LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Viewgraphs	G950098-00-	R	11/29/95
Document Type	*Doc Number*	*Group-Id*	*Date*

Searching for Gravitational Waves with LIGO (presentation at Notre Dame)

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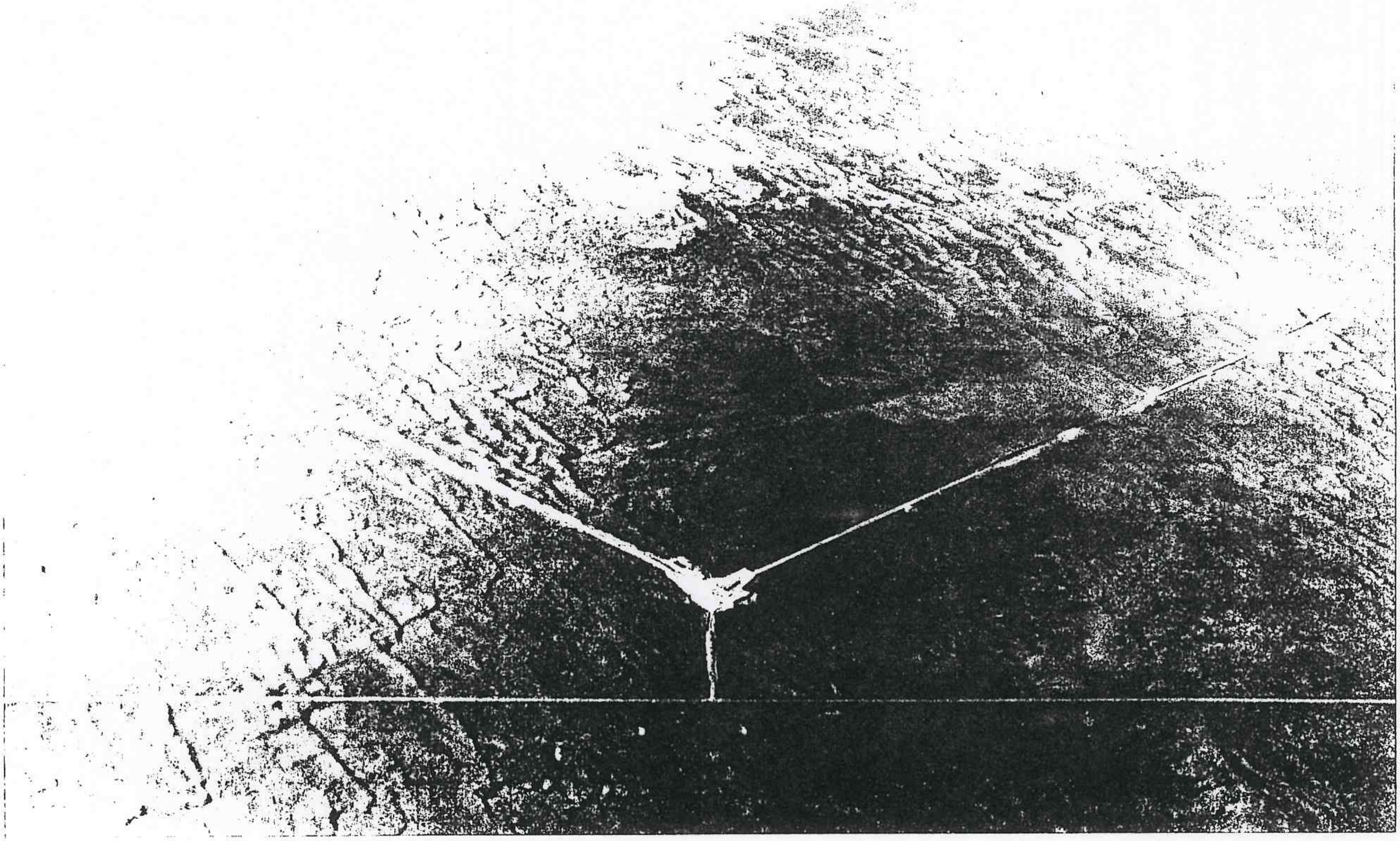
SEARCHING FOR GRAVITATIONAL WAVES WITH LIGO

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

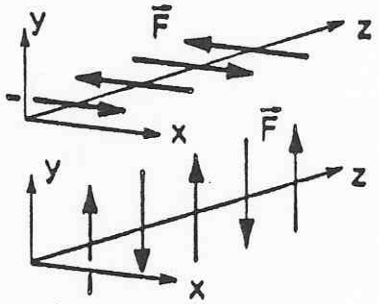
Electromagnetic

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

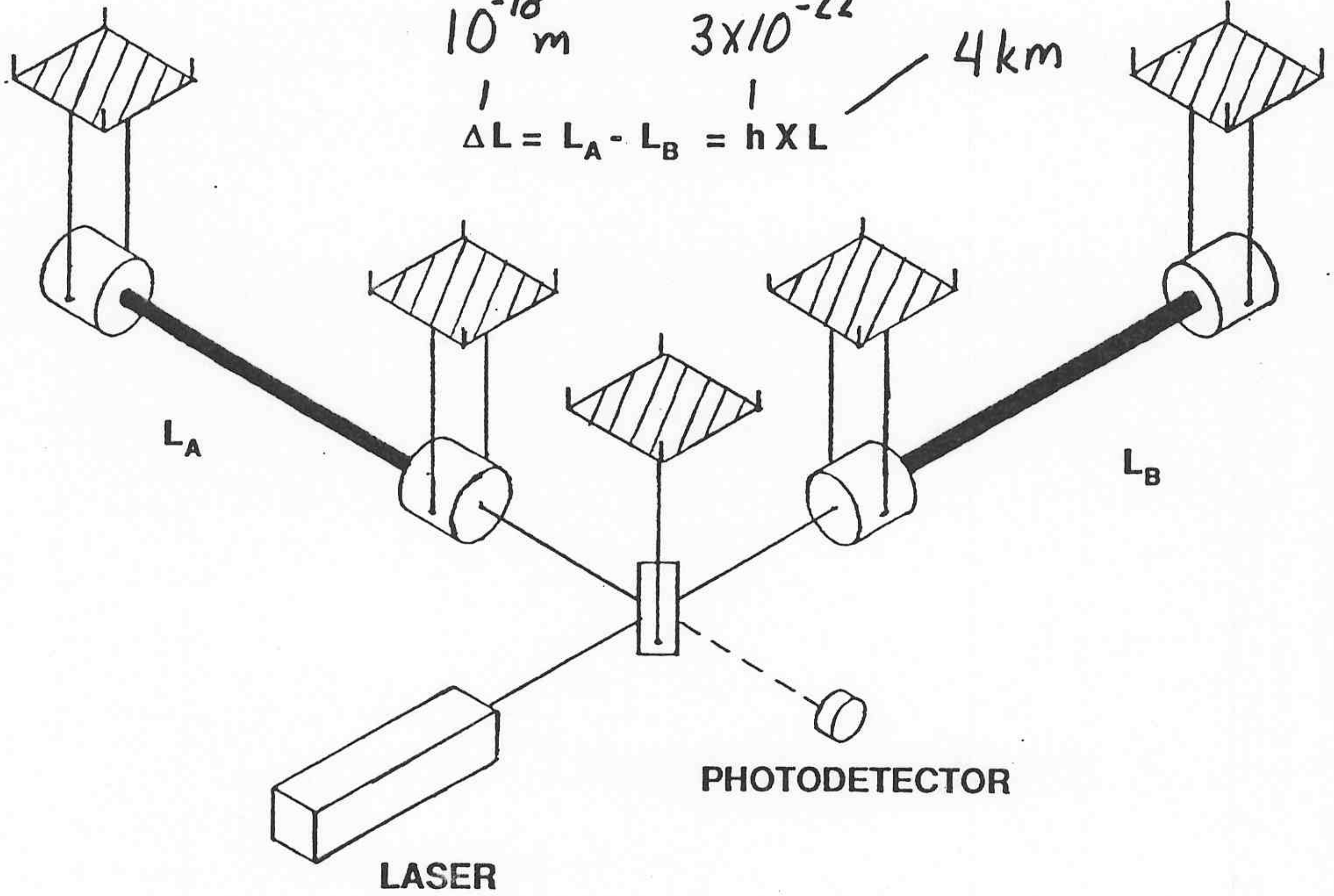
$$h \sim \frac{G}{C^4}\,\frac{\ddot{Q}}{r}$$

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

LIGO

SCHEMATIC INTERFEROMETRIC DETECTOR

$$\overset{10^{-18}\,m}{\Delta L} = L_A - L_B = \overset{3\times10^{-22}}{h} \times \overset{4km}{L}$$



EM vs. GW Sources

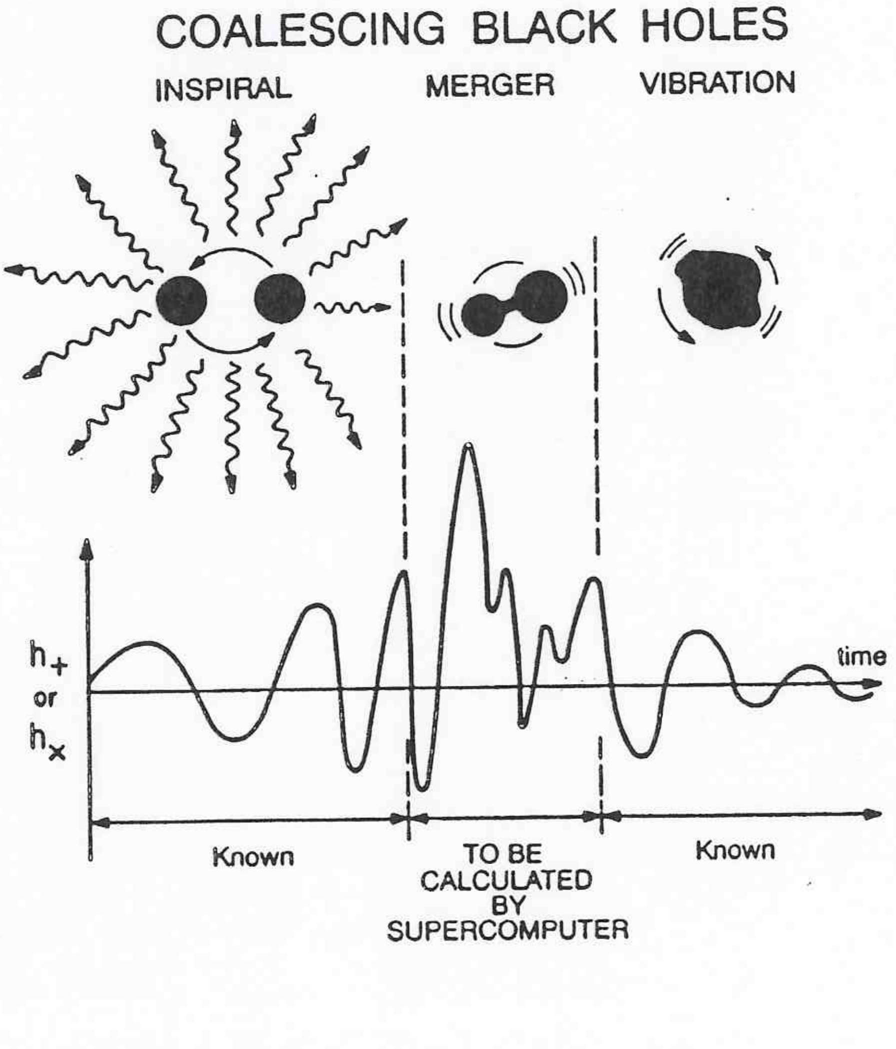
	Electromagnetic Radiation	Gravitational Radiation
Emission Mechanism	Individual Atoms, Molecules, Electrons Incoherent Superposition	Large Scale Mass Motion Coherent Superposition
Examples of Sources	Stellar Atmospheres Interstellar Gas	Supernova Core Binary Black-Holes
Interaction With Matter	Dispersion, 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

