DCC

# The LIGO Project - Probing the Limits of Optical Measurements

## Viewgraphs for P/T Colloquium Series

## Los Alamos National Laboratory

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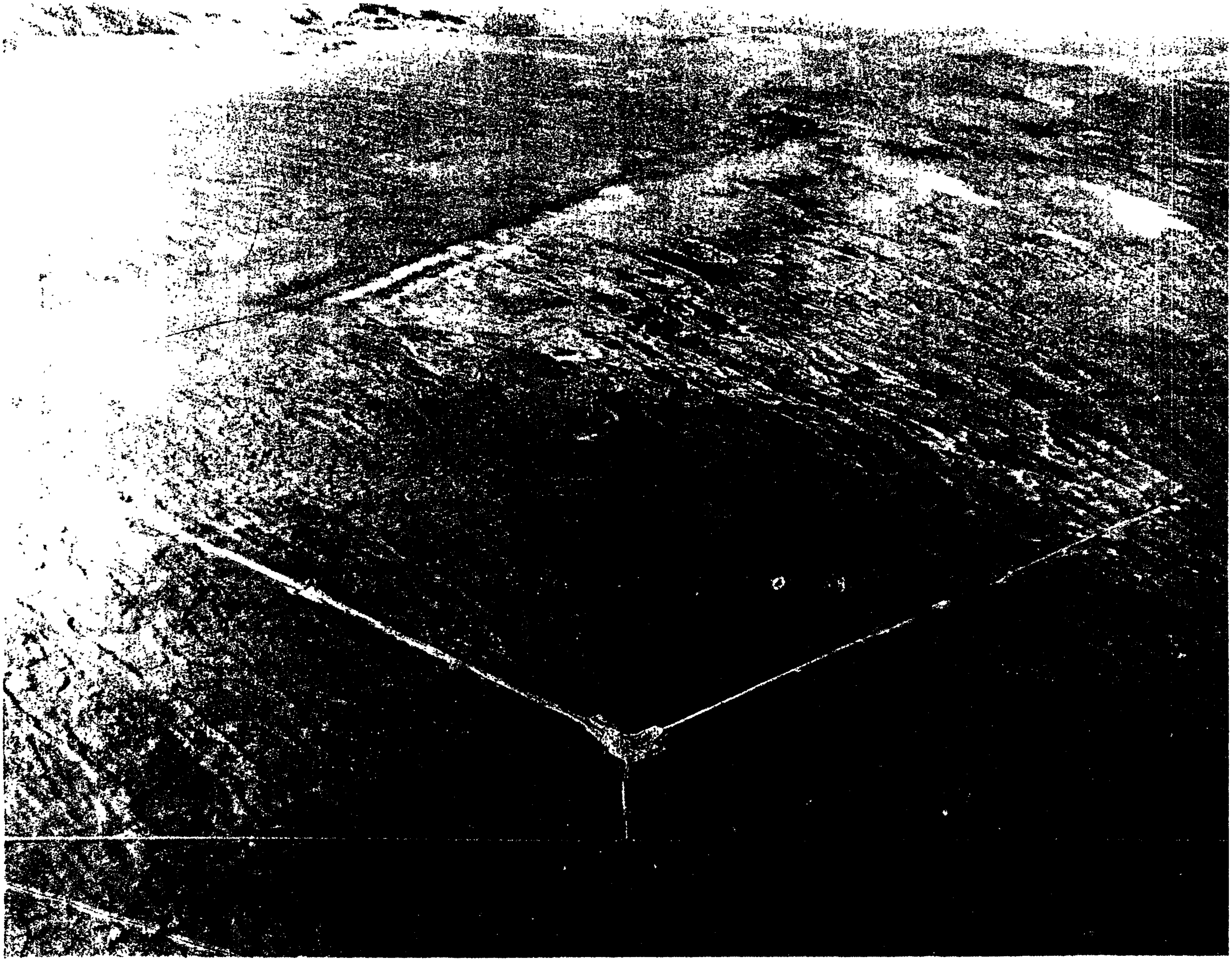
## May 8, 1997


## Stan Whitcomb



LIGO-G970163-00-D


LIGO

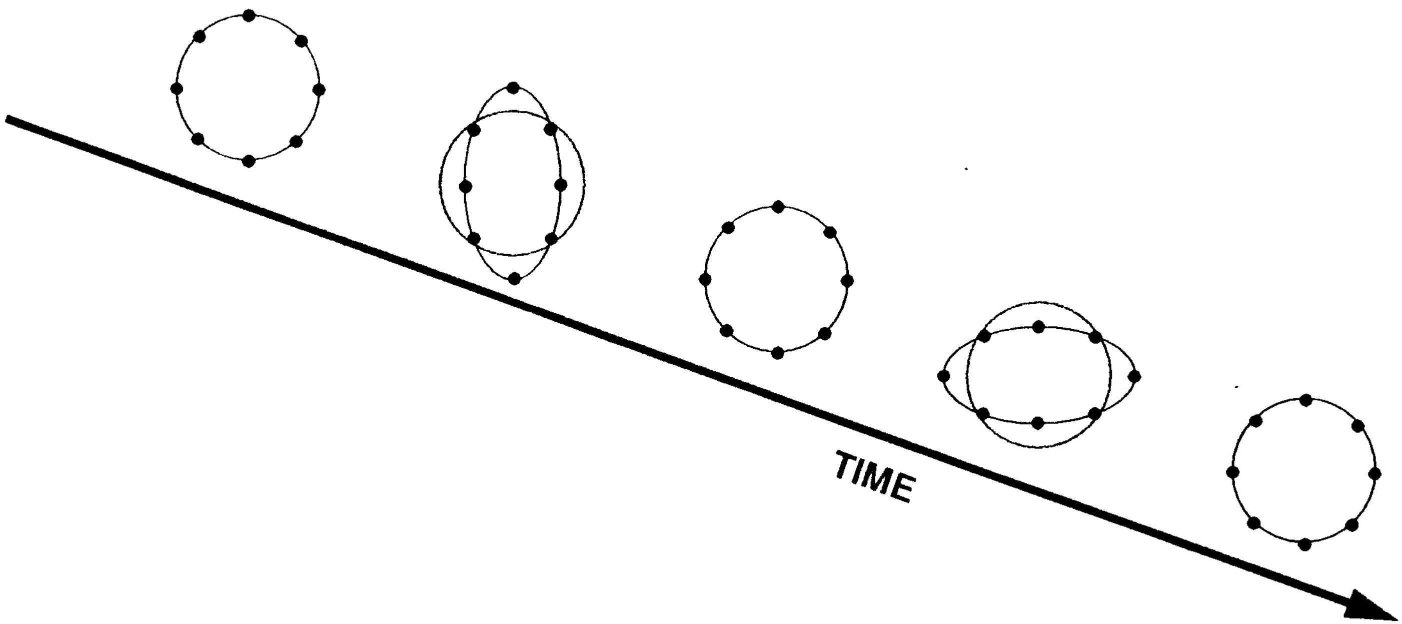


# LIGO OVERVIEW

- NATIONAL SCIENCE FOUNDATION (NSF) PROJECT BEING DEVELOPED JOINTLY BY:
  - CALIFORNIA INSTITUTE OF TECHNOLOGY
  - MASSACHUSETTS INSTITUTE OF TECHNOLOGY
- GOALS:
  - DIRECT DETECTION OF GRAVITATIONAL WAVES (GW)
  - OPEN NEW WINDOW ON THE UNIVERSE
- REQUIRE COINCIDENCE BETWEEN TWO WIDELY-SEPARATED SITES TO ELIMINATE LOCAL DISTURBANCES

