The Detection of Gravitational Waves

Academic Lecture Series

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CERN

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LIGO

LIGO-G960139-00-M

Lecture 1

B. Barish

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

GENERAL RELATIVITY + GRAVITATIONAL WAVES

- **General Relativity** '**fixes**' the problem posed by moving sources of gravitational field.

⇓

- **gravitational field** (eg curvature of space time)

  does not change instantaneously at arbitrary distances from moving source.

- Analogous to E.M. the 'news' travels at speed of light.

WAVES IN GENERAL RELATIVITY

- Space-time interval ds between points

$$ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2$$

(OR)

SPECIAL THEORY OF RELATIVITY

$$ds^2 = \eta_{\mu\nu} \, dx^\mu \, dx^\nu$$

with Minkowski metric

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

μ, ν indices over t, x, y, z

- Same physical concept carried over to General Theory of Relativity

(*except*,)

<u>spacetime no longer necessarily flat</u>

- general definition of space-time interval

$$ds^2 = g_{\mu\nu}\, dx^{\mu} dx^{\nu}$$

↑ space time curvature in this metric.

- for our purpose, we only need special case of a small perturbation to flat space-time.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

↑ metric perturbation away from Minkowski space.

  - Key physics in $h_{\mu\nu}$
  - In weak field limit, non-linear Einstein equations can be approximated as linear equations

- useful gauge is "<u>transverse</u> <u>traceless</u> <u>gauge</u>" [TT gauge]
- in this gauge, coordinates are marked by world lines of free falling test masses
- with this choice, weak field limit of Einstein's field equation becomes a wave equation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0$$

- $h_{\mu\nu}$ can take form of plane wave propogating in direction $\hat{k}$ with speed c.

$$h\left(2\pi f t - \vec{k}\cdot\vec{x}\right) \quad \text{with } f = |\vec{k}|/2\pi c$$

<u>Note</u>: speed c due to way space-time brought together in relativity.

- Consider the wave propogating along the z axis

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & a & b & 0 \\ 0 & b & -a & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

<u>transverse</u> and <u>traceless</u> —

∴ can write as sum of two components

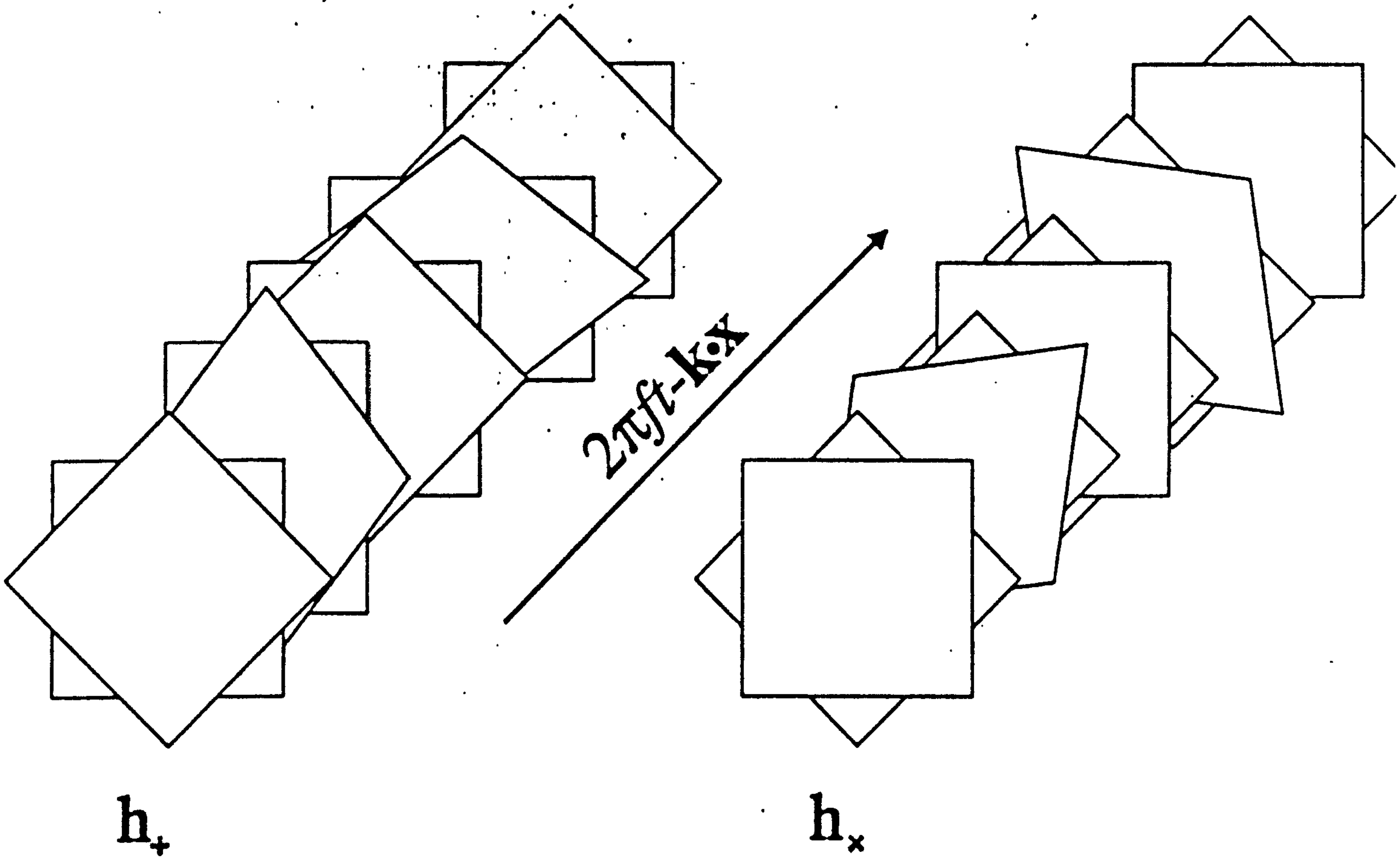
$$h = a\,\hat{h}_+ + b\,\hat{h}_\times$$

two <u>orthoganal</u> polarizations (45°)

$$\hat{h}_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Gravitational Waves

Two Polarizations



LIGO

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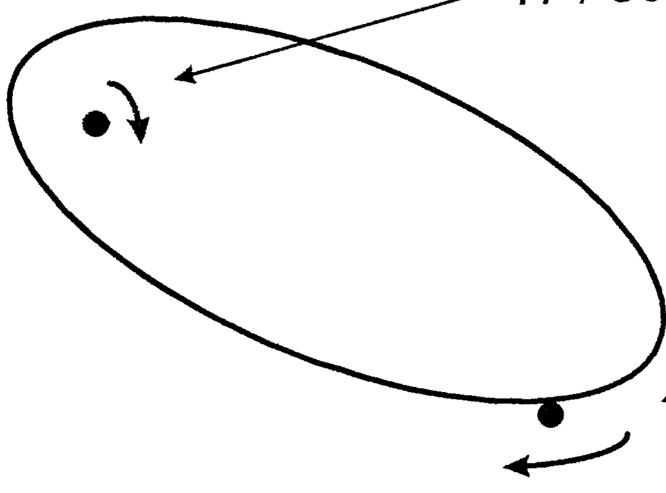
Gravitational vs E.M. Waves

	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

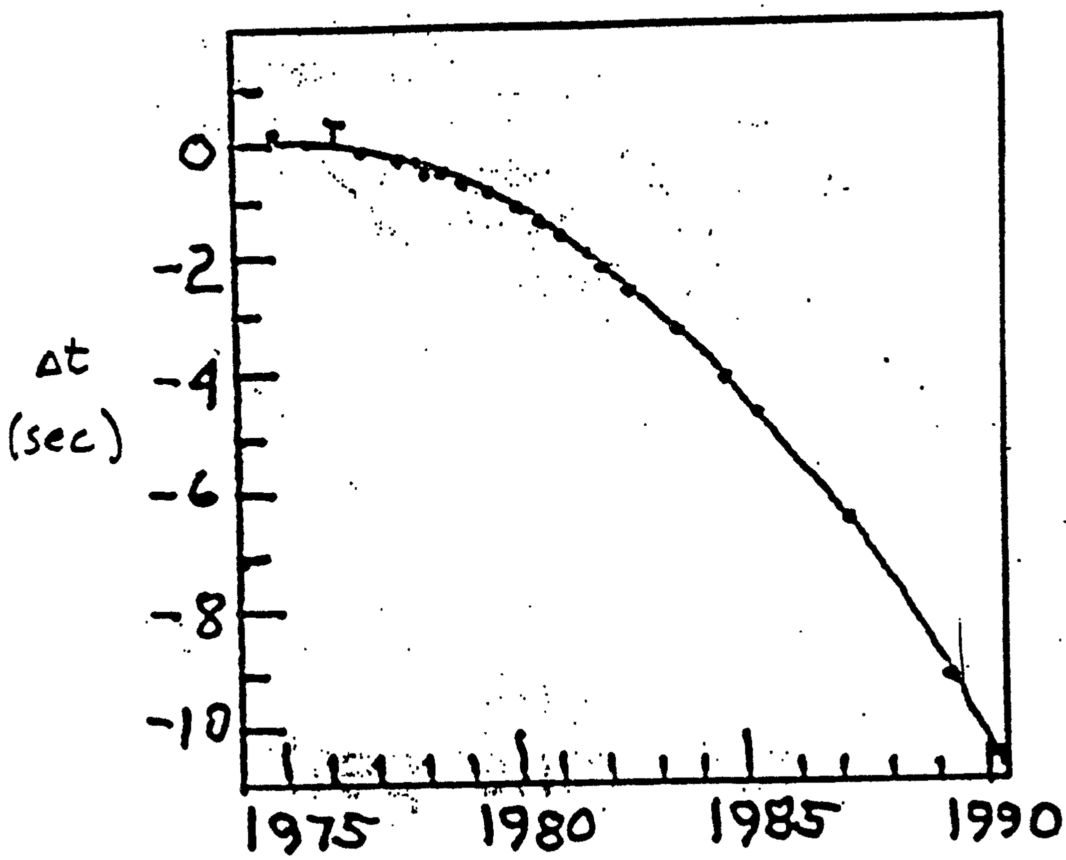
Gravitational Waves
Evidence

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



Hulse and Taylor
Timing of Orbit

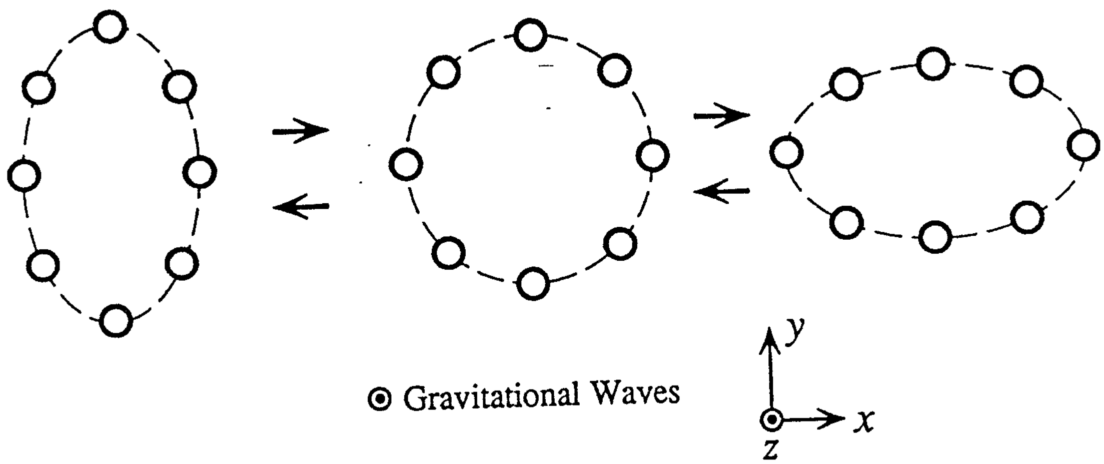
- Speed up 10 sec in 15 years
  - measured to ~50 μsec accuracy
- Deviation grows quadratically in time



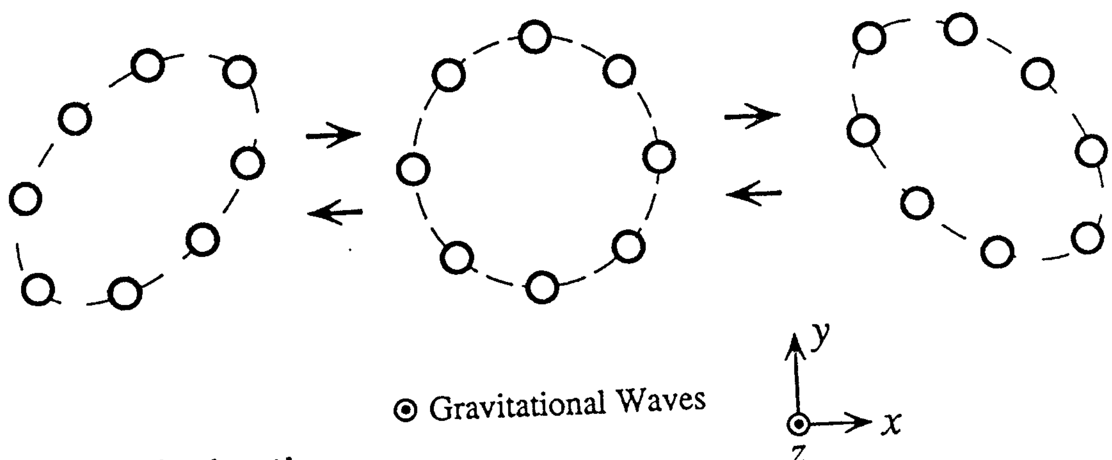
- Due to loss of orbital energy, from emission of gravitational waves

Gravitational Waves
Effects

- Displacement of free particles

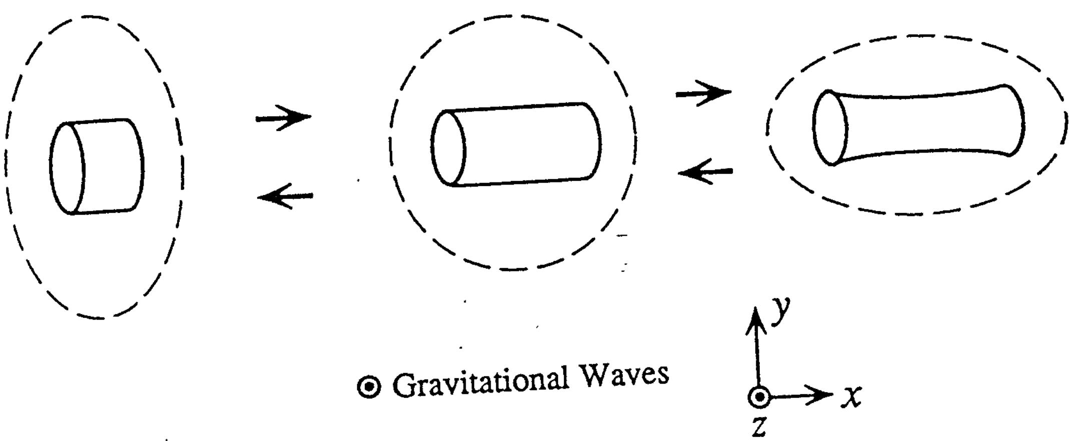


» h_+ polarization

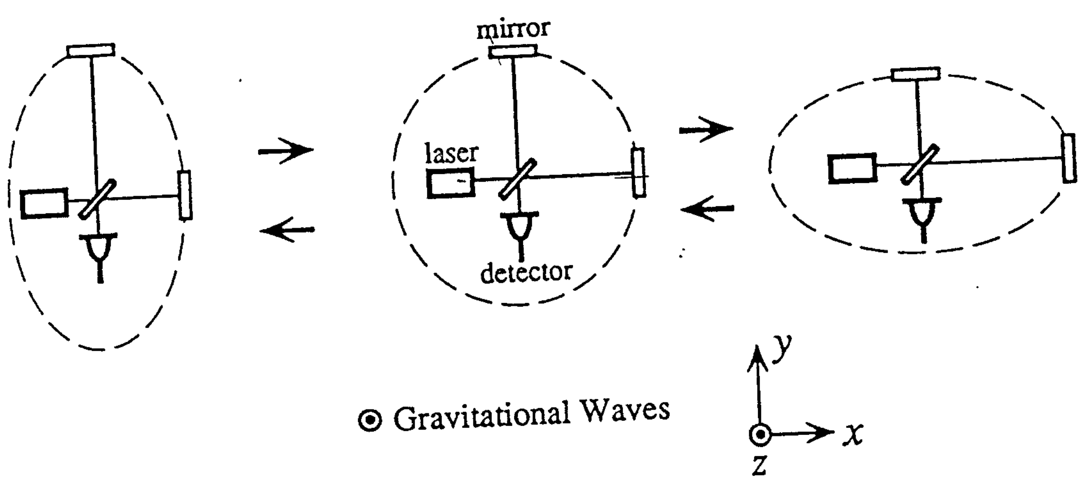


» h_x polarization

Gravitational Waves
Detection



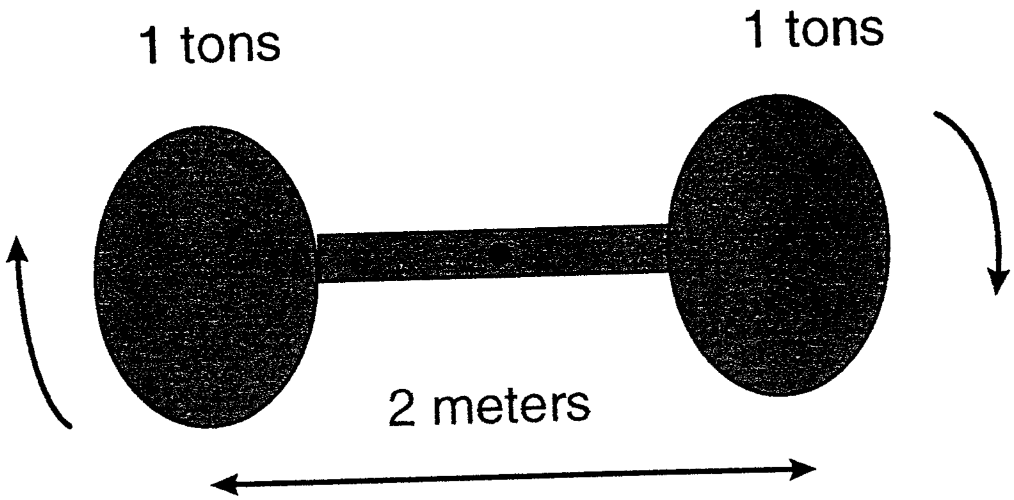
- Bar detector



- Interferometer detector

Laboratory Experiment
(a la Hertz)

Laboratory Dumbbell System



$f_{rot} = 1$ kHz

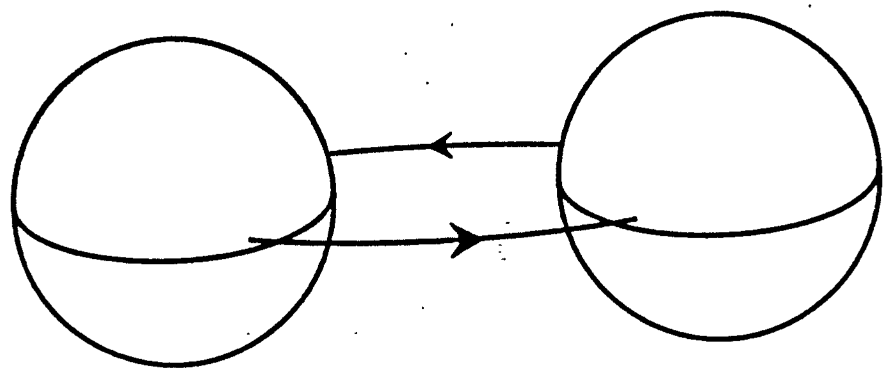
$h_{lab} = 2.6\ 10^{-33}$ m x 1/R

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



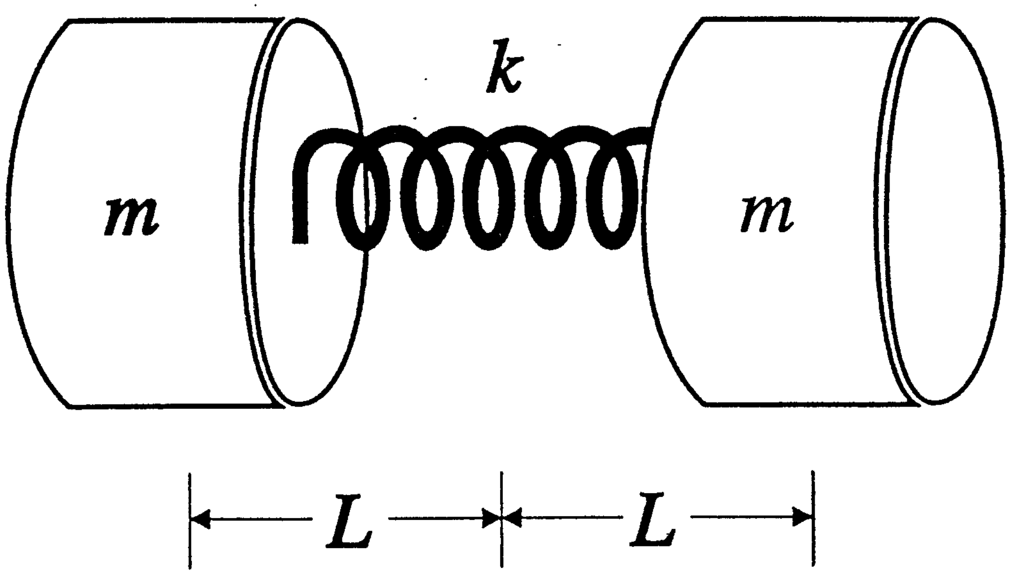
- binary star system

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

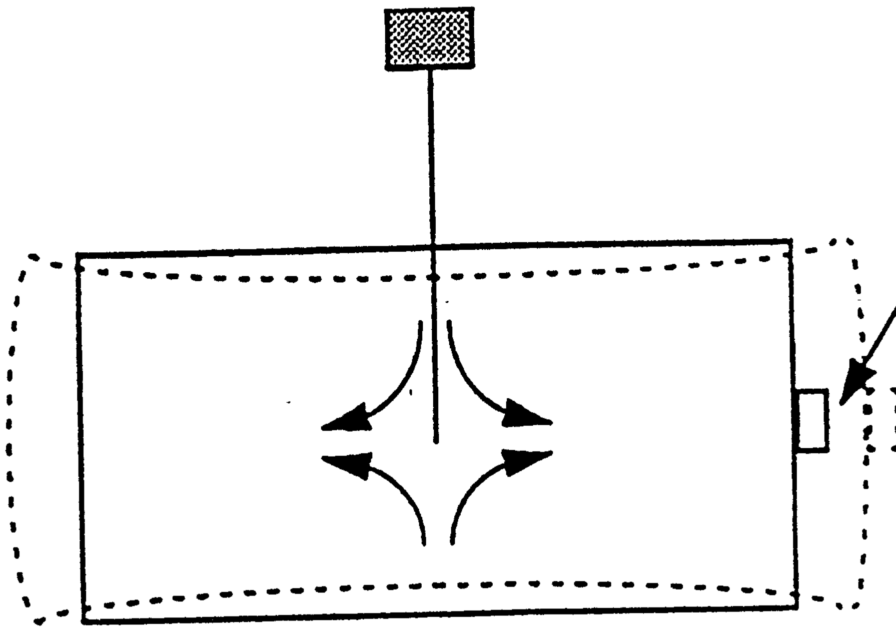
Gravitational Waves
Resonant Bar Detector

- Schematic Version



Gravitational Waves

Resonant Bar Detection



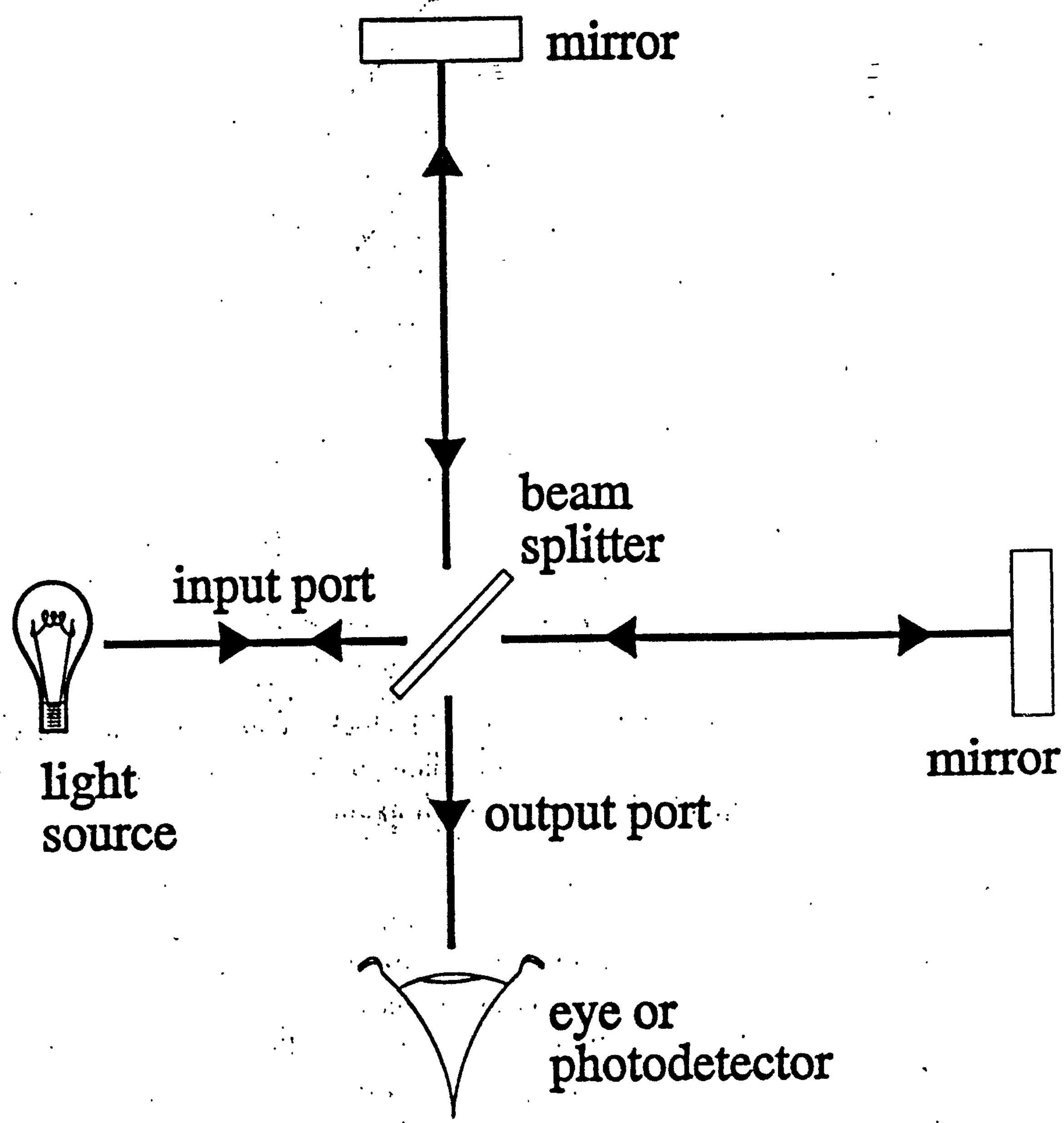
- Bar detector

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

Michelson Interferometer
Schematic Diagram

- Michelson Morley Experiment



The Michelson-Morley Experiment

- (1887) Michelson Interferometer
- Detect an apparent shift in speed of light due to Earth's motion through the 'ether'. (predated theory of relativity)
- **Experiment** –
  - input light $E_0 e^{i(2\pi f t - kx)}$
  - 50/50 beam splitter $r = 1/\sqrt{2}$ $t = i/\sqrt{2}$
  - x axis light $i(E_0/\sqrt{2})e^{i(2\pi f t - k_x x)}$
  - y axis light $(E_0/\sqrt{2})e^{i(2\pi f t - k_y y)}$

k_x, k_y allow possible different speed of light in the two arms

- Reflection at far mirrors $(\times -1)$ ← multiplies waves
- Light exiting thru output port

$$E_{out} = \left(\frac{i}{2}\right) E_0 e^{i(2\pi f t - 2k_x L_x)} + \left(\frac{i}{2}\right) E_0 e^{i(2\pi f t - 2k_y L_y)}$$

$$E_{out} = i e^{i(2\pi f t - k_x L_x - k_y L_y)} E_0 \cos(k_x L_x - k_y L_y)$$

also

$$E_{refl} = i e^{i(2\pi f t - k_x L_x - k_y L_y)} E_0 \sin(k_x L_x - k_y L_y)$$

(toward lamp)

- Light leaving depends on difference of phase accumulated by light travelling in two arms

Power $\propto E^2 \Rightarrow$

$$P_{out} = \frac{P_{in}}{2} \left(1 + \cos 2(k_x L_x - k_y L_y)\right)$$

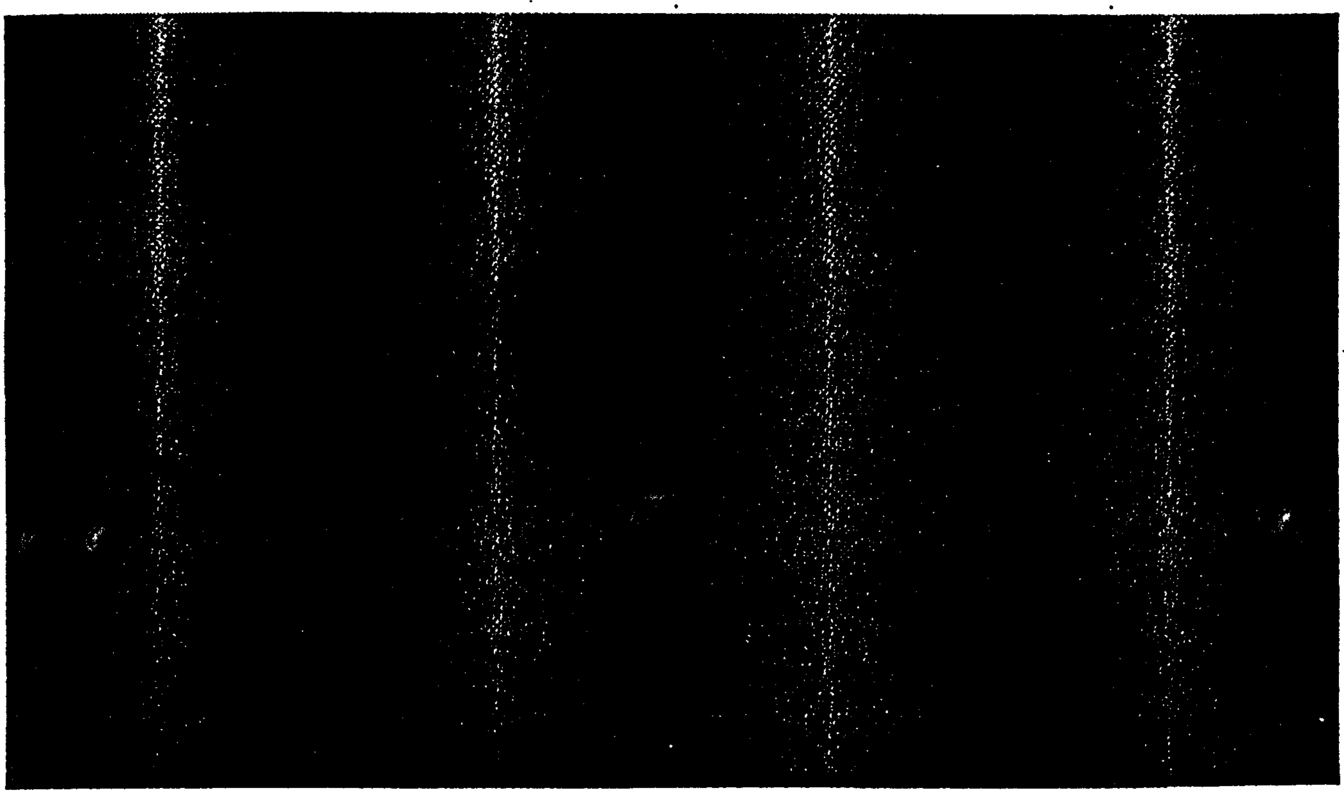
$$P_{out} + P_{refl} = P_{in}$$

- Measure difference in brightness (modern)

Actual – slightly mis-aligned

Michelson Interferometer
Interference Fringes

- Michelson Morley Experiment
  - » Two beams misaligned
- Impressionistic rendering



- Settings arms to same length ?
  (hard, but 'coherence' length)

- sensitivity of Michelson-Morley

L_{opt} = 22 meters (extra mirrors)

Measured shift in fringe $\lambda/20$

⇓

$\Delta t = 8\ 10^{-17}$ sec.

- Limitation — external vibrations
  (despite mirrors on massive stone slab in pool of mercury)

Lecture 2

B. Barish

Gravitational Wave Detection

- 'gedanken' version of Michelson (1887)
  - mirrors rest on freely-falling mass
  - 50/50 splitter
  - far end flat mirror

- **History**

(idea) - Gertsenshtein and Pustovoit (1962)

- Weber & Forward 1960's (unpublished)

(1st IFO) - Moss, Miller + Forward (1971)

(LIGO) - Weiss (1972)

Gravitational Wave Signal

- Consider light along $\hat{x}$ axis

$$ds^2 = 0 = g_{\mu\nu}\, dx^\mu dx^\nu$$
$$= (\eta_{\mu\nu} + h_{\mu\nu})\, dx^\mu dx^\nu$$
$$= -c^2 dt^2 + \left(1 + h_{11}(2\pi f t - \vec{k}\cdot\vec{x})\right) dx^2$$

(neighboring space-time events)

time - beam splitter to end of $\hat{x}$ arm

$$\int_0^{\tau_{out}} dt = \frac{1}{c}\int_0^L \sqrt{1 + h_{11}}\, dx \approx \frac{1}{c}\int_0^L \left(1 + \frac{1}{2} h_{11}(2\pi f t - \vec{k}\cdot\vec{x})\right) dx$$

$h \ll 1$ binomial expansion

Round trip →

$$\tau_{rt} = \frac{2L}{c} + \frac{1}{2c}\int_0^L h_{11}(2\pi f t - \vec{k}\cdot\vec{x})\, dx - \frac{1}{2c}\int_L^0 h_{11}(2\pi f t - \vec{k}\cdot\vec{x})\, dx$$

similar for y-arm.

Consider special case,

- sinsusoidal wave in + polarizarition
- frequency = f_{gw}
- amplitude $h_{11} = -h_{22} = h$

If $2\pi f_{gw} \tau_{rt} \ll 1$ can treat the metric perturbation as approximately constant during time wavefront is present in the apparatus

- equal and opposite perturbations to light travel time in two arms
- total travel time difference

$$\boxed{\Delta\tau(t) = h(t)\frac{2L}{c} = h(t)\,\tau_{rto}}$$

where $\tau_{rto} \equiv \frac{2L}{c}$.

Comparing travel time to (reduced) period of oscillation of the light gives phase shift

$$\Delta\phi(t) = h(t)\,\tau_{rto}\,\frac{2\pi c}{\lambda}$$

In words, phase shift between light traveled in the two arms equals a fraction h of the total phase a light beam accumulates as it traverses the apparatus.

Scaling law won't hold for arbitrarily long arms. (e.g. $2\pi f_{gw}\tau_{rt} \ll 1$ no longer holds)

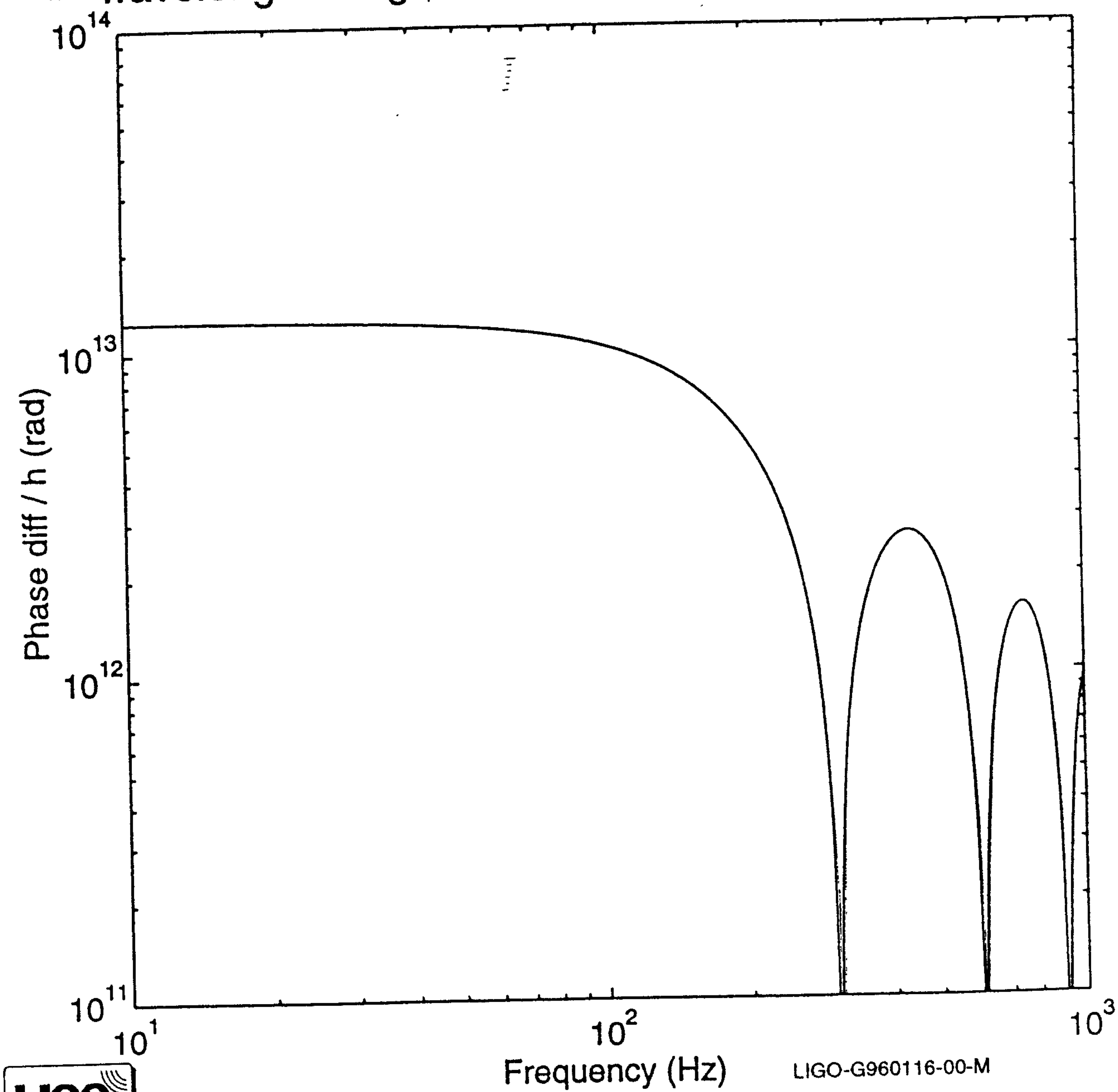
<u>NO</u> NET MODULATION IF

$$f_{gw}\,\tau_{rt} = 1$$

Michelson Interferometer

Transfer function

- Example
  - » mirrors are defined at 500 km from beam splitter
  - » wavelength of light = 0.5 microns



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LIGO

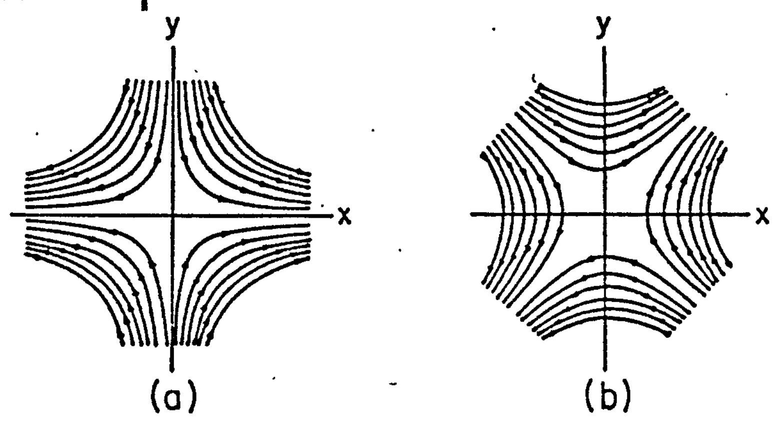
Gravitational Wave
Forces

IF

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

THEN

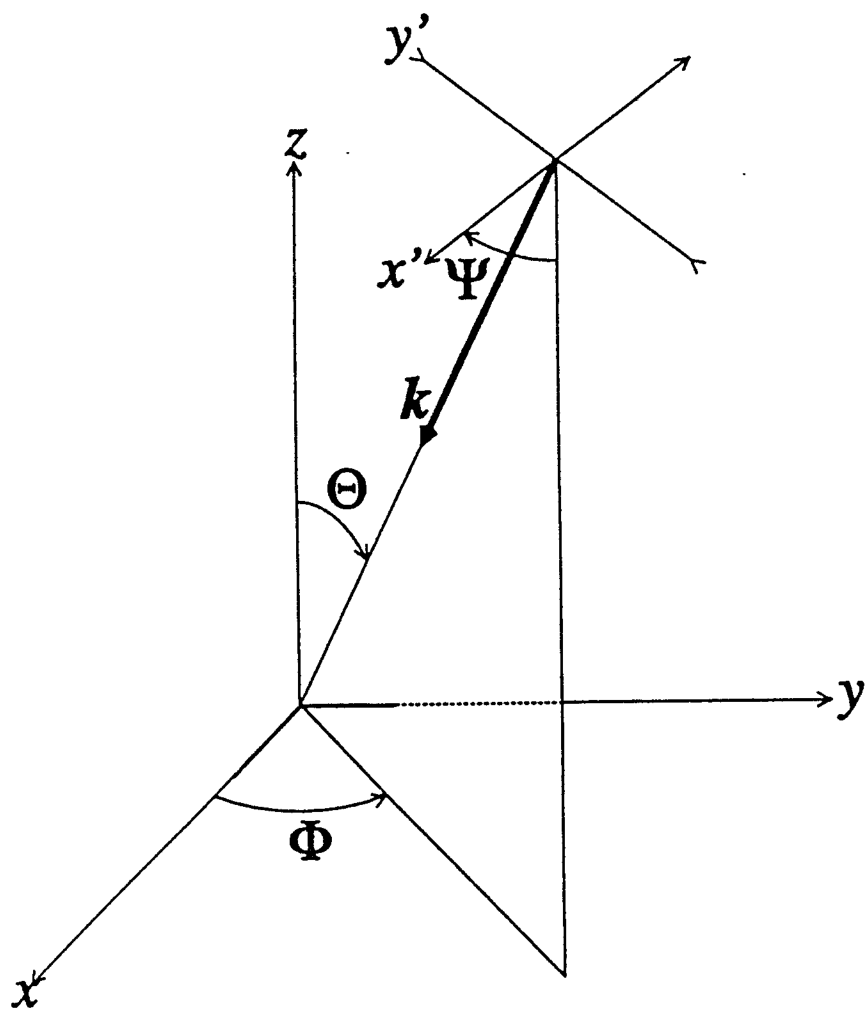
- Free Masses
- Quadrupolar Lines of Force



\+ Polarization x Polarization

Gravitational Wave Detector

- Antenna Pattern
  - » coordinate system



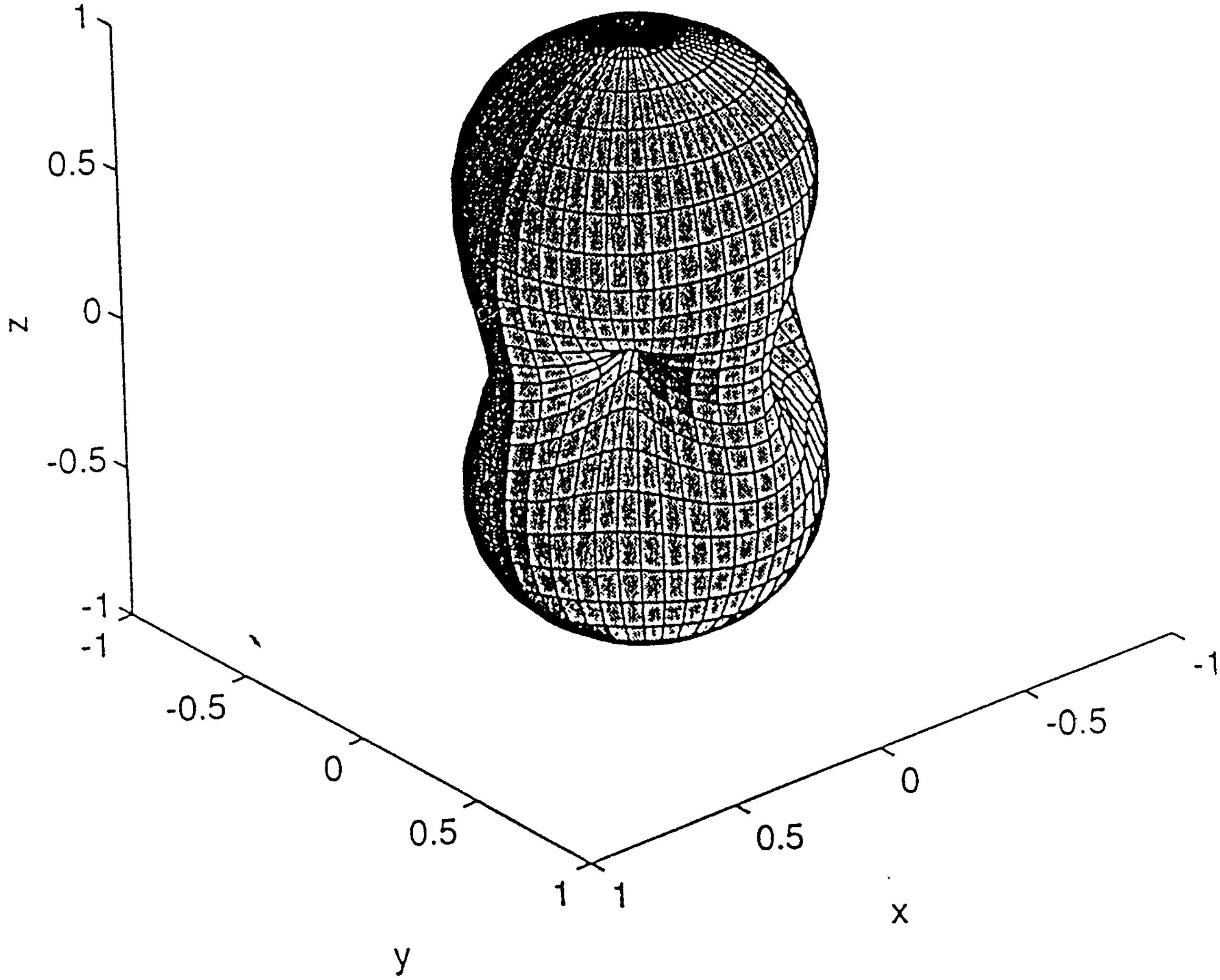
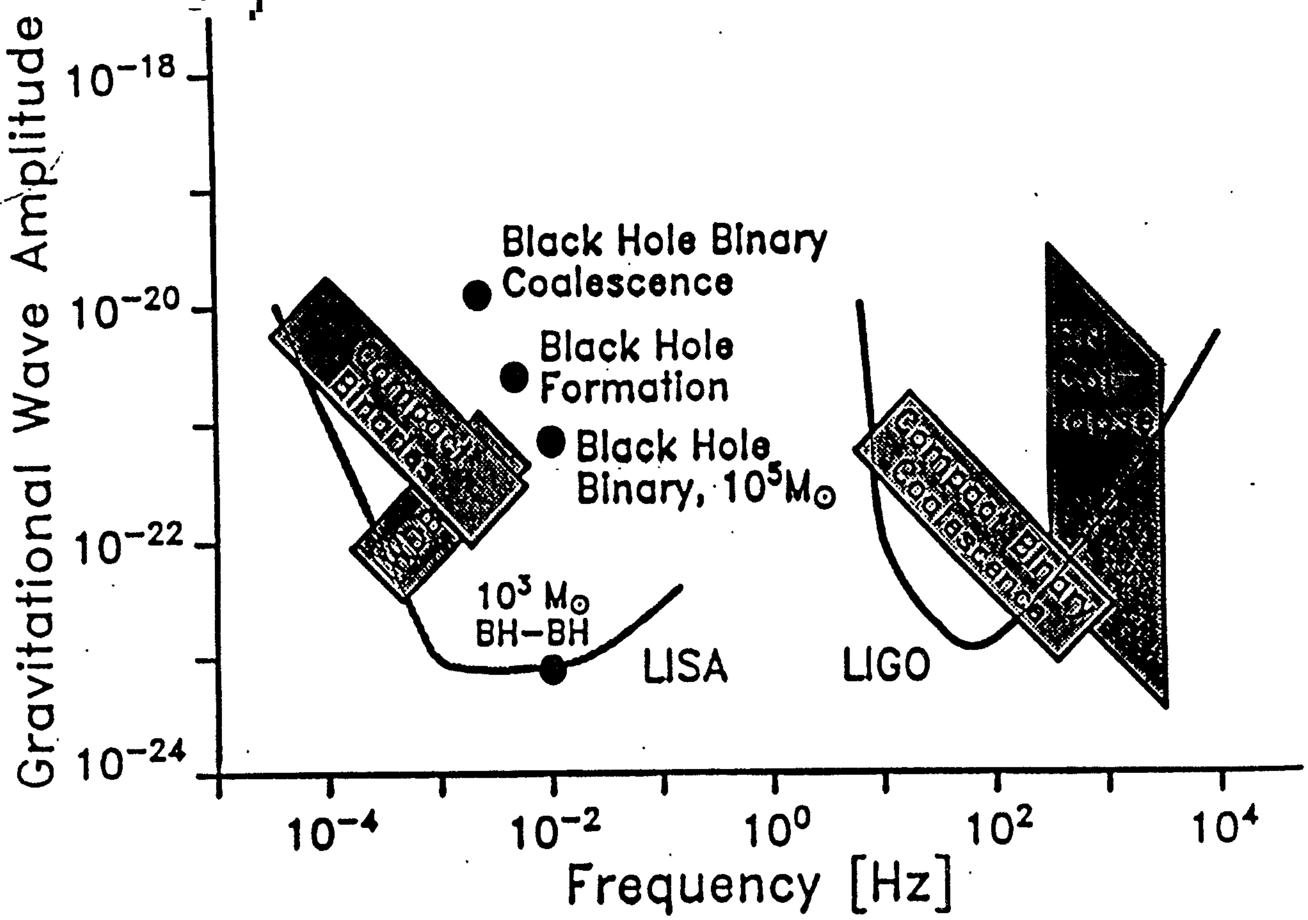


Figure 2.7 The sensitivity, as a function of direction, of an interferometric gravitational wave detector to unpolarized gravitational waves. The interferometer arms are oriented along the x and y axes.

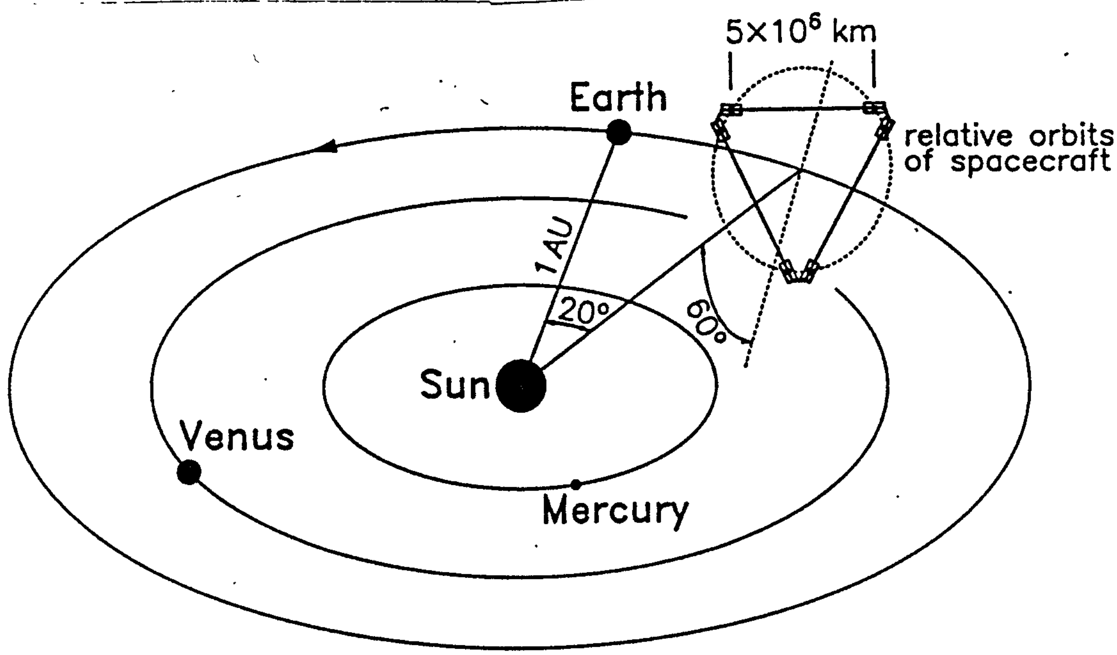
Astrophysical Sources
Frequency Range

- 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

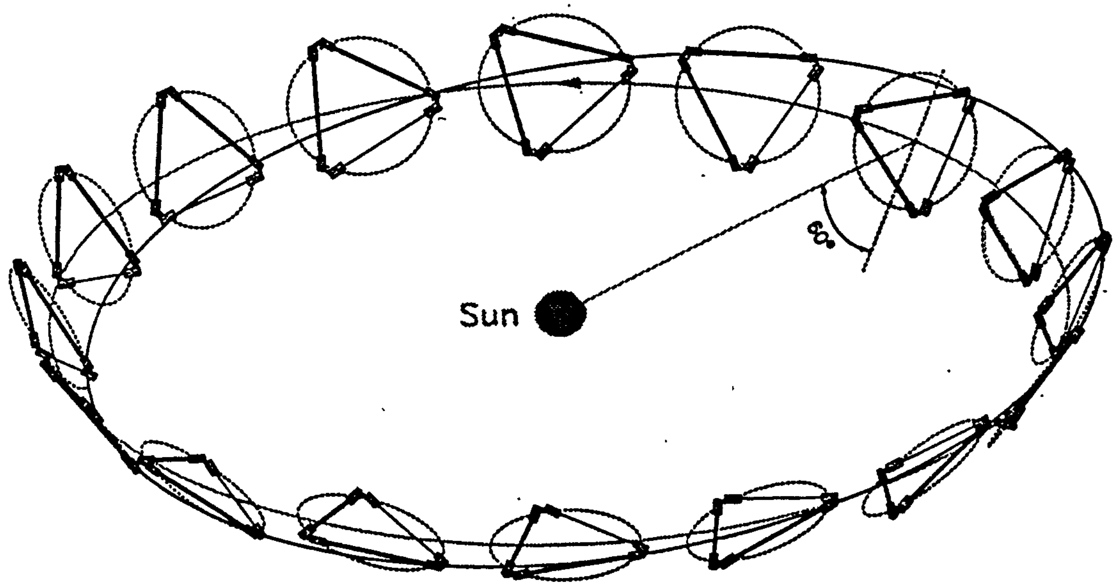
- LISA - Laser Interferometer Space Antenna
  - » six spacecraft in triangle (four needed)
  - » pair at each vertex



LISA

Annual Revolution

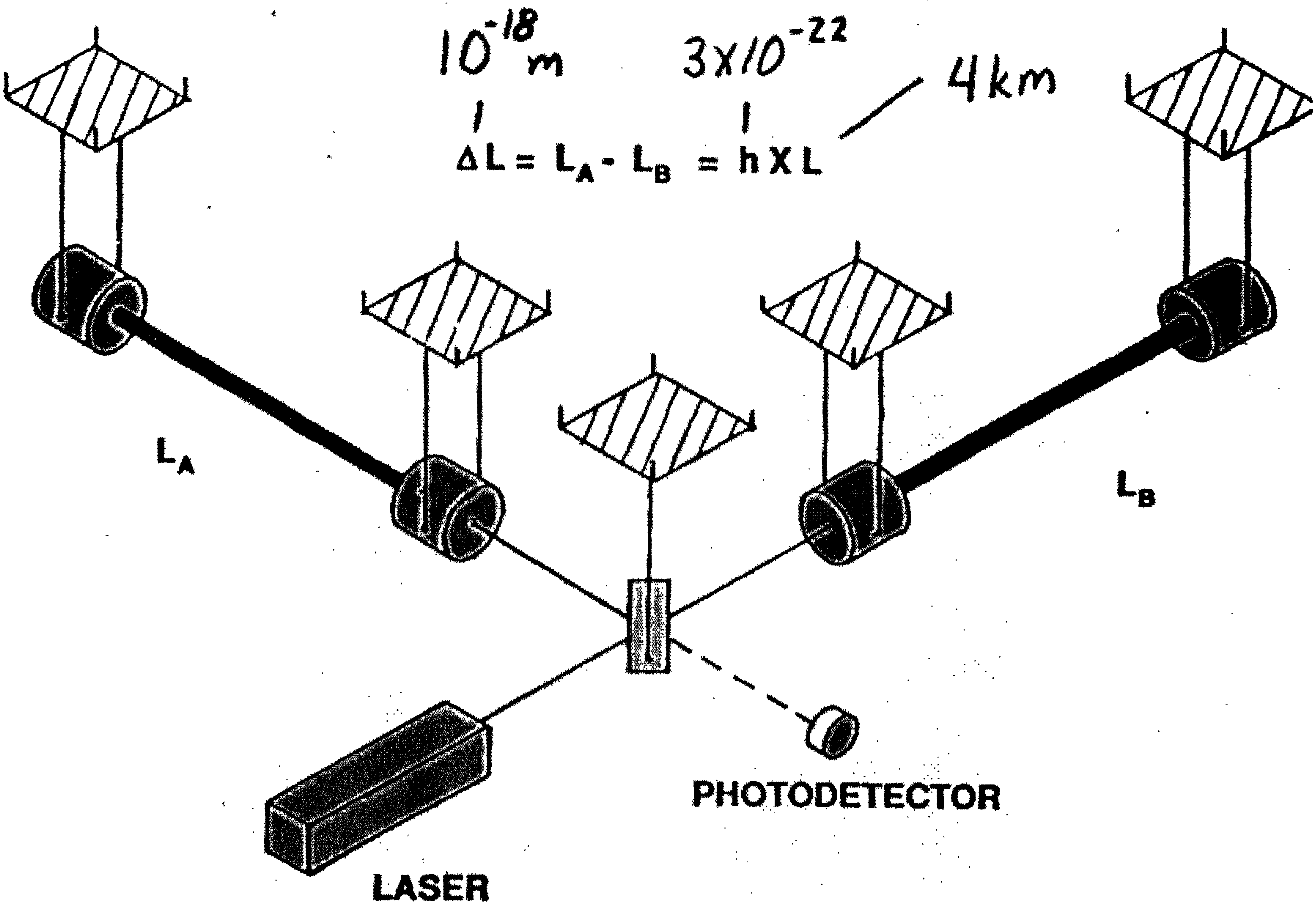
- 60 degree half opening angle
- 'tumbling' allows determination of position of source and polarization of wave



Gravitational Waves
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

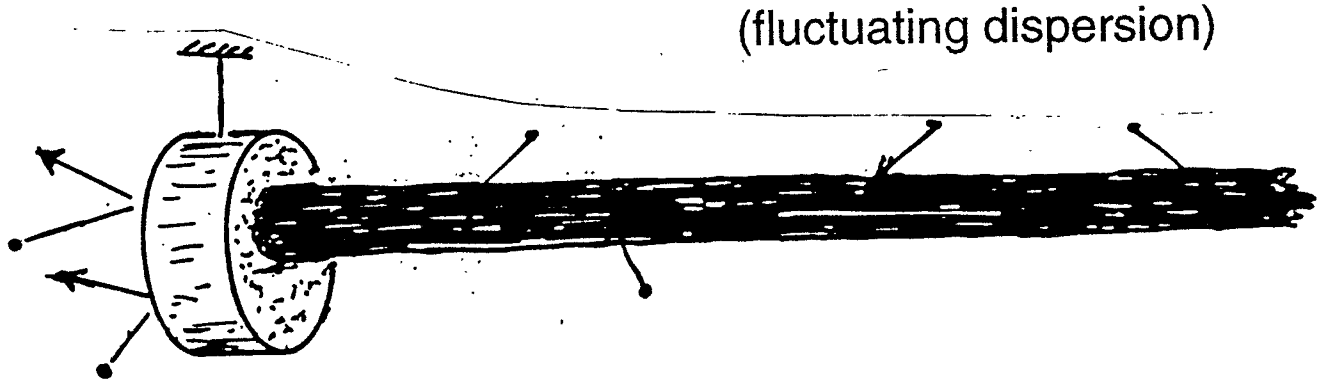
Achieving 10^{-18} m Sensitivity

How is it possible????

