
The Detection of Gravitational Waves

Academic Lecture Series

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CERN

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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

11

• 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

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

with Minkowski metric

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

SPECIAL
THEORY
OF
RELATIVITY

μ, ν indices over t, x, y, z

- Same physical concept carried over to General Theory of Relativity

except,

spacetime no longer necessarily flat

- general definition of space-time interval ⁽²⁾

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

↙ spacetime 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 "transverse traceless gauge" [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 propagating in direction \hat{k} with speed c .

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

Note: speed c due to way space-time brought together in relativity.

- Consider the wave propagating along the z axis (5)

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

transverse and traceless -

- can write as sum of two components

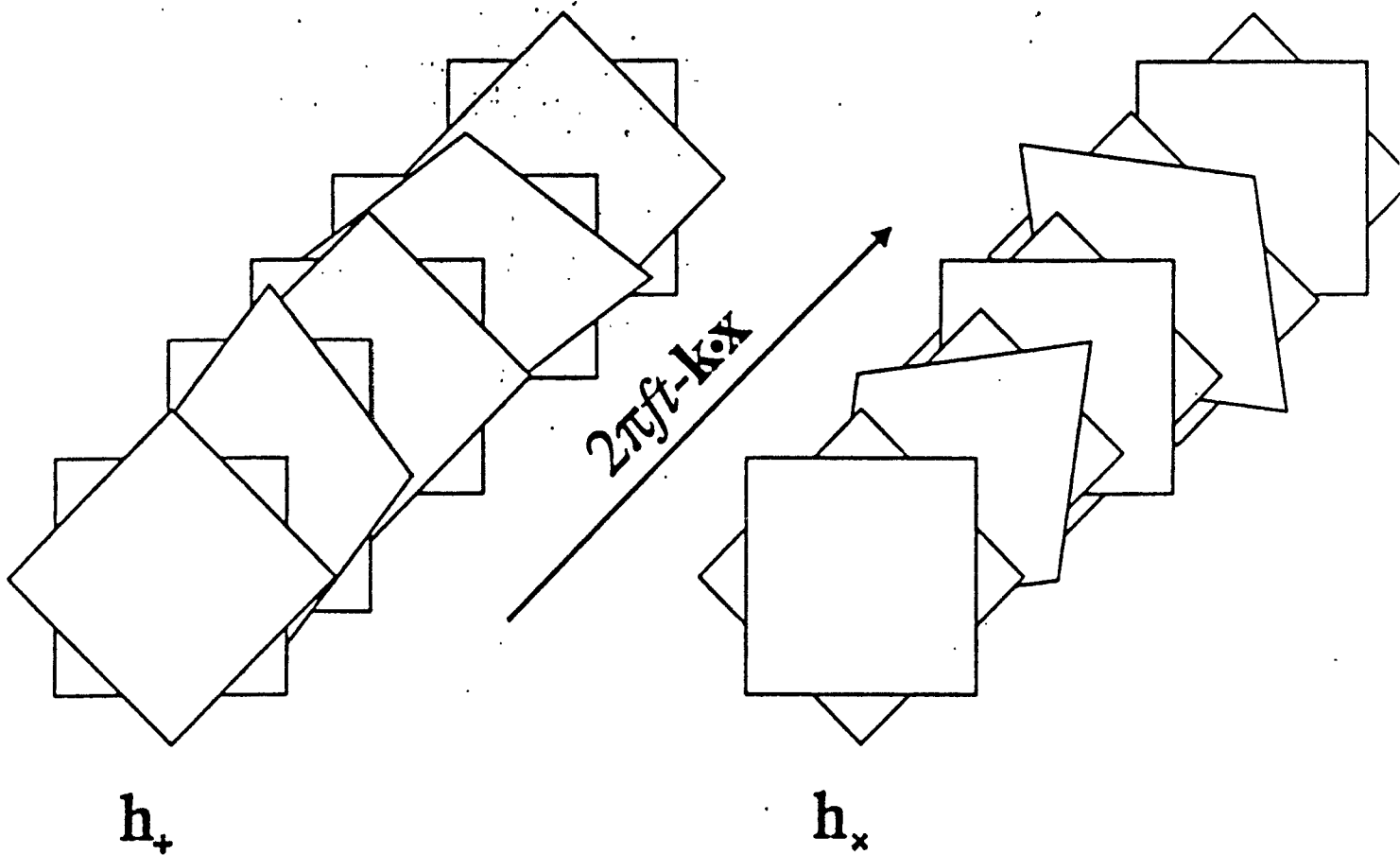
$$h = a \hat{h}_+ + b \hat{h}_x$$

two orthogonal polarizations (45°)

$$\hat{h}_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \hat{h}_x = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Gravitational Waves

Two Polarizations



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	$f > 10^7 \text{ Hz}$	$f < 10^4 \text{ Hz}$

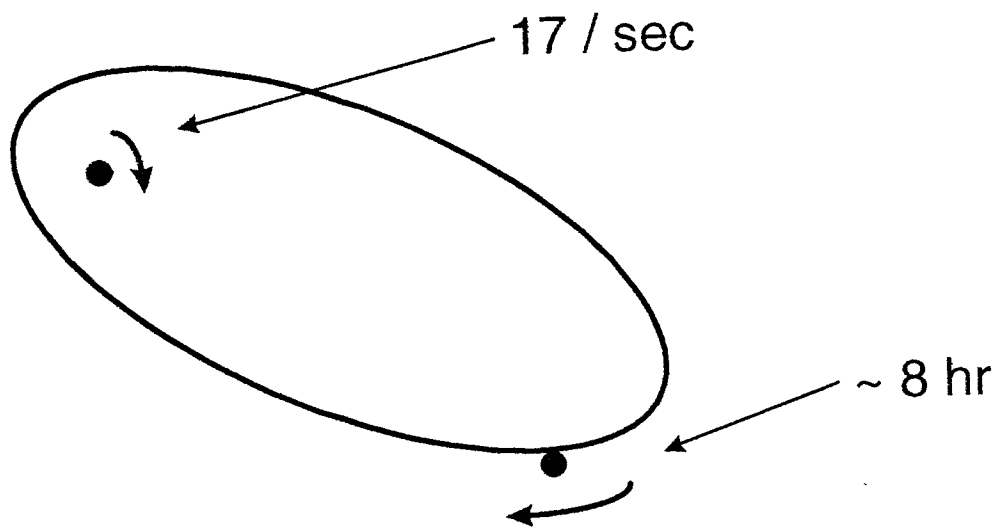
■ Implications

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

Gravitational Waves

Evidence

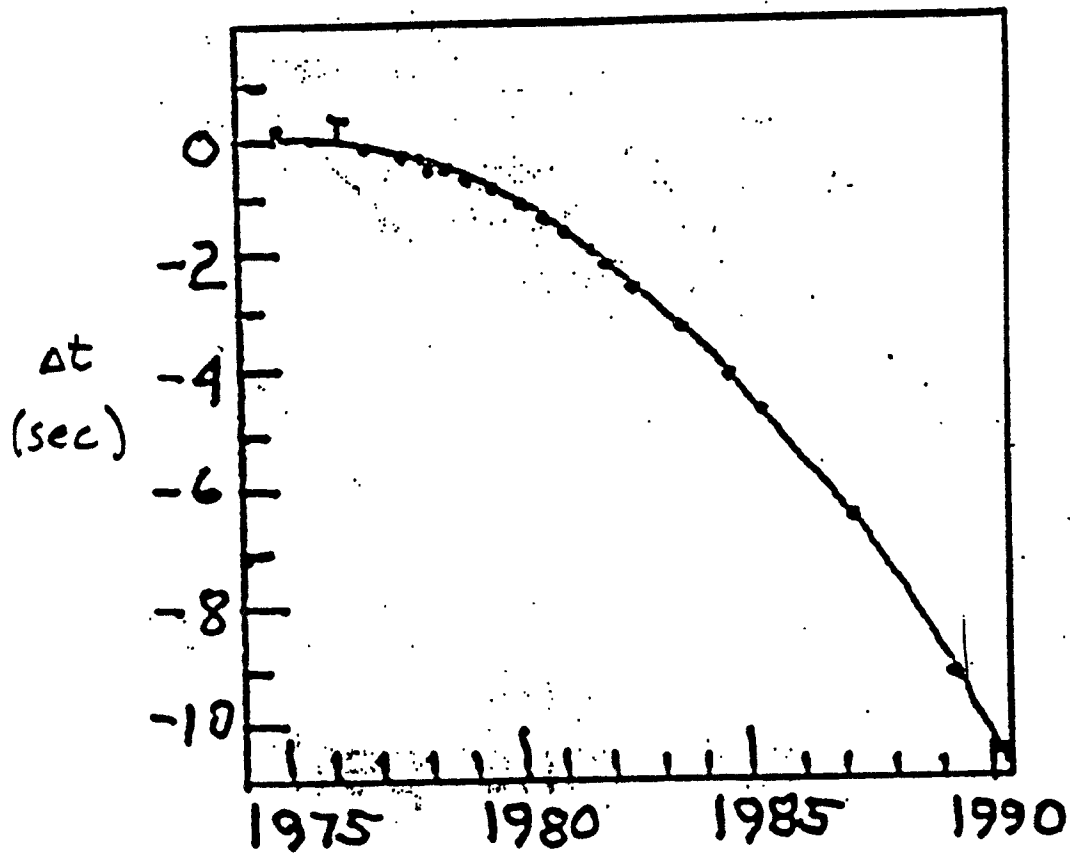
- **Russell Hulse and Joseph Taylor**
- **Neutron Binary System**
 - » PSR 1913 + 16 -- Timing of Pulsars



Hulse and Taylor

Timing of Orbit

- Speed up 10 sec in 15 years
 - » measured to $\sim 50 \mu\text{sec}$ accuracy
- Deviation grows quadratically in time

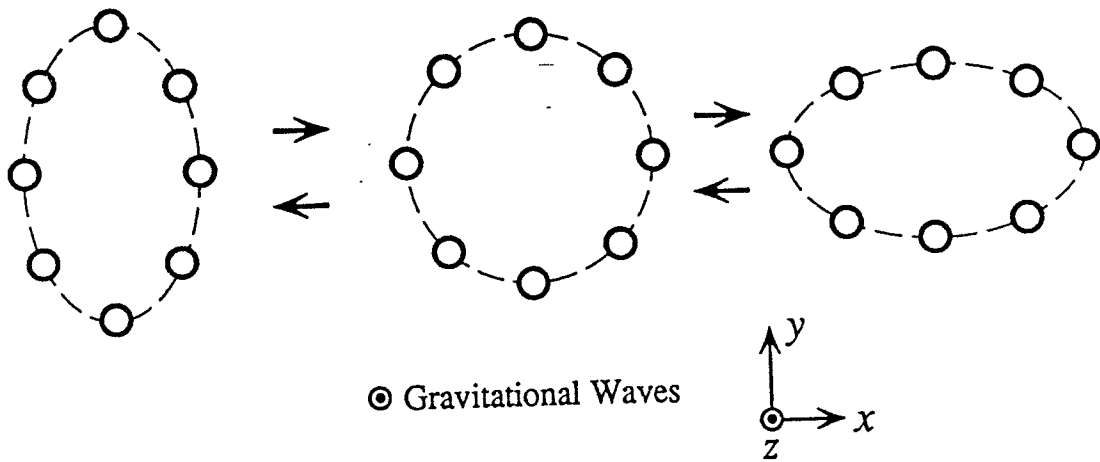


- Due to loss of orbital energy, from emission of gravitational waves

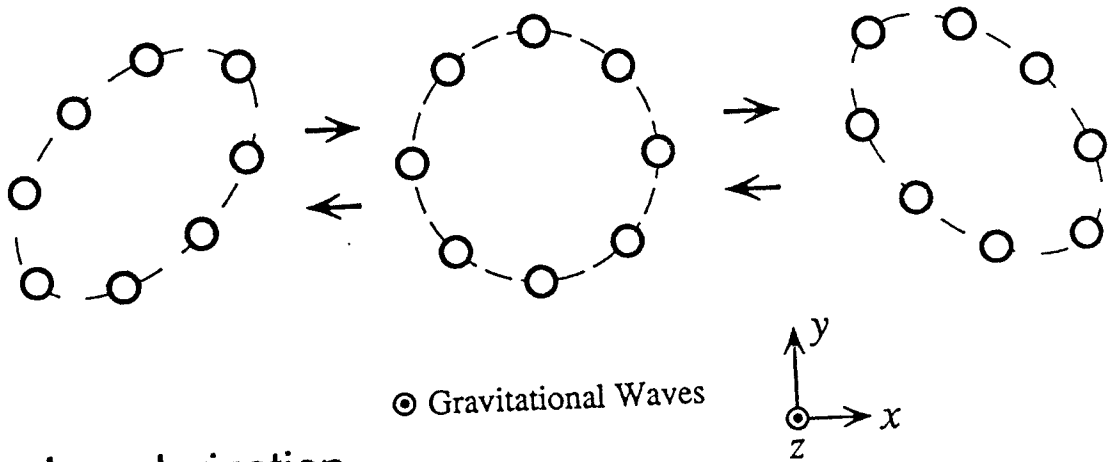
Gravitational Waves

Effects

- Displacement of free particles



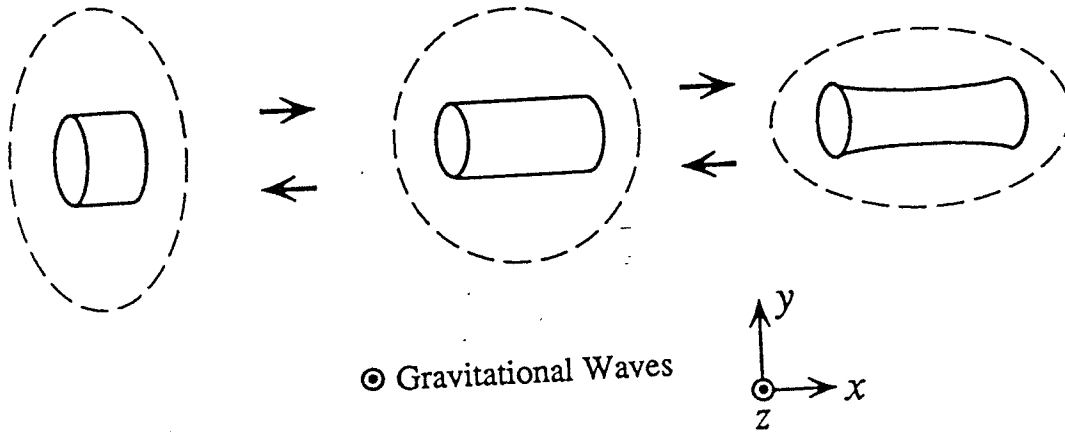
» h_+ polarization



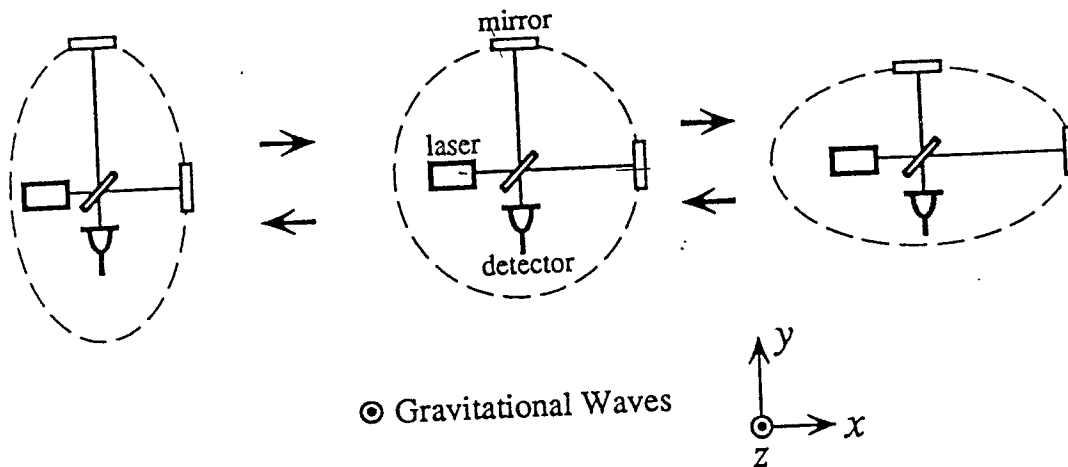
» h_x polarization

Gravitational Waves

Detection



● Bar detector

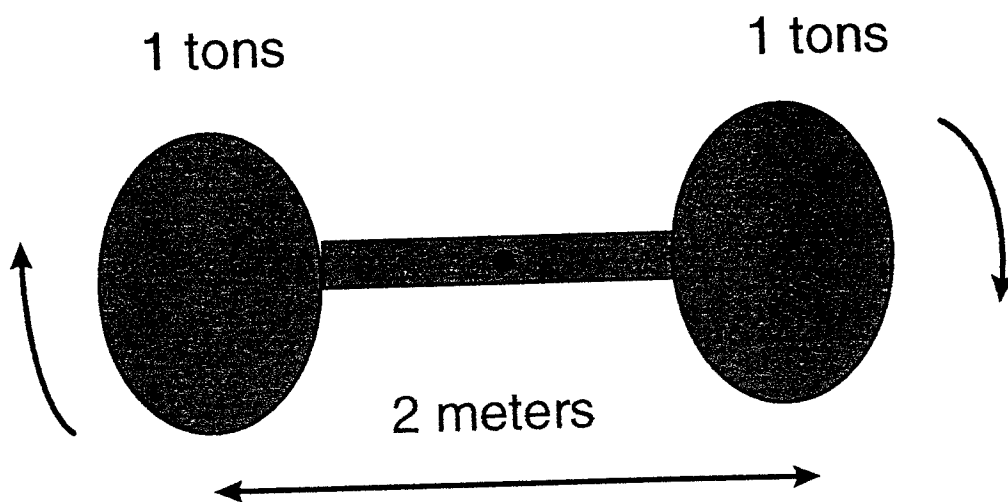


● Interferometer detector



Laboratory Experiment (a la Hertz)

Laboratory Dumbbell System



$$f_{\text{rot}} = 1 \text{ kHz}$$

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

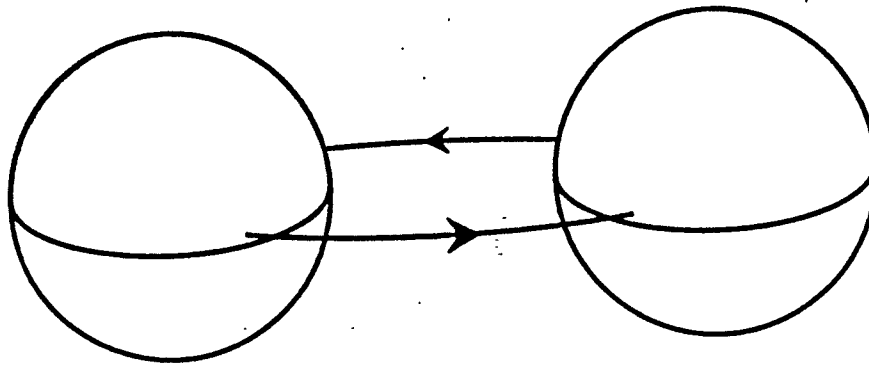
$$R = \text{detector distance } (> 1 \text{ wavelength}) = 300 \text{ km}$$

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

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

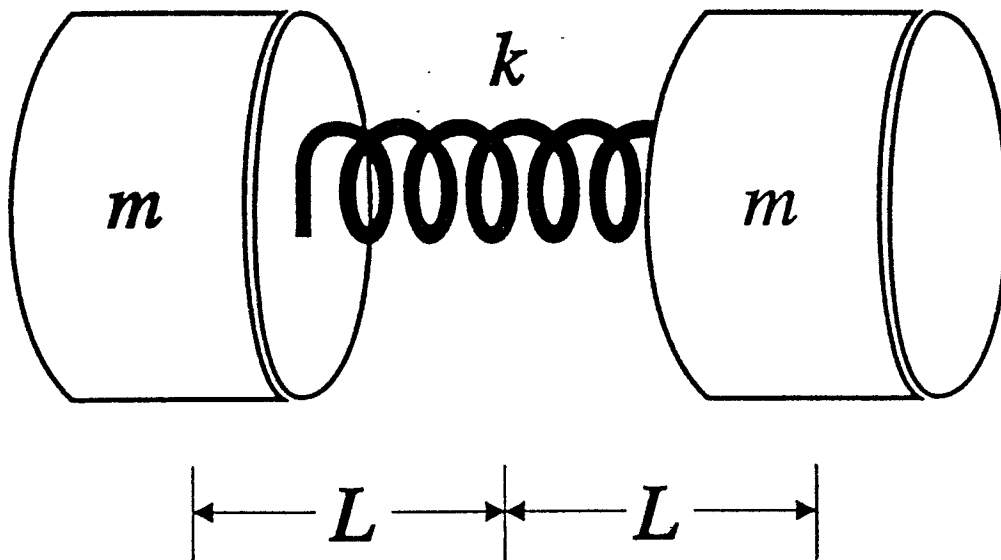
- sources and detection



Gravitational Waves

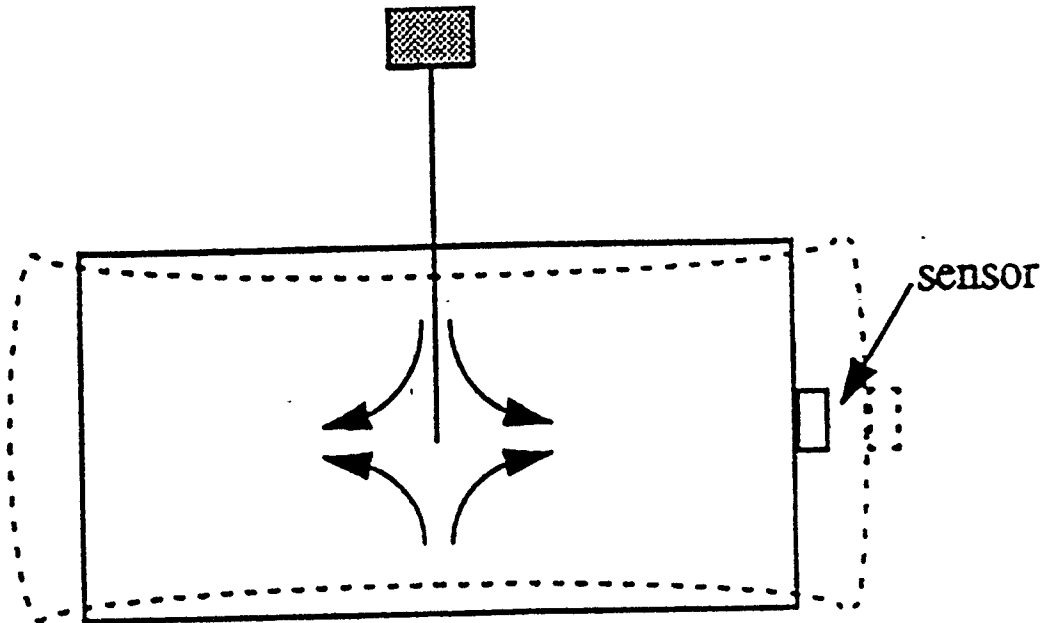
Resonant Bar Detector

- Schematic Version



Gravitational Waves

Resonant Bar Detection



- Bar detector

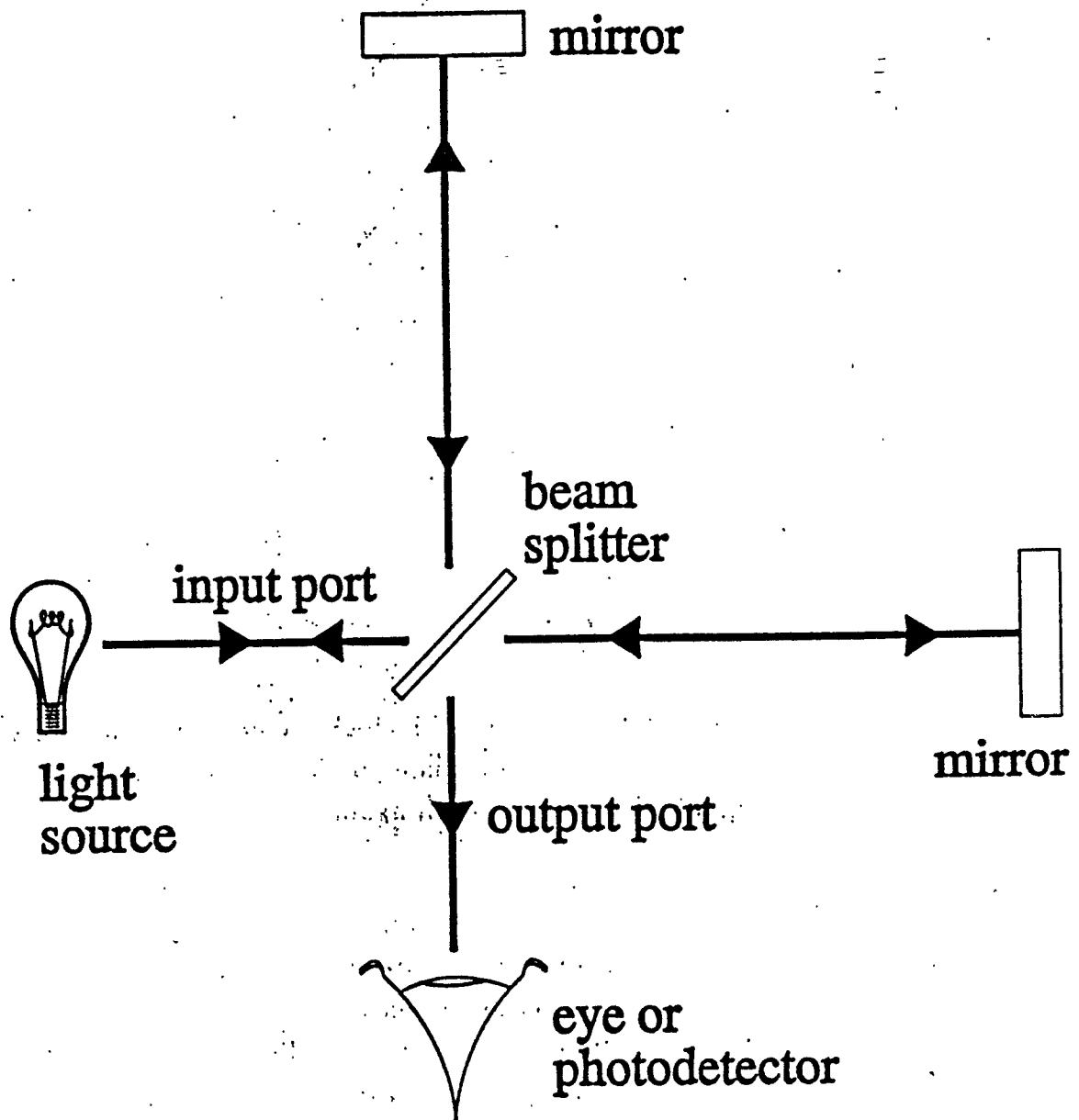
Group	Antenna	Transducer	Sensitivity (h)
CERN/Rome	Al5056, 2.3ton, 2.6K	Capacitive+SQUID	7×10^{-19}
CERN	Al5056, 2.3ton, 0.1K	Capacitive+SQUID	2×10^{-18}
LSU(USA)	Al5056, 1.1ton, 4.2K	Inductive+SQUID	7×10^{-19}
Stanford	Al6061, 4.8ton, 4.2K	Inductive+SQUID	10^{-18}
UWA(Australia)	Nb, 1.5ton, 5K	RF cavity	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 $E_0 e^{i(2\pi ft - kx)}$

