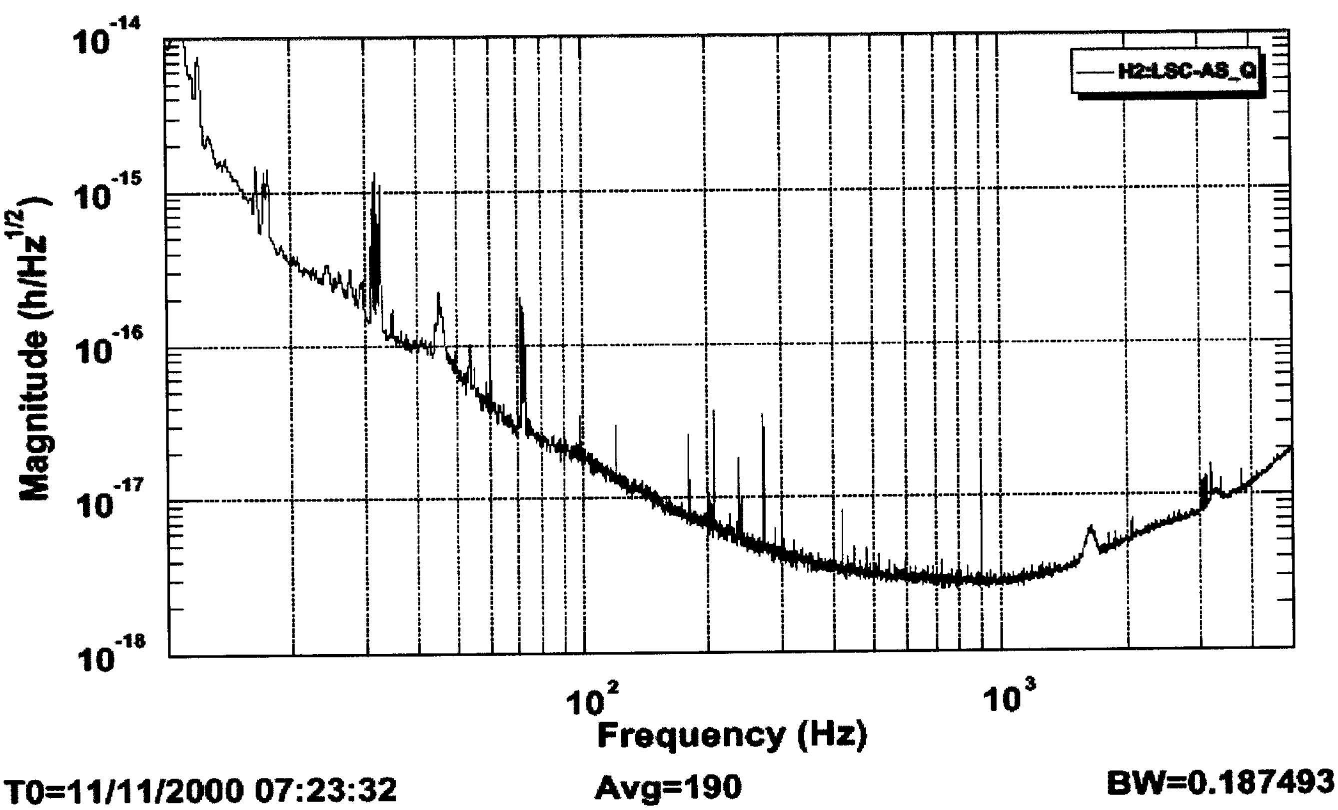
National Science Foundation Review of LIGO

January 29 – February 1, 2001

Caltech

Pasadena, California



LIGO PROJECT
California Institute of Technology/Massachusetts Institute of Technology

National Science Foundation Review
January 29 – February 1, 2001
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Charge to the LIGO Review Panel

January 29 – February 1, 2001

The NSF Grant Proposal Guide (http://www.nsf.gov/pubs/2001/nsf()12/toc.html) contains instructions and guidelines for individual investigator proposals. The National Science Board approved review criteria are included in the section from the Proposal Guide reproduced below and they should be followed in this review:

III. NSF Proposal Processing and Review

Proposals received by the NSF Proposal Processing Unit are assigned to the appropriate NSF program for acknowledgement and, if they meet NSF requirements, for review. All proposals are carefully reviewed by a scientist, engineer, or educator serving as an NSF Program Officer, and usually by three to ten other persons outside NSF who are experts in the particular fields represented by the proposal. Proposers are invited to suggest names of persons they believe are especially well qualified to review the proposal and/or persons they would prefer not review the proposal. These suggestions may serve as one source in the reviewer selection process at the Program Officer's discretion. Program Officers may obtain comments from assembled review panels or from site visits before recommending final action on proposals. Senior NSF staff further review recommendations for awards.

A. REVIEW CRITERIA

The National Science Board approved revised criteria for evaluating proposals at its meeting on March 28, 1997 (NSB 97-72). The criteria are designed to be useful and relevant across NSF's many different programs, however, NSF will employ special criteria as required to highlight the specific objectives of certain programs and activities.

On September 20, 1999, the NSF Director issued Important Notice 125, Merit Review Criteria. This Important Notice reminds proposers of the importance of ensuring that, in addition to the criterion relating to intellectual merit, the criterion relating to broader impacts is considered and addressed in the preparation and review of proposals submitted to NSF. The Important Notice also indicates NSF's intent to continue to strengthen its internal processes to ensure that both criteria are appropriately addressed when making funding decisions.

The merit review criteria are listed below. Following each criterion are considerations that the reviewer may employ in the evaluation. These considerations are suggestions and not all will apply to any given proposal. While reviewers are expected to address both merit review criteria, each reviewer will be asked to address only those considerations that are relevant to the proposal and for which he/she is qualified to make judgments.

What is the intellectual merit of the proposed activity?

How important is the proposed activity to advancing knowledge and understanding within its own field or across different fields? How well qualified is the proposer (individual or team) to conduct the project? (If appropriate, the reviewer will comment on the quality of prior work.) To what extent does the proposed activity suggest and explore creative and original concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?

What are the broader impacts of the proposed activity?

How well does the activity advance discovery and understanding while promoting teaching, training, and learning? How well does the proposed activity broaden the participation of underrepresented groups (e.g., gender, ethnicity, disability, geographic, etc.)? To what extent will it enhance the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships? Will the results be disseminated broadly to enhance scientific and technological understanding? What may be the benefits of the proposed activity to society?

PIs should address the following elements in their proposal to provide reviewers with the information necessary to respond fully to the above-described NSF merit review criteria. NSF staff will give these elements careful consideration in making funding decisions.

Integration of Research and Education

One of the principal strategies in support of NSF's goals is to foster integration of research and education through the programs, projects and activities it supports at academic and research institutions. These institutions provide abundant opportunities where individuals may concurrently assume responsibilities as researchers, educators, and students, and where all can engage in joint efforts that infuse education with the excitement of discovery and enrich research through the diversity of learning perspectives.

Integrating Diversity into NSF Programs, Projects, and Activities

Broadening opportunities and enabling the participation of all citizens -- women and men, underrepresented minorities, and persons with disabilities -- are essential to the health and vitality of science and engineering. NSF is committed to this principle of diversity and deems it central to the programs, projects, and activities it considers and supports.

Specific Charge to the LIGO Review Panel.

The proposal includes three major activities; operations of the LIGO facilities; scientific research; detector research and development. To address this wide range of activities, the Review Panel will be divided into two sub-panels. The first will concentrate on detector research and development. The second will concentrate on operation of the LIGO facilities and scientific research. The broader issues of scientific merit and the overlap in manpower and other resources assigned to the three activities will require both sub-panels to consider the total proposal in their evaluations.

A. Detector Research and Development Sub-Panel

This sub-panel will concentrate on detector research and development to improve the science reach of the LIGO observatories. A major contribution to this R&D program is provided by members of the LSC at institutions other than Cal Tech and MIT. Funds to support those LSC member research programs are provided directly to the LSC institutions.

- While this sub-panel is not charged with reviewing each of the LSC proposals, it is asked to evaluate the total detector R&D plan as presented by the LIGO Laboratory in this proposal. Are the LSC R&D activities (including Cal Tech and MIT) appropriate to achieve the scientific goals of the proposal and are they well-coordinated ?

- The Sub-Panel should review the schedule and milestones for progress in the detector R&D program. Is the schedule achievable with the available and proposed resources and are there sufficient significant milestones provided ?

- The sub-panel is asked to review the LIGO Laboratory R&D program (Cal Tech and MIT) in detail, including manpower allocation and budget.

The final report of this Sub-Panel is to be completed at this meeting so that it can be made available to the Operations and Scientific Research Sub-Panel before the meeting of that sub-panel.

B. Operations and Scientific Research Sub-Panel

The activities to be reviewed by this sub-panel include completion of installation and commissioning of the interferometers, operation of the facility for engineering and science runs, creating and maintaining the infrastructure for data acquisition and analysis by the LIGO Scientific Collaboration (LSC), and scientific research proposed by the LIGO Laboratory. The Sub-Panel is asked to review and evaluate the proposal with regard to each of the following items:

- Is the proposed budget for LIGO Laboratory operations and the scientific research program justified and adequate to carry out the activities listed above?
- Is the proposed LIGO Laboratory infrastructure, including manpower and facilities, adequate for effective participation in the science by the LSC members ?
- Are the schedule and milestones for LIGO Laboratory commissioning and for proposed engineering and scientific running achievable with the available and proposed resources. Are there sufficient significant milestones provided ?
- Is the proposed outreach and education plan well-designed and are proposed manpower and funds adequate to carry out the plan ?
- What is the status of international collaboration between LIGO and other gravity wave centers around the world ?
- Is the plan for public access to LIGO data appropriate ?

The final report of the Detector Research and Development Sub-Panel will be provided as input to the Operations and Scientific Research Sub-Panel which is requested to determine if there are issues involving allocation of manpower or other resources between the major activities presented in the proposal. If there are, a teleconference will be arranged during the meeting of the Operations and Scientific Research Sub-Panel and members of the Detector Research and Development Sub-Panel to discuss these issues.

AGENDA for LIGO PANEL REVIEW—R&D Sub-Panel

Monday January 29, 2001

8:30 - 9:00	Panel Executive Session
9:00 - 9:15	Introduction of Panel and Reading of Panel Charge
9:15 - 9:45	LIGO Status and Introduction—B. Barish
9:45 - 10:15	Overview of R&D Proposal—G. Sanders
10:15 - 10:45	Advanced LIGO Science—K. Thorne
10:45 - 11:00	Break
11:00 - 12:30	LIGO R& D Program—D. Shoemaker
12:30 - 2:30	Lunch and tour of Caltech facilities
2:30 - 4:00	Parallel Detector R&D Sessions
4:00 - 5:30	Panel Executive Session *[Reports from panel members attending parallel sessions; request for information to LIGO/LSC Staff at end of Session.]*
6:30 -	Dinner at the Athenaeum Library

Tuesday January 30, 2001

8:30 - 9:30	Panel Executive Session *[Review requests for info; make writing assignments]*
9:00 - 10:30	Response of LIGO/LSC Staff to panel Request
10:30 - 11:00	Break
11:00 - 12:30	Continue response of LIGO/LSC Staff to Panel Requests
12:30 - 2:30	Lunch and Panel Executive Session *[discuss outline of report]*
2:30 - 3:30	Panel LIGO/LSC Staff meet as necessary *[Panel members begin writing]*
3:30 - 4:00	Break
4:00 - 6:00	Panel Executive Session *[Panel members continue writing]*

Wednesday January 31, 2001

8:30 - 10:30	Panel Executive Session *[discuss what is necessary to complete review]*
10:30 - 11:00	Break
11:00 - 12:30	Panel Executive Session *[Panel members complete parallel session reports]*
12:30 - 1:30	Lunch
1:30 - 3:30	Panel Executive Session *[panel members integrate report sections]*
3:30 - 4:00	Break
4:00 - 6:00	Panel Executive Session *[complete report; discuss close-out presentation]*
6:30 -	Dinner

Thursday February 1, 2001

9:00 - 10:00	Panel Executive Session *[Final discussion of report and close-out presentation]*
10:00 - 11:00	Close-out; Adjourn

Parallel meetings and suggested assignments:

- Suspensions and Isolation – Hyde (scribe) and Cerdonio
- Lasers and Optics – Houle (scribe) and Man
- Interferometry, Controls, and Electronics – Frisch (scribe) and Hall

Acronyms and Abbreviations

Acronym	
ACIGA	Australian Consortium for Interferometric Gravitational Astronomy
ACWP	Actual Cost of Work Performed
ADC	Analog-to-Digital Converter
AMU	Atomic Mass Unit
ANU	Australian National University
API	Application Programmer Interface
BAC	Budget at Completion
BCWP	Budgeted Cost of Work Performed
BCWS	Budgeted Cost of Work Scheduled
BH	Black Hole
BSC	Basic Symmetric Chamber
BSC	Beam Splitter Chamber
CACR	Center for Advanced Computer Research (Caltech)
CAD	Computer-Assisted Design
CB&I	Chicago Bridge & Iron
CDS	Control and Data System
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CSSR	Cost Schedule Status Report
DAC	Data Analysis and Computing
DAC	Digital-to-Analog Converter
DcAPI	Data Conditioning Application Programmer Interface
DMRO	Differential Mode Read-Out
EAC	Estimate at Completion
EPICS	Experimental Physics and Industrial Control System
ER1	LIGO Engineering Run, April 2000
ER2	LIGO Engineering Run, November 2000
ETF	Engineering Test Facility
ETM	End Test Mass
FDR	Final Design Review
FFT	Fast (Discrete) Fourier Transform
FTE	Full Time Equivalent
GASF	Geometrical Anti-Spring Filter
GEO	British-German Cooperation for Gravity Wave Experiment
GFLOPS	1000 MFLOPS
GRB	Gamma-Ray Burst
GWADW	Gravitational Wave Data Analysis Workshop
GWIC	Gravitational Wave International Committee
HAM	Horizontal Access Modules
HPSS	High Performance Storage System (IBM)
HVAC	Heating, Ventilation and Air Conditioning
IDE	Integrated Drive Electronics (disk standard)
IFO	Interferometer
InGaAs	Induim-Gallium-Arsenide

INSA	French National Institute for Applied Science
IO	Input Optics
IP	Inverted Pendulum
ISC	Interferometer Sensing and Control
ITM	Input Test Mass
IV&V	Integration, Verification, and Validation
kpc	Kiloparsec
LASTI	LIGO Advanced System Test Interferometer
LDAS	LIGO Data Analysis System
LHO	LIGO Hanford Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory
LLO	LIGO Livingston Observatory
LMXB	Low-Mass X-Ray Binary
LSC	LIGO Scientific Collaboration also Length Sensing and Control System
LVDT	Linear Variable Differential Transducer
LVEA	Laser and Vacuum Equipment Area
LZH	Laser Zentrum Hannover
MB	Megabytes
MC	Mode Cleaner
MDC	Mock Data Challenges
MFLOPS	Million Floating Point Operations Per Second
MGASF	Monolithic Geometrical Anti-Spring Filter
MIMO	Multiple Input, Multiple Output
MOPA	Master Oscillator-Power Amplifier
MOU	Memorandum of Understanding
Mpc	Megaparsec
MPI	Message Passing Interface
MSU	Moscow State University
NBI	Neutron Star Binary Inspiral
NPRO	Non-Planar Ring Oscillator
NS	Neutron Star
OSB	Operations Support Building
OSEM	Optical Shadow Sensor and Magnetic Actuator
PEM	Physics and Environmental Monitor
PM	Project Management
PMP	Project Management Plan
Ppm	Parts per million
PSL	Prestabilized Laser
QND	Quantum Non-Demolition
R&D	Research and Development
RAID	Redundant Array of Inexpensive Disks
REO	Research Electro-Optics (Company Name)
REU	Research Experience for Undergraduates
RF	Radio Frequency
RMS	Root mean square
RSE	Resonant Sideband Extraction
s	Second

s/s	Samples/second
SAS	Seismic Attenuation System
SEI	Seismic Isolation
SEM	Secondary Emission Monitor
SIOM	Shanghai Institute of Optical Materials
SOS	Small Optics Suspensions
SURF	Summer Undergraduate Research Foundation
TAMA	Japanese Interferometric Gravitational-Wave Project
TB	Terabytes
TES	Technical and Engineering Support
TNI	Thermal Noise Interferometer
TRW	Company Name
UHV	Ultra high vacuum
VME	Versa Modular Eurocard (IEEE 1014)
WAN	Wide Area Network
WBS	Work Breakdown Structure

LIGO
Introduction and Status

Barry Barish

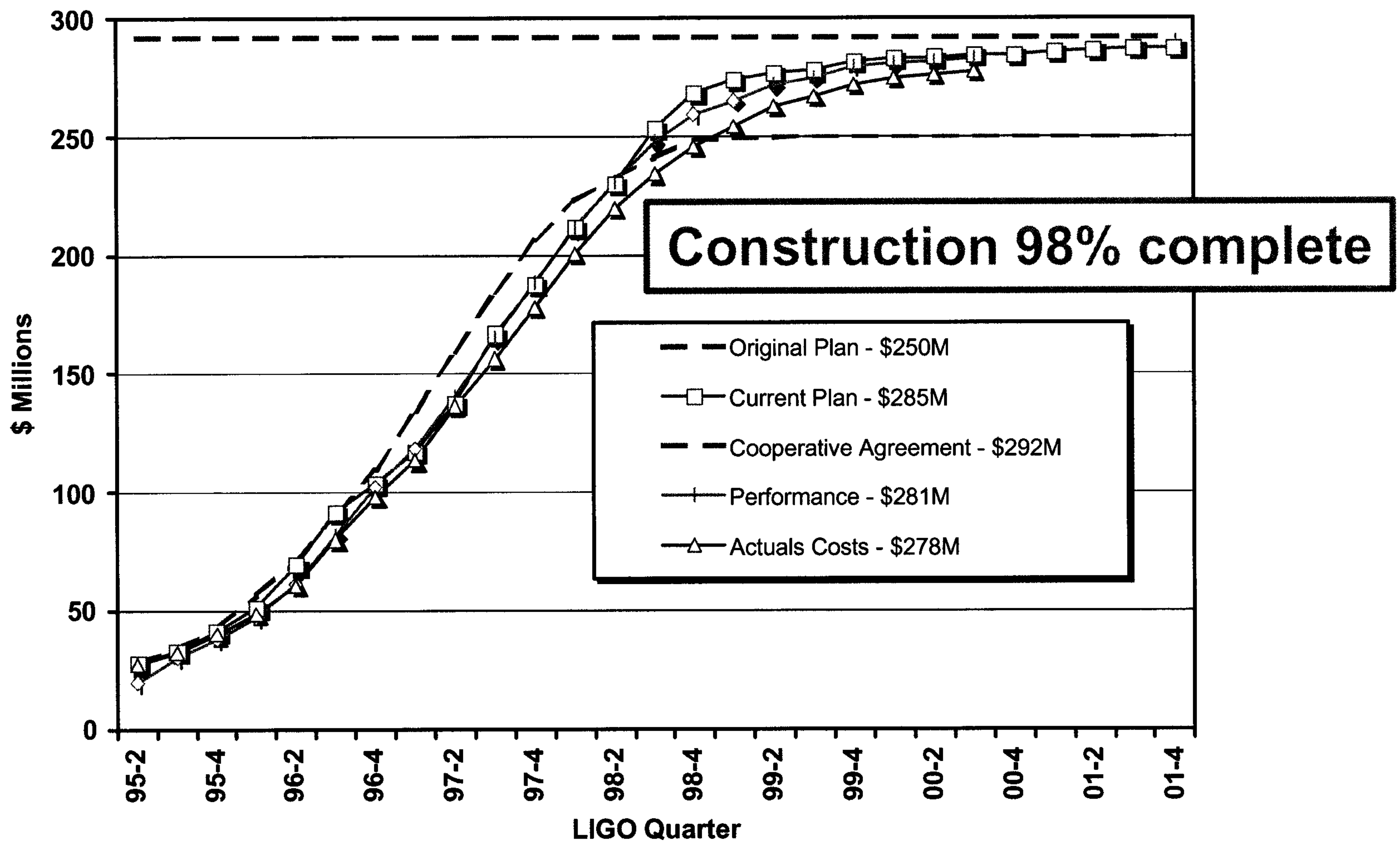
Operations Proposal Review
NSF Advanced R&D Panel
January 29, 2001

LIGO-G010008-00-M

LIGO Plans
schedule

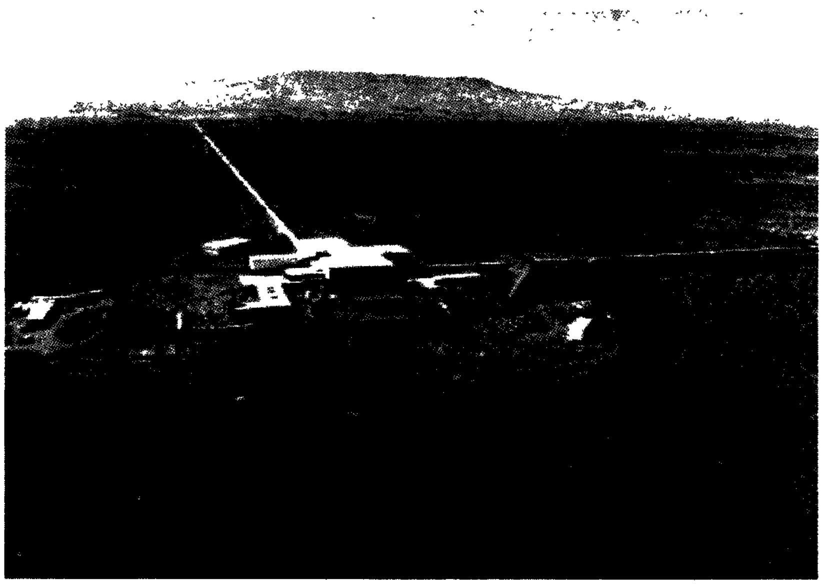
1996	**Construction Underway** (mostly civil)
1997	**Facility Construction** (vacuum system)
1998	**Interferometer Construction** (complete facilities)
1999	**Construction Complete** (interferometers in vacuum)
2000	**Detector Installation** (commissioning subsystems)
2001	**Commission Interferometers** (first coincidences)
2002	**Sensitivity studies** (initiate LIGO I Science Run)
2003+	**LIGO I data run** (one year integrated data at $h \sim 10^{-21}$)
2006+	**Begin 'advanced' LIGO installation**

LIGO Project
construction and related R&D costs

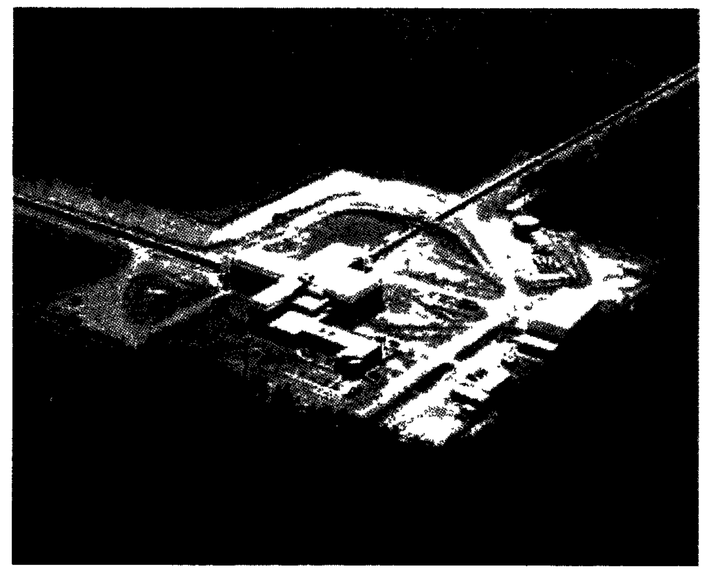


LIGO
civil construction

LIGO (Washington)

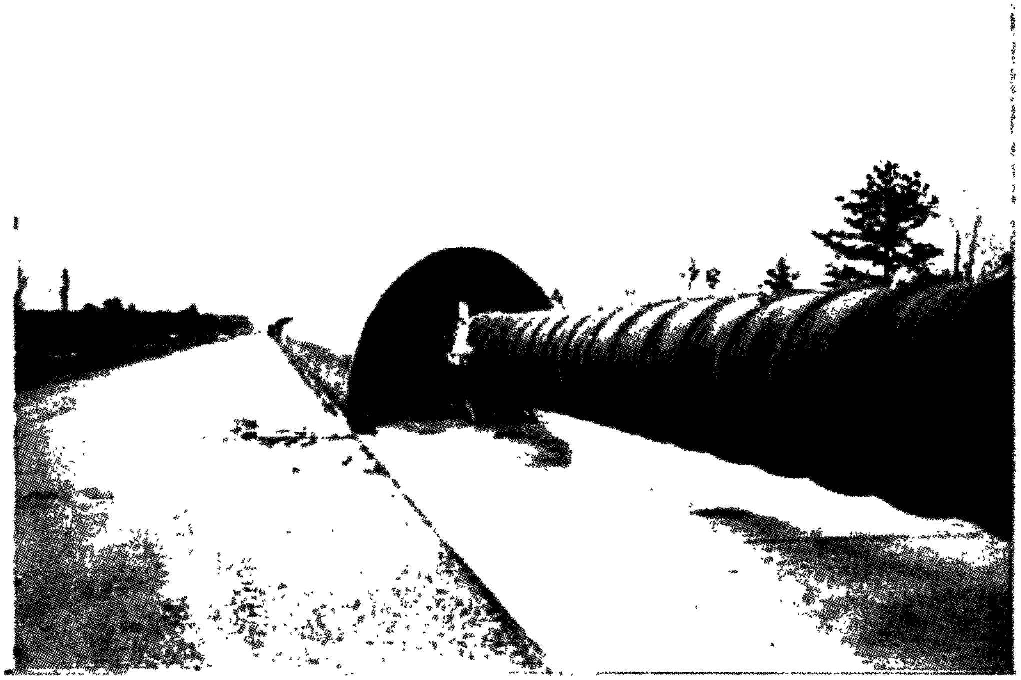


LIGO (Louisiana)



LIGO
vacuum chambers

LIGO
beam tube



- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

LIGO Facilities
beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

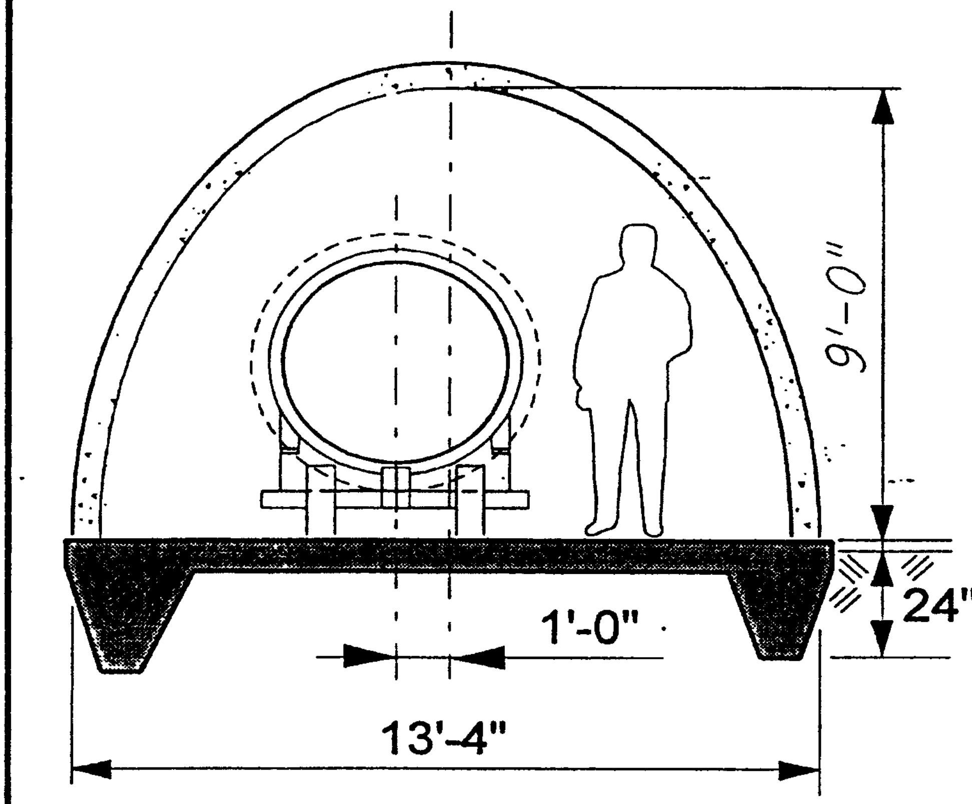
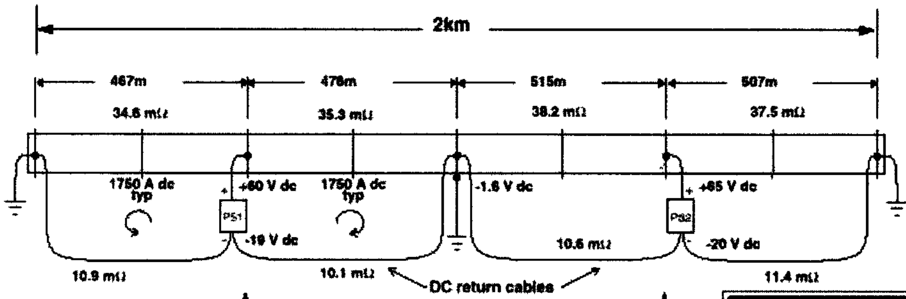
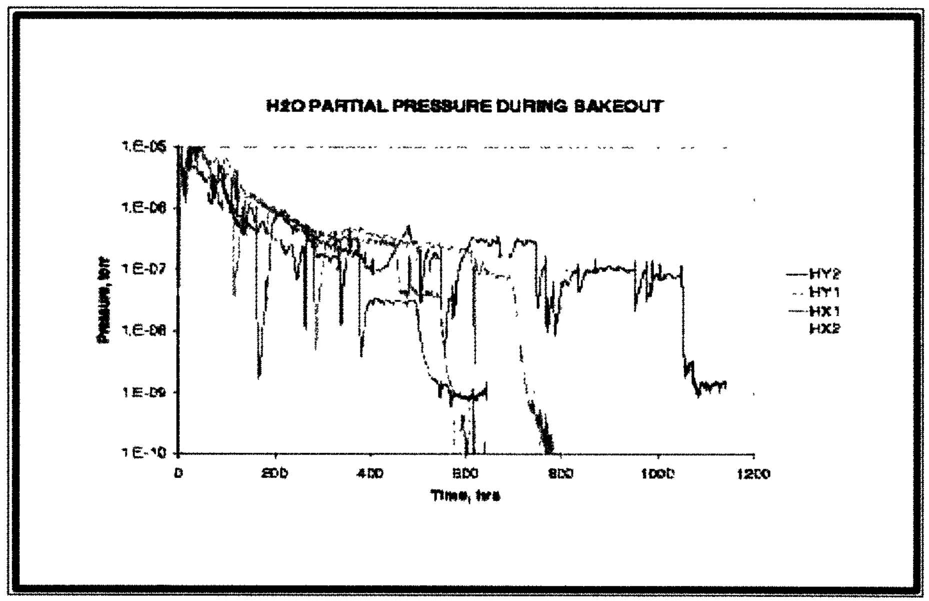


