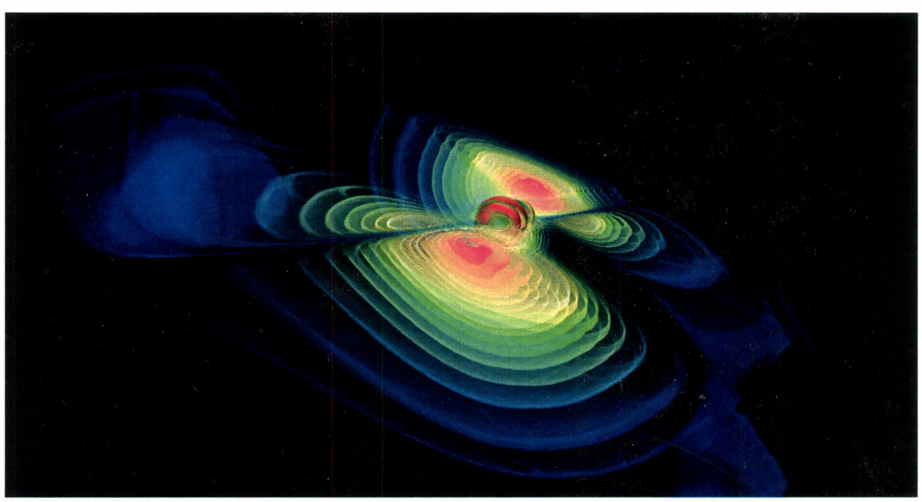
LIGO LABORATORY

California Institute of Technology
Massachusetts Institute of Technology

National Science Foundation
Review of Advanced LIGO
June 11-13, 2003
Pasadena, California

LIGO



LIGO-G030319-00-M

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Charge to the Review Panel

The NSF Grant Proposal Guide contains instructions and guidelines for individual investigator proposals. The National Science Board approved review criteria from the Grant Proposal Guide are reproduced below and should be addressed in the review of this proposal.

Review Criteria

The National Science Board approved revised criteria for evaluating proposals at its meeting on March 28, 1997 (NSB 97-72). All NSF proposals are evaluated through use of the two merit review criteria. In some instances, however, NSF will employ additional criteria as required to highlight the specific objectives of certain programs and activities. For example, proposals for large facility projects also might be subject to special review criteria outlined in the program solicitation.

The two NSB-approved merit review criteria are listed below. The criteria include considerations that help define them. These considerations are suggestions, and not all will apply to any given proposal. While proposers must address both merit review criteria, reviewers will be asked to address only those considerations that are relevant to the proposal being considered 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?

NSF staff will give careful consideration to the following 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 for Advanced LIGO Review Panel

The original LIGO proposal called for a staged approach to reach the full sensitivity necessary to detect and analyze gravitational radiation from predicted astronomical sources. The installation of detector system upgrades to make this possible was planned to occur after the initial LIGO observation period of 2003 through 2006. The current proposal represents the technical approach to extend the detector sensitivity by a factor of at least ten over the original LIGO design goal and extend the low frequency response from 40 Hz to 10 Hz. The technical plan to achieve this goal is described in the proposal and supporting documents, along with the cost, schedule, and management structure.

We ask that the Panel review the proposed work in technical detail. In carrying out this task, we ask that the following questions be addressed:

- Is the scientific case for the needed upgrade convincing? Are the scientific requirements achieved in a cost-effective manner?
- Is the specific proposed Advanced Detector upgrade appropriate to accomplish the scientific goals? In particular, is the decision to convert the 2-km Hanford interferometer to a second 4-km interferometer well founded, and will the specific subsystems each meet the required performance specifications?
- Are the requested budget (including contingency) and manpower levels appropriate to carry out the proposed upgrade?
- Are the schedule and milestones achievable with the proposed resources? Does the phasing of the downtime of detectors achieve a proper balance of cost, manpower, and observation time?
- Is the proposed management plan appropriate to oversee the R&D, construction, installation and commissioning of the upgrade?
- Has the issue of cost effectiveness in operating the more complex Advanced LIGO system been addressed?
- Is the proposed education and outreach plan well designed, and are the proposed manpower and funds appropriate to carry it out?

AGENDA

Wednesday, 6/11

08:00	Panel Executive Session (closed)	
08:25	Introduction and Reading of Panel Charge	
08:30	Welcoming remarks	Barish
08:30	LIGO Overview	Sanders
09:15	Initial LIGO Commissioning and First Observations	Whitcomb
10:00	Break	
10:15	Astrophysics	Thorne
11:00	Overview of Advanced LIGO	Shoemaker
12:00	Executive lunch (closed; lunch provided)	
13:00	Cost, Schedule, Management	Sanders
13:45	Panel Executive Session (closed)	
14:30	Breakout Sessions:	