- 50/50 beam splitter $r = 1/\sqrt{2}$ $t = i/\sqrt{2}$

- z axis light $i(E_0/\sqrt{2}) e^{i(2\pi ft - k_x x)}$

- y axis light $(E_0/\sqrt{2}) e^{i(2\pi ft - k_y y)}$

k_x, k_y allow possible different

speed of light in the two arms

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

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

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

also

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

toward lamp

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

Power $\propto E^2 \Rightarrow$

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

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

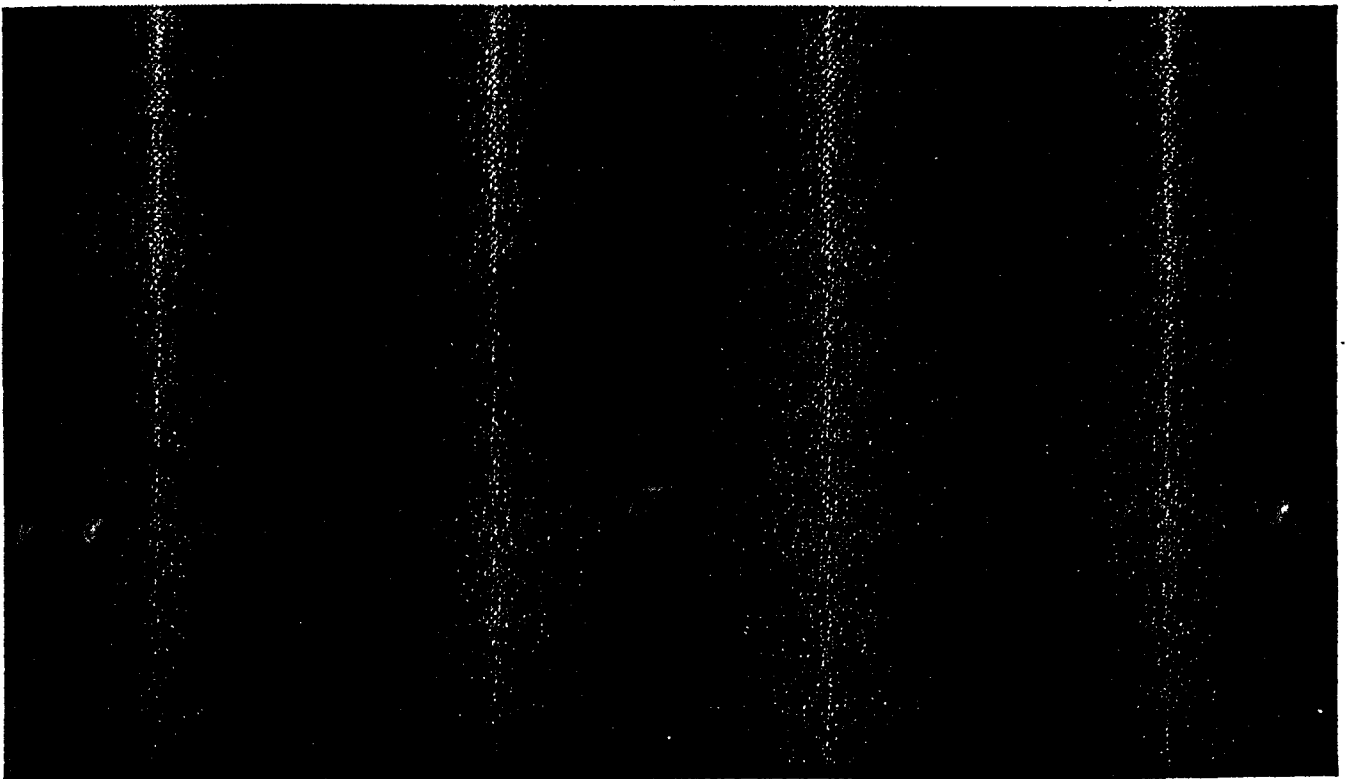
- Measure difference in brightness (modern)

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 $\lambda/20$

⇓

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

• 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

$$\begin{aligned}
 ds^2 = 0 &= g_{\mu\nu} dx^\mu dx^\nu \\
 &= (\eta_{\mu\nu} + h_{\mu\nu}) dx^\mu dx^\nu \\
 &= -c^2 dt^2 + (1 + h_{11}(2\pi ft - \vec{k} \cdot \vec{x})) dx^2
 \end{aligned}$$

(neighboring space-time events)

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

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

\Rightarrow
 $h \ll 1$ binomial expansion.

Round trip -

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

similar for y-arm.

Consider special case,

- sinusoidal wave in + polarization
- 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

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

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

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

$$\Delta\phi(t) = h(t) \tau_{rt0} \frac{2\pi c}{\lambda}$$

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)

NO NET MODULATION IF

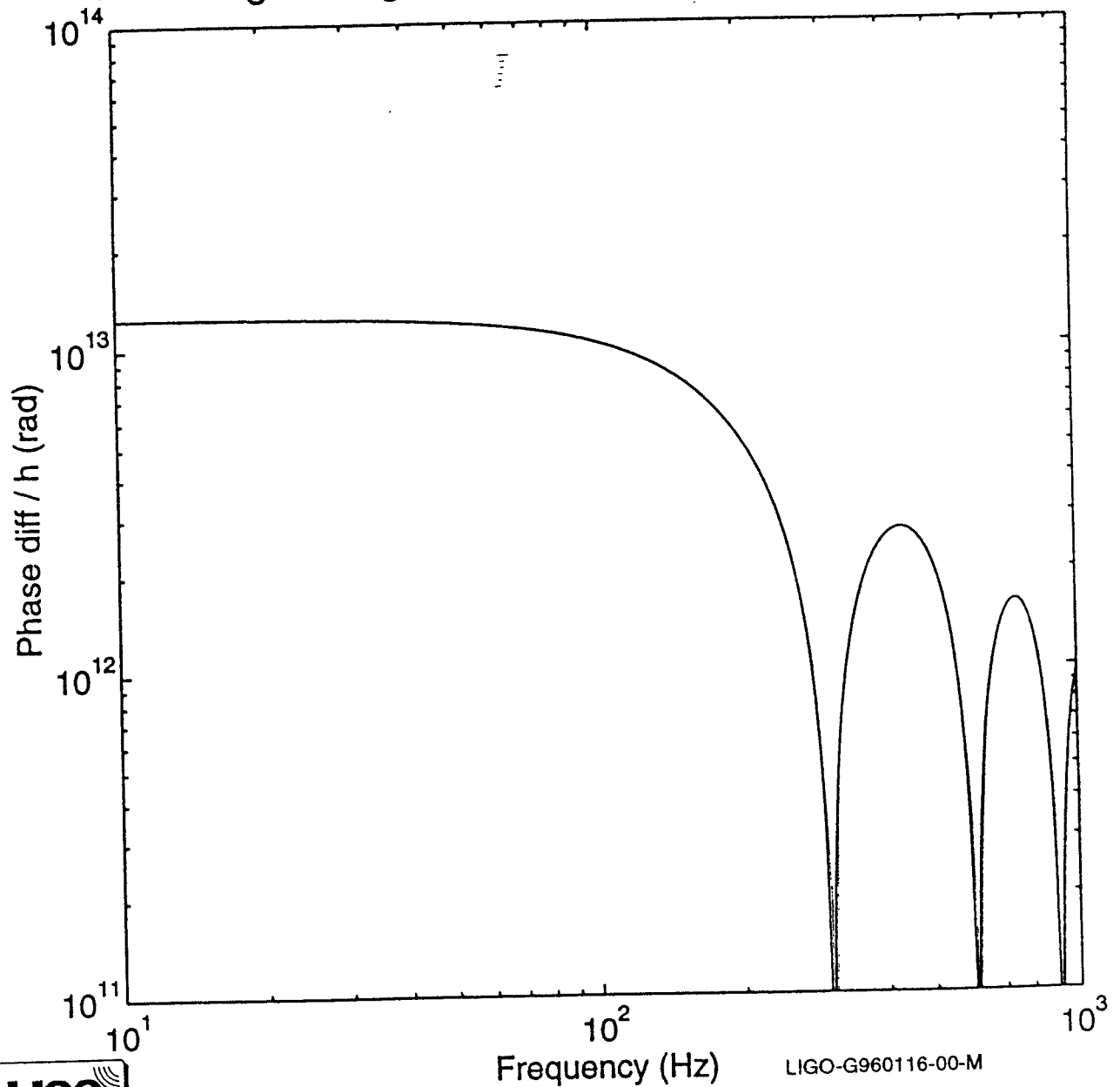
$$f_{gw} \tau_{rt} = 1$$

Michelson Interferometer

Transfer function

- Example

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



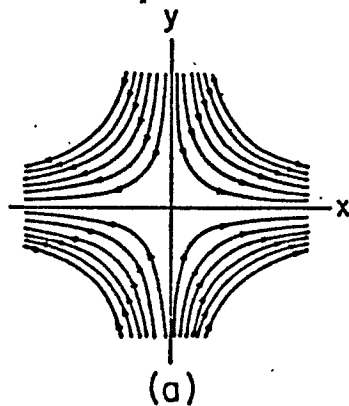
Gravitational Wave *Forces*

IF

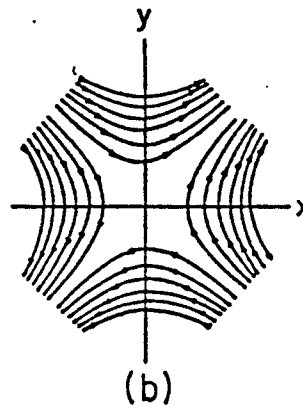
- Detector Size \ll Wavelength
(4 km) (300-30,000km)
(10 kHz - 10 Hz LIGO)

THEN

- Free Masses
- Quadrupolar Lines of Force



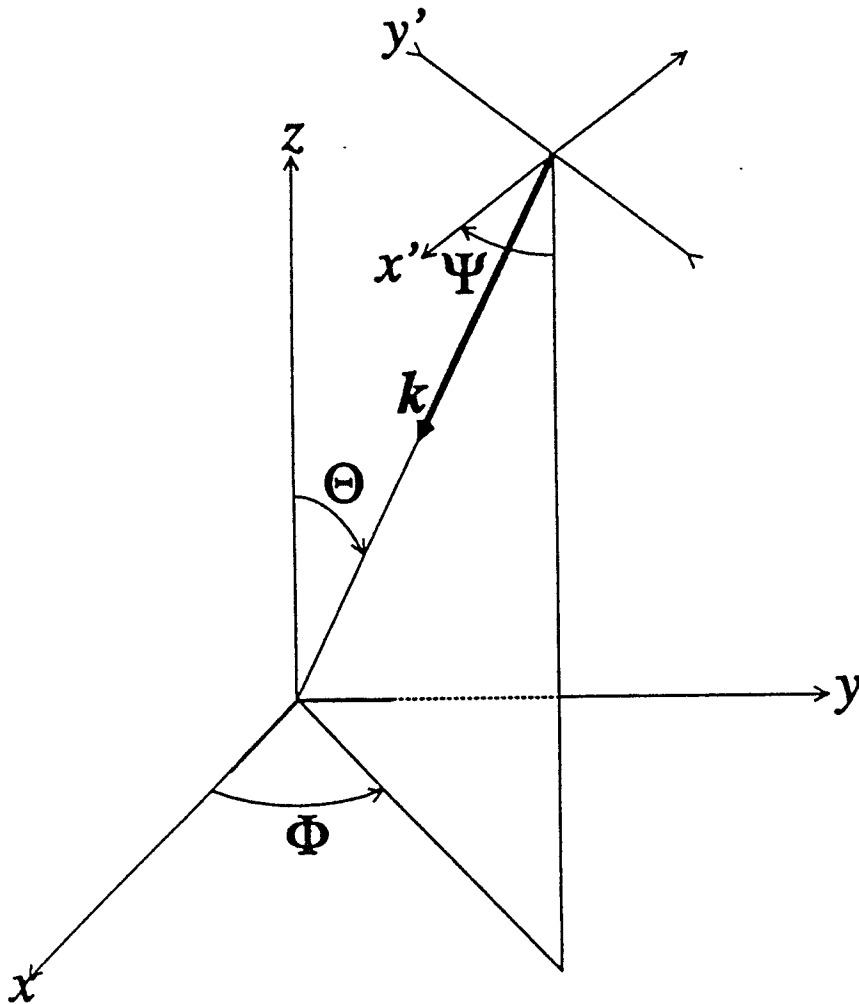
+ Polarization



x Polarization

Gravitational Wave Detector

- Antenna Pattern
 - » coordinate system



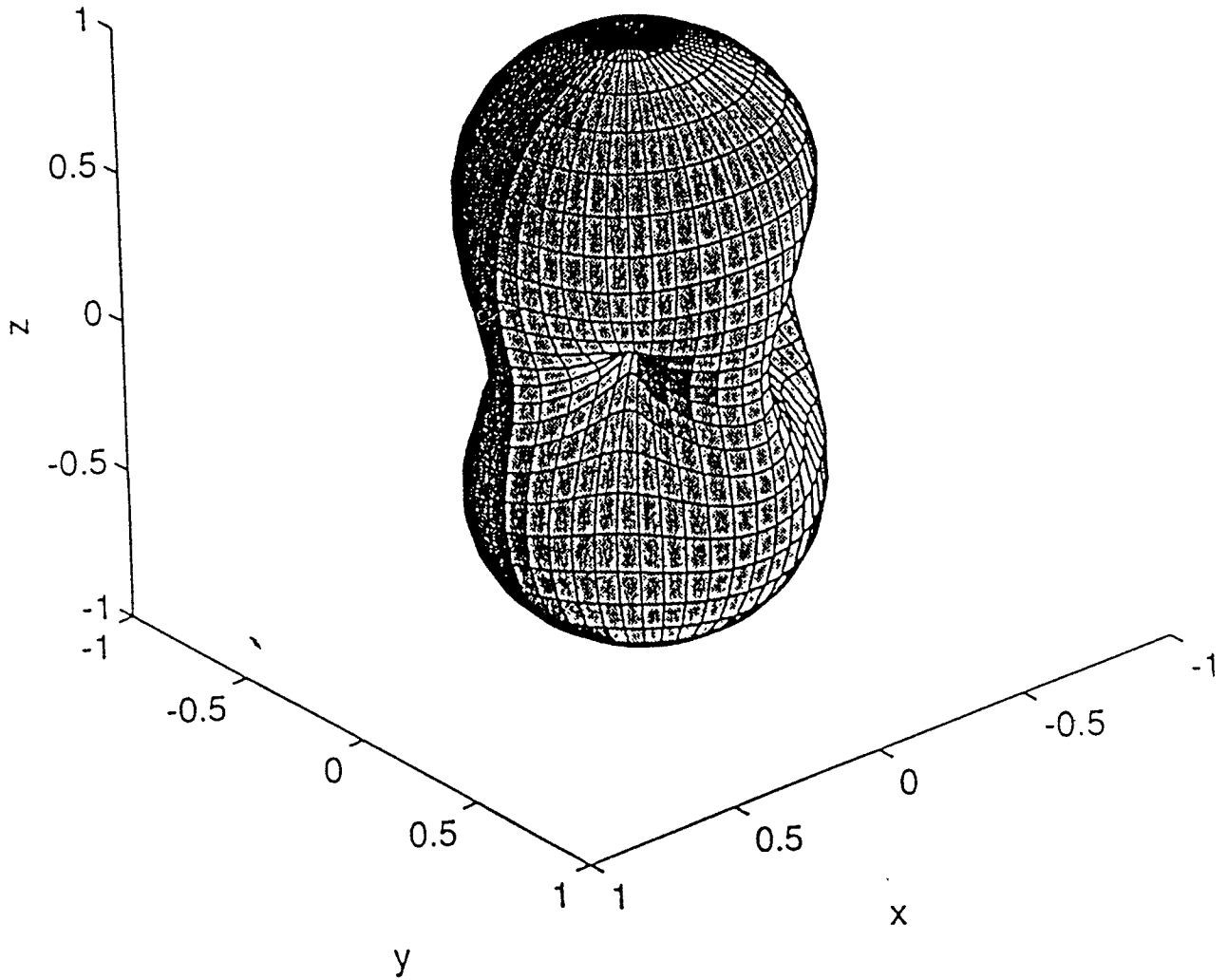
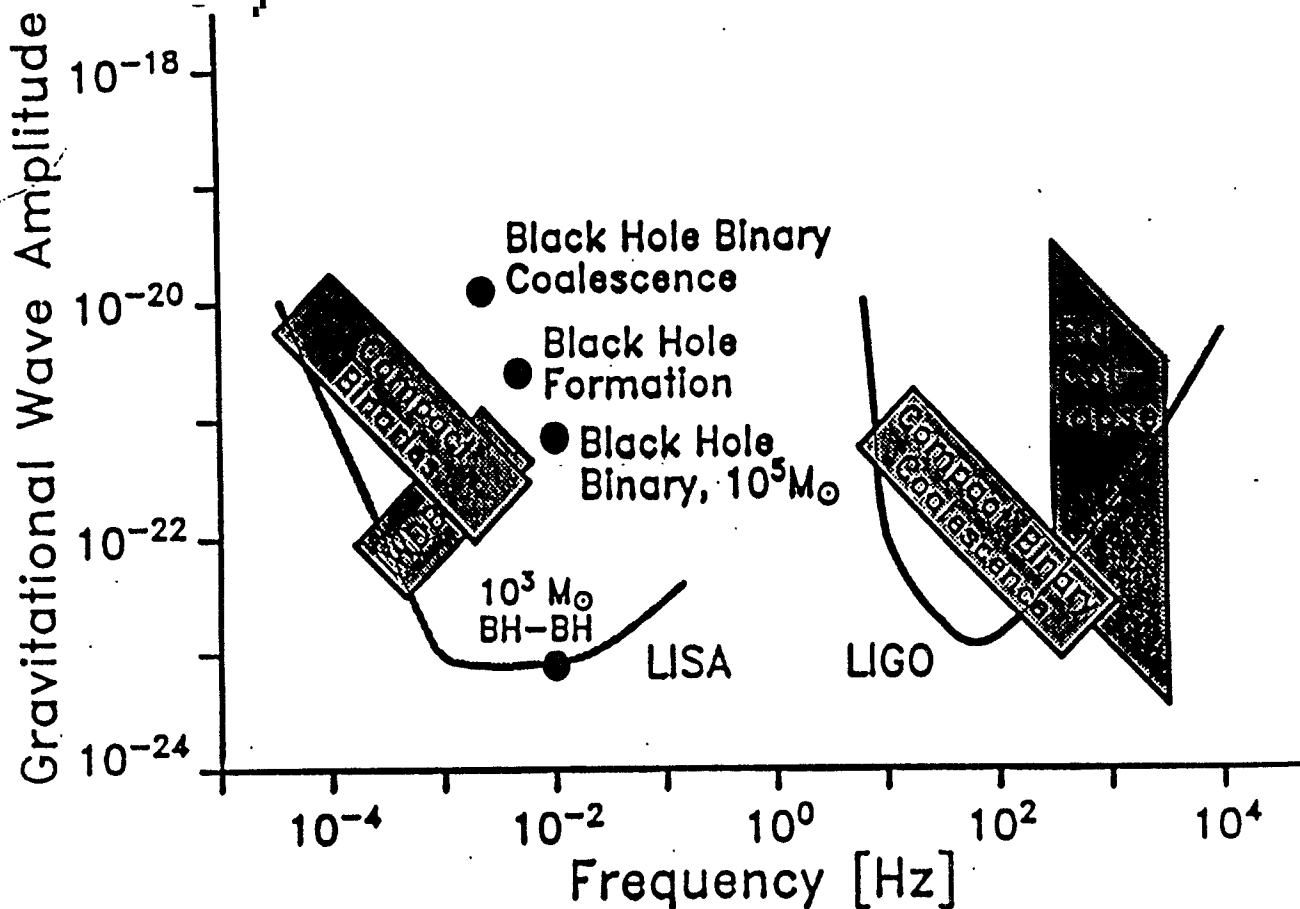


Figure 2.7 The sensitivity, as a function of direction, of an interferometric gravitational wave detector to unpolarized gravitational waves. The interferometer arms are oriented along the x and y axes.

Astrophysical Sources

Frequency Range

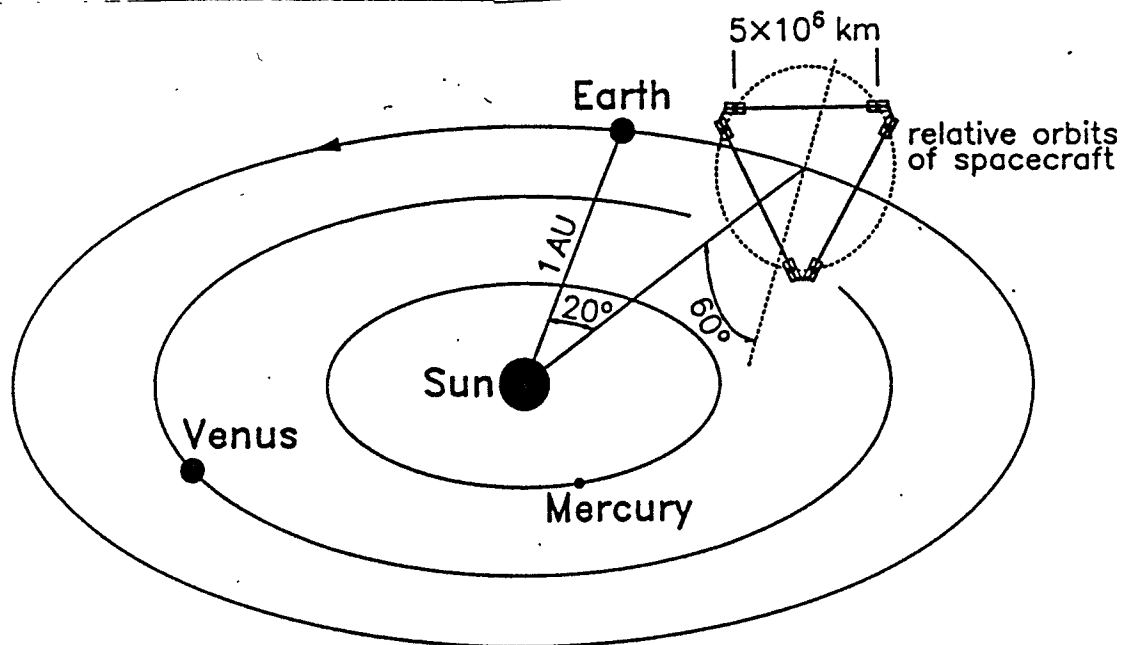
- Electromagnetic Waves - ~ 20 orders of magnitude (ULF radio -> HE γ rays)
- Gravitational Waves - ~ 10 orders of magnitude
- Combination of terrestrial and space experiments



Gravitational Waves

Space Experiment

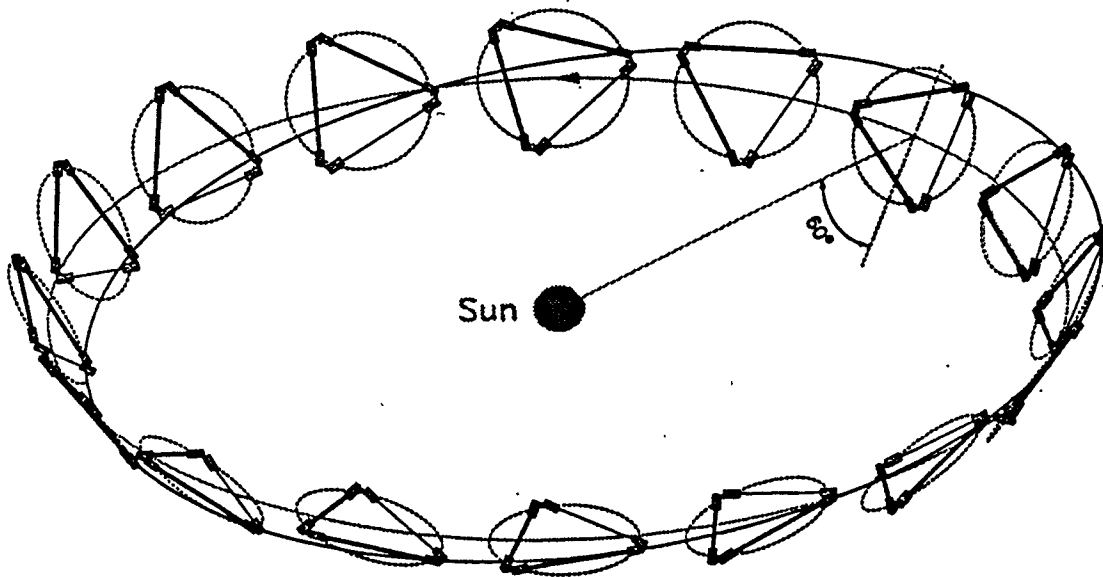
- LISA - Laser Interferometer Space Antenna
 - » six spacecraft in triangle (four needed)
 - » pair at each vertex



LISA

Annual Revolution

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



Gravitational Waves

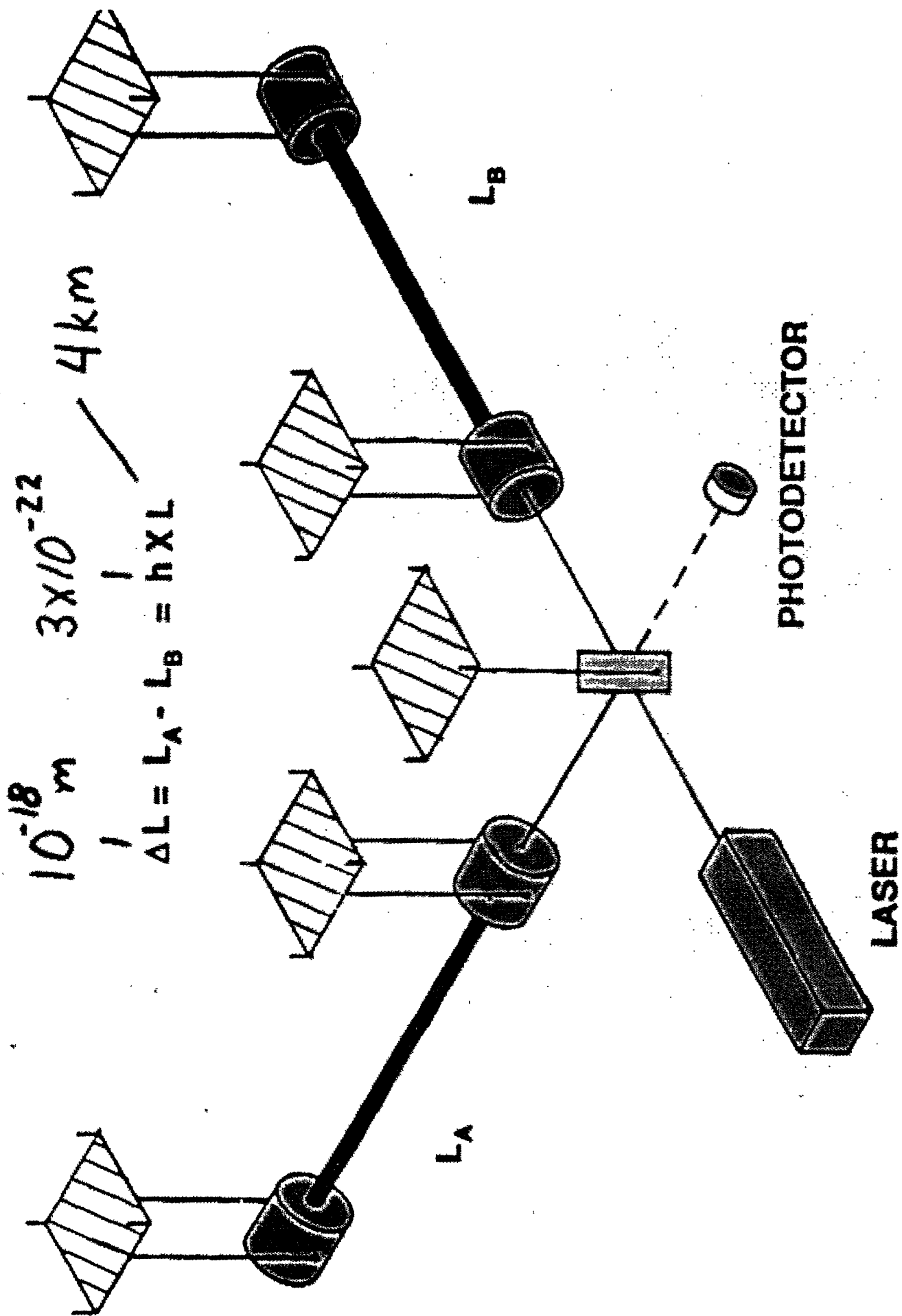
International Effort

- 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



LIGO

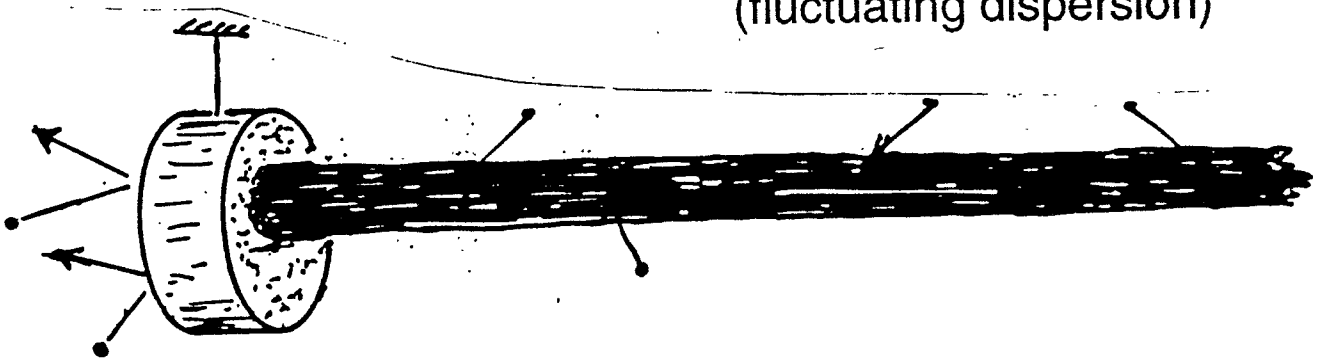
Achieving 10^{-18} m Sensitivity

How is it possible????