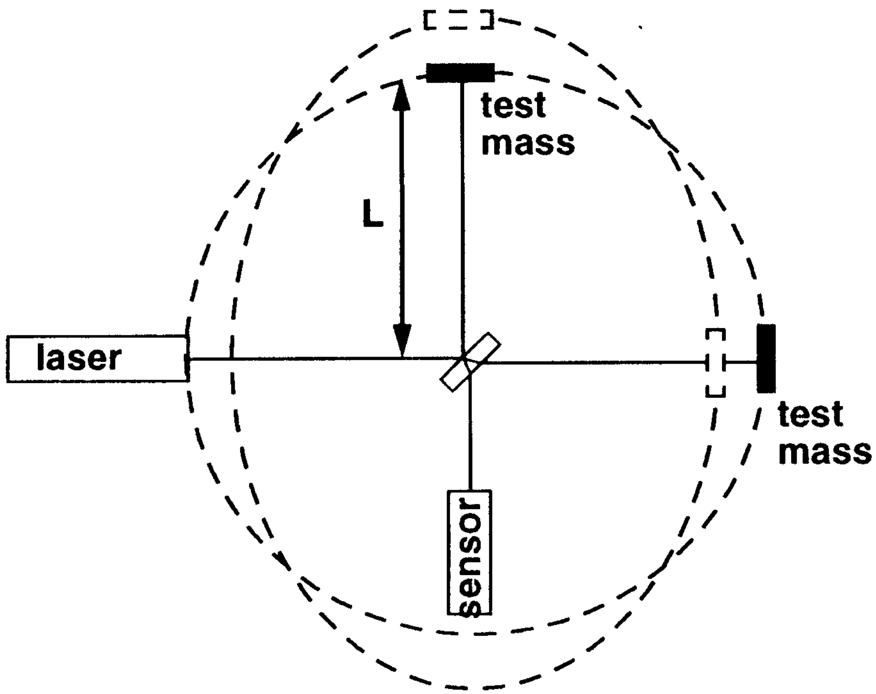
# GRAVITATIONAL WAVE (GW) EFFECTS

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



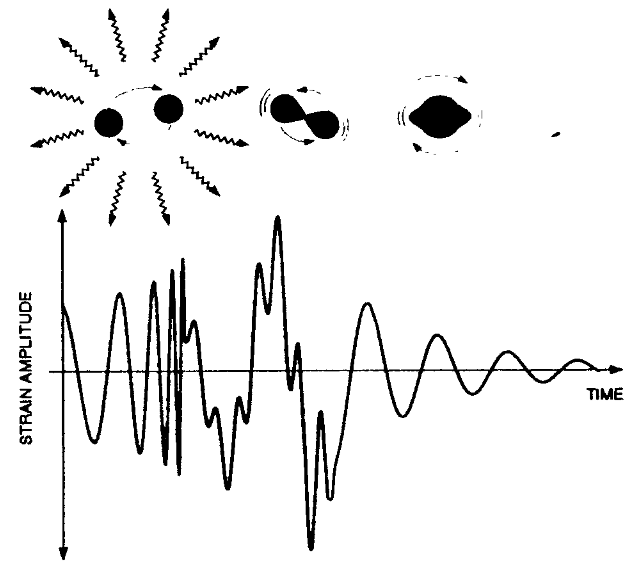
# GW OPTICAL DETECTION

- **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



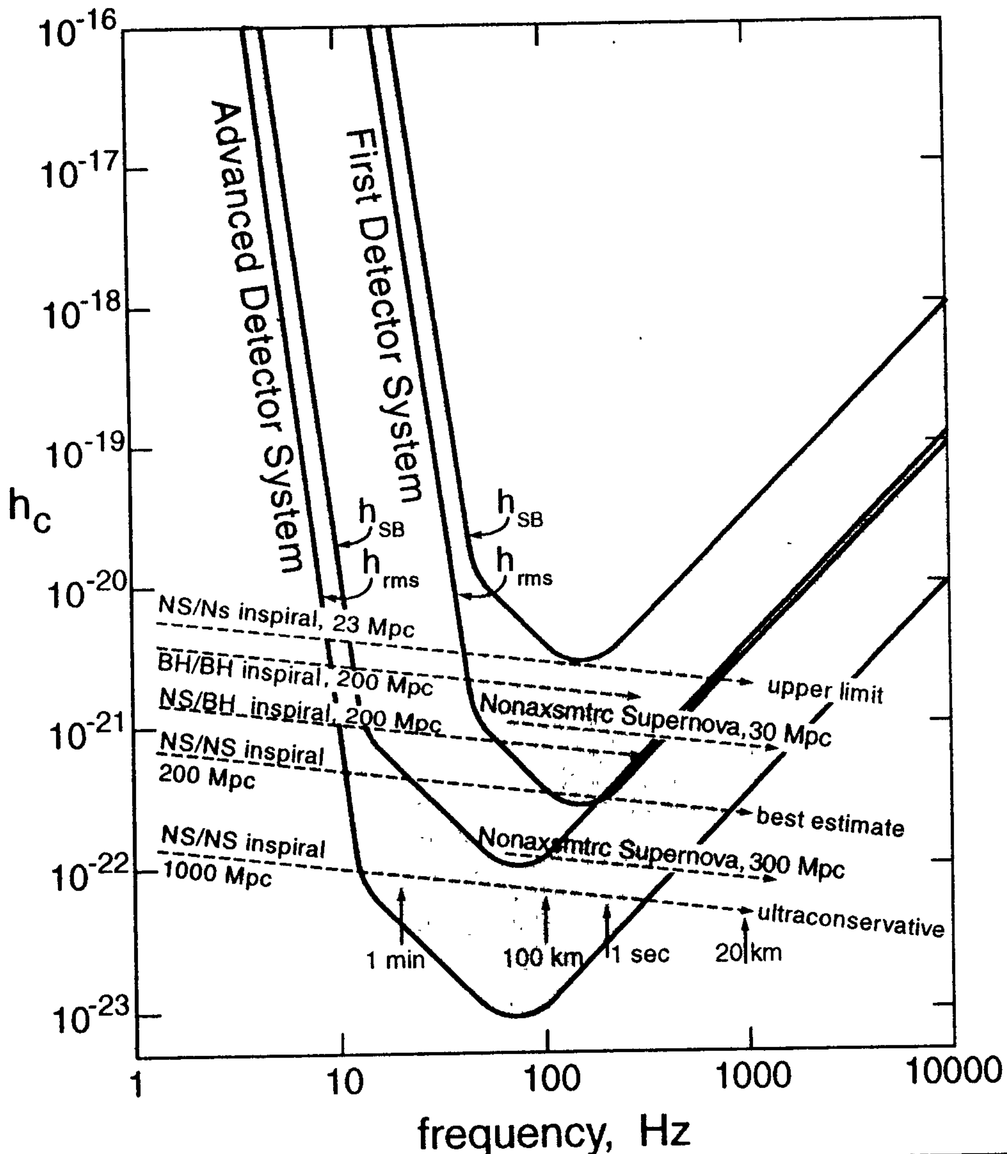
# GW SOURCES

- **COMPACT BINARY COALESCENCE**
  - NEUTRON STAR (NS)
  - BLACK HOLE (BH)
  - SIGNALS RANGE FROM 10 Hz TO 1000 Hz
  - SHORT DURATION (~ 1 MINUTE)



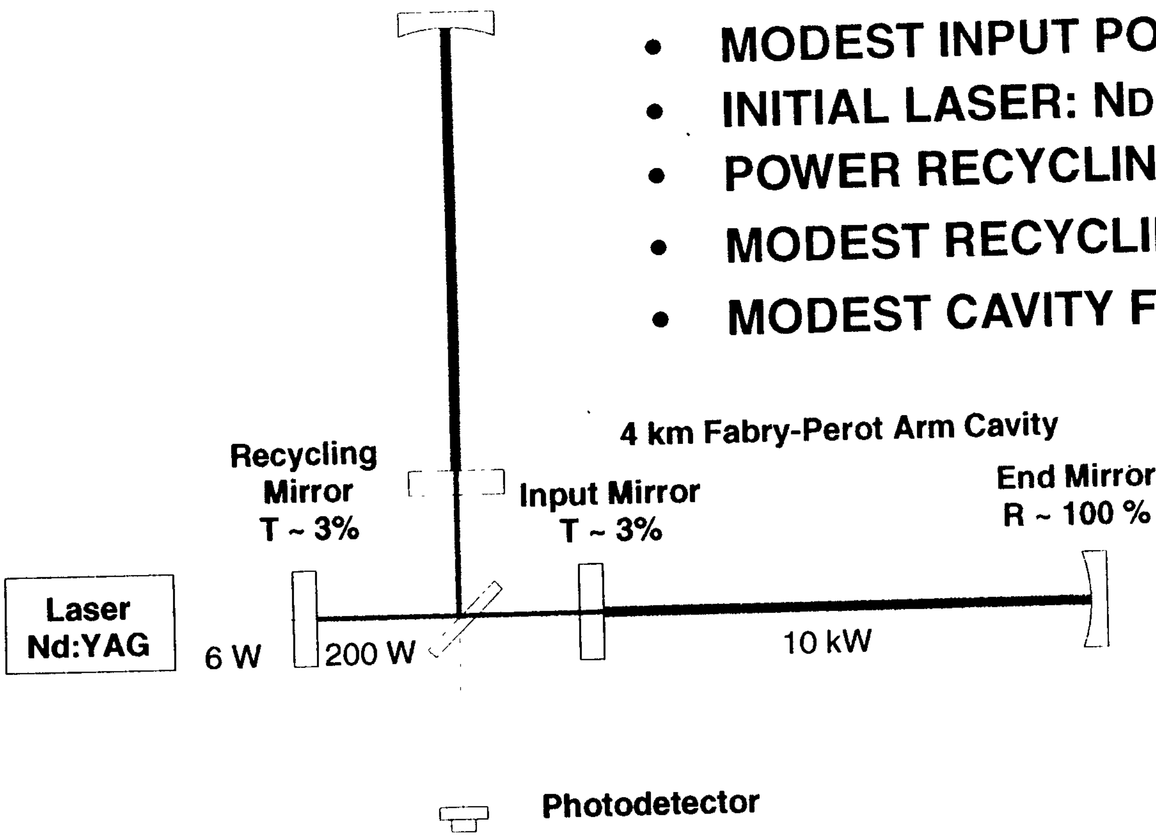

- **SUPERNOVA**
  - ASYMMETRIC COLLAPSE OF STELLAR CORE TO FORM NEUTRON STAR
  - VERY SHORT DURATION (~ millisecond)
- **COSMIC BACKGROUND**
  - GW ANALOG TO THE COSMIC MICROWAVE ("3 Degree") BACKGROUND
  - EXTREMELY WEAK SIGNAL

# COMPARISON OF LIGO SENSITIVITY GOALS AND ESTIMATED GW SOURCES

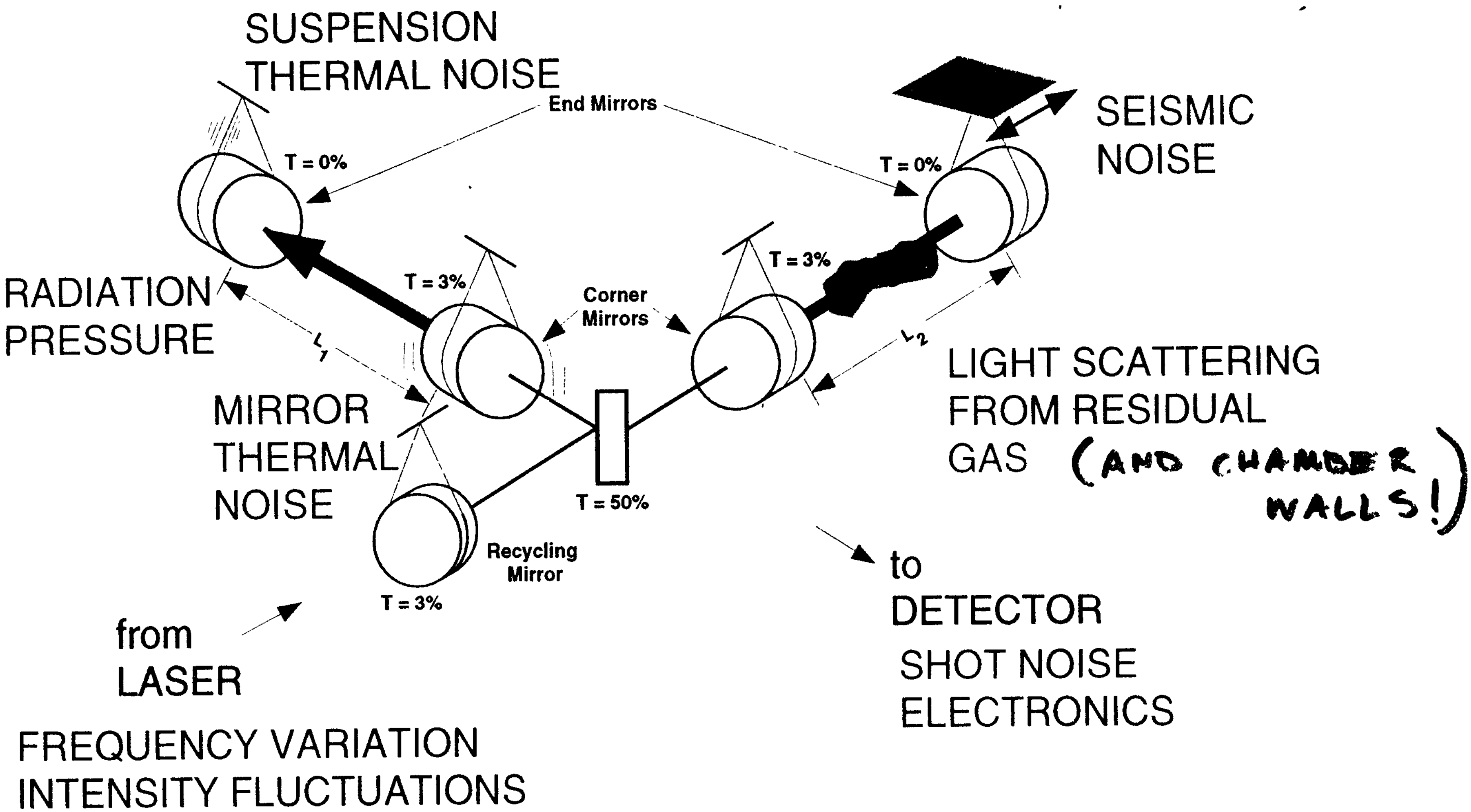


# INITIAL INTERFEROMETER CONFIGURATION

- 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 ($\mathcal{F} \sim 50$)