- Air molecules:

Buffer mirrors

Buffet light beam (fluctuating dispersion)



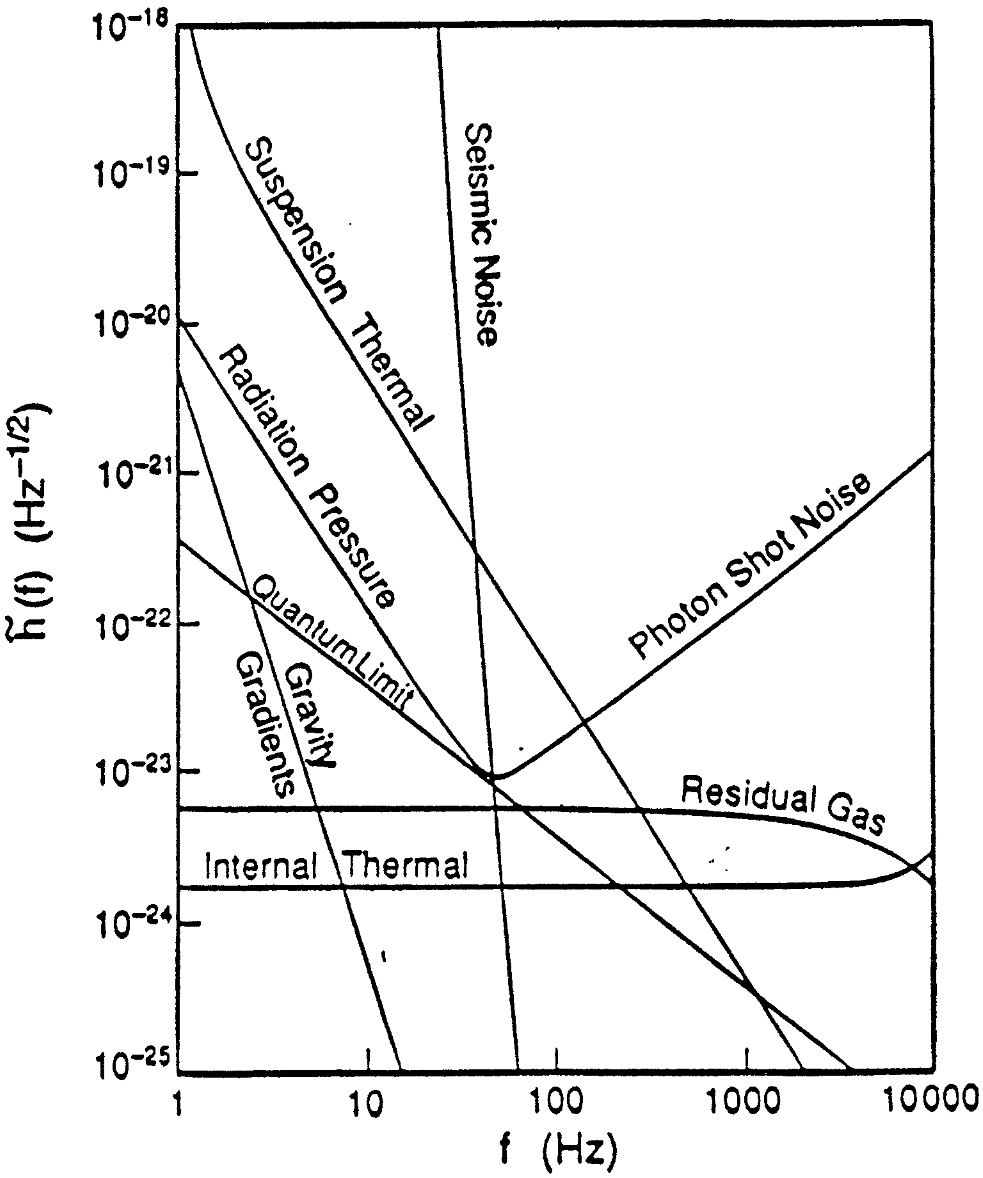
  - » **Mirrors and light beam must be in vacuum**

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

Gravitational Wave Generation

- analogous to EM waves
- expressed in terms of retarded potential
- simplest to work with approximation
  - multipole expansion
  - ok if $r_{source}/\lambda \ll 1$

(size of source much smaller than wavelength)

- EM ⇒ radiation field from time variation of electric dipole moment

$$\vec{E} = \frac{1}{Rc^2}\left((\ddot{d} \times \hat{n}) \times \hat{n} \right)$$

R = distance from source to observer

$\hat{n}$ = unit vector source to observer

$\vec{d}$ = electric dipole moment

$$\vec{d} = \int dV \, \rho_q(r) \, r$$

ρ_q = charge density

integrate over source

Next term,

magnetic dipole

electric quadrupole

(weaker by r_{source}/λ)

Why no electric monopole radiation?

(requires time variation in monopole moment (eg electric charge)

∴ Radiation forbidden

Gravity vs EM

Note pre-relativistic differences

- electric charge (two signs)
- gravity (one sign)

Also,

gravitational charge (by Principal of Equivalence) measures inertia of body

Conservation of energy for gravitation same role as charge conservation in EM, therefore **NO** monopole radiation (grav)

What about dipole moment? (gravity)

$$\vec{d}_g = \int dV \, \rho(r) \, r$$

$\rho(r)$ = mass density

(conservation of momentum <u>requires</u>
$\dot{d}_g$ constant for isolated systems)

∴ FORBIDDEN

<u>Out of conservation</u> laws, higher moments of mass distribution will generate gravitational waves

Time variation of gravitational quadrupole moment contribute most strongly.

Reduced quadrupole moment,

$$I_{\mu\nu} \equiv \int dV \left(x_\mu x_\nu - \frac{1}{3} \delta_{\mu\nu} r^2 \right) \rho(\vec{r})$$

Strongest allowed component of gravitational radiation

$$h_{\mu\nu} = \frac{2G}{Rc^4} \ddot{I}_{\mu\nu}$$

evaluate at retarded time $t - R/c$

Astronomical Sources of Gravitational Waves

- mostly compact objects
  (neutron stars, black holes)

- for now, consider terrestrial instruments (eg few H_3 → few kH_3)

- Problem –
  - consider kind of source
  - study dynamics to calculate history of quadrupole moment
  - yields strength, temporal behavior or special characteristics of gravitational radiation it emits

- difficulties more in complexity of astronomical systems than subtleties of Gen. Rel.

Examine a special case,

- pair of equal point masses moving in circular orbit about COM. (binary star system)

Assume: each mass $= M$
separation $= 2r_0$
orbit freq. $= f_{orb}$

$$I_{xx} = 2Mr_0^2 \left(\cos^2 2\pi f_{orb} t - \frac{1}{3} \right)$$

$$I_{yy} = 2Mr_0^2 \left(\sin^2 2\pi f_{orb} t - \frac{1}{3} \right)$$

$$I_{xy} = I_{yx} = 2Mr_0^2 \cos 2\pi f_{orb} t \sin 2\pi f_{orb} t$$

components in z uninteresting,

$I_{zz} = -\frac{1}{3} Mr_0$ (constant)   cross terms with x, y VANISH

Calculate second time derivative, $\ddot{I}_{\mu\nu}$

(eg. point along z axis, distance R)

$$h_{xx} = -h_{yy} = \frac{32\pi^2 G}{Rc^4} M r_0^2 f_{orb}^2 \cos 2(2\pi f_{orb})t$$

$$h_{xy} = h_{yx} = -\frac{32\pi^2 G}{Rc^4} M r_0^2 f_{orb}^2 \sin 2(2\pi f_{orb})t$$

can be re-arranged in more dimensionless form

$$|h| \approx \frac{r_{s_1} r_{s_1}}{r_0 R}$$

plug in to get representative strength of grav. waves h

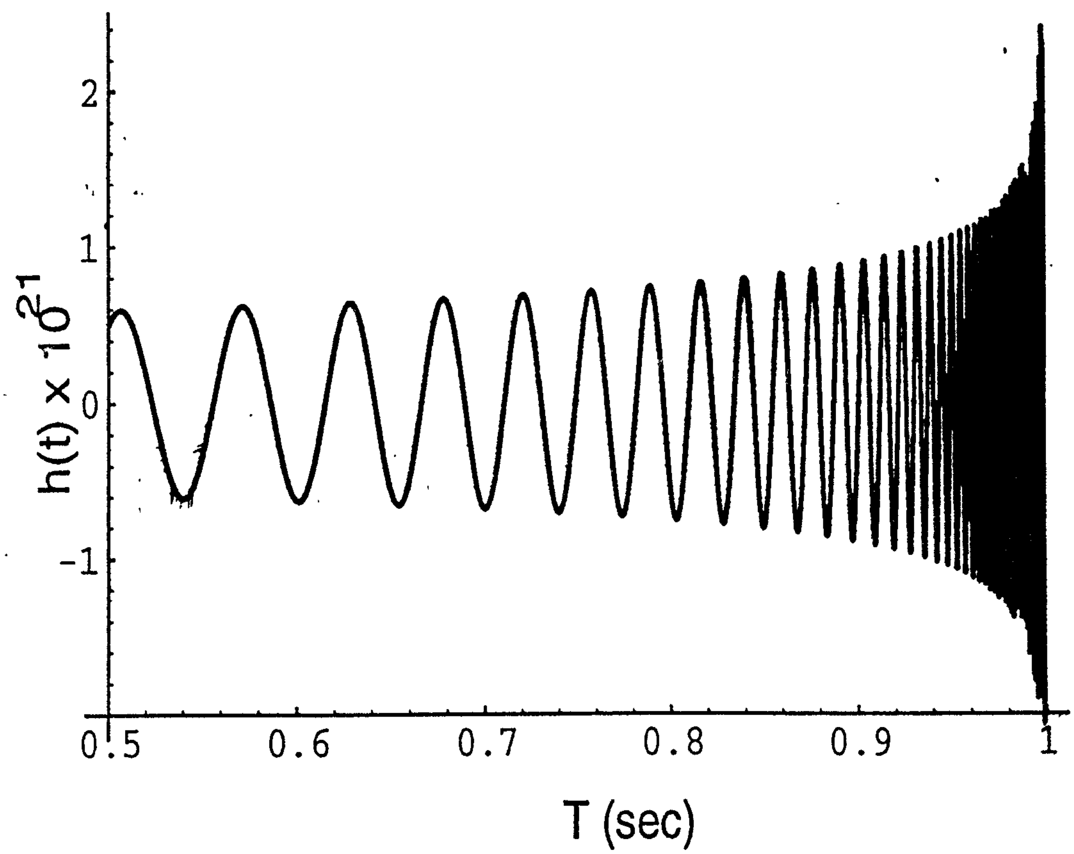
- binary neutron stars $M = 1.4 M_\odot \approx 3\ 10^{30}$ kg
- almost touching $r_0 = 20$ km
- orbital frequency $f_{orb} \approx 400$ Hz (relativistic)
- assume @ VIRGO Cluster $R \approx 15$ Mpc $\approx 4.5\ 10^{23}$ m

$$\boxed{h \equiv h_{\mu\nu} \approx 10^{-21}}$$

$f_{gw} = 2 f_{orb}$
[illegible]

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



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

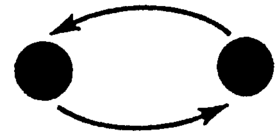
Method	***Our Galaxy***	***Distance for 3/yr***
Progenitor Death Rate	~1/1000 yr	130 M.L.yr
Binary Pulsar Searches and Discoveries	$\sim 1/10^{5\pm1}$ yr	600 M.L.yr.
Ultra-conservtive Limit from Binary Pulsar Searches	$\sim 1/10^{7}$ yr	3000 M.L.yr

Lecture 3

B. BARISH

NEUTRON STAR BINARIES

[our best understood source]



- **Hulse/Taylor (1993 Nobel Prize):**
  - *Observed slight inspiral of PSR1913+16, due to energy lost to grav'l waves*
  - *Thereby proved (indirectly) that gravitational waves exist*

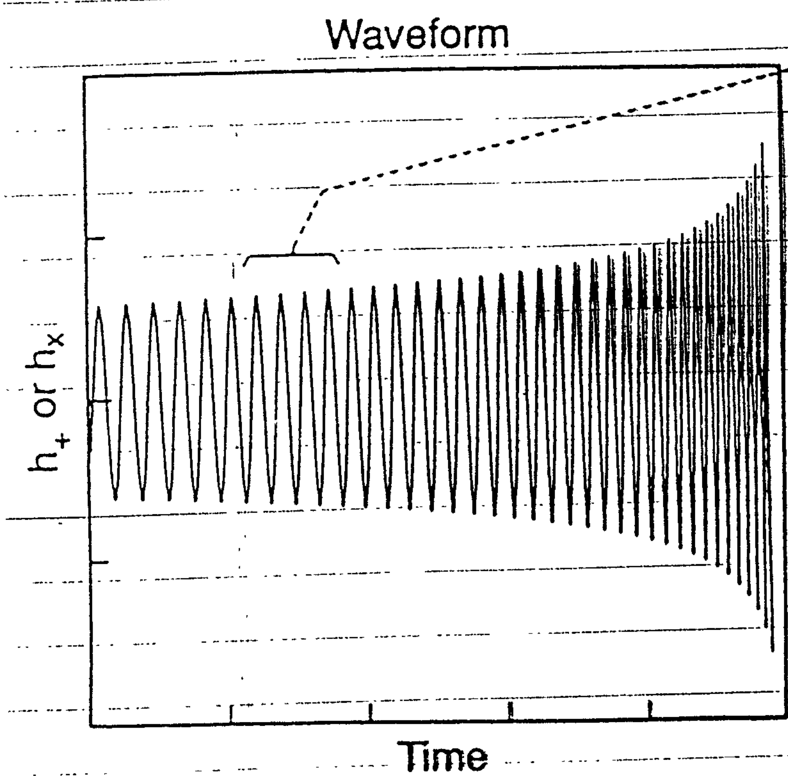
- **LIGO's Goals:**
  To detect the waves directly, and by extracting the rich information they carry, use them to study:
  - *The nature and dynamics of gravity (spacetime warpage)*
  - *The "dark side" of the universe*

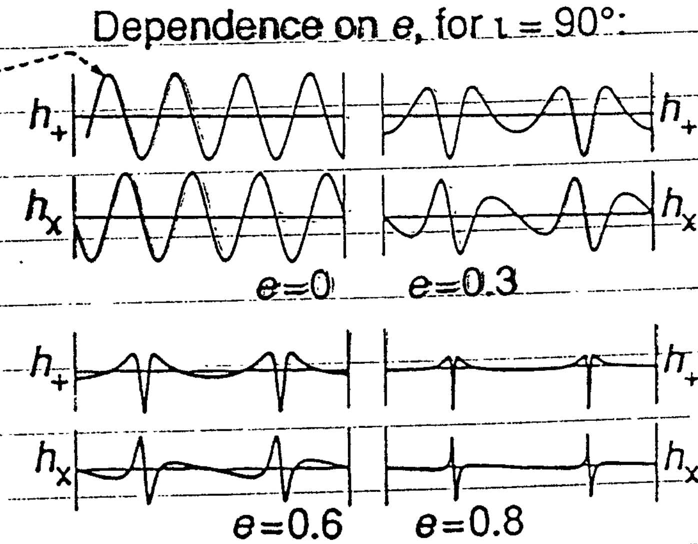
- **The trouble with PSR1913+16:**
  - *It's wave frequency is 0.0001 Hz*
  - *LIGO's band is 10 to 1000 Hz*
  - *We must wait 100 million yrs for PSR1913+16 to reach LIGO's band*

Gravitational Waveforms

binary inspiral

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





Dependence on ι, for $e = 0$:

$$\frac{\text{Amp }(h_\times)}{\text{Amp }(h_+)} = \frac{2\cos\iota}{1+\cos^2\iota}$$

LIGO

Neutron Star Binaries

- shortest known period WZ Sge
  (only in space – 81 minutes)

- PSR 1913 +16 $f = 2 f_{orb} \approx 4\ hr^{-1}$
  in 10^8 yrs $\Rightarrow$ 10 – 1000 Hz band
  CHIRP Signal

---

in weak field approximation

$$f(t) = 2.1 Hz \times \left(\frac{M_1 + M_2}{M_1^3 M_2^3} \right)^{1/8} \left(\frac{1\ day}{\tau} \right)^{3/8}$$

$$h(t) = 6.6\ 10^{-24}\ \frac{15 Mpc}{R} \left(\frac{M_1^3 M_2^3}{M_1 + M_2} \right)^{1/4} \left(\frac{1 day}{\tau} \right) \left(1 + 6 \cos^2\theta + \cos^4\theta \right)$$

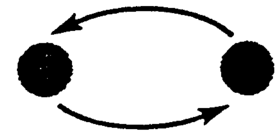
M_1, M_2 masses of neutron stars
τ time to collision
θ inclination of orbit
R distance away

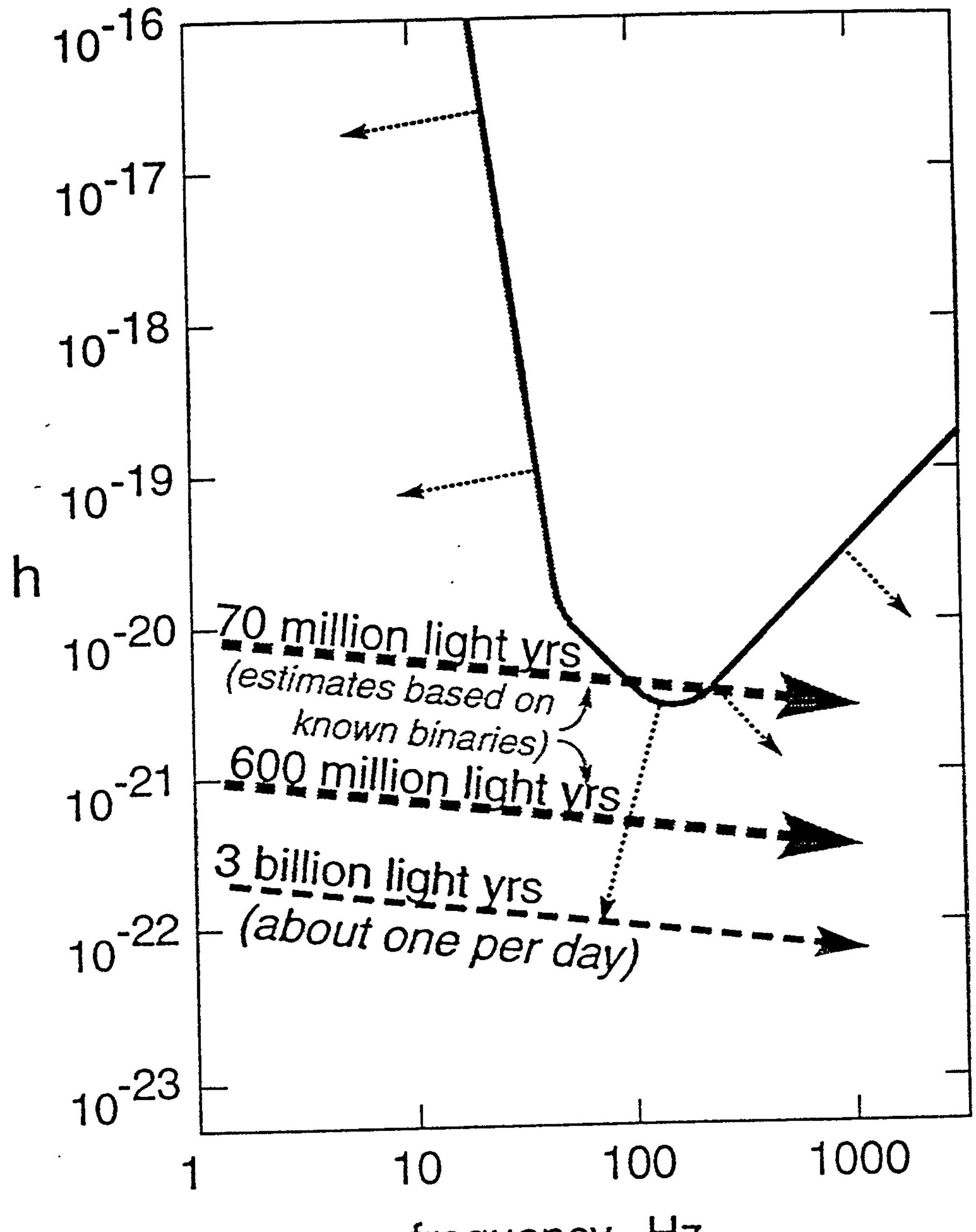
at collision, $f \sim 1 kHz$; $h \sim 10^{-21}$ @ VIRGO

(several percent of rest mass radiated away)

NEUTRON STAR BINARIES

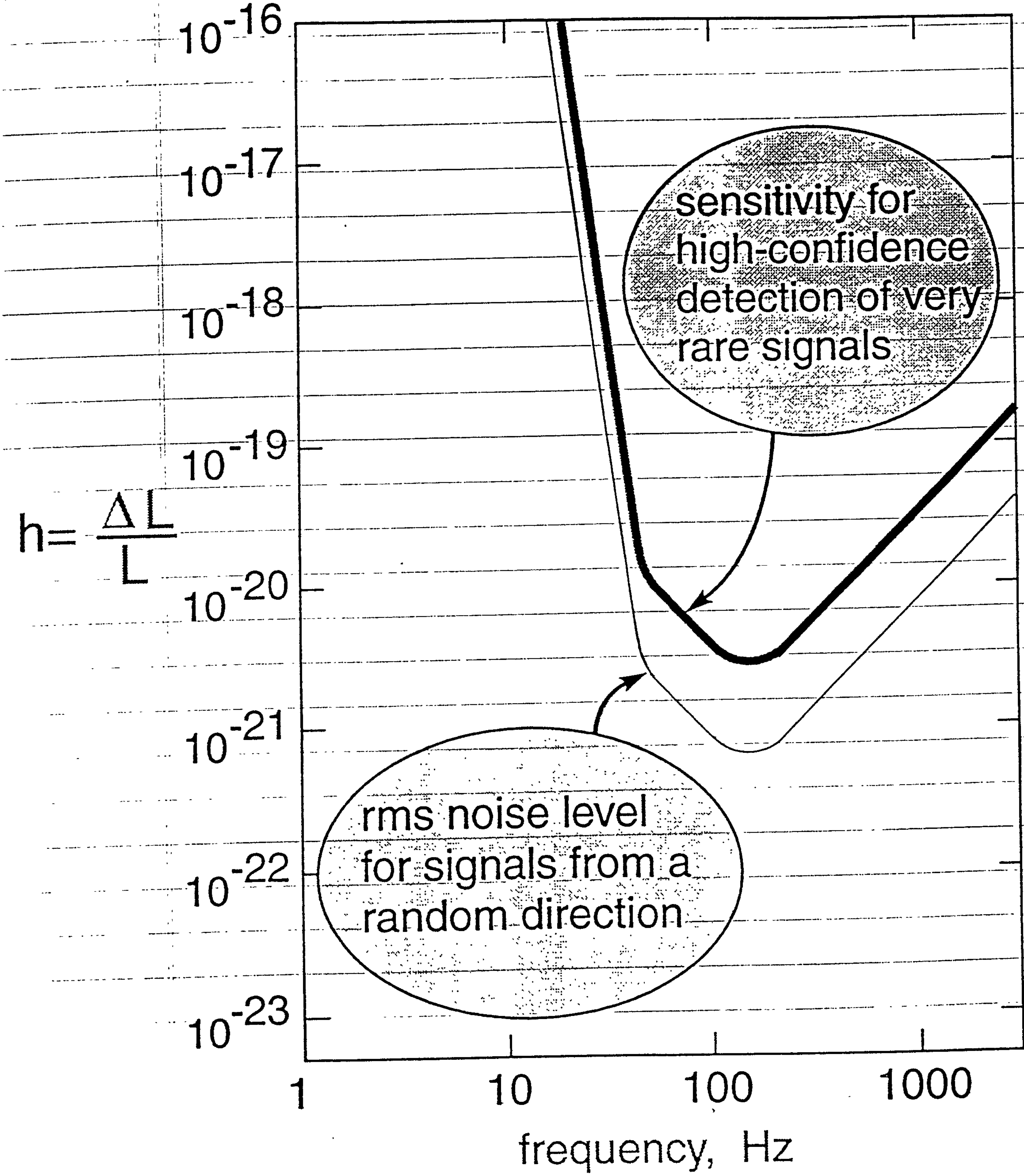
["Guaranteed" source]

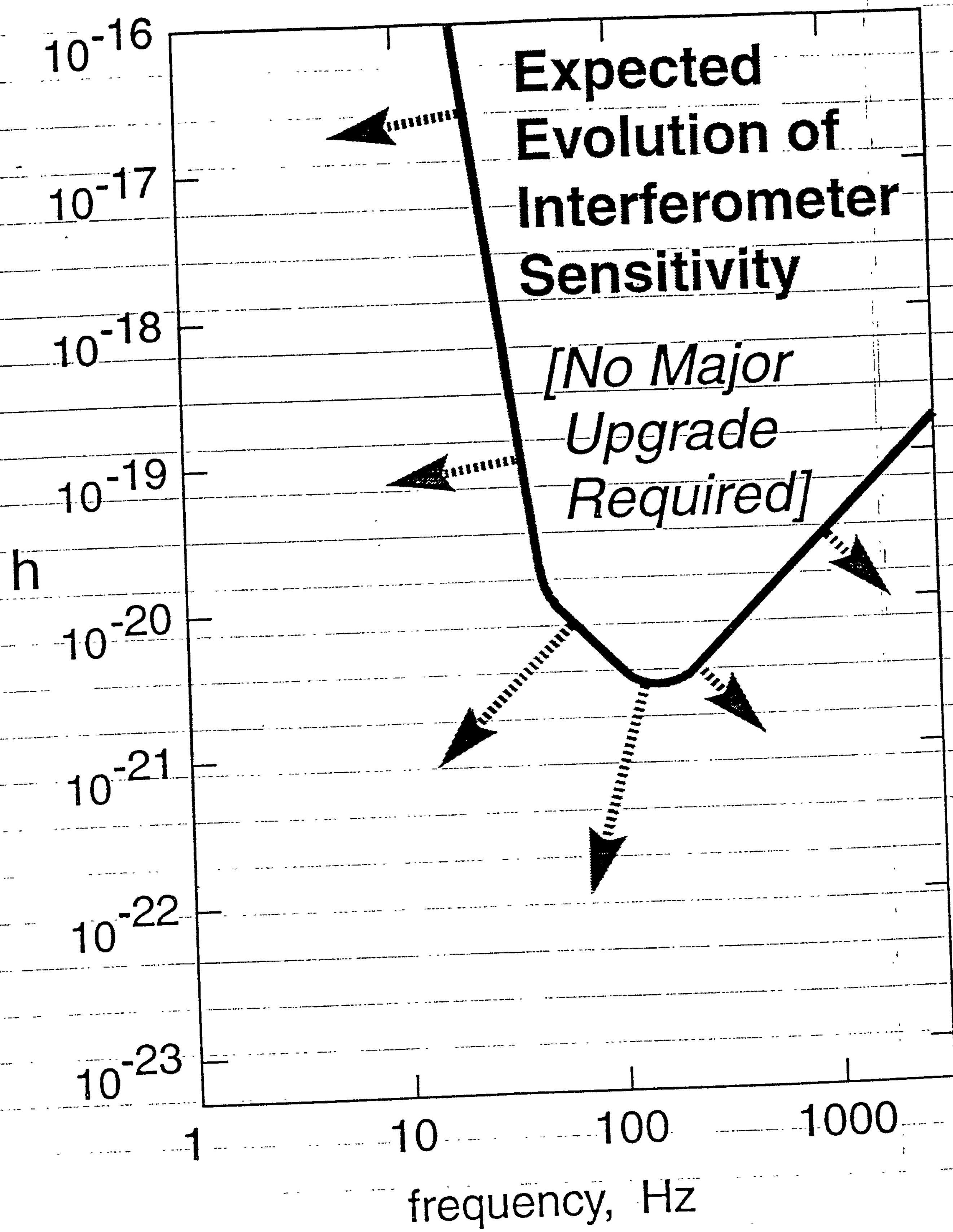




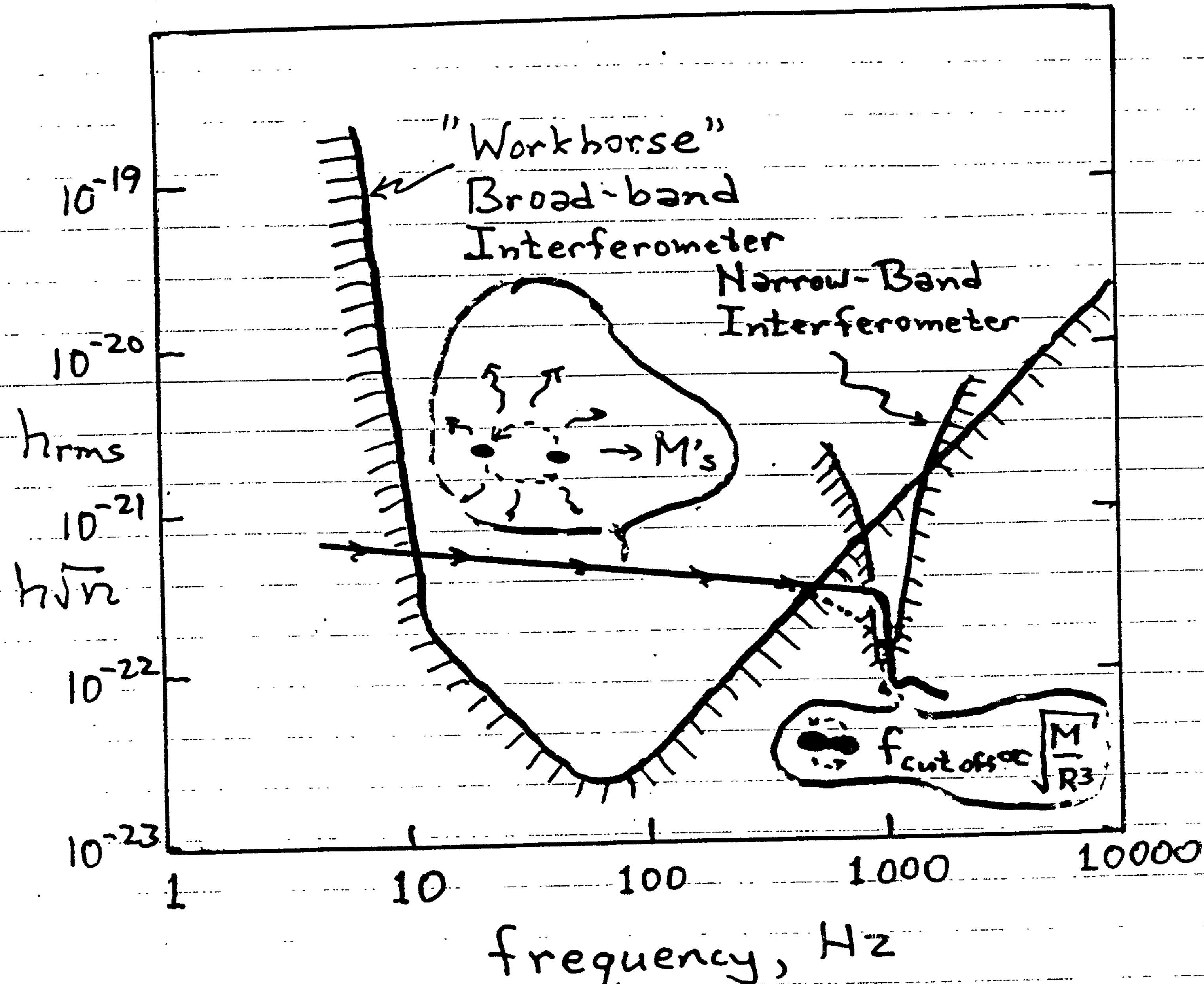
- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

SENSITIVITY OF LIGO'S FIRST INTERFEROMETERS




Expected
Evolution of
Interferometer
Sensitivity
[No Major
Upgrade
Required]
h
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
1
10
100
1000
frequency, Hz

NEUTRON STAR COALESCENCE

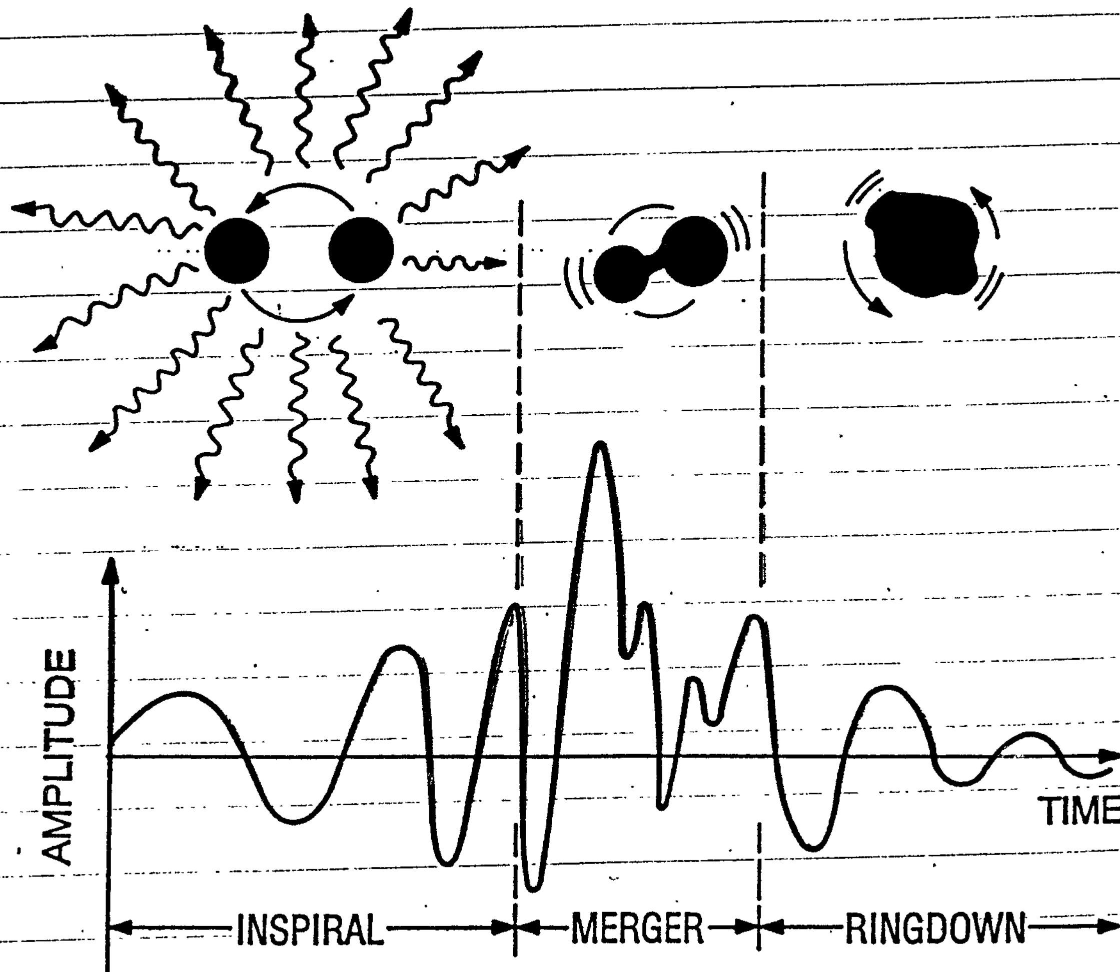


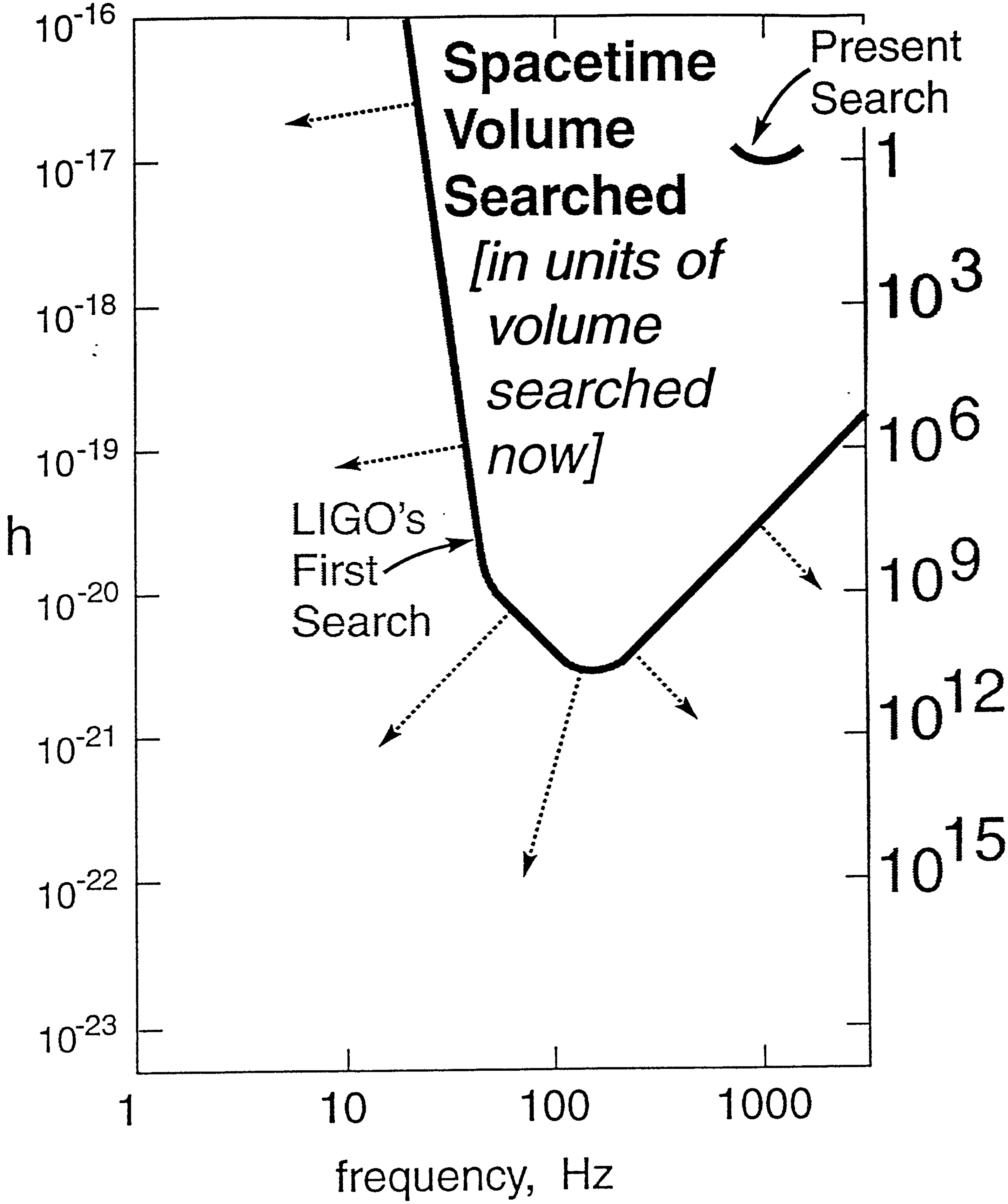
Neutron-Star M(R) → Nuclear Equation of State $P(\rho)$

- Requires several interferometers, with different optical designs, in same vacuum system

[Possible after future upgrade]

Binary Sources
Inspiral and Coalescence



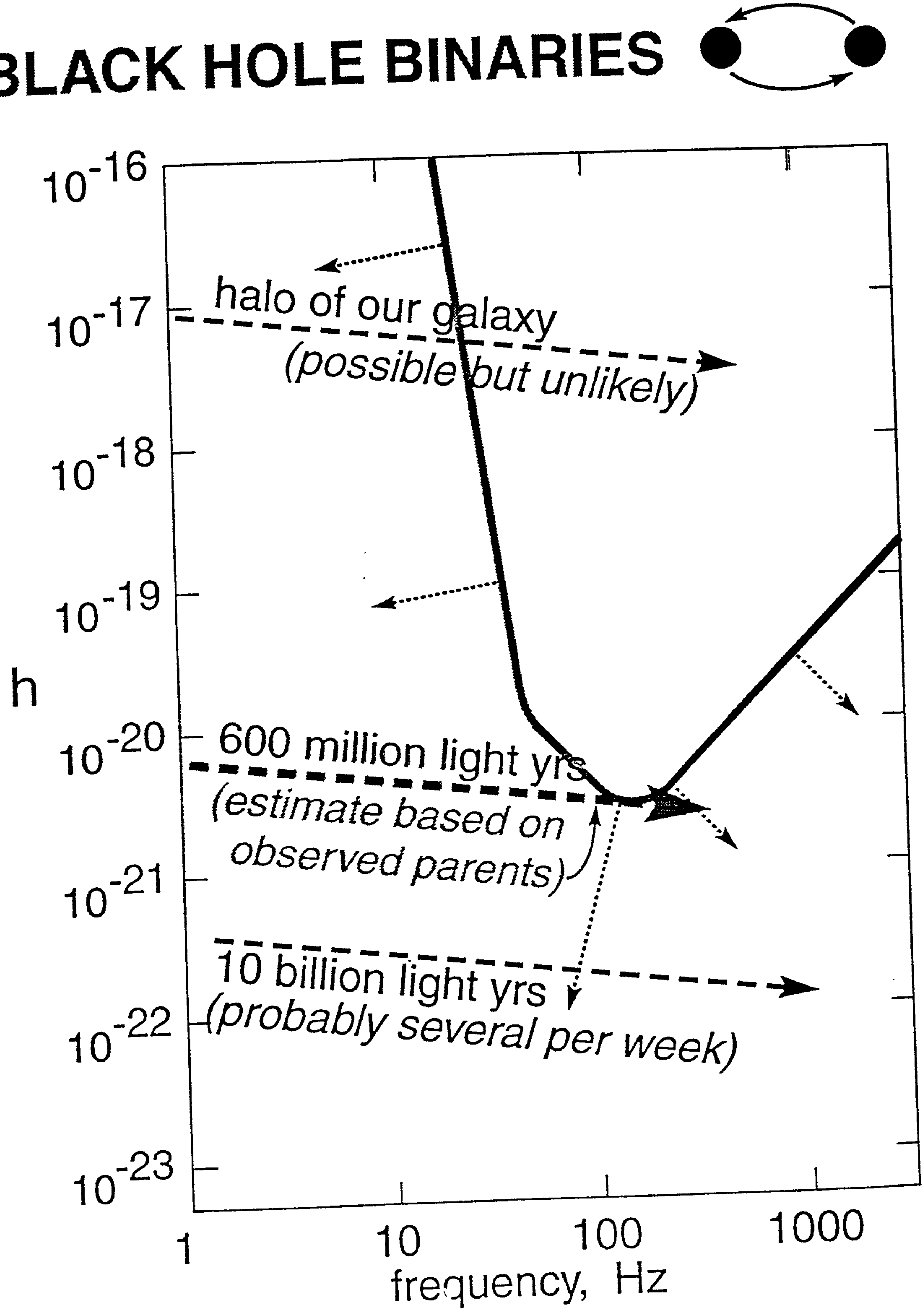


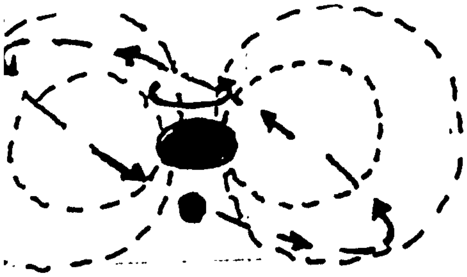
Spacetime
Volume
Searched
[in units of
volume
searched
now]
Present
Search
LIGO's
First
Search
h
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
1
10^3
10^6
10^9
10^{12}
10^{15}
1
10
100
1000
frequency, Hz

LIGO
Long Range Goals

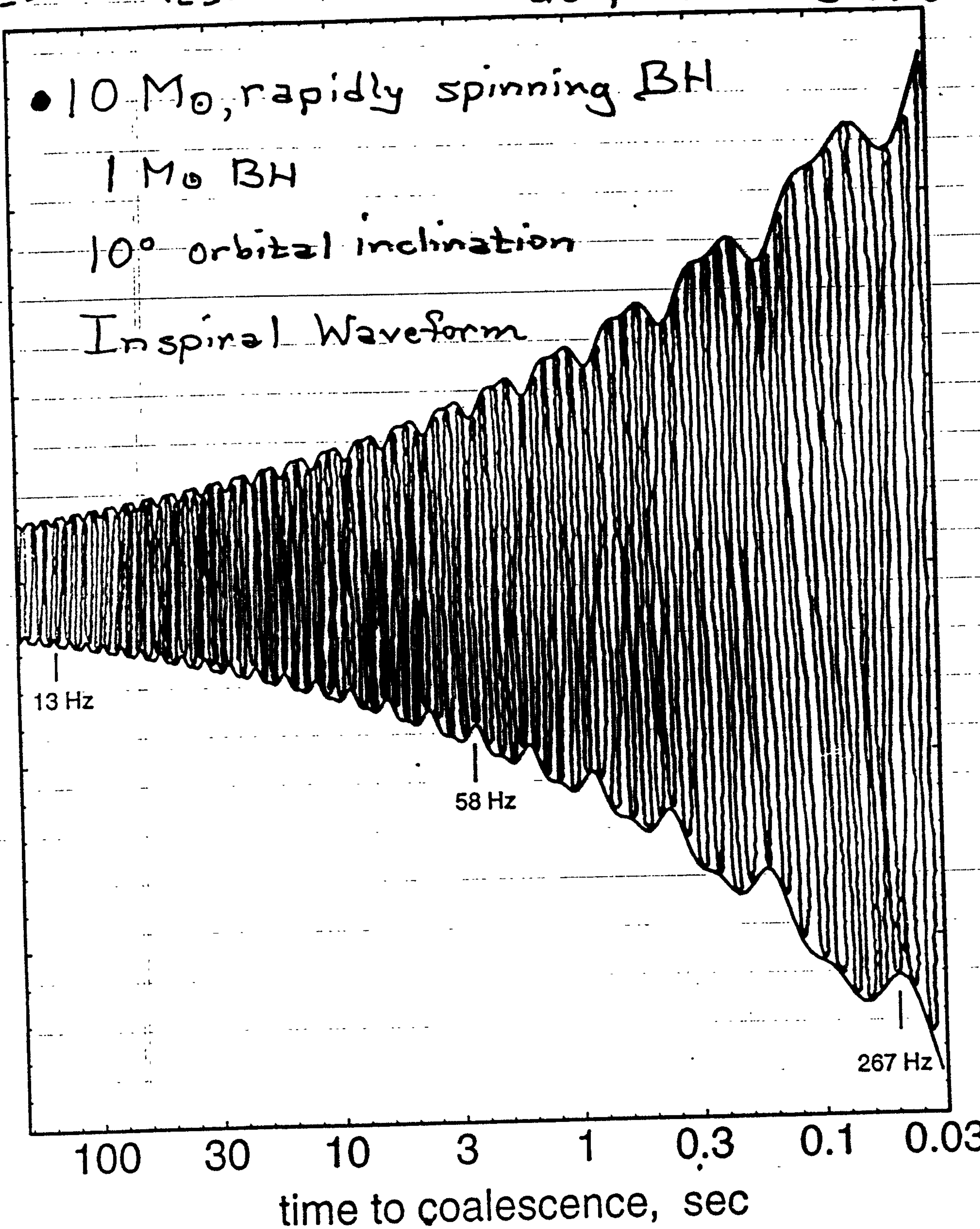
- Final Coalescence of Binary Systems
  - » Neutron Star/Neutron Star
    - – Design Benchmark: last 15 min
      20,000 cycles
      600 MLyr
  - » Black-hole/Black-hole
  - » Black-hole/Neutron Star
- Supernovae
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr
- Early Universe
  - »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

BLACK HOLE BINARIES

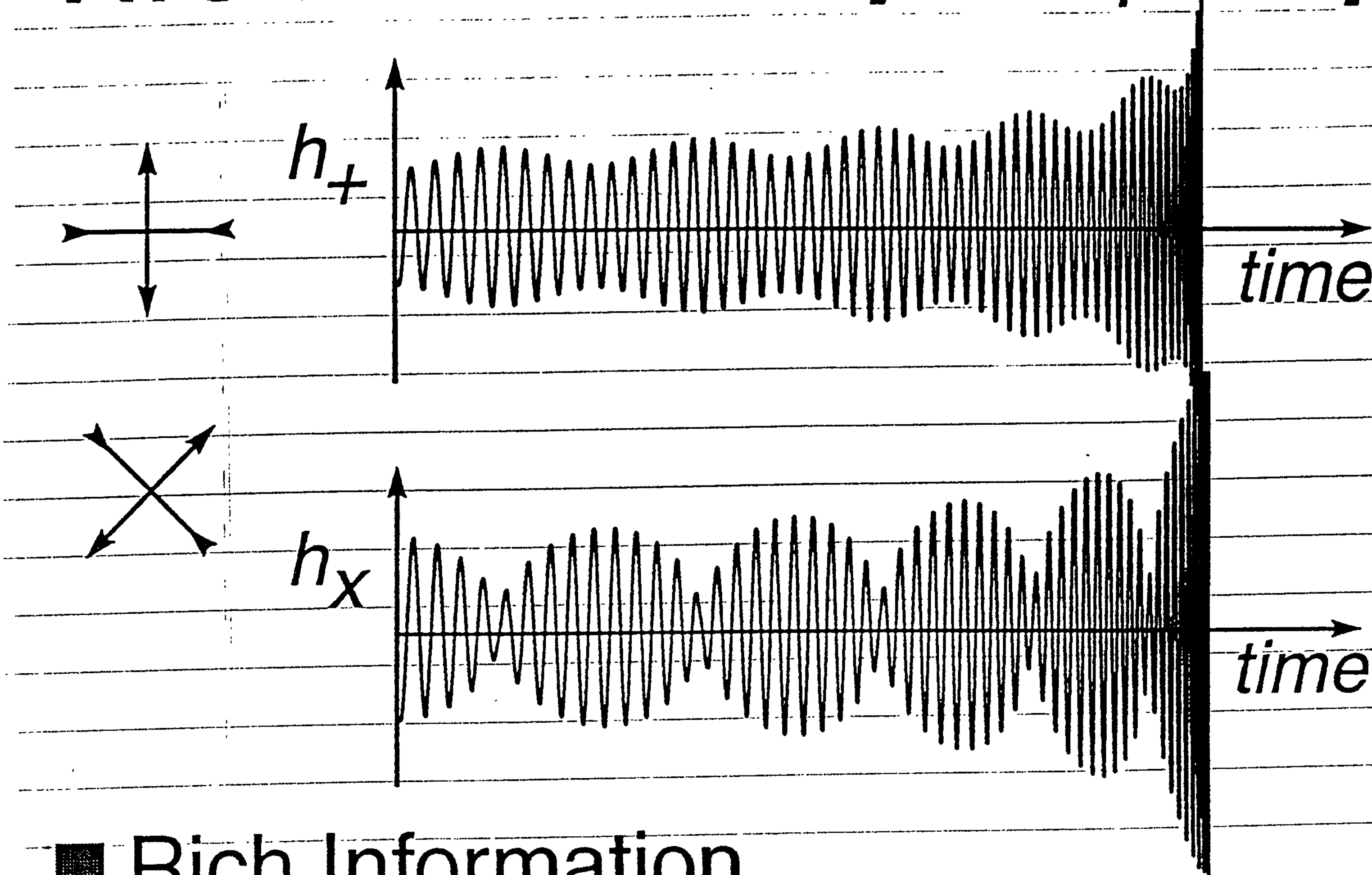




BH Spin → "gravitomagnetic field"
(frame dragging)
→ ~20 precessions of orbit

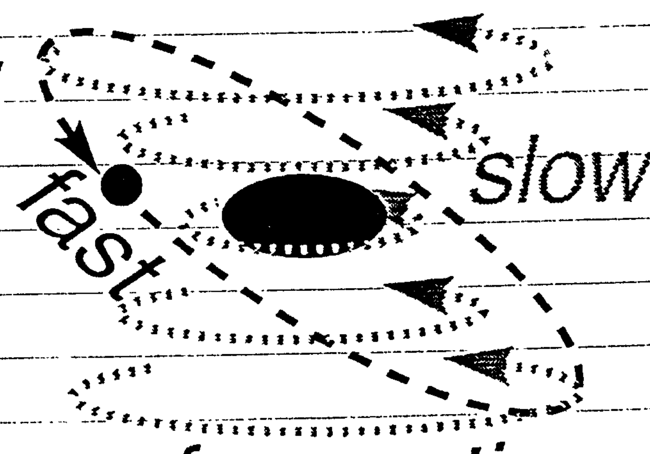


TWO WAVEFORMS *[Stereophonic]*



■ Rich Information

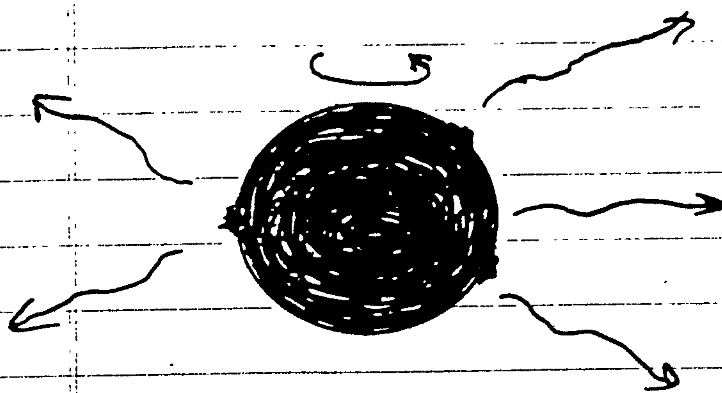
- *Map of spacetime warpage*
- *Tornado-like swirl of space around big hole*



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

OTHER POSSIBLE SOURCES

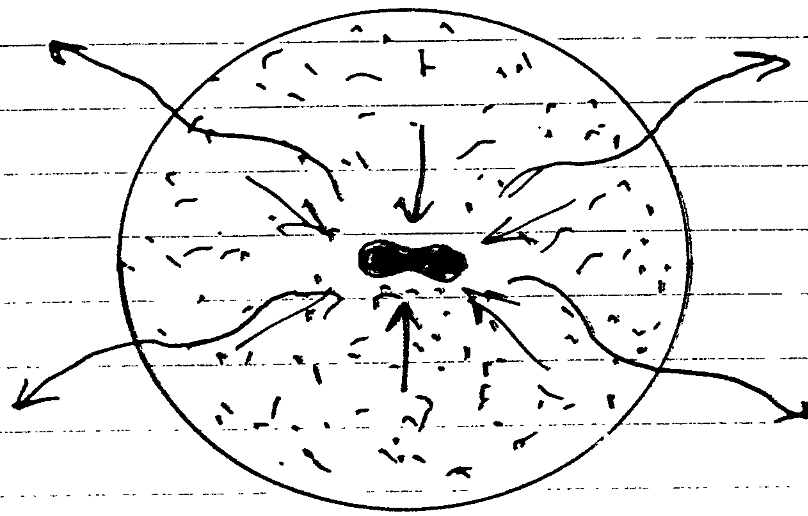
SPINNING, "MOUNTAINOUS" NEUTRON STAR



Periodic

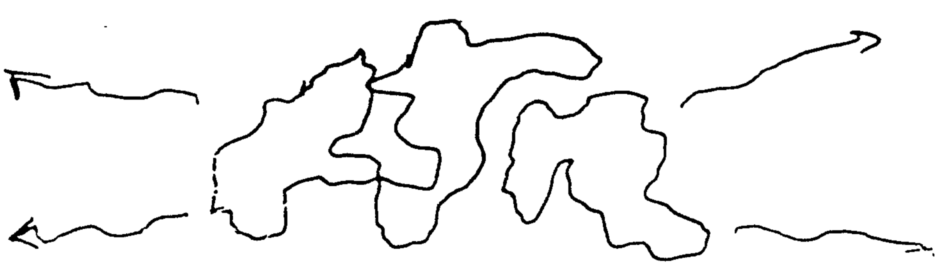
IMPLOSION OF A STAR'S CORE

— WHICH TRIGGERS A SUPERNOVA



Bursts

VIBRATING LOOPS OF COSMIC STRING



Stochastic

Pulsars

periodic sources

- 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

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

ϵ = equitorial ellipticity

↖ Poorly known

Estimate distortion due to dipole magnetic field

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

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

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

(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 $B \simeq 10^8$ 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 ($\sim 3\; 10^{14}\, gm/cm^3$)

FIGURES

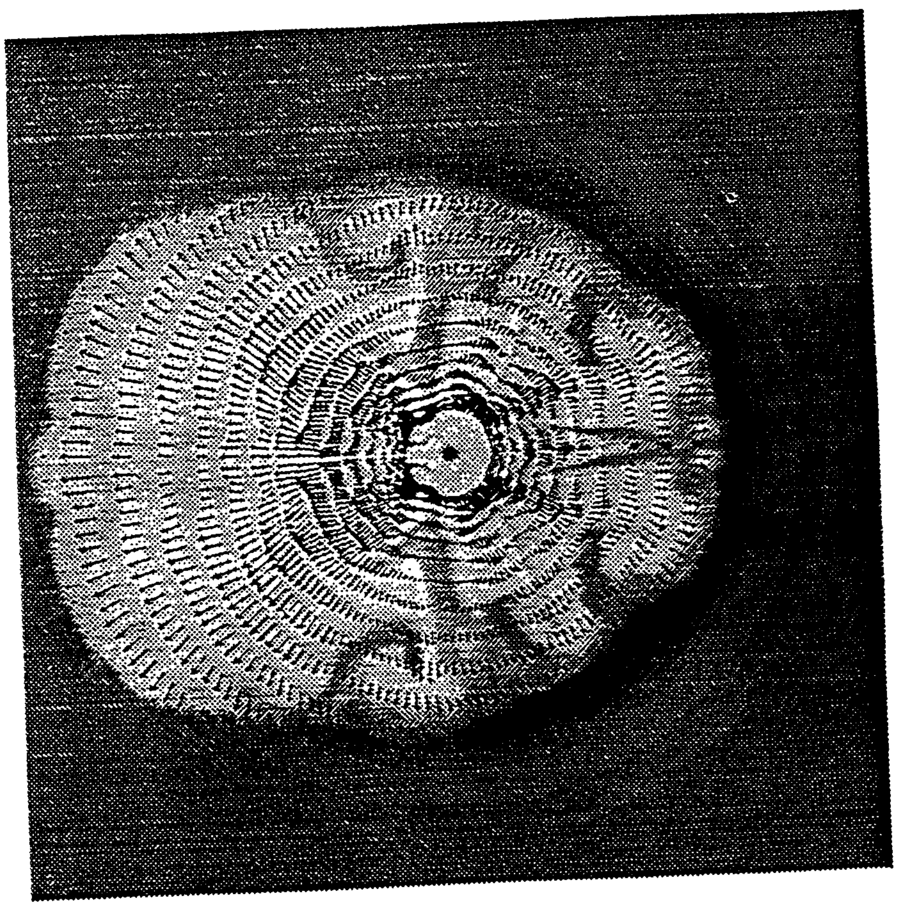


FIG. 1. A grey-scale rendering of the entropy distribution at the end of the simulation, about 50 milliseconds into the explosion. Note the pronounced pole–to–pole asymmetry in the ejecta and the velocity field (as depicted with the velocity vectors). The physical scale is 2000 km from the center to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

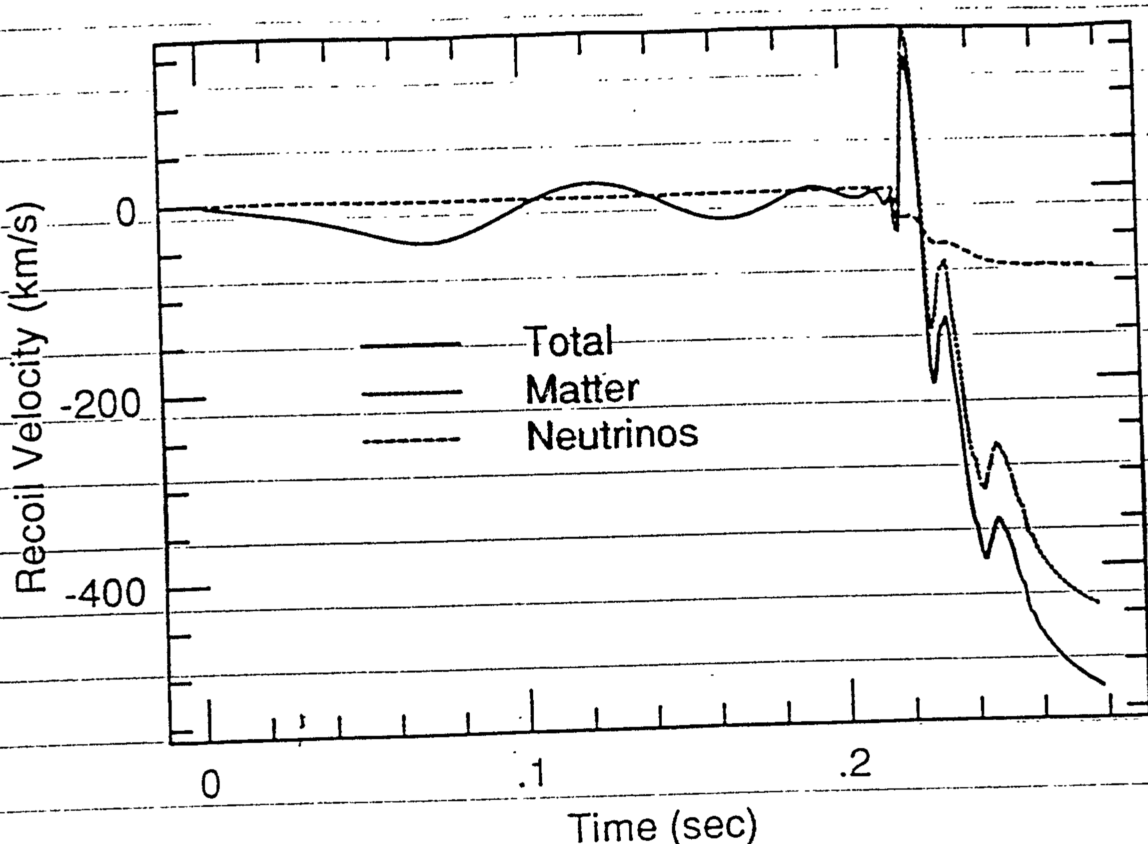


FIG. 2. The inferred recoil speed (in km s^{-1}) imparted to the core versus time (in seconds) for the simulation highlighted in this paper. The initial momentum is approximately zero, but grows systematically after bounce in the direction opposite to the artificial wedge, cut into the core to mimic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

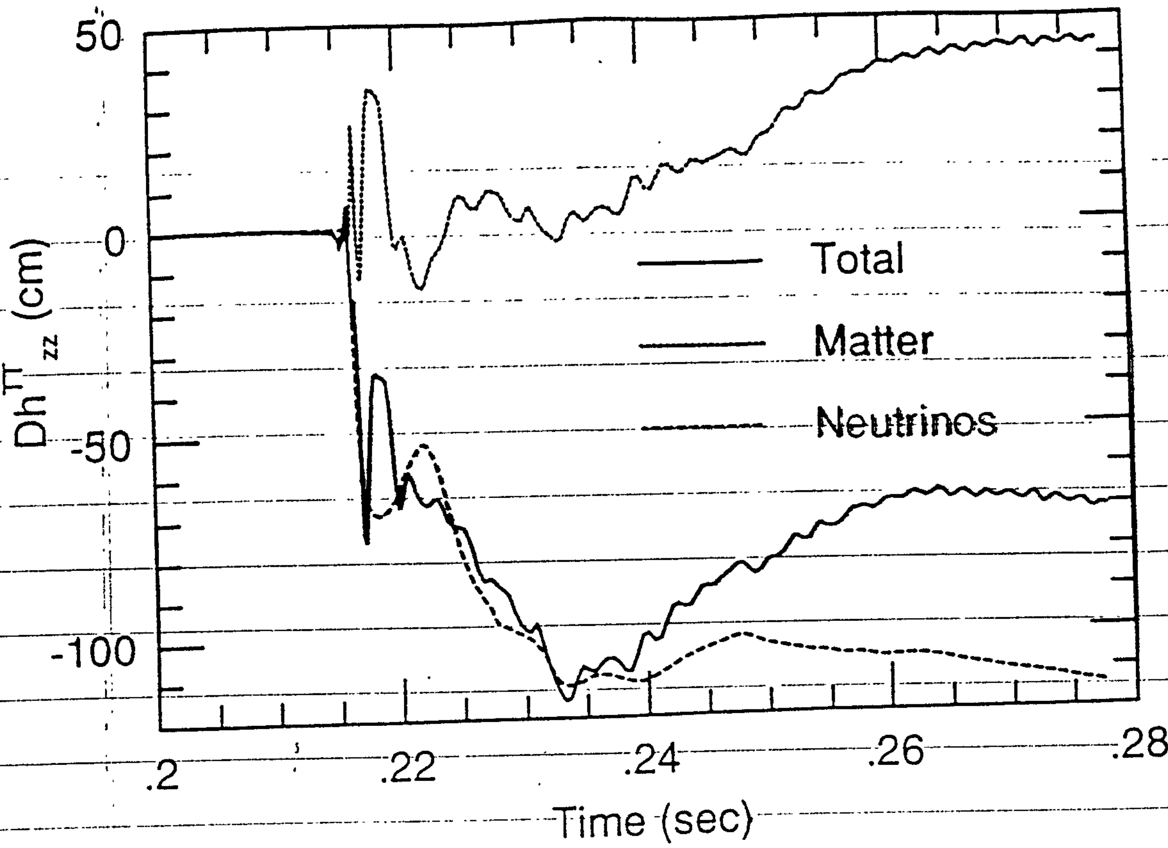


FIG. 3. The gravitational wave strain, h^{TT}_{zz}, times the distance to the supernova, D, versus time (in seconds). Core bounce is at 0.215 seconds. The total, matter, and neutrino waveforms are rendered with the solid, dotted, and dashed lines, respectively.