- Air molecules:

Buffer mirrors

Buffer light beam
(fluctuating dispersion)



» Mirrors and light beam must be in vacuum

- Mirror's atoms vibrate (thermal noise)

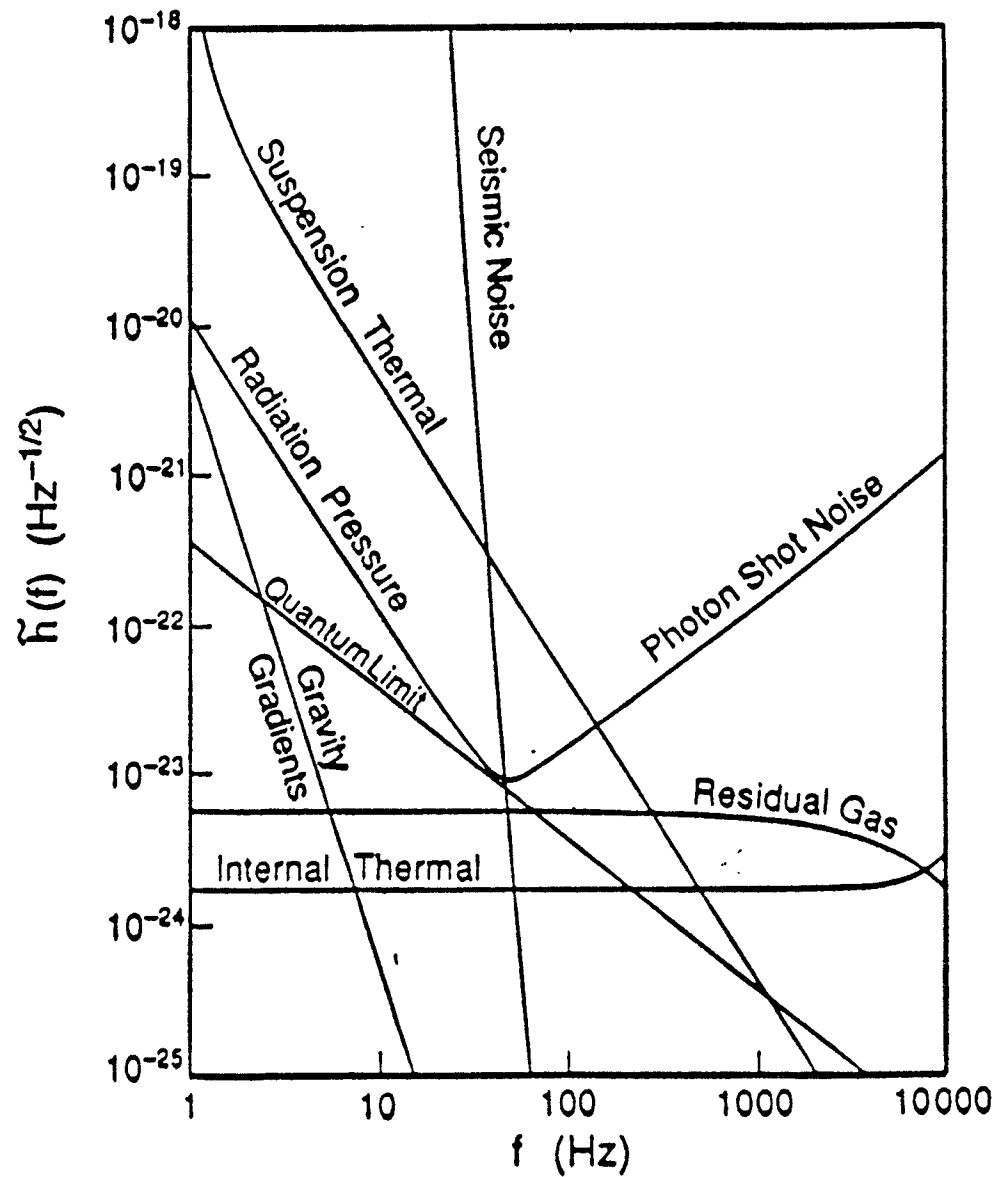
- » light beam feels 10^{18} atoms
- » atoms vibrate fast: $\sim 10^{13}$ Hz
- » beam measures slow variables: ~ 100 Hz

- 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 $Q=10^7$



Gravitational Wave Generation

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

(size of source much smaller than wavelength)

- EM \Rightarrow radiation field from time variation of electric dipole moment

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

R = distance from source to observer
 \hat{n} = unit vector source to observer
 \vec{d} = electric dipole moment

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

ρ_q = charge density
integrate over source

Next term,

magnetic dipole
electric quadrupole

(weaker by r_{source}/r)

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)
L gravity (one sign)

Also,

[gravitational charge (by Principle
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)

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

$\rho(r)$ = mass density

(conservation of momentum requires
 $\dot{\vec{d}}_g$ constant for isolated systems)

∴ FORBIDDEN

Out of conservation 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 Hz \rightarrow few kHz)
- 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,

$$I_{zz} = -\frac{1}{3} Mr_0^2 \quad (\text{constant}) \quad \text{cross terms with } x, y \quad \text{VANISH}$$

Calculate second time derivative, $\ddot{I}_{\mu\nu}$
 (eg. point along z axis, distance R)

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

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

can be re-arranged in more dimensionless form

$$|h| \approx \frac{r_{s1} r_{s2}}{r_0 R}$$

plug in to get representative strength of grav. waves h

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

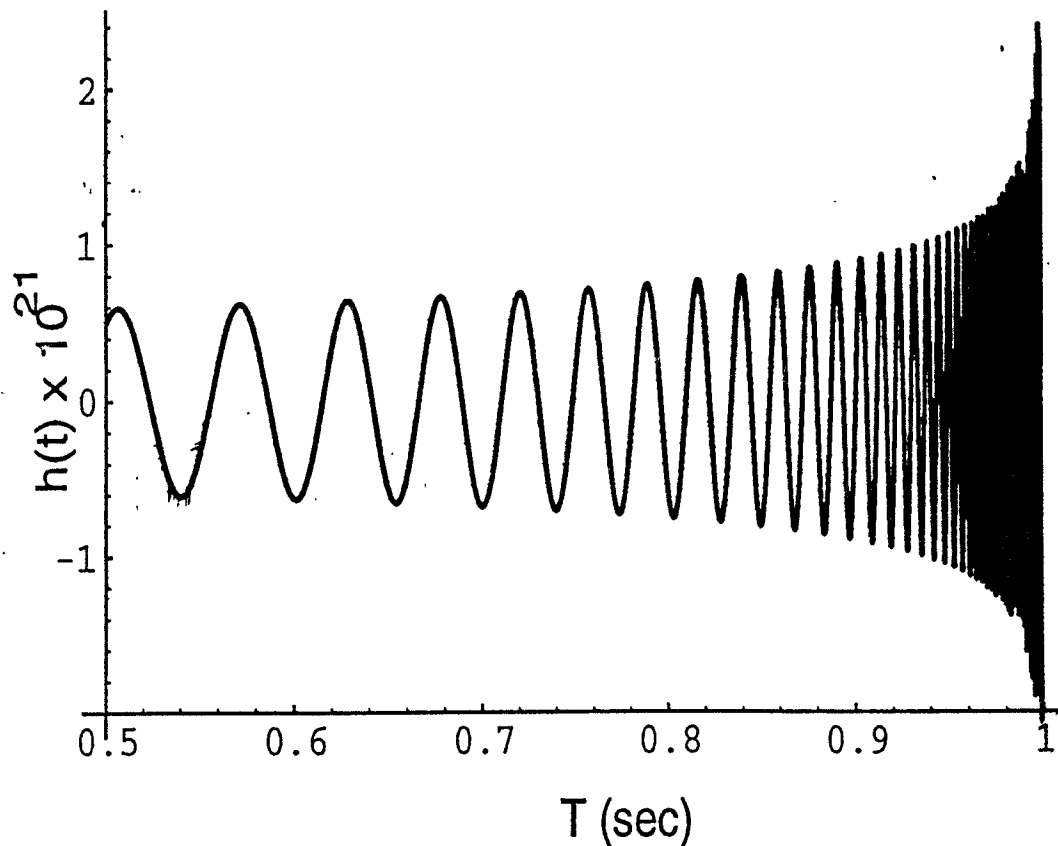
$$h \equiv h_{\mu\nu} \approx 10^{-21}$$

$$f_{gw} = 2 f_{orb}$$

Neutron Binary Systems

Inspiral

- LIGO frequency band
 - » last 15 minutes ($\sim 10^4$ 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

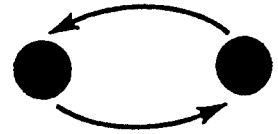
<u>Method</u>	<u>Our Galaxy</u>	<u>Distance for 3/yr</u>
Progenitor Death Rate	$\sim 1/1000$ yr	130 M.L.yr
Binary Pulsar Searches and Discoveries	$\sim 1/10^{5\pm 1}$ yr	600 M.L.yr.
Ultra-conservative Limit from Binary Pulsar Searches	$\sim 1/10^7$ yr	3000 M.L.yr

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:*

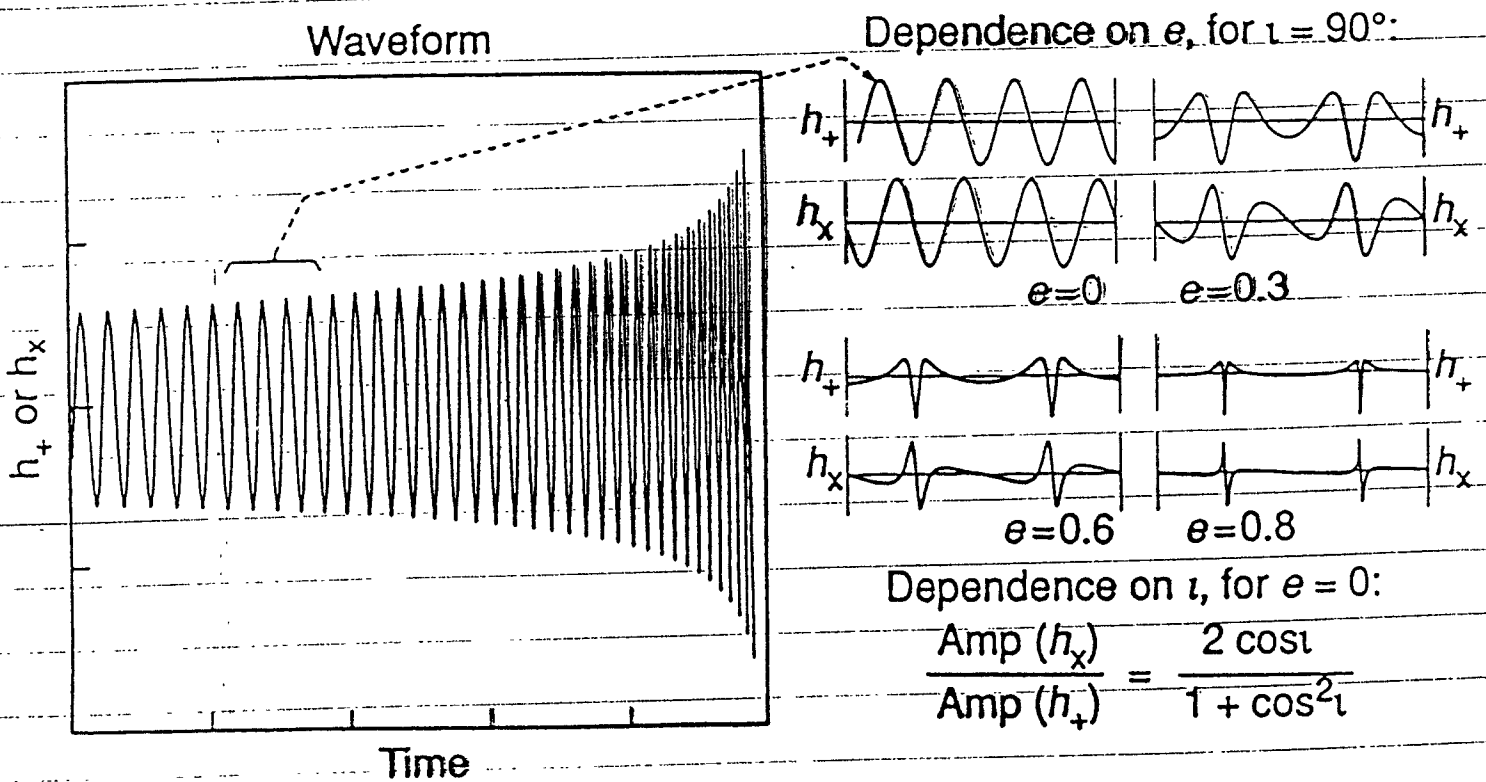
- *It's wave frequency is 0.0001 Hz*
- *LIGO's band is 10 to 1000 Hz*
- *We must wait 100 million yrs for PSR1913+16 to reach LIGO's band*

Gravitational Waveforms

binary inspiral

- can determine

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



Neutron Star Binaries

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

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

in weak field approximation

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

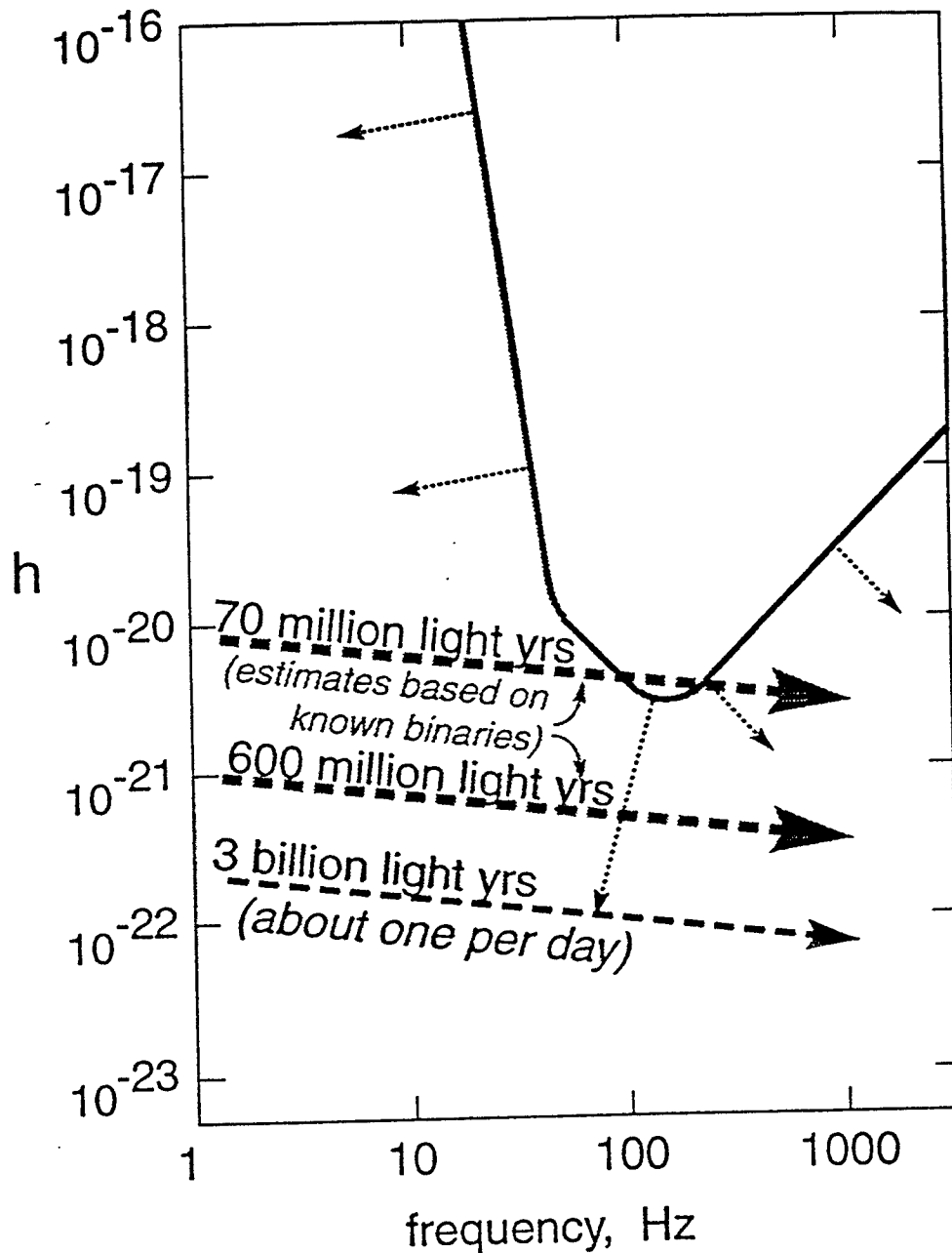
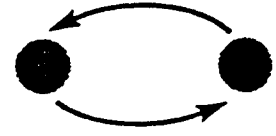
$$h(t) = 6.6 \cdot 10^{-24} \frac{15 \text{ Mpc}}{R} \left(\frac{M_1^3 M_2^3}{M_1 + M_2} \right)^{1/4} \left(\frac{1 \text{ day}}{\tau} \right) (1 + 6 \cos^2 \theta + \cos^4 \theta)$$

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

at collision, $f \sim 1 \text{ kHz}$; $h \sim 10^{-21}$ @ VIRGO (several percent of rest mass radiated away)

NEUTRON STAR BINARIES

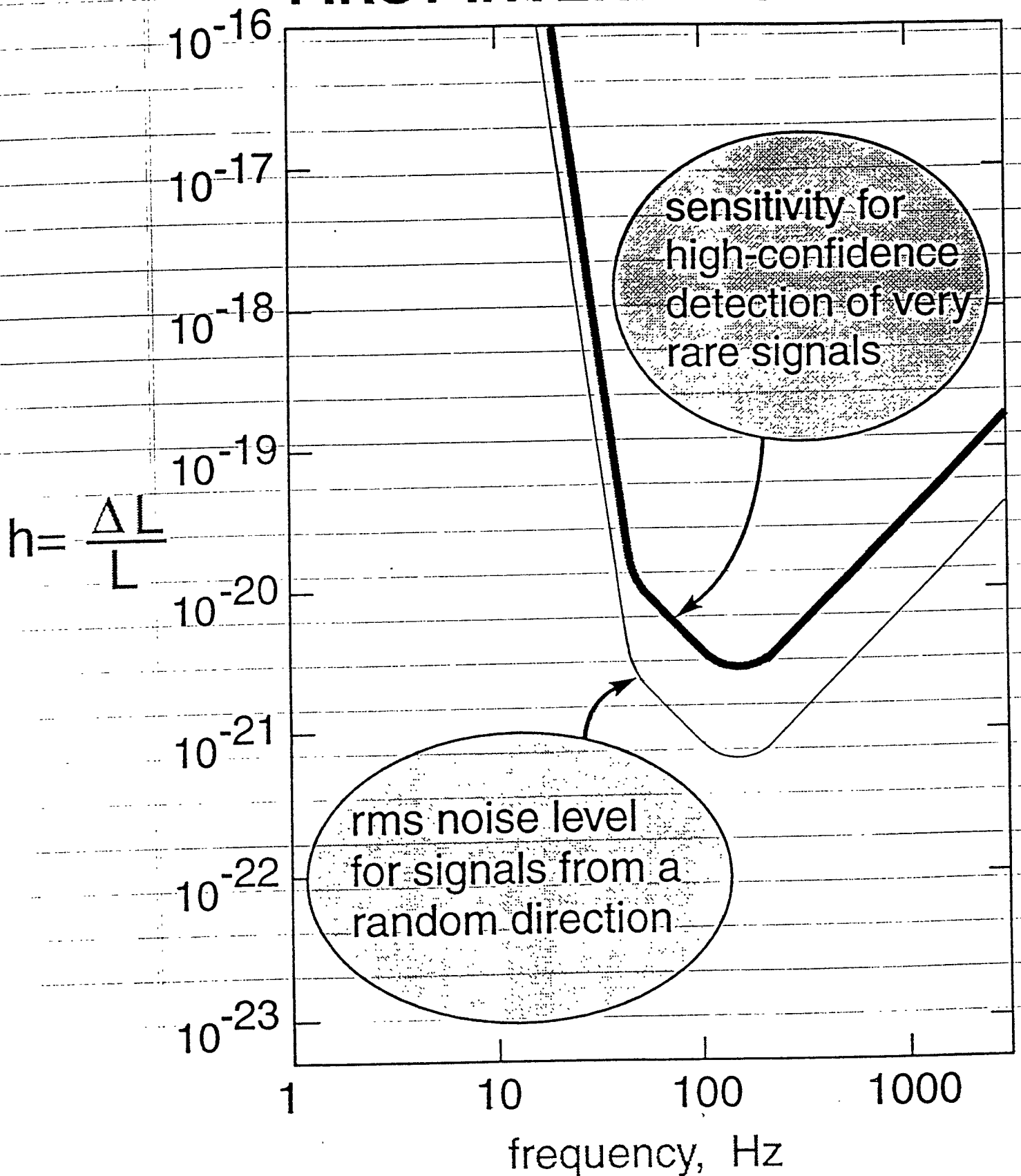
[“Guaranteed” source]

