The Detection of Gravitational Waves

LIGO

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Rice University

Nov 6, 1996

LIGO

LIGO-G0231-00-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

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

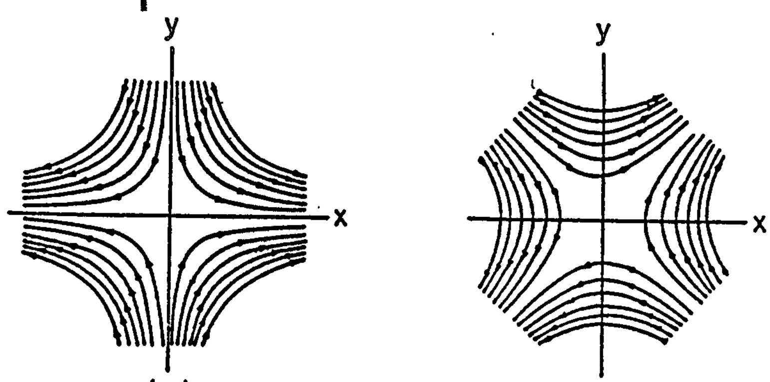
- Detector Size << Wavelength

  (4 km) (300-30,000km)

  (10 kHz - 10 Hz LIGO)

THEN

- Free Masses
- Quadrupolar Lines of Force

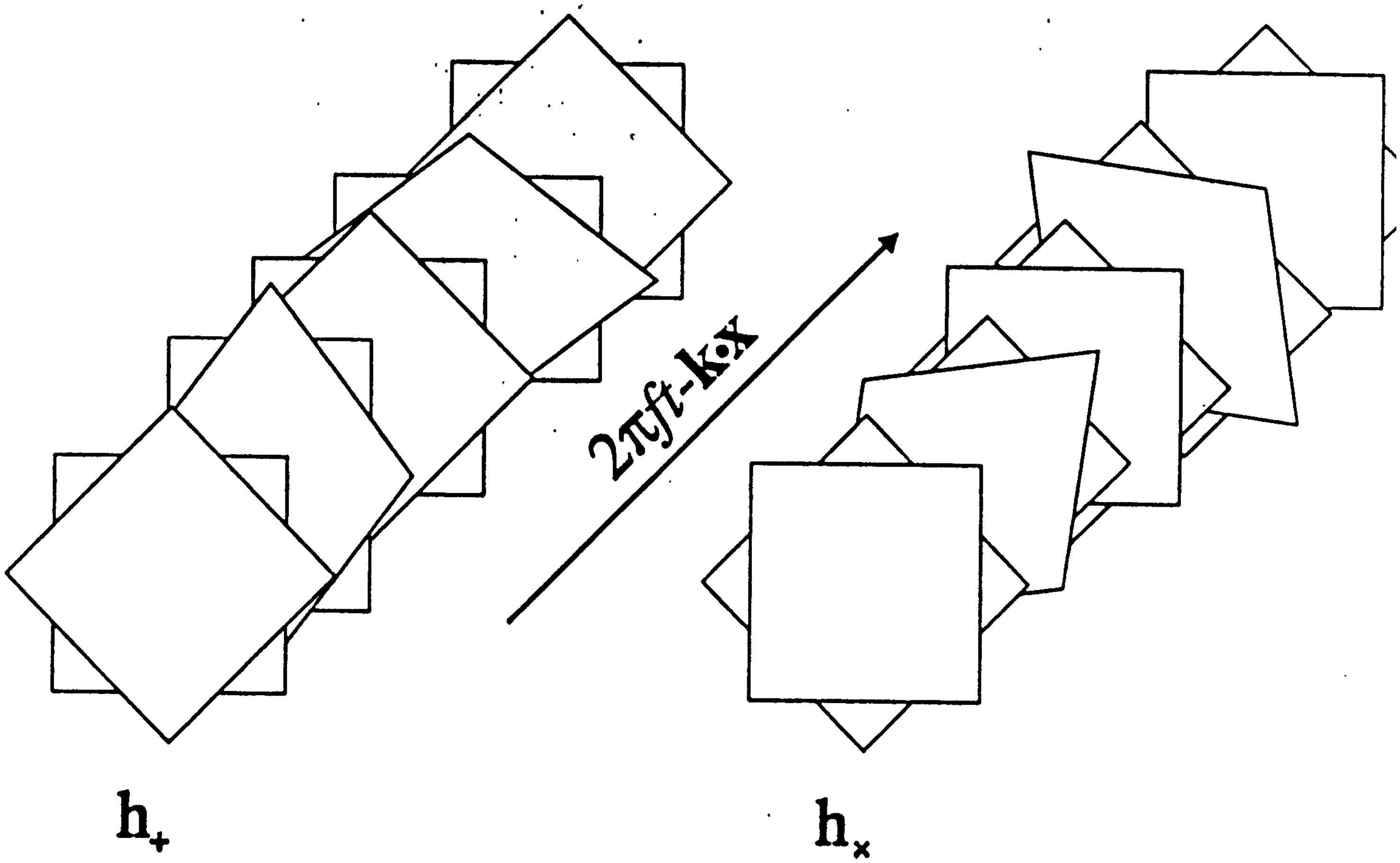


(a) (b)

+ Polarization x Polarization

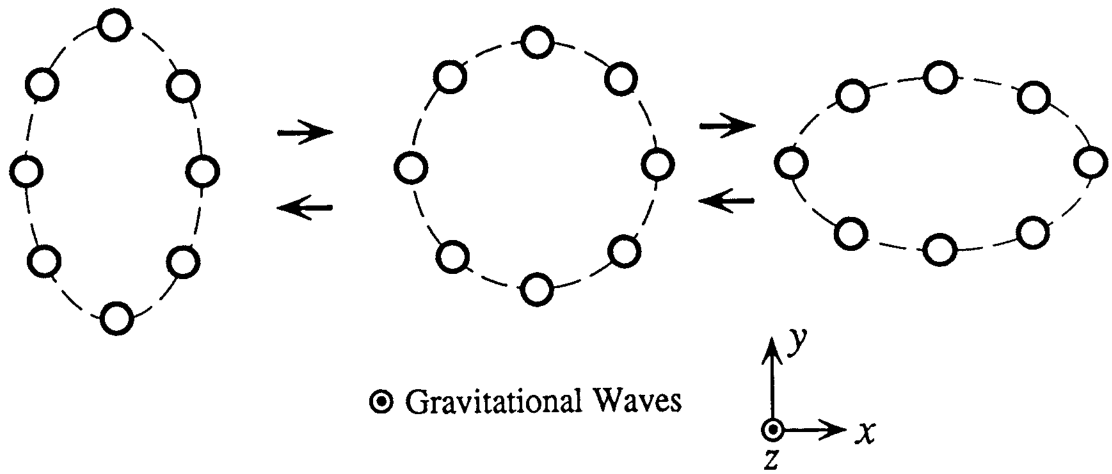
Gravitational Waves

Two Polarizations

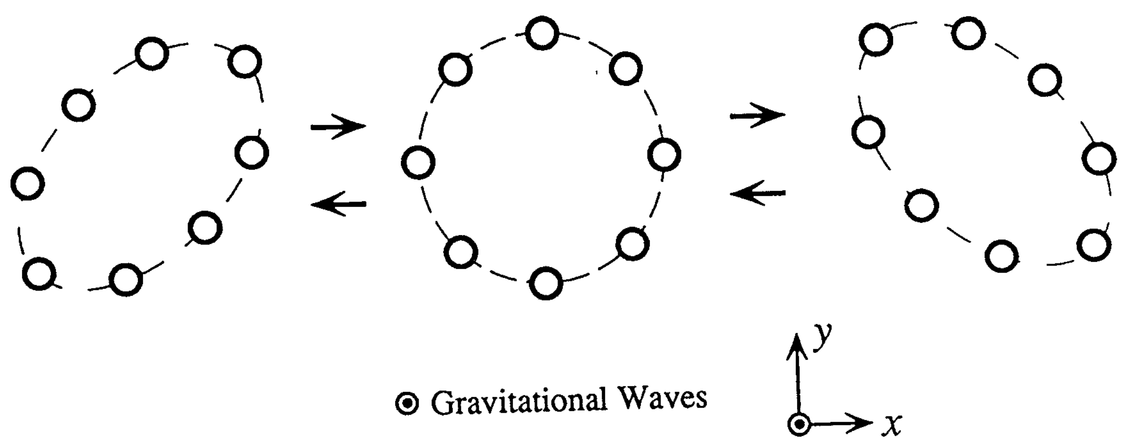


Gravitational Waves
Effects

- Displacement of free particles



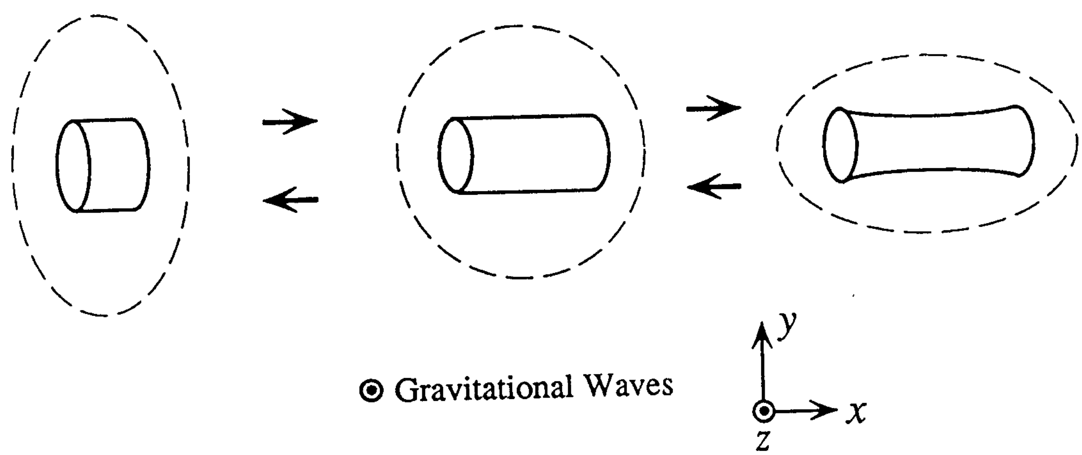
» h_+ polarization



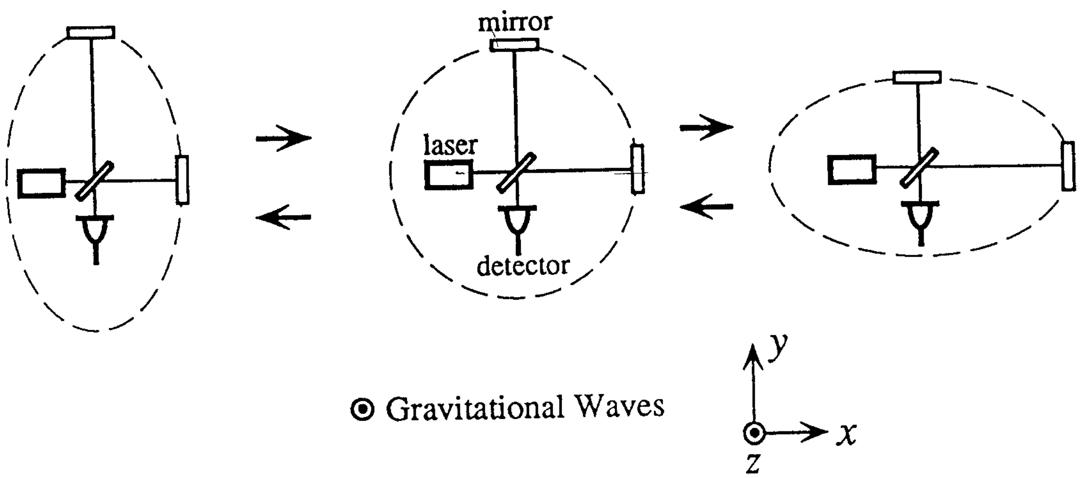
» h_x polarization

Gravitational Waves

Detection



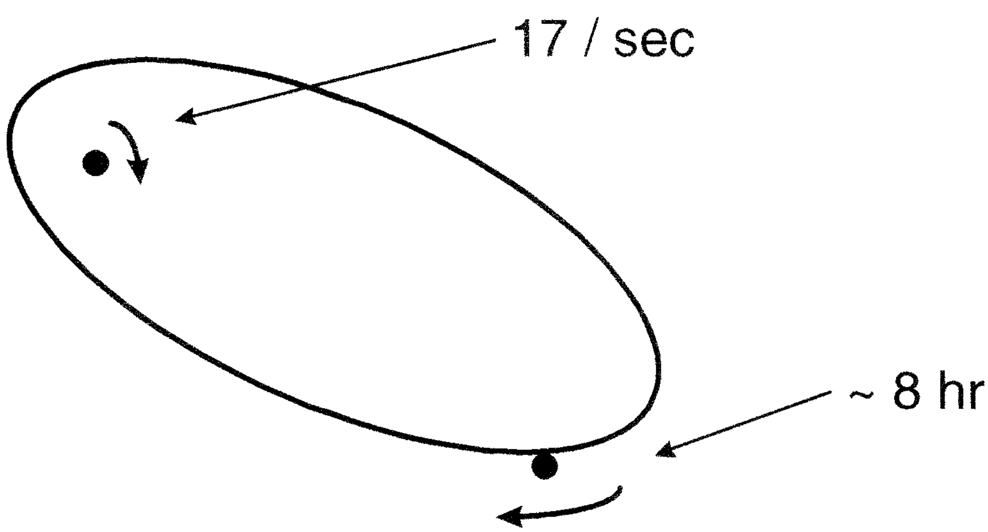
- Bar detector



- Interferometer detector

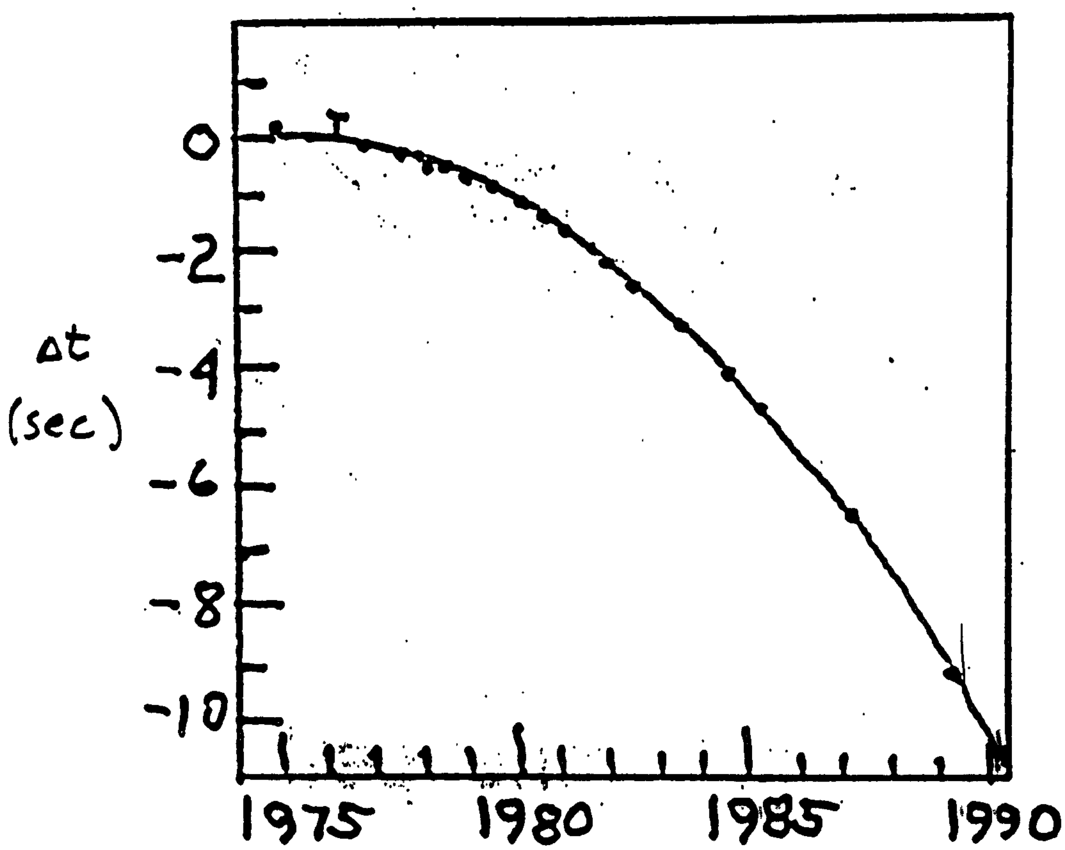
Gravitational Waves
Evidence

- **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

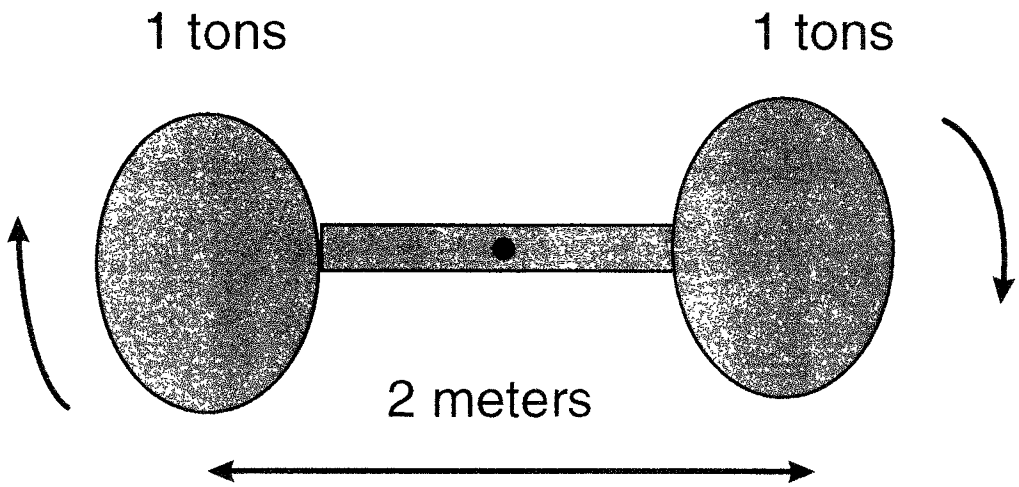


- Due to loss of orbital energy, from emission of gravitational waves

Laboratory Experiment

(a la Hertz)

Laboratory Dumbbell System



$f_{rot} = 1$ kHz

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

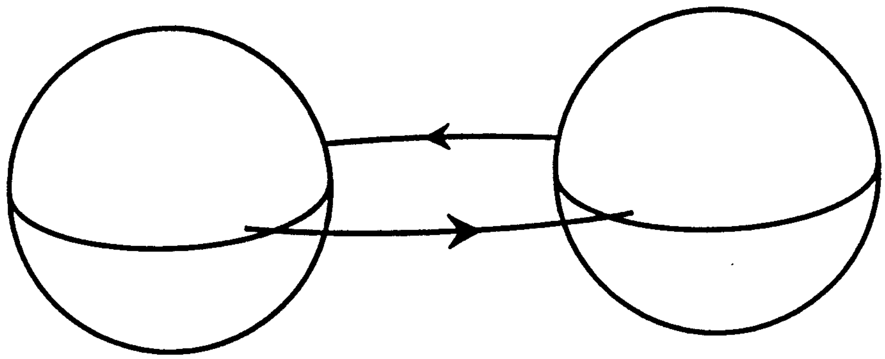
R = detector distance (> 1 wavelength) = 300 km

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

This is too weak by about 16 orders of magnitude!

Gravitational Waves

Sources and Detection



- binary star system

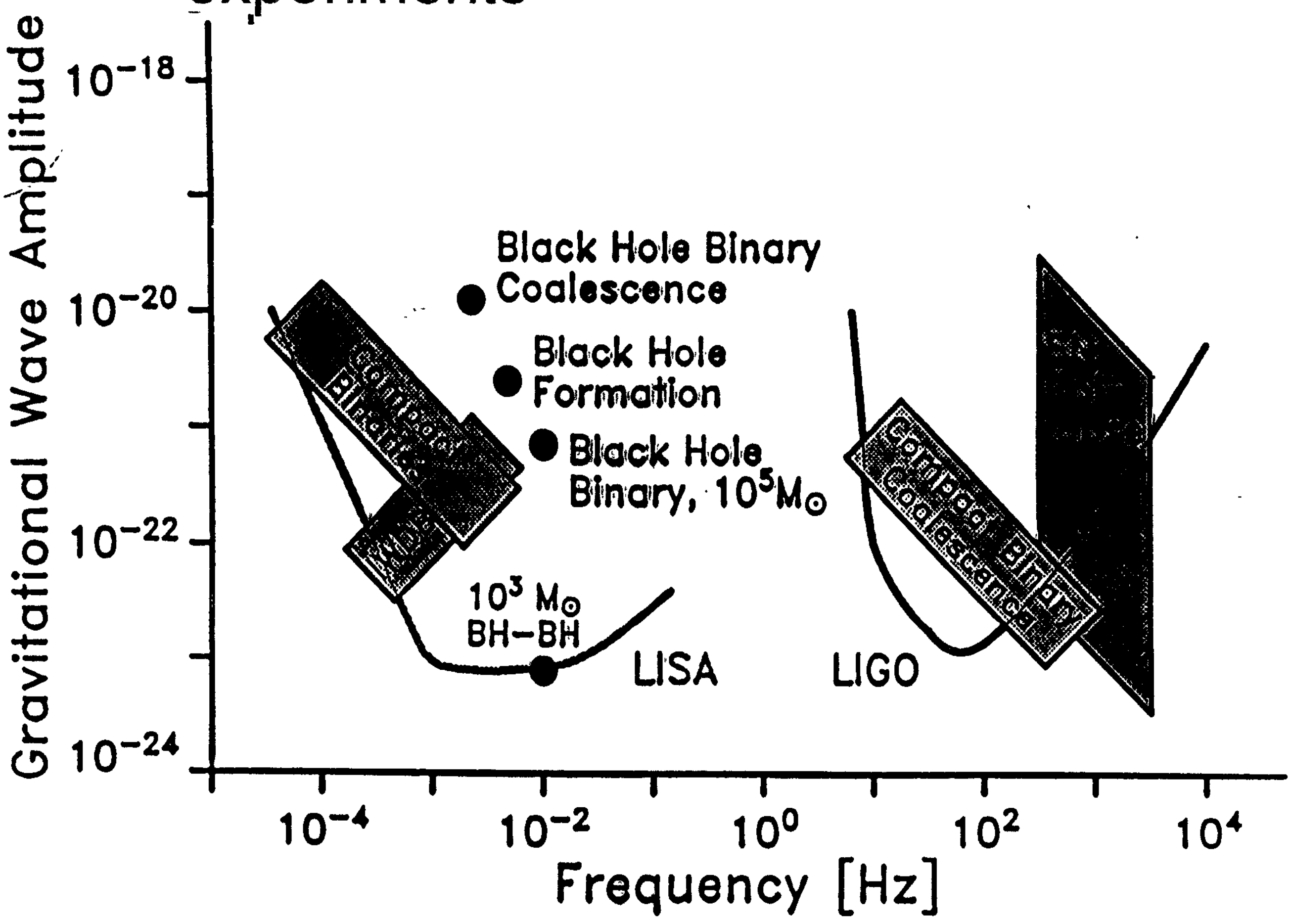
Sources	Frequency	h	Event Rate	Detection
Coalescing Binary Neutron Stars (200 Mpc)	10~1000 Hz	10^{-22}	~3/year	Interferometer +Template
Supernovae (in our Galaxy)	~1 kHz	10^{-18}	~3/century	Interferometer, Resonant
Supernovae (in Virgo)	~1 kHz	10^{-21}	several/year	Interferometer
Generation of Large 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