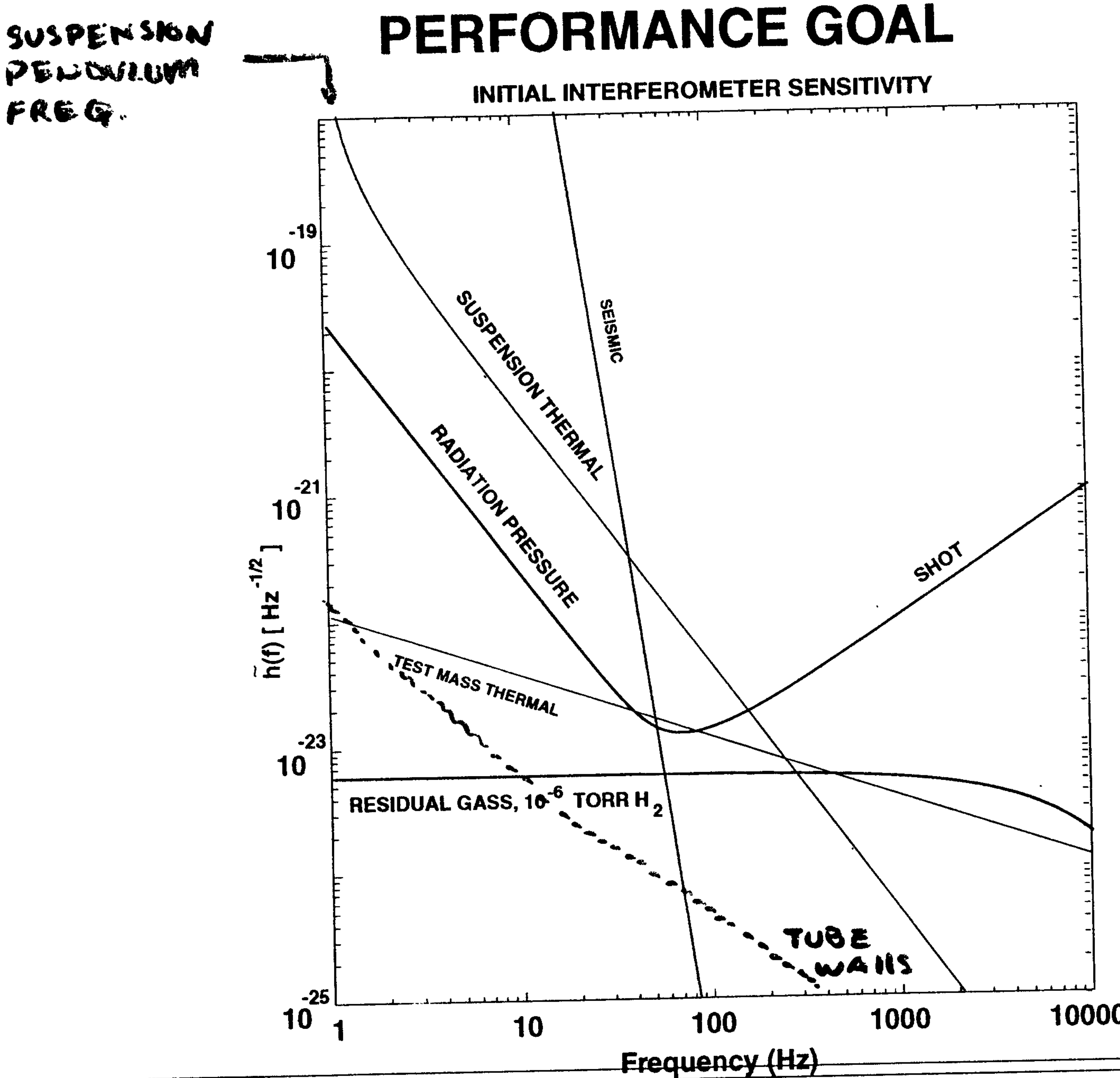
# NOISE SOURCES



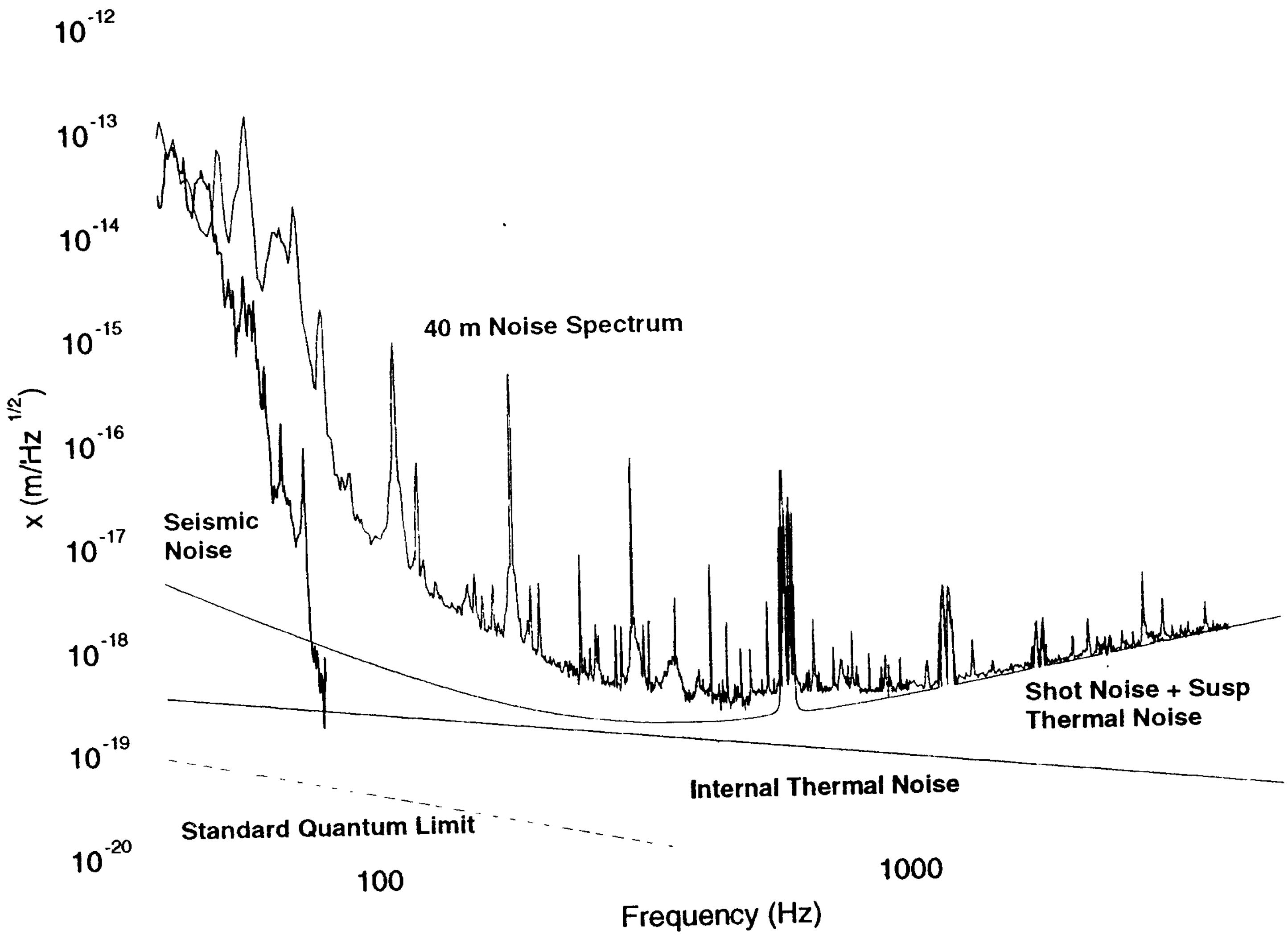
# INITIAL LIMITS TO SENSITIVITY

- DISPLACEMENT NOISE (PHYSICAL MOTION)
  - SEISMIC NOISE
    - SEISMICALY QUIET SITES
    - MULTI-STAGE SEISMIC ISOLATION SYSTEM & PENDULUM SUSPENSIONS FOR THE TEST MASSES
  - THERMAL NOISE
    - THERMAL NOISE DUE TO PENDULUM MODE
    - THERMAL NOISE DUE TO INTERNAL VIBRATIONAL MODES
    - CAREFUL MECHANICAL DESIGN TO ENSURE NO MECHANICAL MODES AT LIGO FREQUENCIES
- SENSING NOISE
  - SHOT NOISE
    - HIGH POWER STABILIZED LASER
    - NEARLY PERFECT OPTICS TO USE LASER POWER EFFICIENTLY

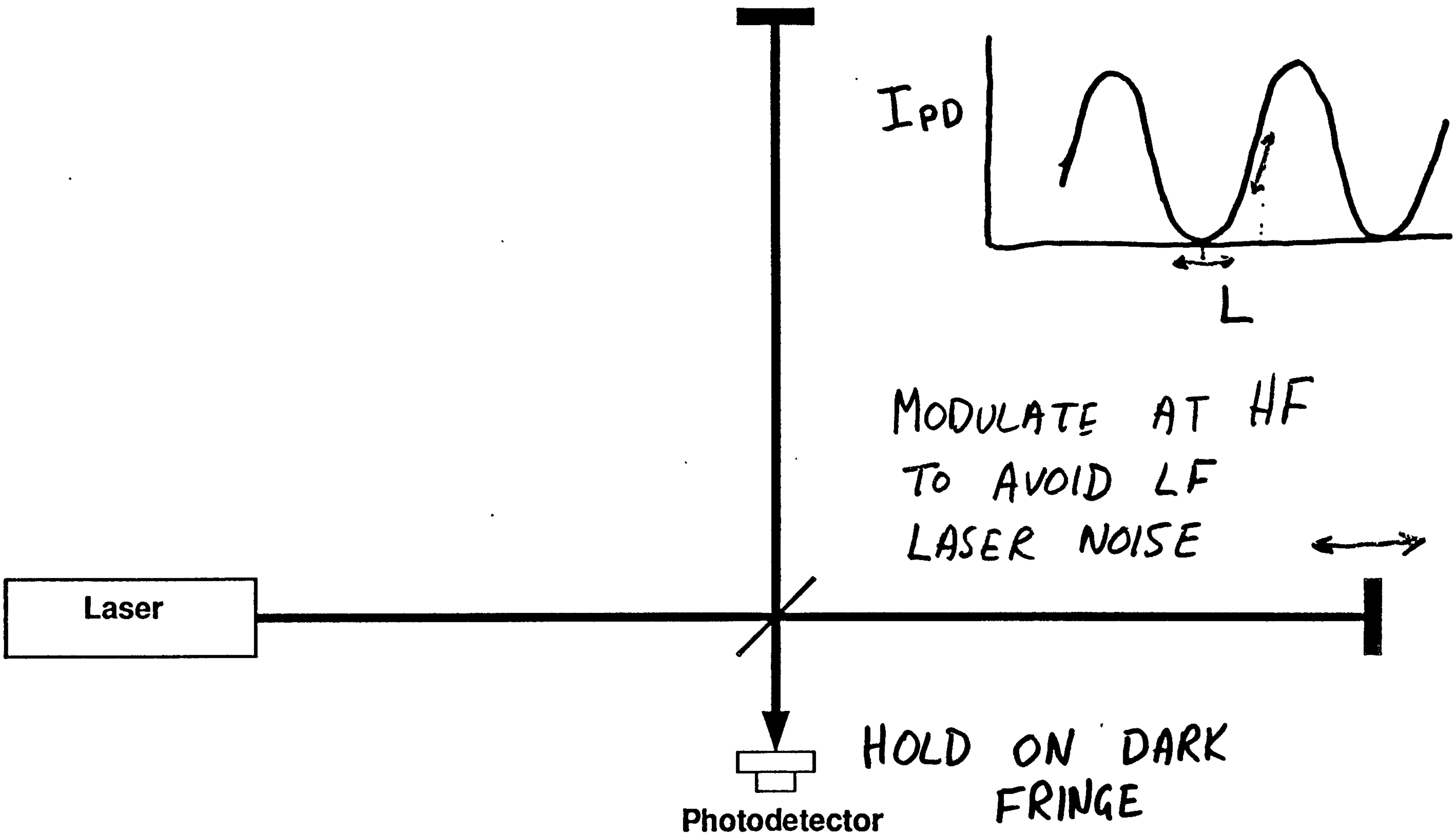
# INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL



# 40-METER DISPLACEMENT SPECTRUM



## Optical Layout and Operation



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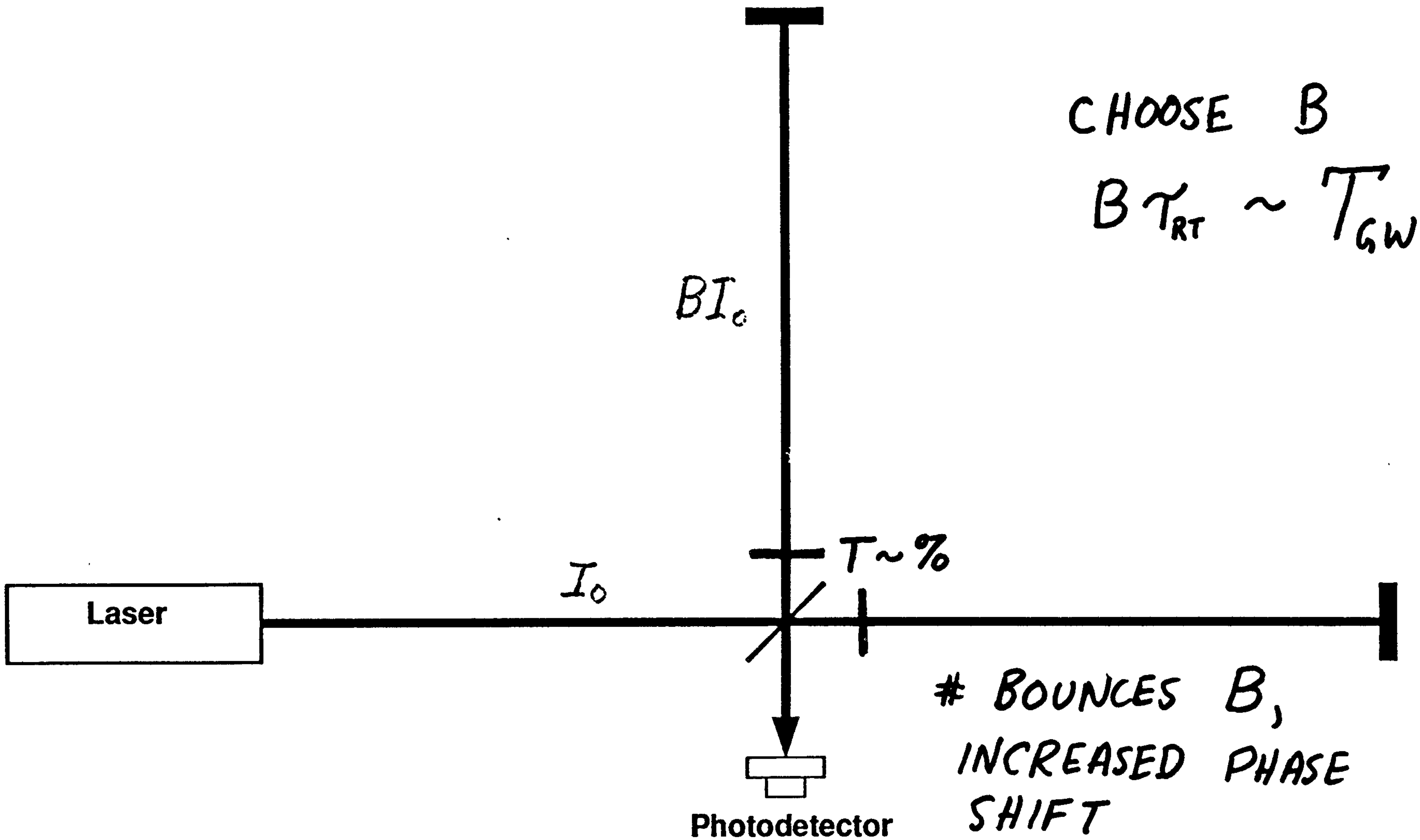