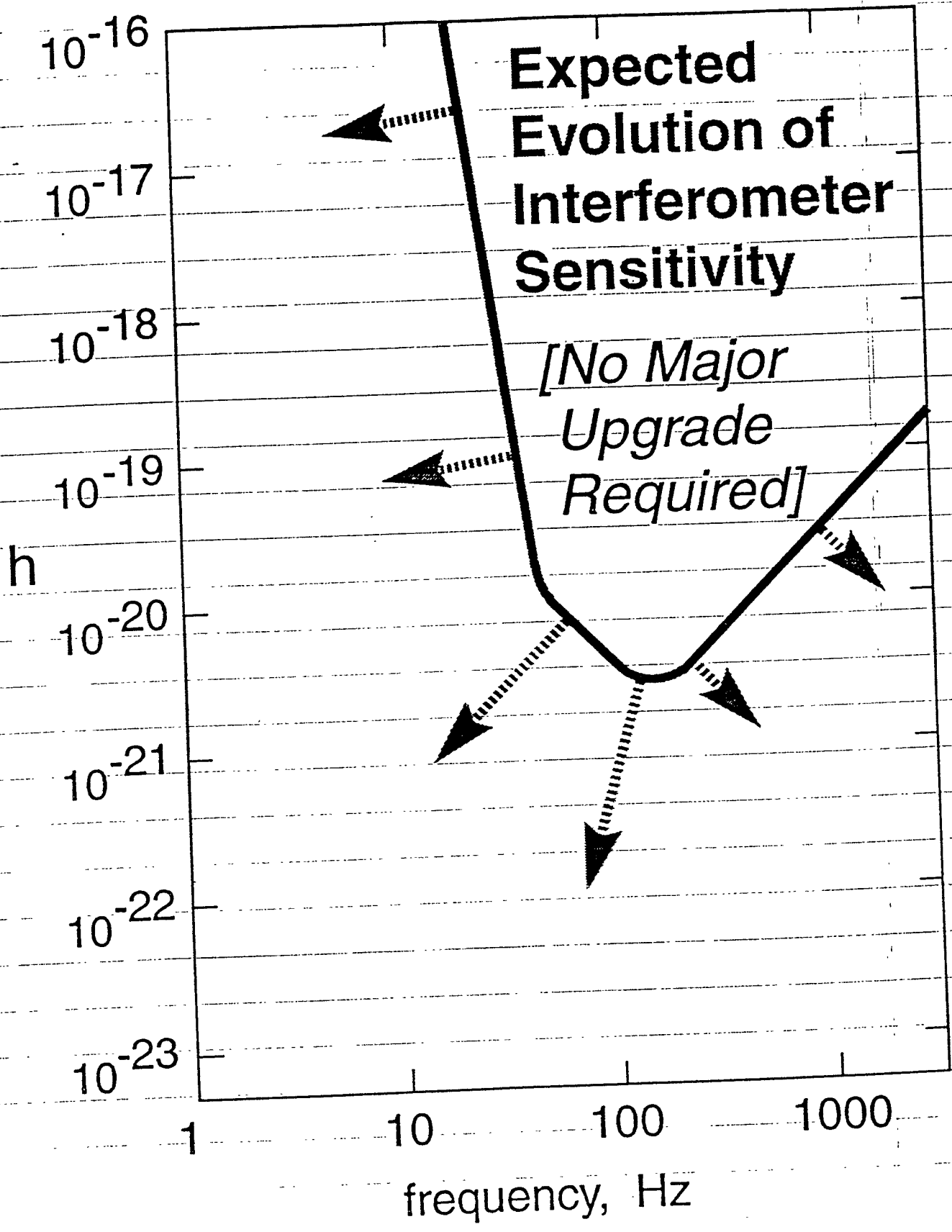


■ 15 minutes & 10,000 orbits in LIGO band

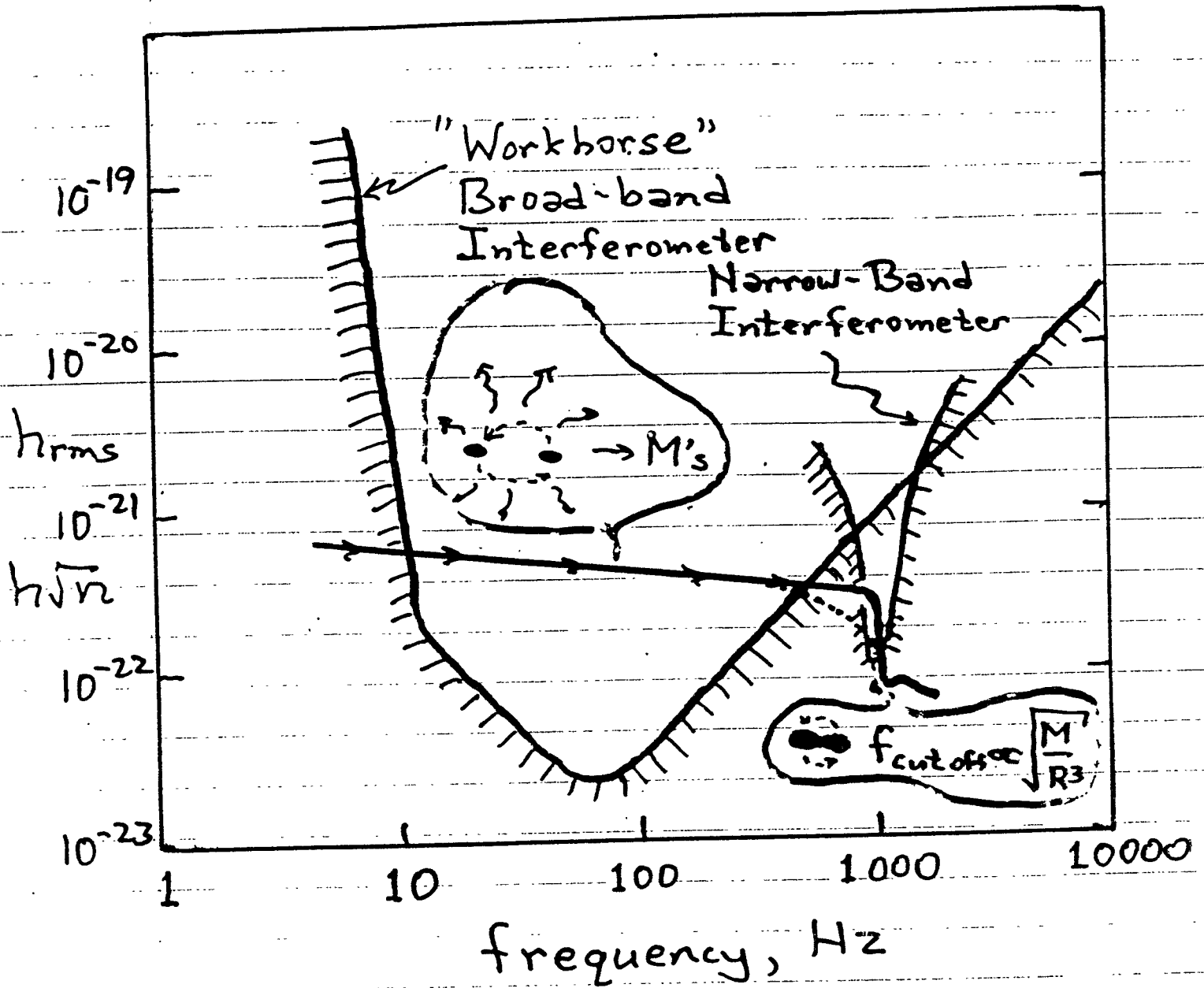
■ Rich information in waveforms:
masses, spins, distance, direction,
nuclear equation of state

SENSITIVITY OF LIGO'S FIRST INTERFEROMETERS





NEUTRON STAR QUALESCENCE



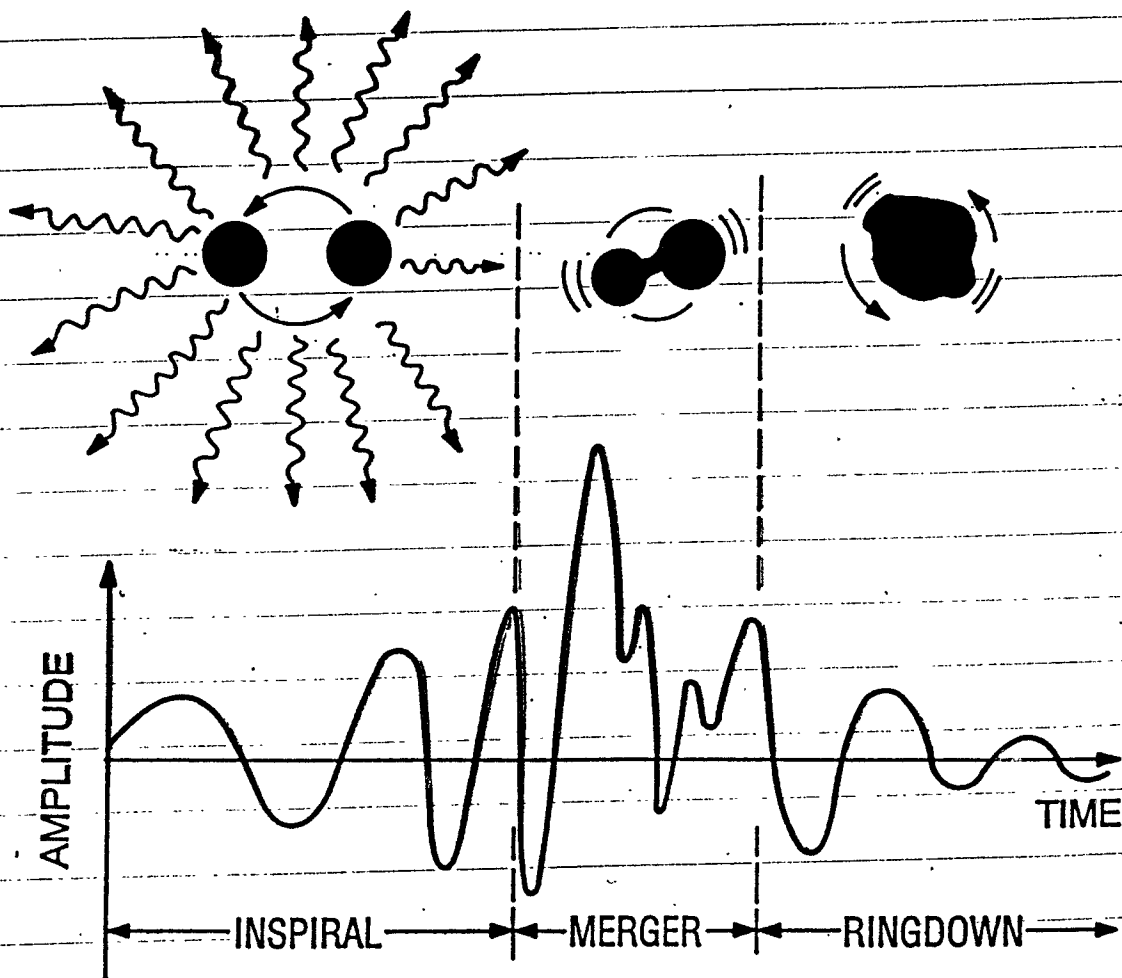
Neutron-Star $M(R)$

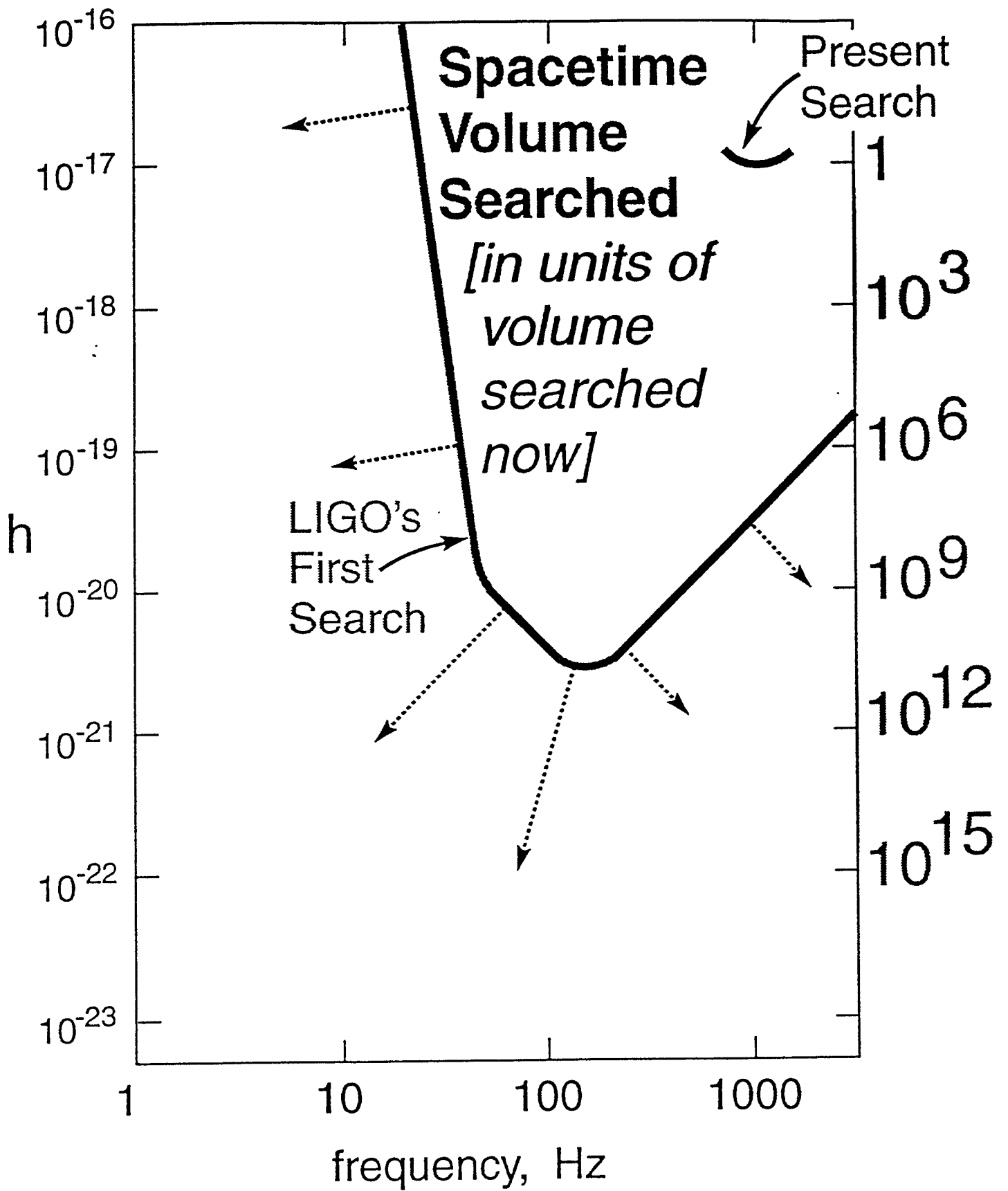
→ Nuclear Equation of State $P(\rho)$

- Requires several interferometers, with different optical designs, in same vacuum system
[Possible after future upgrade]

Binary Sources

Inspiral and Coalescence





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

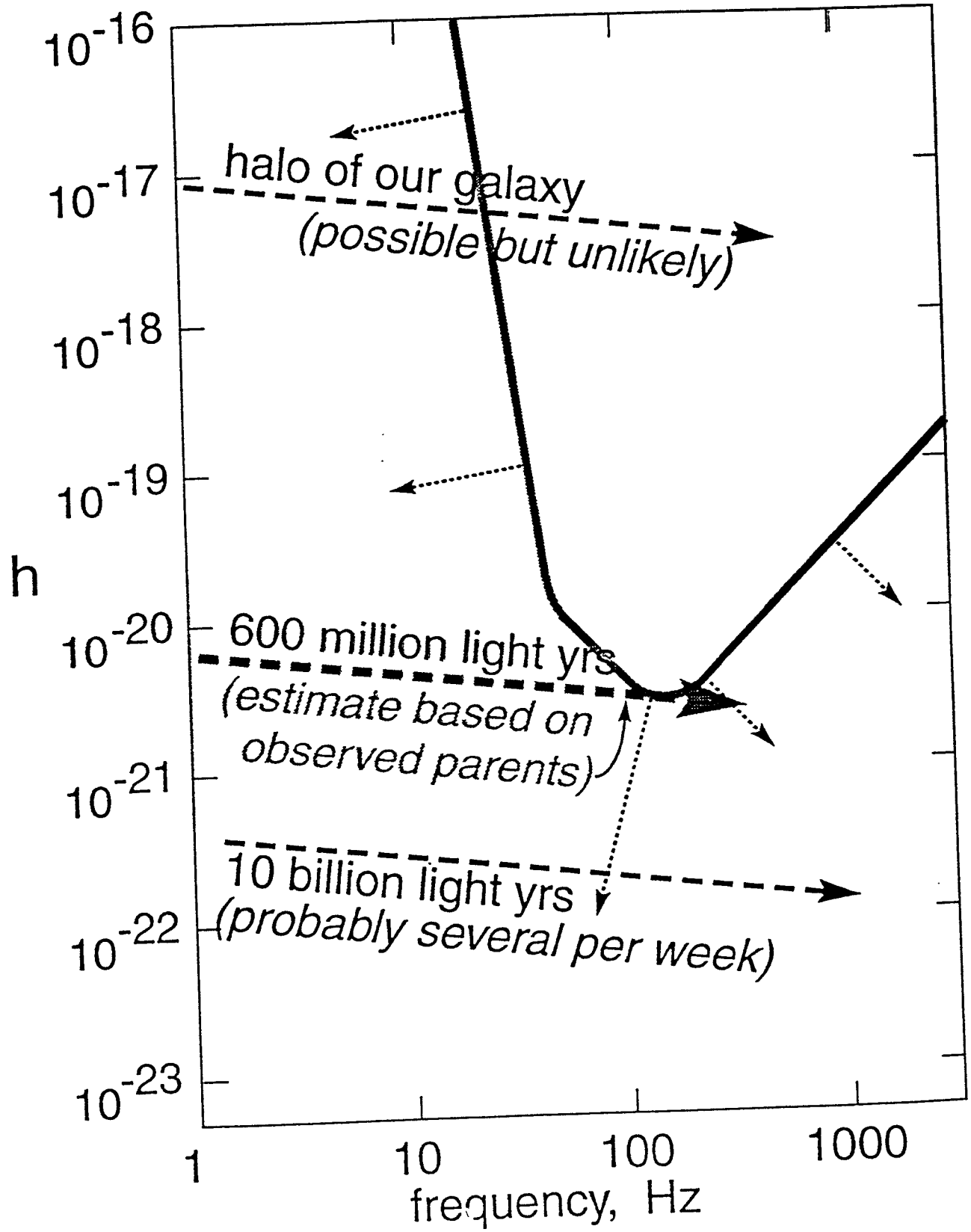
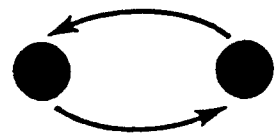
- » Vacuum Phase Transitions

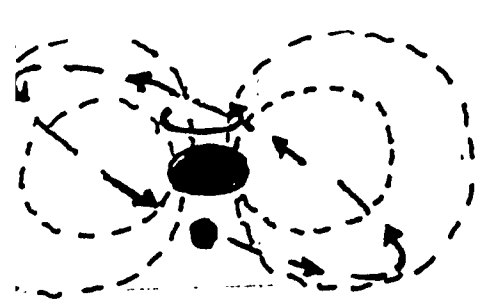
- » Vacuum Fluctuations from Planck Era

- Unknown Sources



BLACK HOLE BINARIES





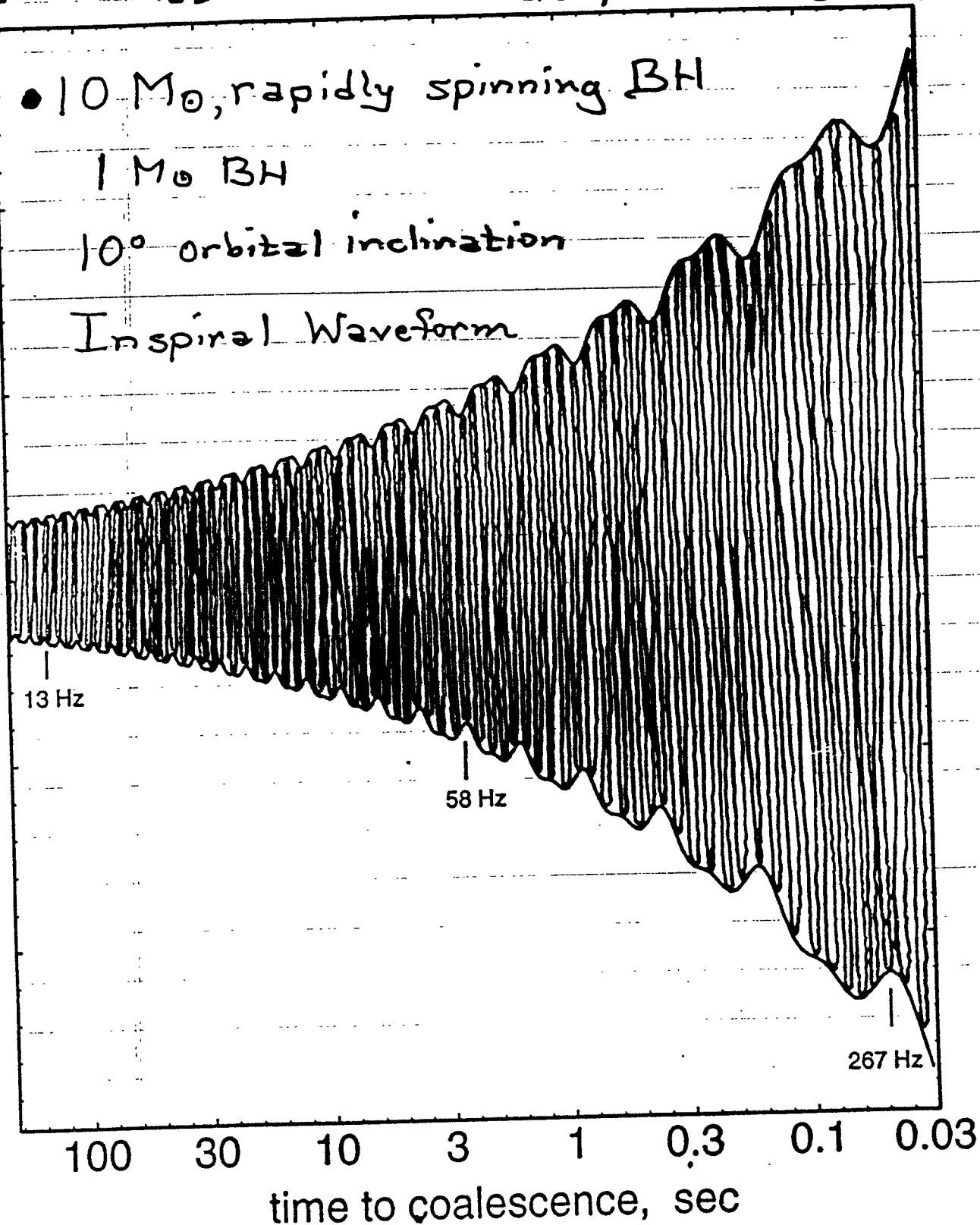
BH Spin \rightarrow "gravitomagnetic field"
 (frame dragging)
 $\rightarrow \sim 20$ precessions of orbit

• $10 M_{\odot}$, rapidly spinning BH

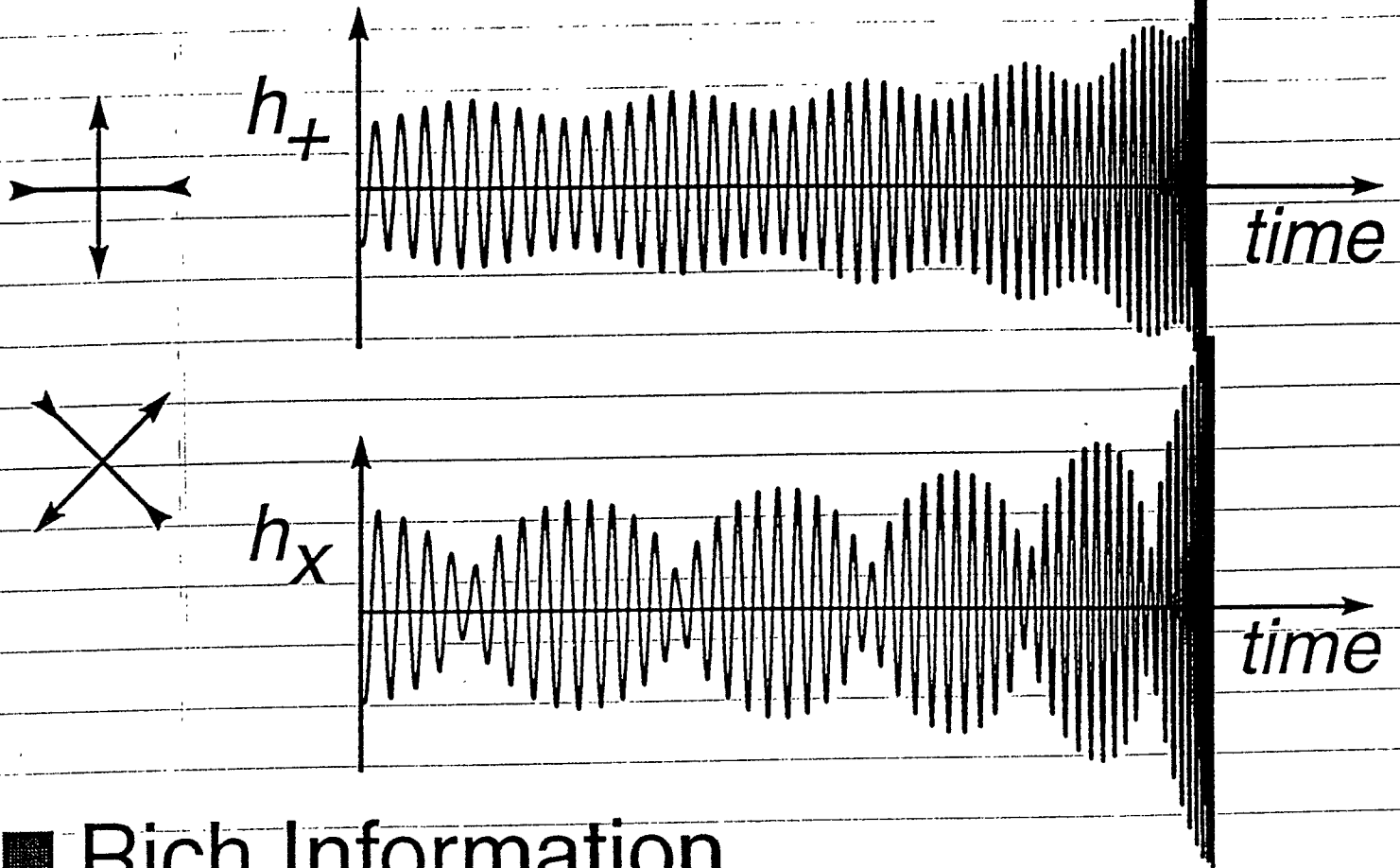
$1 M_{\odot}$ BH

10° orbital inclination

Inspiral Waveform



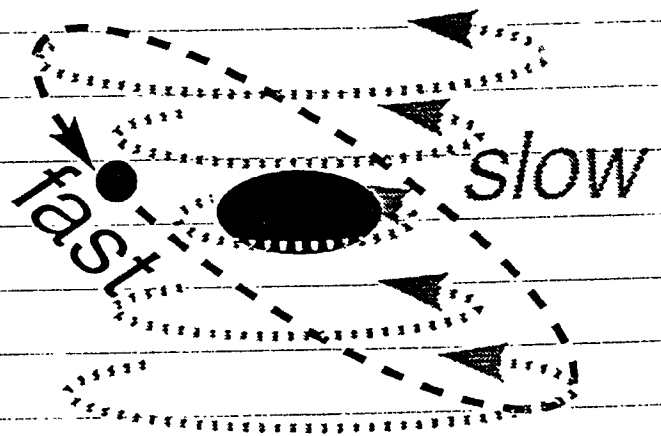
TWO WAVEFORMS [Stereophonic]



■ Rich Information

- *Map of spacetime warpage*

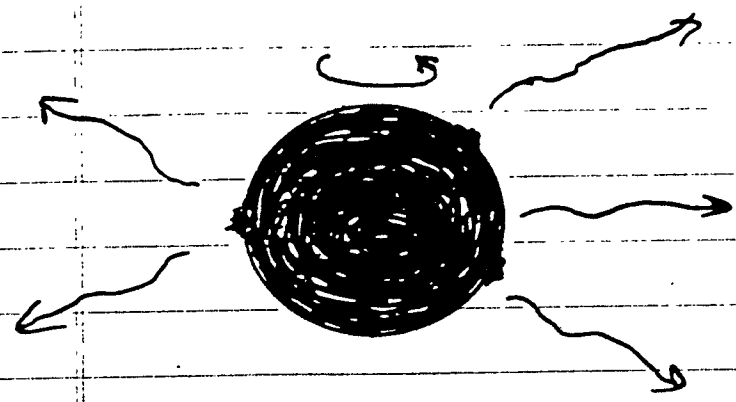
- *Tornado-like swirl of space around big hole*



