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LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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LIGO Presentation to NSF
Panel on Long Range uses of LIGO

B. Barish, A. Lazzarini, R. Weiss

Distribution of this draft:

LIGO

This is an internal working note
of the LIGO Project.
NOTE: Two LIGO DCC are included in this material.

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

LIGO

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

PRESENTATION TO THE

PANEL ON THE LONG RANGE USE OF LIGO

NATIONAL SCIENCE FOUNDATION
24,25 JUNE 1996
ARLINGTON, VA 22230

BARRY BARISH - CALTECH
LIGO PROJECT PRINCIPAL INVESTIGATOR

ALBERT LAZZARINI - CALTECH
LIGO PROJECT INTEGRATION MANAGER

RAINER WEISS - MIT
LIGO PROJECT INTEGRATION SCIENTIST

OVERVIEW

- **LIGO SCIENCE - B. Barish**
- **LIGO DESIGN - A. Lazzarini**
- **MAJOR LIGO SYSTEMS - A. Lazzarini**
    - CIVIL CONSTRUCTION
    - BEAM TUBE SYSTEM
    - VACUUM EQUIPMENT
    - DETECTOR/R&D
- **LIGO R&D - R. Weiss**
    - PRESENT
    - ADVANCED
- **LIGO COLLABORATIVE RESEARCH - B. Barish**

LIGO
The Science

Barry Barish

NSF Panel

"Future Uses of LIGO"

June 24-25, 1996

LIGO
The Project

- Joint Caltech/MIT Project funded by the National Science Foundation

- Under Construction 1995-1999
  - » Two Sites -- Louisiana and Washington

- **DIRECT** Detection of Gravitational Waves
  - » Fundamental Physics (GR)
    - – test General Relativity in strong field and high velocity limit
    - – measure polarization and propagation speed
  - » Astrophysics
    - – compact binary systems
    - – stellar collapse
    - – early universe

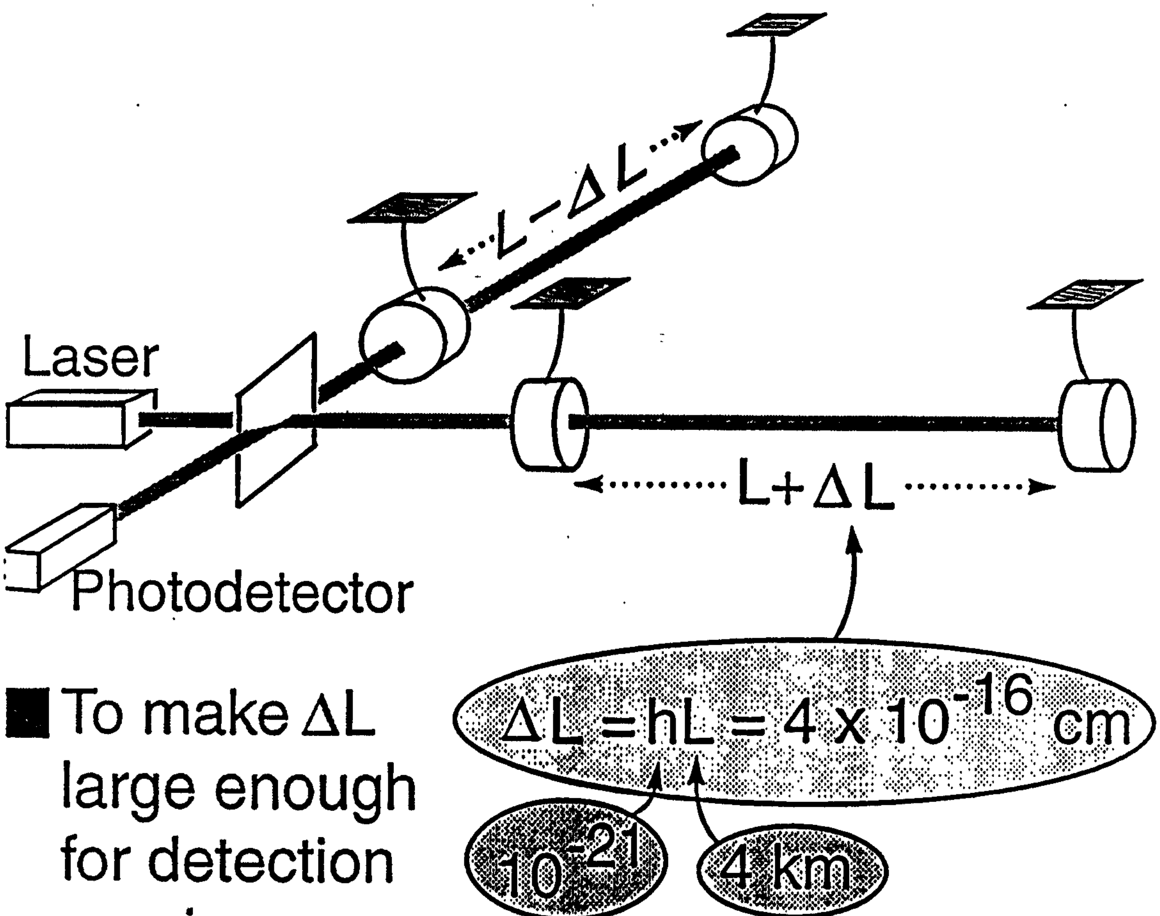
Gravitational Waves
International Effort

- 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

LIGO
Interferometers



- To make ΔL large enough for detection requires L ≳ 4 km
- Measured waveform, h(*time*) = ΔL/L, is a linear combination of h_+ and h_x , which depends on interferometer's orientation

Gravitational Waves
General Relativity

- Non-spherically symmetric accelerations of mass

- Main term - time dependence of quadrupole moment
  - » binary systems always radiate
  - » non-sherically symmetric supernova collapse
  - » non-axisymmetric rotations

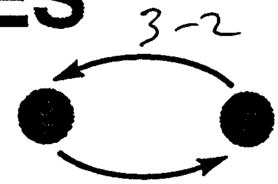
- Types of waves
  - » bursts, periodic or quasi-periodic waves
  - » stochastic background from compact binaries, primordial waves and cosmic strings or phase transitions

