Viewgraphs for Physics Colloquium

New Mexico State University

1 March 1996

Stan Whitcomb

LIGO-G960037

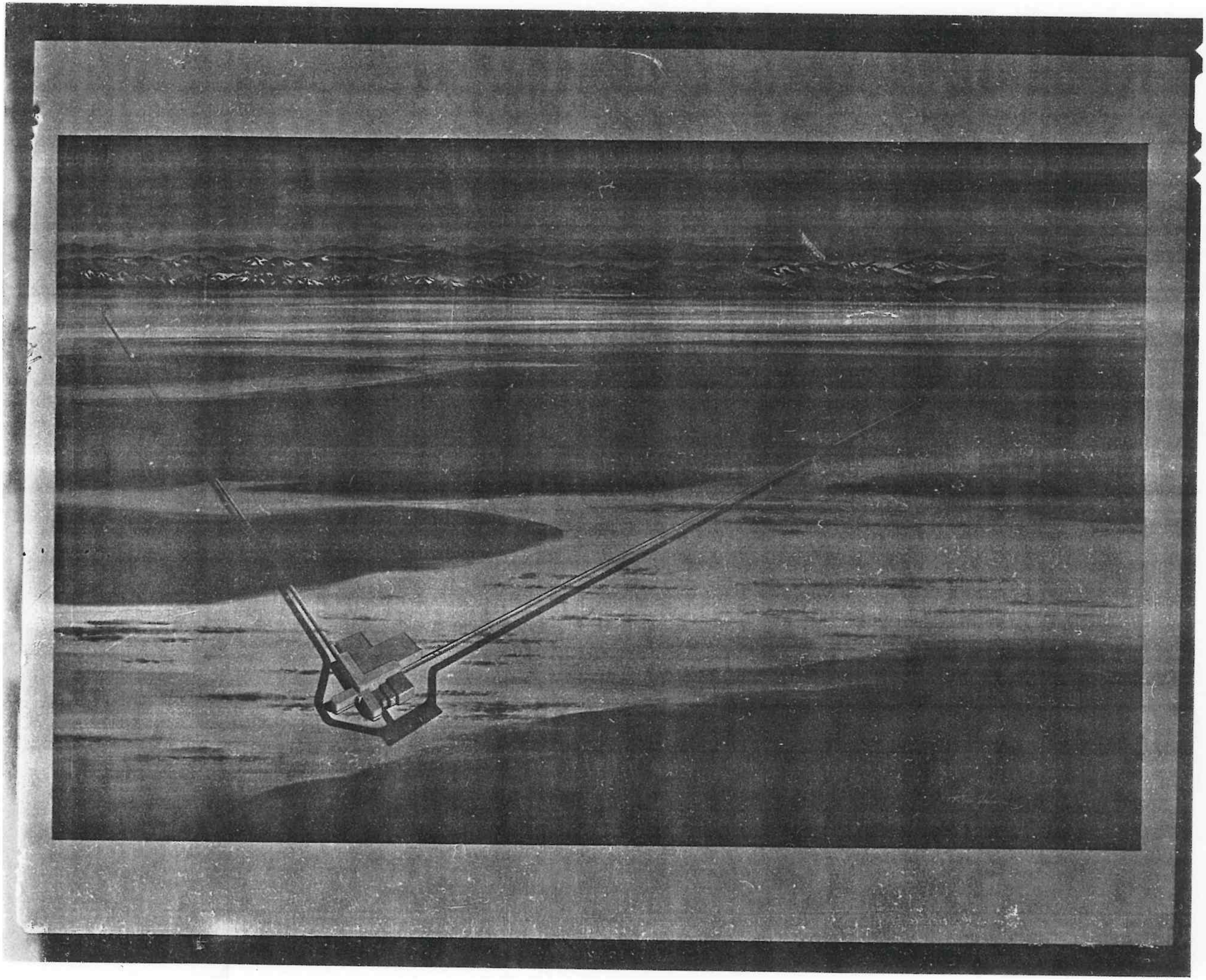
SEARCHING FOR GRAVITATIONAL WAVES WITH LIGO

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY*

STAN WHITCOMB**
(CALTECH)

* COLLABORATION BETWEEN CALTECH AND MIT

** WORK DESCRIBED HERE REPRESENTS EFFORT OF ~80 CURRENT (AND ~40 PAST) SCIENTISTS, ENGINEERS, STUDENTS, TECHNICIANS, AND ADMINISTRATORS



Physics of Gravitational Waves

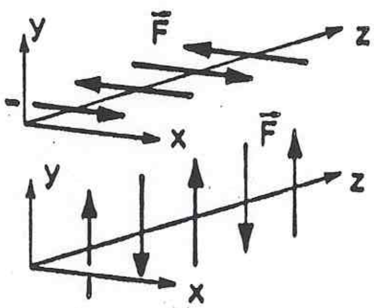
Electromagnetic

Photon

$$m = 0$$
$$v = c$$
$$s = 1$$

Transverse Polarization

$$E_v, \; E_h$$



electric field

Gravitational

Graviton

$$m = 0$$
$$v = c$$
$$s = 2$$

Transverse Polarization

$$h_+, \; h_\times$$

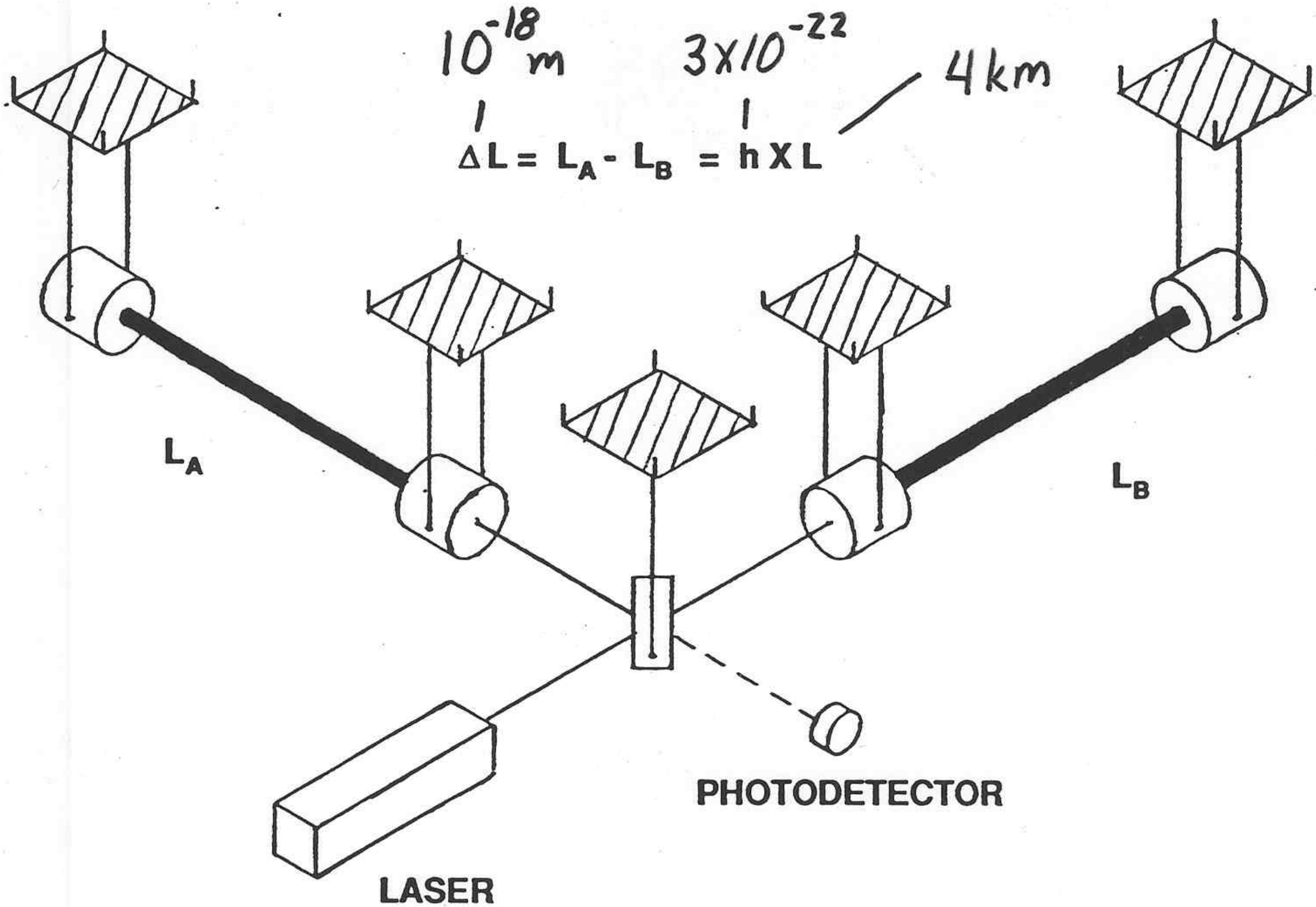
gravitational field

$$h \sim \frac{G}{c^4} \frac{\ddot{Q}}{r}$$

$$\sim 10^{-20} \left[\frac{E_{kin}}{M_\odot c^2}\right] \left[\frac{10\,\mathrm{Mpc}}{r}\right]$$

LIGO

SCHEMATIC INTERFEROMETRIC DETECTOR



EM vs. GW Sources

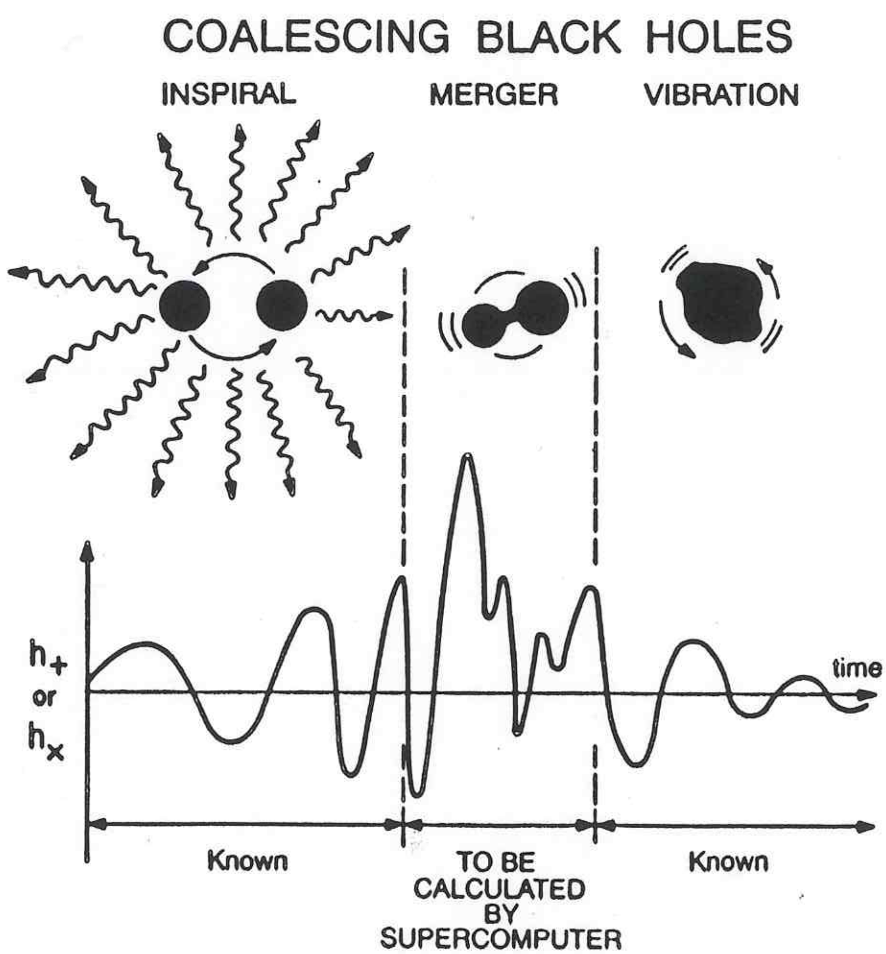
	Electromagnetic Radiation	Gravitational Radiation
Emission Mechanism	Individual Atoms, Molecules, Electrons Incoherent Superposition	Large Scale Mass Motion Coherent Superposition
Examples of Sources	Stellar Atmospheres Interstellar Gas	Supernova Core Binary Black-Holes
Interaction With Matter	Dispersion, Absorption	Negligible in terms of Propagation
Examples of Interaction	"Primordial" Radiation From $\tau = 10^6$ yrs Electromagnetic Telescopes Look Up	"Primordial" Radiation From $\tau = 10^{-43}$ sec Gravitational Detectors Are Omnidirectional

Consequences

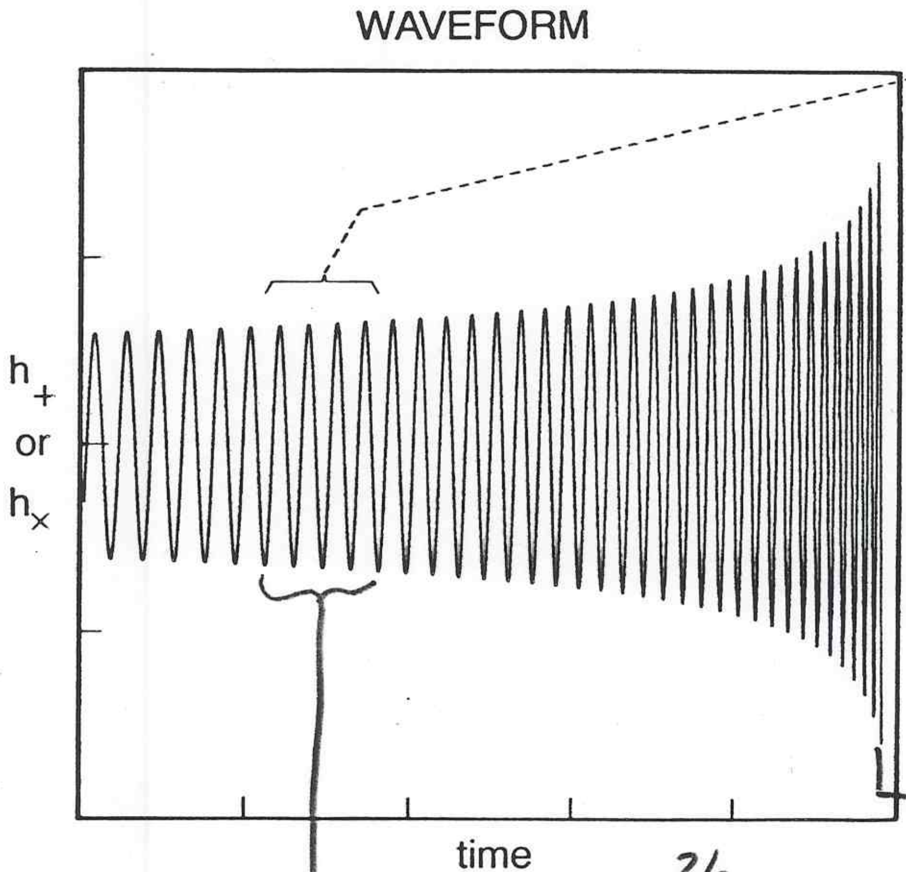
- Great Uncertainty About GW Sources, Either in Strength or Frequency of Occurrence
- Many (Most?) Gravitational Wave Sources May Never Be Seen Electromagnetically
- Potential For Great Surprises!