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

Beam Tube *bakeout*

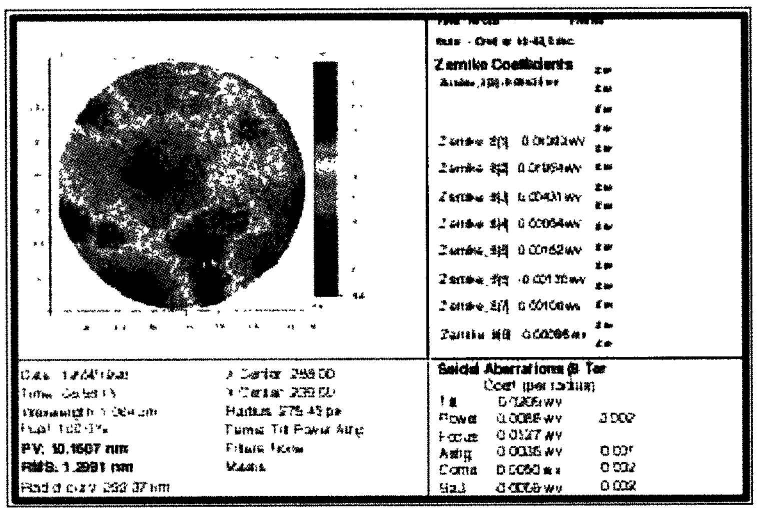


- I = 2000 amps for ~ 1 month
- no leaks !!
- final vacuum at level where it is not source of limiting noise (even future detectors)

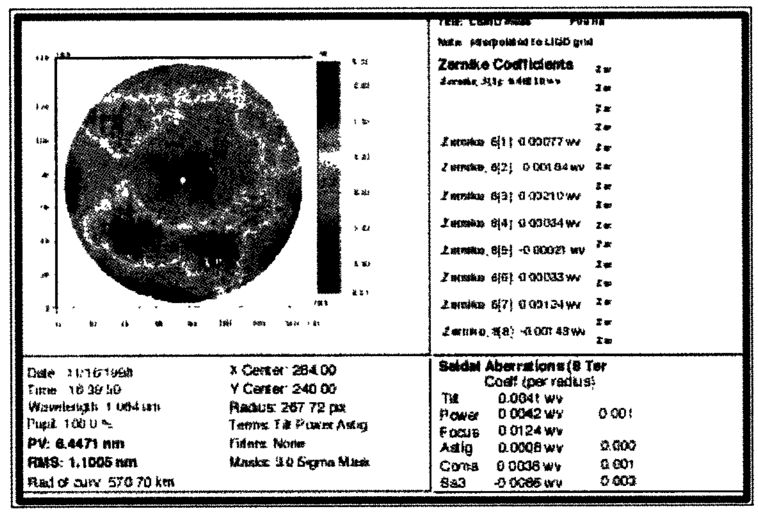


Core Optics
fused silica

- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q's > 2 x 10^6

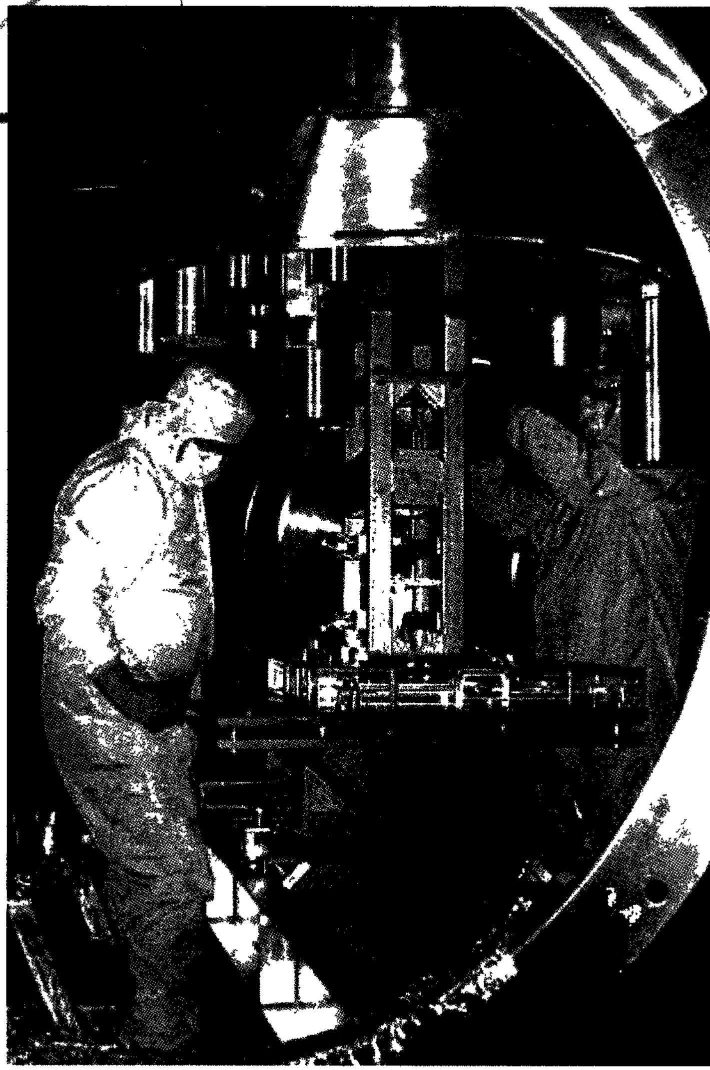


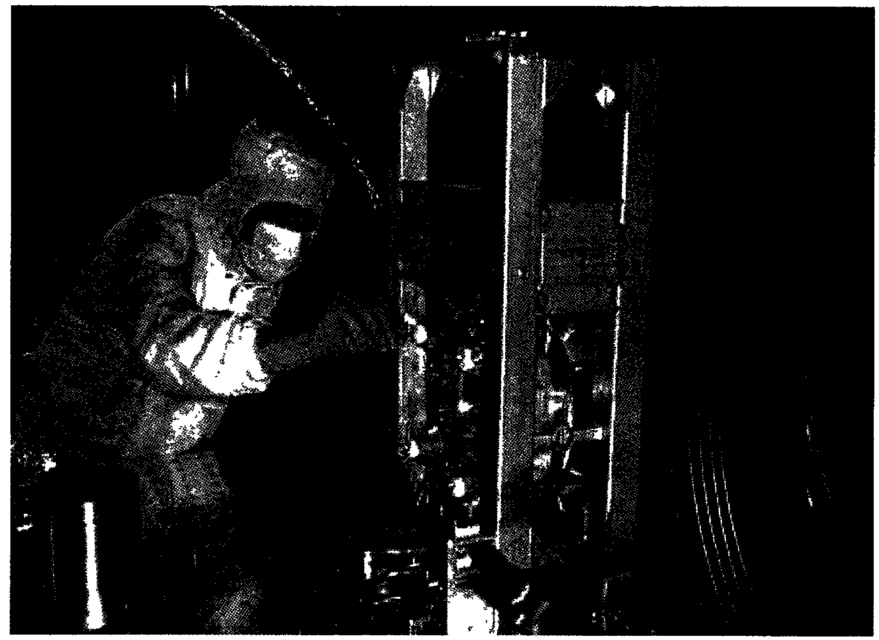
Caltech data



CSIRO data

Core Optics
installation and alignment





Commissioning
configurations

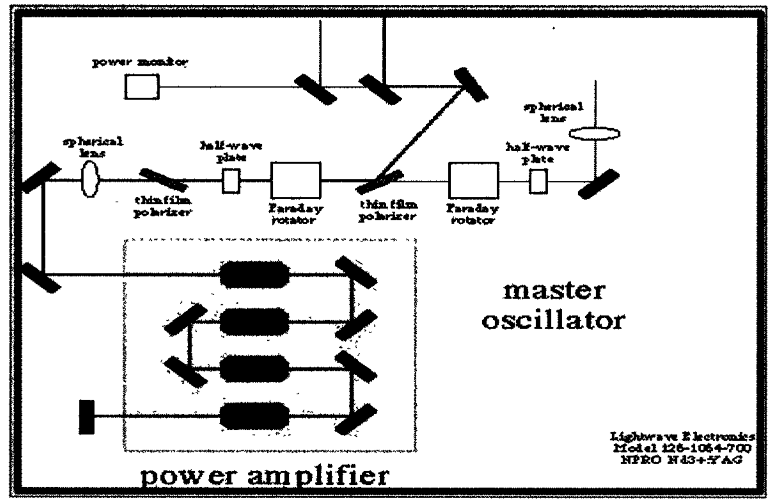
- Mode cleaner and Pre-Stabilized Laser
- 2km one-arm cavity
- short Michelson interferometer studies

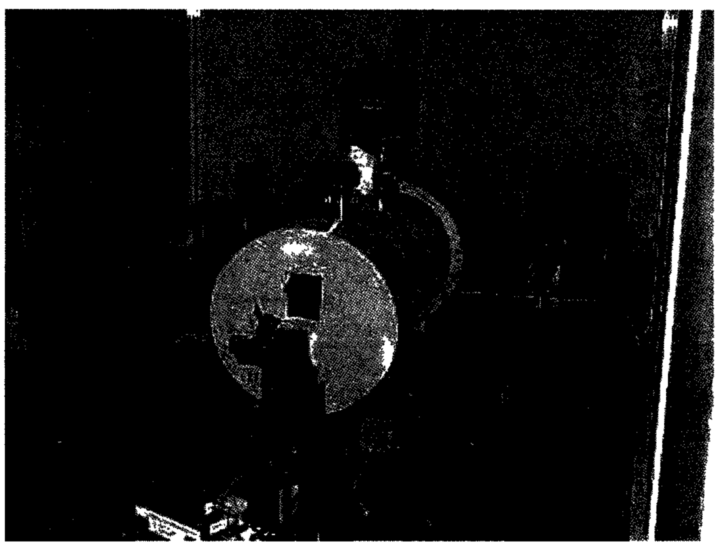
- Lock entire Michelson Fabry-Perot interferometer

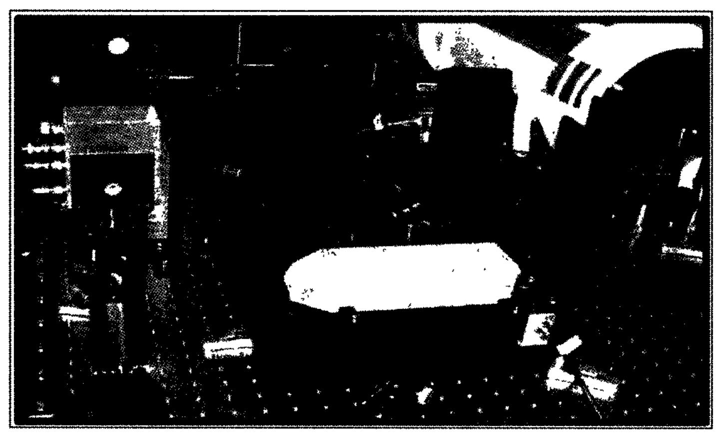
"First Lock"

LIGO
laser

- Nd:YAG
- 1.064 μm
- Output power > 8W in TEM00 mode

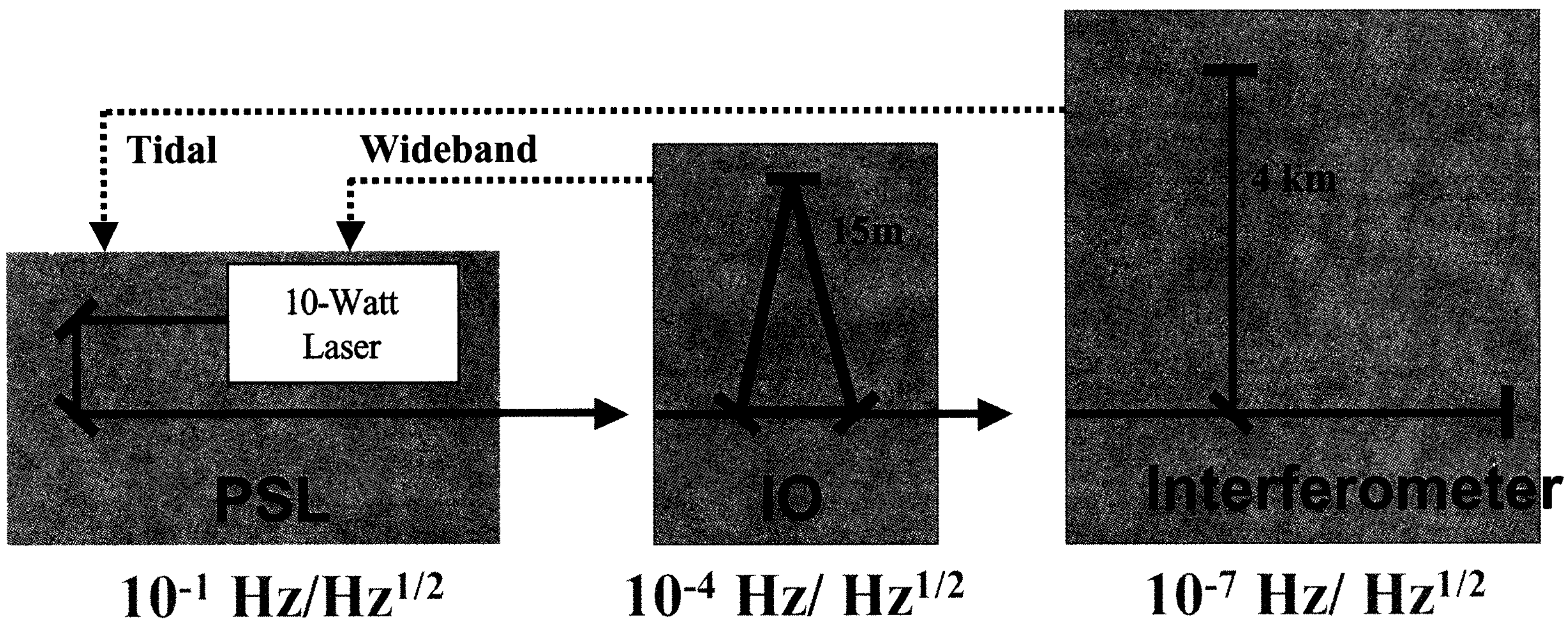




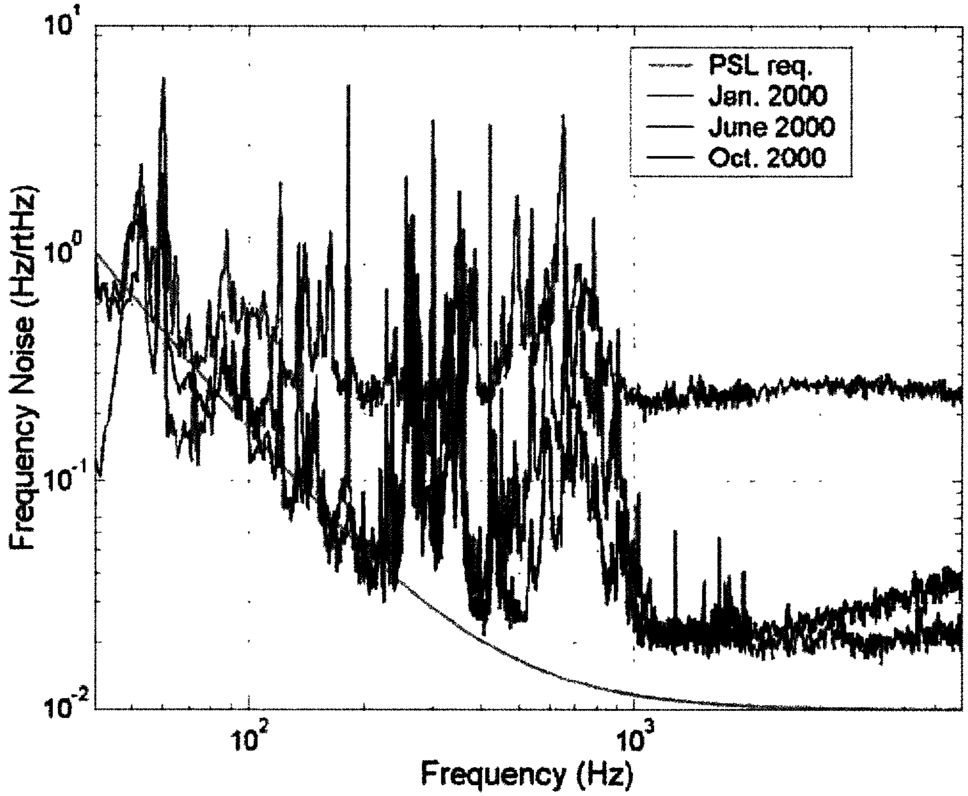


Laser *stabilization*

- Deliver pre-stabilized laser light to the 15-m mode cleaner
  - Frequency fluctuations
  - In-band power fluctuations
  - Power fluctuations at 25 MHz
- Provide actuator inputs for further stabilization
  - Wideband
  - Tidal

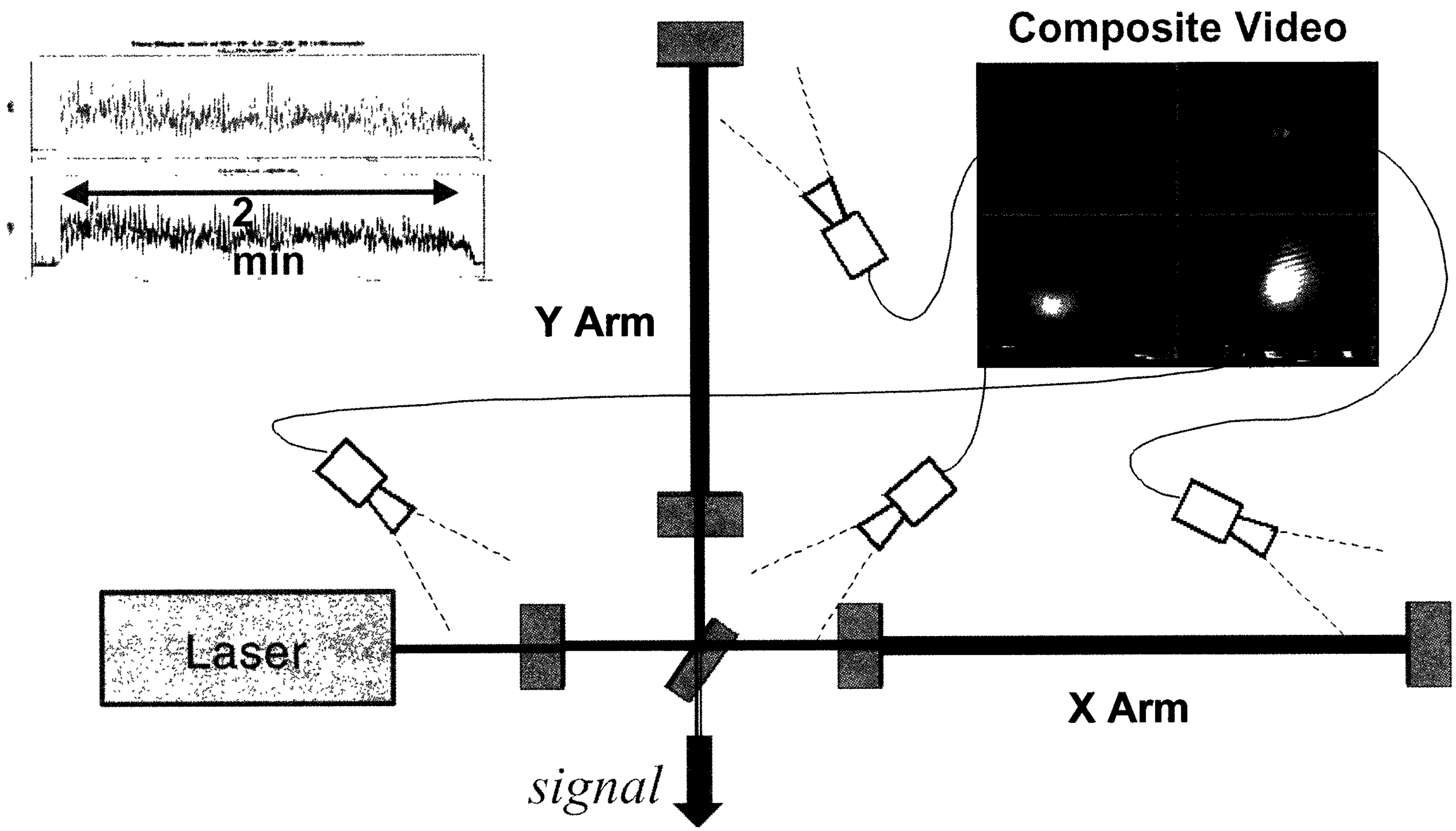


Pre-stabilized Laser
performance



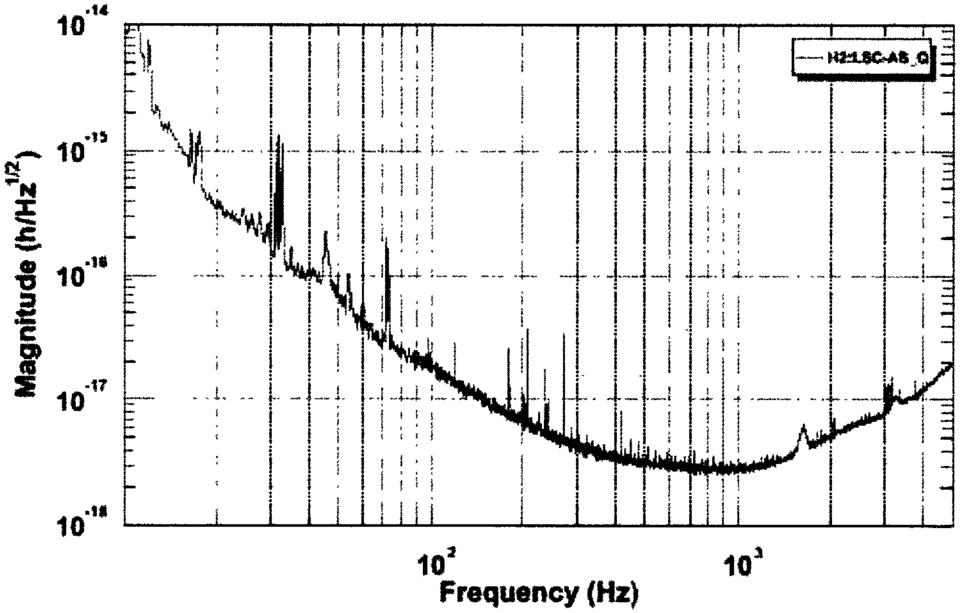
- > 18,000 hours continuous operation
- Frequency and lock very robust
- TEM_{00} power > 8 watts
- Non-TEM_{00} power < 10%

LIGO
first lock



Strain Sensitivity
Nov 2000

2-km Hanford Interferometer



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- •operating as a Michelson with Fabry-Perot arms
- •reduced input laser power (about 100 mW)
- •without recycling
- •noise level is a factor of 10^4-10^5 above the final specification
- •sources of excess noise are under investigation

Significant Events

Hanford 2km interferometer	Single arm test complete installation complete interferometer locked robust locking	6/00 8/00 10/00 1/01
Livingston 4km interferometer	Input Optics completed interferometer installed short Michelson locked interferometer locked	7/00 10/00 1/01 3/01
Coincidence Engineering Run (Hanford 2km & Livingston 4km)	Initiate (Upper Limit Run) Complete Engineering Runs	9/01 7/02
Hanford 4km interferometer	All in-vacuum seismic installed interferometer installed interferometer locked	1/00 6/01 8/01
LIGO I Science Run (3 interferometers)	Initiate Complete (obtain 1 yr @ $h \sim 10^{-21}$)	7/02 1/05

LIGO I

steps prior to science run

- commissioning interferometer
  - » robust locking
  - » three interferometers
  - » sensitivity
  - » duty cycle

- interleave engineering runs (LIGO Scientific Collaboration – LSC)
  - » implement and test acquisition and analysis tools
  - » characterization and diagnostics studies
  - » reduced data sets
  - » merging data streams
  - » upper limits

Science in LIGO I
LSC data analysis

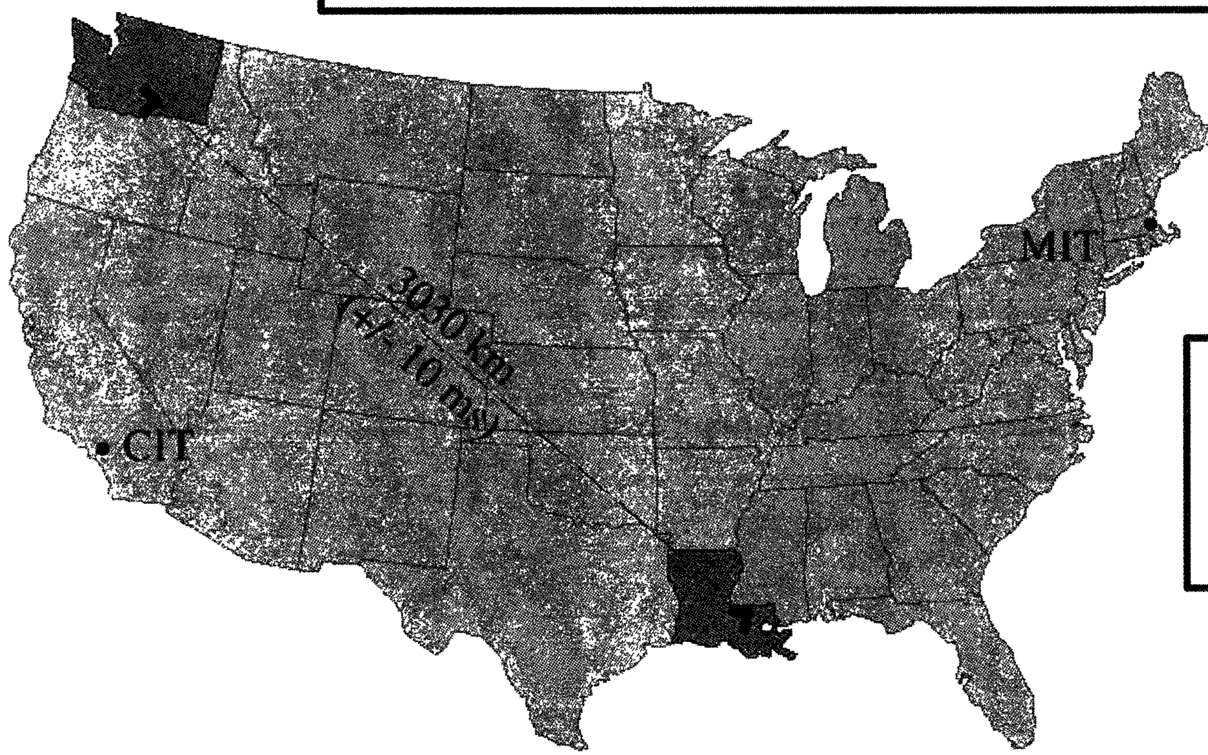
- Compact binary inspiral: *"chirps"*
  - » **NS-NS waveforms are well described**
  - » **BH-BH need better waveforms**
  - » **search technique: matched templates**

- Supernovae / GRBs: *"bursts"*
  - » **burst search algorithms – eg. excess power; time-frequency patterns**
  - » **burst signals in coincidence with signals in electromagnetic radiation**
  - » **prompt alarm (~ one hour) with neutrino detectors**

- Pulsars in our galaxy: *"periodic"*
  - » **search for observed neutron stars (frequency, doppler shift)**
  - » **all sky search (computing challenge)**
  - » **r-modes**

- Cosmological Signals *"stochastic background"*

- **Two Sites - Three Interferometers**
  - » **Single Interferometer   non-gaussian level ~50/hr**
  - » **Hanford (Doubles)   correlated rate (x1000) ~1/day**
  - » **Hanford + Livingston   uncorrelated   (x5000)   <0.1/yr**

