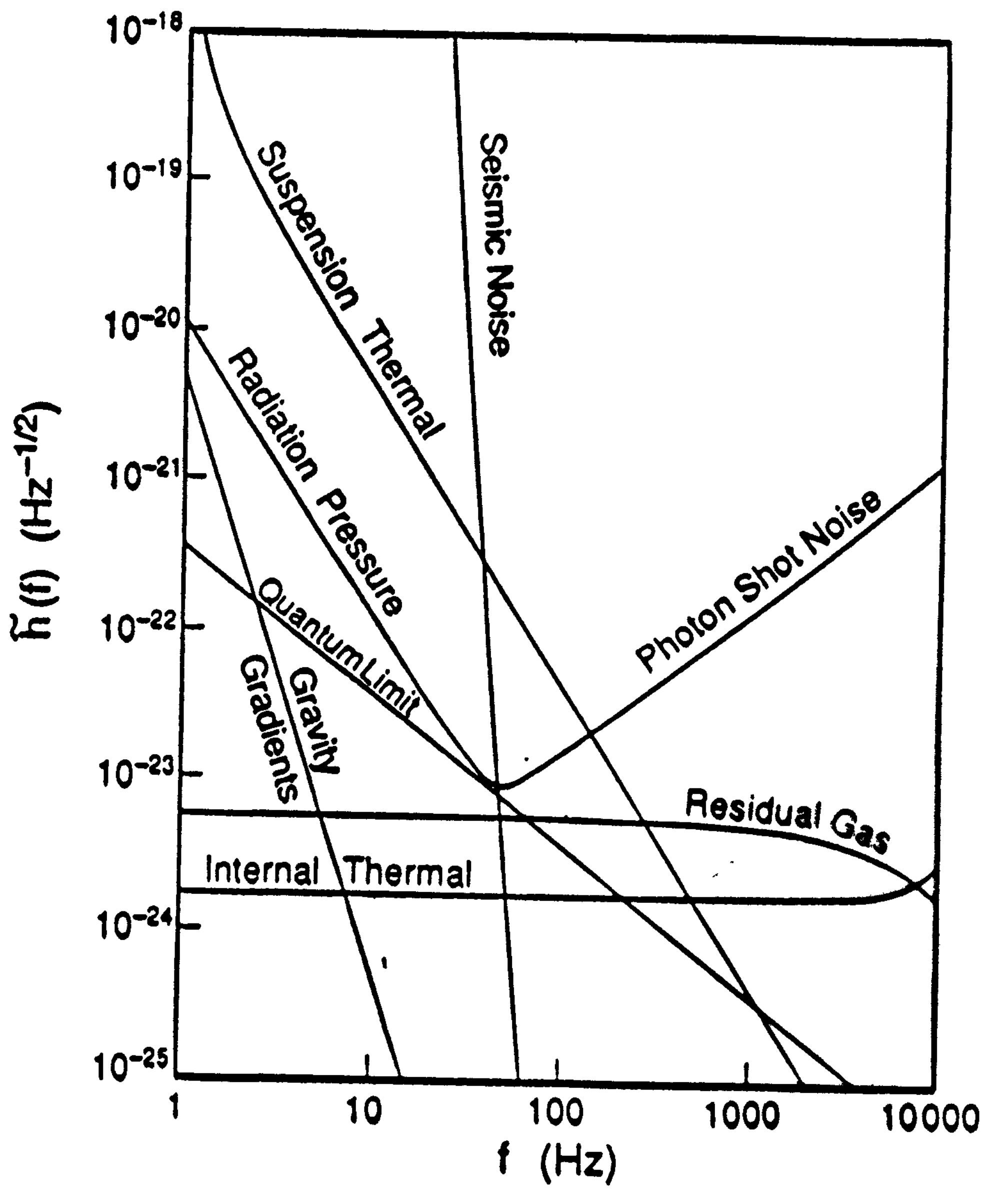
  » **<u>Mirrors and light beam must be in vacuum</u>**

- Mirror's atoms vibrate (thermal noise)
  - » light beam feels 10^{18} atoms
  - » atoms vibrate fast: $\sim 10^{13}$ Hz
  - » beam measures slow variables: ~ 100 Hz

- Earth vibrates and shakes mirrors
  - » **<u>anti-vibration suspension</u>**
  - » **<u>quiet environment</u>**

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

LIGO
Scientific Mission

- Direct Detection of Gravitational Waves
  - Benchmark Source: Neutron Binary Coalescence
    - Detect the last 15 minutes of Hulse/Taylor type binary system (eg. 100 million years)
    - Sensitivity -- detection rate >3 year
  - Other Sources

- Fundamental Physics (GR)
  - » Test General Relativity in Strong Field and High Velocity Limit
  - » Measure Polarization and Propagation Speed

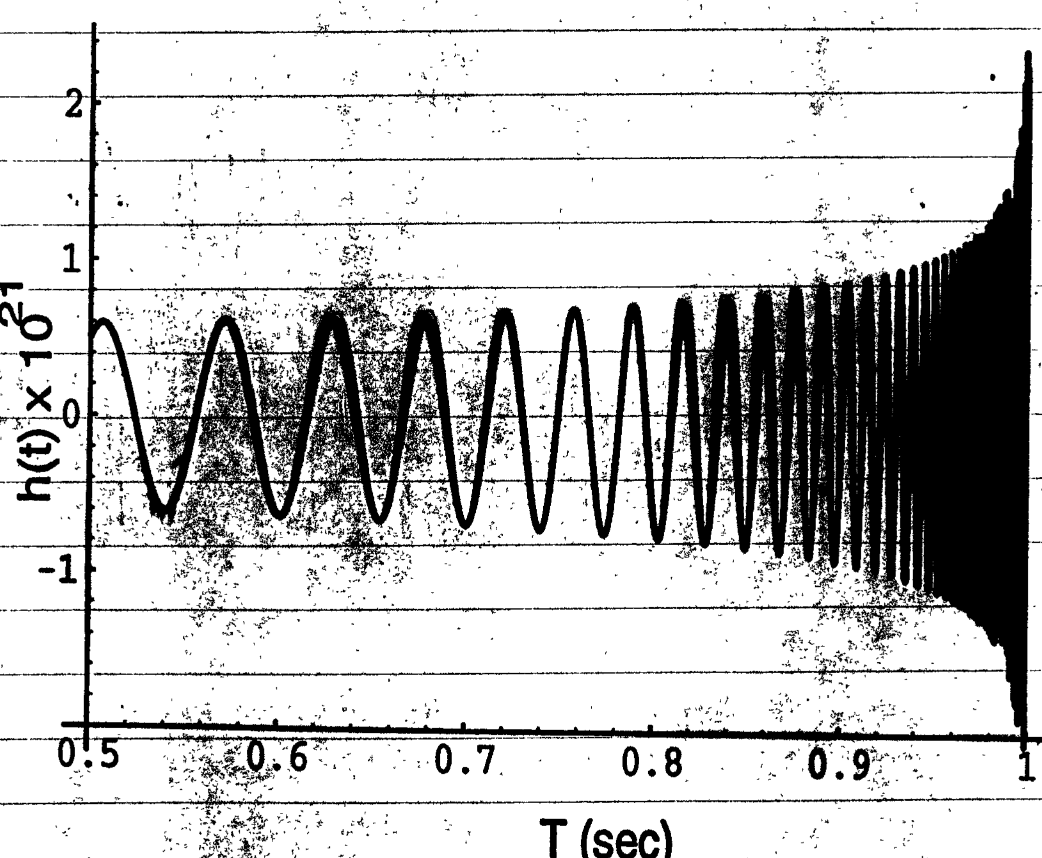
Neutron Star Binary Coalescence

Method	***Our Galaxy***	***Distance for 3/yr***
Progenitor Death Rate	**~1/1000 yr**	**130 M.L.yr**
Binary Pulsar Searches and Discoveries	**~1/10$^{5\pm1}$ yr**	**600 M.L.yr.**
Ultra-conservtive Limit from Binary Pulsar Searches	**~1/10^{7} yr**	**3000 M.L.yr**

Neutron Binary Systems

Inspiral

- LIGO frequency band
  - » last 15 minutes (~10^4 cycles)
- 'Chirp Signal'
- Detailed waveform gives masses, spins, distance, eccentricity of orbit, etc



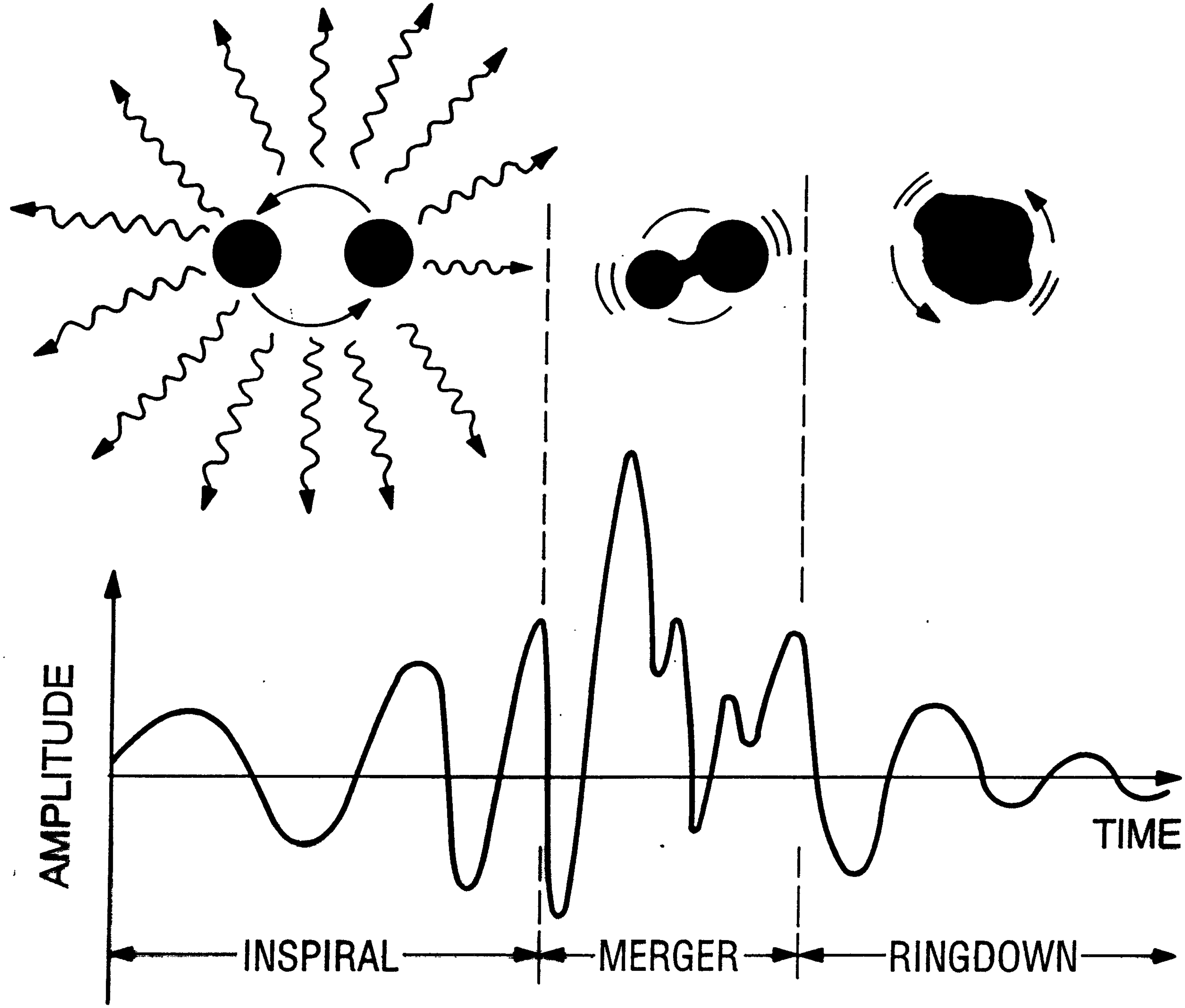
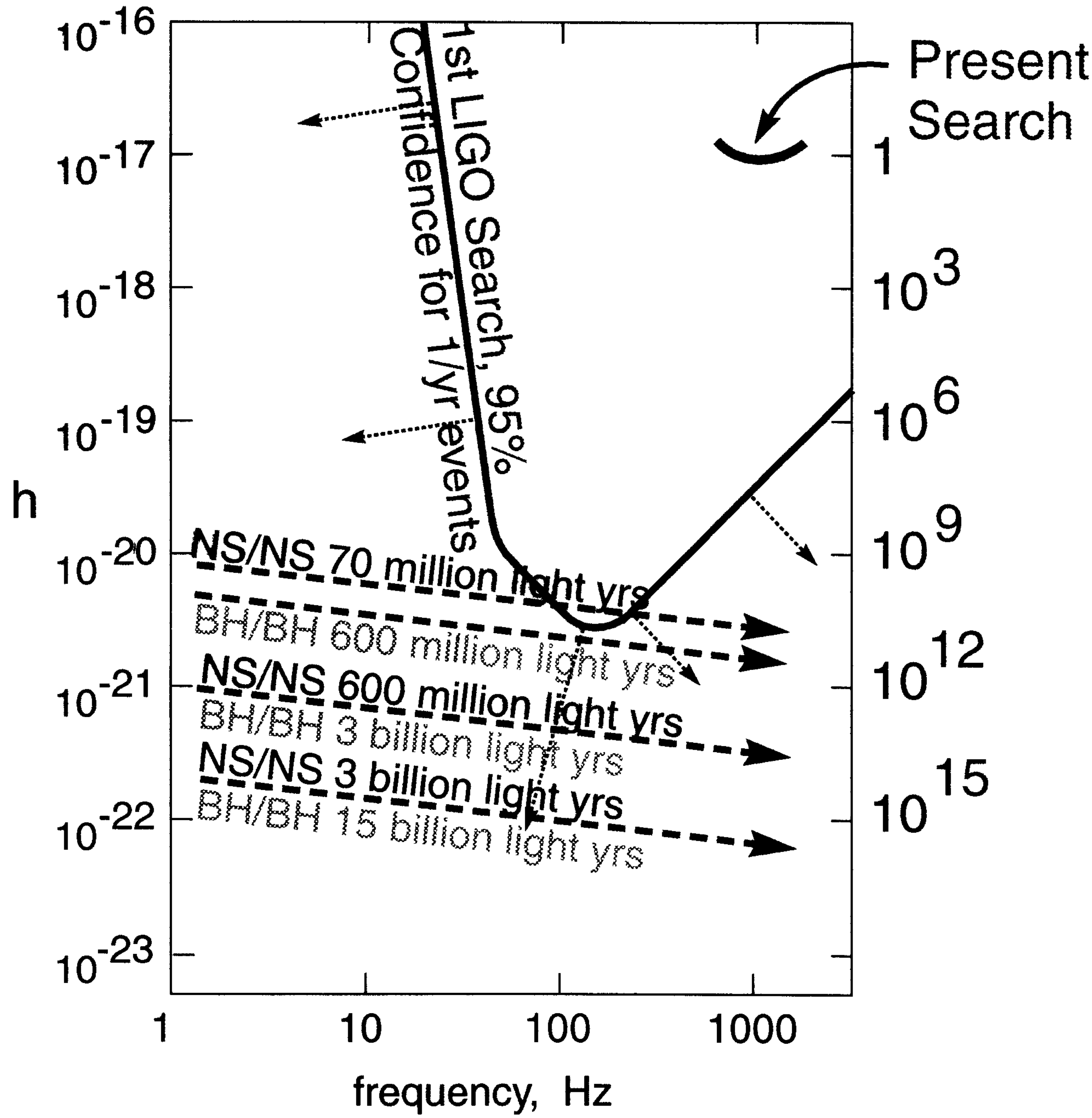