GW Information Obtained by Waveform Analysis

- Almost All Electromagnetic Astronomy Is Based on Spatial or Spectral Analysis
- Extraction of Information From Gravitational Wave Depends on Waveform Analysis

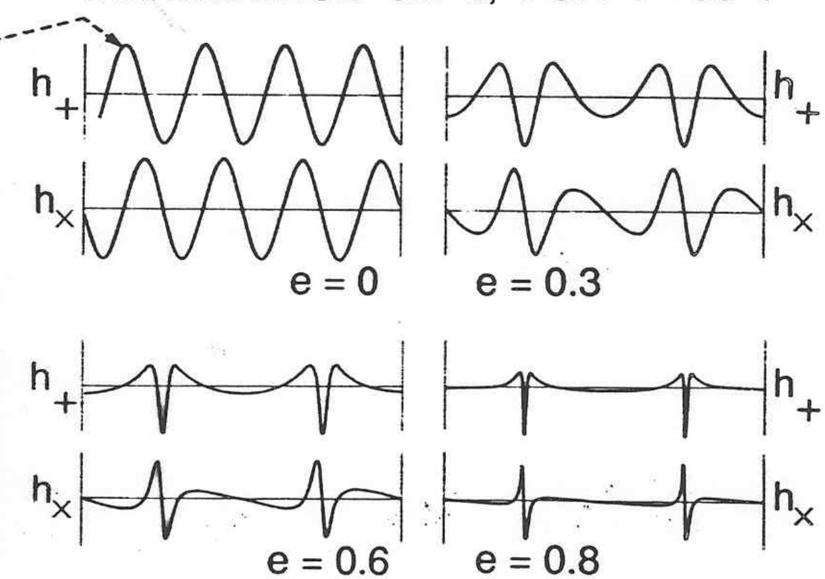


COMPACT BINARY



$$h \propto \frac{\mu M^{2/3}}{r} f^{2/3}$$

$$\frac{df}{dt} \propto \mu M^{2/3} f^{11/3}$$



DEPENDENCE ON ι, FOR e = 0 :

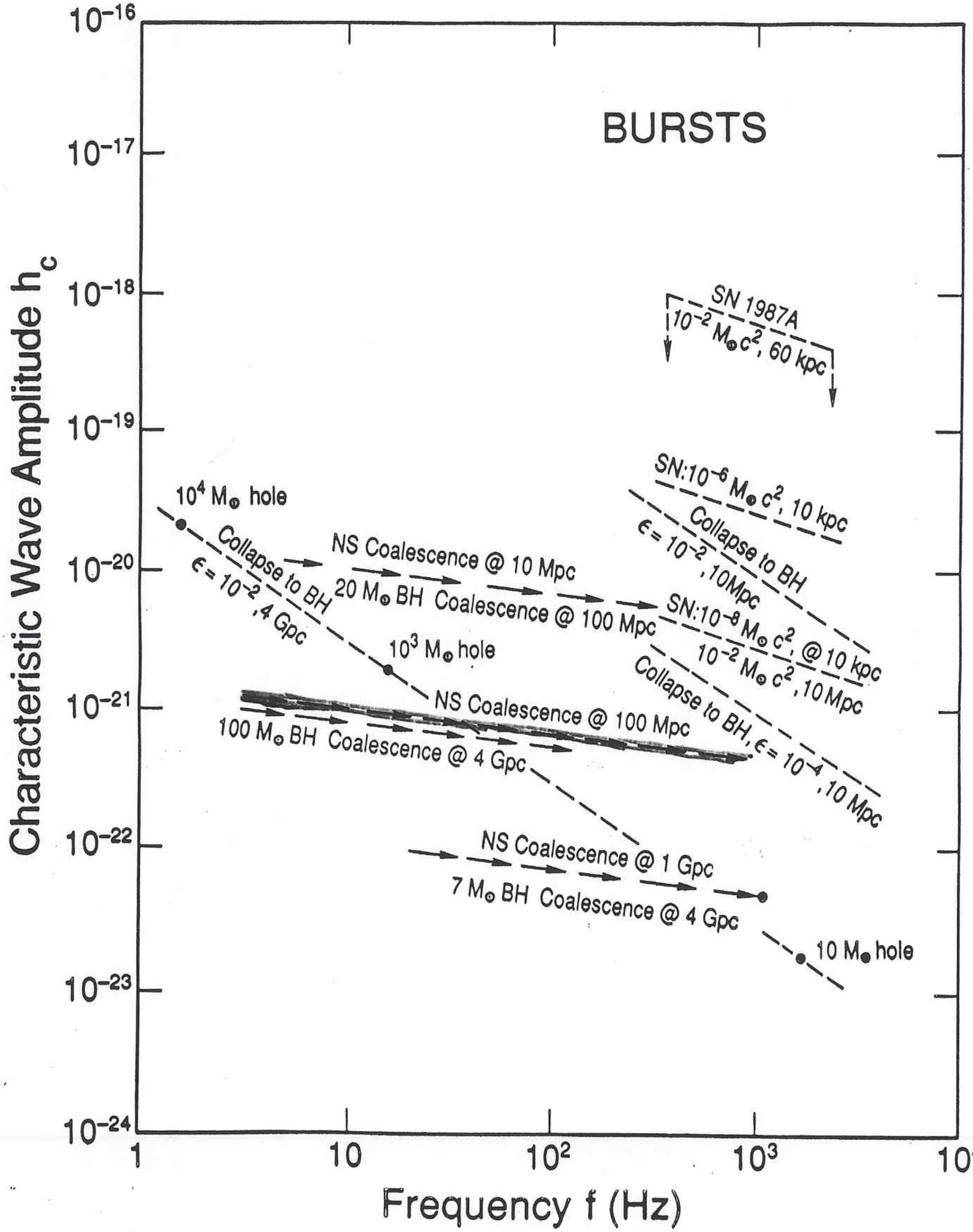
$$\frac{\text{Amp }(h_\times)}{\text{Amp }(h_+)} = \frac{2\cos\iota}{1+\cos^2\iota}$$

FINAL FREQUENCY

$\Rightarrow M$

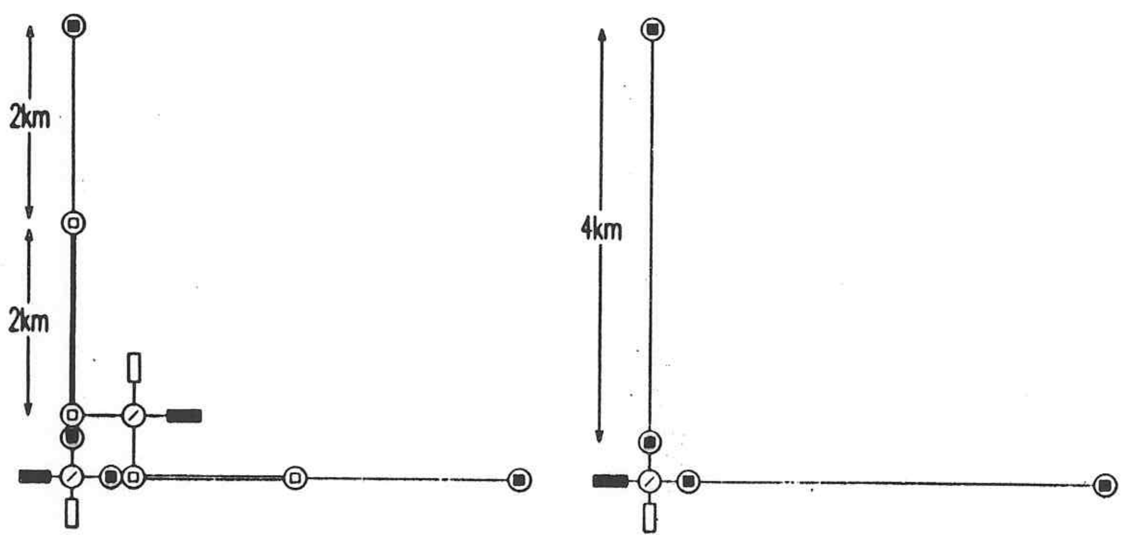
NS-NS BINARIES

- IMPORTANT GW SOURCE BECAUSE THEY PROVIDE KNOWN BENCHMARK
  - KNOWN SOURCE STRENGTH
  - KNOWN MINIMUM EVENT RATE
- FIRST BINARY PULSAR (PSR 1913+16) DISCOVERED 1975
  - FIRST ESTIMATES OF EVENT RATE SUBJECT TO LARGE UNCERTAINTY
- NEW ESTIMATES BASED ON RECENT DISCOVERIES OF 3 ADDITIONAL BINARY PULSAR SYSTEMS
  - EXTRAPOLATE SURVEYED VOLUME TO FULL GALAXY
  - EXTRAPOLATE TO OTHER GALAXIES
- PHINNEY : 3/YR WITHIN 200 Mpc
- NARAYAN, PIRAN, + SHEMI : 1/YR WITHIN 200 Mpc
- BOTH PAPERS: NS-BH BINARIES MAY HAVE COMPARABLE RATES

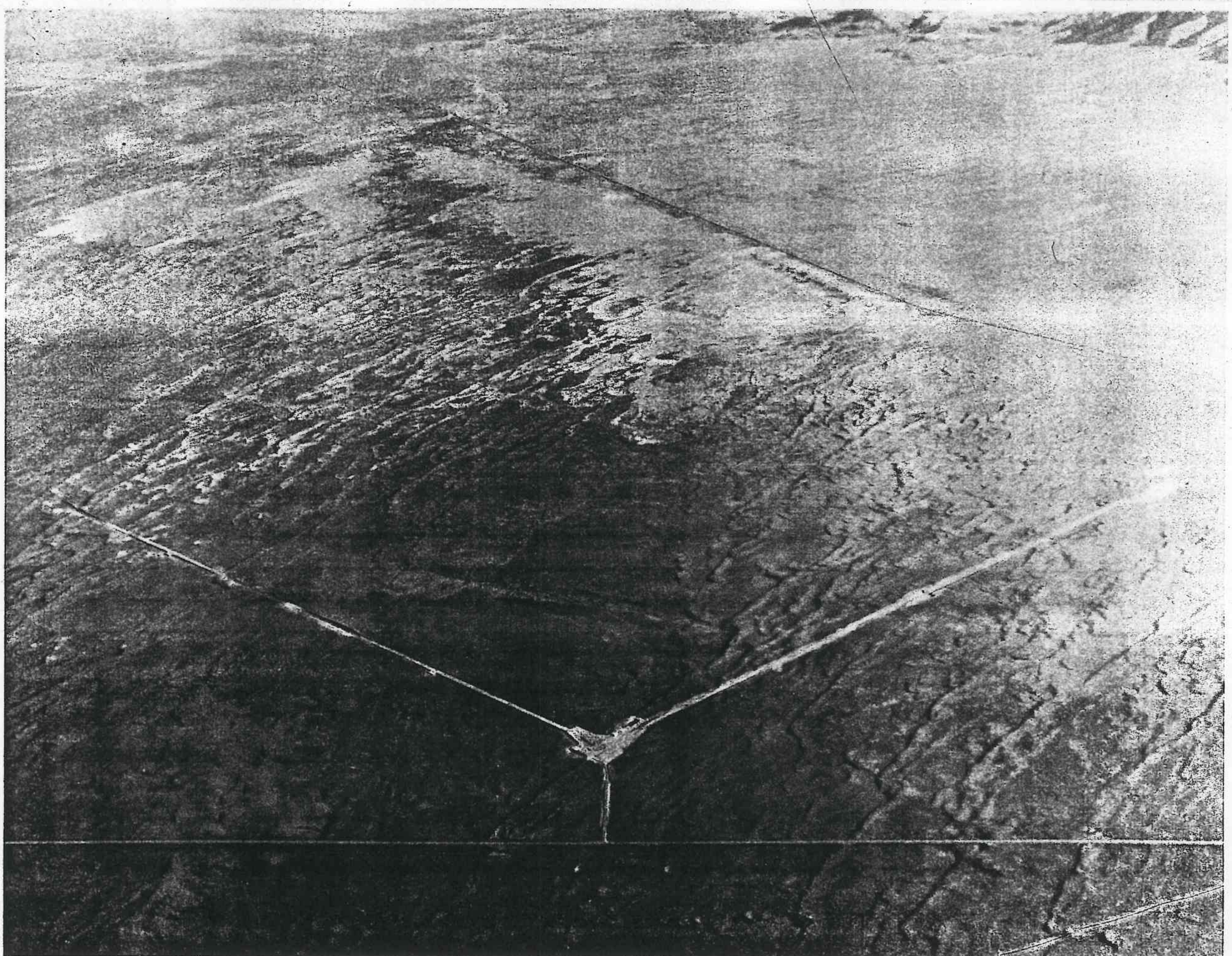

BURSTS
Characteristic Wave Amplitude h_c
Frequency f (Hz)
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
1
10
10^2
10^3
10^4
SN 1987A
10^-2 M⊙c^2, 60 kpc
SN:10^-6 M⊙c^2, 10 kpc
Collapse to BH
ϵ = 10^-2, 10Mpc
10^4 M⊙ hole
Collapse to BH
ϵ = 10^-2, 4 Gpc
NS Coalescence @ 10 Mpc
20 M⊙ BH Coalescence @ 100 Mpc
SN:10^-8 M⊙c^2, @ 10 kpc
10^-2 M⊙c^2, 10 Mpc
10^3 M⊙ hole
NS Coalescence @ 100 Mpc
100 M⊙ BH Coalescence @ 4 Gpc
Collapse to BH, ϵ = 10^-4, 10 Mpc
NS Coalescence @ 1 Gpc
7 M⊙ BH Coalescence @ 4 Gpc
10 M⊙ hole

