LIGO

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

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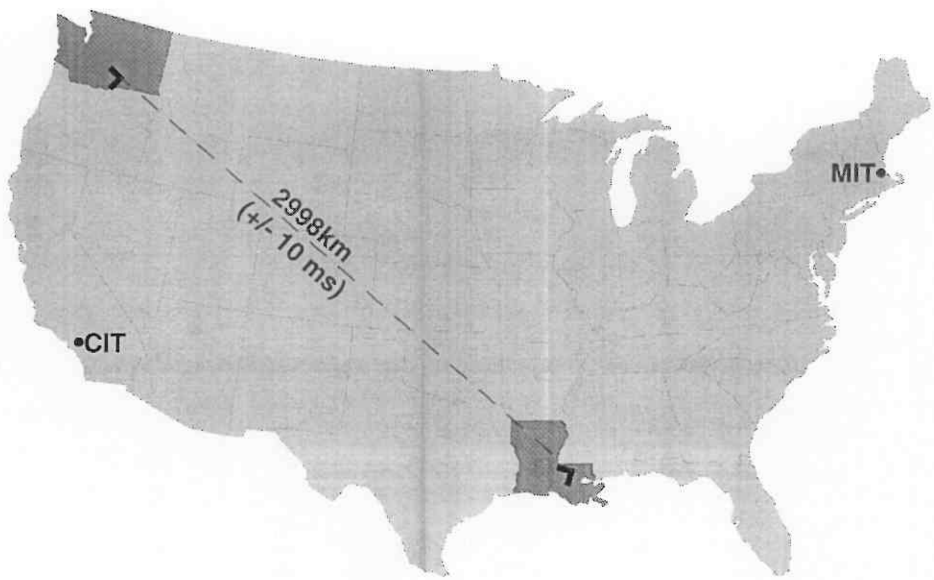
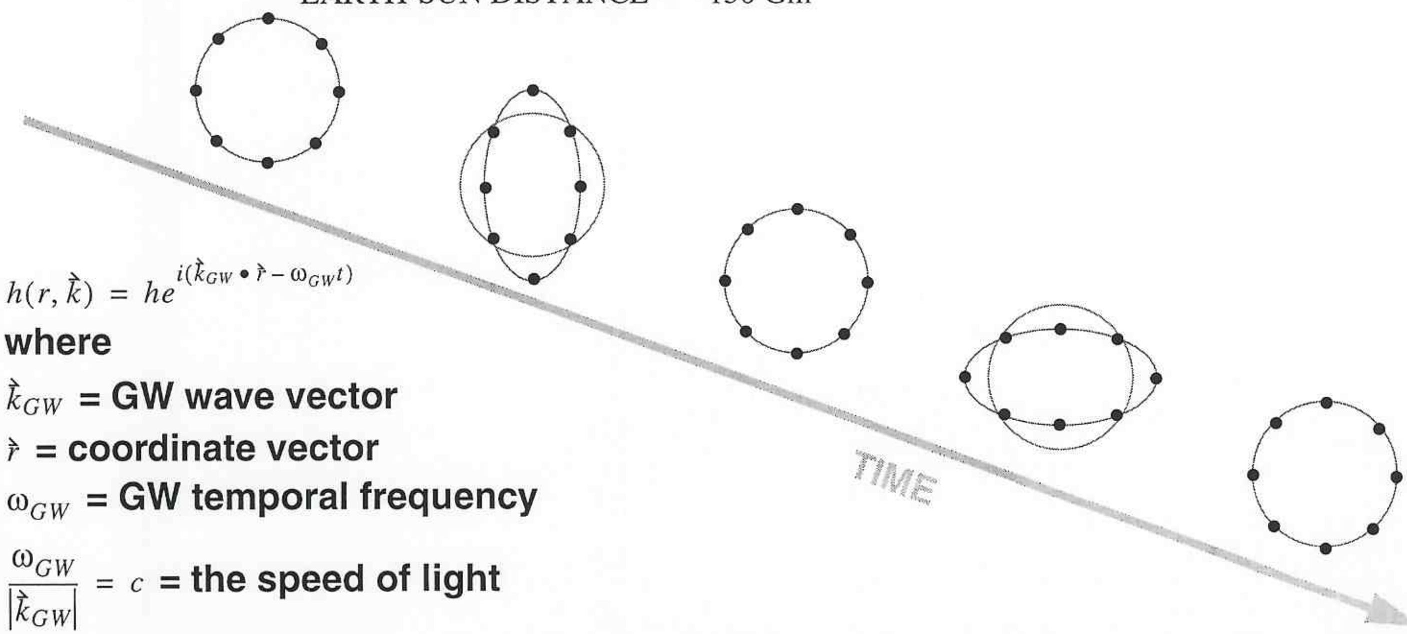
LIGO OVERVIEW

- NATIONAL SCIENCE FOUNDATION (NSF) PROJECT BEING DEVELOPED JOINTLY BY:
  - CALIFORNIA INSTITUTE OF TECHNOLOGY
  - MASSACHUSETTS INSTITUTE OF TECHNOLOGY
- PURPOSE:
  - EXPERIMENTAL VERIFICATION OF THE EXISTENCE OF GRAVITATIONAL WAVES (GW)
  - OPEN NEW WINDOW ON THE UNIVERSE



GRAVITATIONAL WAVE (GW) EFFECTS

- **GWs CAUSE GEOMETRY/LENGTH FLUCTUATIONS**
- **QUADRUPOLAR**
  - X and + POLARIZATIONS
- **DIMENSIONLESS AMPLITUDE, STRAIN $h = \Delta L/L \sim 10^{-21}$**
  - $\sim \dfrac{\text{ATOMIC DIAMETER}}{\text{EARTH-SUN DISTANCE}} \approx \dfrac{\text{1 Angstrom}}{\text{150 Gm}}$



$$h(r, \vec{k}) = he^{i(\vec{k}_{GW} \bullet \vec{r} - \omega_{GW} t)}$$

where

$\vec{k}_{GW}$ **= GW wave vector**

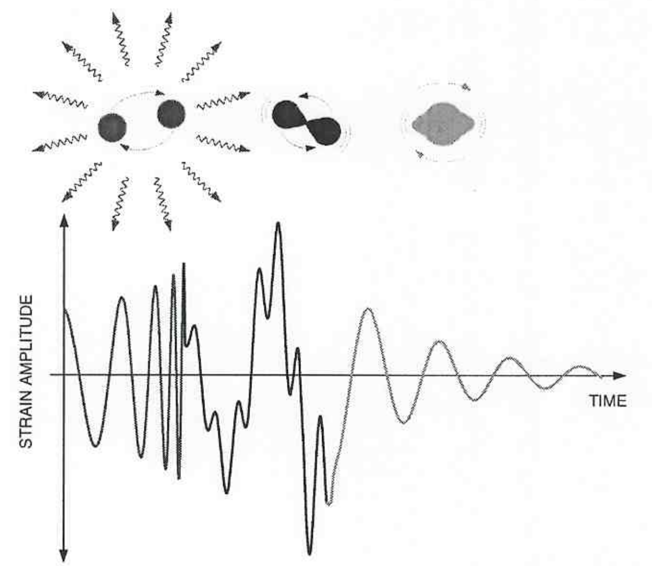
$\vec{r}$ **= coordinate vector**

ω_{GW} **= GW temporal frequency**

$\dfrac{\omega_{GW}}{|\vec{k}_{GW}|} = c$ **= the speed of light**

GW SOURCES

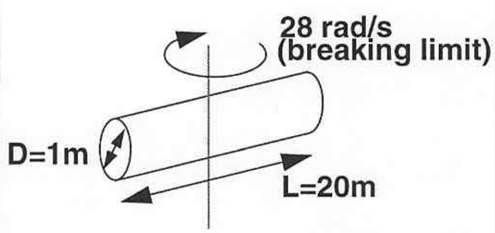
- COMPACT BINARY COALESCENCES
  - NEUTRON STAR (NS)
  - BLACK HOLE (BH)
  - kHz SIGNALS
  - SHORT DURATION (~ 1 MINUTE)