1. Laser, Input Optics, Core Optics, Auxiliary Optics
   351 W. Bridge [Science Conference Rm]
2. Suspensions, Seismic Isolation, Systems, Sensing/Control, e2e Modelling
   39 Bridge Annex [Engineering Conference Rm]
3. Astrophysics, Data Analysis Hardware, Data Acquisition
   621 Millikan [Millikan Large Rm]
4. Installation, Facilities, Project Management, Cost/Schedule
   619 Millikan [Millikan Small Rm]
5. International Partners, LSC, Outreach
   102 E. Bridge

17:00	Panel Executive Session (closed). Discussion of issues to be revisited is next set of breakout sessions and assignments to breakout sessions
18:30	Lab Tour (optional, per committee preference)
19:30	Dinner: Holly Street Cafe

Thursday, 6/12

08:30	Panel Executive Session [Review requests for information] (closed)
09:00	Response of LIGO/LSC staff to Panel Request and/or Parallel Sessions
10:30	Break
11:15	Response of LIGO/LSC Staff to Panel Request and/or Parallel Sessions
12:30	Lunch and Panel Executive Session (closed)
13:30	Executive Session (closed), Interaction with LIGO/LSC staff as desired

Friday, 6/13

09:00	Panel Executive Session [Final discussion of report and closeout presentation] (closed)
10:00	Closeout
12:00	Adjourn

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
AR	Anti-Reflective
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
COBE	Cosmic Background Explorer
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
DOF	Degrees of Freedom
EAC	Estimate at Completion
EPI	External Pre-Isolation
EPICS	Experimental Physics and Industrial Control System
ER	LIGO Engineering Run
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
GW	Gravitational Wave
GWADW	Gravitational Wave Data Analysis Workshop
GWIC	Gravitational Wave International Committee
HAM	Horizontal Access Modules
HEPI	Hydraulic External Pre-Isolation

HPSS	High Performance Storage System (IBM)
HVAC	Heating, Ventilation and Air Conditioning
IAP	Institute for Applied Physics
IDE	Integrated Drive Electronics (disk standard)
IFO	Interferometer
IGEC	International Gravitational Event Collaboration
InGaAs	Induim-Gallium-Arsenide
INSA	French National Institute for Applied Science
IO	Input Optics
IP	Inverted Pendulum
ISC	Interferometer Sensing and Control
ISCT	Interferometer Sensing and Control Table
ISS	Intensity Stabilization Servo
ITM	Input Test Mass
ITM-X	X-Arm 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
LMC	Large Magellanic Cloluds
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
MEPI	Electro-Magnetic External Pre-Isolation
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
NCSA	National Center for Supercomputing Applications
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
RFP	Request for Proposal
RM	Recycling Mirror
RMS	Root mean square
ROC	Radius of Curvature
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
SMC	Small Magellanic Clouds
SNR	Signal to Noise Ratio
SOS	Small Optics Suspensions
SRD	Science Requirements Document
SUBR	Southern Louisiana University at Baton Rouge
SURF	Summer Undergraduate Research Fellowship
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
WFS	Wave Front Sensor
WMAP	Wilkinson Microwave Anisotropy Probe