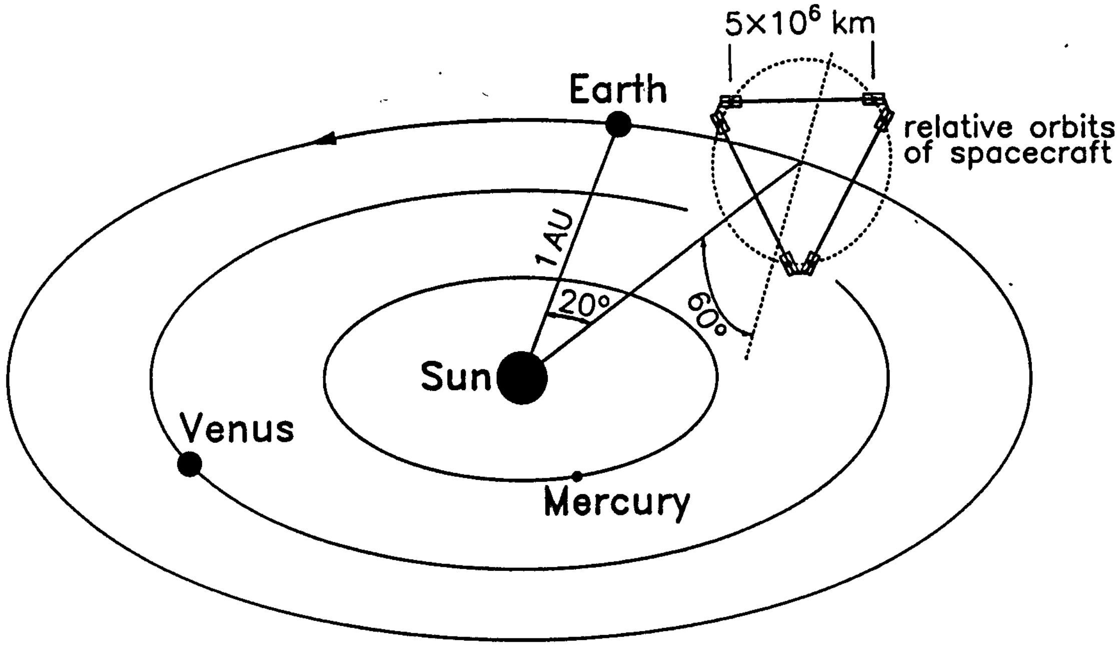
Frequency Range

- 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

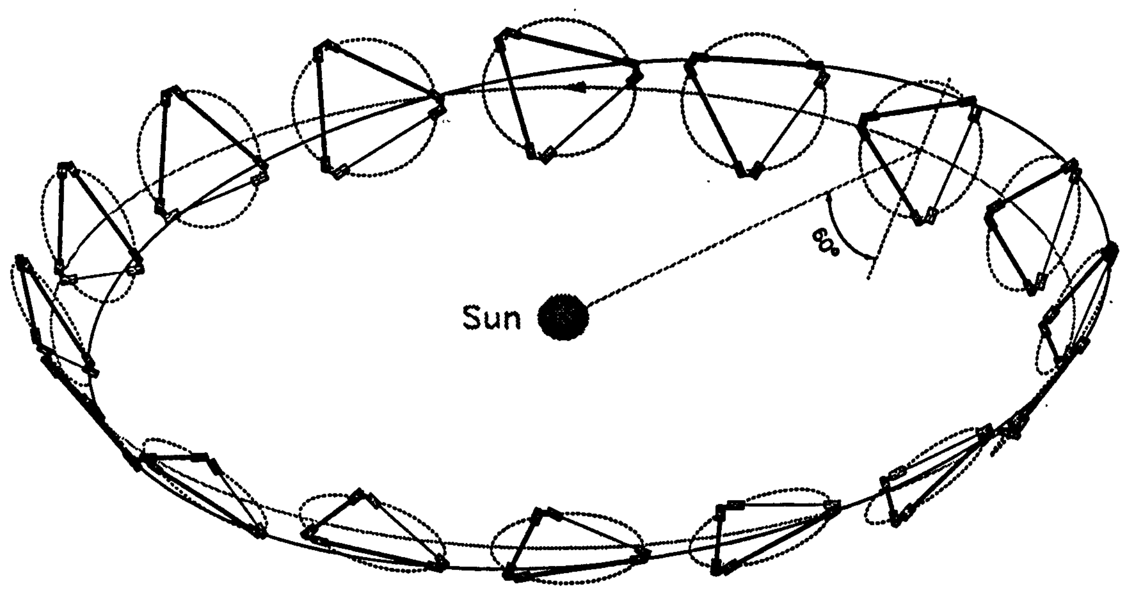
- LISA - Laser Interferometer Space Antenna
  - » six spacecraft in triangle (four needed)
  - » pair at each vertex



LISA

Annual Revolution

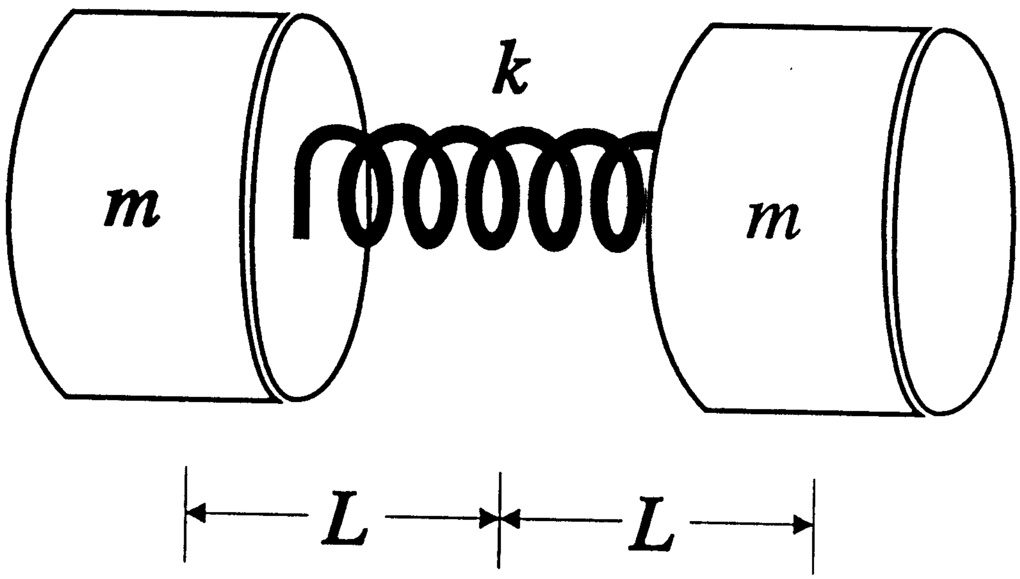
- 60 degree half opening angle
- 'tumbling' allows determination of position of source and polarization of wave



Gravitational Waves

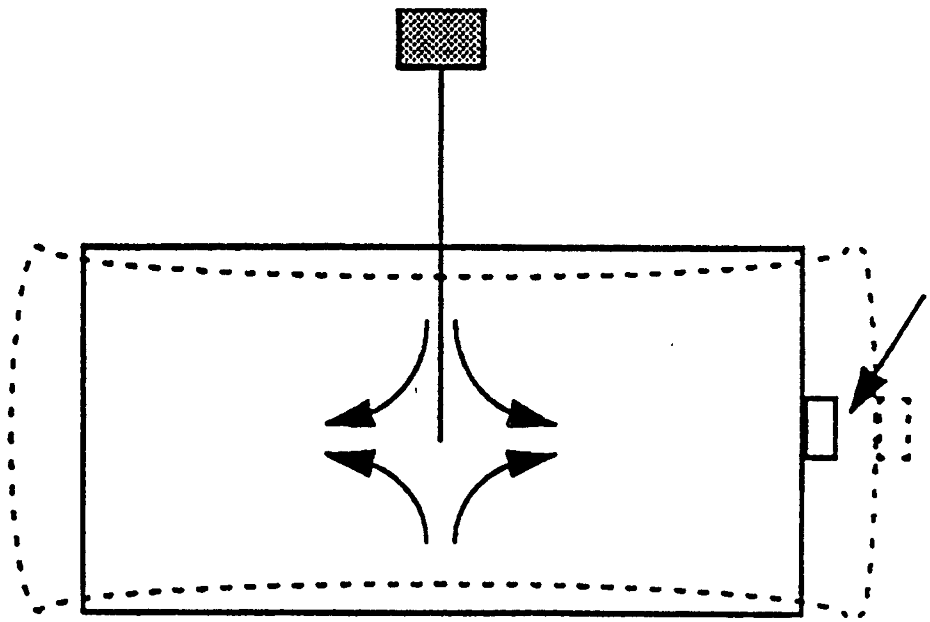
Resonant Bar Detector

- 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

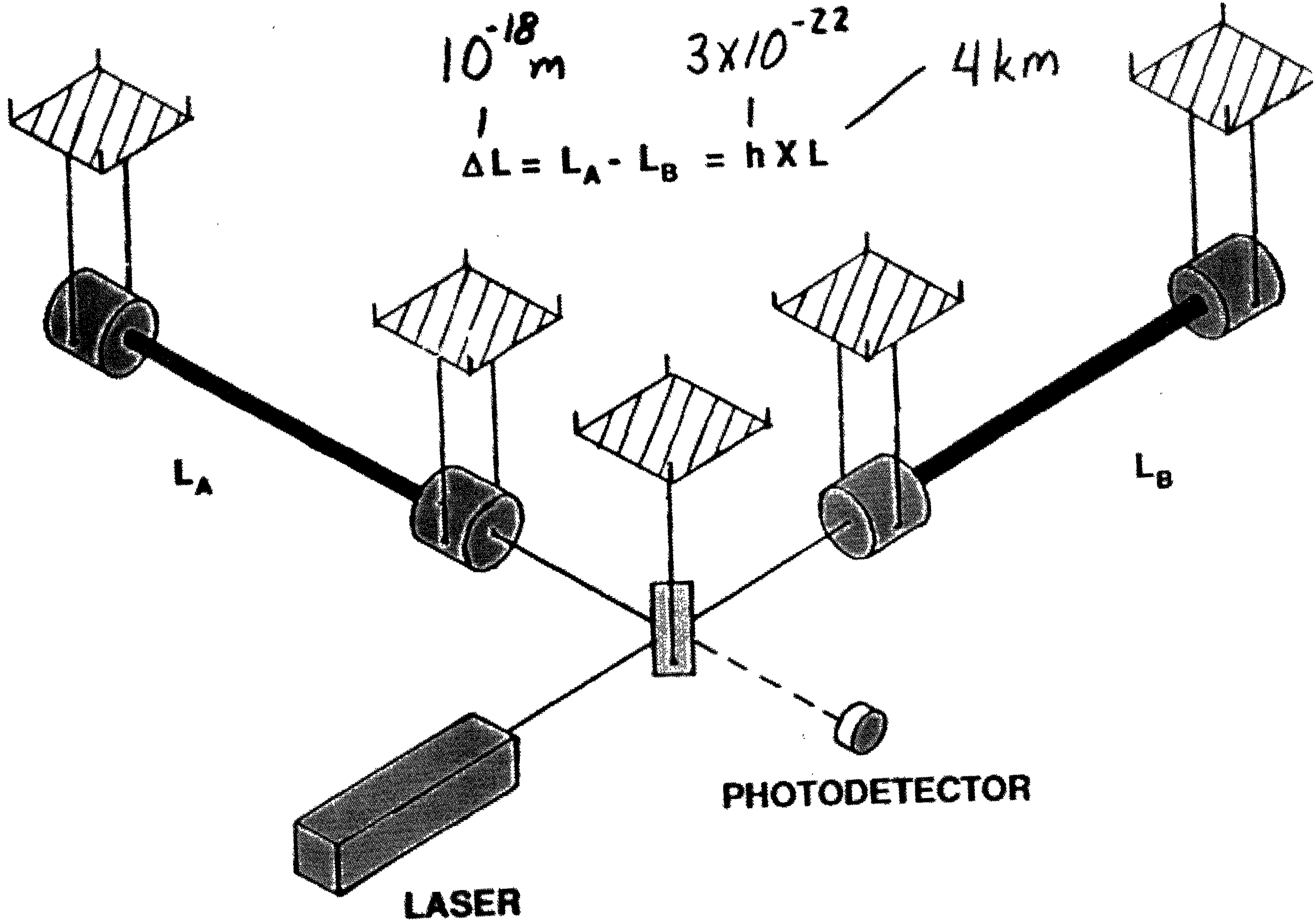
Gravitational Waves
International Effort

- 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



LIGO

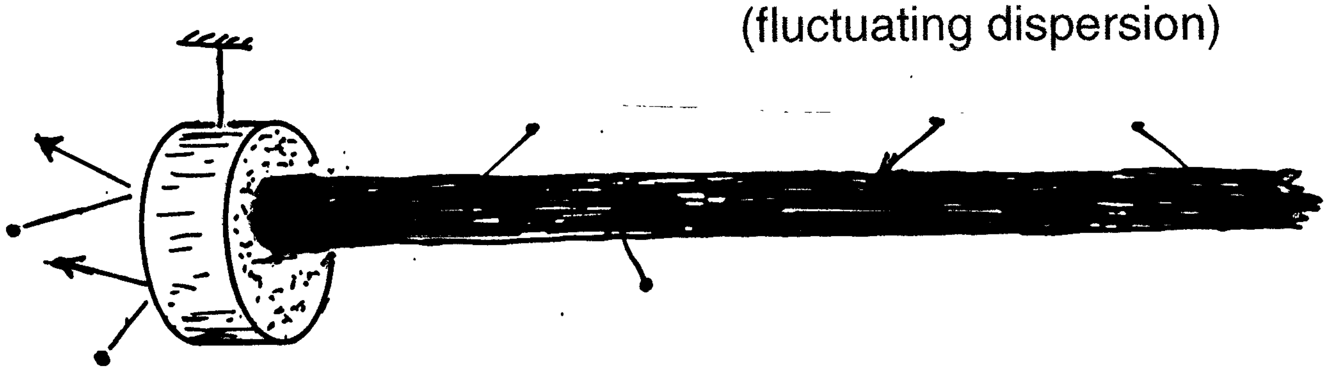
Achieving 10^{-18} m Sensitivity

How is it possible????

- Air molecules:

Buffer mirrors

Buffet light beam (fluctuating dispersion)



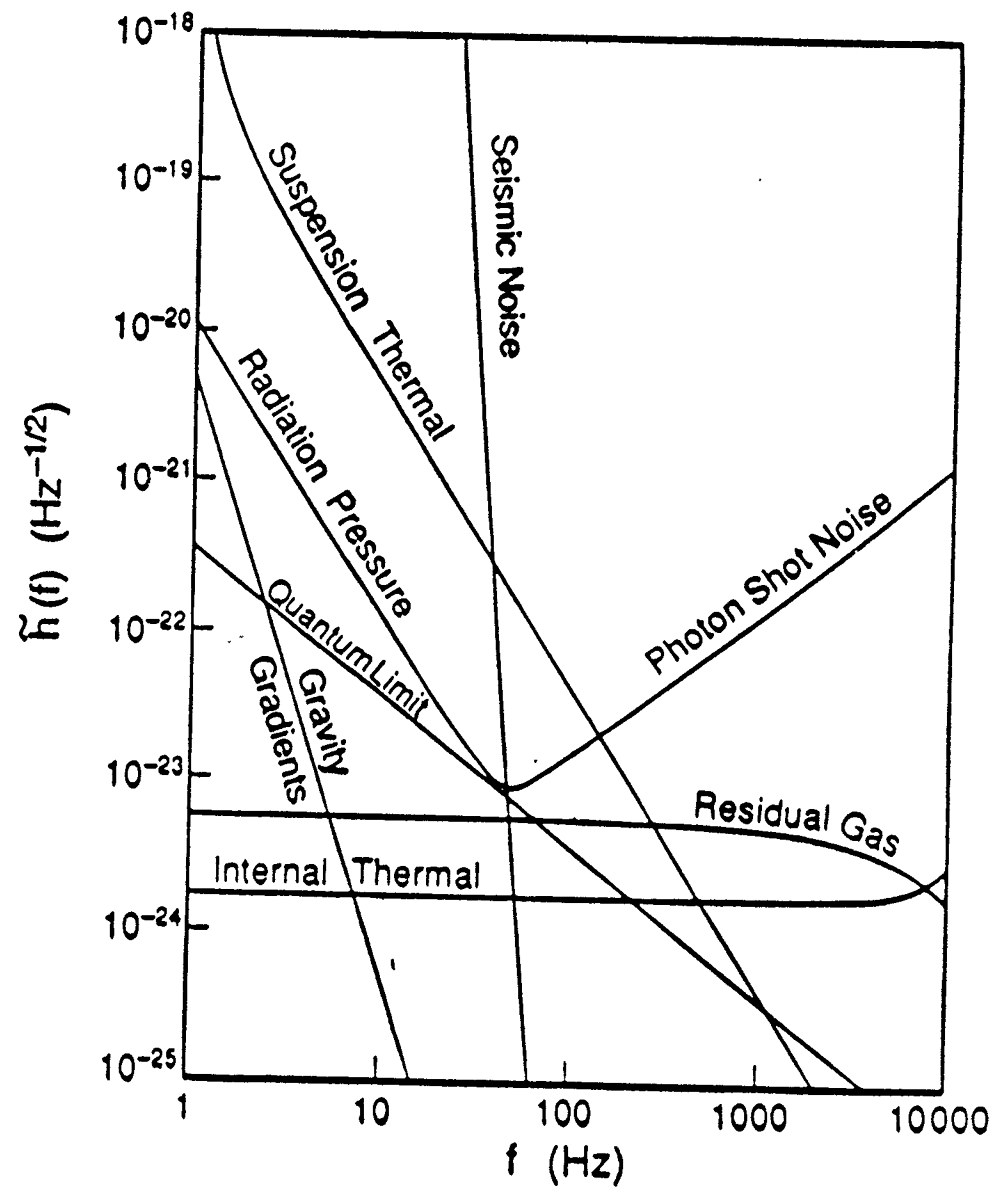
  - » **Mirrors and light beam must be in vacuum**

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

- Earth vibrates and shakes mirrors
  - » **anti-vibration suspension**
  - » **quiet environment**

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

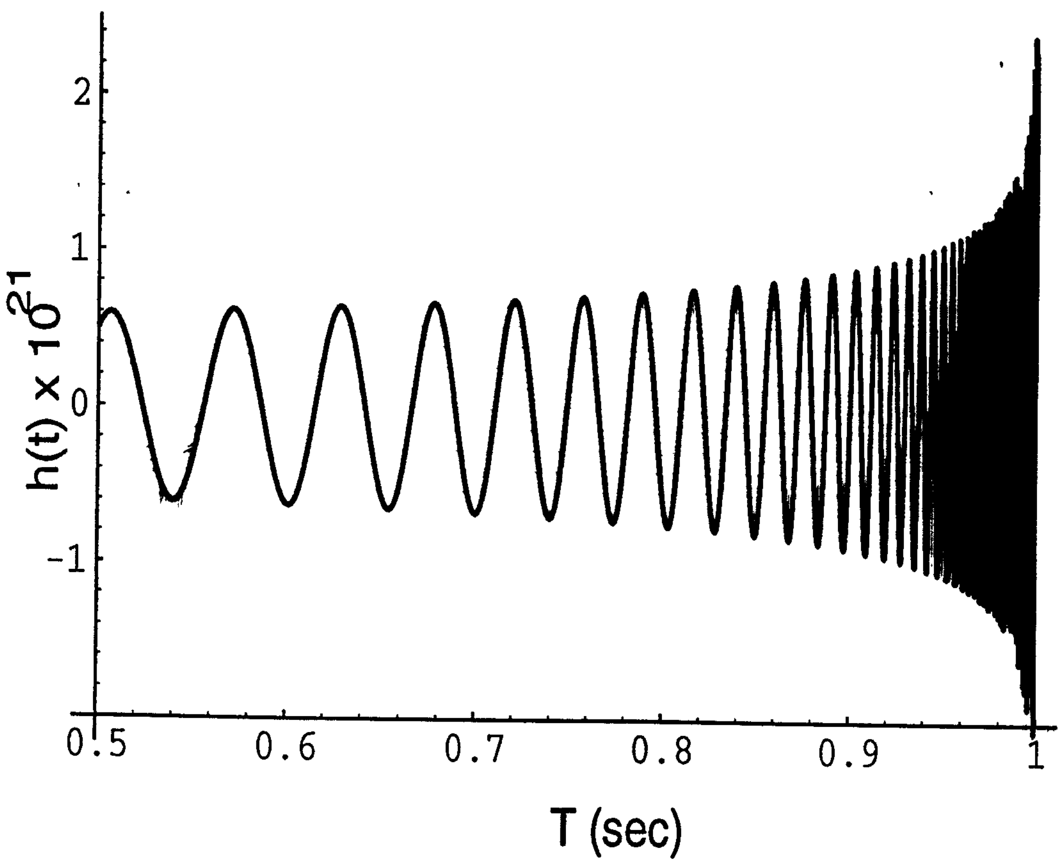
- Fundamental Physics (GR)
  - » Test General Relativity in Strong Field and High Velocity Limit
  - » Measure Polarization and Propagation Speed