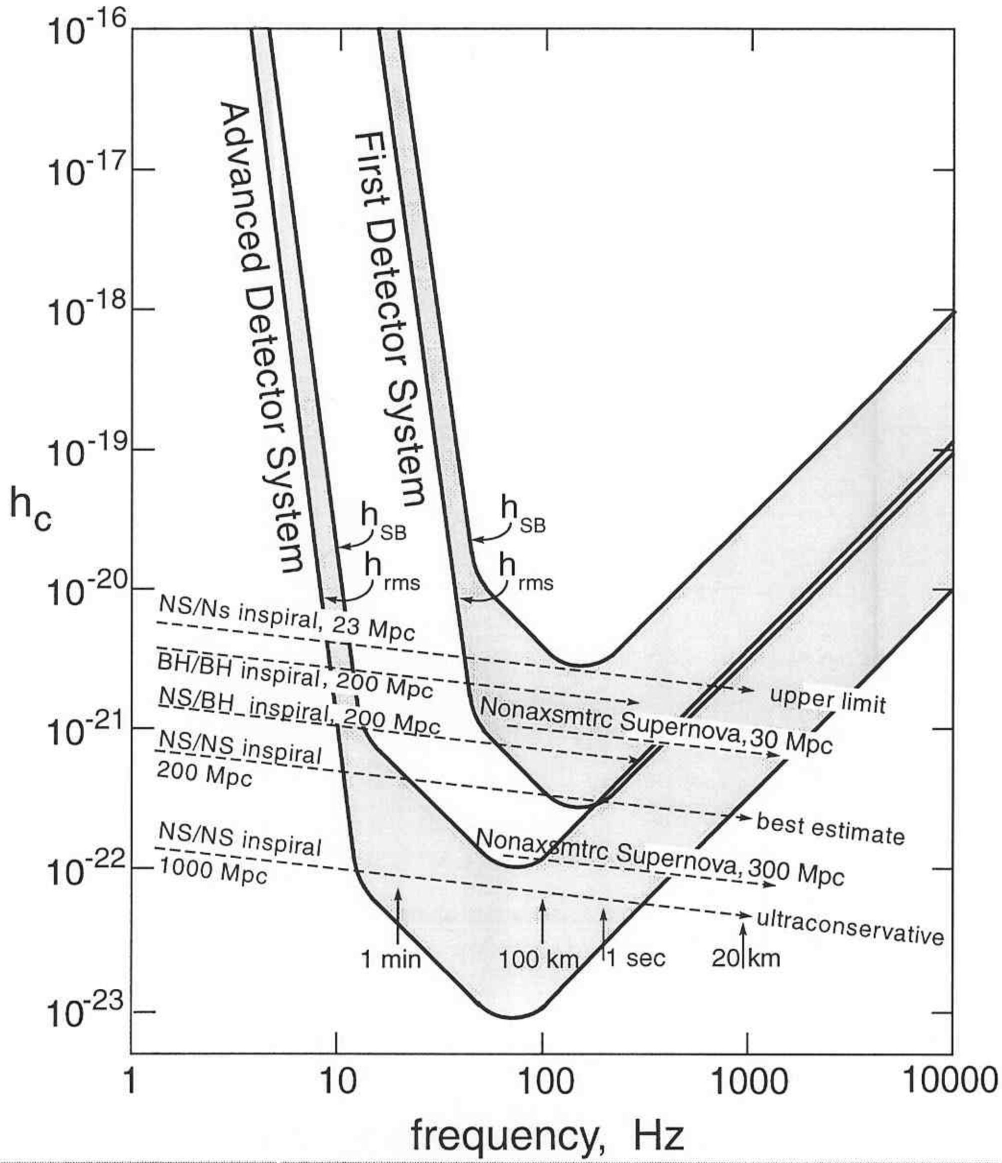
- SUPERNOVAE
  - ASYMMETRIC COLLAPSE
  - VERY SHORT DURATION (~ ms)
- COSMIC BACKGROUND
  - GW ANALOGY TO THE COSMIC MICROWAVE BACKGROUND
  - EXTREMELY WEAK SIGNAL

GW SOURCES

- **ROTATING QUADRUPOLES**
  - LOW FREQUENCY (2 x ROTATION RATE)
  - EXAMPLES:

SYSTEM	EMITTED POWER
EARTH-MOON	7 μW
EARTH-SUN	190 W
TWO BHs WITH SOLAR MASS AND 3 km SEPARATION (extreme case)	2×10^{50} W IF IN THE VIRGO GALAXY CLUSTER (3×10^{7} LIGHT YEARS), THEN 10^{2} W/m^{2}
ROTATING STEEL CYLINDER 	2×10^{-30}

COMPARISON OF LIGO SENSITIVITY GOALS AND ESTIMATED GW SOURCES



IS THE MEASUREMENT MEANINGFUL?

RANDOM, THERMALLY INDUCED MOTIONS OF THE ATOMS IN THE MIRROR FACES >> ΔL

$$\Delta L \sim 10^{-18} m \sim \frac{\text{Dia. of Nucleus of Atom}}{1000}$$

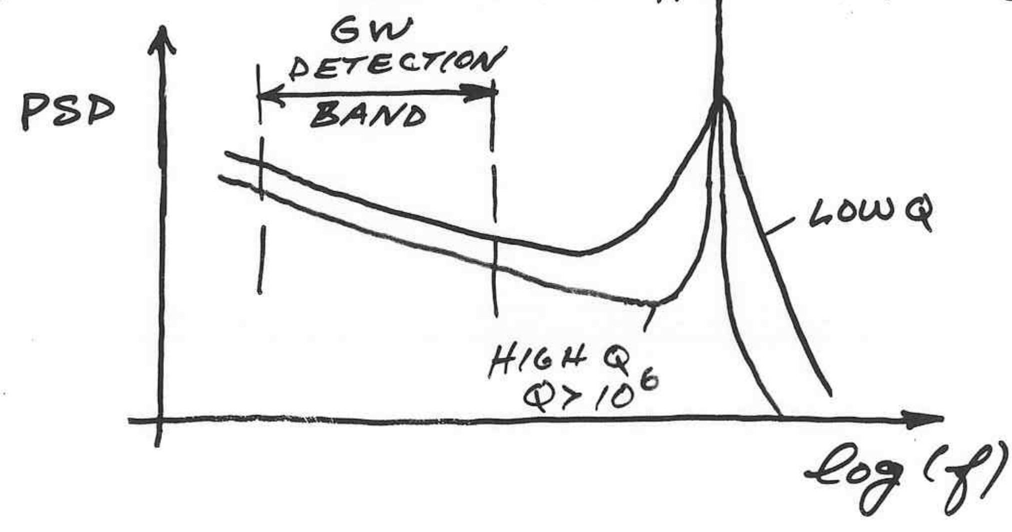
YES, IT IS MEANINGFUL!