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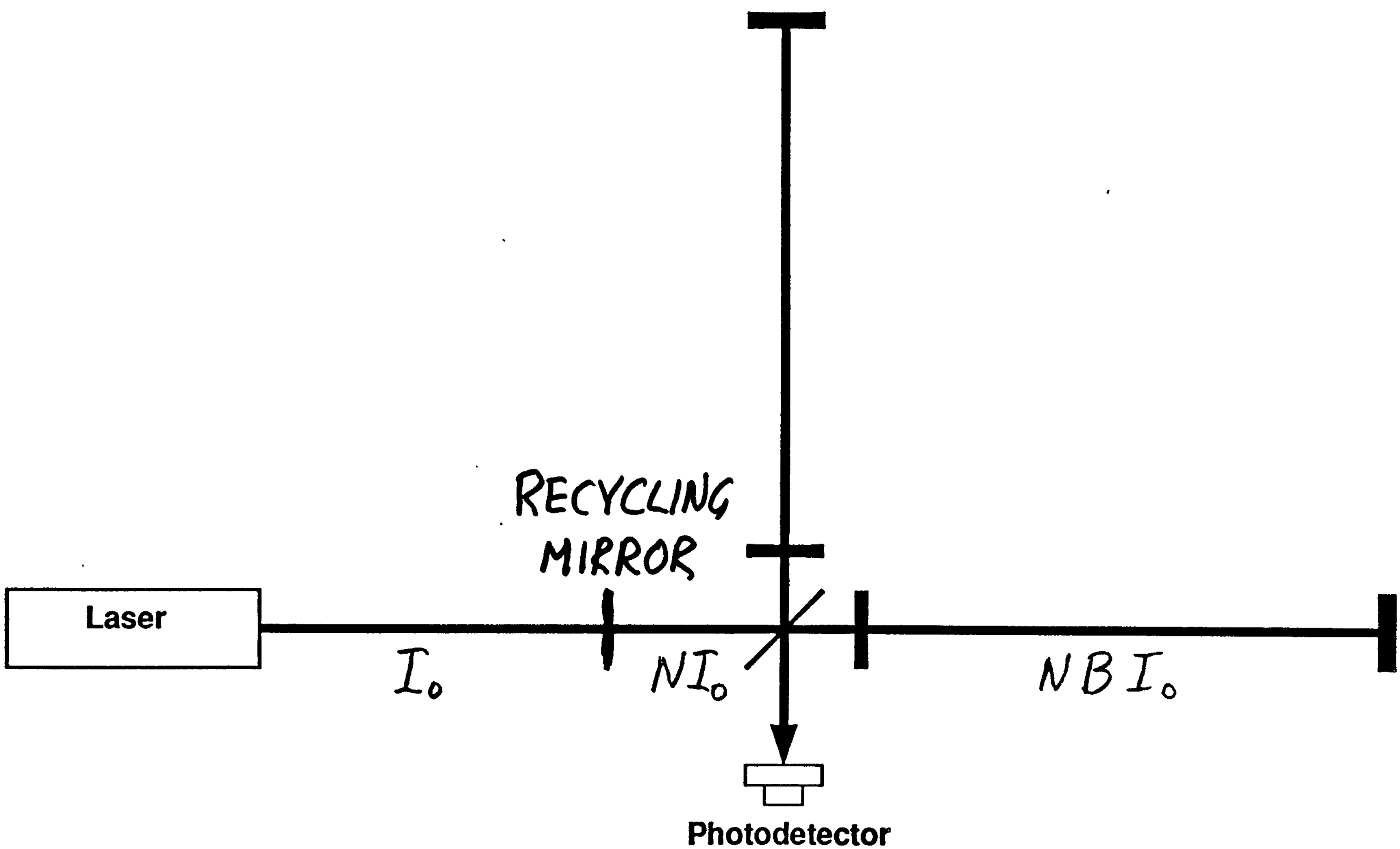
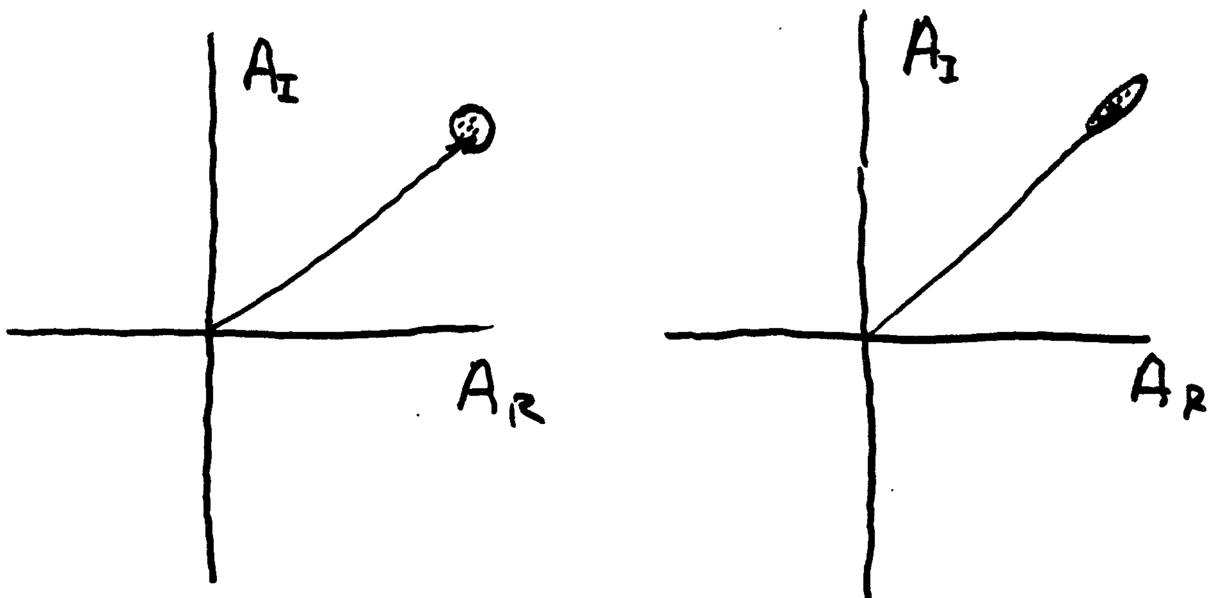


# LIMIT TO OPTICAL PHASE MEASUREMENT

$$\delta\varphi \, \delta A \gtrsim 1$$




"NORMAL"  "SQUEEZED"

EXAMPLE: $\delta\varphi \sim 10^{-10}$ RAD/$\sqrt{\text{HZ}}$

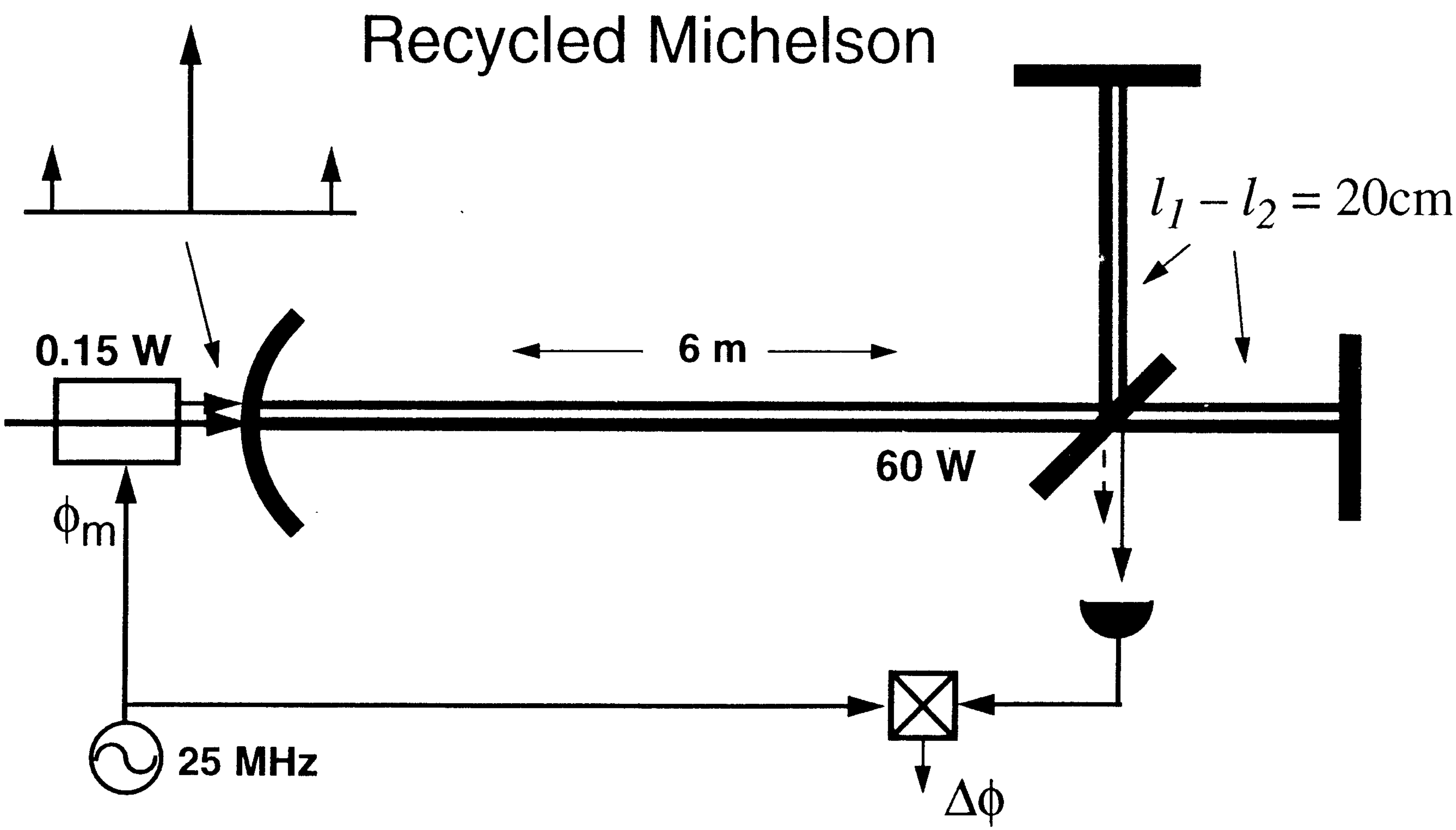
$\Rightarrow \quad \delta A \sim 10^{10}/\sqrt{\text{SEC}}$

$\Rightarrow \quad I \sim 10^{20}$ PHOTONS/SEC

# Phase Noise Interferometer (PNI)

- Demonstrate optical phase measurement sensitivity
  - LIGO requires $\tilde{\phi}(f) < 10^{-10} \mathrm{rad}/\sqrt{\mathrm{Hz}}$
- Optimize optical configuration to emphasize phase noise over displacement noise
- Discover and understand technical noise sources
  - Scattered light
  - Laser noise & modulation artifacts
  - Unknown...
- Develop and test LIGO sensing hardware
  - high-power photodetectors
  - length and alignment controls