- physics modeling very difficult
  (departure from spherical shape)

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

    $J = 2\ 10^{47}$ erg-sec

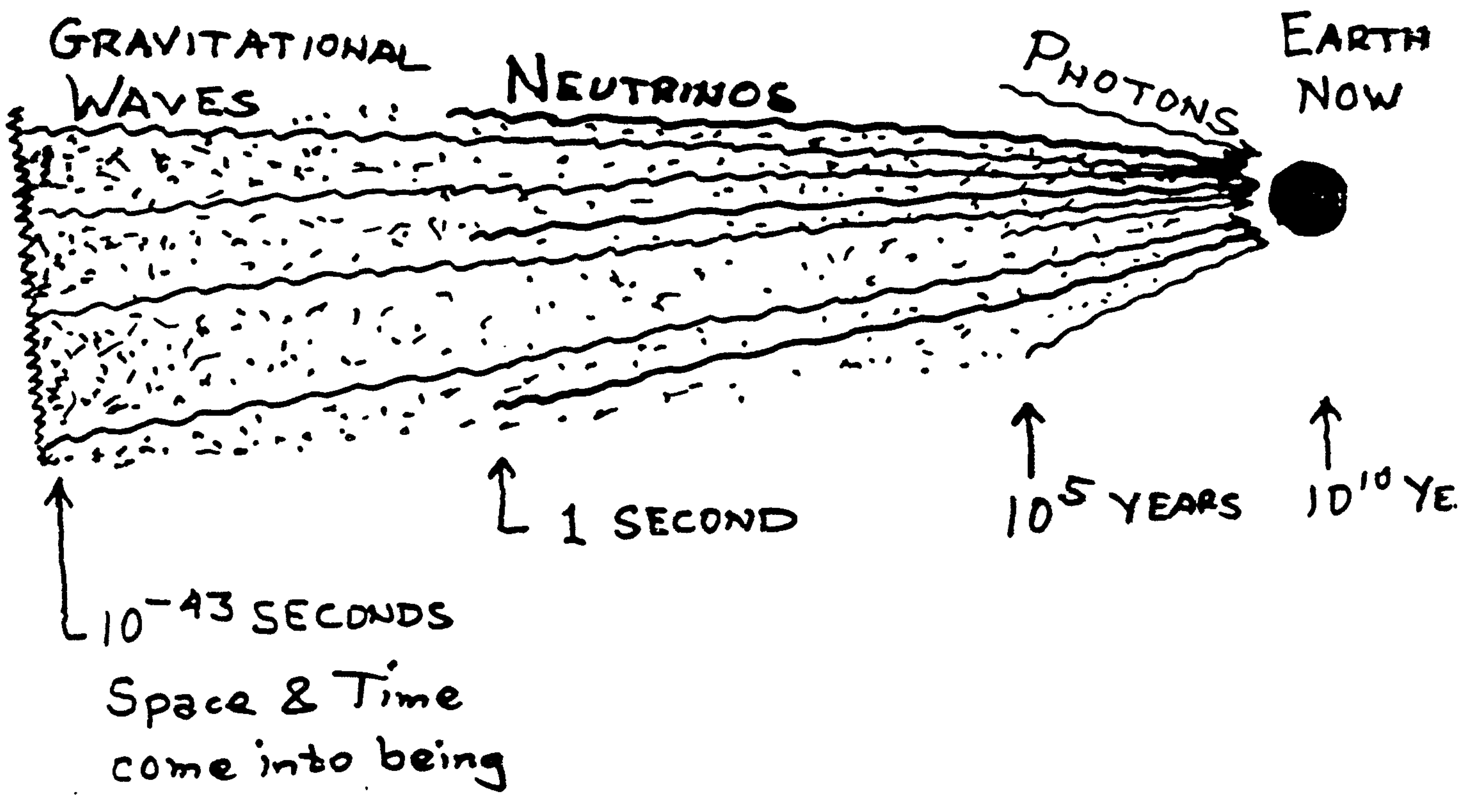
    (Saenz-Shapiro → radiate gravitational

    $3\ 10^{-6}$ of rest mass

    $h \approx 10^{-23}$ @ VIRGO

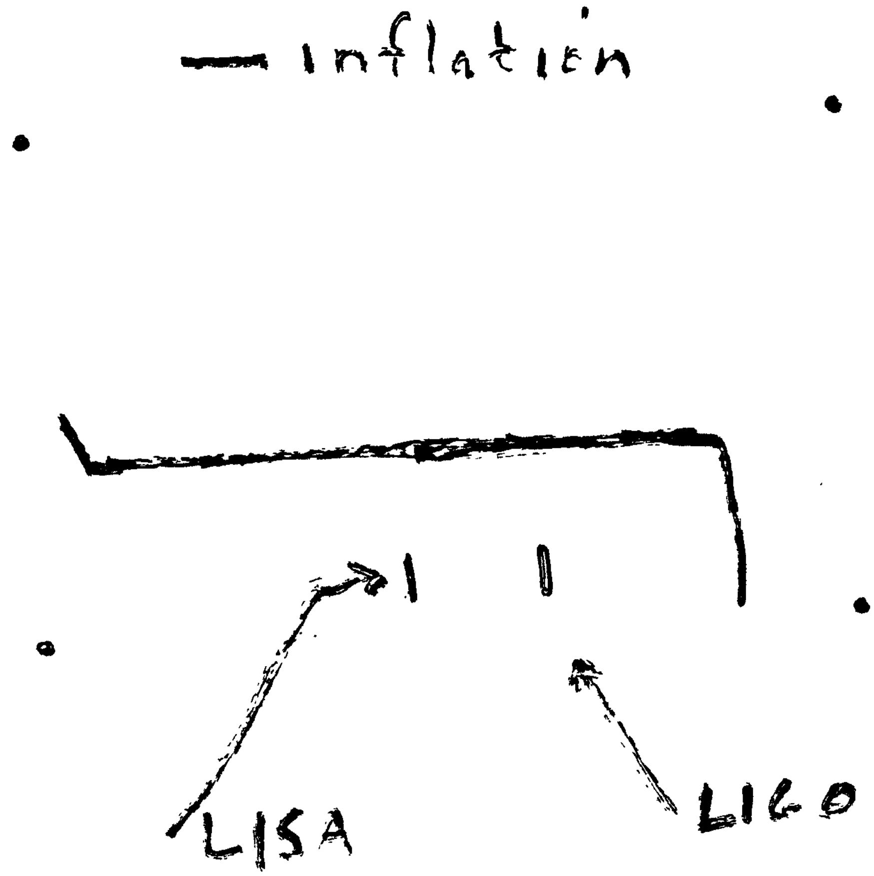
  - collapsing cores w/ high angular momentum?
    (eg "millisecond pulsars)

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 (electrowk)
graviton $\sim$ 1 keV


— inflation
LISA
LIGO

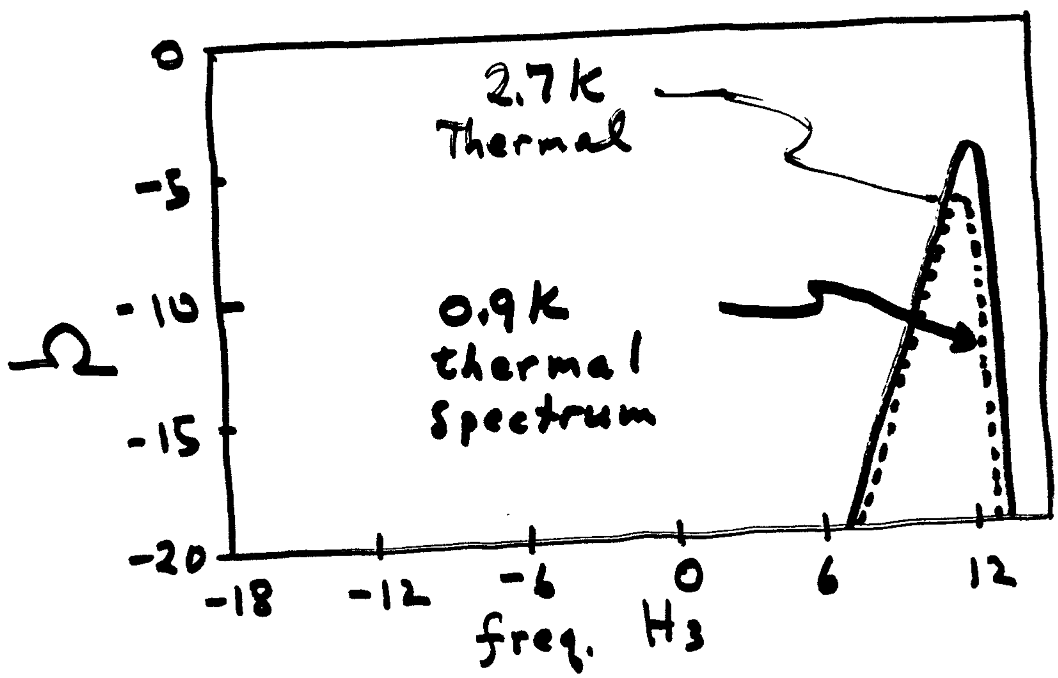
Stochastic Gravity-Wave Background

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

  (also could be overwhelmed by more recent sources)

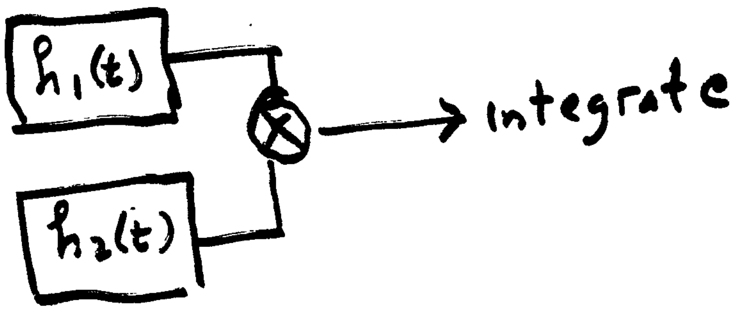
- graviton background analogous to Ω_{em}
  THERMAL SPECTRUM $T \sim 0.9$ K

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



- 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 $h_1(t)\, h_2(t) > 0$

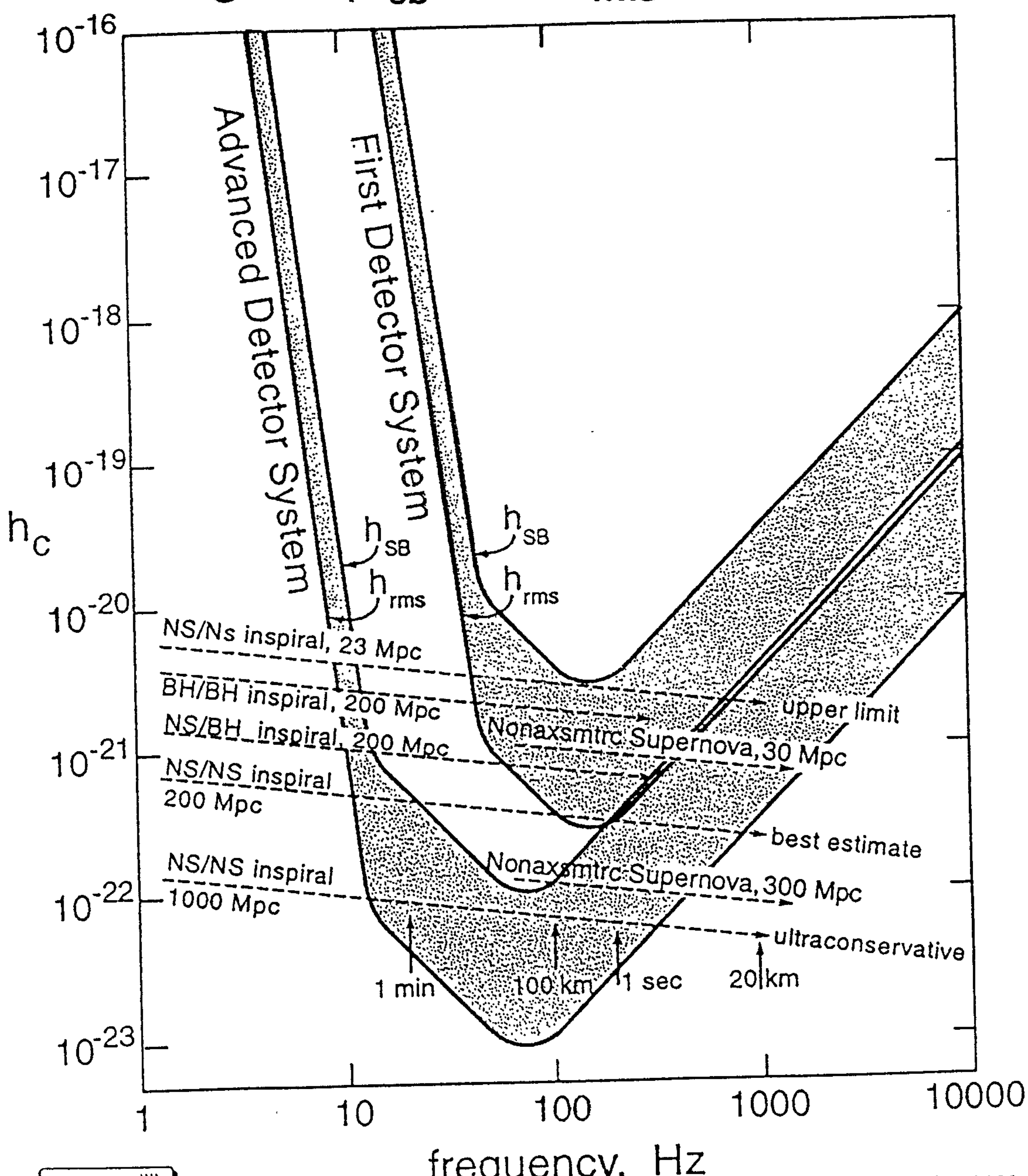
In absence of background (and other signals)
average product $h_1(t)\, h_2(t) \to 0$

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

LIGO

Sensitivity

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



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

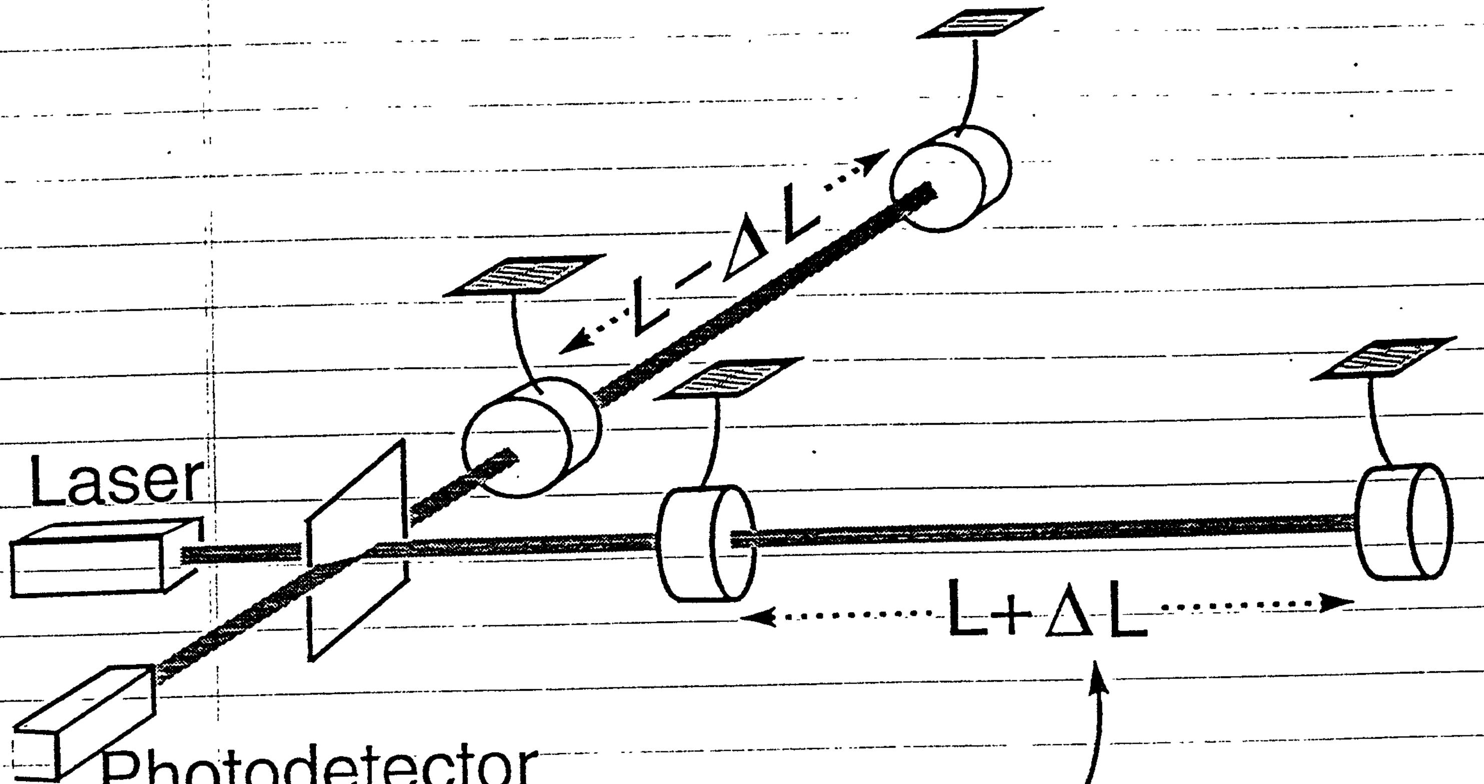
LIGO Site Pair

- Hanford, Washington
  - Located on U.S. Dept. of Energy Reservation
  - Treeless, Semi-arid Desert
  - Approx. 25 km from Richland (Metropolitan Pop. 140,000)
- Livingston, Louisiana
  - Located in Forested Rural Area
  - Approx. 50 km from Baton Rouge (Pop. 450,000)

LIGO

BB
clm

LIGO INTERFEROMETERS



$$\Delta L = hL = 4 \times 10^{-16}\ \text{cm}$$

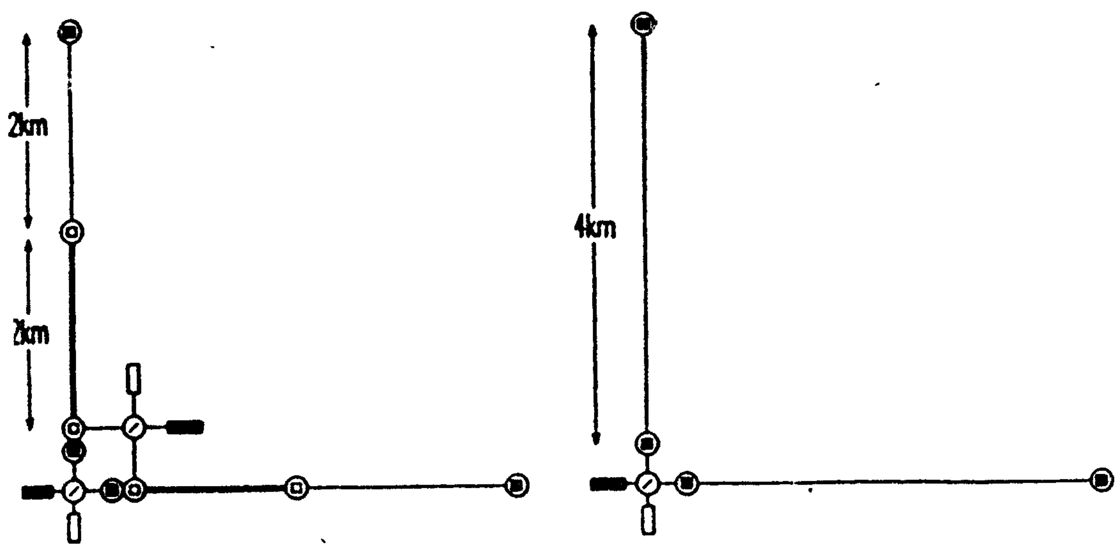
(h: 10^{-21}; L: 4 km)

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

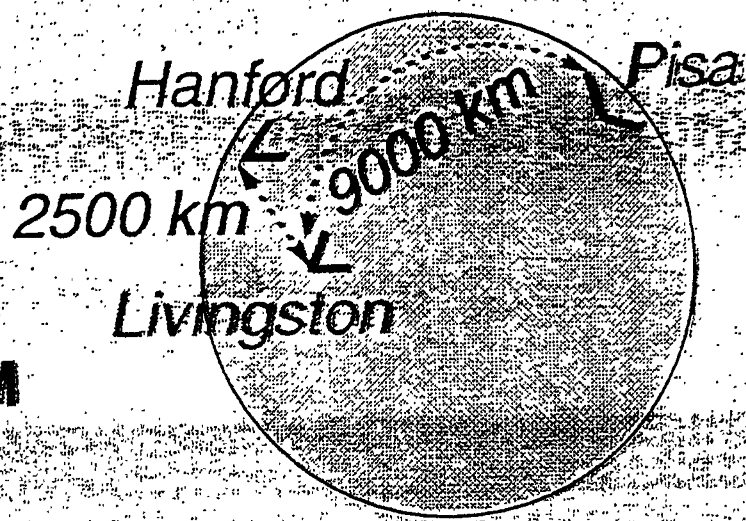
- Measured waveform, $h(time) = \Delta L/L$, is a linear combination of h_+ and $h_\times$, which depends on interferometer's orientation

Description of LIGO

- Two Sites - Widely Separated
- Hanford, Washington
  - 4km and 2km Interferometers
- Livingston, Louisiana
  - 4 km Interferometer
- Expansion for Advanced Detectors



THE LIGO/VIRGO NETWORK



- Hanford & Livingston: close enough together to be nearly in same plane; same orientation. **SEE SAME WAVEFORM**

- Hanford/Livingston plane is approximately perpendicular to Pisa plane; so orientations are very different. Thus, **DIFFERENT WAVEFORMS**

- Consequences:

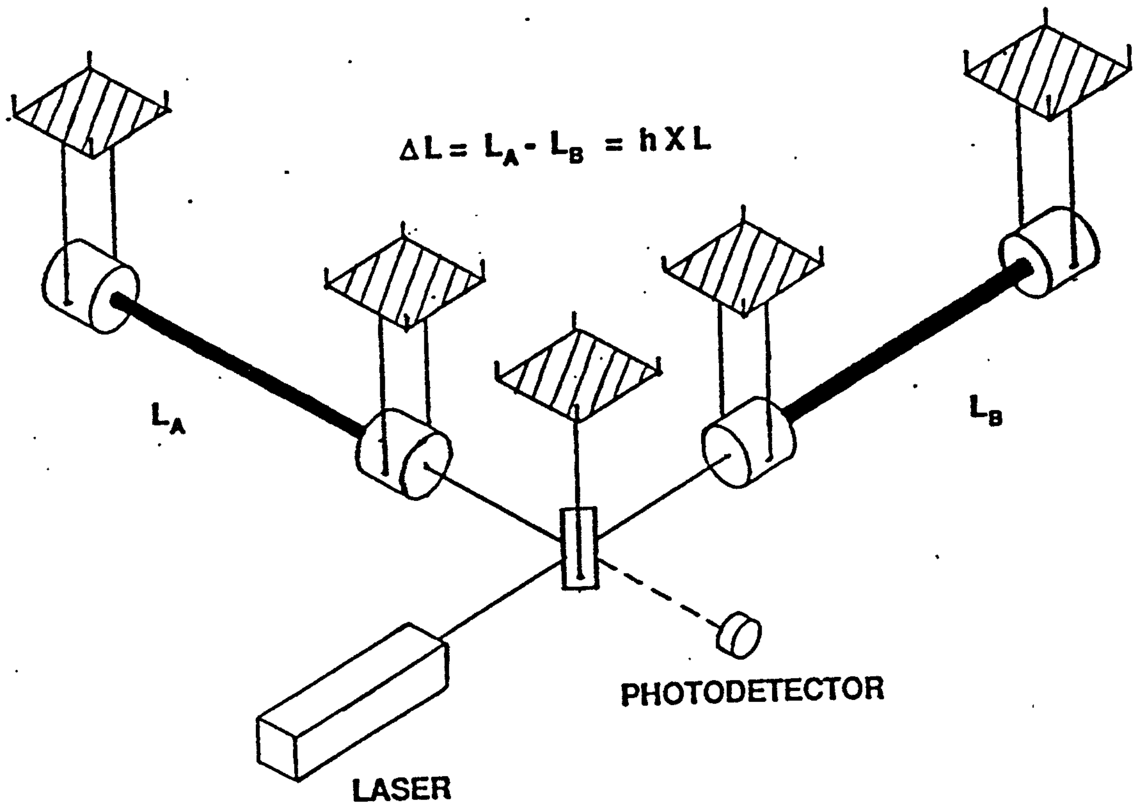
  Pisa **CANNOT** be used, together with Hanford or Livingston, to search for waves

  Pisa must be added to the Network, in order to extract full information from the waves:

  Both Waveforms: h_+, h_X
  Direction to Source

Interferometers

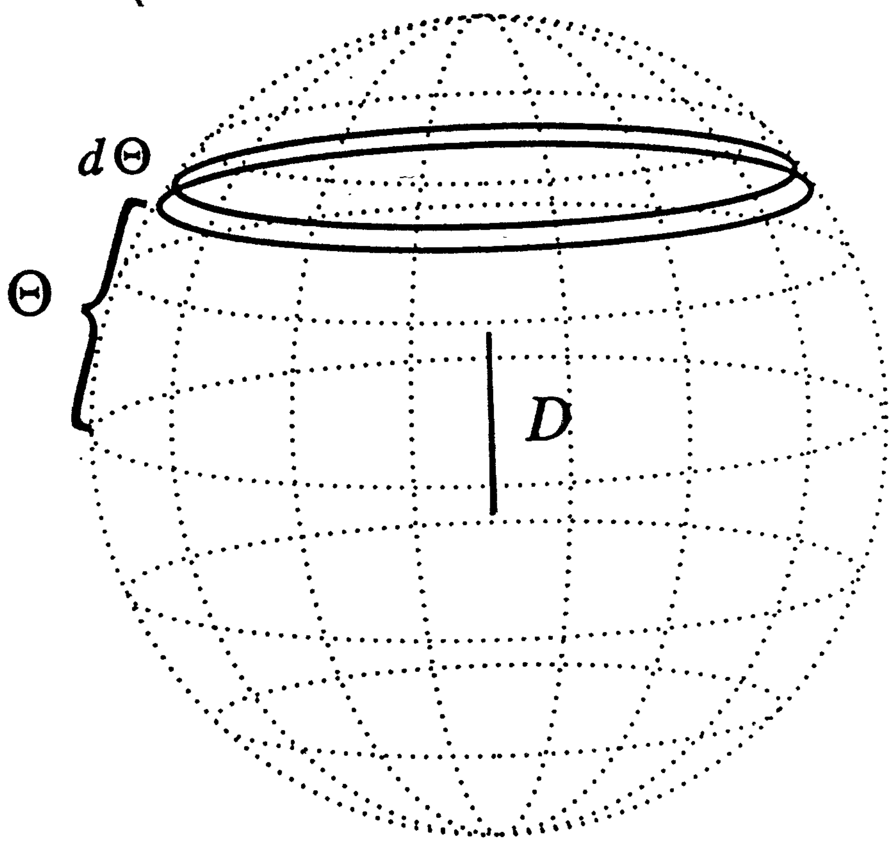
- $\Delta L/L = h = F_+ h_+(t) + F_x h_x(t)$



- 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)

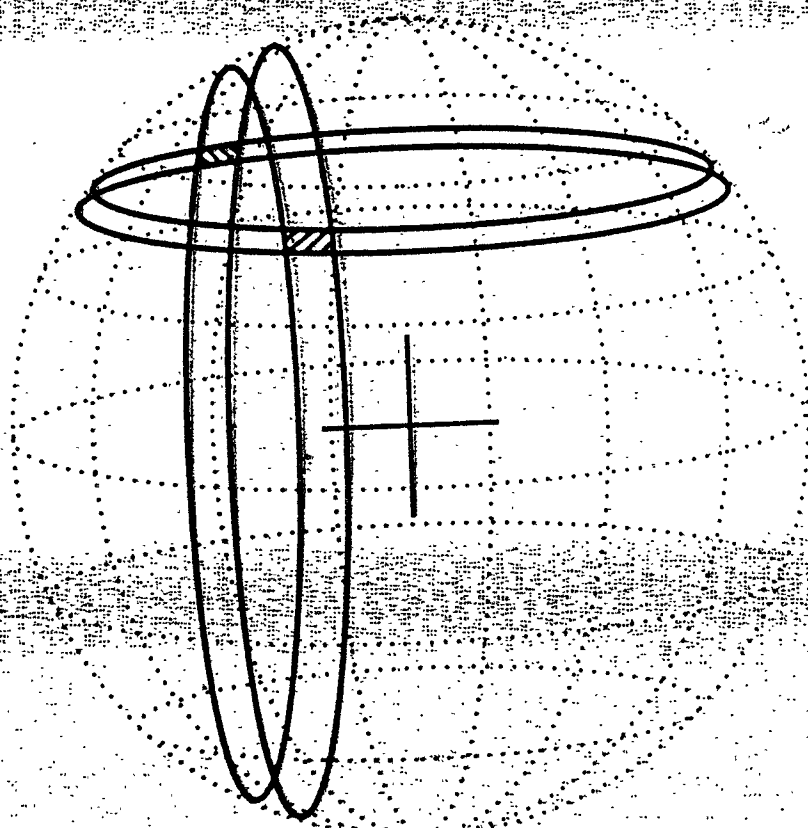


- determine from time shift between detectors (~.1 msec accuracy)
- 'declination angle' of circle (ring)

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

Source Positions
LIGO + VIRGO

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



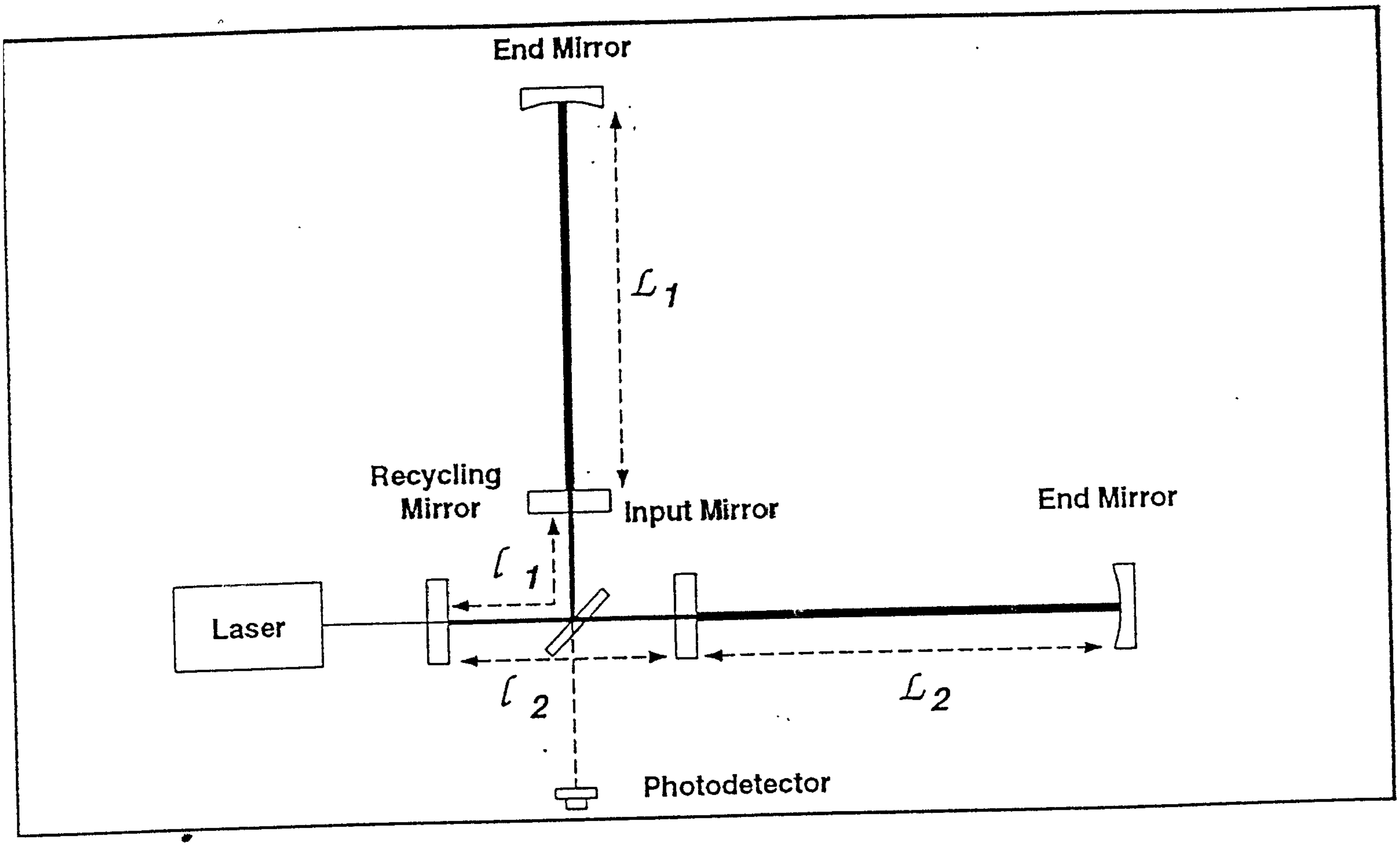
LIGO-G960116-00-M

Lecture 4

B. BARISH

LIGO
Basic Configuration

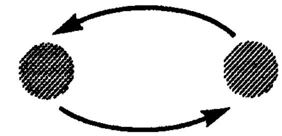
- Michelson with Fabry-Perot cavities



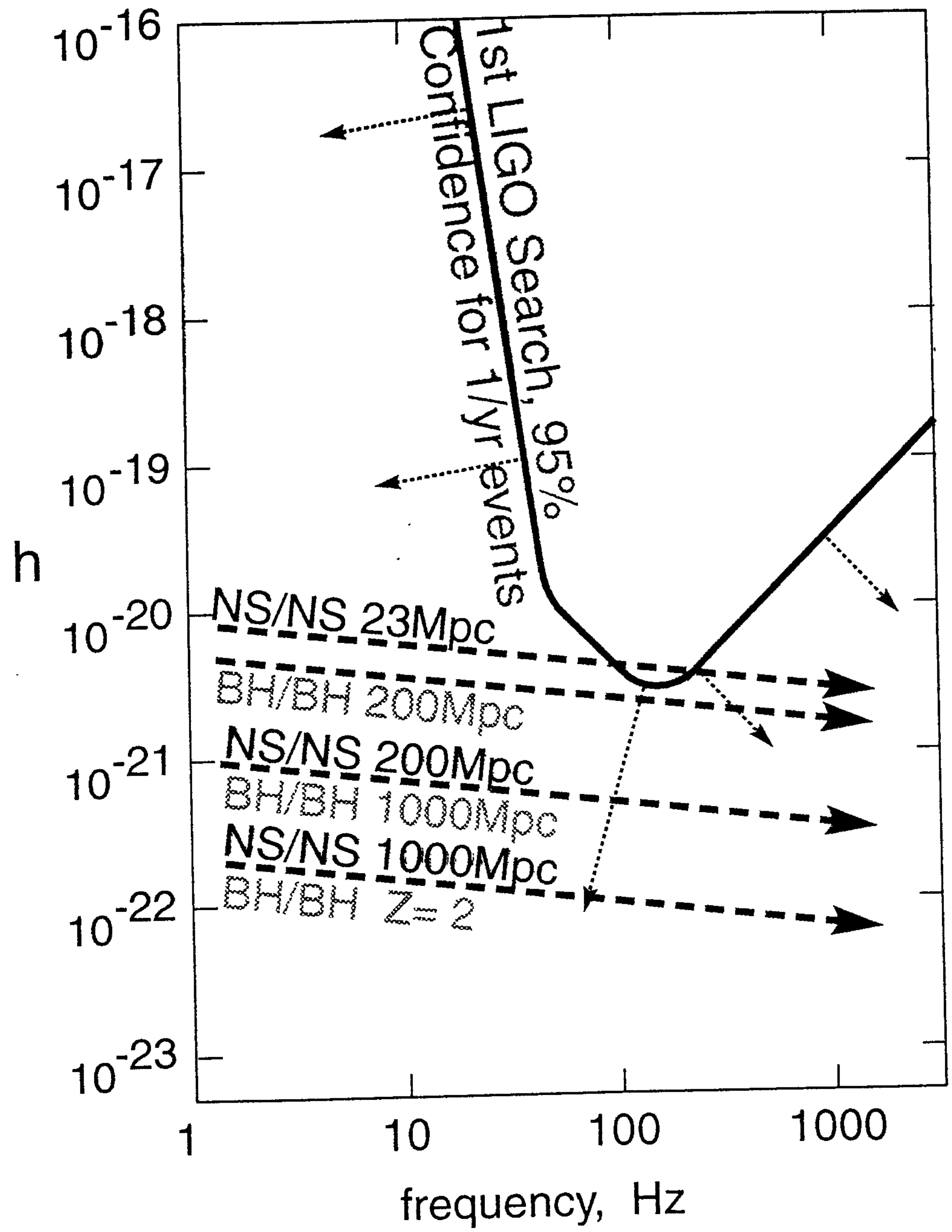
Initial Interferometer
Specifications

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*

NEUTRON STAR BINARIES

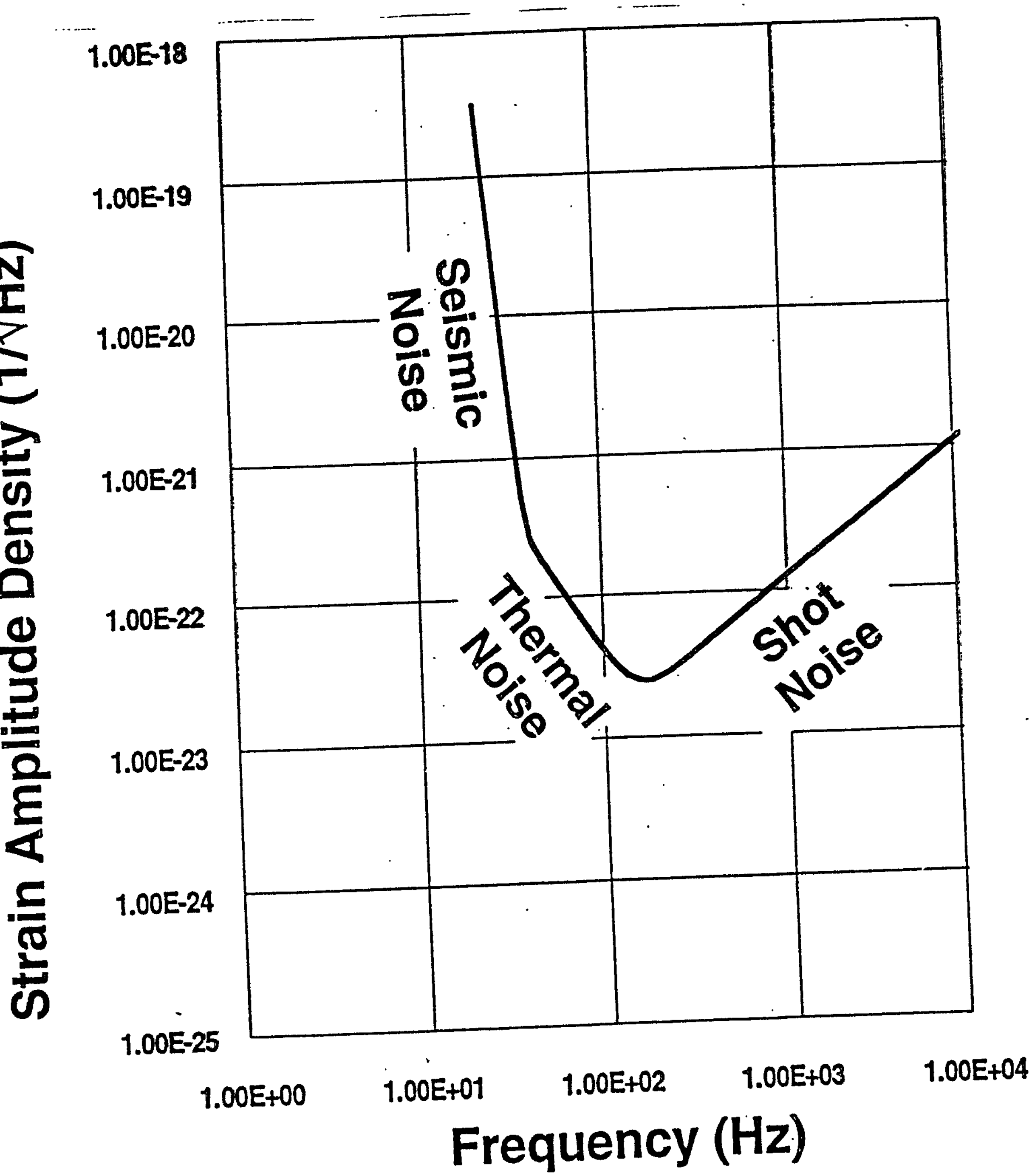


["Near-Guaranteed" source]



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

Initial Interferometers
Noise Floor



LIGO

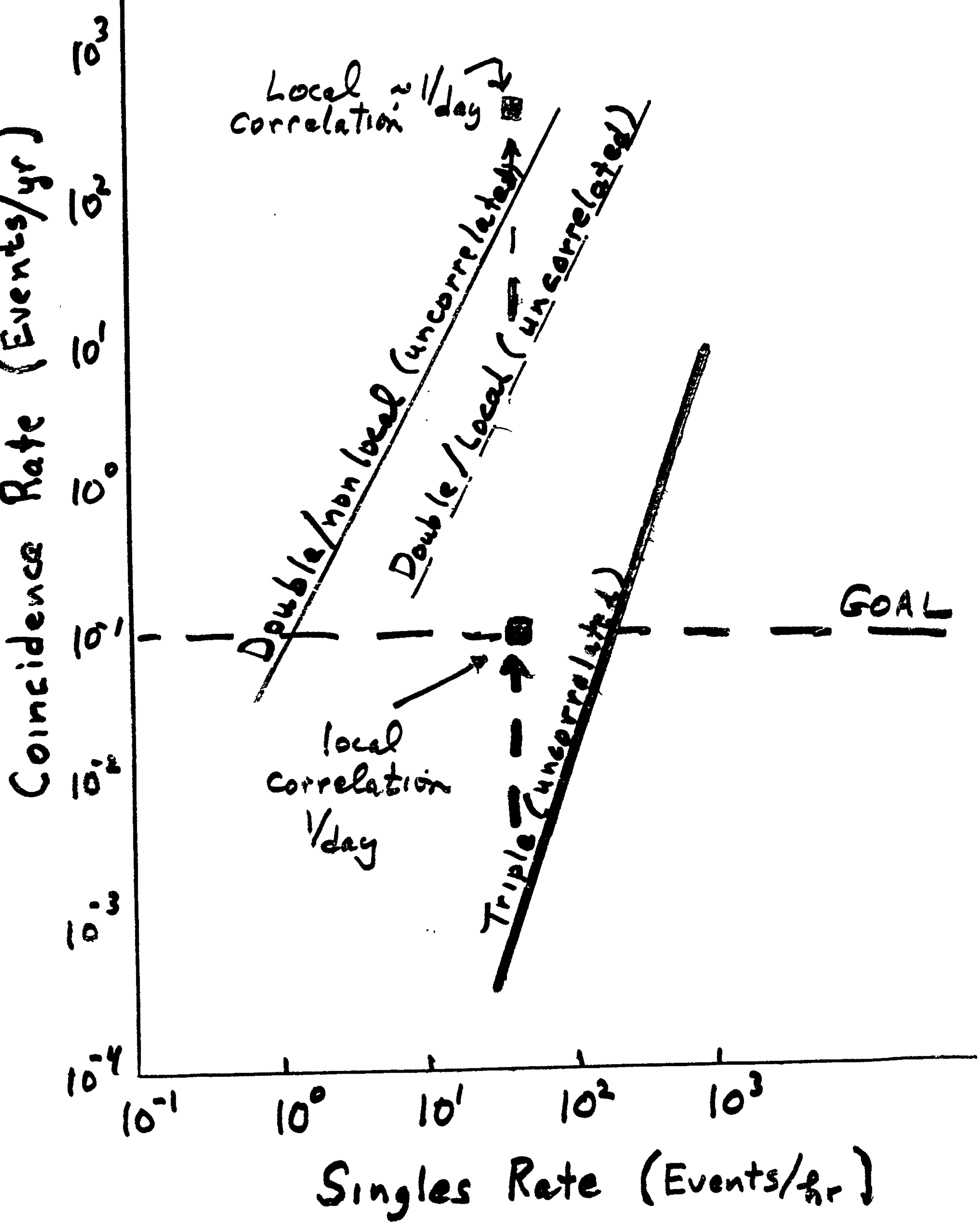
LIGO-G960108-00-M

Gravitational Wave Detection Strategy

- Interferometer Sensitivity
  - ⇒ R&D Program
    - Technology Development
    - Demonstration Experiments
  - ⇒ Engineering Implementation
    - Precision Engineering Design
    - Quality Control
- 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)

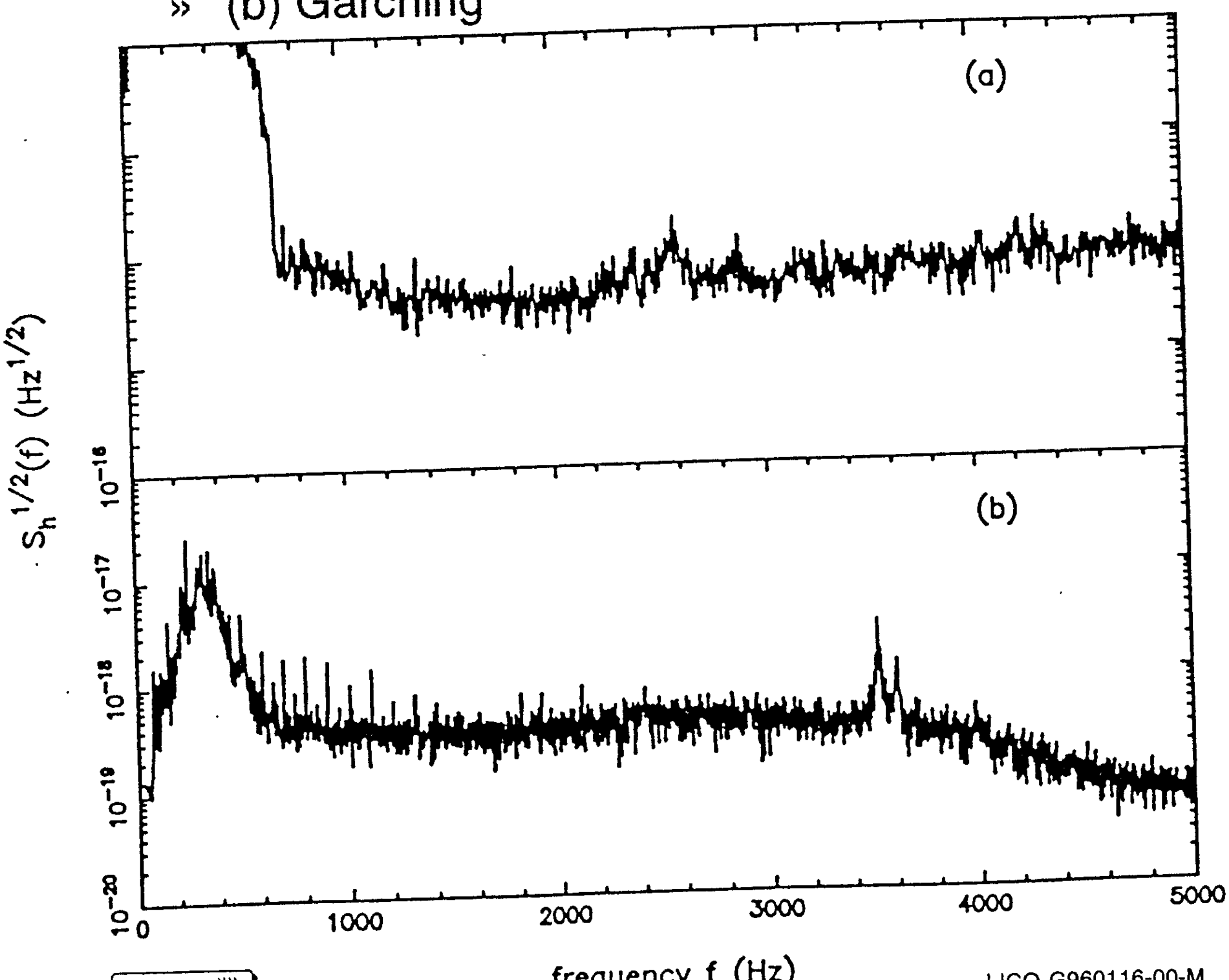
MULTIPLE COINCIDENCES

local window 1msec
non-local window 20msec



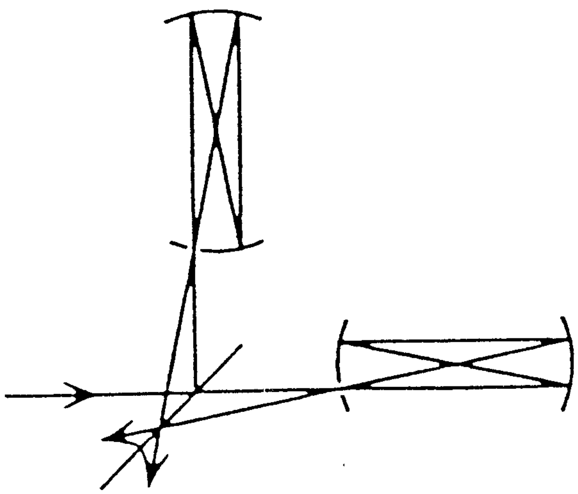
Interferometers
Coincidence Experiment

- Interferometers
  - » Glasgow (Fabry-Perot interferometer)
  - » Garching (Michelson delay-line interferometer)
- Strain Sensitivities (~10^{-17} rms noise)
  - » (a) Glasgow
  - » (b) Garching

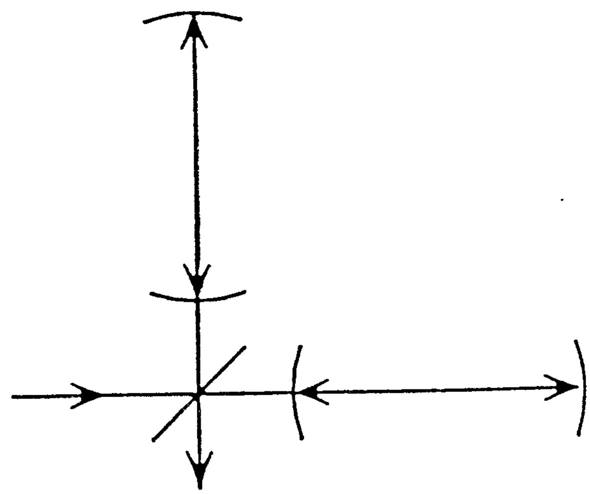


Interferometer
types

- Folded interferometers
  - » Delay-Line (N=4)
  - » Fabry-Perot



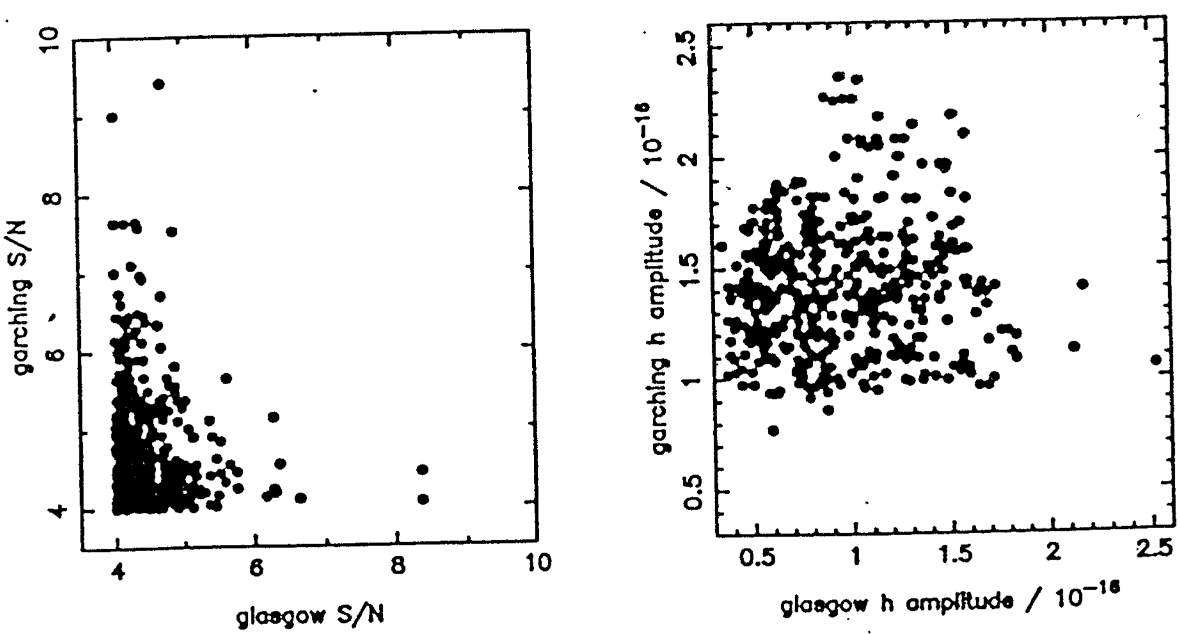
Delay-Line (N=4)



Fabry-Perot

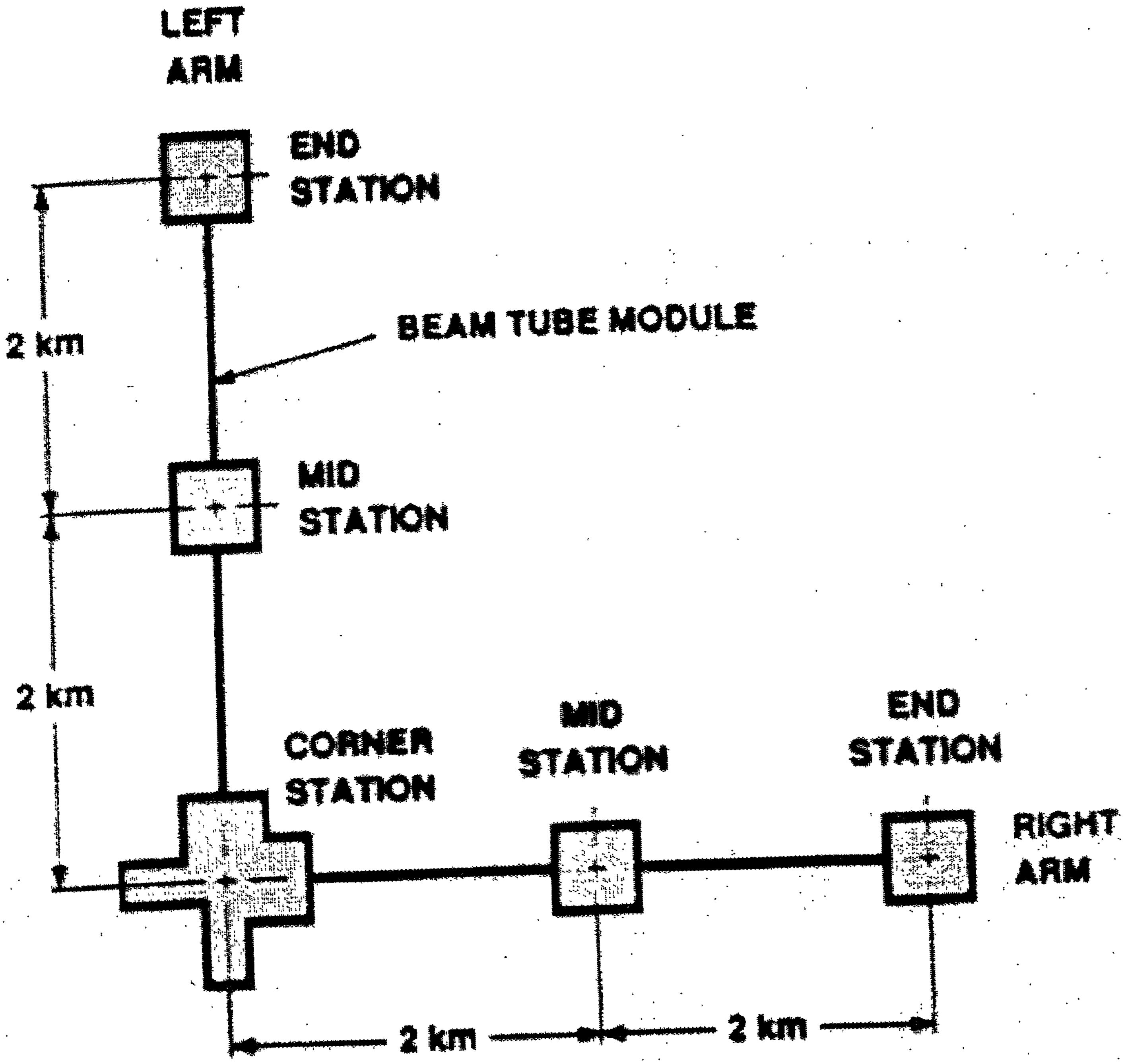
Interferometers
Coincidence Experiment

- Glasgow - Garching
- 100 hour coincidence experiment
  - » Analysis
    - level 1 - housekeeping vetoes
    - level 2 - 62 hrs good data (<4 10-17 for 1.6 sec)
    - level 3 - require same strain in both detectors
  - » Result
    - $h < 1.6\ 10^{-16}$ from zenith and optimumpolarization
    - $h < 3.6\ 10^{-16}$ any direction and any polarization