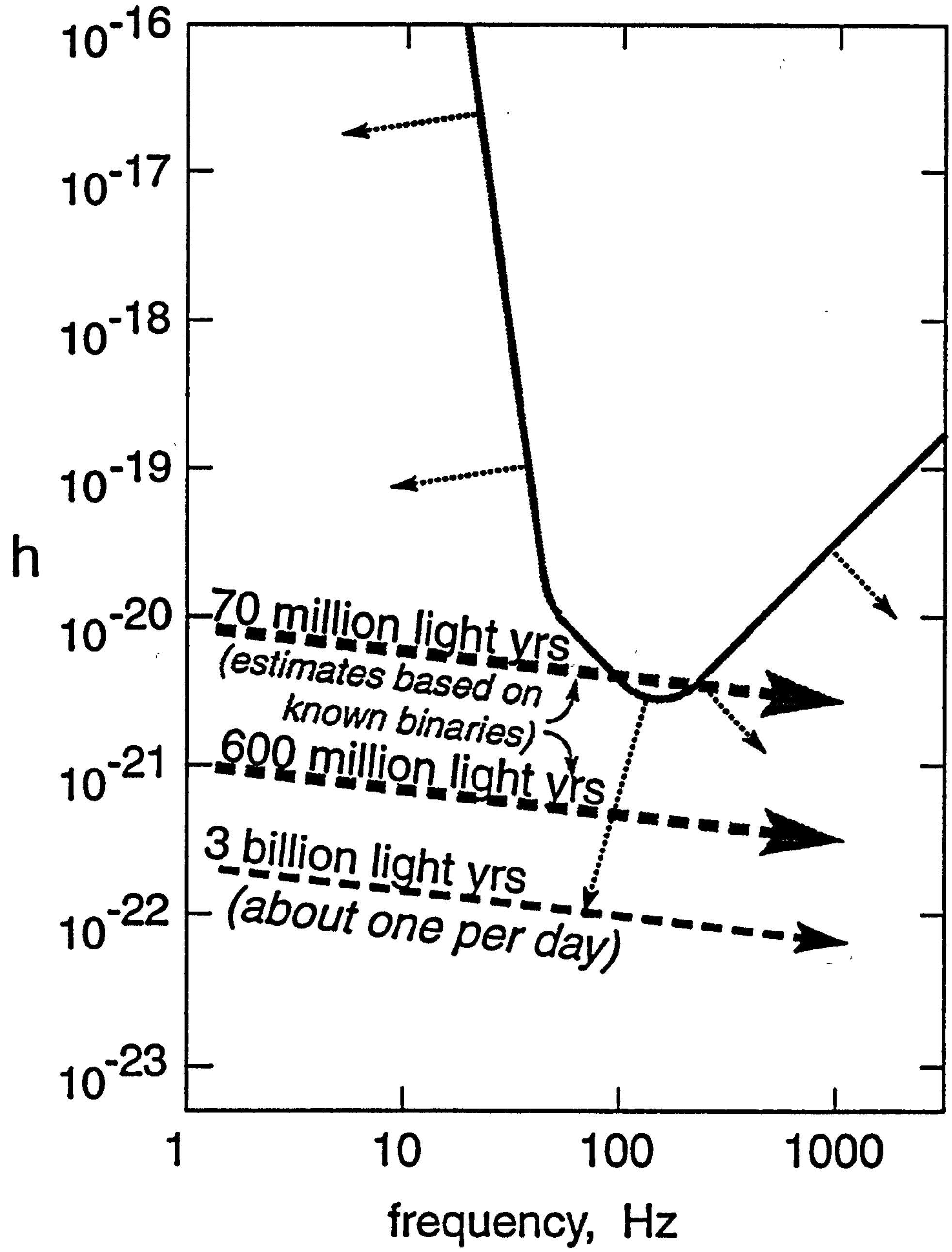
LIGO
Long Range Goals

- Inspiral of Compact Binary ***[chirps]***
  - » Neutron Star/Neutron Star Inspiral
    - – Design Benchmark: last 15 min
      20,000 cycles
      600 MLyr
  - » Black-hole/Black-hole Inspiral and Coalescence
  - » Black-hole/Neutron Star Inspiral
- Supernovae ***[bursts]***
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr
- Pulsars ***[periodic]***
  - » rotating non-axisymmetric neutron stars
- Early Universe ***[stochastic]***
  - » Vibrating Cosmic Strings
  - » Vacuum Phase Transitions
  - » Vacuum Fluctuations from Planck Era
- Unknown Sources ***[??]***

NEUTRON STAR BINARIES

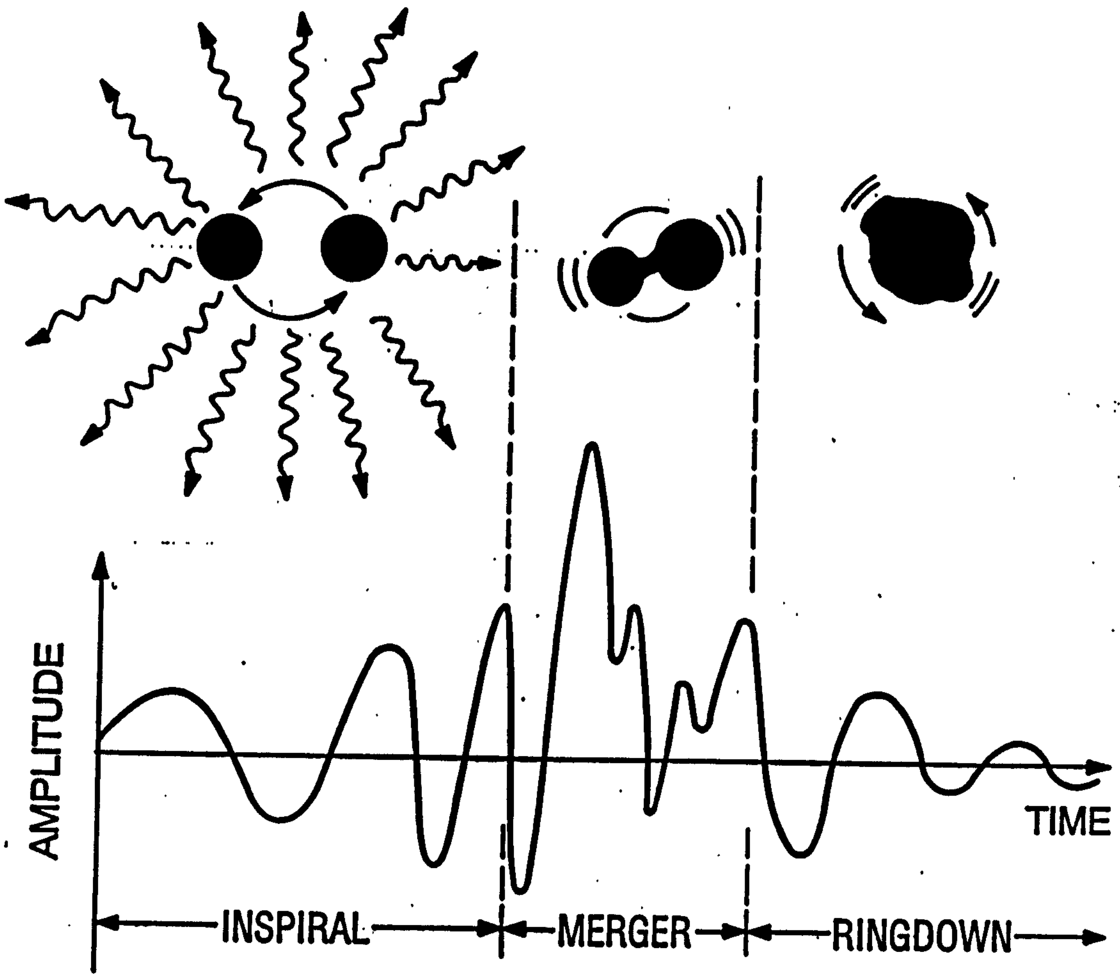
["Guaranteed" source]





- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

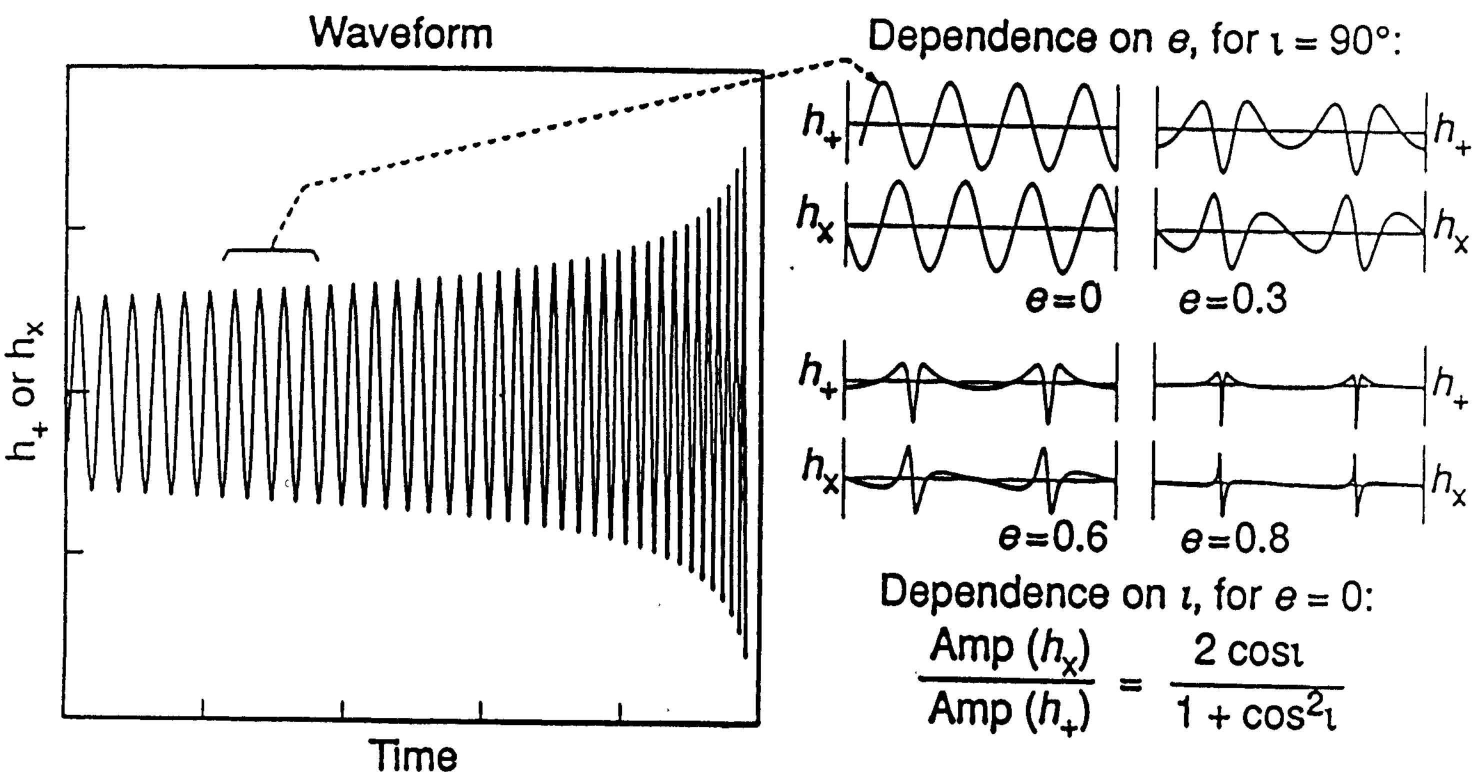
Binary Sources
Inspiral and Coalescence



Gravitational Waveforms

binary inspiral

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

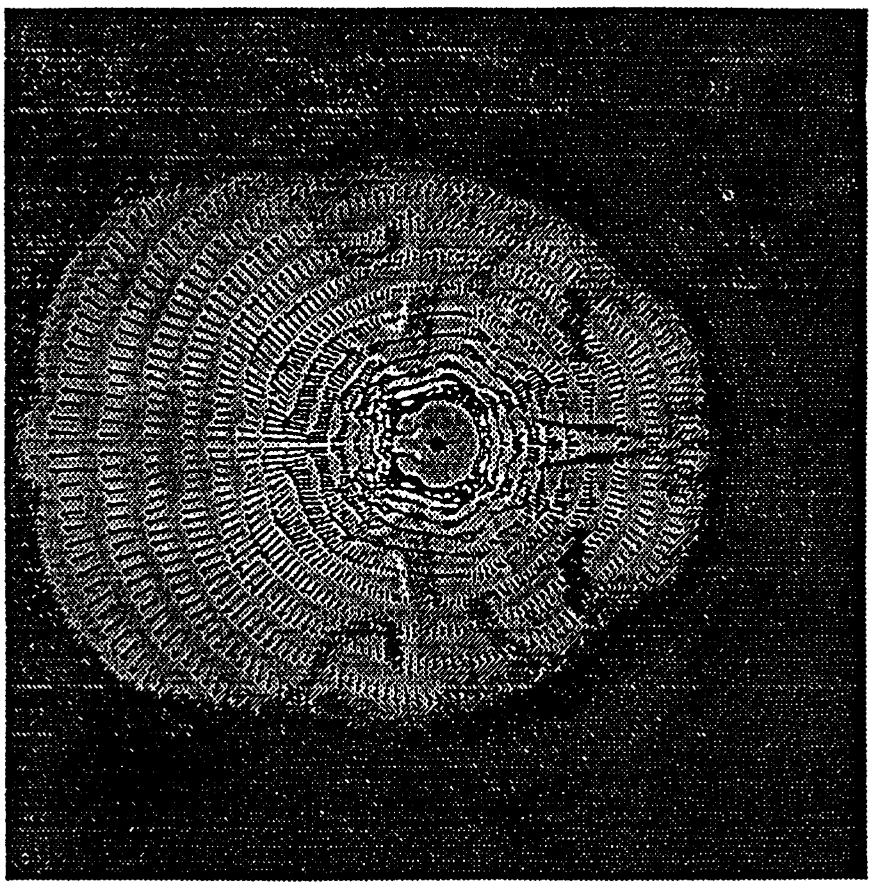


Dependence on ι, for $e = 0$:

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

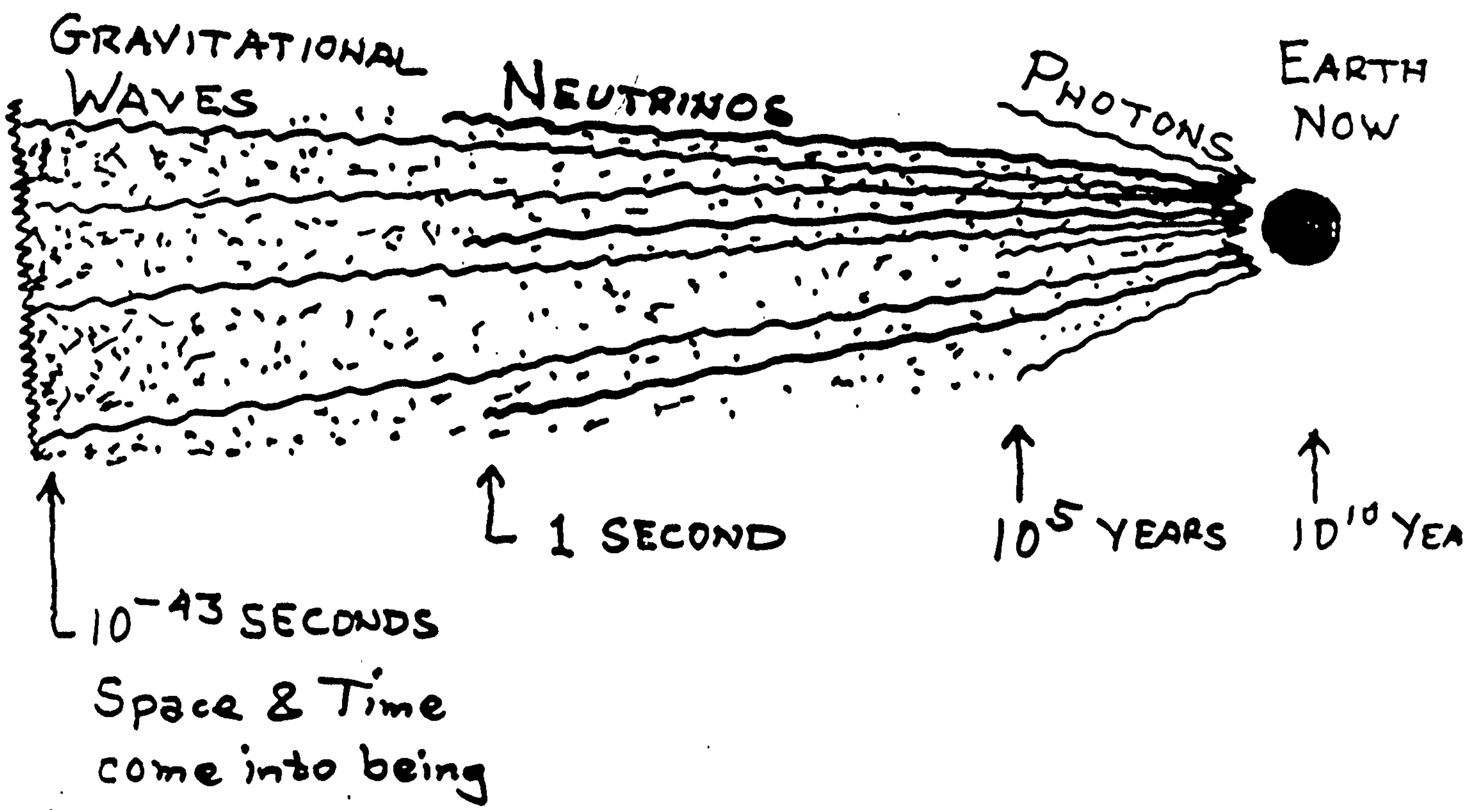
Supernovae
simulation

- A. Burrows
  - » 2 - dim model
  - » 50 msec into the explosion



The Early Universe
Stochastic Background

- The Big Bang Singularity

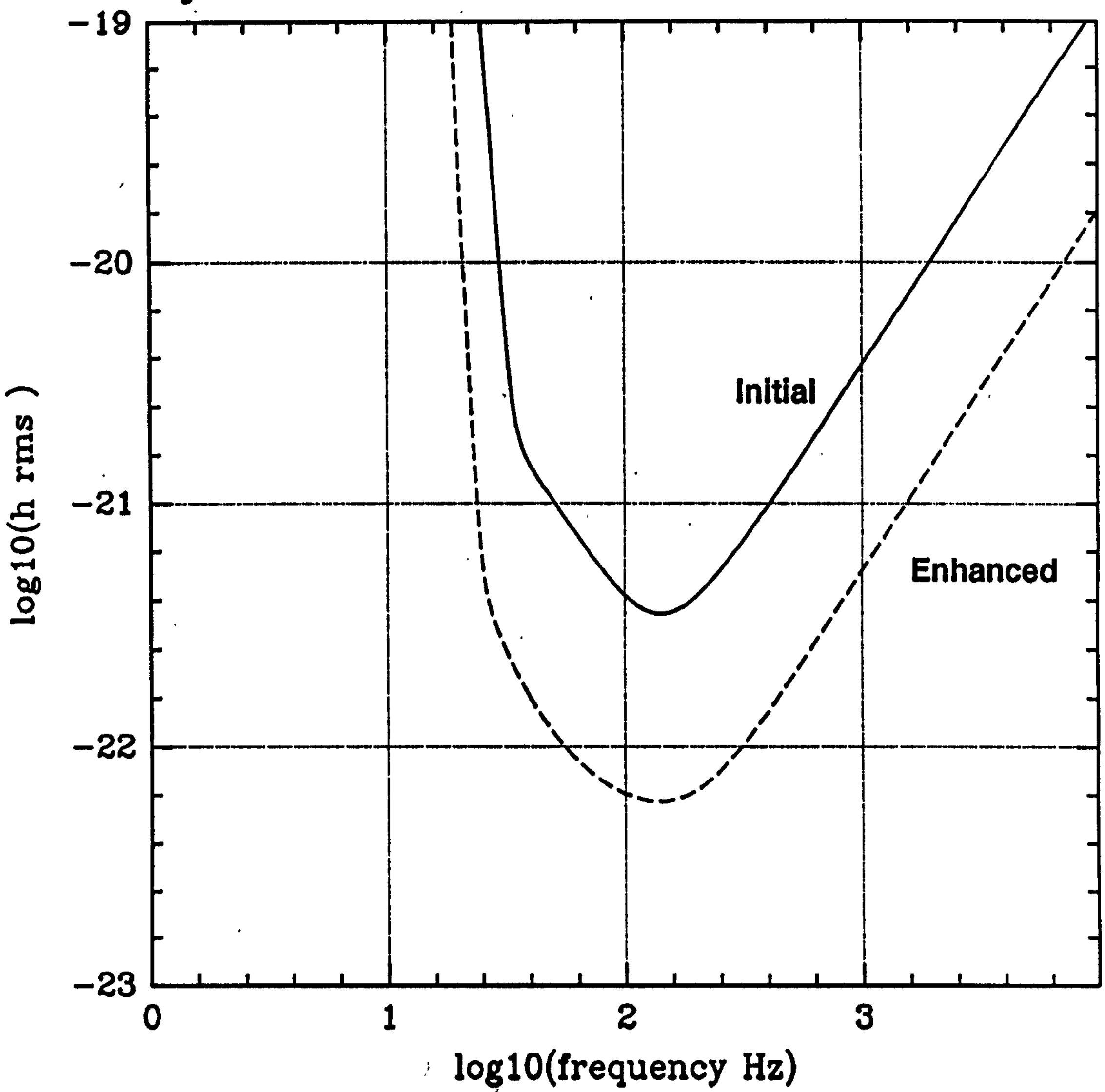


- LIGO
  - » time ~10^{-22} sec
  - » temp ~ 10^6 GeV
  - » graviton ~ 10 MeV

Detectors

Capability

- Initial Detector - end of 2001
- Fully Enhanced - about 2007 ?