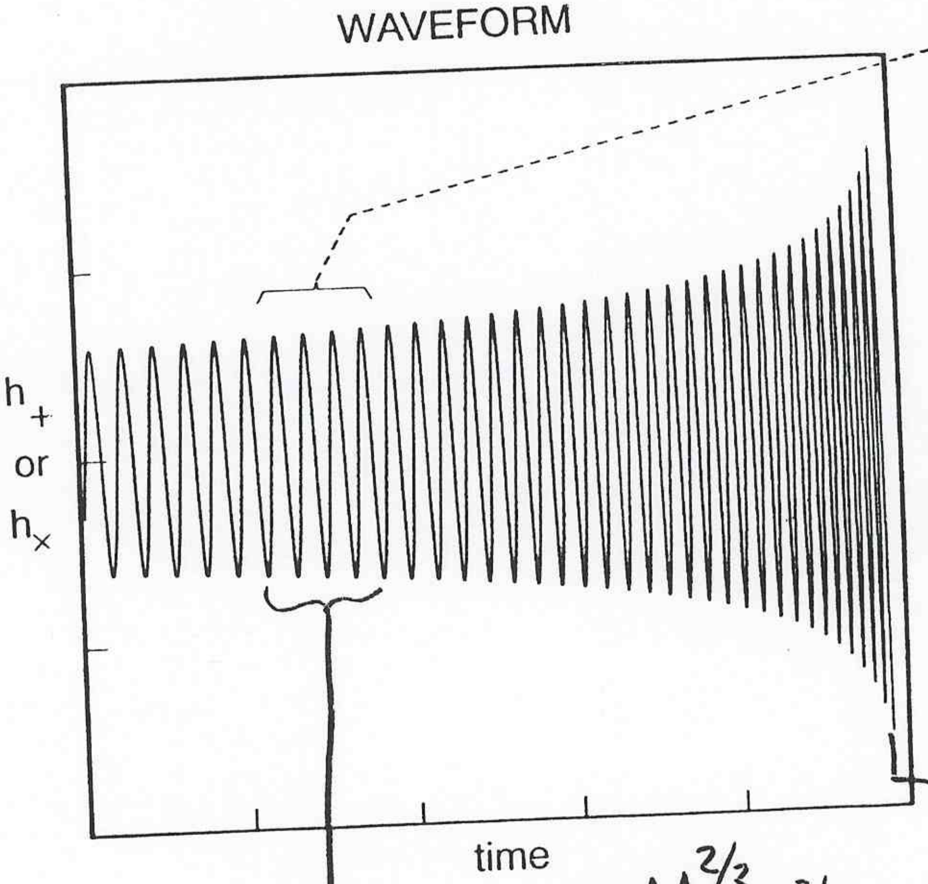
- Great Uncertainty About GW Sources, Either in Strength or Frequency of Occurrence
- Many (Most?) Gravitational Wave Sources May Never Be Seen Electromagnetically
- Potential For Great Surprises!

GW Information Obtained by Waveform Analysis

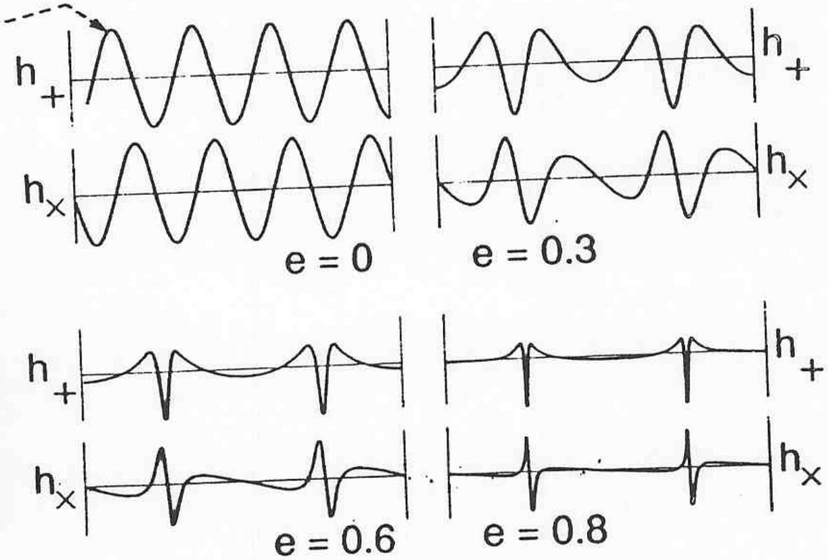
- Almost All Electromagnetic Astronomy Is Based on Spatial or Spectral Analysis
- Extraction of Information From Gravitational Wave Depends on Waveform Analysis



COMPACT BINARY



DEPENDENCE ON e, FOR $\iota = 90°$:



DEPENDENCE ON ι, FOR $e = 0$:

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

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

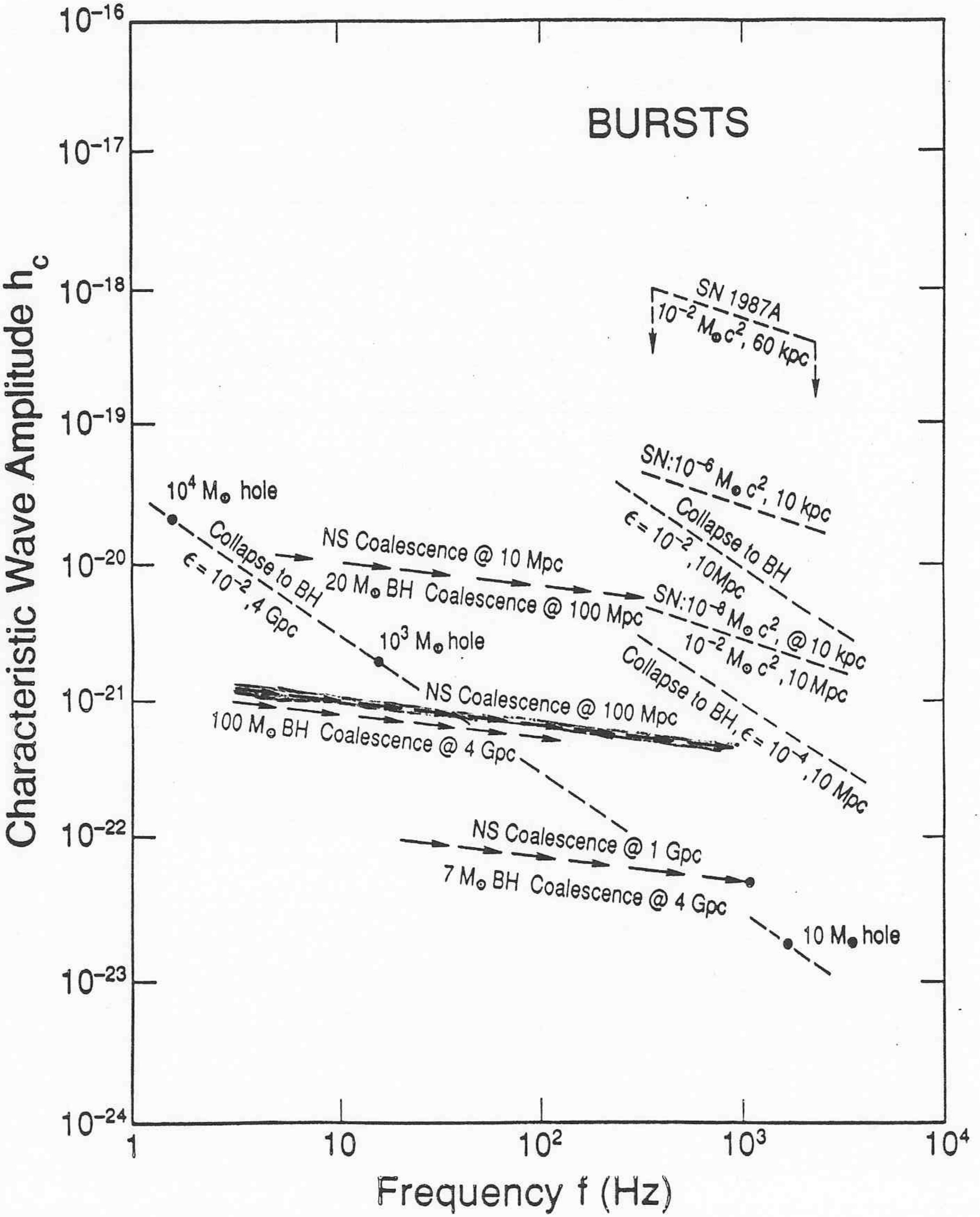
$$\frac{df}{dt} \propto \mu M^{2/3} f^{11/3}$$