Laser Interferometer Gravitational-Wave Observatory (LIGO)

- Two Sites, Widely Separated, Operating as a Single Observatory
- Each Site Has 4 km Long L-Shaped Vacuum System Housing a Full-Length Interferometer
- One Site has Mid-Stations For Half-Length Interferometer
- Can Be Upgraded to Support Subsequent Generations of More Sensitive Detectors

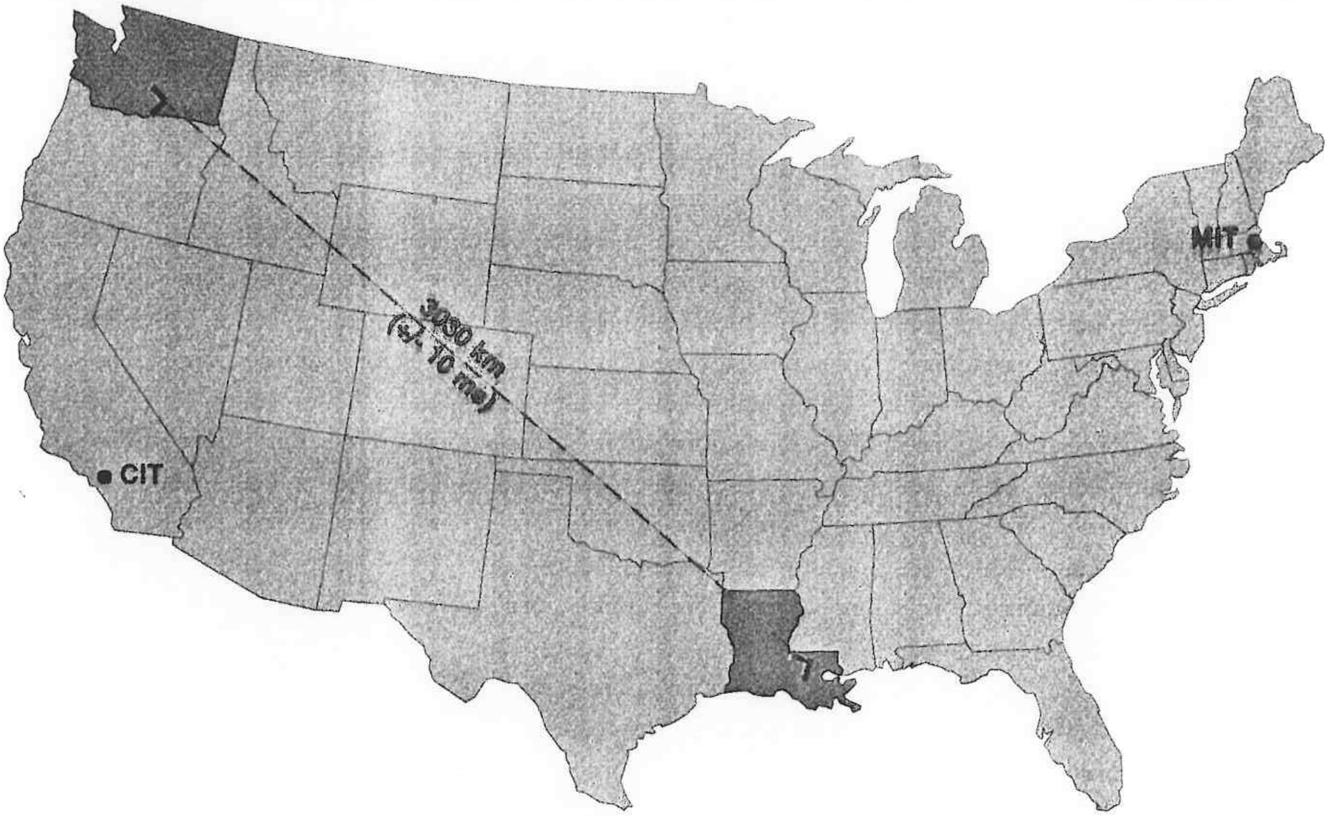


LIGO



PBA

LIGO SITES



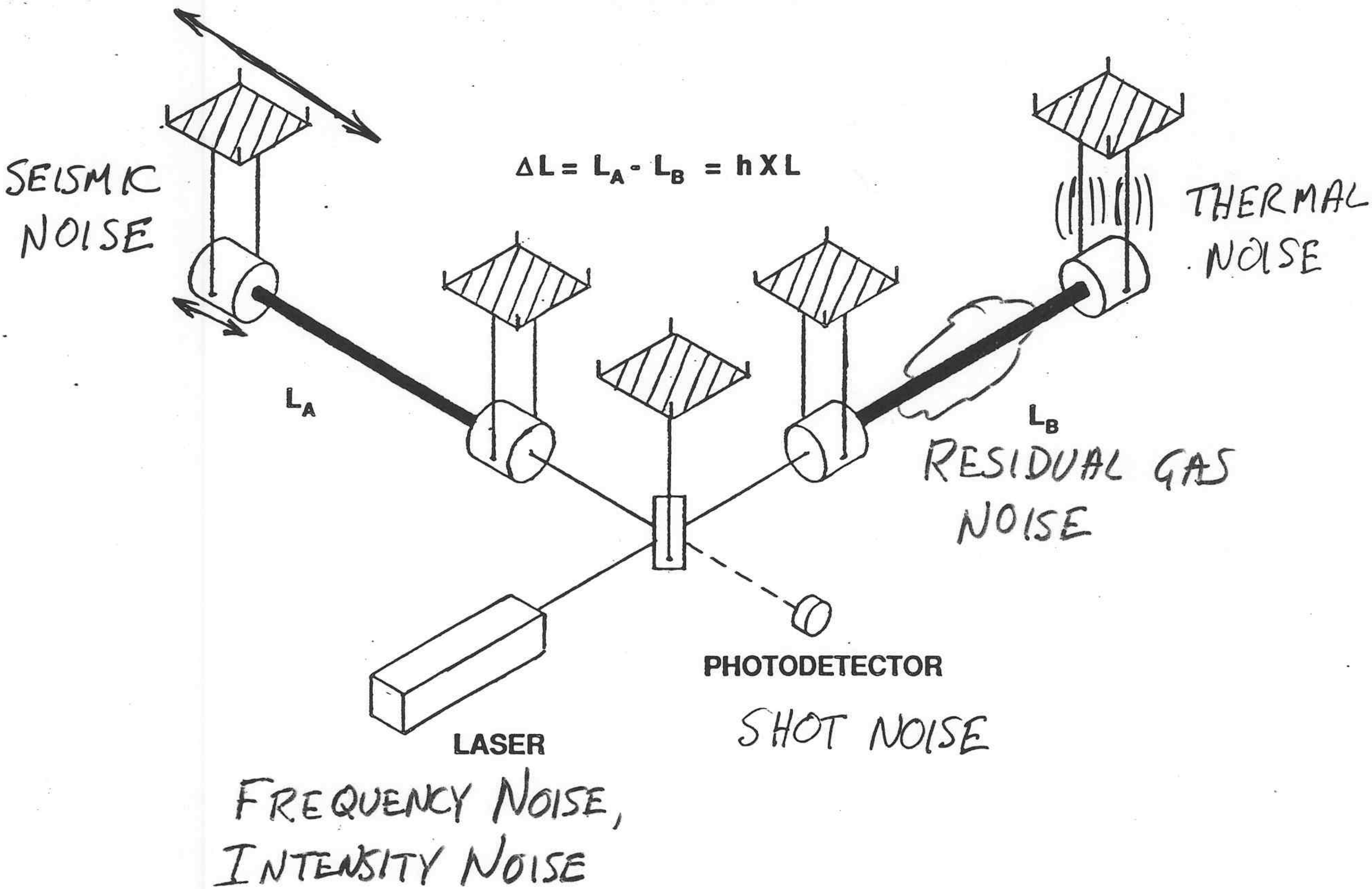
HANFORD, WASHINGTON

- LOCATED ON U.S. DOE RESERVATION
- TREELESS, SEMI-ARID HIGH DESERT
- APPROX. 25 KM FROM RICHLAND, WA (POPULATION :140,000)

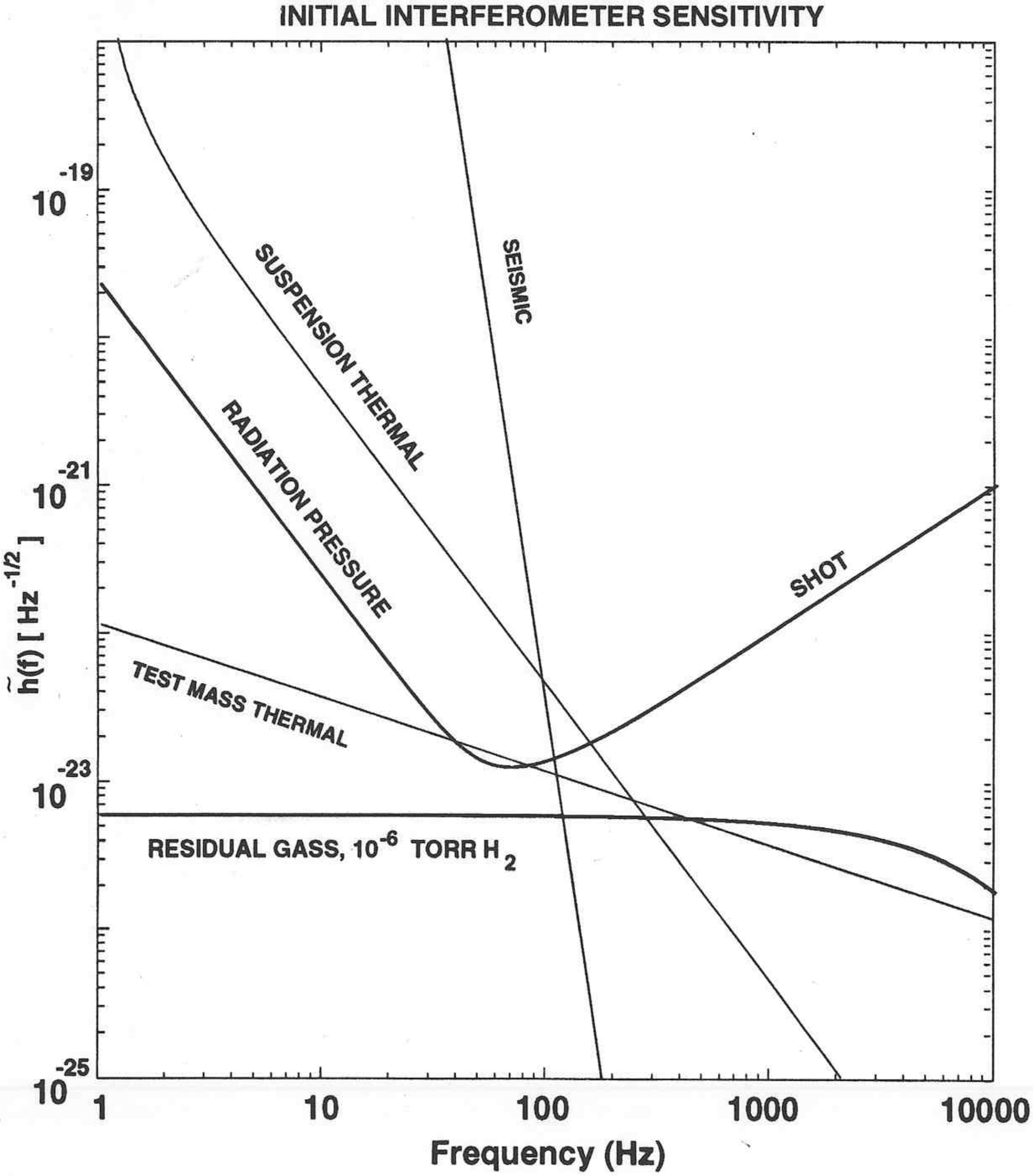
LIVINGSTON, LOUISIANA

- LOCATED IN FORESTED RURAL AREA
- MIXED FOREST; LOW-LYING; POOR DRAINAGE
- APPROX. 50 KM FROM BATON ROUGE, LA (POPULATION :450,000)