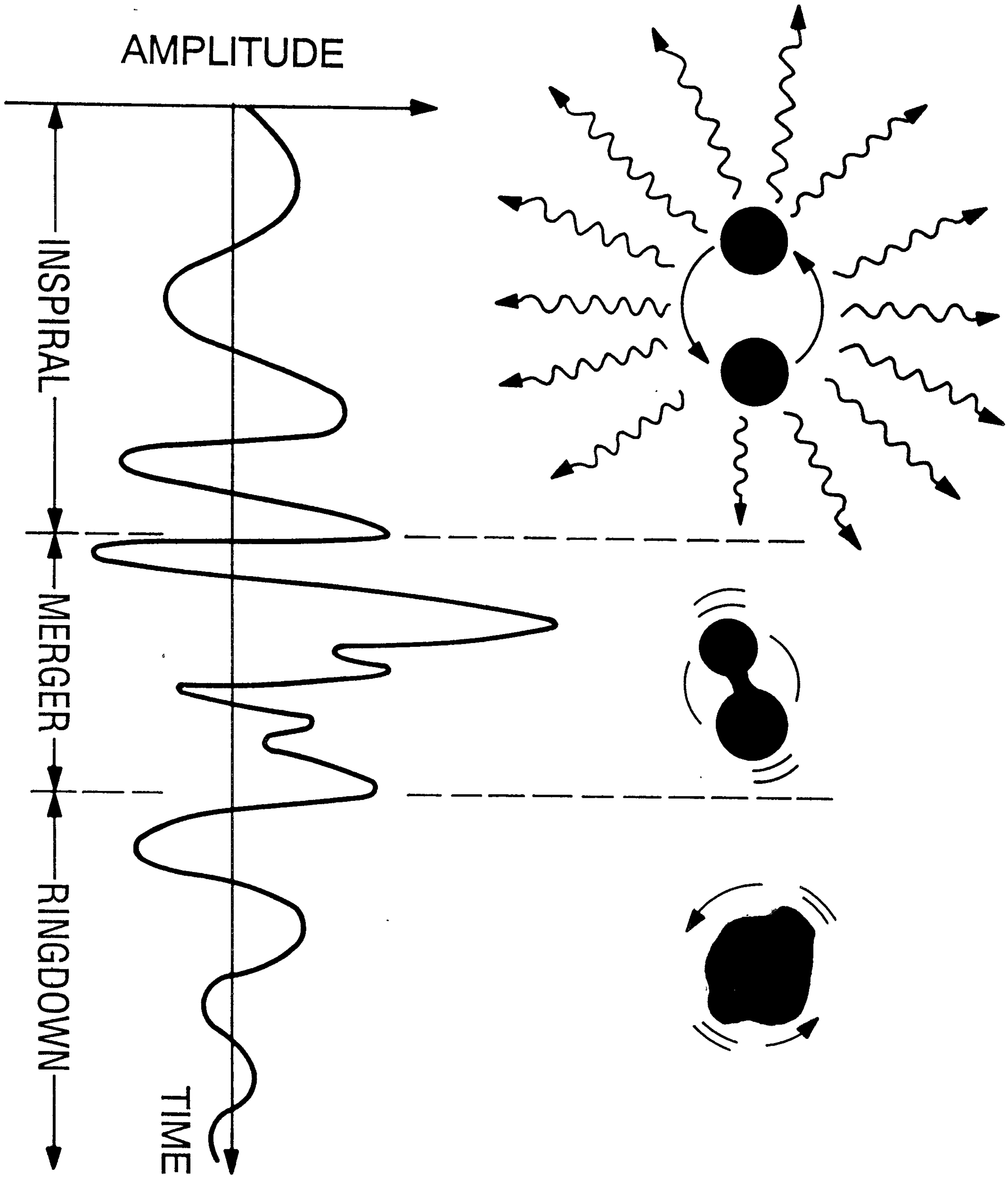
Neutron Star Binary Coalescence

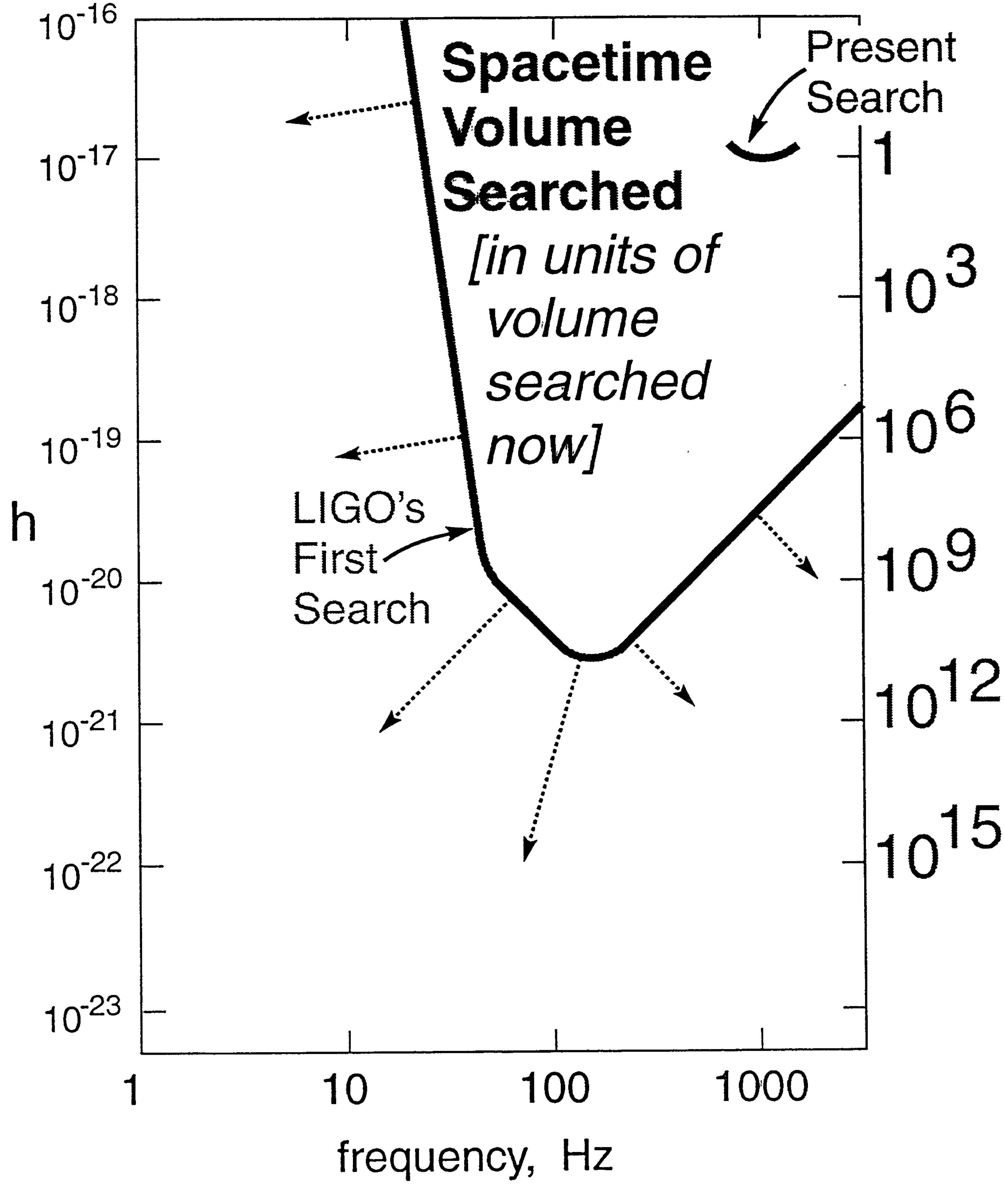
Method	*Our Galaxy*	*Distance for 3/yr*
Progenitor Death Rate	~1/1000 yr	130 M.L.yr
Binary Pulsar Searches and Discoveries	~1/$10^{5\pm1}$ yr	600 M.L.yr.
Ultra-conservtive Limit from Binary Pulsar Searches	~1/10^{7} yr	3000 M.L.yr

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




AMPLITUDE
INSPIRAL
MERGER
RINGDOWN
TIME



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

LIGO
Long Range Goals

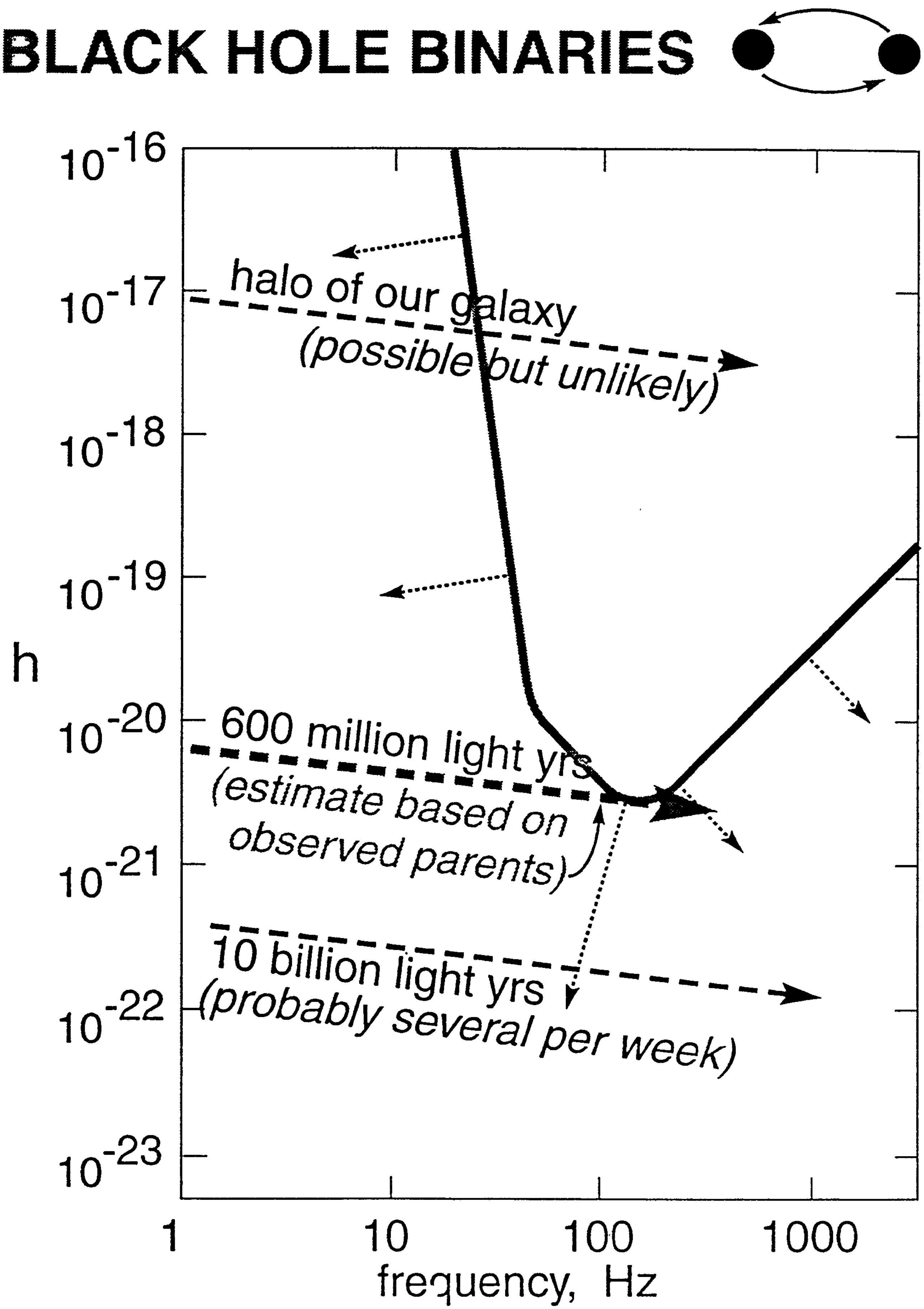
- Final Coalescence of Binary Systems
  - » Neutron Star/Neutron Star
    - – Design Benchmark: last 15 min
20,000 cycles
600 MLyr
  - » Black-hole/Black-hole
  - » Black-hole/Neutron Star

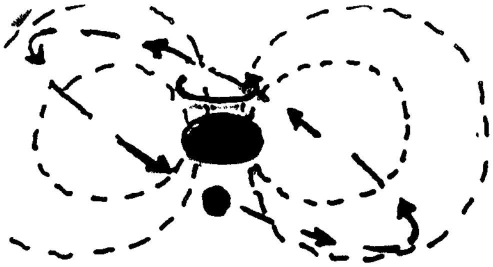
- Supernovae
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr

- Early Universe
  - » Vibrating Cosmic Strings
  - » Vacuum Phase Transitions
  - » Vacuum Fluctuations from Planck Era

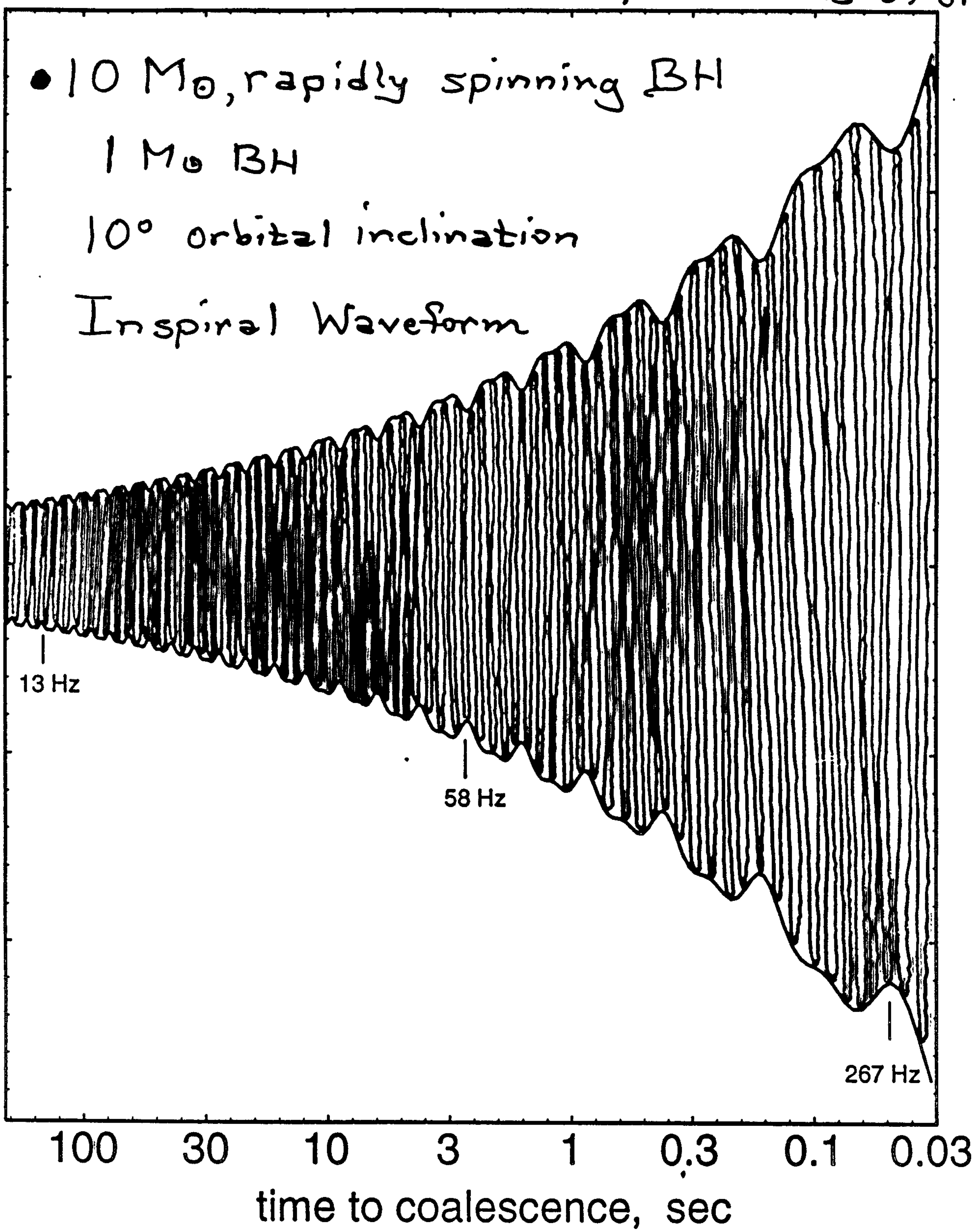
- Unknown Sources

BLACK HOLE BINARIES

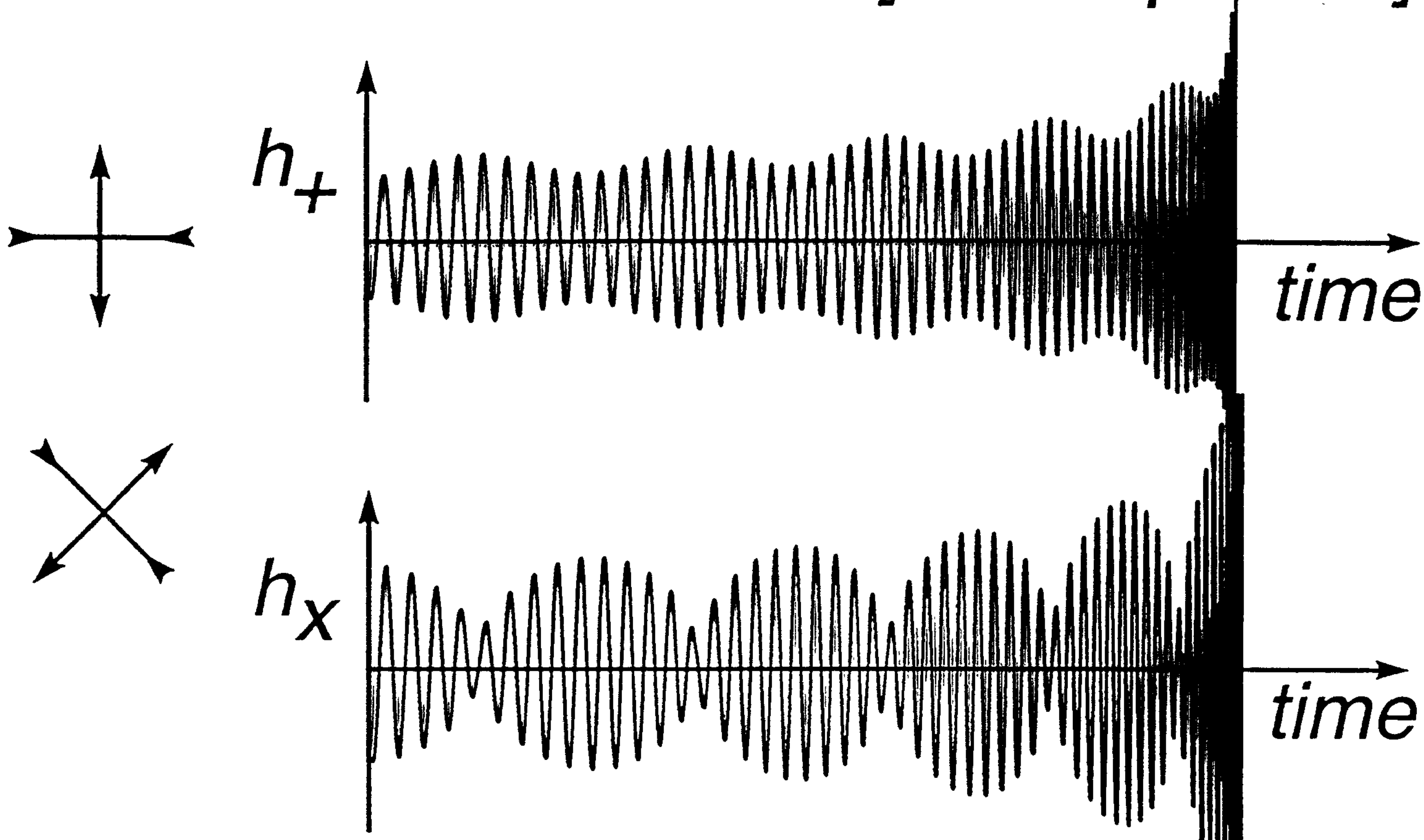




BH Spin → "gravitomagnetic field"
(frame dragging)
→ ~20 precessions of orbit



TWO WAVEFORMS *[Stereophonic]*

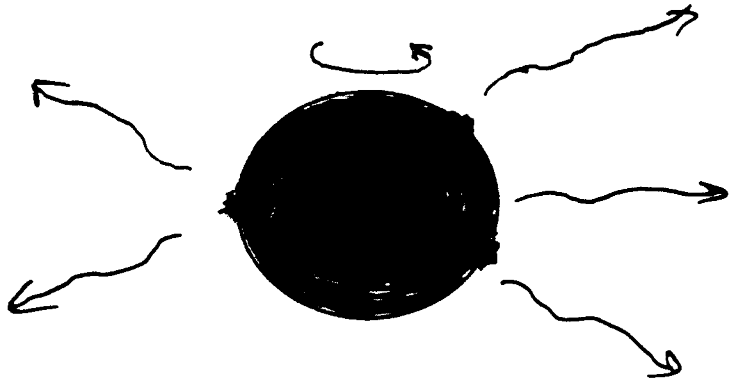


- **Rich Information**
  - *Map of spacetime warpage*
  - *Tornado-like swirl of space around big hole*

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

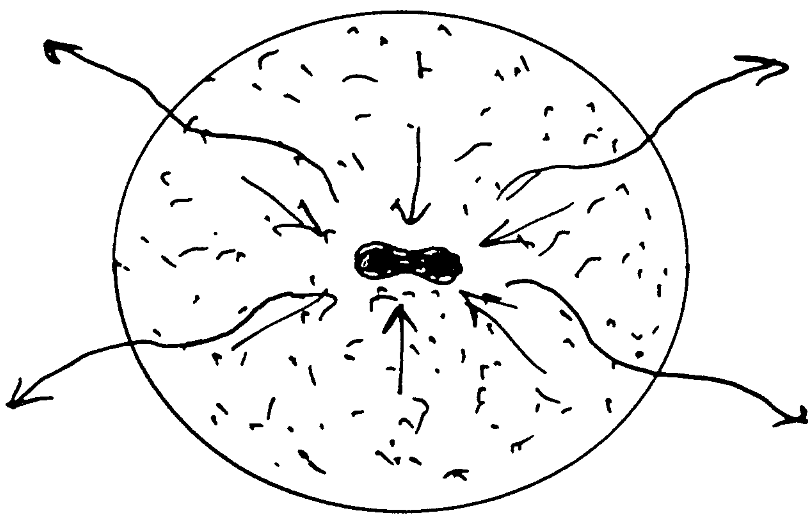
OTHER POSSIBLE SOURCES

SPINNING, "MOUNTAINOUS" NEUTRON STAR



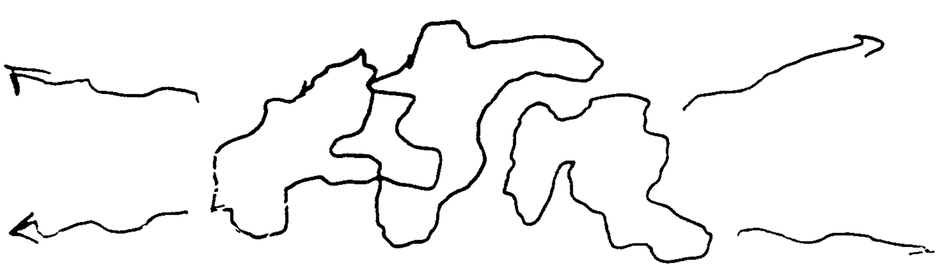
Periodic

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



Bursts

VIBRATING LOOPS OF COSMIC STRING



Stochastic

Pulsars

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

Simple model:

$M = 1.4\, M_\odot$

$r = 10$ km

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

f

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

ϵ = equatorial ellipticity

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)

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

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 ($\sim 3\ 10^{14}\ \mathrm{gm/cm^3}$)

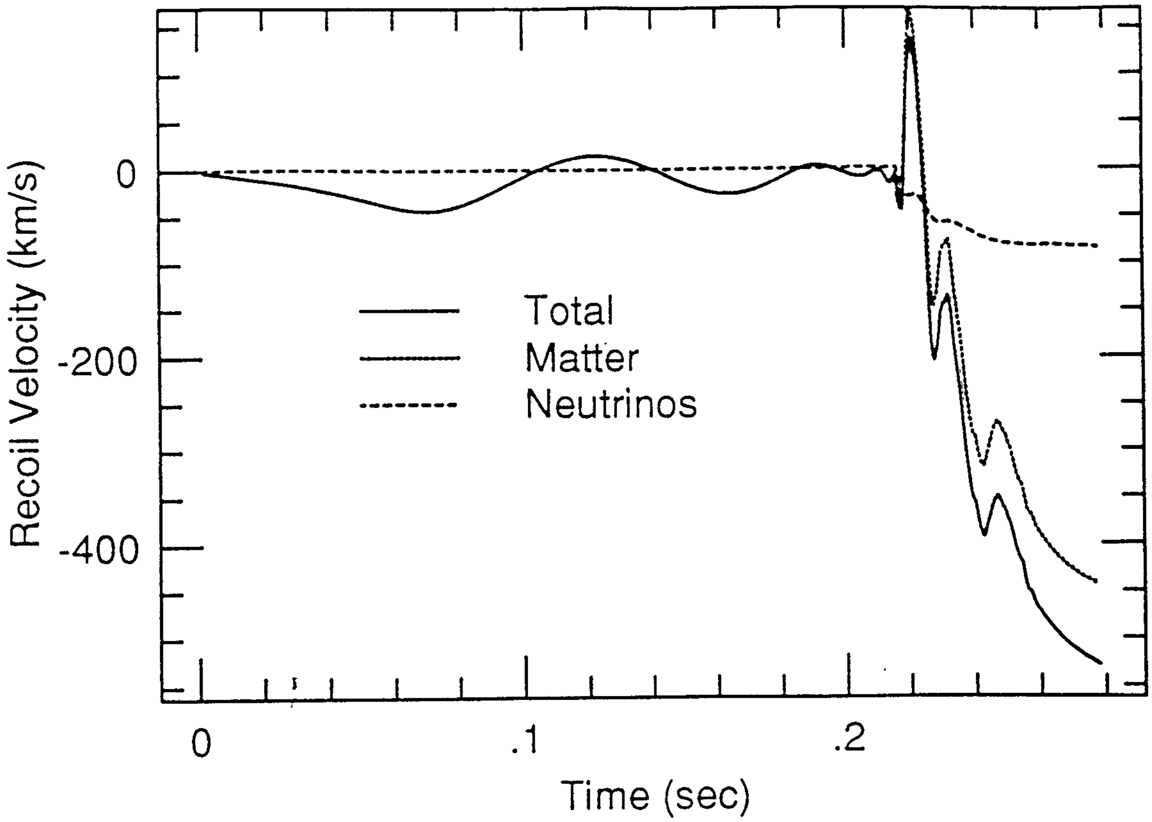


FIG. 2. The inferred recoil speed (in km s^{-1}) imparted to the core versus time (in seconds) for the simulation highlighted in this paper. The initial momentum is approximately zero, but grows systematically after bounce in the direction opposite to the artificial wedge, cut into the core to mimic 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).