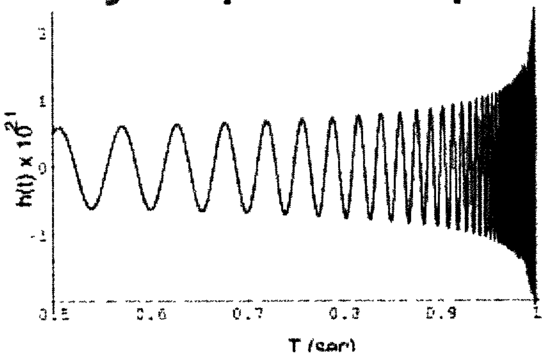


Coincidences between LLO & LHO

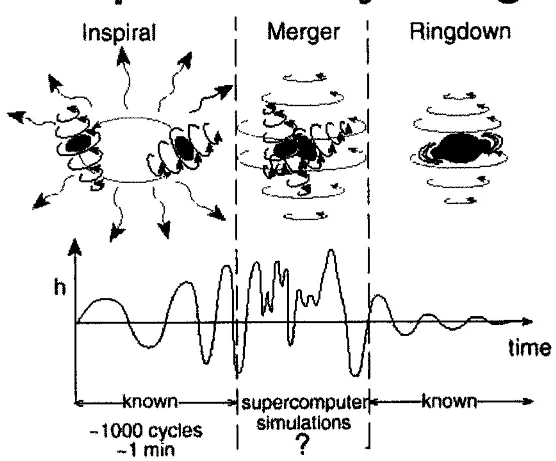
Astrophysics Sources

binary inspiral

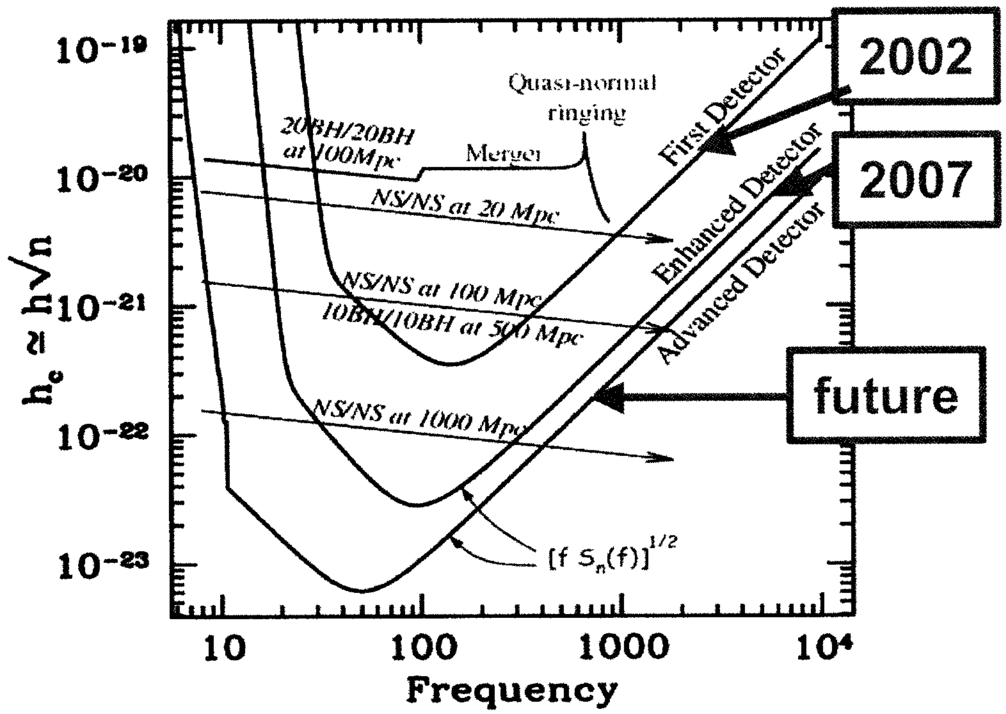
Binary inspiral 'chirp' signal



Compact binary mergers



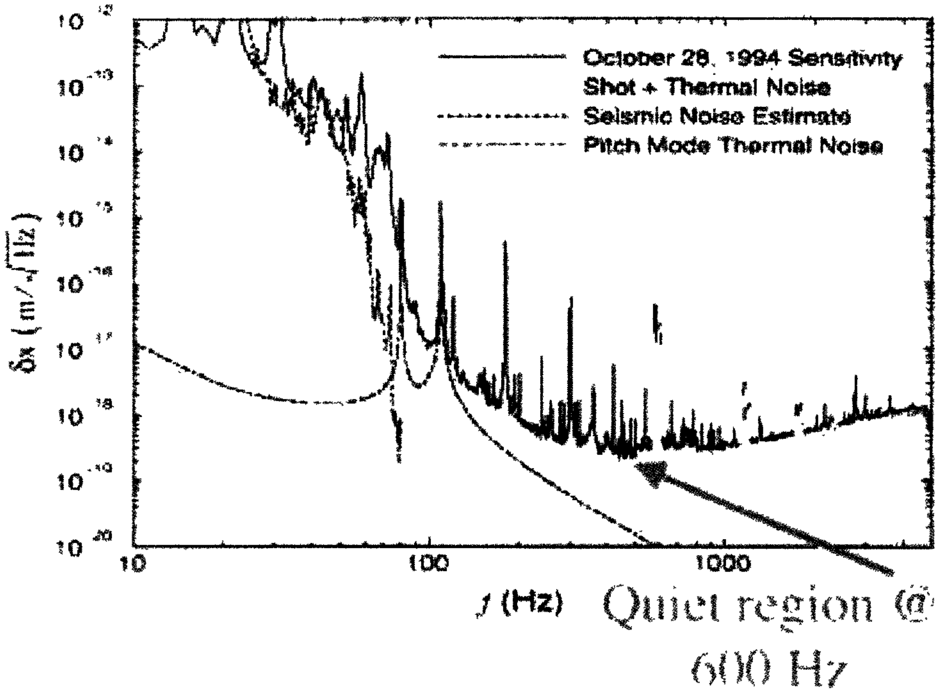
Sensitivity to coalescing binaries



(curves from 1989 proposal)

The Problem

How much does real data degrade complicate the data analysis and degrade the sensitivity ??



40 m data

Test with real data by setting an upper limit on galactic neutron star inspiral rate

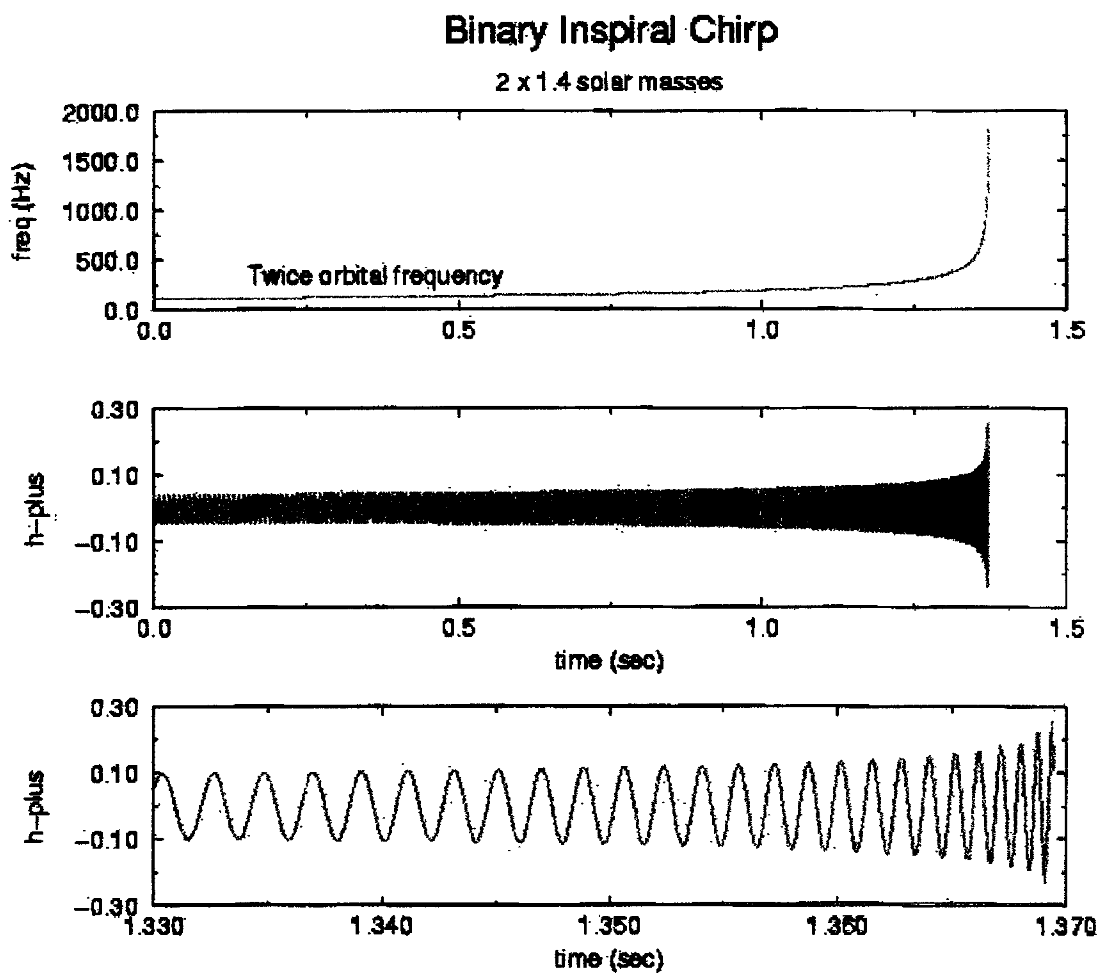
Inspiral 'Chirp' Signal
40m prototype data

Template Waveforms

"matched filtering"
687 filters

44.8 hrs of data
39.9 hrs arms locked
25.0 hrs good data

sensitivity to our galaxy
$h \sim 3.5\ 10^{-19}\ \mathrm{mHz}^{-1/2}$
expected rate $\sim 10^{-6}$/yr

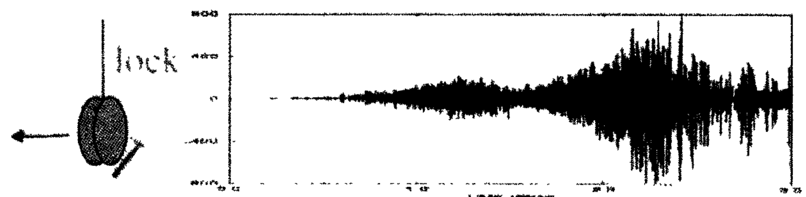


Interferometer Data

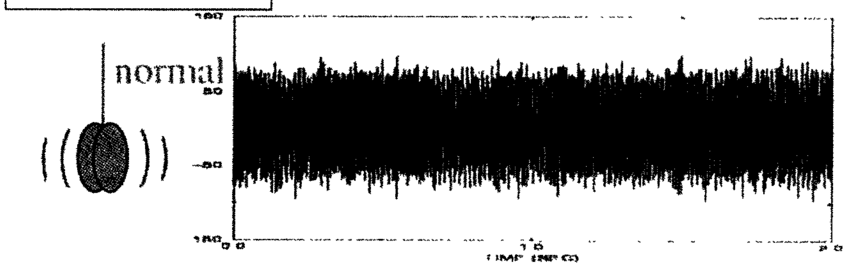
40 m

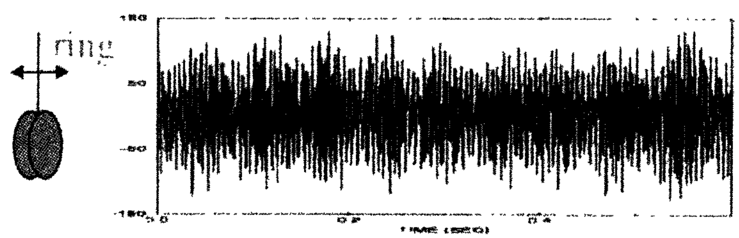
Real interferometer data is UGLY!!!
(Gliches - known and unknown)

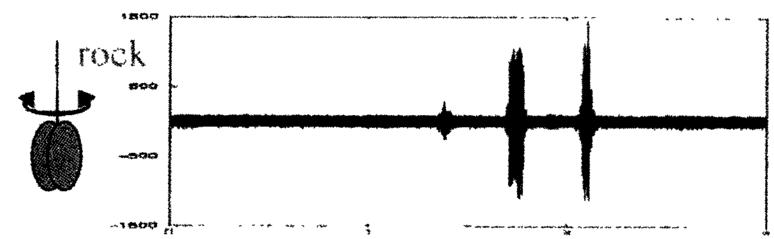
LOCKING



NORMAL



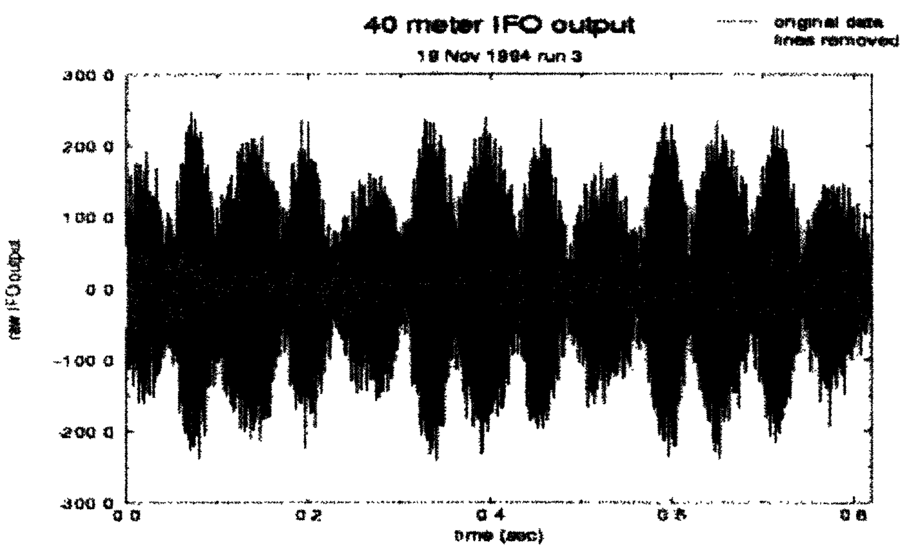




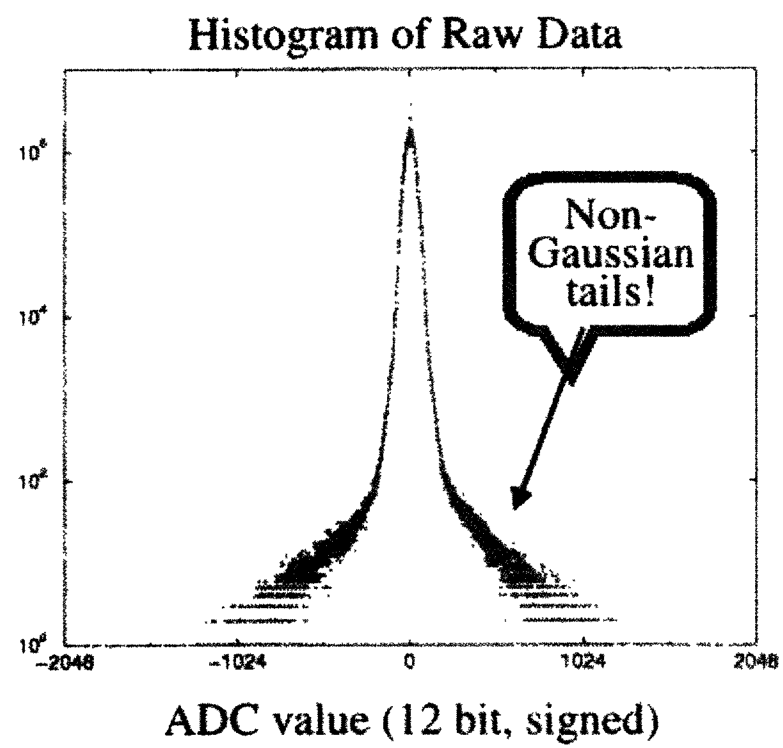
RINGING

ROCKING

"Clean up" data stream
40m prototype



Effect of removing sinusoidal artifacts using multi-taper methods

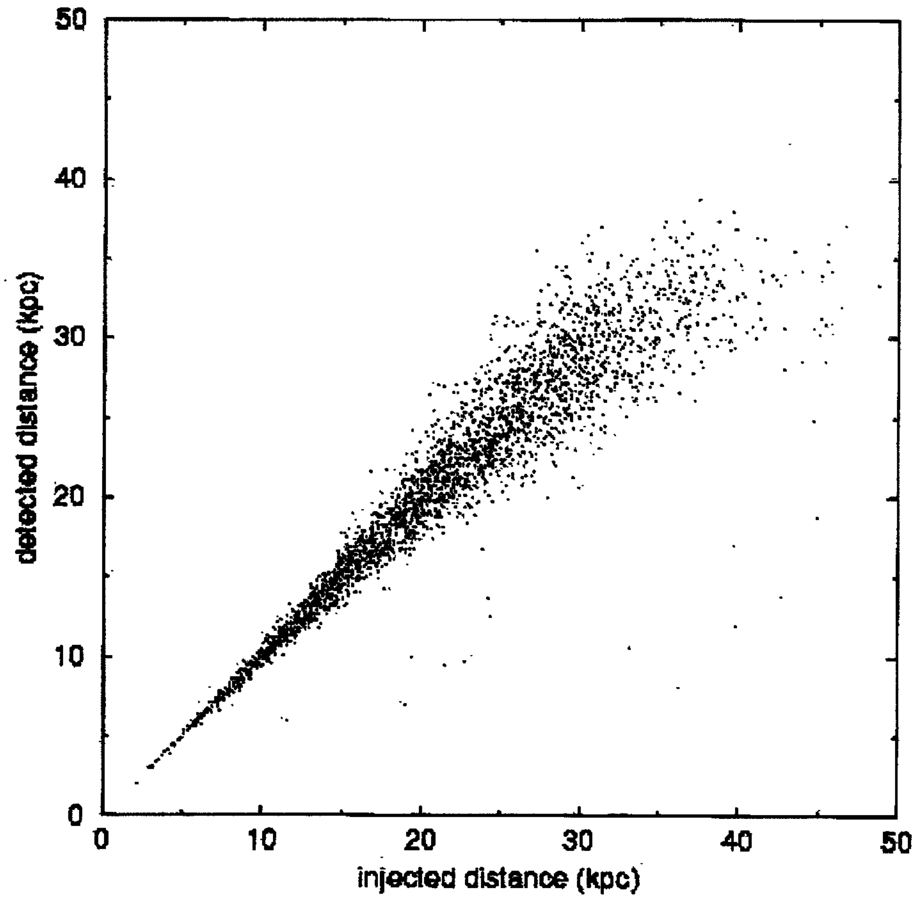


Non stationary noise
Non gaussian tails

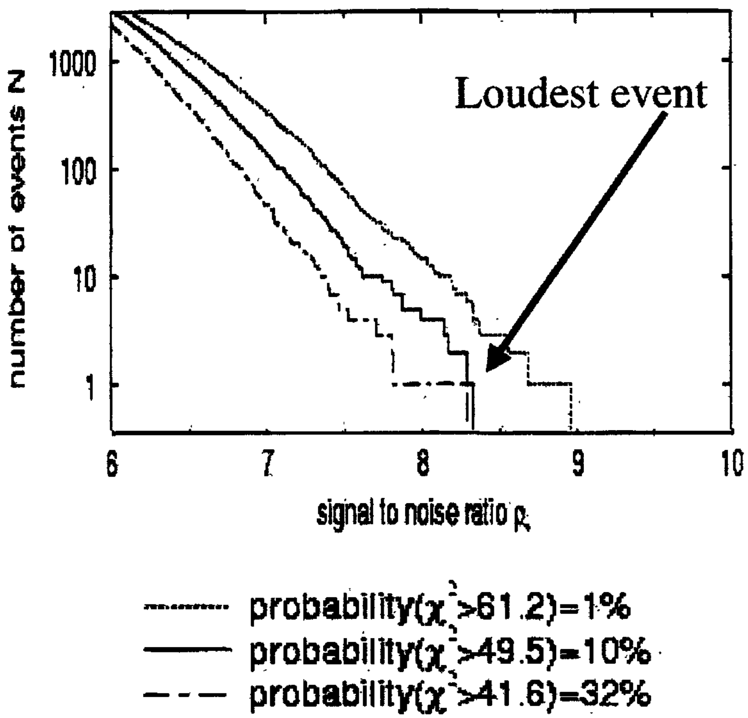
Detection Efficiency

• Simulated inspiral events provide end to end test of analysis and simulation code for reconstruction efficiency

• Errors in distance measurements from presence of noise are consistent with SNR fluctuations



Setting a limit



Upper limit on event rate can be determined from SNR of 'loudest' event

Limit on rate:

R < 0.5/hour with 90% CL

ε = 0.33 = detection efficiency

An ideal detector would set a limit:

R < 0.16/hour

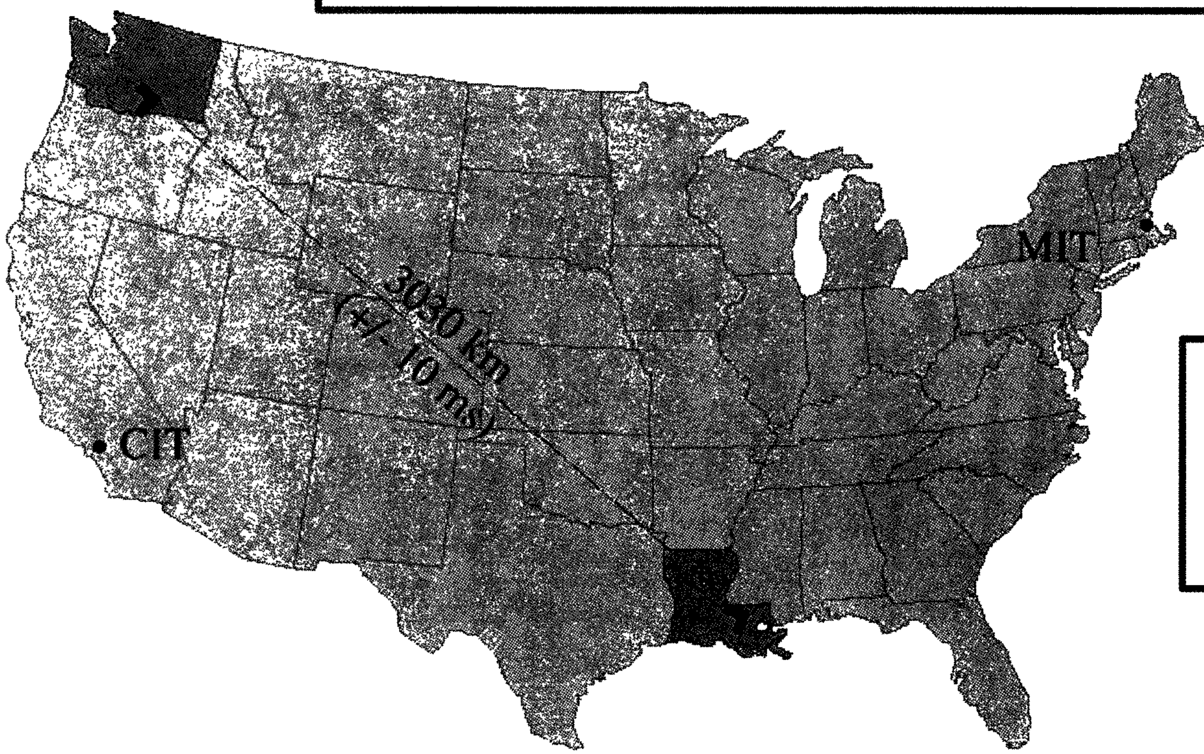
LIGO

▪Two Sites - Three Interferometers

Single Interferometer non-gaussian level ~50/hr

Hanford (Doubles) correlated rate (x1000) ~1/day

Hanford + Livingston uncorrelated (x5000) <0.1/yr



Coincidences between LLO & LHO

LIGO I

science run

- Strategy:
  - initiate science run when good coincidence data can be reliably taken and straightforward sensitivity improvements have been implemented
  - interleave periods of science running with periods of sensitivity improvements as are optimal for the program
  - exploit science at $h \sim 10^{-21}$ before initiating 'advanced' LIGO upgrades

- Goal obtain 1 year of integrated data at $h \sim 10^{-21}$
  - searches in coincidence with astronomical observations: supernovae, GRBs
  - searches for known sources: observed neutron stars, etc
  - stand alone searches: compact binary inspirals, periodic sources, burst sources, stochastic background and unknown sources

LIGO
status and plans

- LIGO Construction
  - » completed (97%) on cost and schedule
  - » final buildings and computing systems implemented 2001, 2002
- LIGO Operations
  - » supporting detector installation/commissioning
  - » computing and data analysis systems for LIGO science
  - » engineering runs for LSC collaboration

  - » LIGO I science run support
  - » engineering support for LIGO I and advanced LIGO R&D

Exploit science at h ~ 10^{-21} before initiating 'advanced' LIGO upgrades

LIGO Science

physics schedule

- LIGO I (~2002-2006)
  - » **LIGO I Collaboration of LSC**
  - » **obtain integrated data for one year of live time at $h \sim 10^{-21}$ (by 2005)**
  - » **plus one extra year for special running or coincidences with Virgo etc.**

- Advanced LIGO (implement ~2006+)
  - » **broad LSC participation in R&D, design and implementation**
  - » **design sensitivity $h \sim 10^{-22}$ or better**
  - » **Rate increase ∝ sensitivity cubed** ➡ 2.5 hr will exceed <u>all</u> LIGO I

- 'Facility Limited' Detectors (> 2010 +)
  - » **new optical configurations, new vacuum chambers, cryogenic, QND, etc**
  - » **sensitivity $h \sim 10^{-23}$**

Overview of LIGO R&D and Planning for Advanced LIGO Detectors

Gary Sanders

NSF R&D Review

Caltech, January 29, 2001

LIGO Program and Mission of the LIGO Laboratory

- **observe gravitational wave sources**;
- develop advanced detectors that approach and exploit the facility limits on interferometer performance;
- operate the LIGO facilities to support the national and international scientific community;
- and support scientific education and public outreach related to gravitational wave astronomy.

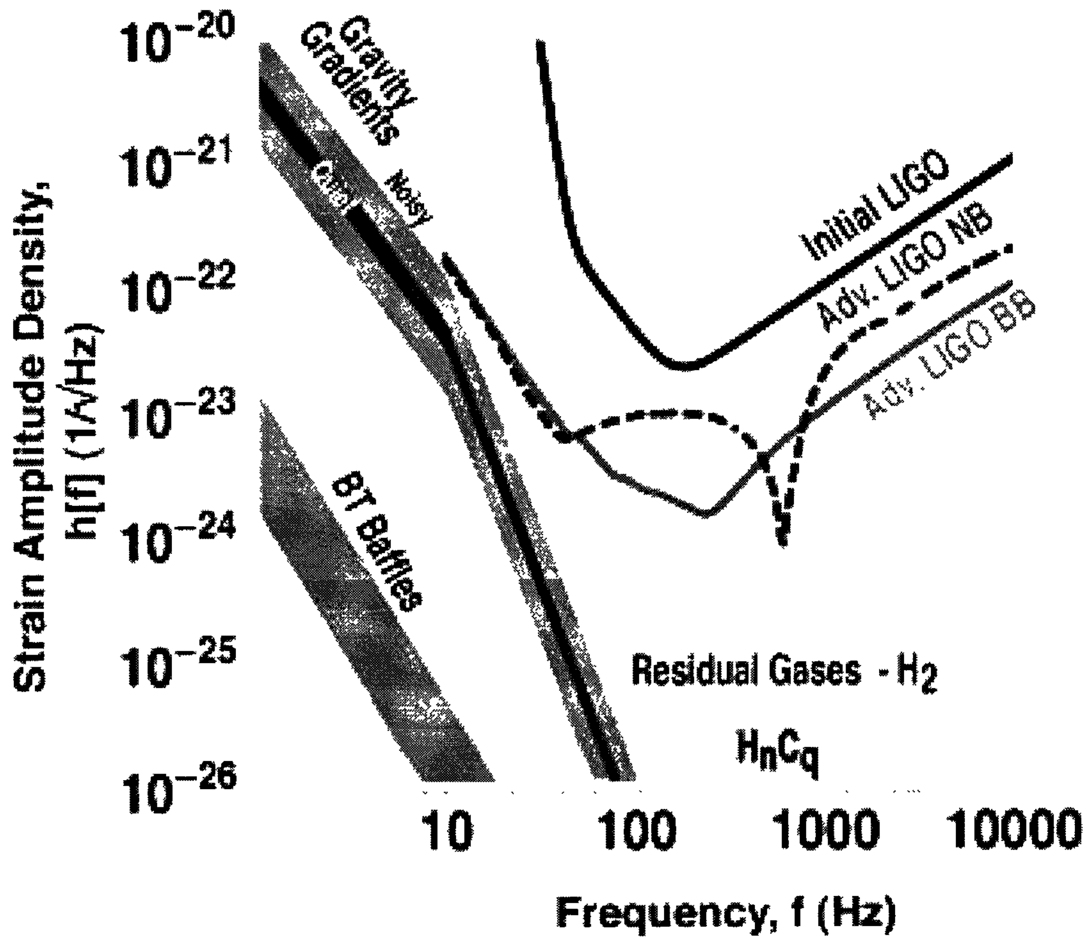
LIGO Proposes To:

- Complete commissioning of the initial LIGO interferometers;
- operate the LIGO interferometers for the initial LIGO Science Run;
- process and analyze the Science Run data and publish the results of the first scientific searches for gravitational wave sources;
- characterize and improve the sensitivity and availability of the operating interferometers;
- ***define interferometer upgrades and carry out a research and development program to underpin future upgrade proposals***;
- support the development and research of the LIGO Scientific Collaboration;
- support the development of the international network of gravitational wave detectors;
- interpret the LIGO program to the public;
- leverage LIGO in educational settings;
- and address new industrial technologies and applications stimulated by the requirements of gravitational wave observation.

The Original Vision for LIGO

- LIGO was conceived as a **program** to detect gravitational waves
- LIGO construction was approved to provide an initial set of feasible detectors and a set of facilities capable of supporting much more sensitive detectors
- It was planned that the initial detectors would have a **plausible** chance to make direct detections
- It was planned that more sensitive detectors would be required to enable **confident** detection
- This R&D proposal describes the program to enable the exploitation of the large investment in the facilities.