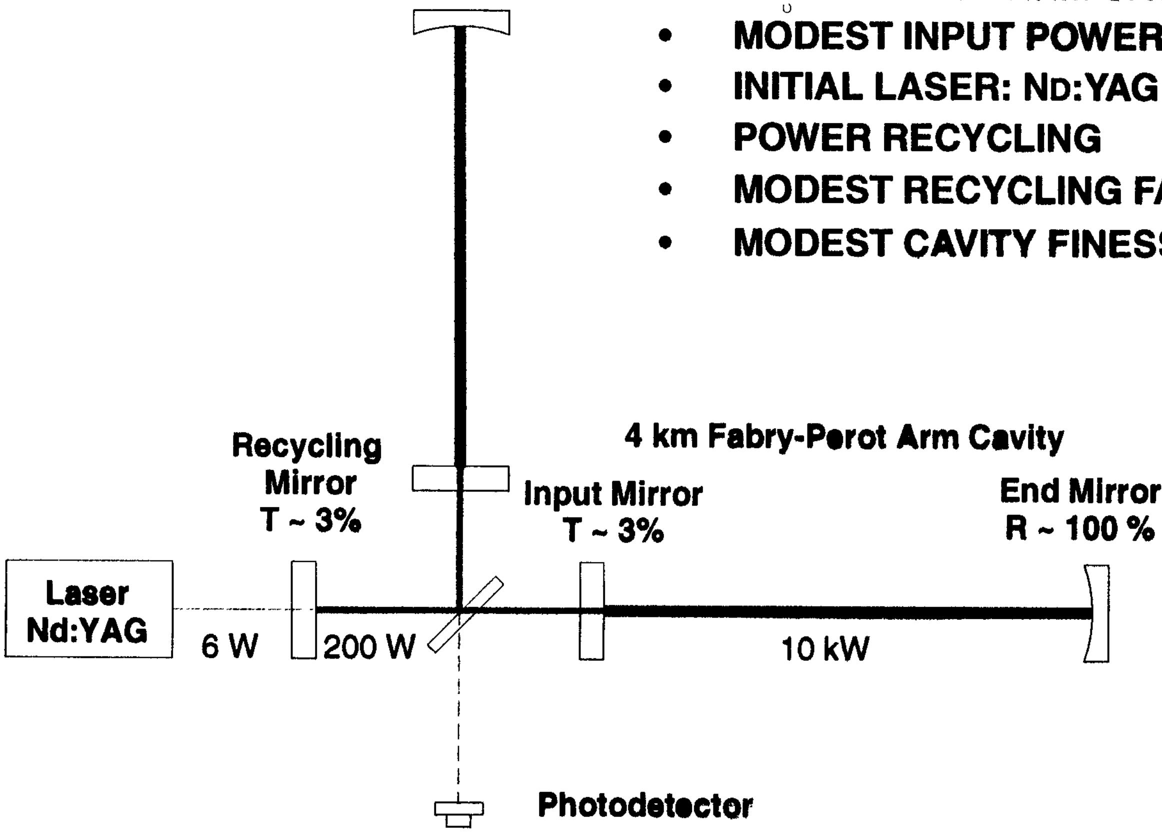
LIGO DESIGN

• OBSERVATORY CHARACTERISTICS

- TWO SITES:
  - HANFORD, WASHINGTON
  - LIVINGSTON, LOUISIANA
  - $L_{12}/c = 10$ msec.
- THREE INSTRUMENTS:
  - TWO 4 km INTERFEROMETERS (WA/LA)
  - ONE 2 km INTERFEROMETER (HANFORD)
- ARMS ORIENTED "PARALLEL" TO ONE ANOTHER
- COINCIDENT OBSERVATIONS AMONG ALL THREE INTERFEROMETERS
  - $R_{3X}^{BKGND} \approx (\tau_P + 2L_{12}/c)\tau_P R_{12} R_{23} < 1/\text{year}$
- INITIAL SENSITIVITY: $h_{rms} \leq 10^{-21}$ WITHIN 100 HZ BAND CENTERED AT MAXIMUM SENSITIVITY
  - $f_{GW} \approx 100$ Hz; $\lambda_{GW} \approx 3 \times 10^6$ m;
- OBSERVATORY EXTENSIBILITY:
  - EVENTUAL EXPANSION TO 8 INTERFEROMETERS
  - LIMITING SENSITIVITIES:
    - Naturally occurring gravity gradients (at lowest frequencies)
    - Scattered light phase noise (in the mid-frequency range)
    - Residual gas phase noise (at the highest high-frequencies)

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



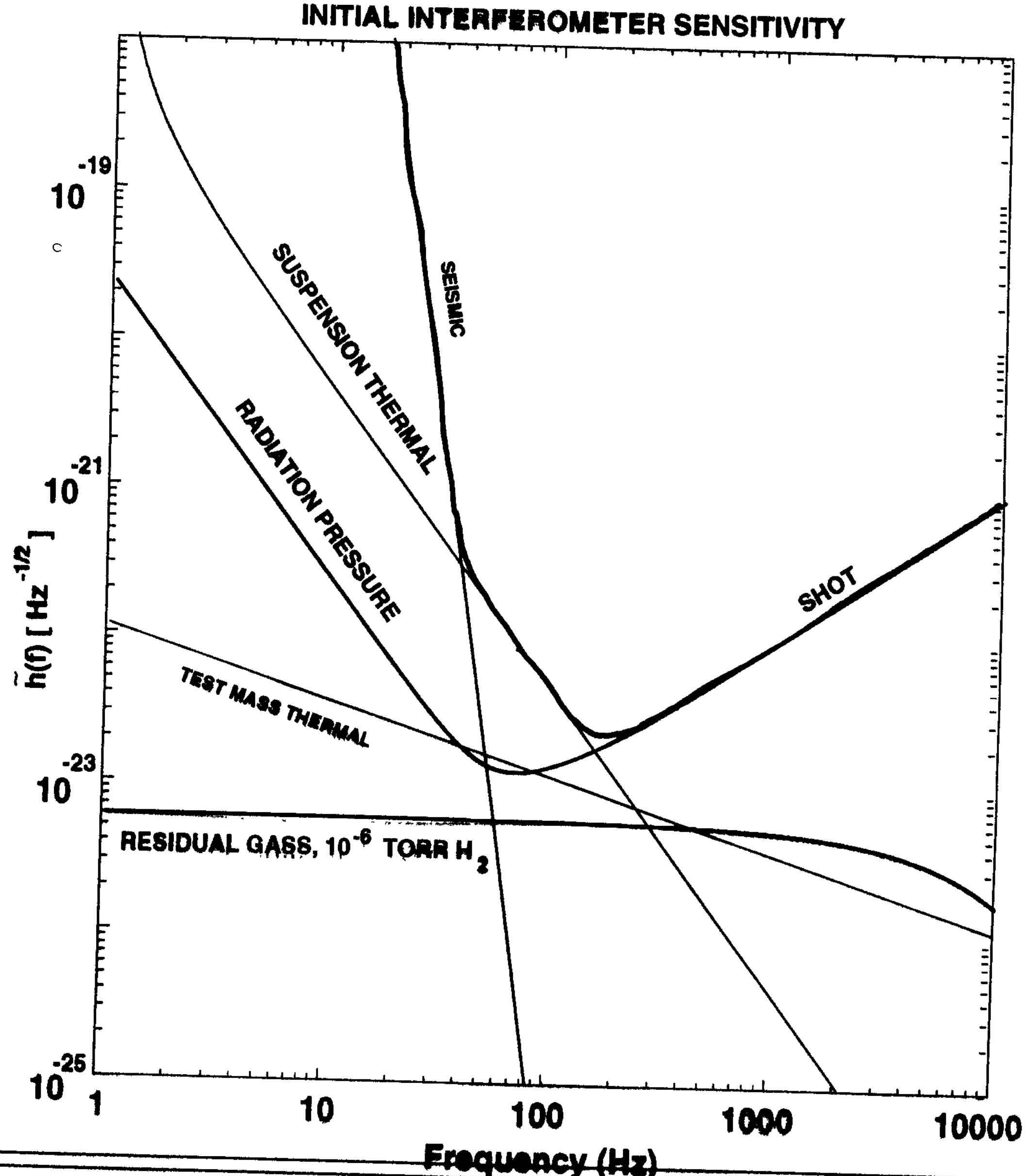
Interferometer Response Function:

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

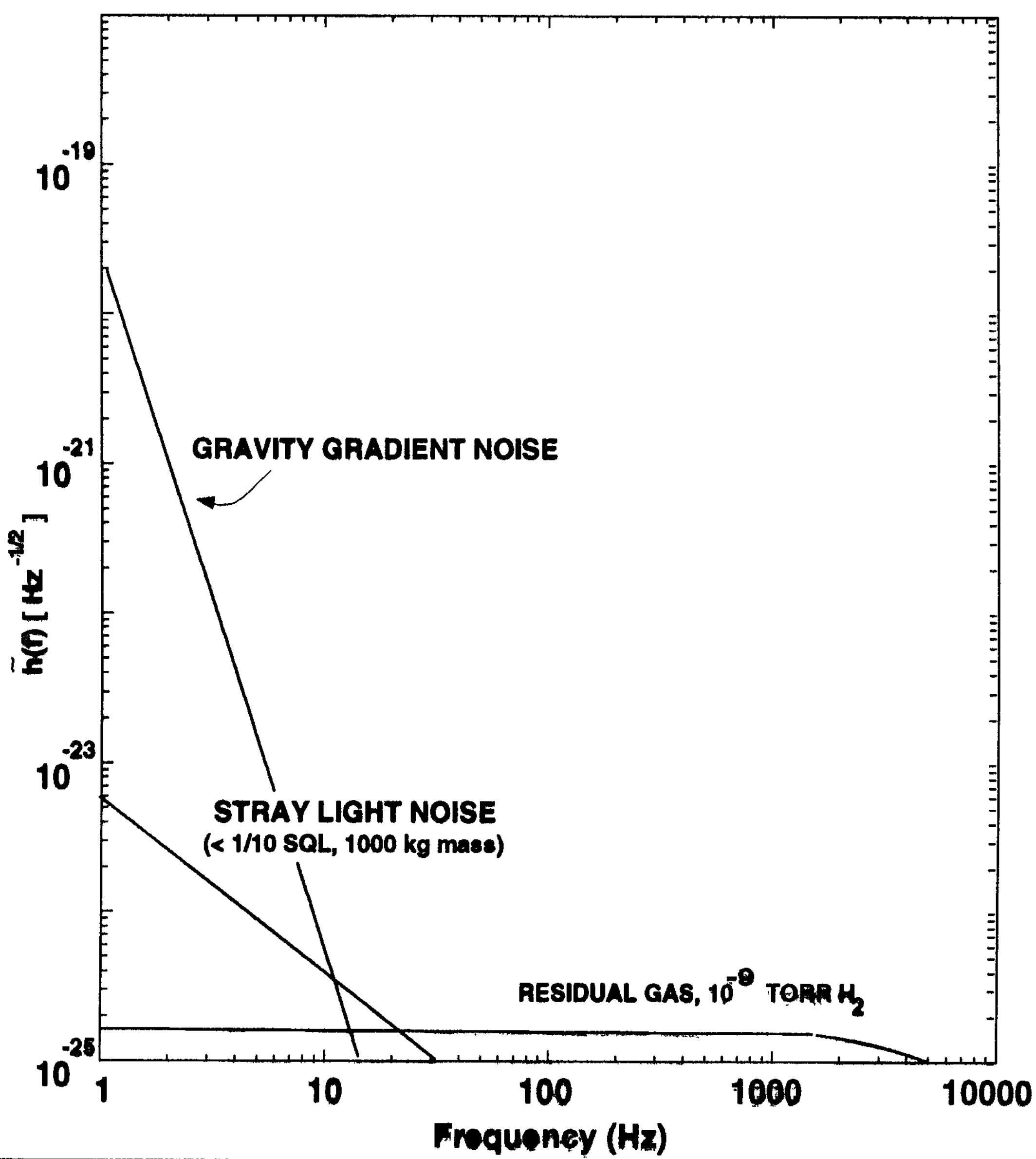
where

$\delta\varphi$ = 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

INITIAL INTERFEROMETER DESIGN PERFORMANCE GOAL



LIMITING PERFORMANCE DUE TO FACILITIES



LIGO DESIGN (cont.)

- OBSERVATORY EXTENSIBILITY (CONT.):
  - EXTREME CARE IN DESIGNING QUIET FACILITIES
    - site selection
    - design considerations
  - APERTURE & BAFFLING DESIGNED TO MINIMIZE SCATTERED STRAY LIGHT
  - VACUUM CHARACTERISTICS OF BEAM TUBES AND VACUUM EQUIPMENT DESIGNED TO PROVIDE ULTRA-HIGH VACUUM OPERATING CONDITIONS.

• OPERATIONAL CONSIDERATIONS

- ASTROPHYSICAL RESEARCH
  - HIGH ON-LINE AVAILABILITY
  - MULTIPLE MODES OF OPERATION:
    - 3X ; $T_{online} > 75\%$
    - 2X: (WA-LA); $T_{online} > 85\%$
    - 1X: $T_{online} > 90\%$
- ALLOCATION OF OBSERVING TIME BY PI/PAC/NSF
- TIME FOR DEVELOPMENT OF IMPROVED DETECTORS

LIGO DESIGN (cont.)