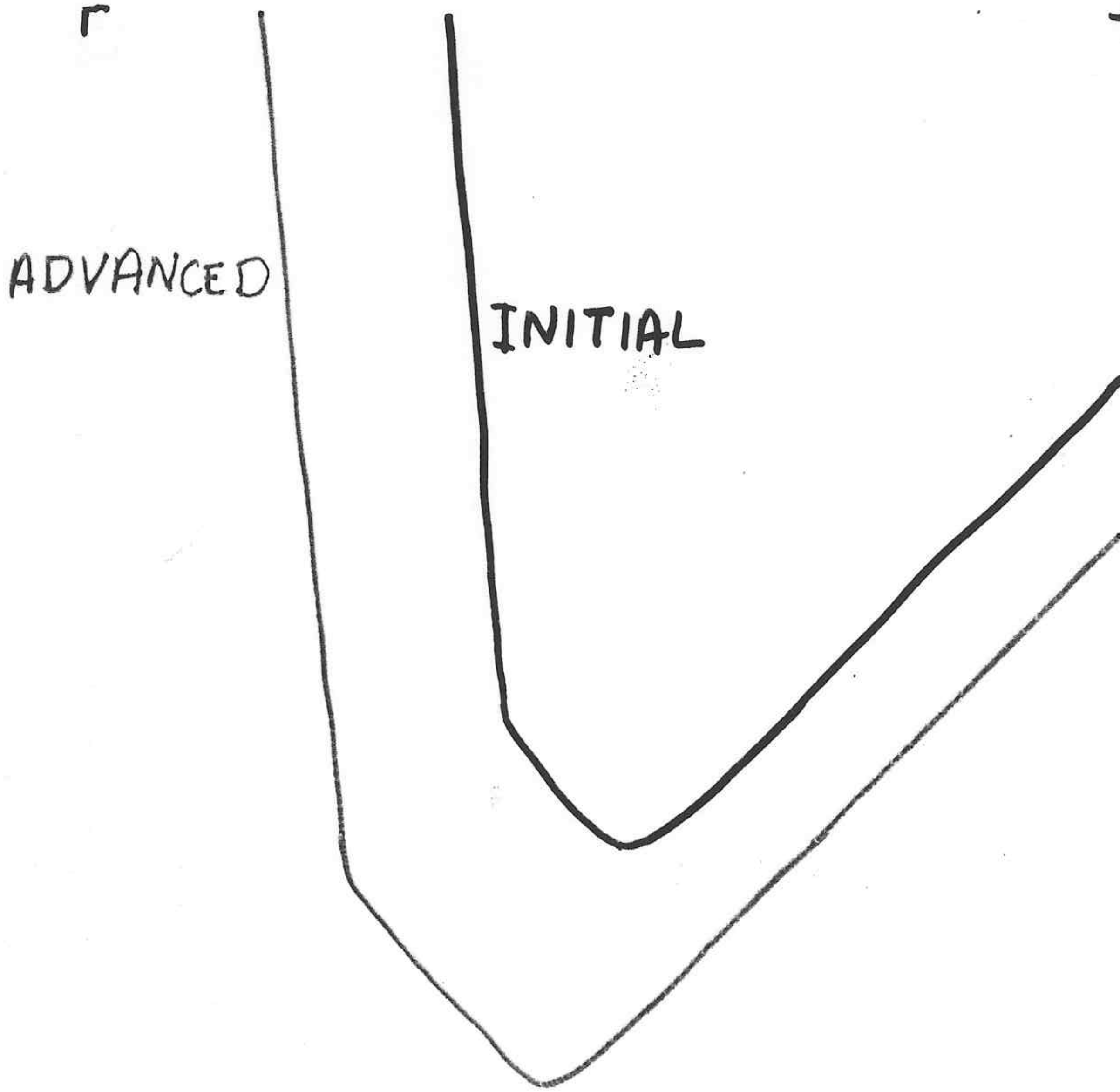
SCHEMATIC INTERFEROMETRIC DETECTOR

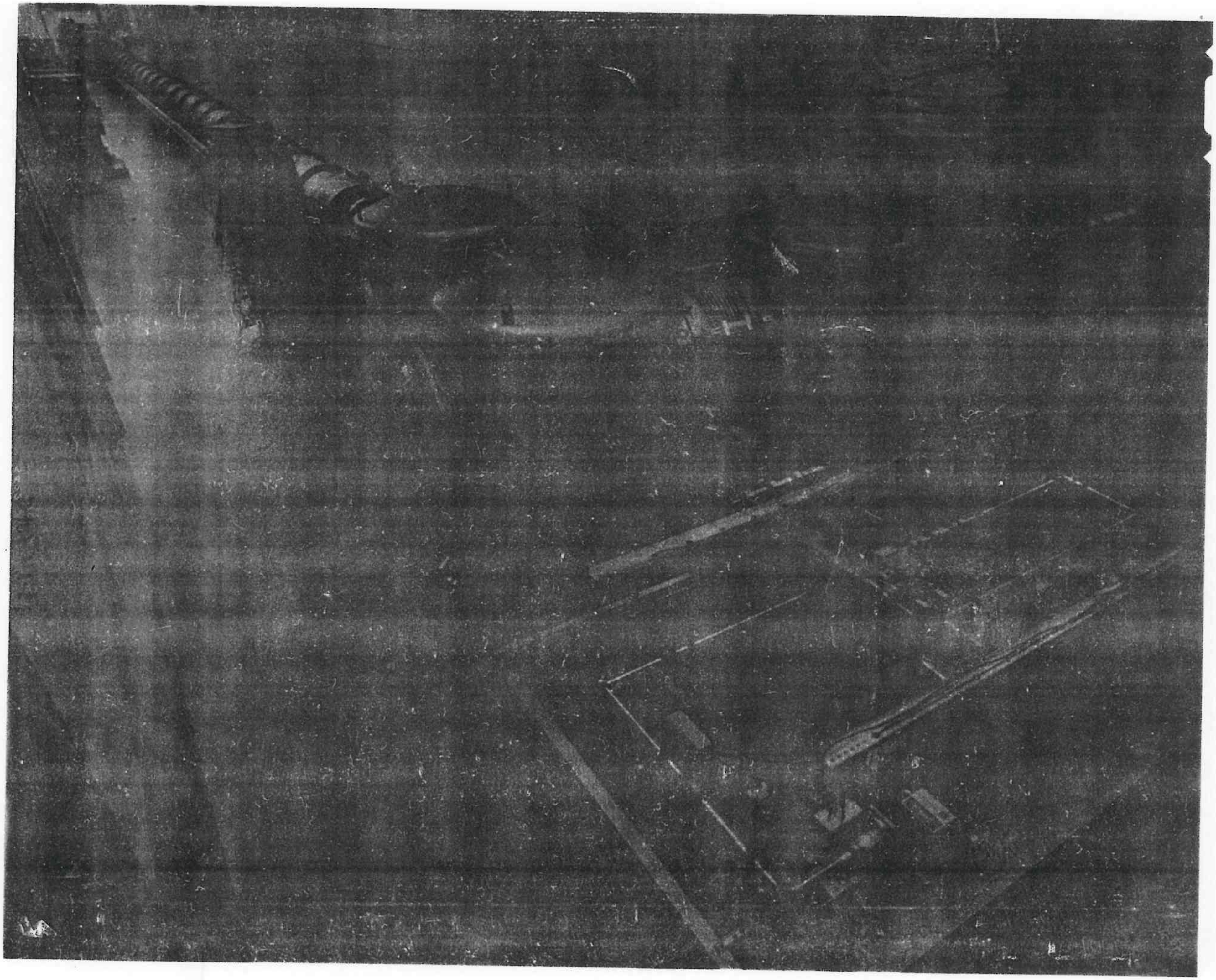


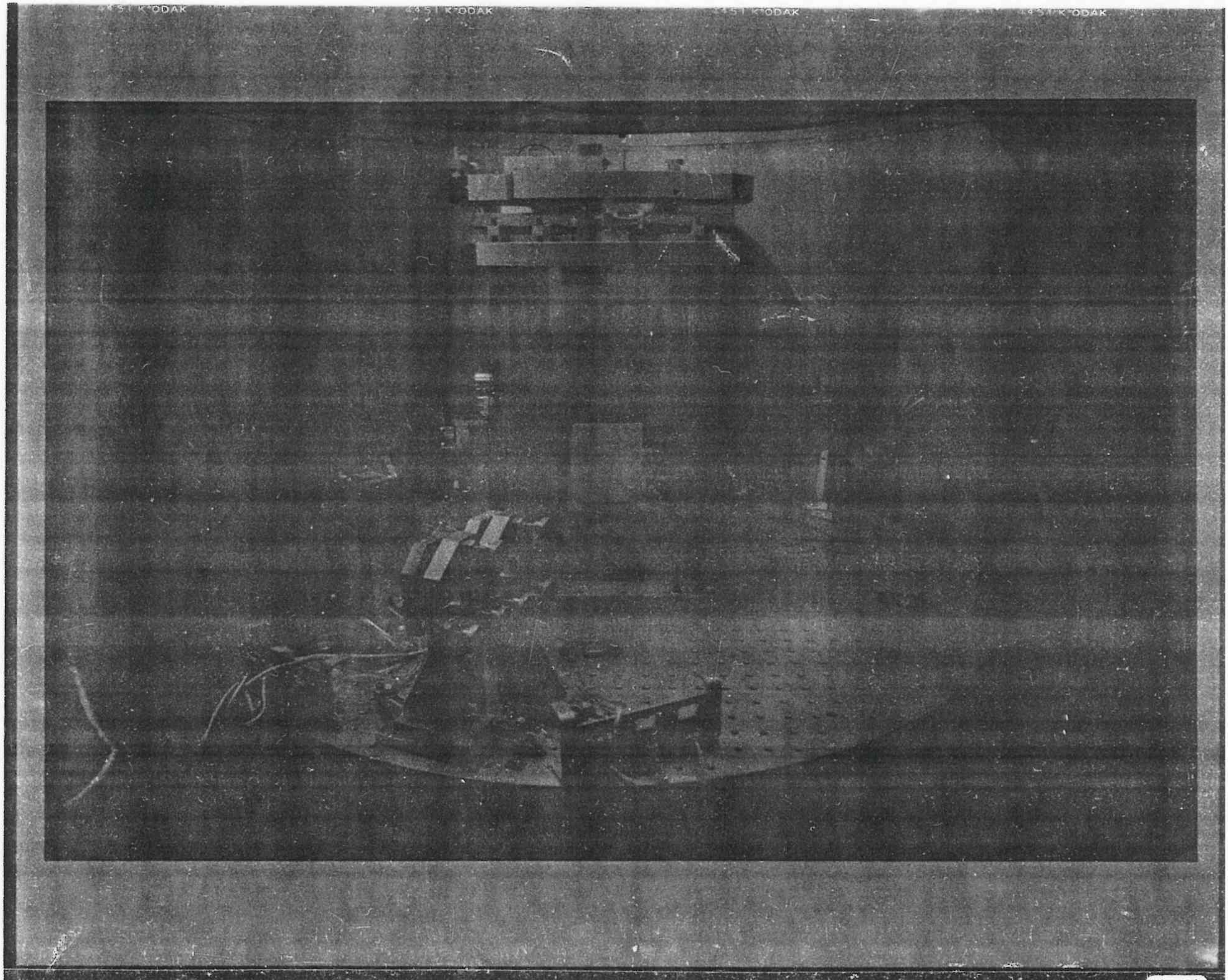
INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL



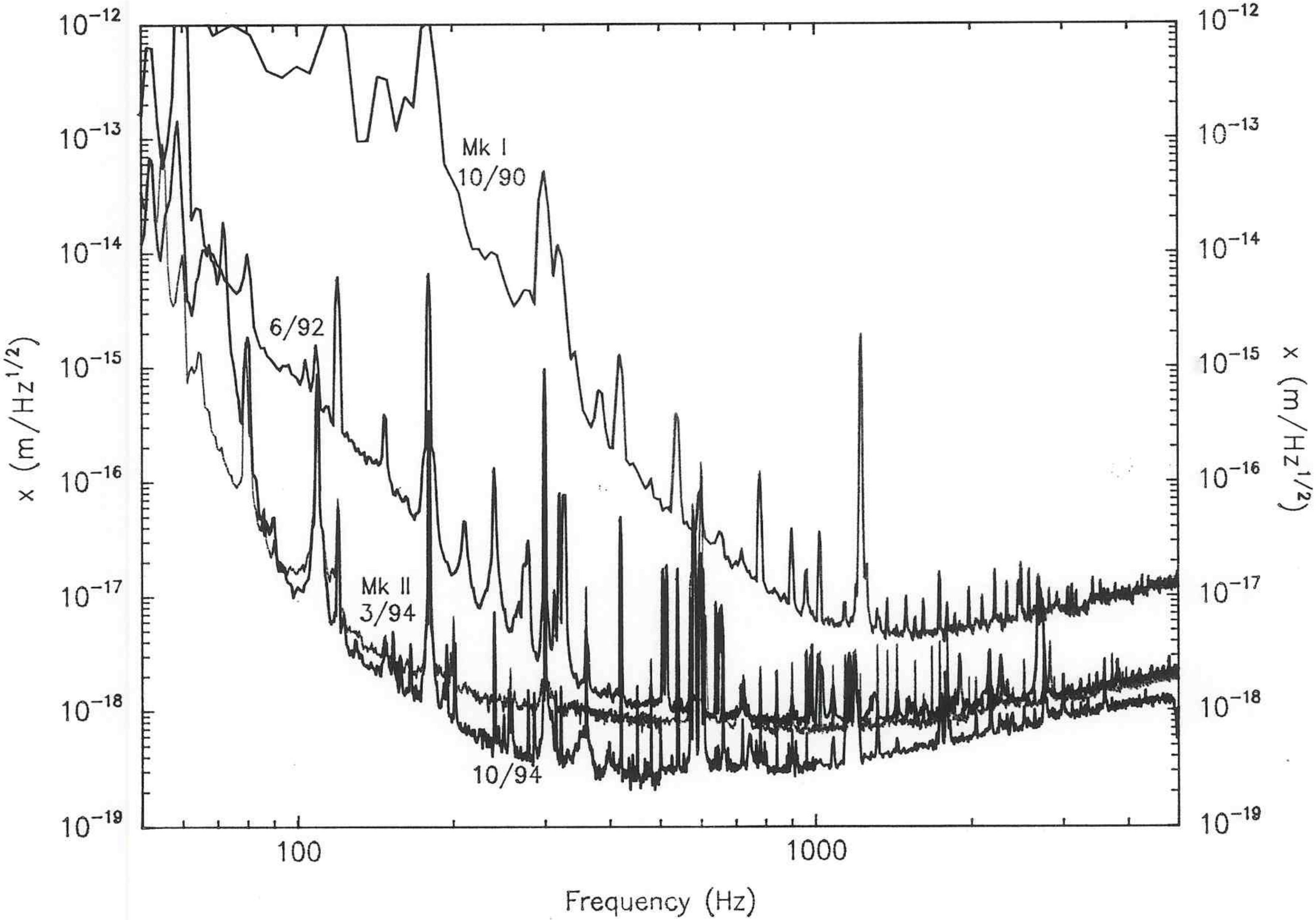
LIGO
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY


ADVANCED
INITIAL





Displacement Sensitivity of Caltech 40 m Interferometer



Shot Noise

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

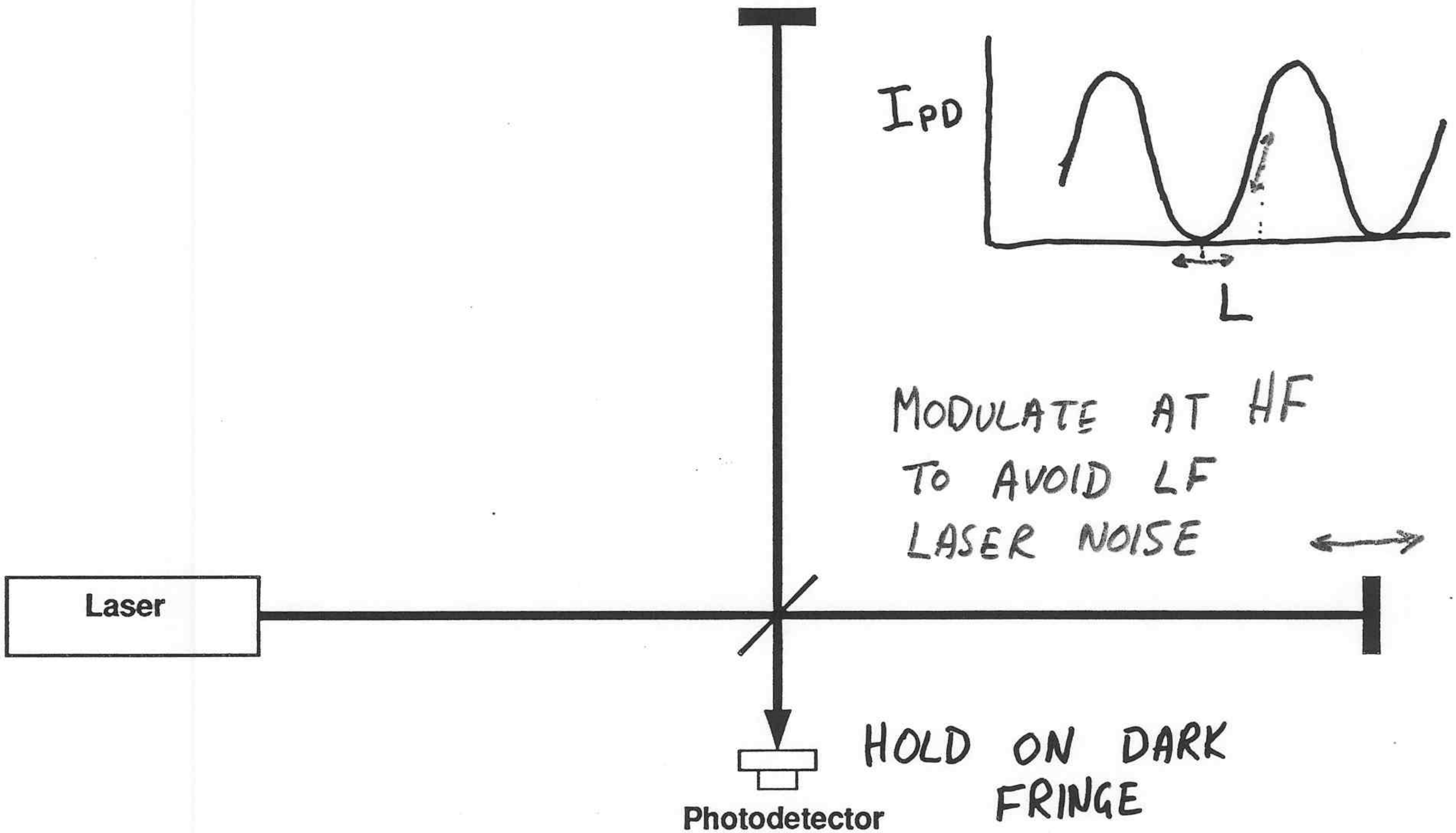
PROPERTY OF INTERFEROMETER OPTICAL CONFIGURATION (MIRROR R'S, ETC.)

DETERMINED PRIMARILY BY EFFECTIVE OPTICAL POWER

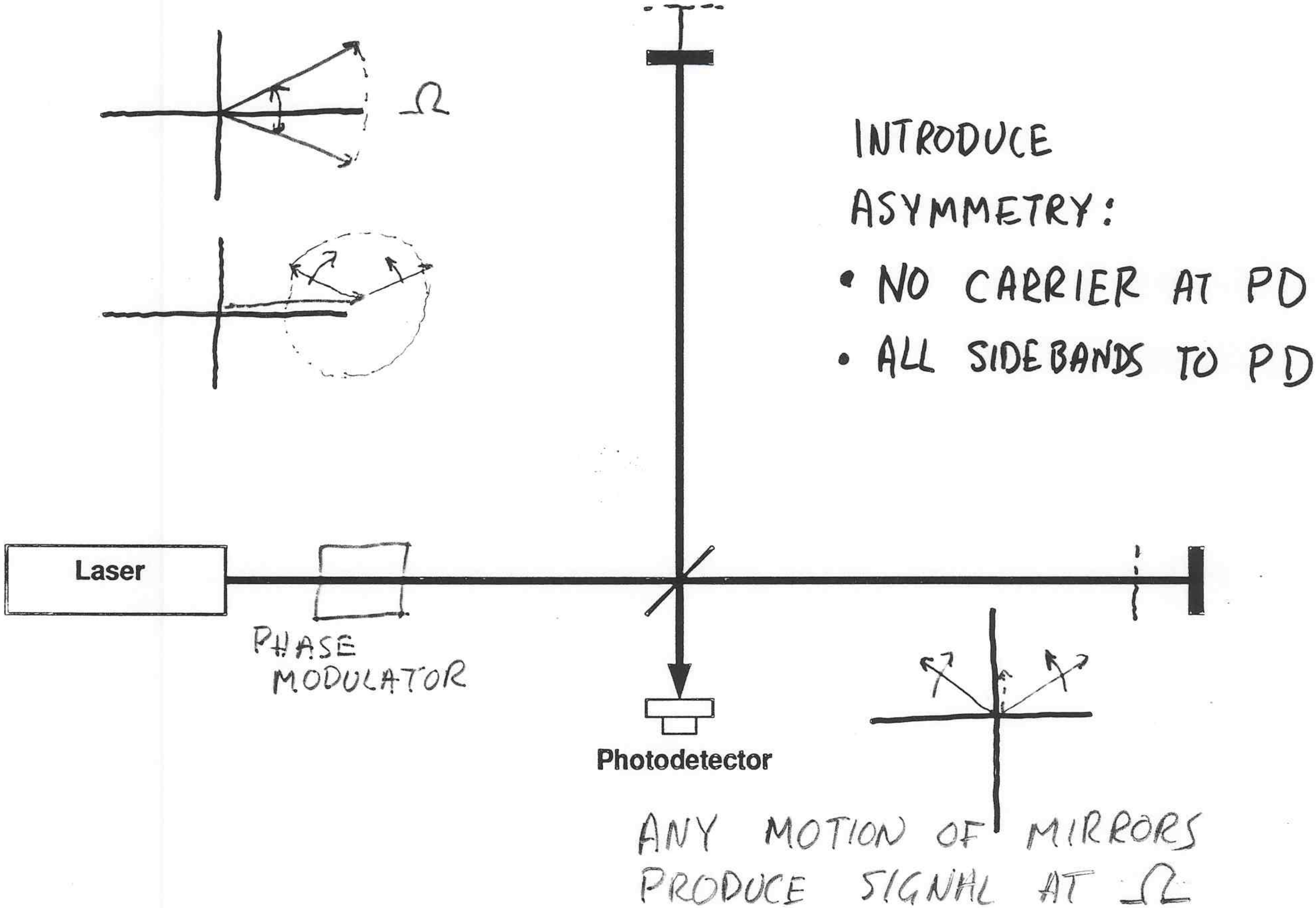
- Achieving Shot-Noise Limited Phase Sensitivity Requires Understanding and Control of All Other Optical Sources of Noise
  - Laser Noise
  - Photodiode Uniformity
  - Modulator-Induced Noise
  - Scattered Light