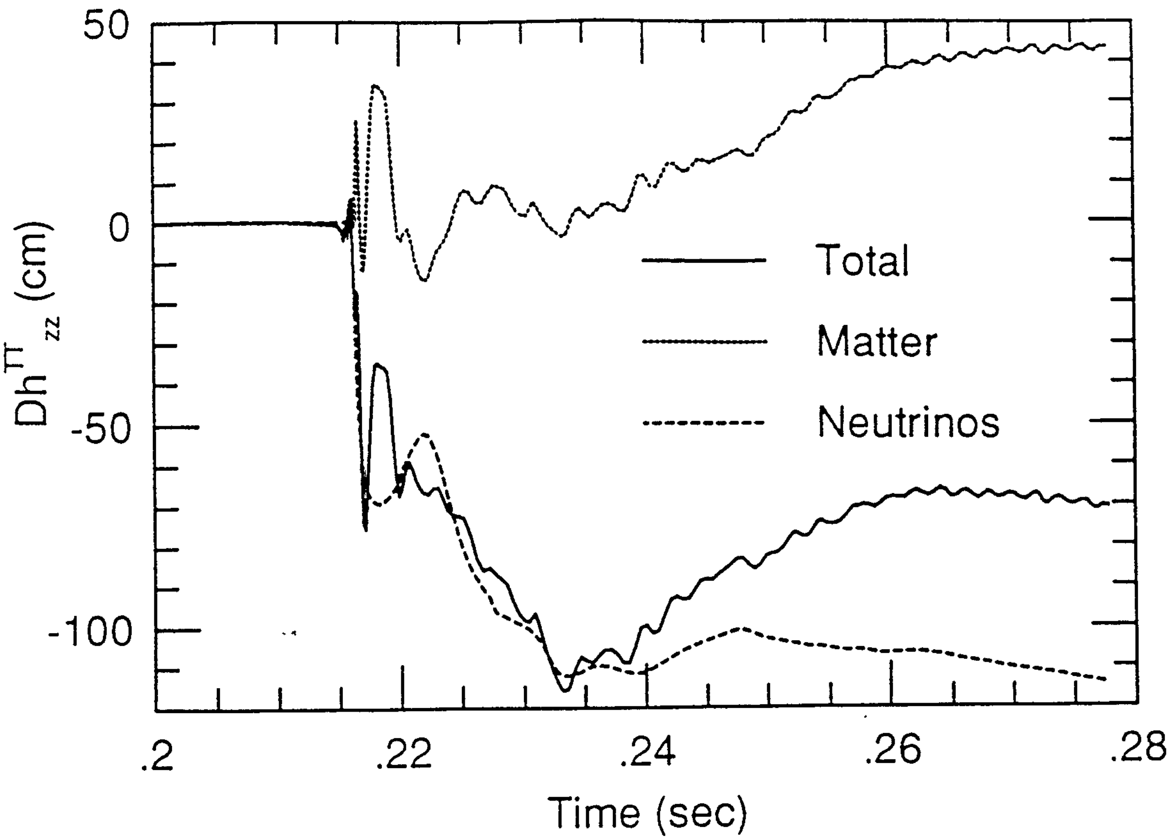


FIG. 3. The gravitational wave strain, h^{TT}_{zz}, times the distance to the supernova, D, versus time (in seconds). Core bounce is at 0.215 seconds. The total, matter, and neutrino waveforms are rendered with the solid, dotted, and dashed lines, respectively.

- physics modeling very difficult
  (departure from spherical shape)

- guidance (unclear)
  - supercomputers <u>assume</u> spherical sym.
  - 2D models (Burrows)
  - crab pulsar $\quad f_{rot} \approx 30.3$ 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)

FIGURES

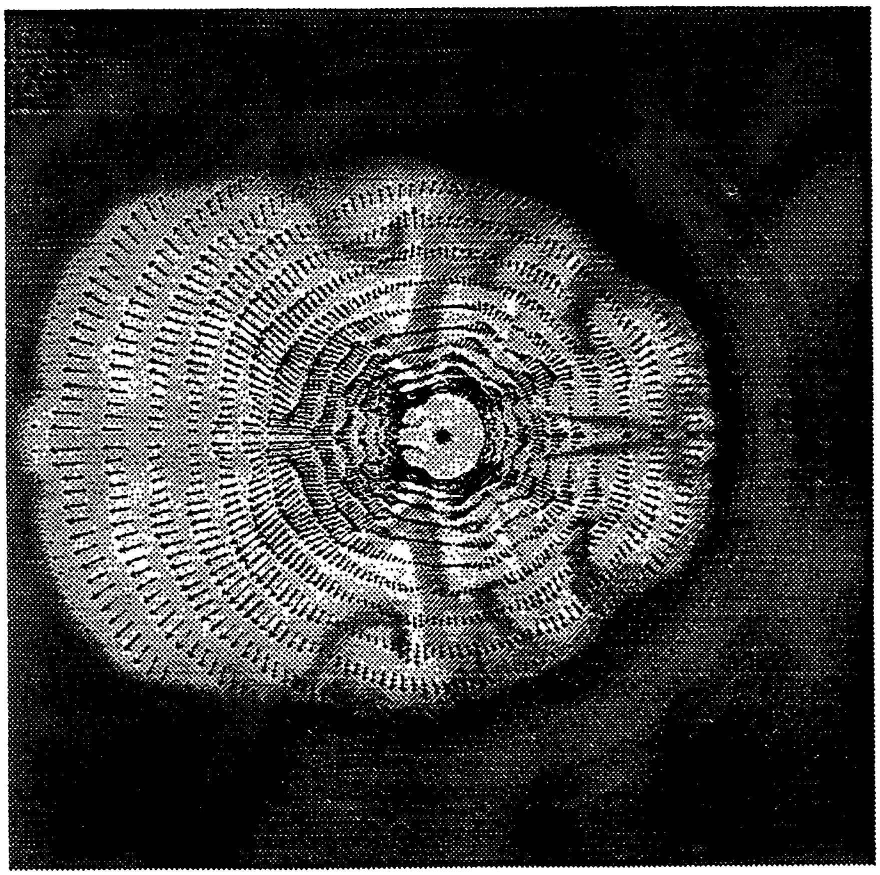


FIG. 1. A grey-scale rendering of the entropy distribution at the end of the simulation, about 50 milliseconds into the explosion. Note the pronounced pole–to–pole asymmetry in the ejecta and the velocity field (as depicted with the velocity vectors). The physical scale is 2000 km from the center to 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

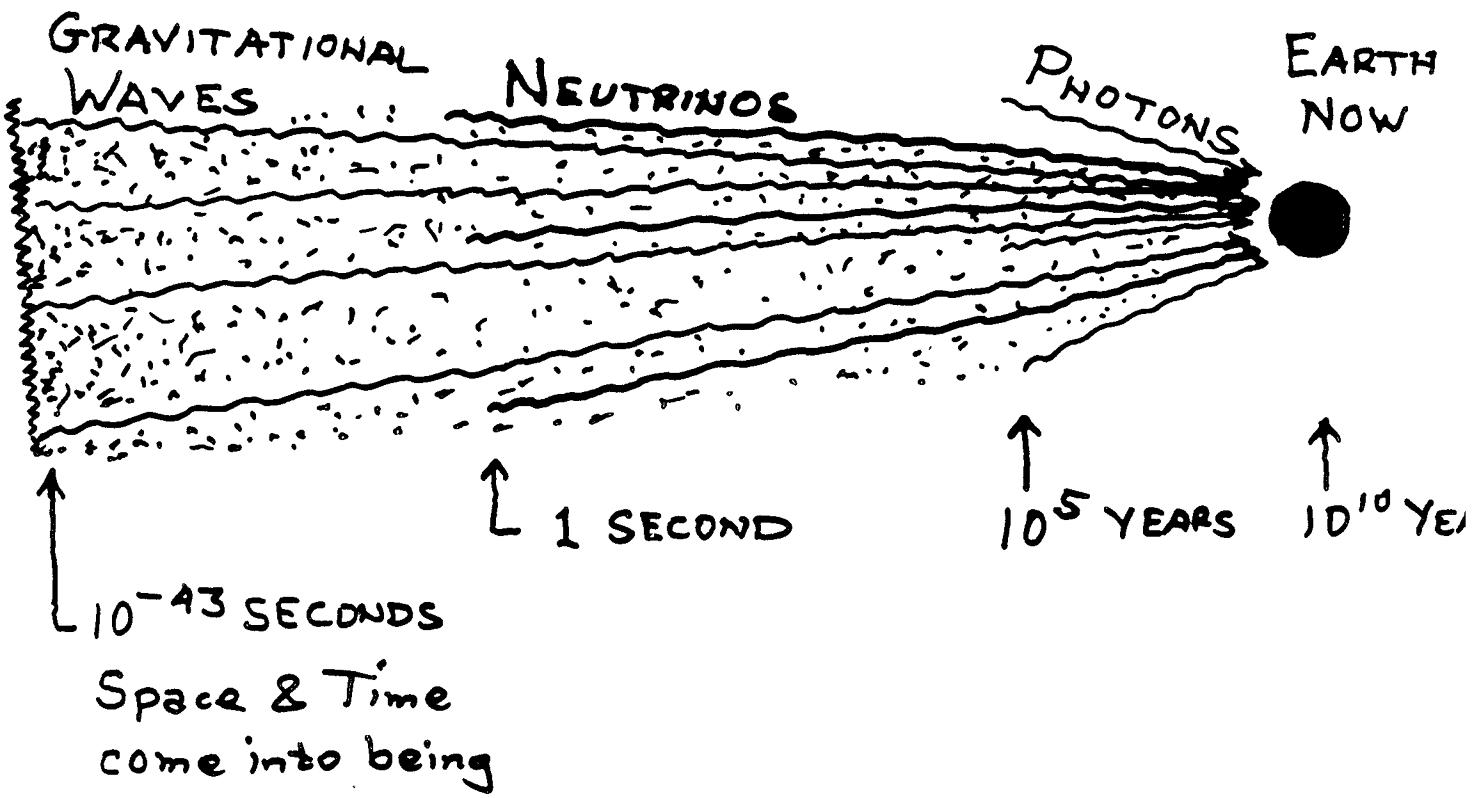
  (also could be overwhelmed by more recent sources)

- graviton background analogous to Ω_{em}

  THERMAL SPECTRUM $T \sim 0.9$ K

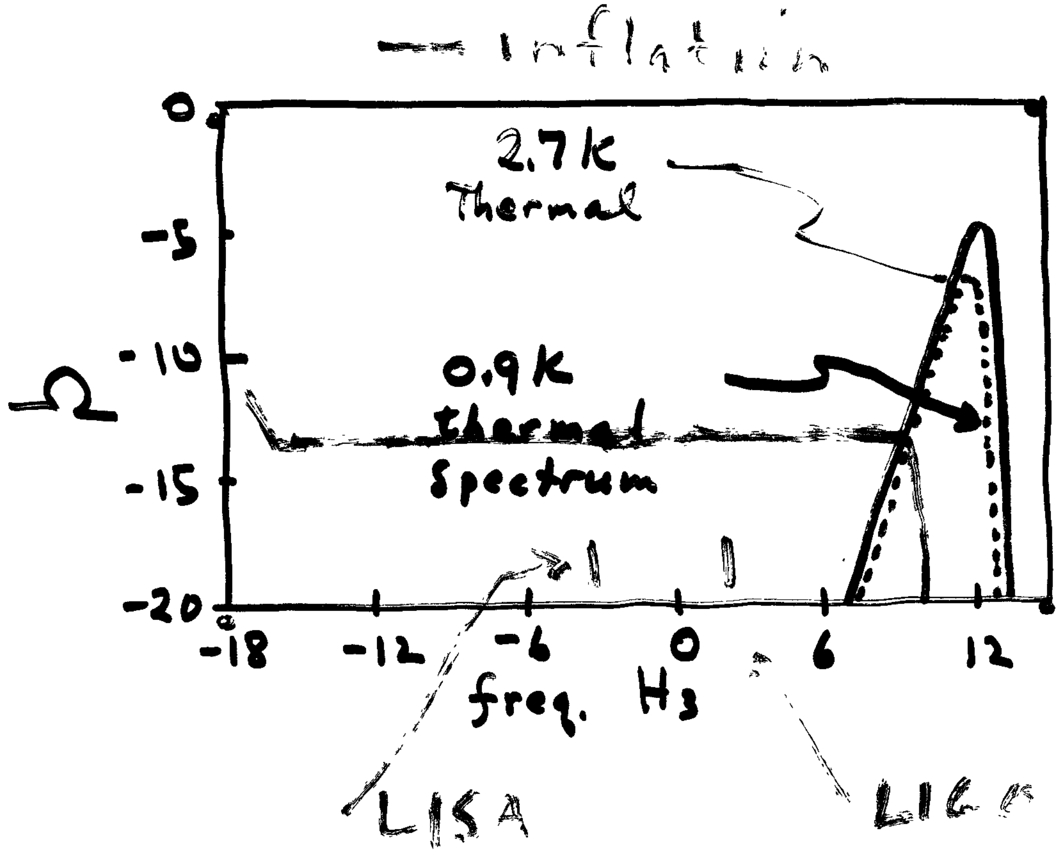
  (smaller than Cosmic Microwave Background Radiation because in conventional hot big bang model, gravitons decoupled when temperature of Universe dropped below Planck temp)

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

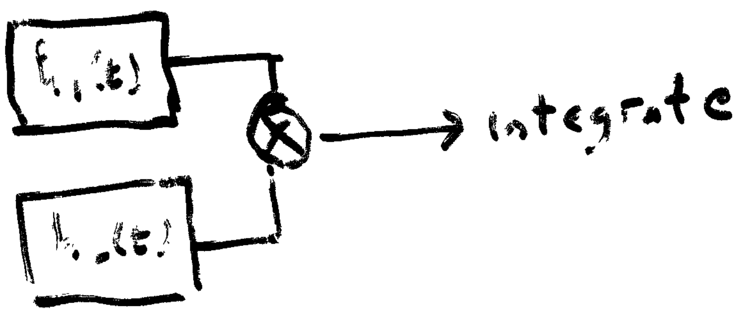


- unlikely equilibrium was established
  since gravitational interactions so weak
  (time required longer than expansion time

- useful benchmark

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

How to detect Stochastic Background



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

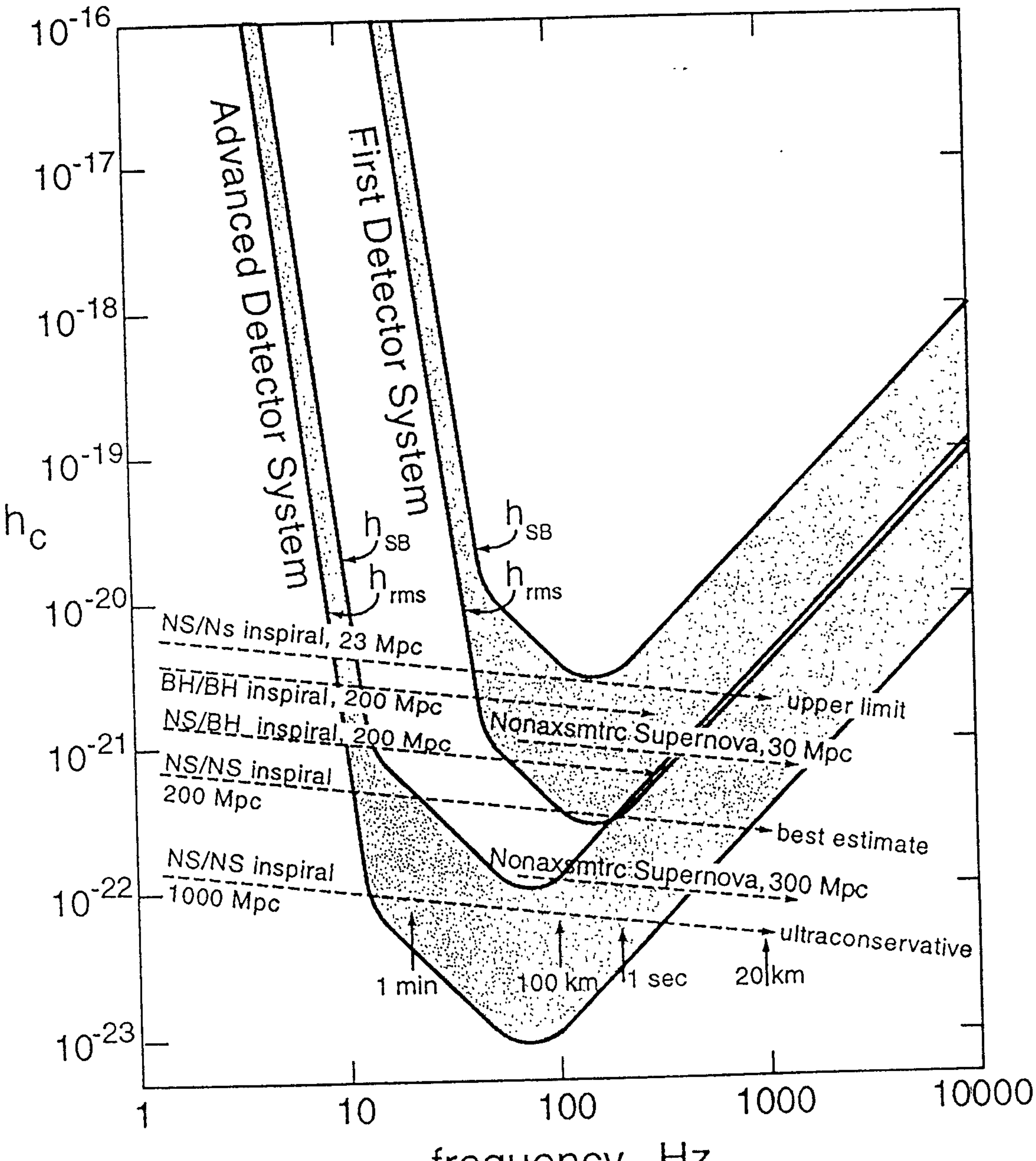
In absence of background (and other signals)
average product $h_1(t) h_2(t) \to 0$