- ATOMIC MOTIONS OCCUR AT VERY HIGH FREQUENCIES
  - ATOMIC MOTION AVERAGED AWAY DURING THE ~1 ms COLLECTION OF ~10^{16} PHOTONS

- SPATIALLY AVERAGING OVER MANY ATOMS SO THAT ONLY THE LOW SPATIAL ORDER MODES ARE POTENTIALLY SIGNIFICANT (i.e. "Drum Head" modes)
  - MIRROR LOWEST FREQ., $f_0 > 10$ kHz
  - $\delta x = \frac{(kT/m)^{1/2}}{2\pi f_0} \sim 3 \times 10^{-16}$ m for $T = 300$K, $m = 10$ kg

$$\delta x \sim \frac{\text{dia. of Nucleus of Atom}}{3} \sim 300 \times \text{GW signal}$$

  - OUT OF THE GW BAND
  - HIGH Q ASSOCIATED WITH f_0 SO THAT THE "TAIL" OF THE RESONANCE HAS A SMALL EFFECT



IS THE MEASUREMENT POSSIBLE?

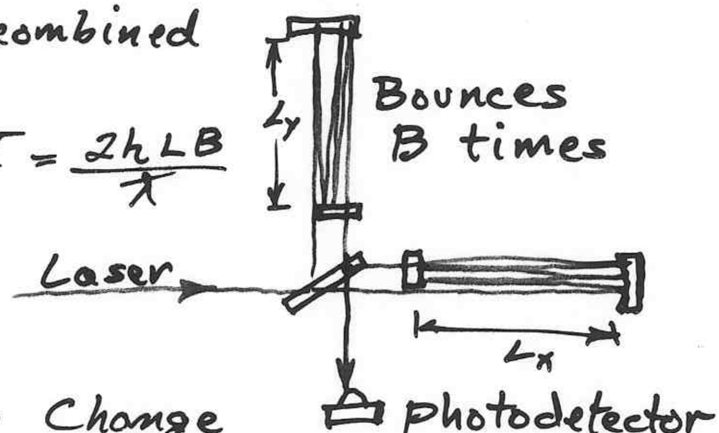
STRAIN, $h = \frac{\Delta L}{L} \sim 10^{-21}$ OR $\Delta L = 4\,km \times 10^{-21}$

$\Delta L \sim 10^{-18}\,m \sim 10^{-12}\lambda$ (LASER WAVELENGTH $\lambda = 1.06\,\mu m$)

OUTRAGEOUS? ⟹ NOT AT ALL:

- Phase Difference of Recombined Light:

$$\Delta\varphi = \frac{2B(\Delta L_x - \Delta L_y)2\pi}{\lambda} = \frac{2hLB}{\bar{\lambda}}$$



- Photodetector Intensity Change Limited by Shot Noise:

$$\Delta\varphi \simeq \frac{\Delta I}{I_0} \sim \frac{1}{\sqrt{\#\,photons}}$$

- Photodetector Can Integrate for 1/2 GW period

$$\frac{1}{2f} \sim 1\,ms$$

Consequently:

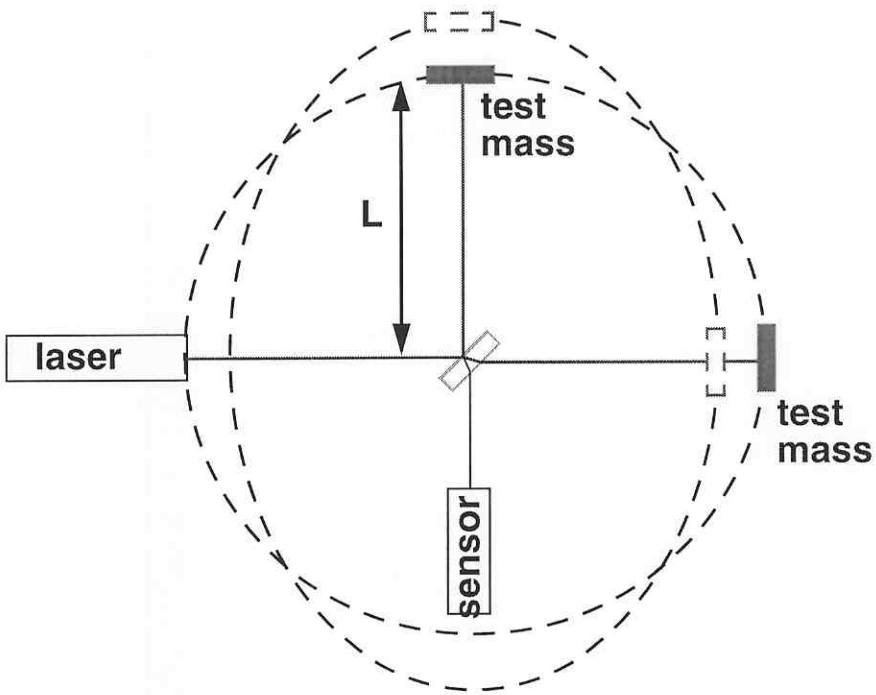
$$h_{min} \simeq \frac{\bar{\lambda}}{2BL}\frac{1}{\sqrt{N}} = \frac{\bar{\lambda}}{2BL}\left(\frac{2\hbar c f}{I_0 \bar{\lambda}}\right)^{1/2}$$

$$h_{min} \simeq \underline{\underline{3\times10^{-21}}}\left(\frac{50}{B}\right)\left(\frac{4\,km}{L}\right)\left(\frac{\lambda}{1.06\,\mu m}\right)^{1/2}\left(\frac{10\,W}{I_0}\right)^{1/2}\left(\frac{f}{1000\,Hz}\right)^{1/2}$$

∴ MEASUREMENT IS POSSIBLE

GW OPTICAL DETECTION

- MICHELSON INTERFEROMETER
  - QUADRUPOLAR GW → TWO ORTHOGONAL ARMS
  - LASER FREQUENCY FLUCTUATIONS → EQUAL ARM LENGTHS
  - MINUTE STRAIN → LARGE L = 4 km
    → STORE LIGHT IN ARMS TO INCREASE EFFECTIVE LENGTH