FIG 1

NEUTRON STAR BINARIES

["Near-Guaranteed" source]



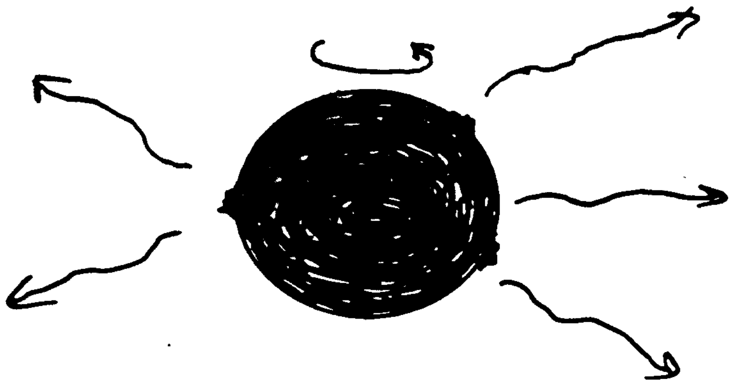
- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

LIGO

Long Range Goals

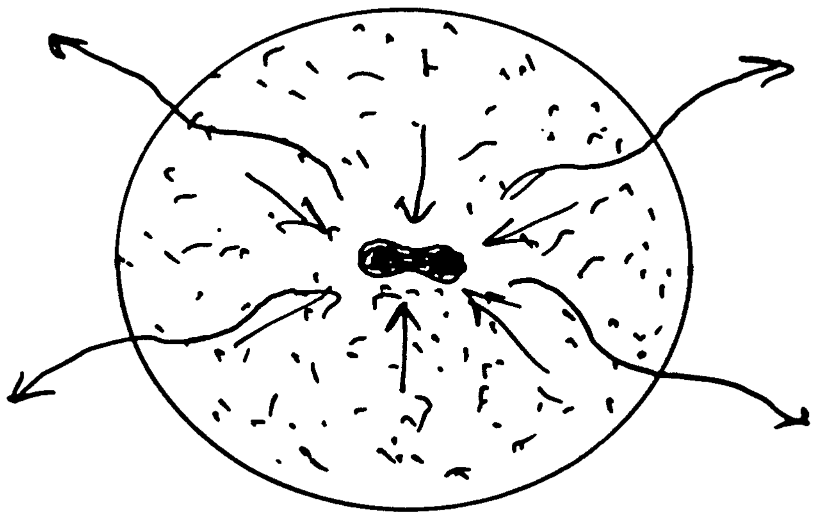
- Final Coalescence of Binary Systems
  - » Neutron Star/Neutron Star
    - – Design Benchmark: last 15 min
      20,000 cycles
      600 MLyr
  - » Black-hole/Black-hole
  - » Black-hole/Neutron Star
- Supernovae
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr
- Early Universe
  - » Vibrating Cosmic Strings
  - » Vacuum Phase Transitions
  - » Vacuum Fluctuations from Planck Era
- Unknown Sources

SPINNING, "MOUNTAINOUS" NEUTRON STAR



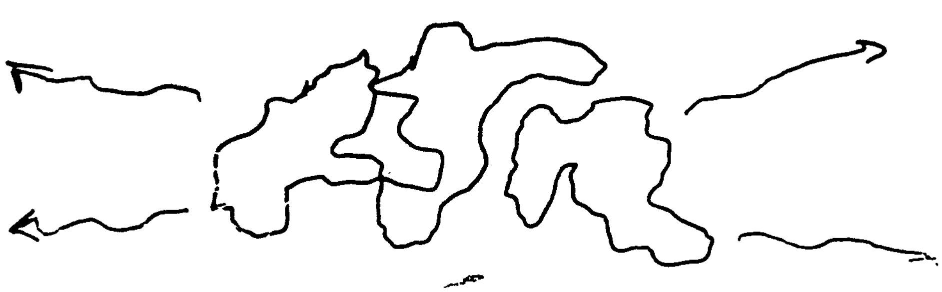
Periodic

IMPLOSION OF A STAR'S CORE
— WHICH TRIGGERS A SUPERNOVA



Bursts

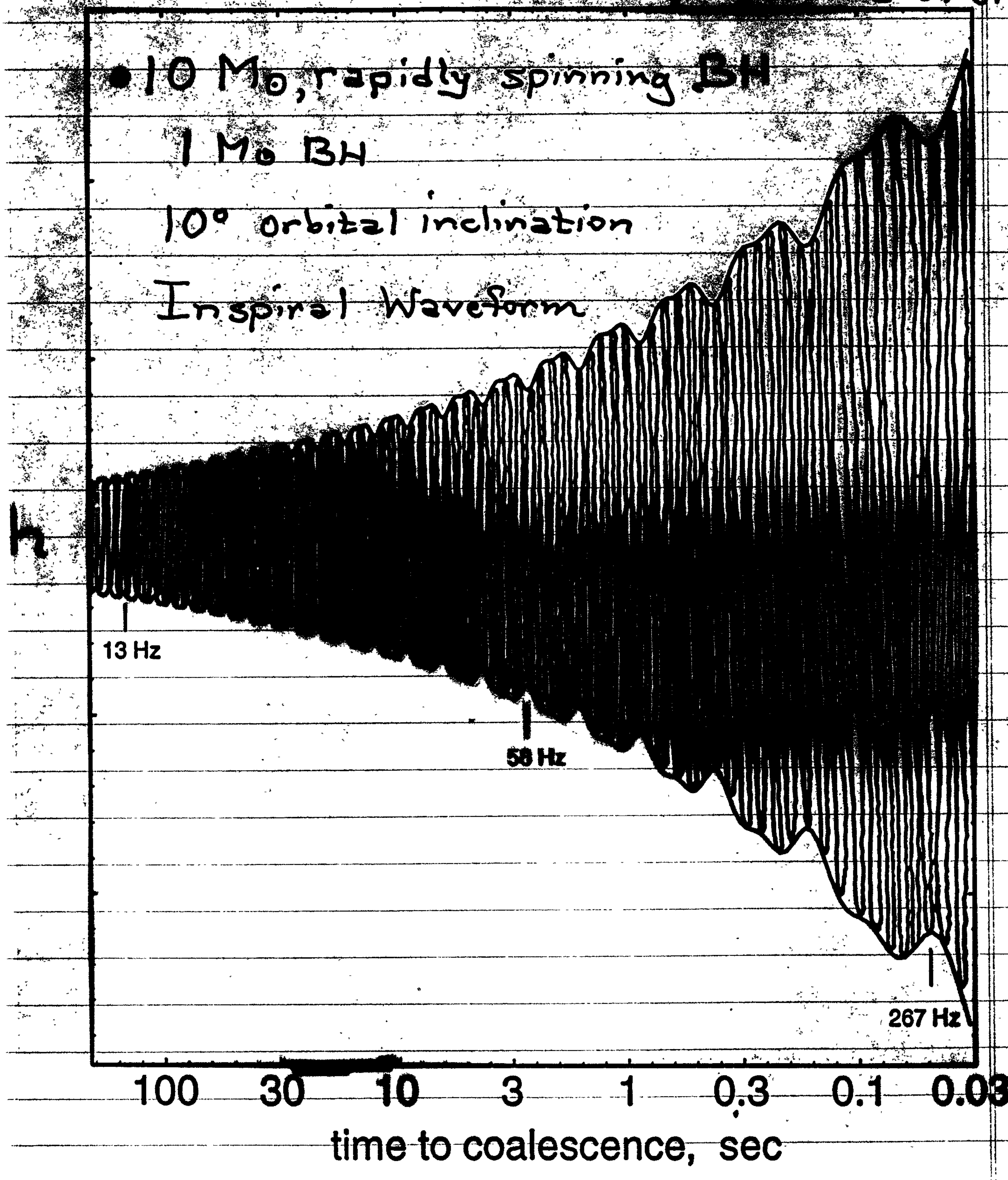
VIBRATING LOOPS OF COSMIC STRING



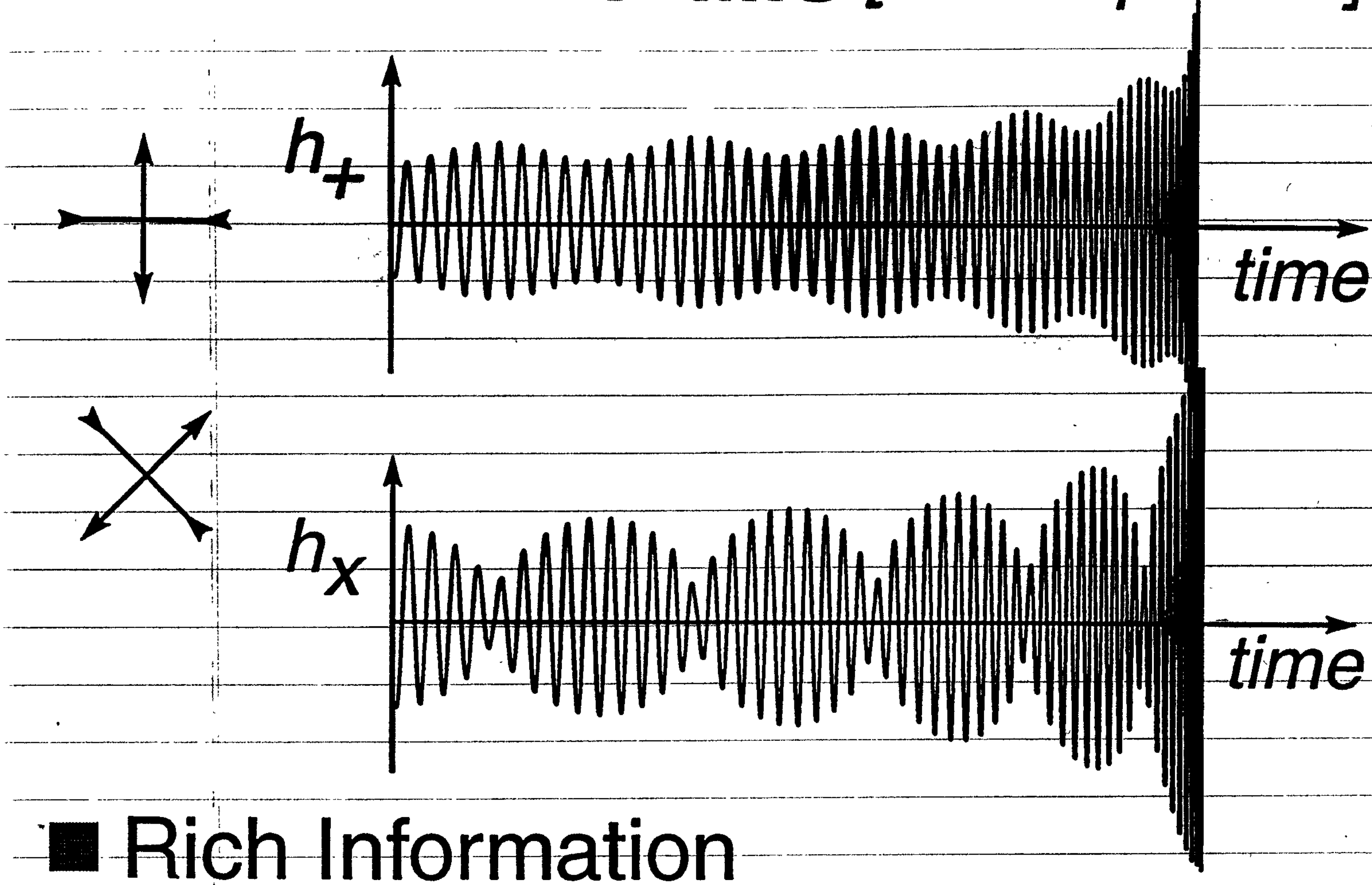
Stochastic

BH Spin → "gravitomagnetic field"
(frame dragging)
~20 precessions of orbit

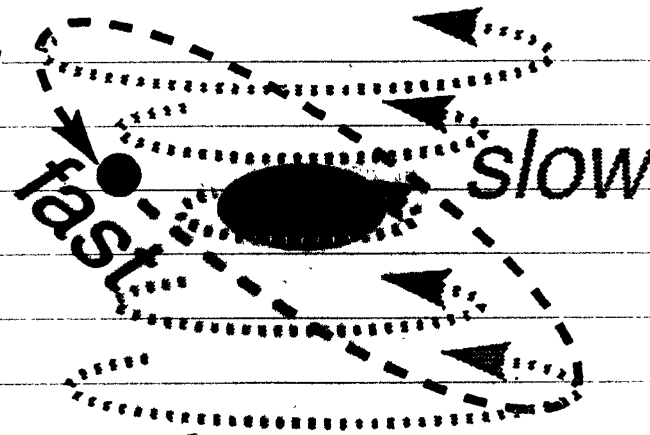
• $10\,M_\odot$, rapidly spinning BH
$1\,M_\odot$ BH
10° orbital inclination
Inspiral Waveform