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

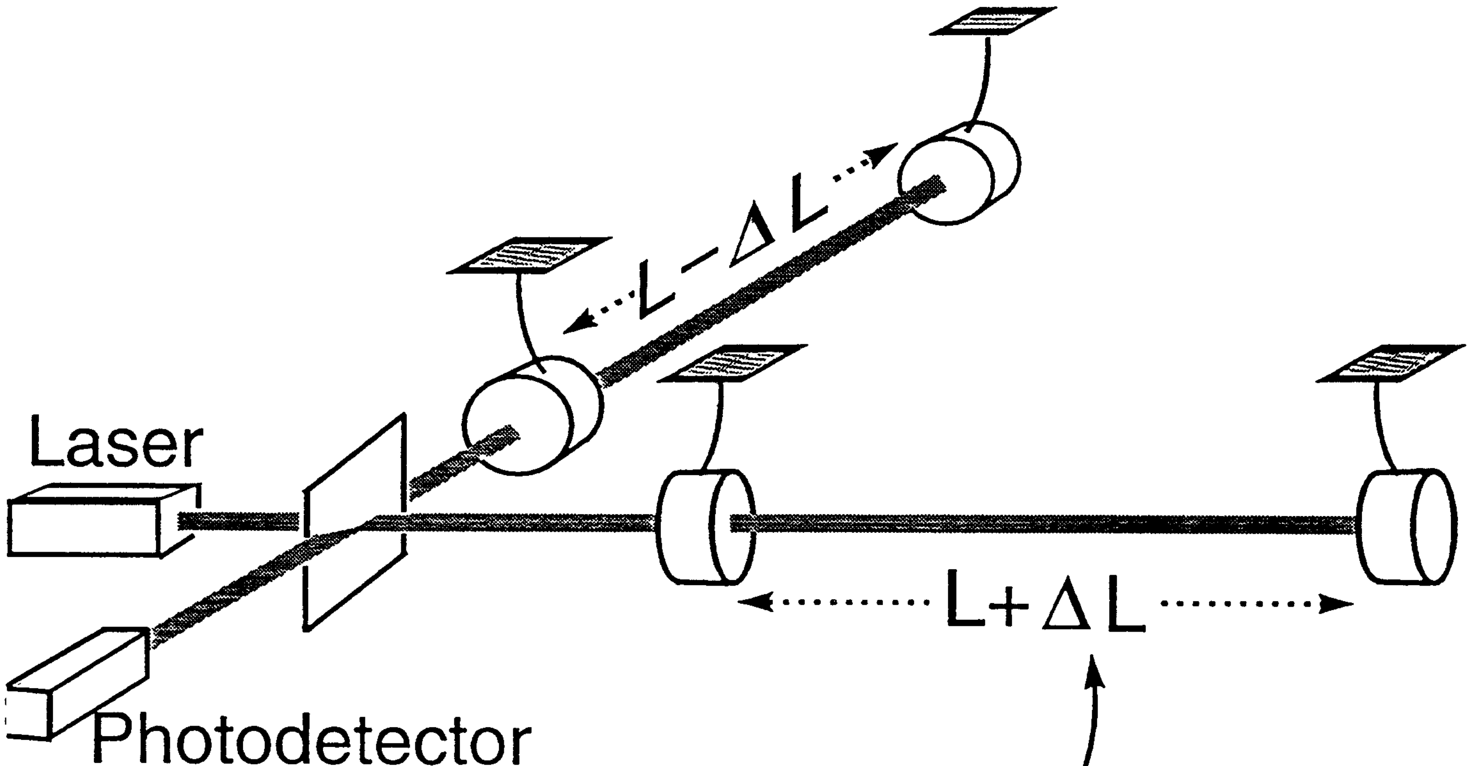
LIGO

Sensitivity

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



LIGO INTERFEROMETERS



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

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

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

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

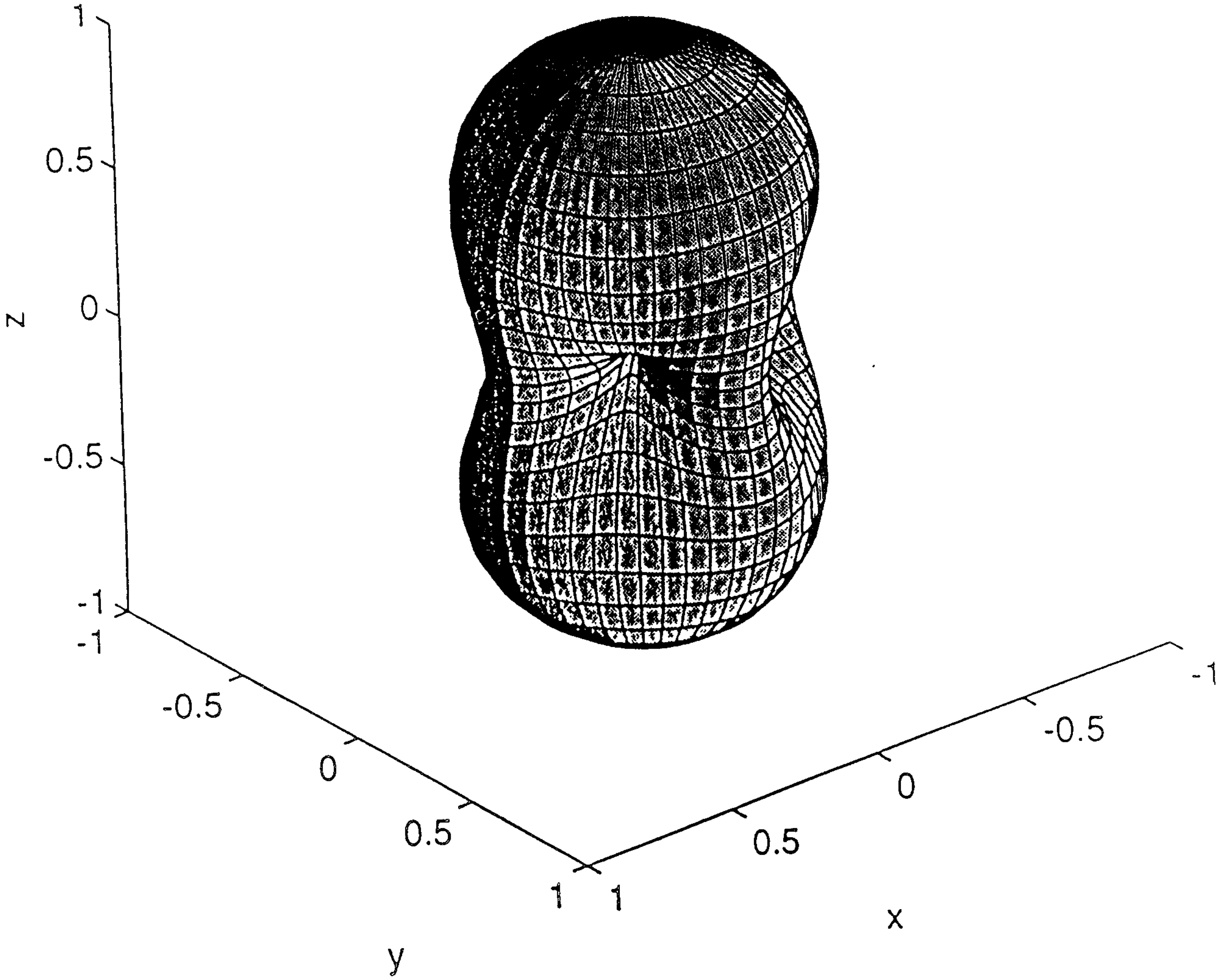
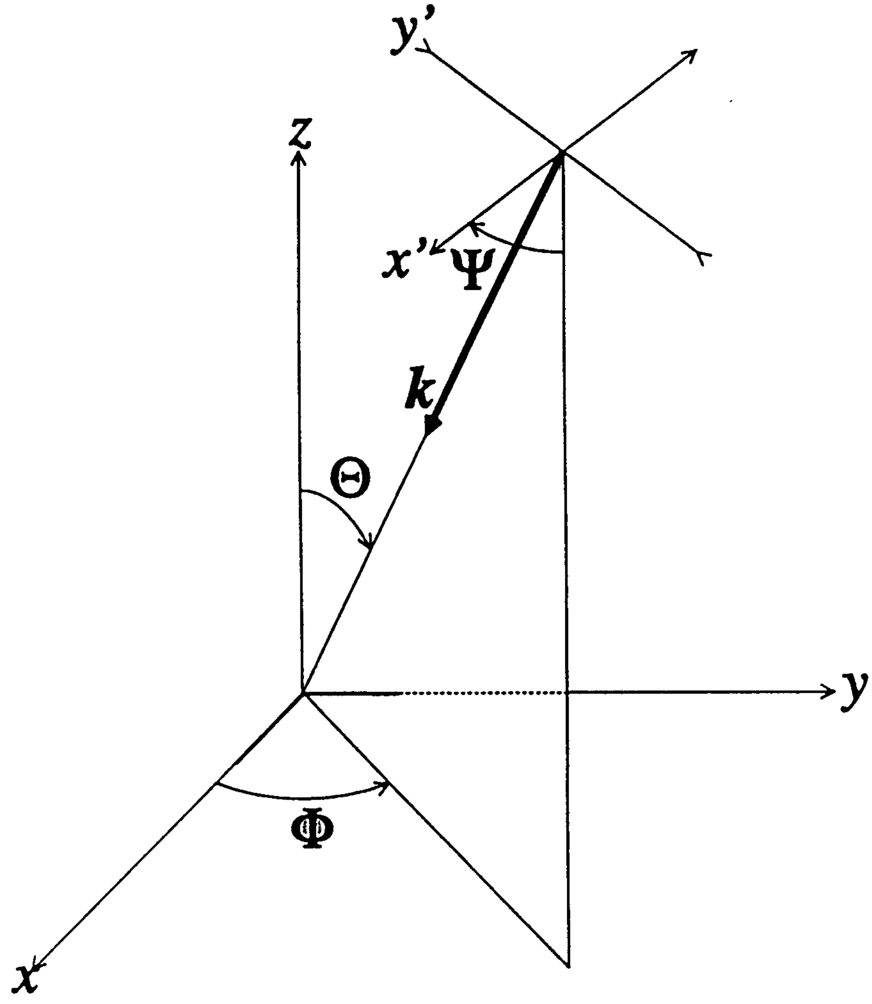
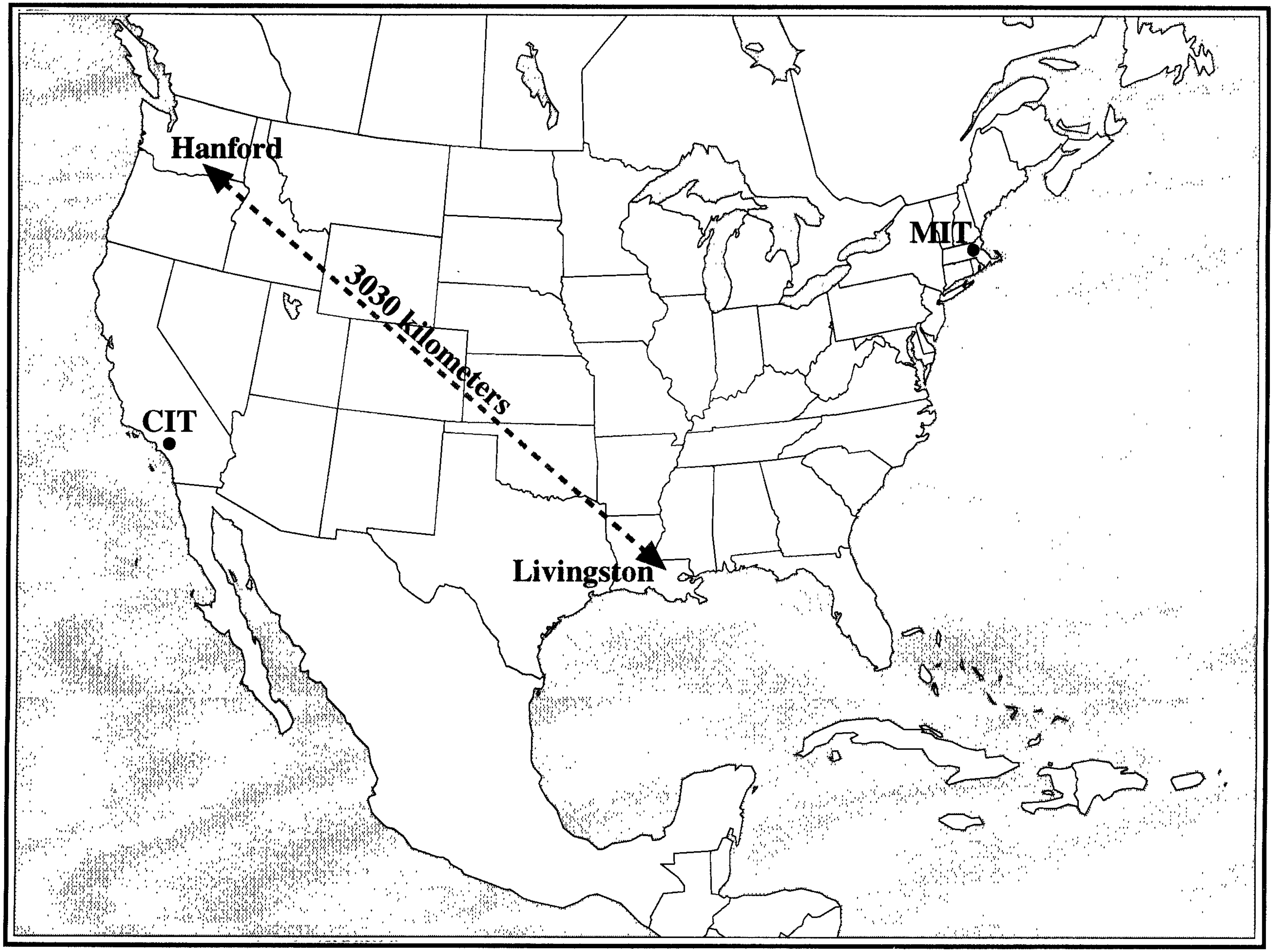


Figure 2.7 The sensitivity, as a function of direction, of an interferometric gravitational wave detector to unpolarized gravitational waves. The interferometer arms are oriented along the x and y axes.

Gravitational Wave Detector

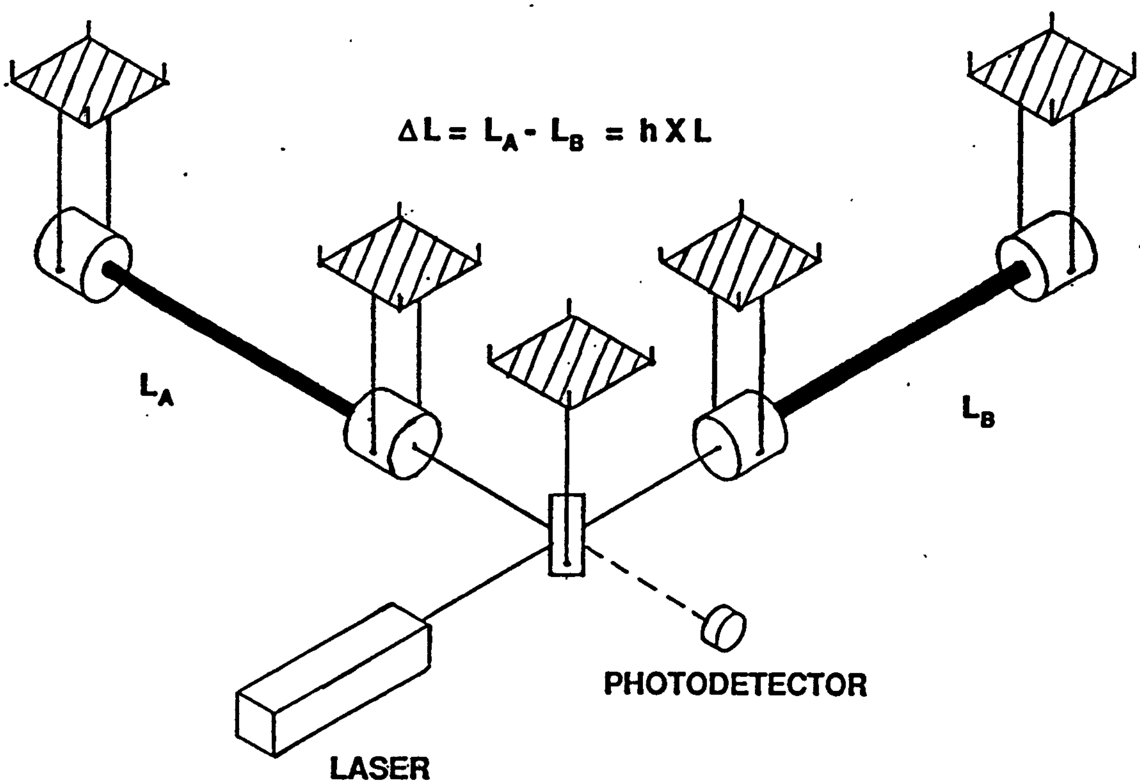
- Antenna Pattern
  - » coordinate system




Hanford
MIT
3030 kilometers
CIT
Livingston

Interferometers

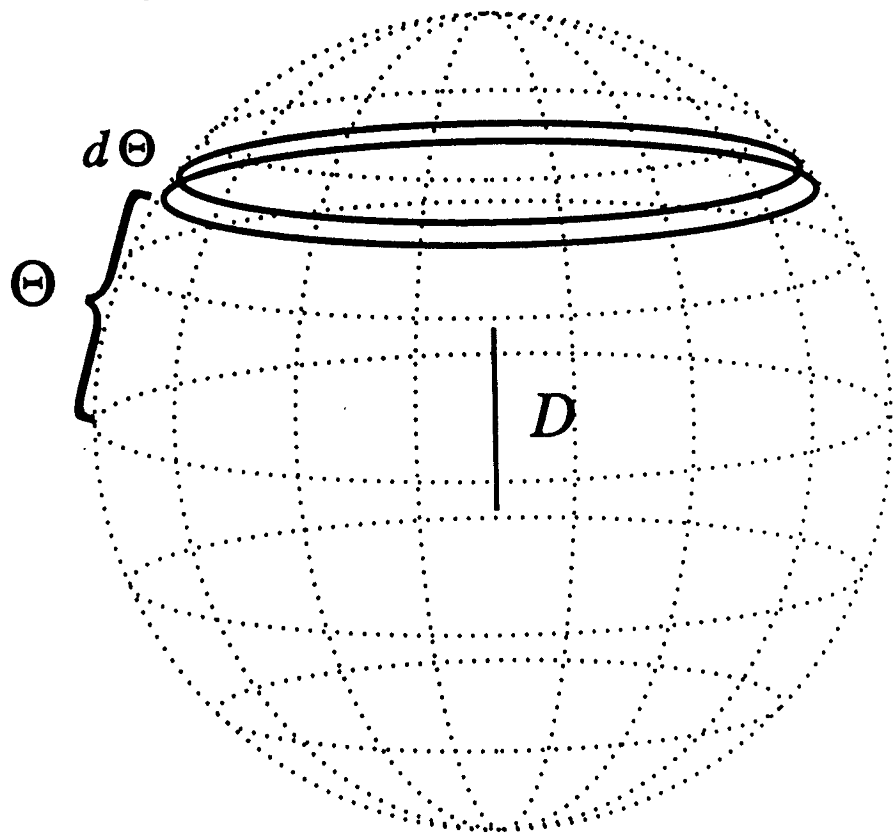
- $\Delta L/L = h = F_+ h_+(t) + F_x h_x(t)$



- 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

Source Positions

- Celestial Sphere position location from LIGO (two interferometers)



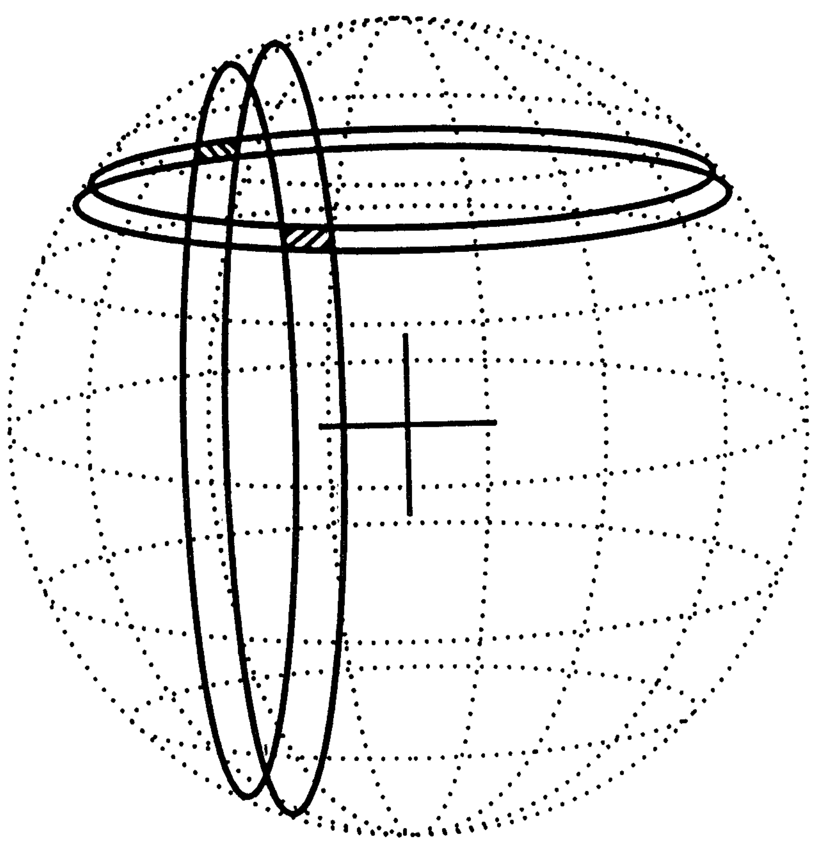
- determine from time shift between detectors (~.1 msec accuracy)
- 'declination angle' of circle (ring)

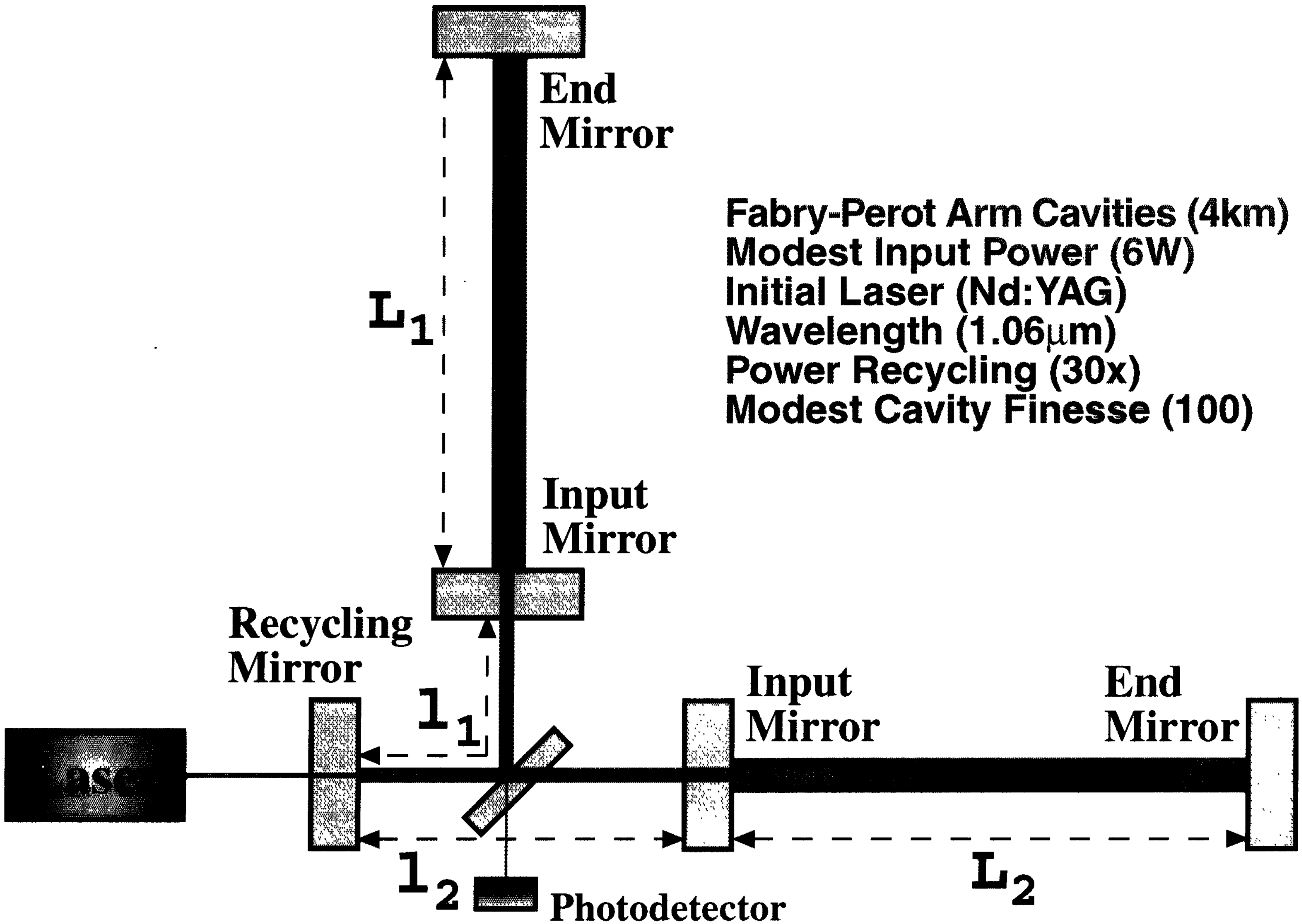
$$\Theta = \arcsin \frac{c\Delta t_{sig}}{D}$$

Source Positions

LIGO + VIRGO

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





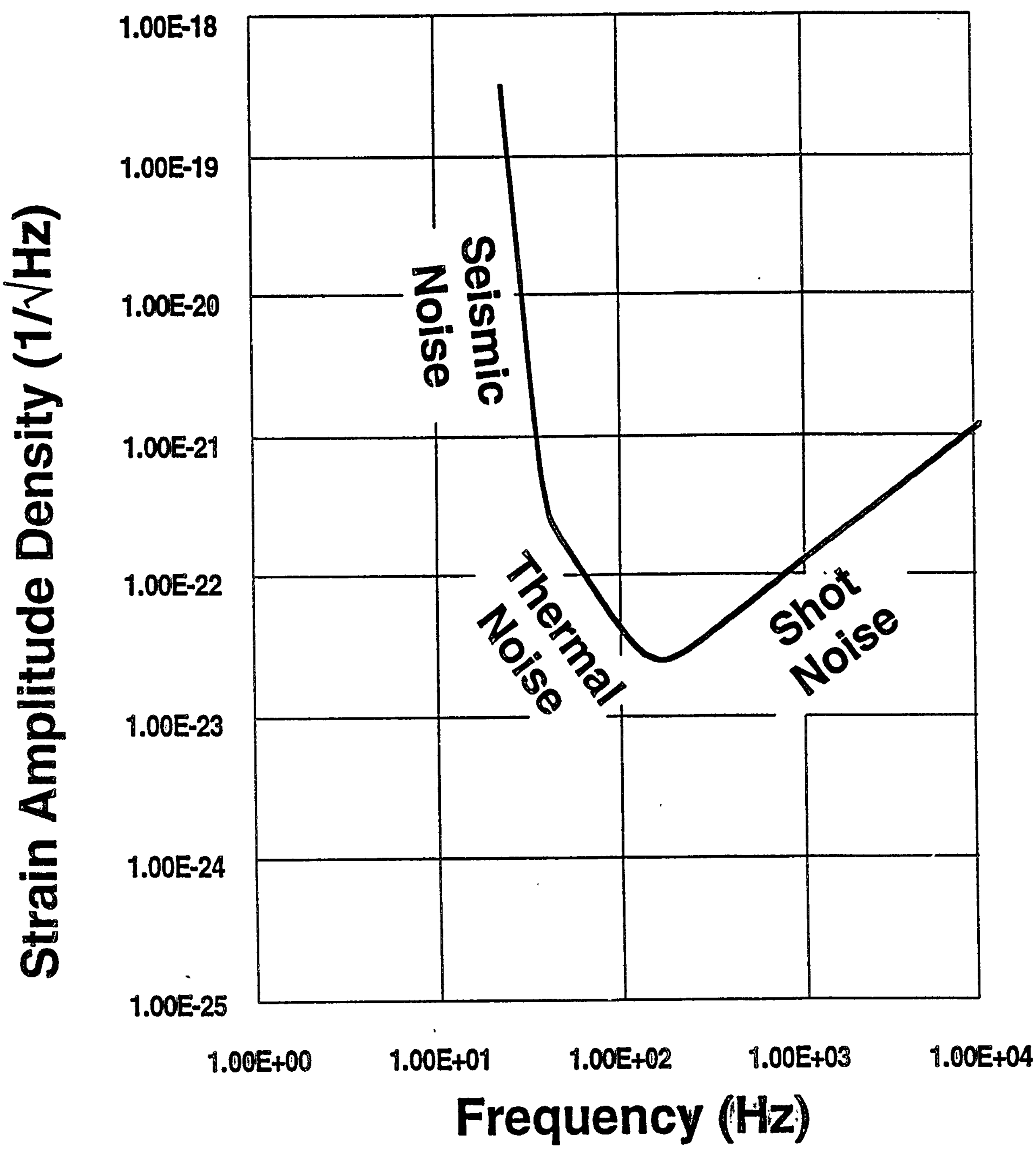
End Mirror
Fabry-Perot Arm Cavities (4km)
Modest Input Power (6W)
Initial Laser (Nd:YAG)
Wavelength (1.06μm)
Power Recycling (30x)
Modest Cavity Finesse (100)
L_1
Input Mirror
Recycling Mirror
l_1
Input Mirror
End Mirror
l_2
Photodetector
L_2