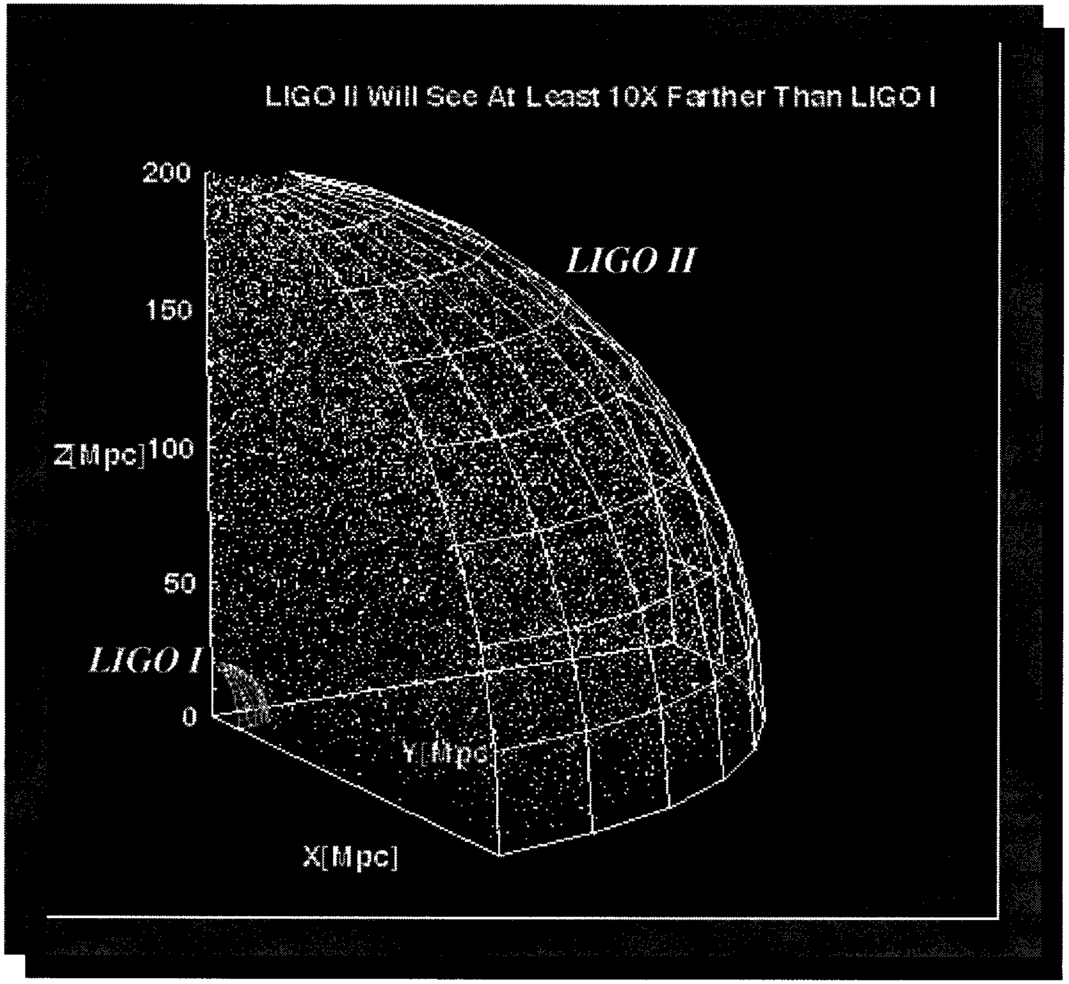
LIGO Facilities Support Detector Upgrades



LIGO

Advanced LIGO Detector Reach

"...2.5 hours of operation will exceed the integrated observations of the 1 year LIGO Science Run..."



LIGO

An Example from Thorne Survey

• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15, 2] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4 M_\odot$ for NS and $\sim 10 M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and advanced WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

	NS/NS	NS/BH	BH/BH in field	BH/BH in clusters
$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–5×10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	$\sim 10^{-6}$–10^{-5}
$\mathcal{D}_{\rm I}$	20 Mpc	43 Mpc	100	100
$\mathcal{R}_{\rm I}$, yr^{-1}	$\boxed{3 \times 10^{-4} - 0.3}$	$\lesssim 4 \times 10^{-4} - 0.6$	$\lesssim 4 \times 10^{-3} - 0.6$	$\sim 0.04 - 0.6$
$\mathcal{D}_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
$\mathcal{R}_{\rm WB}$, yr^{-1}	$\boxed{1 - 800}$	$\lesssim 1 - 1500$	$\lesssim 30 - 4000$	$\sim 300 - 4000$

History of LIGO R&D

- Early R&D leading to initial LIGO took place during the 1970's and 1980's
- Preconstruction R&D for initial LIGO was included in the award for the LIGO construction
  - » LIGO construction $272 million
  - » Preconstruction R&D $20 million (addressing final issues)
  - » Early operations $69 million
- NSF invited proposals for R&D in support of more advanced detectors in 1996
- LIGO Laboratory has been receiving $2.7 million/year of a ~$6.9 million program

LIGO

LIGO Laboratory Funding To Date

MRE

Fiscal Year	Construction	R&D	Operations	Advanced R&D	Total
Through 1994	35.9	11.2			47.1
1995	85	4			89
1996	70	2.4			72.4
1997	55	1.6	0.3	0.8	57.7
1998	26	0.9	7.3	1.6	35.8
1999	0.2		20.9	2.5	22.5
2000			21.1	2.6	23.7
2001			19.1 (10 months)	2.7	22.9
Total	272.1	20	68.7	10.2	371.1

Role of LIGO Scientific Collaboration ...

- A research community around LIGO was formally stimulated as early as 1995
- Following the 1996 McDaniel Panel, the LIGO Scientific Collaboration was formed in 1997
- During 1996, proposals submitted to NSF for R&D support were already highly collaborative
- The 1996 and 1997 R&D plans and proposals were built around certain sensitivity levels as targets for next generation detectors
- During 1999, the Lab/LSC established a reference design for the advanced LIGO detectors

… Role of LIGO Scientific Collaboration

- The LSC and Lab submitted a White Paper and a Conceptual Project plan in late 1999
  - » this was reviewed by NSF -----------> encouraging current R&D
- This LIGO study sharpened the design and the R&D focus
- The R&D program has been highly coordinated across the LSC by the Lab and LSC
  - » all R&D tasks are defined in MOU's with the Laboratory
  - » the program is conducted as the early stages of a construction project
  - » systems engineering is carried out
  - » the R&D is organized with a detailed cost estimate and schedule
  - » monthly coordinating meetings are held to monitor progress

LIGO

LSC Participation in Advanced LIGO R&D

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA) *Australian National University (ANU), University of Adelaide (AU), and University of Western Australia (UWA)*	13.5 FTE
Caltech Experimental Gravitational-Physics Group	1.3 FTE
German British Collaboration for the Detection of Gravitational Waves (GEO 600) *University of Hannover, Garching, Albert Einstein Institute in Potsdam, University of Glasgow, and Cardiff University*	17 FTE
Institute of Applied Physics of the Russian Academy of Sciences at Nizhny Novgorod	9.5 FTE
Iowa State University, Eddy-Current Subgroup	0.5 FTE
University of Colorado, JILA Gravity Group	1.5 FTE
Louisiana State University, Experimental Relativity Group	1.5 FTE
Moscow State University	10 FTE
National Astronomical Observatory of Japan TAMA Group	2 FTE
Pennsylvania State University Experimental Relativity Group	4.7 FTE
Department of Physics of Southern University and A&M College	1.5 FTE
Stanford Advanced Gravitational Wave Interferometry Group	12 FTE
Syracuse University Experimental Relativity Group	4 FTE
University of Florida Laser Interferometric Gravitational Wave Group	2.5 FTE

The Advanced LIGO Detector

- Fabry-Perot Michelson interferometers
- Power recycling AND signal recycling
- 180 W Nd:YAG laser
- possible sapphire core optics
- much better isolation through the use of a fully active seismic isolation system, and a multiple pendulum suspension with silica suspension fibers

R&D Challenges

- Suspension and test mass thermal noise
- Management of thermal consequences of high laser power
- Prestabilized laser performance
- Seismic isolation
- The controls problem

LIGO

Approach to Interferometer Upgrades

- Gravitational wave interferometers are "point" designs
  - » substantial improvements in performance are difficult to achieve with incremental upgrades
  - » lowering one noise floor encounters another
  - » changing the performance of one subsystem causes system mismatch with other subsystems
- Installing an interferometer into the vacuum system is a major campaign
  - » much of the campaign overhead is encountered even with subsystem upgrades
- Installing an interferometer has a high cost in missed scientific opportunity

Upgrade should be a major increase in sensitivity

LIGO

Advanced LIGO Program Assumption

- R&D in progress now
  - » major equipment expenditures in 2001, 2002-2004
- R&D is substantially completed in 2004
  - » some tests are completed in 2005
- Construction funds will be requested for 2004 start
  - » some long lead purchases occur as early as 2003
  - » assembly outside vacuum system takes place in 2005
- Advanced interferometers will be installed beginning in early 2006
  - » when LIGO Science Run I is producing published results

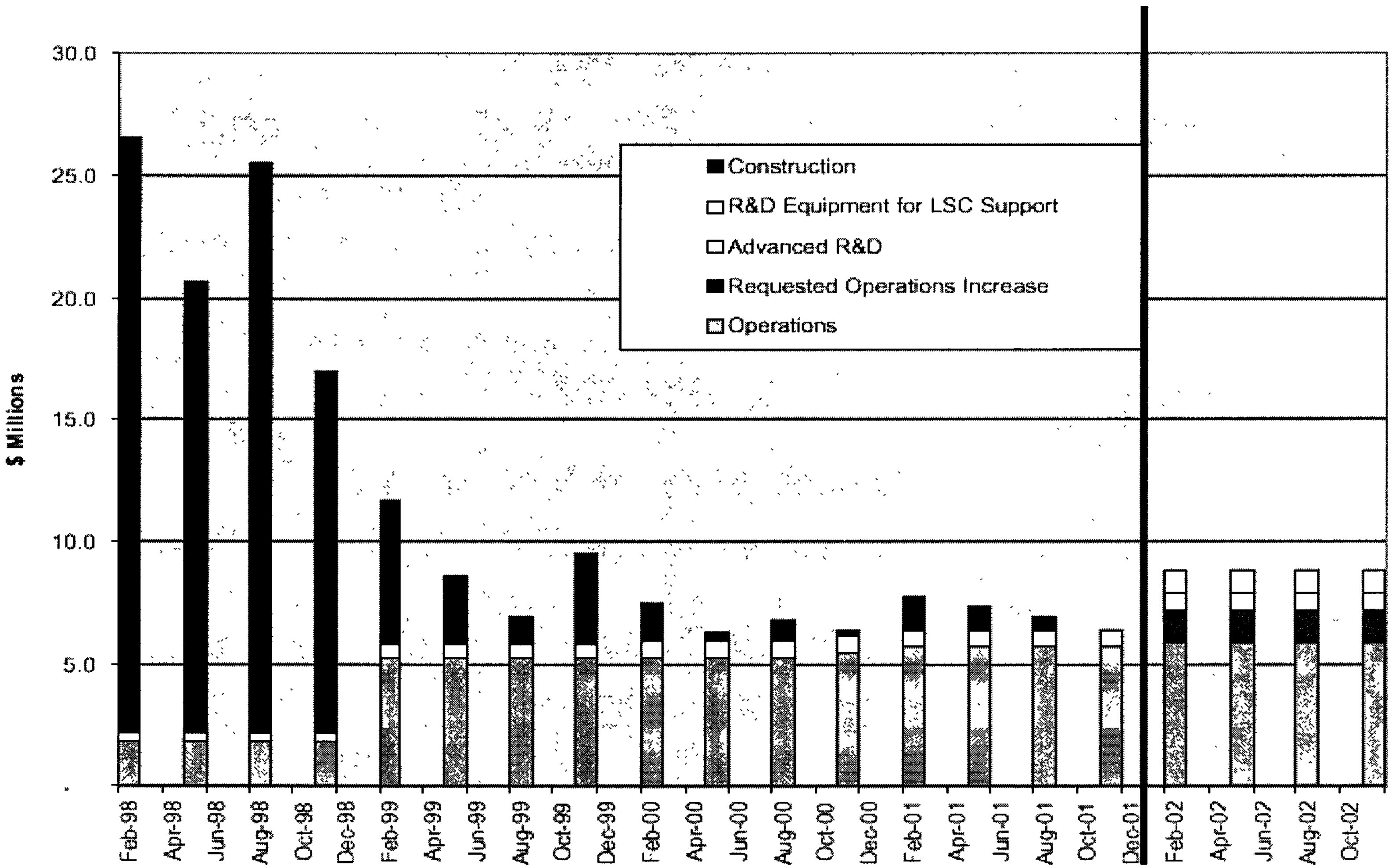
LIGO

R&D Program Approach to Risk Reduction

- All significant risks are planned for measurement or verification during the proposed program
- Faithful prototypes of advanced LIGO subsystems are fully tested in parallel to operating LIGO
- Goal is to fully qualify all designs before installing in LIGO vacuum system
  - » 40 Meter qualifies controls system
  - » LASTI qualifies the isolation/suspension system and the prestabilized laser/input optics systems
- Installation into LIGO vacuum system occurs when new systems are fully ready and qualified

LIGO

LIGO Funding Evolution and Proposal Request



LIGO

Proposal Request

Includes technical support for R&D

	FY 2002 $M	FY 2003 $M	FY 2004 $M	FY 2005 $M	FY 2006 $M	Total $M
Currently Funded Operations	23.63	24.32	25.05	25.87	26.65	125.52
Increase for Full Operations	5.21	5.20	4.79	4.86	4.95	25.01
Advanced R&D	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment in Support of LSC Research	3.30	3.84	3.14			10.28
Total Budgets	**34.91**	**36.21**	**35.93**	**33.77**	**34.74**	**175.57**

The R&D Program

- Most work supports Advanced LIGO realization
- Some far reaching research
- All work highly collaborative
- Lab coordinates program through LSC
  - » full cost/schedule planning in use
  - » monthly telecons with each working group
- Engineering and some senior effort supported from Lab Operations
- Big ticket equipment items for LSC program in Lab proposal

LIGO Increased Staffing to Support R&D and Modeling

• Increased staff in the Technical and Engineering Support and Detector Support Groups. The Caltech campus-based support to the observatories declines significantly after the Detector is commissioned. However, the increase for the R&D for an advanced LIGO (planned for installation in 2005-2006) is significant and results in a net increase.	$920,868
• Increment for engineering and technician labor (4 FTEs) at Livingston to support the LSC science team responsible for Seismic Isolation development. This effort is for two years only and is non-recurring.	$506,300
• Increased support staff for Modeling and Simulation Group. The increase was suggested by an NSF Review panel.	$282,485

LIGO

R&D Effort

•	Stochastic Noise. LASTI integrated system tests of the advanced seismic isolation and suspension prototypes.	$275,222
•	Thermal Noise Interferometer. Direct measurement of test mass thermal noise for initial and advanced LIGO designs.	$176,697
•	Advanced Core Optics including Sapphire Optics	$283,937
•	Advanced Interferometer Sensing and Control including Photodetector Development	$298,779
•	Stiff Seismic Isolation System Development	$46,353
•	Auxiliary Optics Systems including Active Thermal Control	$366,088
•	Advanced Suspensions including Fiber Research.	$208,725
•	Improved Low Frequency Strain Sensitivity.	$345,637
•	40-Meter Advanced R&D. Tests of controls and electronics for a signal and power recycled configuration with the read-out scheme and control topology intended for advanced LIGO.	$235,075
•	Advanced Controls & System Identification. Research on application of advanced system identification and control concepts to LIGO.	$188,677
•	Advanced (highly stabilized) Input Optics Systems.	$347,423

LIGO R&D Equipment in Support of LSC Research Program

- Equipment costs for the development of advanced seismic isolation prototypes.
- Equipment costs for the development of multiple pendulum, fused silica fiber suspension prototypes.
- Materials and manufacturing subcontracts to support the development of sapphire test masses and high Q test mass materials and coatings research.
- Investment and non-recurring engineering costs for a large coating chamber and its commissioning
  - » study of coating strategy in progress

LIGO

Isolation Research

(STO, SUS, TNI, SEI)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
ISOLATION						
Sci & PD	MIT	1	0	2.4	3.4	8.1
	CIT	3	0	1.7	4.7	
UG & Grads	MIT	3	0	0.0	3.0	5.0
	CIT	2	0	0.0	2.0	
Eng & Techs	MIT	0	0	2.8	2.8	14.2
	CIT	0	0	6.9	6.9	
	LLO	0	0	4.5	4.5	
Totals (FTE):		9	0	18.3	**27.3**	
Equip. & Supplies		$54	$1,595	0.0	**$1,649**	

N.B.: Does not include LSC research staff.

LIGO

Lasers & Optics Research

(LAS, OPT, IOS, AOS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
LASERS & OPTICS						
Sci & PD	MIT	0	0	0.1	0.1	3.3
	CIT	1	0	2.3	3.3	
UG & Grads	MIT	1	0	0.0	1.0	2.0
	CIT	1	0	0.0	1.0	
Eng & Techs	MIT	0	0	0.0	0.0	2.0
	CIT	0.5	0	1.5	2.0	
Totals (FTE):		3.5	0	3.8	**7.3**	
Equip. & Supplies		$755	$1,706	0.0	**$2,461**	

N.B.: Does not include LSC research staff.

LIGO Advanced Interferometer Systems, Sensing & Control (ISC, 40m, SID, SYS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0	0	1.7	1.7	6.9
	CIT	2	0	3.2	5.2	
UG & Grads	MIT	1	0	1.0	2.0	5.0
	CIT	3	0	0.0	3.0	
Eng & Techs	MIT	0	0	0.8	0.8	10.2
	CIT	0	0	9.5	9.5	
Totals (FTE):		6	0	16.1	**22.1**	
Equip. & Supplies		$313	$0	0.0	**$313**	

N.B.: Does not include LSC research staff.

LIGO

Total LIGO Laboratory R&D

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
TOTAL for advanced LIGO R&D (including CRY)						
Sci & PD	MIT	1	0	4.2	5.2	20.3
	CIT	8	0	7.2	15.2	
UG & Grads	MIT	5	0	1.0	6.0	13.0
	CIT	7	0	0.0	7.0	
Eng & Techs	MIT	0	0	3.5	3.5	26.4
	CIT	0.5	0	17.9	18.4	
	LLO	0	0	4.5	4.5	
Totals (FTE):		21.5	0	38.2	**59.7**	
Equip. & Supplies		$1,139	$3,301	0.0	**$4,440**	
				MIT	14.7	
				CIT	40.5	
				LLO	4.5	

N.B.: Does not include LSC research staff.

Major International Roles in Advanced LIGO

- GEO (UK, Germany) project has joined the LSC
  - » Initial LIGO involvement is in data algorithms and analysis
  - » advanced LIGO involvement includes leading roles in suspensions, configurations, prestabilized laser.
  - » GEO is proposing a capital contribution/partnership in construction of advanced LIGO
- ACIGA project has joined LSC
  - » Initial LIGO involvement is in data algorithms and analysis
  - » advanced LIGO involvement includes laser development, sapphire development and high power issues
- Recent discussions have begun with Virgo on collaboration in coating development and in joint data taking and data analysis

Advanced LIGO Plan

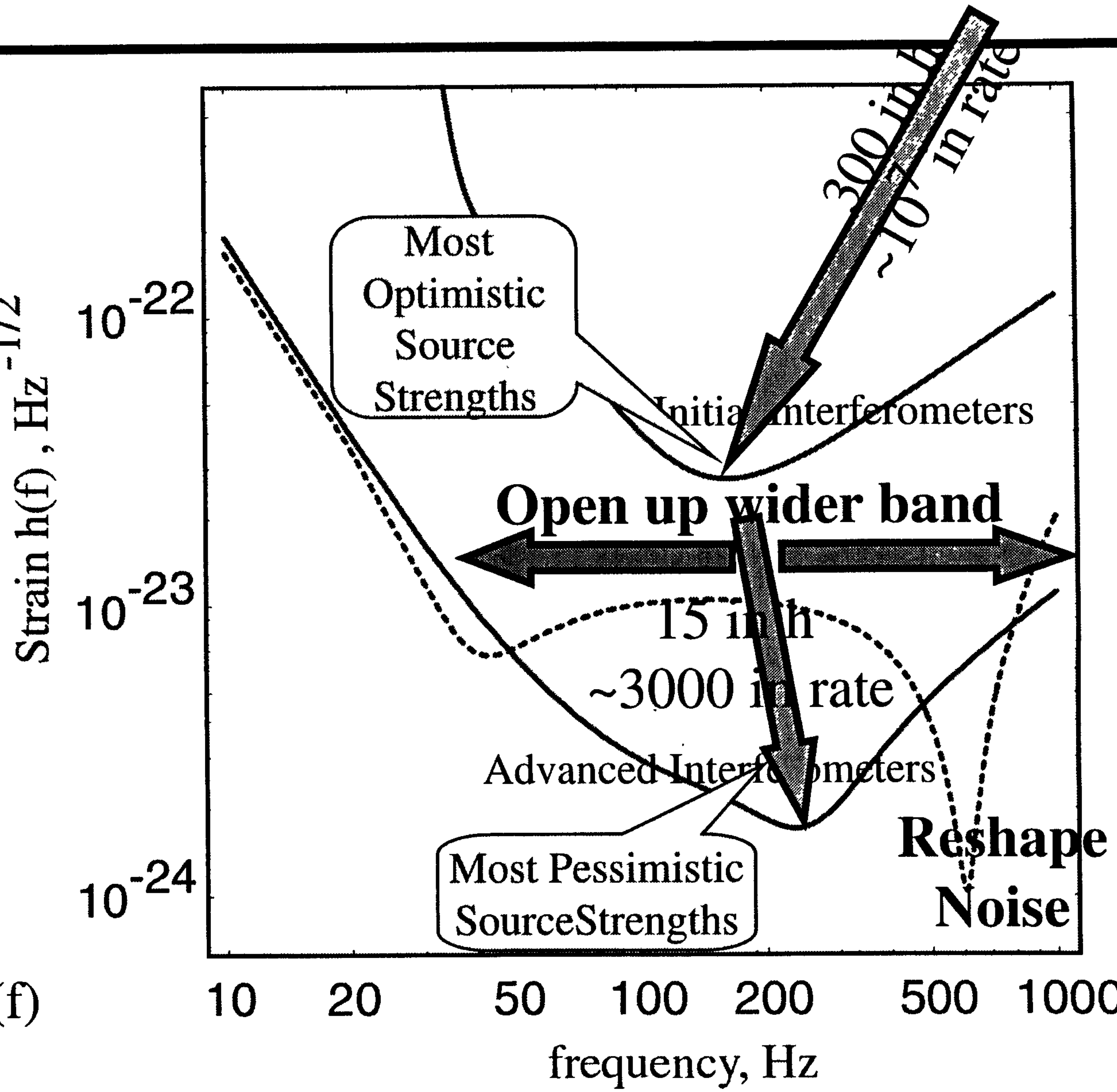
- R&D for a baselined detector proceeds through 2004
- LIGO will propose construction to start in 2004
  - » proposal submitted late this year for 2 year review cycle
- Installation commences in 2006
  - » R&D complete
  - » assembly outside vacuum sufficiently advanced
  - » initial LIGO results in publication

ADVANCED LIGO SCIENCE

Kip S. Thorne
CaRT, California Institute of Technology

NSF Advanced R&D Panel - 29 January 2001

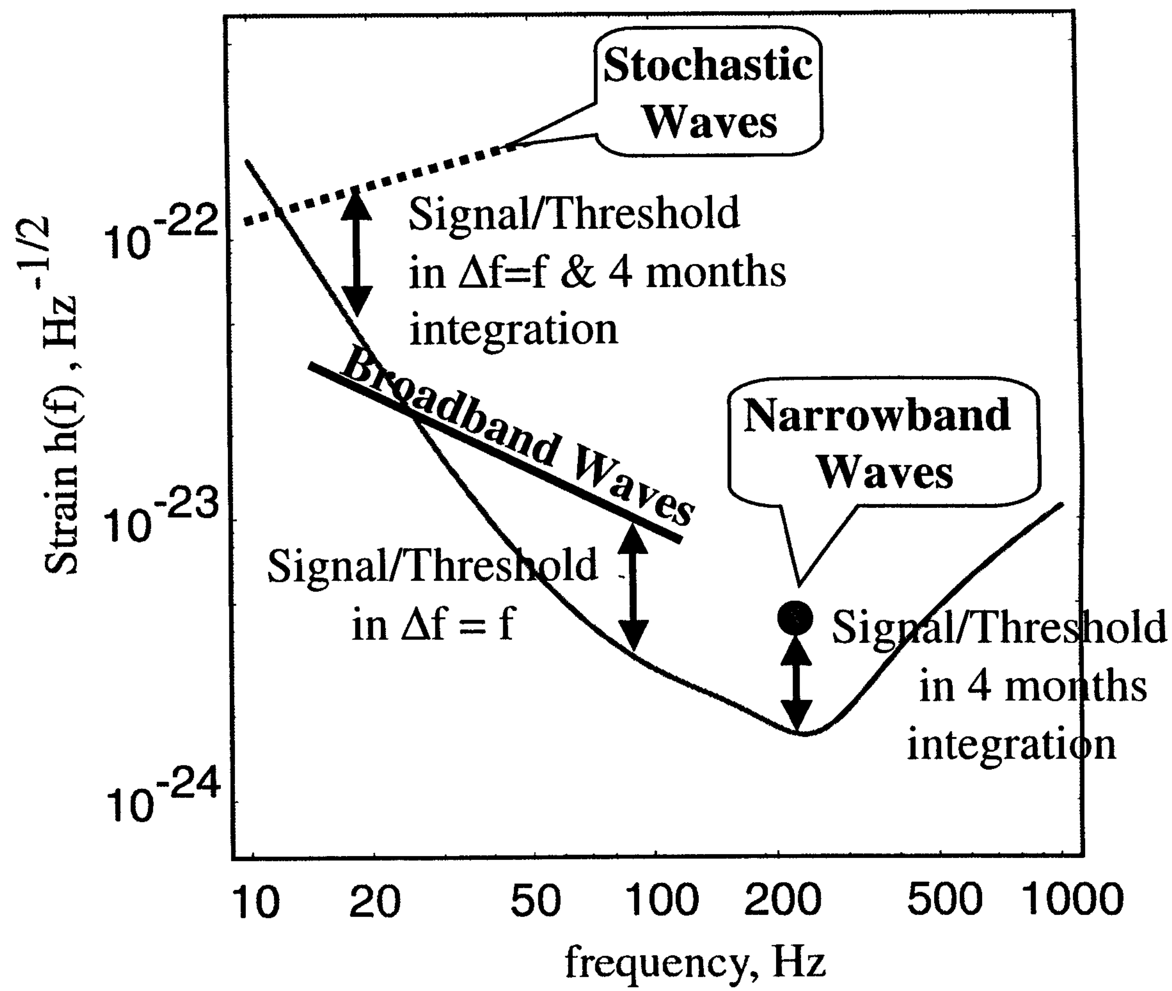
From Initial Interferometers to Advanced



$h_{rms} = h(f)\sqrt{f} \sim 10\, h(f)$

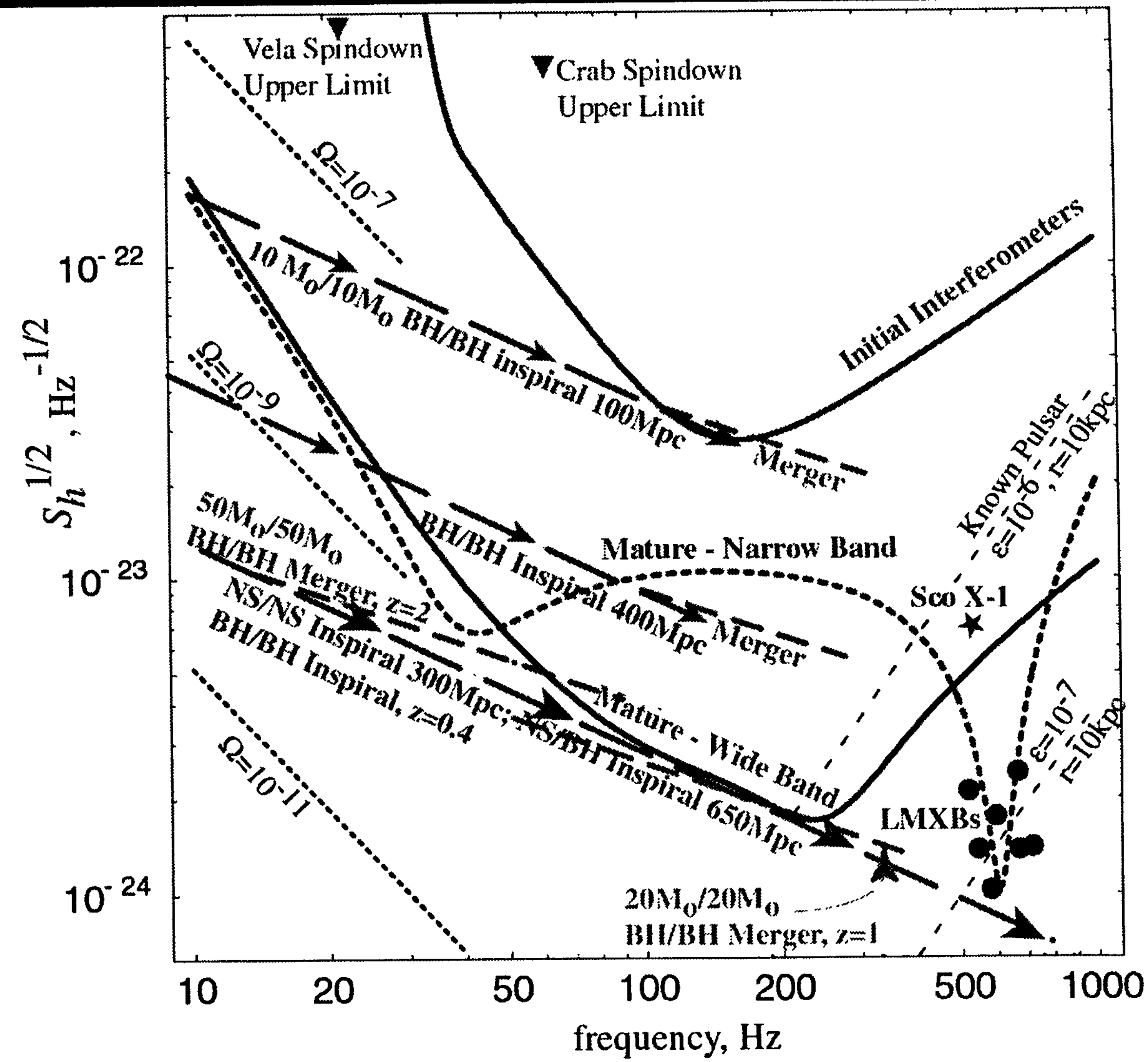
Conventions on Source/Sensitivity Plots

- **Advanced Interferometer:**
  - » sapphire test masses
  - » (If silica, event rate reduced by ~ 2)
- **Data Analysis:**
  - » Assume the best search algorithm now known
- **Threshold:**
  - » Set so false alarm probability = 1%