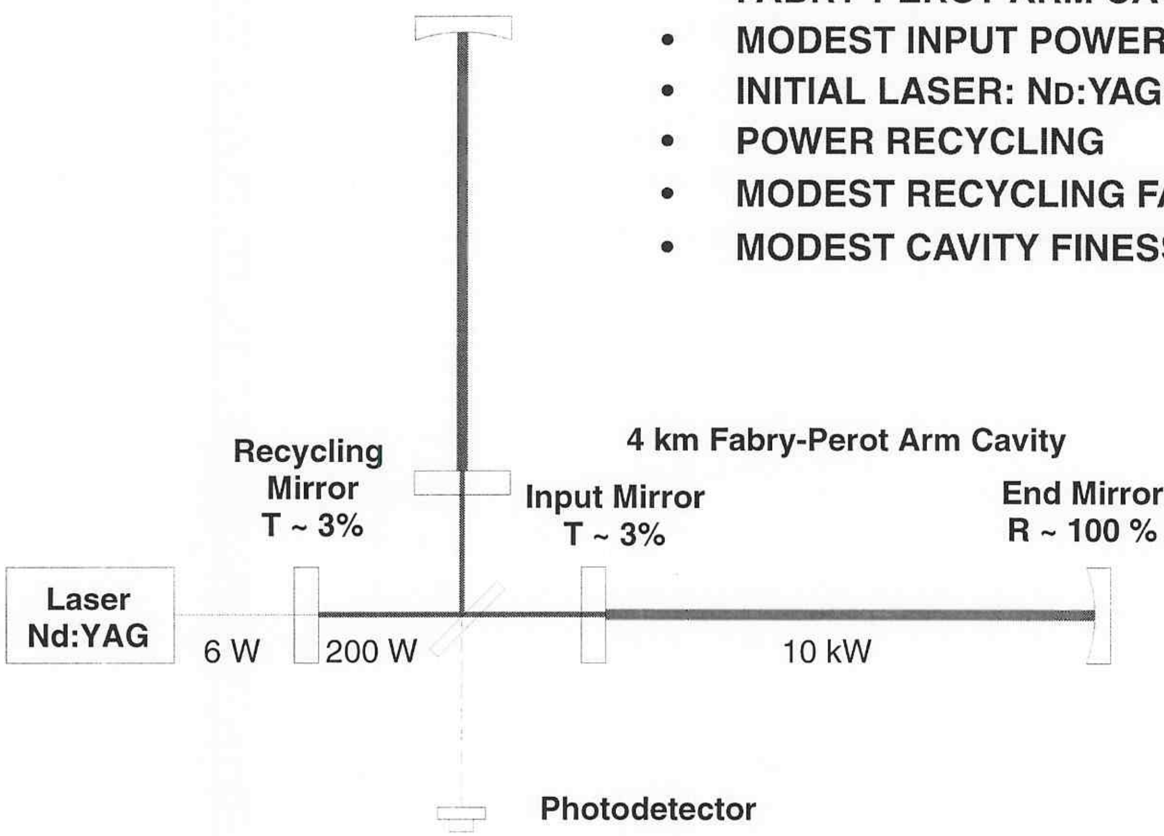
Interferometer Response Function:

$$\delta\varphi = h\frac{\omega L}{c}2\,\mathrm{sinc}\left(\frac{\Omega L}{c}\right)$$

where
$\delta\varphi$ = optical light phase change
ω = laser frequency
Ω = GW frequency
c = speed of light
h = strain amplitude
L = arm length

INITIAL INTERFEROMETER CONFIGURATION

- FABRY-PEROT ARM CAVITIES
- MODEST INPUT POWER (6 w)
- INITIAL LASER: ND:YAG $\lambda = 1.06\ \mu m$
- POWER RECYCLING
- MODEST RECYCLING FACTOR ($\mathcal{R} \sim 30X$)
- MODEST CAVITY FINESSE ($\mathcal{F} \sim 50$)



Interferometer Response Function:

$$\varphi = h\frac{\omega L}{c}\frac{2F}{\pi\sqrt{1+(\Omega\tau)^2}}$$

where

$\delta\varphi$ = optical light phase change

ω = laser frequency

Ω = GW frequency

c = speed of light

h = strain amplitude

L = arm length

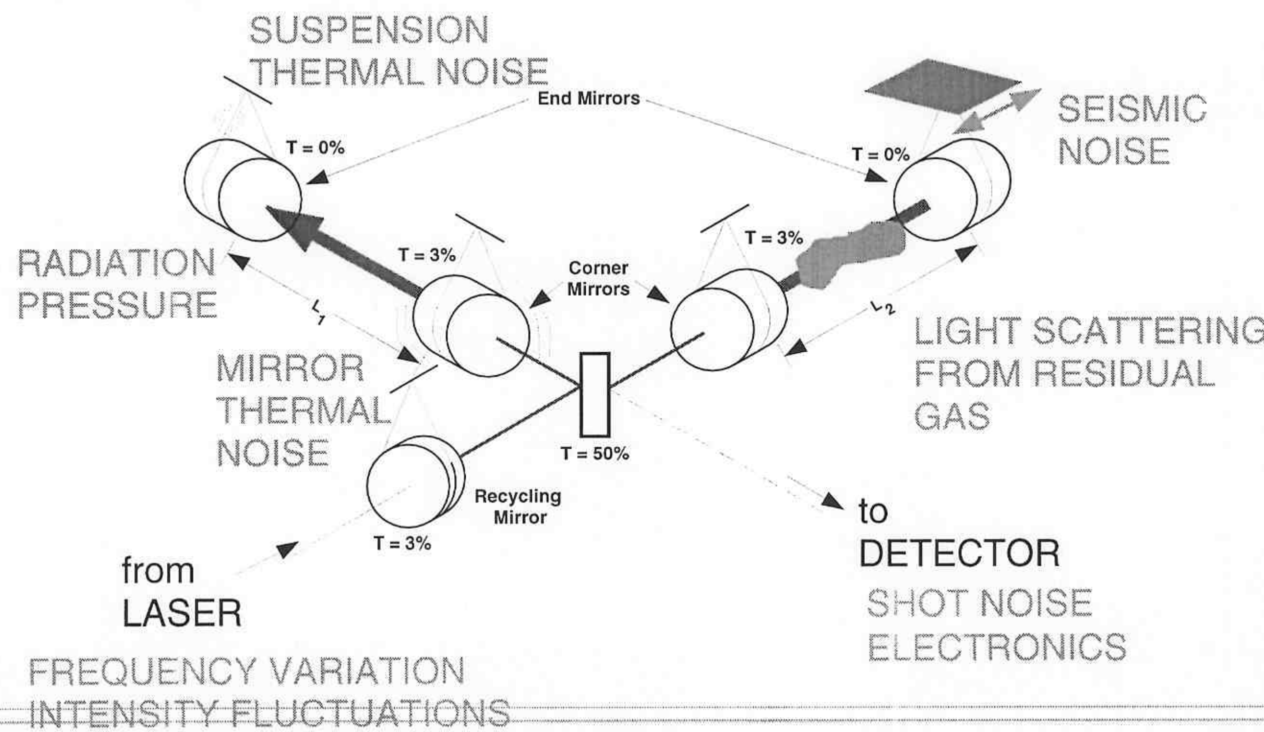
F = Fabry-Perot finesse

τ = Fabry-Perot time constant

NOISE SOURCES

THERMAL	QUANTUM	MECHANICAL
PENDULUM	SHOT NOISE	SEISMIC
MIRROR	RADIATION PRESSURE	SCATTERED LIGHT

LASER	ELECTROMAGNETIC	GRAVITATIONAL
FREQUENCY	AMPLIFIERS	MOVING PEOPLE
POWER	SERVO LOOPS	MOVING VEHICLES
ALIGNMENT JITTER	EMI	