LIGO Project
Technical

- Major Facilities
  - » Beam Tube
  - » Vacuum Systems
  - » Civil Construction
- Detector
  - » Detection Strategy
  - » Interferometers
- R&D
  - » Noise Sources and Sensitivity
  - » Demonstration Experiments
- Status and Plans


LEFT ARM
END STATION
2 km
BEAM TUBE MODULE
MID STATION
2 km
CORNER STATION
MID STATION
END STATION
RIGHT ARM
2 km
2 km

Gravitational Wave Strength

Strain Sensitivity

$$h \approx \frac{G(E_{kin}^{ns} / c^2)}{r} \frac{1}{c^2}$$

for $E_{kin}^{ns} / c^2 \sim M_\Theta$

$h \sim 10^{-20}$ for Virgo Cluster of Galaxies

$h \sim 10^{-23}$ at Hubble Distance

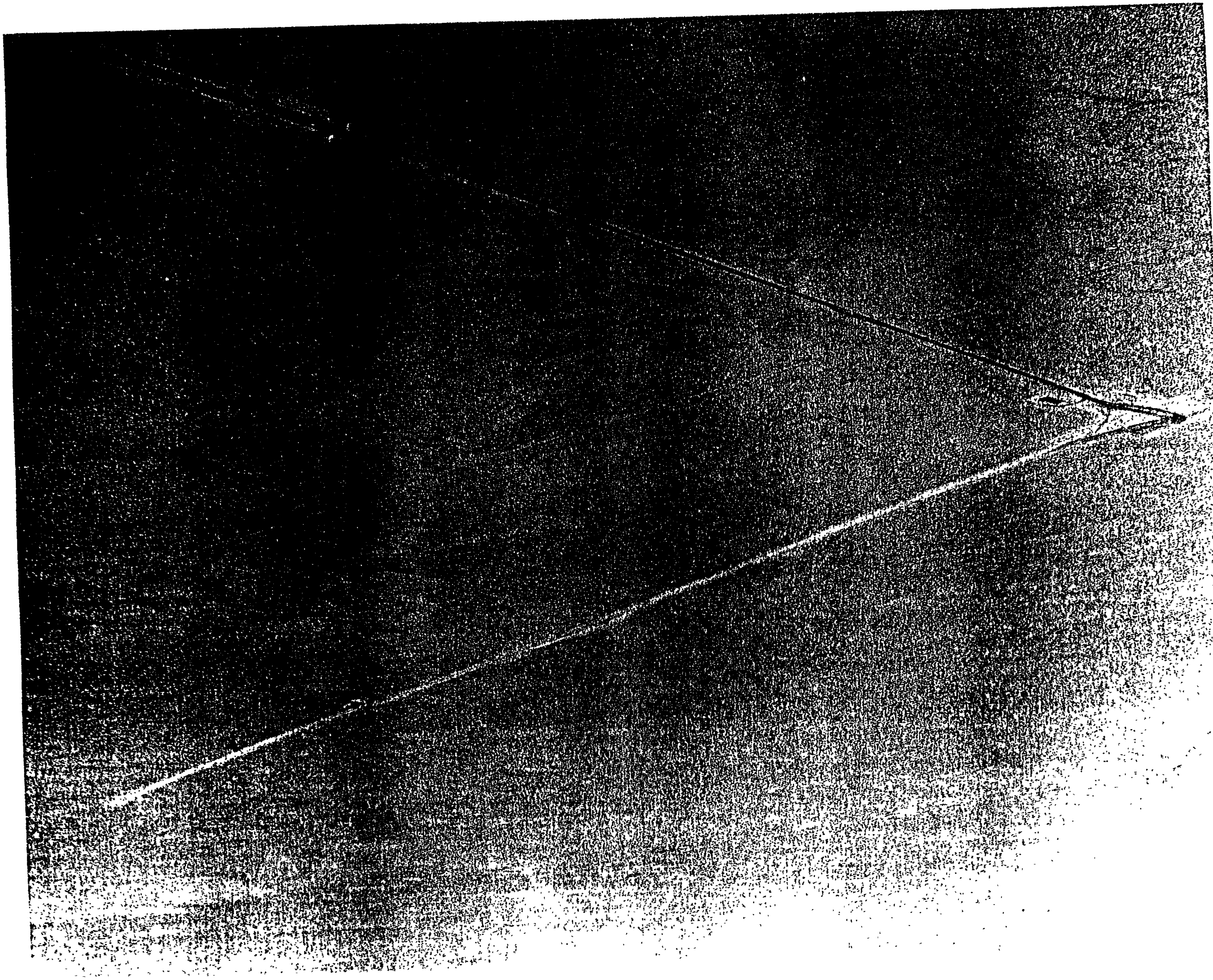
LIGO Goal: $h \sim 10^{-22}$

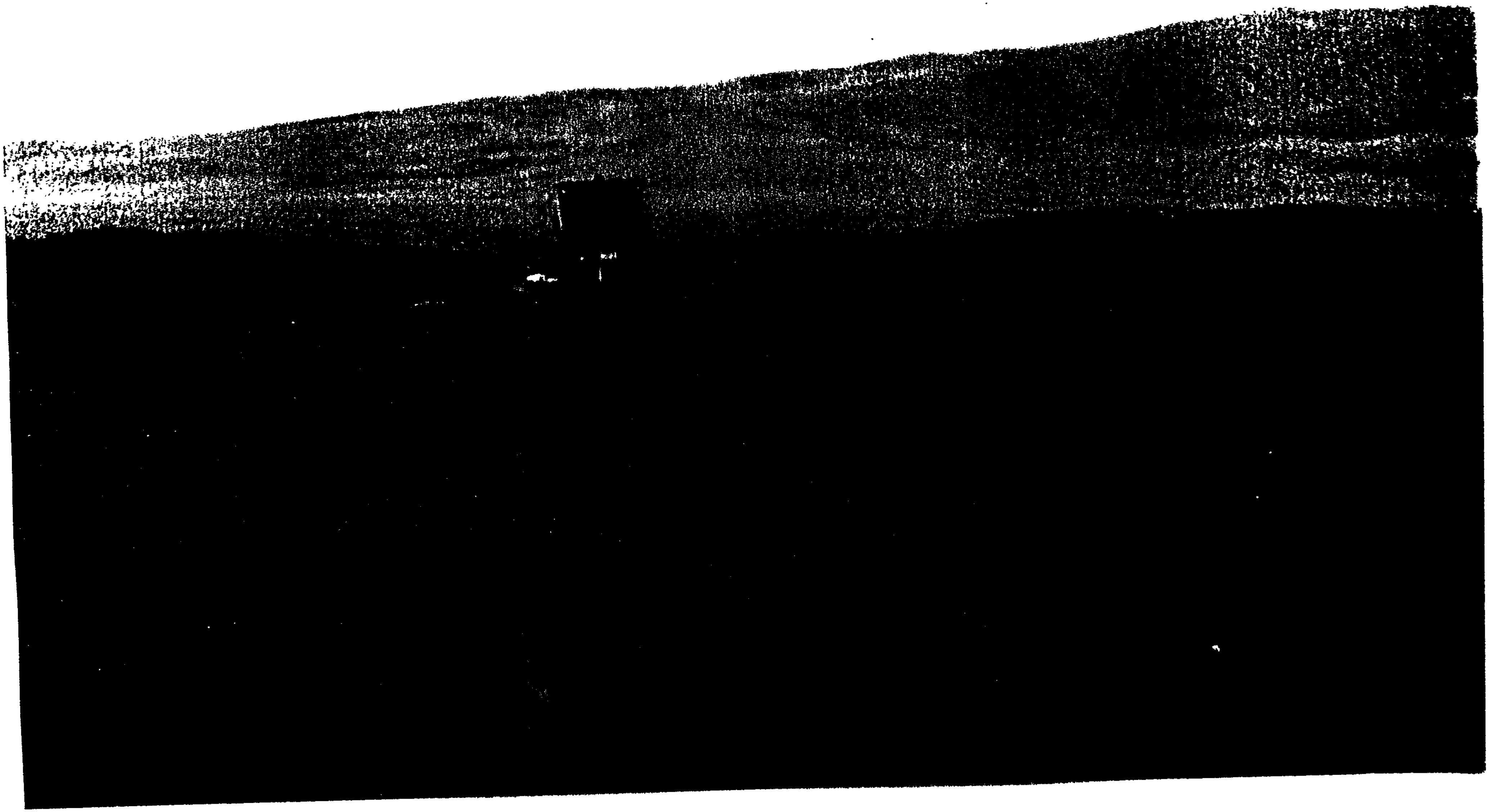
Detector $\Delta L = hL$

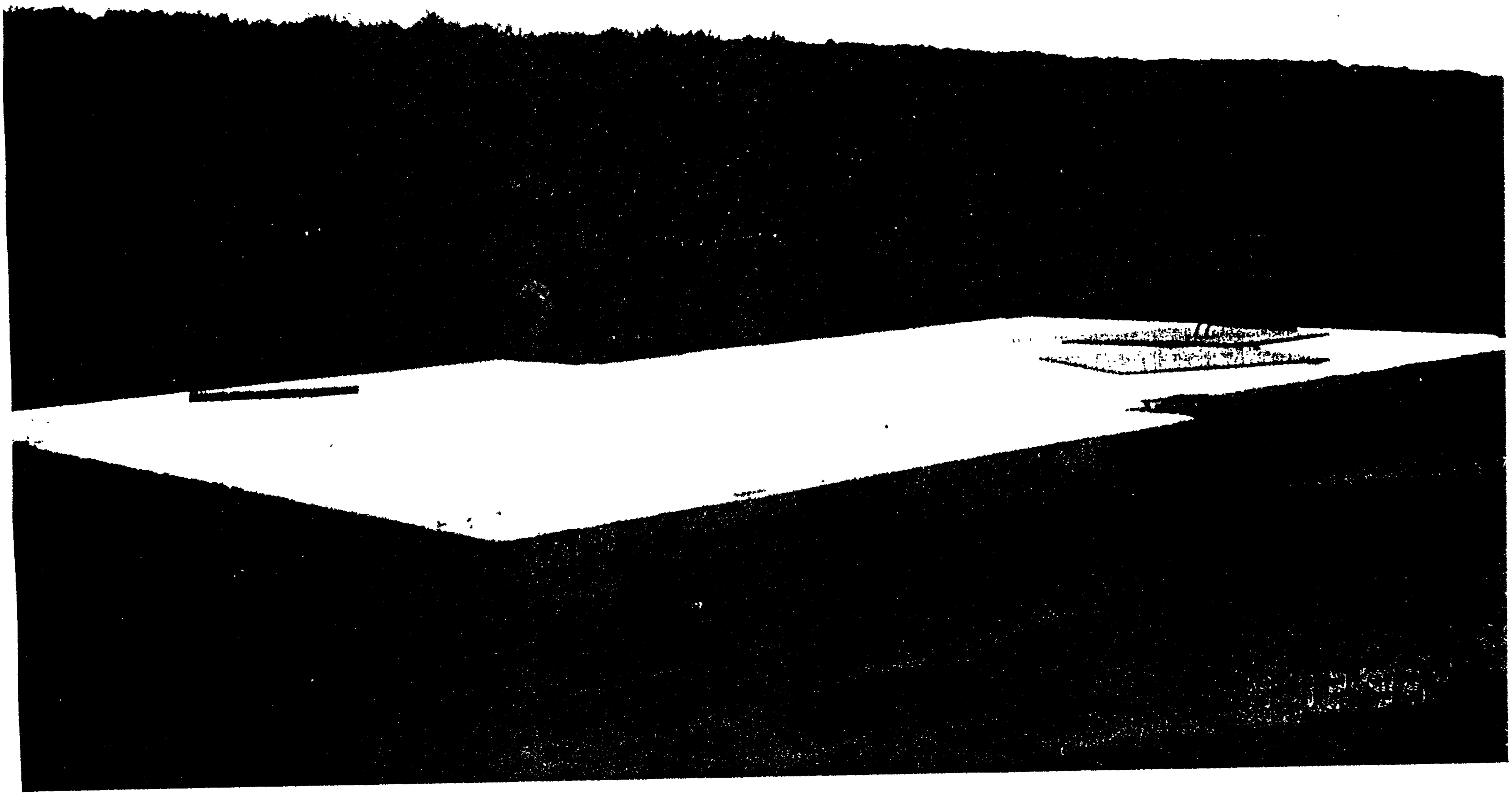
$L = 4km \Rightarrow \Delta L = 10^{-16} cm$

This leads to Stringent Specifications:

- Vacuum
- Seismic and Acoustic Isolation
- Test Mass Suspensions
- Optics
- etc.



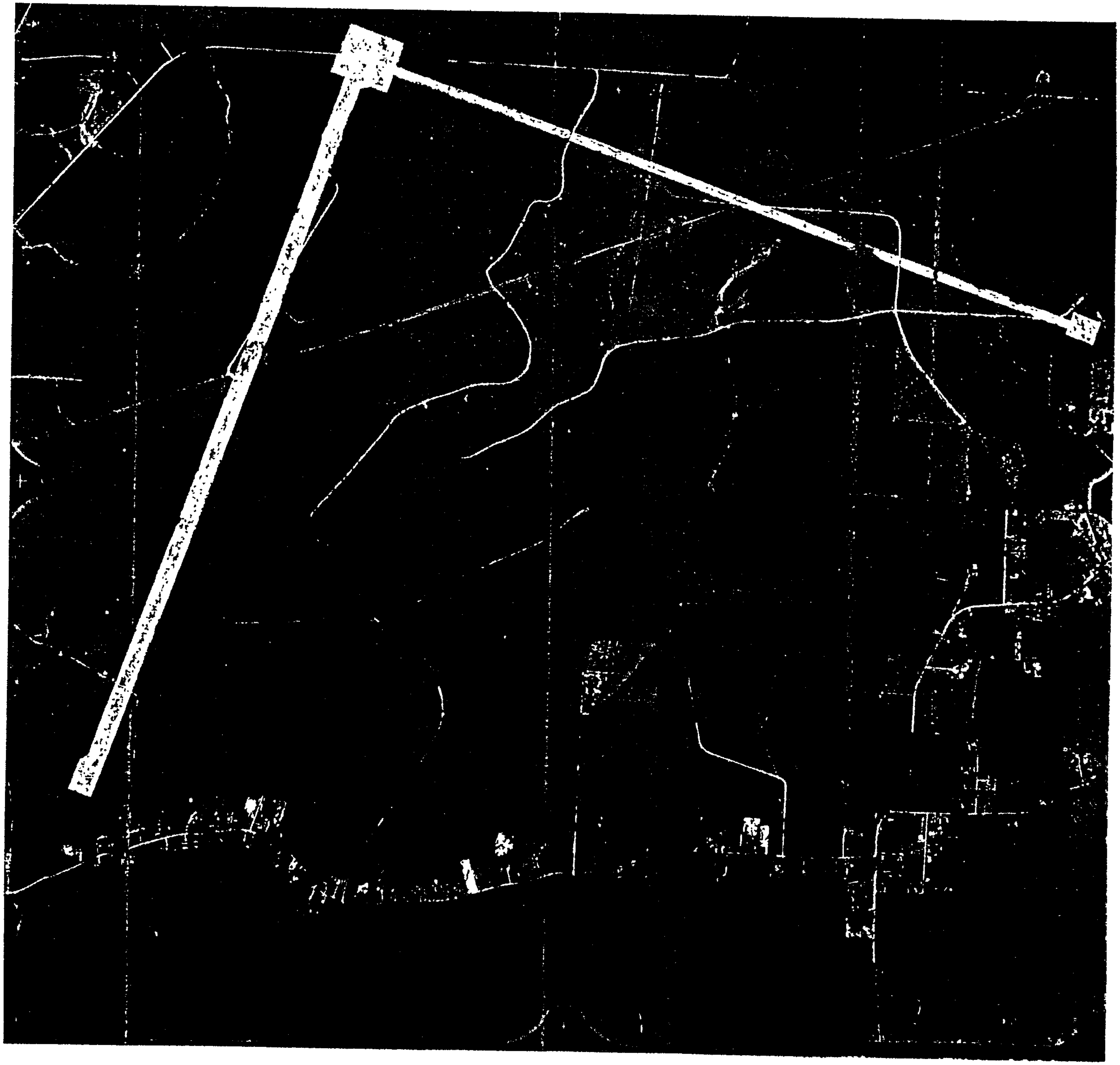




LIGO

LIVINGSTON PARISH

LOUISIANA

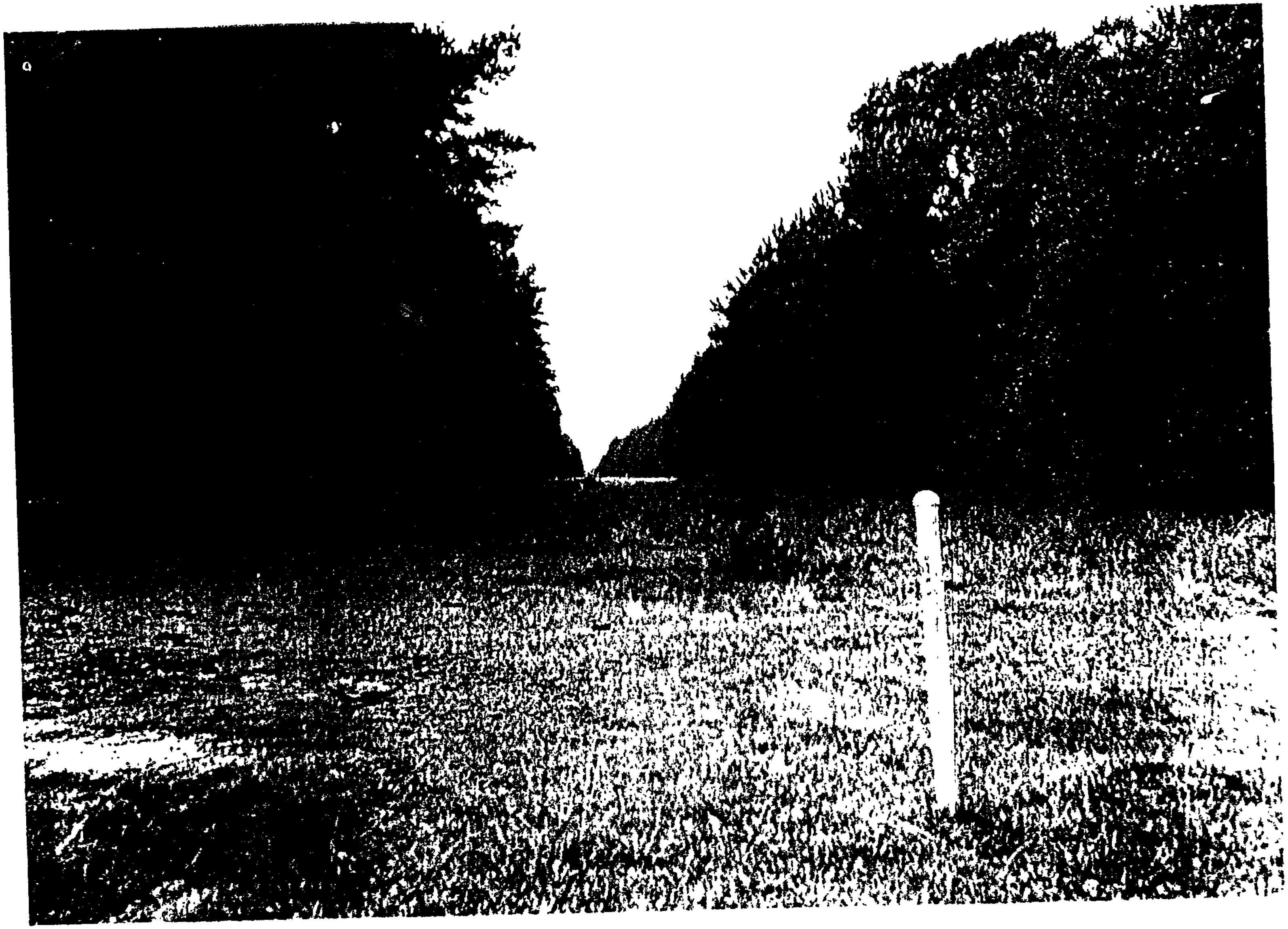


AERIAL PHOTO BY:

GULF COAST AERIAL MAPPING

FLOWN: AUGUST 25, 1995

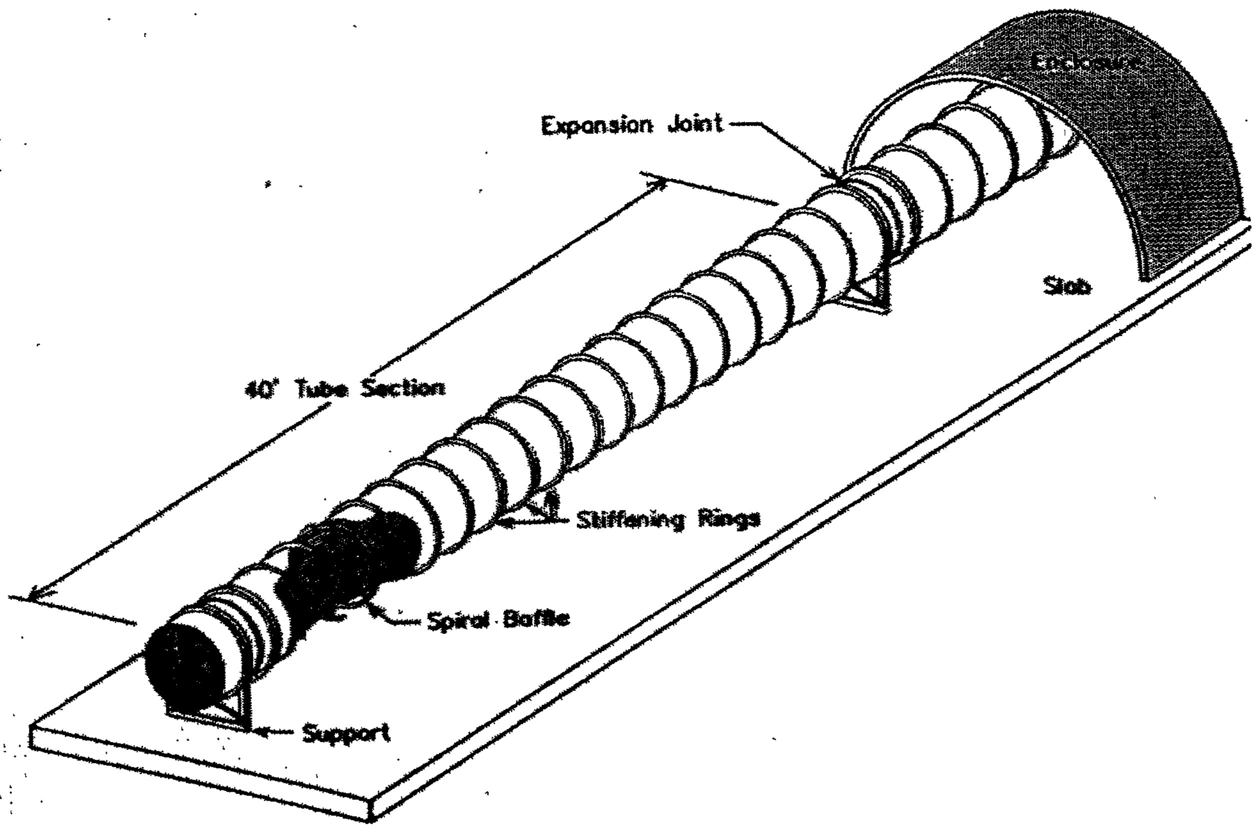
ALTITUDE: 12,000 FEET



G960025-02-0-V

G960028-17-O-V

Beam Tube


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

Beam Tube

- Characteristics
  - ⇒ Arm Lengths - 4km
  - ⇒ Tube Diameter - 4 ft
  - ⇒ Initial Detector
    - 10^{-6} torr Hydrogen; 10^{-7} torr Water
  - ⇒ Advanced Detectors
    - 10^{-9} torr Hydrogen; 10^{-10} torr Water
  - ⇒ Quality Control
    - (materials, welding, cleaning, etc)

- Status and Plans
  - ⇒ Design Contract was with CBI
    - Final Design Report Accepted (6/94)
  - ⇒ Qualification Test
    - 130 ft Section - success (4/95)
  - ⇒ Contract Options

LIGO Facilities
Beam Tube Enclosure

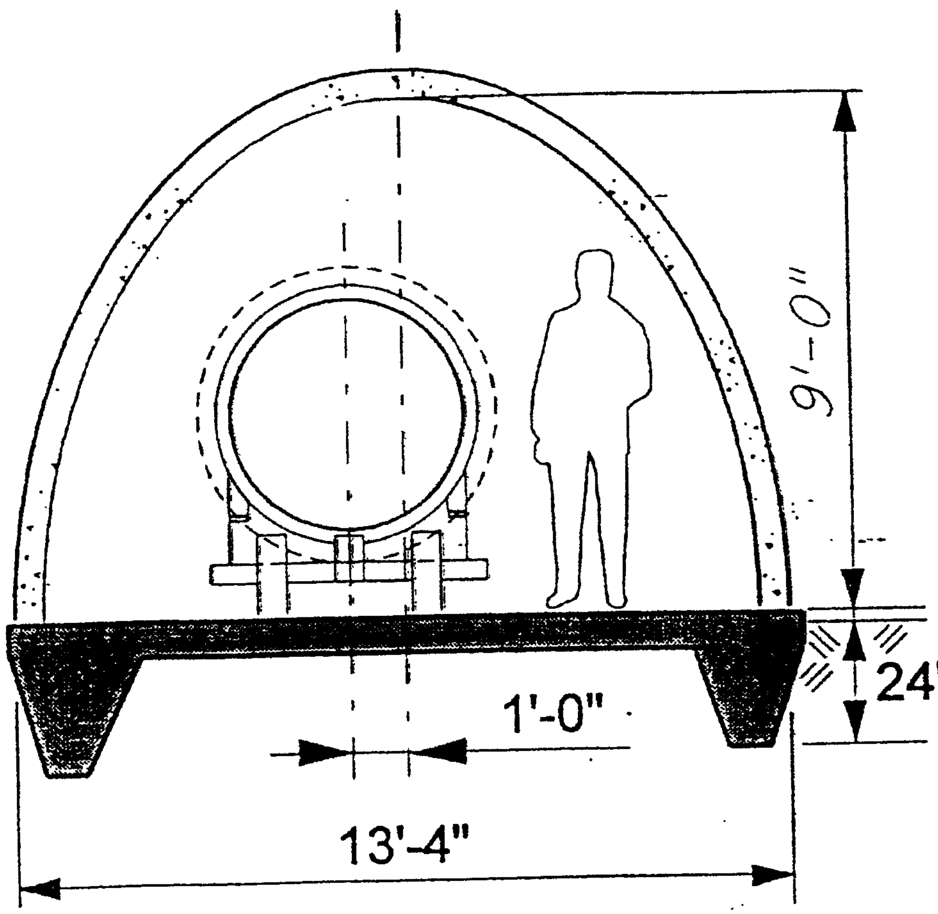
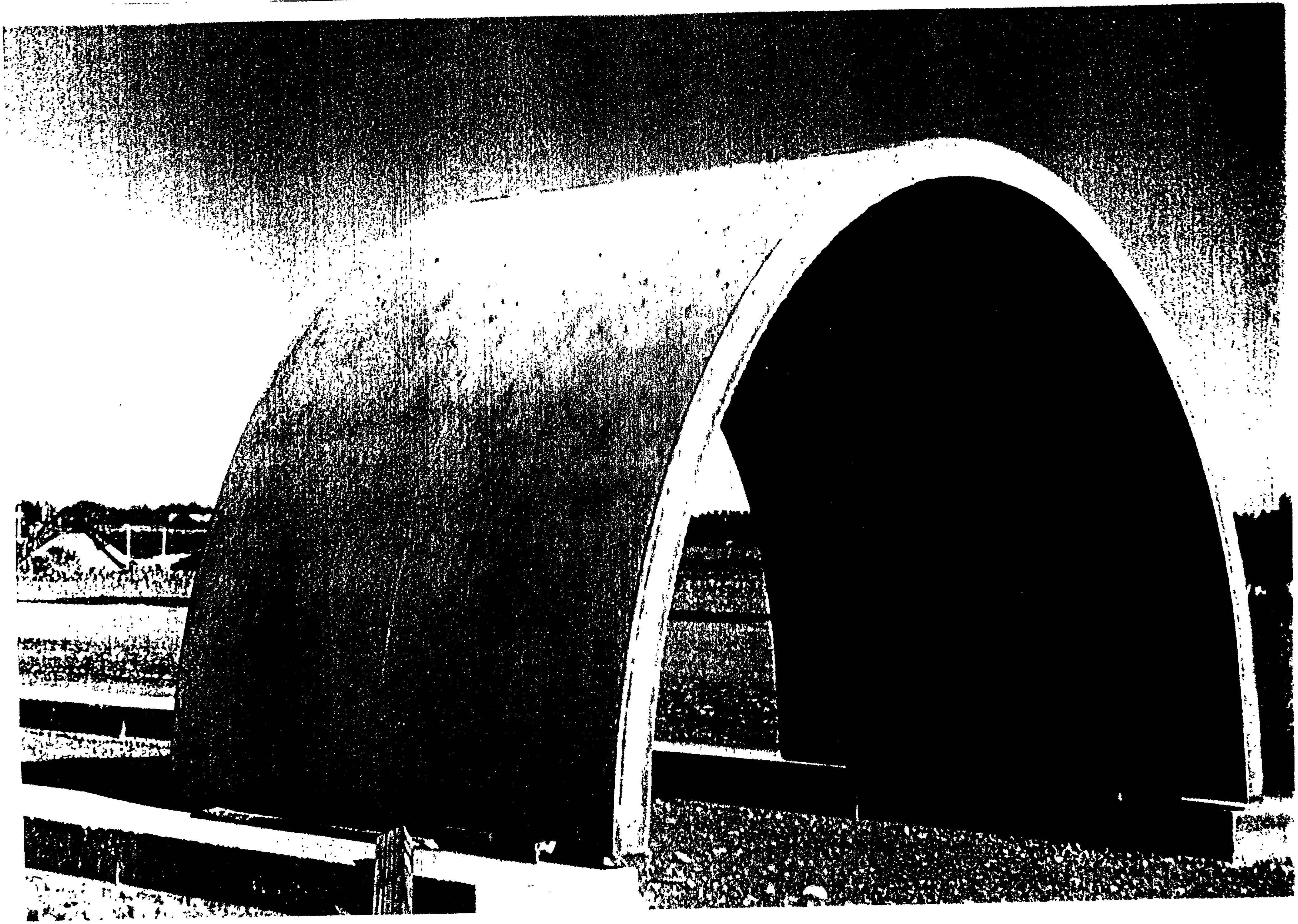
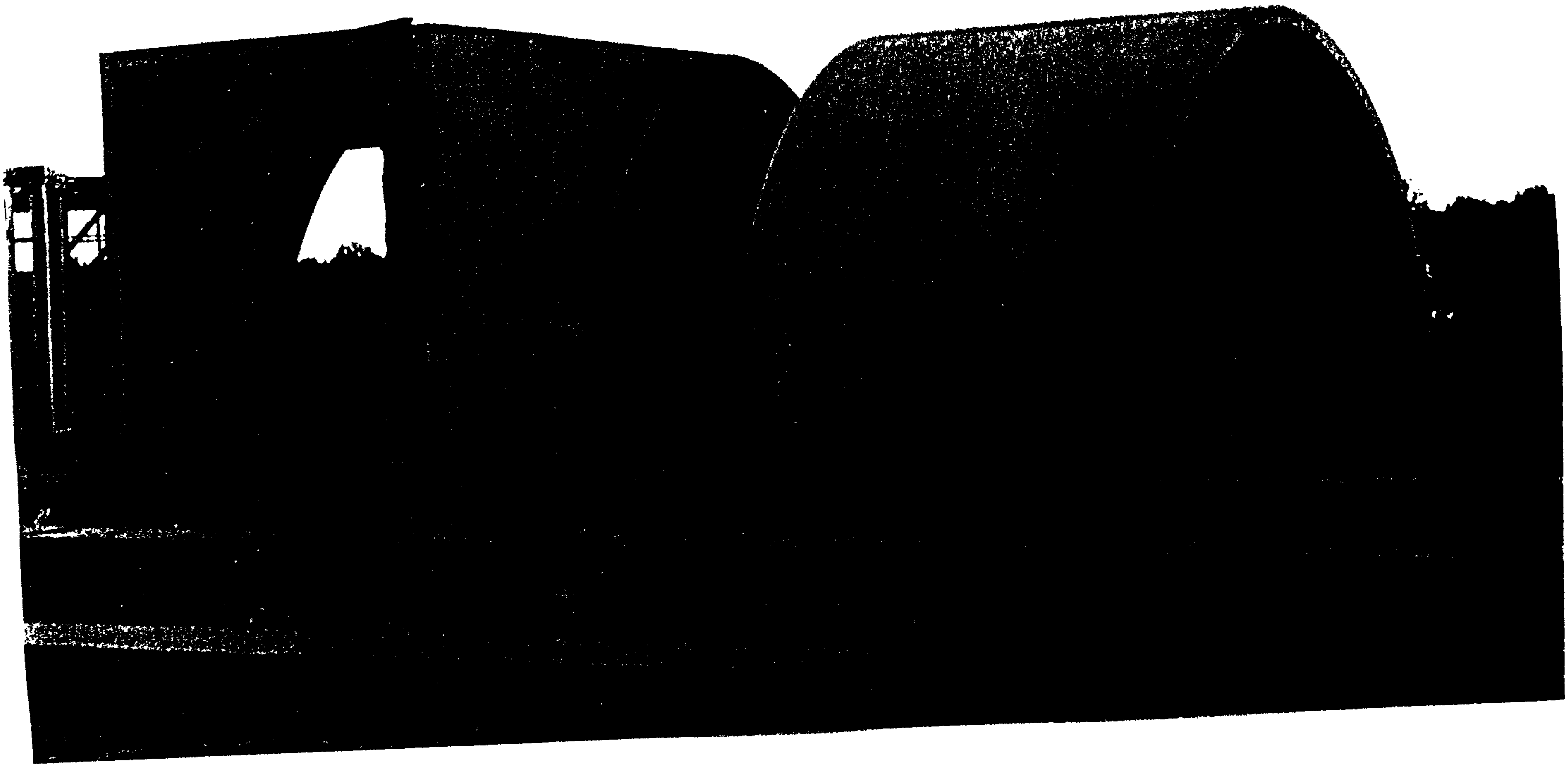
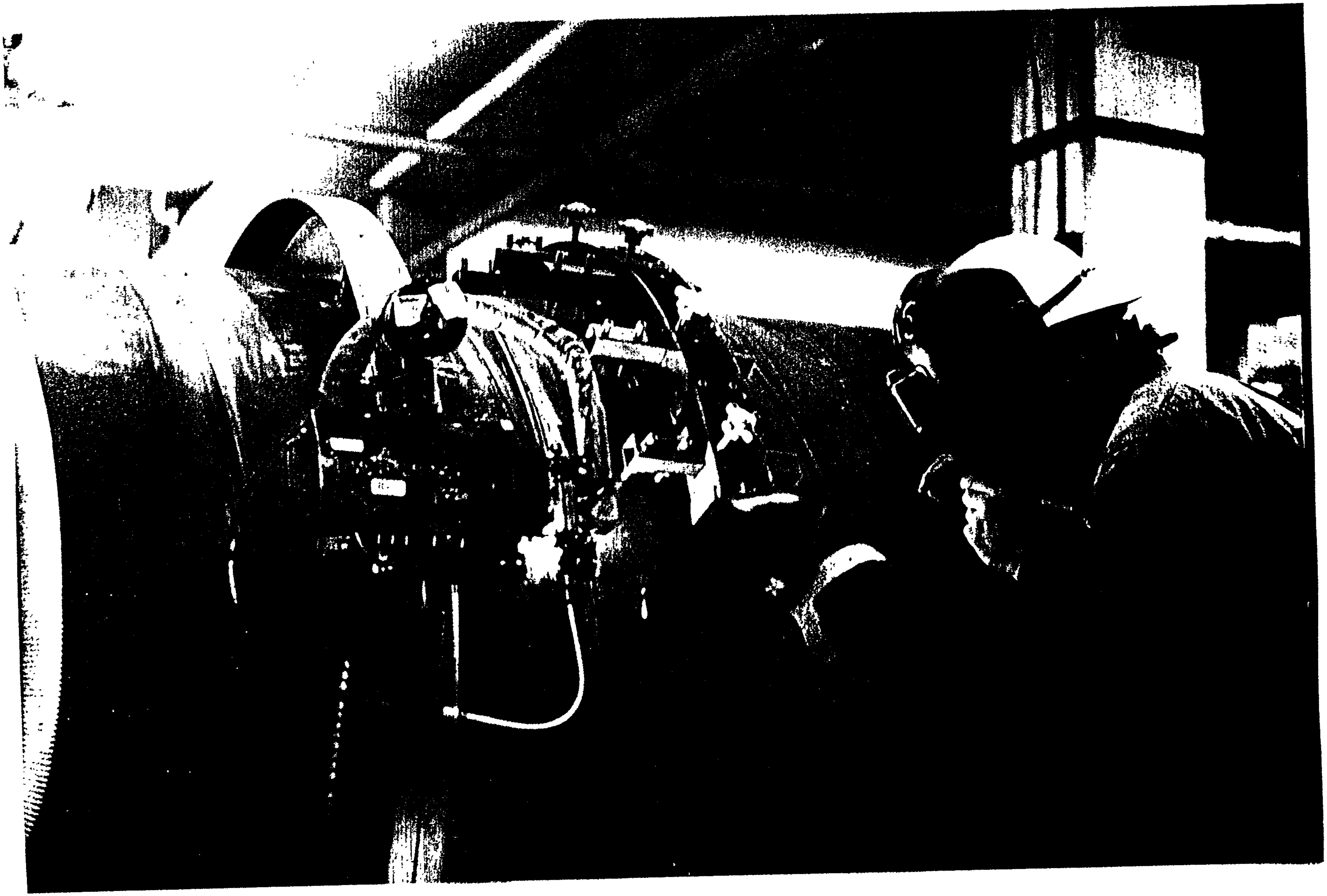


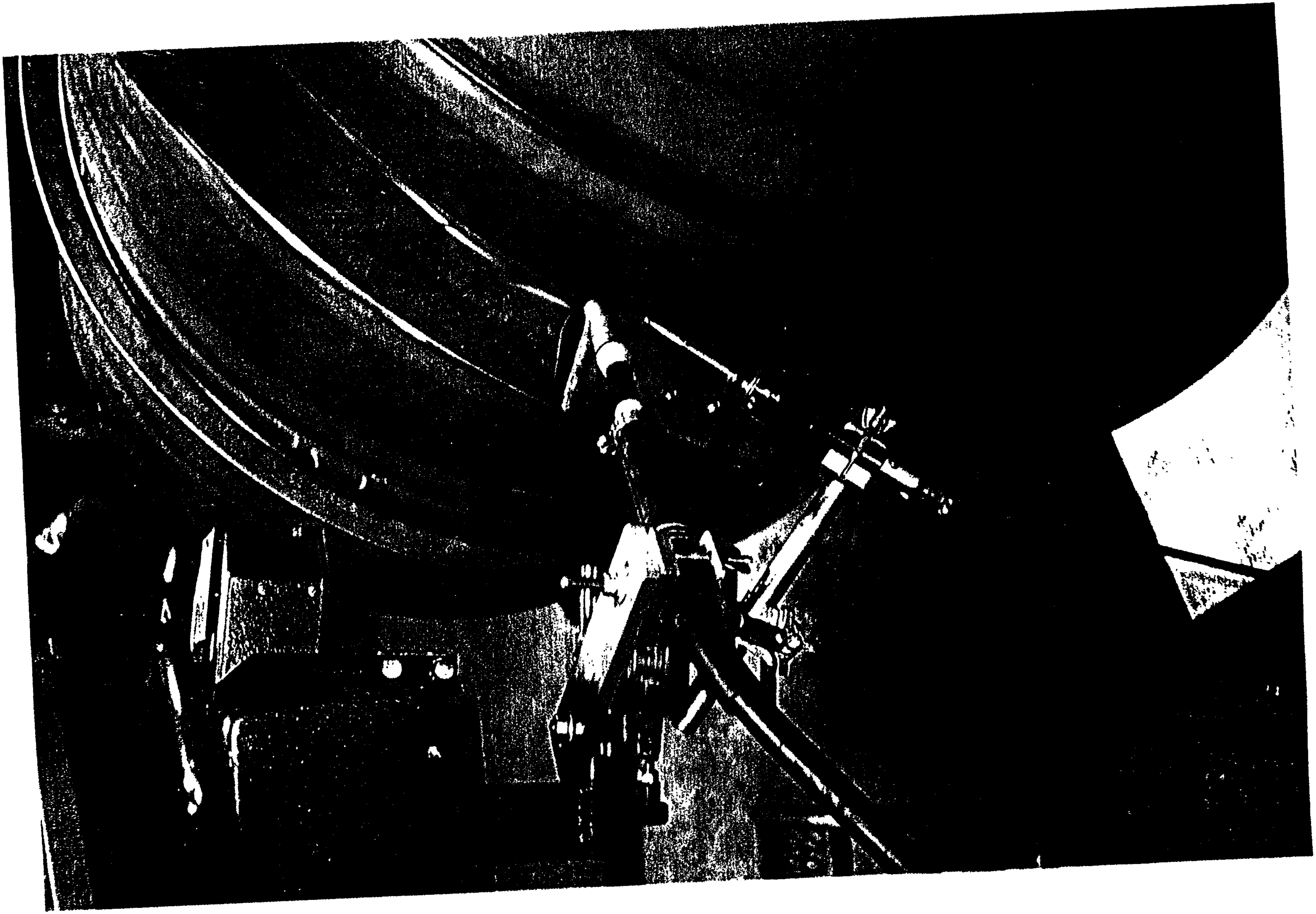
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

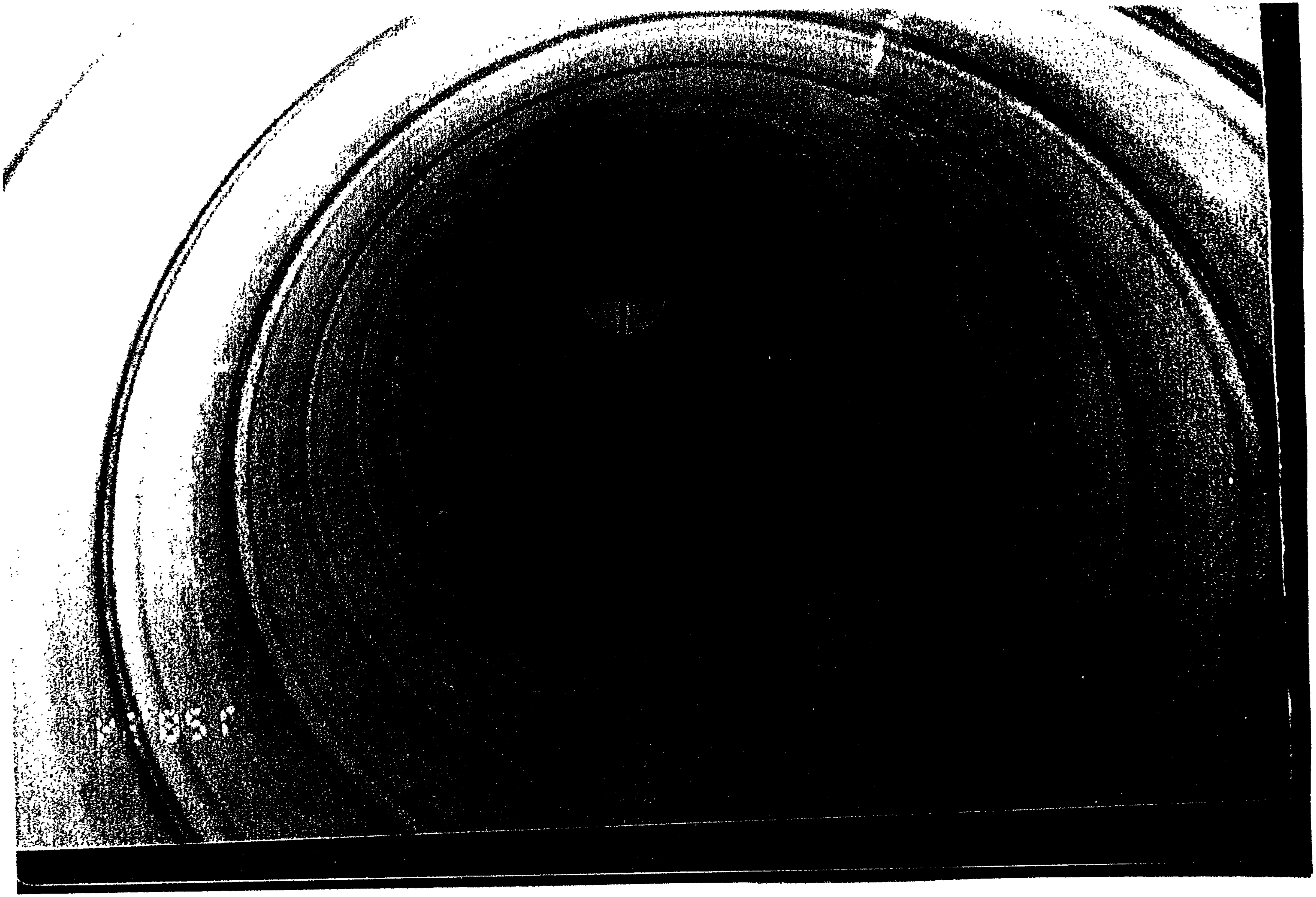




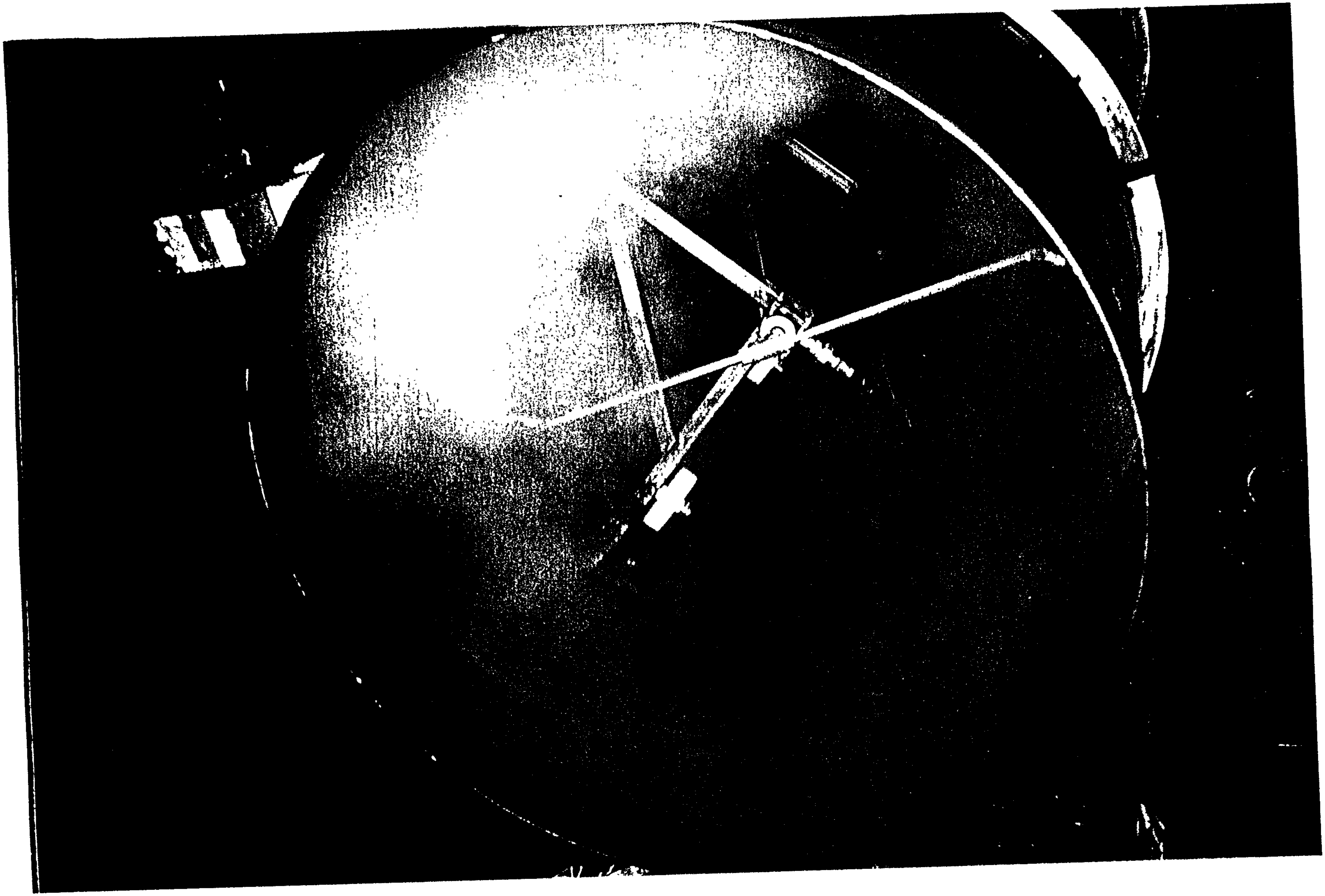


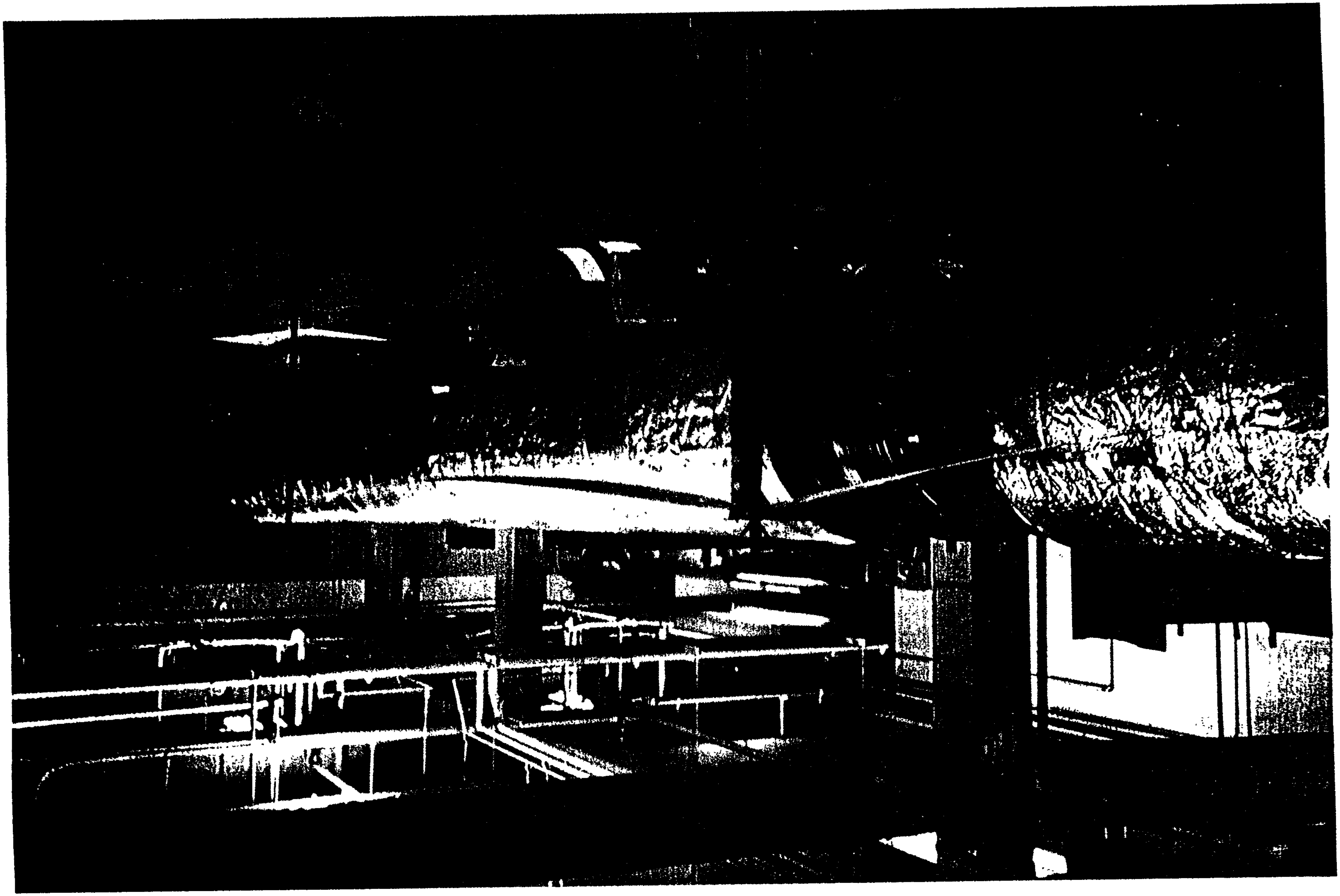
BT QT RING WELDING UNIT





B1 PT STEAM CLEANING SPRAY UNIT





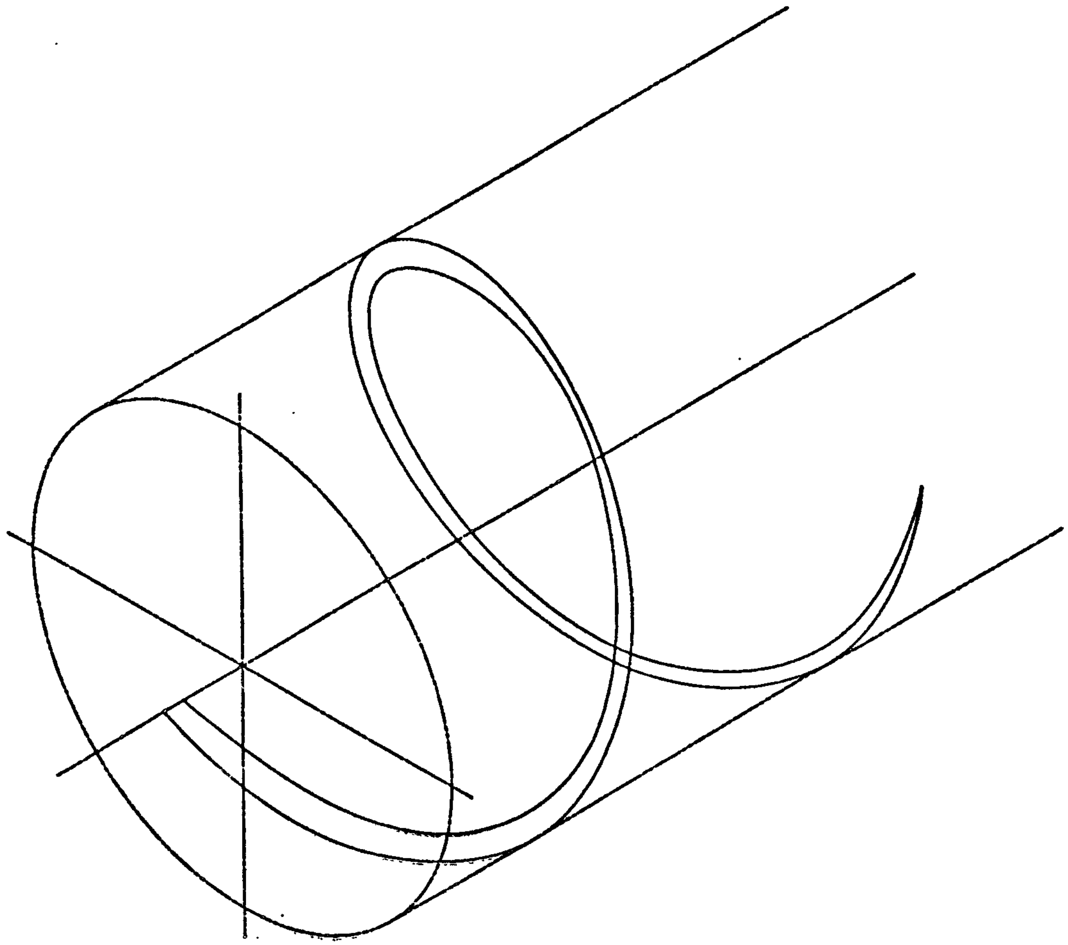
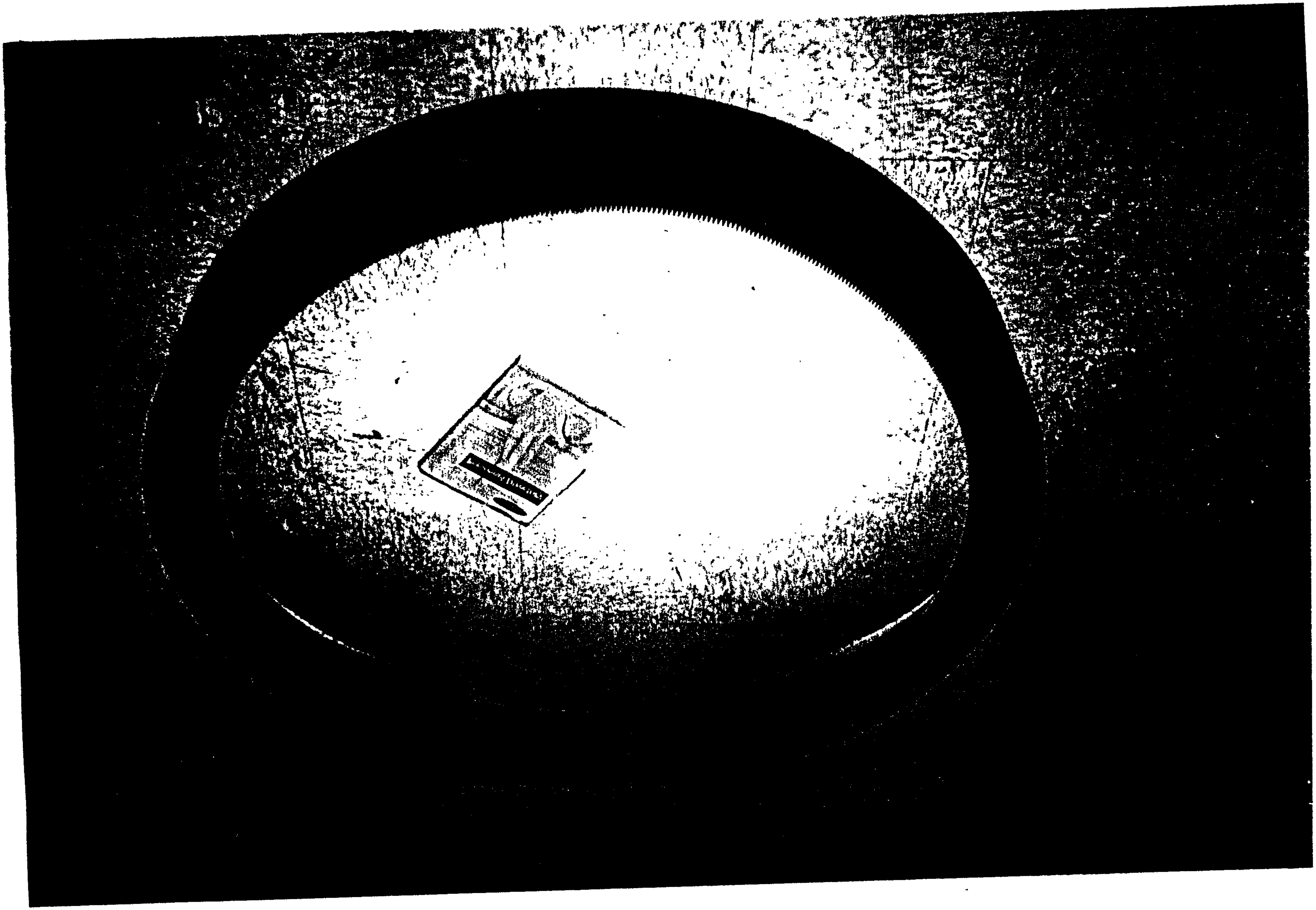
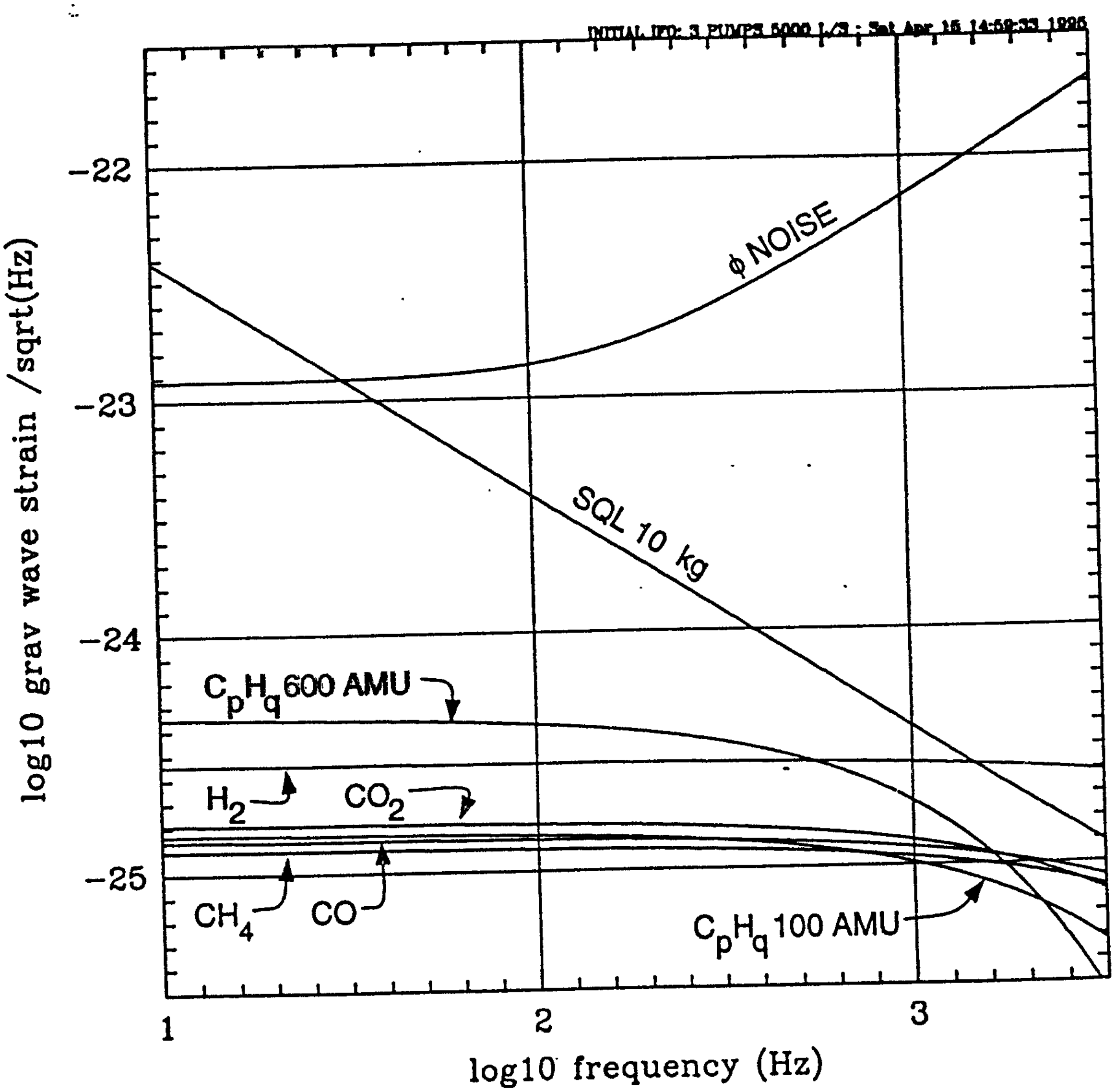