LIGO

LIGO Overview

Gary H Sanders

NSF Review of Advanced LIGO

Caltech, June 11, 2003

LIGO-G030250-01-M

This talk

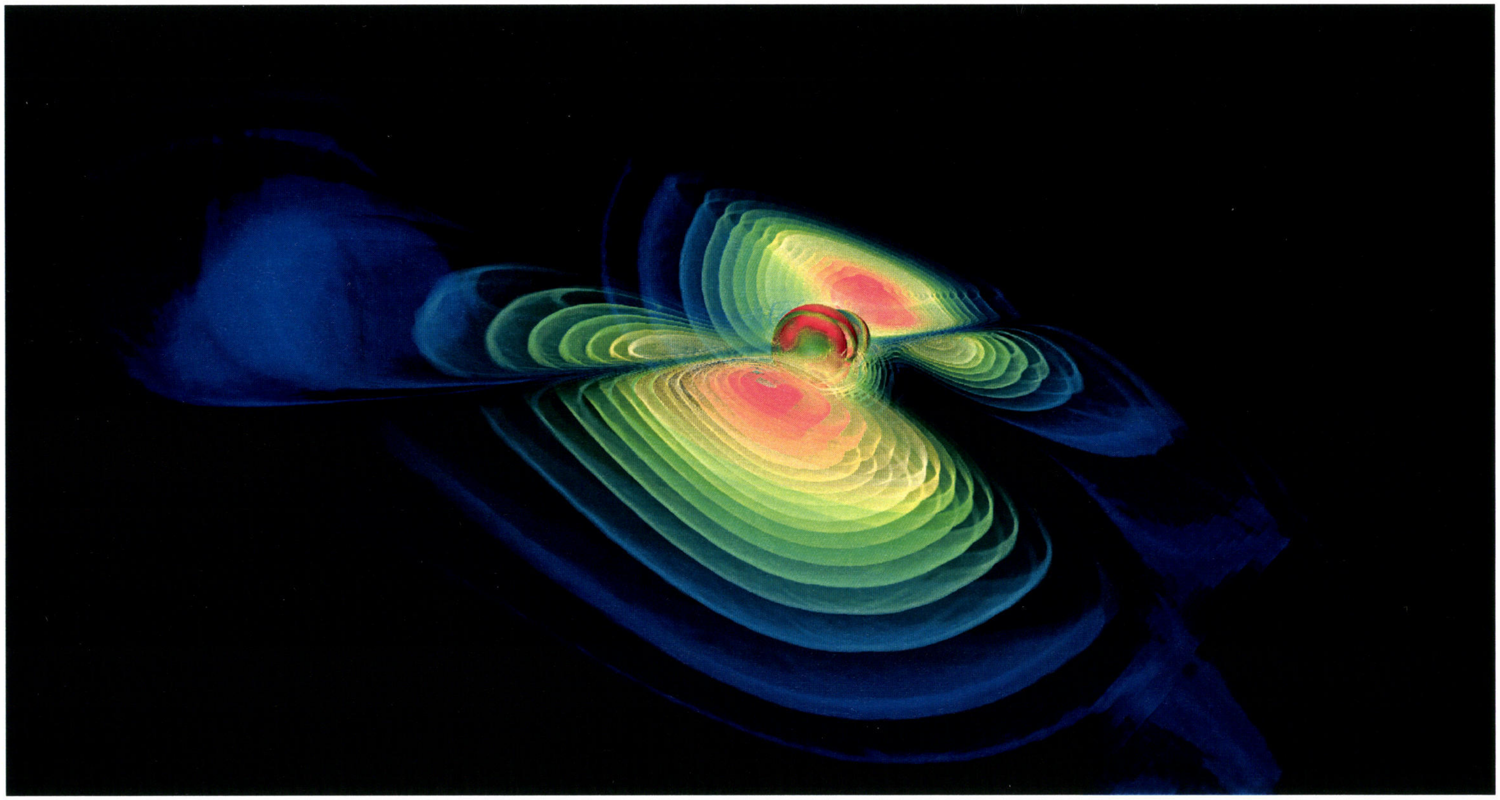
- Introduction to LIGO and terrestrial gravitational wave detectors
- The LIGO mission and the upgrade strategy
- The scientific reach and impact of Advanced LIGO
- How we are organized for Advanced LIGO
- Broader impacts

LIGO

Advanced LIGO In Context

- LIGO construction is complete
  - NSF investment in LIGO now totals about $400 million
  - Construction cost $292 million
  - LIGO facilities represent ~ 2/3 of the construction investment and are intended to support successive detectors
- Initial LIGO detectors are operating and have carried out early scientific running
  - Initial LIGO should accomplish its sensitive observation goal by late 2006
- Advanced LIGO development is defining the detailed design and retiring risks
- The experienced LIGO team will be ready to install Advanced LIGO in 2007
- Observations for probable gravitational wave detection can commence in 2010