# Optical Configuration

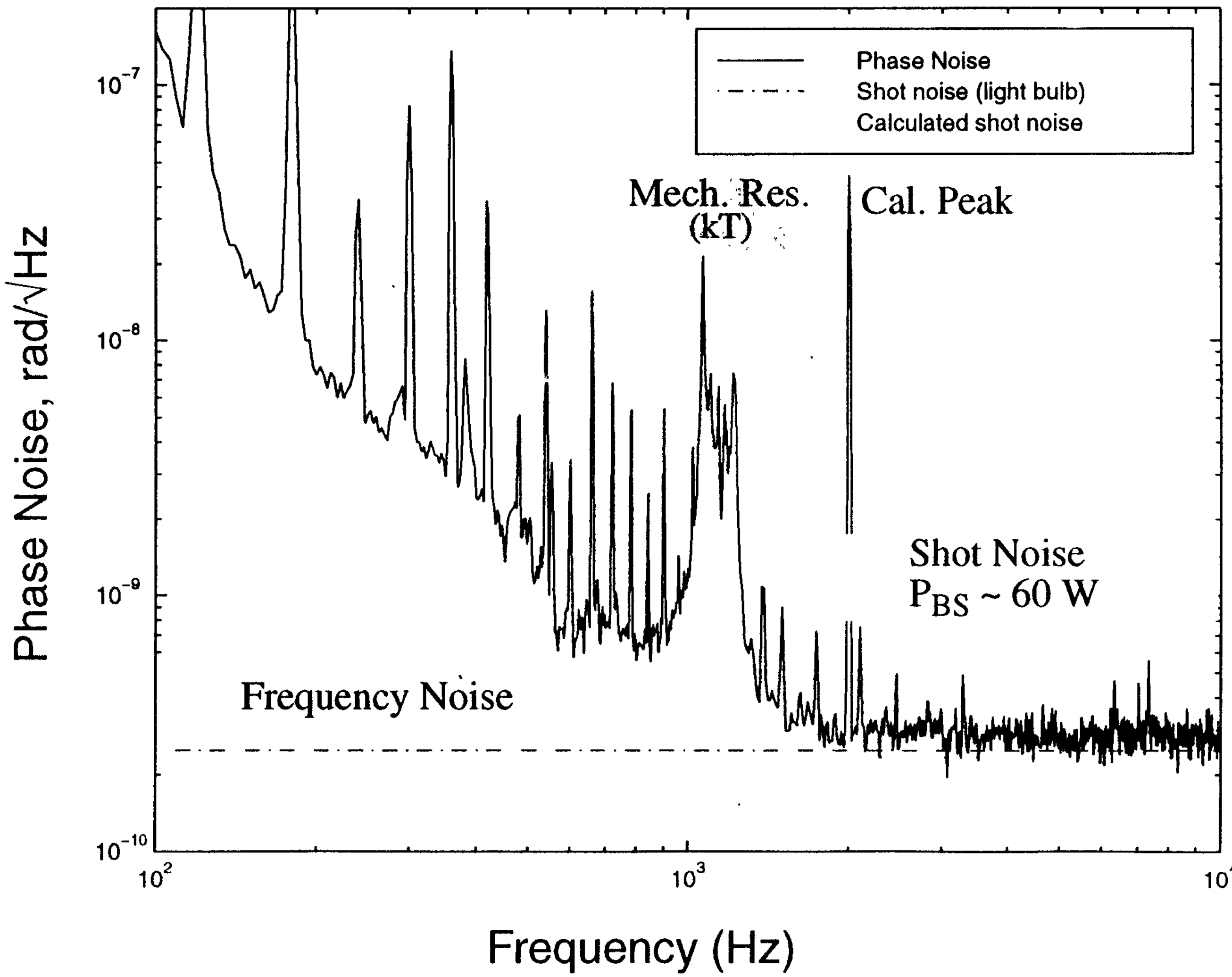



LIGO

# PNI Results to Date

- Initial investigations with Ar laser (515 nm) completed in January
- Highest optical phase sensitivity: $2.9 \times 10^{-10}$ rad/$\sqrt{\text{Hz}}$
  - 60 Watts of optical power incident on beamsplitter
  - Recycling factor ~450
- Consistent with shot noise above ~1 kHz
- Good understanding of other noise sources

# PNI Spectrum: Dominant Noise Sources

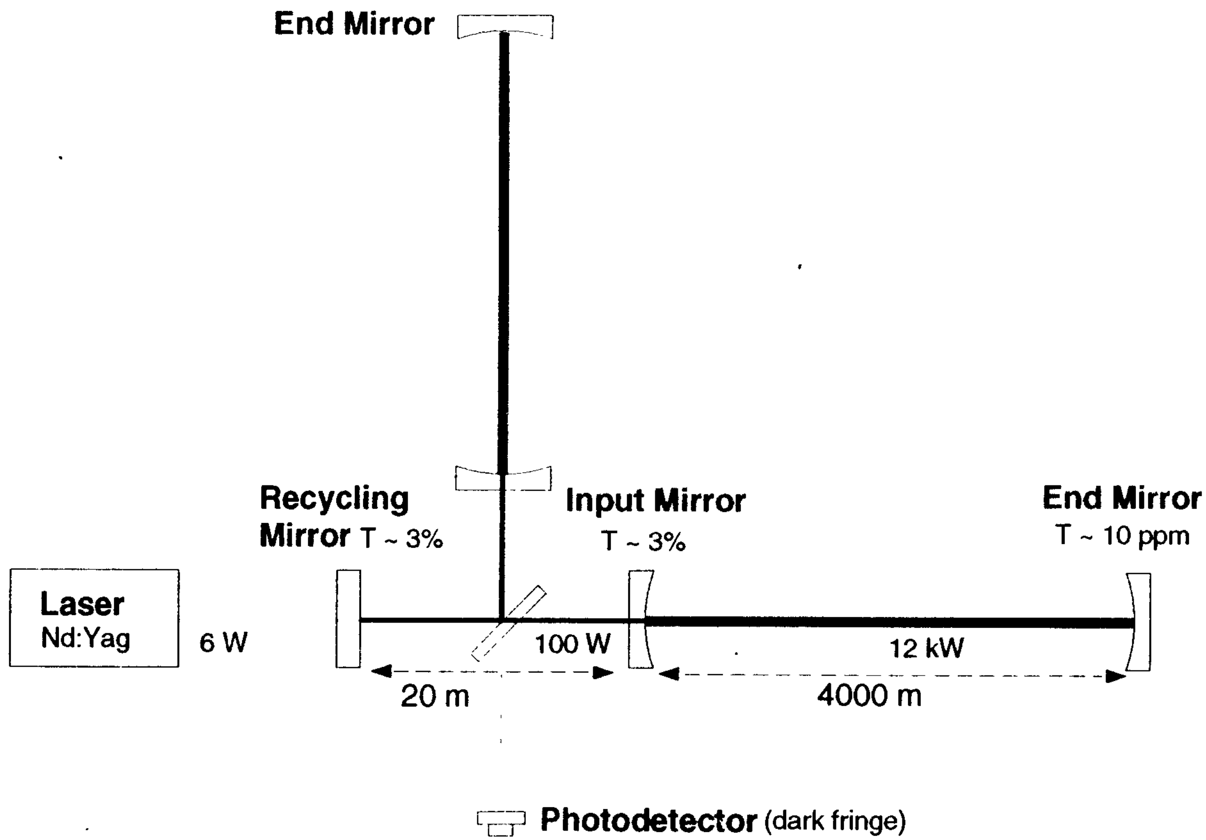


# Future Plans for the PNI

- Conversion to Nd:YAG laser/1064 nm
  - Installation of frequency-stabilized diode-pumped Nd:YAG laser
  - Input laser/optic table setup is complete
  - Two-mirror suspended cavity installed in vacuum system and locked to laser
  - Test frequency stability of Nd:YAG laser
- Next step: Recycled Michelson
  - Installation will commence early June
  - Test high-power photodetector prototype
  - Test digital length control prototype hard/software
- Completion end of '97

# Large Optical Components
# ("Core Optics")

- Test Masses
  - End Mirror
  - Input Mirror
- Beamsplitter
- Recycling Mirror
- Total Number: 20
  - WA 4km: 6 Optics
  - WA 2km: 8 Optics
  - LA 4km: 6 Optics
  - + Spares



# Core Optics

- High purity fused silica
  - 25 cm diameter x 10 cm thick (except beamsplitter: 4cm thick)
  - Beams fill some optics (to ~1ppm level)
  - 1064 nm HR mirrors and AR second surface coatings.
- Principal performance requirements:
  - < 50 ppm loss per surface (limits resonant stored energy: shot noise)
  - Surface figure errors to scatter negligible power from $TEM_{00}$ (best dark fringe)
    - Similar requirement for bulk inhomogeneity
  - High mechanical Q to "suppress" thermal noise ($Q \geq$ few x $10^6$)
  - Low bulk (<~5ppm/cm) and coating (<2ppm) absorption (thermal lensing limit to beam power and dark fringe contrast).

# Optics Development Program ("Pathfinder")

- Purchase and evaluate fused silica blanks (5/94)
  - ››Corning 7940 OAA Grade
- Best effort polishing of substrates (8/95-4/96)
  - ››Commonwealth Scientific and Industrial Research Organization (CSIRO)
  - ››General Optics (GO)
  - ››Hughes-Danbury Optical Systems (HDOS)
- Independent substrate metrology (4/96-8/96)
  - ››National Institute of Standards and Technology (NIST)
- Coating uniformity development (7/95-ongoing)
  - ››Research Electro Optics (REO)
- Coated optic metrology (NIST, early '97)
- Analysis of all data in LIGO computer model

# Core Optics-Polishing

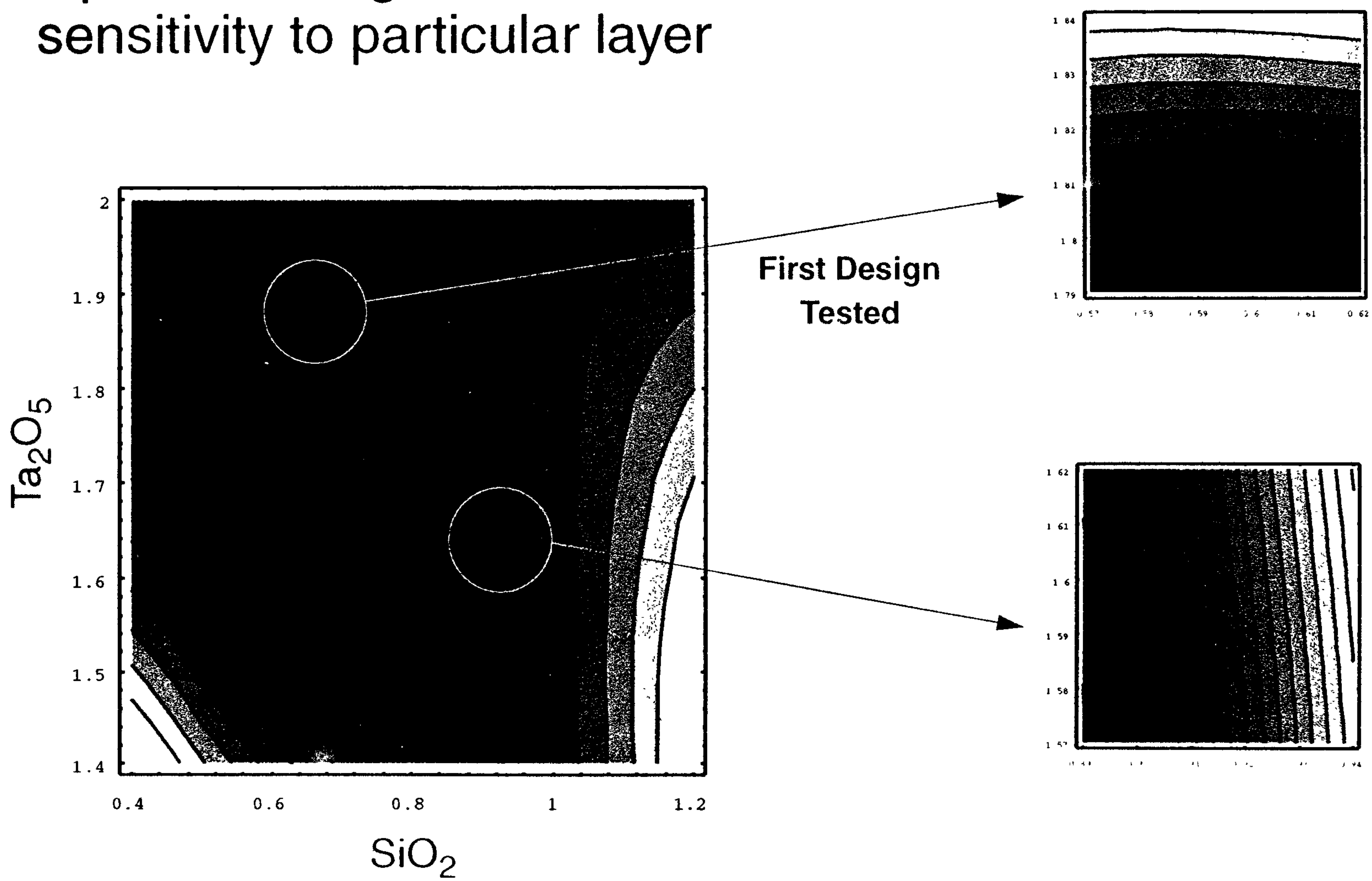
- Conclusion: deviations from perfect spherical surface < 1nm rms over 20cm diameter are achievable!
  - In some cases, apparent rms ~0.5 nm measured
- Microroughness 0.06 - 0.3 nm obtained simultaneously
- Reliable metrology also possible at the <1 nm level
  - Reproducible features seen; Consistent intercomparisons demonstrated
  - Small, subtle systematic effects noticed
- GO and CSIRO selected to polish LIGO Core Optics