TWO WAVEFORMS *[Stereophonic]*

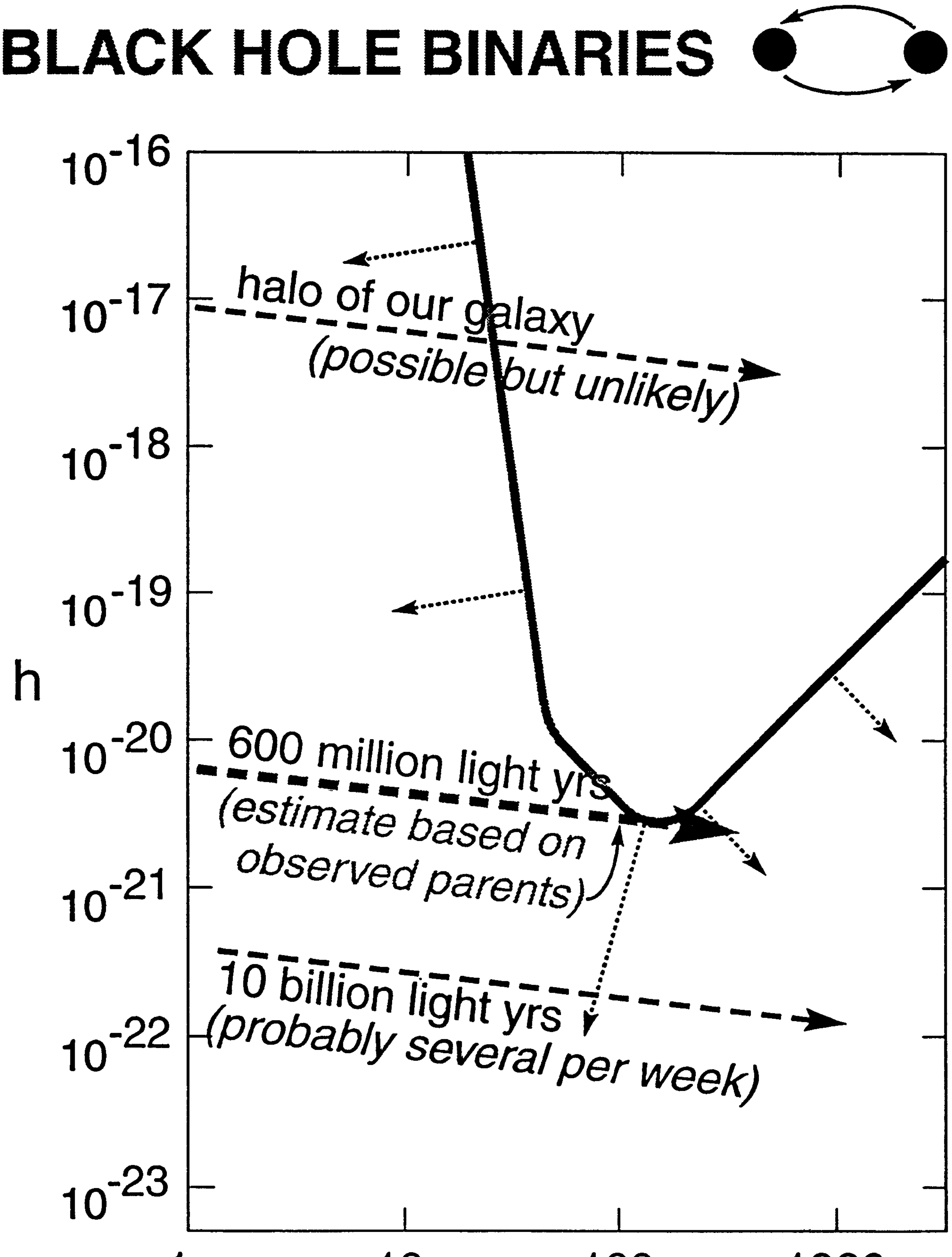


- Rich Information
  - *Map of spacetime warpage*
  - *Tornado-like swirl of space around big hole*



  - *Nonlinear vibrations of spacetime [Compare with Grand Challenge Supercomputer Simulations]*

BLACK HOLE BINARIES



Pulsars

periodic sources

- periodic waveform (integrate for long time)
- rotating non-axisymmetric neutron stars

Simple model:

$M = 1.4 \, M_\odot$

$r = 10 \text{ km}$

$I = 10^{45} \text{ gm cm}^2$

f

$$h \sim \frac{4\pi^2 G}{R c^4} \epsilon I f^2$$

ϵ = equitorial ellipticity

Poorly known

Estimate distortion due to dipole magnetic field

$$\epsilon \approx \frac{U_{mag}}{U_{grav}} \approx \frac{B^2 R^4}{G M^2} \approx 10^{-12}$$

if $B \approx 10^{12}$ gauss (typical of pulsars)

$$h \approx 3 \; 10^{-31} \left(\frac{f}{1 \text{ kHz}} \right)^2 \left(\frac{10 \text{ kpc}}{R} \right)$$

if pulsars born rapidly rotating then several most recent pulsars with such amplitude in our galaxy any time

---

Note fastest known pulsar PSR1937+214 only has $B \approx 10^8$ gauss, but it is thought this pulsar was 'spun up' by consuming low mass companion

ALSO "Wagoner star" enhancement.

Supernovae

Type I - explosive detonation of a white dwarf star (no substantial emission of gravitational waves)

Type II - may emit strong gravitational waves

'naked eye' observations

16th century (Tycho)

SN 1987A (neutrinos)

Gravitational radiation (mechanism)

- massive star produces core $\sim 1.4\, M_\odot$ which has burned to iron (white dwarf)
- electron degeneracy pressure no longer can support the core
- matter converts into neutrons
- collapses
- bounce @ nuclear densities ($\sim 3\ 10^{14}\ gm/cm^3$)

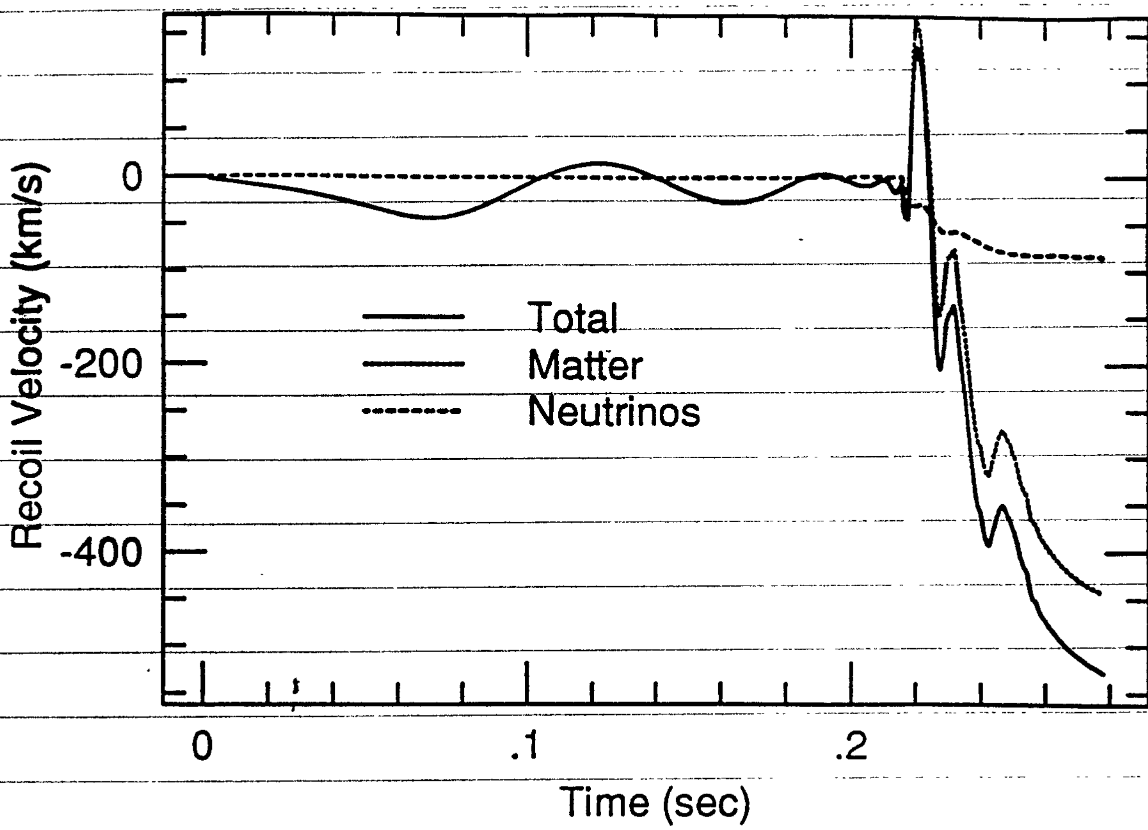


FIG. 2. The inferred recoil speed (in km s^{-1}) imparted to the core versus time (in seconds) for the simulation highlighted in this paper. The initial momentum is approximately zero, but grows systematically after bounce in the direction opposite to the artificial wedge, cut into the core to mimic an asymmetry just before collapse. Shown are the total recoil (solid) and the contributions due to the neutrino emission anisotropy (dashed) and the ejecta motions (dotted).

- physics modeling very difficult
  (departure from spherical shape)

- guidance (unclear)
  - supercomputers <u>assume</u> spherical sym.
  - 2D models (Burrows)
  - crab pulsar $f_{rot} \approx 30.3$ Hz
    $J = 2\ 10^{47}$ erg-sec

    (Saenz-Shapiro → radiate gravitational $3\ 10^{-6}$ of rest mass
    $h \approx 10^{-23}$ @ VIRGO

  - collapsing cores w/ high angular momentum?
    (eg "millisecond pulsars)

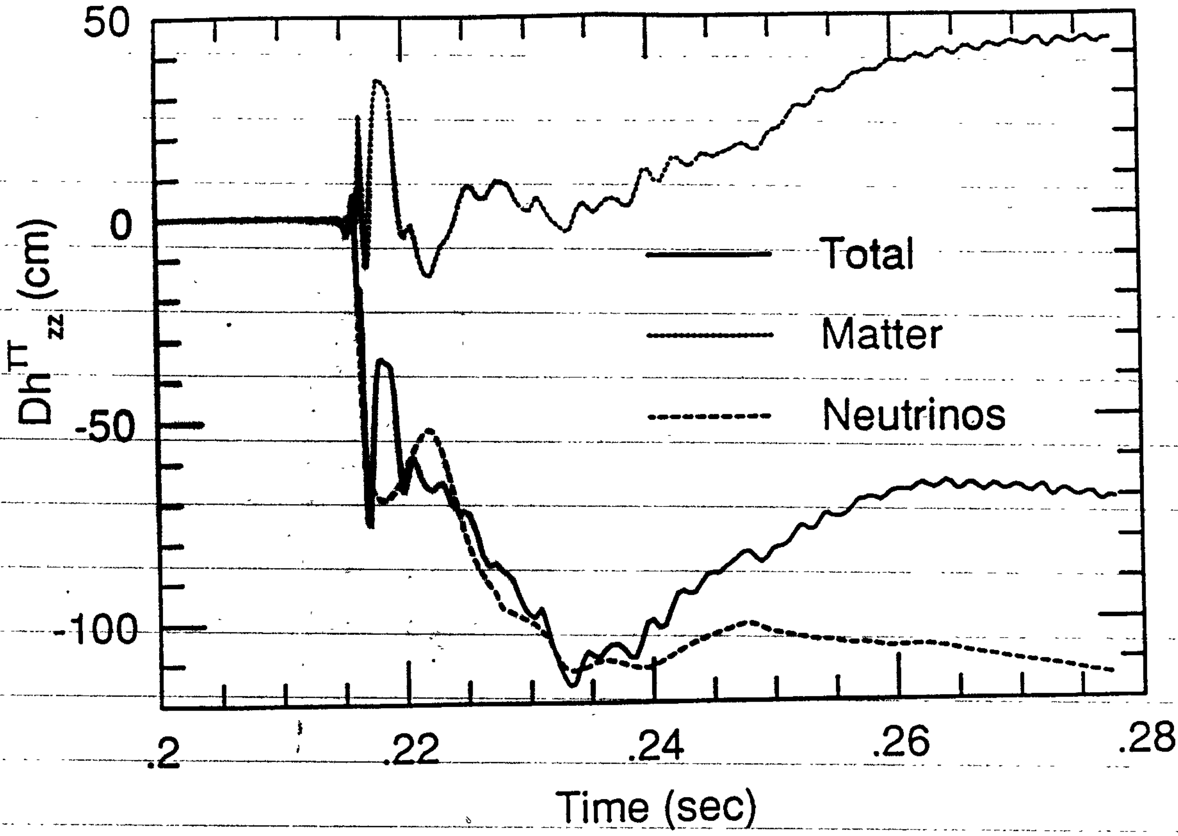


FIG. 3. The gravitational wave strain, h^{TT}_{zz}, times the distance to the supernova, D, versus time (in seconds). Core bounce is at 0.215 seconds. The total, matter, and neutrino waveforms are rendered with the solid, dotted, and dashed lines, respectively.

FIGURES

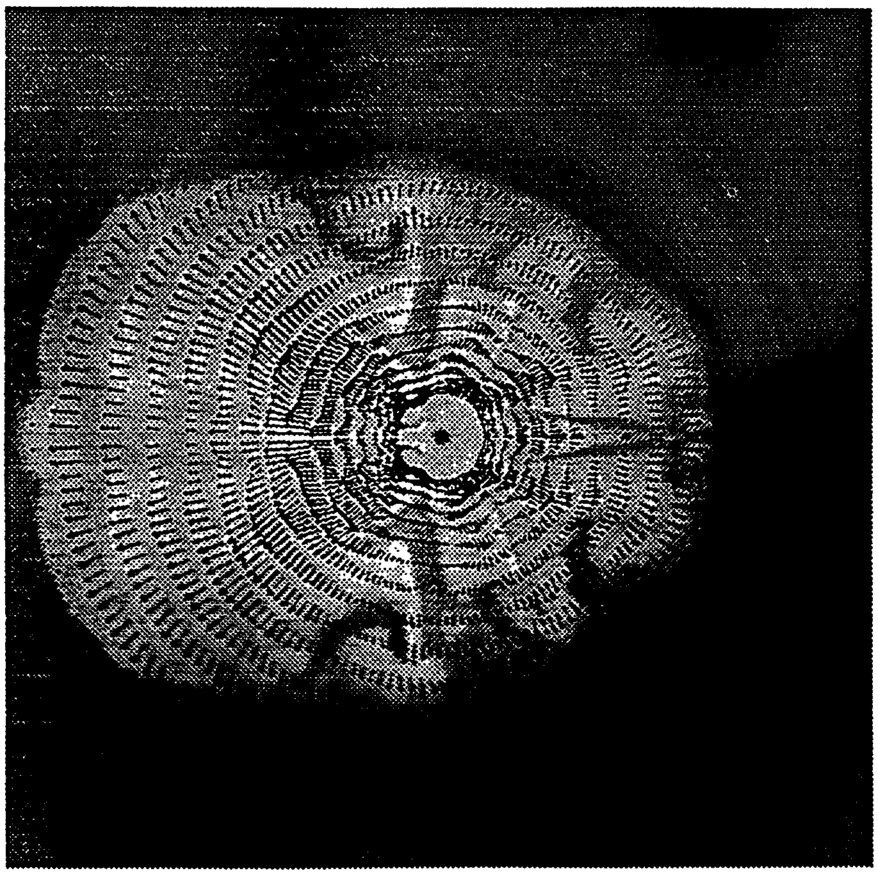


FIG. 1. A grey-scale rendering of the entropy distribution at the end of the simulation, about 50 milliseconds into the explosion. Note the pronounced pole–to–pole asymmetry in the ejecta and the velocity field (as depicted with the velocity vectors). The physical scale is 2000 km from the center to the edge. Darker color indicates lower entropy and $\theta = 0$ on the bulge side of the symmetry axis.