LIGO Overview

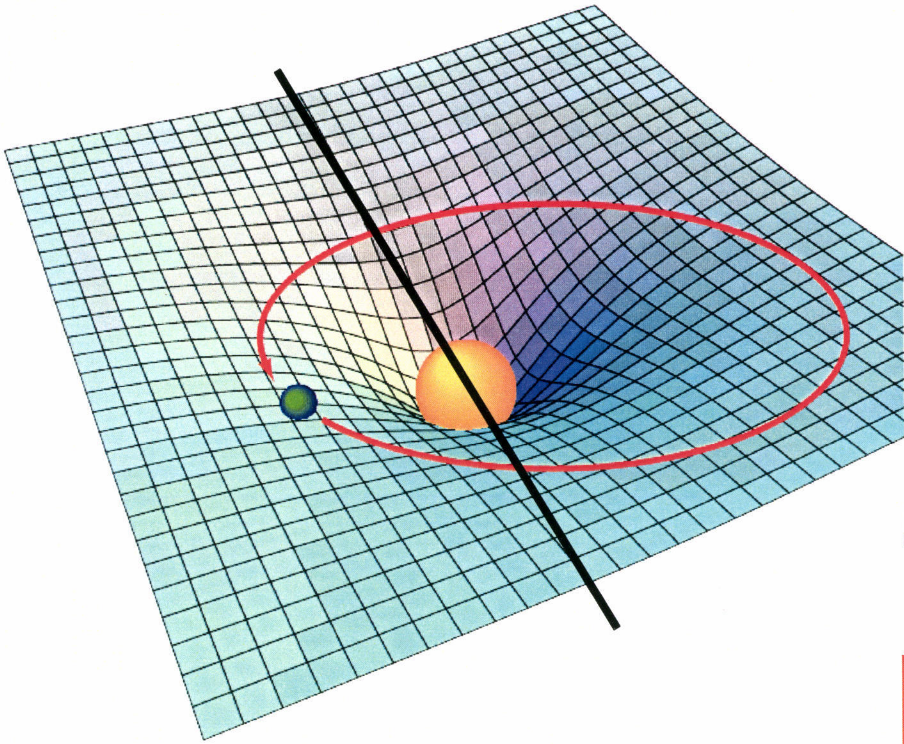


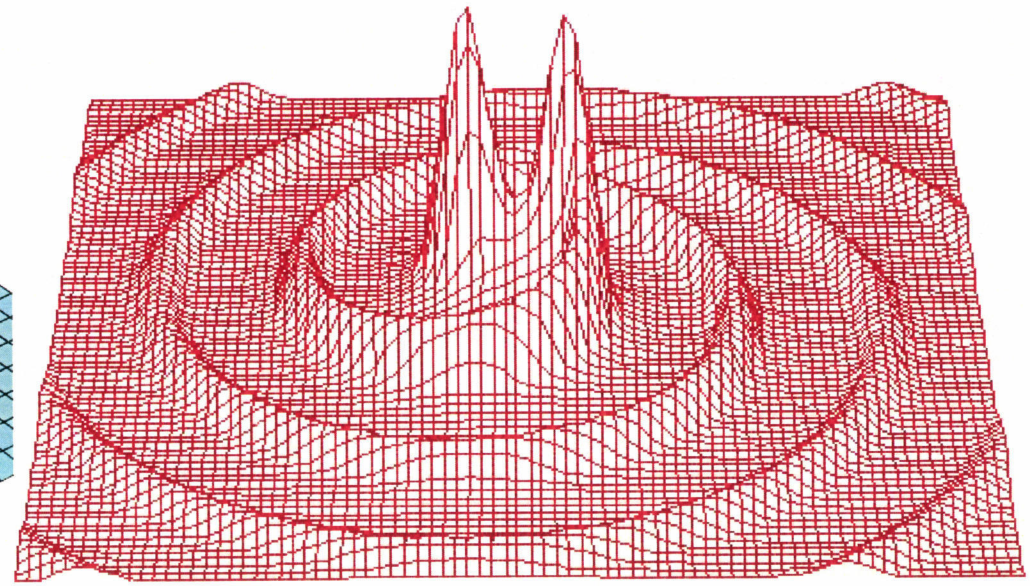
"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)

LIGO-G030250-01-M

Gravity as a "Strain" of Flat Space-Time



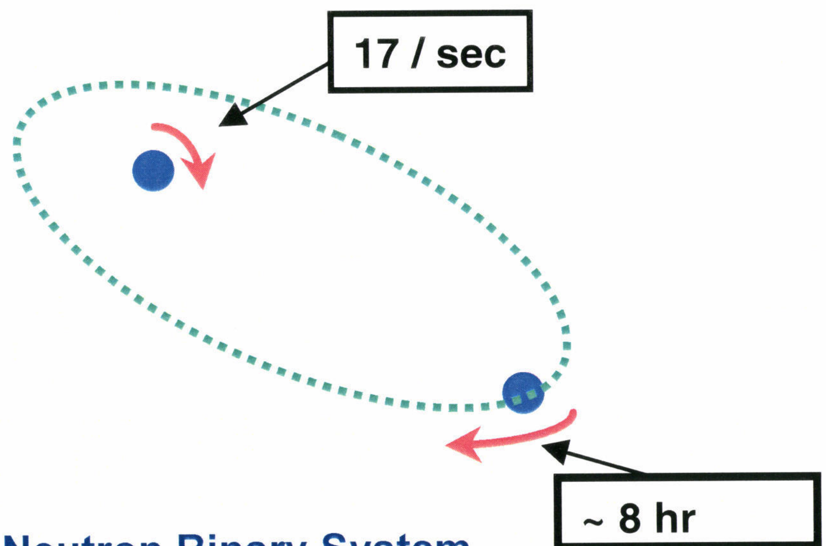


gravitational radiation from binary inspiral of compact objects

Evidence for Gravitational Waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