FINAL FREQUENCY

$\Rightarrow M$

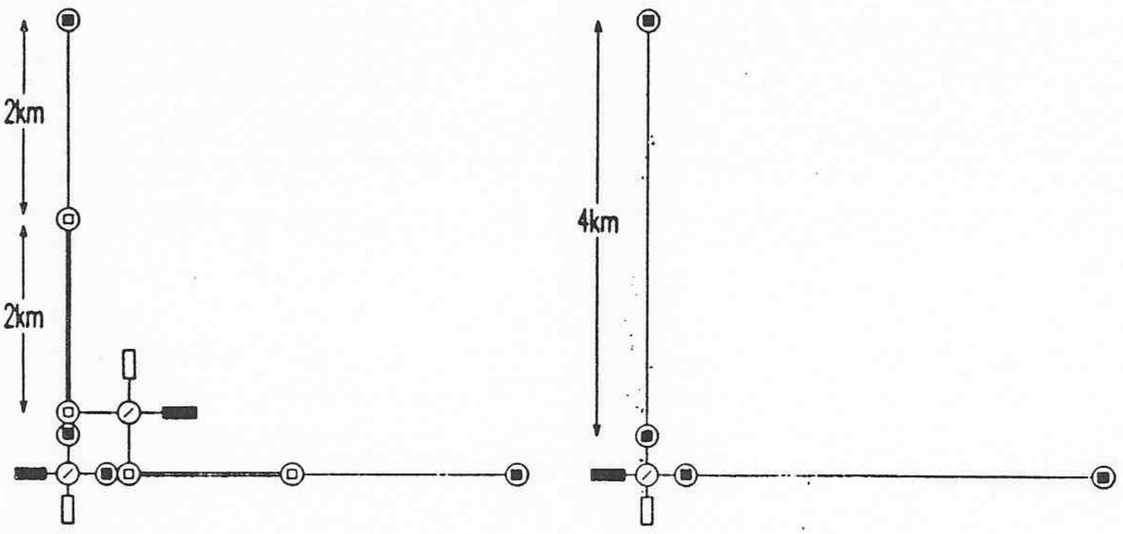
NS-NS BINARIES

- 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

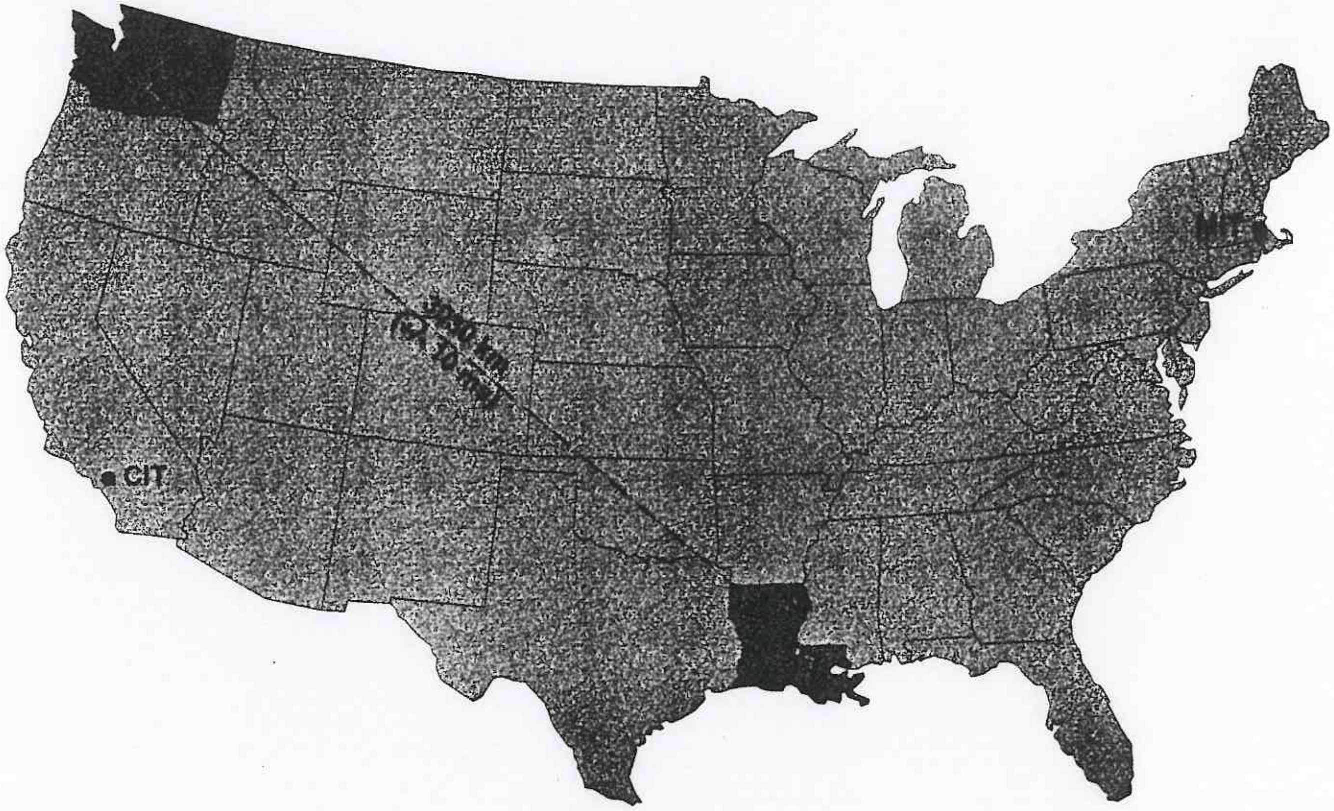

BURSTS
Characteristic Wave Amplitude h_c
Frequency f (Hz)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
1
10
10^2
10^3
10^4
SN 1987A
$10^{-2}\ M_\odot c^2$, 60 kpc
SN: $10^{-6}\ M_\odot c^2$, 10 kpc
Collapse to BH
$\epsilon = 10^{-2}$, 10Mpc
SN: $10^{-8}\ M_\odot c^2$,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



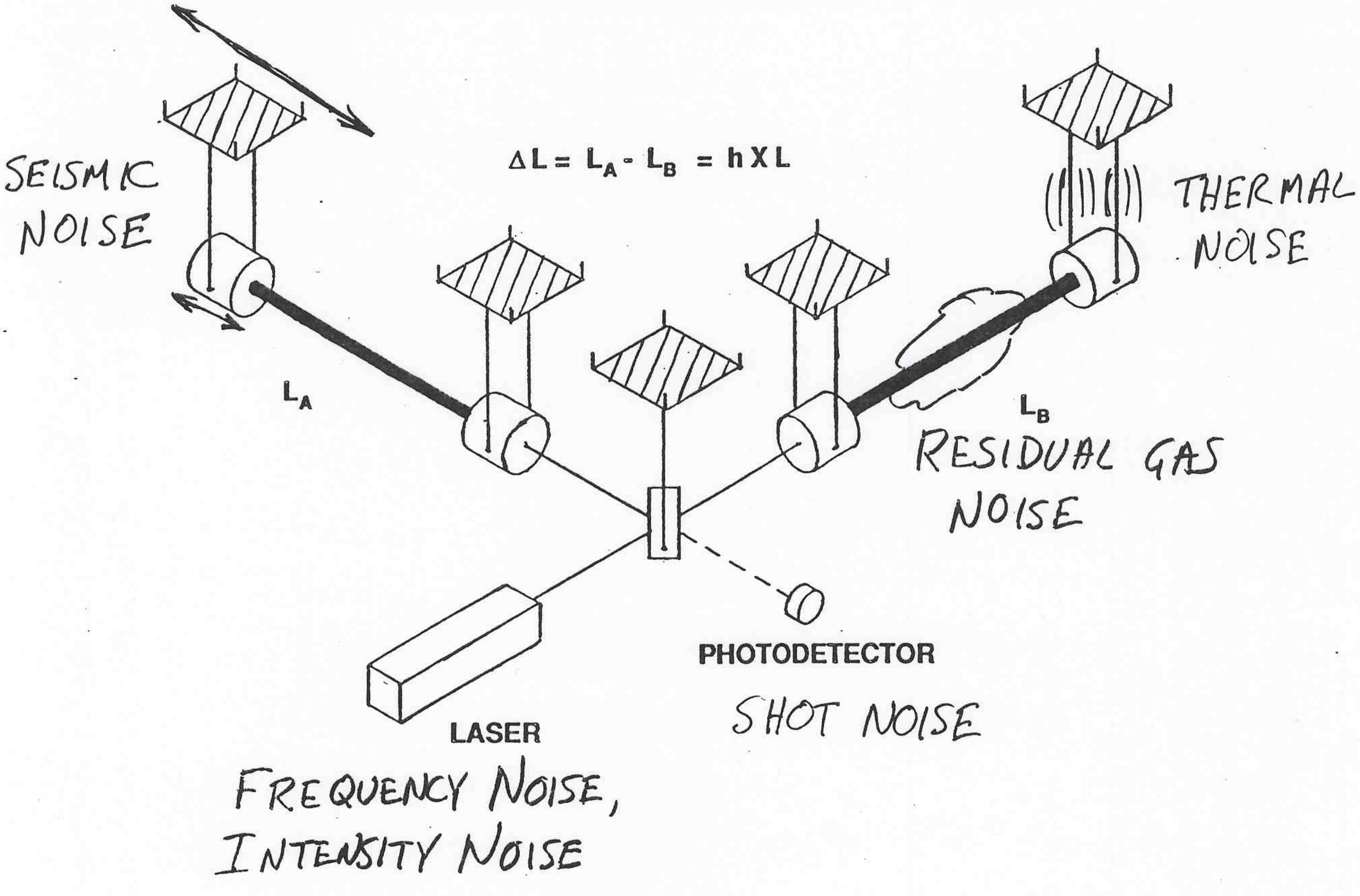
HANFORD, WASHINGTON

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

LIVINGSTON, LOUISIANA

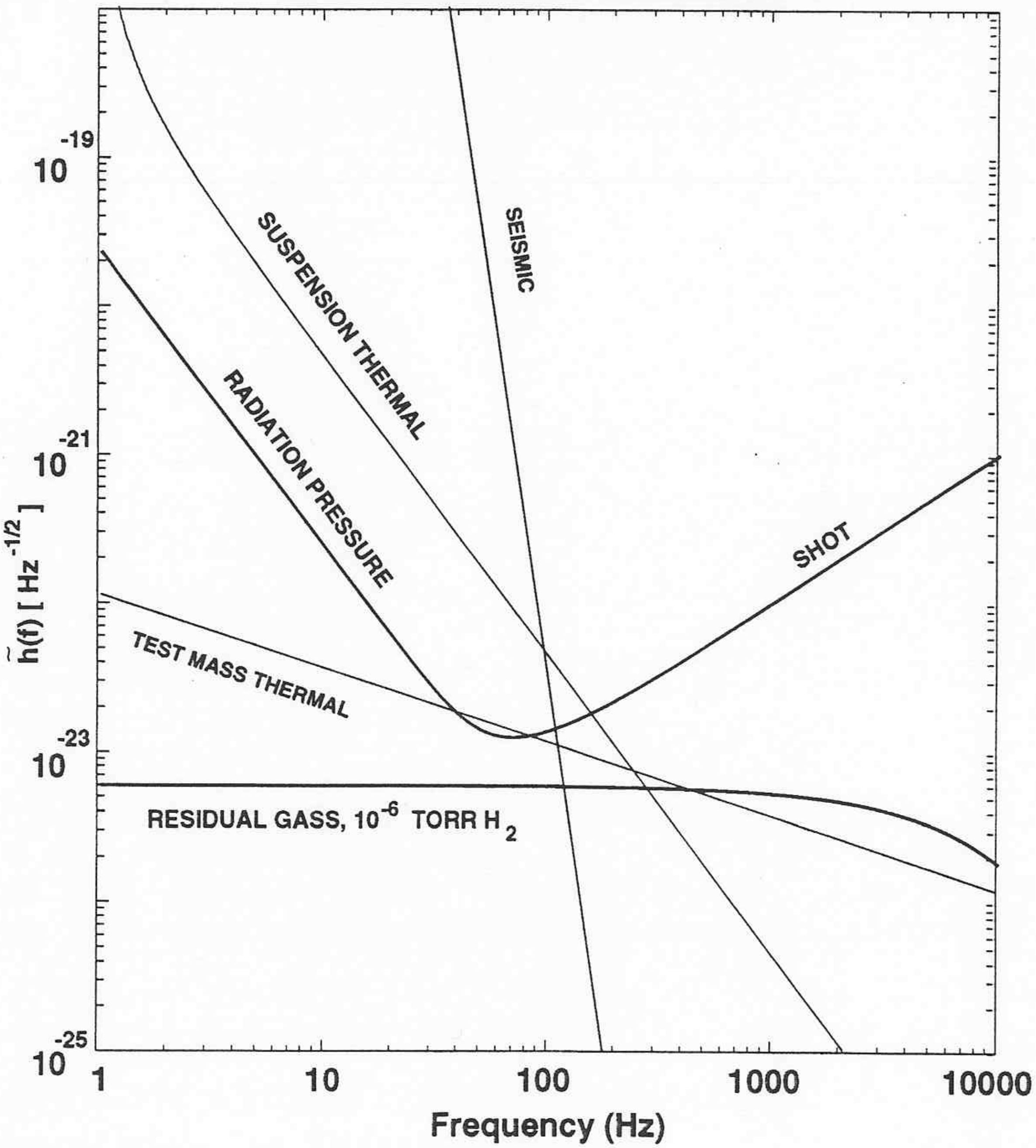
- LOCATED IN FORESTED RURAL AREA
- MIXED FOREST; LOW-LYING; POOR DRAINAGE
- APPROX. 50 KM FROM BATON ROUGE, LA (POPULATION :450,000)