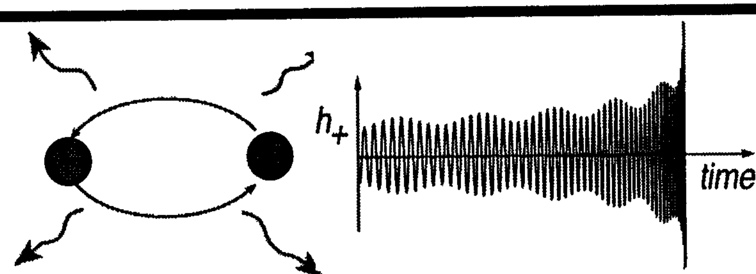


Overview of Sources

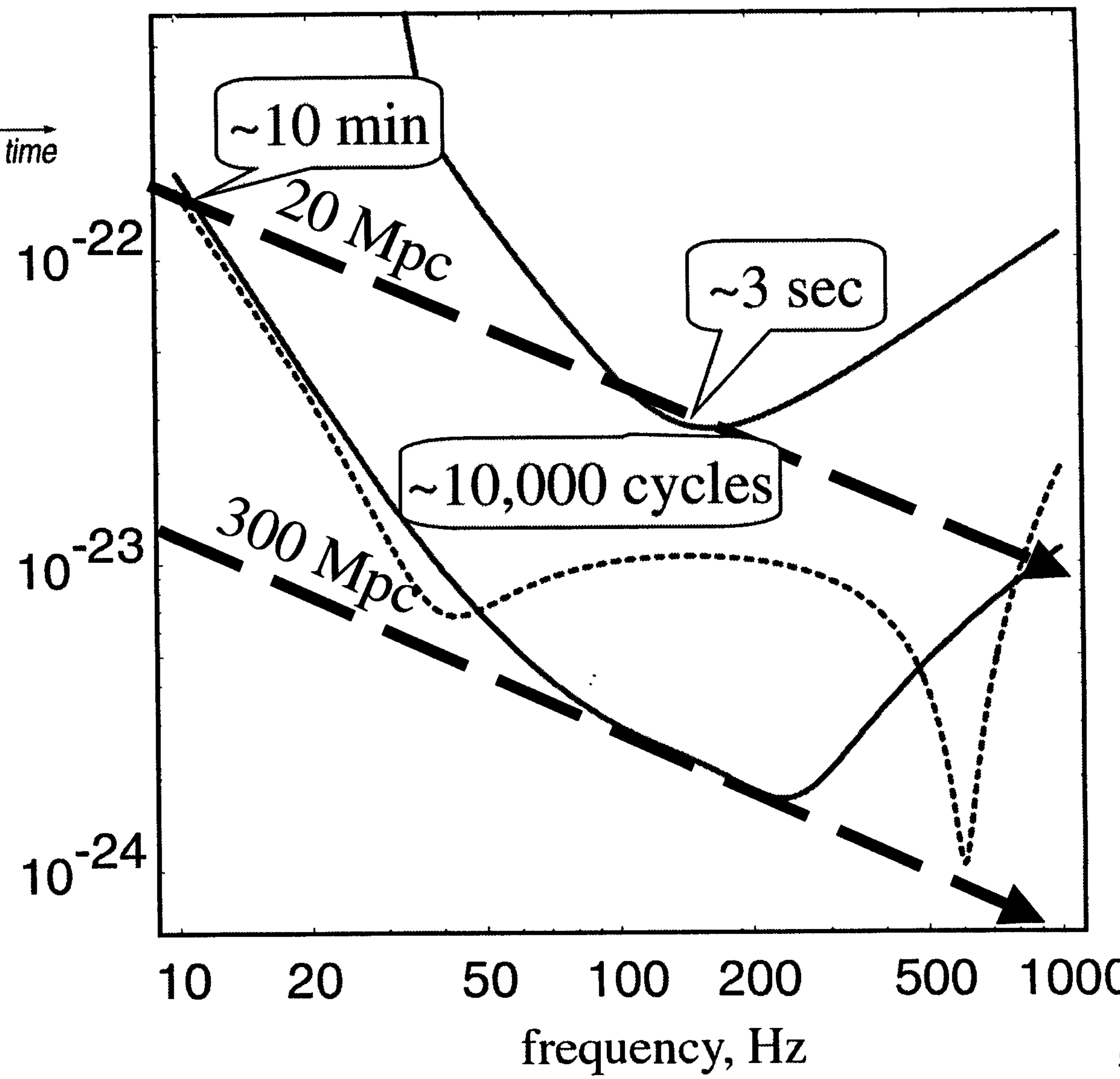
- **Neutron Star & Black Hole Binaries**
  - » inspiral
  - » merger
- **Spinning NS's**
  - » LMXBs
  - » known pulsars
  - » previously unknown
- **Stochastic background**
  - » big bang
  - » early universe



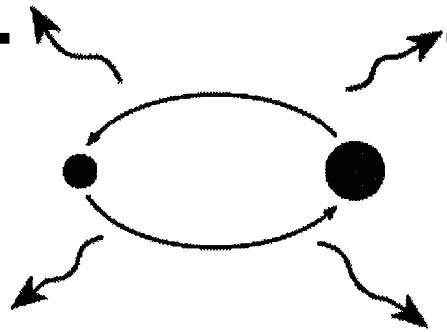
Neutron Star / Neutron Star Inspiral (our most reliably understood source)

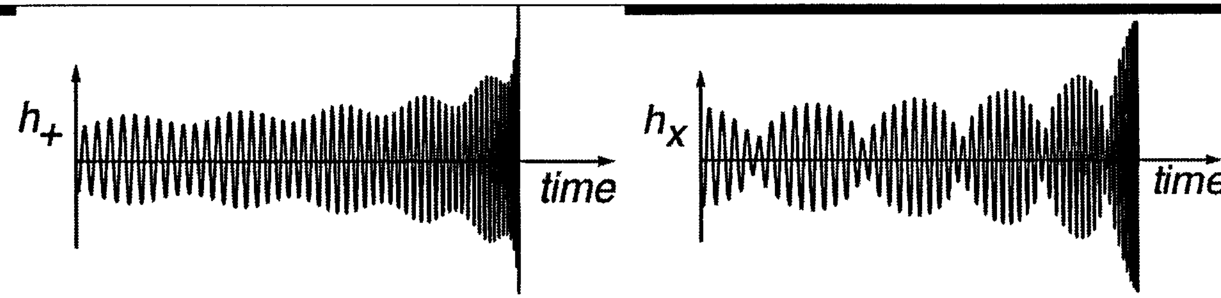


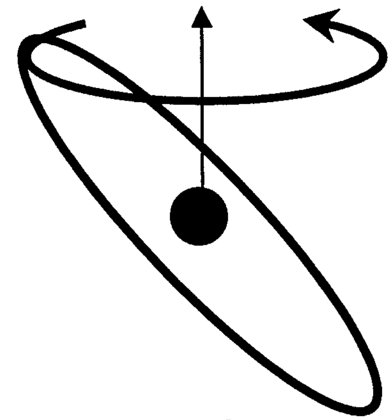
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor astro-ph/0012038
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to 1 / 3yrs
- **Advanced IFOs -**
  - » Range: 300Mpc
  - » 1 / yr to 2 / day



Science From Observed Inspirals: NS/NS, NS/BH, BH/BH

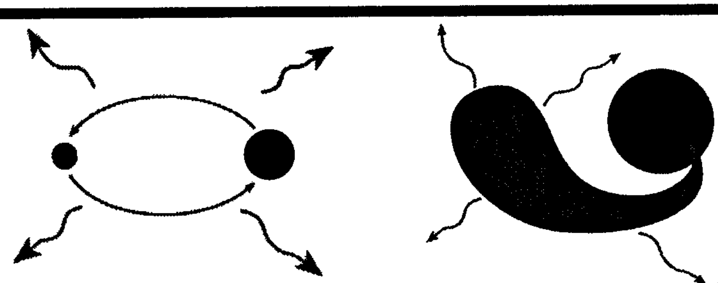






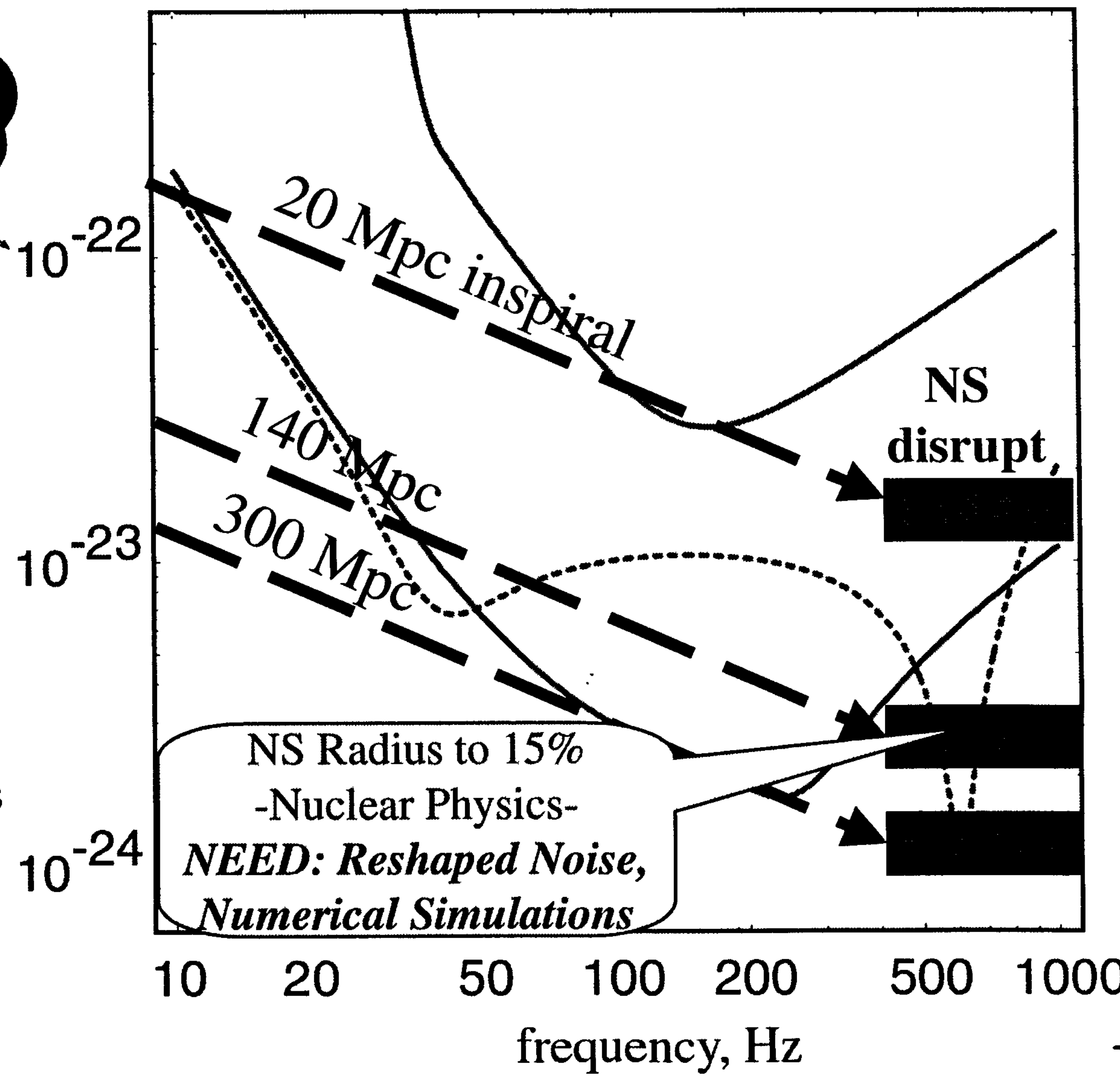
- Relativistic effects are very strong -- e.g.
  - » ***Frame dragging by spins ⇒ precession ⇒ modulation***
  - » ***Tails of waves modify the inspiral rate***
- Information carried:
  - » ***Masses (a few %), Spins (?few%?), Distance [not redshift!] (~10%), Location on sky (~1 degree)***
    - $M_{\mathbf{chirp}} = \mu^{3/5} M^{2/5}$ to ~10^{-3}
- Search for EM counterpart, e.g. γ-burst. If found:
  - » ***Learn the nature of the trigger for that γ-burst***
  - » ***deduce relative speed of light and gw's to ~ 1 sec / 3x10^9 yrs ~ 10^{-17}***

Neutron Star / Black Hole Inspiral and NS Tidal Disruption



1.4Msun / 1.4 Msun NS/NS Binaries

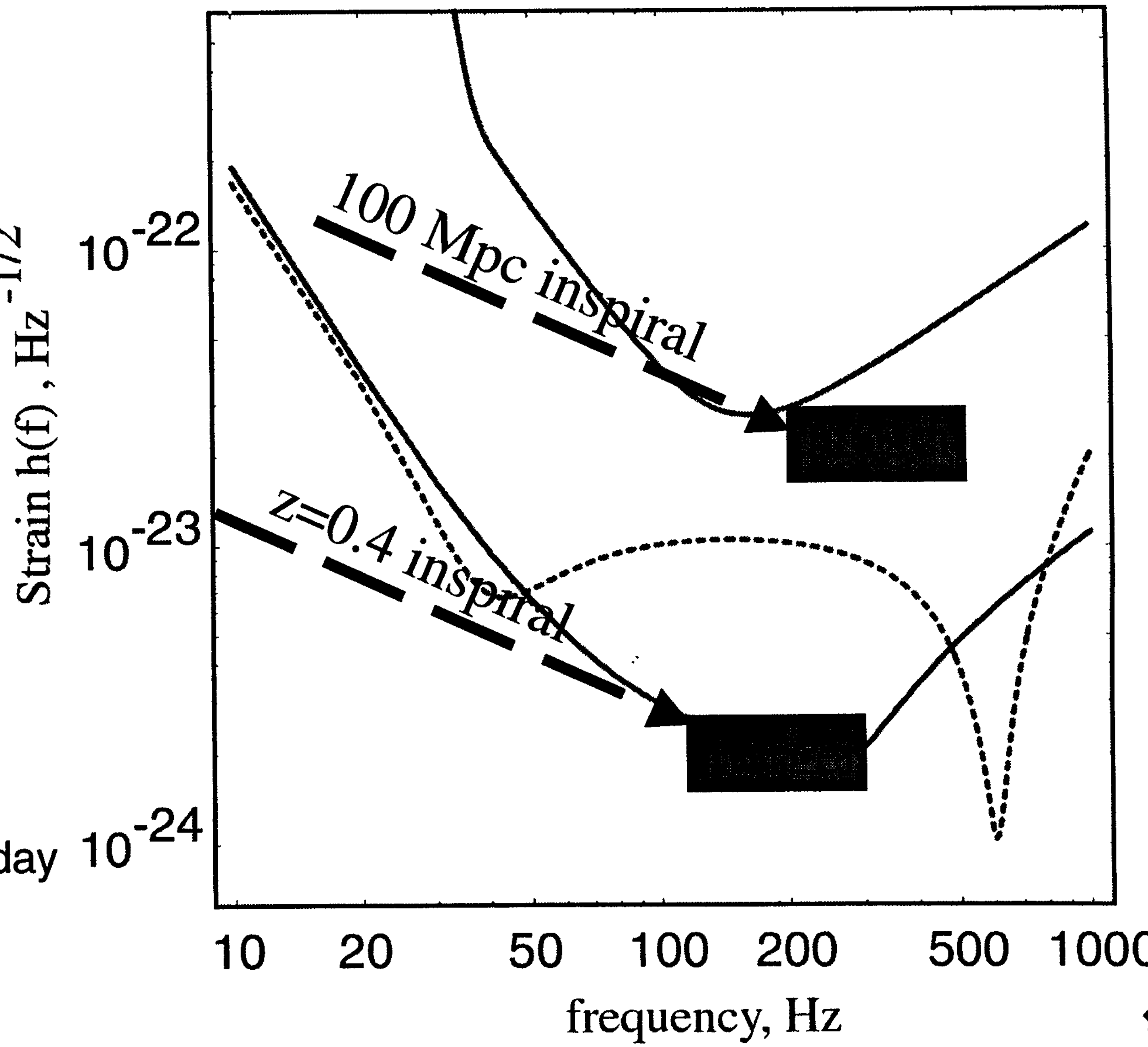
- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » $\lesssim$ 1 / 2500 yrs to 1 / 2yrs
- **Advanced IFOs**
  - » Range: 300Mpc
  - » $\lesssim$ 1 / yr to 4 / day



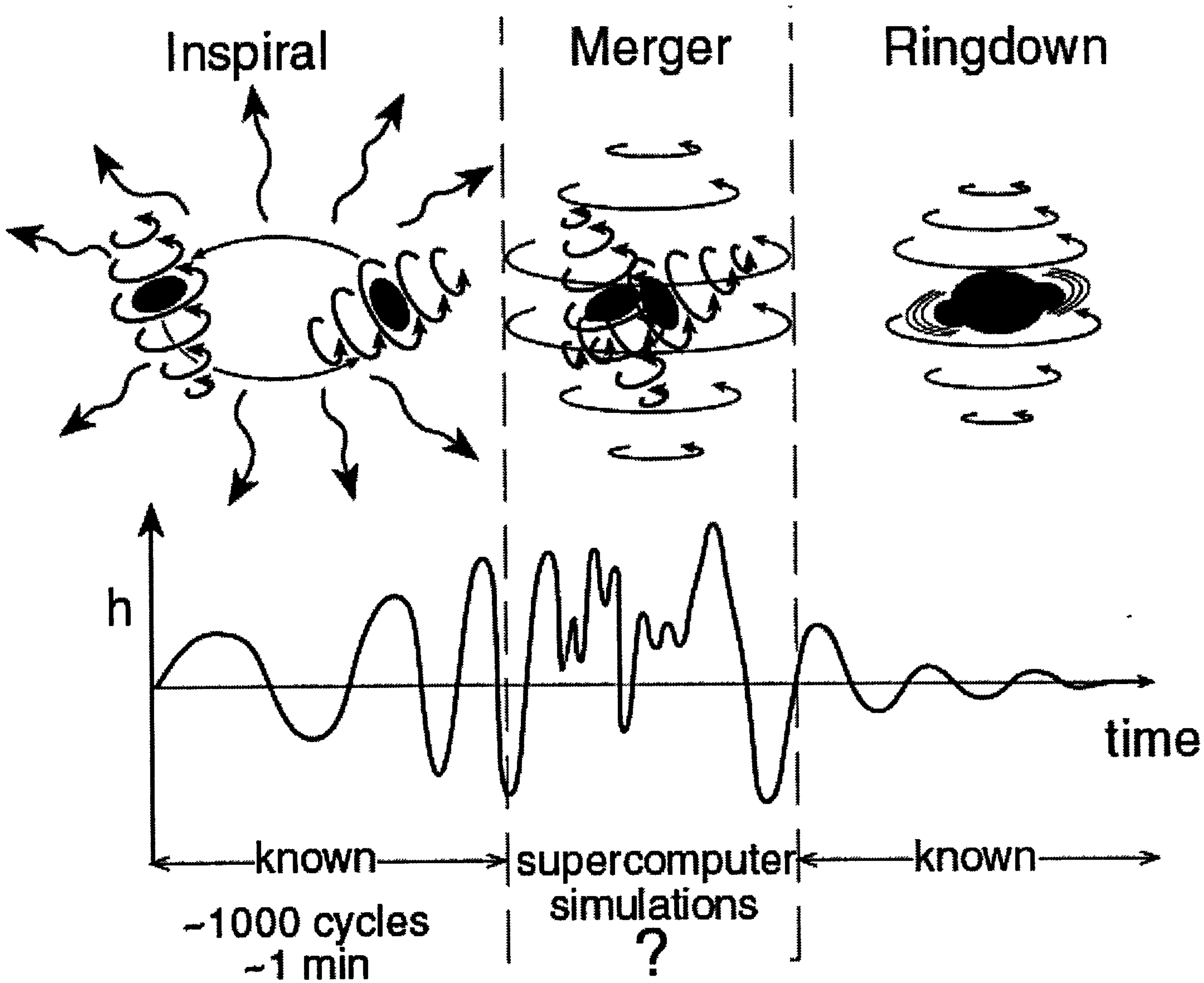
Black Hole / Black Hole Inspiral and Merger

- **10Msun / 10 Msun BH/BH Binaries**
- **Event rates**
  - » Based on population synthesis [Kalogera's
  - » summary of literature]

  Initial IFOs
  - » Range: 100 Mpc
  - » ≲1 / 300yrs to ~1 / yr
- **Advanced IFOs -**
  - » Range: z=0.4
  - » ≲ 2 / month to ~10 / day

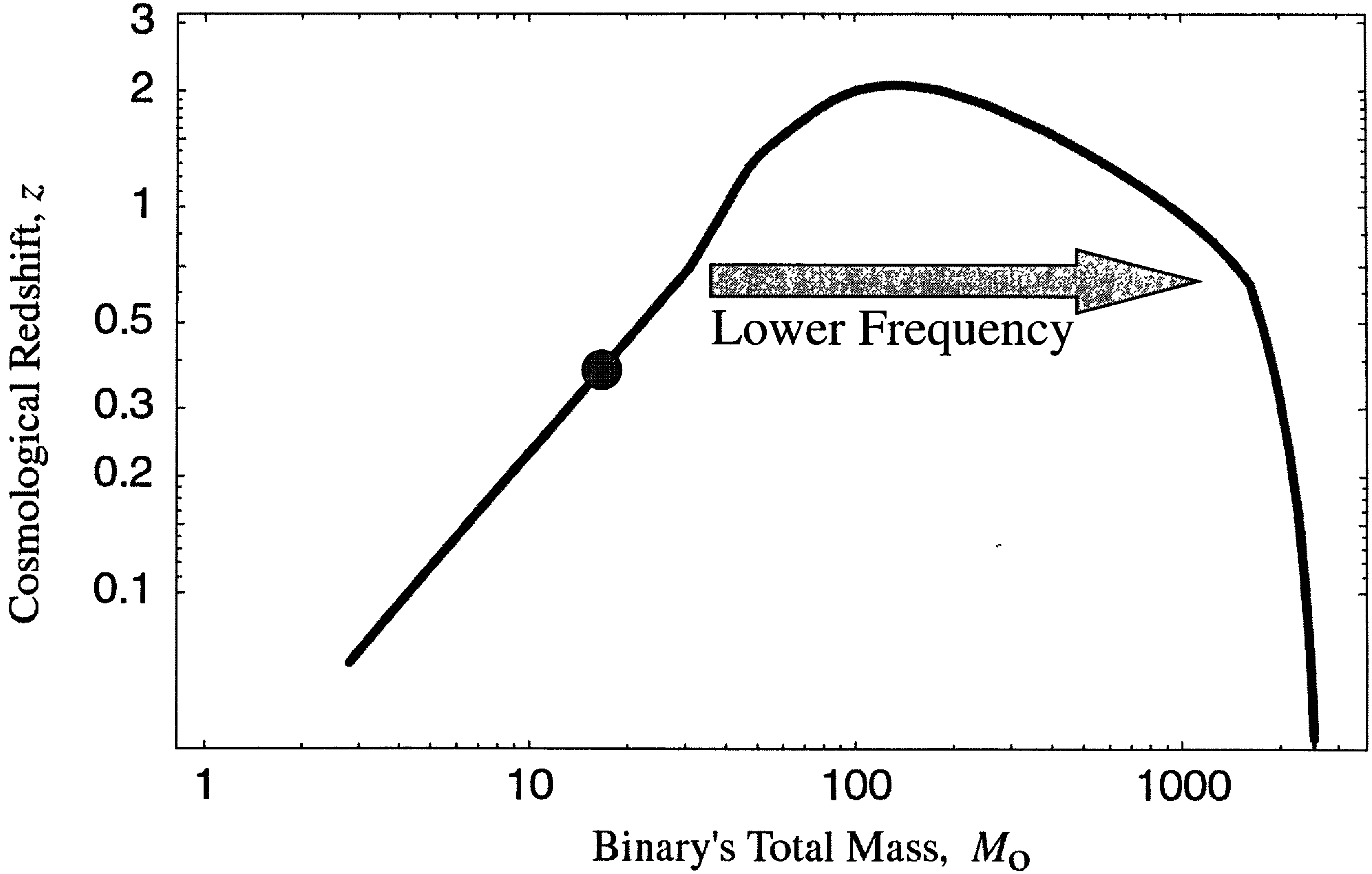


BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



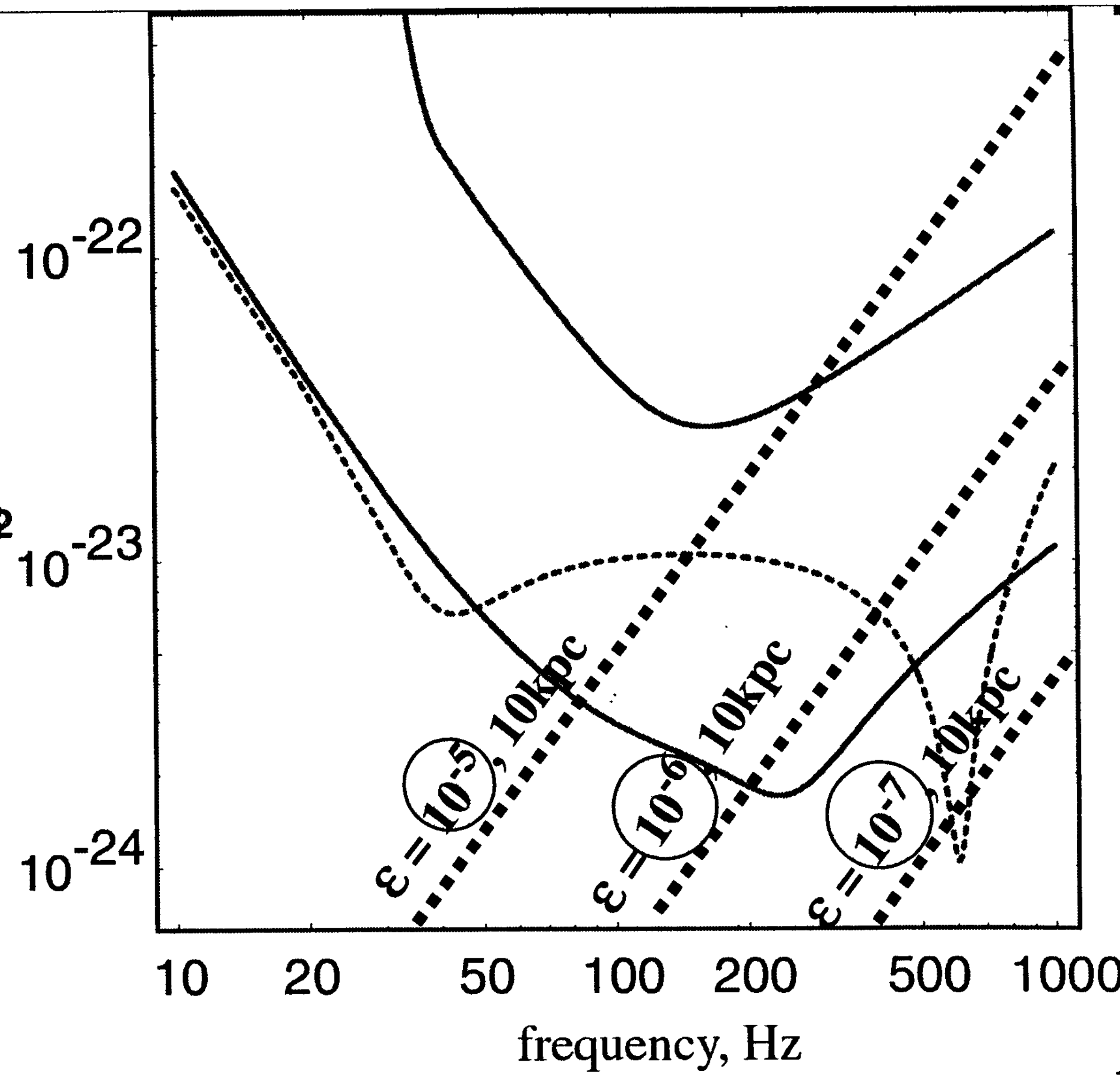
Numerical Relativity Simulations Are Badly Needed!