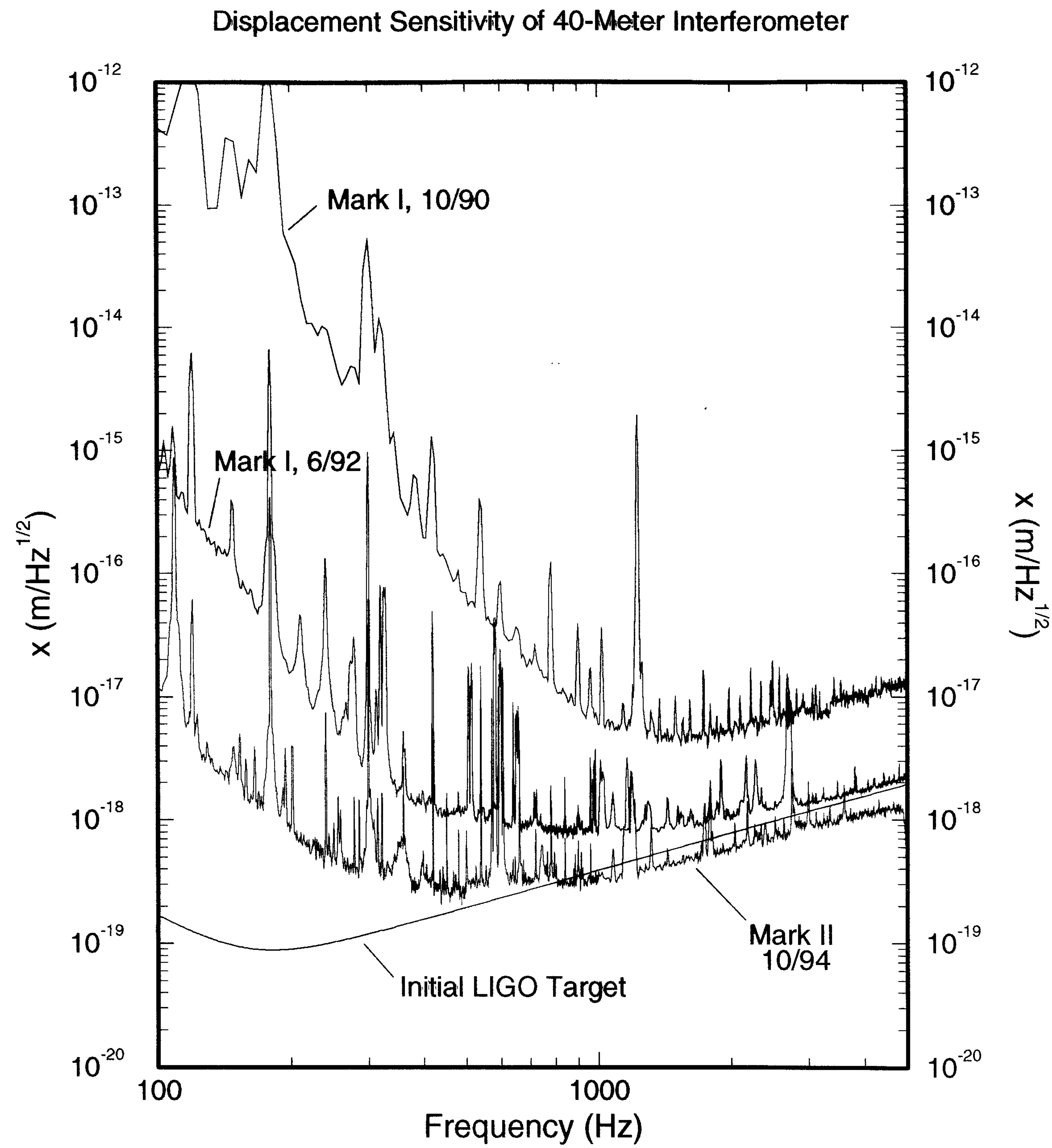
Initial Interferometer
Specifications

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	$\geq 10^{-7}$ (100 *Hz*)
Maximum Background Pulse Rate	1 *per minute*

Initial Interferometers

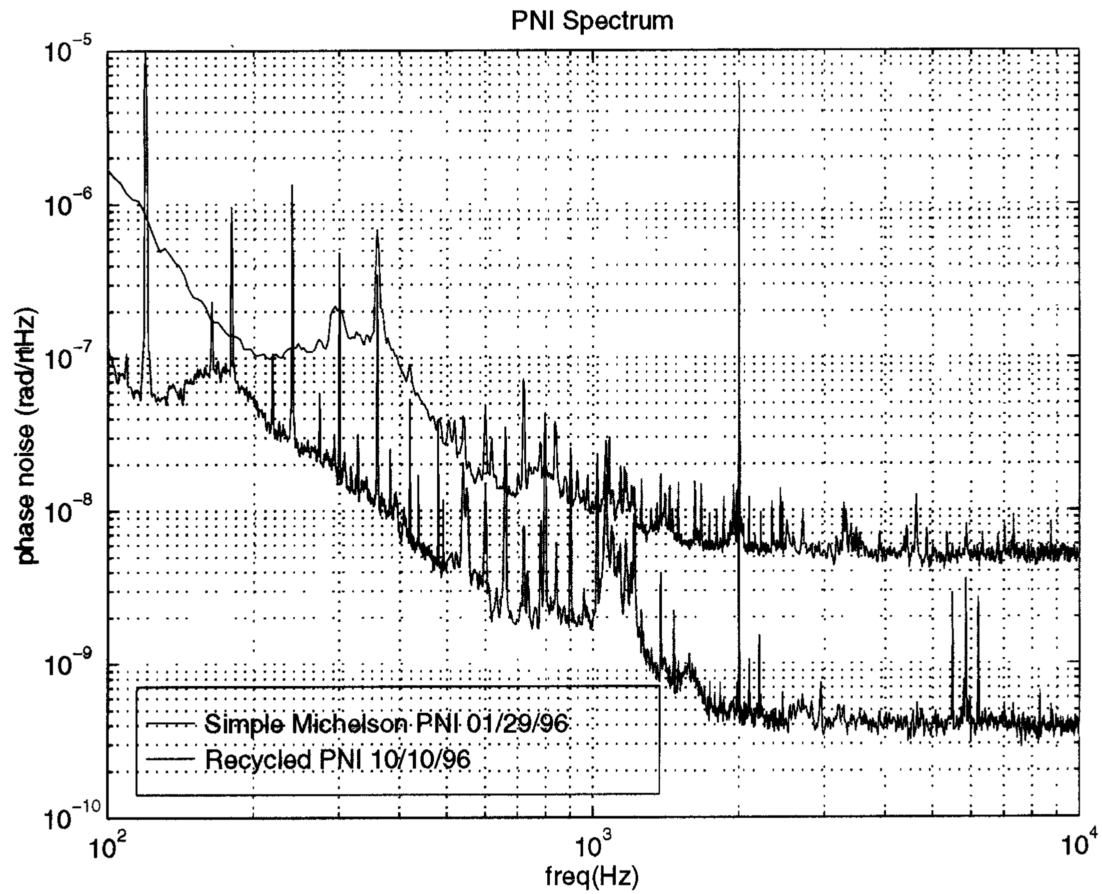
Noise Floor





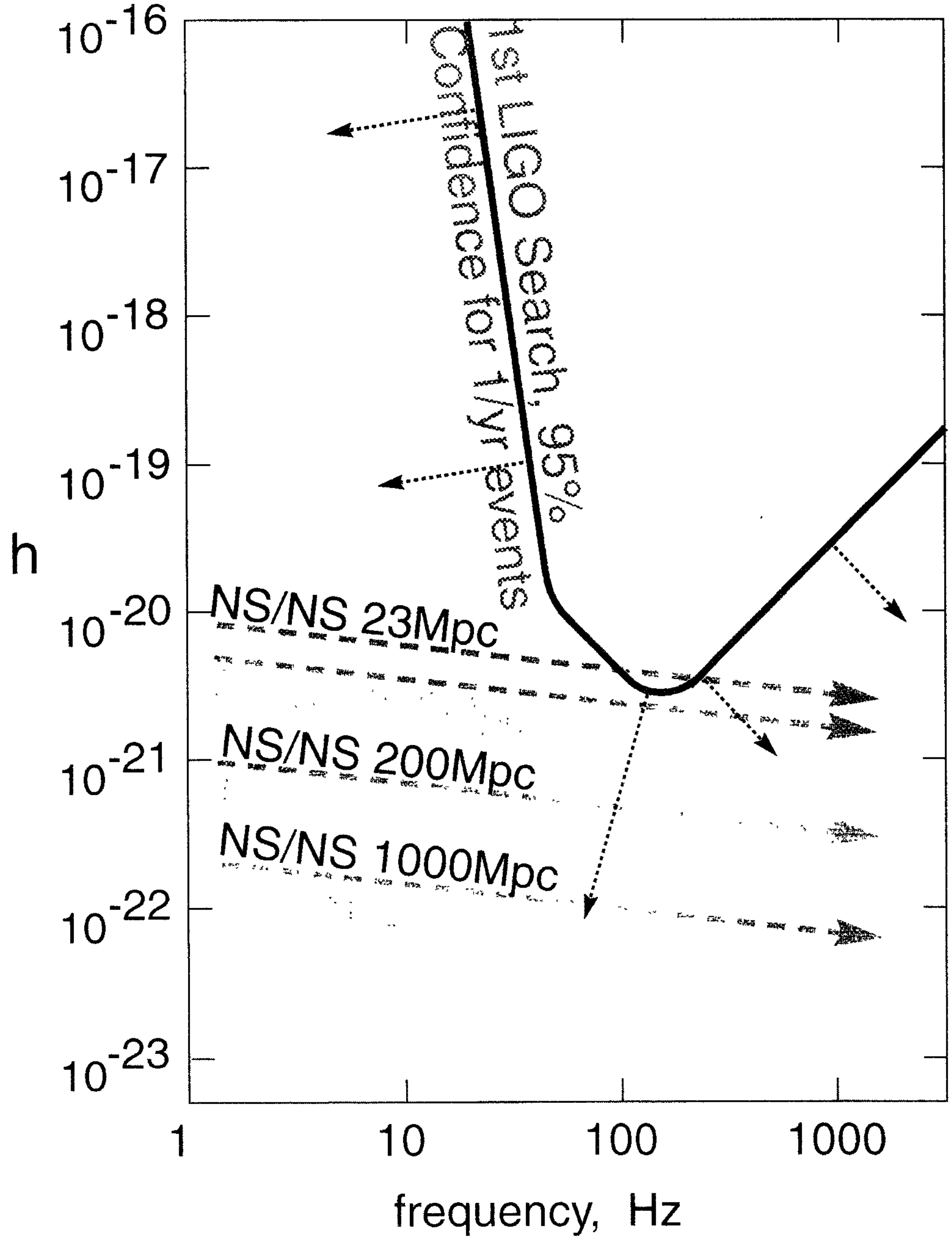
~fjr/fort/mk2/port_90_94.xvgr

Phase Noise Sensitivity From MIT Interferometer



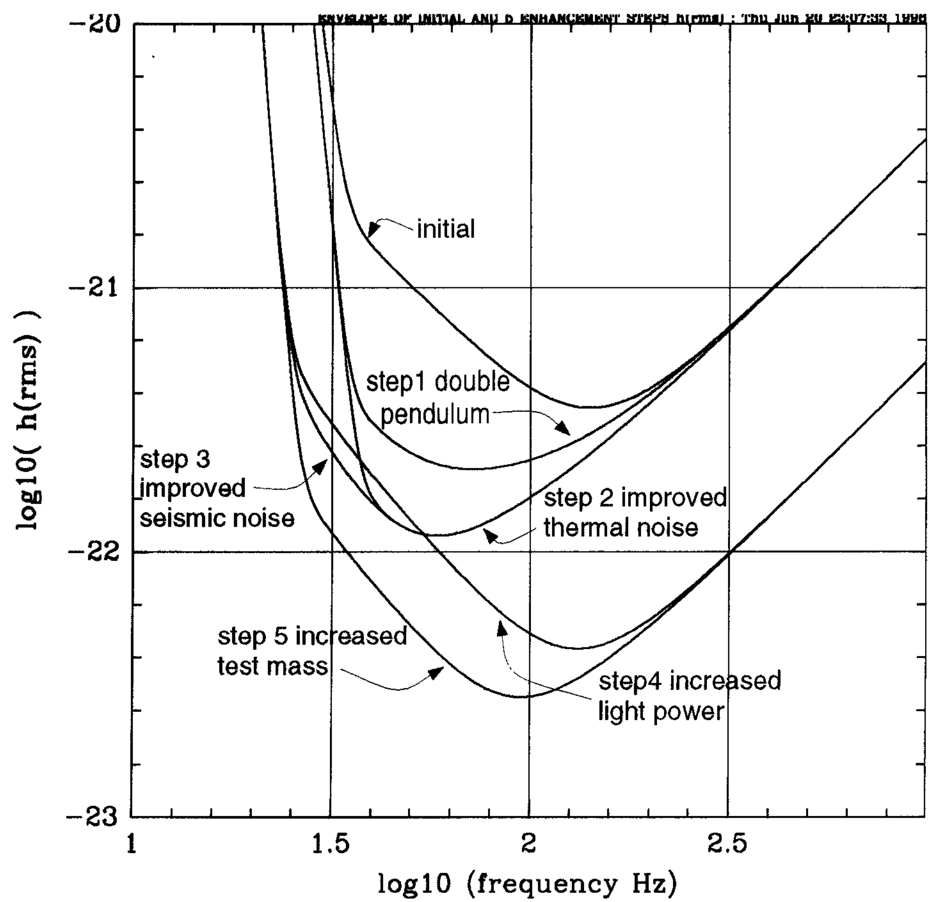
NEUTRON STAR BINARIES

["Near-Guaranteed" source]

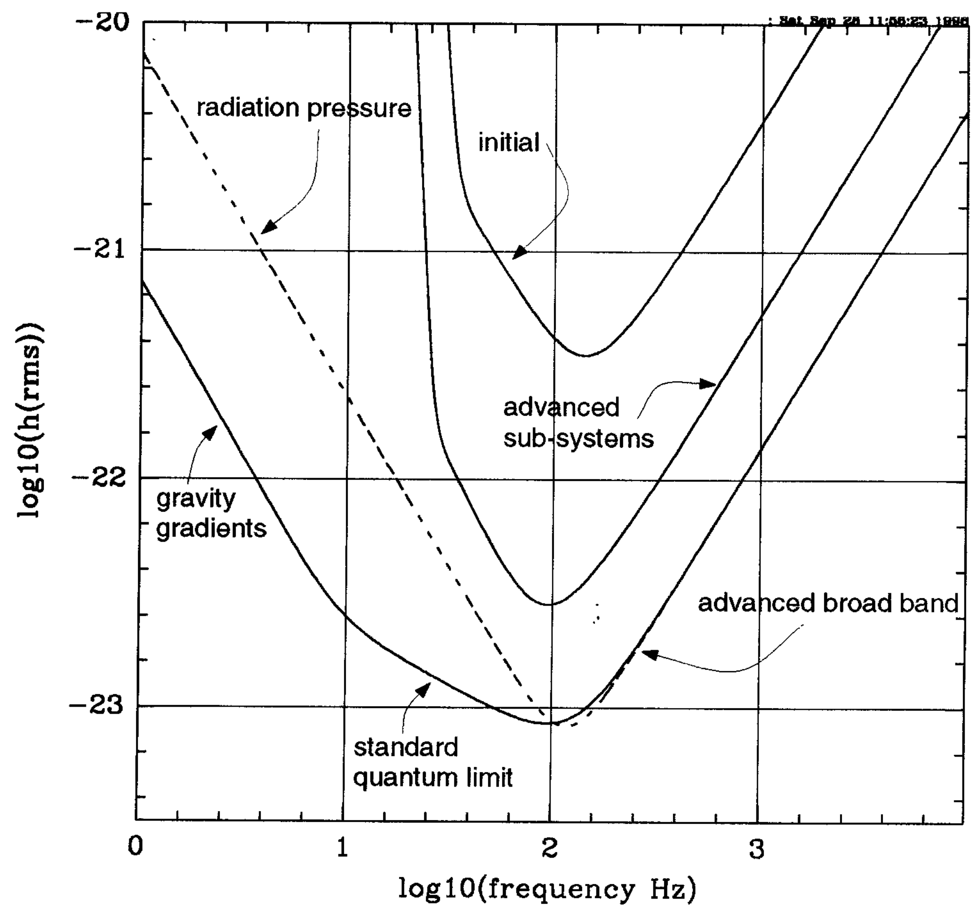


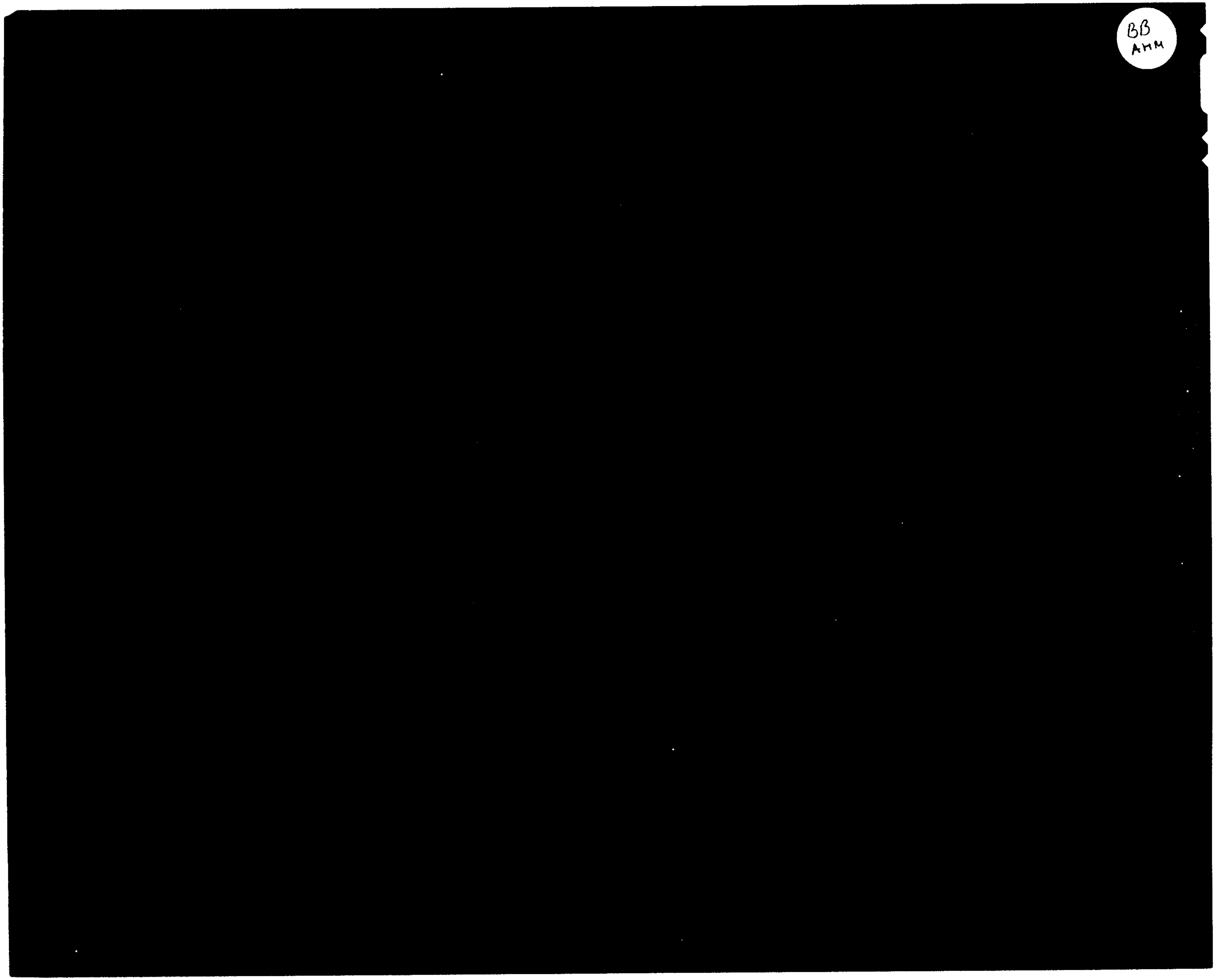
- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

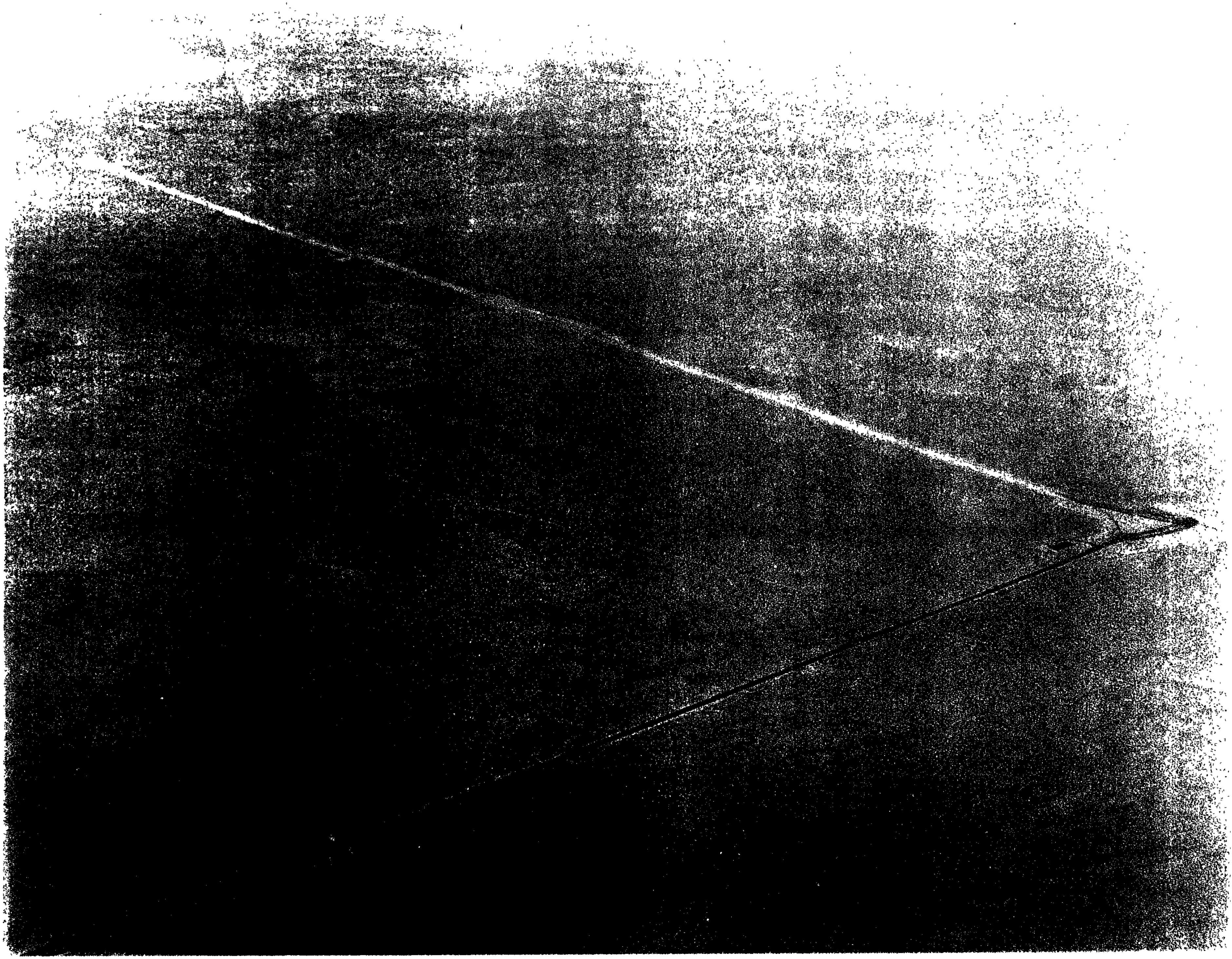
Steps in the Advanced Subsystems Research