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

OTHER POSSIBLE SOURCES

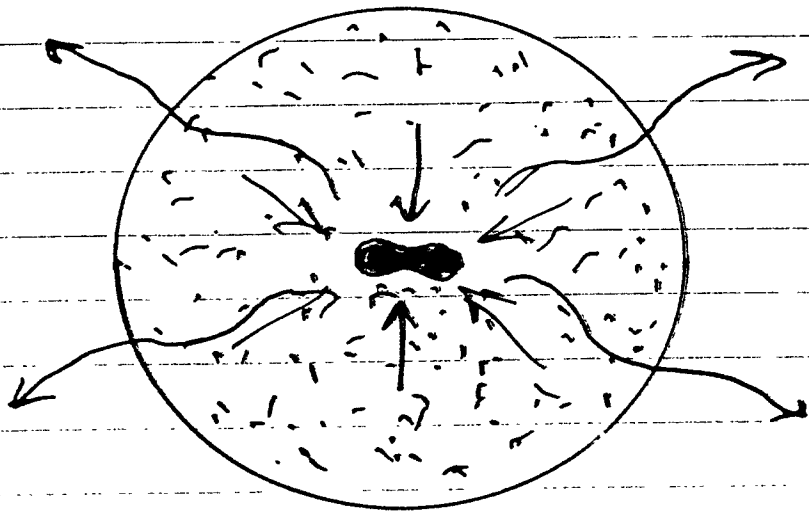
SPINNING, "MOUNTAINOUS" NEUTRON STAR



Periodic

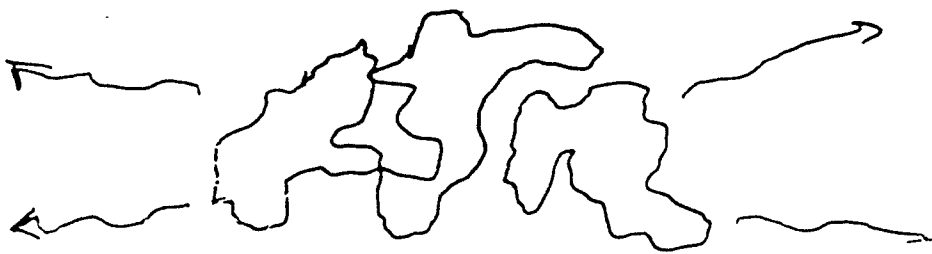
IMPLOSION OF A STAR'S CORE

— 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:

$$M = 1.4 M_{\odot}$$

$$r = 10 \text{ km}$$

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

f

$$\dot{\gamma} = 4\pi^2 G \frac{R^2}{R^4} \epsilon I f^2$$

$\epsilon = \text{equatorial ellipticity}$

Typical known

Estimate distortion due to dipole magnetic field

$$\epsilon \approx \frac{U_{\text{mag}}}{U_{\text{grav}}} \approx \frac{B^2 R^4}{6 M^2} \approx 10^{-12}$$

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

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

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

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

Supernovae

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

Type II - may emit strong gravitational waves

'naked eye' observations

16th century (Tycho)

SN 1987A (neutrinos)

Gravitational radiation (mechanism)

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

FIGURES

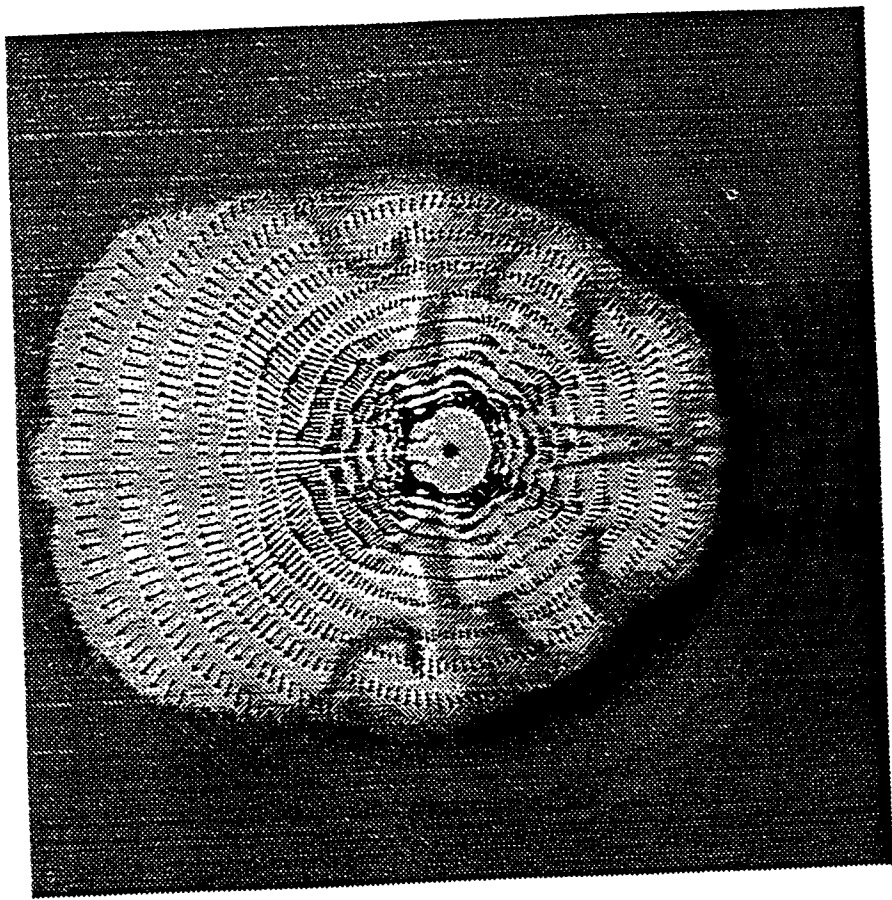


FIG. 1. A grey-scale rendering of the entropy distribution at the end of the simulation, about 50 milliseconds into the explosion. Note the pronounced pole-to-pole asymmetry in the ejecta and the velocity field (as depicted with the velocity vectors). The physical scale is 2000 km from the center to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

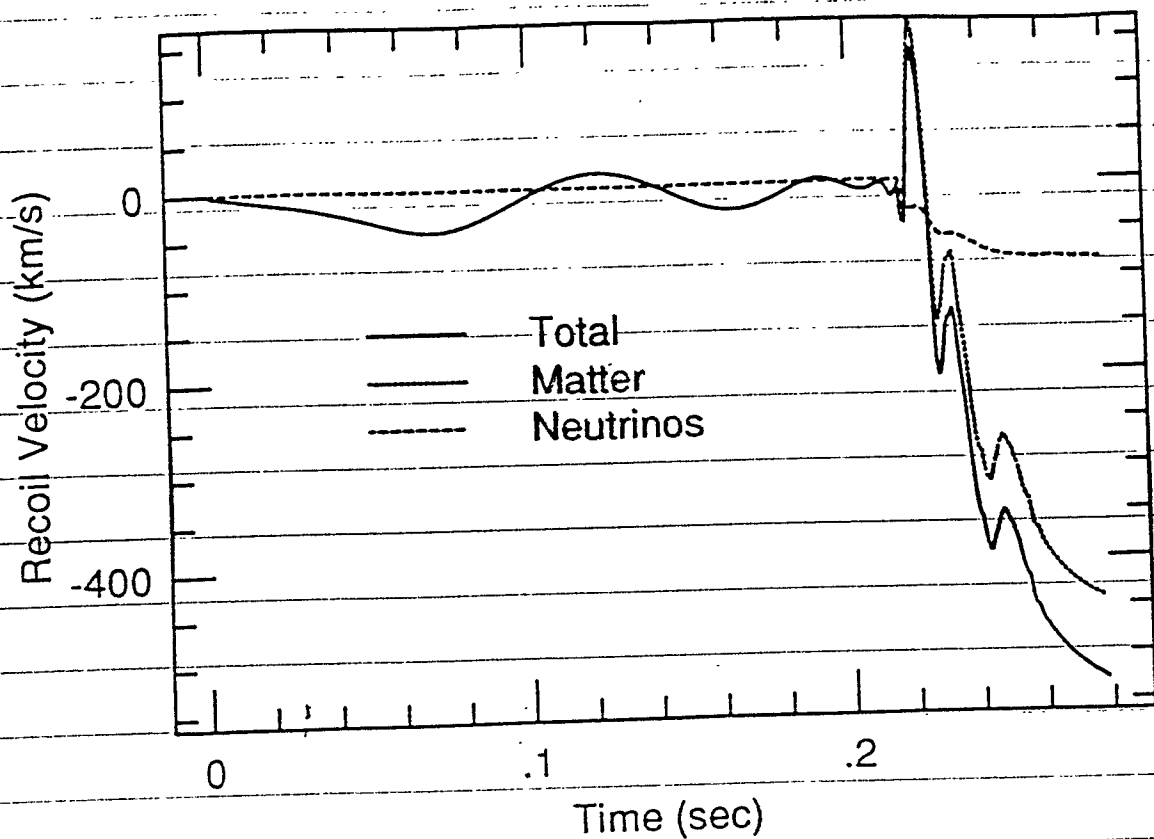


FIG. 2. The inferred recoil speed (in km s^{-1}) imparted to the core versus time (in seconds) for the simulation highlighted in this paper. The initial momentum is approximately zero, but grows systematically after bounce in the direction opposite to the artificial wedge, cut into the core to mimic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

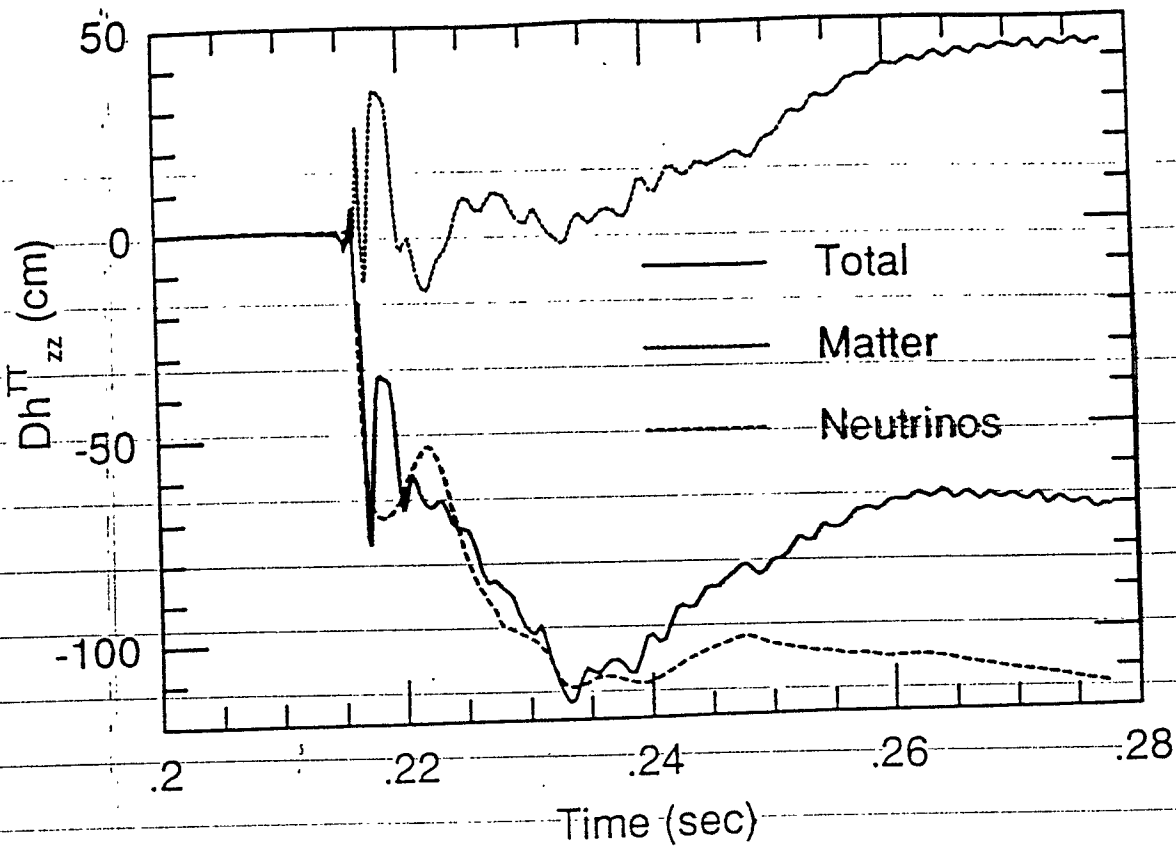


FIG. 3. The gravitational wave strain, h_{zz}^{TT} , times the distance to the supernova, D , versus time (in seconds). Core bounce is at 0.215 seconds. The total, matter, and neutrino waveforms are rendered with the solid, dotted, and dashed lines, respectively.

• physics modeling very difficult
(departure from spherical shape)

• guidance (unclear)

- supercomputers assume spherical sym.

- 2D models (Burrows)

- crab pulsar $f_{rot} \approx 30.3 \text{ Hz}$

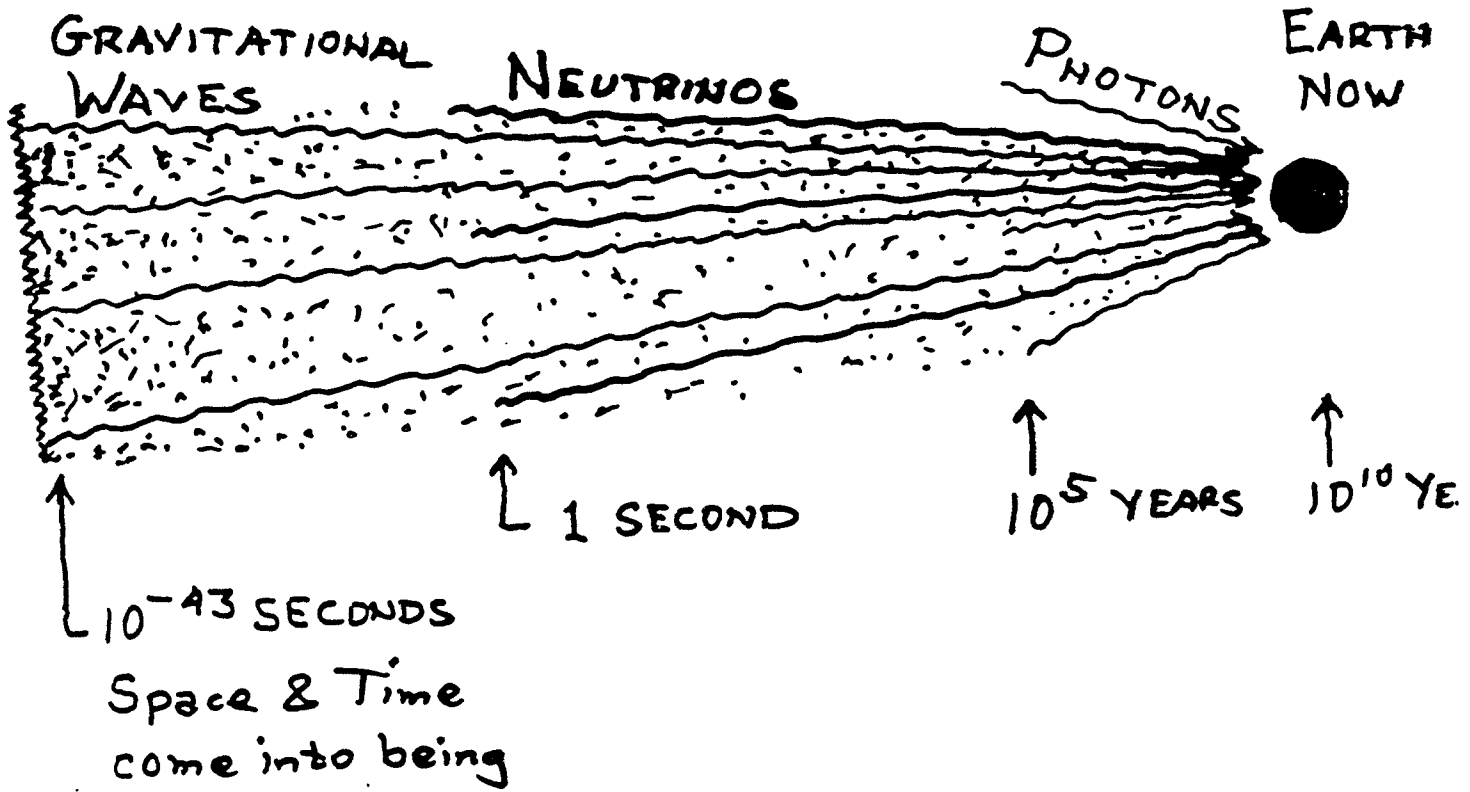
$$J = 2 \cdot 10^{47} \text{ erg-sec}$$

(Saenz-Shapiro \rightarrow radiate gravitational
 $3 \cdot 10^6$ of rest mass

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

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

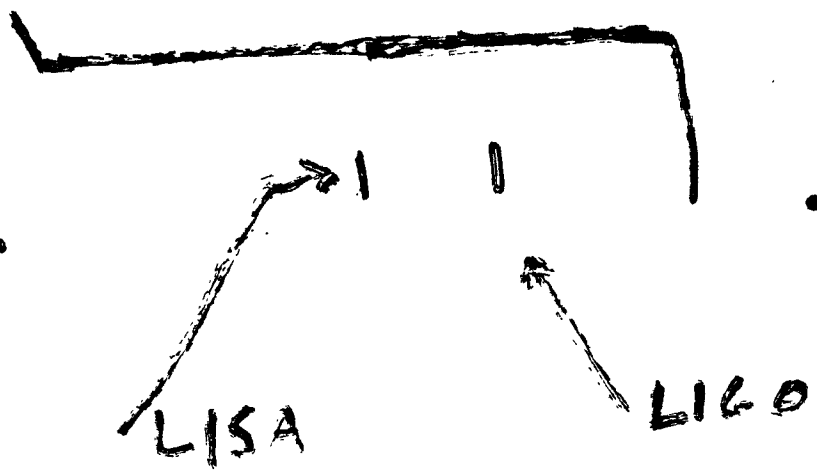
THE BIG BANG SINGULARITY



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

LISA (10^{-22} Hz) 10^{-14} sec Temp $\sim 10^2$ GeV (electroweak)
graviton ~ 1 keV

— inflation



Stochastic Gravity-Wave Background

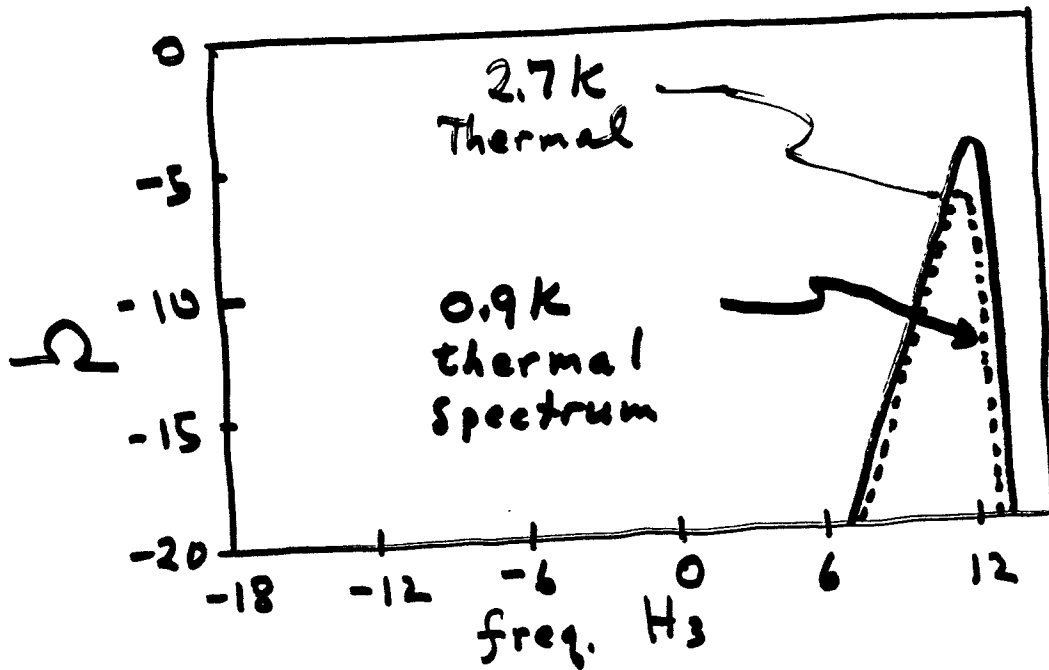
- could come from early Universe
LIGO Band $\sim 10^{-22}$ sec

(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)



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

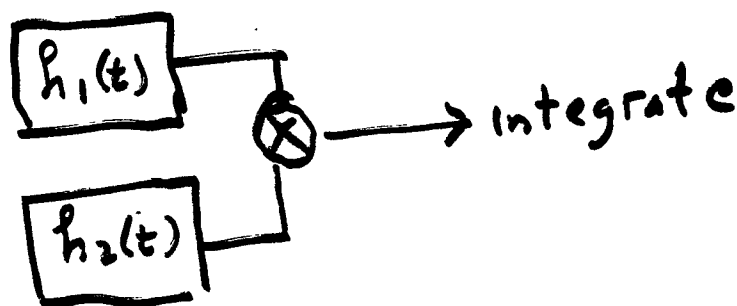
- o useful benchmark

- o detection

correlate (anticorrelate) signals from different detectors

(eg <64 Hz LIGO detectors correlated)

How to detect Stochastic Background



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

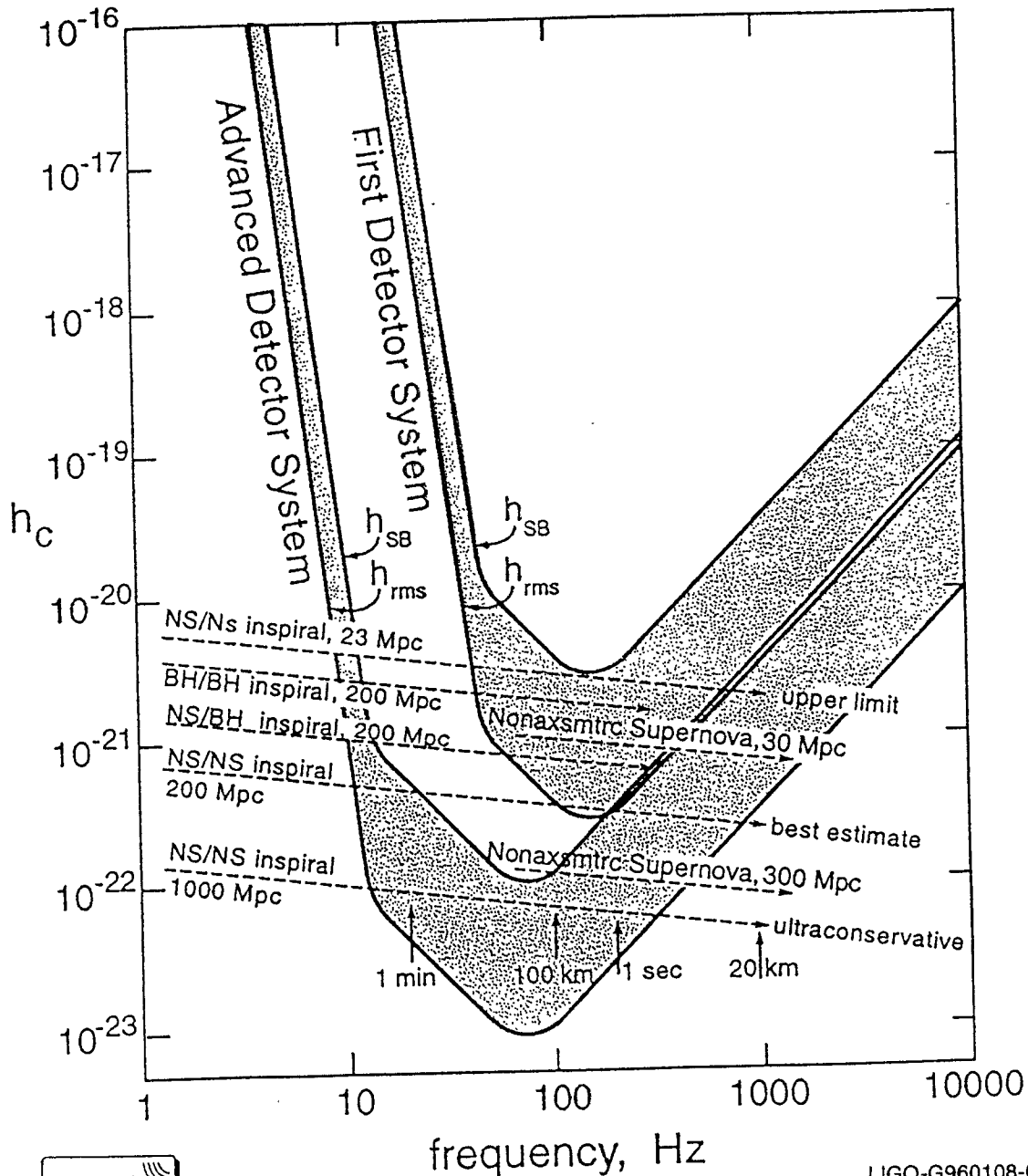
In absence of background (and other signals)
 average product $\langle h_1(t) h_2(t) \rangle \rightarrow 0$