FIGURE1.1.2 #4 BAFFLE SCHEMATIC

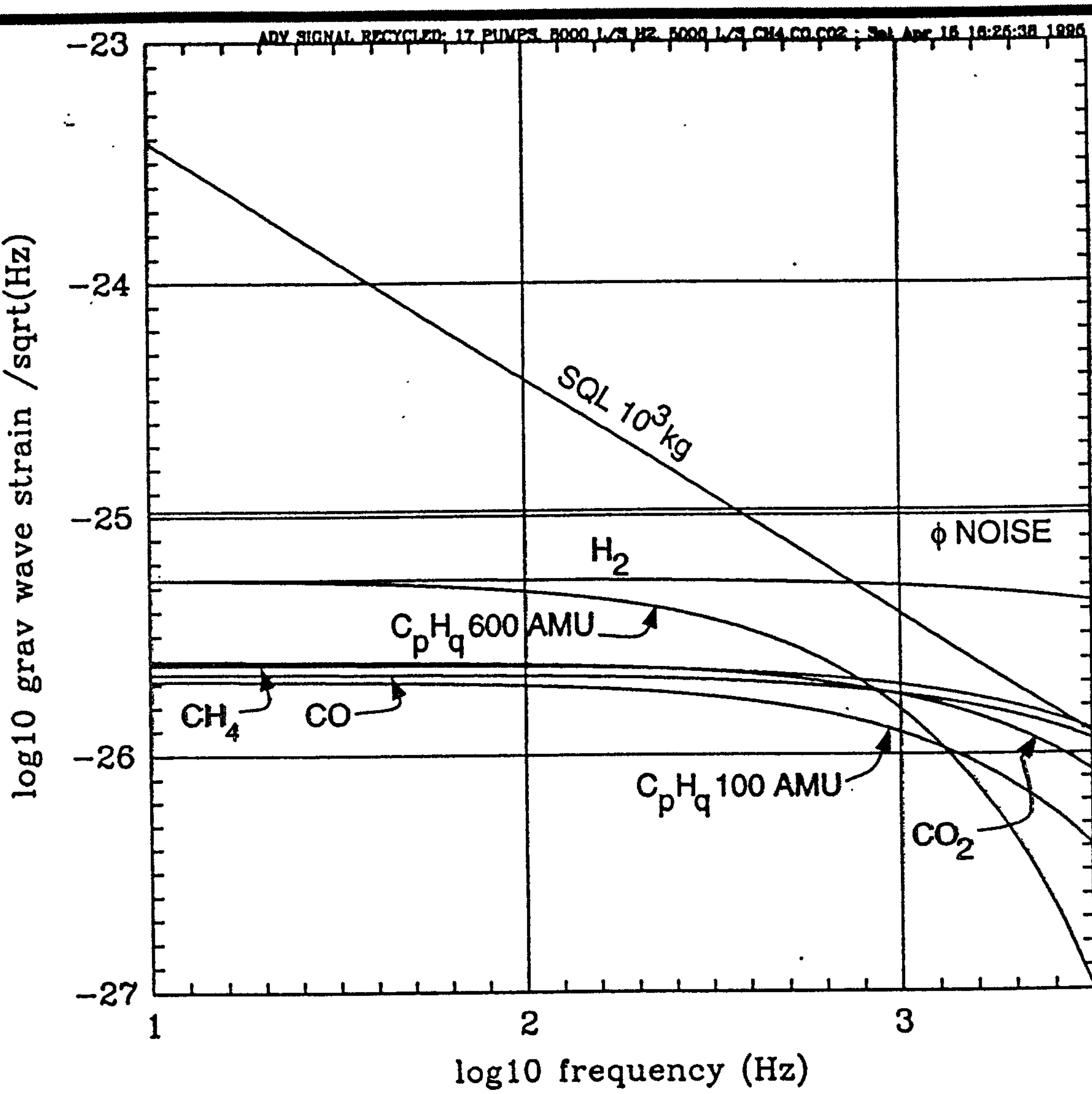


Initial Interferometer Noise Budget



LIGO-G952001-00-B

Advanced Interferometer Noise Budget



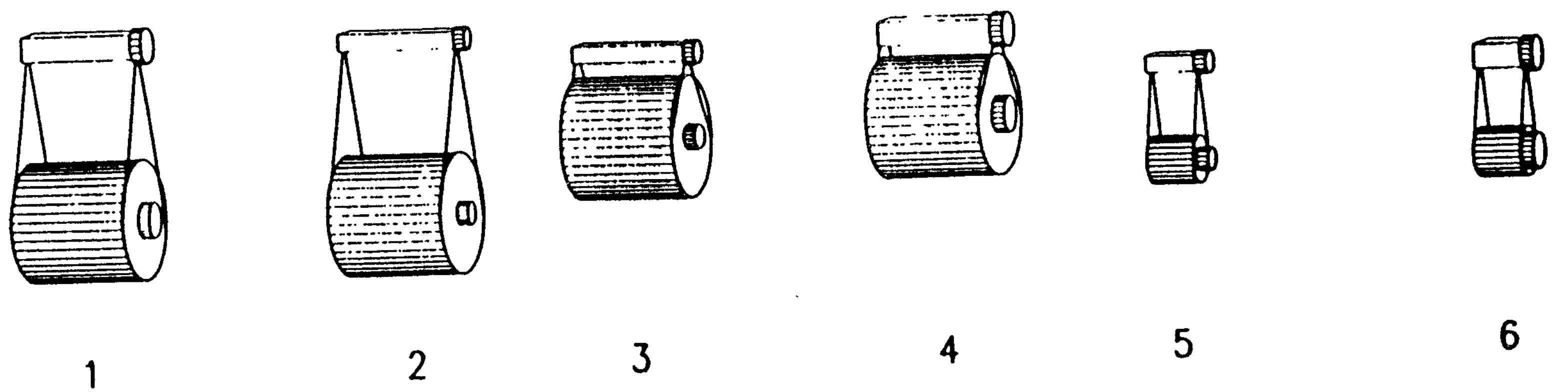
Advanced amplitude recycled interferometer parameters:

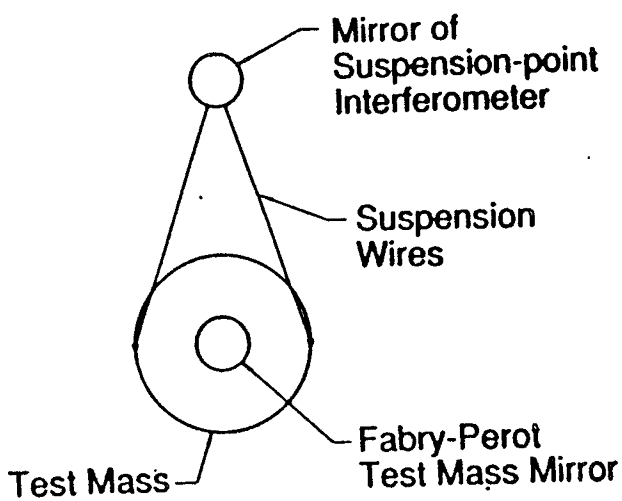
$A_m = 10^{-5}$

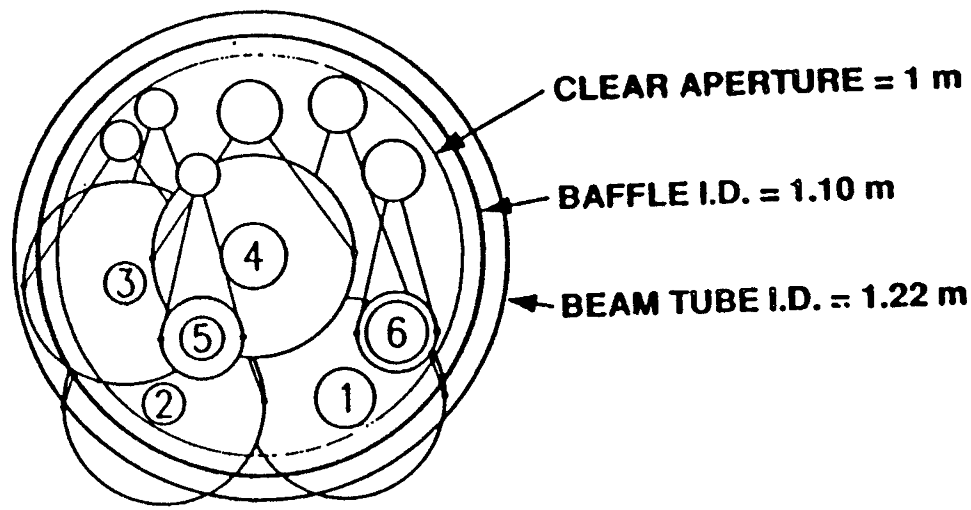
$P_{in} = 100$ W $\qquad P_{circ} \sim 1$ MW

$\varepsilon_{opt} = 0.3$

$\lambda = 1.06\ \mu$

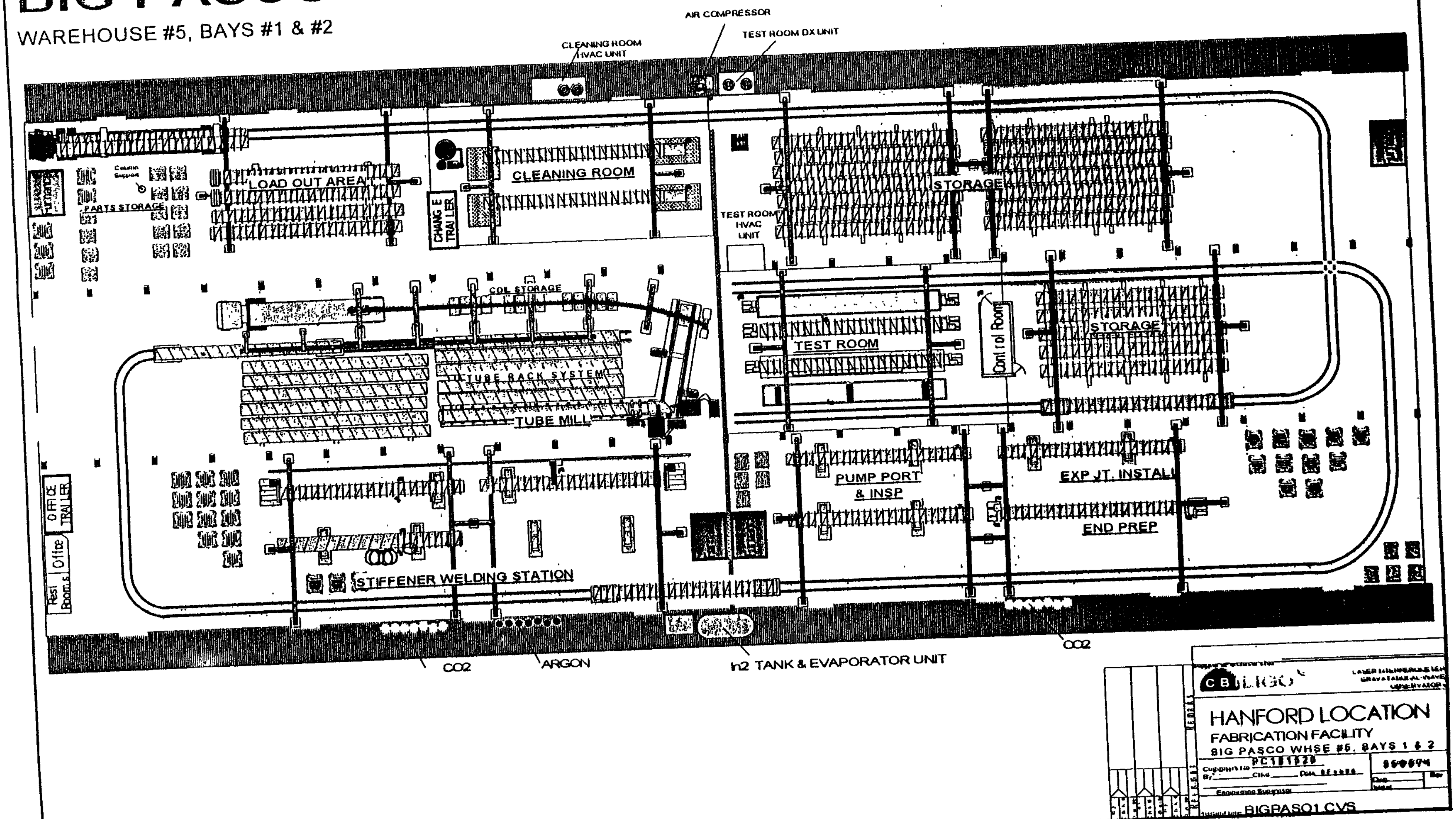

1
2
3
4
5
6


Mirror of Suspension-point Interferometer
Suspension Wires
Test Mass
Fabry-Perot Test Mass Mirror

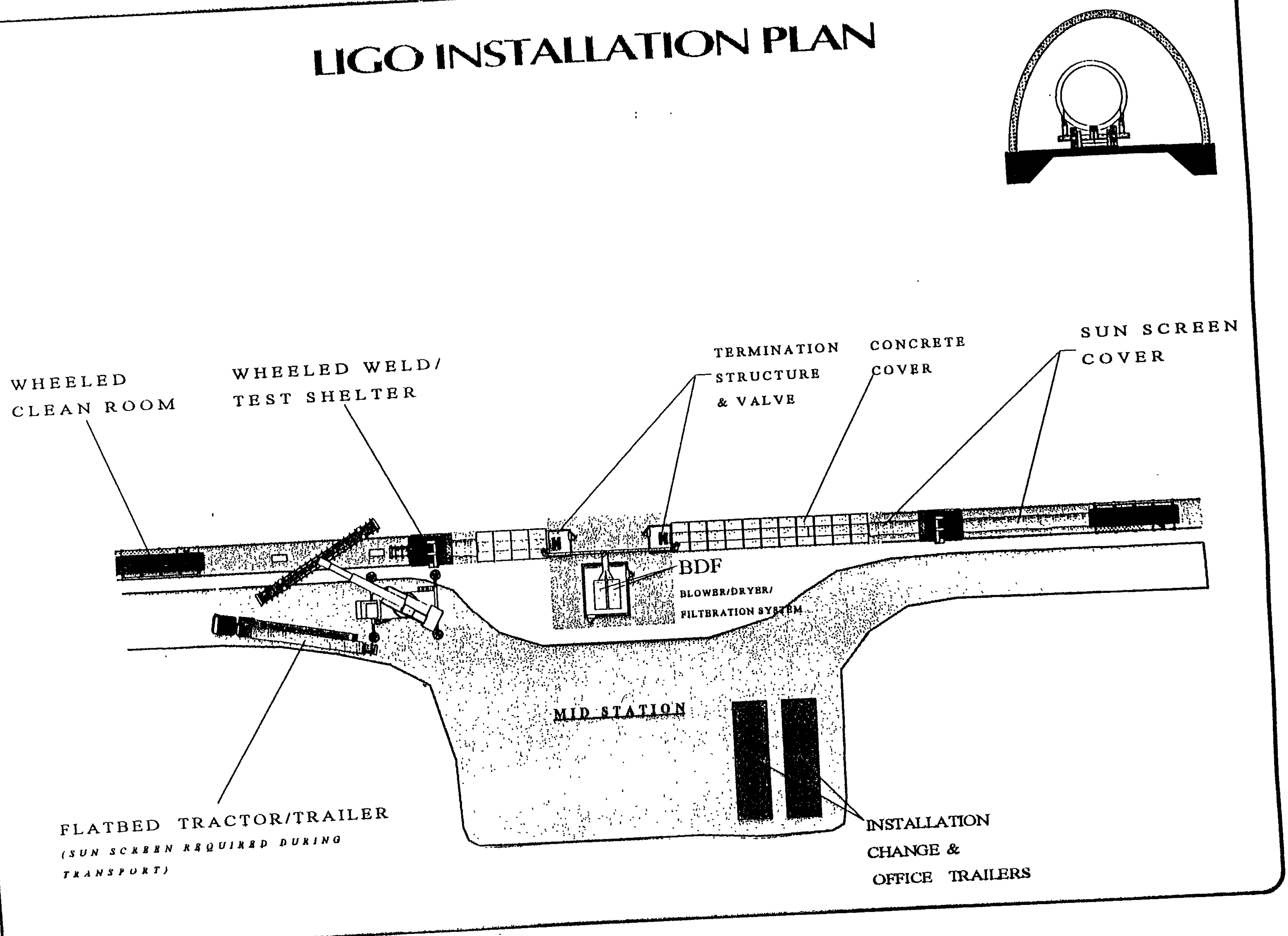

CLEAR APERTURE = 1 m
BAFFLE I.D. = 1.10 m
BEAM TUBE I.D. = 1.22 m
1
2
3
4
5
6

BIG PASCO

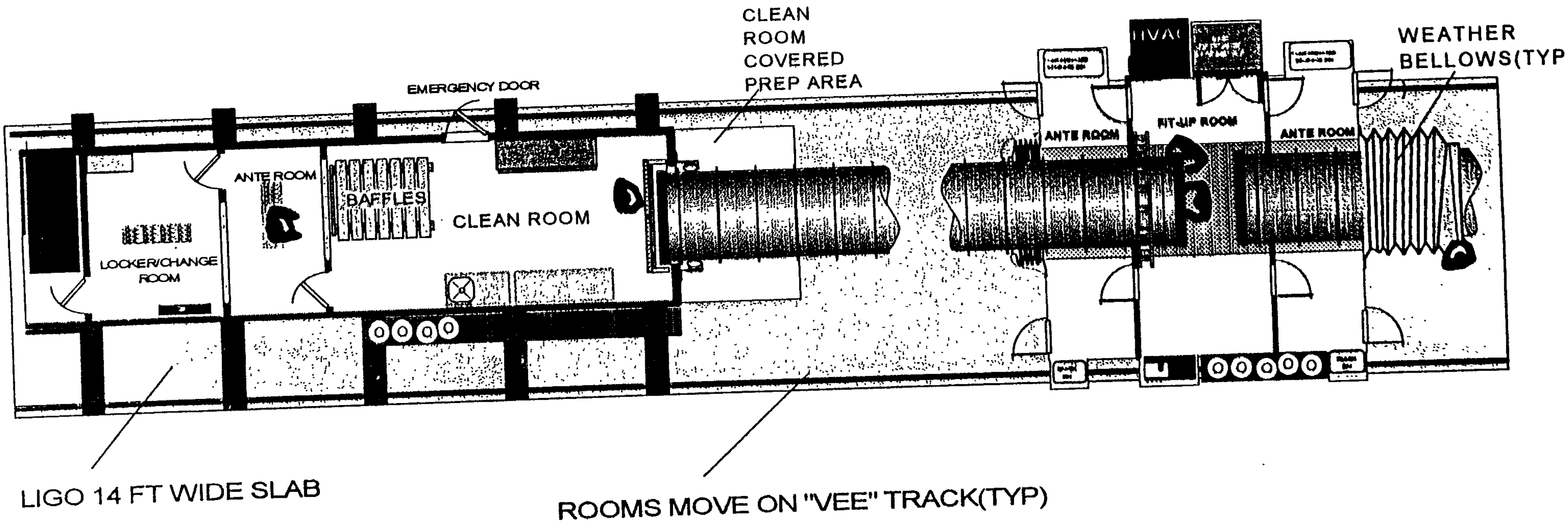
WAREHOUSE #5, BAYS #1 & #2



LIGO INSTALLATION PLAN



INSTALLATION PLAN



LIGO Facilities
Vacuum Equipment

- Characteristics
  - » mostly standard vacuum equipment
    - 1st stage roughing atm -> 0.1 torr
    - 2nd stage roughing 0.1 torr -> 10^{-6} torr
    - steady state - ion/getter pumps
  - » large gate valves (4 ft diam)
    - access and flexibility
  - » controls and monitoring

- Status
  - » Science requirements and review 6/94
  - » RFP issued for design contract only
  - » Two competitive contracts awarded (CB&I, PSI)
  - » Final design and manufacturing
    - down select (6/95) to PSI
    - CDR approved 10/95
    - FDR May 96; some prototype/acquisitions now

JTSS 7001 -

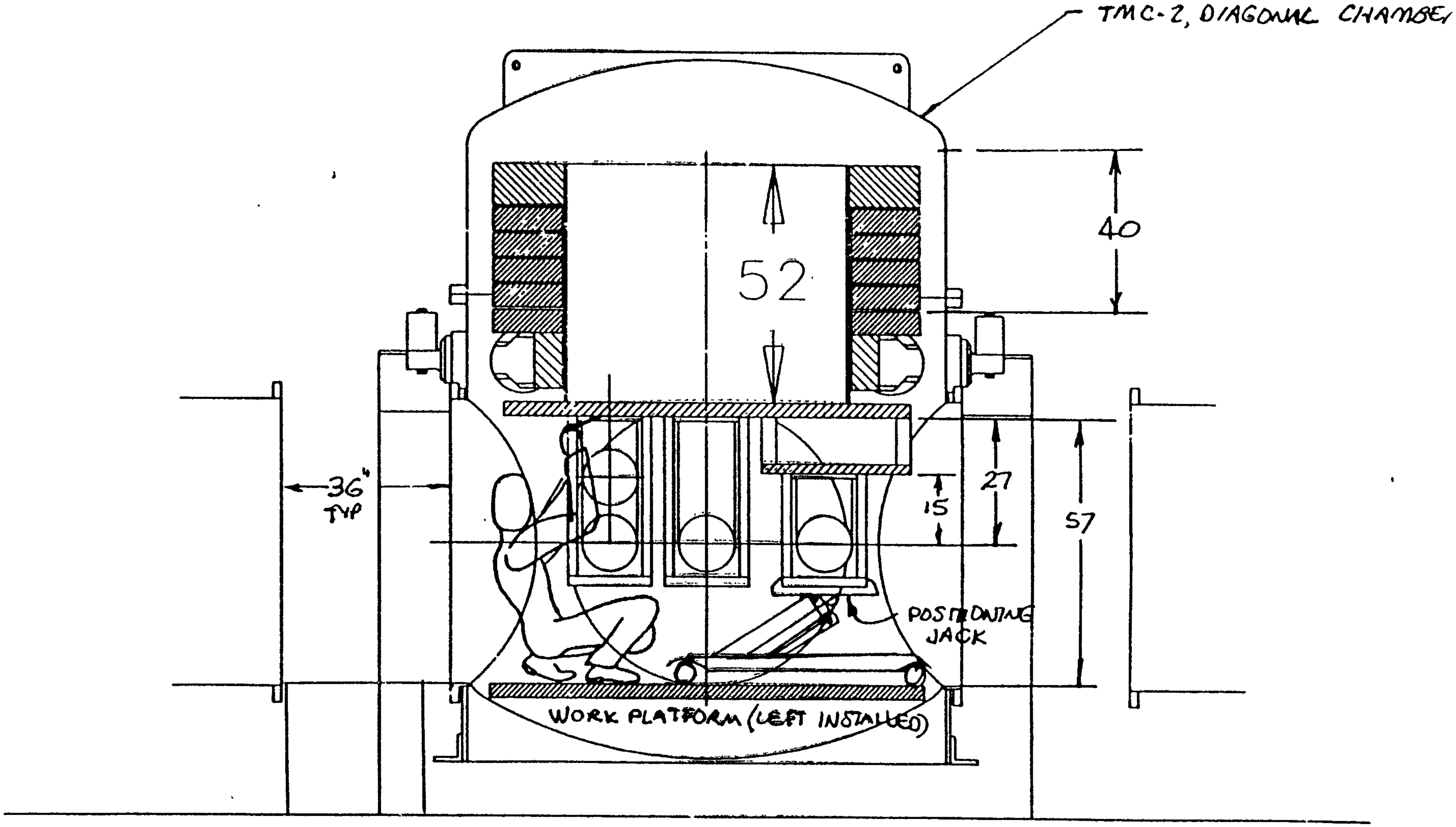
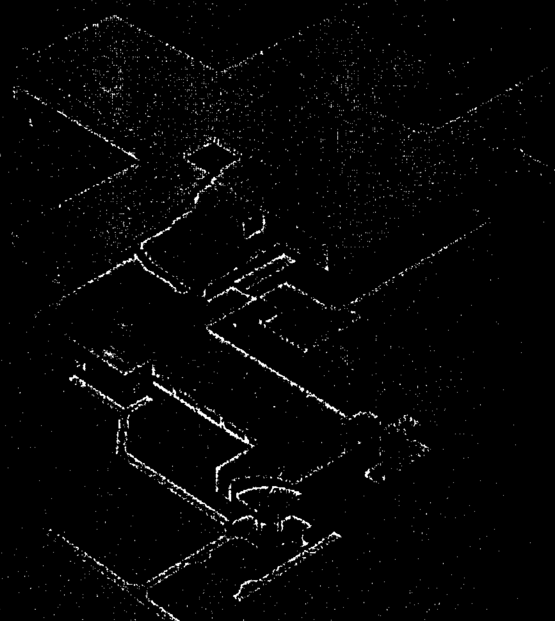


FIG. 3 INTERNAL ACCESS

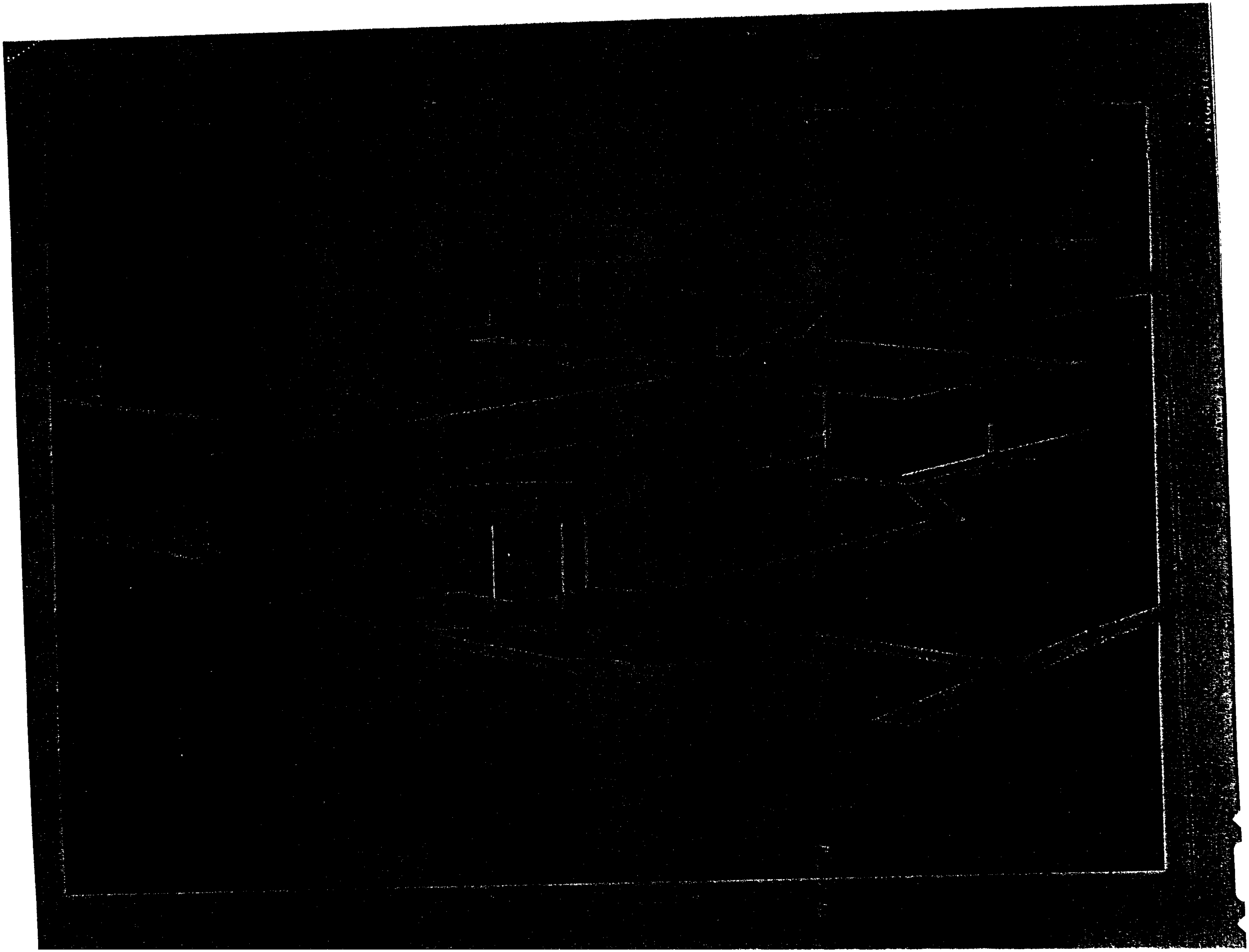
9-2-92

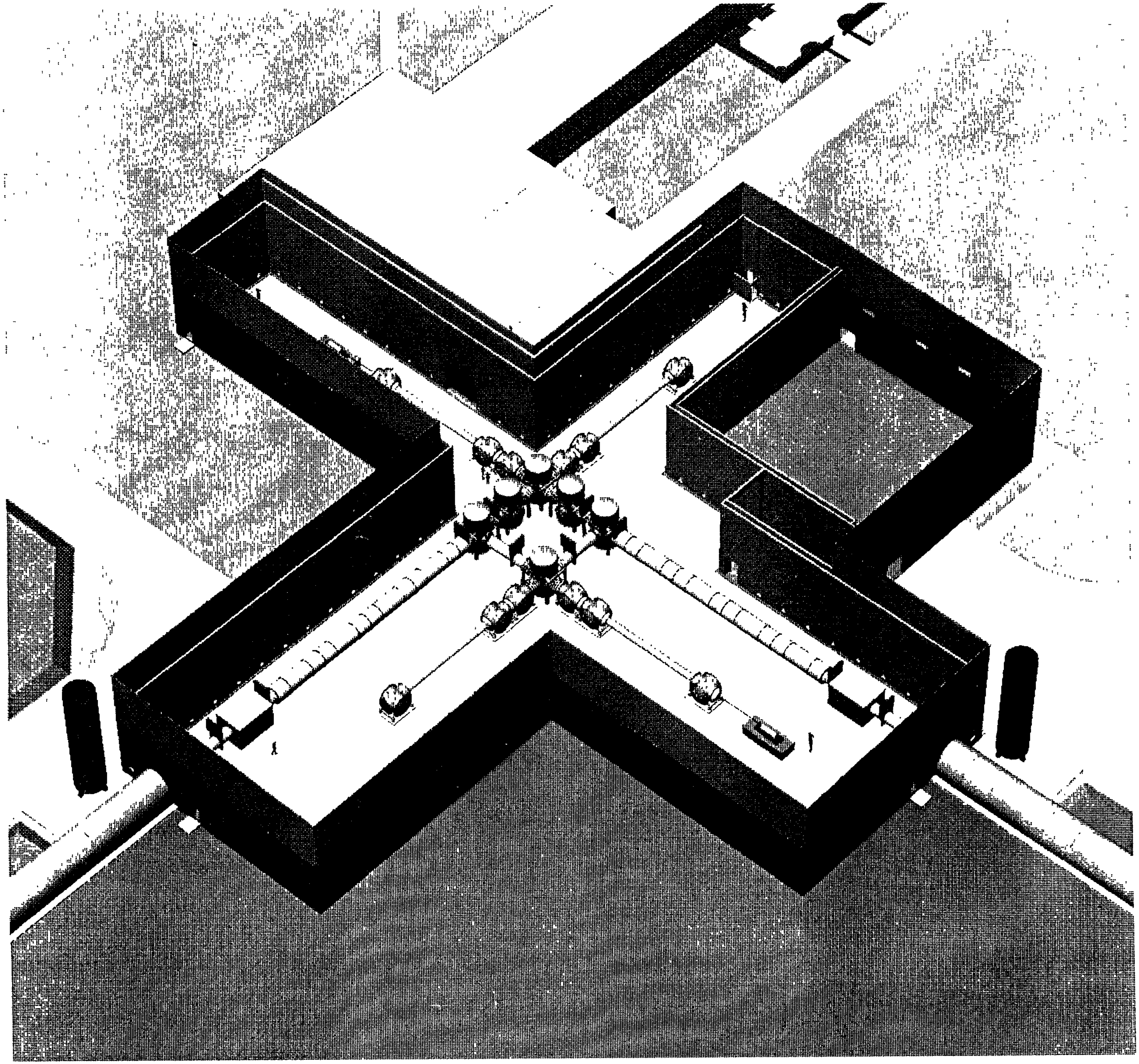
[illegible]O

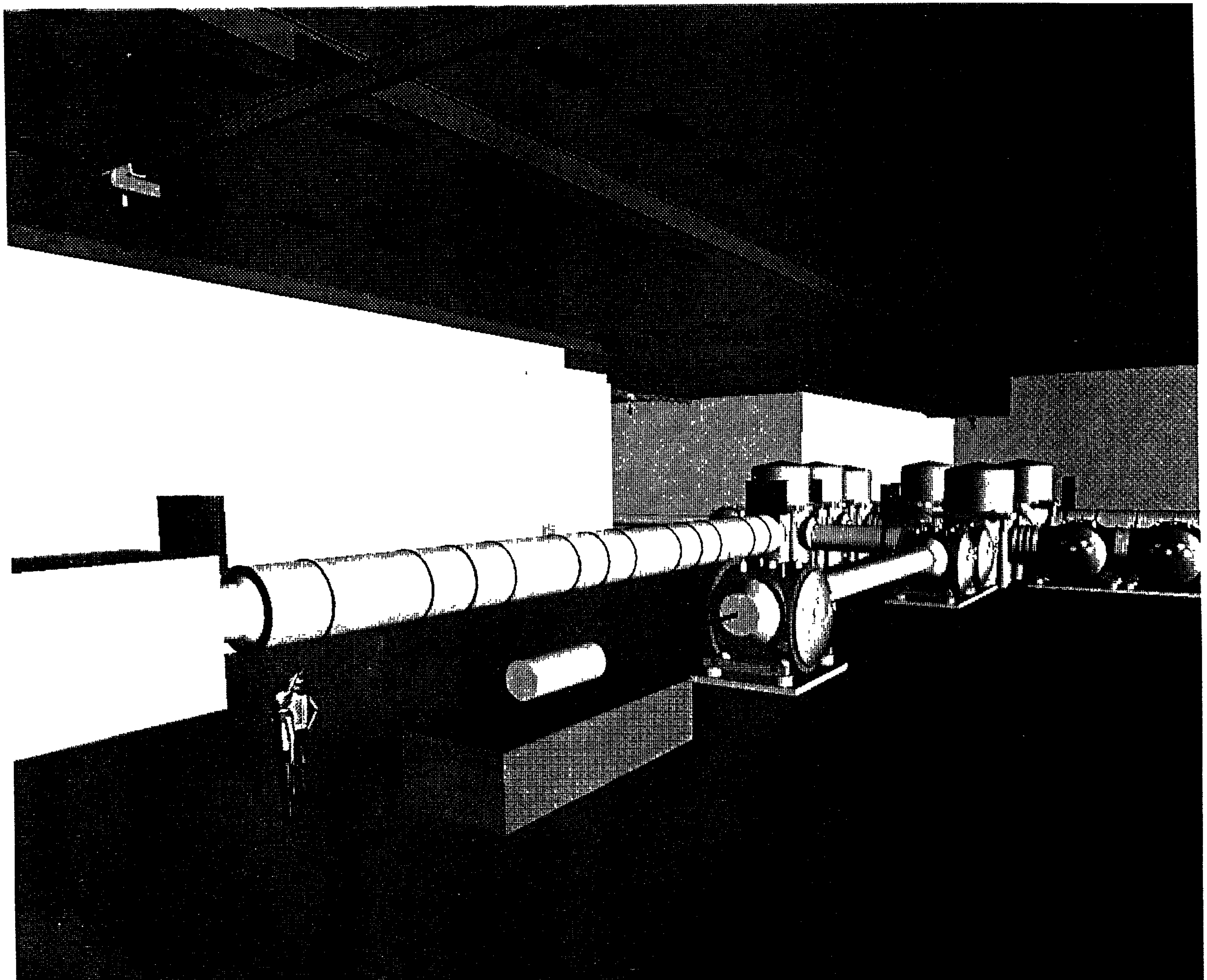
FINAL DESIGN REVIEW



APRIL 1996





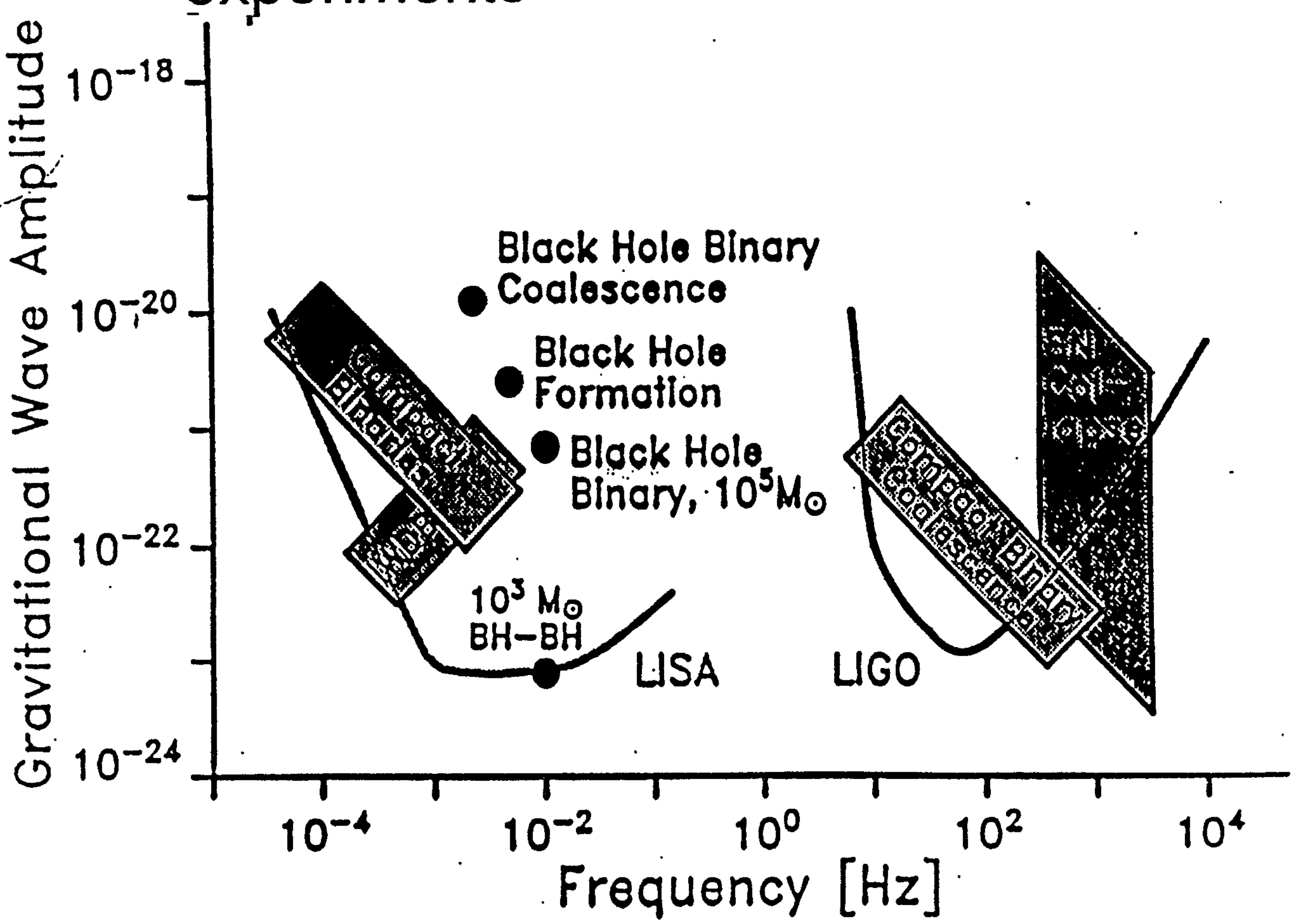


Lecture 5

B. BARISH

Astrophysical Sources
Frequency Range

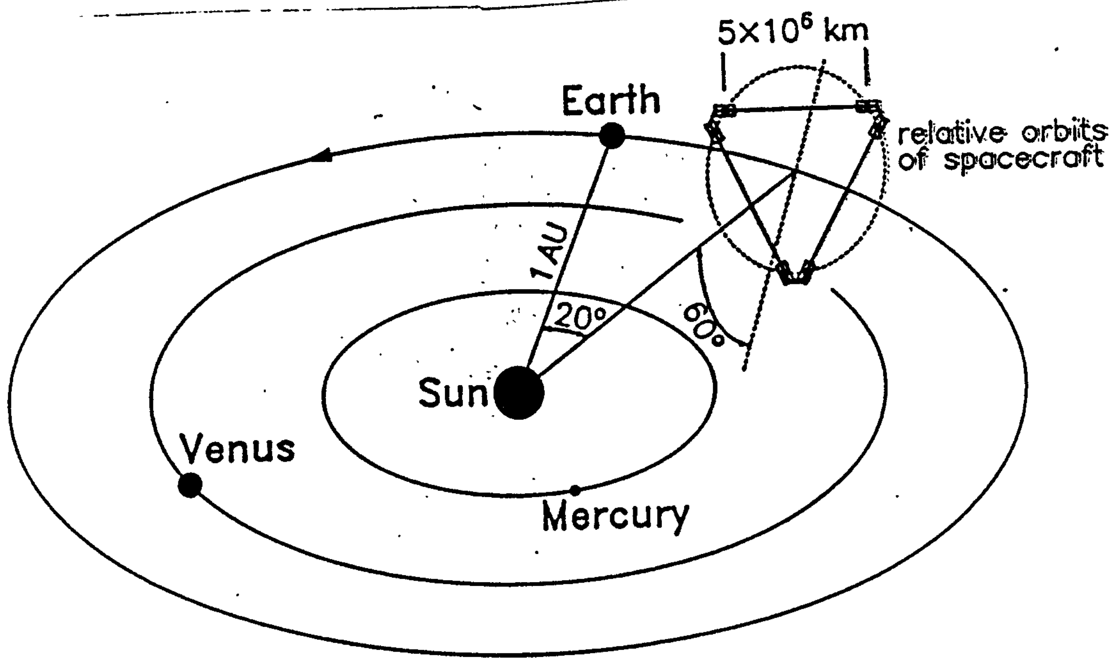
- Electromagnetic Waves - ~ 20 orders of magnnitude (ULF radio -> HE γ rays)
- Gravitational Waves - ~ 10 orders of magnitude
- Combination of terrestrial and space experiments



Gravitational Waves

Space Experiment

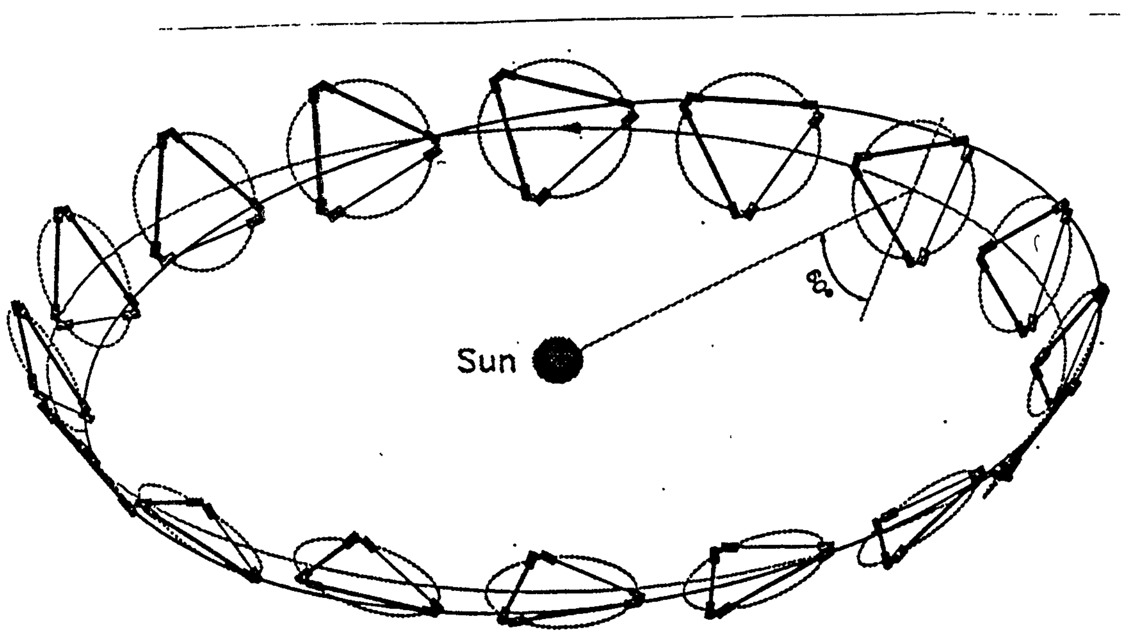
- LISA - Laser Interferometer Space Antenna
  - » six spacecraft in triangle (four needed)
  - » pair at each vertex



LISA

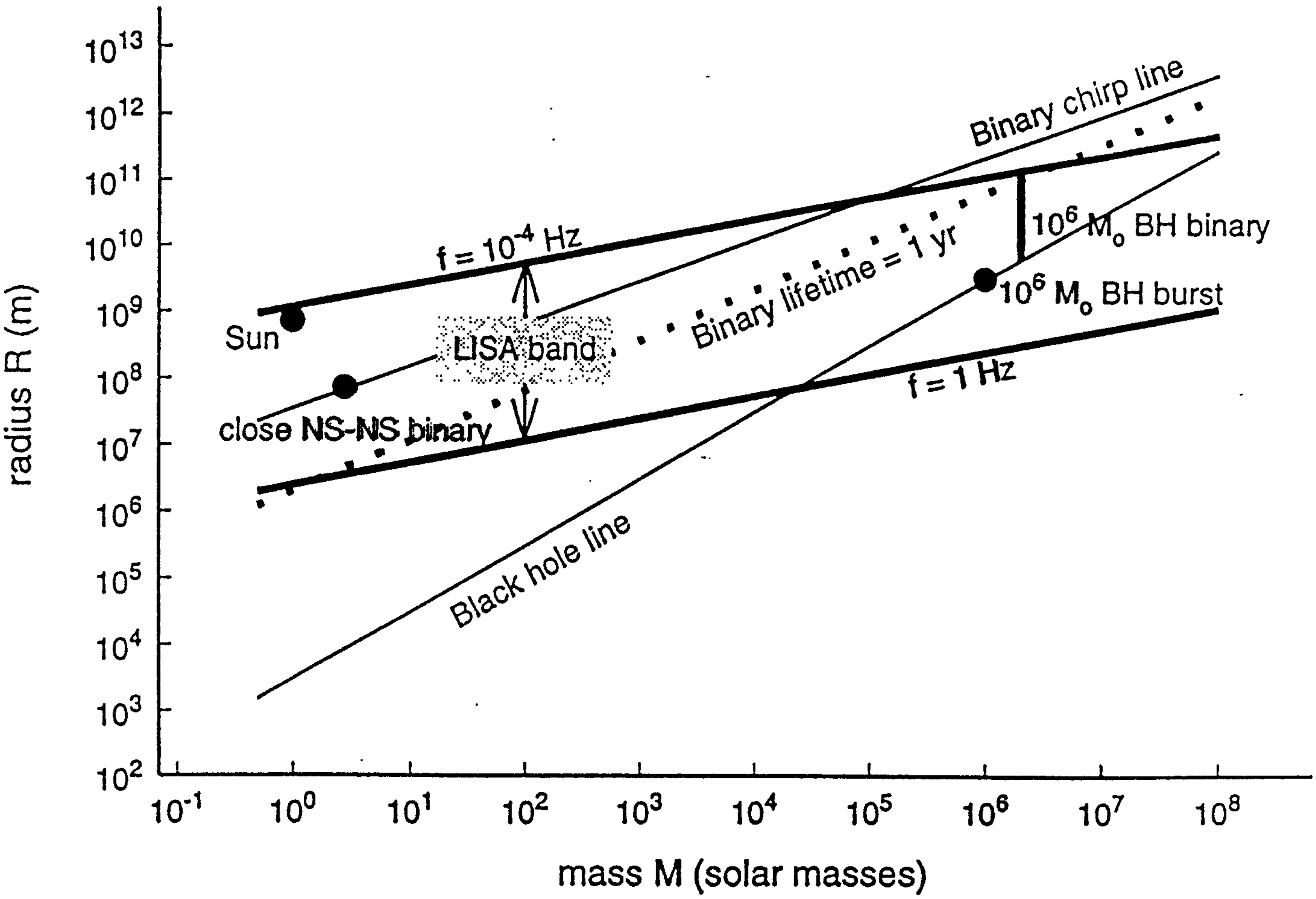
Annual Revolution

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



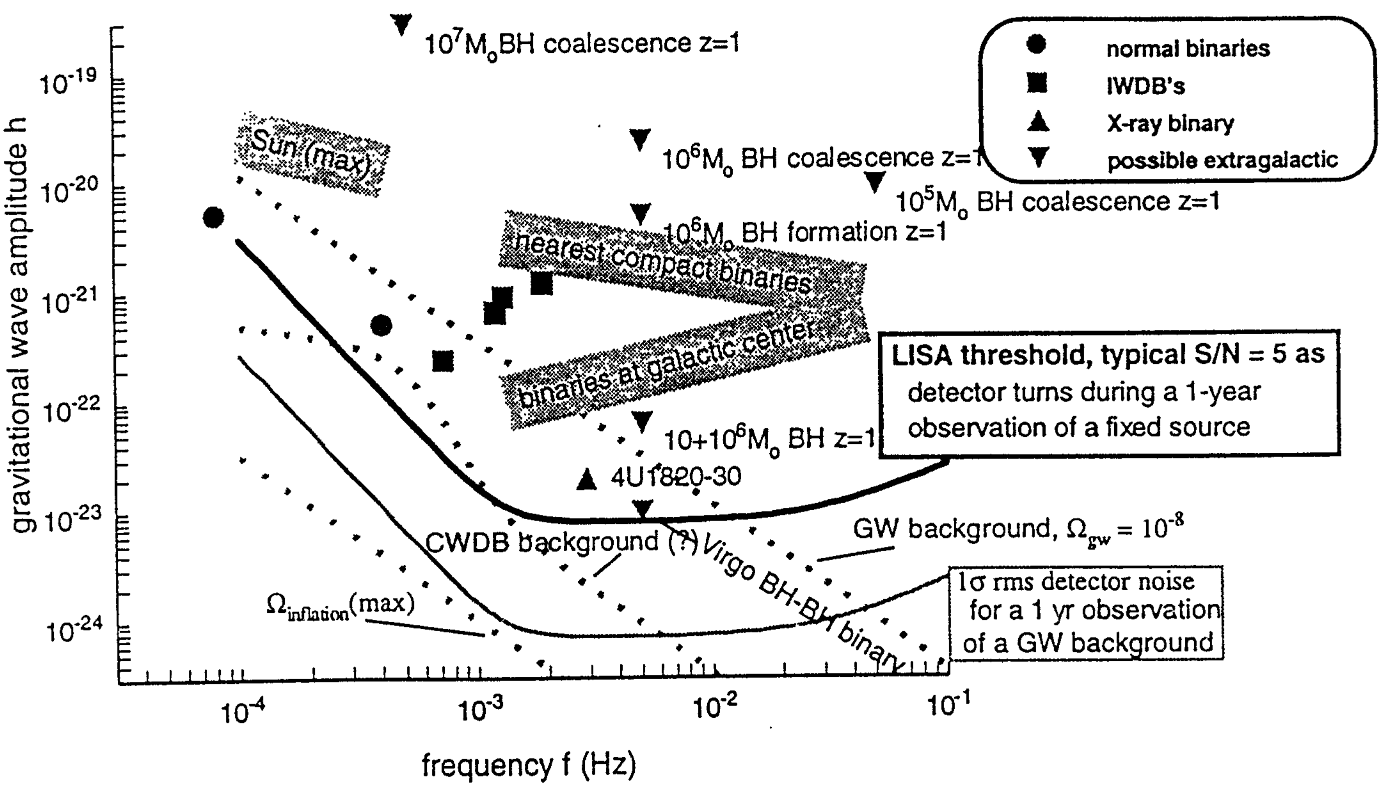
LISA
Space Interferometry

- Gravitational dynamics
  - » wide range of masses and radii or sources with natural dynamical frequency in the LISA band



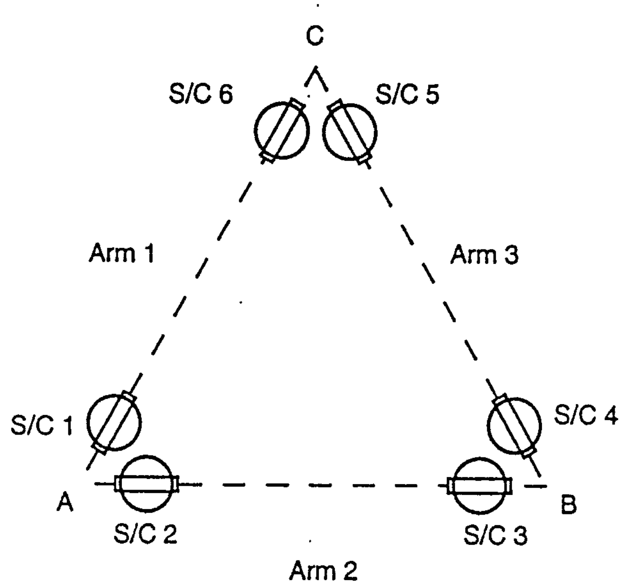
LISA
Sensitivity

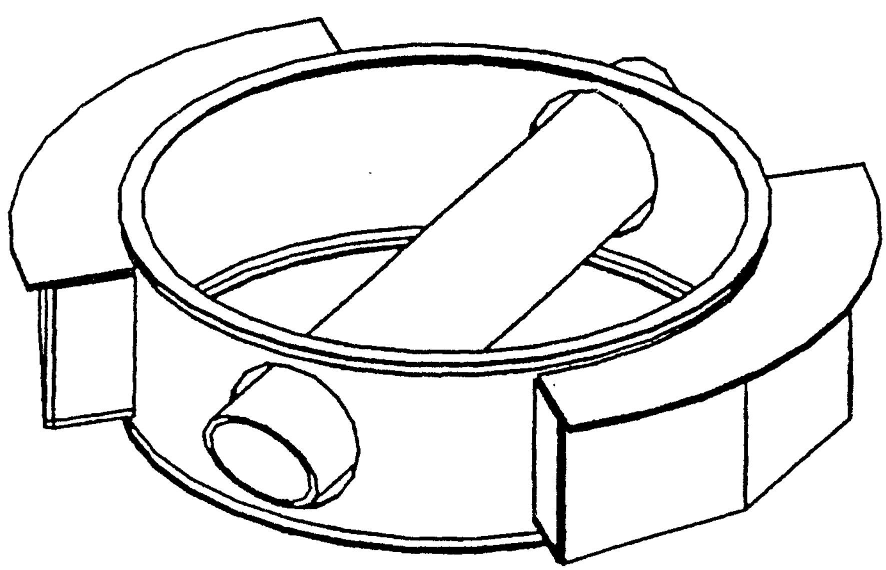
- Strength of various sources and sensitivity curve of LISA



LISA
spacecraft layout

- six identical spacecraft

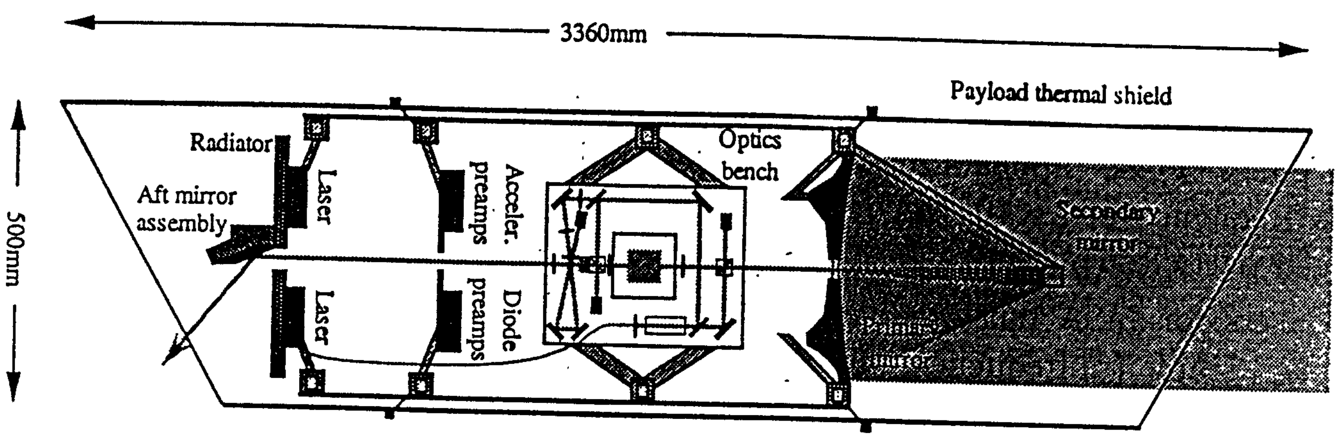




LISA

payload and optical bench

- cross section of payload



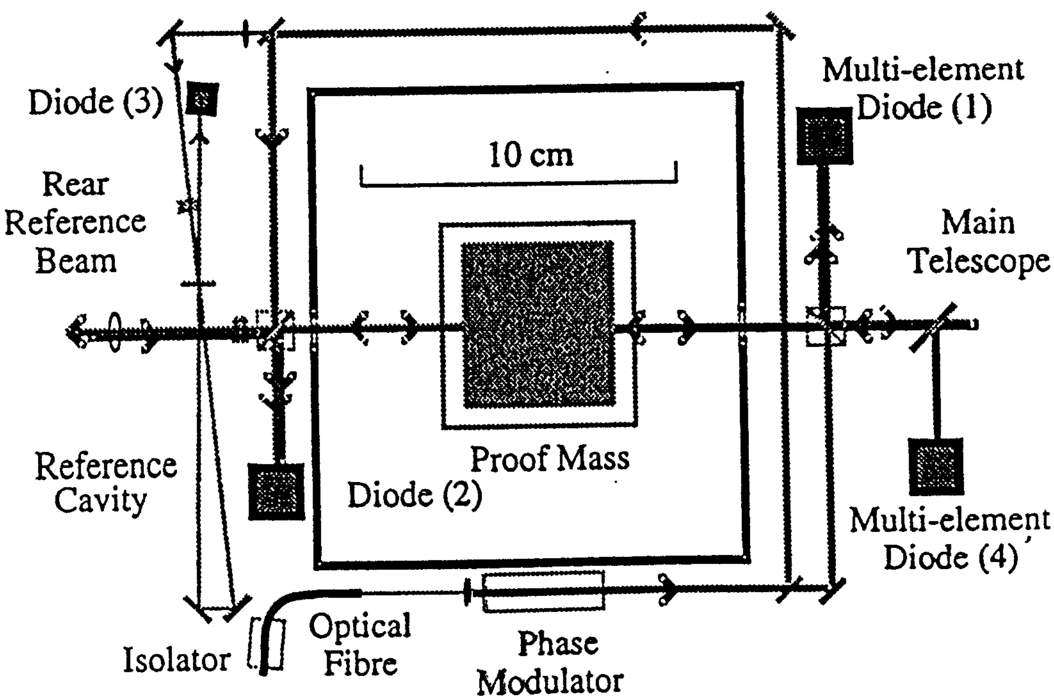
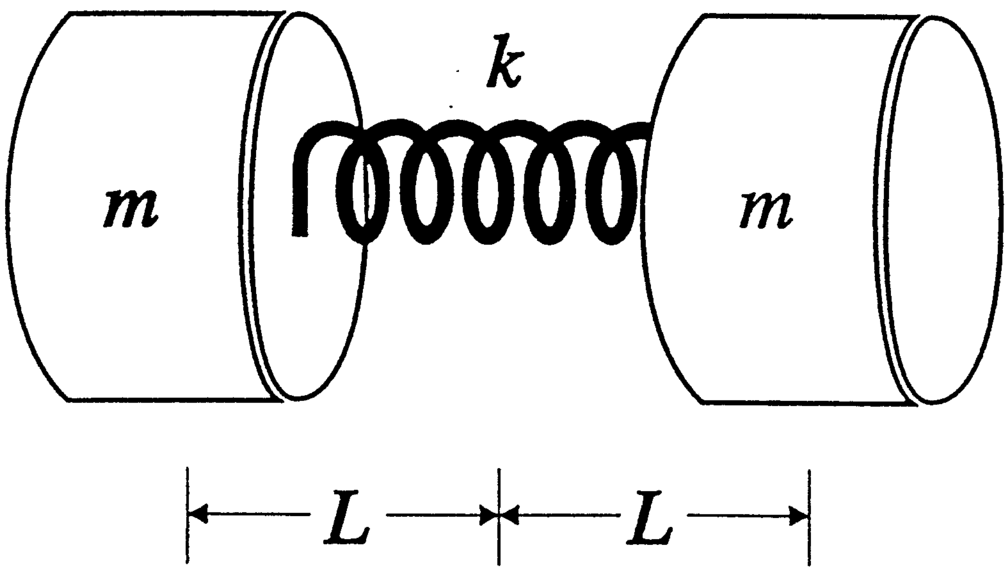