Massive BH/BH Mergers with Fast Spins



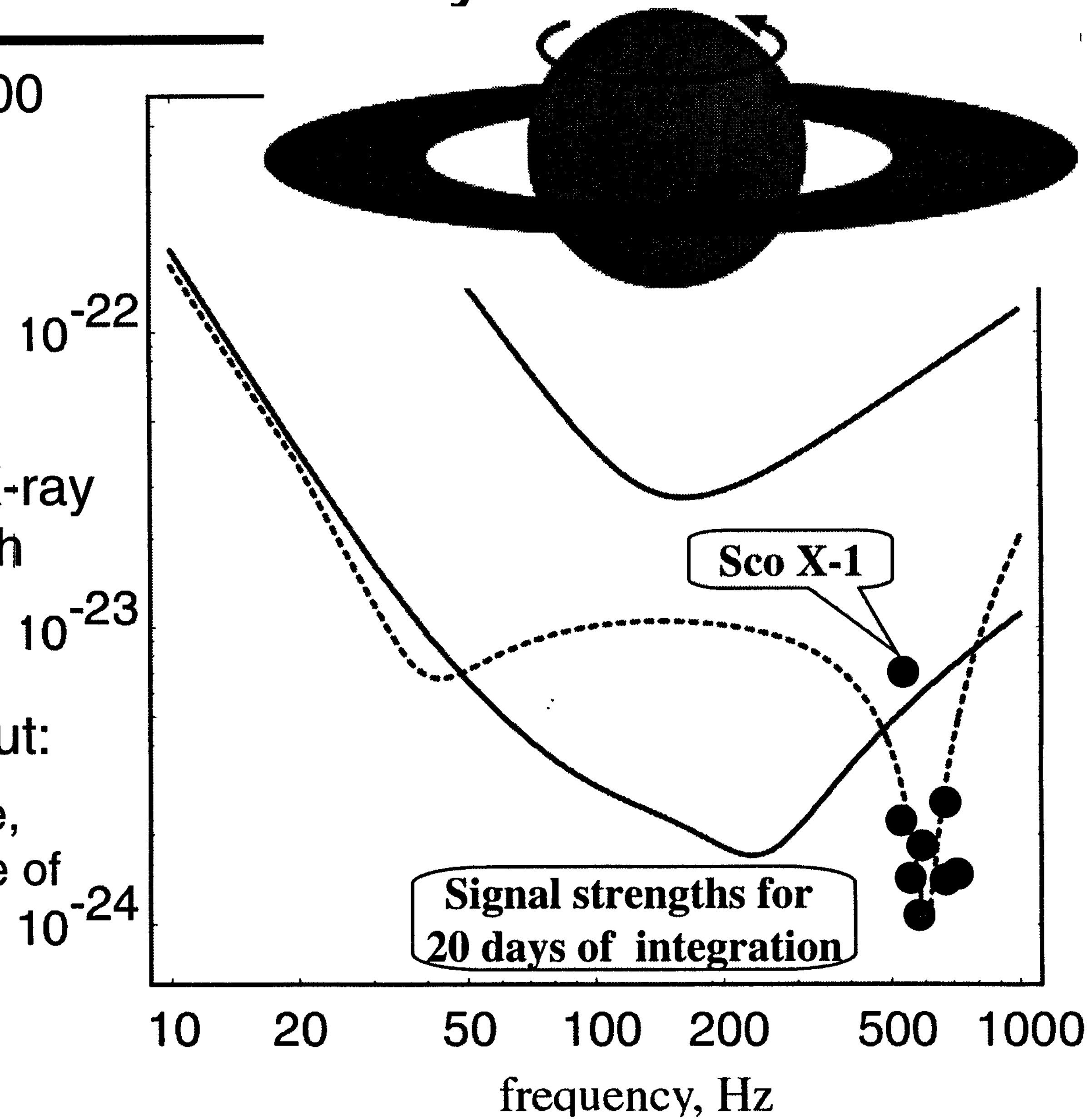
Spinning NS's: Pulsars

- NS Ellipticity:
  - » Crust strength ⇒ $\varepsilon \lesssim 10^{-6}$; possibly 10^{-5}
- Known Pulsars:
  - » Detectable by Narrow-Band IFO if
  - » $\varepsilon \gtrsim 2\times10^{-8}\,(f/1000\mathrm{Hz})^2 \times (\mathrm{distance}/10\mathrm{kpc})$
- Unknown NS's - All sky search:
  - » Sensitivity ~5 to 15 worse



Spinning Neutron Stars: Low-Mass X-Ray Binaries

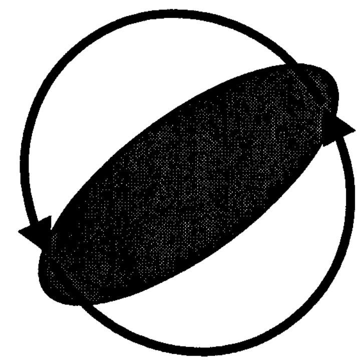
- Rotation rates ~250 to 700 revolutions / sec
  - Why not faster?
  - **Bildsten**: Spin-up torque balanced by GW emission torque
- If so, and steady state: X-ray luminosity ⇒ GW strength
- Combined GW & EM obs's ⇒ information about:
  - crust strength & structure, temperature dependence of viscosity, ...



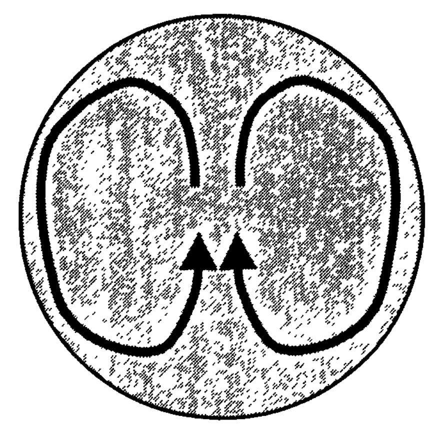
NS Birth: Tumbling Bar; Convection

- **Born in:**
  - » Supernovae
  - » Accretion-Induced Collapse of White Dwarf

- **If very fast spin:**
  - » Centrifugal hangup
  - » **Tumbling bar** - episodic? (for a few sec or min)
  - » Detectable to ~100Mpc ***if modeling has given us enough waveform information***

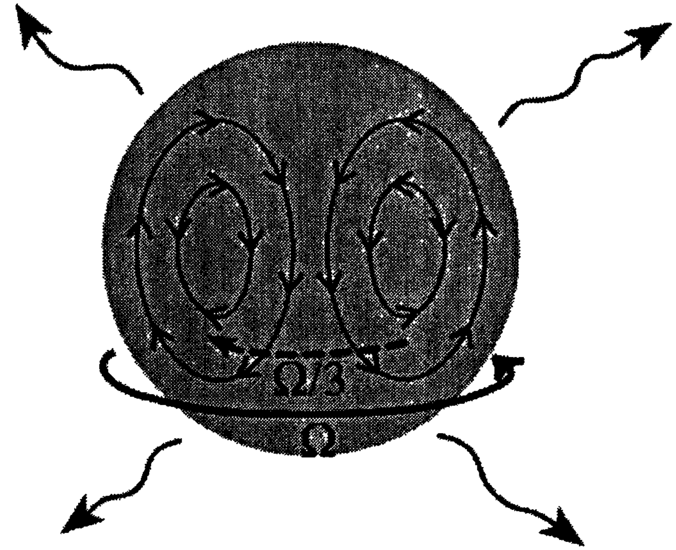


- **If slow spin:**
  - » **Convection** in first ~1 sec.
  - » Detectable only in our Galaxy (~1/30yrs)
  - » GW / neutrino correlations!



Neutron-Star Births: R-Mode Sloshing in First ~1yr of Life

- **NS formed in supernova or accretion-induced collapse of a white dwarf.**
  - » *If* NS born with $P_{\mathbf{spin}}$ < 10 msec: ***R-Mode instability:***
  - » Gravitational radiation reaction drives sloshing



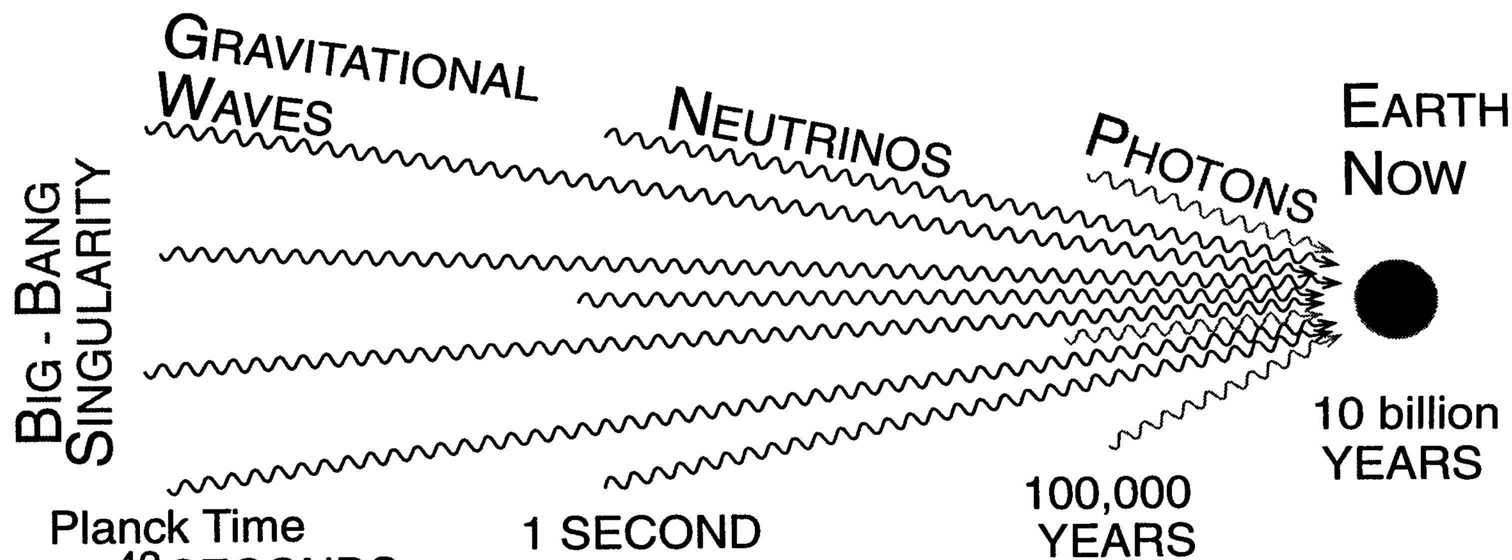
- **Physics complexities: What stops the growth of sloshing & at what amplitude?**
  - » Crust formation in presence of sloshing?
  - » Coupling of R-modes to other modes?
  - » Wave breaking & shock formation?
  - » Magnetic-field torques?
  - » ....

Depending on this, GW's may be detectable in Virgo (supernova rate several per year)

GW's carry information about these

Stochastic Background from Very Early Universe

- **GW's are the ideal tool for probing the very early universe**

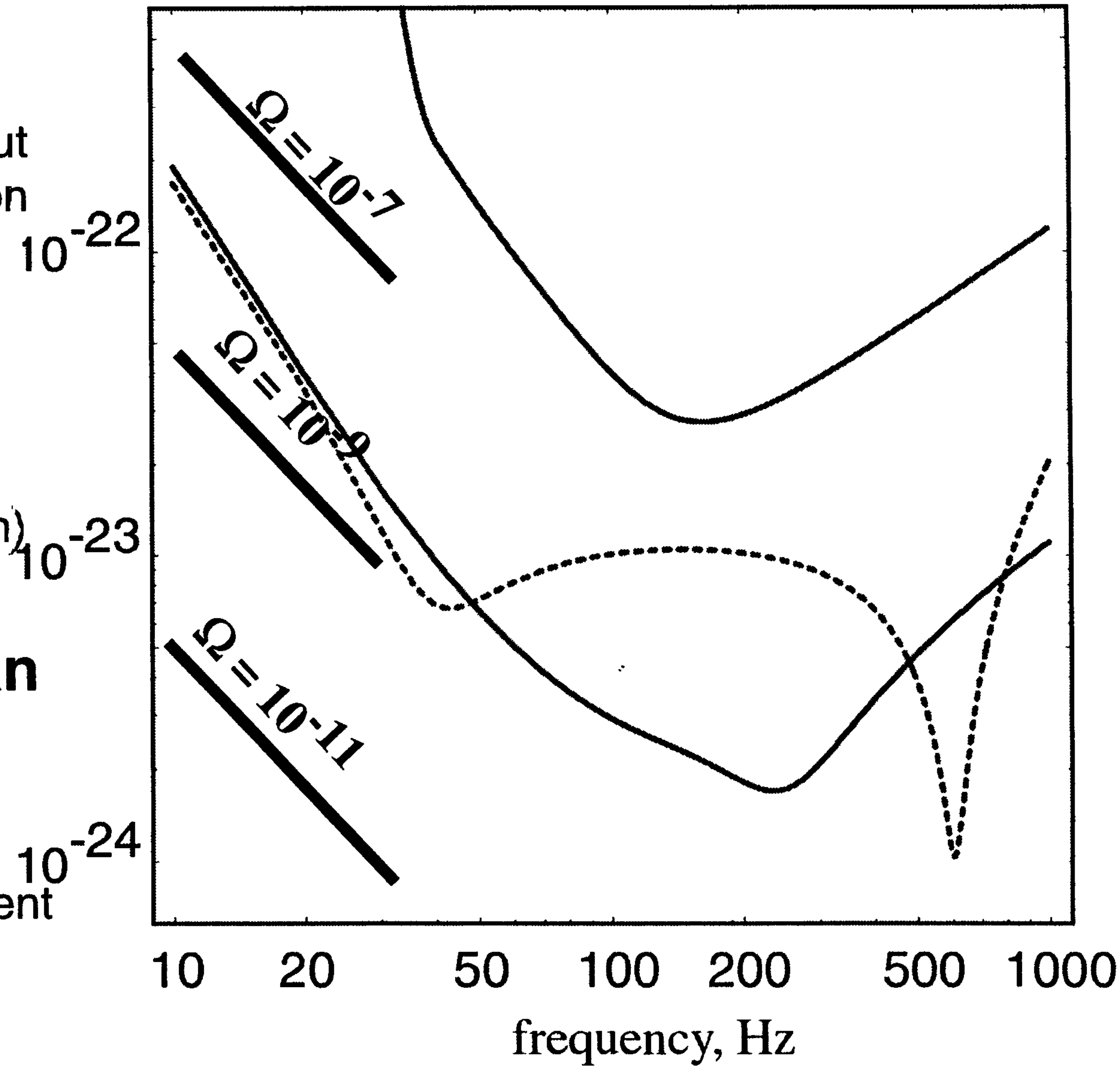


Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe

- **Present limit on GWs**
  - » From effect on primordial nucleosynthesis
  - » $\boxed{\Omega = \text{(GW energy density)/(closure density)} \lesssim \mathbf{10^{-5}}}$

Stochastic Background from Very Early Universe

- **Detect by**
  - » cross correlating output of Hanford & Livingston 4km IFOs
- **Good sensitivity requires**
  - » (GW wavelength) $\gtrsim$ **2x**(detector separation)
  - » f $\lesssim$ 40 Hz
- **Advanced IFOs can detect**
  - » $\boxed{\Omega \gtrsim 5\text{x}10^{-9}}$
  - » much better than current 10^{-5} limit



LIGO Grav'l Waves from Very Early Universe.
Unknown Sources

- Waves from standard inflation: $\sim 10^{-15}$: much too weak
- BUT: Crude string models of big bang suggest waves ***might be strong enough*** for detection by Advanced LIGO
- Energetic processes at (universe age) ~ 10^{-25} sec and (universe temperature) ~ 10^{9} Gev ⇒ GWs in LIGO band
  - » phase transition at 10^{9} Gev
  - » **excitations of our universe as a 3-dimensional "brane" (membrane) in higher dimensions:**
    - **Brane forms wrinkled** 
    - **When wrinkles "come inside the cosmological horizon", they start to oscillate; oscillation energy goes into gravitational waves**
    - **LIGO probes waves from wrinkles of length ~ 10^{-10} to 10^{-13} mm**
- Example of hitherto ***UNKNOWN SOURCE*** ***-- the most interesting and likely kind of source!***

R&D for Advanced LIGO 2002-2006

David Shoemaker & Dennis Coyne

29 January 2001

Overview

- Evolution intrinsic to LIGO mission
- Next step in detector design:
  - » Should be of astrophysical significance if it observes GW signals or if it does not
  - » Should be at the limits of reasonable extrapolations of detector physics and technologies
  - » Should lead to a realizable, practical instrument
- Much effort is inextricably entwined with LSC research
  - » LIGO Lab and other LSC members in close-knit teams
  - » Lab coordinates, provides infrastructure/engineering

Overview

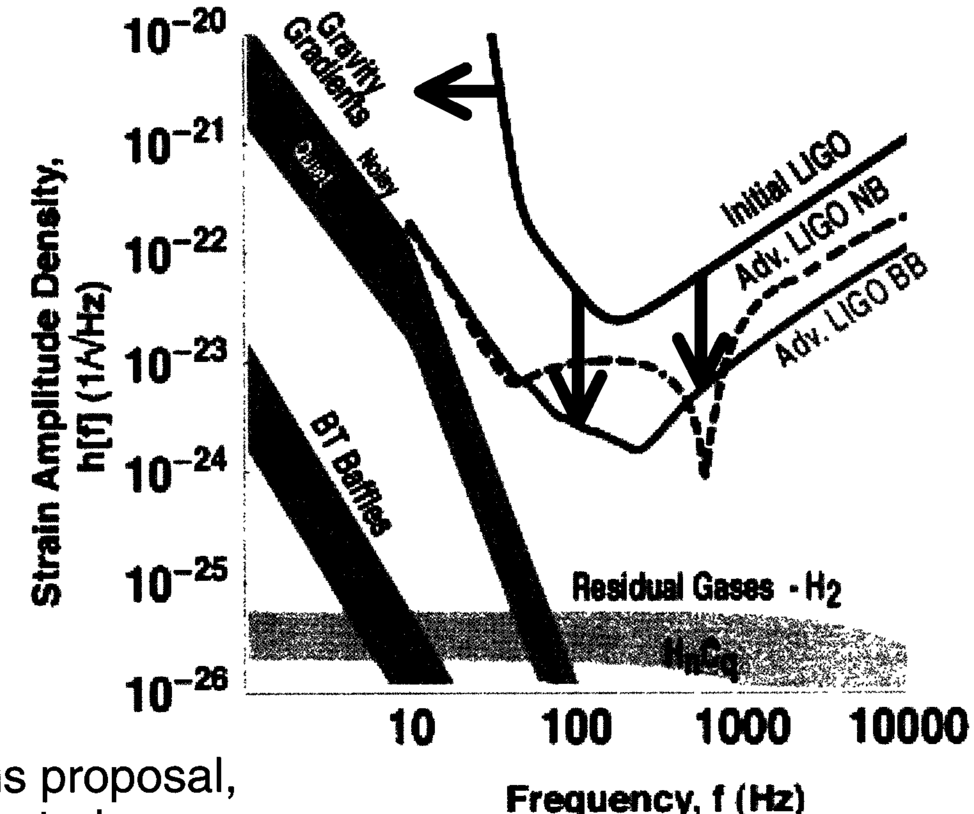
- Talk organization:
  - » Present and future limits to sensitivity; system trades
  - » Introduction to the detector, subsystems, systems issues
  - » Mechanical aspects of design: Isolation, Suspension, Thermal noise, and system tests
  - » Optics: Laser, Test Masses, Input Optics, Auxiliary Optics
  - » Sensing and control: Design and prototype tests
- Detailed technical, schedule, and budget information available

Choosing an upgrade path

- Wish to maximize astrophysics to be gained
  - » Must fully exploit initial LIGO
  - » Any change in instrument leads to lost observing time at an Observatory
  - » Studies based on LIGO I installation and commissioning indicate 1-1.5 years between decommissioning one instrument and starting observation with the next
  - » → Want to make one significant change, not many small changes
- Technical opportunities and challenges
  - » Can profit from evolution of detector technologies since initial LIGO design 'frozen'
  - » 'Fundamental' limits: quantum noise, thermal noise provide point of diminishing returns (for now!)

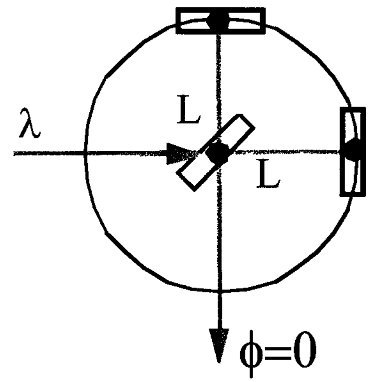
Present and future limits to sensitivity

- Advanced LIGO
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
- Facility limits
  - » Gravity gradients
  - » Residual gas
  - » (scattered light)
- Beyond Adv LIGO
  - » Thermal noise: cooling of test masses
  - » Quantum noise: quantum non-demolition
  - » Not the central focus of this proposal, but exploration must be started now

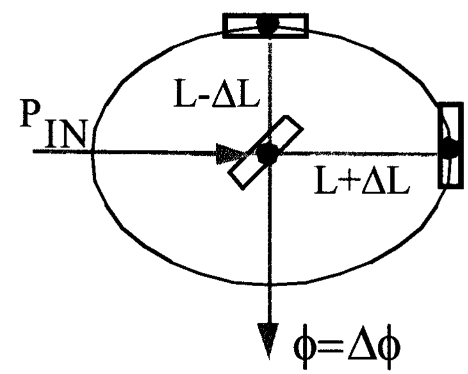


Introduction to the detector

- Michelson as strain sensor
- Sensitive to differential strains
- Insensitive to common-mode motion
- Signal proportional to
  - » length (in short-wavelength limit, true for 4km and kHz)
  - » laser power (shot noise grows as square root, so overall gain as square root of laser power)
- Mechanical isolation needed from external forces
- Stochastic forces due to Thermal noise present (equilibrium with heat bath)
- Fluctuations in light path due to gas also a limit (index fluctuations)

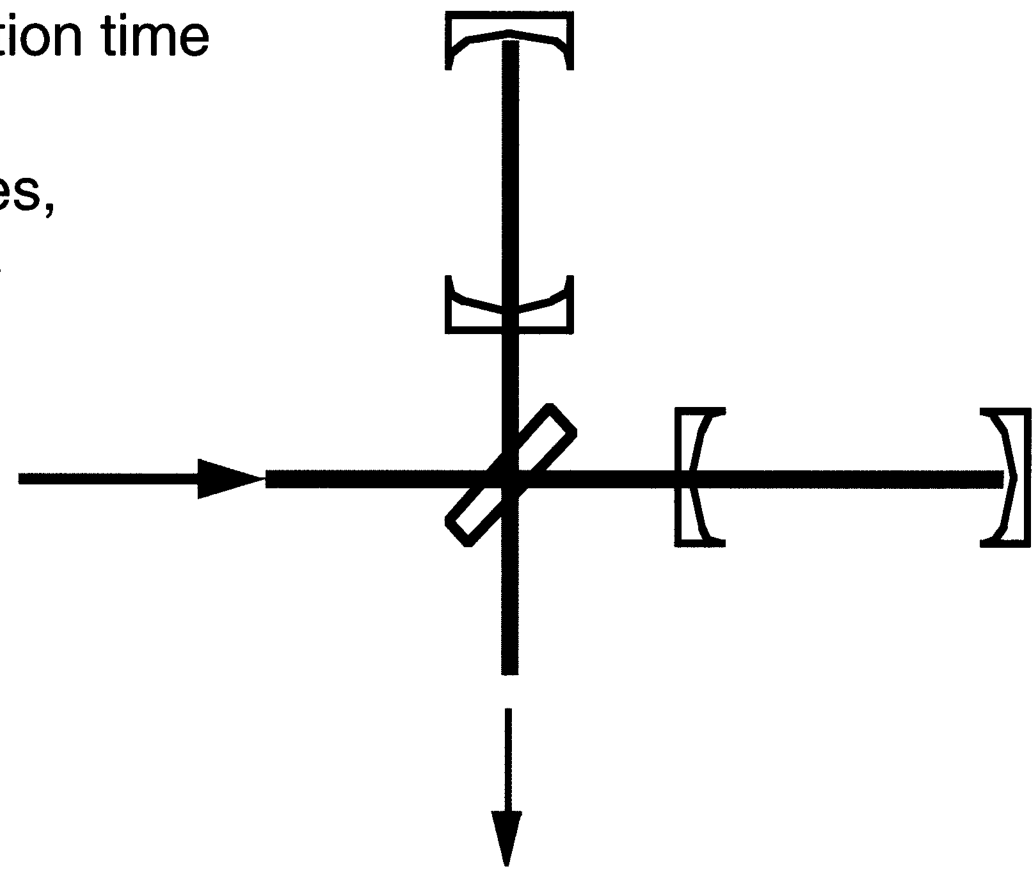


$$\boxed{\Delta L = h\,L}$$



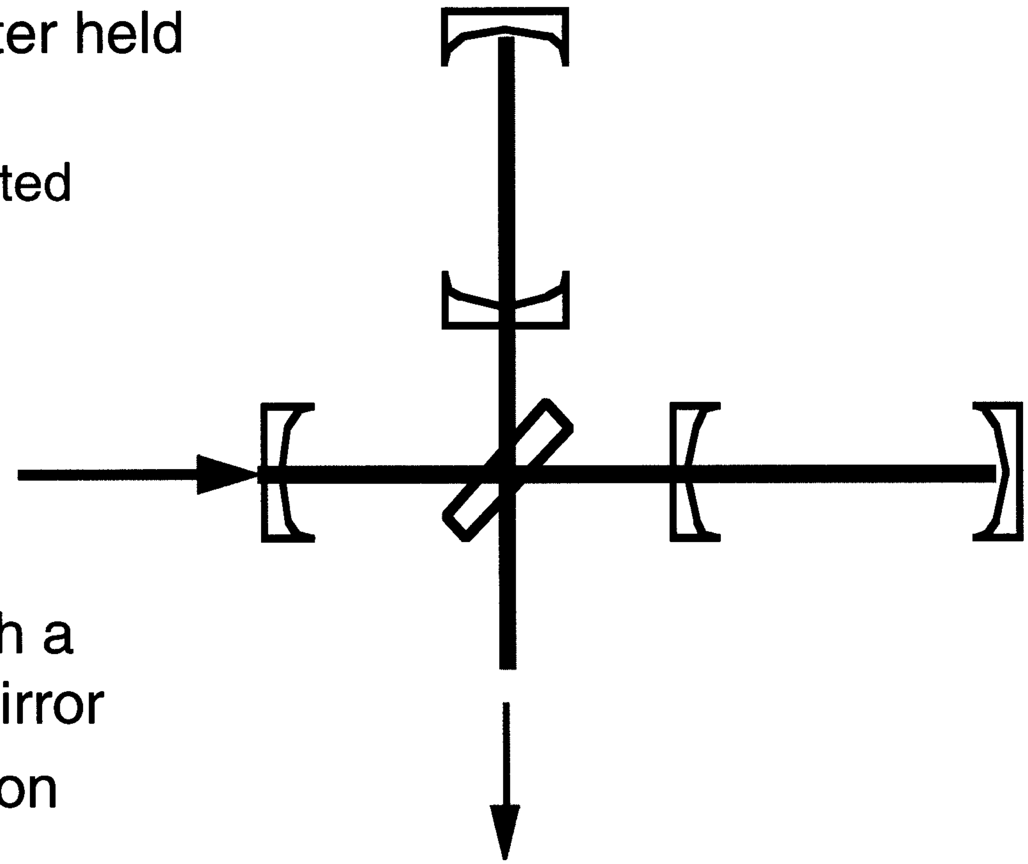
Increasing the interaction time

- Alternative to longer arms
- Increase in the interaction time of strain with light
- Multi-bounce delay lines, or Fabry-Perot cavities



Increasing the circulating power

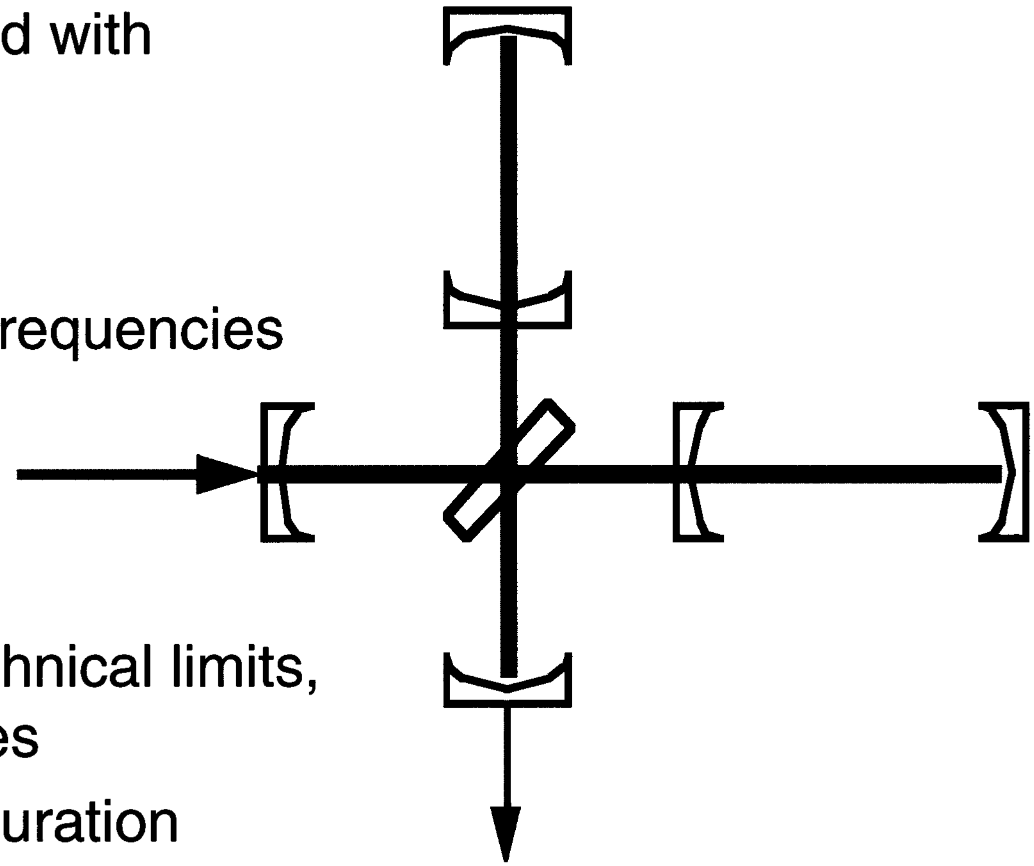
- Introduction of Power Recycling
- Michelson interferometer held at 'dark fringe'
  » Most input light reflected back to laser



- 'Impedance match' with a partially transmitting mirror
- Initial LIGO configuration

Tailoring the frequency response

- Signal Recycling
- Additional cavity formed with mirror at output
- Can be resonant, or anti-resonant, for gravitational wave frequencies