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

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

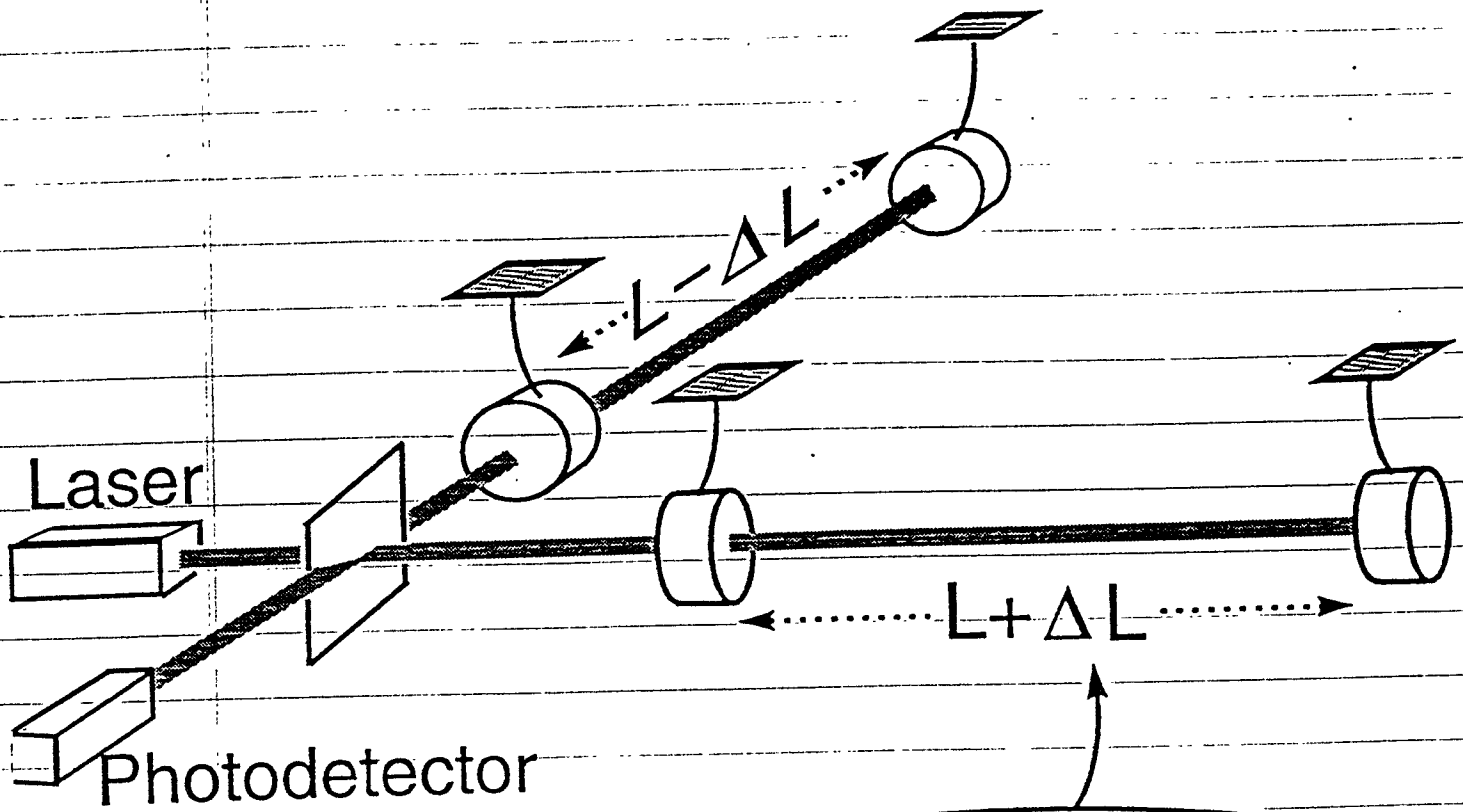


LIGO Site Pair



- **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 INTERFEROMETERS



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

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

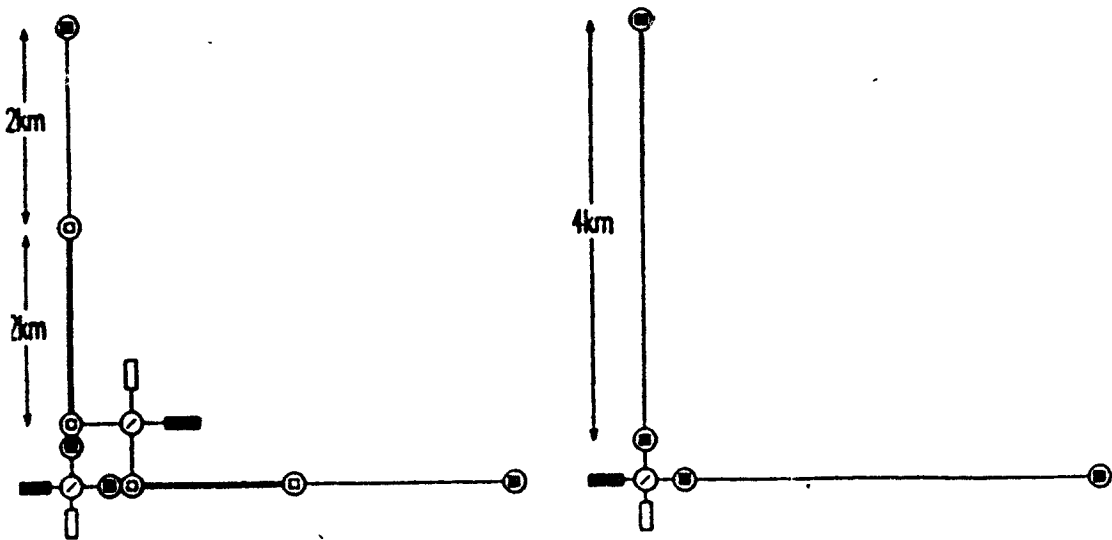
$$10^{-21}$$

$$4 \text{ km}$$

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

Description of LIGO

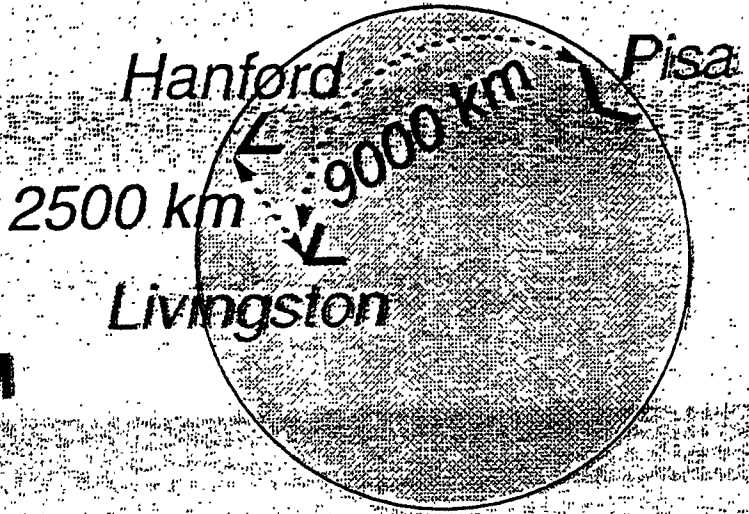
- Two Sites - Widely Separated
- Hanford, Washington
 - 4km and 2km Interferometers
- Livingston, Louisiana
 - 4 km Interferometer
- Expansion for Advanced Detectors



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:

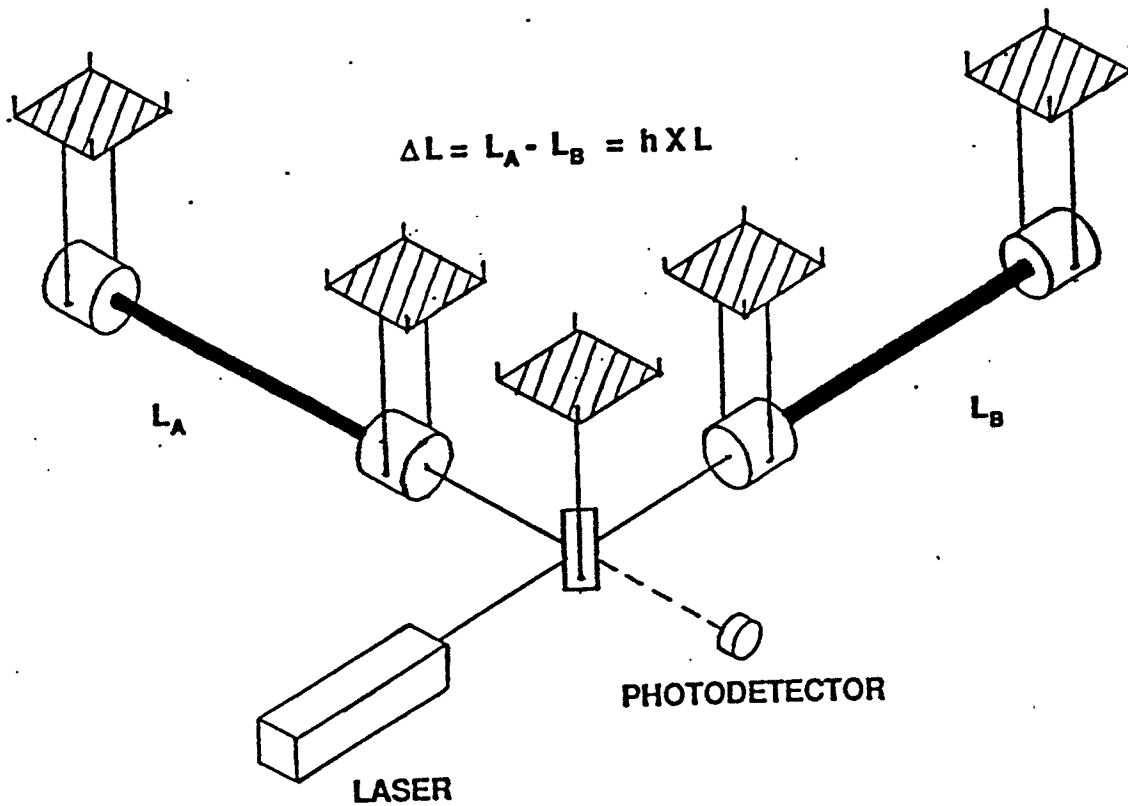
Pisa **CANNOT** be used,
together with Hanford or Livingston,
to search for waves

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

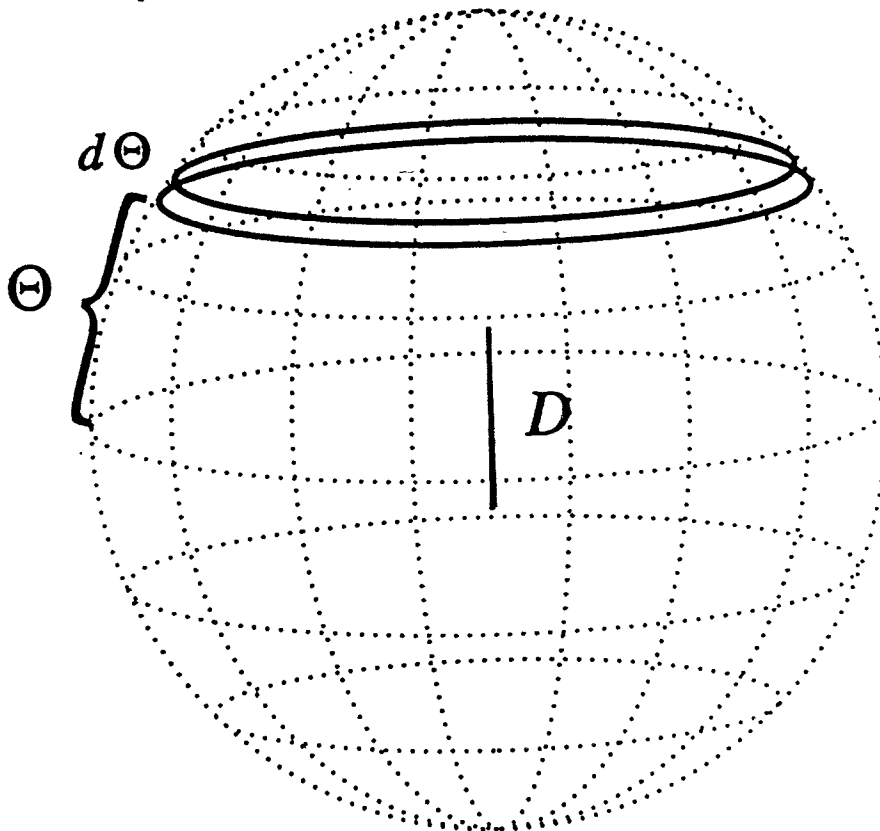
- $\Delta L/L = h = F_+ h_+(t) + F_x h_x(t)$



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

Source Positions

- Celestial Sphere position location from LIGO (two interferometers)



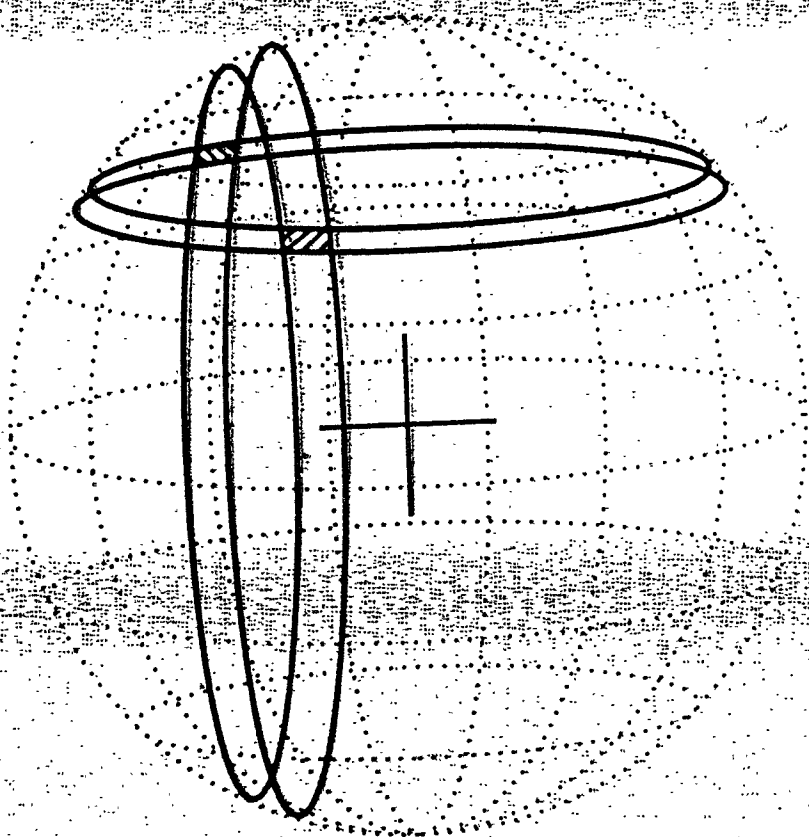
- determine from time shift between detectors ($\sim .1$ msec accuracy)
- 'declination angle' of circle (ring)

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

Source Positions

LIGO + VIRGO

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



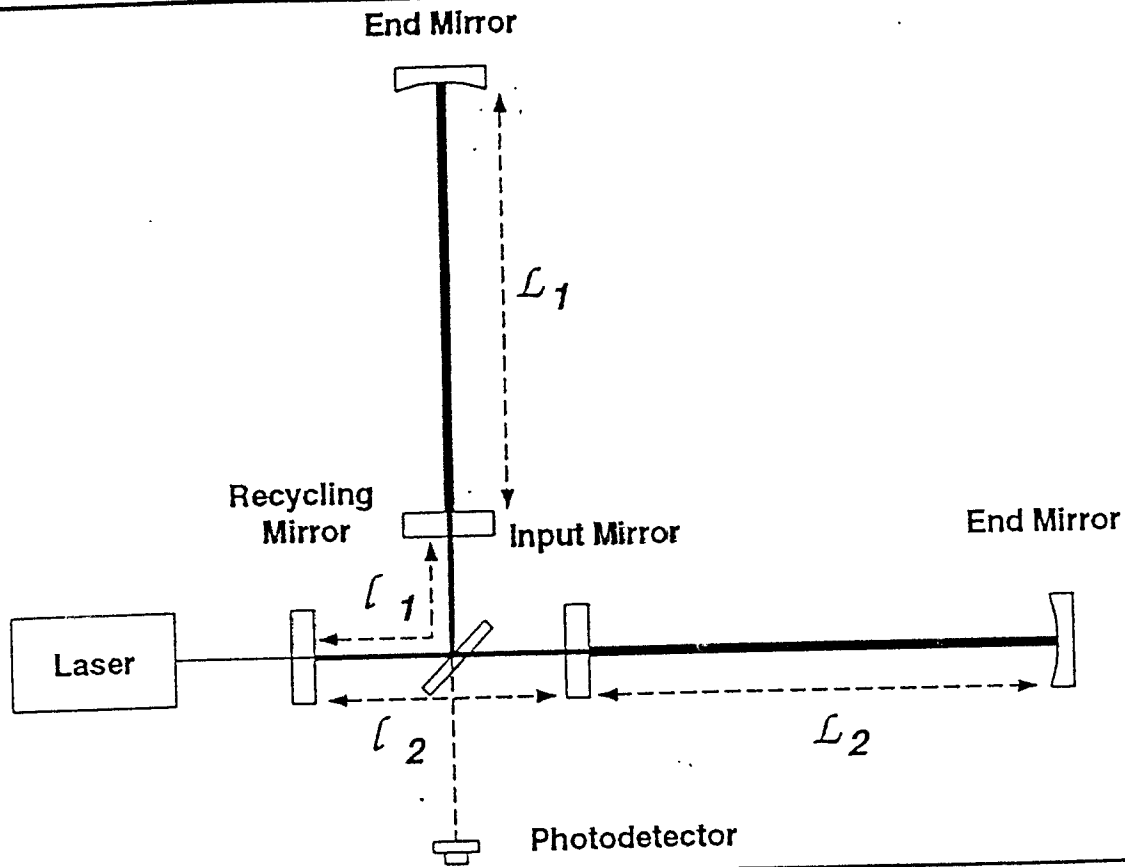
Lecture 4

B. BARISH

LIGO

Basic Configuration

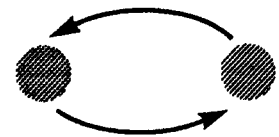
- Michelson with Fabry-Perot cavities



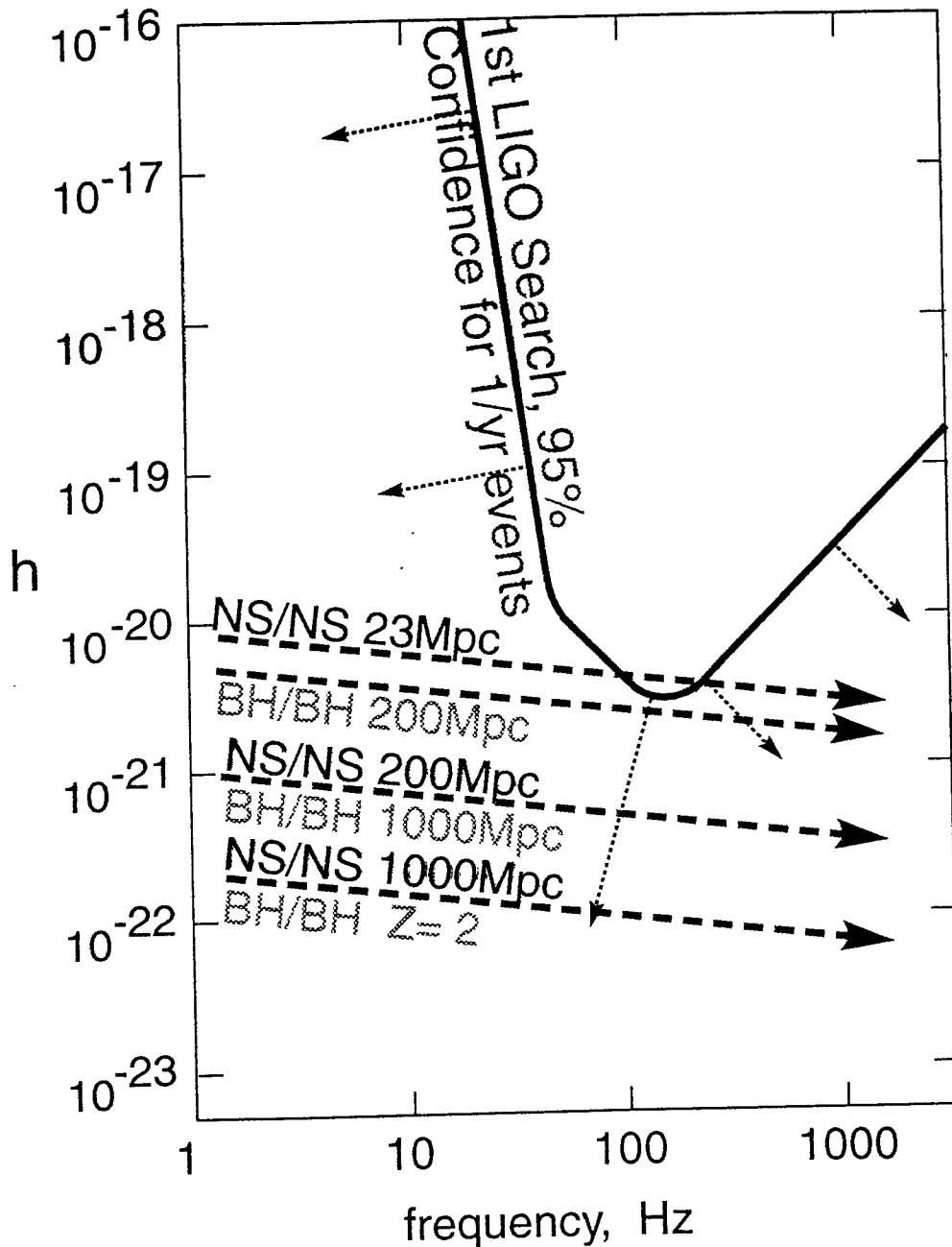
Initial Interferometer Specifications

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

NEUTRON STAR BINARIES



[“Near-Guaranteed” source]

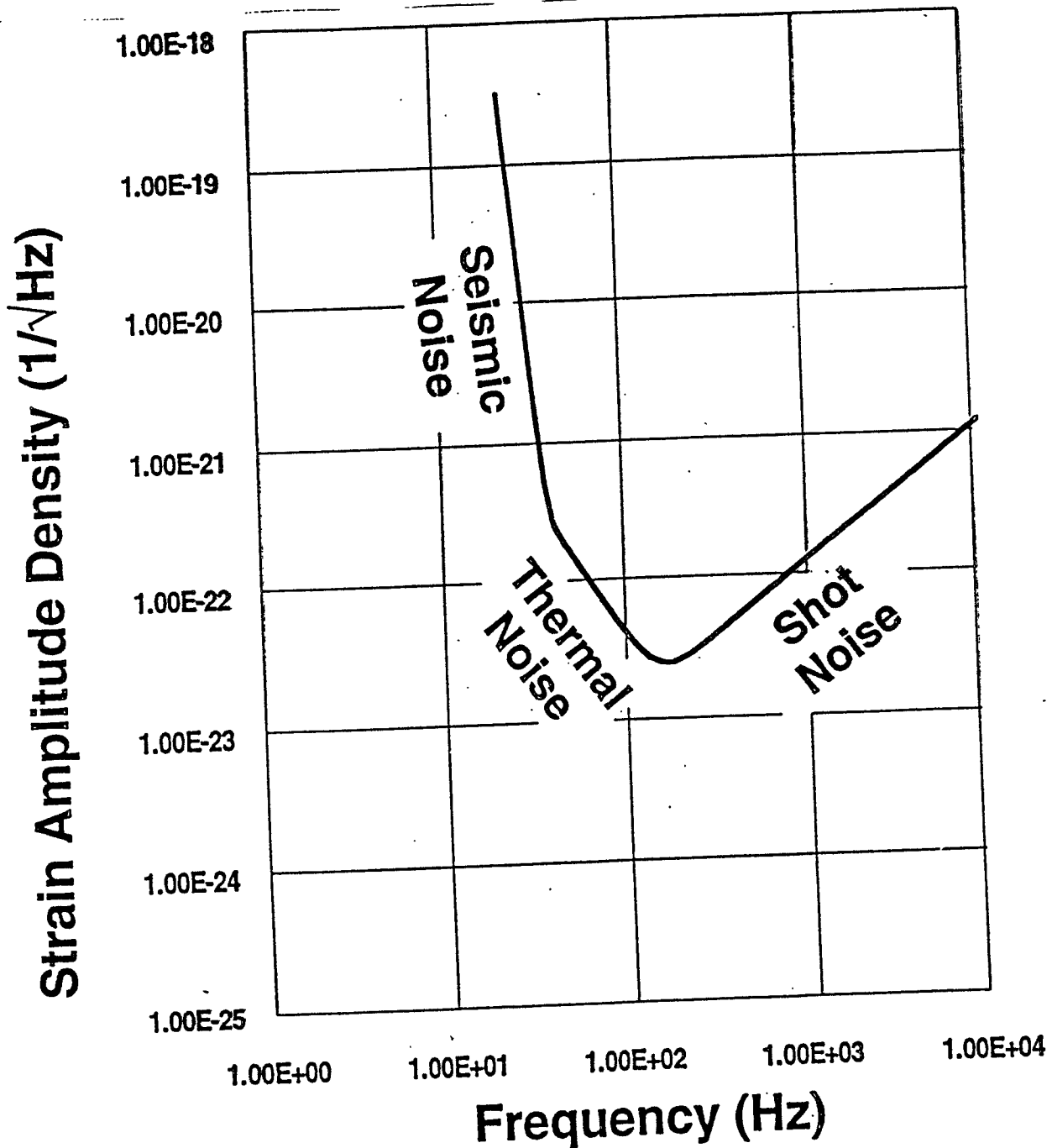


■ 15 minutes & 10,000 orbits in LIGO band

■ Rich information in waveforms:
masses, spins, distance, direction,
nuclear equation of state

Initial Interferometers

Noise Floor



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

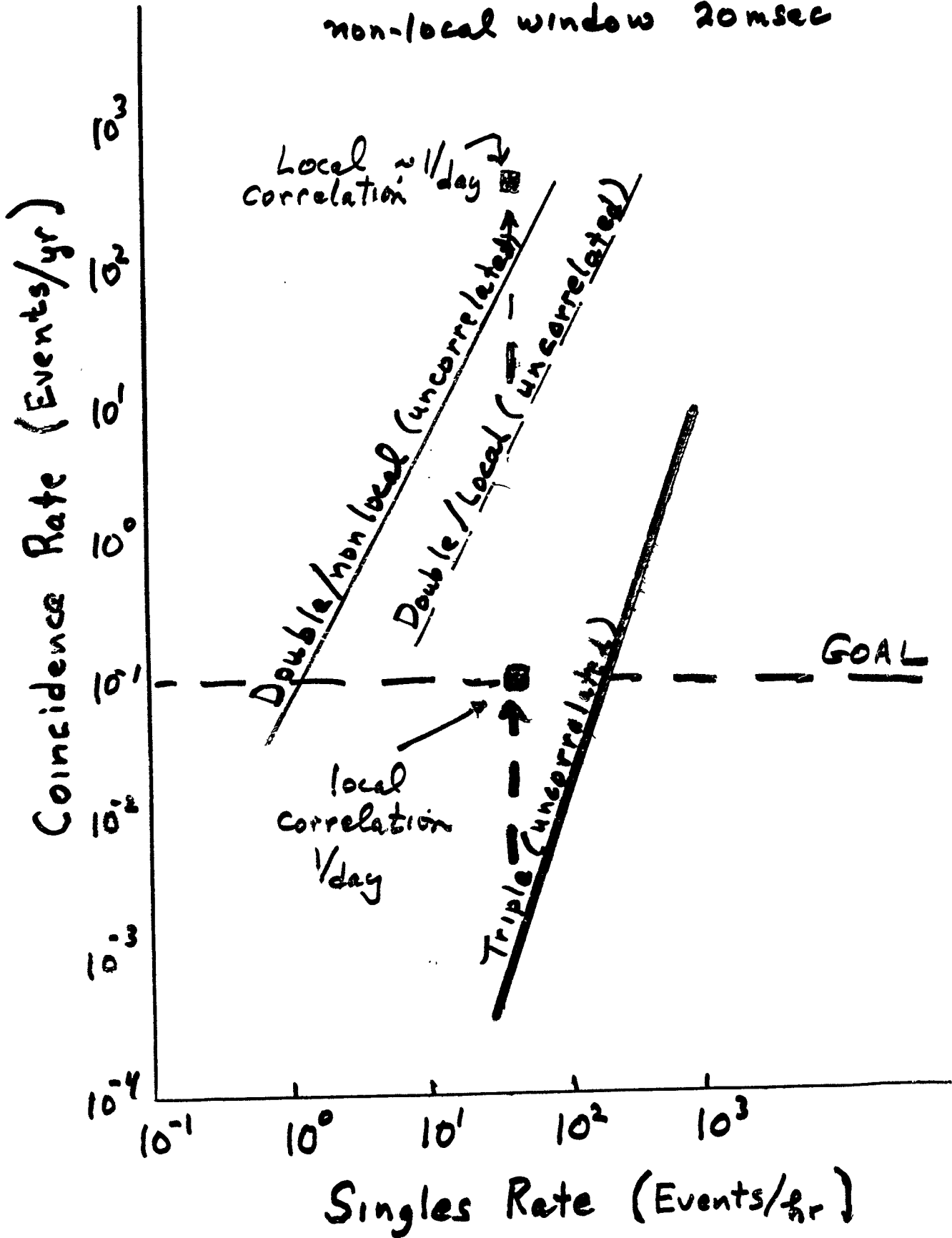
- correlated rate (x1000)