INITIAL LIMITS TO SENSITIVITY

- DISPLACEMENT NOISE (PHYSICAL MOTION)
  - SEISMIC NOISE
    - SEISMICALY QUIET SITES
    - CASCADED, MULTI-STAGE SEISMIC ISOLATION SYSTEM & PENDULUM SUSPENSIONS FOR THE TEST MASSES $T(f) \sim f^{-2n}$
  - THERMAL NOISE
    - PENDULUM THERMAL $T(f) \sim f^{-5/2}$ above resonance
    - HIGH-Q WIRE SUSPENSION TO LIMIT THERMAL NOISE SPECTRAL CONTENT
    - HIGH-Q & HIGH-FREQUENCY (> 20 kHz) TEST MASSES $T(f) \sim f^{-1/2}$ below resonance
- SENSING NOISE
  - SHOT NOISE
    - POWER RECYCLING
    - OPERATE ON DARK FRINGE
    - > 6 W INPUT, > 8 kW RESONANT IN ARM CAVITIES

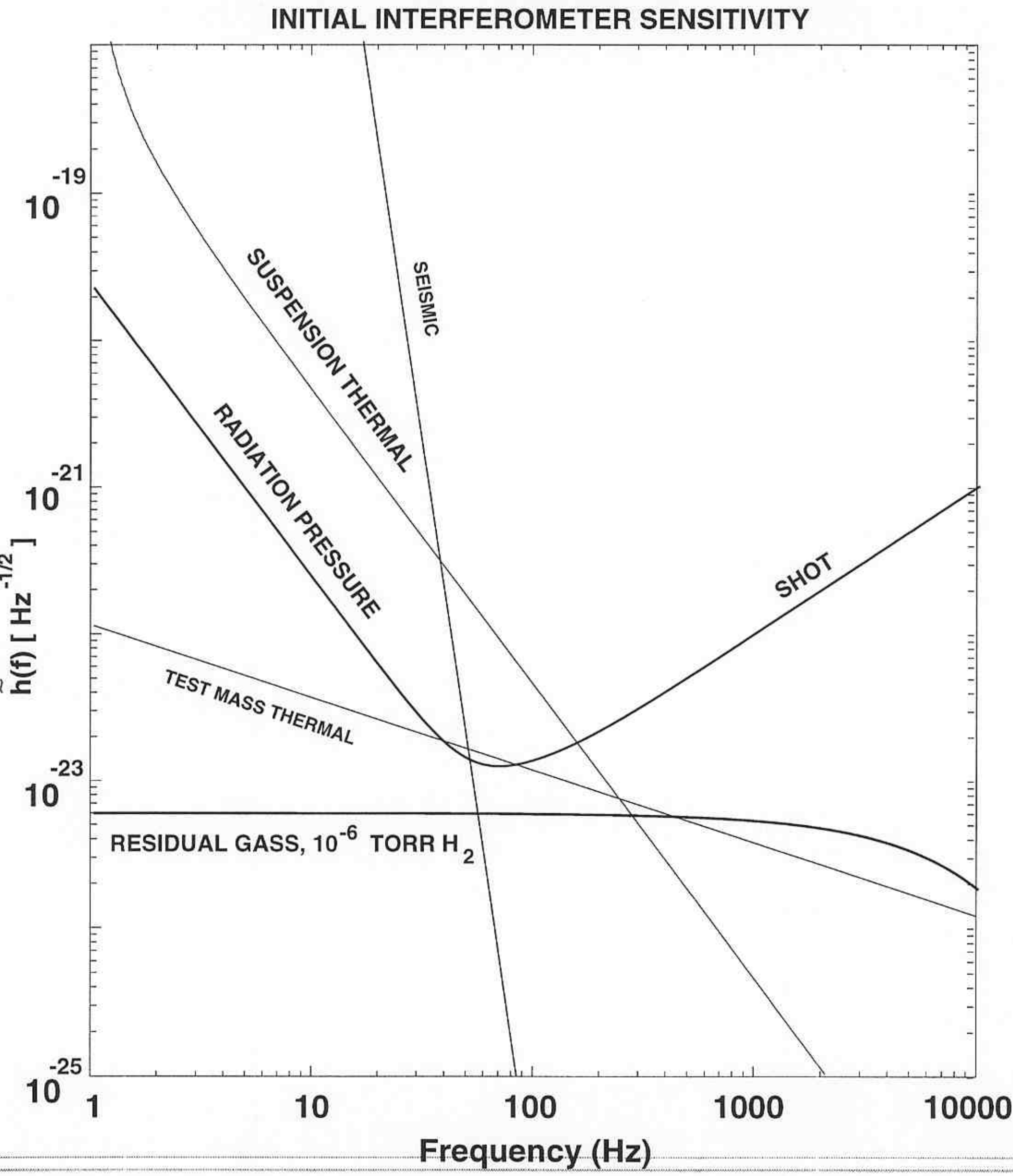
Signal-to-Noise Ratio:

$$\mathrm{SNR} = \frac{\varphi}{\phi_N}$$

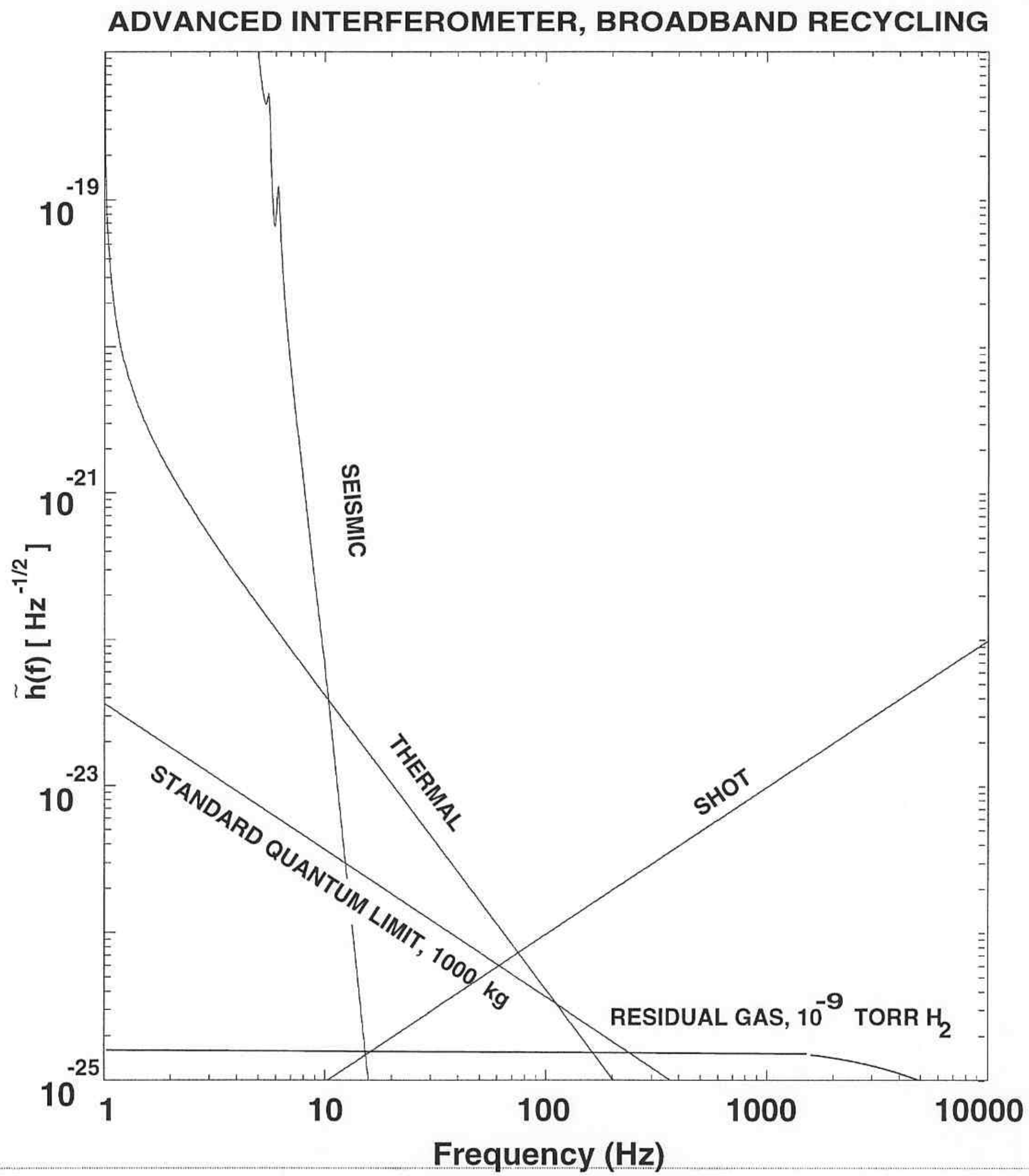
$$\varphi_N = \sqrt{\frac{h\nu}{\eta P}}$$

where
P = Laser Power
η = Detector Quantum Efficiency
h = Planck's constant
ν = Laser Frequency

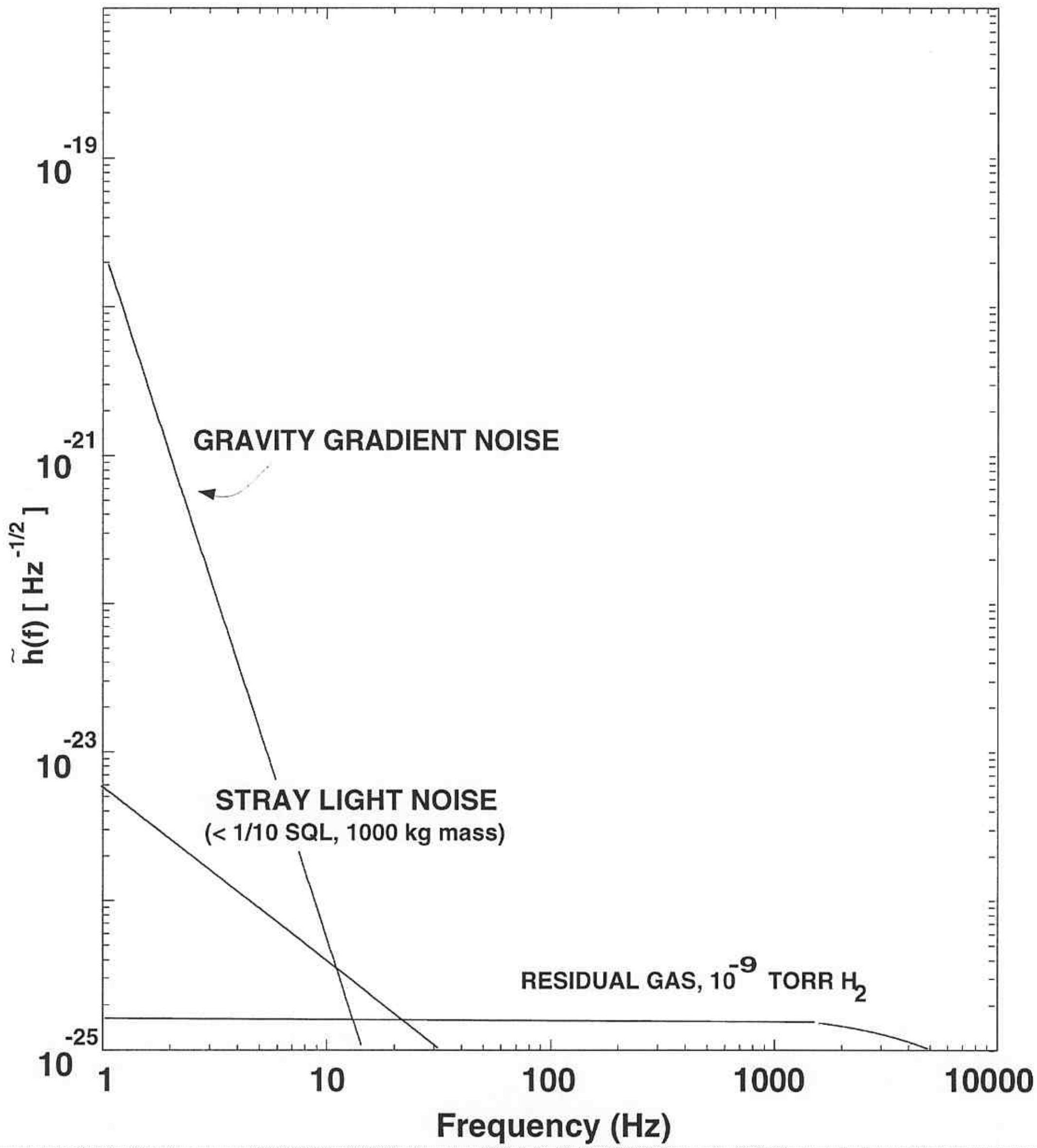
INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL



ADVANCED INTERFEROMETER DESIGN PERFORMANCE GOAL



LIMITING PERFORMANCE DUE TO FACILITIES



VACUUM EQUIPMENT & BEAM TUBE

- WILL BE THE LARGEST ULTRA-HIGH VACUUM ($<10^{-9}$ torr) SYSTEM IN THE WORLD (~ 20,000 m^3)
  - VERY LOW ALLOWED AIR LEAKAGE:
    $\mathcal{F} < 10^{-9}$ ATM CC/S, He
  - VERY LOW OUTGASSING:
    - $P_{Advanced} < 10^{-9}$ TORR (ALL RESIDUALS);
    - $J[H_2]: < 10^{-13}$ torr-liter/cm^2/s
      $J[H_2O]: < 10^{-15}$ torr-liter/cm^2/s
    - PARTIAL PRESSURES FOR $CO + CO_2 + H_{2N}C_N + ...$ MUST BE EVEN LOWER
  - QUALITY CONTROL AND CLEANLINESS MUST BE PURSUED DILIGENTLY THROUGHOUT FABRICATION AND INTEGRATION PROCESS
  - OVER 140 km OF WELDS
- MOSTLY STANDARD VACUUM PUMP & CONTROL HARDWARE
- VERY LARGE APERTURE GATE VALVES TO ISOLATE 1.24 m BEAM TUBES
- LARGE PUMPING SPEEDS AND VOLUMES -- BEAM TUBE PUMPING SOLELY FROM 4km ENDS