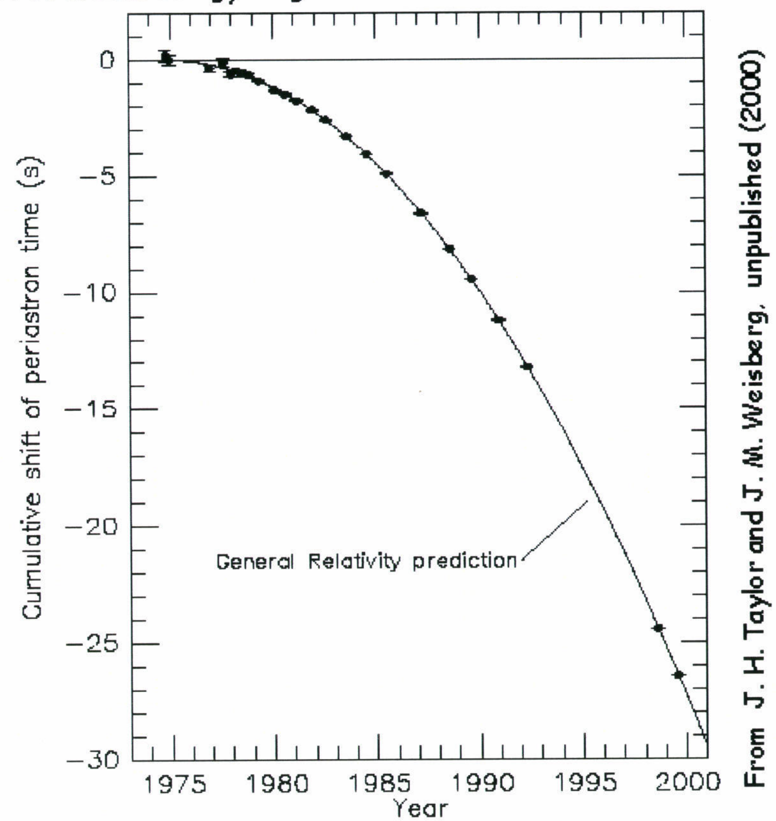


Neutron Binary System
- separated by 10^6 miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

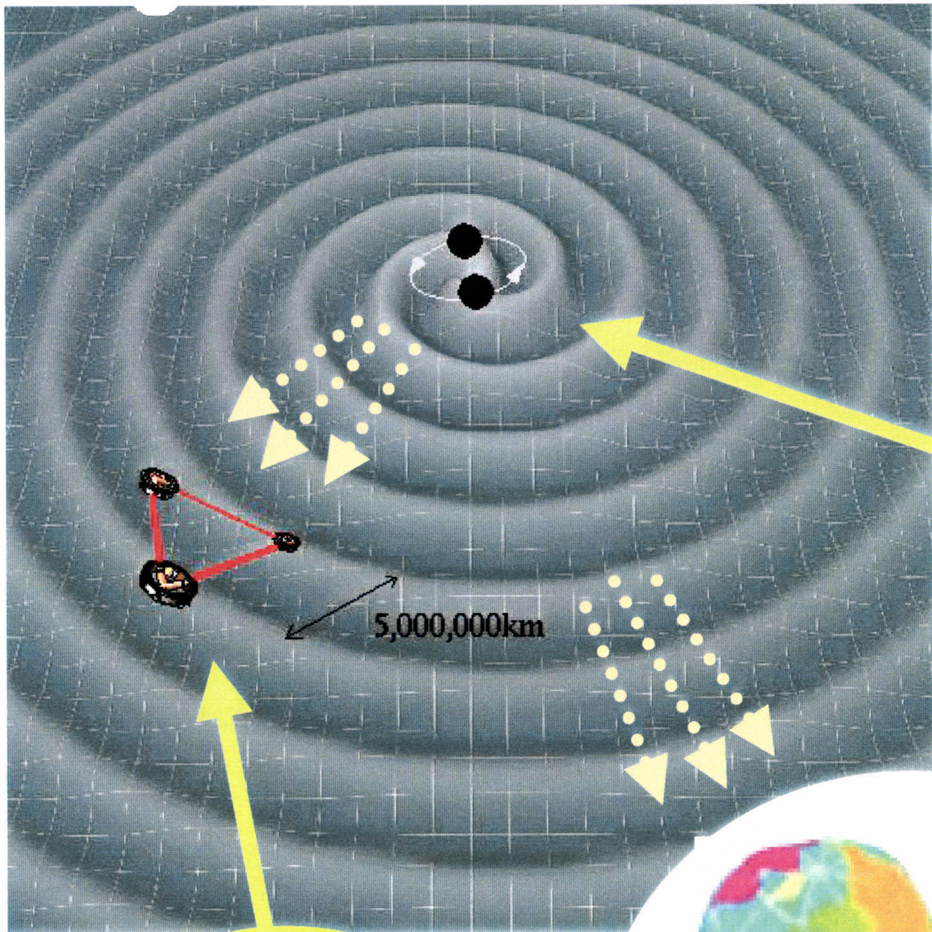
Prediction from general relativity
- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