Stochastic Gravity-Wave Background

- could come from early Universe
  LIGO Band ~ 10^{-22} sec

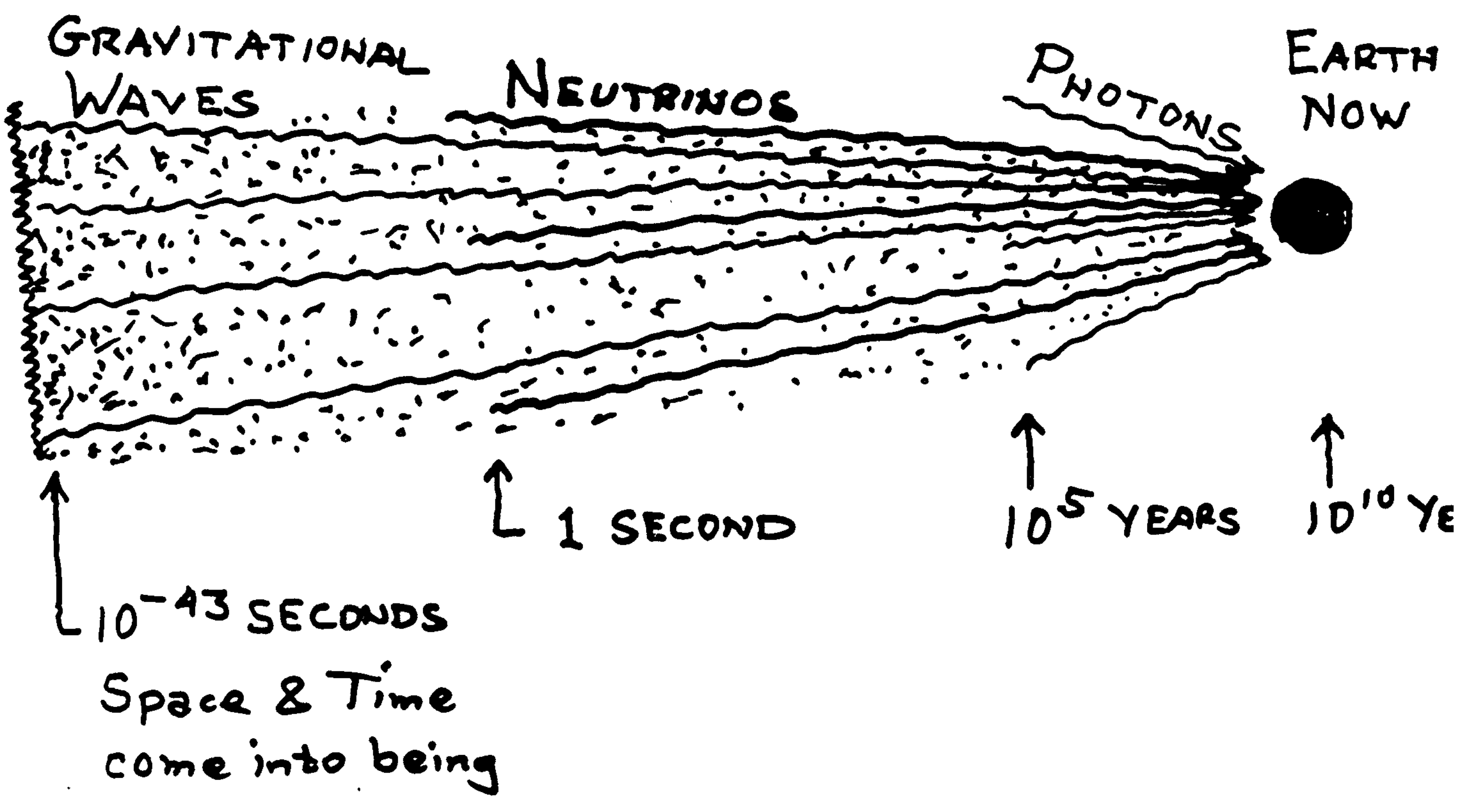
  (also could be overwhelmed by more recent sources)

- graviton background analogous to Ω_{em}
  THERMAL SPECTRUM $T \sim 0.9$ K

  (smaller than Cosmic Microwave Background Radiation because in conventional hot big bang model, gravitons decoupled when temperature of Universe dropped below Planck temp)

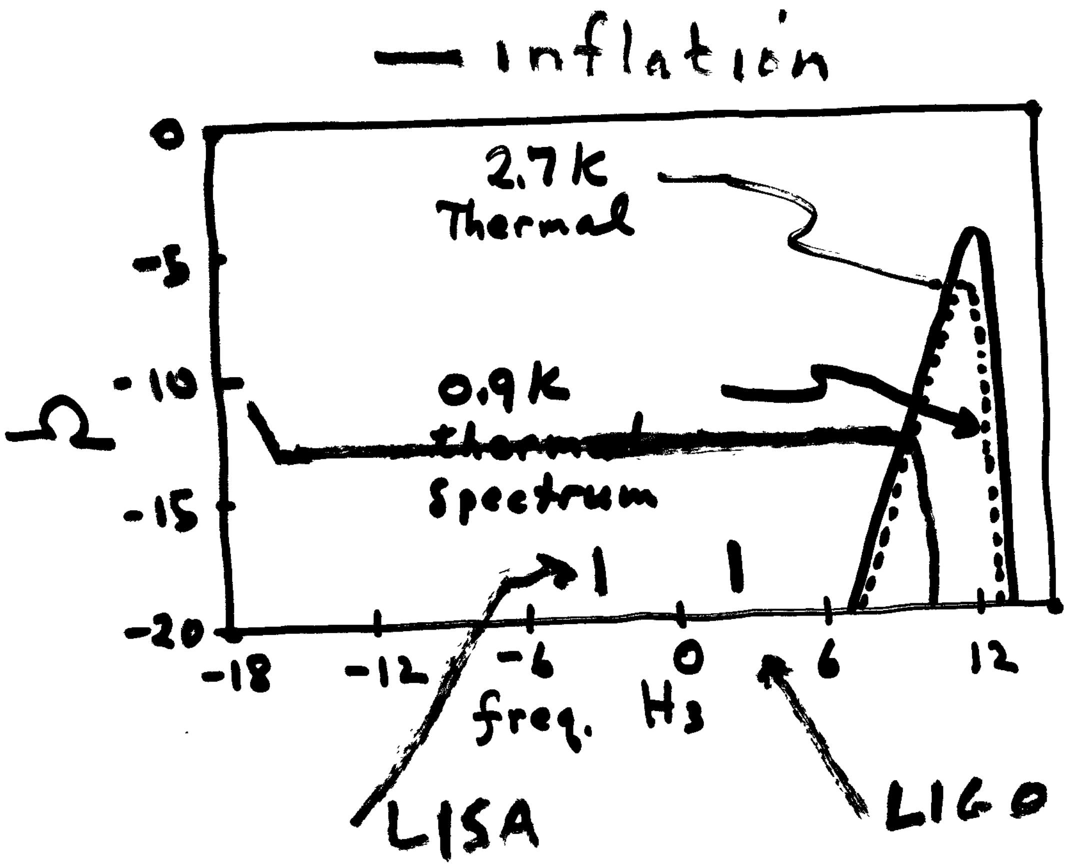
Lecture 5 (B)

THE BIG BANG SINGULARITY



LIGO 10^{-22} sec Temp $\sim 10^6$ GeV
graviton $\sim$ 10 MeV

LISA (10^{-2} Hz) 10^{-14} sec Temp $\sim 10^2$ GeV (electroweak
graviton $\sim$ 1 keV

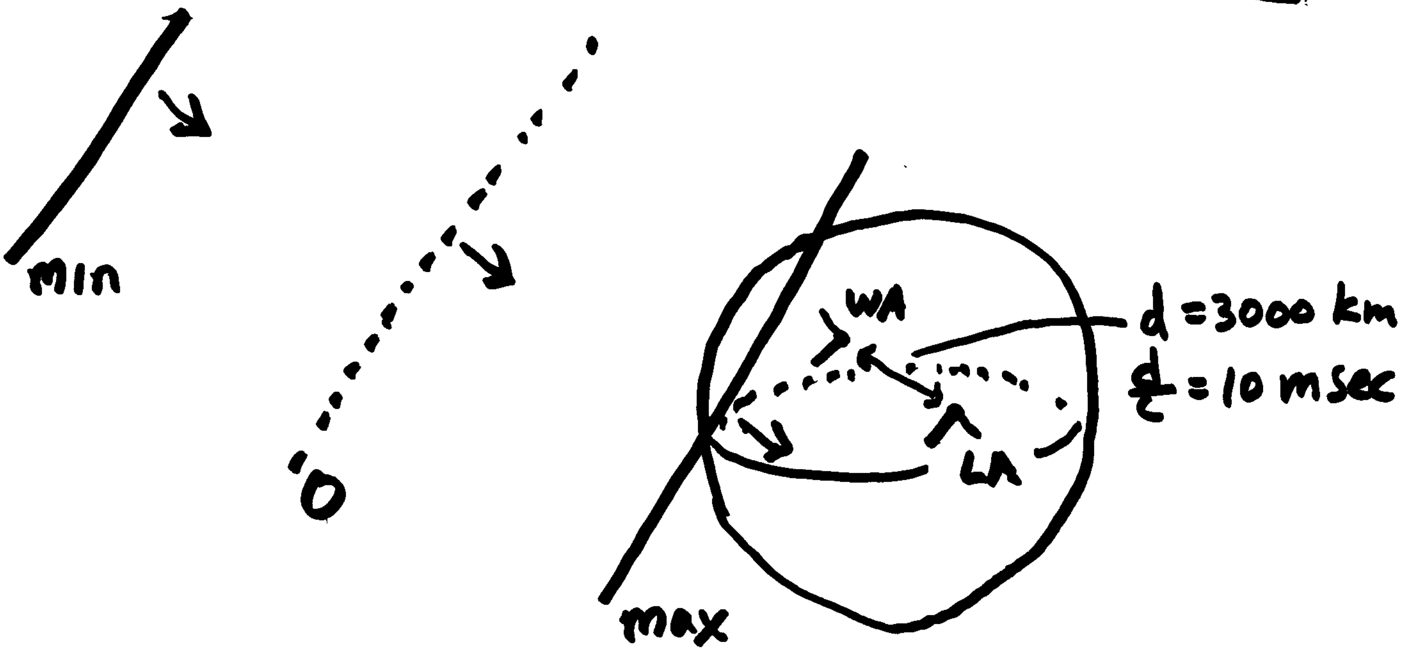


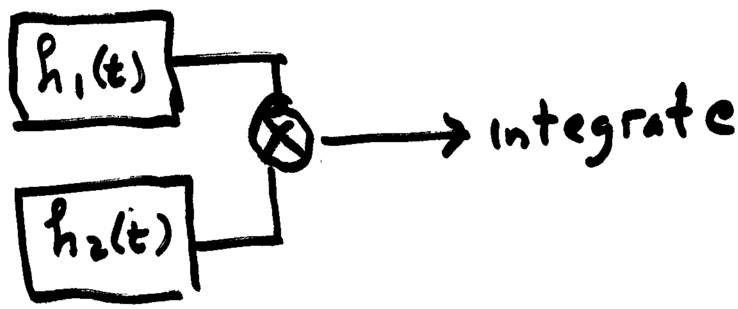
- unlikely equilibrium was established since gravitational interactions so weak (time required longer than expansion time)

- useful benchmark

- detection
  correlate (anticorrelate) signals from diffenent detectors (eg <64 Hz LIGO detectors correlated)

How to detect Stochastic Background



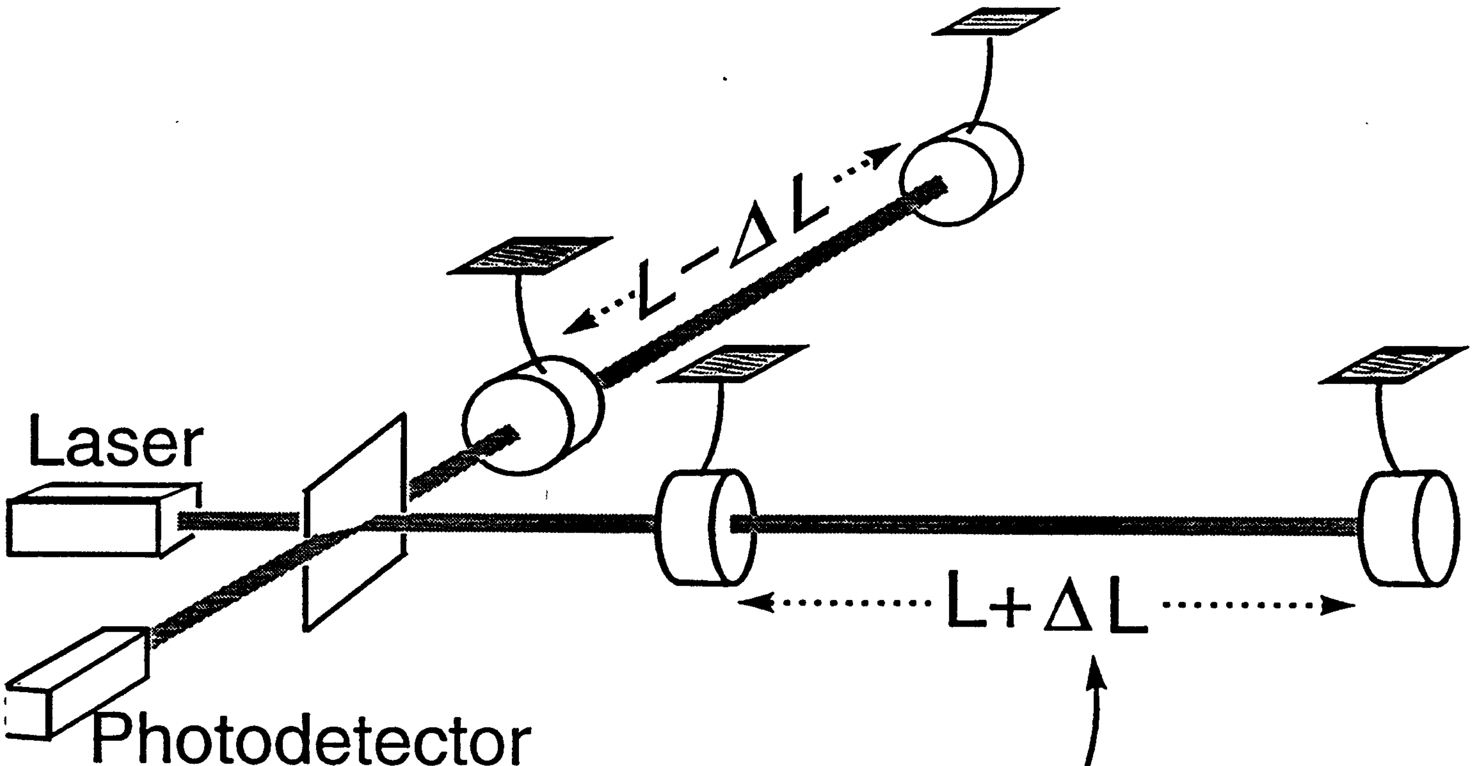


For waves with $\frac{\lambda}{2} > 3000$ km $\left(f \lesssim 50 \text{ Hz} \right)$.
detector arms move in phase (together) so
average product $h_1(t)\, h_2(t) > 0$