SCHEMATIC INTERFEROMETRIC DETECTOR



INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL

INITIAL INTERFEROMETER SENSITIVITY



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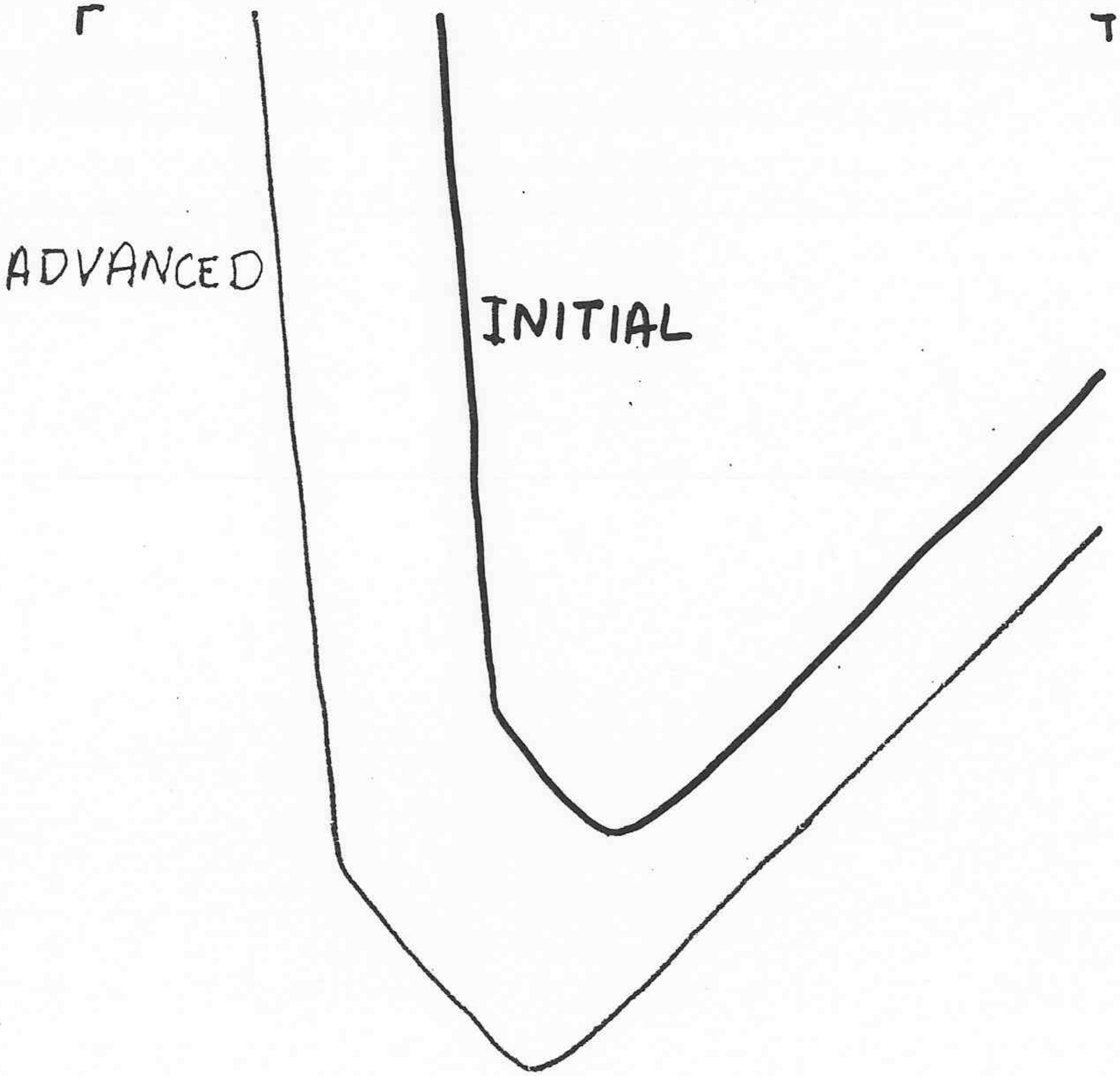
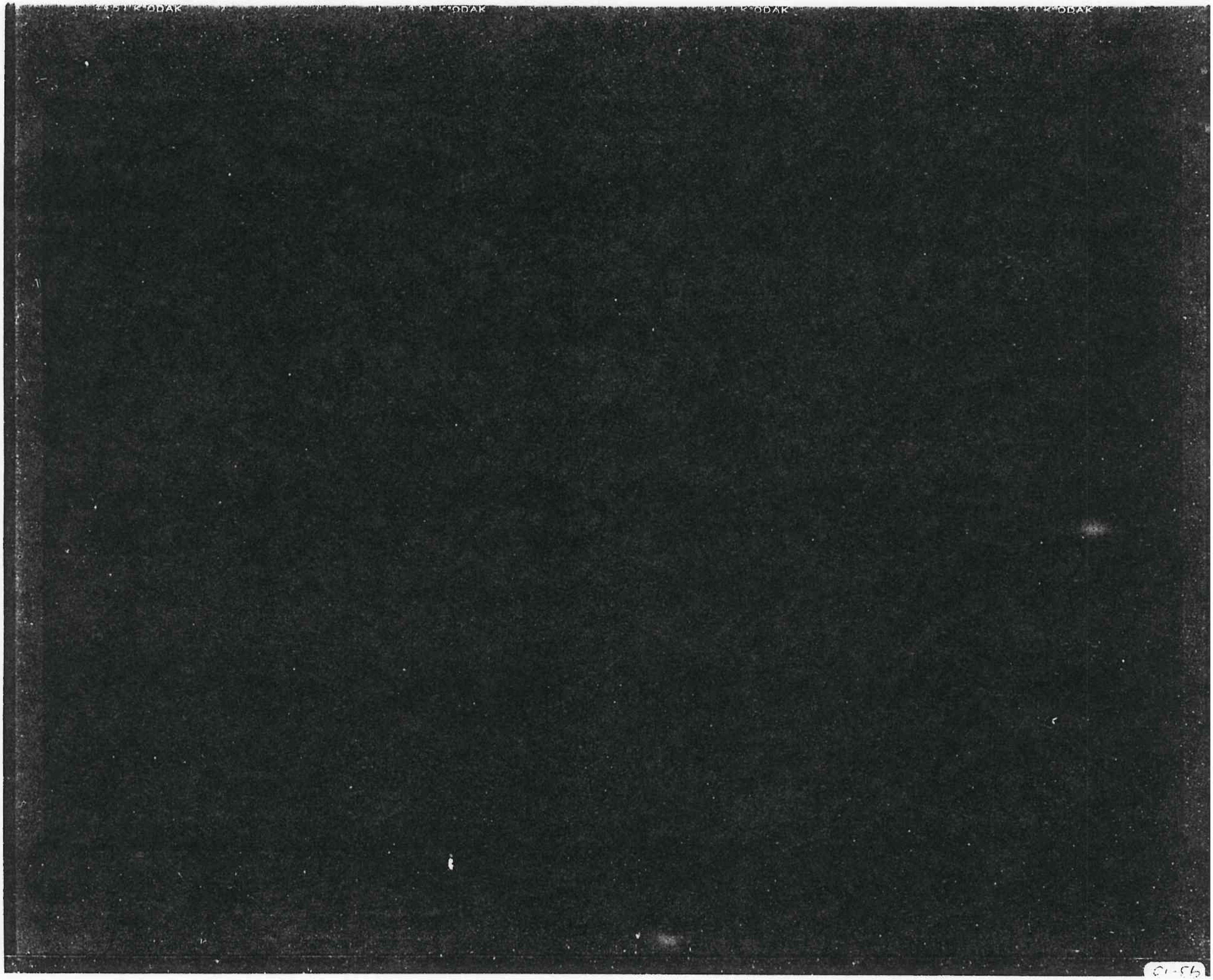


SKW



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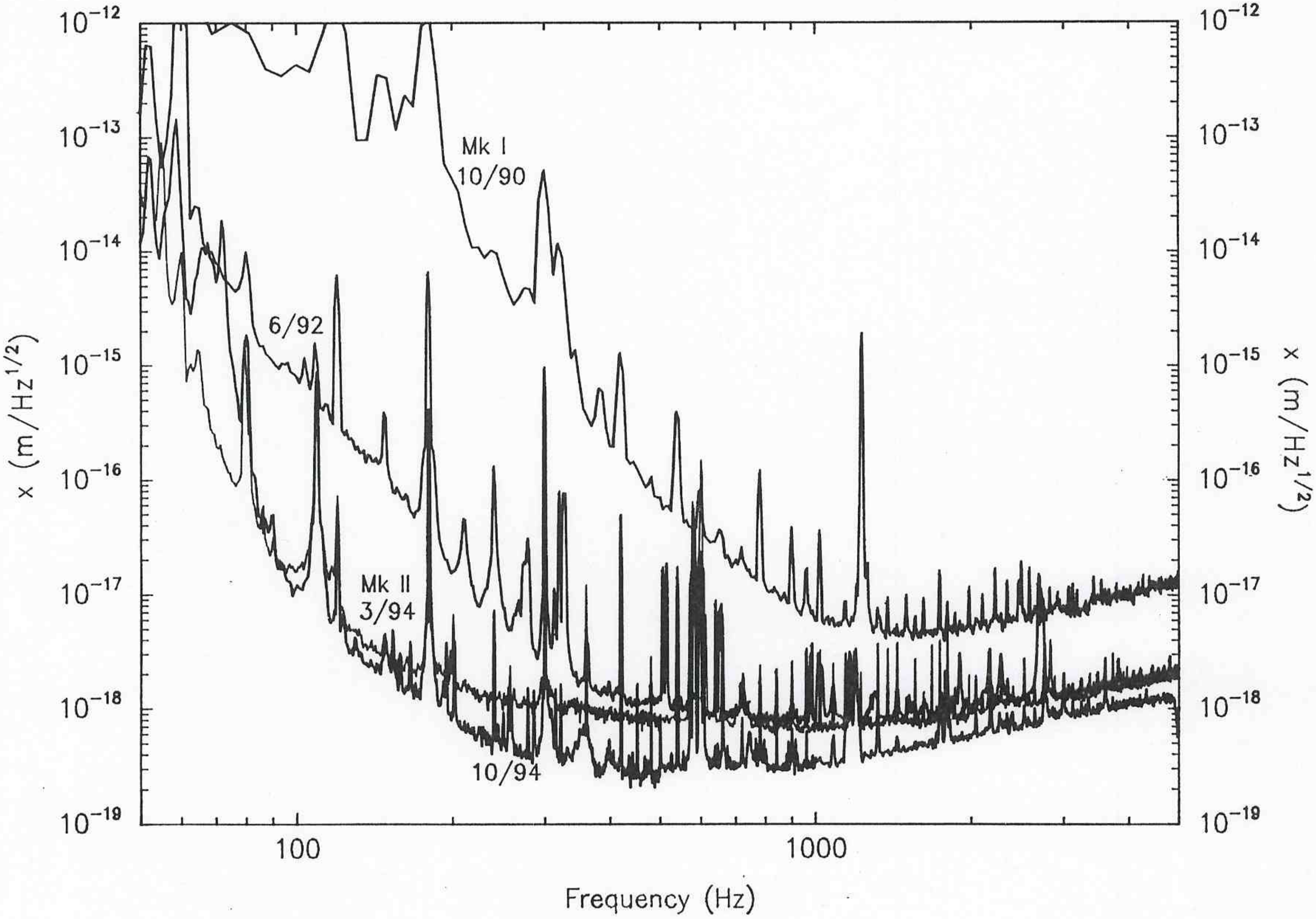
Displacement Sensitivity of Caltech 40 m Interferometer