DETECTOR SYSTEM

- BASELINE CONFIGURATION EMPLOYS PROVEN TECHNIQUES
  - 40M AND 5M SCALE SYSTEMS (AT CIT & MIT)
  - OPTICAL CONFIGURATIONS, MODULATION & CONTROL CONCEPTS BEING VALIDATED IN R&D TASKS
  - SUSPENSIONS & SEISMIC ISOLATION SYSTEMS
  - LASER FREQUENCY STABILIZATION
- COLLABORATIVE STUDIES WITH INDUSTRIAL PARTNERS
  - MIRROR SUBSTRATE POLISHING (HDOS, CSIRO)
  - MIRROR, HIGH REFLECTANCE COATINGS (REO)
  - ACTIVE SEISMIC ISOLATION (BARRY)
  - SEISMIC ISOLATION (HYTEC)
- STATE-OF-THE-ART PROCESS CONTROL TECHNIQUES FOR INSTRUMENT CONTROL & STATE VECTOR / DATA REPRESENTATION
  - EPICS
  - AVS

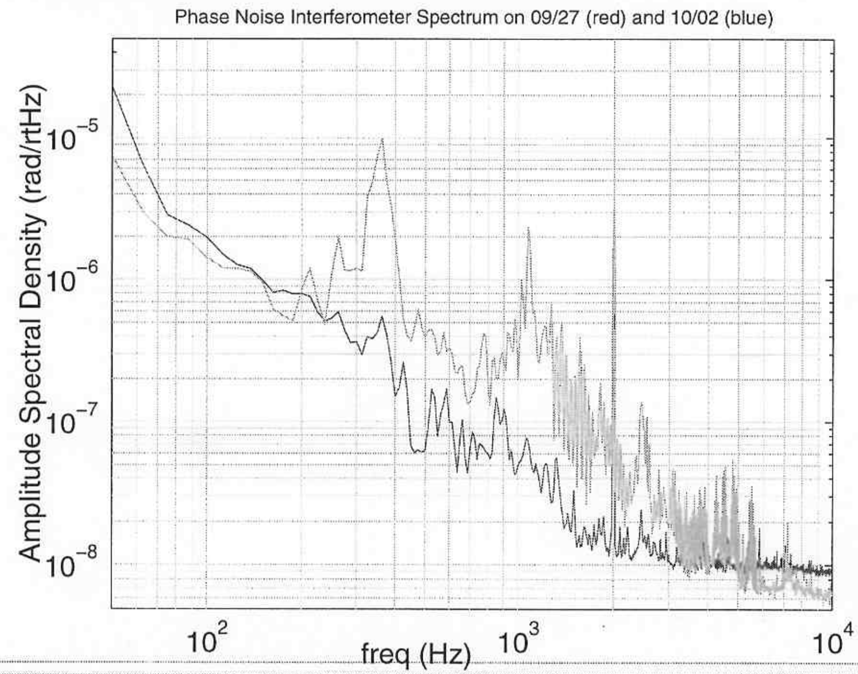
RESEARCH AND DEVELOPMENT

- FOCAL POINT OF R&D EFFORT IS TO CONTINUE TO RECONFIGURE EXISTING 40 m INTERFEROMETER AT CALTECH TO MORE CLOSELY REFLECT LIGO OPTICAL CONFIGURATION
  - PROOF-OF-CONCEPT FOR LIGO SUBSYSTEMS
  - DE-BUGGING TESTBED
  - FUNCTIONAL VERIFICATION FOR CERTAIN LIGO-SCALE SUBSYSTEMS
  - PROVIDES TRAINING TESTBED FOR NEW SCIENTIFIC STAFF

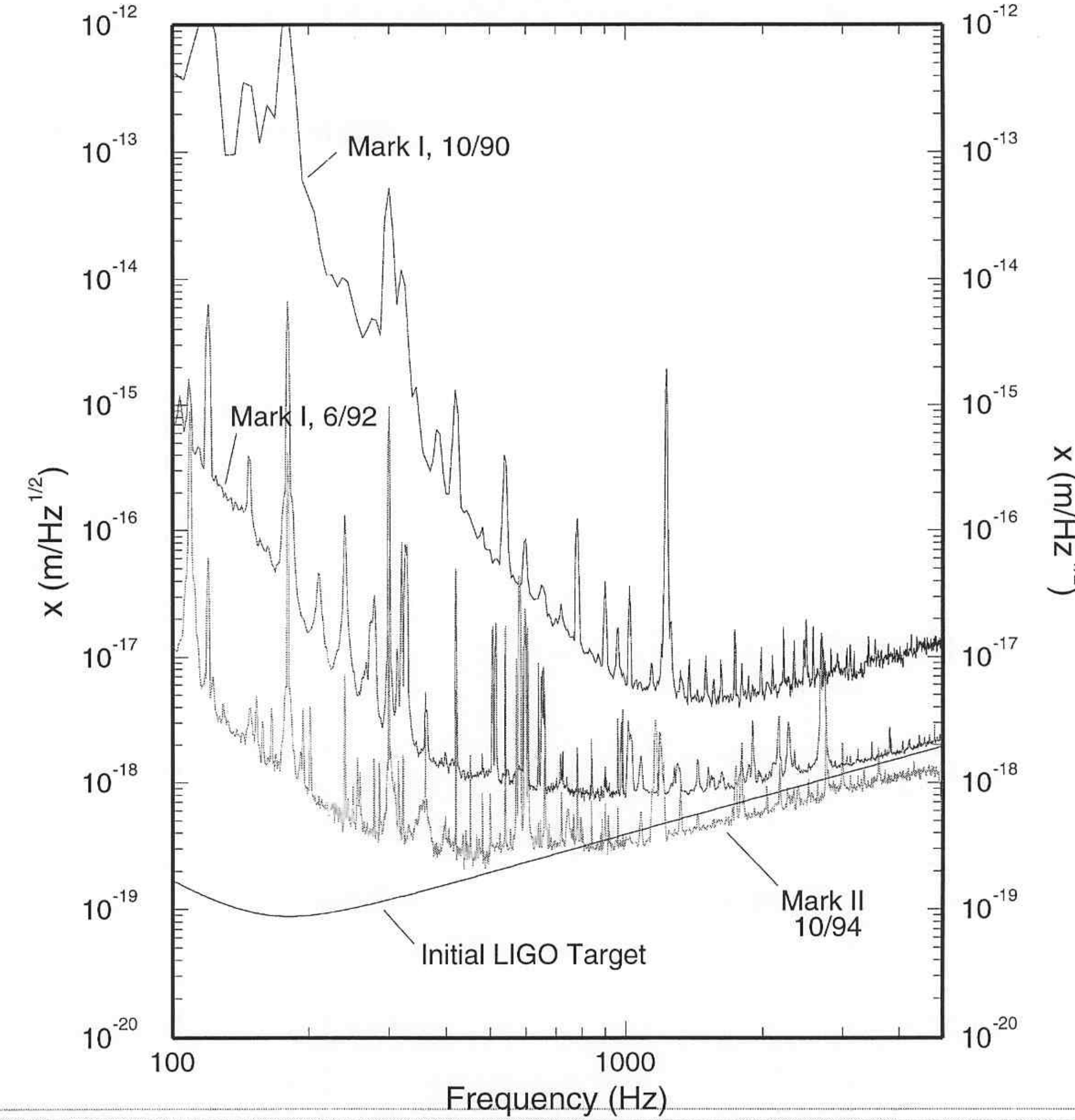
- OTHER MAJOR SUBSYSTEM EFFORTS CARRIED ON IN PARALLEL
  - PHASE NOISE INVESTIGATIONS AT MIT (5 m INTERFEROMETER)
  - ALIGNMENT CONCEPT INVESTIGATIONS
  - ACTIVE SEISMIC ISOLATION AND IMPROVED PASSIVE ISOLATION SYSTEMS
  - MODE CLEANER INTEGRATION AND DEBUGGING
  - PRE-STABILIZED LASER SUBSYSTEM