Table I. LISA Mission Summary	
Objectives:	Detection of low-frequency (10^{-4} to 10^{-1} Hz) gravitational radiation with a strain sensitivity of $10^{-21}/\sqrt{Hz}$. Typical sources are galactic binaries (black holes, neutron stars, white dwarfs), extra-galactic supermassive black hole formations and coalescences, and background gravitational waves from the Big Bang.
Payload:	Laser interferometry with electrostatically controlled drag-free reference mirrors housed in six spacecraft; optical arm lengths 5×10^6 km. Each spacecraft has two lasers (one spare) which operate together in a phase-locked transponder scheme. Diode-pumped Nd-YAG lasers: wavelength 1.064 μm, output power 1 W, Fabry-Perot reference cavity for frequency-stability of 3 $Hz/\sqrt{Hz}$. Quadrant photodiode detectors with interferometer fringe resolution of $10^{-5}\lambda$. 38 cm diameter f/1 Cassegrain telescope (transmit/receive) with $\lambda/30$ wavefront quality. Drag-free proof mass (mirror): 4 cm cube, Au-Pt alloy of extremely low magnetic susceptibility ($< 10^{-6}$); Ti-housing at vacuum $< 10^{-8}$ mbar; six-degree-of-freedom capacitive sensing.
Orbit:	Each spacecraft orbits the Sun at 1 AU. The inclinations are such that their *relative* orbits define a circle with radius 3×10^6 km and a period of 1 year. The plane of the circle is inclined 60° with respect to the ecliptic. On this circle, the spacecraft are distributed at three vertices, defining an equilateral triangle with a side length of 5×10^6 km (interferometer baseline). Each vertex has two closely-spaced spacecraft (200 km apart). This constellation is located at 1 AU from the Sun, 20° behind the Earth.
Launcher:	Ariane 5, dual launch configuration with two sets of two spacecraft in the lower compartment, and one set in the upper, under the short fairing. Each spacecraft has its own jettisonable propulsion module to provide a ΔV of 1000 m/s for final orbit injection. Annual launch window: April – October
Spacecraft:	3-axis stabilized drag-free spacecraft (six)
mass:	290 kg, *each spacecraft in orbit*
propulsion module:	216 kg, *two spacecraft per module*
propellant:	240–920 kg (depending on launch date), *for two spacecraft*
total launch mass:	6200 kg
power:	183 W, *each spacecraft in orbit*
Drag-free performance:	10^{-15} m/s^2 (rms) in the band 10^{-4} to 10^{-1} Hz achieved with 6×4 Cesium FEEP thrusters
Pointing performance:	few nrad/$\sqrt{Hz}$ in the band 10^{-4} to 10^{-1} Hz
Payload, mass:	67 kg, *each spacecraft*
power:	48 W, *each spacecraft*
dimension:	diameter: 0.5 m, height: 1.7 m, *each spacecraft*
Telemetry:	560 bps continuous, *total for all six spacecraft* Ground stations: Villafranca (Spain), Perth (Australia)
Nominal Mission Lifetime:	specification 2 years; 3–10 years feasible

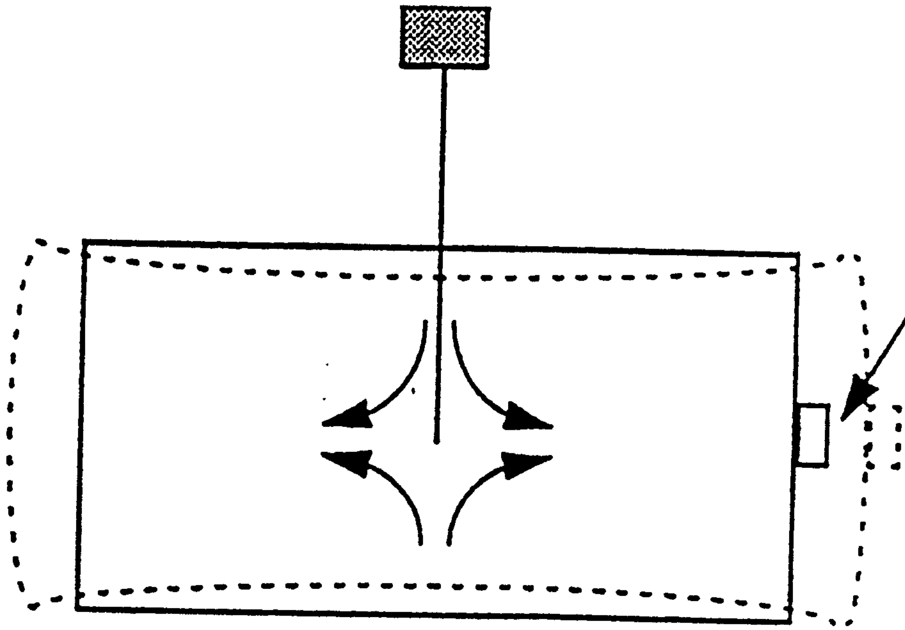
Gravitational Waves
Resonant Bar Detector

- Schematic Version



Gravitational Waves

Resonant Bar Detection



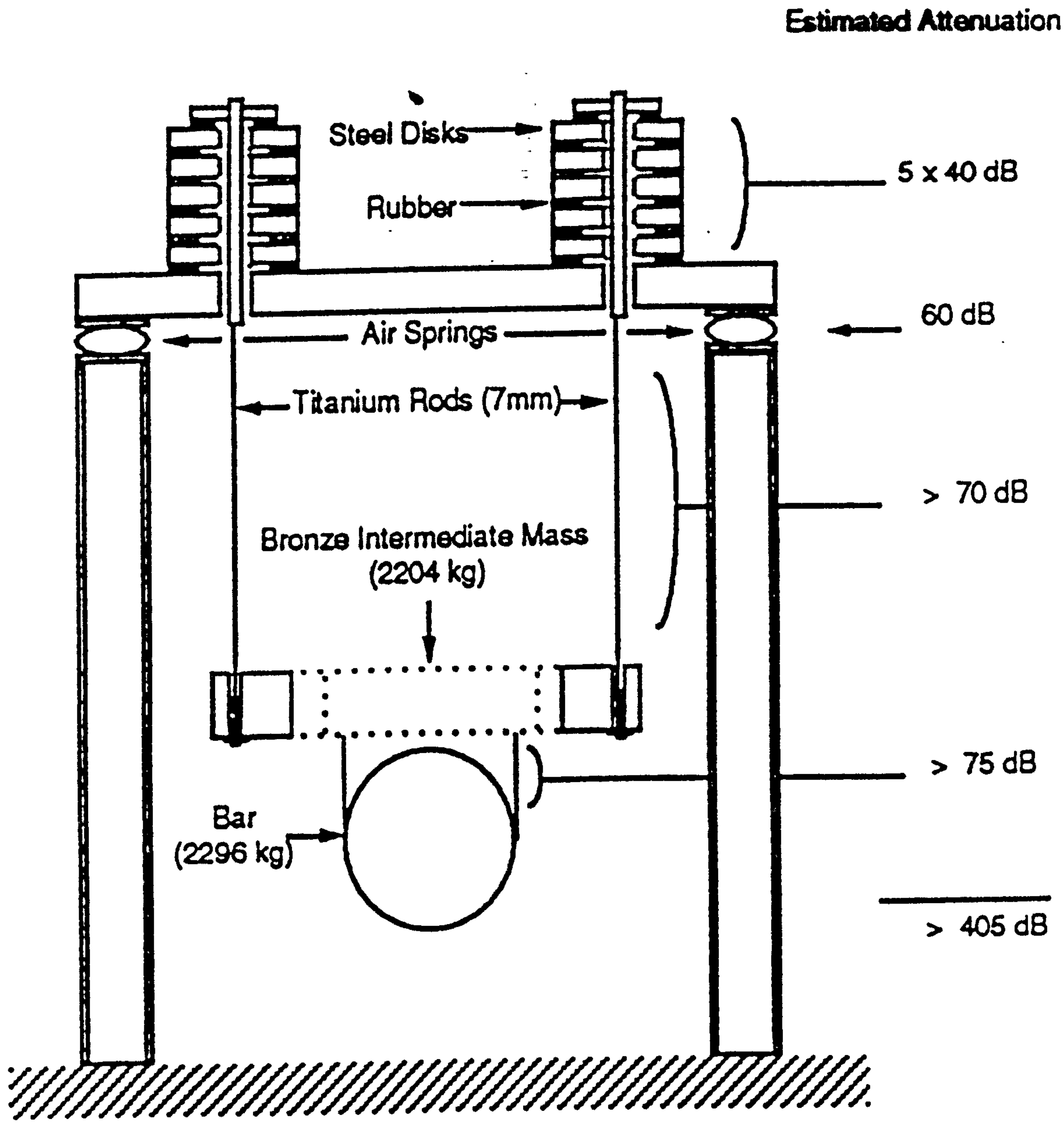
- Bar detector

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

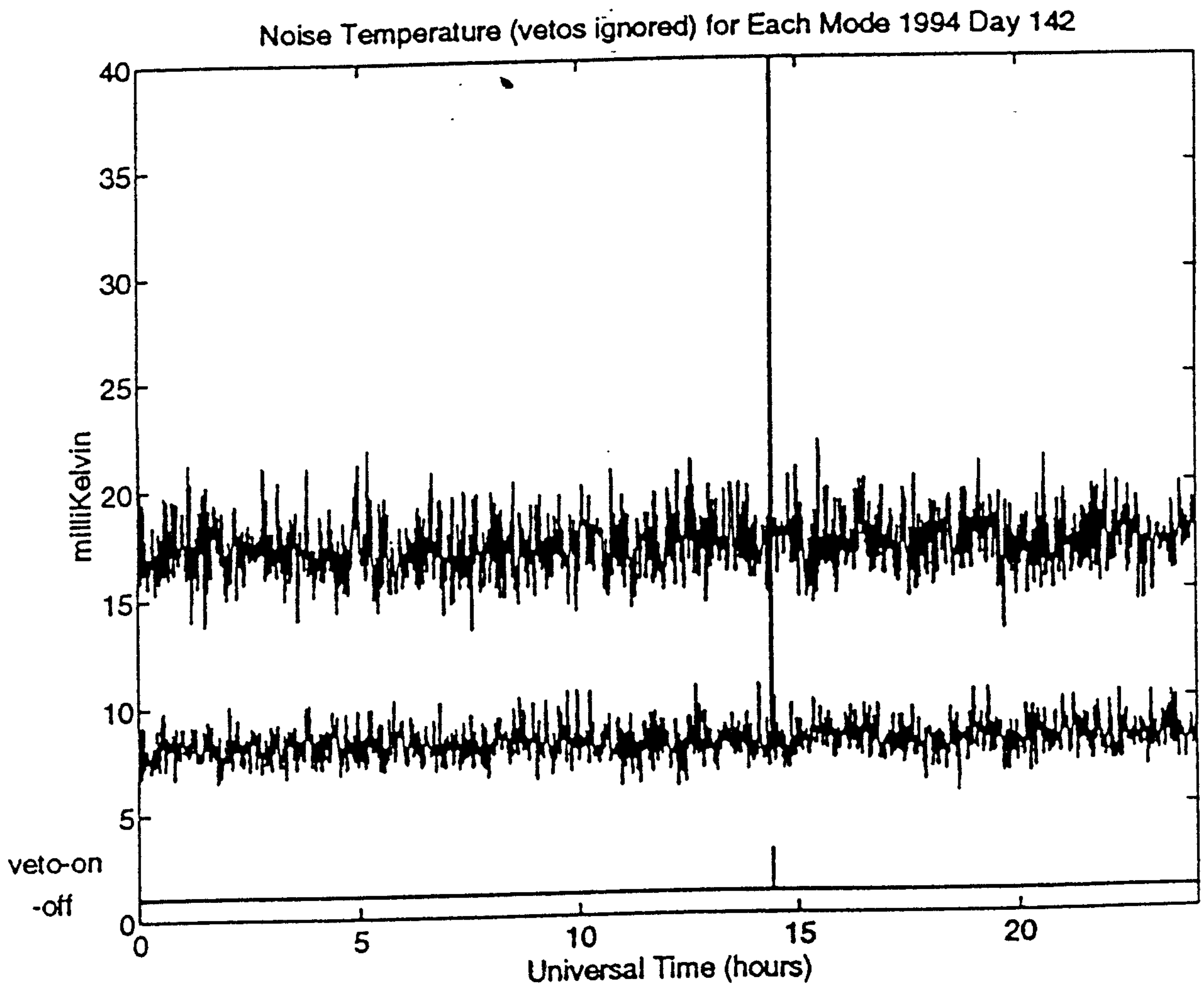
Resonant Bars
Support Scheme

- ALLEGRO detector



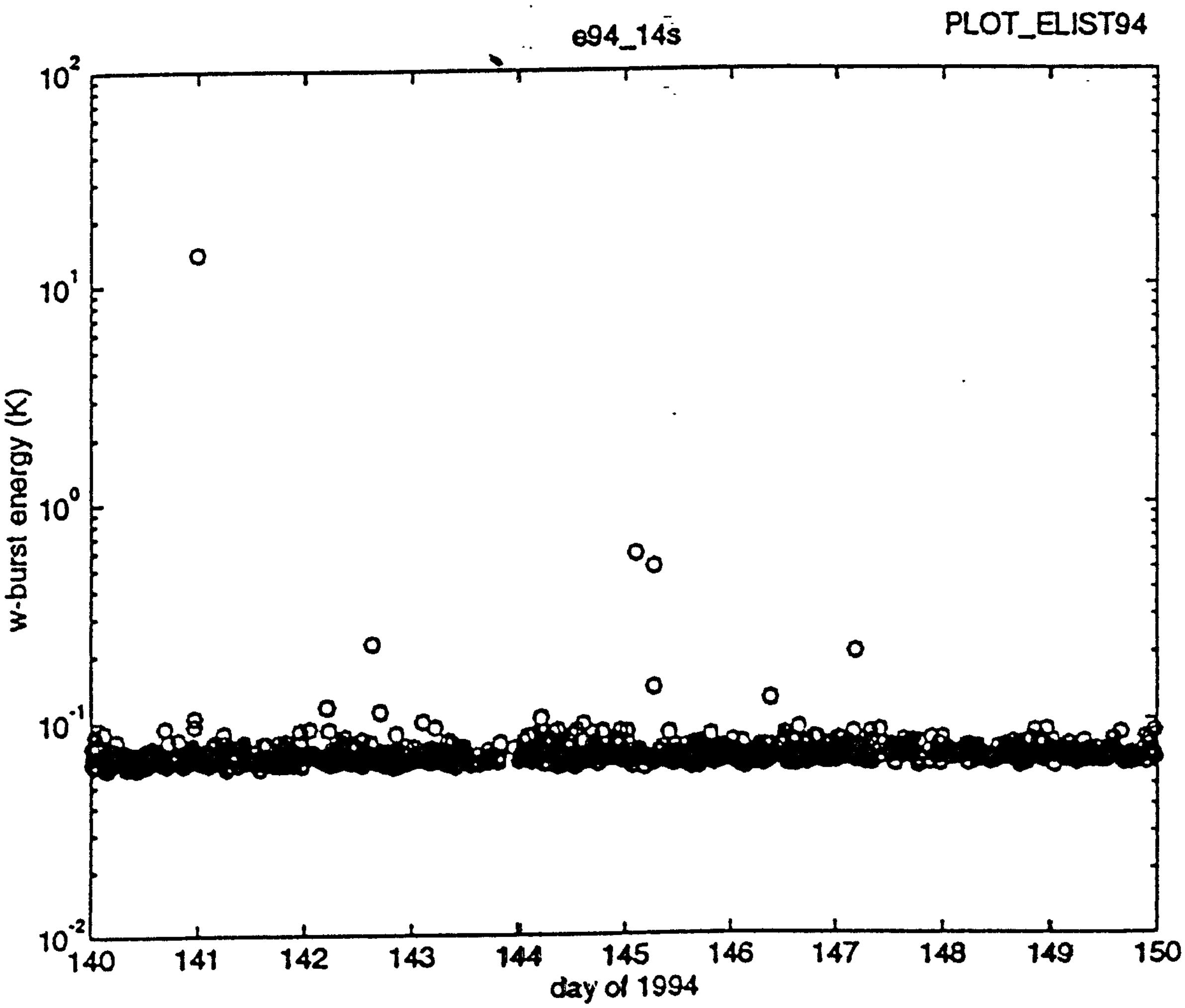
Resonant Bars
ALLEGRO

- average detected noise
  - » (day 142, 1994)
  - » large excursion is squid reset (vetoed)



Resonant Bars
ALLEGRO

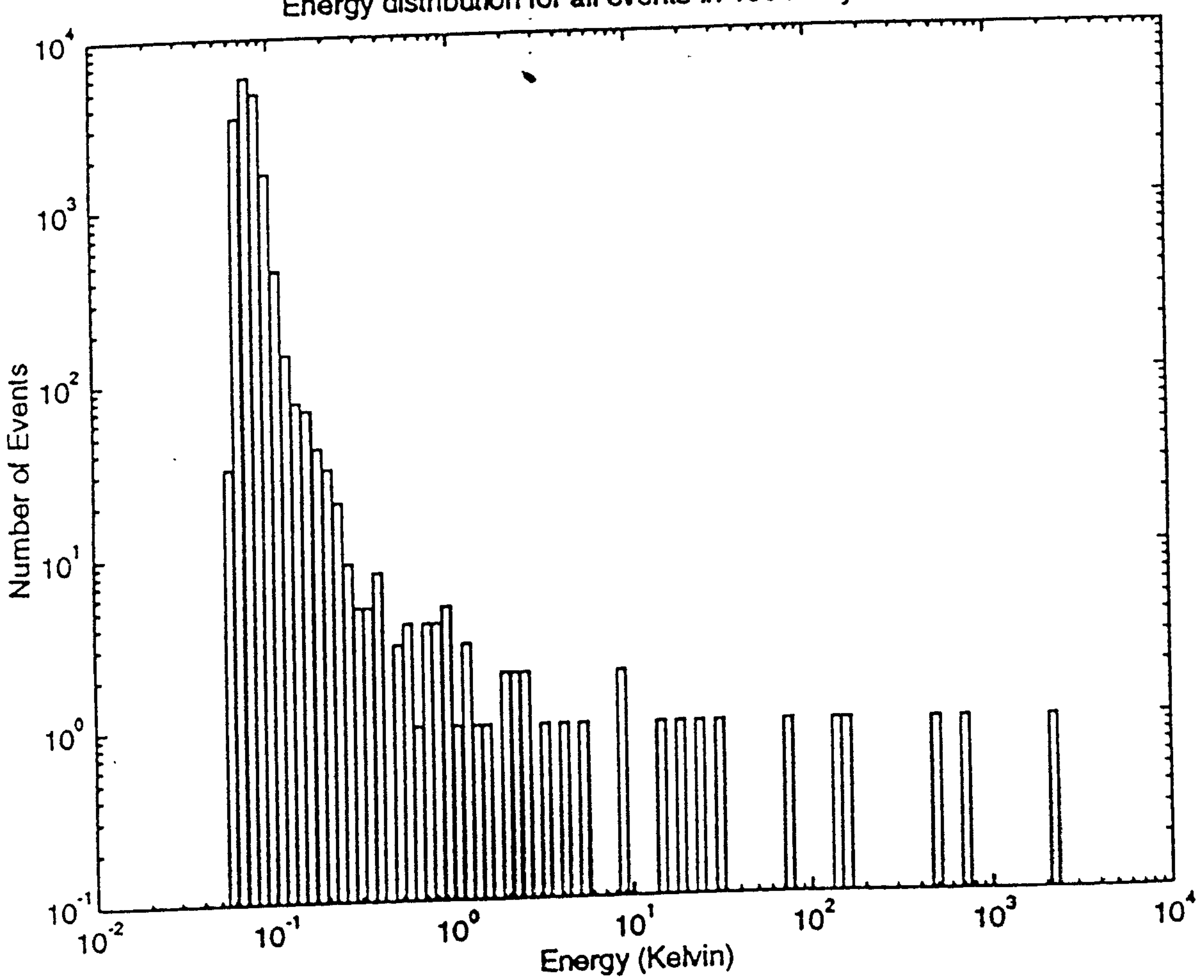
- ~~All events above threshold~~
  - » day 140-150   1994
  - » typical of existing data (LSU and Rome)



Resonant Bars
ALLEGRO

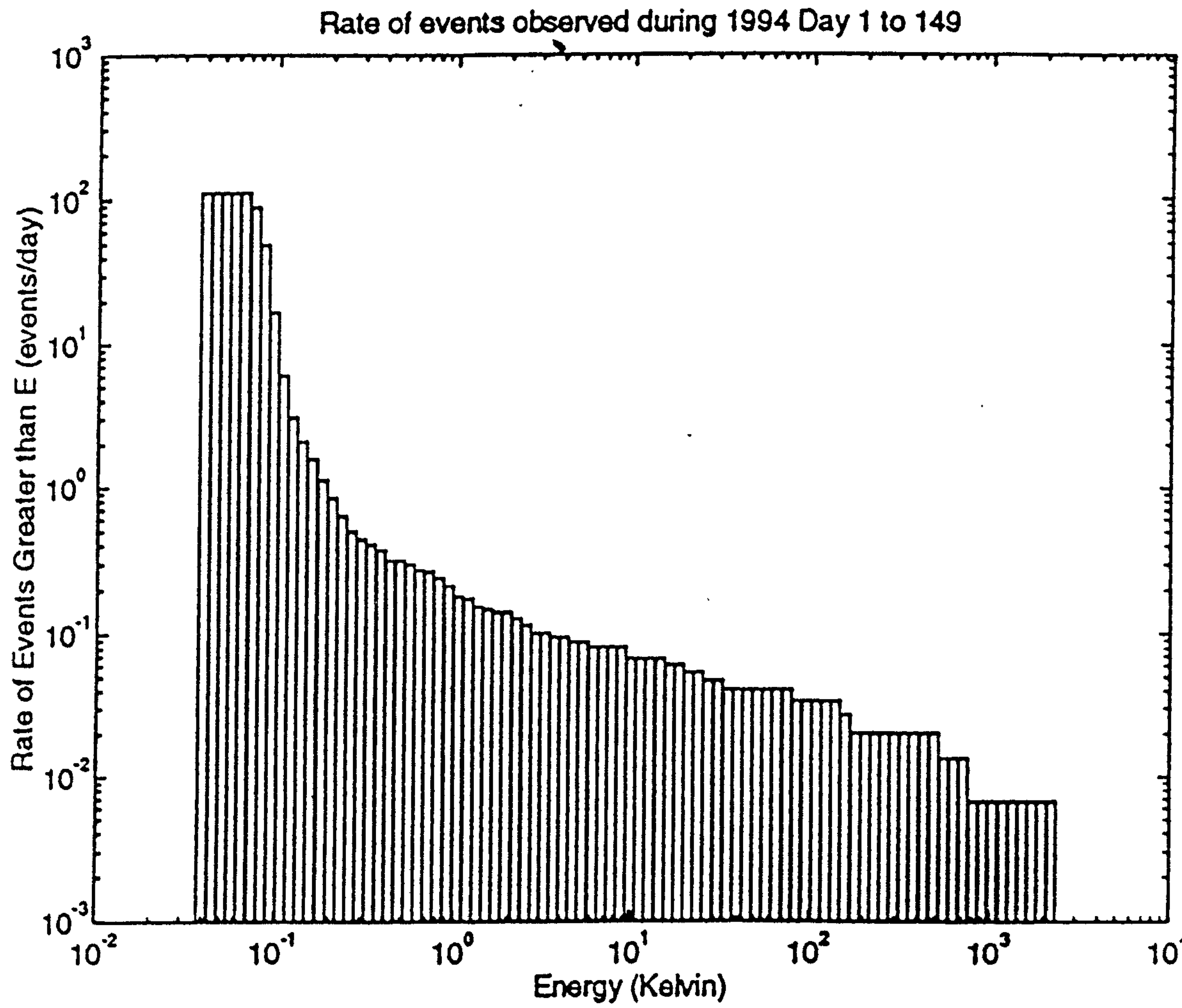
- All events
  - » first 5 months of 1994
- Non-gaussian tail

Energy distribution for all events in 1994 Day 1 to 149



Resonant Bars
ALLEGRO

- Rate of events
  - » First 5 months - 1994
  - » All non-vetoed events included

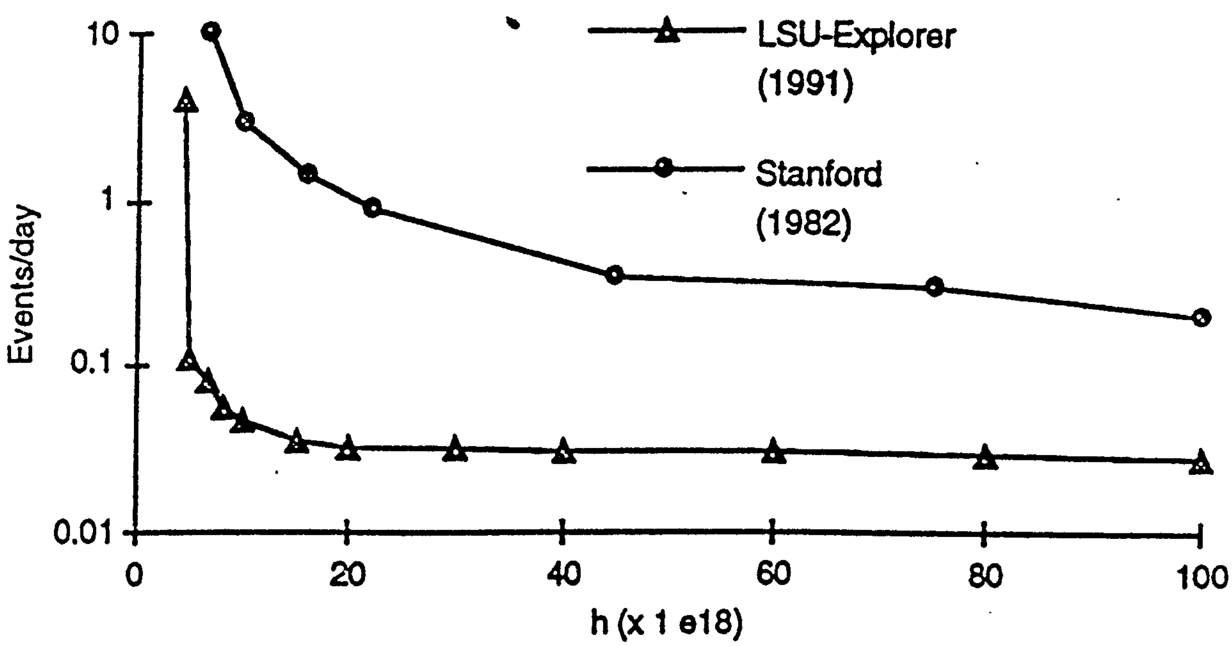


Resonant Bars

Coincidence Run

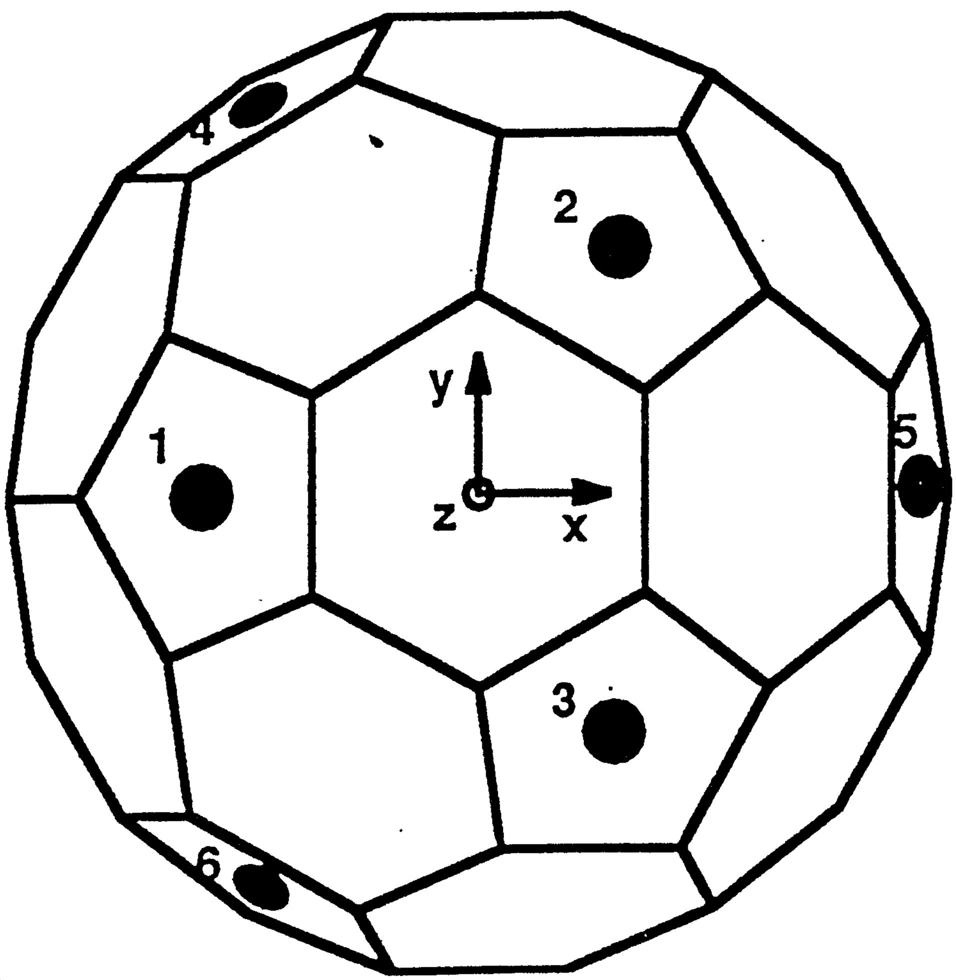
- Stanford 1982
- Explorer and Allegro 1991 - 6 months

Upper Limit for G.W. short bursts



Resonant Detectors
Next Generation

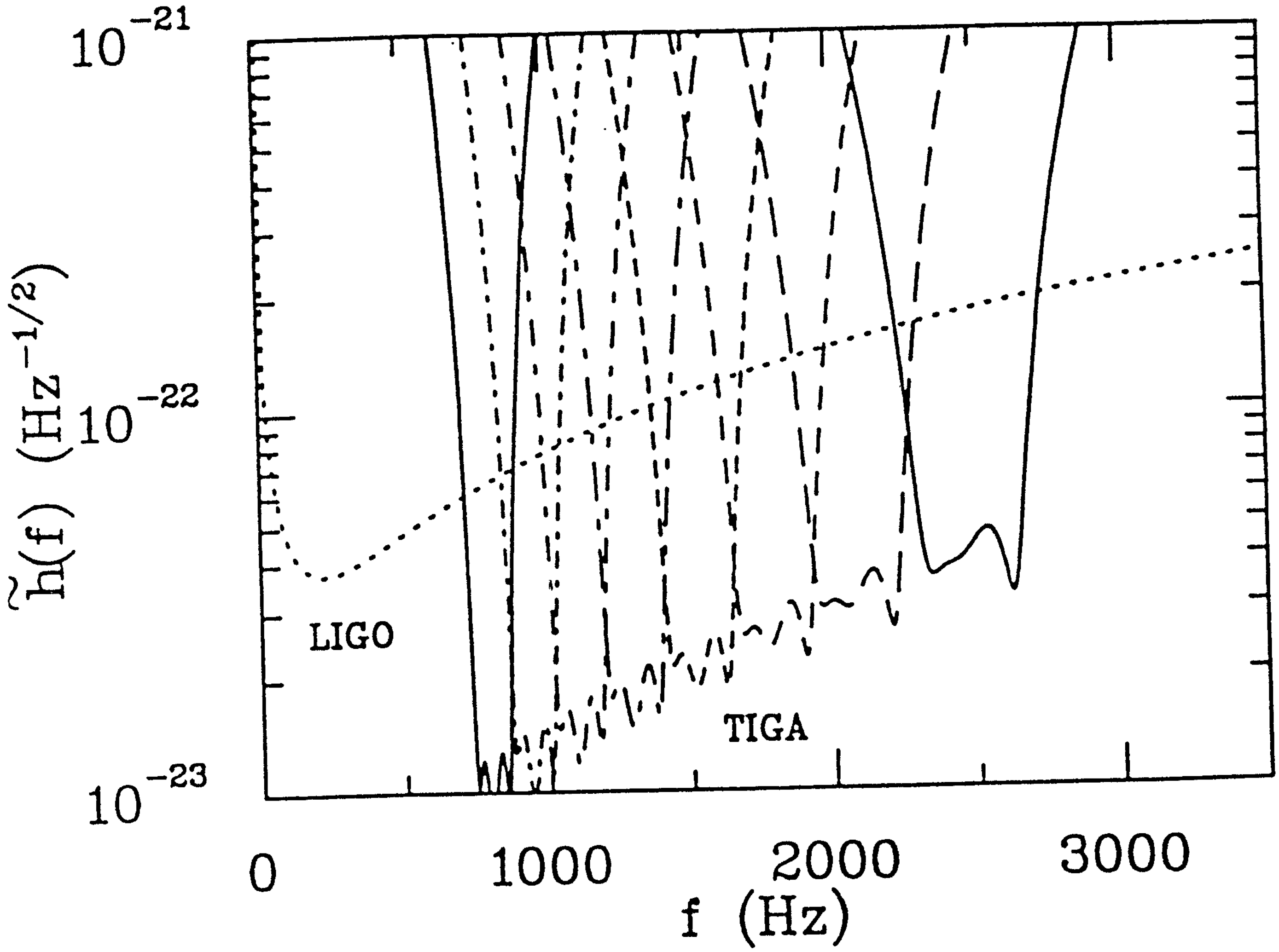
- Omni-directional detectors
- TIGA
  - » attach transducers to faces of inscribed dodecahedron (Johnson and Merkowitz)
  - » 2.6 meter diam, resonant at 1 kHz, 26 metric tons



Resonant Detectors

Spherical Array

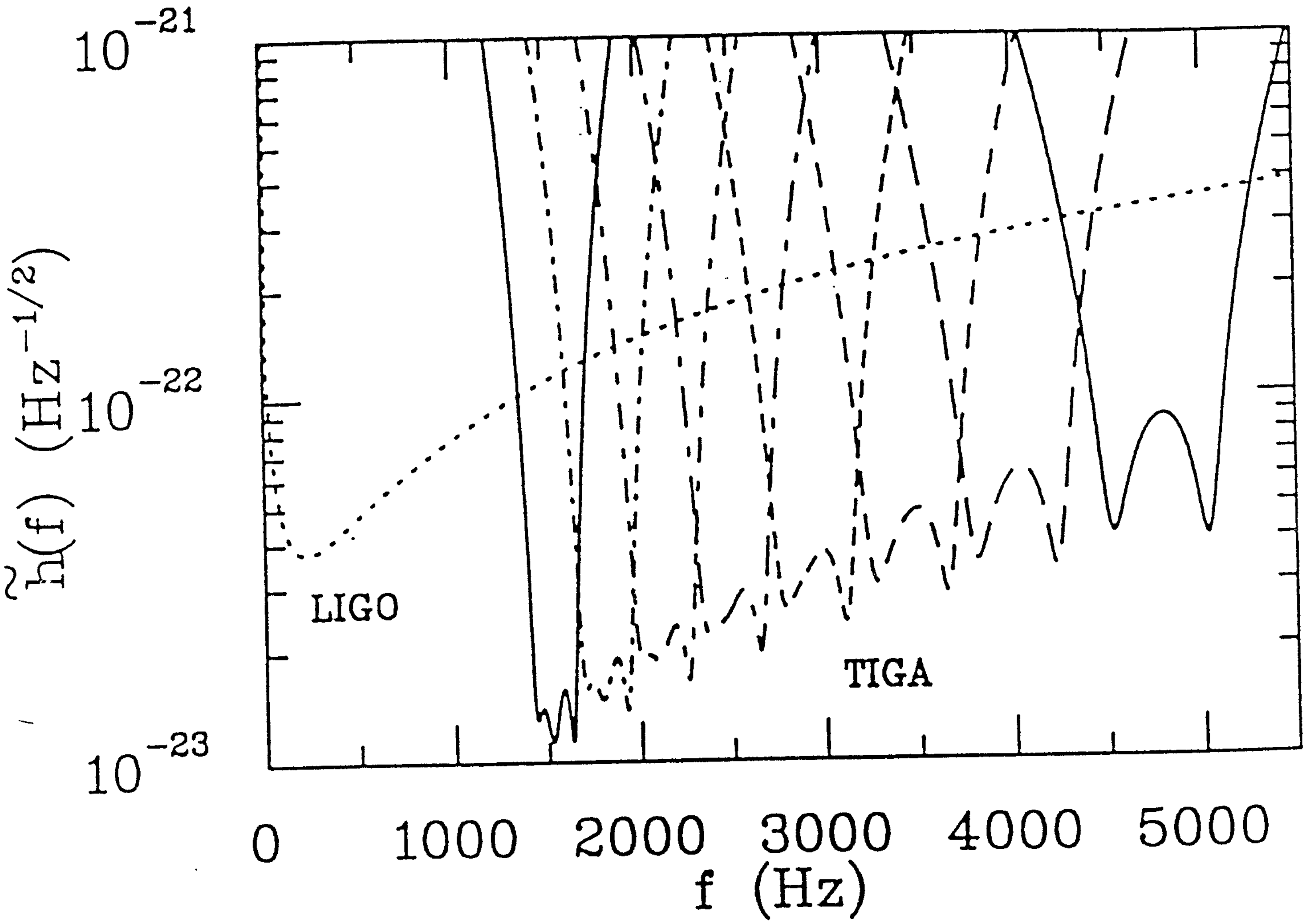
- 8 spherical detectors (xylophone)
  - » lowest quadrupole mode



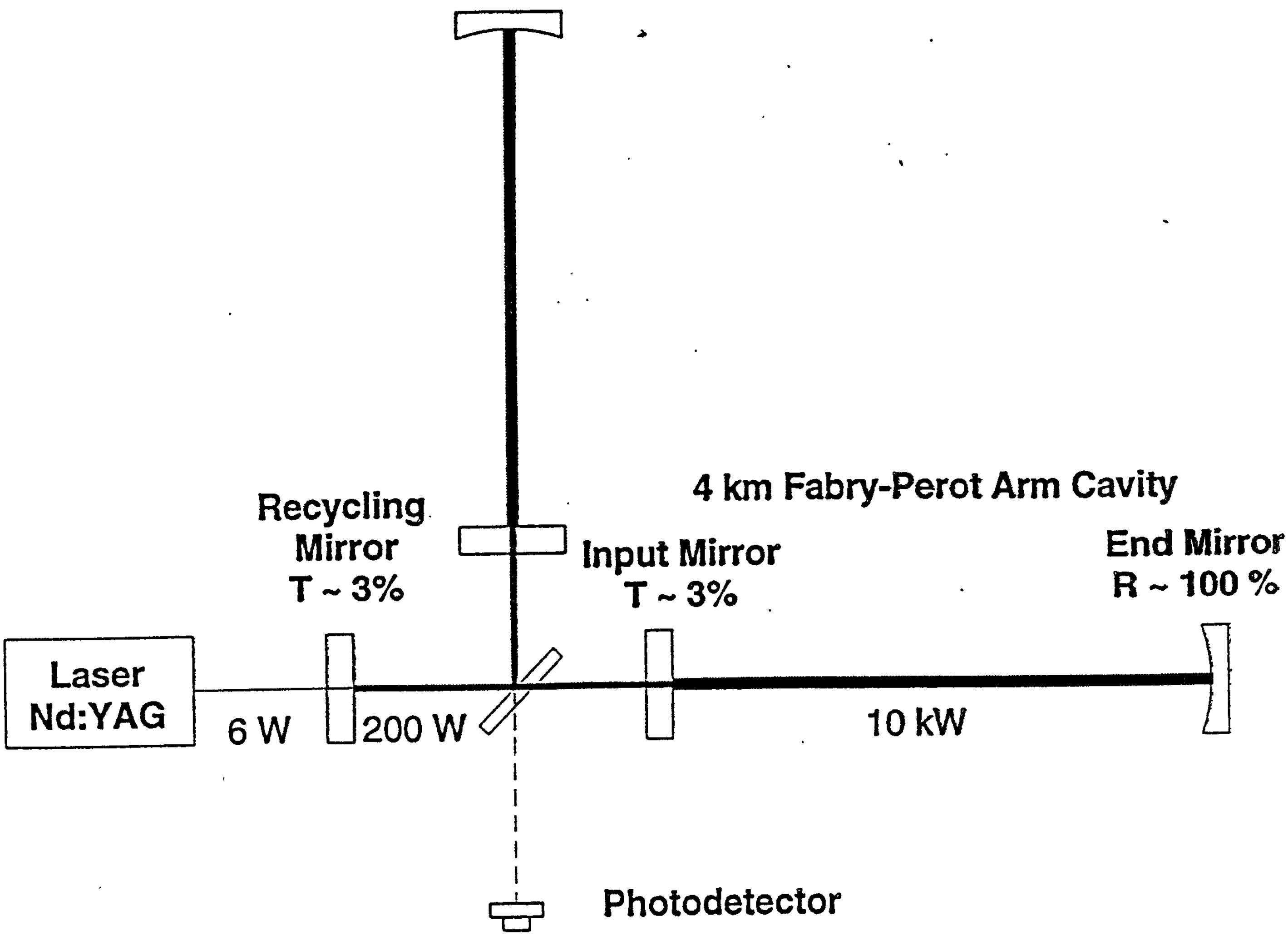
Resonant Detectors

Spherical Array

- 8 spherical detectors (xylophone)
  - » first excited quadrupole mode

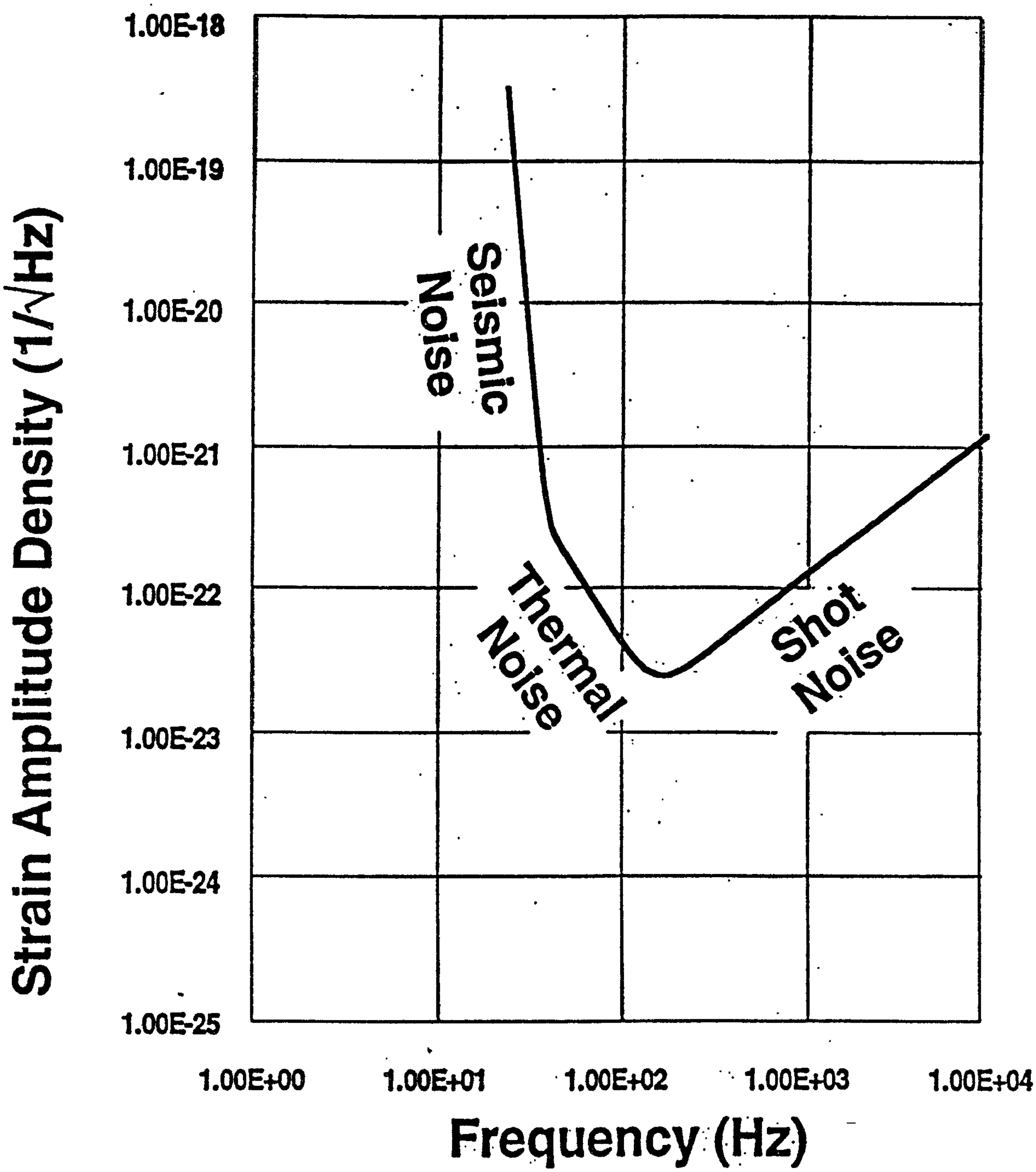


Initial Interferometers
Configuration



Initial Interferometers

Noise Floor



LIGO Interferometers

Optical Parameters

Optical Characteristics	Nominal Initial Interferometer	Sample Enhanced Interferometer
Arm Length	4000 m	4000 m
Laser Type & Wavelength	Nd:YAG, $\lambda = 1.064\ \mu m$	Nd:YAG, $\lambda = 1.064\ \mu m$
Input Power into Recycling Cavity, P	6W	100W
Contrast Defect, 1-c	3×10^{-3}	3×10^{-3}
Mirror Loss, L_M	1×10^{-4}	1.3×10^{-5}
Power Recycling Gain	30	380
Arm Cavity Storage Time, τ_{Arm}	8.8×10^{-4} s	1.3×10^{-3}s
Cavity Input Mirror Transmission, T	3×10^{-2}	2×10^{-2}
Total Optical Loss, L_T = (Absorption + Scattering)	4×10^{-2}	3×10^{-3}

LIGO Interferometers

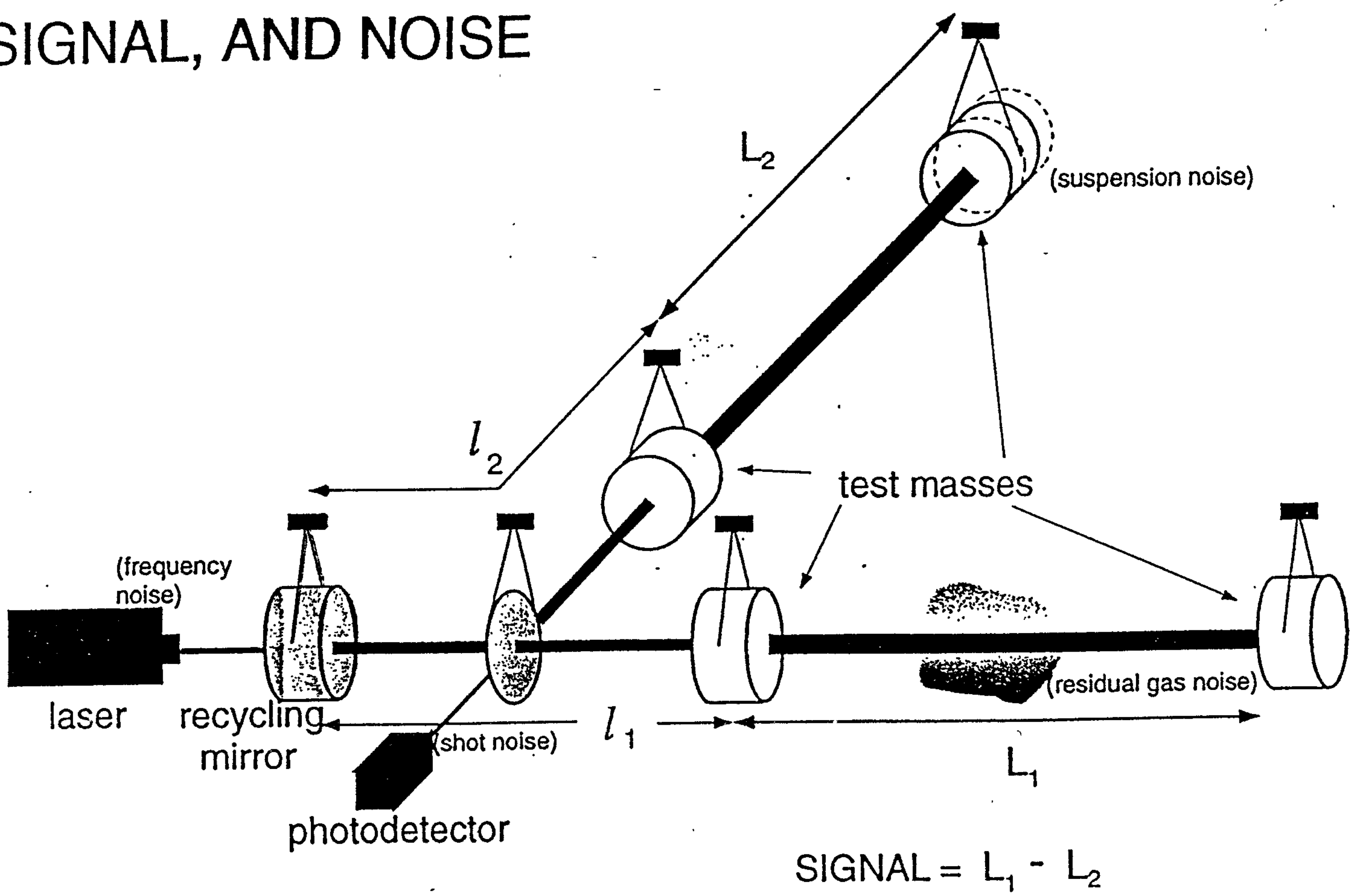
Mechanical Parameters

Mechanical Characteristics	Nominal Initial Interferometer	Sample Enhanced Interferometer
Mirror Mass, M_M	10.7 kg	40 kg
Mirror Diameter, D_M	0.25 m	0.40 m
Mirror Internal Q_M	1×10^6	3×10^7
Pendulum Q_P(damping mechanism)	1×10^5 (material)	1×10^8 (material)
Pendulum Period, T_P	1 s (Single)	1 s (Double)
Seismic Isolation System	T(100 Hz) = -100 dB	T(10 Hz) = -100 dB

Interferometer

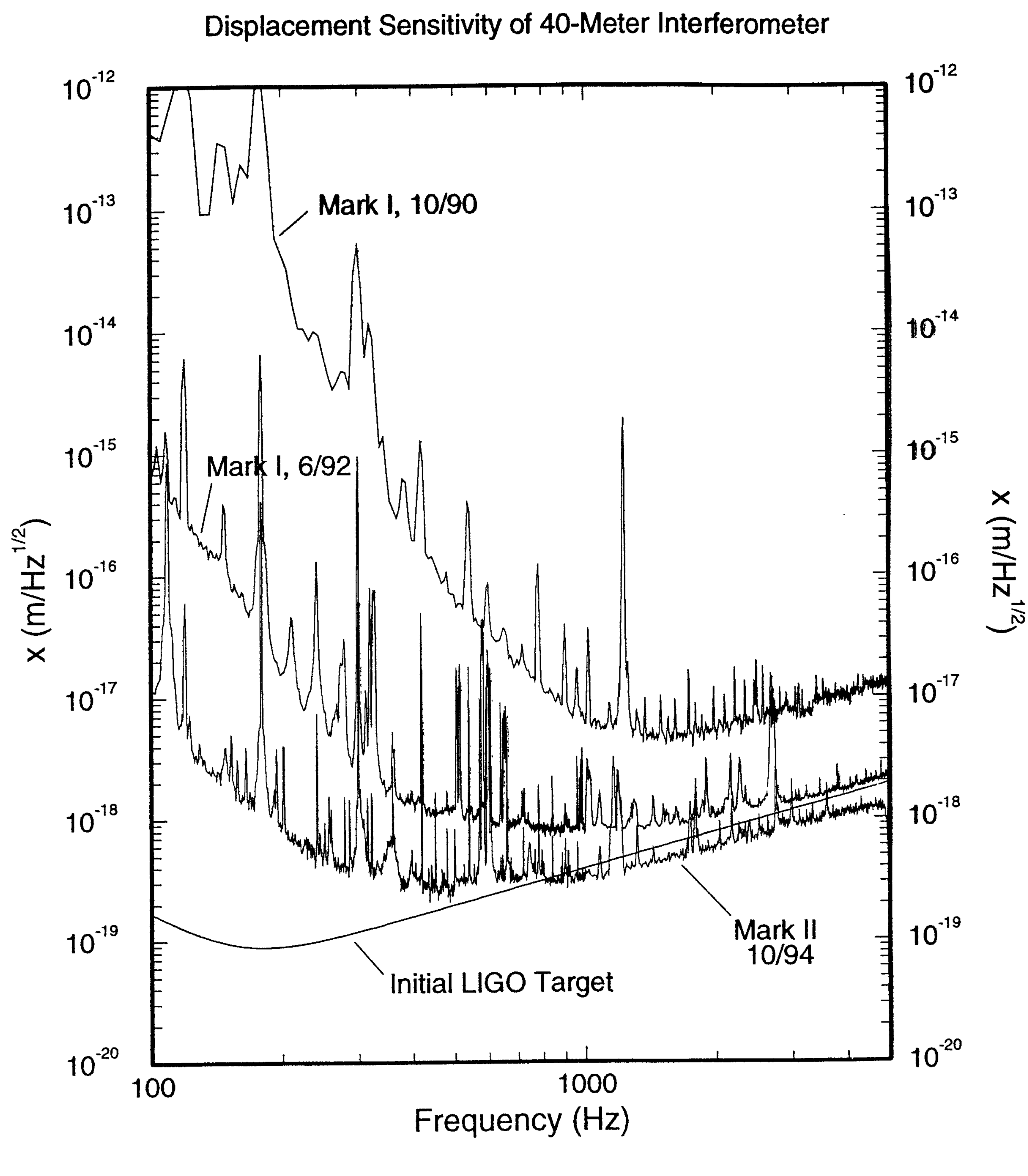
Noise Limitations

INTERFEROMETER, SIGNAL, AND NOISE

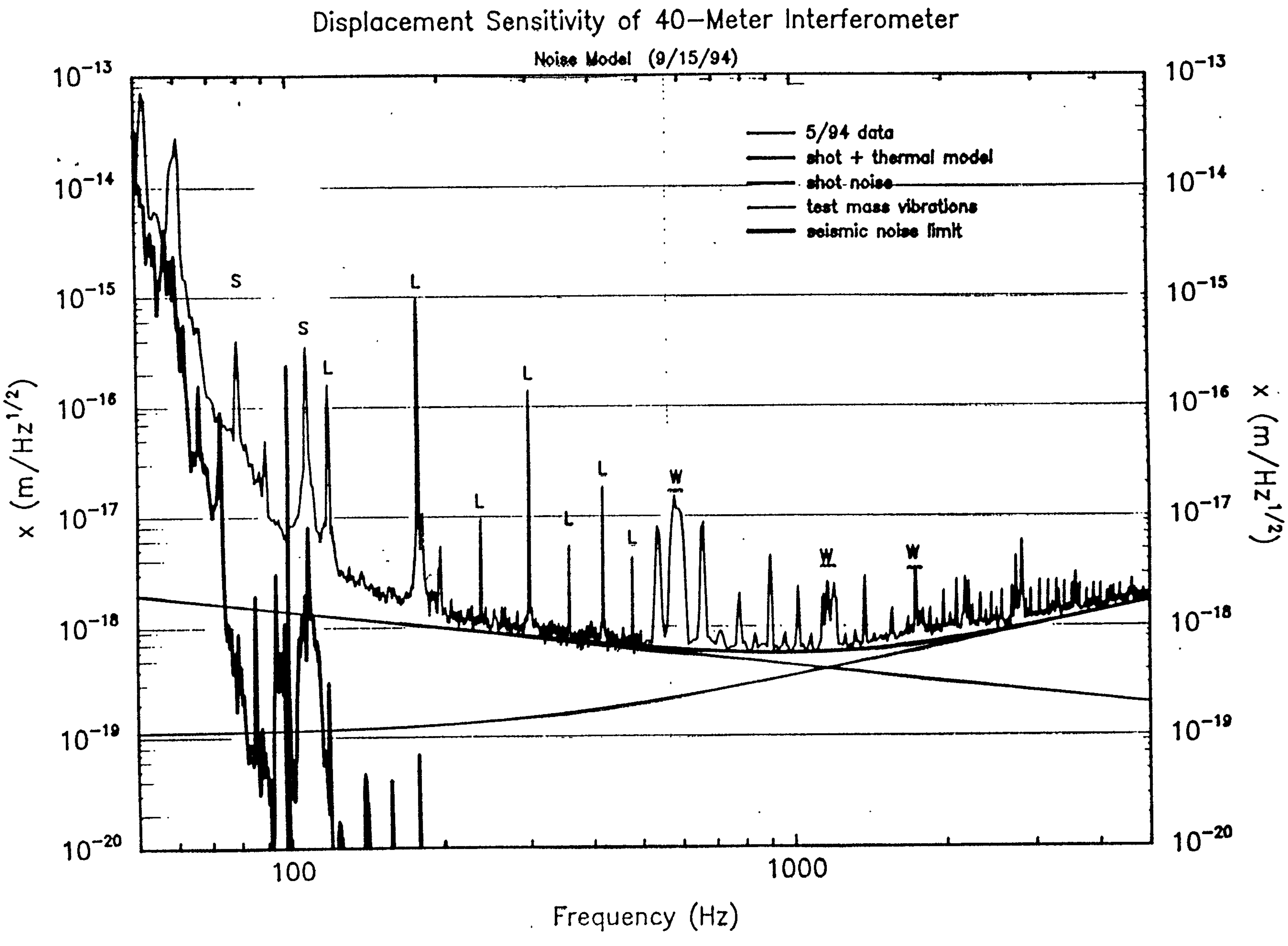


LIGO
R&D Program

- Sensitivity
  - » main features of 40 m spectrum understood
  - » monolithic test masses improve sensitivity
- Demonstration Experiments
  - » optical recombination demonstrated on 40 m
  - » acquisition locking with LIGO controls
  - » MIT phase noise experiments
- Pre- [detector design freeze][<1998]
  - » Program testing directed at tasks that could effect design over the next two years
- Post- [detector design freeze][>1998]
  - » Advanced R&D program on techniques for improved sensitivity;
  - » understand performance - initial interferometer
  - » gain experience running an interferometer facility (perform search)