Shot Noise

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

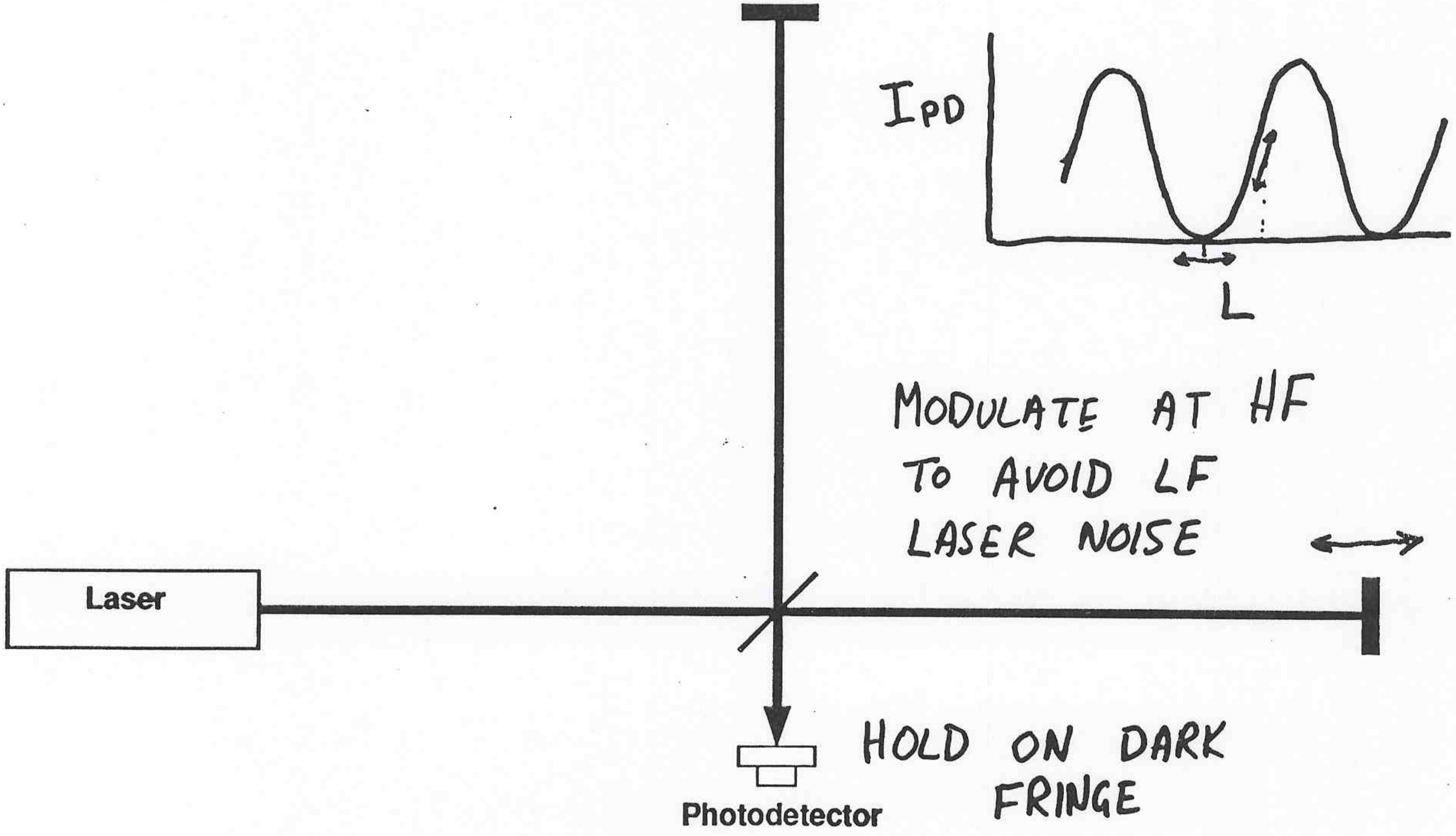
PROPERTY OF
INTERFEROMETER
OPTICAL CONFIGURATION
(MIRROR R's, ETC.)