- **DATA FORMATS**
  - COMPATIBILITY WITH OTHER GRAVITATIONAL WAVE DETECTORS & PARTICLE DETECTORS
  - SAMPLE RATE AND PRECISION COMMENSURATE WITH SCIENTIFIC MISSIONS
- **ENABLING RESEARCH & FACILITIES**
  - LONG-TERM DEVELOPMENT OF ADVANCED DETECTORS
  - UNIVERSITY-BASED INTERFEROMETER FACILITIES
  - LIGO RESEARCH COMMUNITY

MAJOR LIGO SYSTEMS

- CIVIL CONSTRUCTION
- VACUUM EQUIPMENT & BEAM TUBES
- DETECTOR / R&D

LIGO SCHEDULE

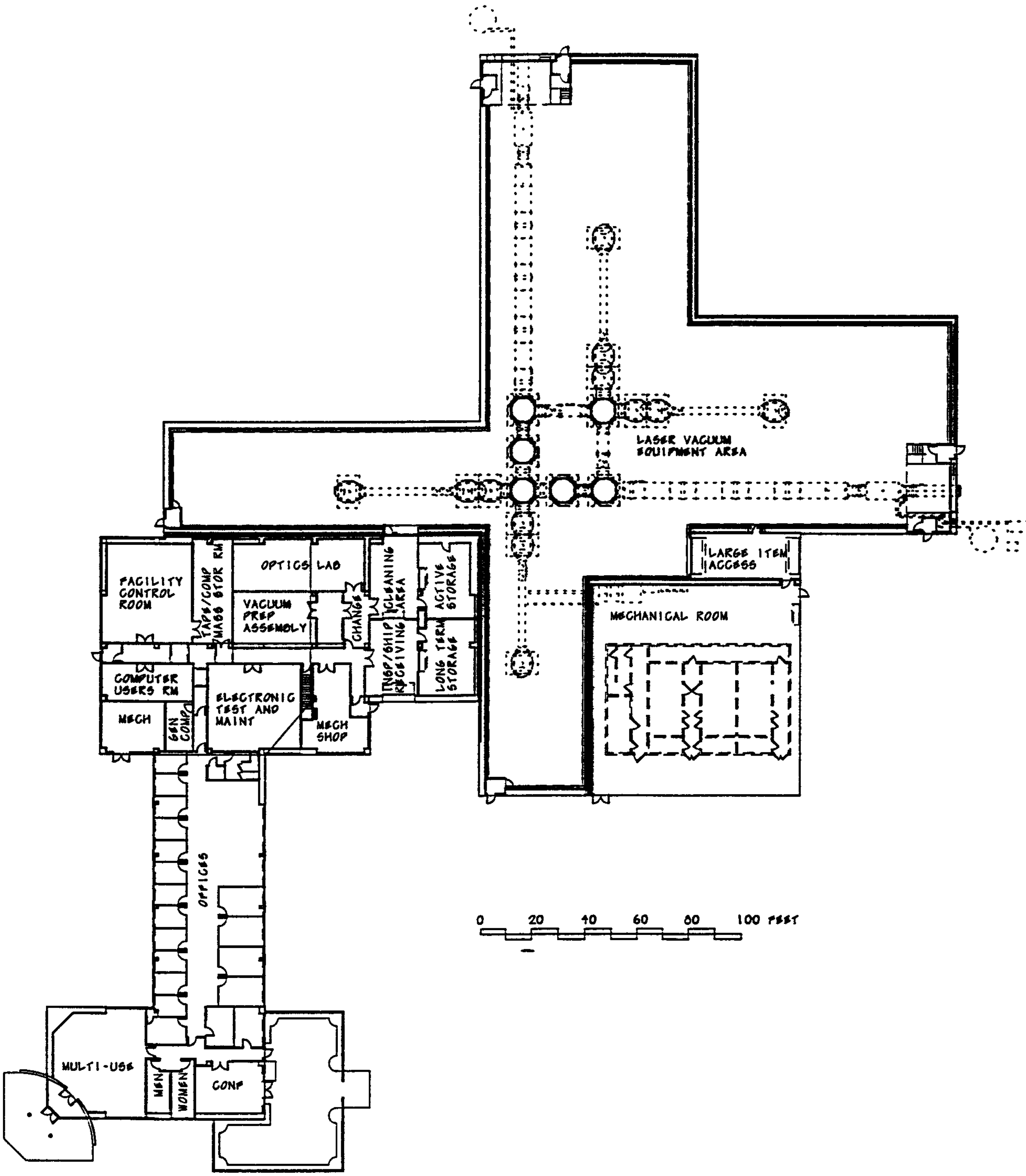
- **1996 - 1998**
  - **CONSTRUCTION OF FACILITIES**
    - **CIVIL CONSTRUCTION/ 7/96 START**
    - **VACUUM EQUIPMENT 5/96 START**
    - **BEAM TUBES 4/96 START**
  - **DETECTOR DESIGN & FABRICATION; R&D**
- **1998 - 2000**
  - **DETECTOR INSTALLATION**
  - **SHAKEDOWN**
- **2001**
  - **"FIRST LIGHT" AT INITIAL DESIGN SENSITIVITY** $h_{RMS} = 10^{-21}$ (Δf = 100 Hz @ 100 Hz).