# Coating Uniformity Development

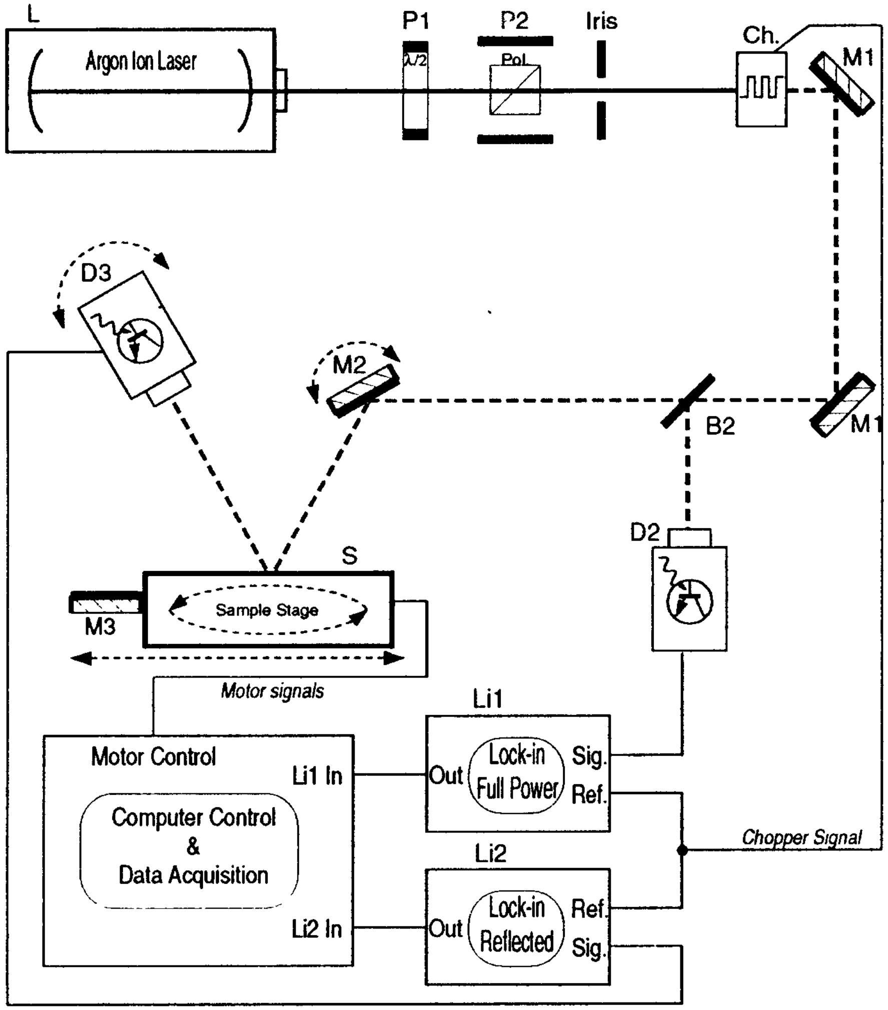
- Coating Uniformity Development: REO
  - ››Goal: Scale up low loss ion beam sputtered coating technology to LIGO diameters
  - ››Preliminary test pieces show good uniformity to 15 cm diameter
  - ››Final verification: Coat Pathfinder optics for 633 nm and test
- Development of new test technique
  - ›› Measurements: Doug Jungwirth, Alex Golovitser
  - ›› Analysis: Hiro Yamamoto, Bill Kells
  - ›› Coatings: Research Electro Optics, Ramin Lalezari

# Test AR Coating Design

- Optimize design for maximum sensitivity to particular layer

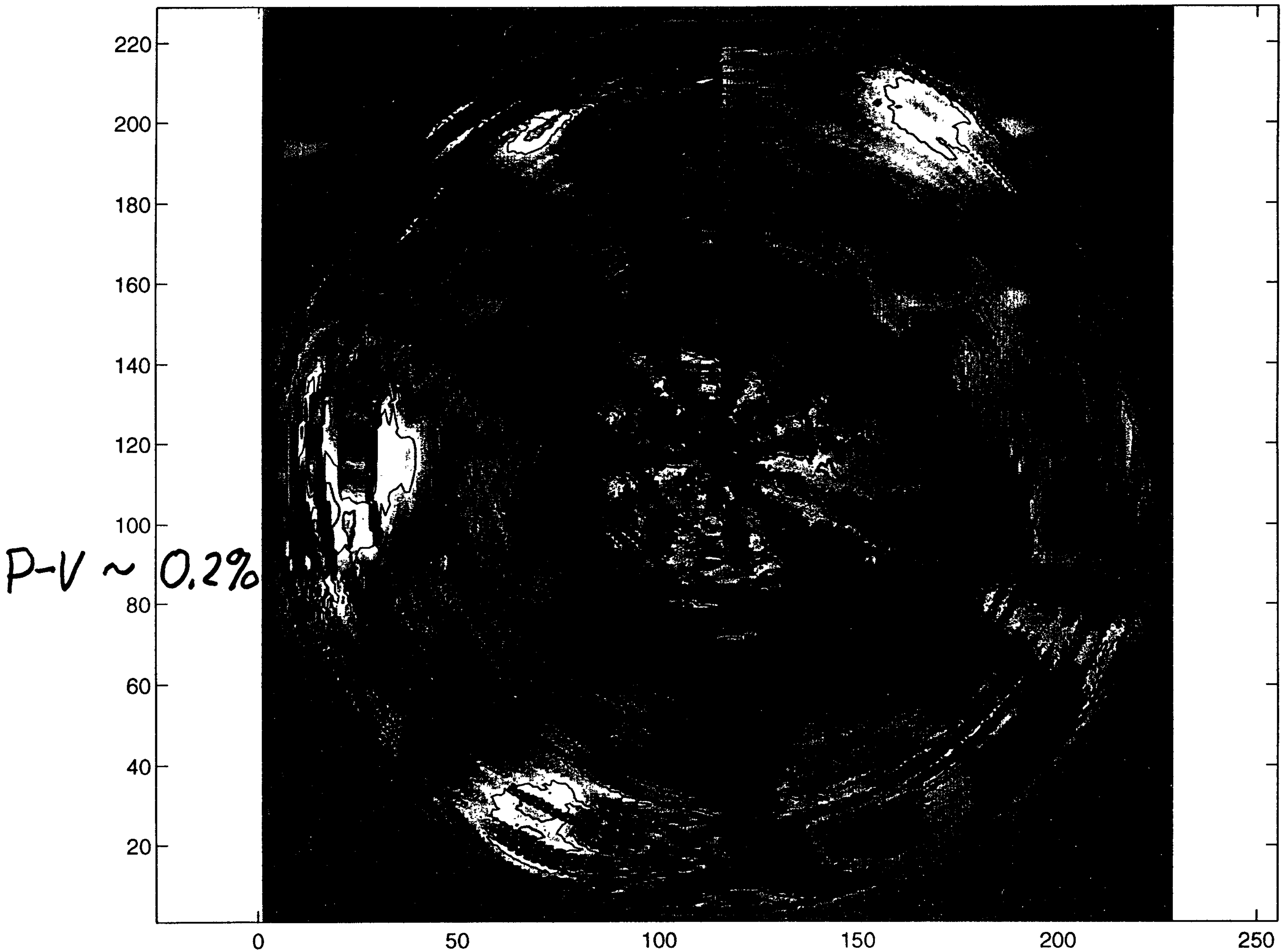


# Coating Uniformity Measurements

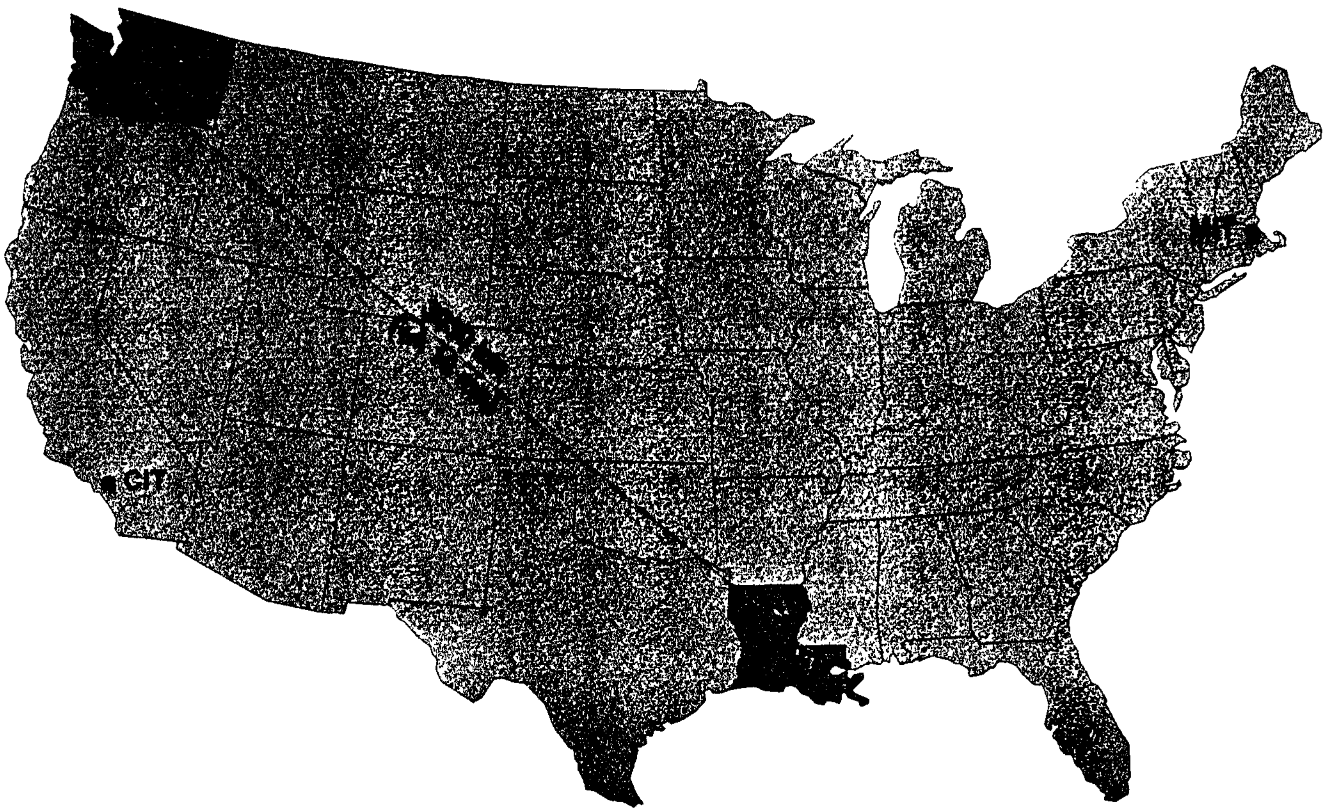



- Map reflectivity of specially designed AR coating
  - ››Insensitive to surface figure of underlying substrate
  - ››Can investigate uniformity of individual coating layers
- Make measurements at:
  - ››2 Polarizations
  - ››3 Angles
- EXTRAPOLATE RESULTS TO HR STACK COATINGS FOR LIGO MODELING.