In absence of background (and other signals)
average product $h_1(t)\, h_2(t) \to 0$

Michelson, Mon. Not. Roy. Astron Soc 227 (1987) 933.
Christensen, Phys. Rev. D46 (1992) 5250.
Flanagan, Phys. Rev. D48 (1993) 2389

LIGO INTERFEROMETERS



- To make ΔL large enough for detection requires $L \gtrsim 4$ km

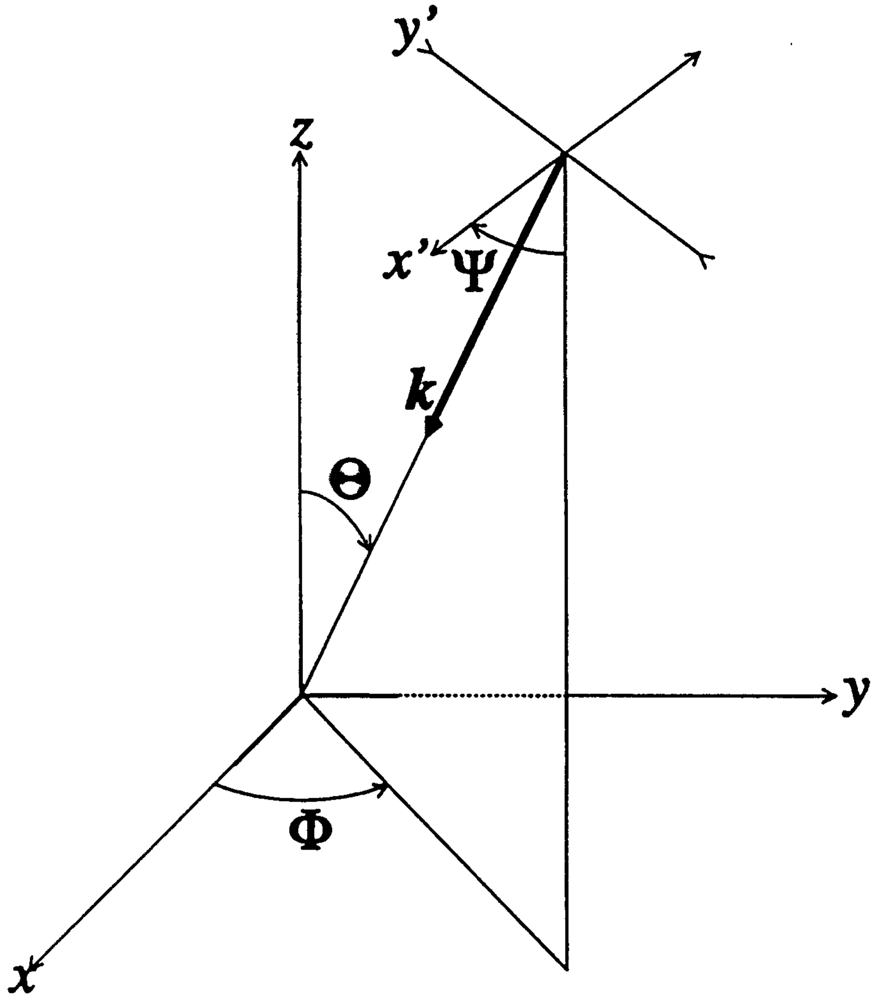
$$\Delta L = \underbrace{h}_{10^{-21}}\underbrace{L}_{4\text{ km}} = 4 \times 10^{-16}\text{ cm}$$

- Measured waveform, h(*time*) = $\Delta L/L$, is a linear combination of h_+ and h_x , which depends on interferometer's orientation

STACK:
OFFENDING COMMAND: timeout
ERROR: timeout

Gravitational Wave Detector

- Antenna Pattern
  - » coordinate system



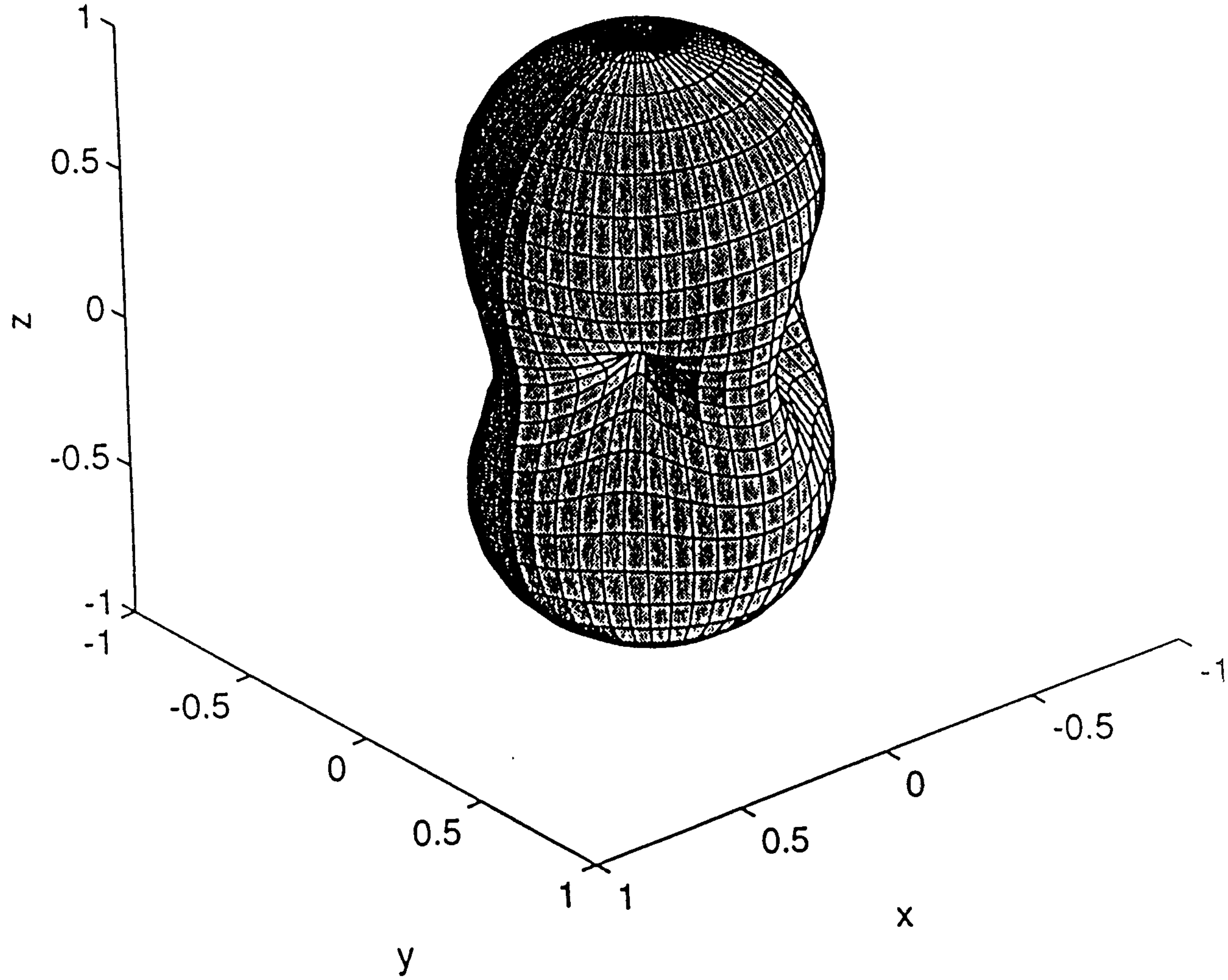
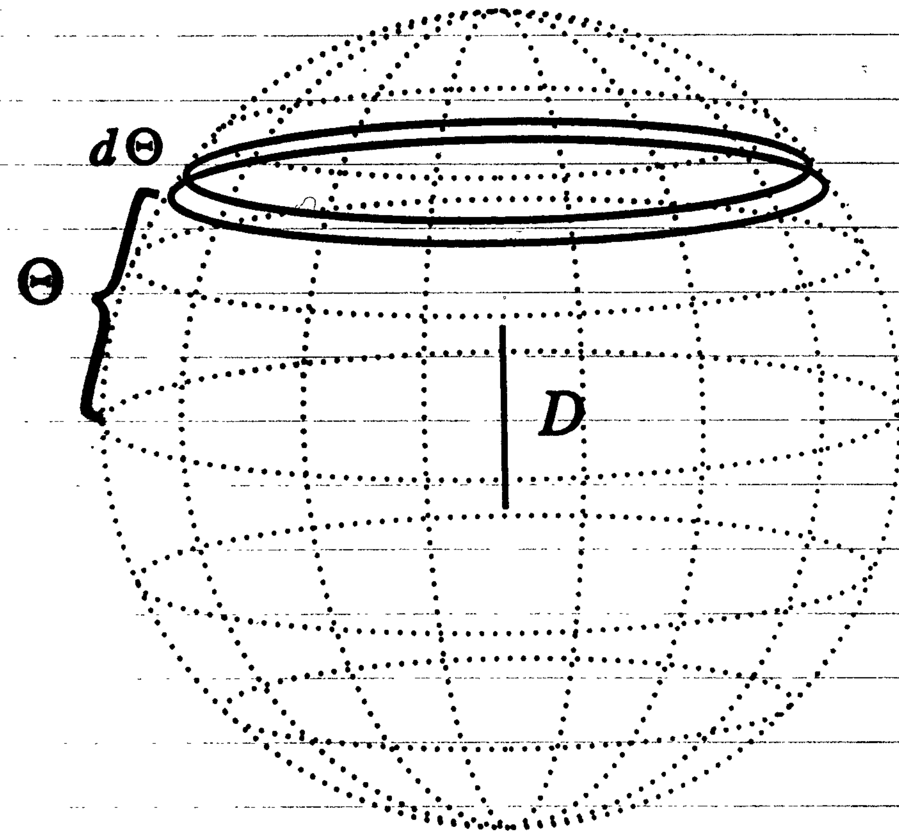


Figure 2.7 The sensitivity, as a function of direction, of an interferometric gravitational wave detector to unpolarized gravitational waves. The interferometer arms are oriented along the x and y axes.

Source Positions

- Celestial Sphere position location from LIGO (two interferometers)



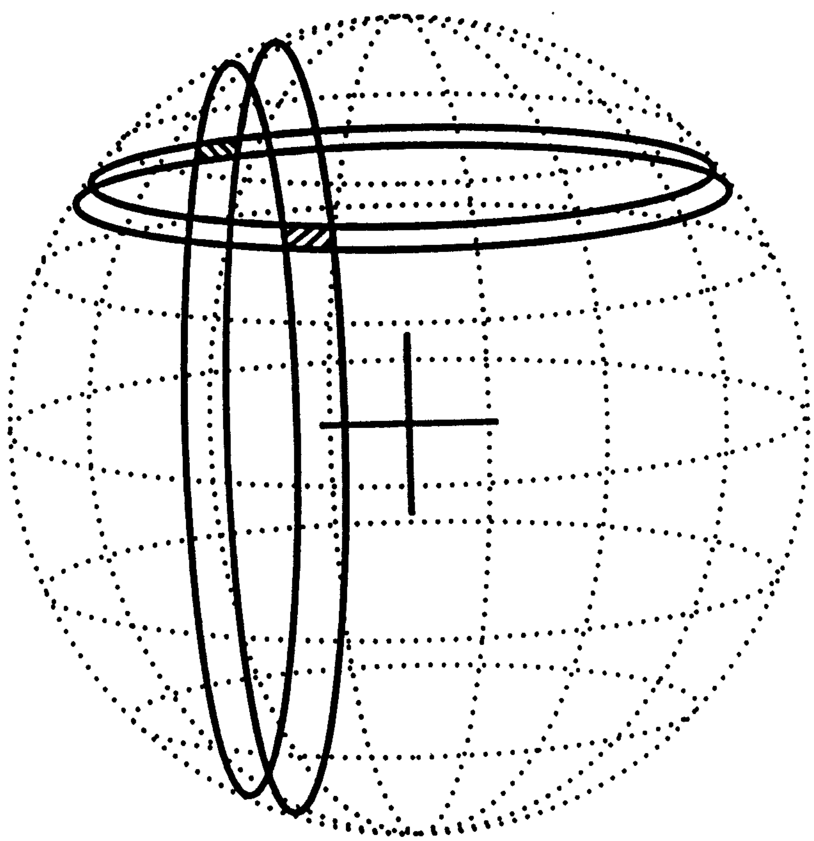
- determine from time shift between detectors (~.1 msec accuracy)
- 'declination angle' of circle (ring)

$$\Theta = \arcsin \frac{c\Delta t_{sig}}{D}$$

Source Positions

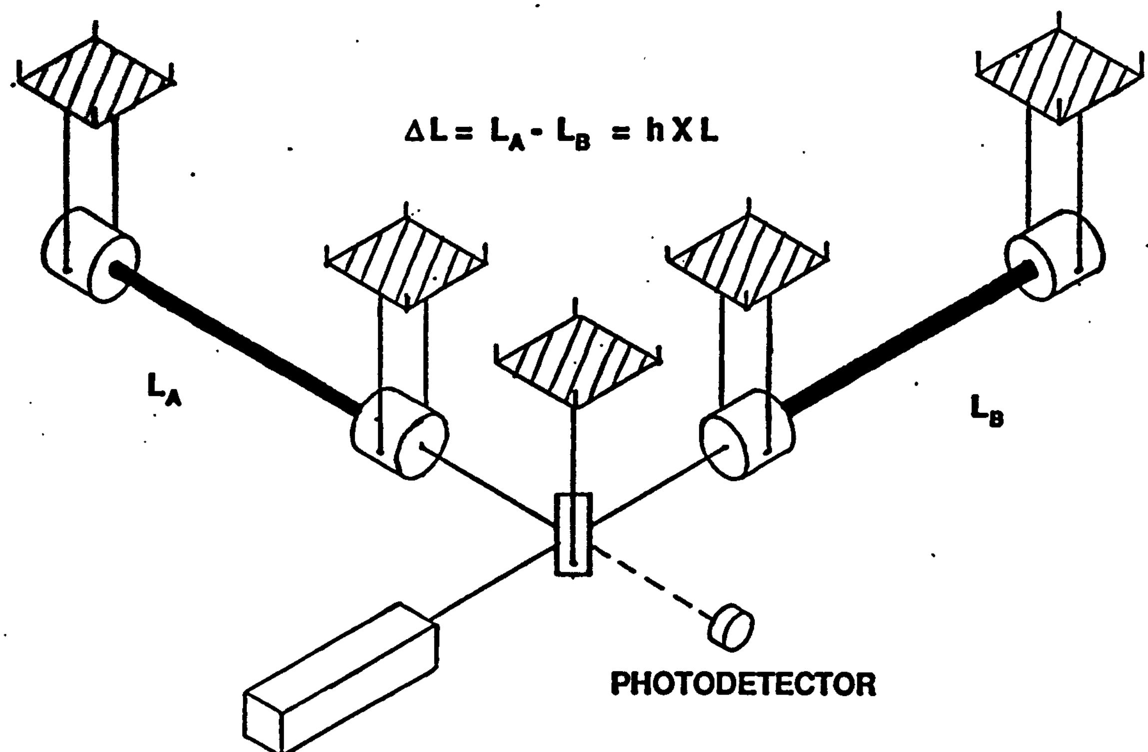
LIGO + VIRGO

- LIGO (2 det) + VIRGO (1 det)
- decomposition of waveforms
  - » $h_x(t)$, $h_+(t)$
- position on sky (two positions)