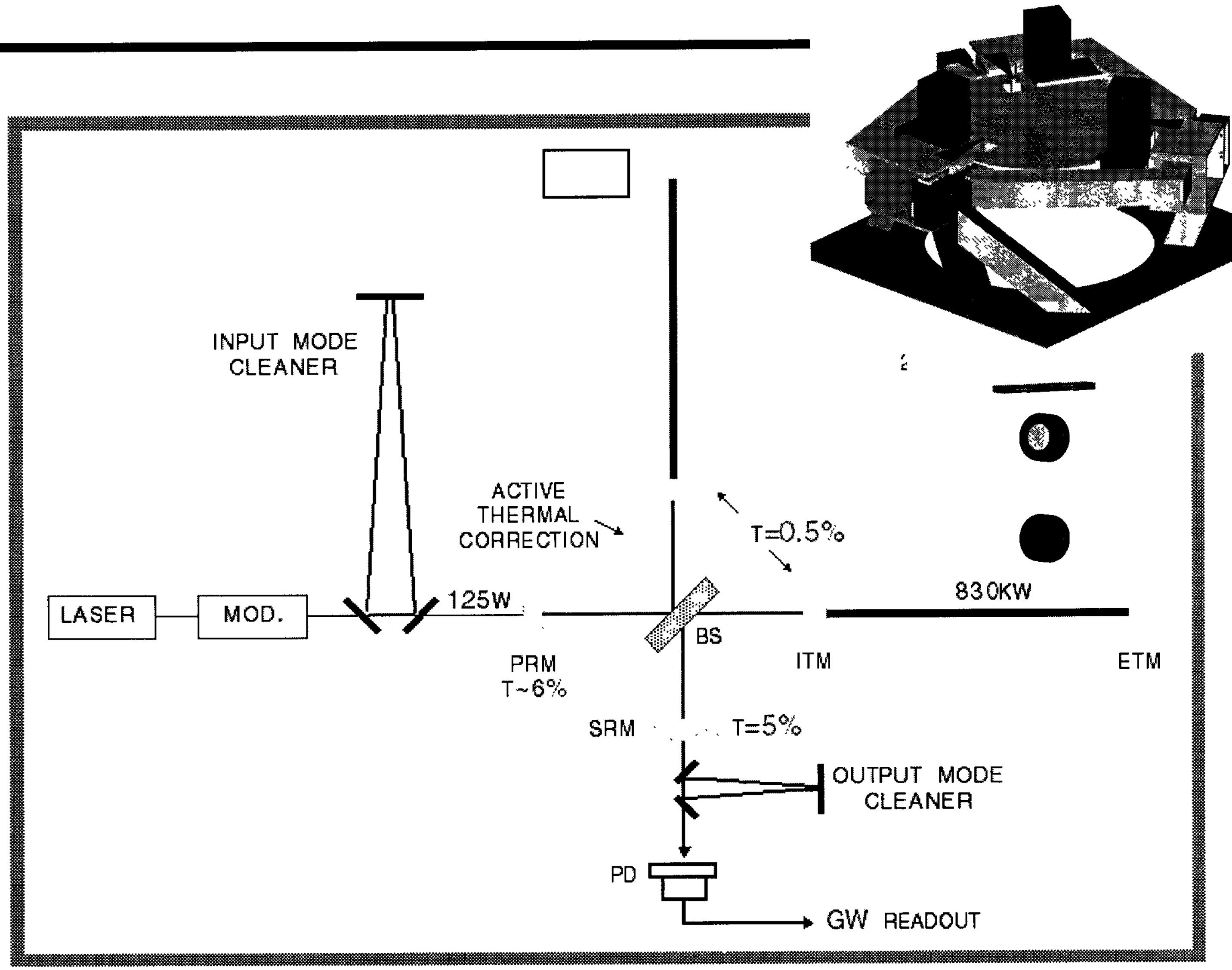


- Allows optimum for technical limits, astrophysical signatures
- Advanced LIGO configuration

Interferometer subsystems

Subsystem	Function	Implementation	Principal challenges
Interferometer Sensing and Control (ISC)	Gravitational Readout; length and angle control of optics	RF modulation/demod techniques, digital real-time control	Lock acquisition, S/N and bandwidth trades
Seismic Isolation (SEI)	Attenuation of environmental forces on test masses	Low-noise sensors, high-gain servo systems	Reduction of test mass velocity due to 0.01-1 Hz input motion
Suspension (SUS)	Establishing 'Free Mass', actuators, seismic isolation	Silica fibers to hold test mass, multiple pendulums	Preserving material thermal noise performance
Pre-stabilized Laser (PSL)	Light for quantum sensing system	Nd:YAG laser, 100-200 W; servo controls	Intensity stabilization: 3e-9 at 10 Hz
Input Optics (IOS)	Spatial stabilization, frequency stabilization	Triangular Fabry-Perot cavity, suspended mirrors	EO modulators, isolators to handle power
Core Optics Components (COC)	Mechanical test mass; Fabry-Perot mirror	40 kg monolithic sapphire (or silica) cylinder, polished and coated	Delivering optical and mechanical promise; Developing sapphire
Auxiliary Optics (AOS)	Couple light out of the interferometer; baffles	Low-aberration telescopes	Thermal lensing compensation

Interferometer subsystems

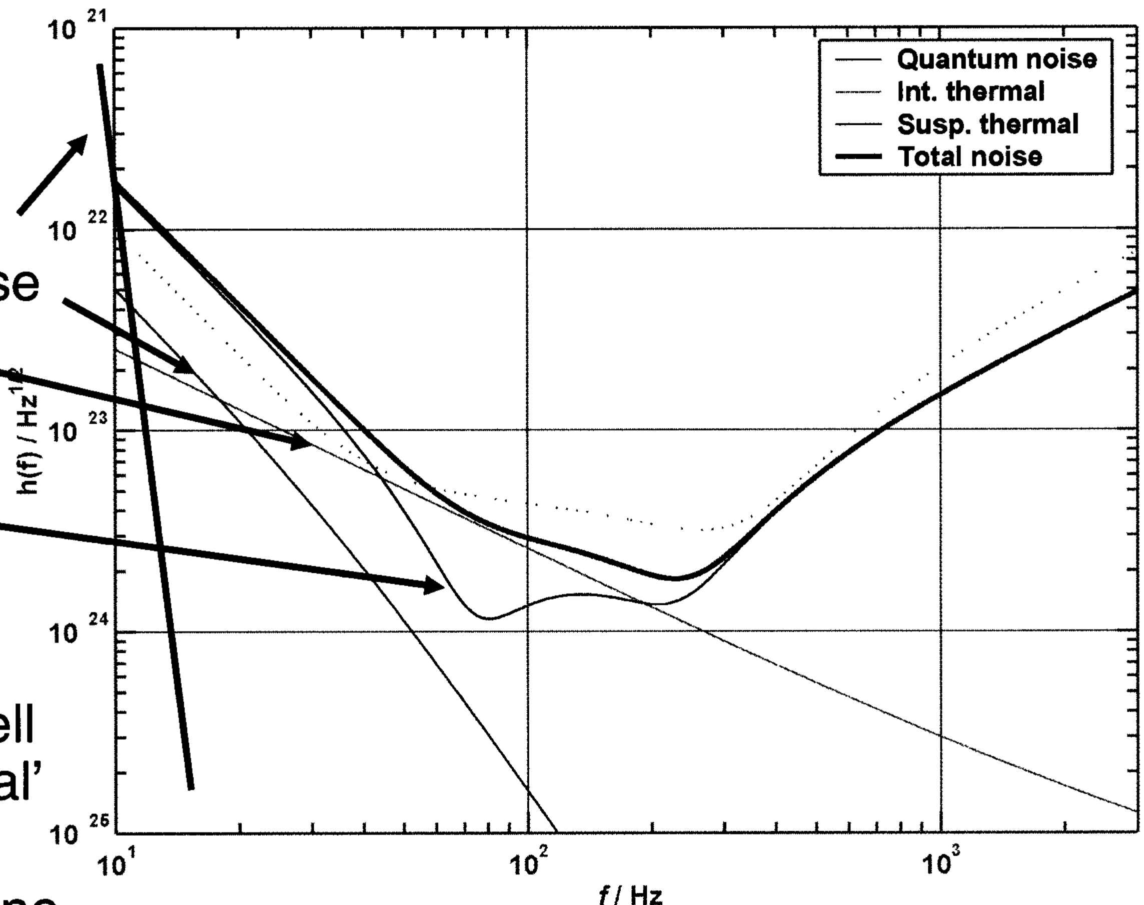


System trades

- Laser power
  - » Trade between improved readout resolution, and momentum transfer from photons to test masses
  - » Distribution of power in interferometer: optimize for material and coating absorption, ability to compensate
- Test mass material
  - » Sapphire: better performance, but development program, crystalline nature
  - » Fused silica: familiar, but large, expensive, poorer performance
- Lower frequency cutoff
  - » 'Firm', likely, and possible astrophysics
  - » Technology thresholds in isolation and suspension design

Anatomy of the projected detector performance

- Sapphire test mass baseline system
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises
- Silica test mass dotted line



Nominal top level parameters

	Sapphire	Fused Silica
Fabry-Perot arm length	4000 m	
Laser wavelength	1064 nm	
Optical power at interferometer input	125 W	80 W
Power recycling factor	17	17
FP Input mirror transmission	0.5%	0.50%
Arm cavity power	830 kW	530 kW
Power on beamsplitter	2.1 kW	1.35 kW
Signal recycling mirror transmission	6.0%	6.0%
Signal recycling mirror tuning phase	0.12 rad	0.09 rad
Test Mass mass	40 kg	30 kg
Test Mass diameter	32 cm	35 cm
Beam radius on test masses	6 cm	6 cm
Neutron star binary inspiral range (Bench)	300 Mpc	250 Mpc
Stochastic GW sensitivity (Bench units)	8 x 10-9	6 x 10-9

LIGO

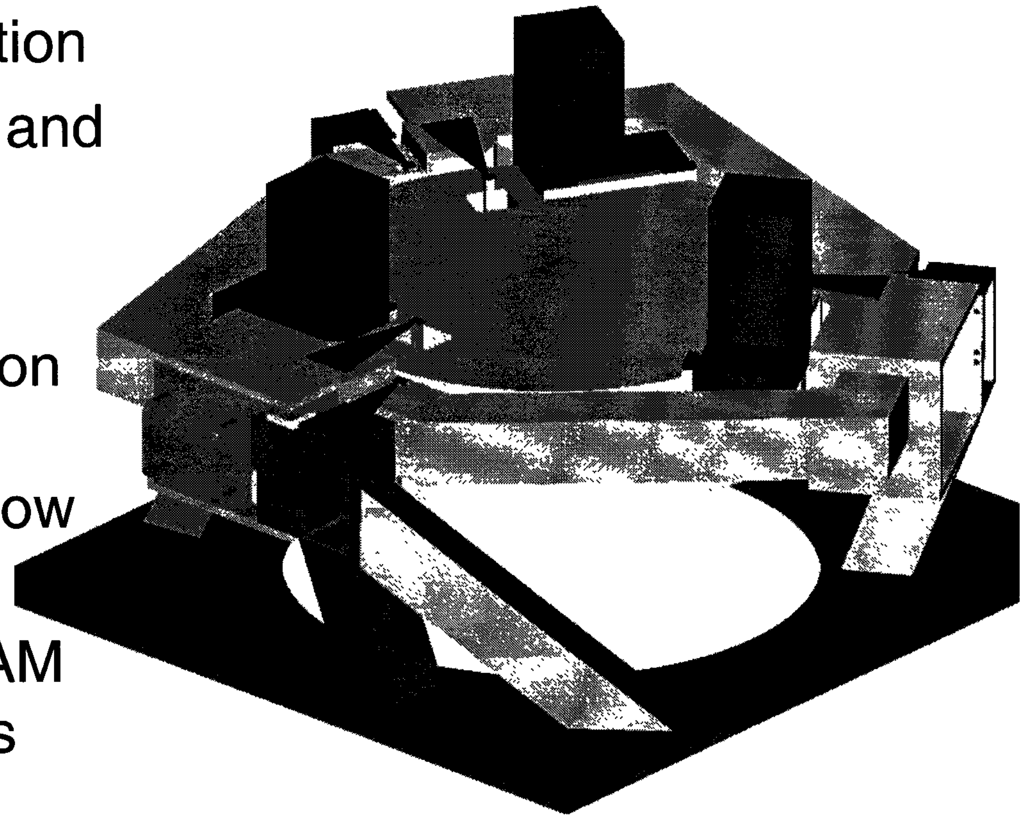
Active Seismic Isolation R&D (SEI): Requirements

- Goal: render seismic noise a negligible limitation to GW searches
  - » Other 'irreducible' noise sources limit sensitivity to uninteresting level for frequencies less than ~20 Hz
  - » Suspension and isolation contribute to attenuation
  - » Choose to require a 10 Hz 'brick wall'
- Goal: reduce or eliminate actuation on test masses
  - » Actuation source of direct noise, also increases thermal noise
  - » Seismic isolation system can reduce RMS/velocity through inertial sensing, and feedback
  - » Acquisition challenge greatly reduced
  - » Choose to require RMS of <10^-11 m

LIGO

SEI: Conceptual Design

- Two in-vacuum stages in series, external slow correction
- Each stage carries sensors and actuators for 6 DOF
- Stage resonances ~5 Hz
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies
- Similar designs for BSC, HAM vacuum chambers; provides optical table for flexibility



SEI: Organization

- Initial work done by teams at Caltech, MIT, Stanford, LSU, JILA – significant input from LSC teams, suspension working group
- Strategic organization by Lab of continued development at LLO, with continued LSC scientific leadership (Giaime/LSU)
- Engineering effort and prototype fabrication managed by LLO (Stapfer)
- Next prototype to be installed and tested in Stanford ETF (Lantz)
- Installation and test at MIT LASTI to be performed by development team of engineers/scientists, plus MIT LASTI staff

SEI: Progress and Plans

- Parallel design effort on passive, active systems
  - ✓ 4Q99: Draft requirements and interface established
  - ✓ 2Q00: SAS reference design, prototype tests
  - ✓ 2Q00: Active reference design, prototype tests
  - ✓ 2Q00: Choice of design to pursue
- Prototyping and test of active systems
  - ✓ 3Q00: All 12 DOF active system locked
  - ✓ 4Q00: initial design and demonstrator bid package ready
  - » 4Q01: demonstrator test complete (at Stanford)
  - » 3Q02: HAM prototype standalone testing completed (MIT LASTI)
  - » 1Q03: BSC prototype standalone testing completed (MIT LASTI)

SEI: Manpower and equipment

FY02

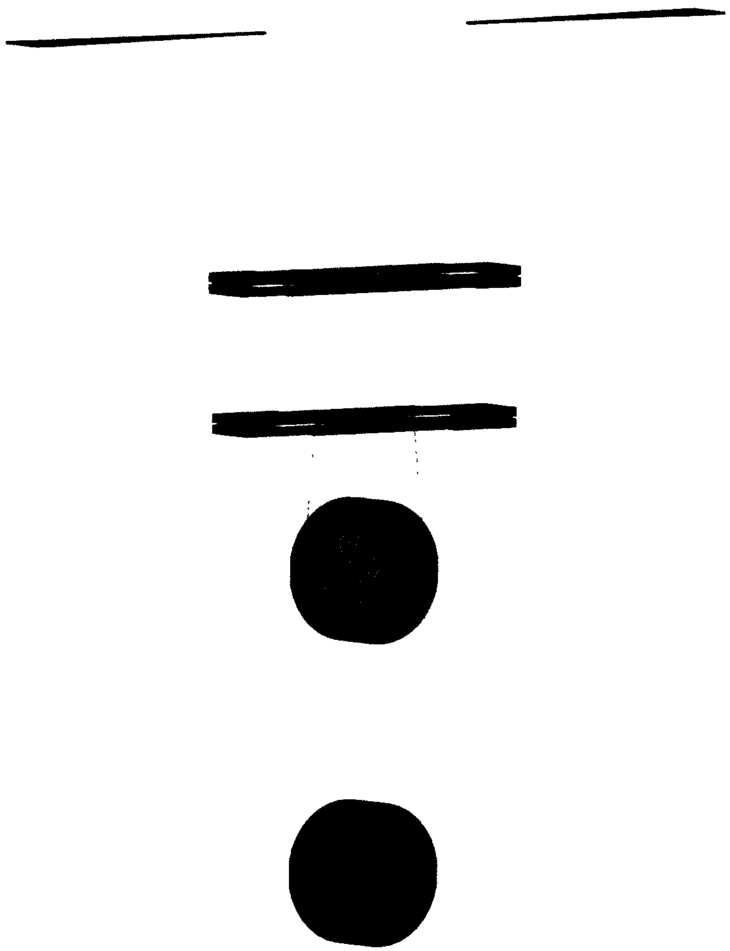
Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE)	
Active Seismic Isolation (SEI)						
Gerry Stapfer	LLO			0.5	0.5	
Joe Giaime	LSU					
Sci & PD	MIT				0	0.5
	CIT	0.5			0.5	
UG & Grads	MIT				0	0
	CIT				0	
Eng & Techs	MIT				0	5
	CIT			0.5	0.5	
	LLO			4	4	
Totals (FTE):		0.5	0	5	5.5	
Equip. & Supplies ($K)		$0	$845	$0	$845	

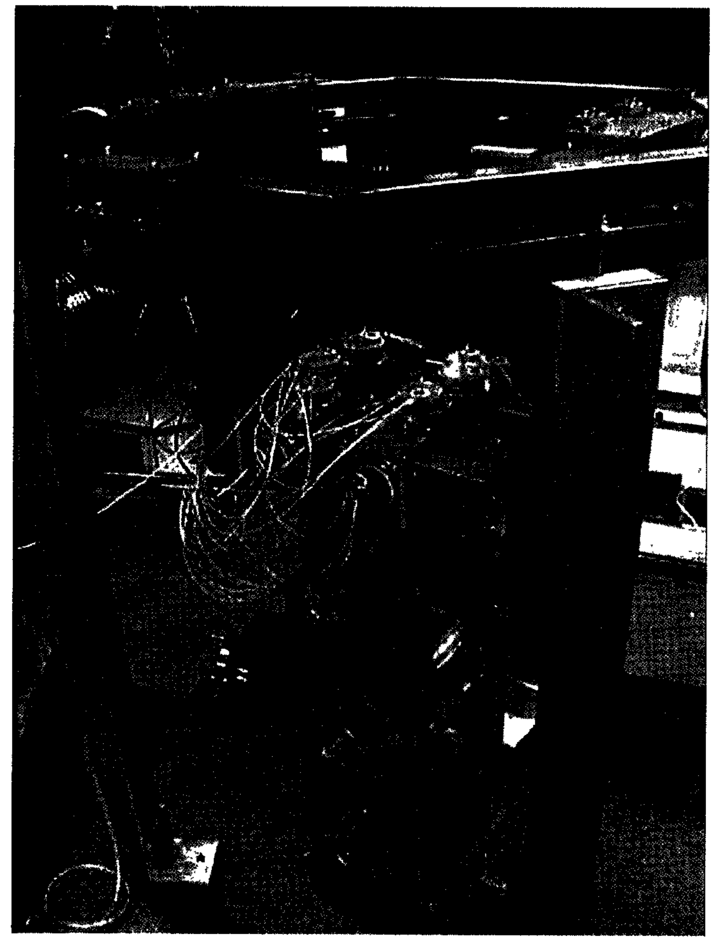
N.B.: Does not include LSC research staff.

Suspension Research (SUS)

- Adopting a multiple-pendulum approach
  - » Allows best thermal noise performance of suspension and test mass; replacement of steel suspension wires with fused silica
  - » Offers seismic isolation, hierarchy of position and angle actuation
- Close collaboration with GEO (German/UK) GW group
  - » Similar design used in GEO-600, being installed now
  - » GEO takes responsibility for initial design
  - » LIGO takes over design as we deal with fabrication/installation issues
- Schedule highlights:
  - » 2Q01: Install first fused silica GEO-600 suspension
  - » 2Q02: Controls prototypes complete, in testing
  - » 2Q03: Noise prototypes complete, in testing

GEO suspension

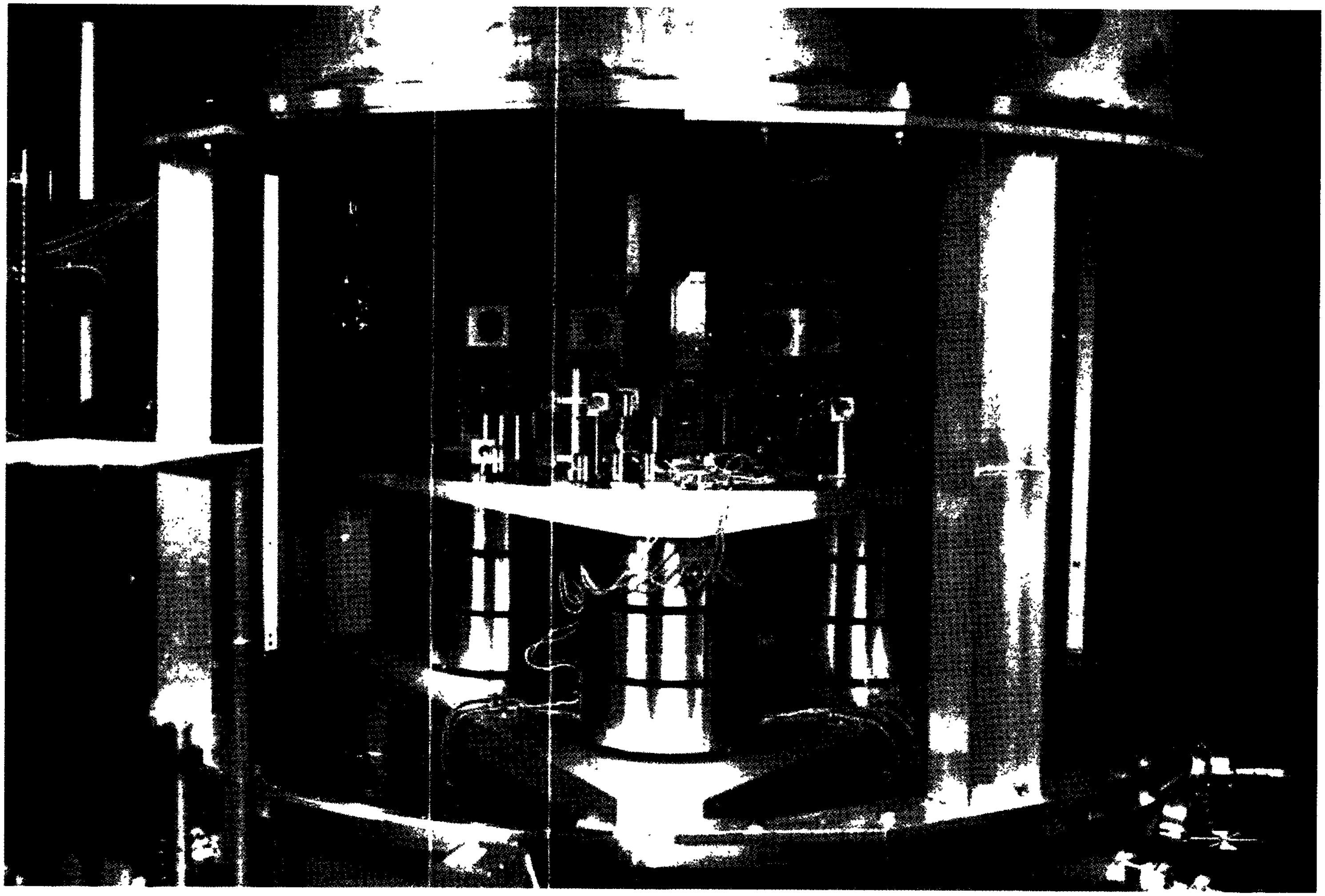




Thermal Noise Interferometer (TNI)

- Direct measurement of thermal noise, at LIGO Caltech
  - » Test of models, materials parameters
  - » Search for excesses (non-stationary?) above anticipated noise floor
- In-vacuum suspended mirror prototype, specialized to task
  - » Optics on common isolated table, ~1cm arm lengths
- Schedule highlights:
  - ✓ 4Q00: TNI cavity locks
  - » 2Q01: TNI studies for initial LIGO completed
  - » 2Q02: Sapphire substrates installed
  - » 1Q03: TNI final Sapphire/fused silica results

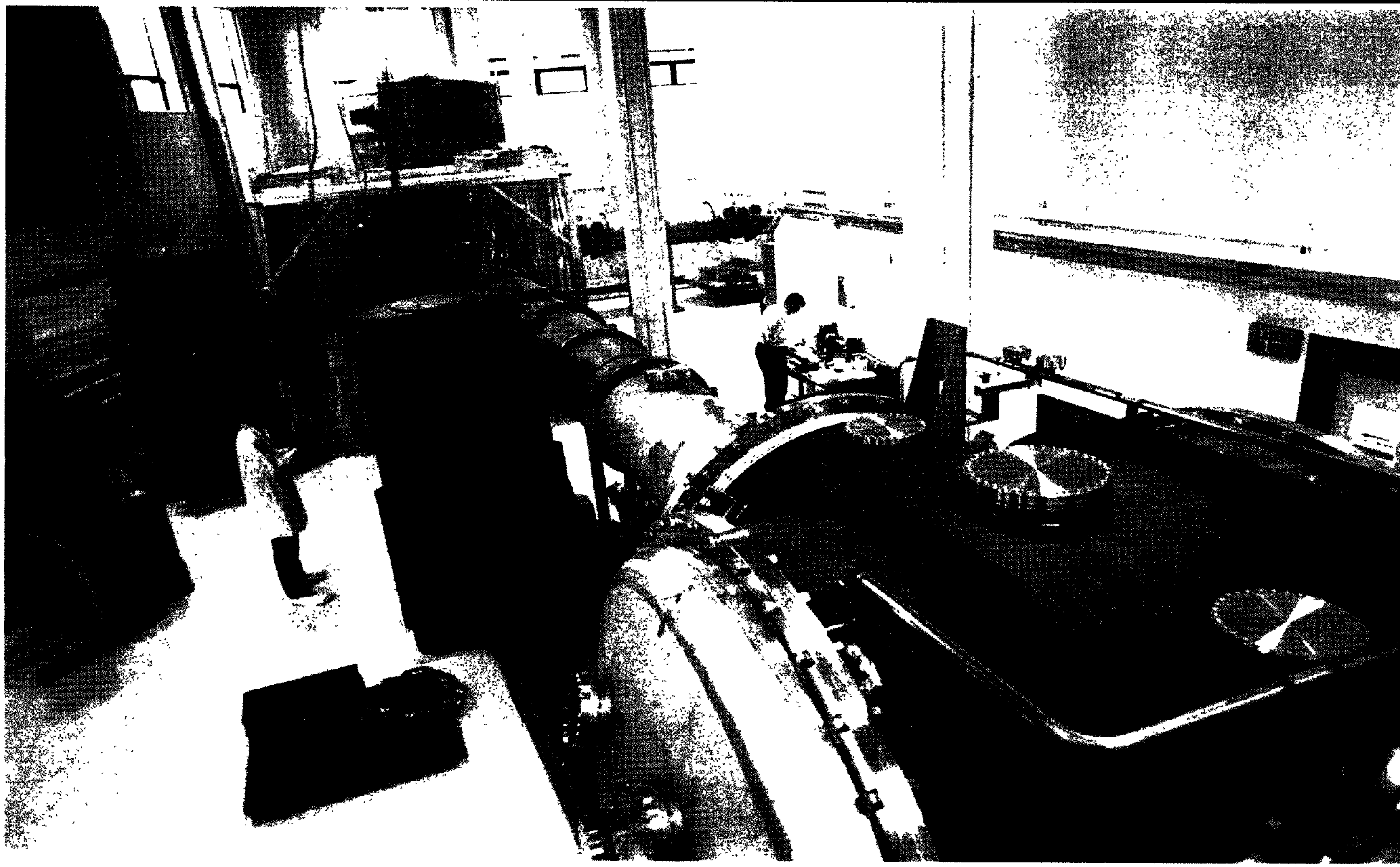
Thermal Noise Interferometer



Stochastic noise system tests: LASTI

- Full-scale tests of Seismic Isolation and Test Mass Suspension.
  - » Takes place in the LIGO Advanced System Test Interferometer (LASTI) at MIT: LIGO-like vacuum system.
  - » Allows system testing, interfaces, installation practice.
  - » Characterization of non-stationary noise, thermal noise.
- Subsystem support to LASTI system tests.
  - » teams learn how their system works, installs, etc.
  - » MIT support of infrastructure, and collaborative shakedown and test.
- Schedule highlights:
  - ✓ 4Q00: Vacuum system qualified, seismic supports in place.
  - » 4Q01: ‘infrastructure’ Laser, test cavity, DAQ, etc. tested.
  - » 3Q02: HAM isolation testing completed.
  - » 2Q03: Suspension noise prototypes installed.
  - » 2Q04: integrated Isolation/suspension testing completed.
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed.