~fjr/fort/mk2/port_90_94.xvgr



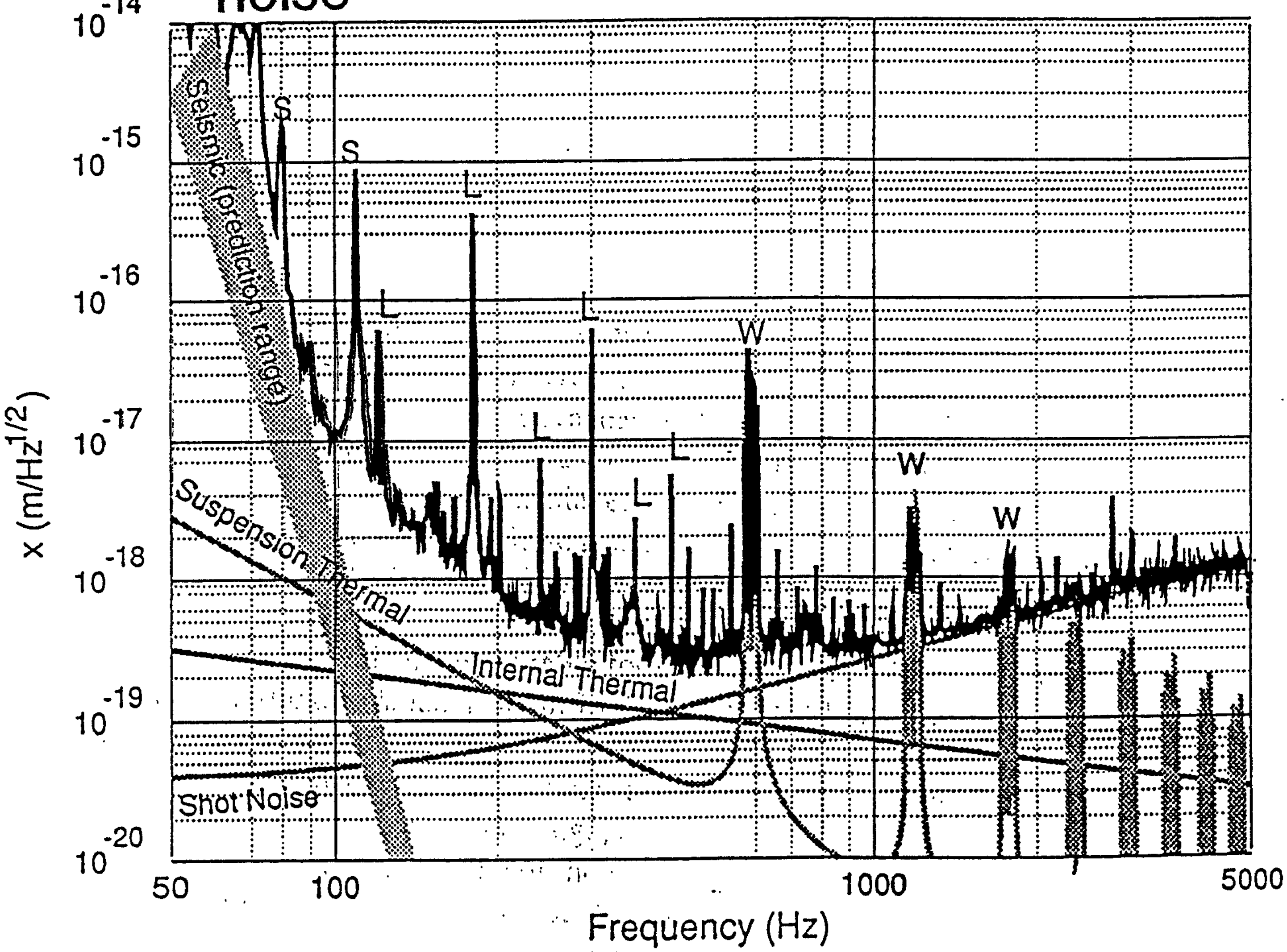
Displacement Sensitivity of 40-Meter Interferometer
Noise Model (9/15/94)
5/94 data
shot + thermal model
shot noise
test mass vibrations
seismic noise limit
S
S
L
L
L
L
L
L
L
L
W
W
W
x (m/Hz^1/2)
Frequency (Hz)
100
1000

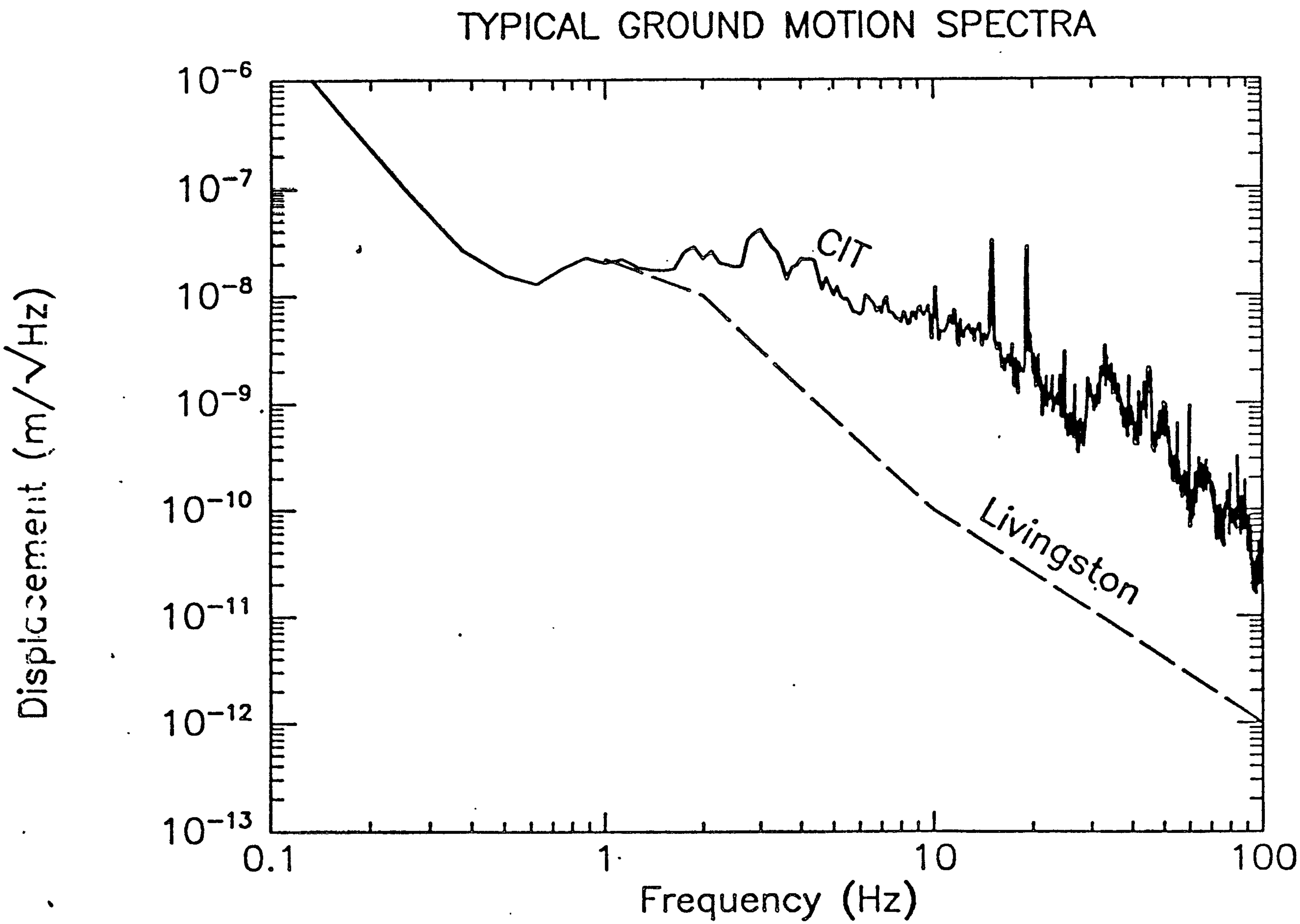
mk2theory2

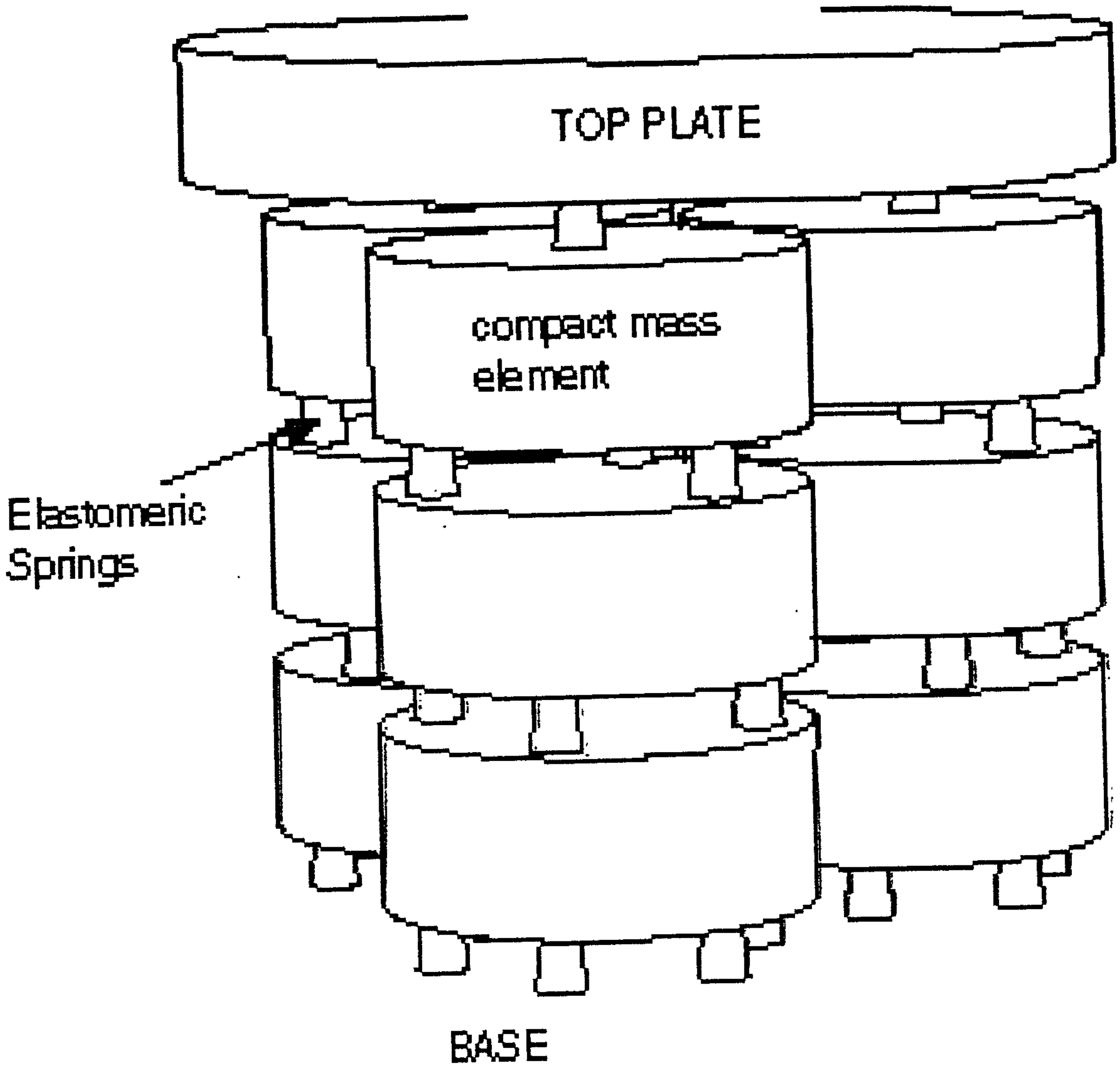
LIGO

40m Prototype

- Measured noise spectrum compared with known broadband sources of noise

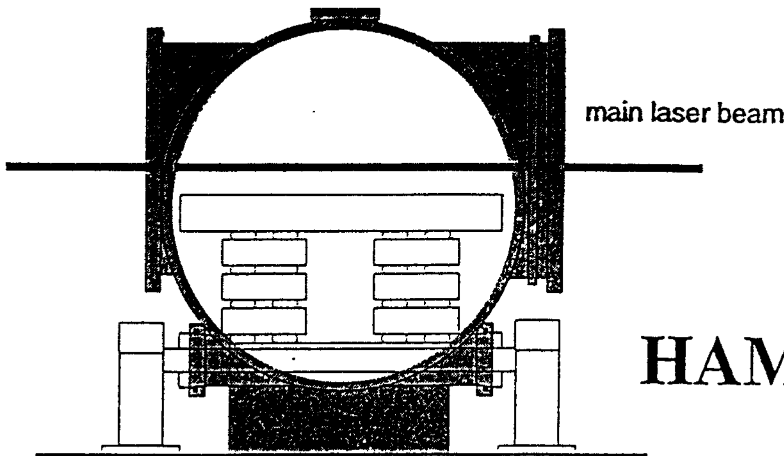



TYPICAL GROUND MOTION SPECTRA
Displacement (m/√Hz)
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
0.1
1
10
100
Frequency (Hz)
CIT
Livingston

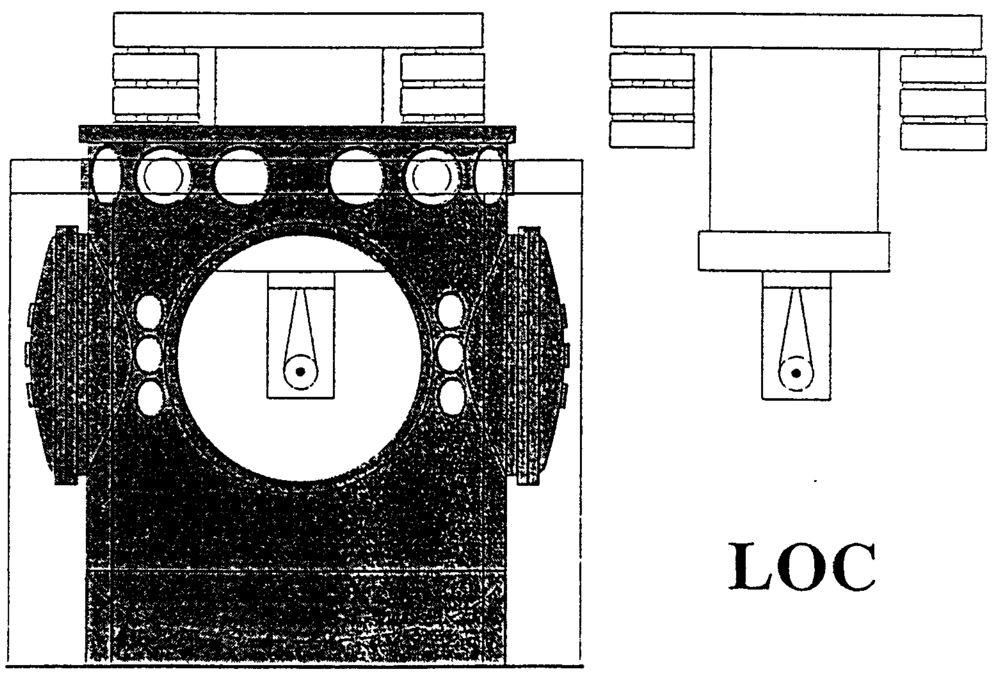


PROTOTYPE ISOLATION STACK

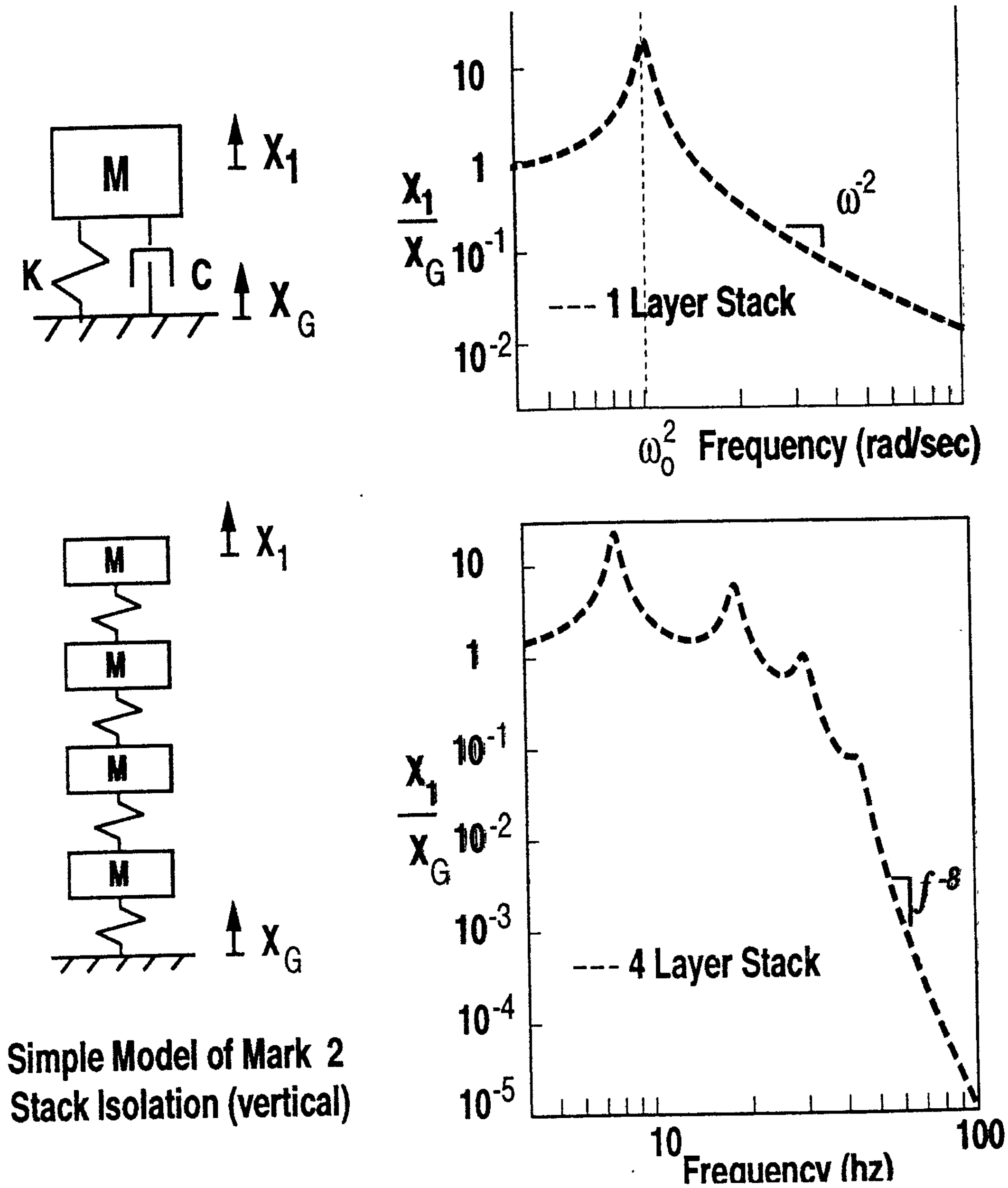
SEI Configuration



HAM



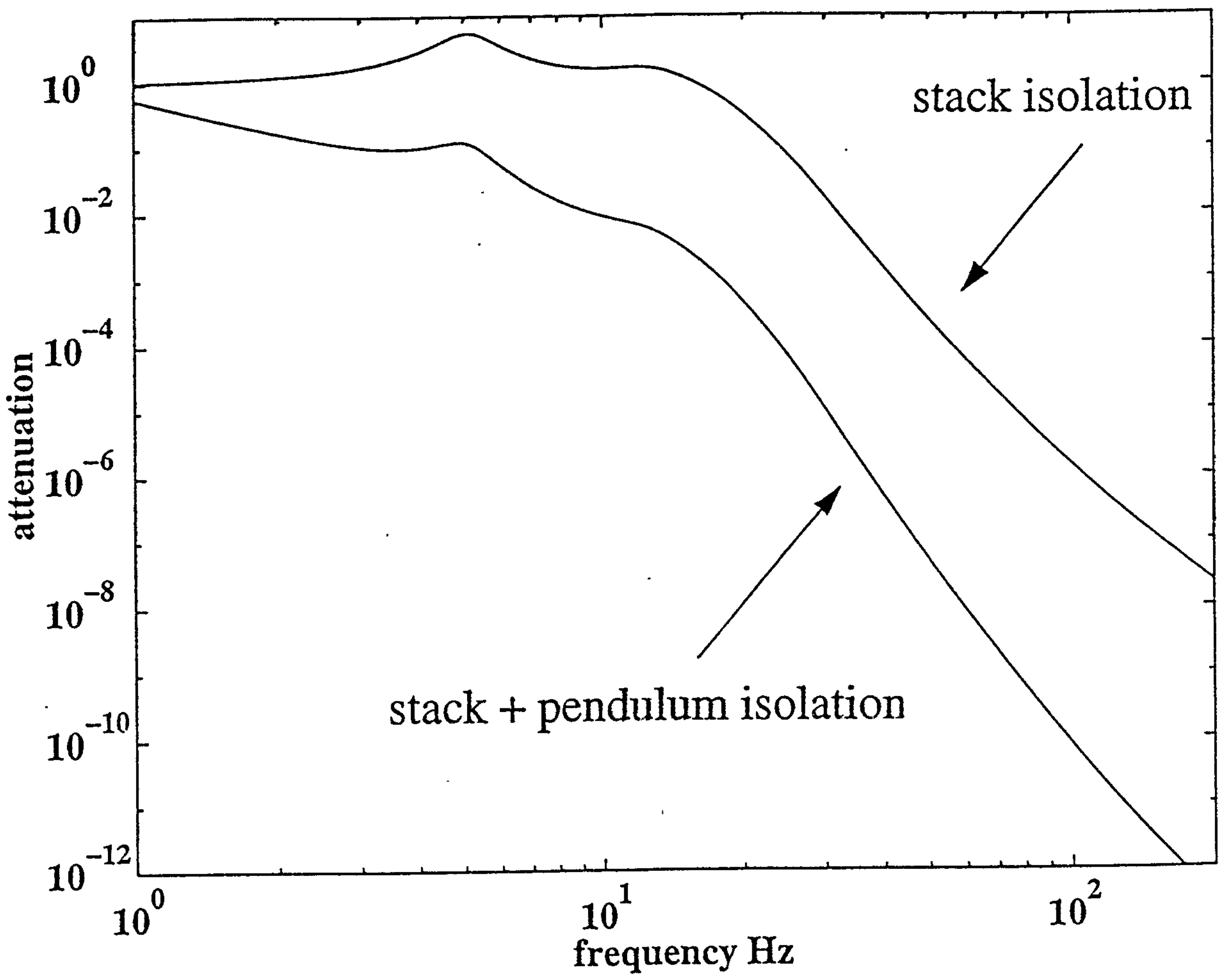
LOC



Simple Model of Mark 2
Stack Isolation (vertical)

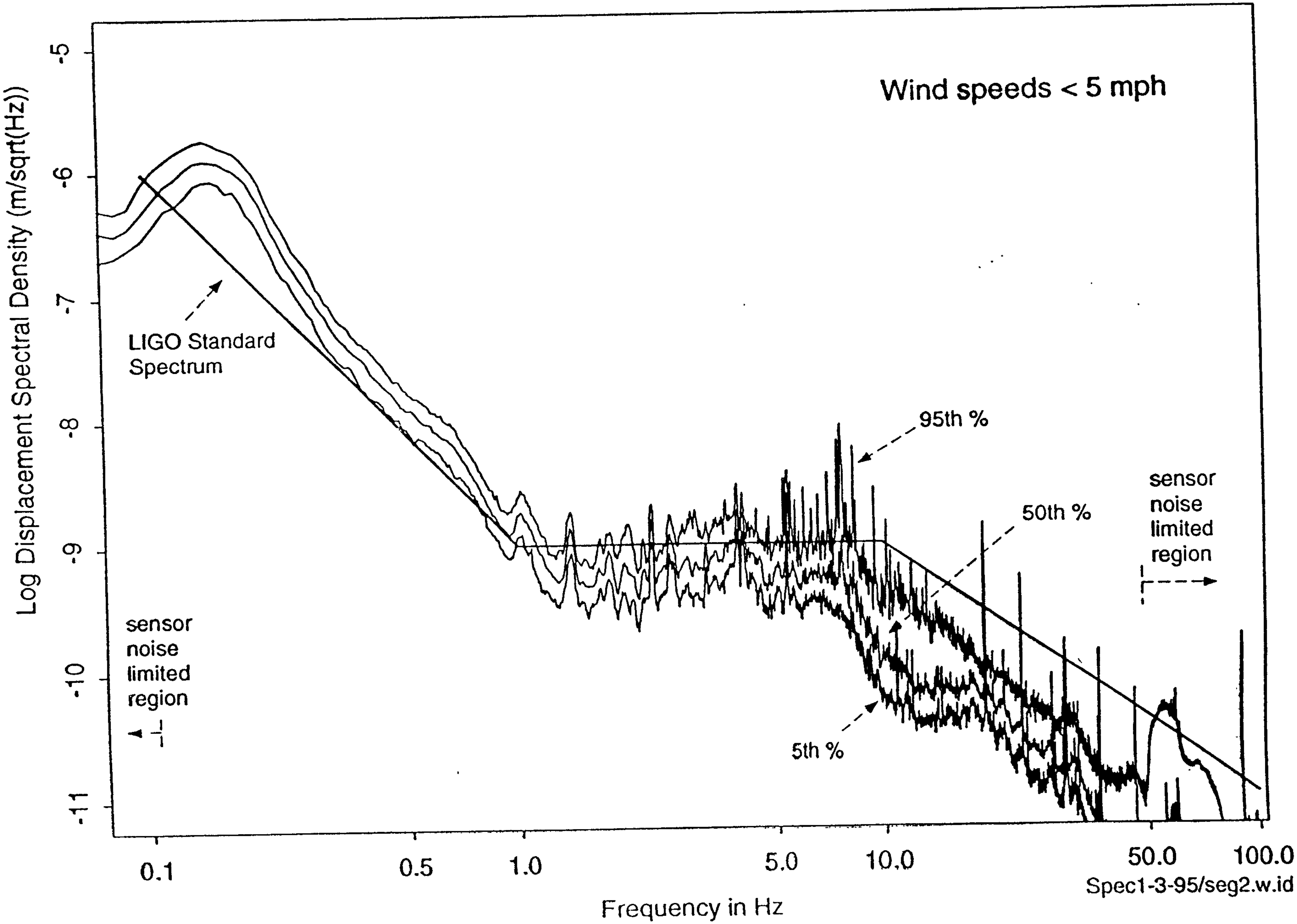
PASSIVE ISOLATION CONCEPT

Baseline Isolation Performance

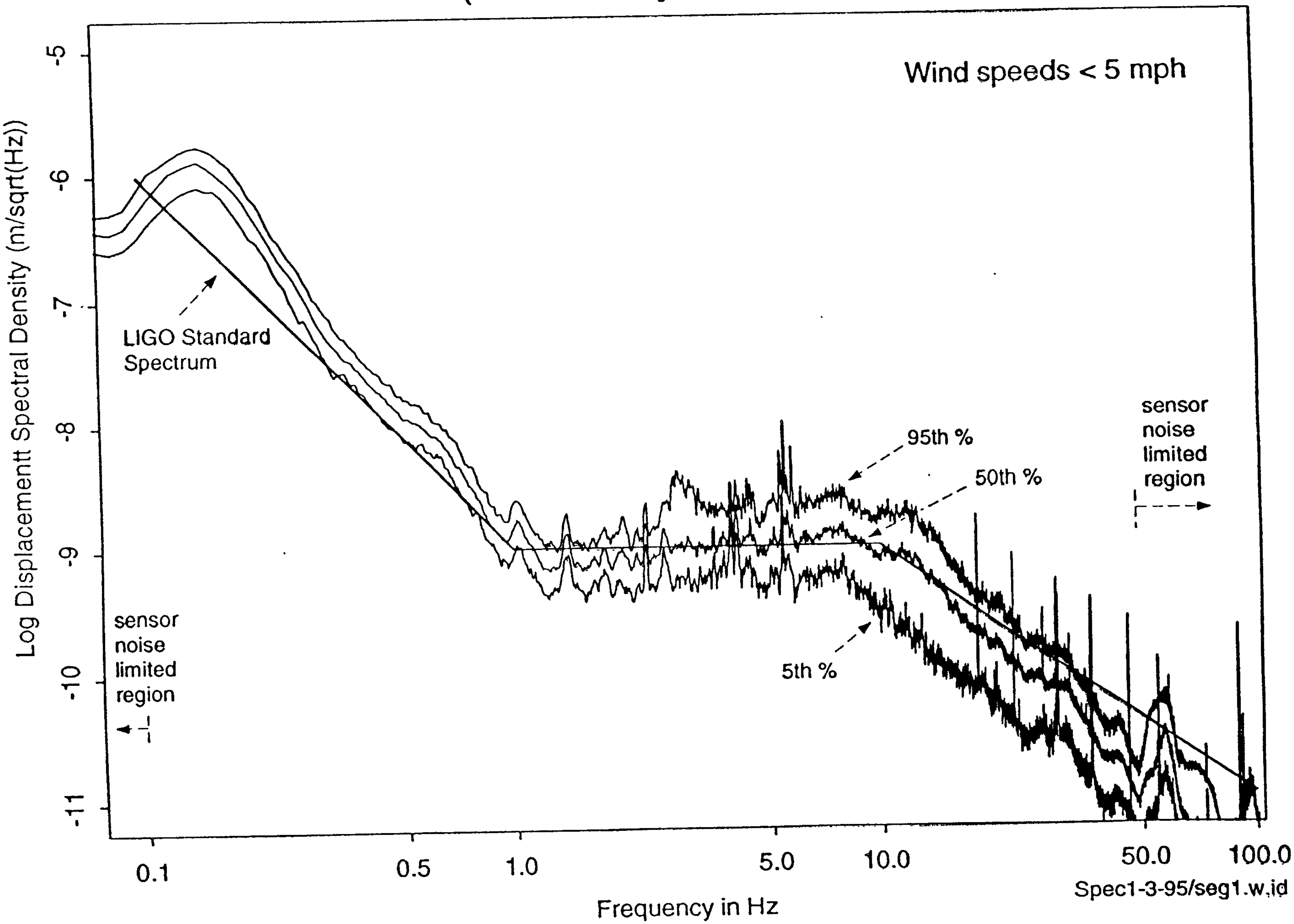


- Displacement noise 10^{-21} m/rHz @ 100 Hz

Hanford Corner Station SW Arm Axis, Late Night December 12,1994
(Preliminary Data)

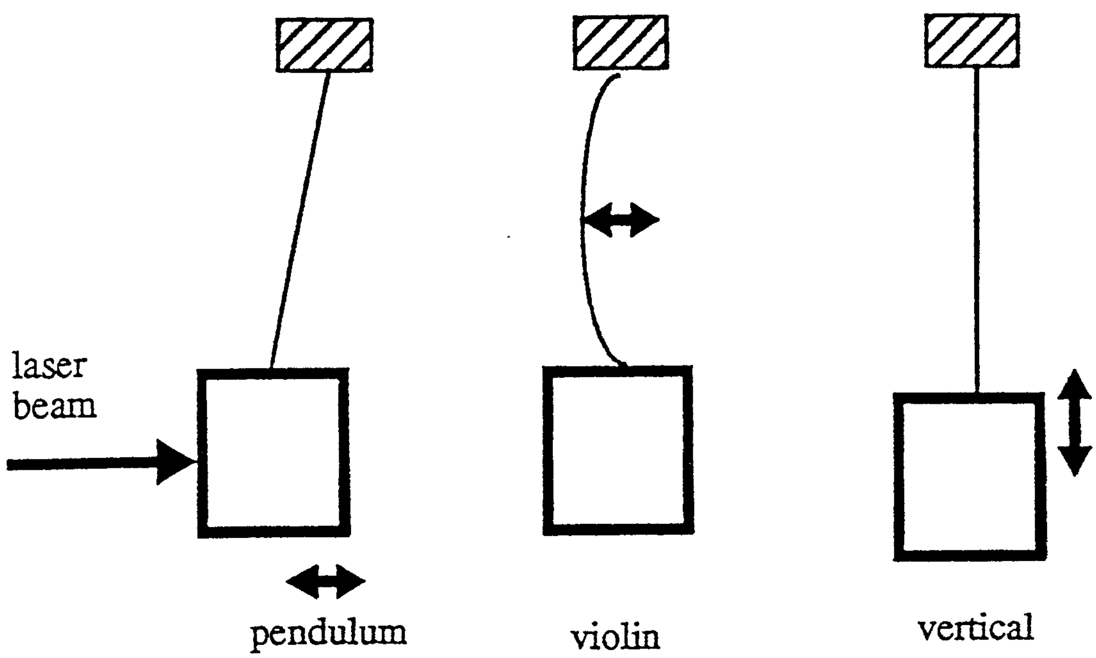


Hanford Corner Station SW Arm Axis, Morning Traffic December 13,1994
(Preliminary Data)



7c

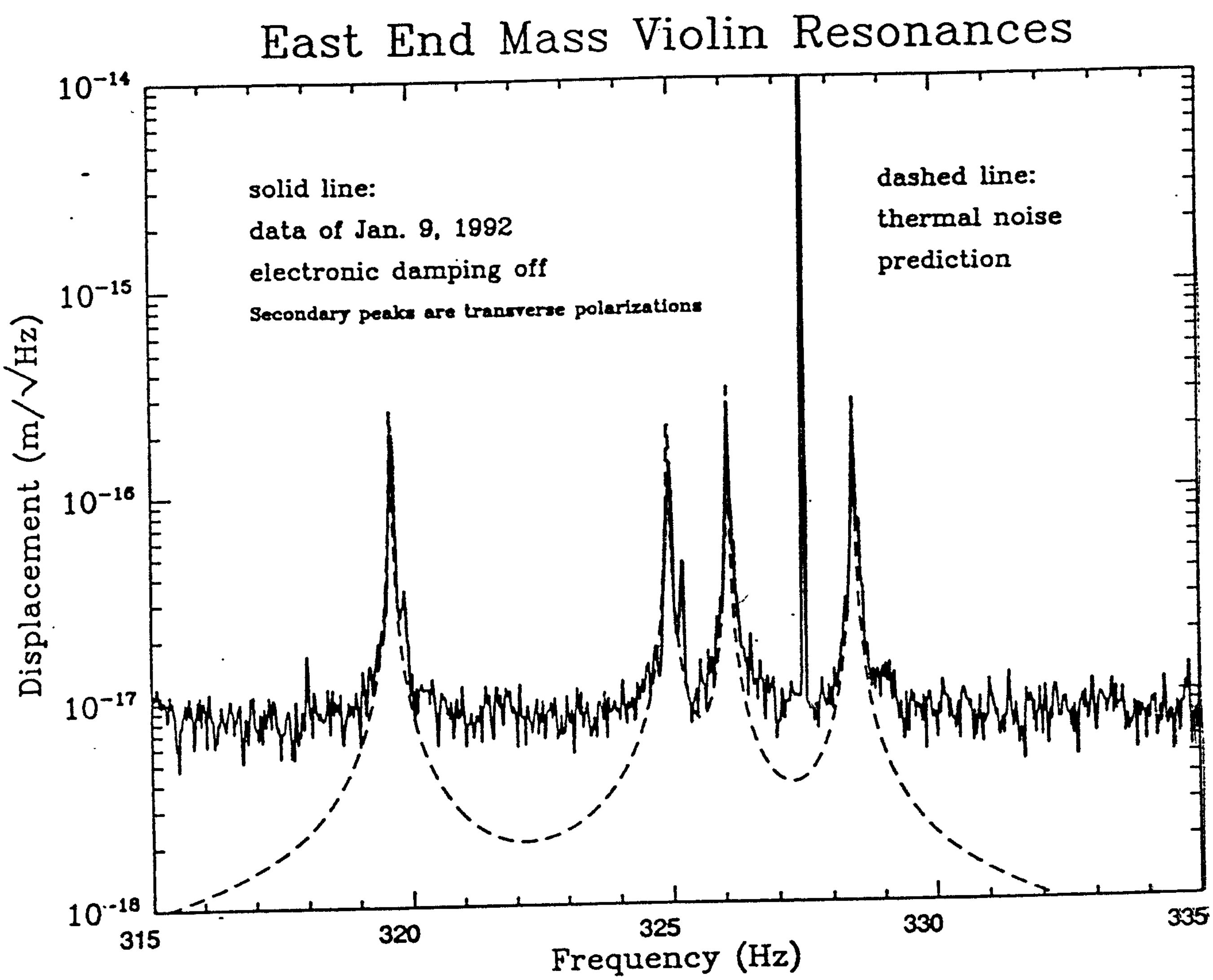
Interferometers
Mechanical Thermal Noise



- 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

Suspension Thermal Noise

Observation of Thermal Noise in Violin Modes of 40–m Test Mass Suspensions

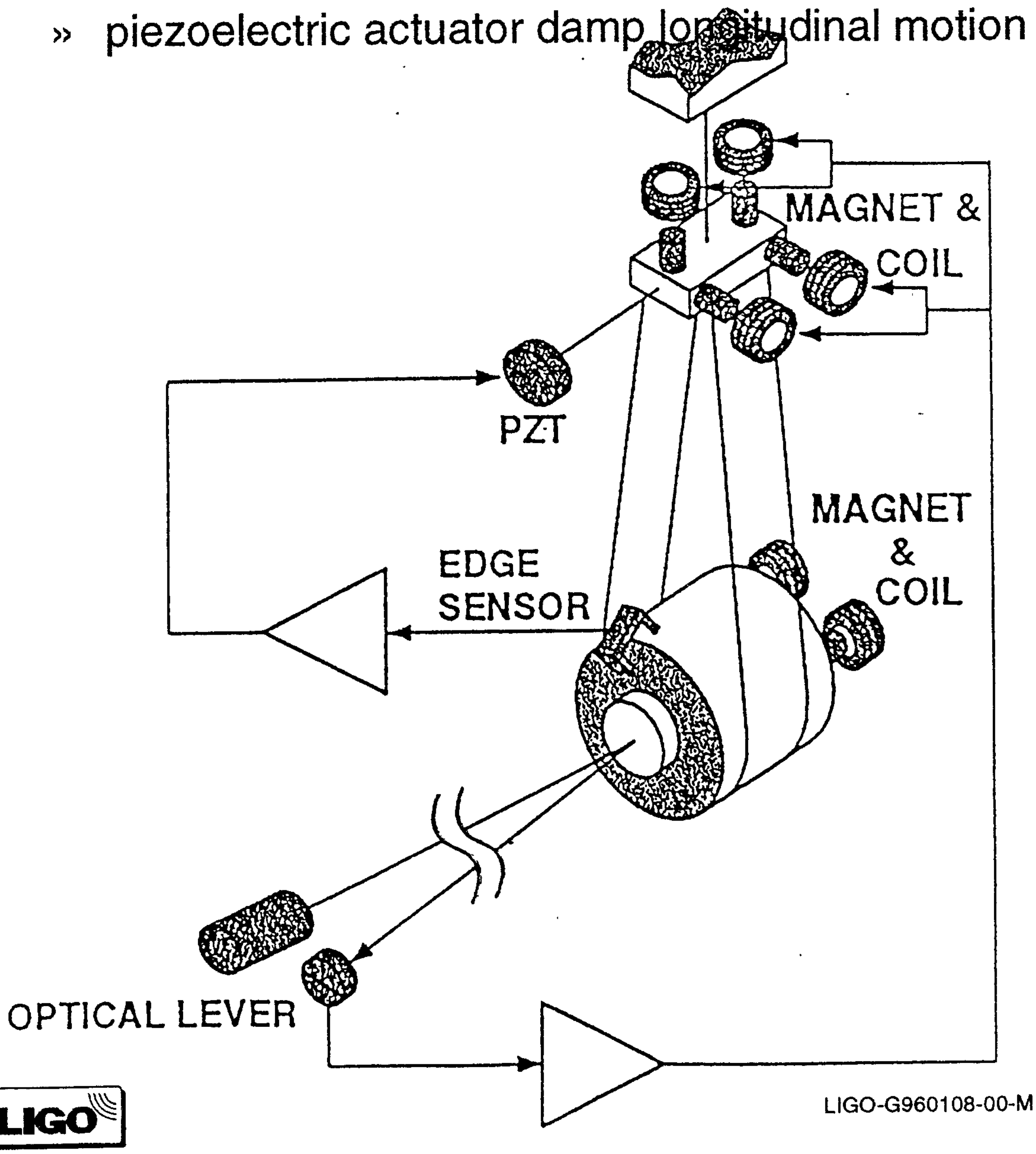


LIGO

LIGO

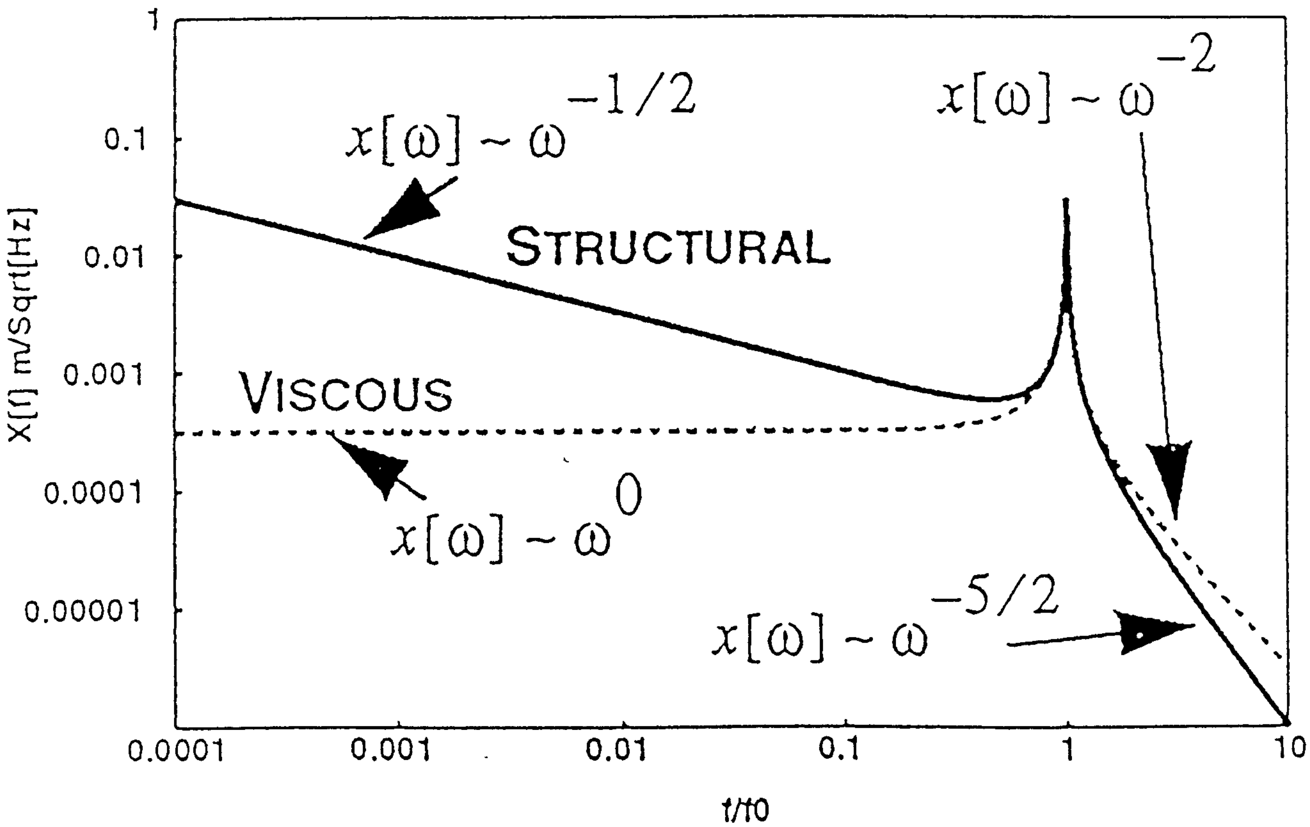
Suspended Test Mass

- 40 m prototype design
- **Pendulum suspension of test mass**
  - » magnetic/coil actuators damp angular motion
  - » piezoelectric actuator damp longitudinal motion

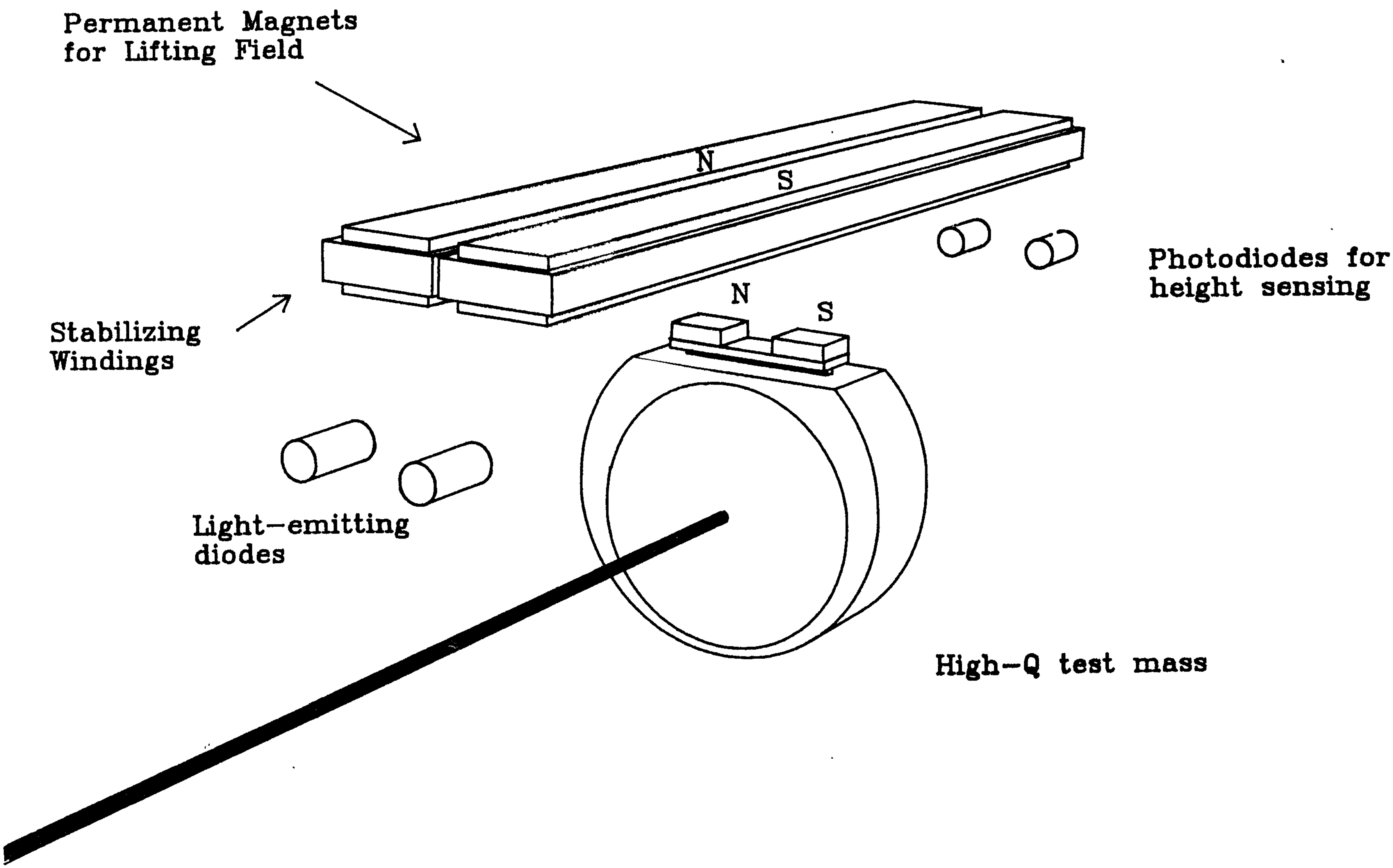


LIGO
Test Masses

- Monollithic fused silica ($Q > 10^6$)
- Internal resonance ~ 30 kHz
- structural vs viscous damping

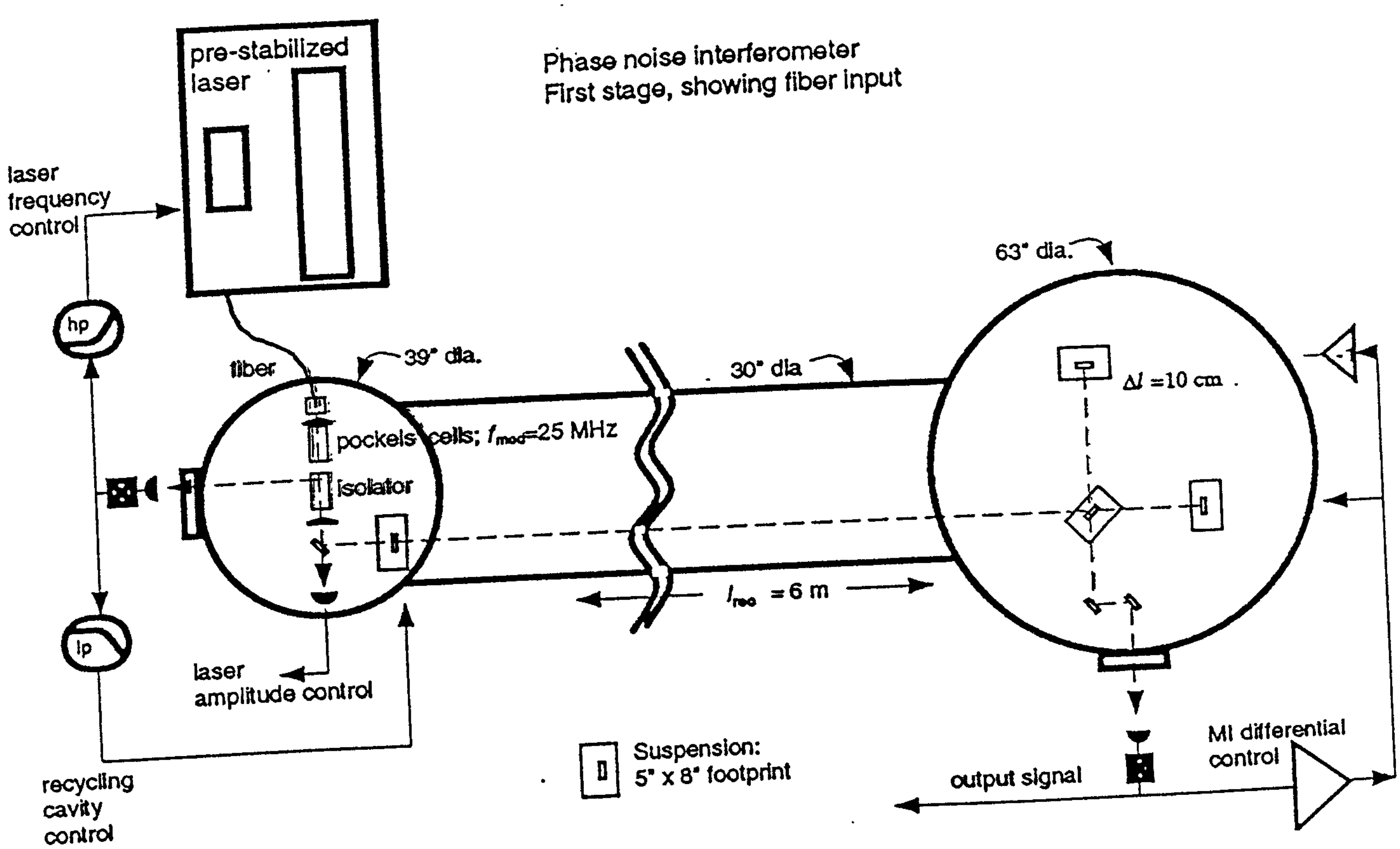


Magnetically Levitated Test Mass



LIGO
Phase Noise

- Phase Noise Interferometer (MIT)
  - » 70 W - recycled configuration
  - » demonstrate phase sensitivity for LIGO



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.)

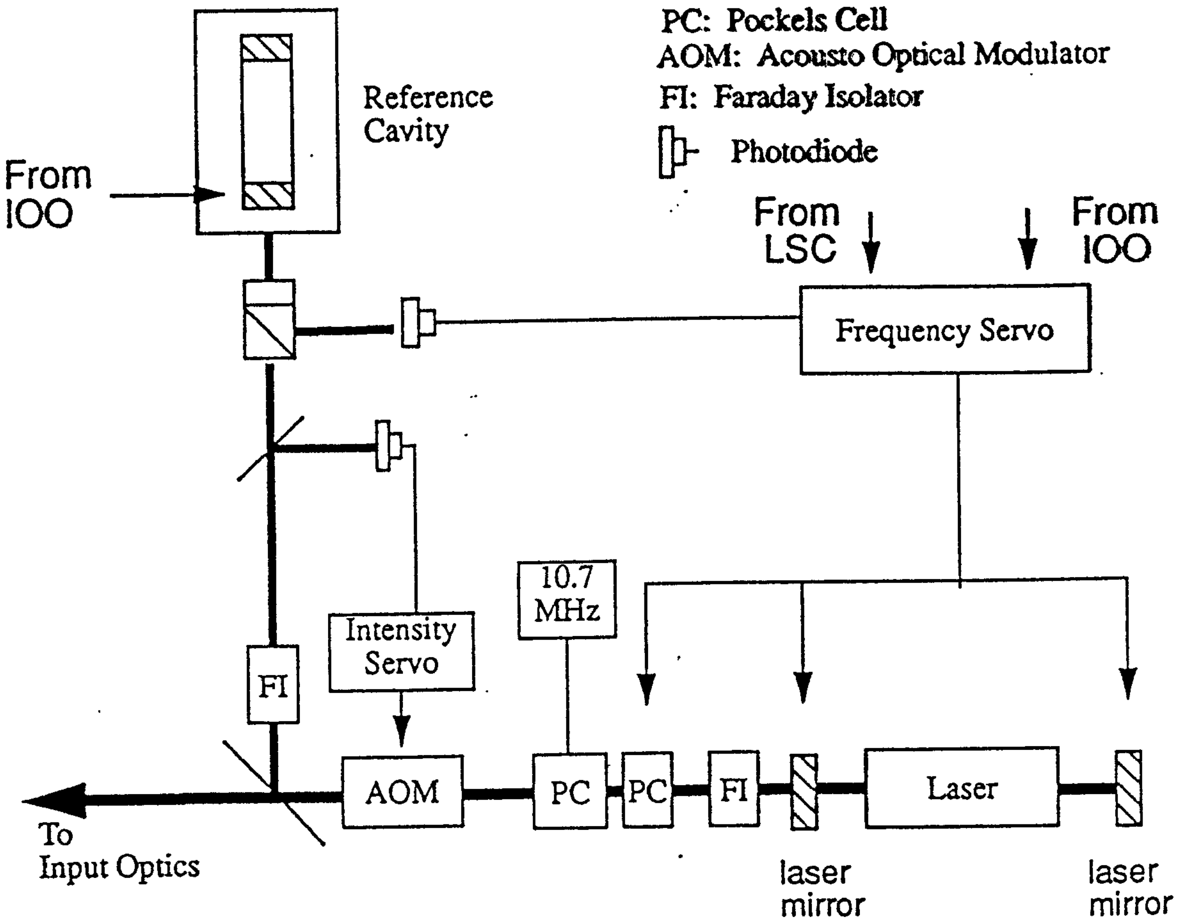
DETERMINED PRIMARILY BY EFFECTIVE OPTICAL POWER

- 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/$\sqrt{\text{Hz}}$

LIGO

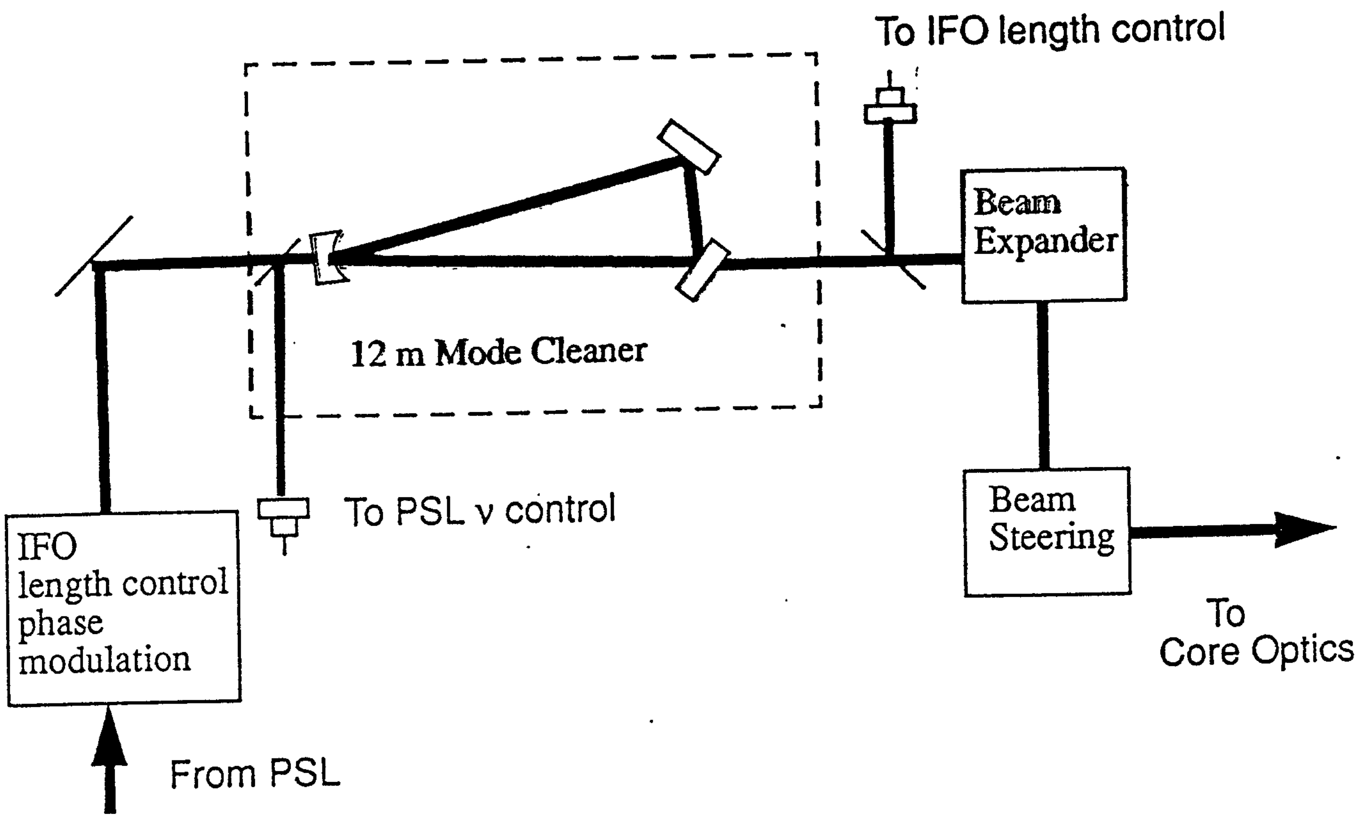
Prestabilized Laser (PSL)



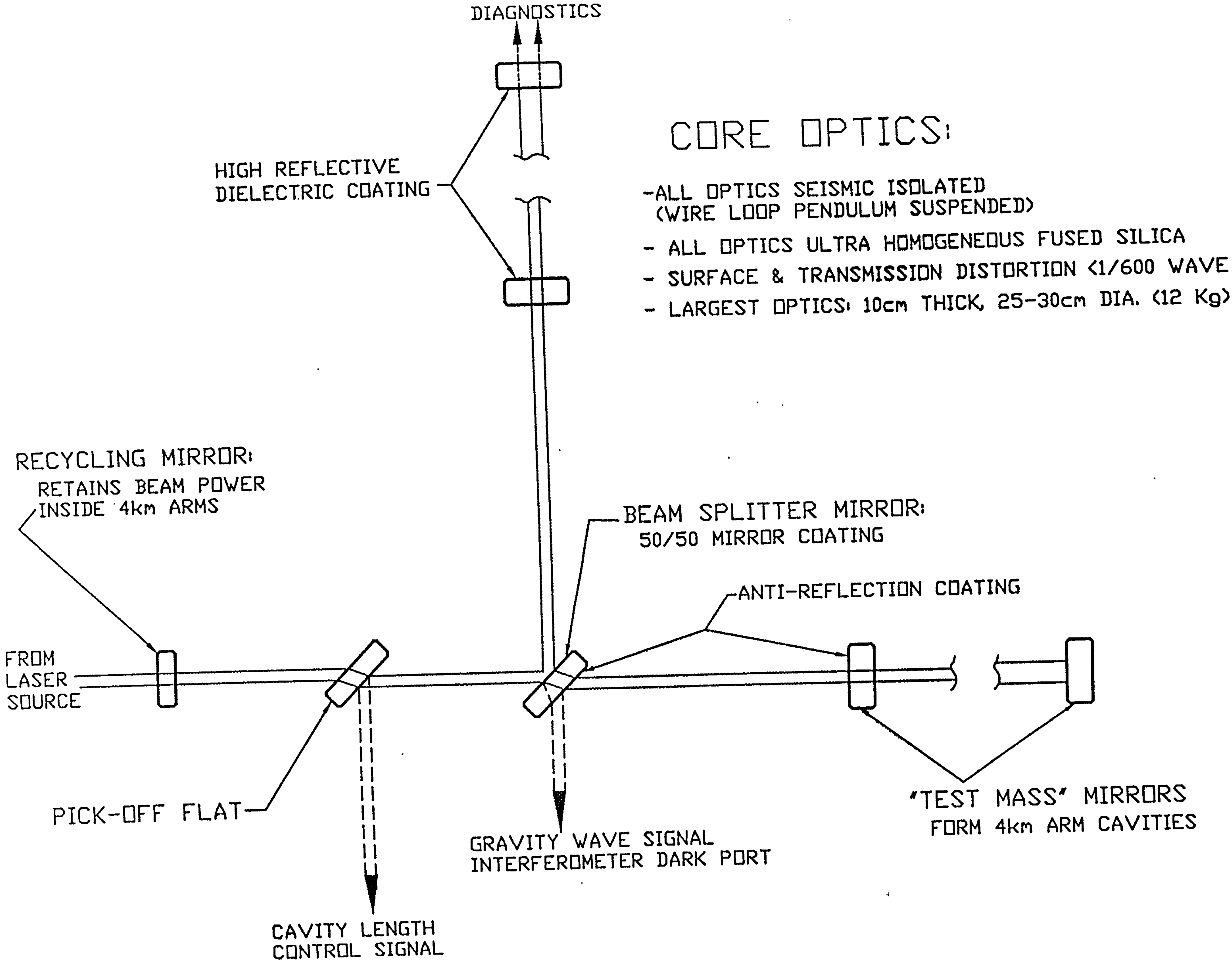
- Power Stabilization $\Delta P / P \sim 10^{-7} / \sqrt{Hz}$
- Frequency Stabilization $\Delta f / f \sim 10^{-15} / \sqrt{Hz}$
- <u>Status:</u> Working LIGO subsystem
  - ››DRR, PDR complete