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

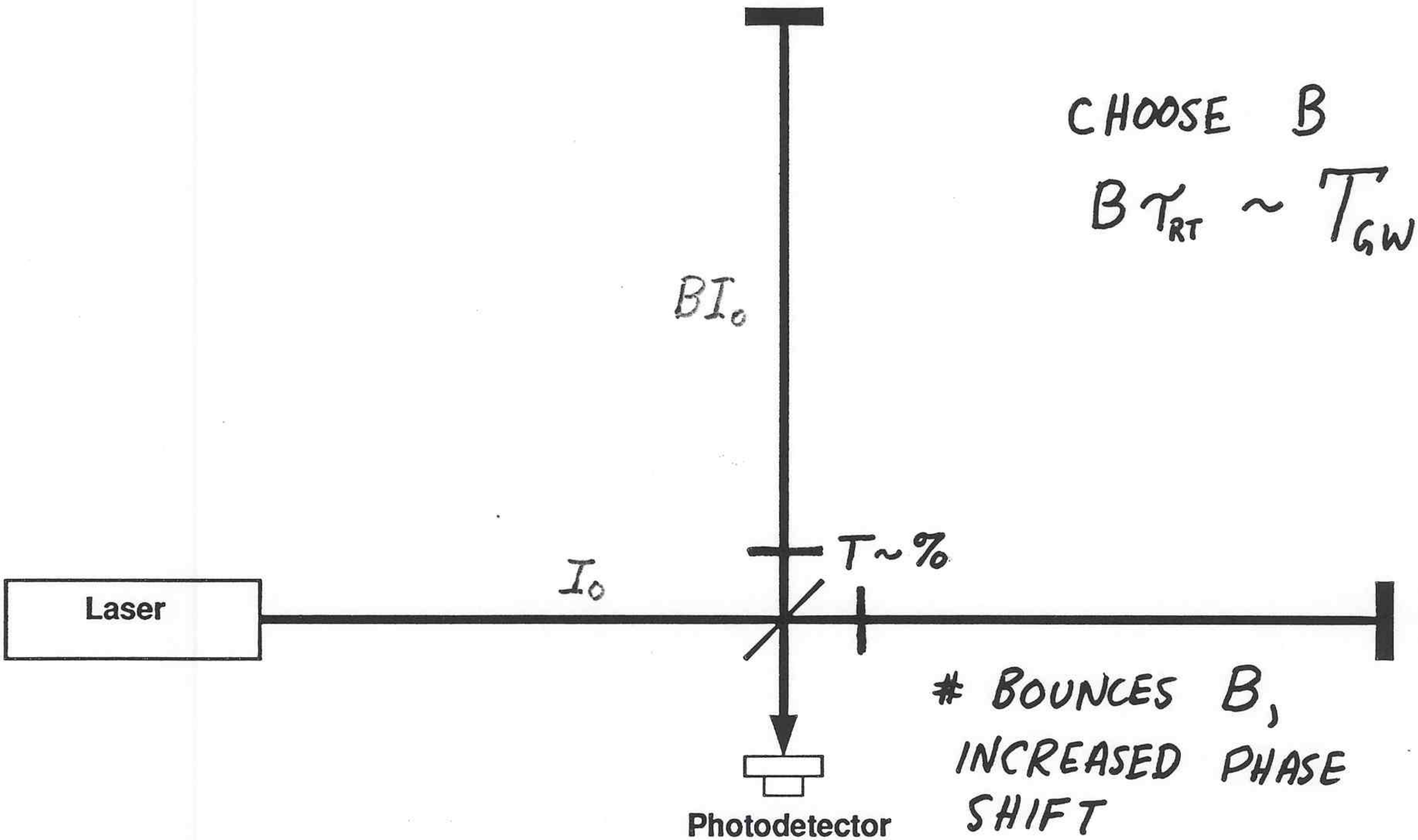
Optical Layout and Operation



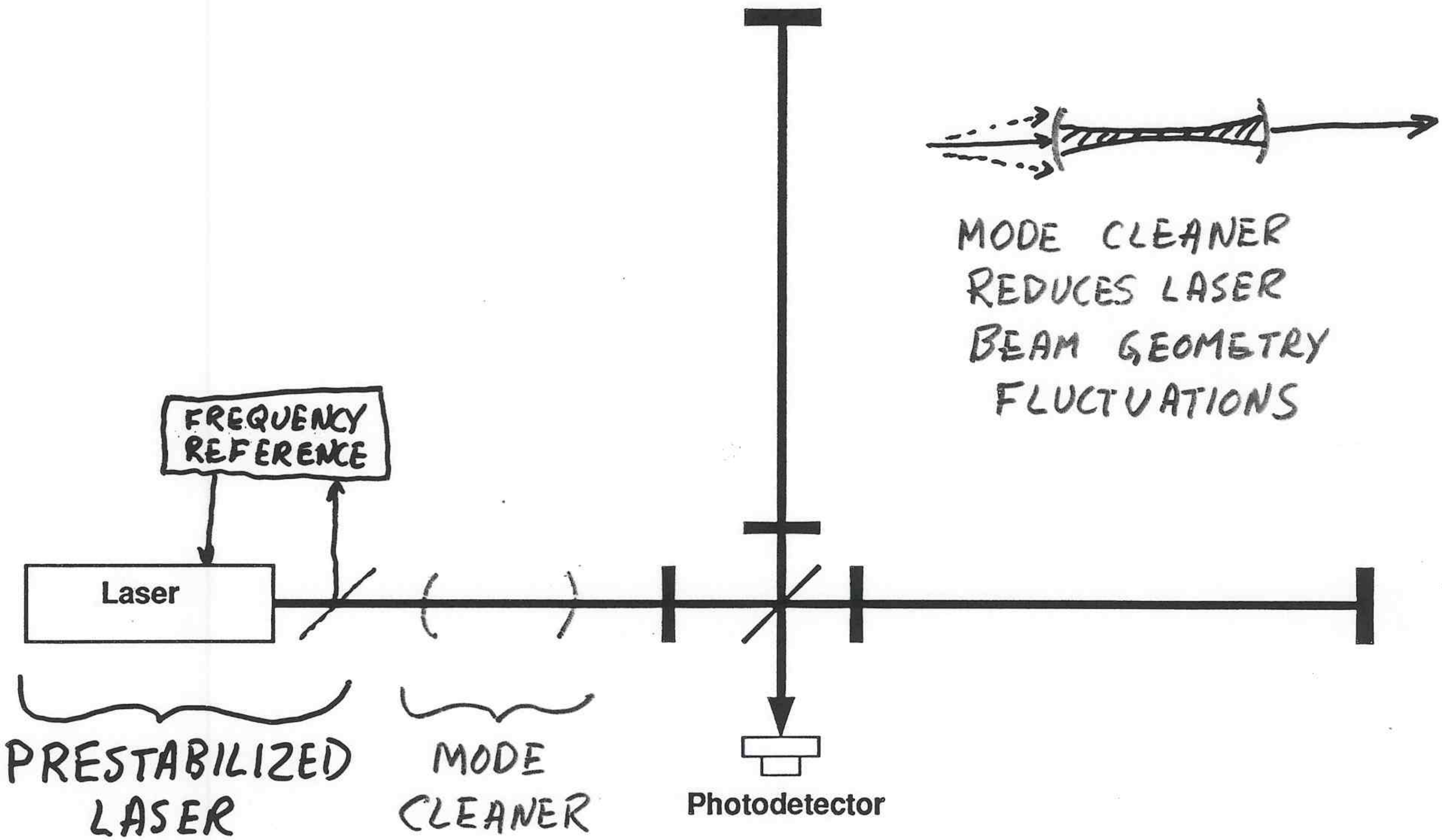
Optical Layout and Operation



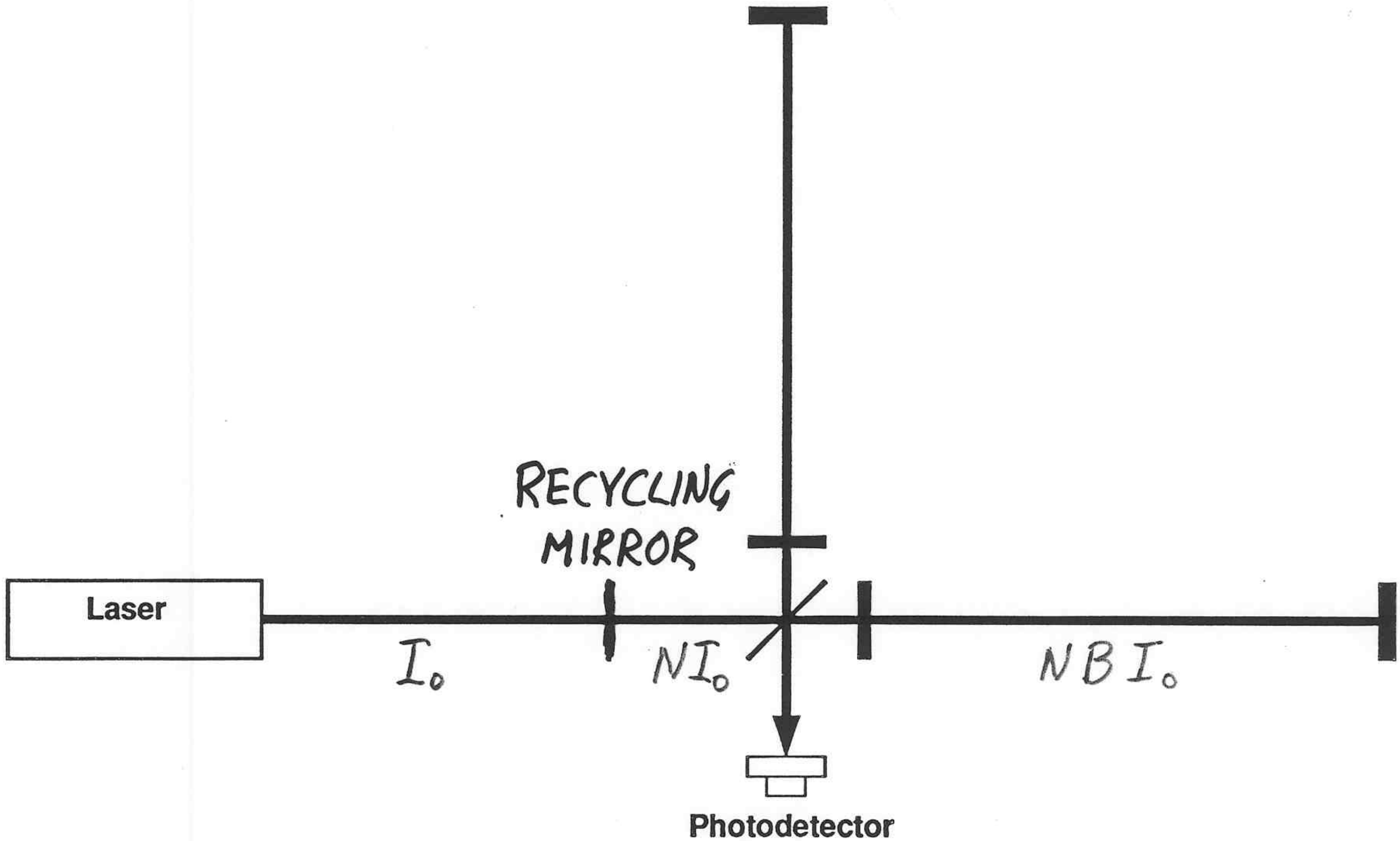
Optical Layout and Operation



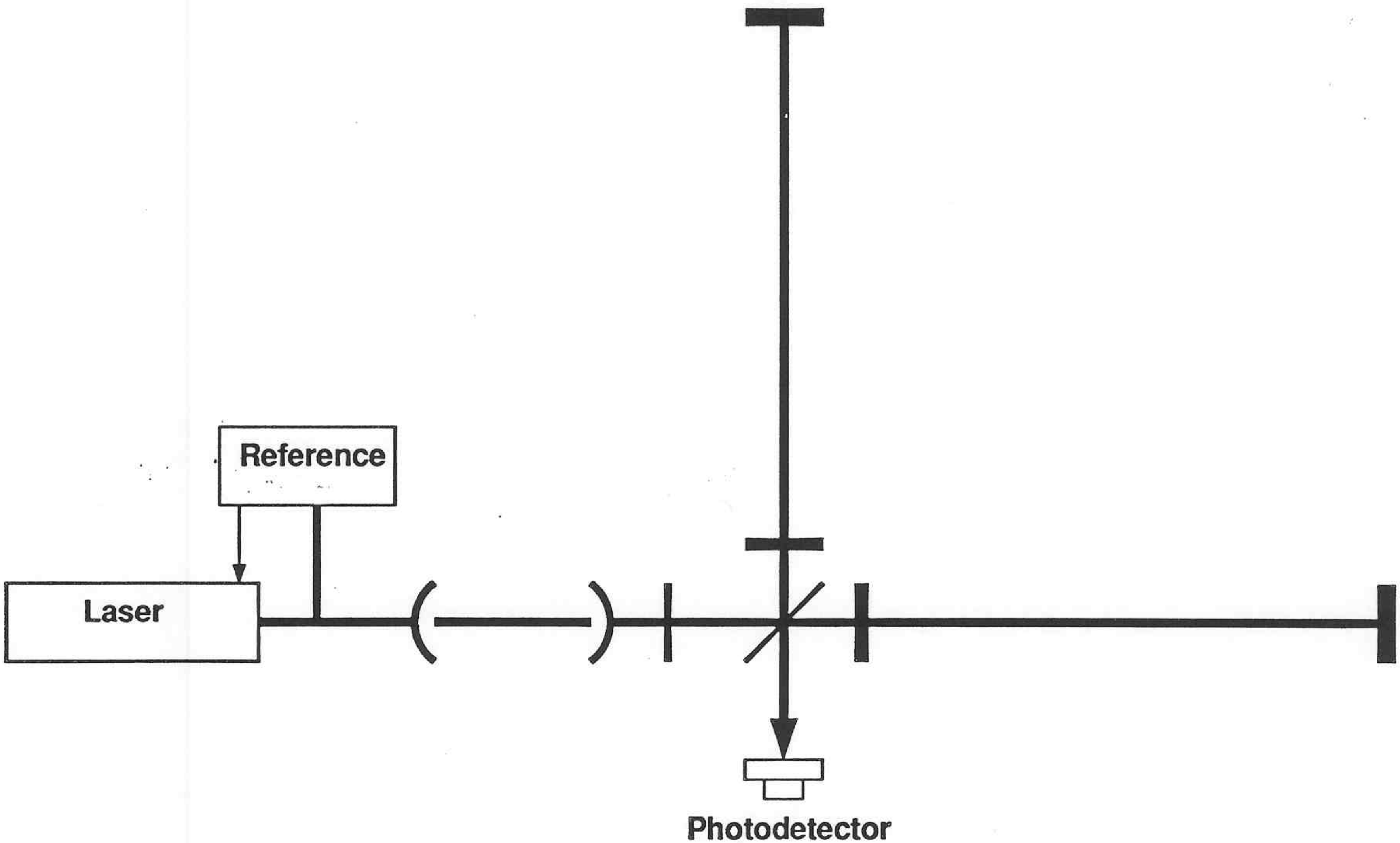
Optical Layout and Operation



Optical Layout and Operation

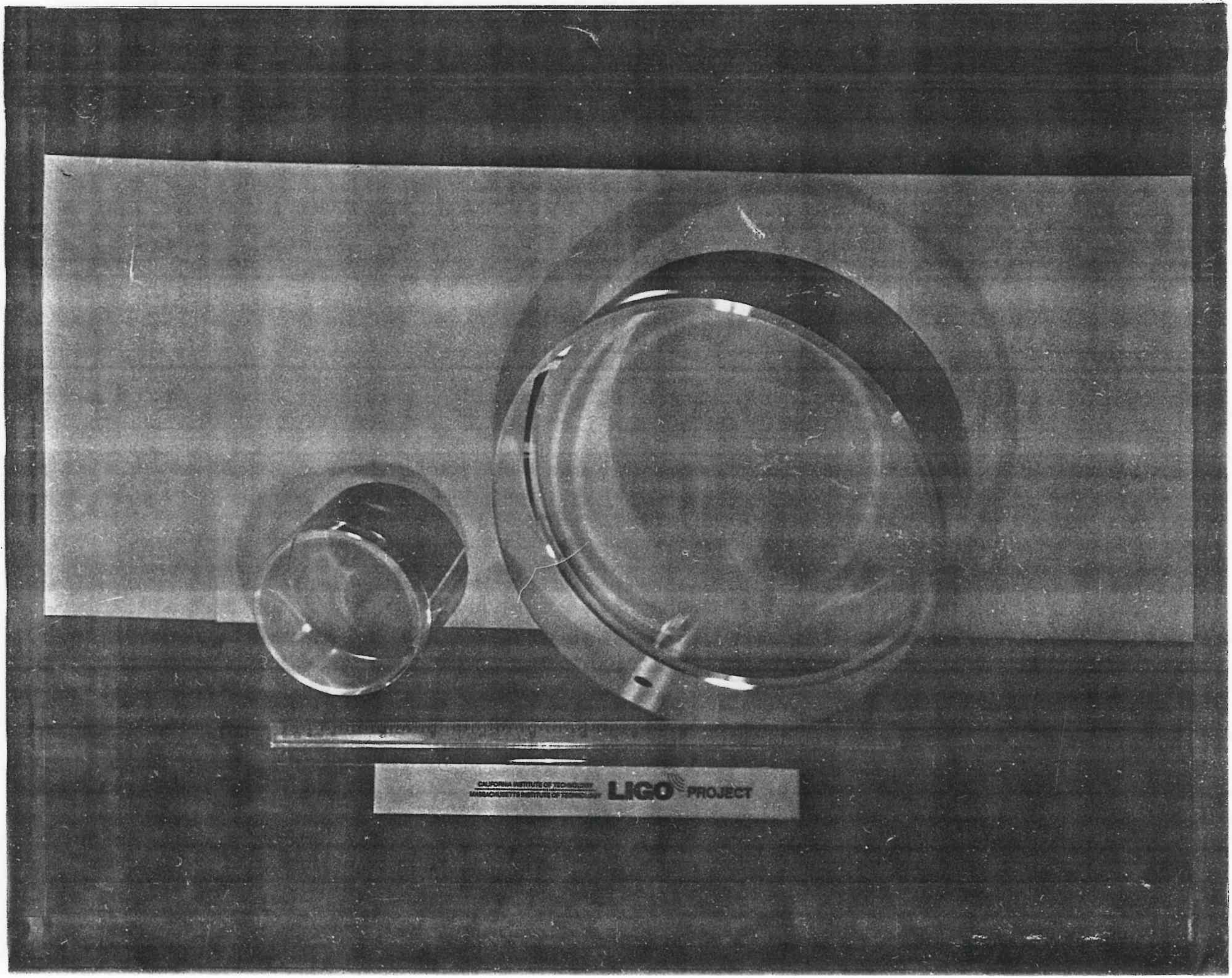


Optical Layout and Operation



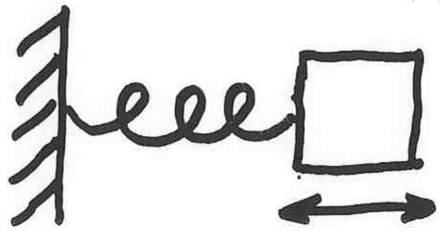
LIGO OPTICS

- SUBSTRATE
  - HIGH PURITY SiO_2
  - LOW SCATTER < 5 ppm/cm
  - LOW ABSORPTION < 2 ppm/cm
- POLISHING
  - ARMS MATCH TO $\lesssim 2\%$
  - MID SPATIAL FREQUENCIES $\leq \frac{\lambda}{1200}$
  - MICRO ROUGHNESS $\lesssim 2$ Å
- COATING
  - PHASE FRONTS SAME AS POLISHED REQ'T
  - COATING ABSORPTION ≤ 2 PPM
  - COATING SCATTER ≤ 50 PPM
- MECHANICAL
  - 25 cm DIA, 10 cm THICK
  - $Q_{INT} \geqq 2 \times 10^6$


CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

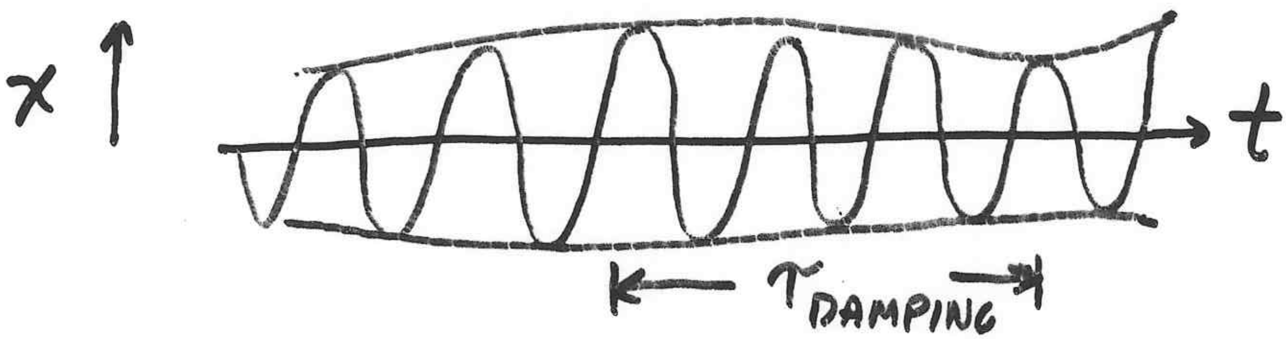
THERMAL NOISE ("BROWNIAN MOTION") IN SIMPLE HARMONIC OSCILLATOR

THERMAL RESERVOIR

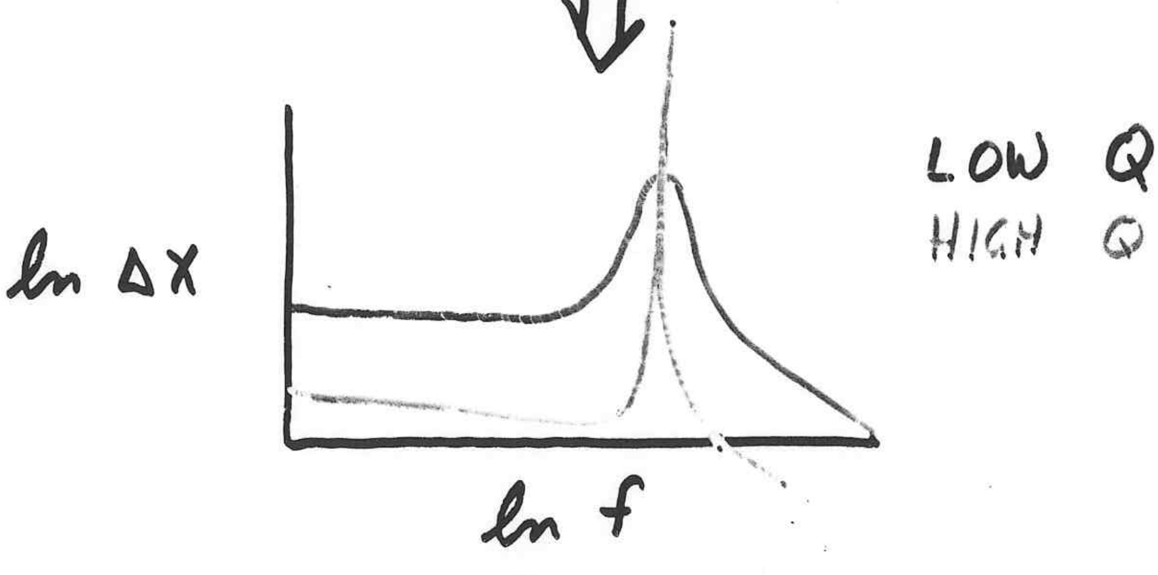


$$\Delta x^2 \sim \frac{kT}{m\,\omega_0^2}$$

EXCHANGE ENERGY WITH RESERVOIR



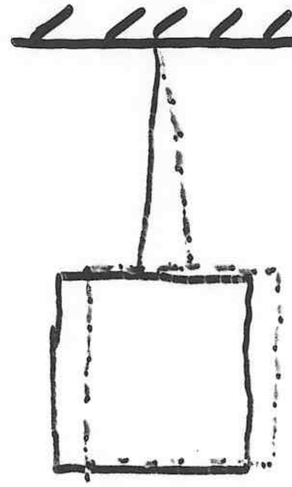
⇓



STRATEGY: 1. MOVE ω_0 OUTSIDE BAND OF INTEREST

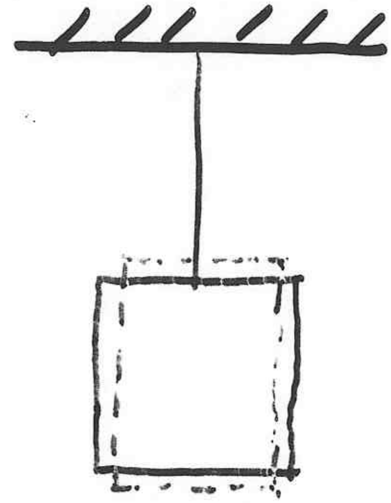
2. MAKE Q HIGH

THERMAL NOISE IN GW INTERFEROMETERS



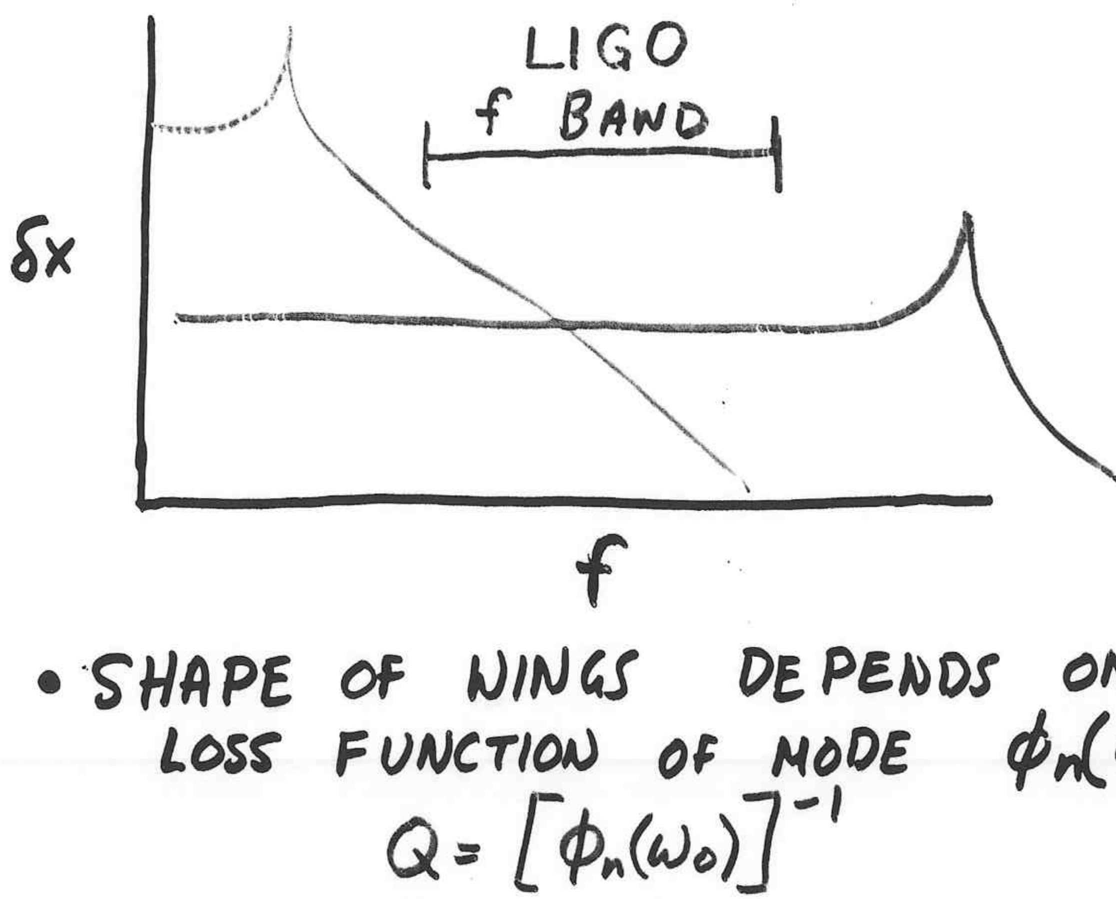
SUSPENSION MODES

$f \sim 1$ Hz



INTERNAL MODES

$f \gtrsim 20$ kHz



- SHAPE OF WINGS DEPENDS ON LOSS FUNCTION OF MODE $\phi_n(\omega)$

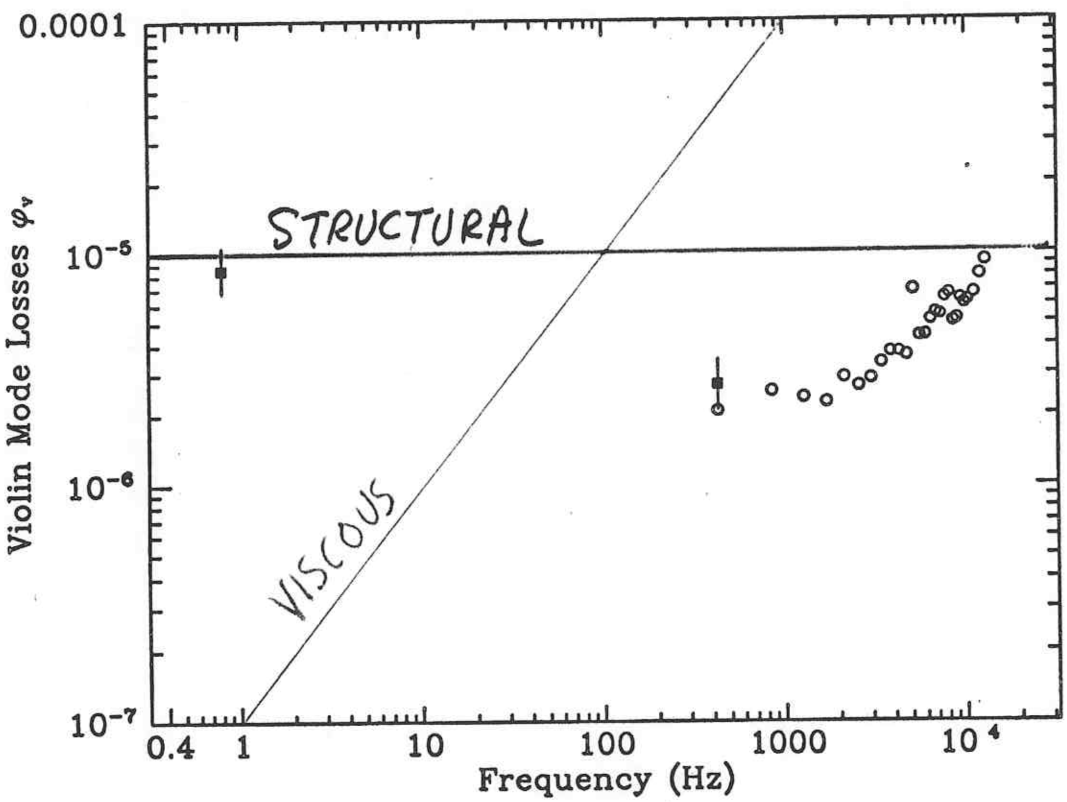
$$Q = \left[\phi_n(\omega_0)\right]^{-1}$$

- COMMON MODELS $\phi \propto \omega$ "VISCOUS"

  $\phi =$ CONST. "STRUCTURAL"

Suspension Thermal Noise

- Have Established Link Between Loss Mechanisms in Pendulum Mode and Violin Modes
- Makes Violin Q Measurements an Important Diagnostic for Suspension Thermal Noise

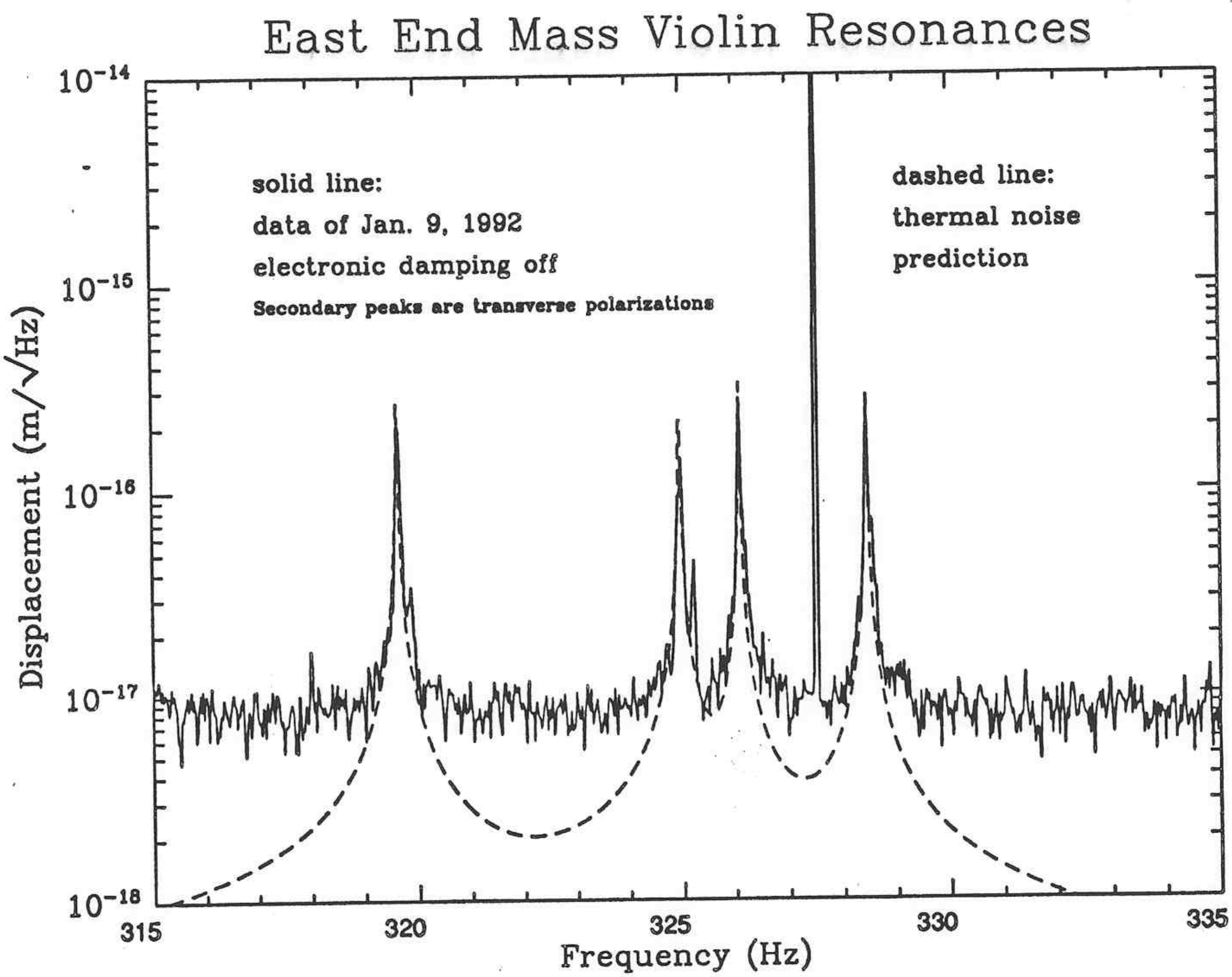


- Data for Steel Wire Suspension System Indicate Best Model for Thermal Noise Uses Frequency Independent Loss Function