⇒ Hanford + Livingston <0.1/yr

- uncorrelated (x5000)

MULTIPLE COINCIDENCES

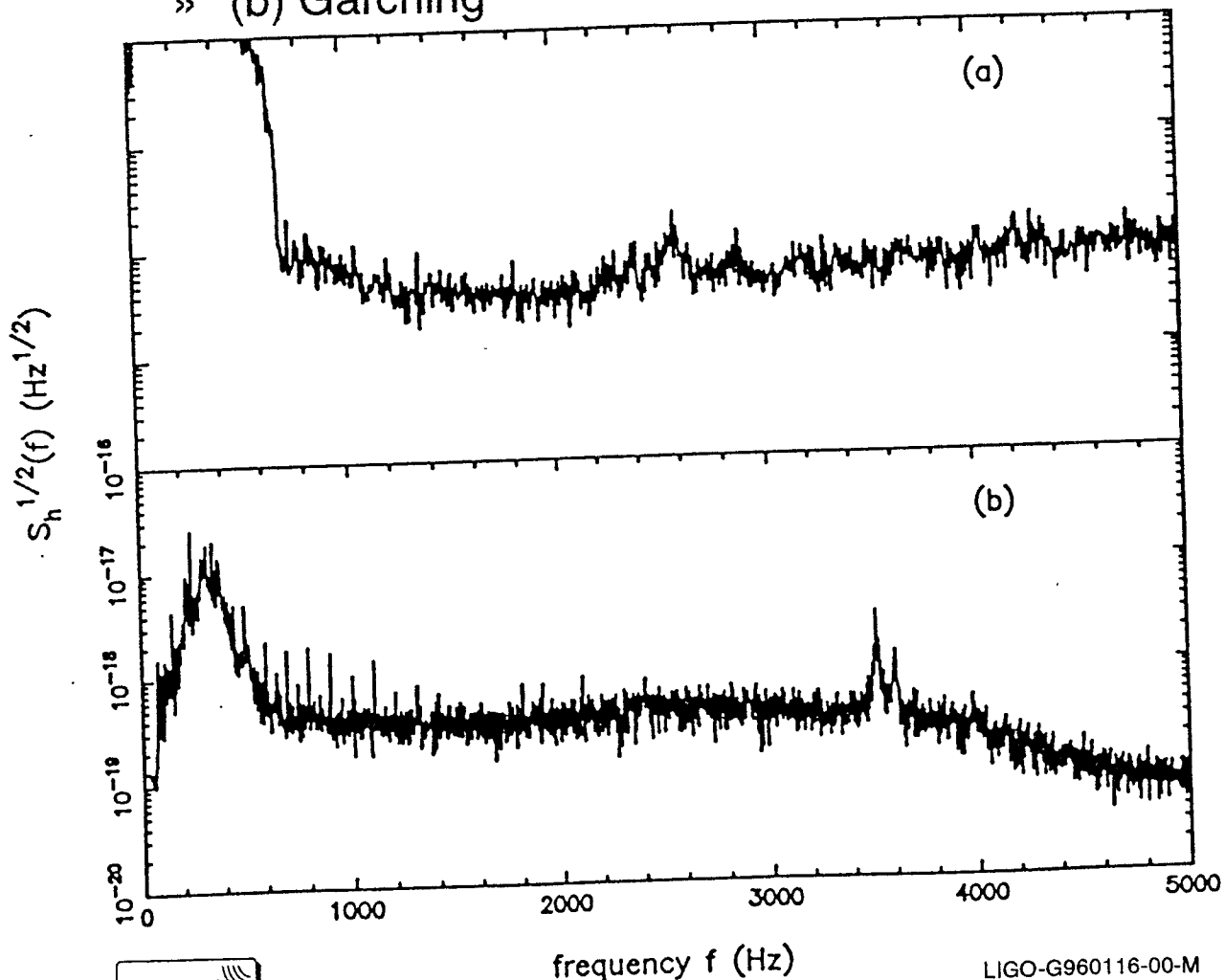
local window 1msec
 non-local window 20msec



Interferometers

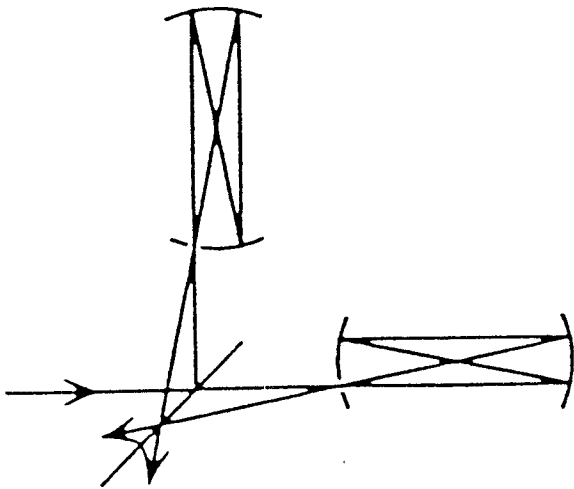
Coincidence Experiment

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

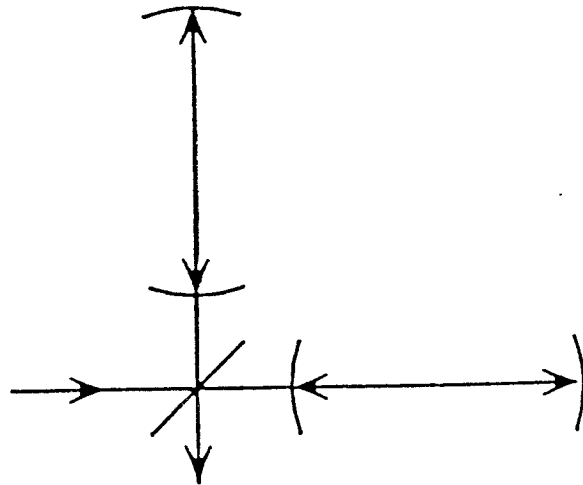


Interferometer *types*

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



Delay-Line ($N=4$)

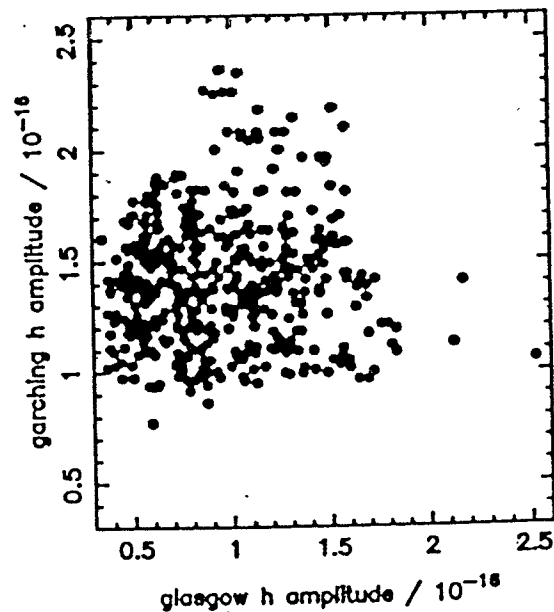
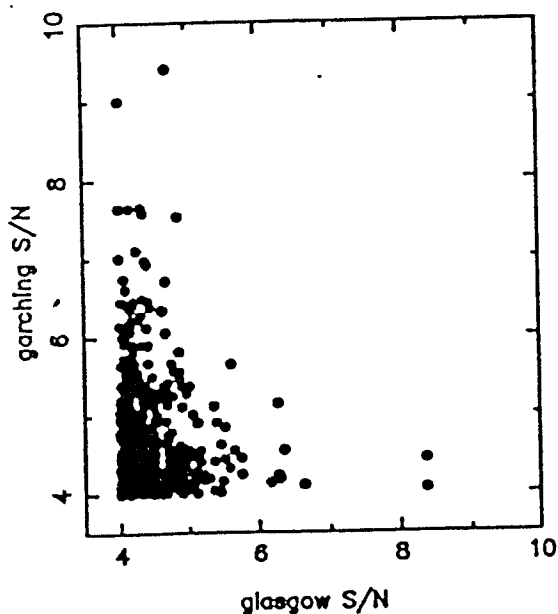


Fabry-Perot

Interferometers

Coincidence Experiment

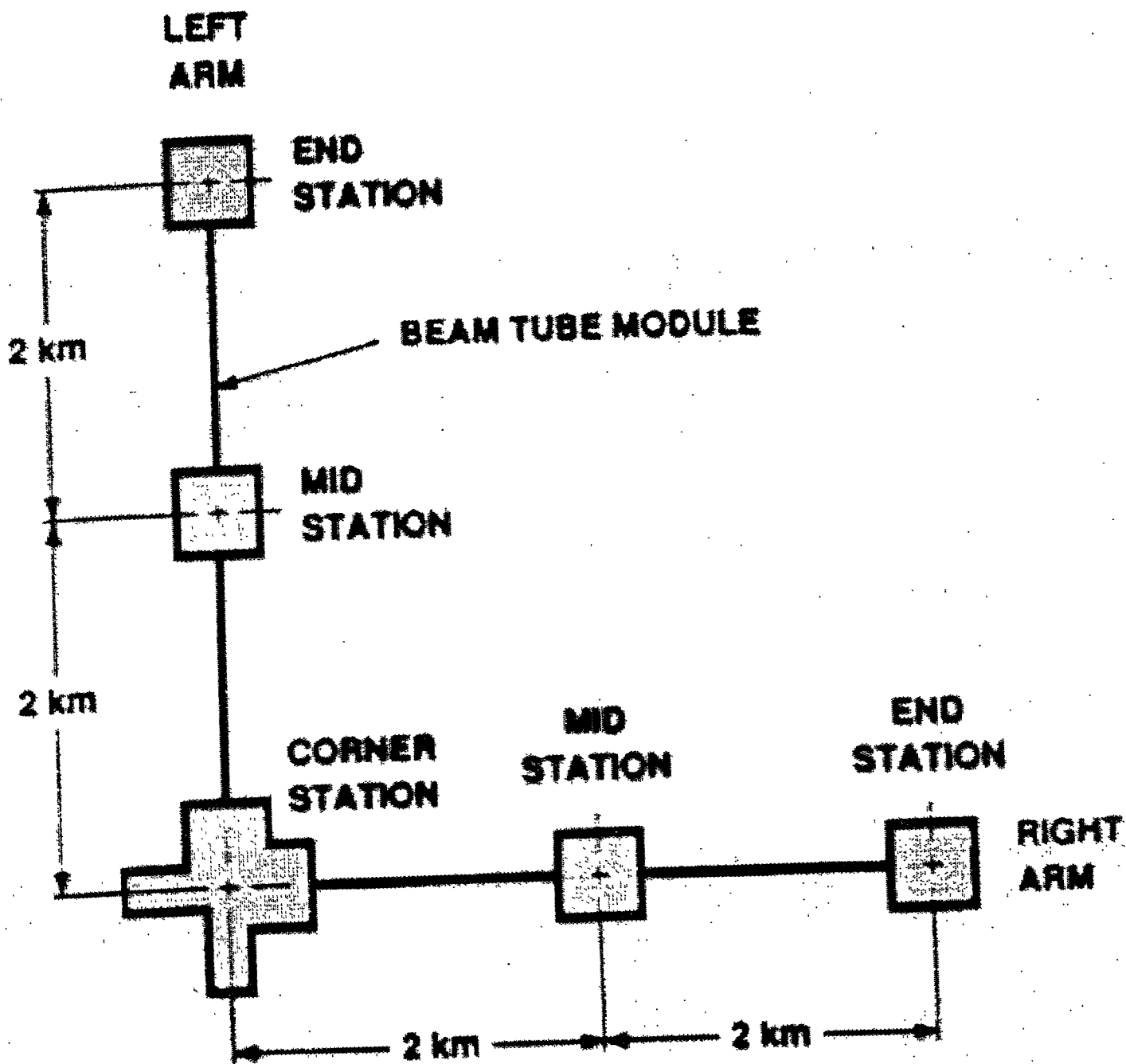
- Glasgow - Garching
- 100 hour coincidence experiment
 - » Analysis
 - level 1 - housekeeping vetoes
 - level 2 - 62 hrs good data ($< 4 \times 10^{-17}$ for 1.6 sec)
 - level 3 - require same strain in both detectors
 - » Result
 - $h < 1.6 \times 10^{-16}$ from zenith and optimum polarization
 - $h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



Gravitational Wave Strength

Strain Sensitivity

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

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

$h \sim 10^{-20}$ 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:

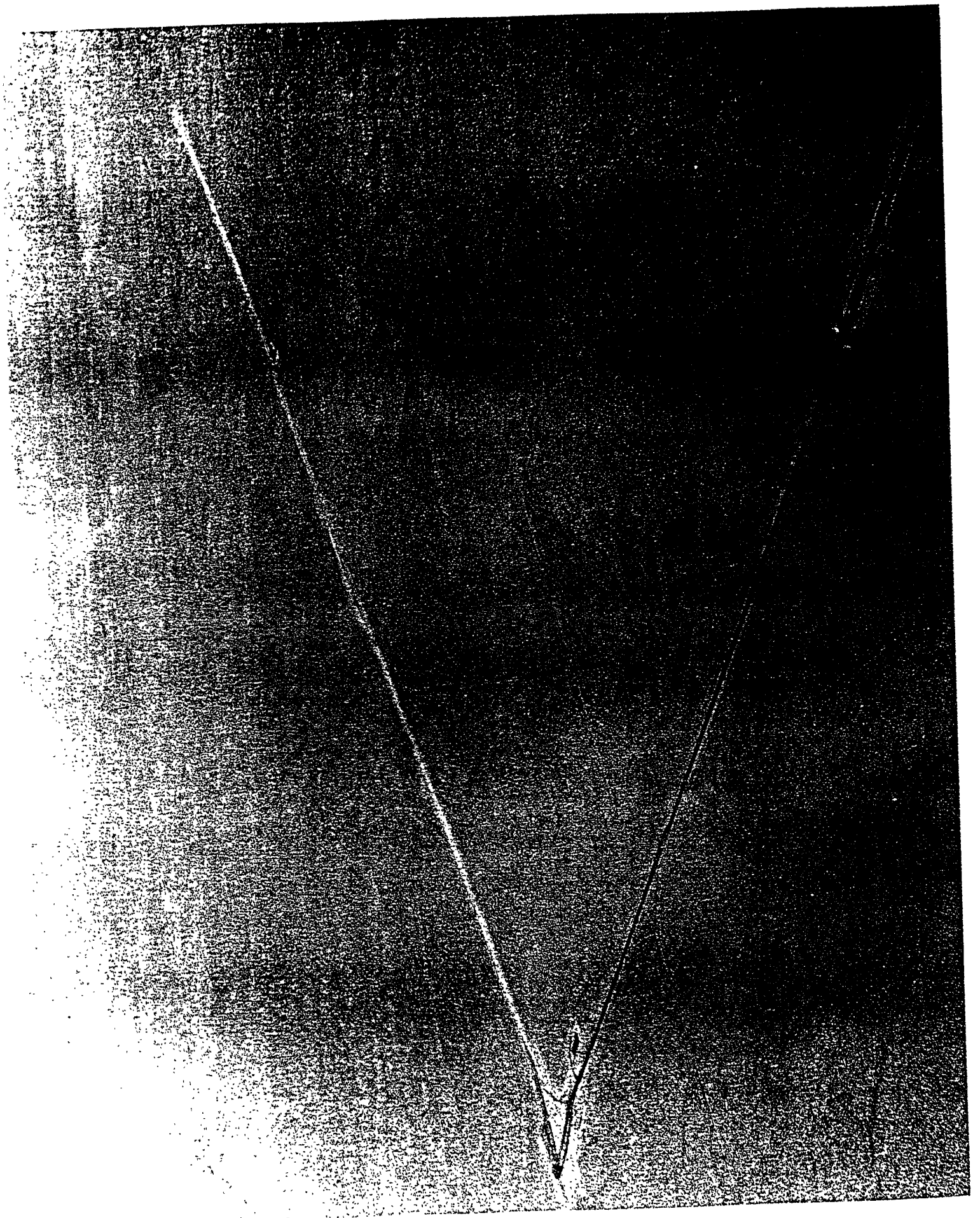
Vacuum

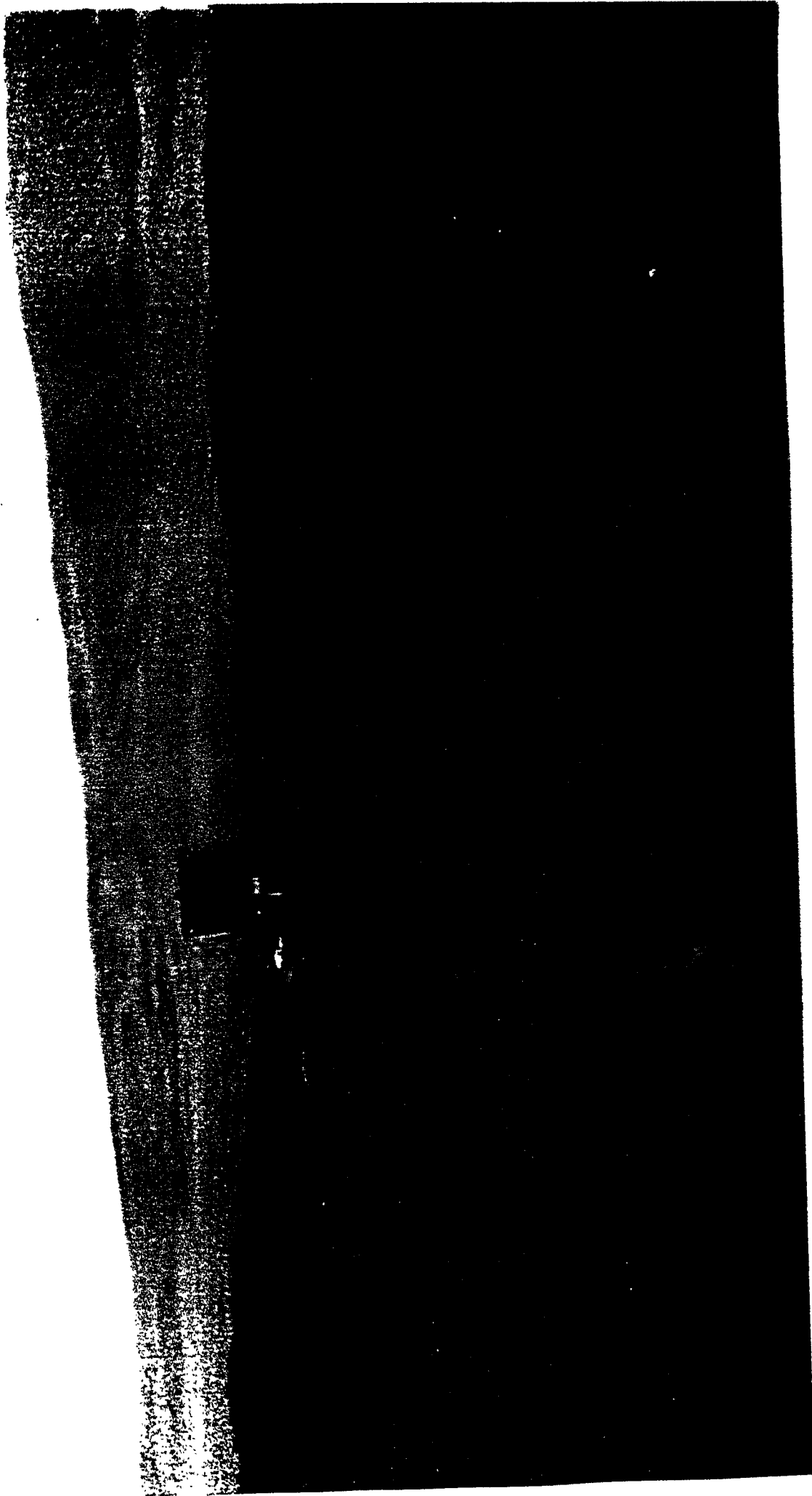
Seismic and Acoustic Isolation

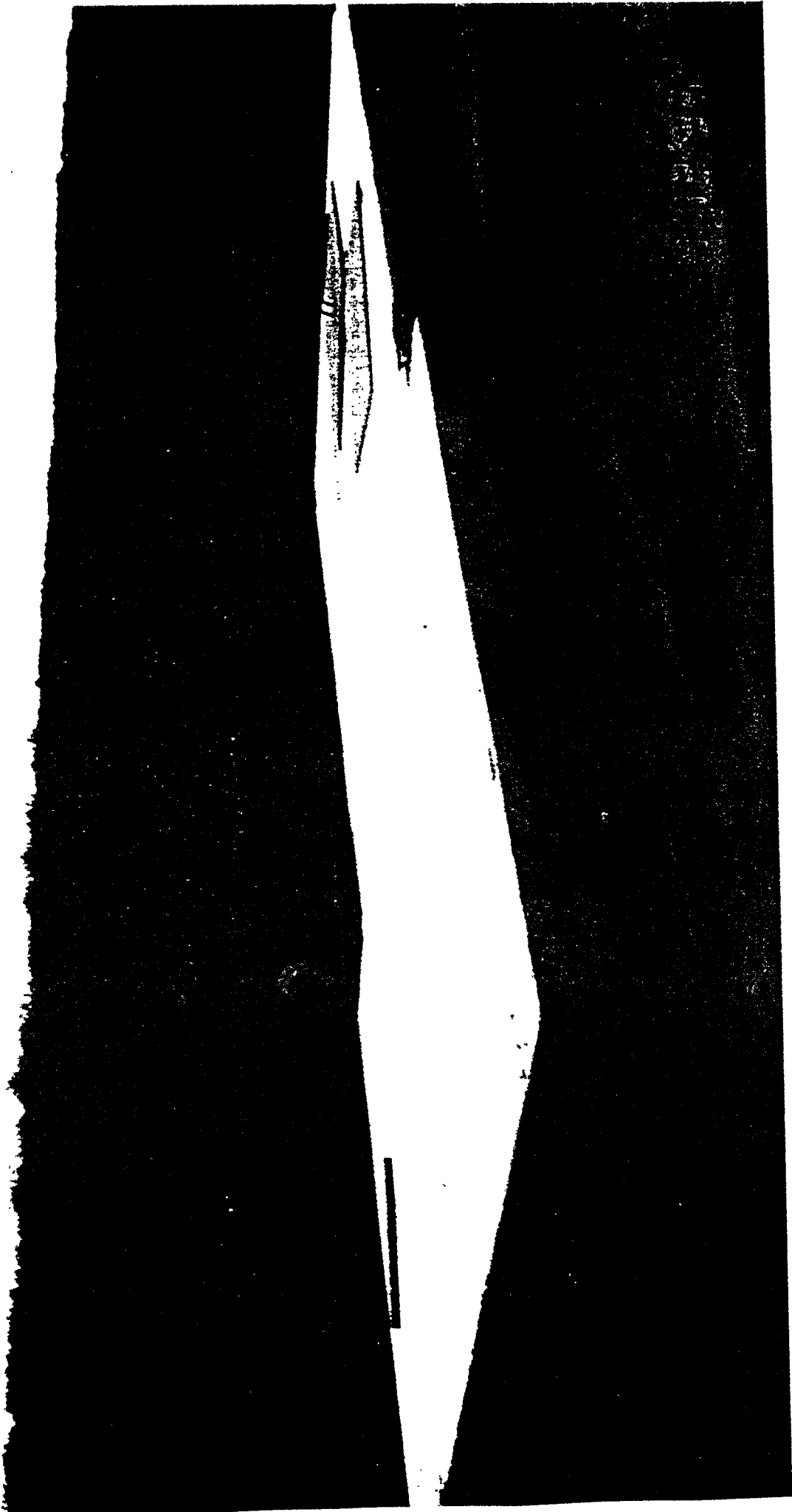
Test Mass Suspensions

Optics

etc.