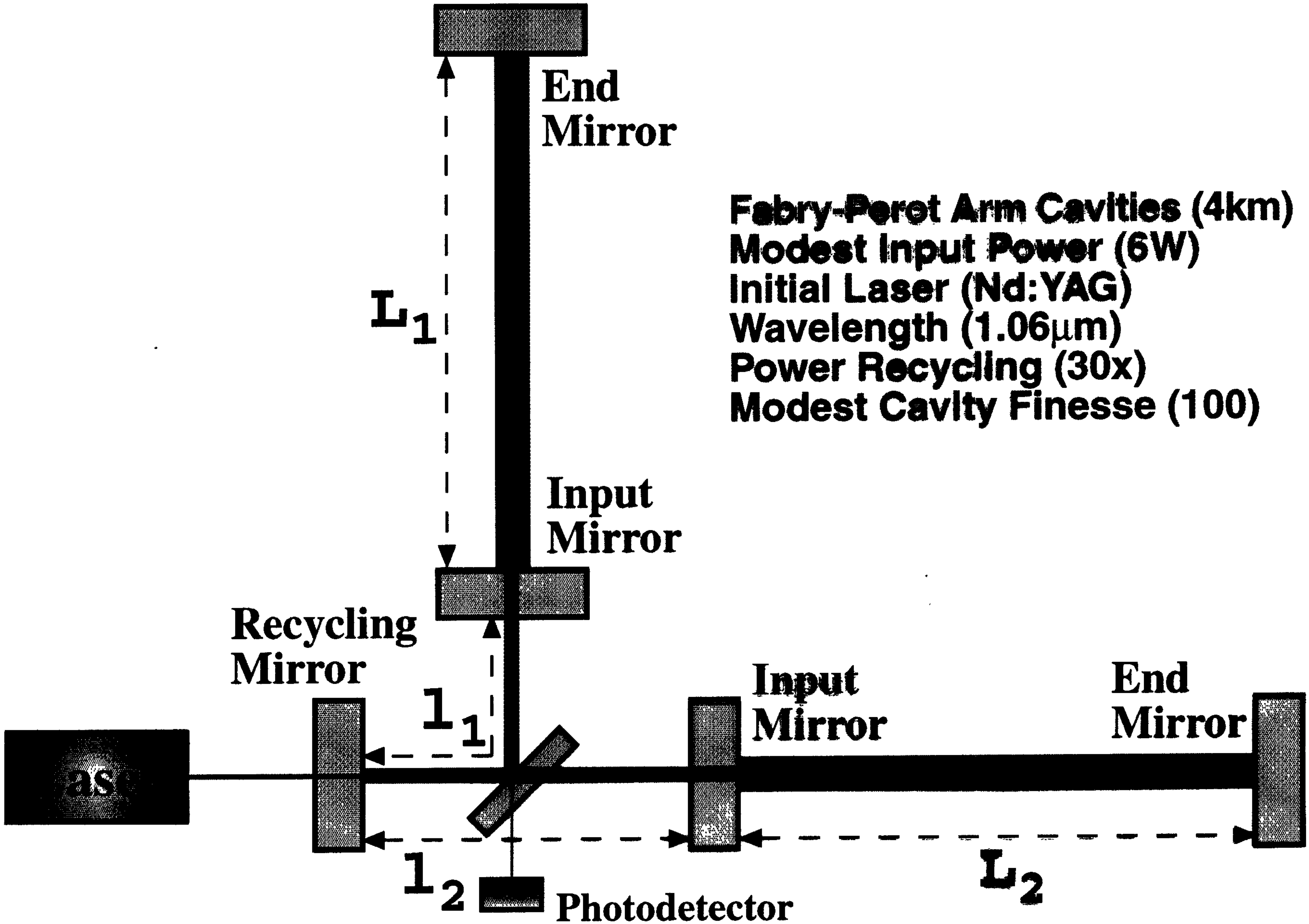


Interferometers

- $\Delta L/L = h = F_+ h_+(t) + F_x h_x(t)$



- LIGO Measures ***one*** waveform
  - » orientation aligned (Washington & Louisiana)
  - » direction(timing) determined ~10' to ~ 1^0 on ring
- LIGO + VIRGO(Italy)
  - » decompose waveforms ($h_+(t)$,$h_x(t)$)
  - » direction 10' to 1^0

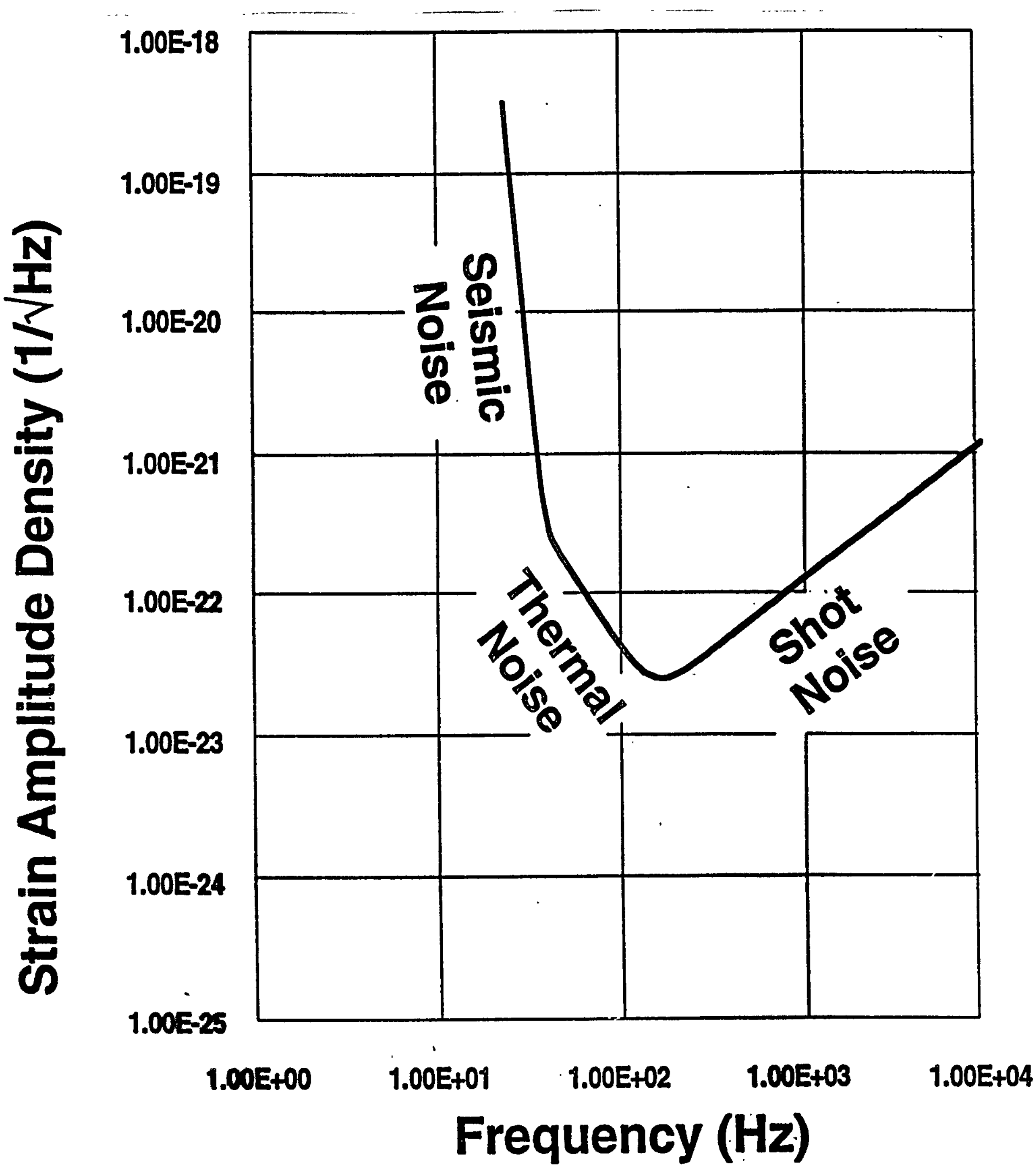

End Mirror
Fabry-Perot Arm Cavities (4km)
Modest Input Power (6W)
Initial Laser (Nd:YAG)
Wavelength (1.06μm)
Power Recycling (30x)
Modest Cavity Finesse (100)
L_1
Input Mirror
Recycling Mirror
l_1
Input Mirror
End Mirror
l_2
Photodetector
L_2

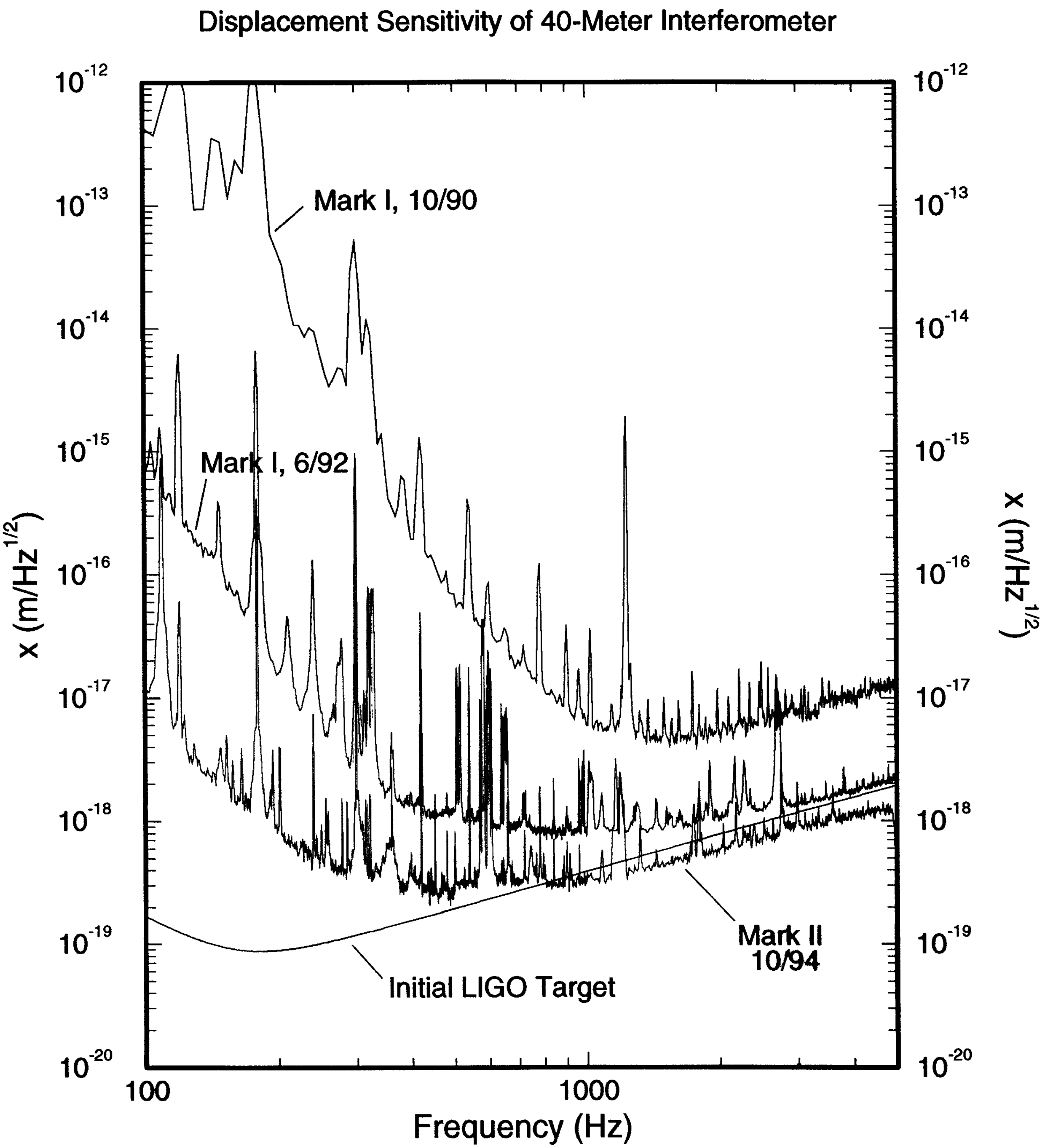
Initial Interferometer
Specifications

Strain Sensitivity [rms, 100 Hz band]	10^{-21}
Displacement Sensitivity [rms, 100 Hz band]	4×10^{-18} *m*
Fabry-Perot Arm Length	4000 *m*
Vacuum Level	< 10^{-6} *torr*
Laser Wavelength	1064 *nm*
Optical Power at Laser Output	10 *W*
Optical Power at Interferometer Input	5 *W*
Power Recycling Factor	30
Input Mirror Properties	Reflectivity = 0.97
End Mirror Properties	Reflectivity > 0.9998
Arm Cavity Optical Loss	≤ 3%
Light Storage Time in Arms	1 *ms*
Test Masses	Fused Silica, 11 *kg*
Mirror Diameter	25 *cm*
Test Mass Period Pendulum	1 *sec*
Seismic Isolation System	Passive, 4 stage
Seismic Isolation System Horizontal Attenuation	≥ 10^{-7} (100 *Hz*)
Maximum Background Pulse Rate	1 *per minute*