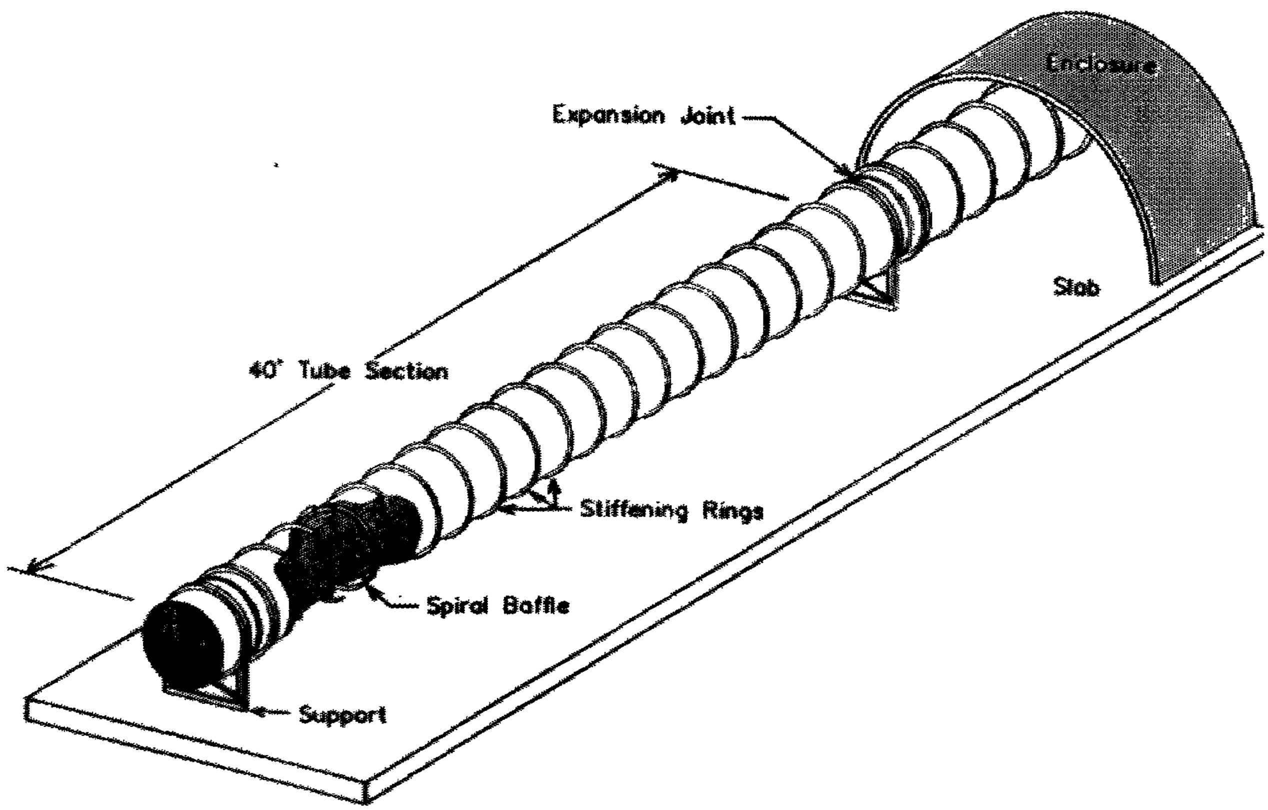
h_{rms} Noise Envelopes for Initial LIGO and Advanced Subsystems/Detectors



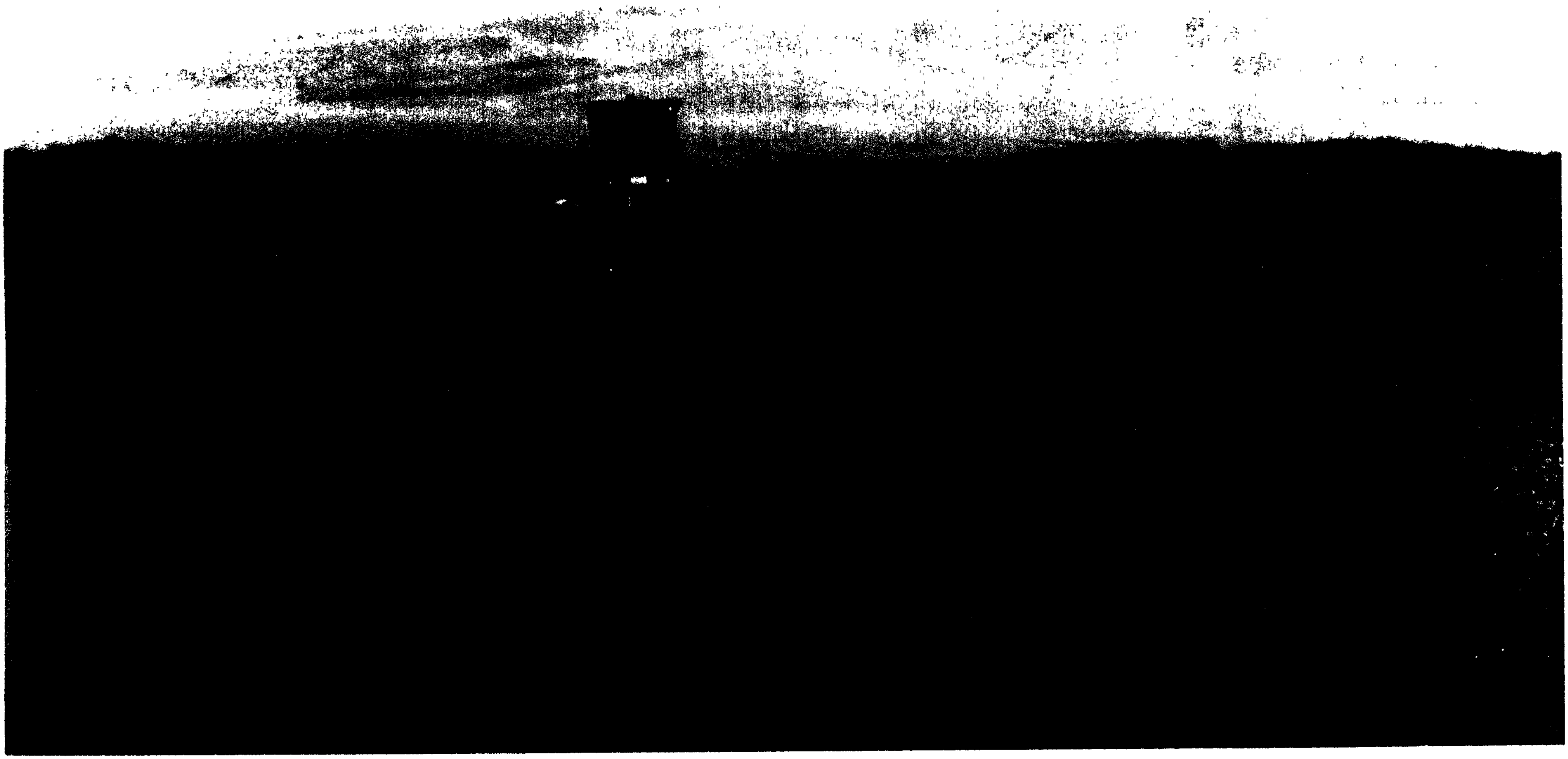

BB
AHM

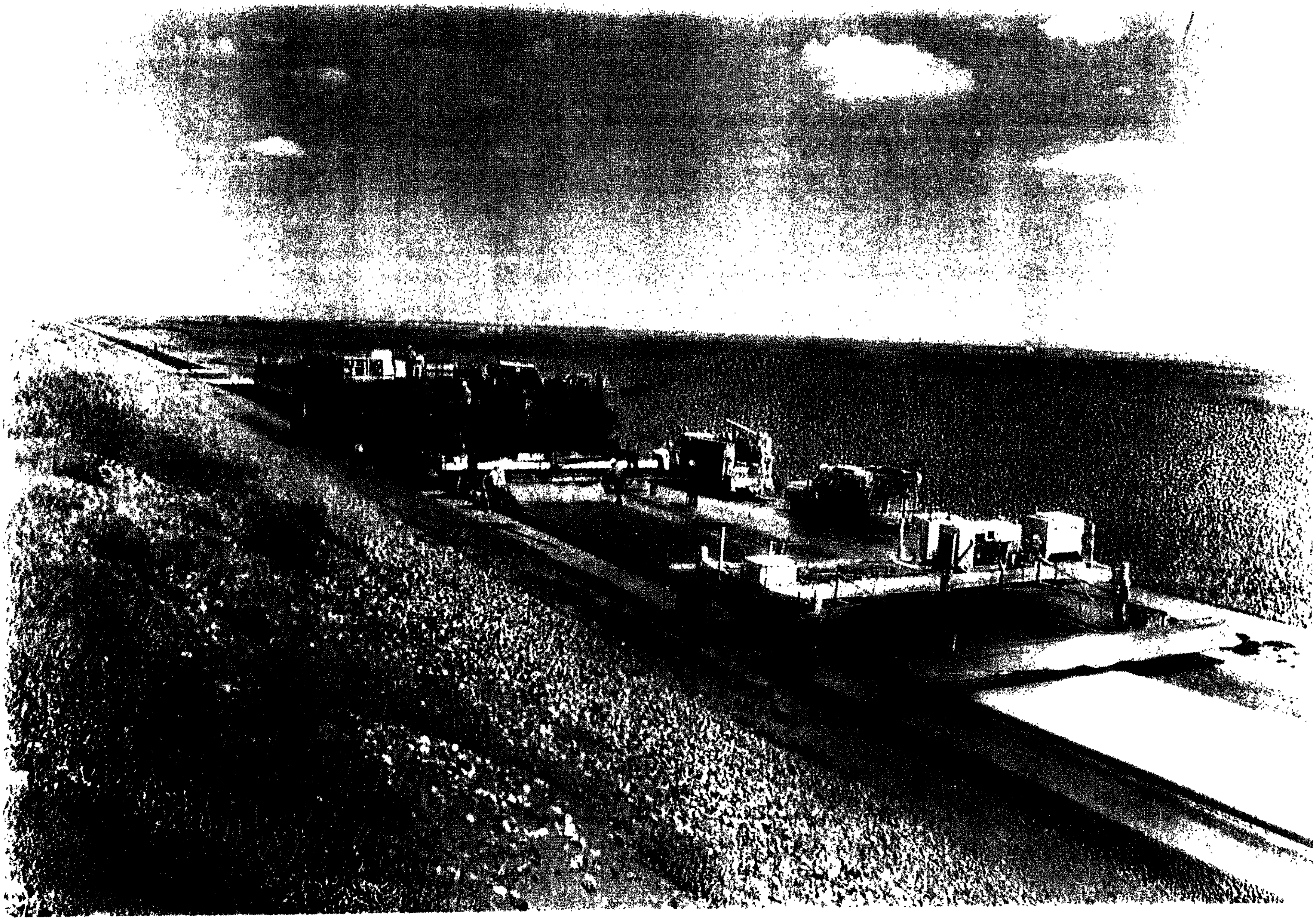


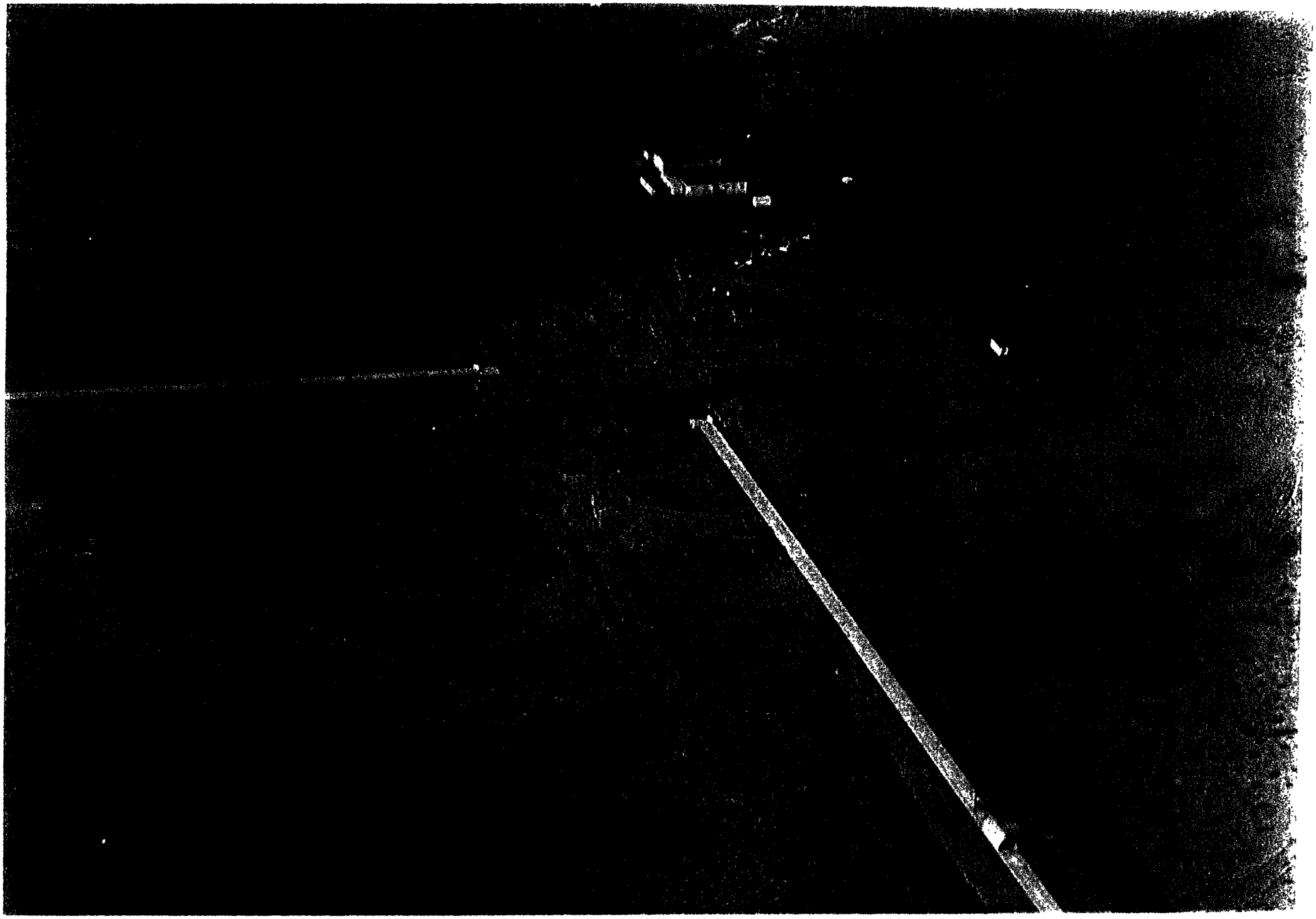
Beam Tube



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







LIGO Facilities
Beam Tube Enclosure

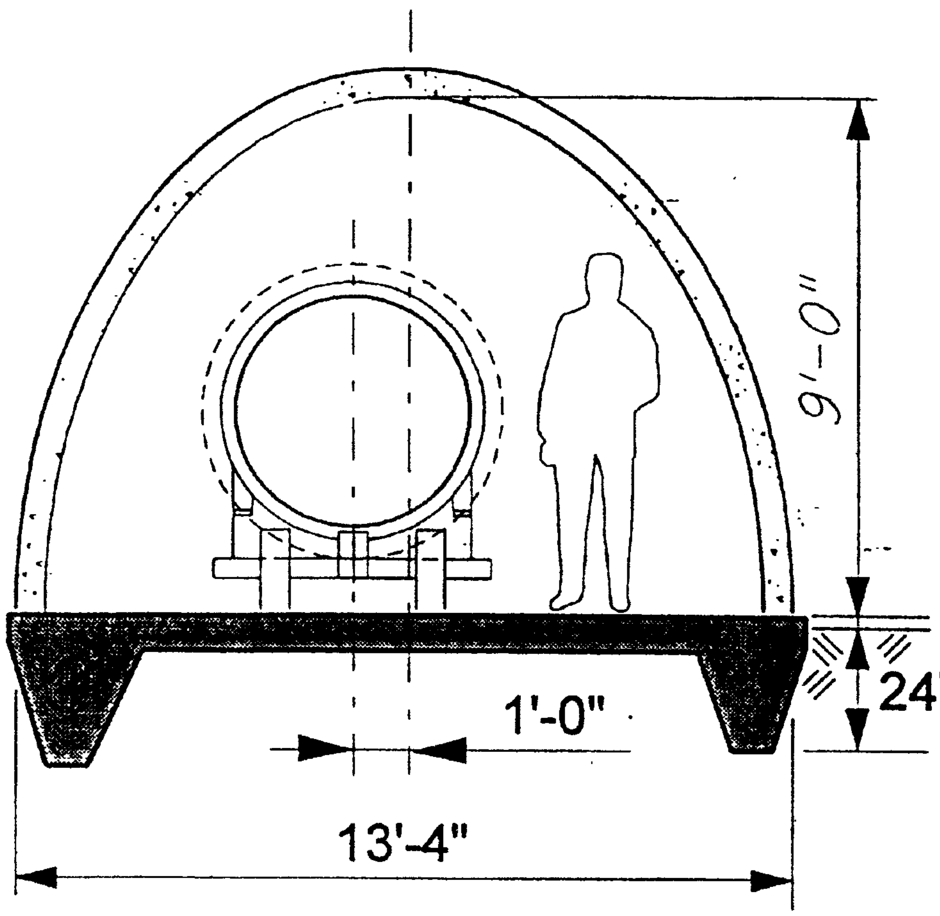
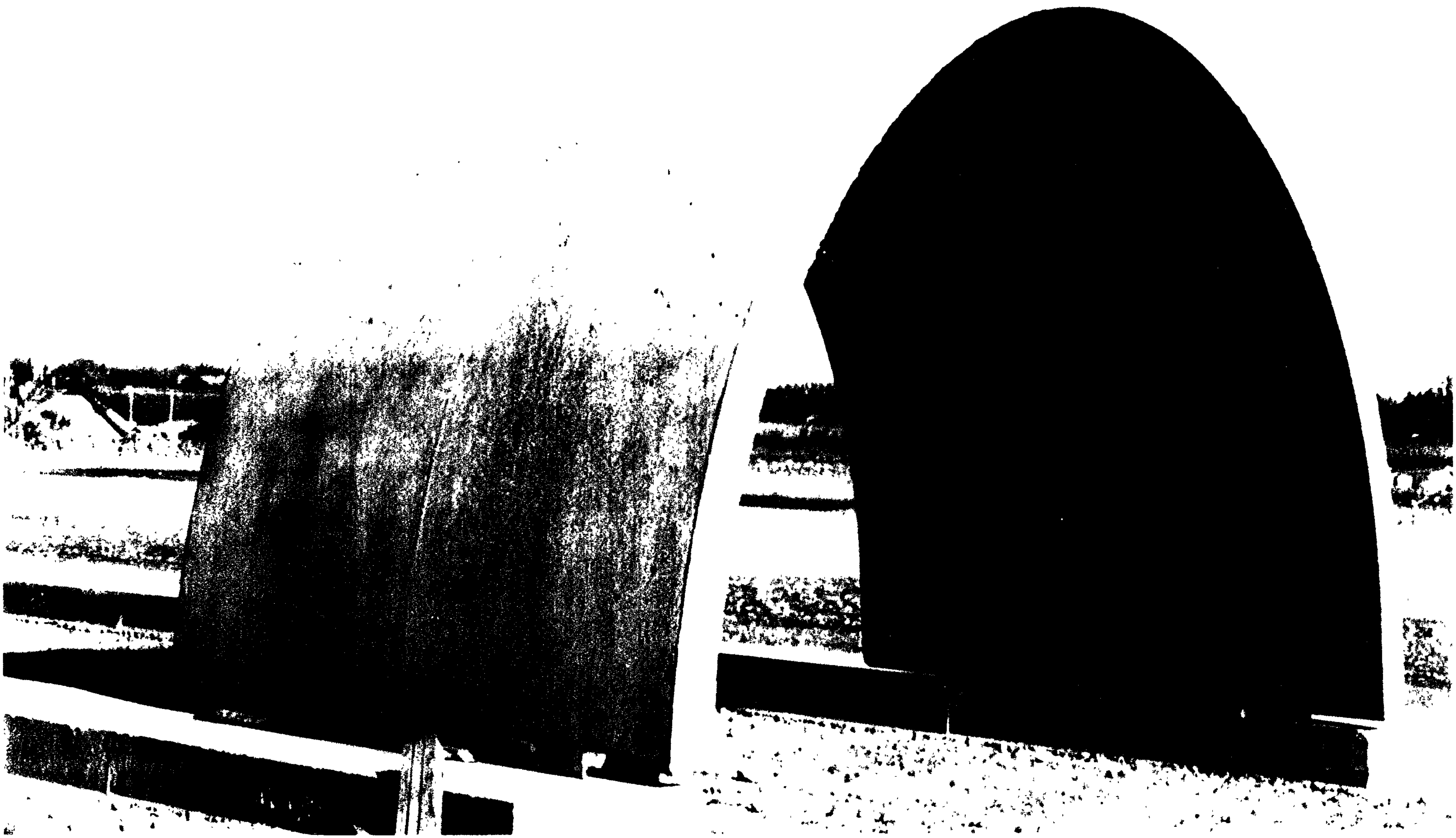
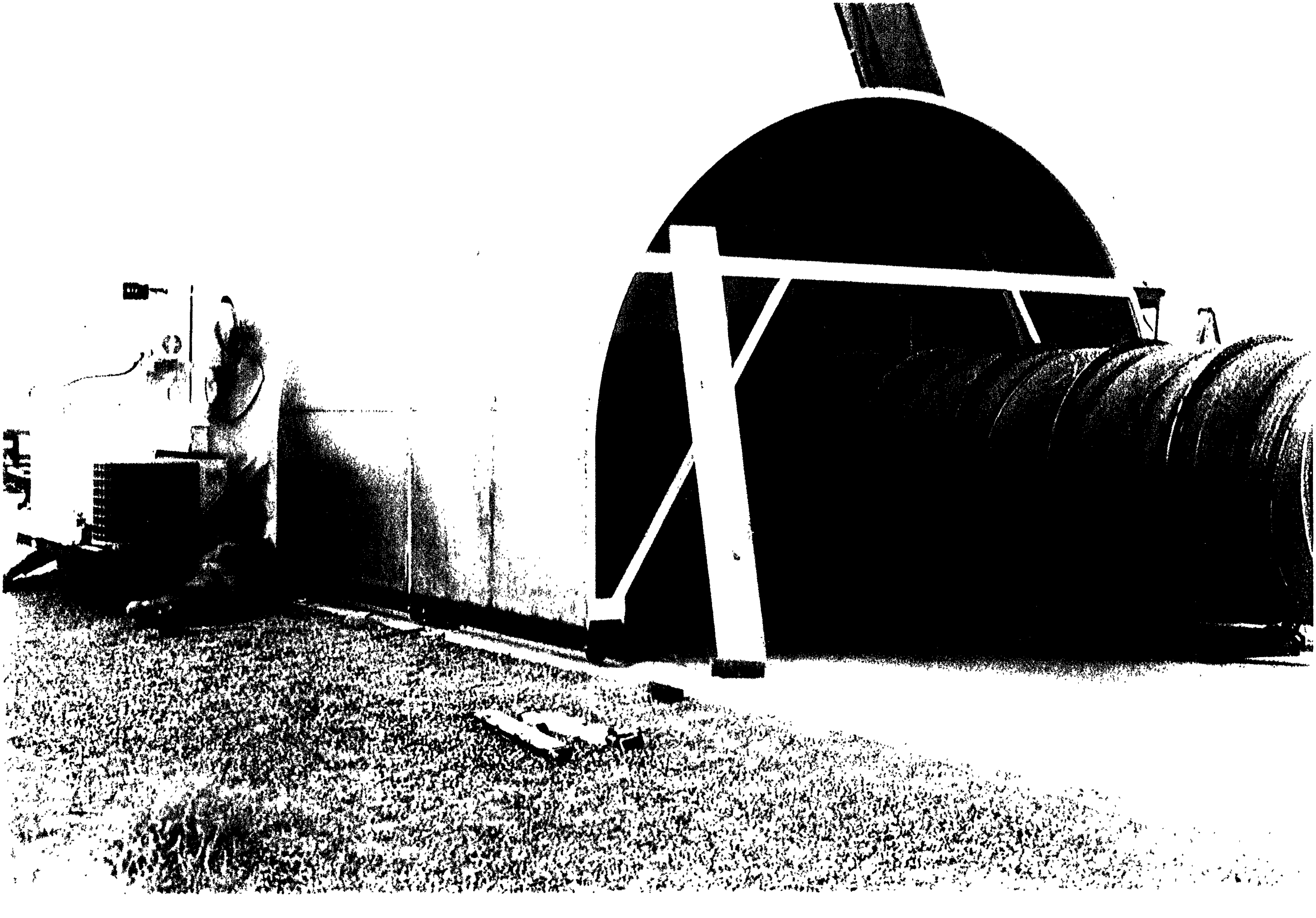
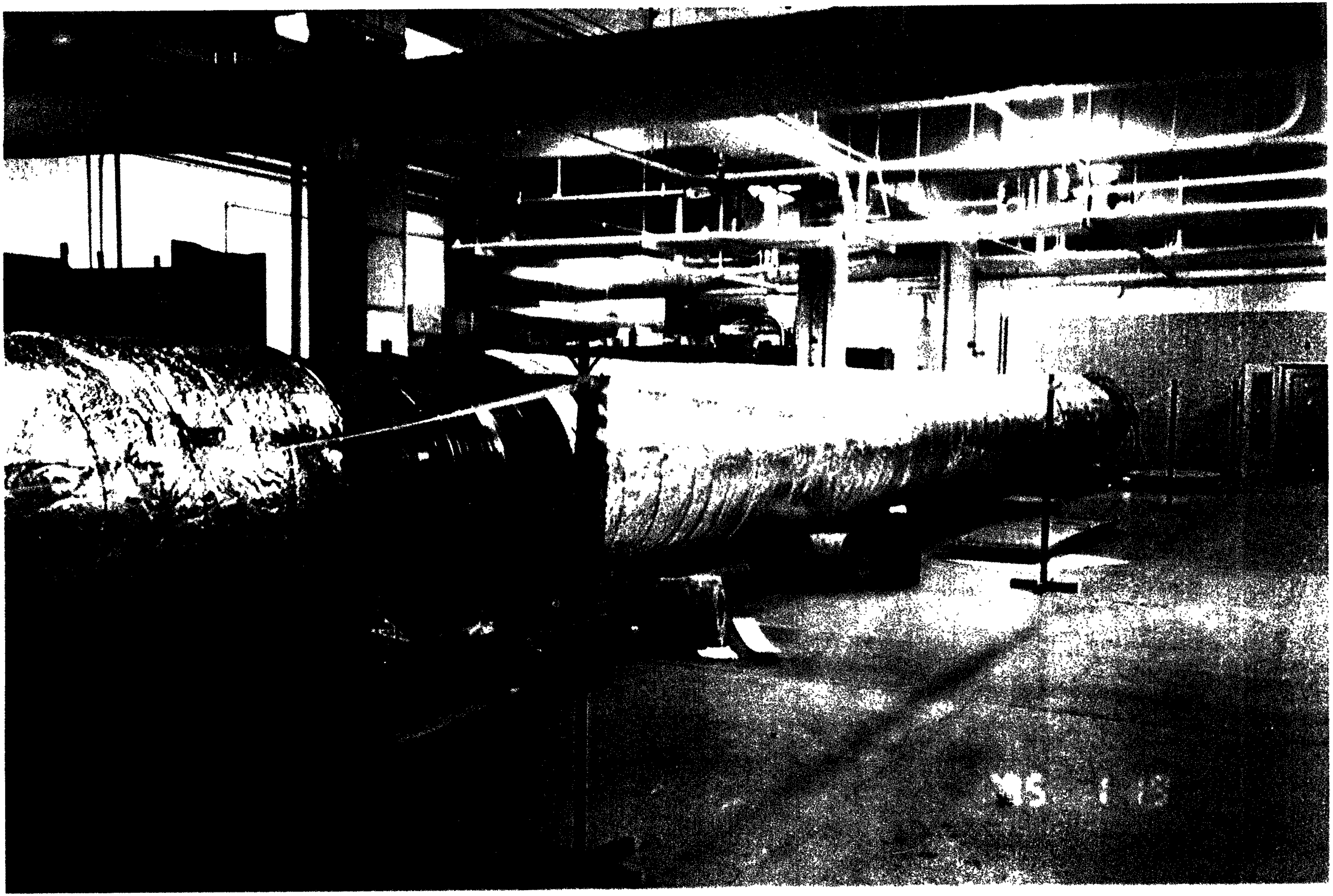
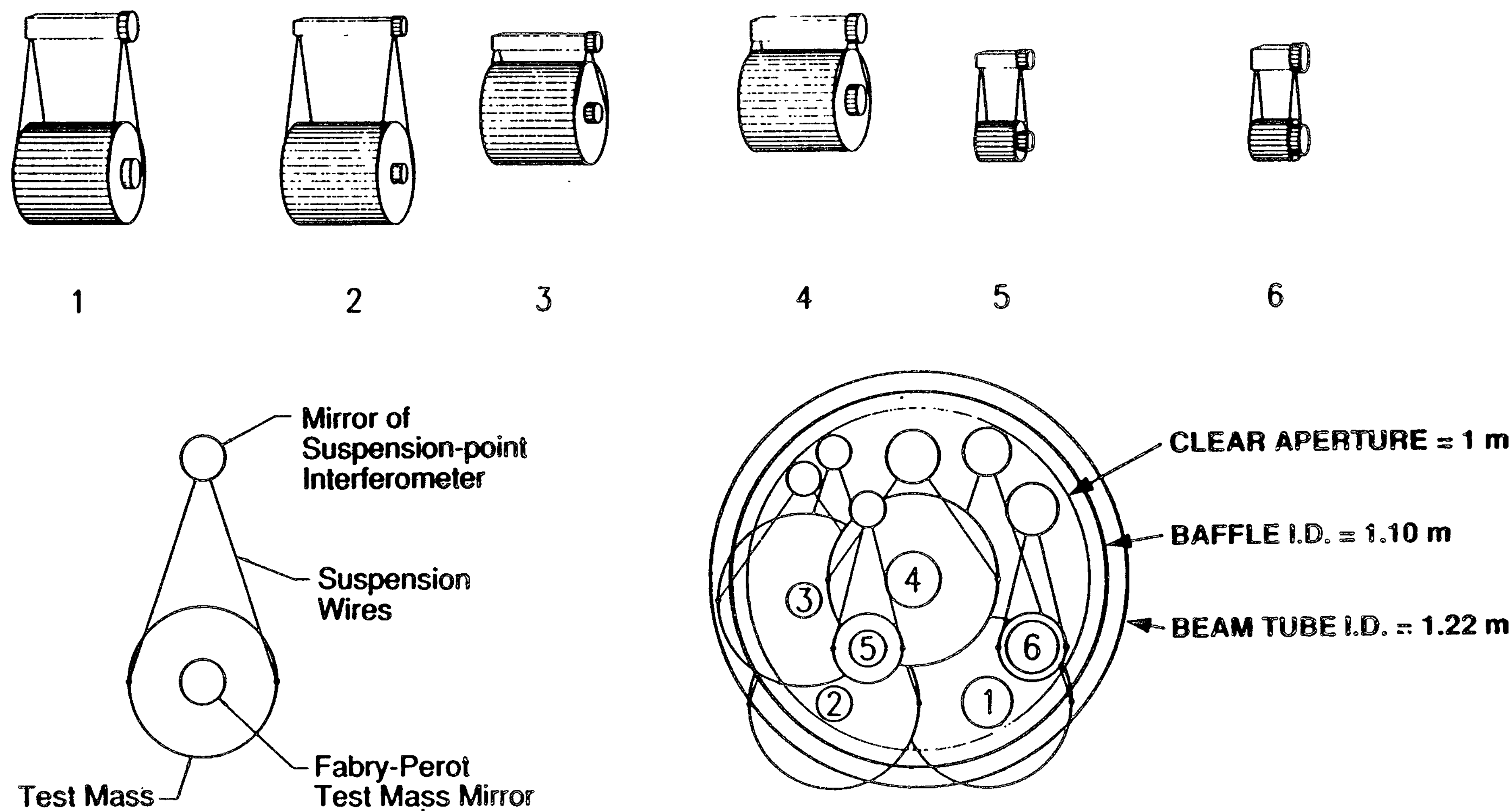