PHASE NOISE RESEARCH

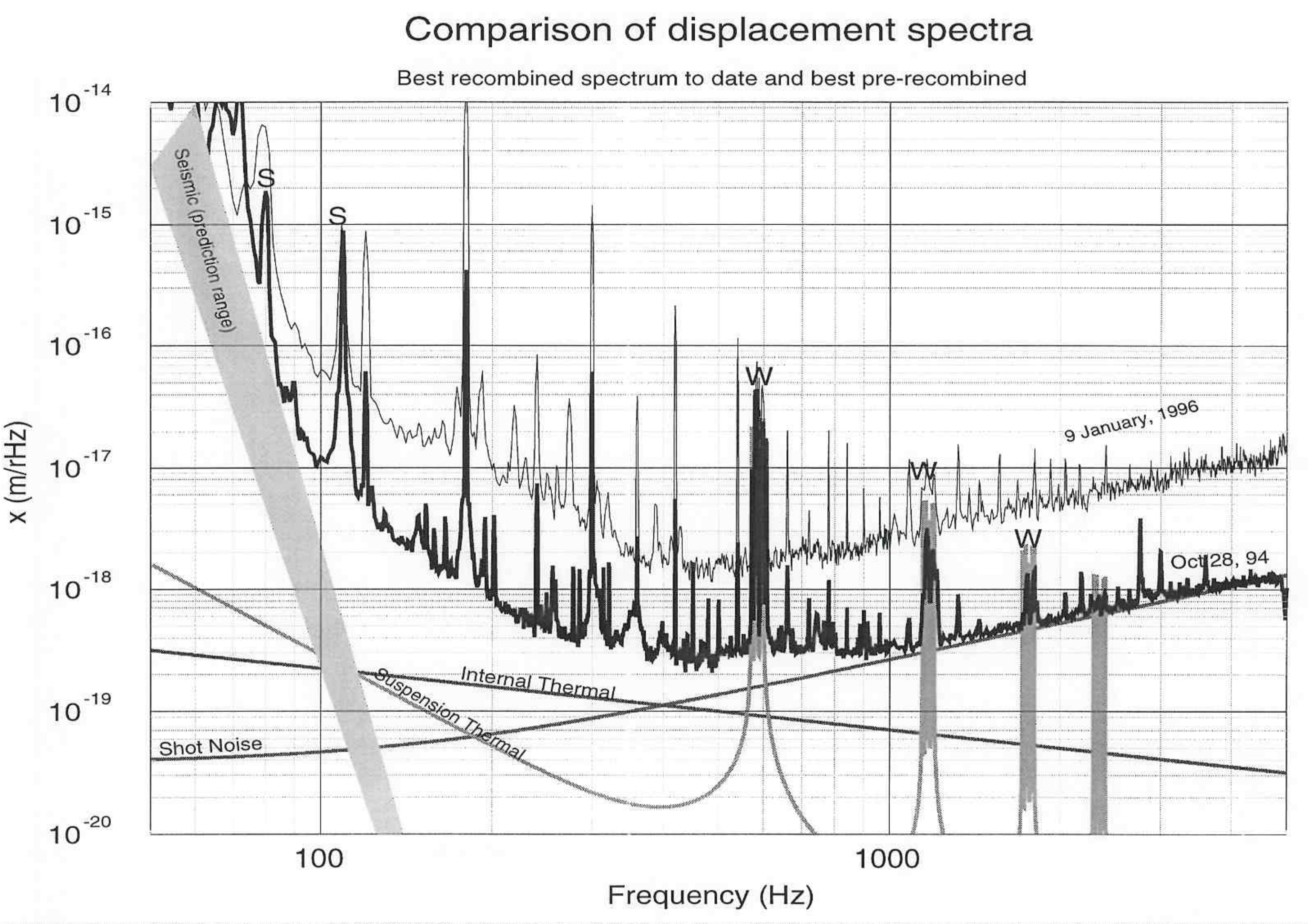
- SHOT NOISE AT HIGH FREQUENCIES
  - BEST TO DATE: $5\times10^{-9}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$
  - REQUIRED: $1\times10^{-10}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$
- LOW FREQUENCY NOISE IS PROBABLY DUE TO BEAM JITTER
  - WILL BE REDUCED SIGNIFICANTLY BY RECYCLING
- NEXT PHASE: ADD RECYCLING MIRROR



PROGRESSIVE IMPROVEMENT IN THE 40-METER PROTOTYPE SENSITIVITY



40-METER DISPLACEMENT SPECTRA



CONCLUSION

- **LIGO WILL OPEN A NEW WINDOW ON THE UNIVERSE**
- **LIGO FACILITIES ARE PROCEEDING FROM FINAL DESIGN INTO FABRICATION & CONSTRUCTION**
  - BUILDINGS
    - FINAL DESIGN REVIEW 5/96
    - CONSTRUCTION 7/96 (START)
  - BEAM TUBES
    - SLABS/ENCLOSURE 2/96 (START)
    - BEAM TUBE INSTALLATION 10/96 (START)
  - VACUUM EQUIPMENT
    - CHAMBER FIRST ARTICLE 1/96 (START)
    - VACUUM EQUIPMENT INSTALLATION 7/97 (START)
- **LIGO DETECTOR SYSTEM DESIGN PROCEEDING**
  - BASELINE DESIGN EXPECTED TO MEET INITIAL GOALS
    - 10^{-8} m rms DISPLACEMENT SENSITIVITY FROM 100 TO 3000 Hz
      $= 10^{-12}$ OF A WAVELENGTH OF VISIBLE LIGHT
      $= 10^{-9}$ rad rms OPTICAL PHASE SENSITIVITY
  - DETECTOR INSTALLATION TO START AT WA SITE 7/98