ALTITUDE: 15,000 FEET

DATE: AUGUST 28, 1962

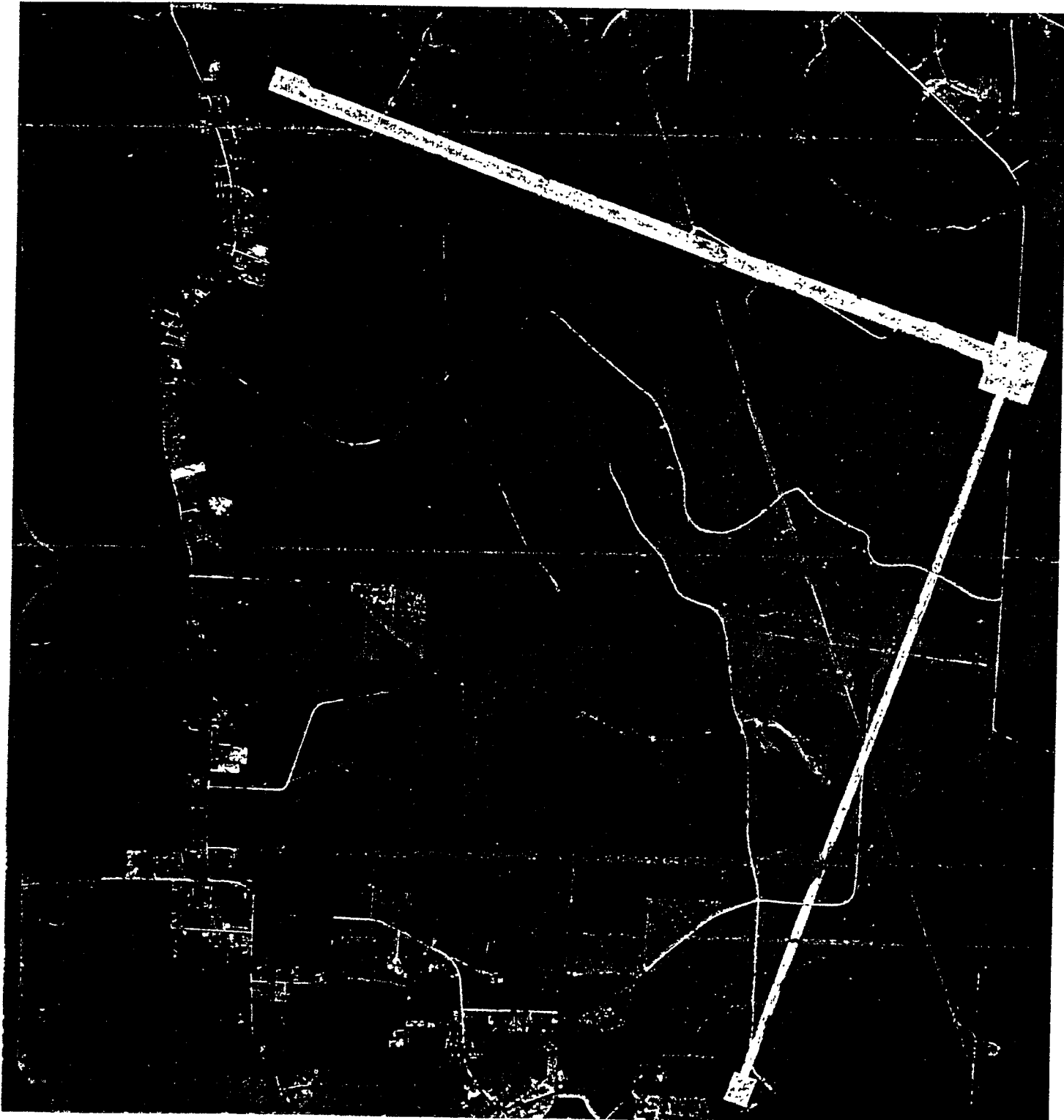
DATE OF PHOTO TAKING

PHOTO NO. 101

ANALYSIS

LIVINGSTON PARISH

FIG 1





G960025-02-O-V



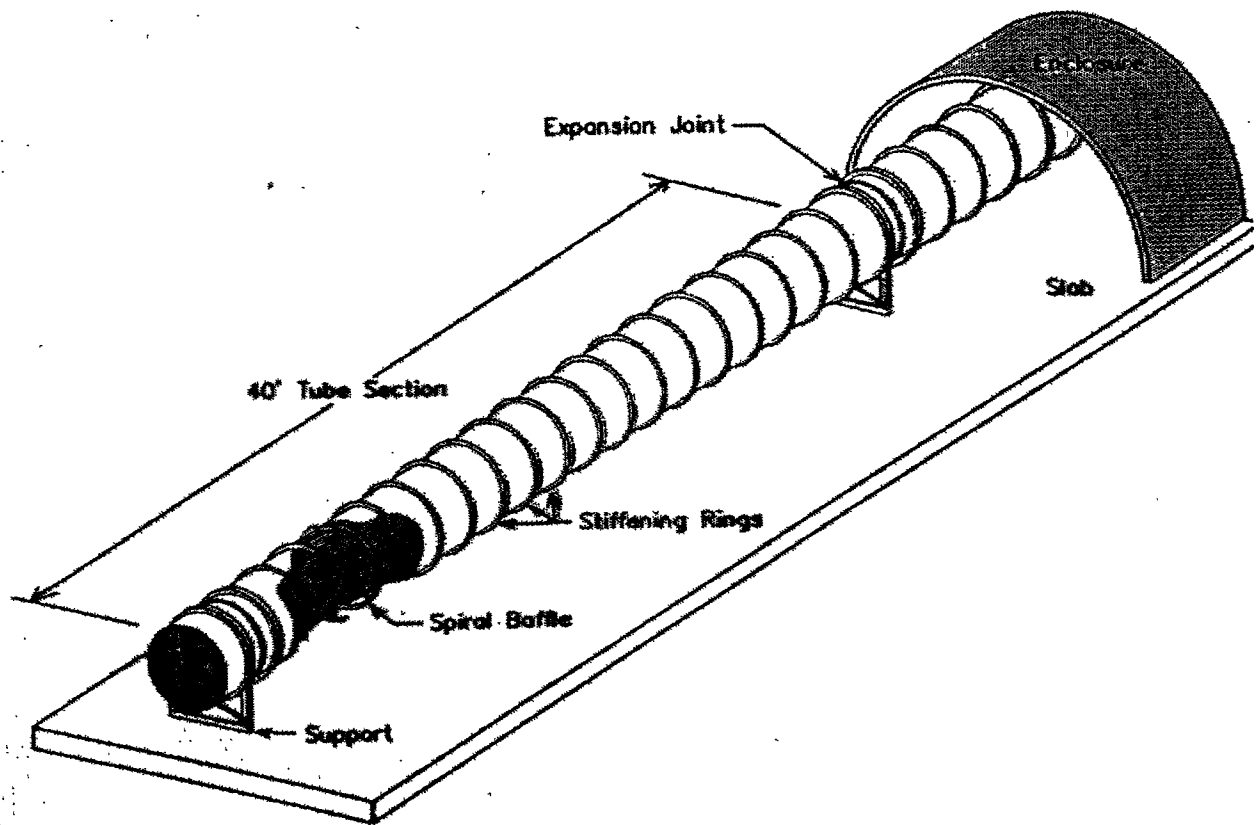
G960028-17-O-V





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Beam Tube



Beam Tube

□ Characteristics

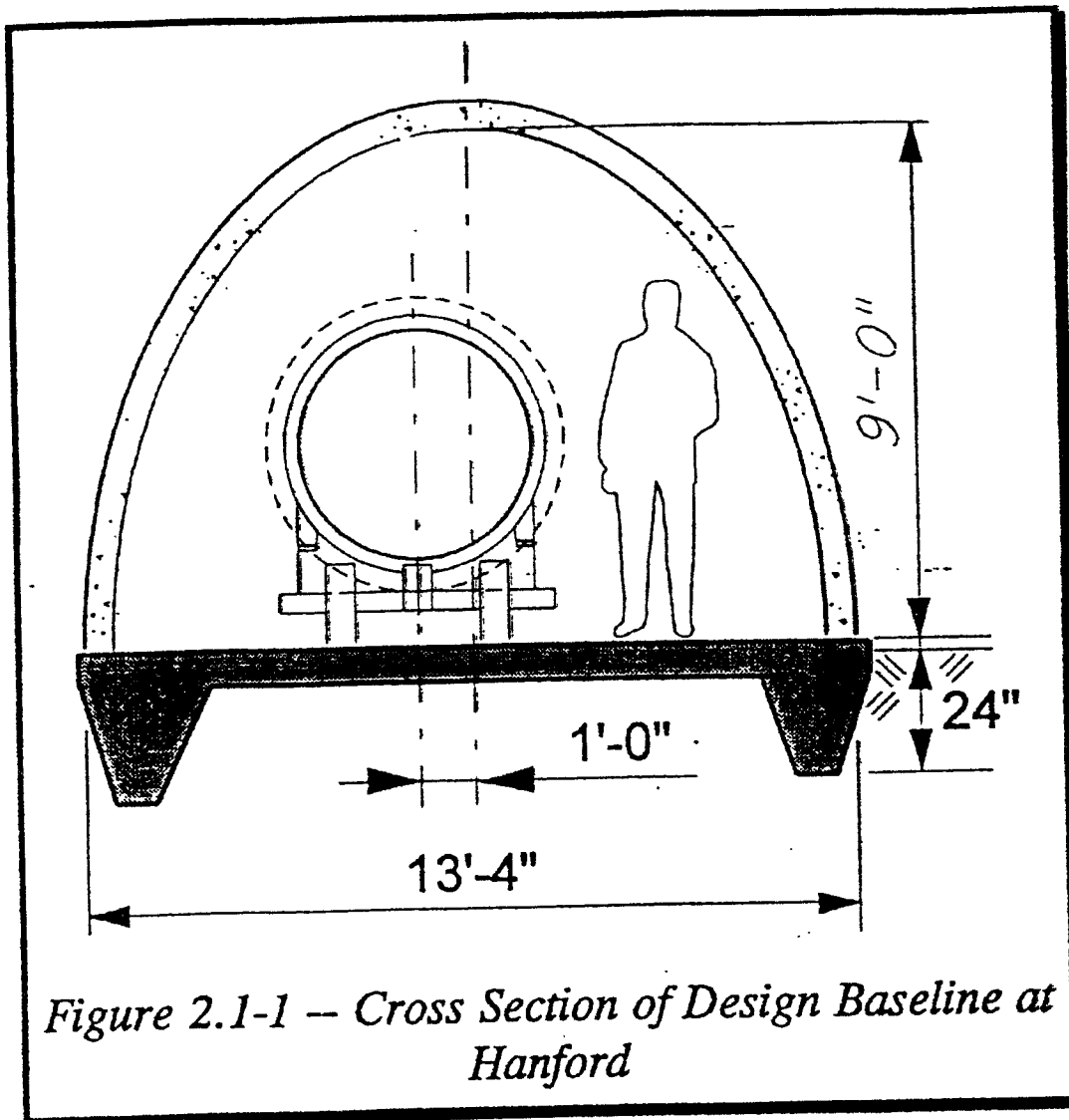
- ⇒ Arm Lengths - 4km
- ⇒ Tube Diameter - 4 ft
- ⇒ Initial Detector
 - 10^{-6} torr Hydrogen; 10^{-7} torr Water
- ⇒ Advanced Detectors
 - 10^{-9} torr Hydrogen; 10^{-10} torr Water
- ⇒ Quality Control
 - (materials, welding, cleaning, etc)

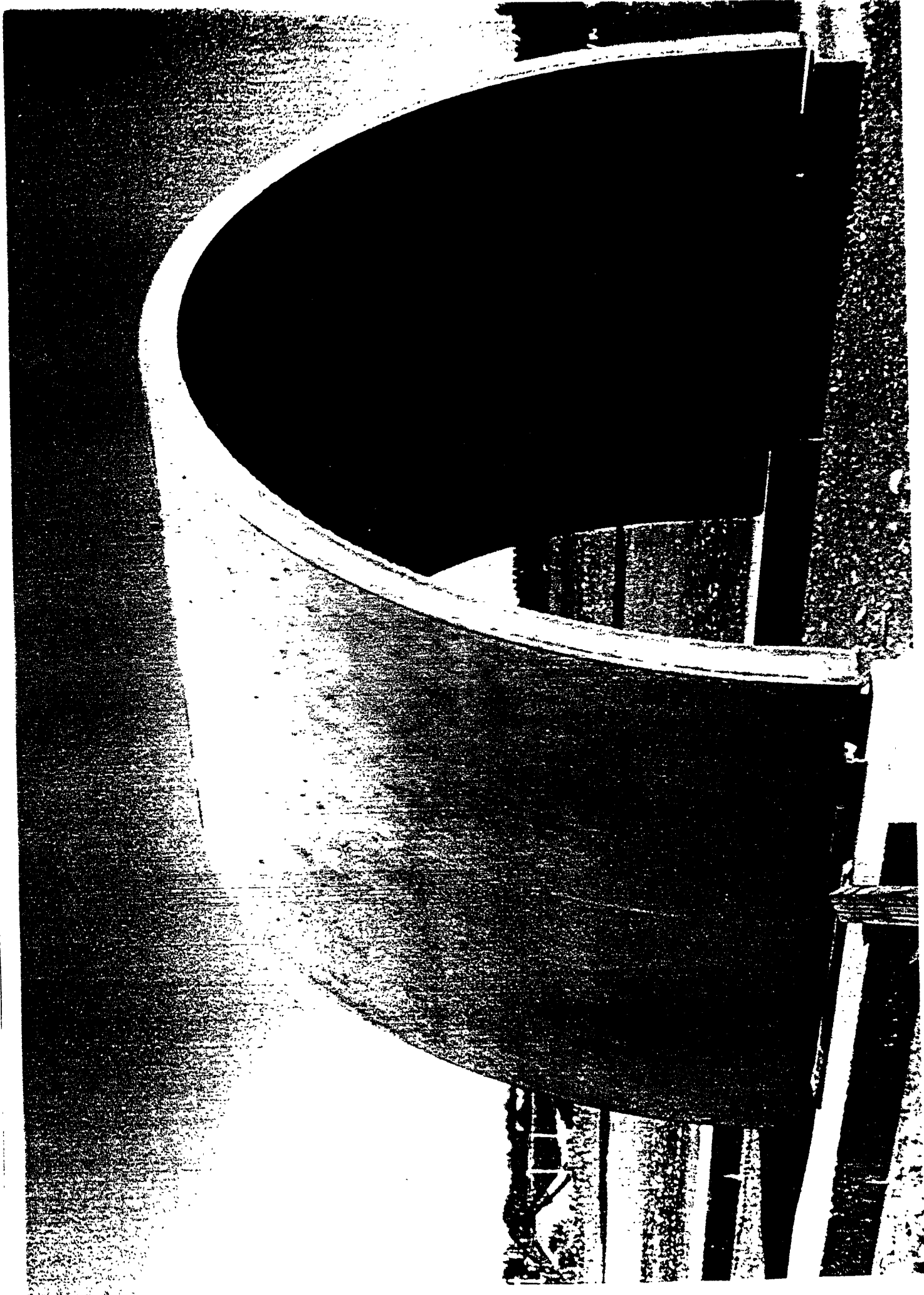
□ Status and Plans

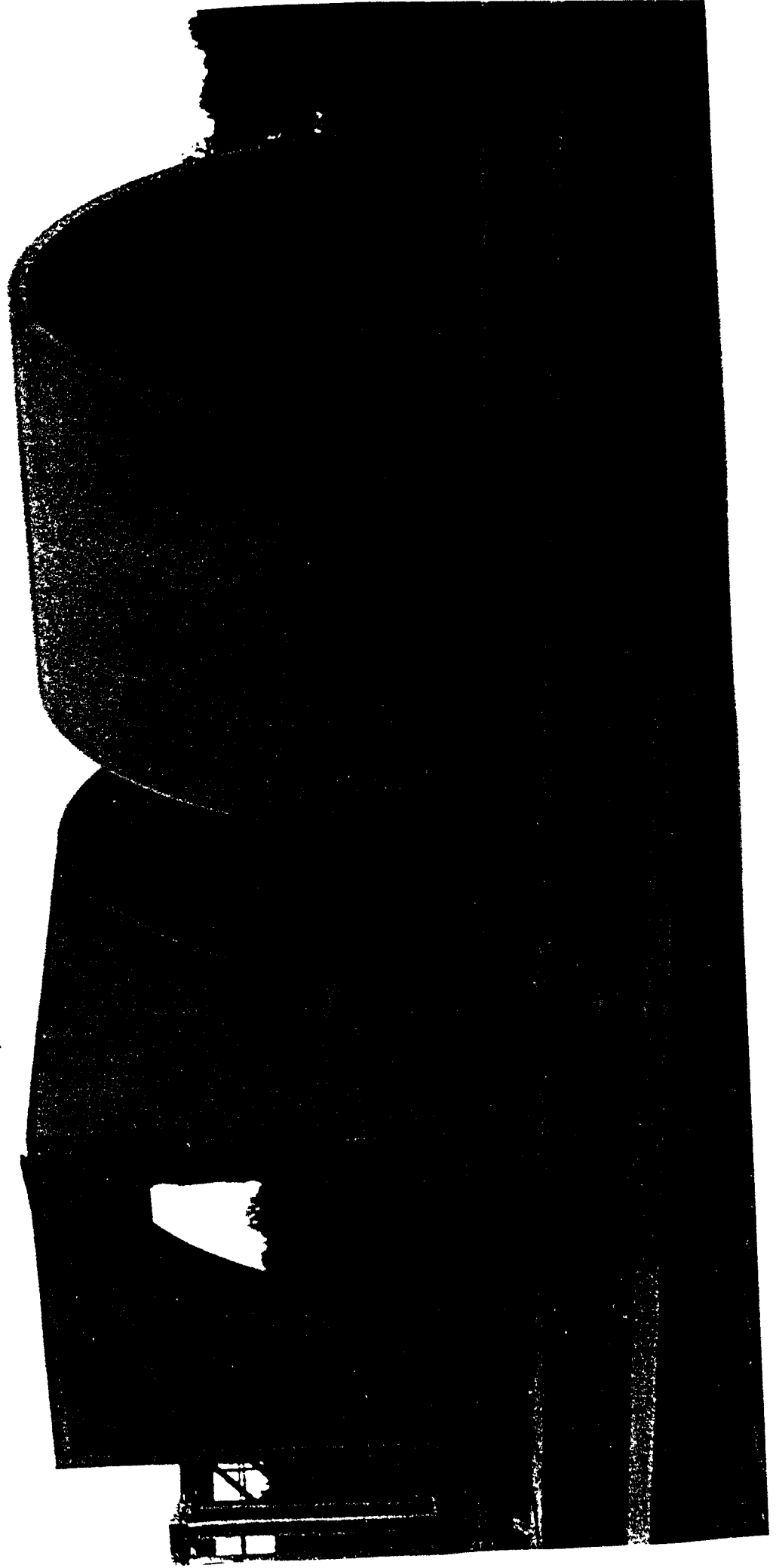
- ⇒ Design Contract was with CBI
 - Final Design Report Accepted (6/94)
- ⇒ Qualification Test
 - 130 ft Section - success (4/95)
- ⇒ Contract Options

LIGO Facilities

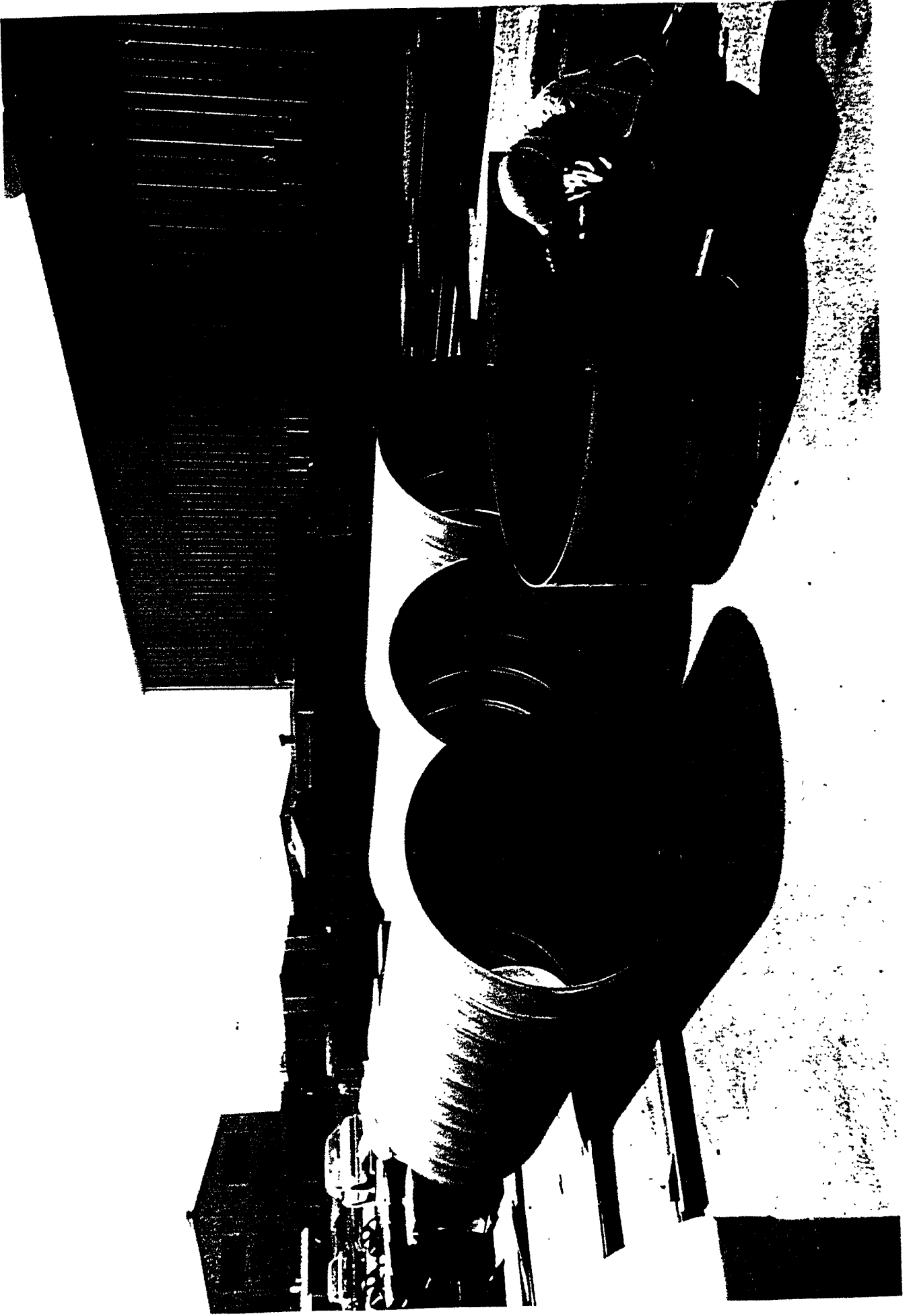
Beam Tube Enclosure

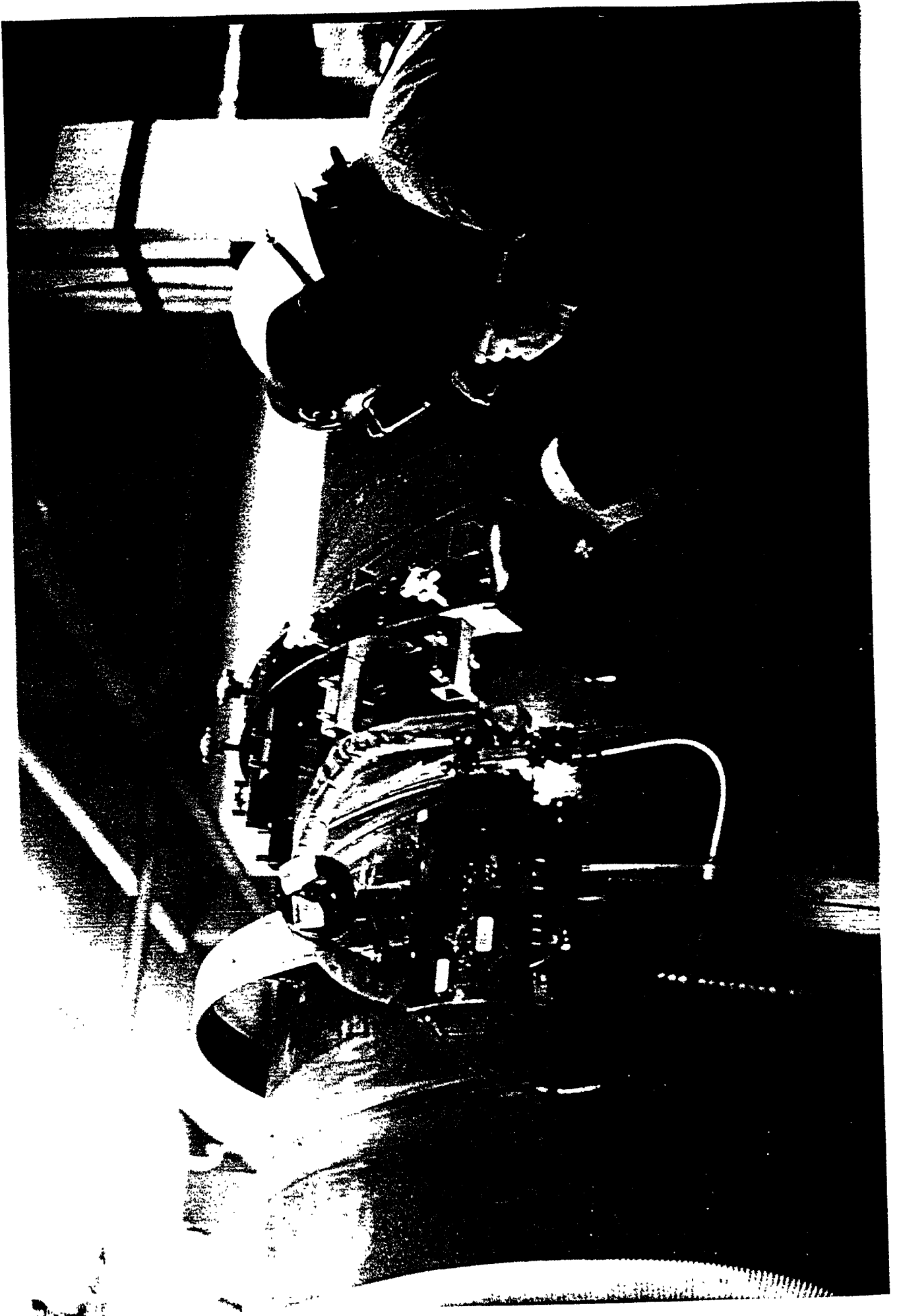






IN THE COURT OF COMMONS

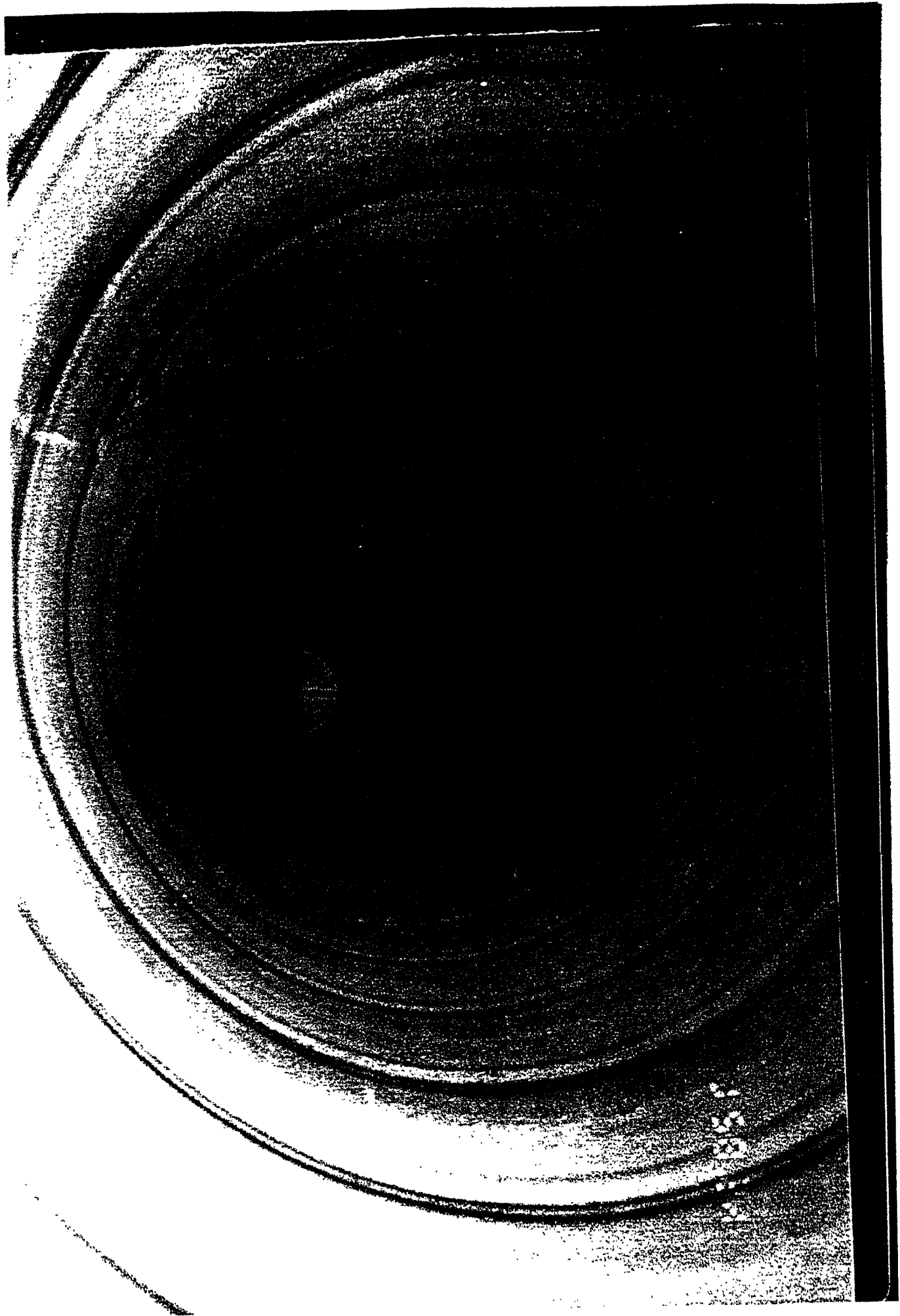




CONFIDENTIAL

BT QT RING WELDING UNIT (with 1200)





1953 10 10



FIGURE 1.1.5 #4 Baffle Schematic