Interpolated, normalized contour map of substrate A7550 (Ta2O5 sensitive side): at 45 degrees, S–polarization.



# LIGO SITES




**HANFORD, WASHINGTON**

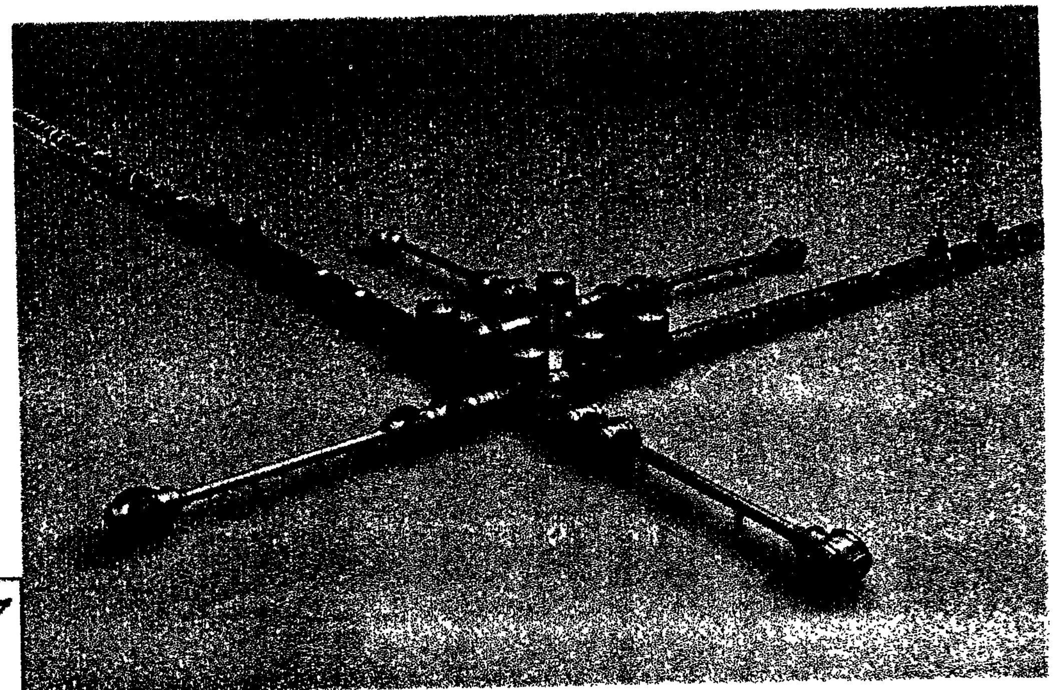
- LOCATED ON U.S. DOE RESERVATION
- TREELESS, SEMI-ARID HIGH DESERT
- APPROX. 25 KM FROM RICHLAND, WA (POPULATION :140,000)

**LIVINGSTON, LOUISIANA**

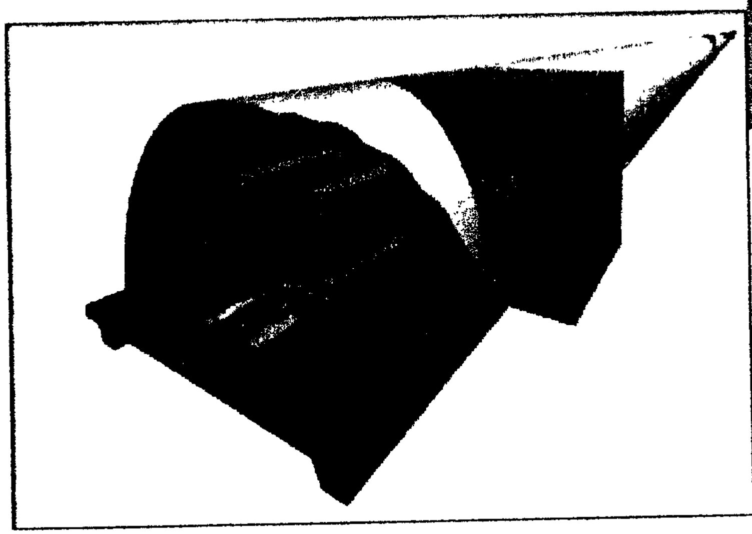
- LOCATED IN FORESTED RURAL AREA
- MIXED FOREST; LOW-LYING; POOR DRAINAGE
- APPROX. 50 KM FROM BATON ROUGE, LA (POPULATION :450,000)