LIGO

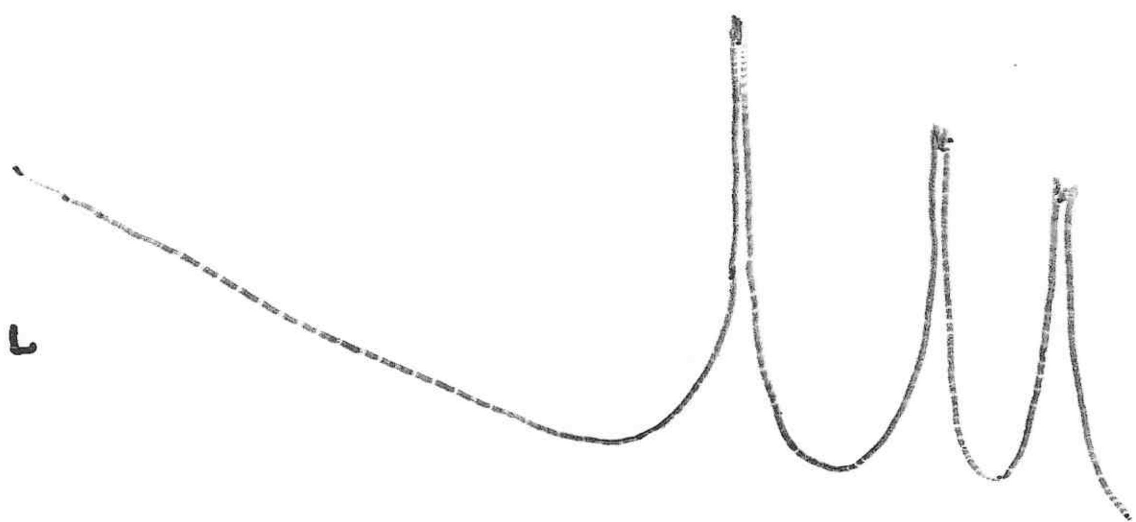
Suspension Thermal Noise

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



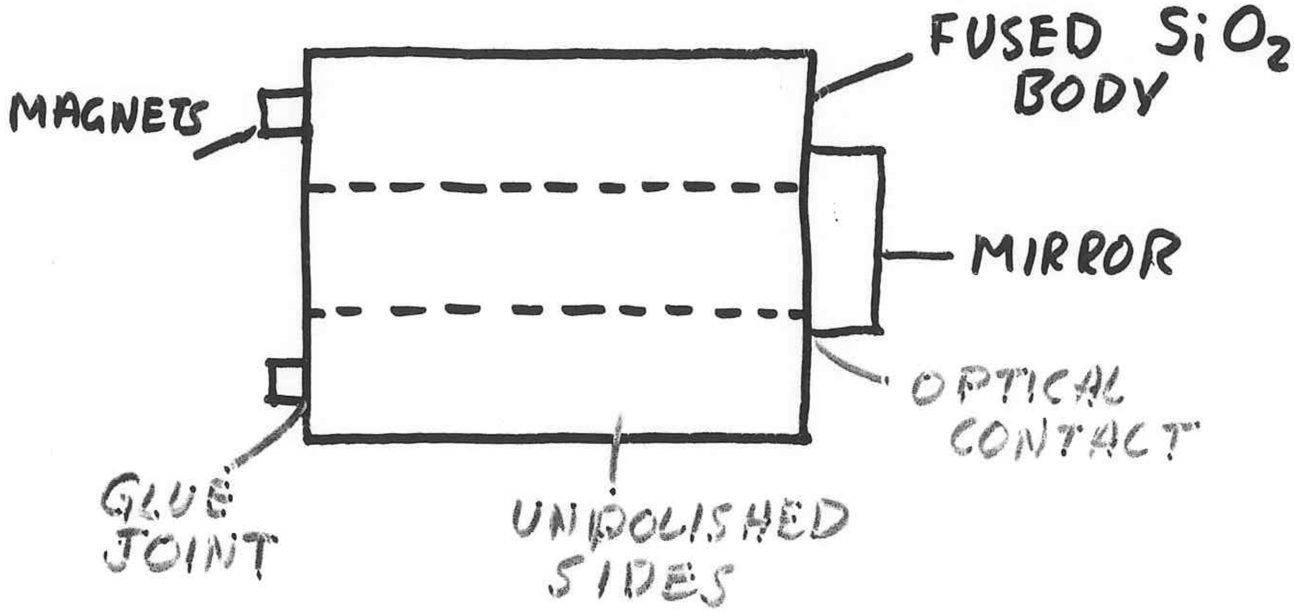
LIGO

SUSPENSION THERMAL NOISE



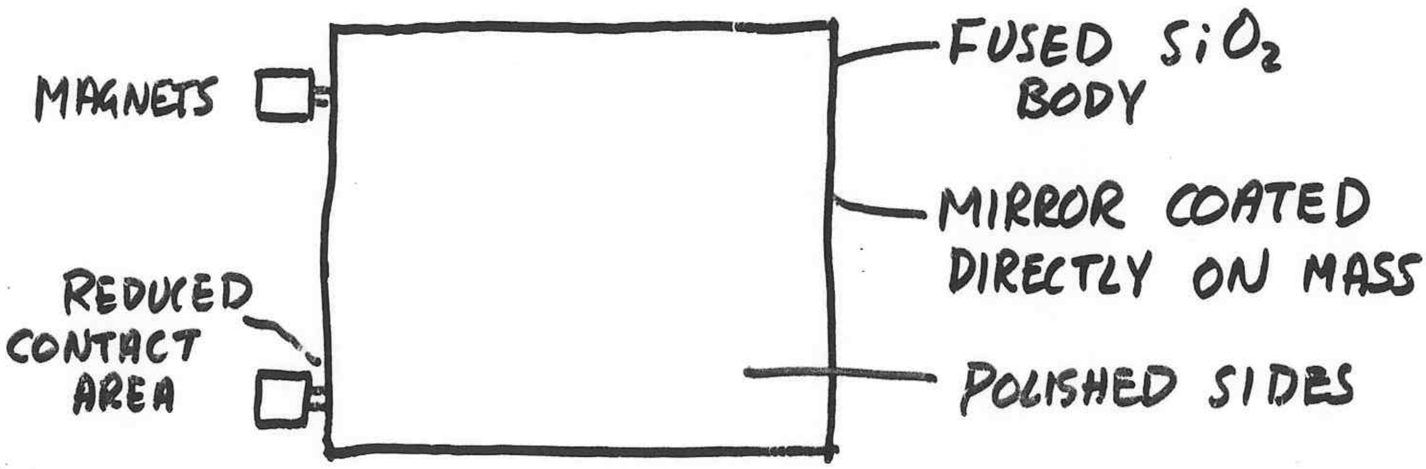
INTERNAL MODES

PRE-1994 TEST MASSES

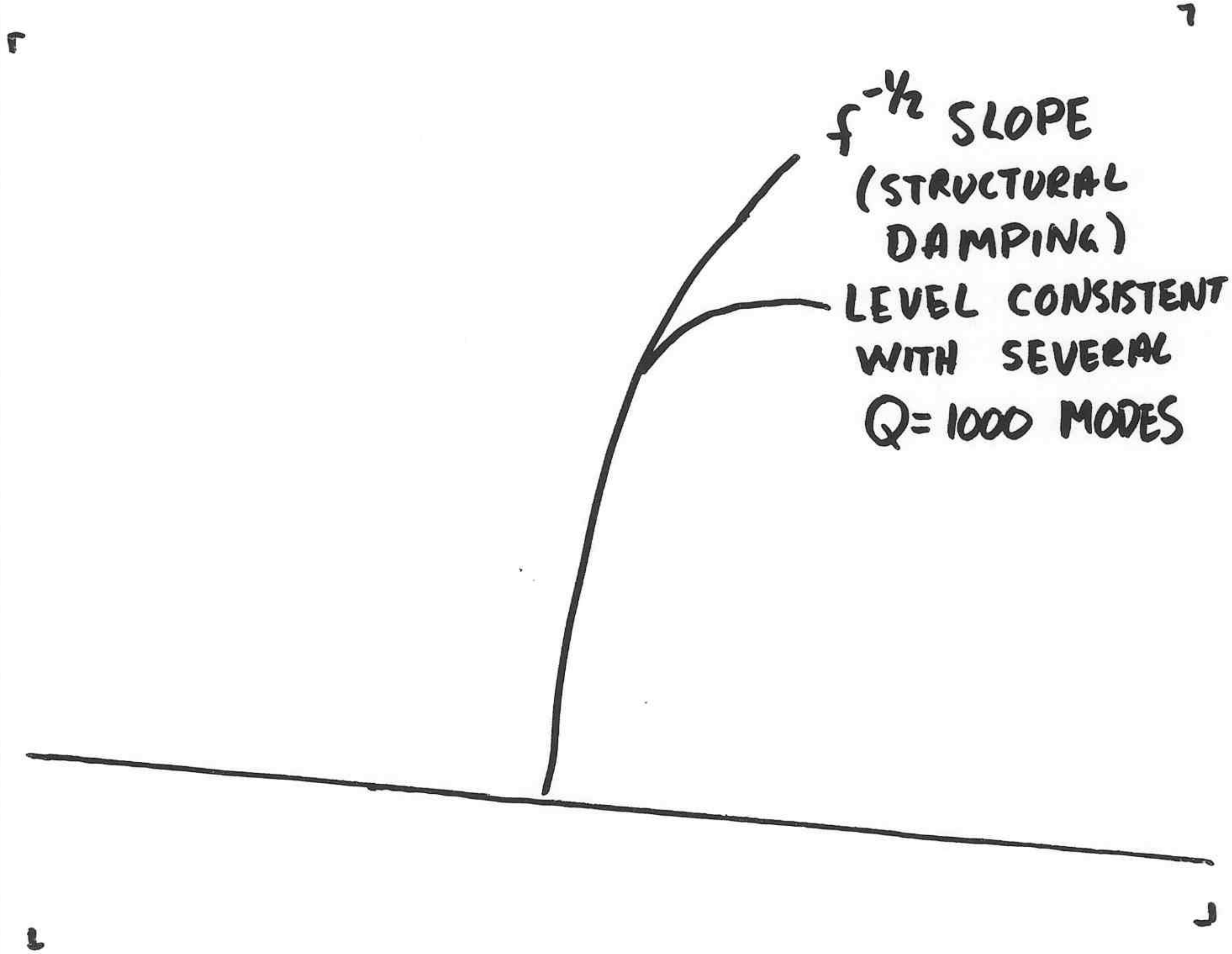


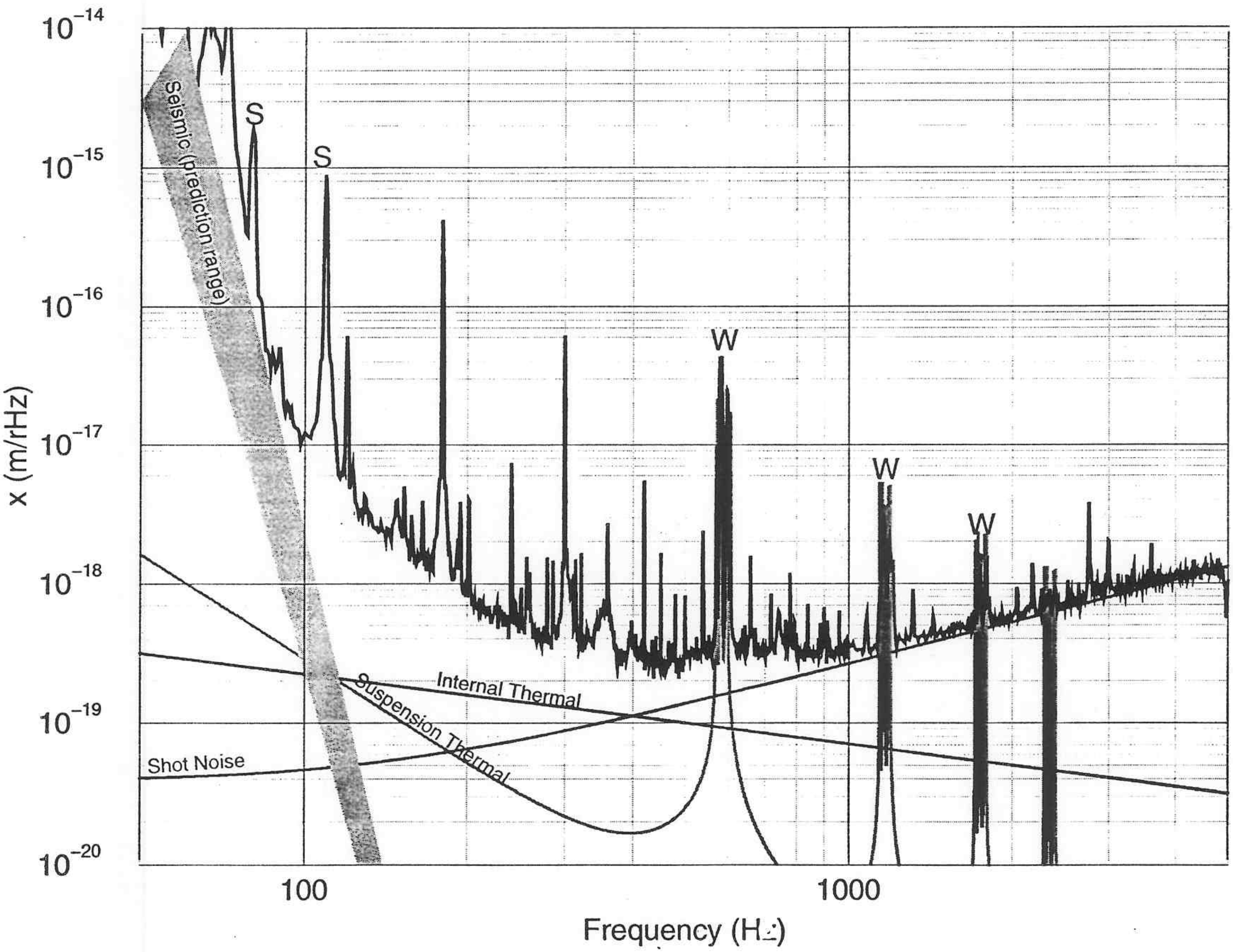
$$Q_{INTERNAL} \sim 800 - 50{,}000$$

NEW TEST MASSES INSTALLED IN 1994



$$\phi_n (f < 5\,kHz) \leq 2.5 \times 10^{-6}$$


$f^{-1/2}$ SLOPE
(STRUCTURAL
DAMPING)
LEVEL CONSISTENT
WITH SEVERAL
Q=1000 MODES



10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
x (m/rHz)
Seismic (prediction range)
S
S
W
W
W
Internal Thermal
Suspension Thermal
Shot Noise
100
1000
Frequency (Hz)

THE QUESTION EVERYONE ASKS

WILL LIGO DETECT GRAVITATIONAL WAVES?

WHEN WILL LIGO DETECT GRAVITATIONAL WAVES?

BEYOND 2000

- LIGO FACILITIES DESIGNED TO HOUSE MUCH MORE SENSITIVE DETECTORS
- DIRECTIONS FOR FUTURE DETECTORS
  - HIGHER LASER POWER
    100 W ? 1 kW ?
  - BETTER OPTICAL COMPONENTS
    BETTER FIGURE, LOWER LOSSES
  - NEW OPTICAL CONFIGURATIONS
    SIGNAL RECYCLING? SAGNAC ?
  - QND ? SQUEEZED LIGHT ?
  - ACTIVE COMPENSATION FOR SEISMIC MOTION
  - MATERIALS AND DESIGNS FOR LOWER THERMAL NOISE

LIMITING PERFORMANCE DUE TO FACILITIES