Initial Interferometers

Noise Floor

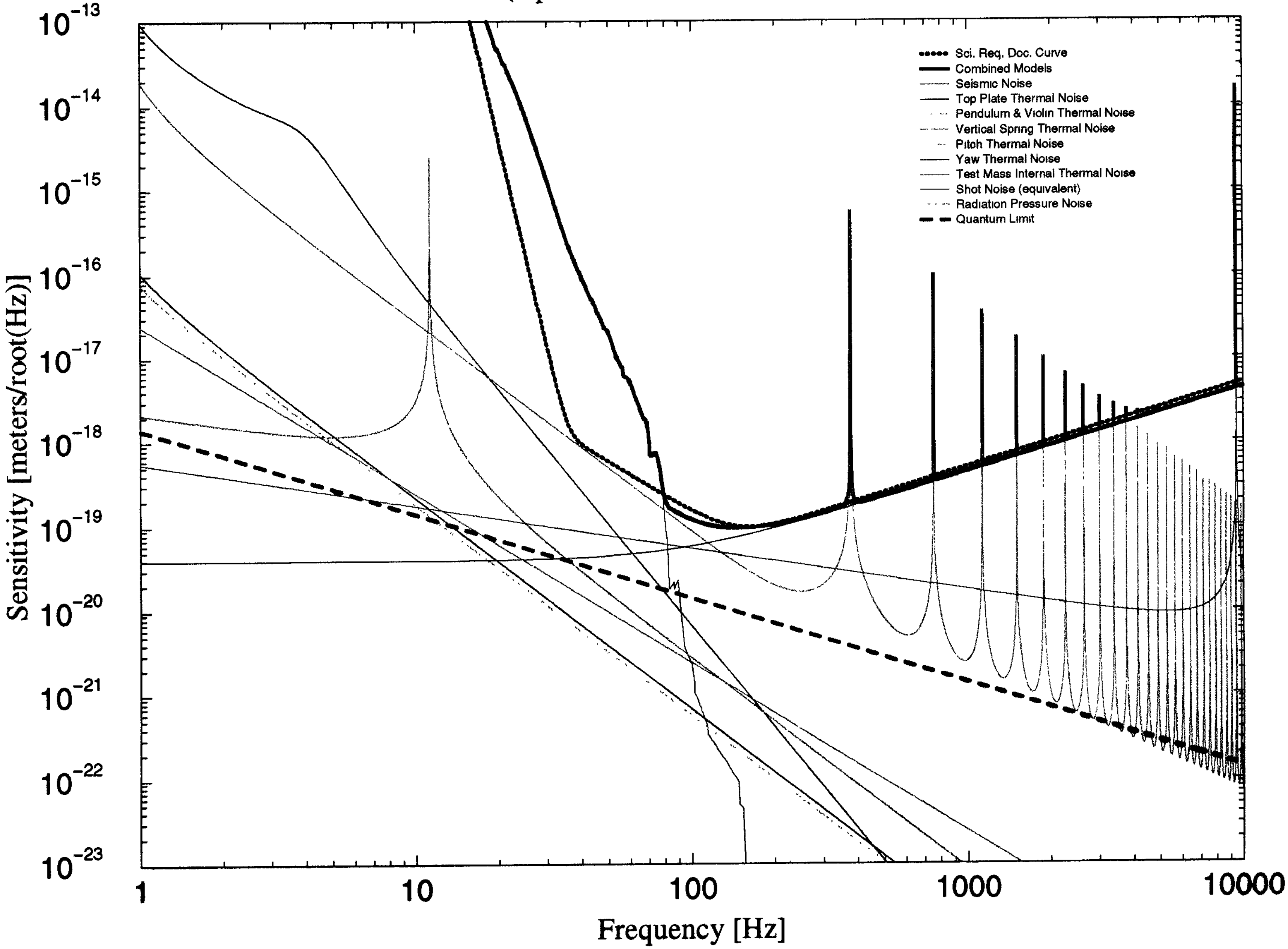




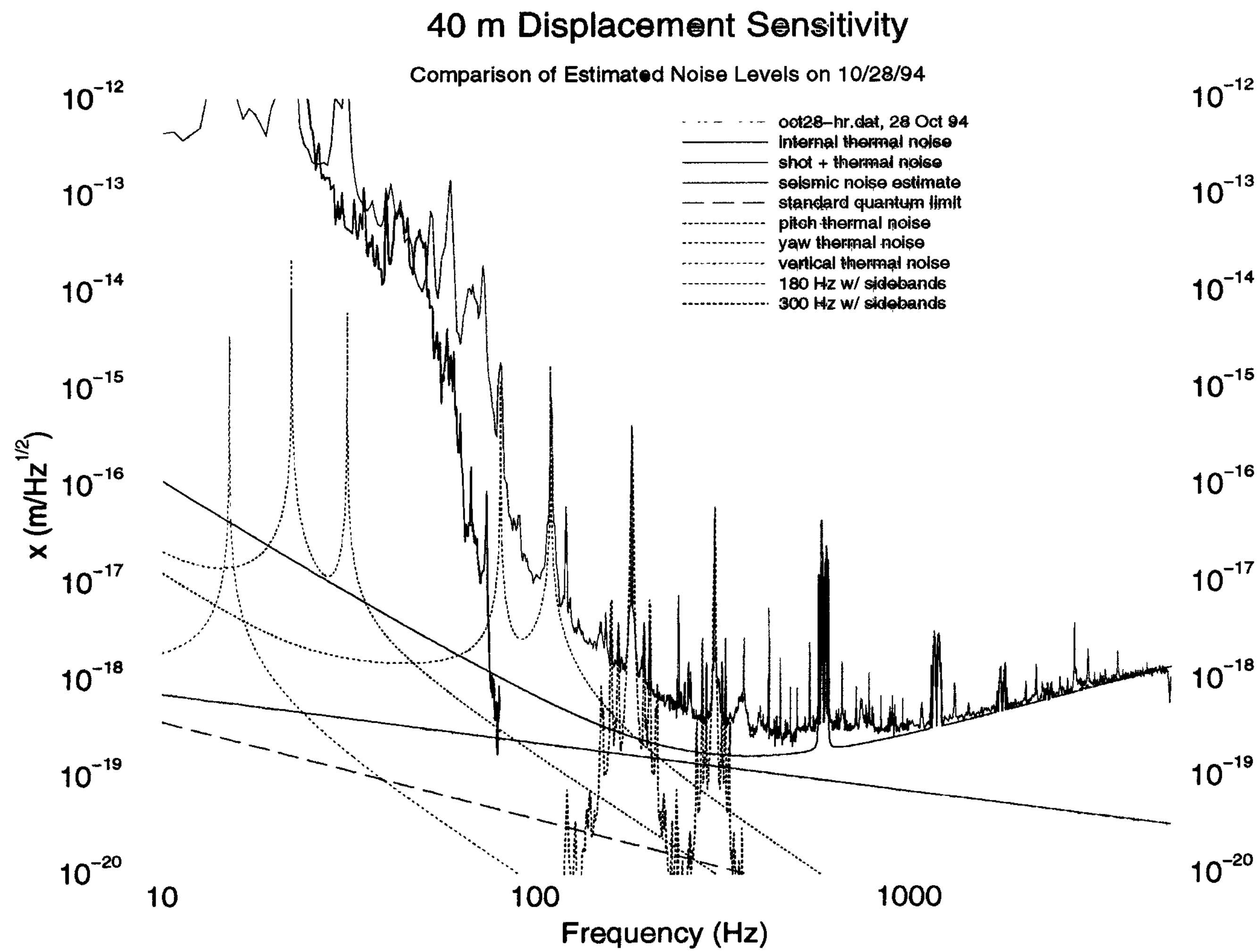
~fjr/fort/mk2/port_90_94.xvgr

Initial LIGO Noise Sources

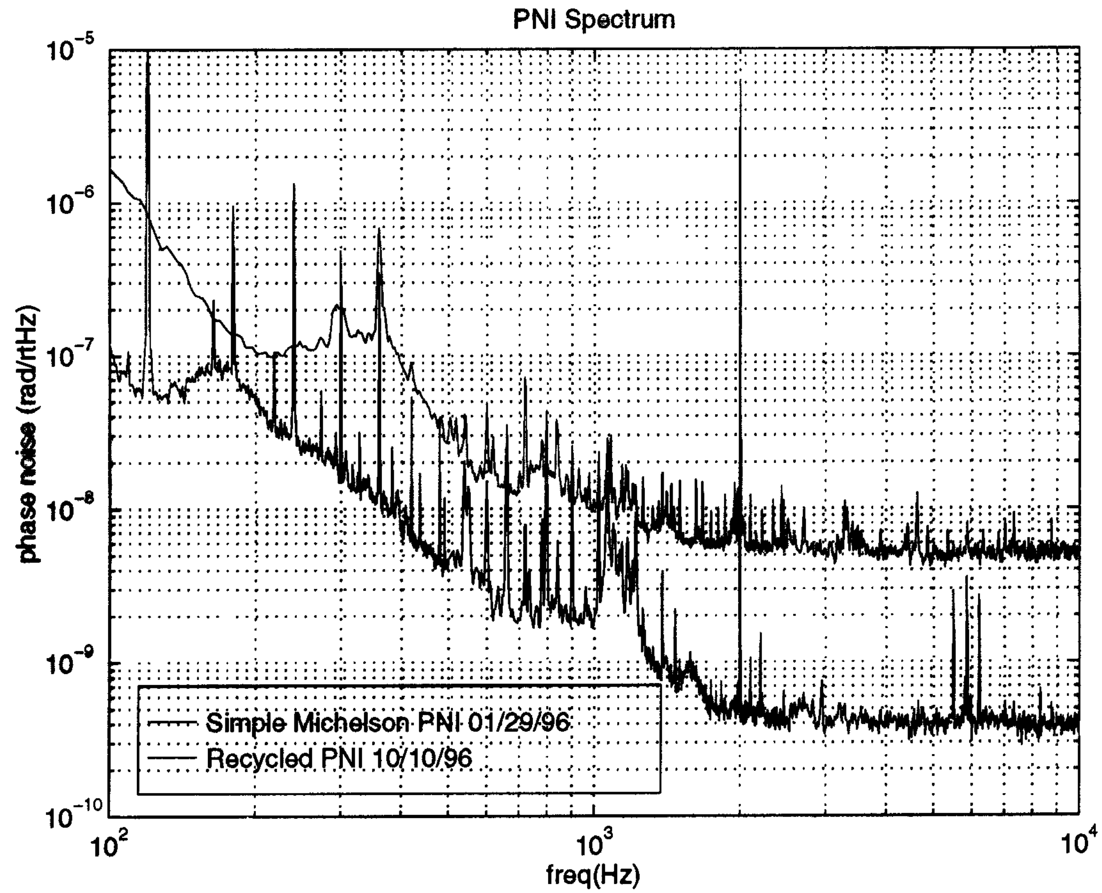
(April 8th 1996 Parameter Set)

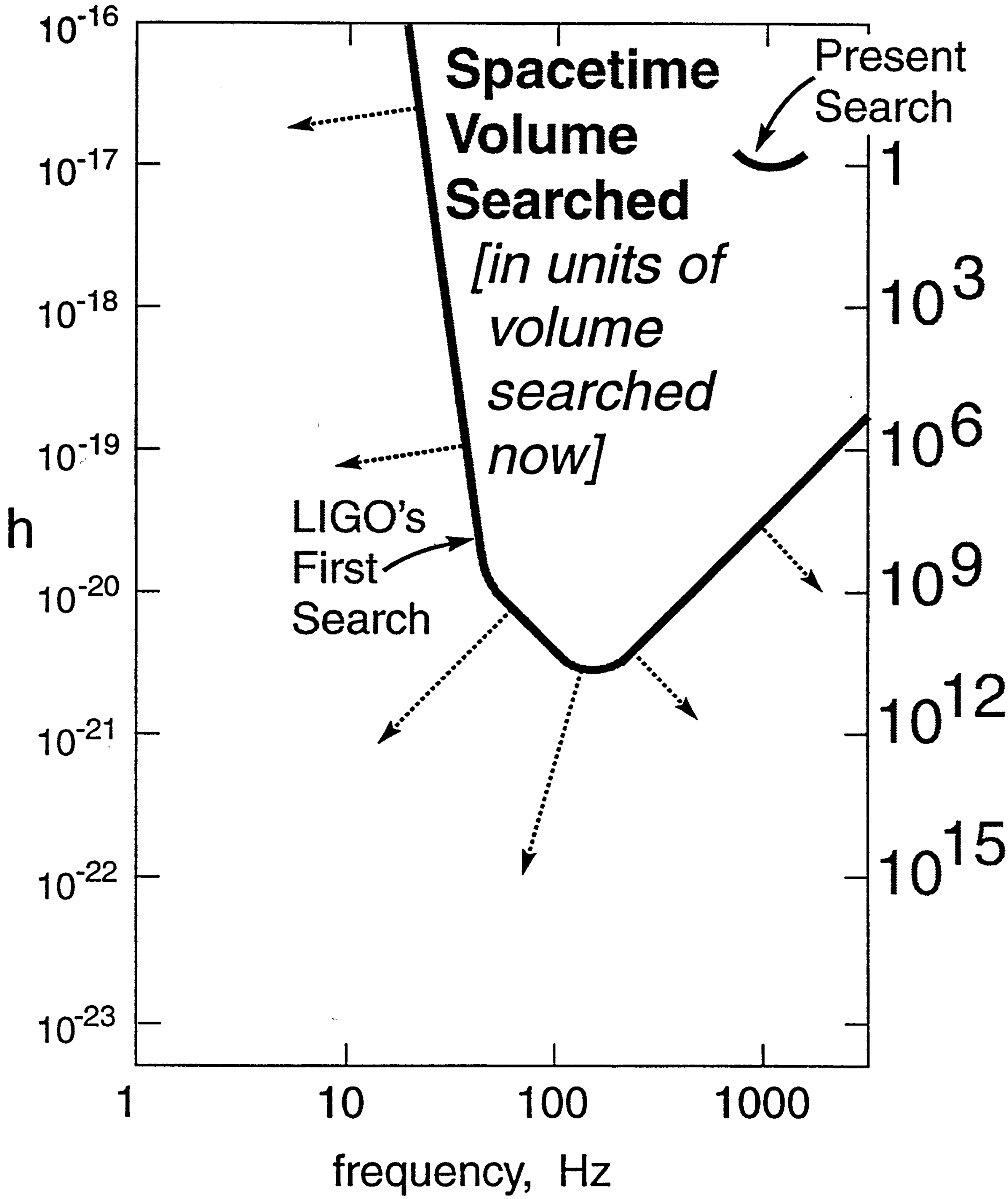


40 m Lab


40 m Displacement Sensitivity
Comparison of Estimated Noise Levels on 10/28/94
oct28–hr.dat, 28 Oct 94
internal thermal noise
shot + thermal noise
seismic noise estimate
standard quantum limit
pitch thermal noise
yaw thermal noise
vertical thermal noise
180 Hz w/ sidebands
300 Hz w/ sidebands
x (m/Hz^1/2)
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10
100
1000
Frequency (Hz)