LASTI Laboratory



Isolation Research
(STO, SUS, TNI, SEI)

FY02

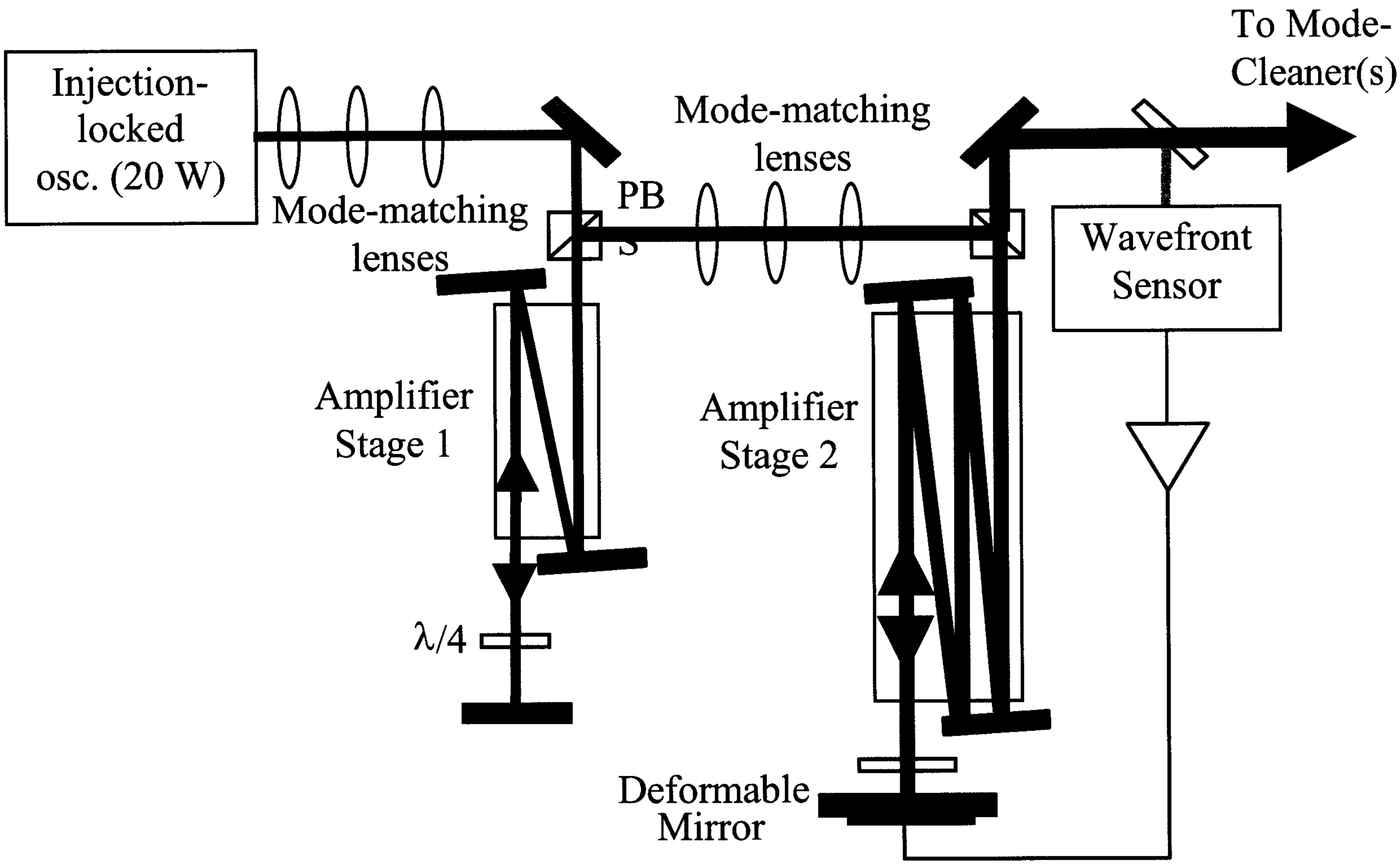
Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
ISOLATI[illegible]						
Sci & PD	MIT	1	0	2.4	3.4	8.1
	CIT	3	0	1.7	4.7	
UG & Grads	MIT	3	0	0.0	3.0	5.0
	CIT	2	0	0.0	2.0	
Eng & Techs	MIT	0	0	2.8	2.8	14.2
	CIT	0	0	6.9	6.9	
	LLO	0	0	4.5	4.5	
Totals (FTE):		9	0	18.3	**27.3**	
Equip. & Supplies		$54	$1,595	0.0	**$1,649**	

N.B.: Does not include LSC research staff.

Advanced Laser R&D (LAS)

- Require optimal power, given fundamental and practical constraints:
  - » Shot noise: having more stored photons improves sensitivity, but:
  - » Radiation pressure: dominates at low frequencies
  - » Thermal focussing in substrates: limits usable power
- Optimum depends on test mass material, 80 – 180 W
- Power amplifier or injection-locked topology in trade study
- Laser Zentrum Hannover/GEO to take lead; LIGO Lab supplies requirements, interface, and test
- Schedule highlights:
  - » 4Q01: laser diode tests done / selection
  - » 1Q02: 100 W demonstration
  - » 2Q02: Laser concept downselect
  - » 2Q04: Install advanced LIGO PSL in the LASTI facility

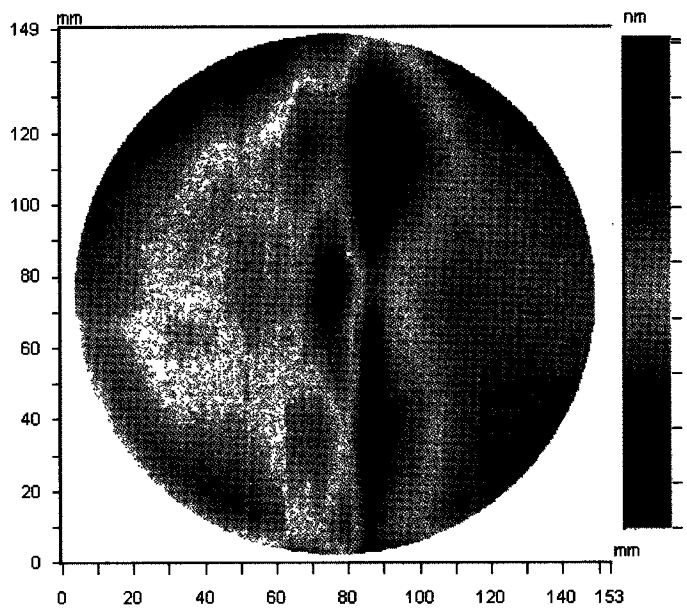
Advanced Laser – One Concept



Advanced Core Optics R&D (OPT)

- A key optical and mechanical element of design
  - » Substrate absorption, homogeneity, birefringence
  - » Ability to polish, coat
  - » Mechanical (thermal noise) performance, suspension design
  - » Mass – to limit radiation pressure noise: ~30-40 Kg required
- Two materials under study, both with real potential
  - » Fused Silica: very expensive, very large, satisfactory performance; familiar, non-crystalline
  - » Sapphire: requires development in size, homogeneity, absorption; high density (small size), lower thermal noise
- Caltech LIGO Lab leads effort, strong LSC input on materials/tests
- Schedule highlights:
  - ✓ 3Q00: m-axis birefringence measured
  - ✓ 3Q00: Initial sapphire refraction index homogeneity measurement
  - » 4Q01: Order LASTI SUS prototype sapphire & fused silica blanks
  - » 2Q02: Selection of test mass material
  - » 3Q03: Dedicated coating chamber installed and commissioned

Sapphire substrate homogeneity



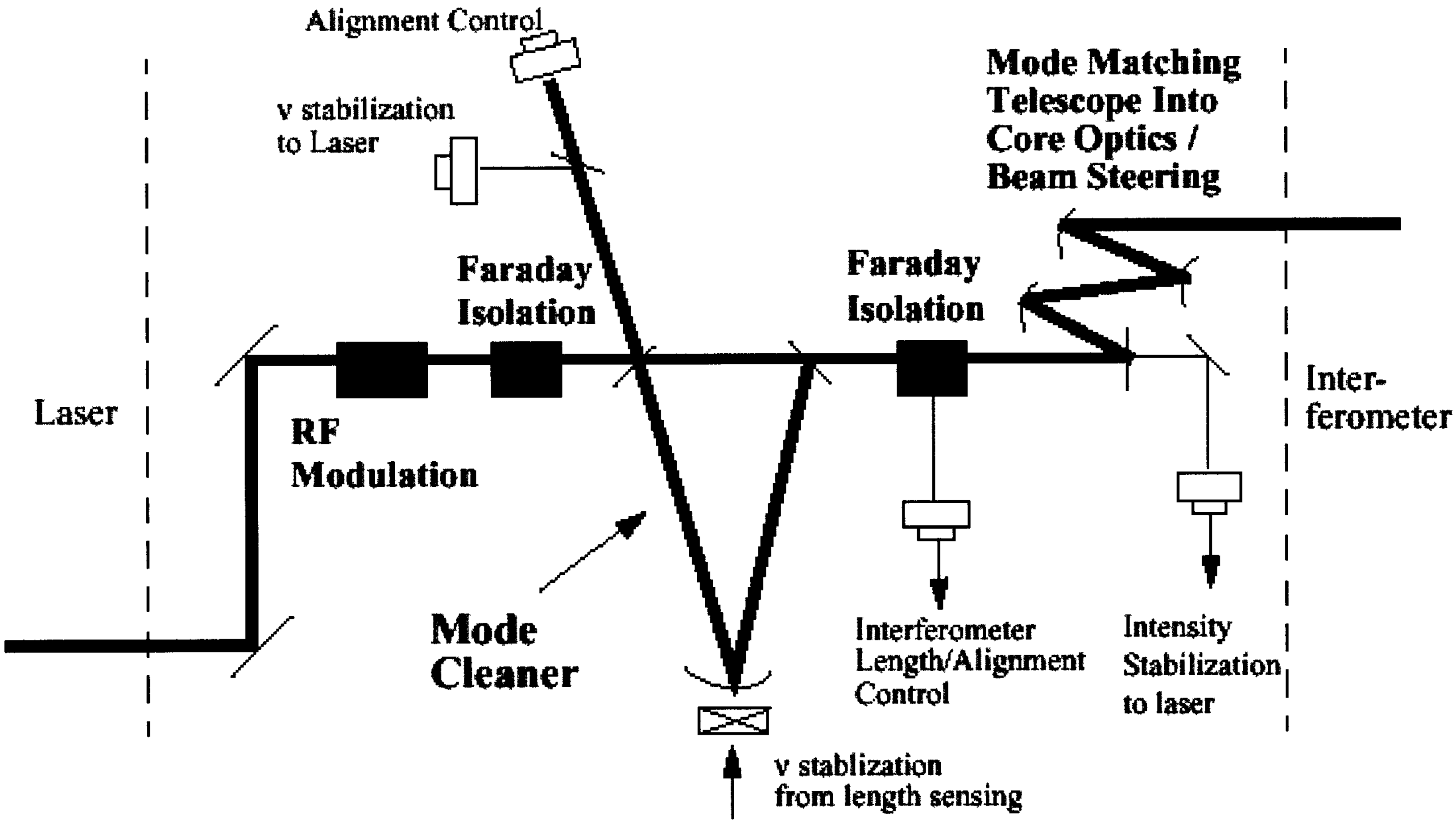
Date 11/08/2000	X Center 287.00	
Time: 13 14.17	Y Center: 240.00	
Wavelength: 1.064 um	Radius: 274 00 pix	
Pupil: 100 0 %	Terms: Tilt	
PV: 444.0355 nm	Filters: None	
RMS: 65.7678 nm	Masks Detector Mask	
Rad of curv: 28.13 km	Ref Sub No	Averages: 8

- CIT measurement of a 25 cm m-axis sapphire substrate, showing the central 150mm.
- The piece is probed with a polarized beam. The structure is related to small local changes in the crystalline axis.
- Plan to apply a compensating polish to side 2 of this piece and reduce the rms variation in bulk homogeneity to roughly 10-20 nm rms

Input Optics System R&D (IOS)

- Subsystem interfaces laser light to main interferometer
  - » Modulation sidebands applied for sensing system
  - » Beam cleaned and stabilized by transmission though cavity
  - » Precision mode matching from ~0.5 cm to ~10 cm beam
- Challenges in handling high power
  - » isolators, modulators
  - » Mirror mass and intensity stabilization (technical radiation pressure)
- University of Florida takes lead, GEO suspensions, LIGO controls
- Schedule highlights:
  - ✓ 3Q00: Isolator demonstrated: >35 dB @ 50 W
  - » 2Q02: Demonstration of prototype phase modulation method
  - » 4Q02: Thermal lensing compensation results, optical layout chosen
  - » 1Q04: Install advanced LIGO IO components at LASTI
  - » 1Q05: PSL-Mode Cleaner integrated performance test completed

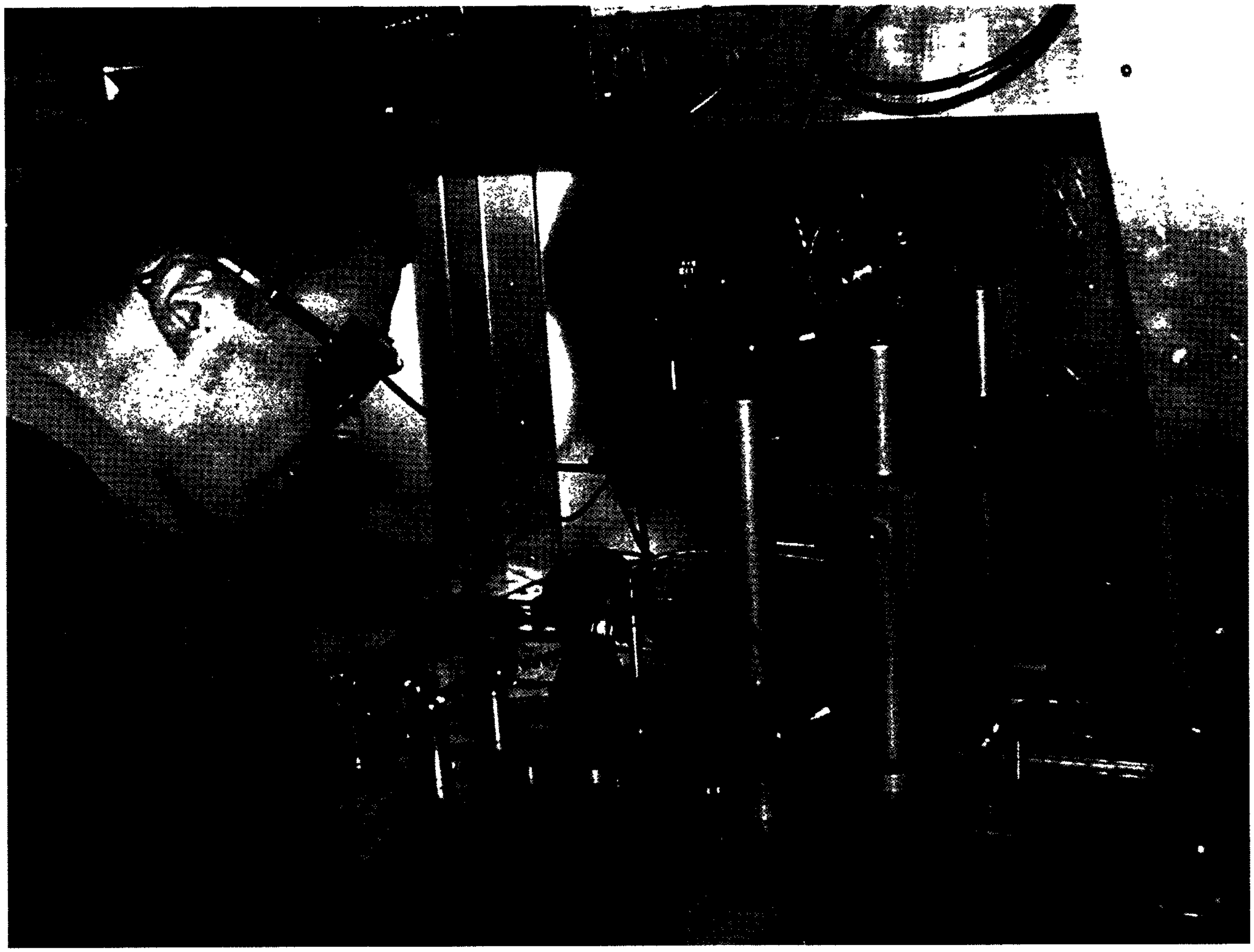
Input Optics



Auxiliary Optics R&D (AOS)

- Subsystem handles output beams from interferometer
  - » Desired beams matched into photodetectors
  - » Undesired beams 'dumped' with negligible backscatter
- Two new challenges requiring R&D:
  - » Substrate thermal focus compensation
  - » Photon actuator for test mass
- LIGO Lab activity
- Thermal focus Schedule Milestones
  - » 1Q01: Proof-of-concept, scaled experiments initial results
  - » 3Q02: Full Scale Radiative Compensator
  - » 4Q04: Full scale Directed Beam Actuation tests complete
- Photon actuator Schedule Milestones
  - » 2Q02: Initial demonstration system assembled
  - » 2Q03: Preliminary test results completed
  - » 2Q04: Final test results on iterated design completed

Thermal Compensation



Lasers & Optics R&D

(LAS, OPT, IOS, AOS)

FY02

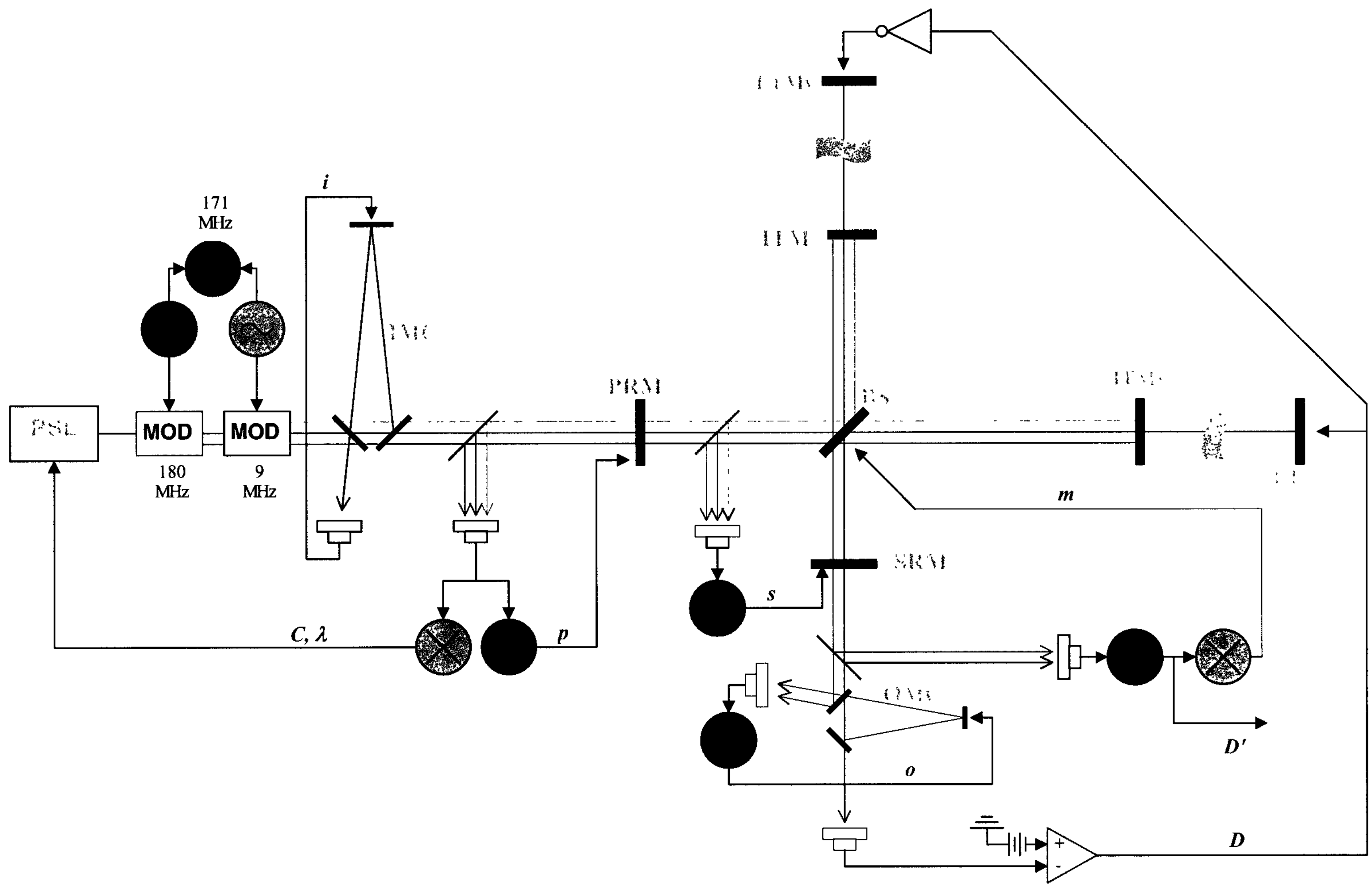
Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
LASERS & OPTICS						
Sci & PD	MIT	0	0	0.1	0.1	3.3
	CIT	1	0	2.3	3.3	
UG & Grads	MIT	1	0	0.0	1.0	2.0
	CIT	1	0	0.0	1.0	
Eng & Techs	MIT	0	0	0.0	0.0	2.0
	CIT	0.5	0	1.5	2.0	
	Totals (FTE):	3.5	0	3.8	**7.3**	
	Equip. & Supplies	$755	$1,706	0.0	**$2,461**	

N.B.: Does not include LSC research staff.

Advanced Interferometer Sensing & Control (ISC)

- Responsible for the GW sensing and overall control systems
- Addition of signal recycling mirror increases complexity
  - » Permits 'tuning' of response to optimize for noise and astrophysical source characteristics
  - » Requires additional sensing and control for length and alignment
- Shift to 'DC readout'
  - » Rather than RF mod/demod scheme, shift interferometer slightly away from dark fringe; relaxes laser requirements, needs photodiode develop
- Requires both proof-of-principle and precision testing (40m)
- LIGO Lab leads, with contributions from LSC, esp. GEO
- Schedule Highlights:
  - ✓ 4Q00: Tabletop configuration experiments concluded
  - » 2Q01: Design Requirements Review
  - » 2Q02: Tabletop DC readout test results
  - » 2Q03: GEO 10m prototype test results/review
  - » 4Q03: Final design complete
  - » DONE mason; delker?

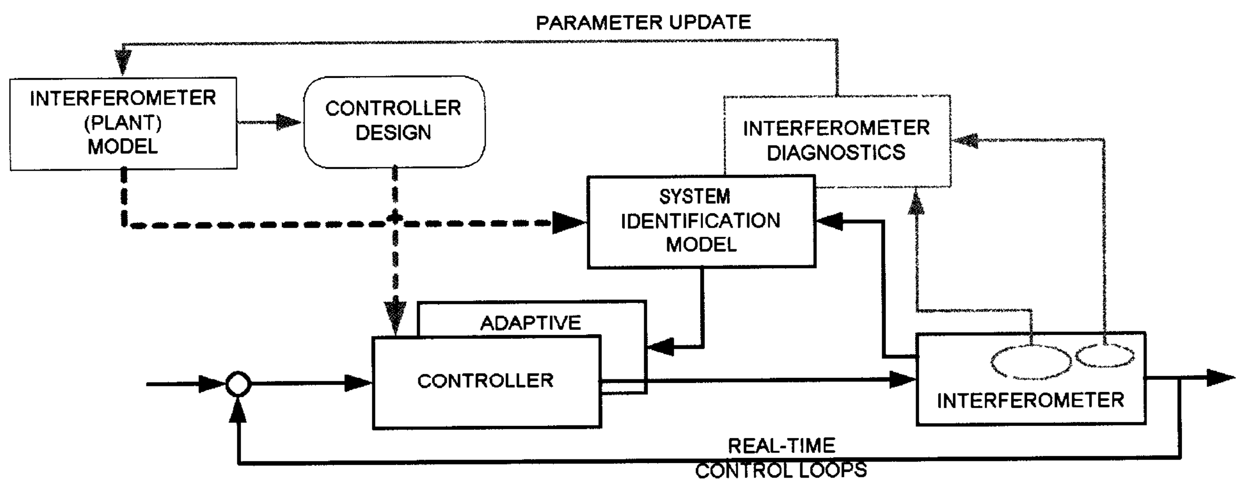
Interferometer layout



Advanced Controls & System Identification (SID)

- Modern controls approach to optimization of system
- Interfaces to existing infrastructure
- Allows both noise performance and robustness to be explored
- Can be static, or apply Adaptive Control techniques if proven
- Schedule Highlights
  - » 4Q02: System identification for the initial LIGO detector
  - » 4Q03: Adaptive control for the initial LIGO detector
  - » 1Q04: Application to 40m configuration testbed
  - » 2Q05: System identification for the advanced LIGO configuration

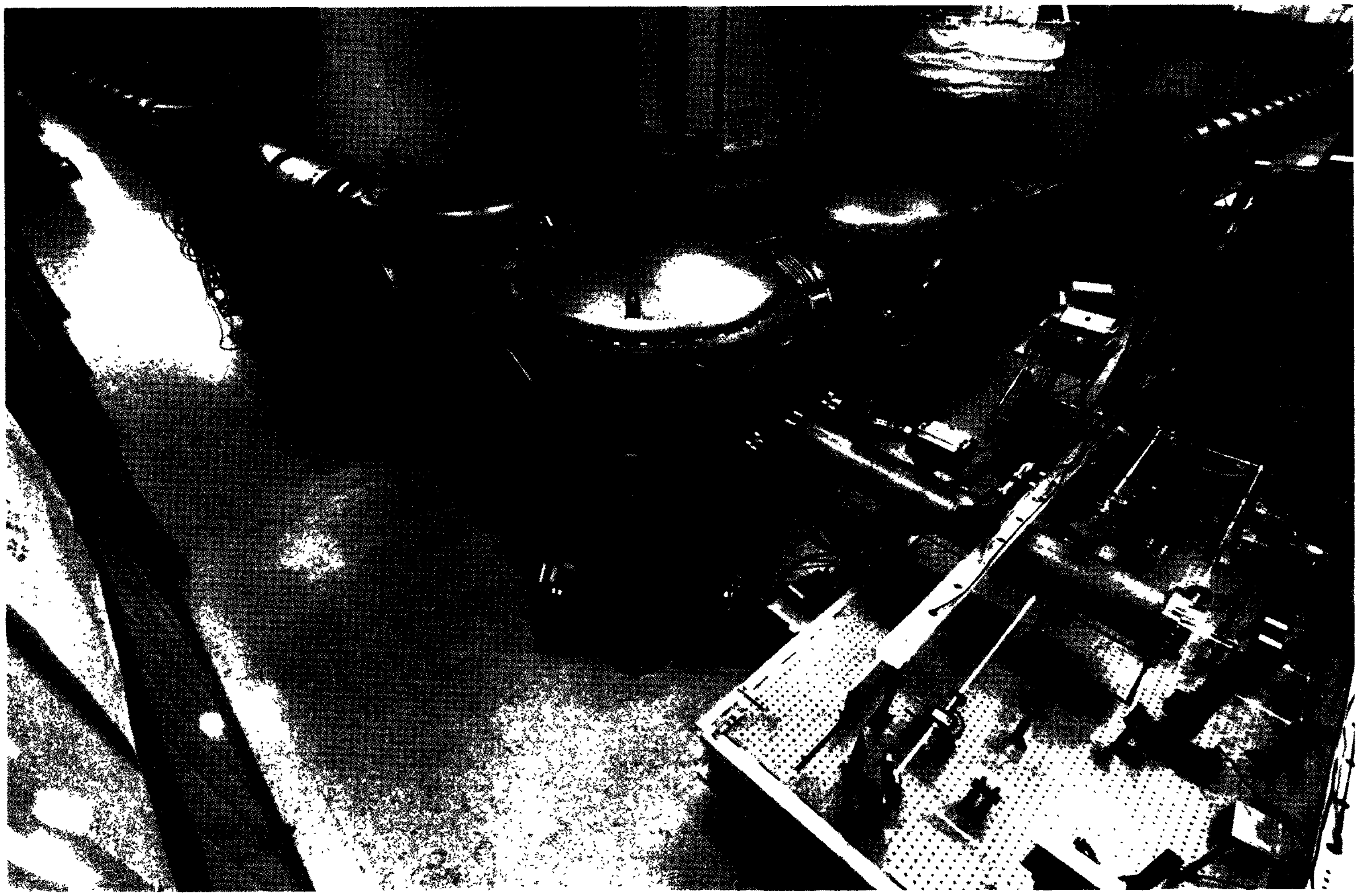
System Identification



40 m RSE Experiment (40m)

- Precision test of selected readout and sensing scheme
  - » Employs/tests final control hardware/software
  - » Dynamics of acquisition of operating state
  - » Frequency response, model validation
- Utilizes unique capability of Caltech 40 meter interferometer --- long arms allow reasonable storage times for light
- Schedule Highlights
  - ✓ 4Q00: LIGO 40 m Lab expansion completed
  - ✓ 1Q01: LIGO 40 m active isolation systems installed
  - » 2Q01: LIGO 40 m Vacuum Envelope commissioned
  - » 2Q01: LIGO 40 m PSL installed
  - » 4Q02: LIGO 40 m suspensions installed
  - » 2Q04: LIGO 40 m configurations research completed; further characterization studies & ISC prototype testing continues

40m Interferometer



Advanced Interferometer Systems, Sensing & Control (ISC, 40m, SID, SYS)

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
Advanced Interferometer Systems, Sensing & Control (ISC)						
Sci & PD	MIT	0	0	1.7	1.7	6.9
	CIT	2	0	3.2	5.2	
UG & Grads	MIT	1	0	1.0	2.0	5.0
	CIT	3	0	0.0	3.0	
Eng & Techs	MIT	0	0	0.8	0.8	10.2
	CIT	0	0	9.5	9.5	
Totals (FTE):		6	0	16.1	**22.1**	
Equip. & Supplies		$313	$0	0.0	**$313**	

N.B.: Does not include LSC research staff.

Total LIGO Lab R&D

FY02

Staff	Org	Adv. R&D (FTE)	LSC Support R&D	Operations (FTE)	LIGO Lab (FTE, $K)	
[illegible]						
Sci & PD	MIT	1	0	4.2	5.2	20.3
	CIT	8	0	7.2	15.2	
UG & Grads	MIT	5	0	1.0	6.0	13.0
	CIT	7	0	0.0	7.0	
Eng & Techs	MIT	0	0	3.5	3.5	26.4
	CIT	0.5	0	17.9	18.4	
	LLO	0	0	4.5	4.5	
Totals (FTE):		21.5	0	38.2	**59.7**	
Equip. & Supplies		$1,139	$3,301	0.0	**$4,440**	
				MIT	14.7	
				CIT	40.5	
				LLO	4.5	

N.B.: Does not include LSC research staff.

LIGO R&D Program

- Focussed on Advanced LIGO Conceptual Design
  - » Exciting astrophysical sensitivity
  - » Challenging but not unrealistic technical goals
  - » Advances the art in materials, optics, lasers, servocontrols
- A tight and rich collaboration
  - » NSF-funded research
  - » International contributors
- Program planned to mesh with fabrication of interferometer components leading to installation of new detectors in 2006
  - » Lessons learned from initial LIGO
  - » Thorough testing at Campus Labs to minimize impact on LIGO observation
  - » Coordination with other networked detectors to ensure continuous global observation

LIGO R&D Program

- With the initial LIGO commissioning, operation, and observation plan, the R&D program forms a blueprint for the LIGO mission:

- operate the LIGO facilities to support the national and international scientific community;
- support scientific education and public outreach related to gravitational wave astronomy.
- develop advanced detectors that approach and exploit the facility limits on interferometer performance;
- **observe gravitational wave sources.**