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

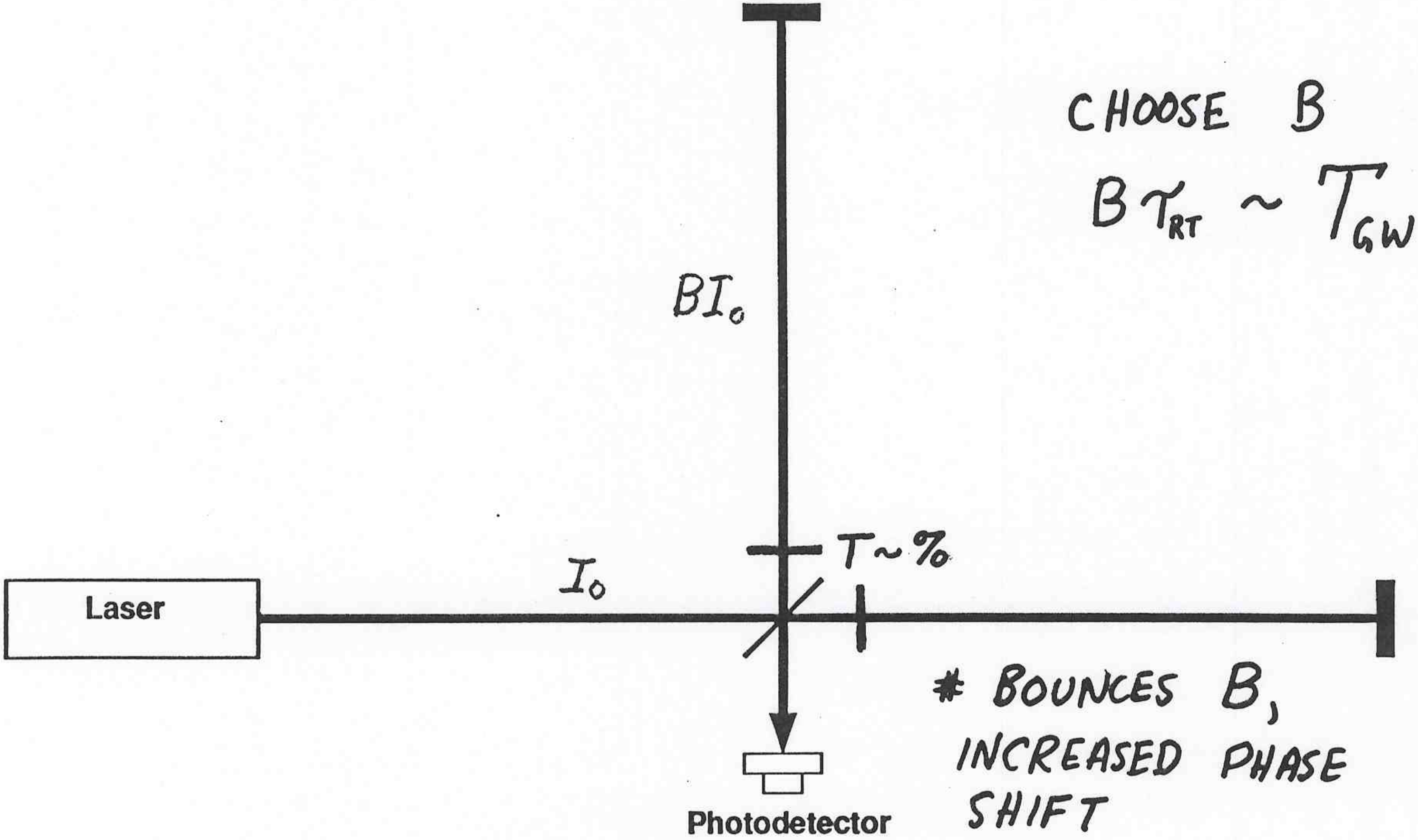
Optical Layout and Operation



MODULATE AT HF TO AVOID LF LASER NOISE

HOLD ON DARK FRINGE

Optical Layout and Operation

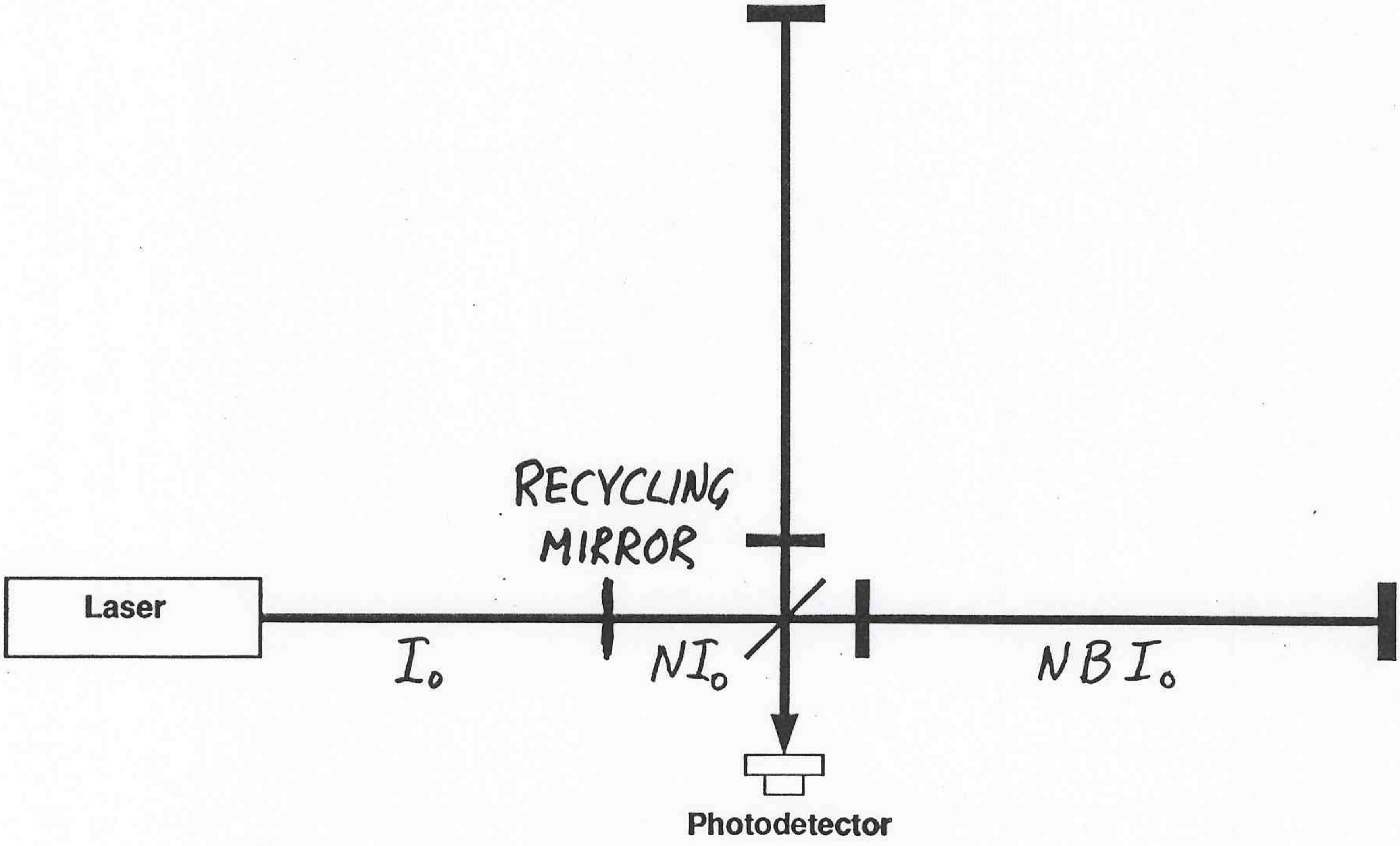


CHOOSE B

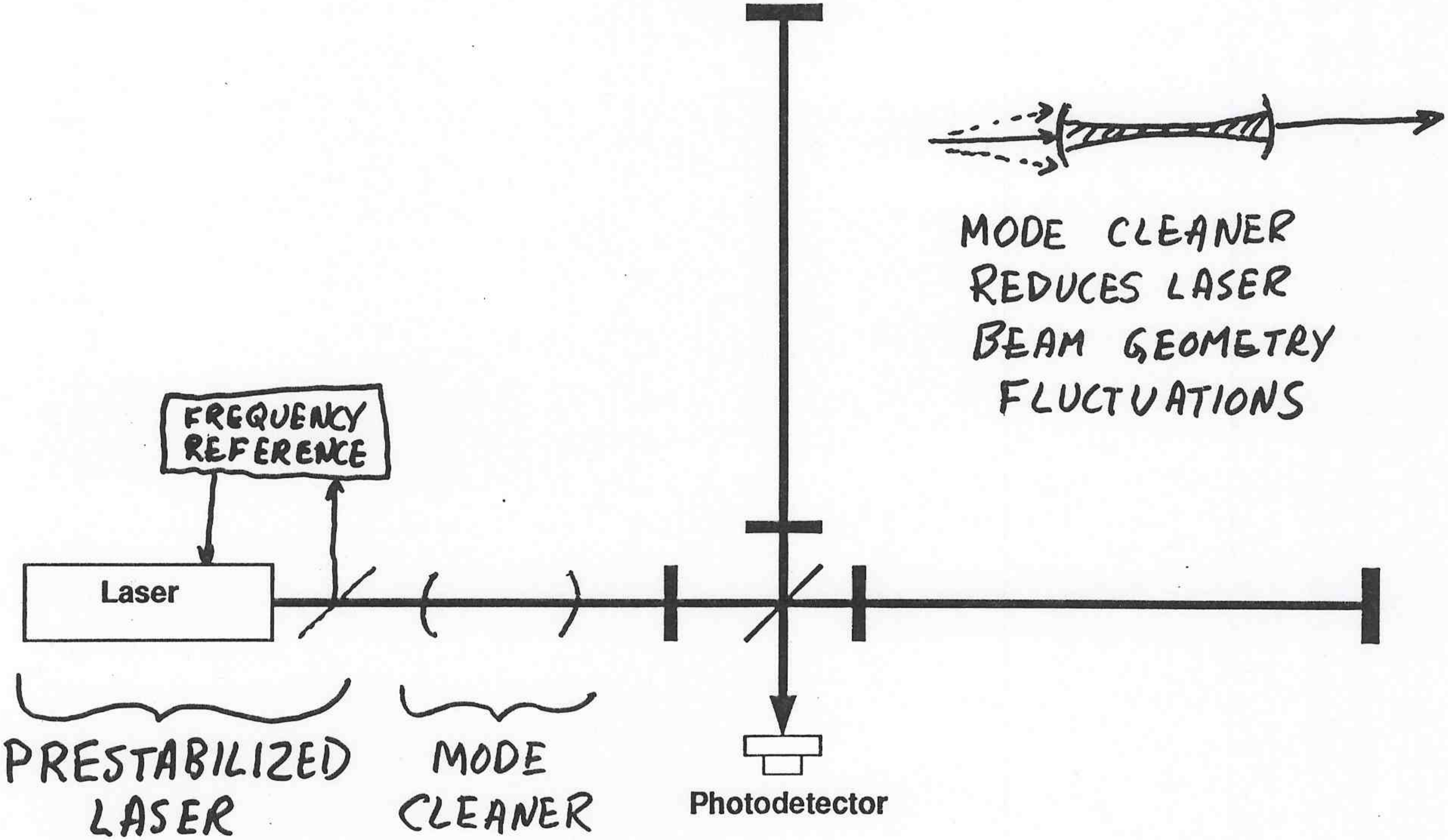
$B\tau_{RT} \sim T_{GW}$

BOUNCES B, INCREASED PHASE SHIFT

Optical Layout and Operation

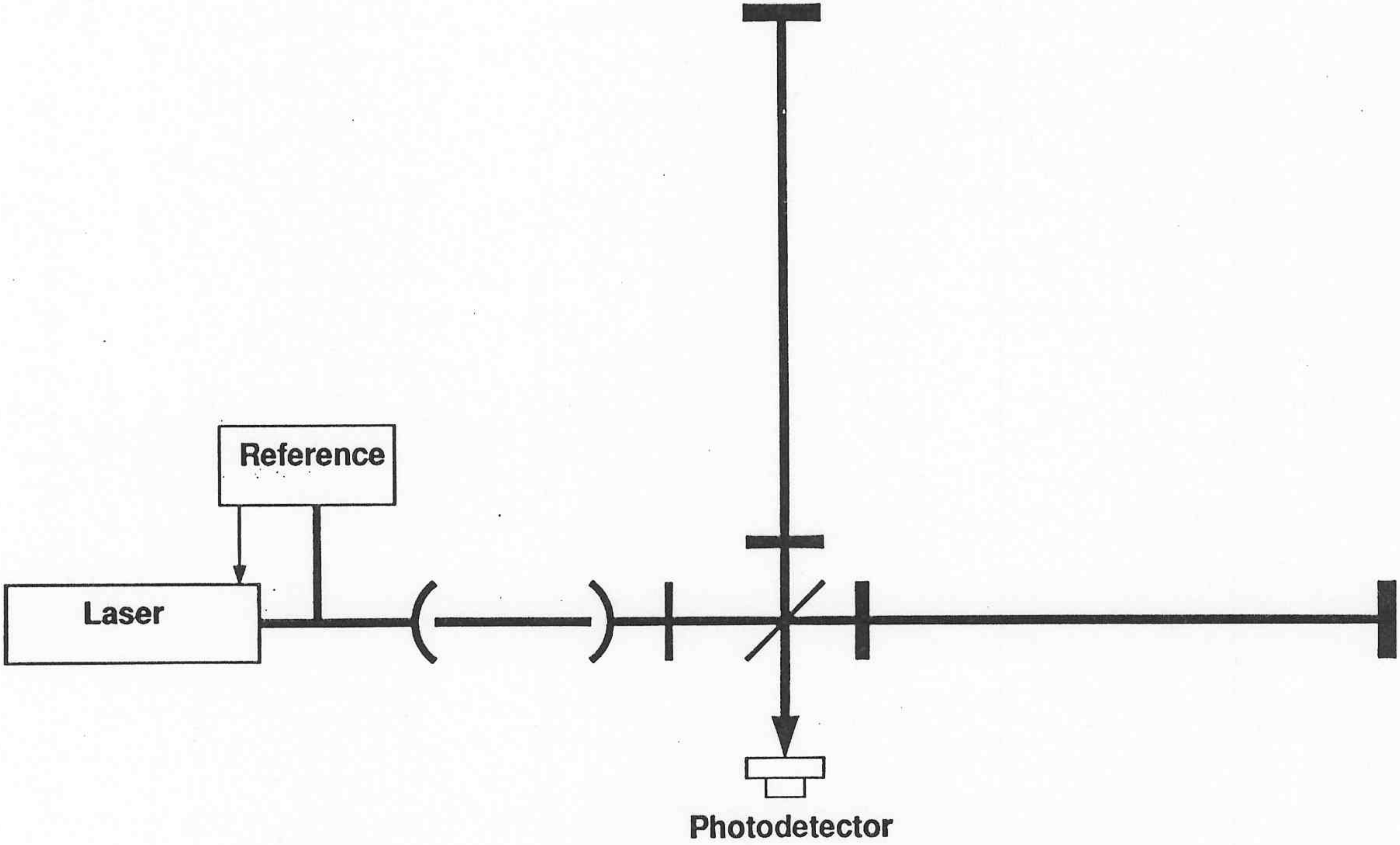


Optical Layout and Operation

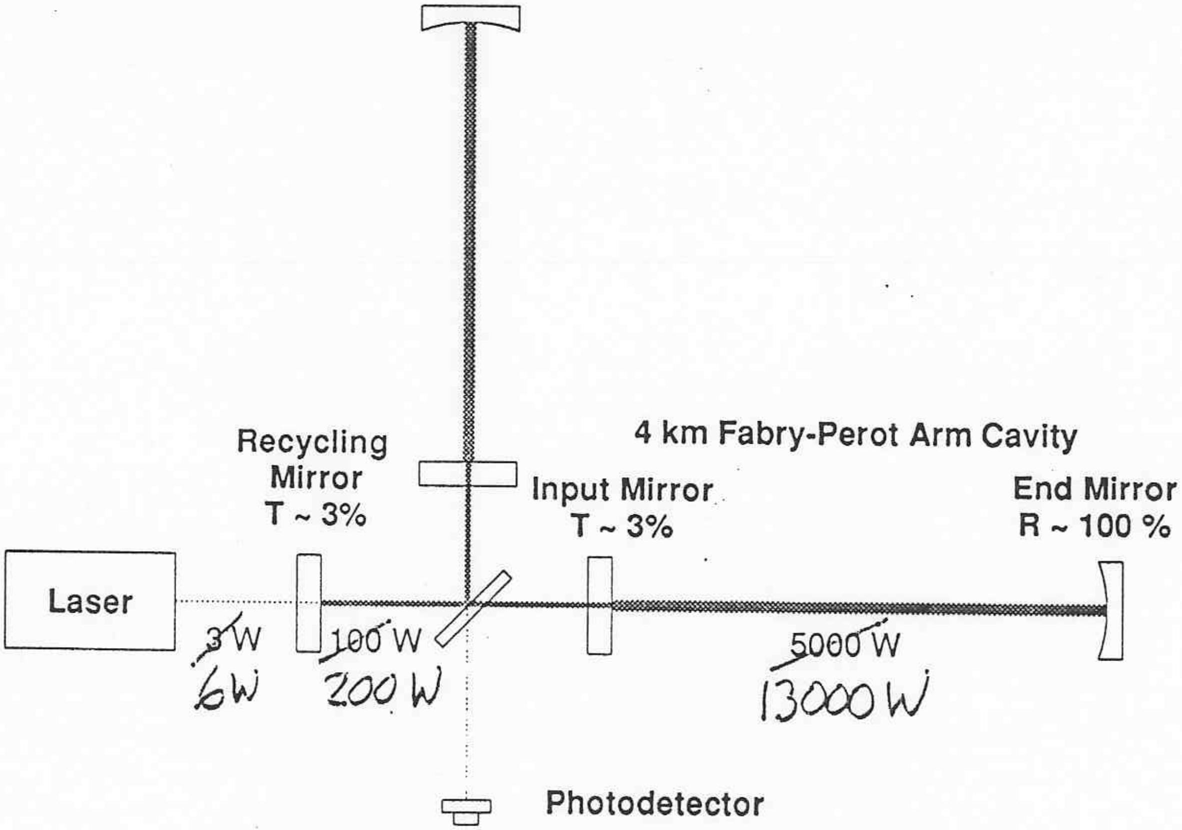


MODE CLEANER REDUCES LASER BEAM GEOMETRY FLUCTUATIONS

Optical Layout and Operation



INITIAL INTERFEROMETER CONFIGURATION

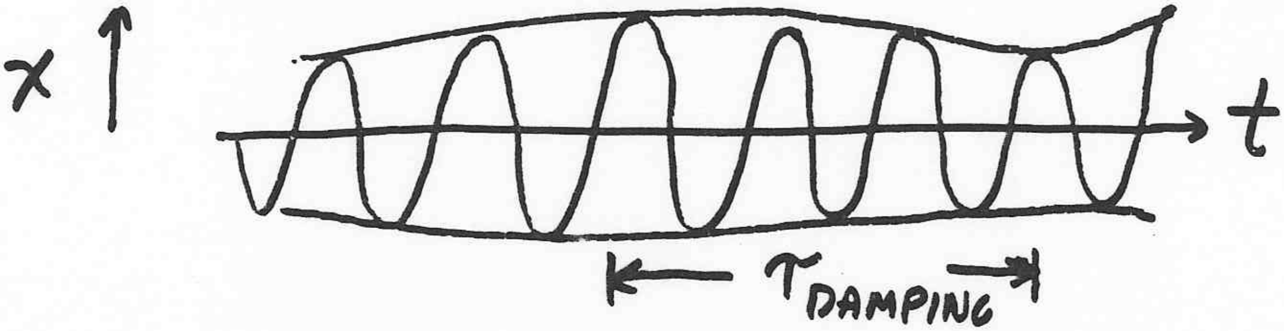


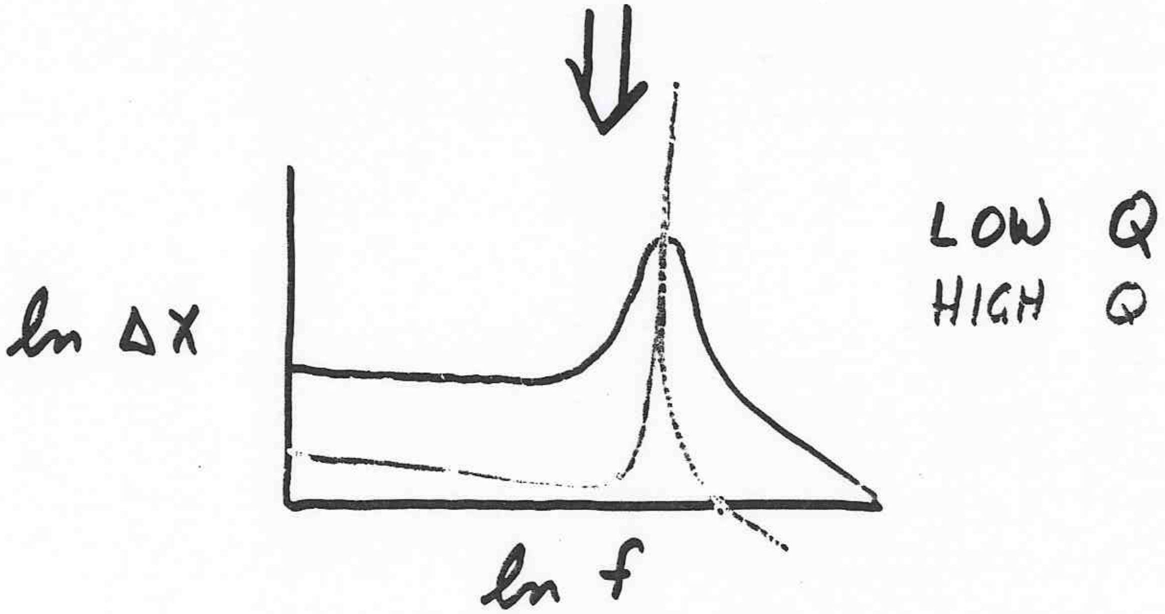
- FABRY-PEROT ARM CAVITIES
- MODEST INPUT POWER ~~(2 - 3 W)~~ Nd:YAG
- INITIAL LASER: ~~Ar$^+$ λ = 0.5145 μm~~ POWER RECYCLING $\lambda = 1.06\ \mu m$
- MODEST RECYCLING FACTOR ($\gamma \sim 30X$) $P = 10\ W$
- MODEST CAVITY FINESSE ($\eta \sim 50$)