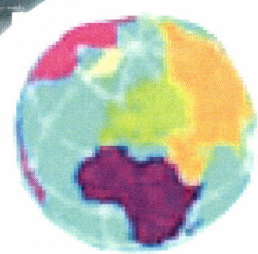


Direct Detection

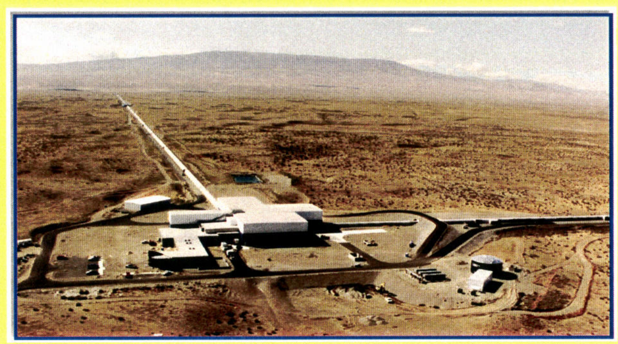


Gravitational Wave
Astrophysical Source

Detectors
in space
LISA

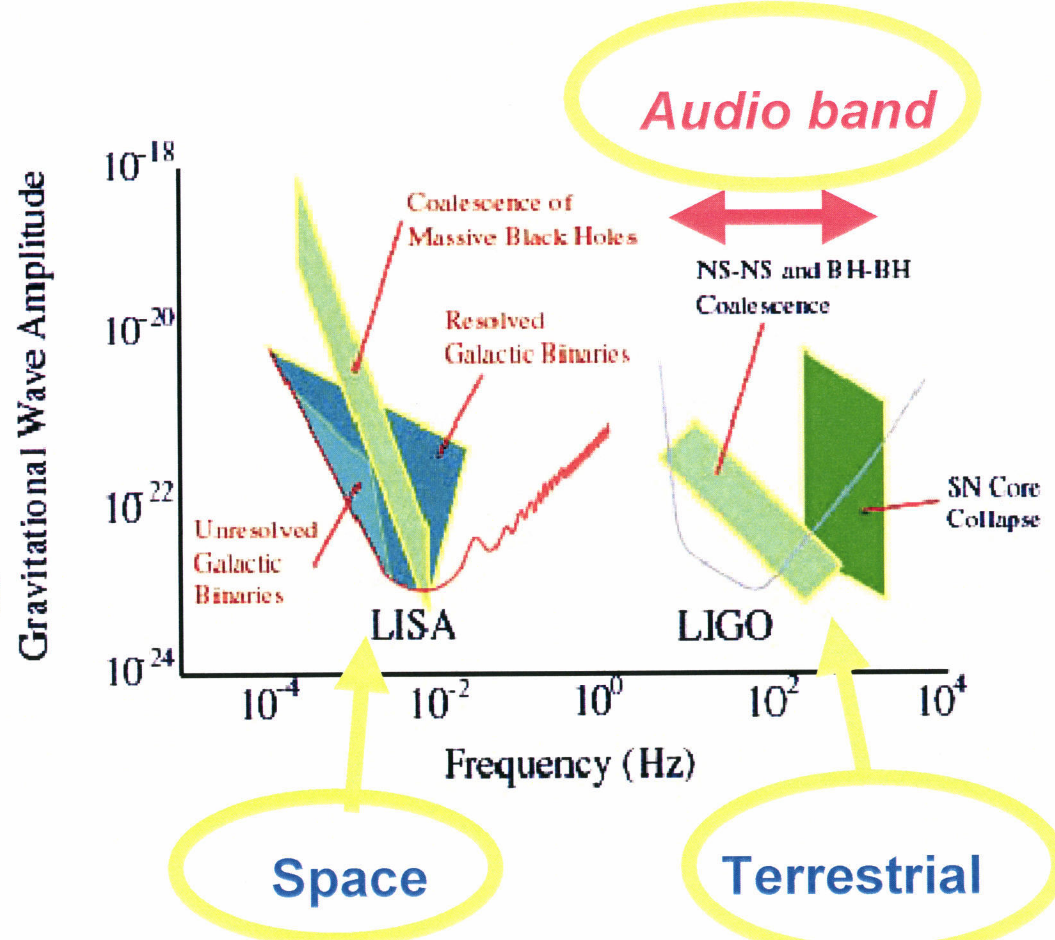


Terrestrial detectors
LIGO, GEO, TAMA, Virgo

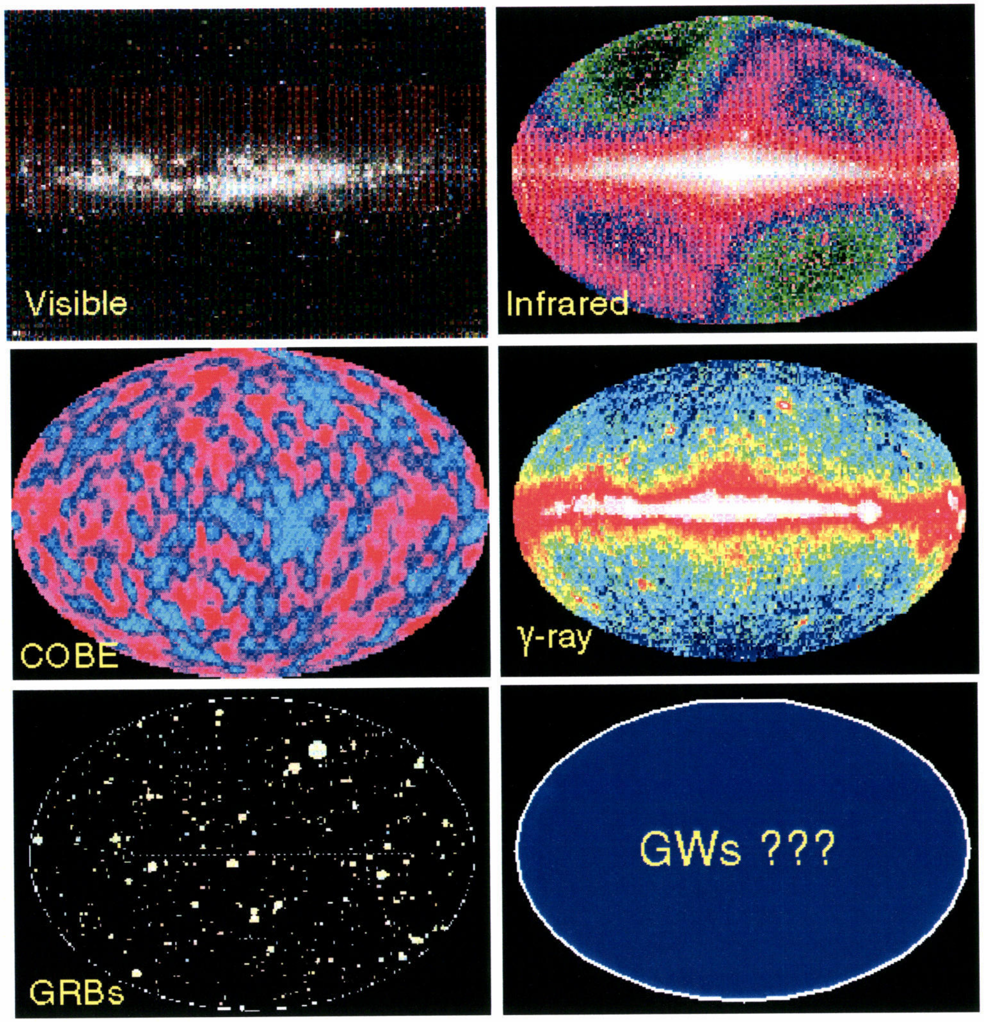


Astrophysics Sources by Frequency

- EM waves are studied over ~20 orders of magnitude
  - » (ULF radio –> HE γ-rays)
- Gravitational Waves over ~10 orders of magnitude
  - » (terrestrial + space)



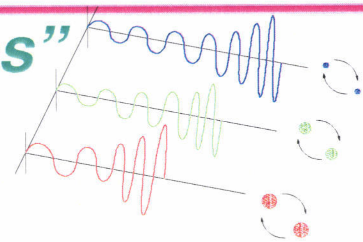
A New Window on the Universe



Gravitational Waves will provide a new way to view the dynamics of the Universe