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

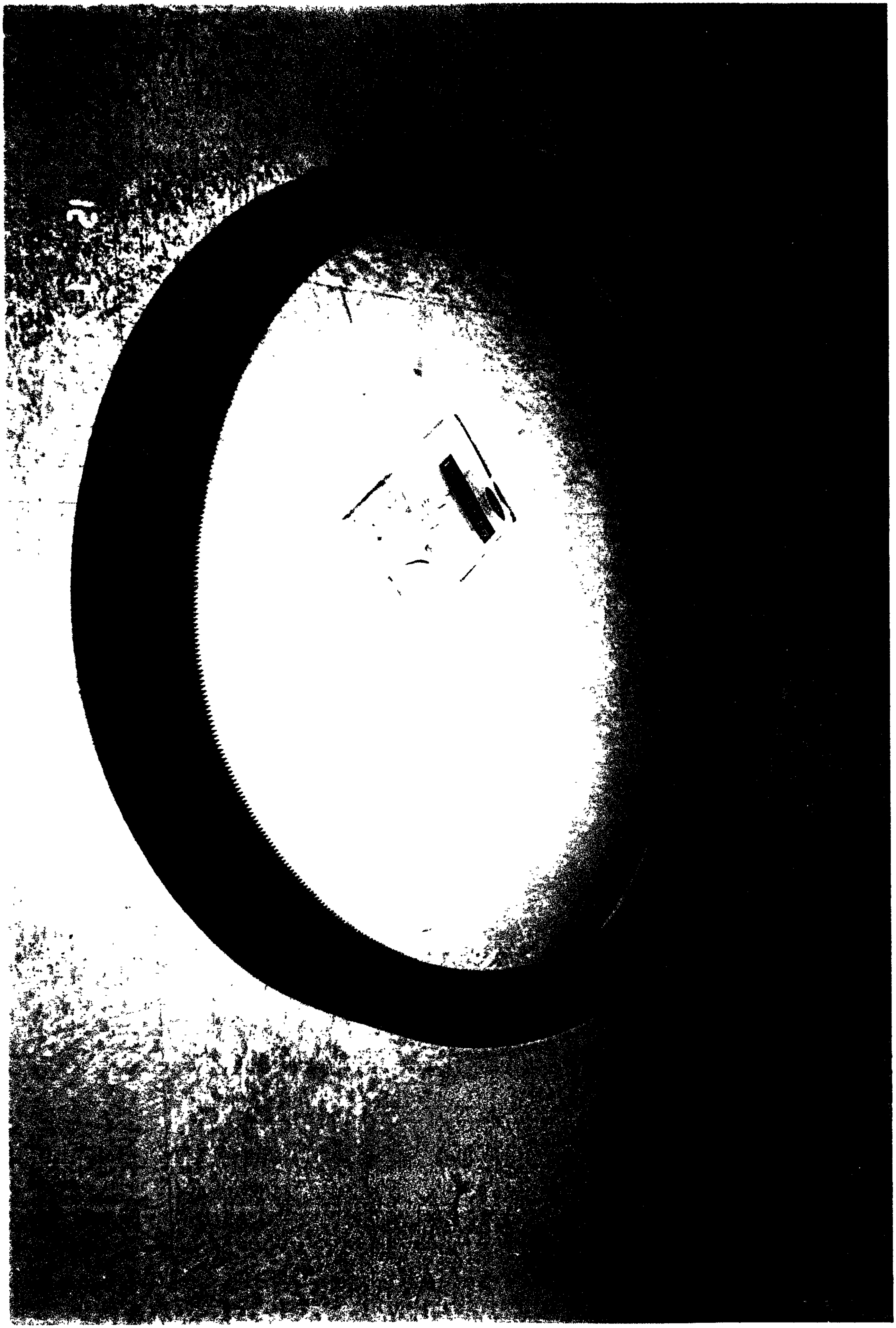


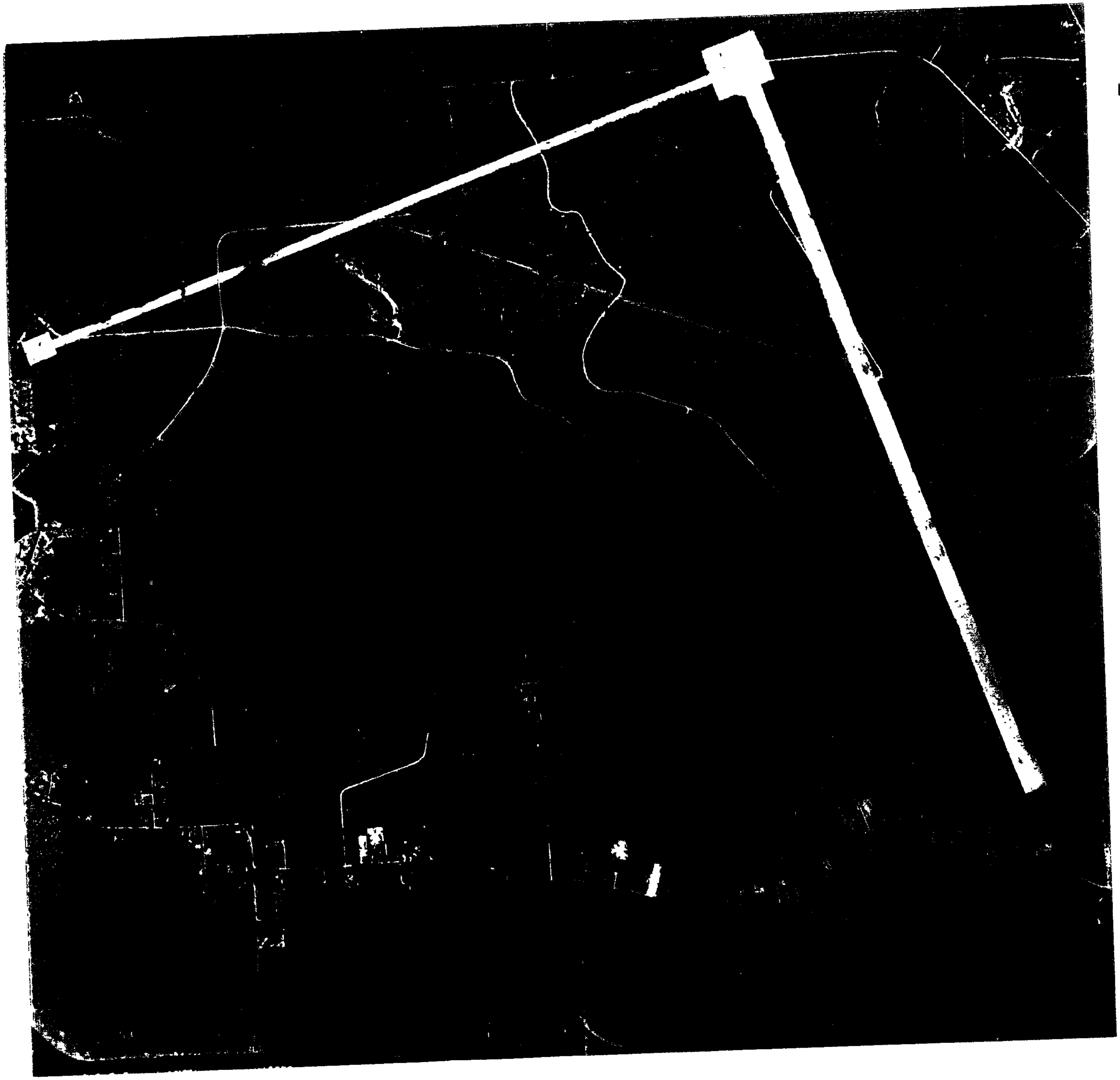






1
2
3
4
5
6
Mirror of Suspension-point Interferometer
Suspension Wires
Test Mass
Fabry-Perot Test Mass Mirror
CLEAR APERTURE = 1 m
BAFFLE I.D. = 1.10 m
BEAM TUBE I.D. = 1.22 m





LIGO

LIVINGSTON PARISH

LOUISIANA

1A

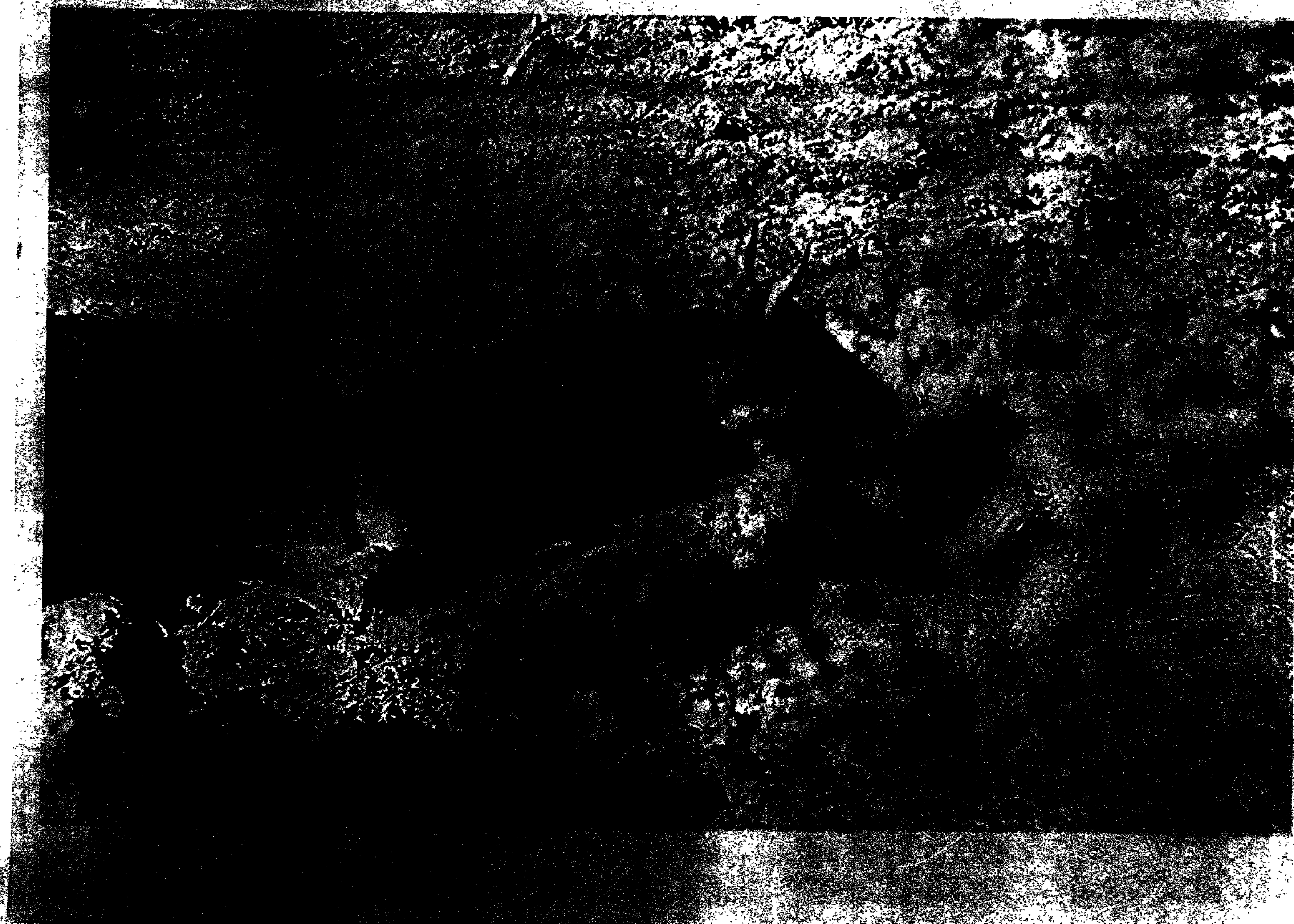
AERIAL PHOTO BY:

GULF COAST AERIAL MAPPING

FLOWN: AUGUST 25, 1995

ALTITUDE: 12,000 FEET

G960028-17-O-V



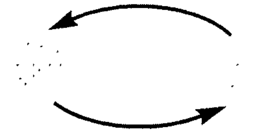
Conclusions

- LIGO Construction is well Underway

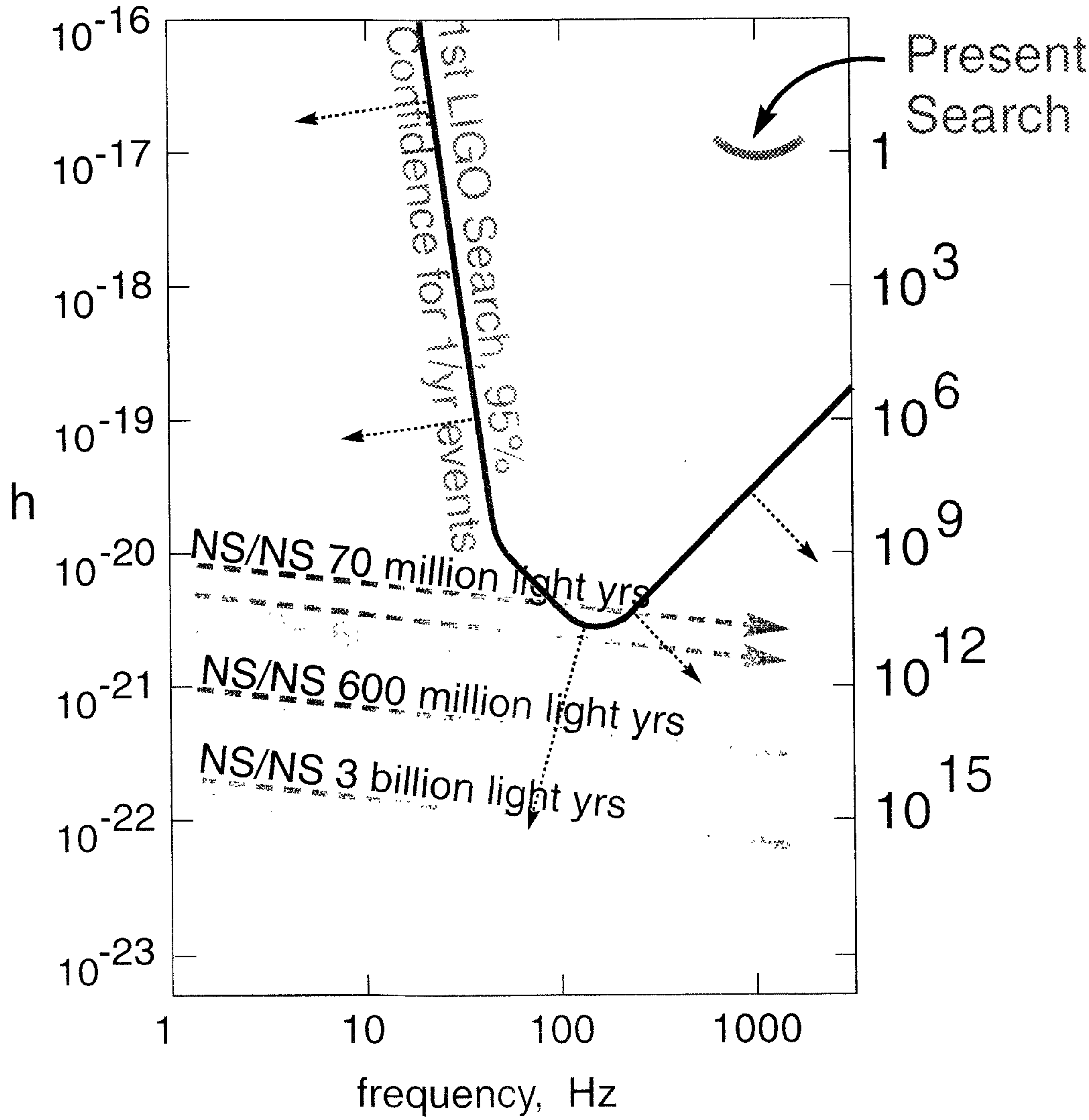
- Direct Detection of Gravitational Waves Appears Realistic within 10 years

- Ultimate Sensitivities Capable of Opening a New Field of Observational Astronomy with Gravitational Waves is the Long Term Goal.

NEUTRON STAR BINARIES



["Near-Guaranteed" source]



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