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

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

EXCHANGE ENERGY WITH RESERVOIR



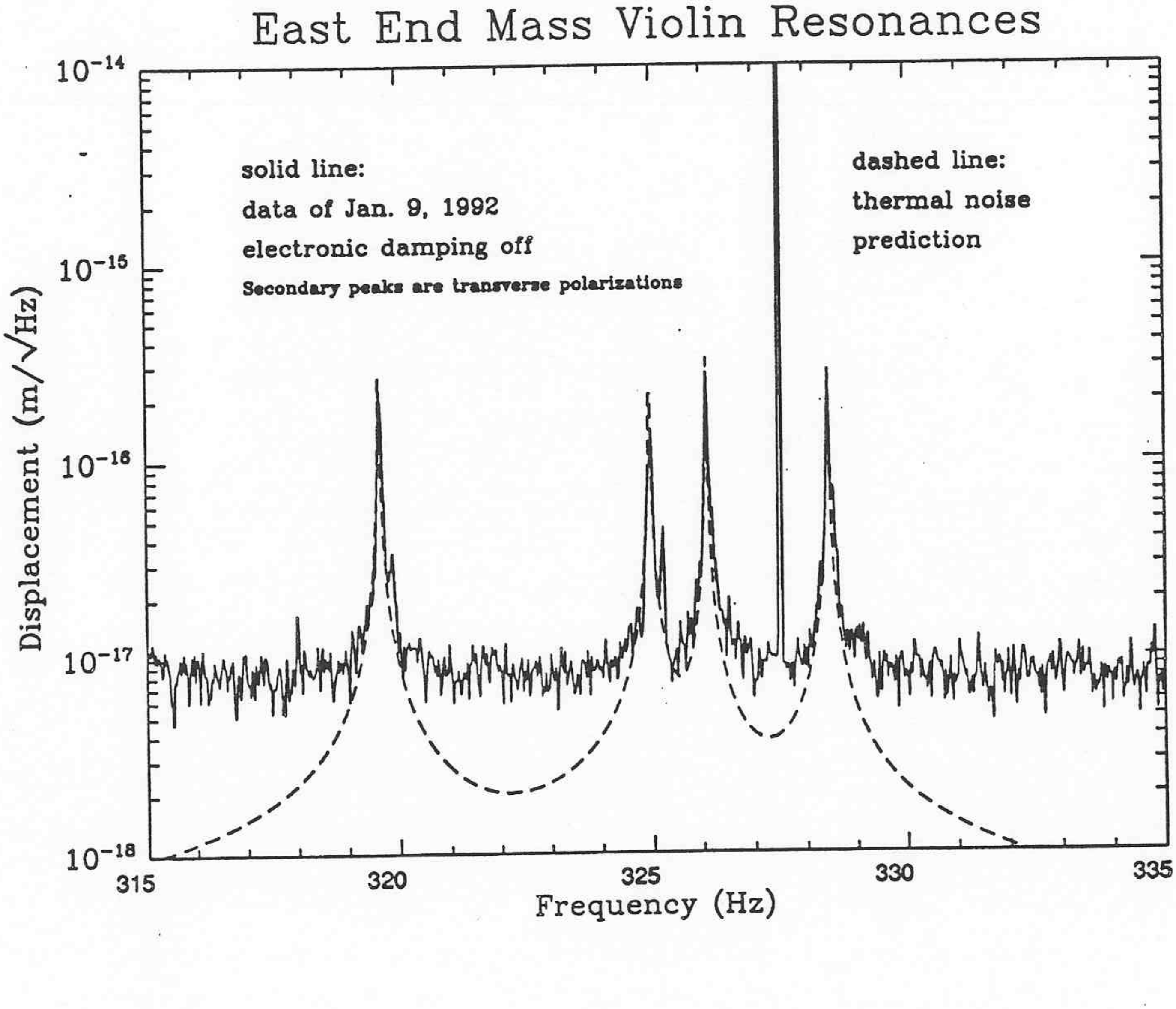


STRATEGY: 1. MOVE ω_0 OUTSIDE BAND OF INTEREST

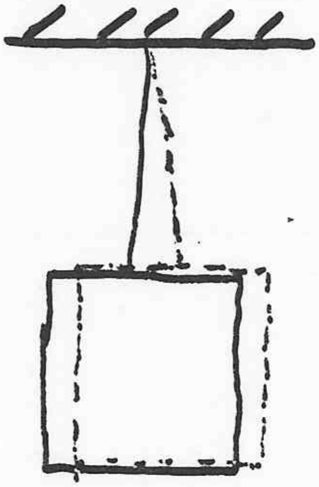
2. MAKE Q HIGH

Suspension Thermal Noise

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

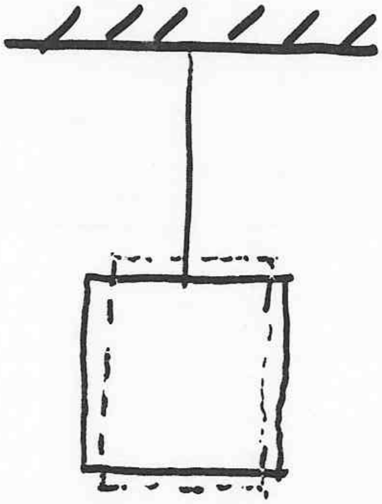


THERMAL NOISE IN GW INTERFEROMETERS



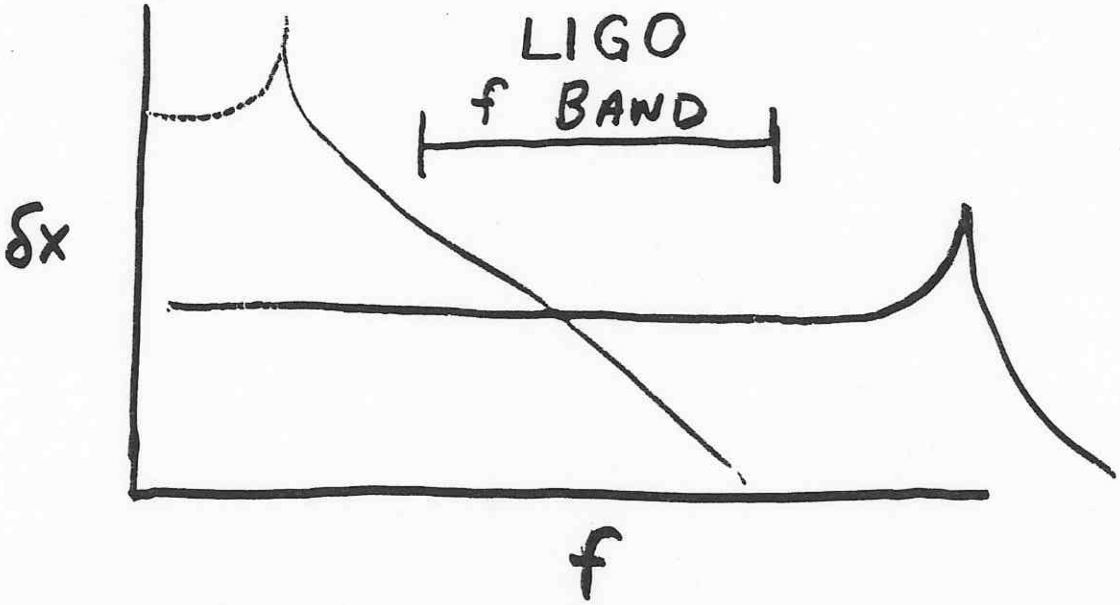
SUSPENSION MODES

$f \sim 1$ Hz



INTERNAL MODES

$f \gtrsim 20$ kHz



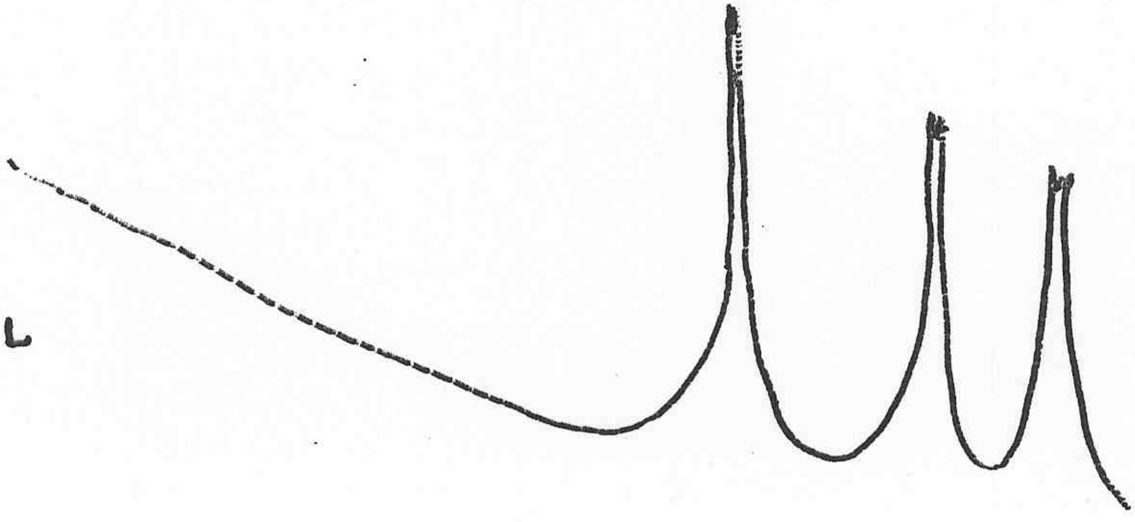
- SHAPE OF WINGS DEPENDS ON LOSS FUNCTION OF MODE $\phi_n(\omega)$