Astrophysical Sources of Gravitational Waves

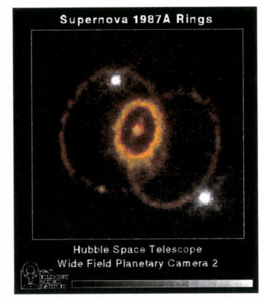
Compact binary inspiral: *"chirps"*



- NS-NS waveforms are well described
- BH-BH need better waveforms
- search technique: matched templates

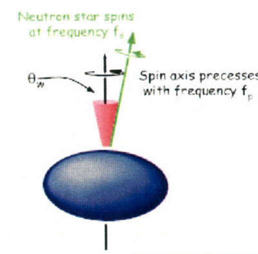
Thorne

Supernovae / GRBs: *"bursts"*



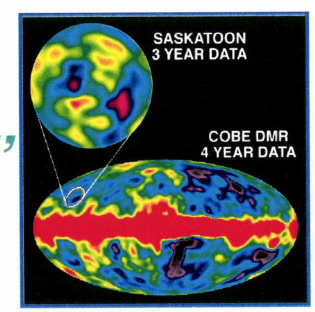
- burst signals in coincidence with signals in electromagnetic radiation
- Challenge to search for untriggered bursts

Pulsars in our galaxy: *"periodic signals"*



- search for observed neutron stars (frequency, doppler shift)
- all sky search (computing challenge)
- r-modes