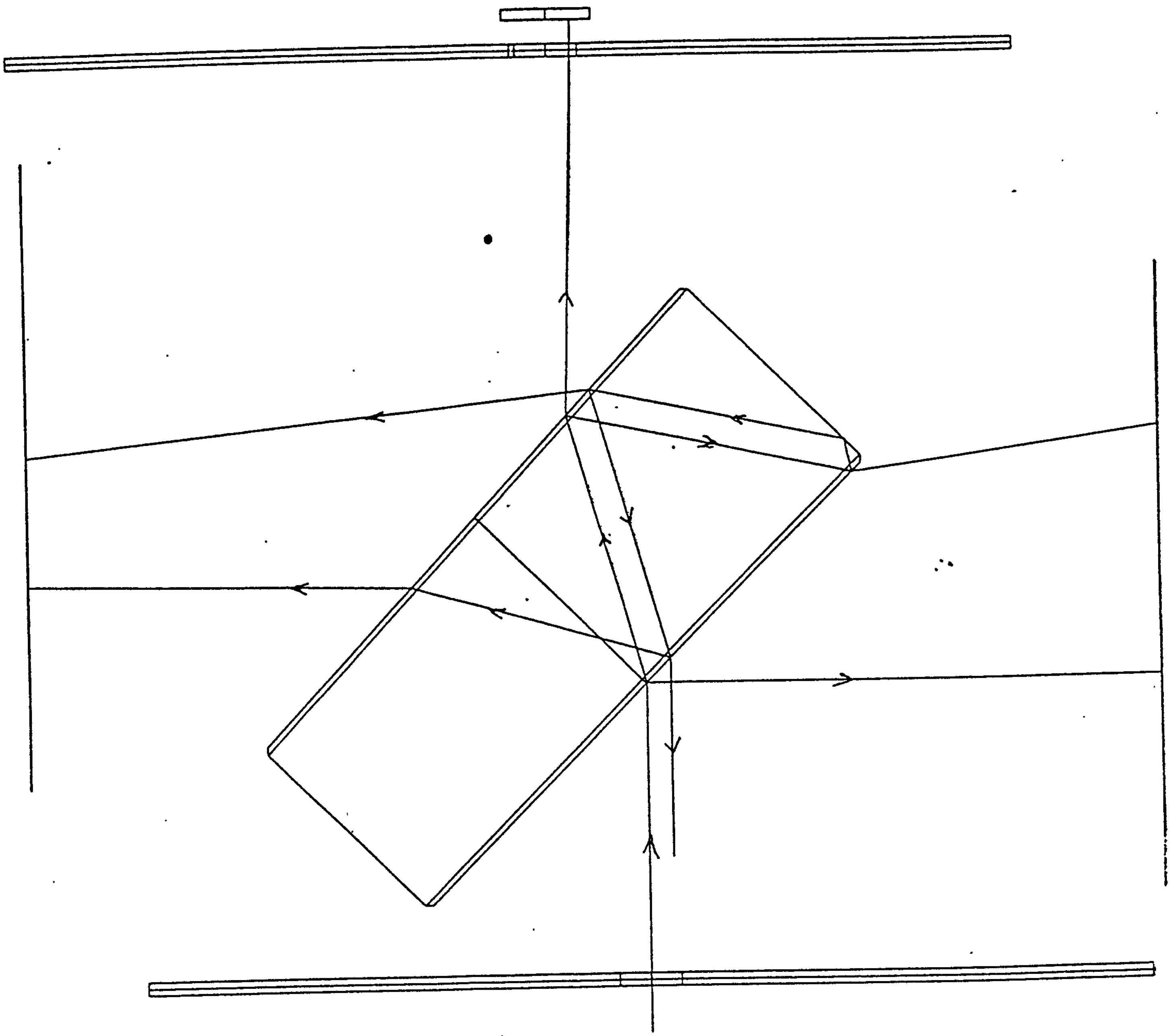
LIGO

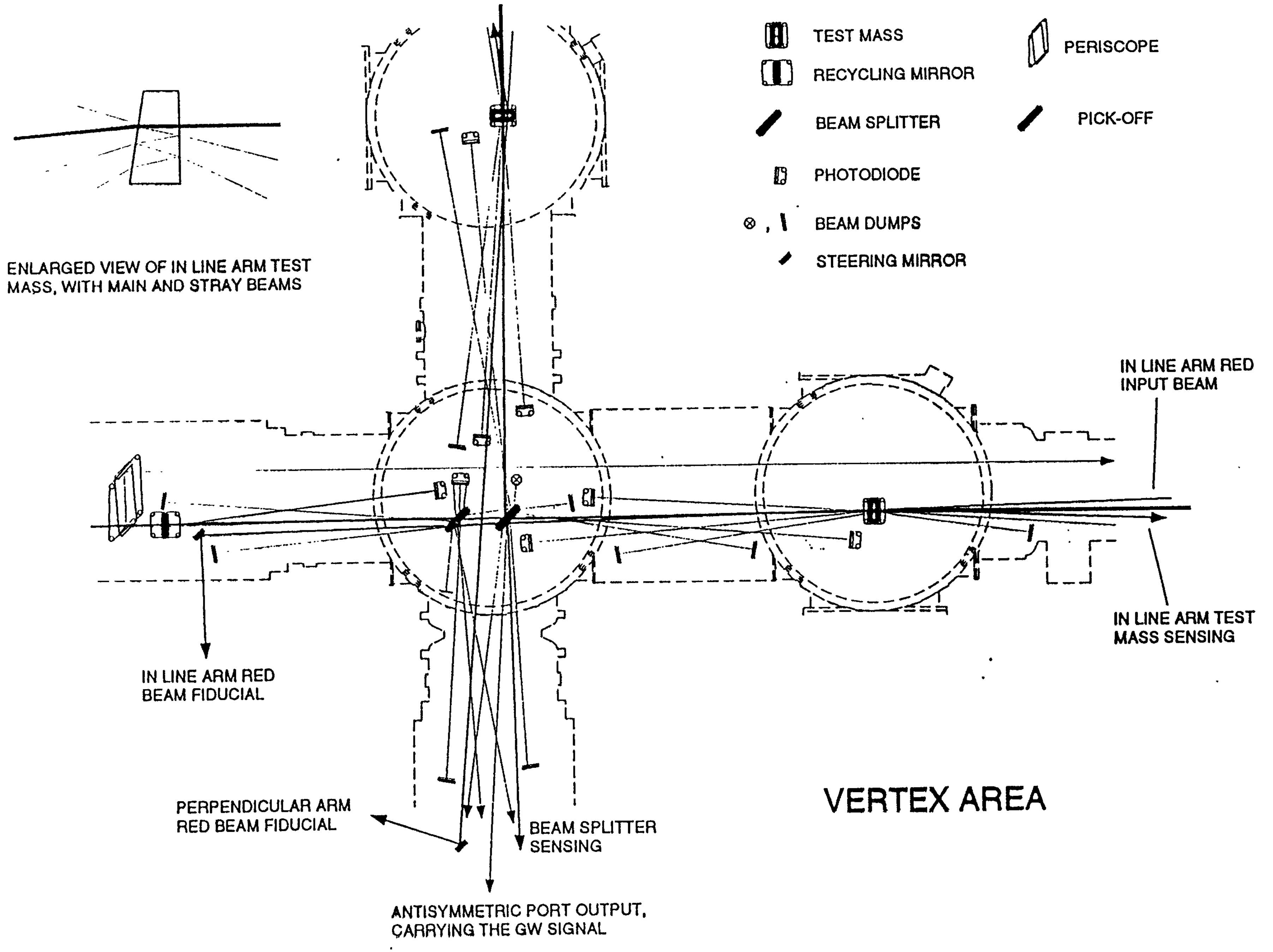
Input Optics



- Phase modulation for IFO length control
- 12 m Mode Cleaner
  - ››Reduces pointing jitter $\Delta\theta_{out} / \Delta\theta_{in} \sim 10^{-3}$
  - ››Additional frequency stabilization $\Delta f / f \sim 10^{-18} / \sqrt{Hz}$
- Mode matching, beam steering to Core Optics
- <u>Status:</u> Conceptual Design Phase

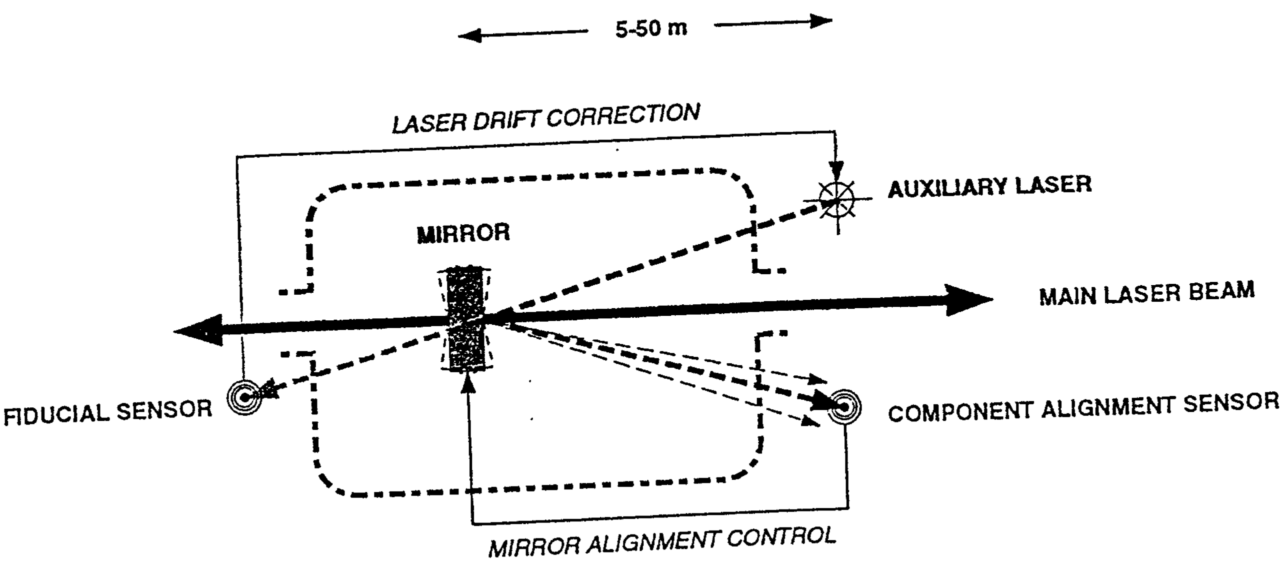

DIAGNOSTICS
CORE OPTICS:
-ALL OPTICS SEISMIC ISOLATED (WIRE LOOP PENDULUM SUSPENDED)
- ALL OPTICS ULTRA HOMOGENEOUS FUSED SILICA
- SURFACE & TRANSMISSION DISTORTION <1/600 WAVE
- LARGEST OPTICS: 10cm THICK, 25-30cm DIA. (12 Kg)
HIGH REFLECTIVE DIELECTRIC COATING
RECYCLING MIRROR:
RETAINS BEAM POWER INSIDE 4km ARMS
BEAM SPLITTER MIRROR:
50/50 MIRROR COATING
ANTI-REFLECTION COATING
FROM LASER SOURCE
PICK-OFF FLAT
"TEST MASS" MIRRORS
FORM 4km ARM CAVITIES
GRAVITY WAVE SIGNAL INTERFEROMETER DARK PORT
CAVITY LENGTH CONTROL SIGNAL

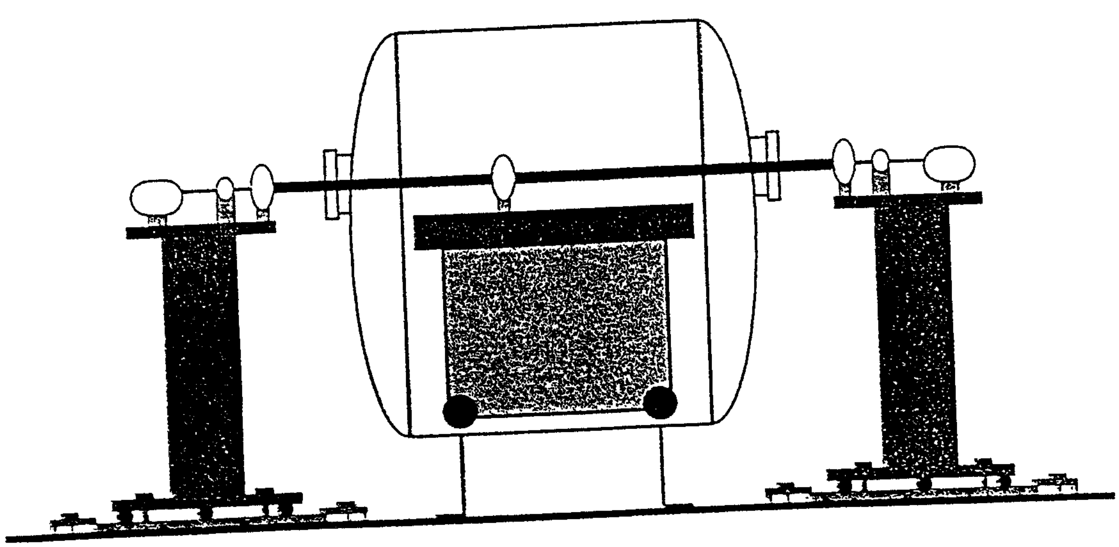



TEST MASS
RECYCLING MIRROR
BEAM SPLITTER
PHOTODIODE
BEAM DUMPS
STEERING MIRROR
PERISCOPE
PICK-OFF
ENLARGED VIEW OF IN LINE ARM TEST MASS, WITH MAIN AND STRAY BEAMS
IN LINE ARM RED INPUT BEAM
IN LINE ARM TEST MASS SENSING
IN LINE ARM RED BEAM FIDUCIAL
PERPENDICULAR ARM RED BEAM FIDUCIAL
BEAM SPLITTER SENSING
ANTISYMMETRIC PORT OUTPUT, CARRYING THE GW SIGNAL

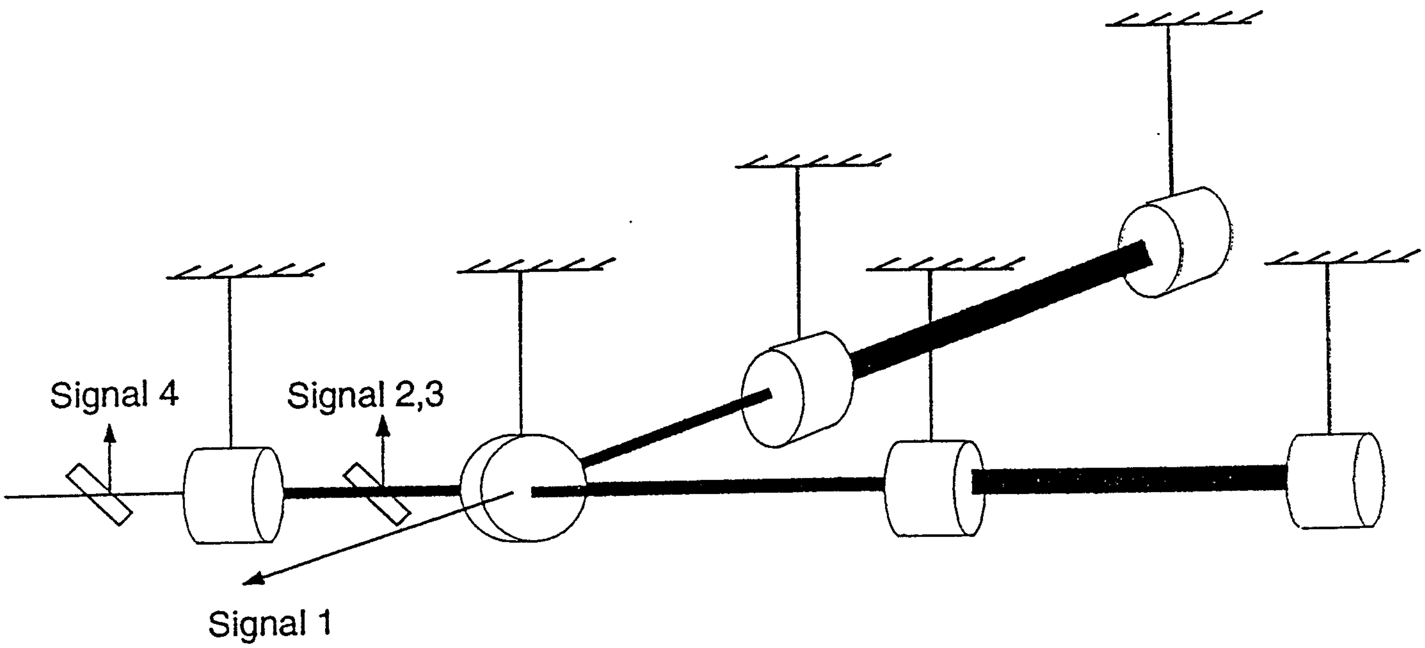
VERTEX AREA

Three-Point Optical Lever





Length Sensing/Control System



LIGO Recycled/Recombined Interferometer

- 4 signals used for controlling 4 degrees of freedom
- Important degrees of freedom: 2 arm cavity lengths and 2 recycling cavity lengths

Control Design for 2 Modes of Operation

- Operations Mode (linear dynamic model)
- Lock Acquisition (highly nonlinear dynamic model)

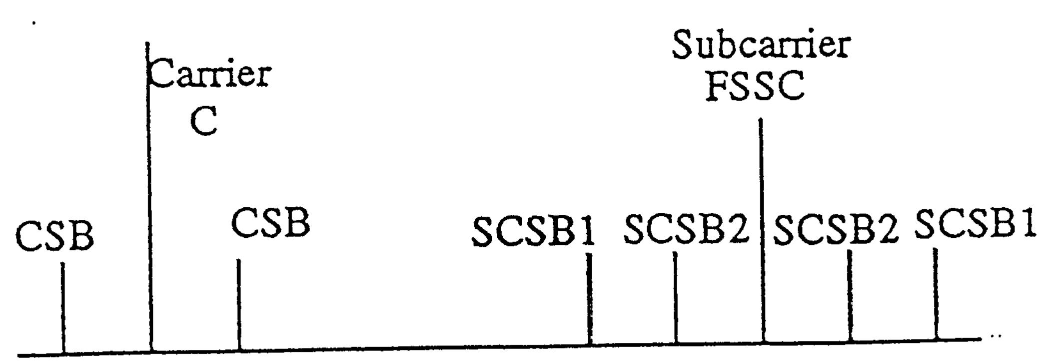
Model Development for Control Design

- Operations Mode model complete
- Acquisition Mode model complete for coupled cavity interferometer

LIGO
Length Sensing

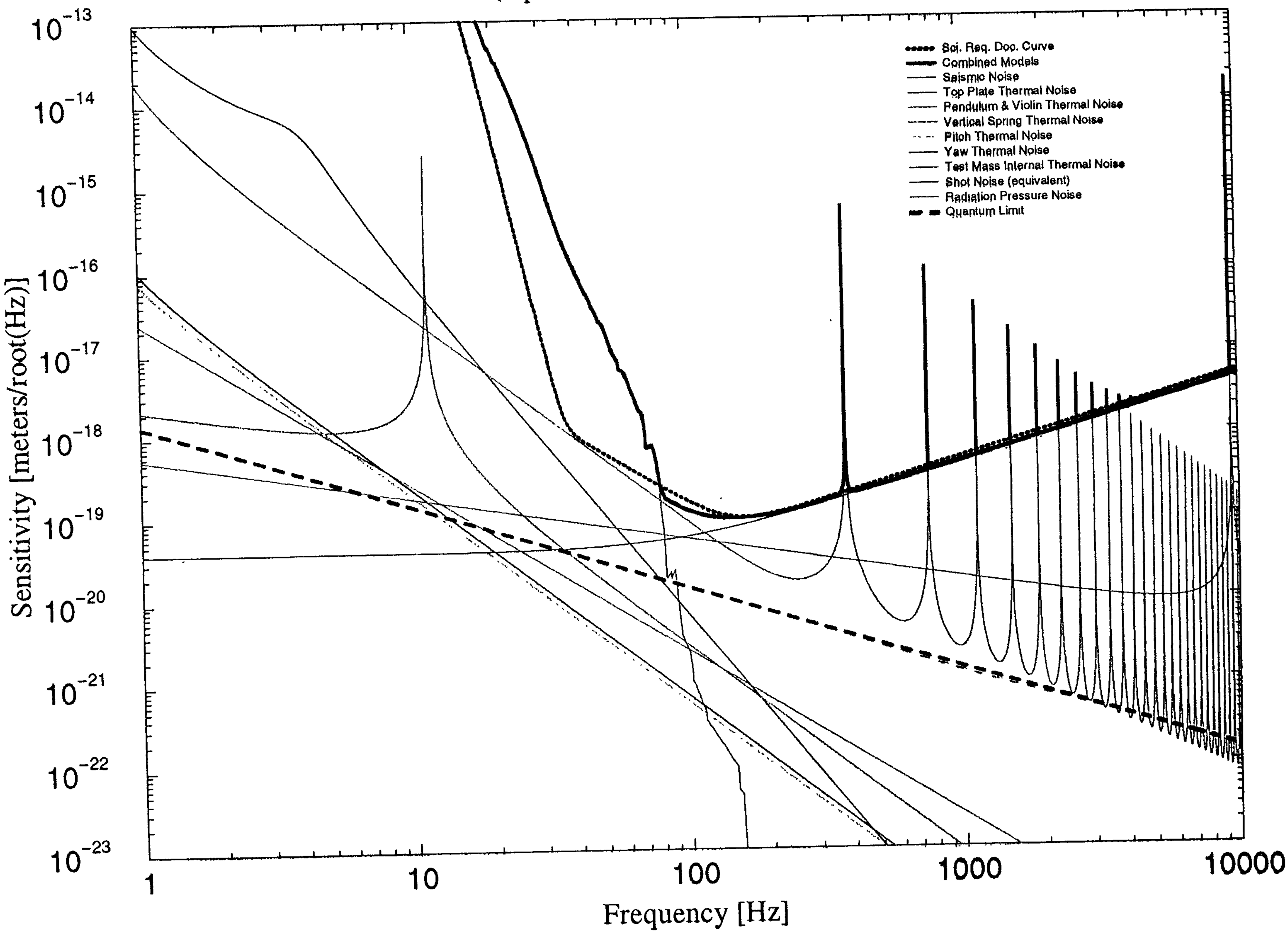
- Signals sensitive to length degrees of freedom

INTERFERING FIELDS	SIGNAL LOCATION	DEGREE OF FREEDOM
C and CSB	anti-symmetric port	L_1-L_2, differential arm cavity length
C and CSB	reflected from recycling mirror	L_1+L_2, common mode arm cavity length
FSSC and SCSB1	anti-symmetric port	l_1-l_2, differential mode Michelson length
FSSC and SCSB2	reflected from recycling mirror	l_1+l_2, common mode Michelson length



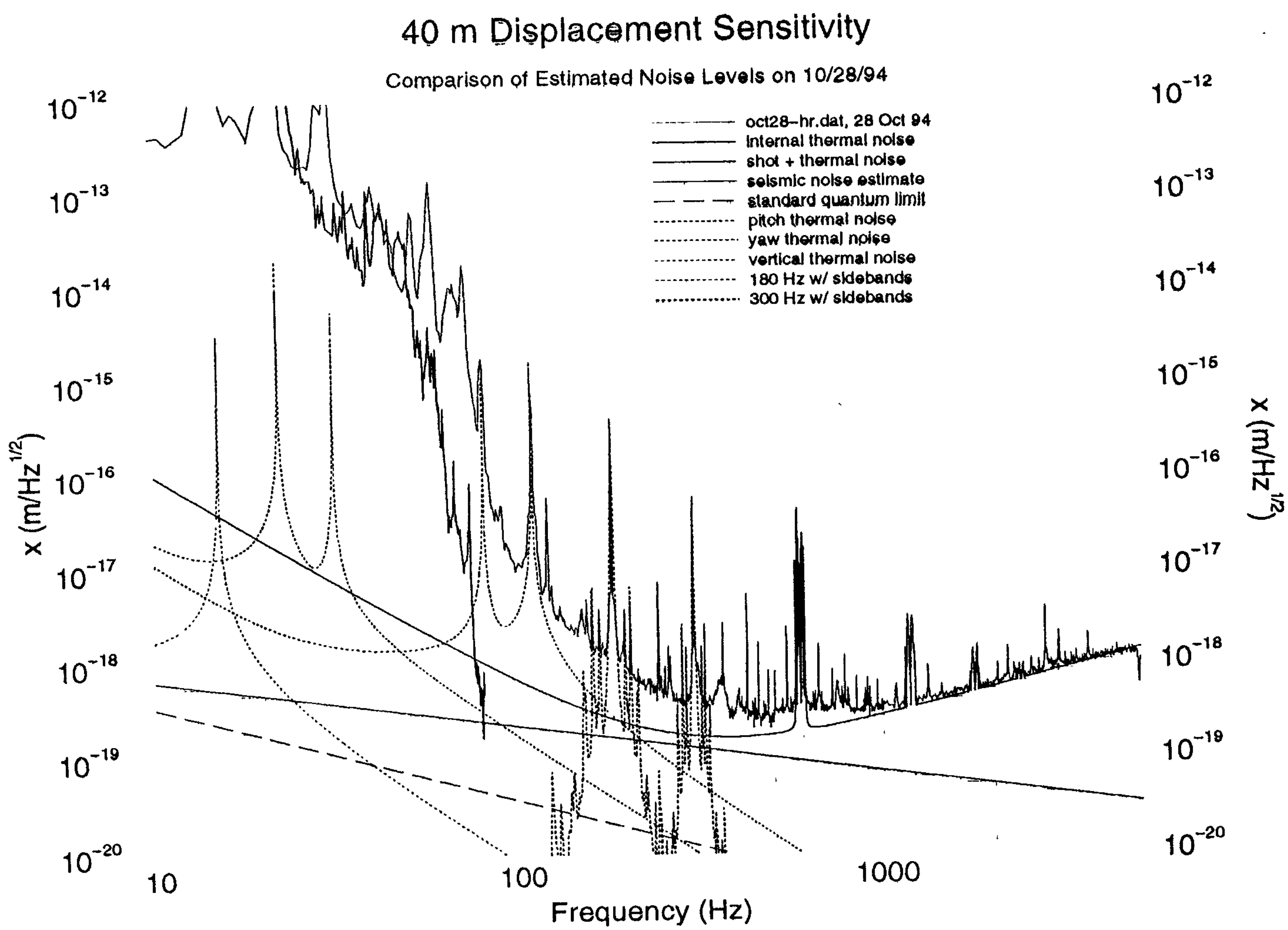
Initial LIGO Noise Sources

(April 8th 1996 Parameter Set)

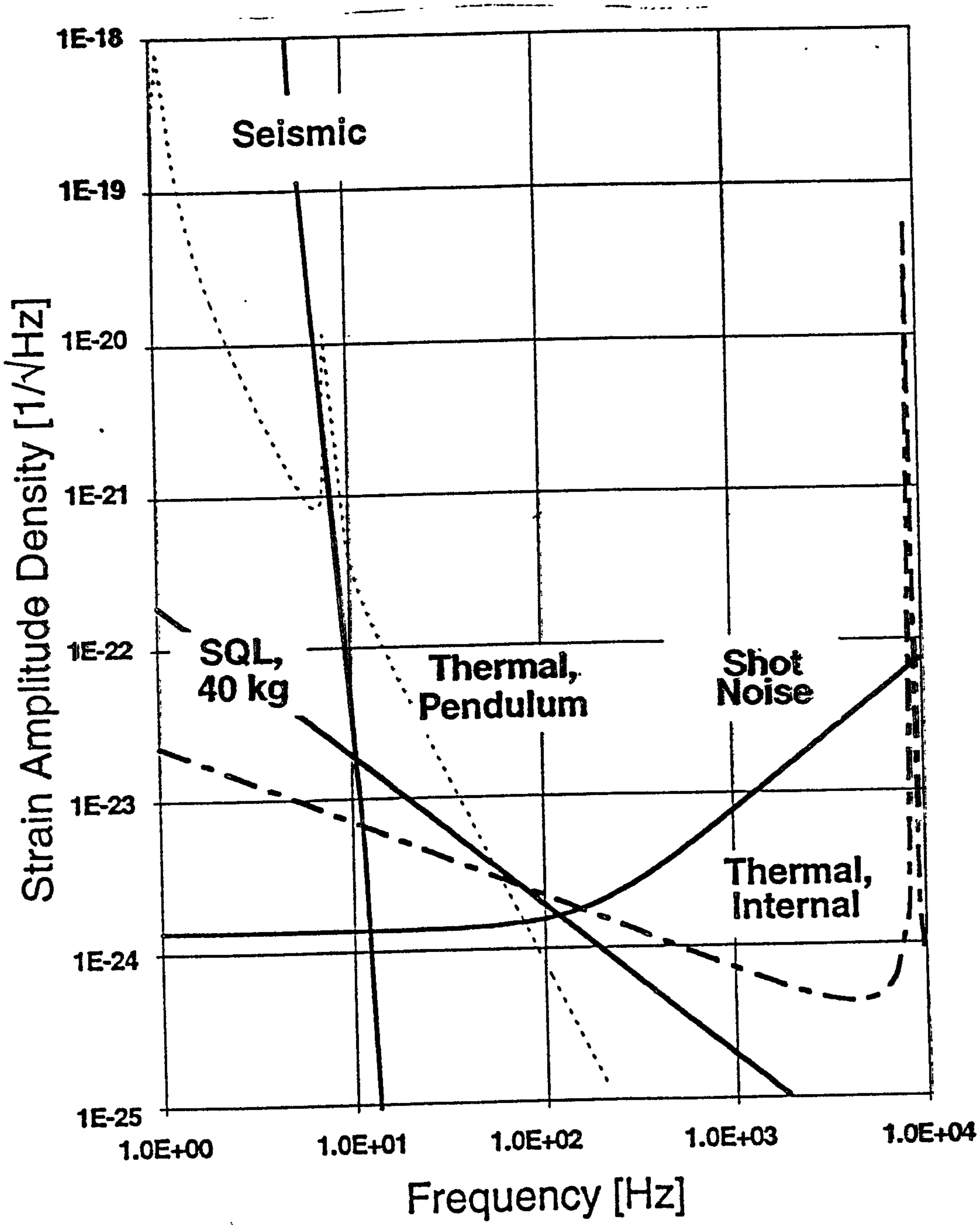


LIGO Systems Engineering and Integration

40 m Lab

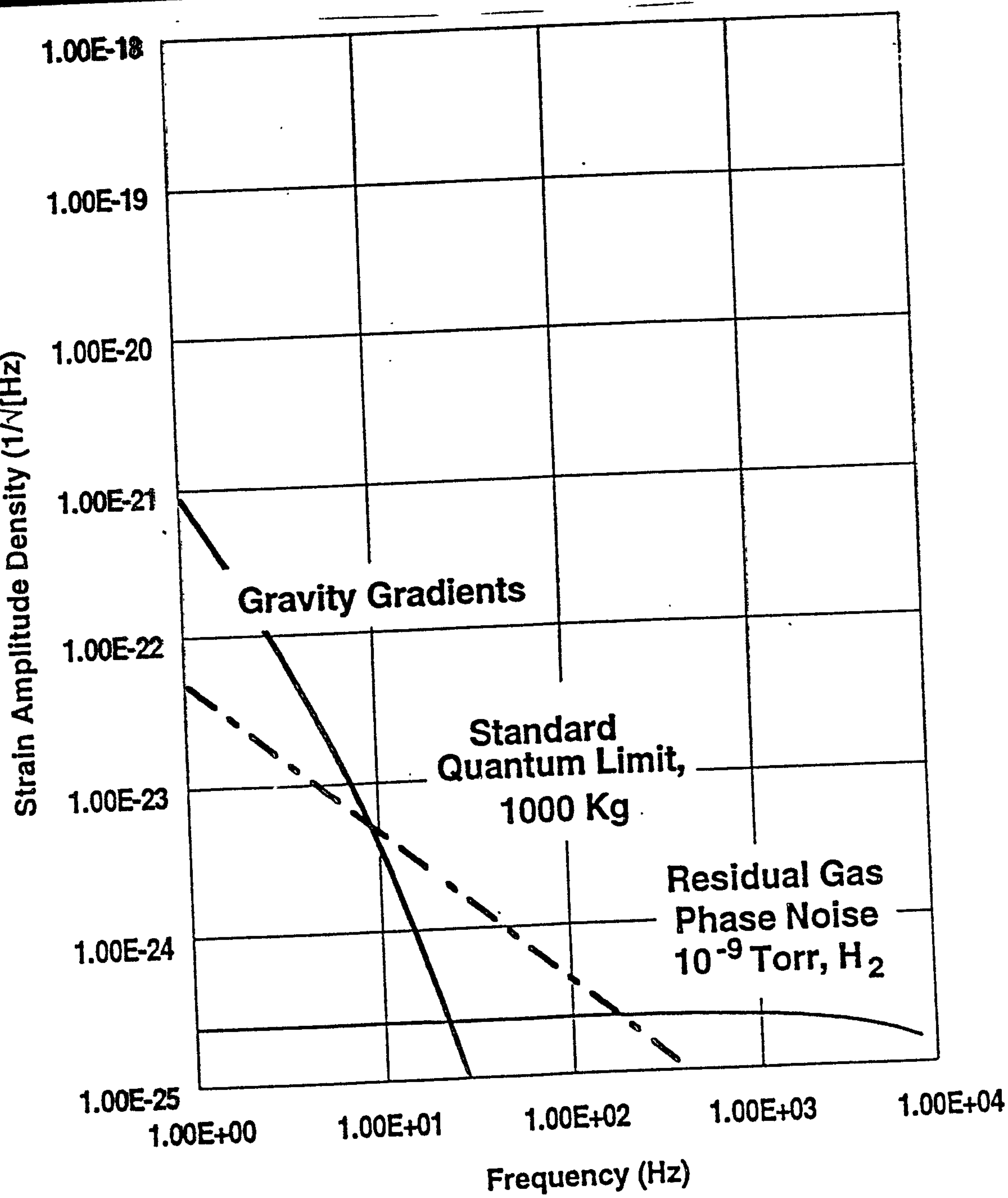


Enhanced Interferometer
Noise Budget



LIGO Facilities

Limiting Noise Floor

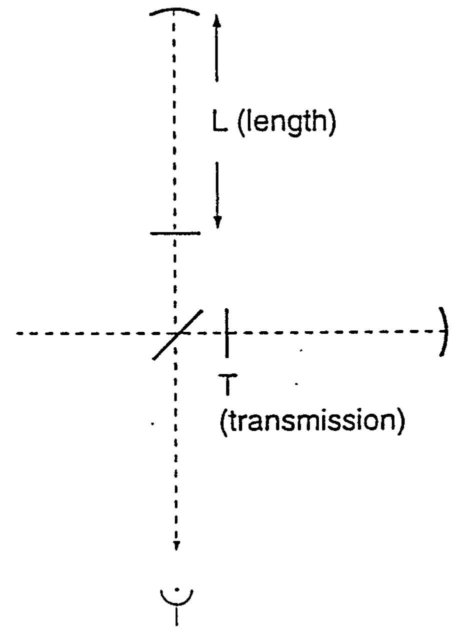


LIGO

LIGO-G960108-00-M

Quantum limit for interferometer performance

Two important noise terms, inverse dependence on light power:



Shot noise
- o fluctuations in number of photons/sec
- o equivalently, shot noise in photocurrent

$$\tilde{h} = \frac{T\lambda}{8\pi L}\sqrt{\frac{\mathrm{h}\nu}{P}}$$

Radiation pressure
- o uncorrelated in arms
- o imparts random momentum to test masses

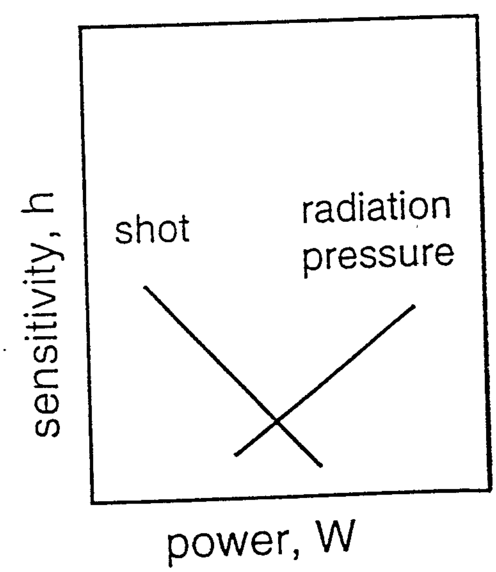
$$\tilde{h} = \frac{4}{cTLm\omega^2}\sqrt{P\mathrm{h}\nu}$$

- o minimum for

$$P_{\mathrm{opt}} = \frac{L^2\lambda m\omega^4}{2\pi c}$$

- o gives quantum limited sensitivity of

$$\tilde{h}_{\mathrm{QL}}(f) = \frac{1}{2\pi Lf}\sqrt{\frac{4\mathrm{h}}{\pi m}}$$

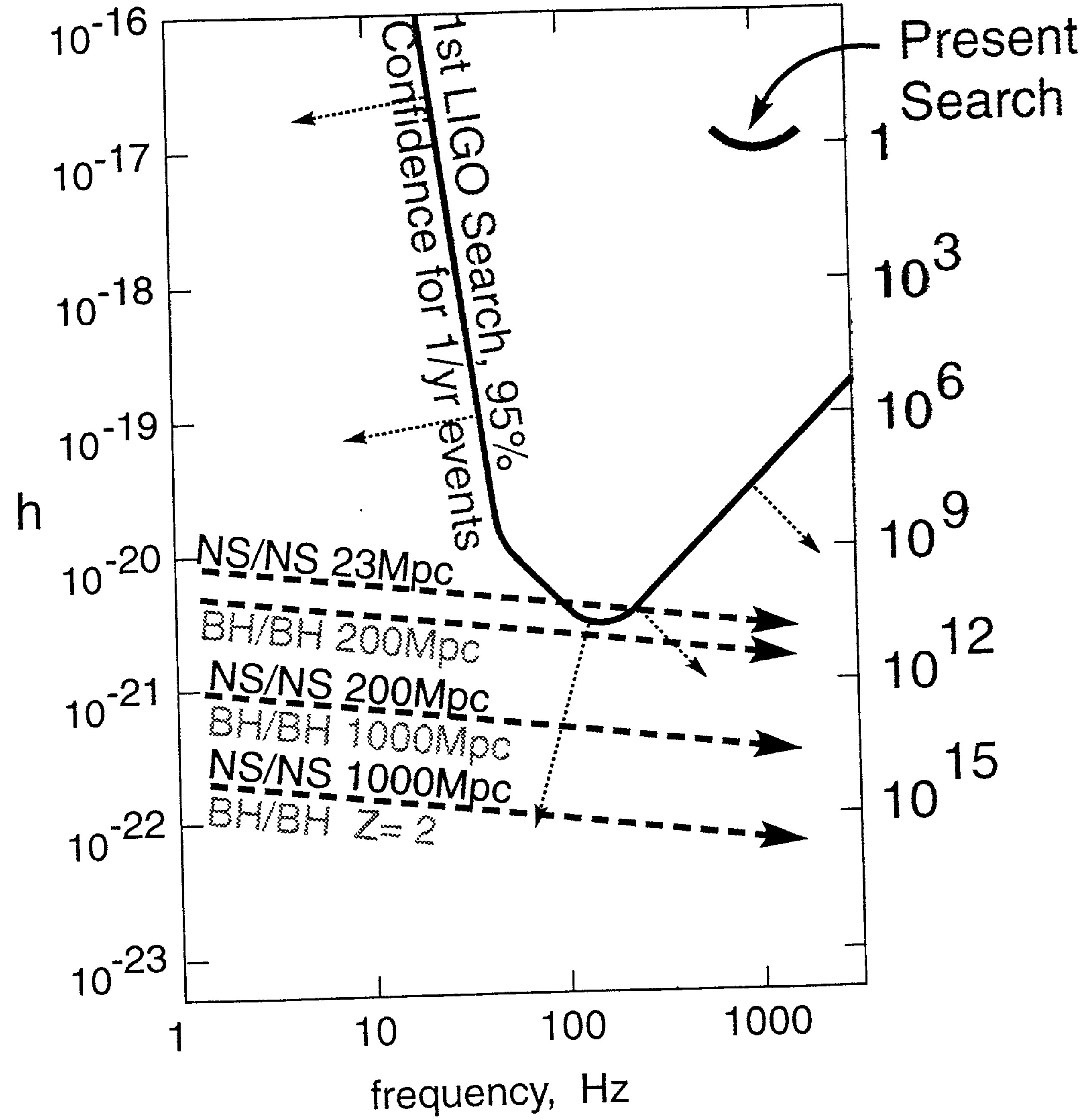


$\tilde{h}_{\mathrm{QL}} = 5\times10^{-24}$ Hz$^{-\frac{1}{2}}$ for $L = 4$ km, $f = 100$ Hz,
$m = 10$ kg, $\lambda = 514$ nm, $P = 7$kW;
a problem for second (or third?) generation antennas.

For now, wish to maximize circulating power.

NEUTRON STAR BINARIES

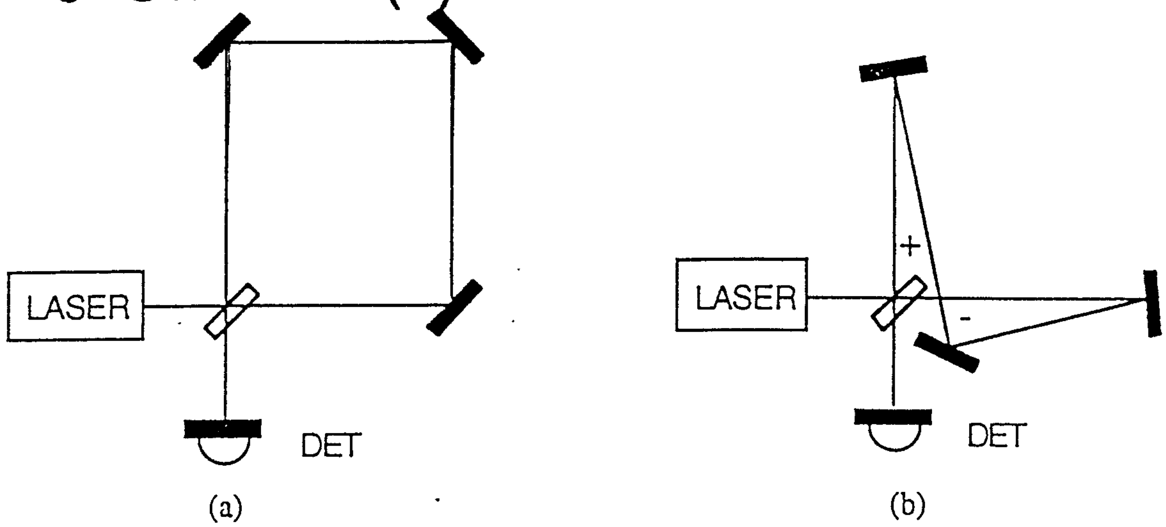
["Near-Guaranteed" source]

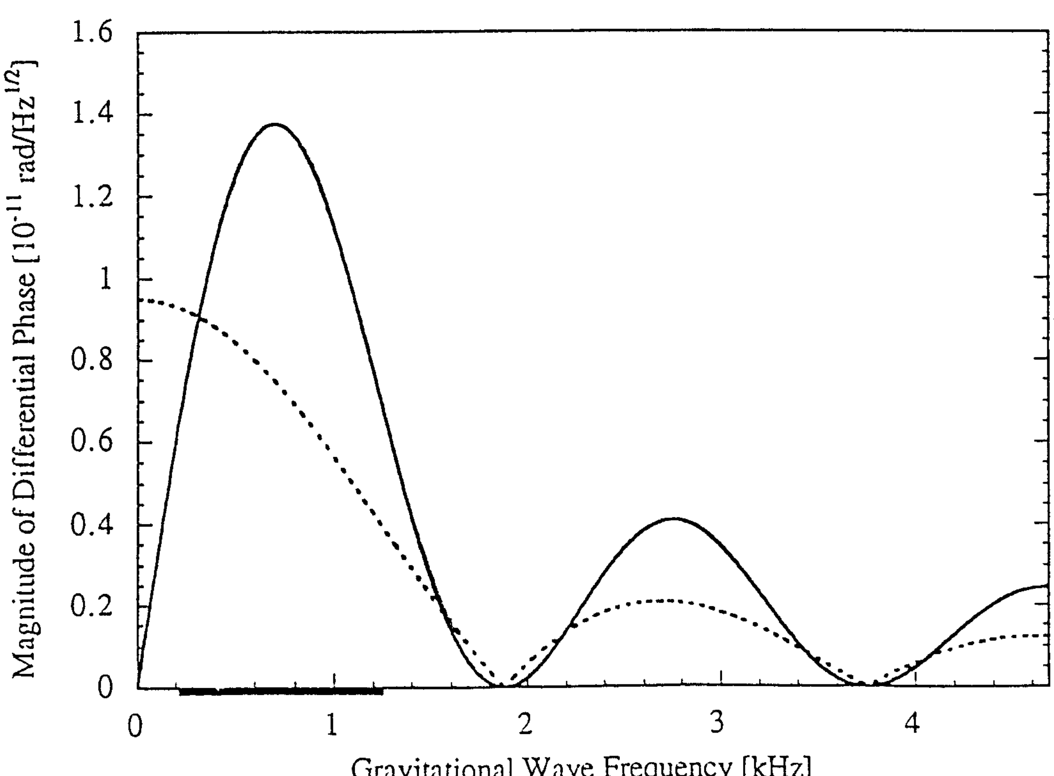


- *15 minutes & 10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

Interferometers
Sagnac

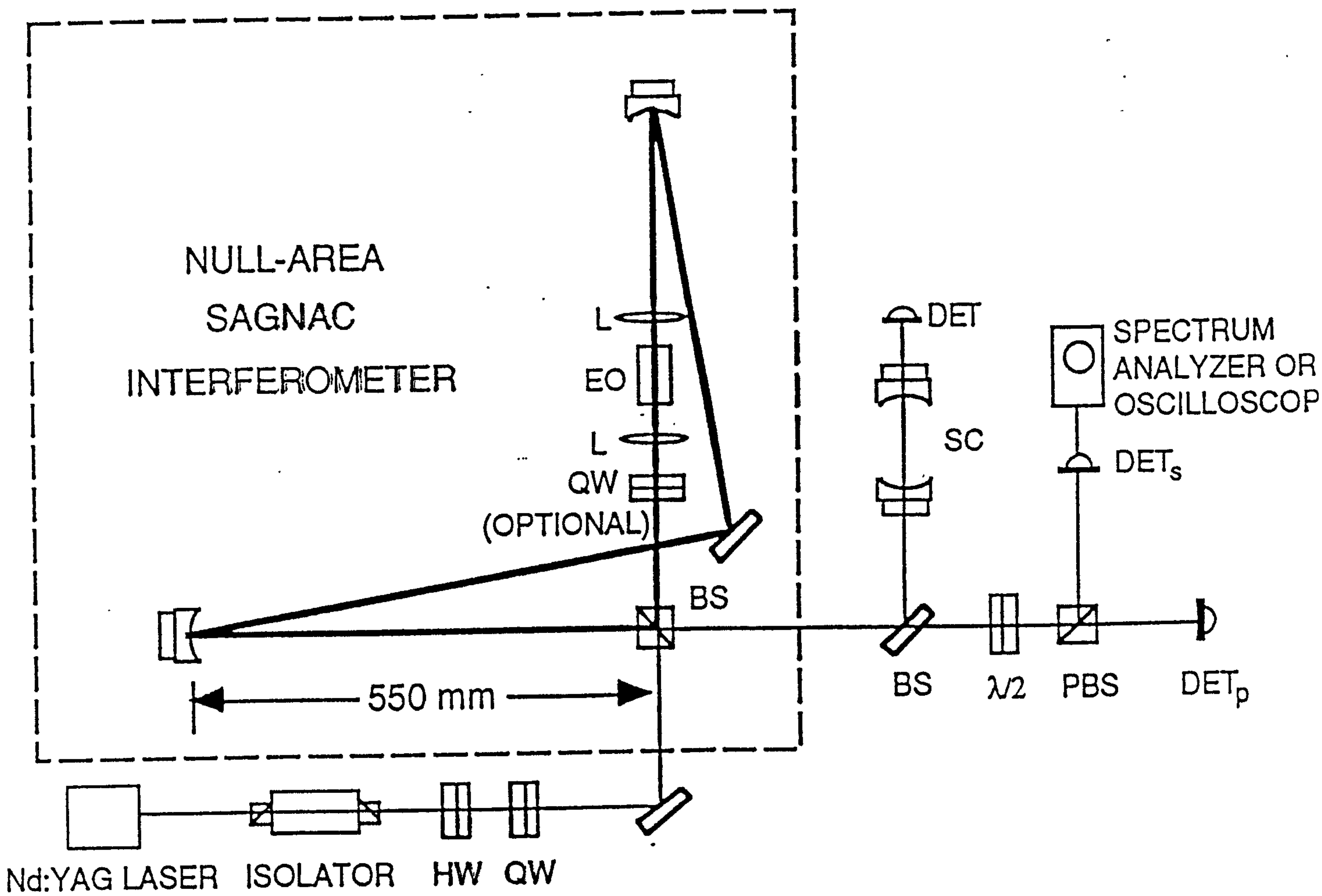
- Stanford (b) for advanced detectors





Interferometers
Sagnac

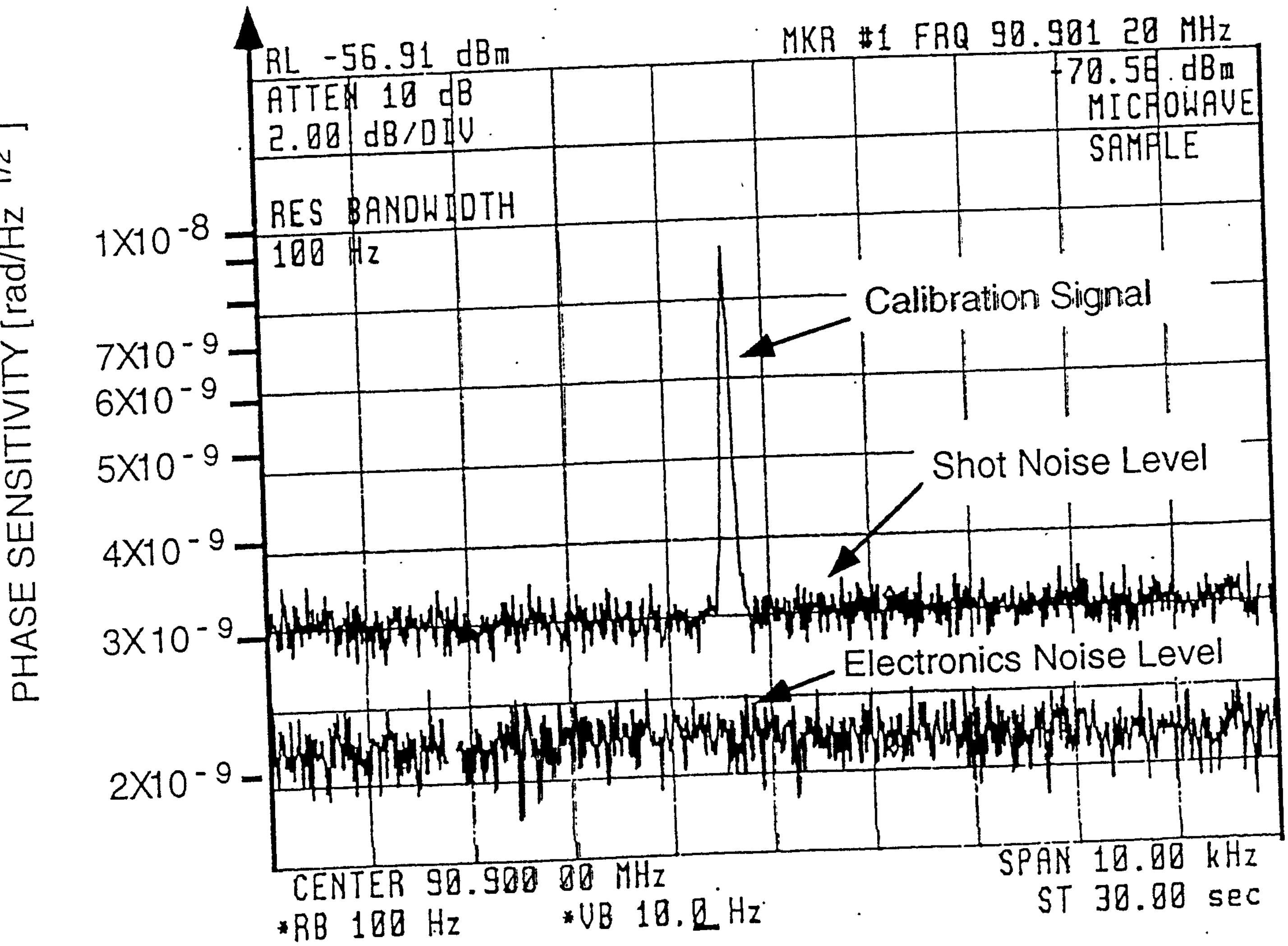
- Stanford test Sagnac



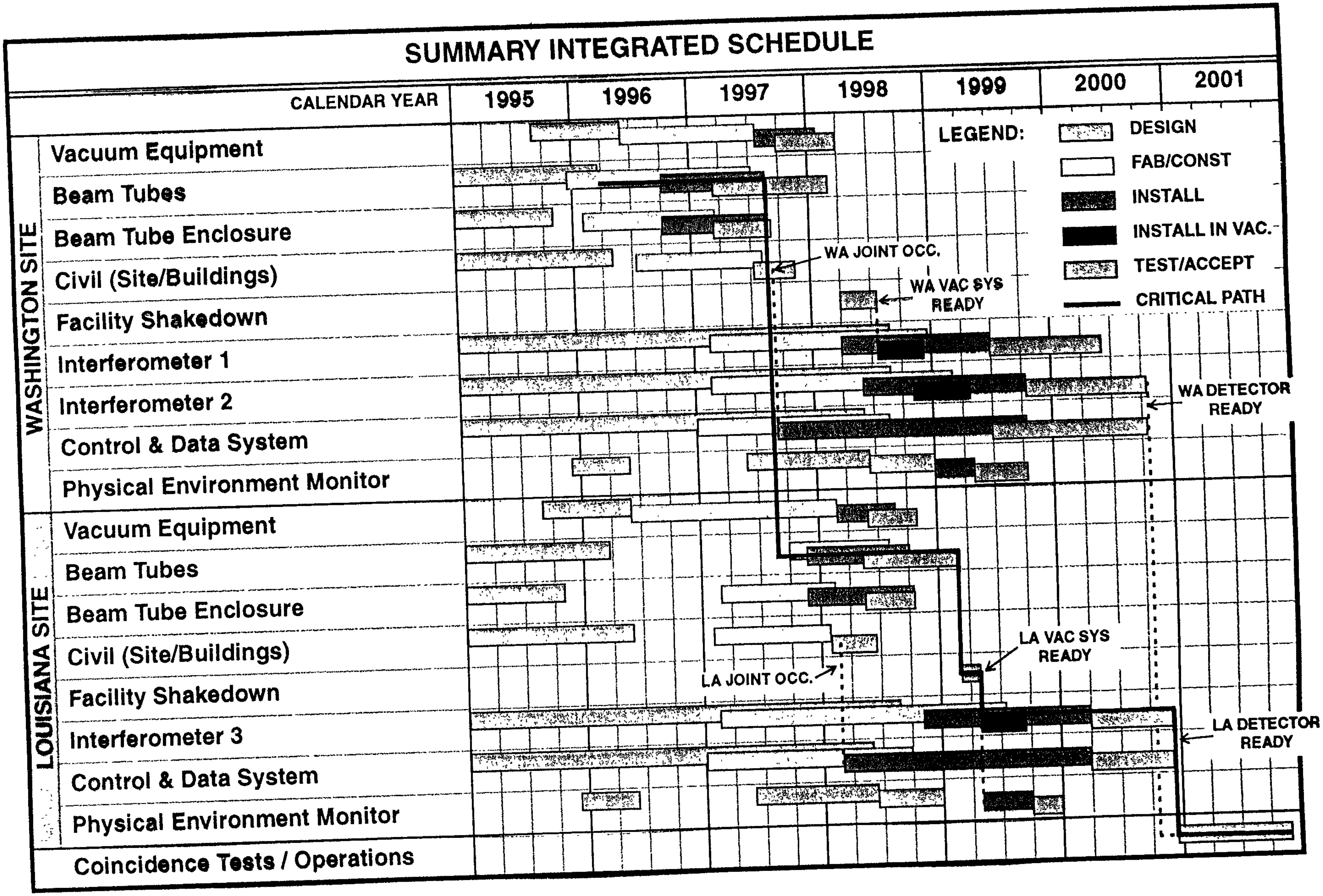
Interferometers

Sagnac

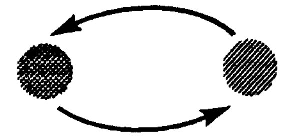
- Shot Noise Phase Sensitivity Measurement
- Phase Sensitivity = 3 10^{-9} rad/$Hz^{1/2}$
  - » (within 3 db of shot noise limit)



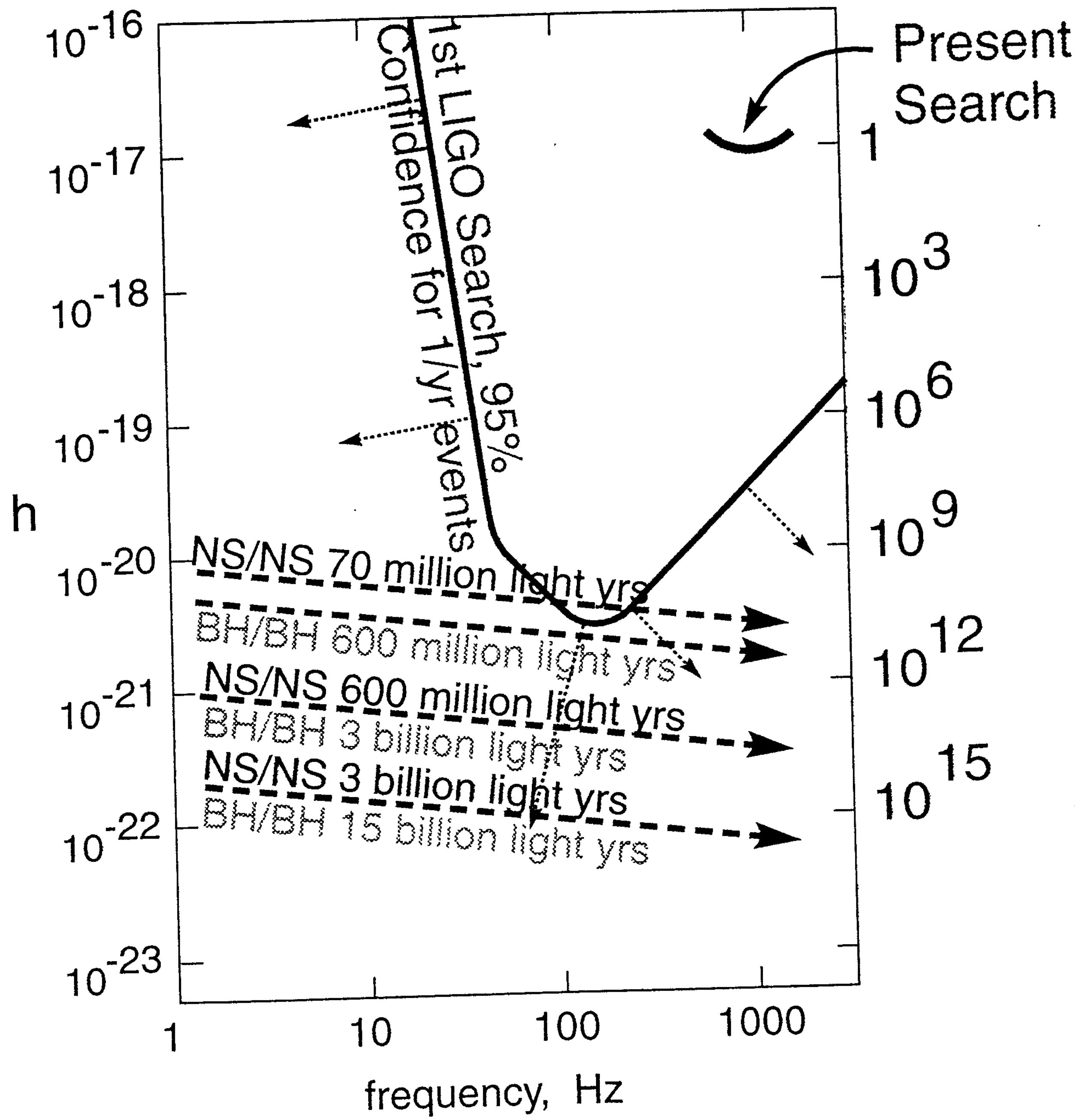
LIGO


SUMMARY INTEGRATED SCHEDULE
CALENDAR YEAR
1995
1996
1997
1998
1999
2000
2001
WASHINGTON SITE
Vacuum Equipment
Beam Tubes
Beam Tube Enclosure
Civil (Site/Buildings)
Facility Shakedown
Interferometer 1
Interferometer 2
Control & Data System
Physical Environment Monitor
LOUISIANA SITE
Vacuum Equipment
Beam Tubes
Beam Tube Enclosure
Civil (Site/Buildings)
Facility Shakedown
Interferometer 3
Control & Data System
Physical Environment Monitor
Coincidence Tests / Operations
LEGEND:
DESIGN
FAB/CONST
INSTALL
INSTALL IN VAC.
TEST/ACCEPT
CRITICAL PATH
WA JOINT OCC.
WA VAC SYS READY
WA DETECTOR READY
LA VAC SYS READY
LA JOINT OCC.
LA DETECTOR READY

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*

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.