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

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

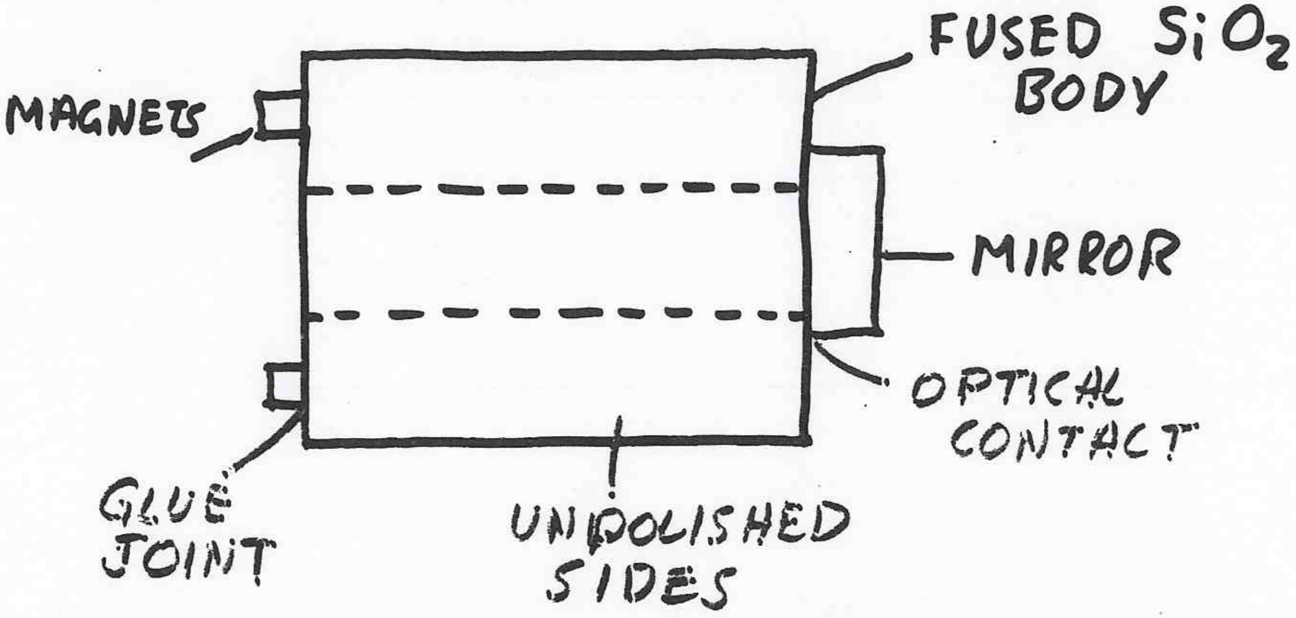
ϕ = CONST. "STRUCTURAL"

SUSPENSION
THERMAL NOISE



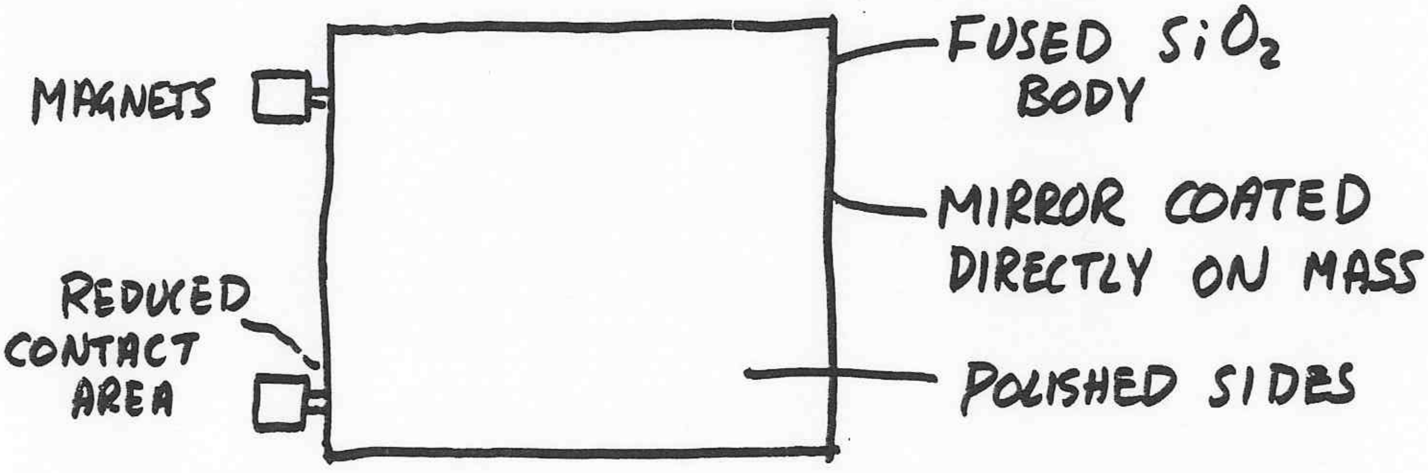
INTERNAL MODES

PRE-1994 TEST MASSES

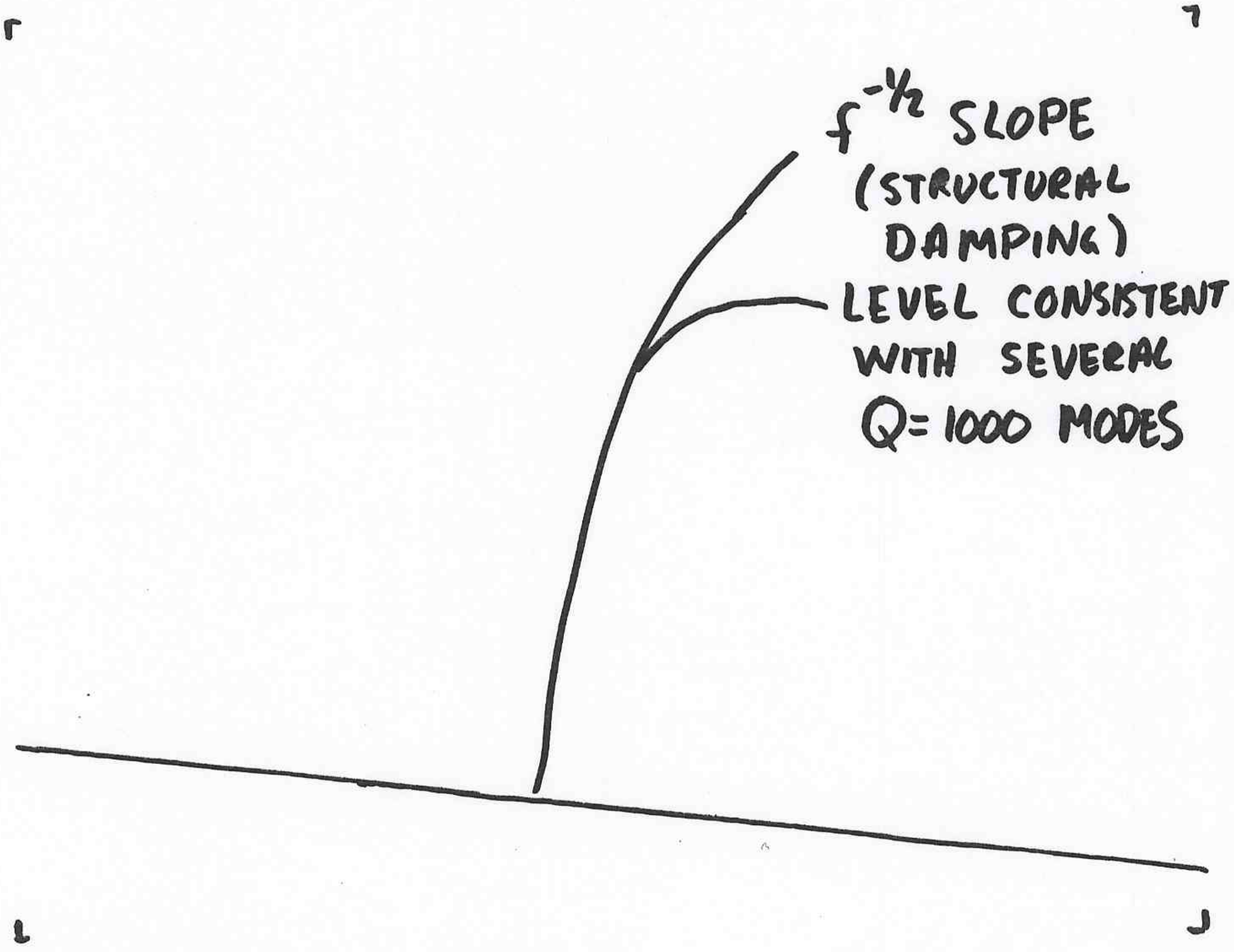


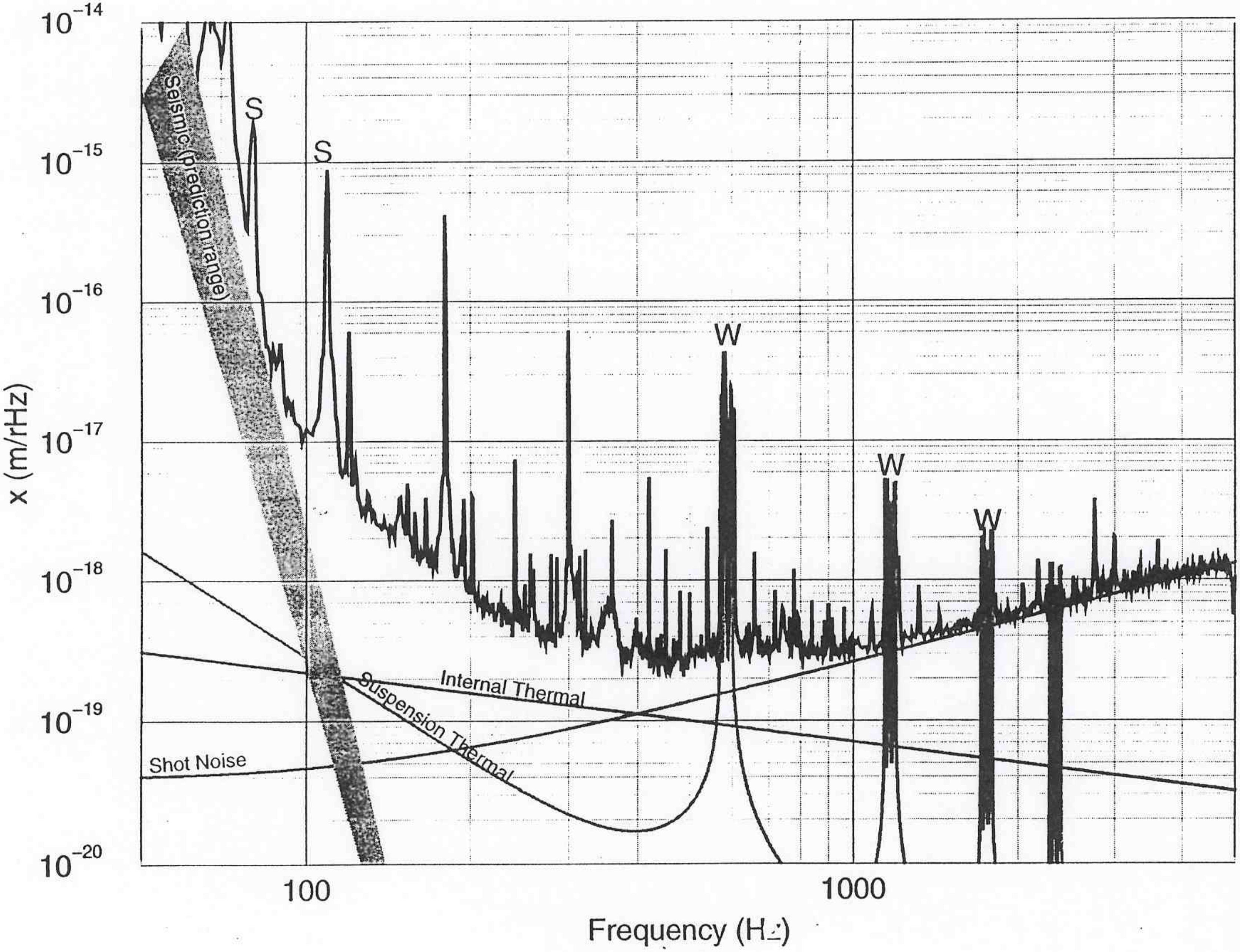
$$Q_{INTERNAL} \sim 800-50,000$$

NEW TEST MASSES INSTALLED IN 1994



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


$f^{-1/2}$ 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)
100
1000
Frequency (Hz)
S
S
W
W
W
Seismic (prediction range)
Internal Thermal
Suspension Thermal
Shot Noise

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