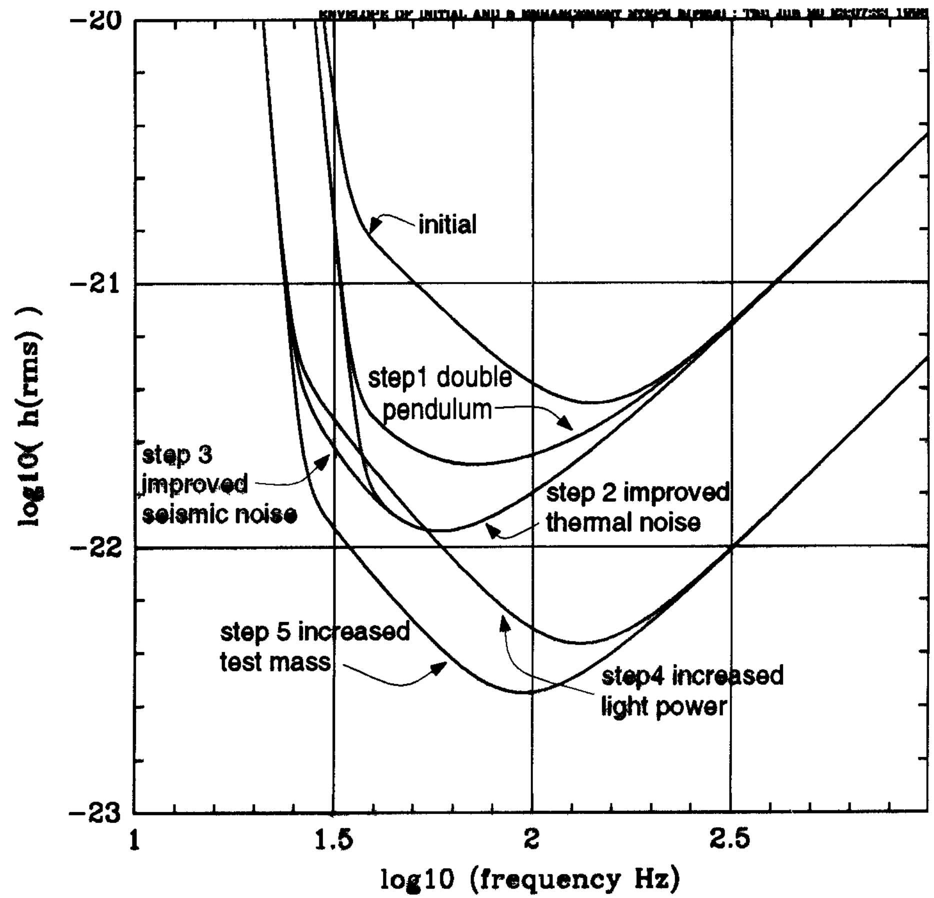
Phase Noise Sensitivity From MIT Interferometer





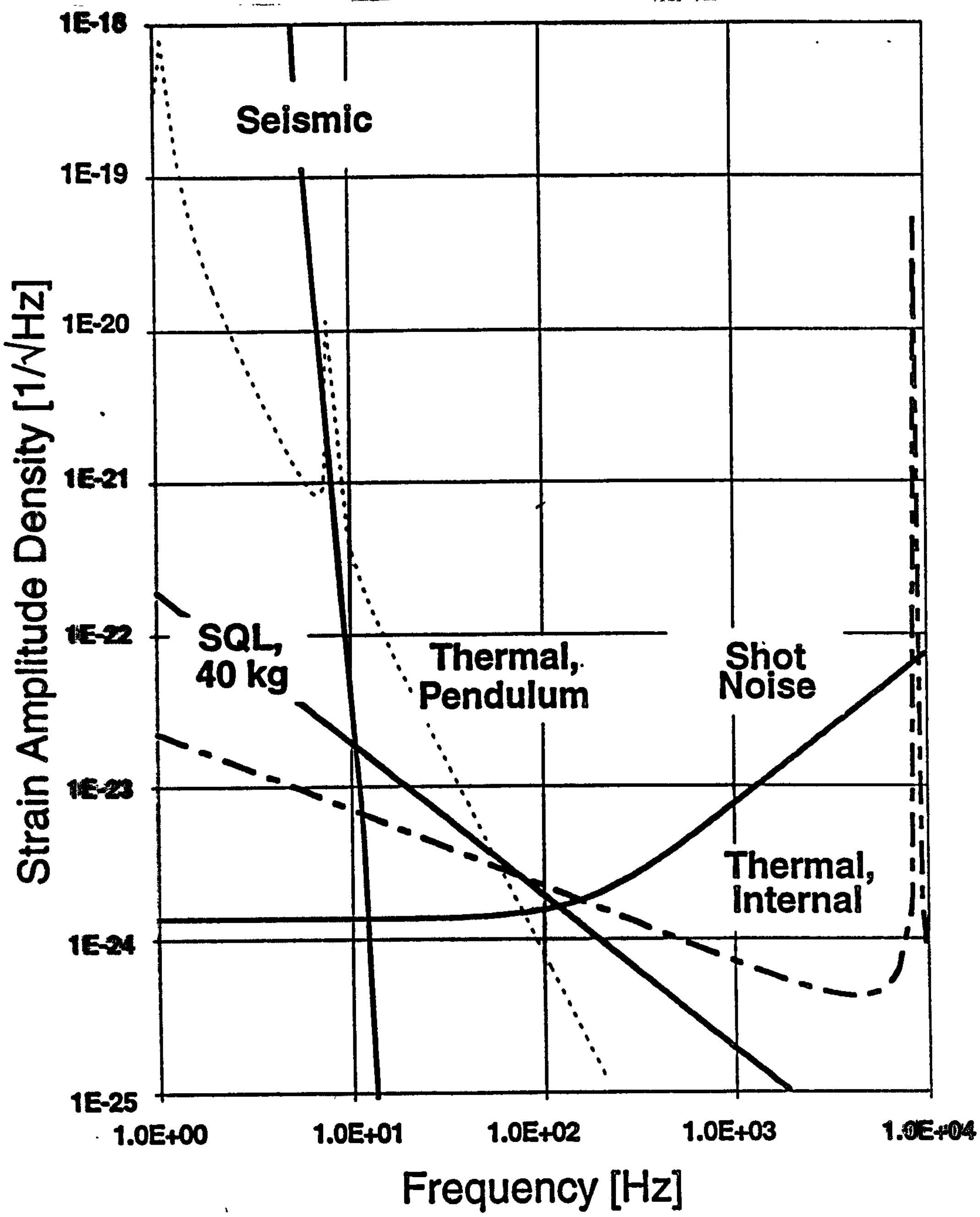
Spacetime Volume Searched
[in units of volume searched now]
Present Search
LIGO's First Search
h
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
1
10^3
10^6
10^9
10^{12}
10^{15}
1
10
100
1000
frequency, Hz

Steps in the Advanced Subsystems Research



Enhanced Interferometer

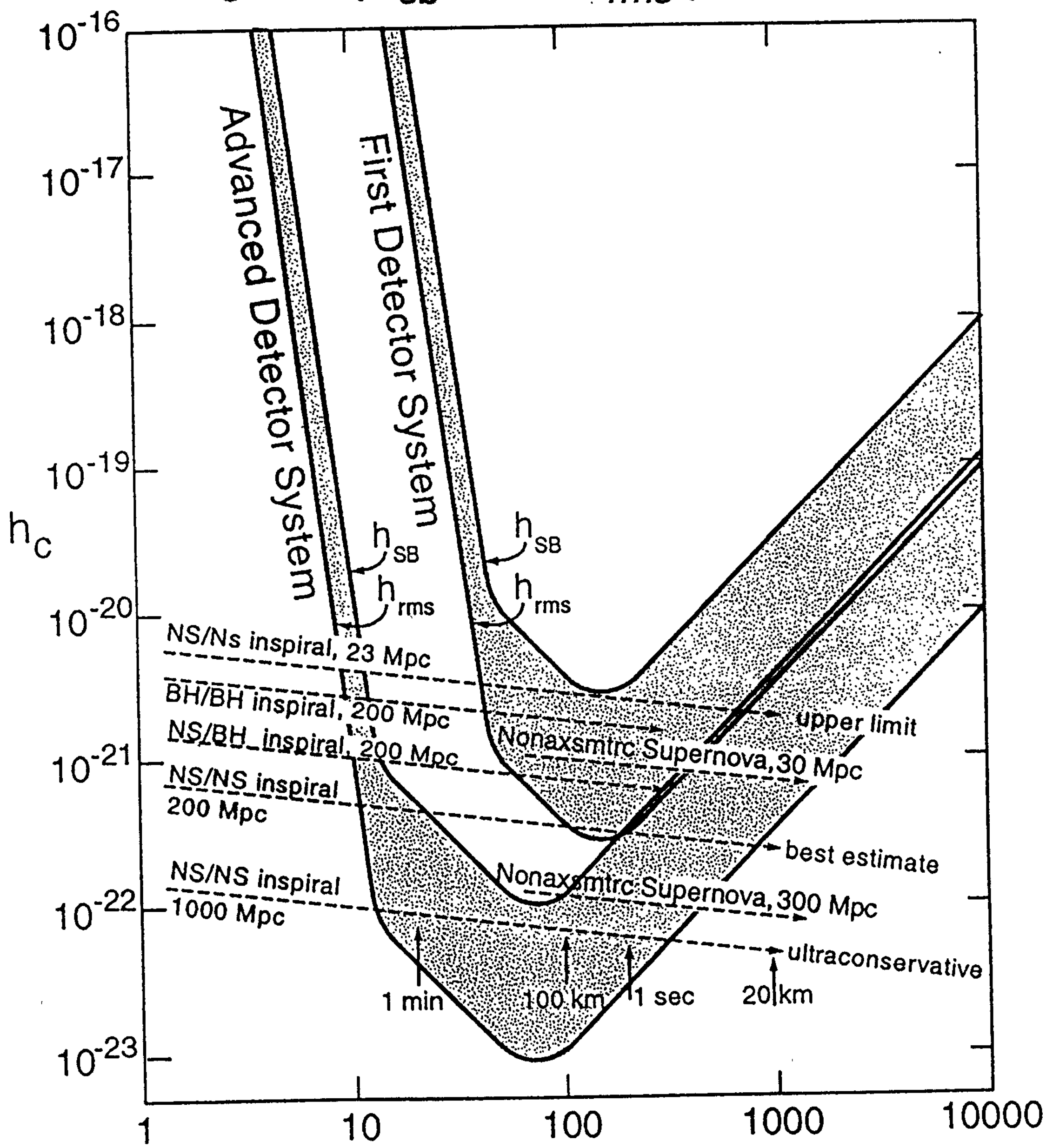
Noise Budget



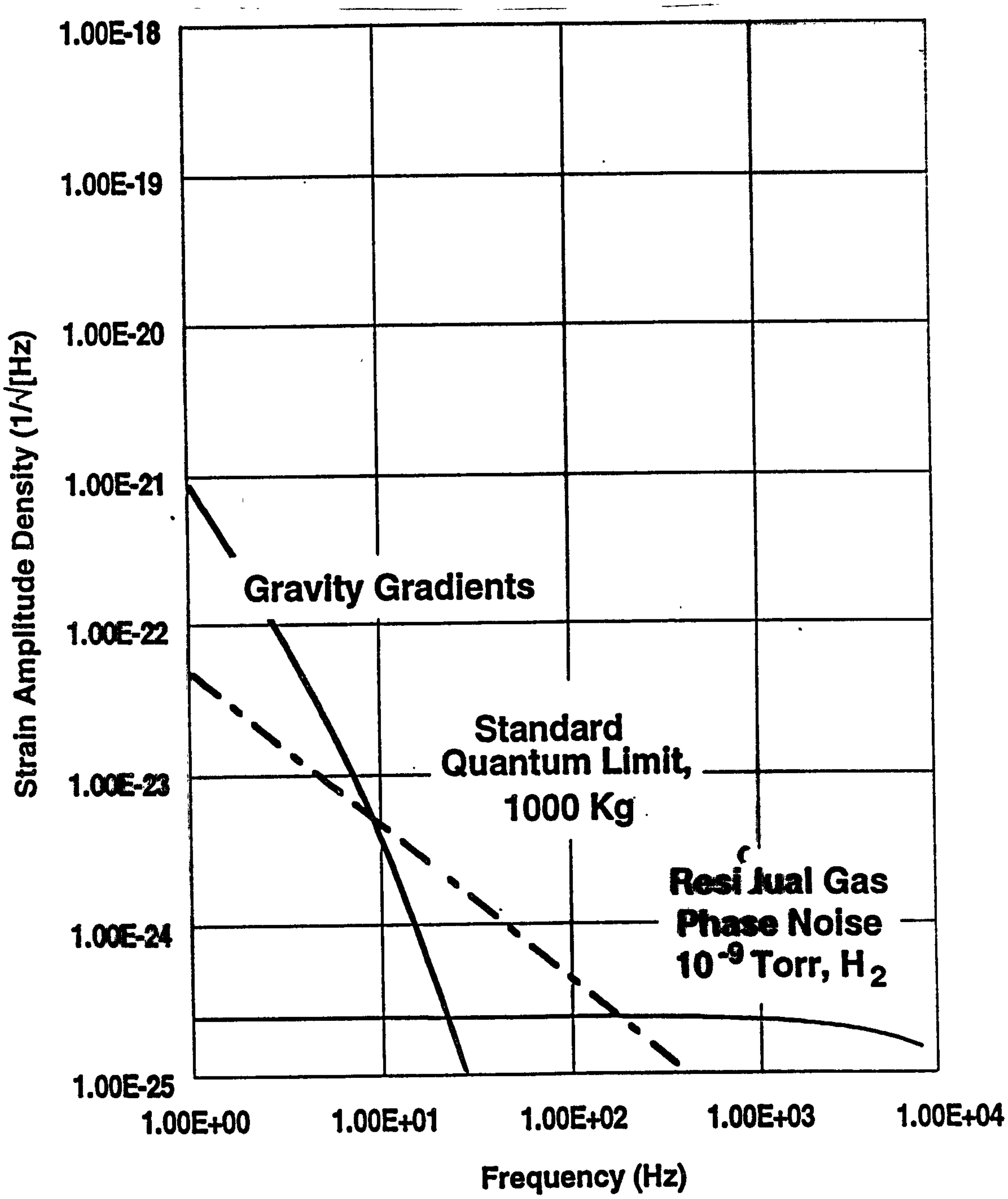
LIGO

LIGO
Sensitivity

- Comparison of sensitivity and wave strengths ($h_{sb} = 11h_{rms}$)



LIGO Facilities
Limiting Noise Floor



LIGO

Conclusions

- LIGO Construction is well Underway
- Direct Detection of Gravitational Waves Appears Realistic within 10 years
- Ultimate Sensitivities Capable of Opening a New Field of Observational Astronomy with Gravitational Waves is the Long Term Goal.