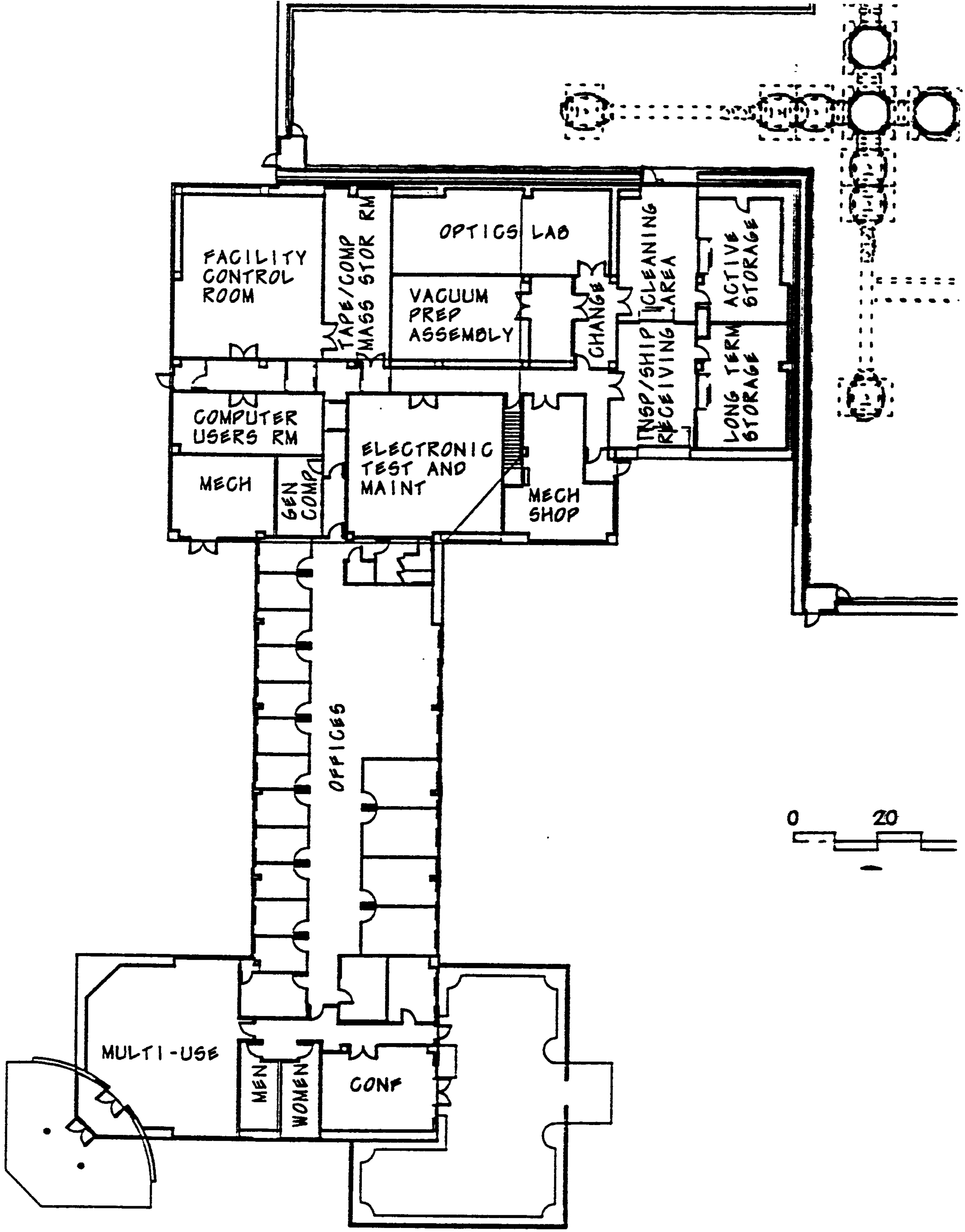
CIVIL CONSTRUCTION

• CHARACTERISTICS

- **INFRASTRUCTURE**
  - LARGE AND CLEAN LABORATORY (CLEAN CONSTRUCTION PRACTICES; HIGH BAY: 9 M HOOK HEIGHT)
  - BEAM TUBE ENCLOSURES TO PROTECT THIN-WALLED TUBE
  - OFFICE SPACE/LABORATORY SPACE TO ACCOMMODATE STAFF AND VISITORS
  - ROADS, FOUNDATIONS, STRUCTURES, ETC.

- **REQUIREMENTS**
  - REMOTE SITES WITH SEISMIC STABILITY -- THICK SLAB;ISOLATED FOUNDATIONS; SEPARATED BUILDINGS
  - FEW INTERNAL NOISE SOURCES, EMI/EMF BACKGROUNDS, ETC.
  - REMOTELY OPERABLE FACILITIES: ENVIRONMENTAL CONTROL AND STATE VECTOR LOGGING
  - CLEANLINESS


LASER VACUUM EQUIPMENT AREA
FACILITY CONTROL ROOM
TAPE/COMP MASS STOR RM
OPTICS LAB
VACUUM PREP ASSEMBLY
CHANGE
CLEANING AREA
ACTIVE STORAGE
RECEIVING
LONG TERM STORAGE
LARGE ITEM ACCESS
MECHANICAL ROOM
COMPUTER USERS RM
MECH
GEN COMP
ELECTRONIC TEST AND MAINT
MECH SHOP
OFFICES
MULTI-USE
MEN
WOMEN
CONF
0
20
40
60
80
100 FEET



FACILITY CONTROL ROOM
TAPE/COMP MASS STOR RM
OPTICS LAB
VACUUM PREP ASSEMBLY
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ELECTRONIC TEST AND MAINT
MECH
GEN COMP
MECH SHOP
OFFICES
MULTI-USE
MEN
WOMEN
CONF
0
20

Support Facilities in Operations Support Building

Area	Purpose
Control Room / Analysis Area	All equipment control functions, machine diagnostics, data analysis and archiving
Optics Laboratory	Cleaning, maintenance, test and calibration of lasers and optics
Vacuum Preparation	Vacuum preparation and certification, mechanical-Q testing
Electronics Test/Mainte-nance	Control/Data systems staging, test, and maintenance
Mechanical / Technical	Mechanical staging, assembly and testing; vacuum-pump maintenance
Equipment Rooms	Telecommunications, computer networking, etc.
Shipping / Receiving	Outdoors<-->Clean-Room interfaces; cleaning; storage
Changing / Cleaning	Clean-room transition space for people, small equipment entering LVEA
Office / Library Space	Resident staff, detached-duty staff, visiting scientists/students
Conference room	Smaller group meetings, drawing layout space
Multi-Use Space	Seminars, “all-hands meetings”, and public entry/reception
Kitchen/shower/restrooms	

CIVIL CONSTRUCTION

- **STATUS**
  - **BOTH SITES UNDER CONSTRUCTION**
  - **WASHINGTON SITE**
    - GRADED TO FINAL TOPOGRAPHY; SOIL SETTLEMENT COMPLETED
    - BEAM TUBE SLAB/ROADS/ENCLOSURES UNDER CONSTRUCTION (2/96)
  - **LOUISIANA SITE**
    - LOGGED
    - GROUND BREAKING TOOK PLACE 7/95
    - SITE CLEARED AND GRUBBED
    - BEING GRADED TO INTERFEROMETER PLANE (8/96)
  - **FINAL DESIGN OF THE LIGO FACILITIES (BUILDINGS) COMPLETED 4/96**
    - LASER & VACCUM EQUIPMENT AREAS (LVEA/VEA)
    - OPERATIONS & SUPPORT BUILDING (OSB)
    - MECHANICAL EQUIPMENT ROOM
    - CHILLED WATER PLANT
  - **PROCUREMENT FOR FACILITY CONSTRUCTION UNDER WAY:**
    - BIDS IN FOR 3 INTERFEROMETER FACILITY AT HANFORD 6/96
    - PREPARING BID PACKAGE FOR 2 INTERFEROMETER FACILITY FOR LA

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 $CO + CO_2 + H_{2N}C_N + \ldots$ 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

VACUUM EQUIPMENT

- **STATUS**
  - SPECIFICATIONS DEFINED -- SCIENCE REQUIREMENTS REVIEW 8/94
  - DESIGN PHASE COMPLETED 10/95
  - PROCCESS SYSTEMS INTERNATIONAL (PSI) SELECTED FOR HARDWARE CONTRACT
  - FINAL DESIGN REVIEW HELD 5/96
  - FIRST ARTICLE CHAMBER (BEAMSPLITTER CHAMBER) UNDER CONSTRUCTION - 8-9/96
  - PROTOTYPE LARGE APERTURE (1.22 M) VALVE FOR BEAM TUBE INTERFACE UNDER CONSTRUCTION
    - FIRST TWO ARTICLES DUE AT HANFORD 8/96

BEAM TUBES

- **PRODUCTION OF 16 KM TUBES FOR LIGO**
  - QUALIFICATION TEST REVIEW HELD 4/95
  - FABRICATION CONTRACT OF BEAM TUBES INITIATED 12/95
  - FINAL DESIGN REVIEW 4/96
  - INFRASTRUCTURE CONSTRUCTION NEAR SITE 4/96 - 7/96
  - INSTALLATION AT WASHINGTON STARTS 10/96
- **BEAM TUBE BAFFLE DESIGN COMPLETE**
  - BAFFLE SURFACE TREATMENT IDENTIFIED
    - OPTICAL BLACK GLASS ENAMELED GLAZE (1 mm; $\tau \sim 400 cm^{-1}$)
    - R < .1 (Averaged over S & P polarizations)
    - $P[Backscatter] \approx 10^{-3} sr^{-1}$
  - BAFFLE MECHANICAL DESIGN COMPLETE
    - SERRATED WITH 8 mm P-P SERRATIONS @ 6 mm PITCH
    - SERRATION PATTERN PSEUDORANDOM (25% VARIATION IN P-P) TO MINIMIZE COHERENCE EFFECTS
    - 1 mm THICK 304 L SS MATERIAL, H_2 DEPLETED