# VACUUM EQUIPMENT & BEAM TUBE

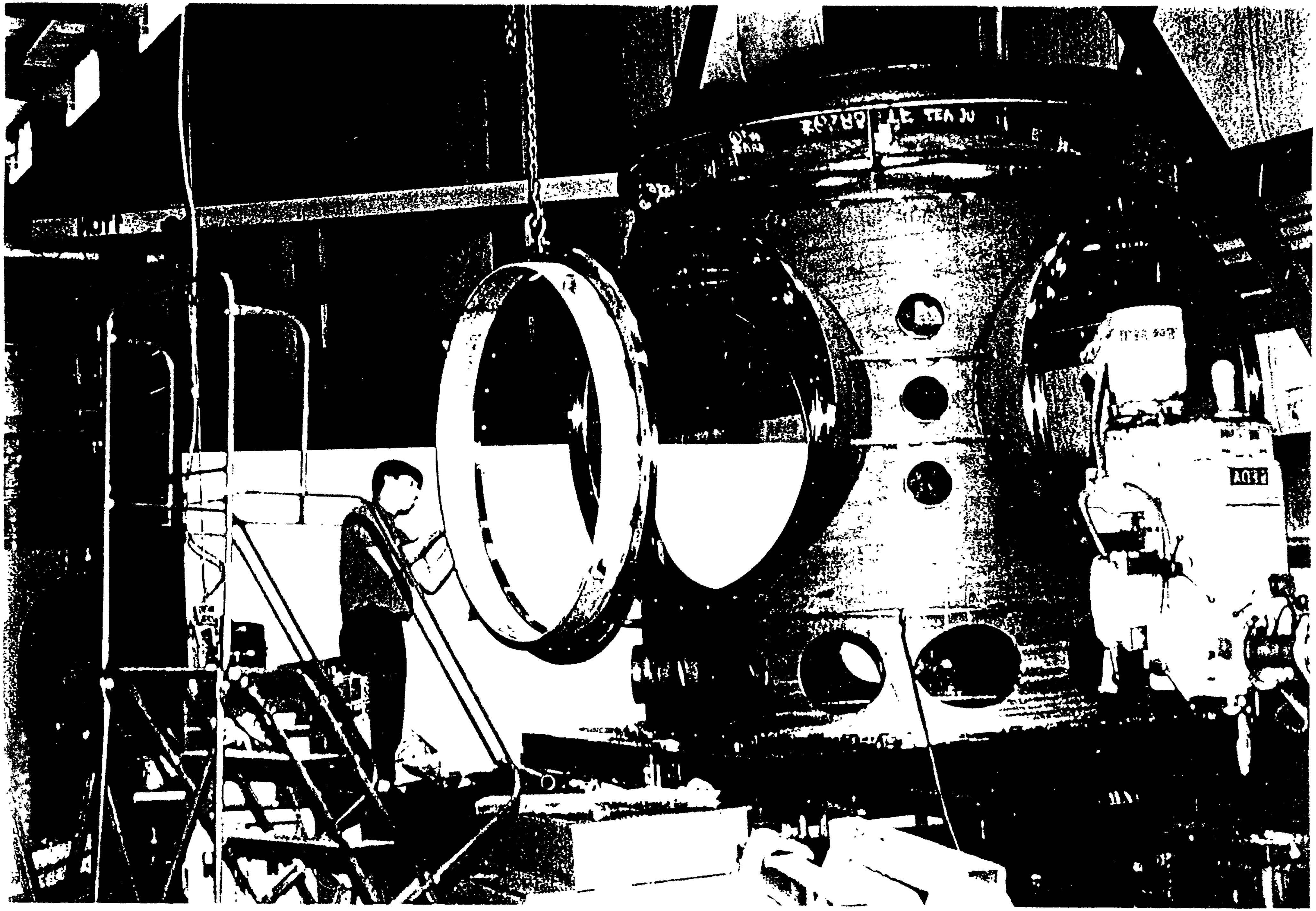
- ONE OF THE LARGEST VACUUM SYSTEMS IN THE WORLD

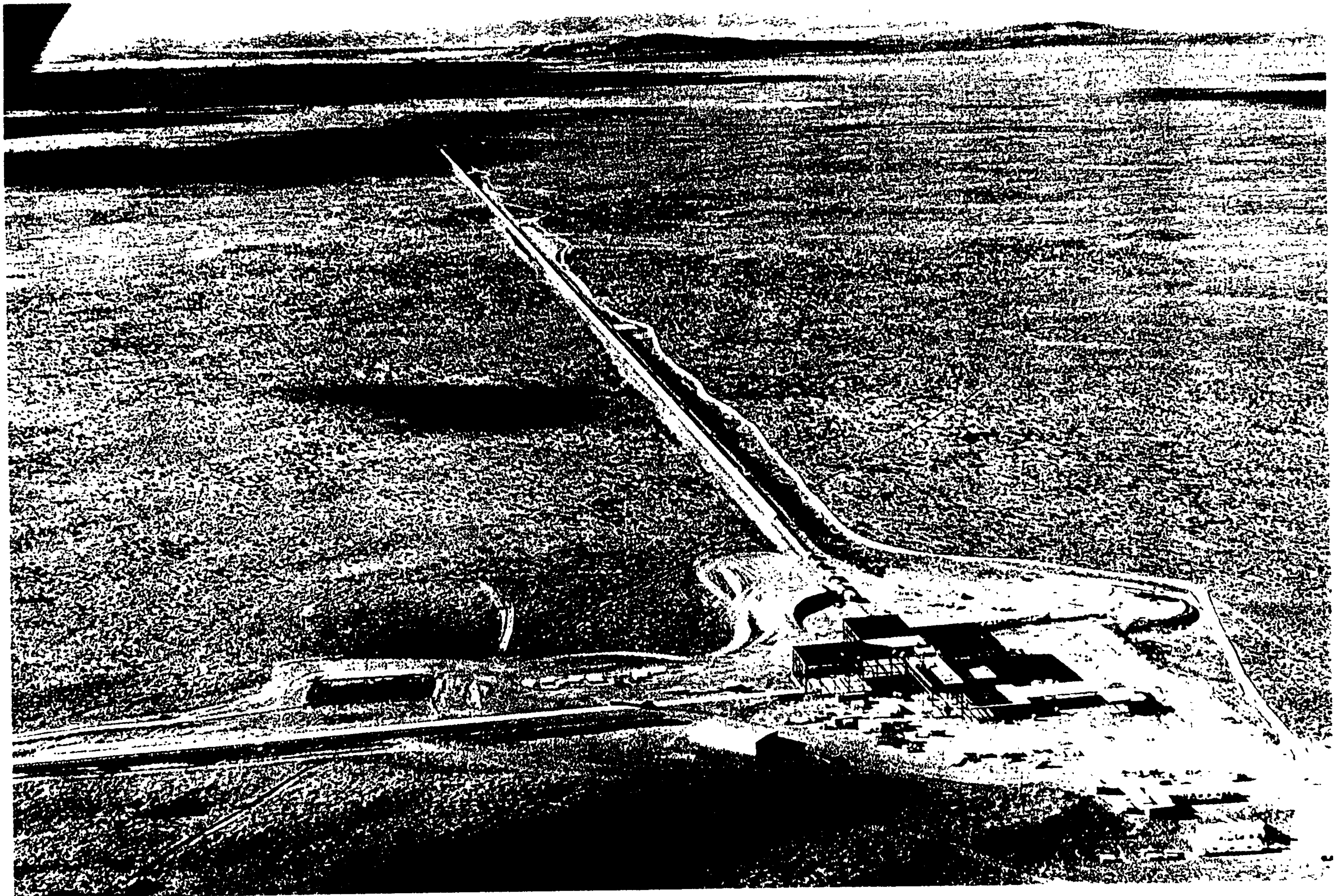


- EXTENSIVE NETWORK OF VACUUM CHAMBERS TO HOUSE SENSITVE INTERFEROMETER COMPONENT



- HIGH VACUUM BEAM TUBES TO CARRY LASER BEAMS DOWN UP AND DOWN ARMS





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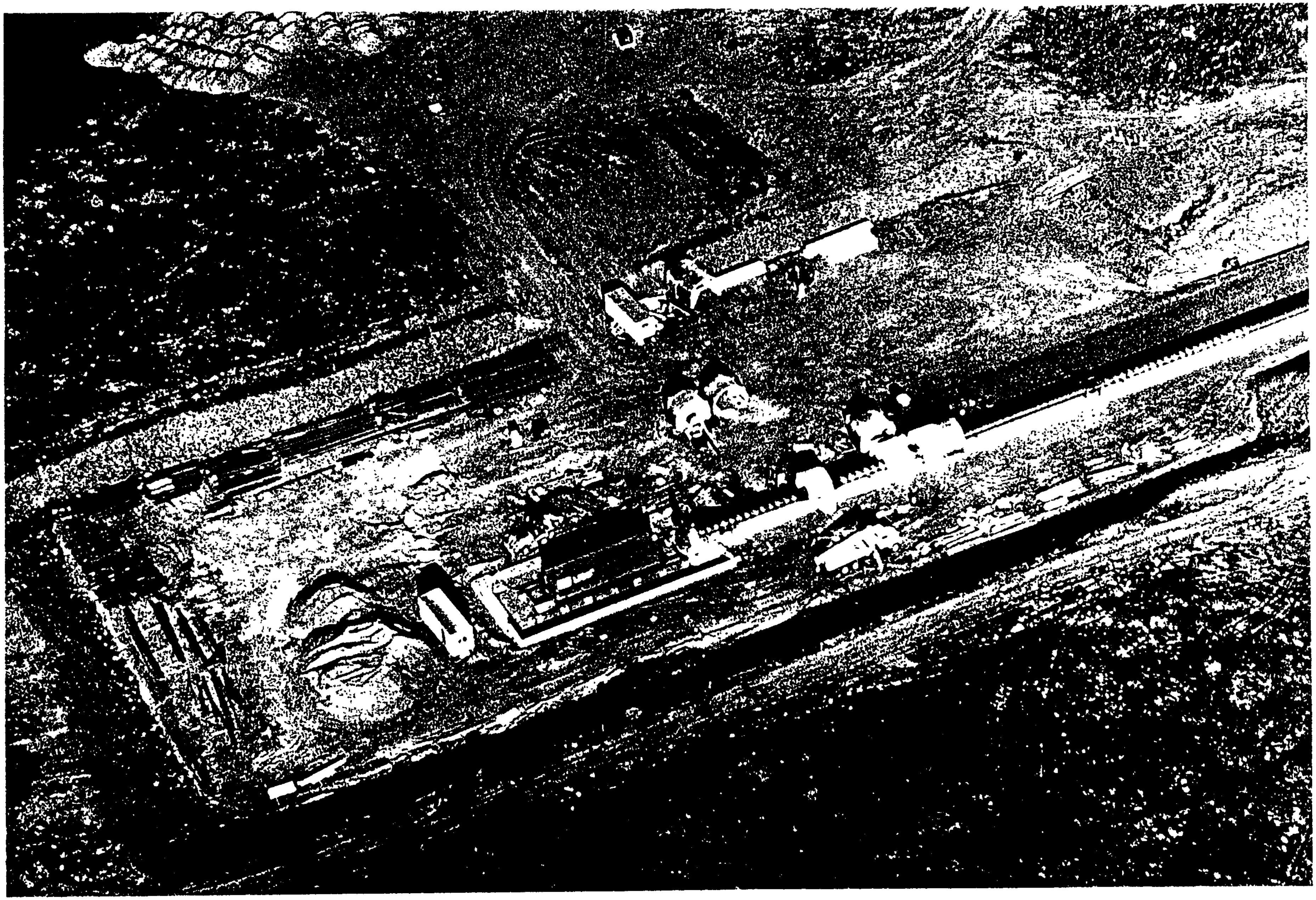

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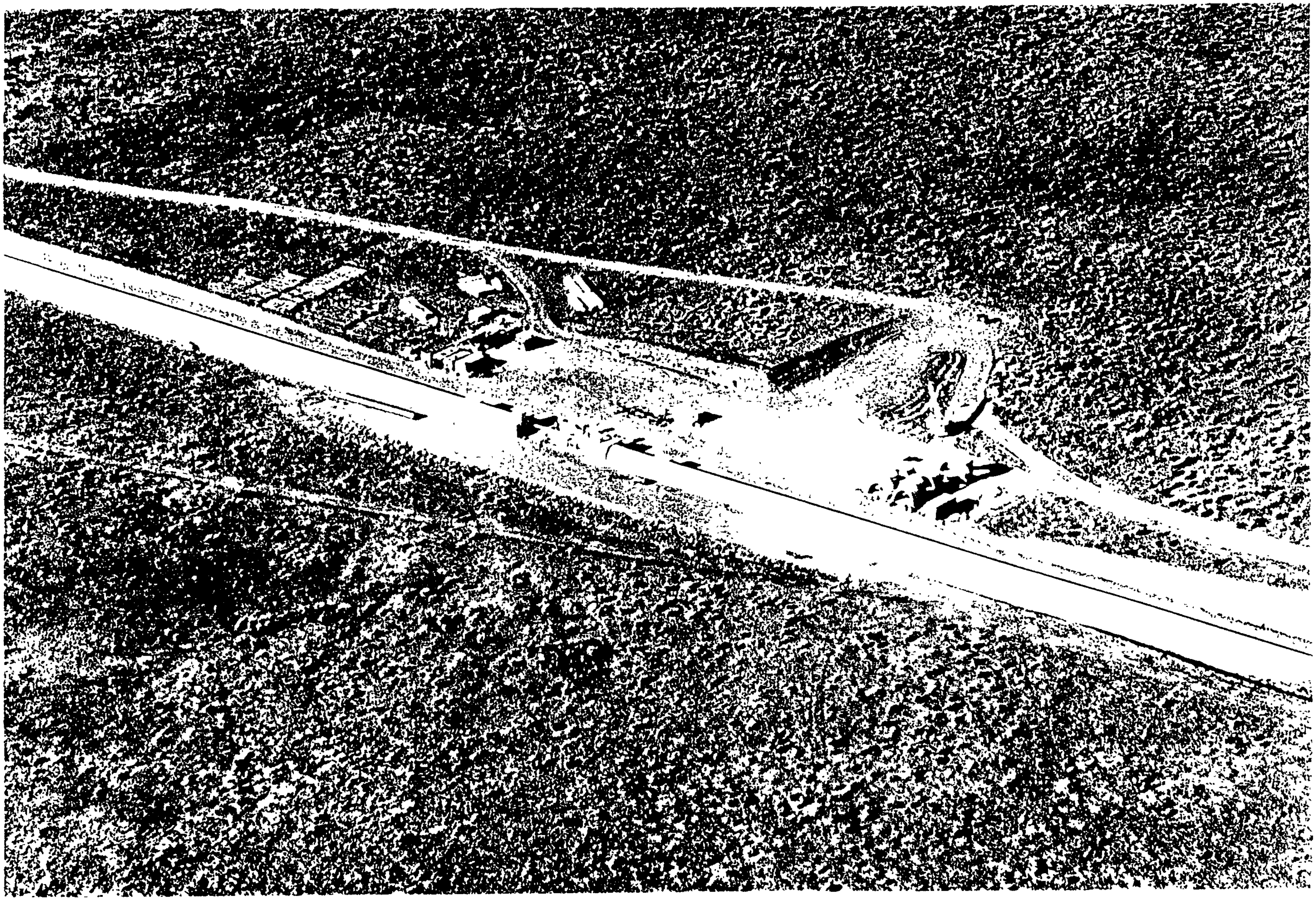

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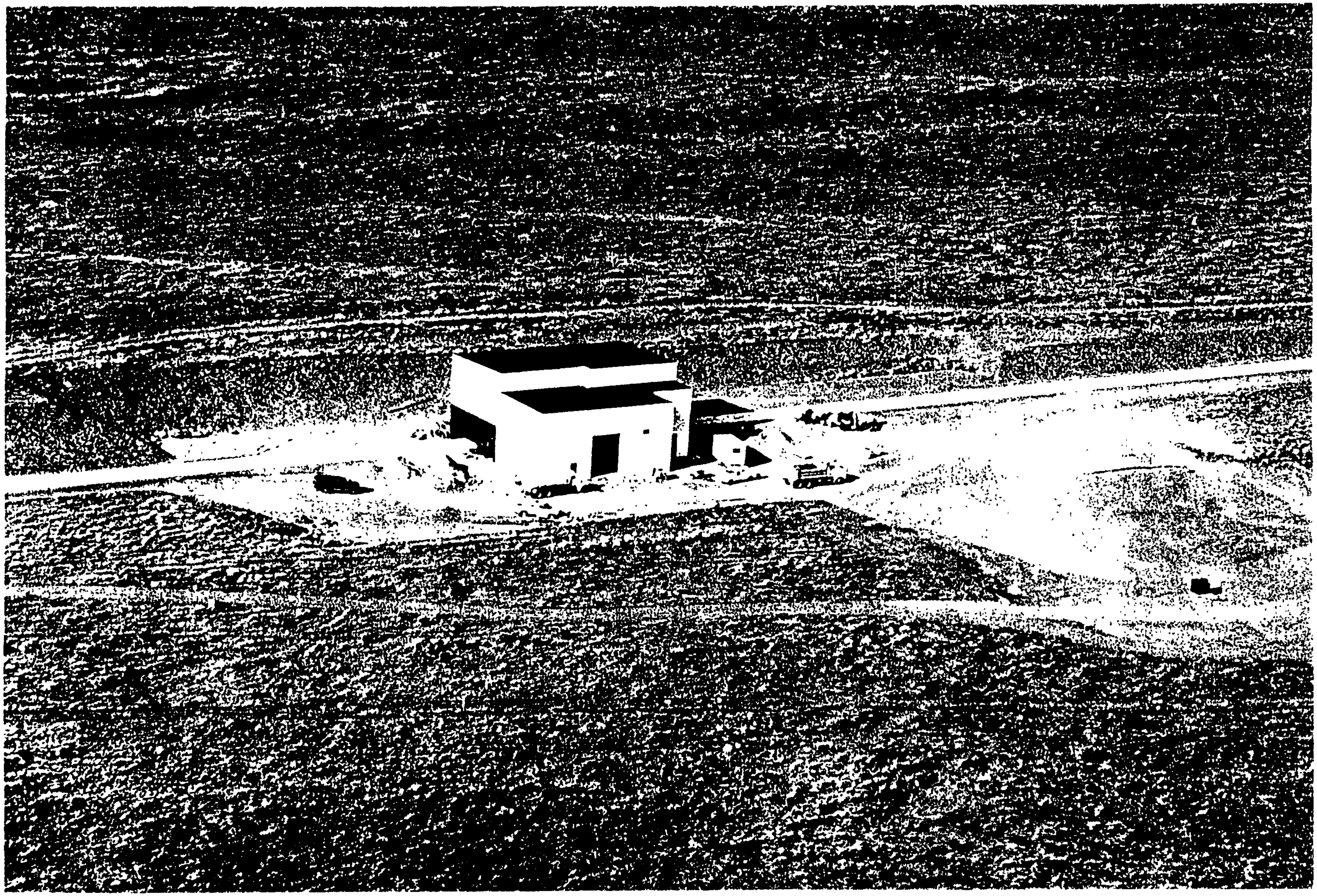

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# THE FUTURE?

- LIGO FACILITIES ARE PROCEEDING FROM FINAL DESIGN INTO FABRICATION & CONSTRUCTION
  - BUILDINGS AND VACUUM SYSTEM READY IN WASHINGTON: SUMMER 1998
  - BUILDINGS AND VACUUM SYSTEM READY IN LOUISIANA: SPRING 1999
  - FIRST COINCIDENCE RUNS WITH DETECTORS: SUMMER 2000

- THE QUESTION THAT ALWAYS GETS ASKED:

  **WILL LIGO SEE GRAVITATIONAL WAVES?**

# THE RIGHT QUESTIONS

- WHEN WILL LIGO SEE GRAVITATIONAL WAVES?
- WHAT NEW AND UNEXPECTED SOURCES OF GRAVITATIONAL WAVES WILL WE SEE?
- HOW WILL OUR STUDY OF GRAVITATIONAL WAVES CHANGE OUR UNDERSTANDING OF THE UNIVERSE?

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# LIMITING PERFORMANCE DUE TO FACILITIES