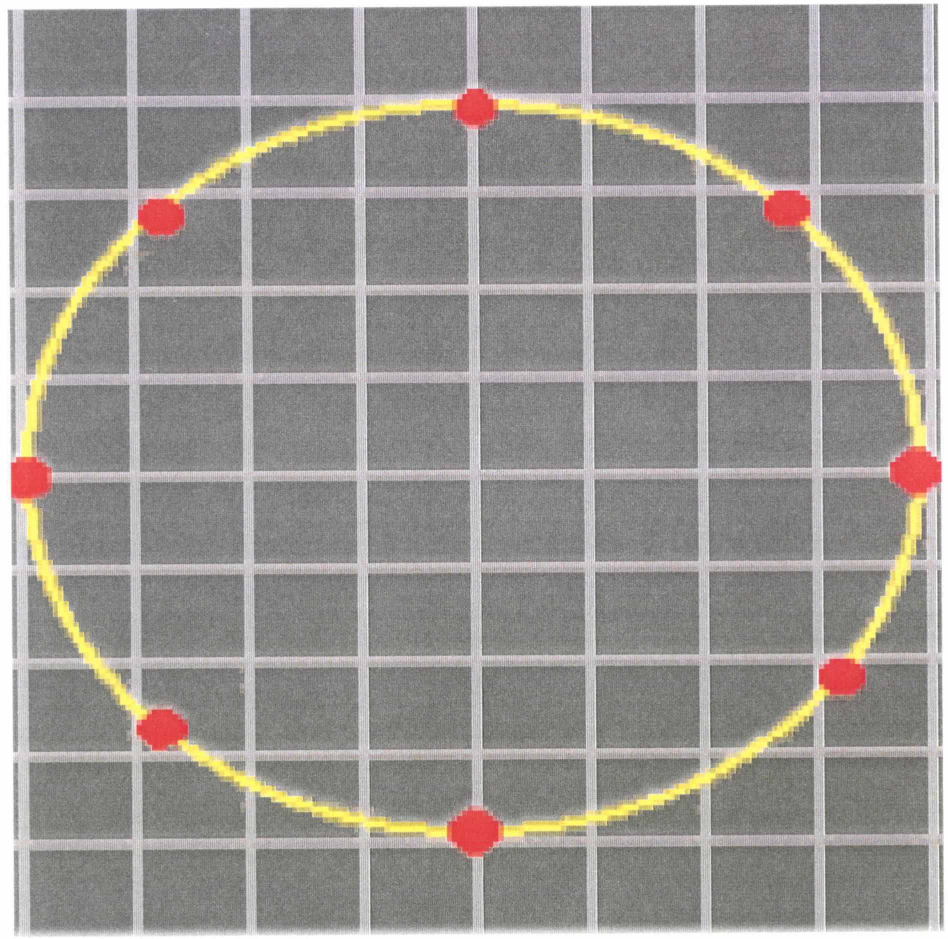
Cosmological Signals *"stochastic background"*



LIGO

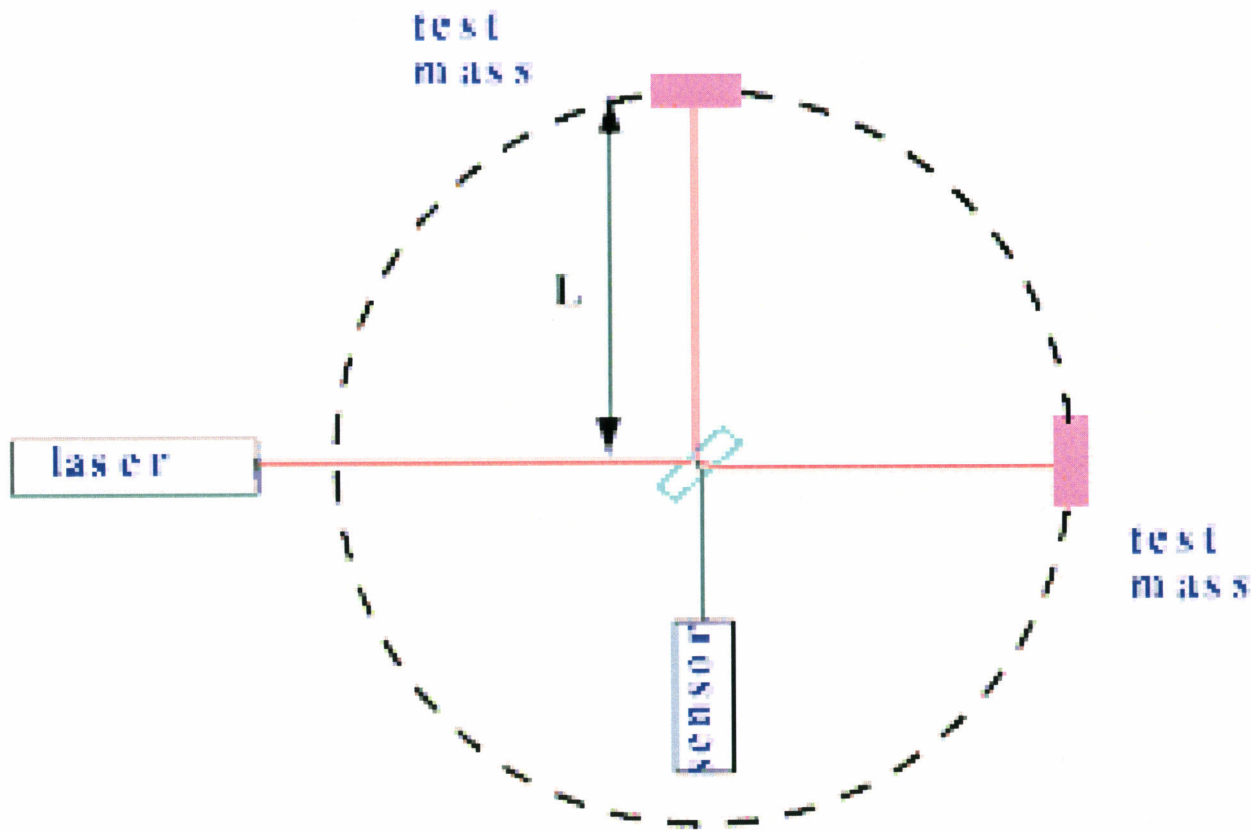
Detecting a passing wave ....

Free masses



Detecting a passing wave ....

Interferometer

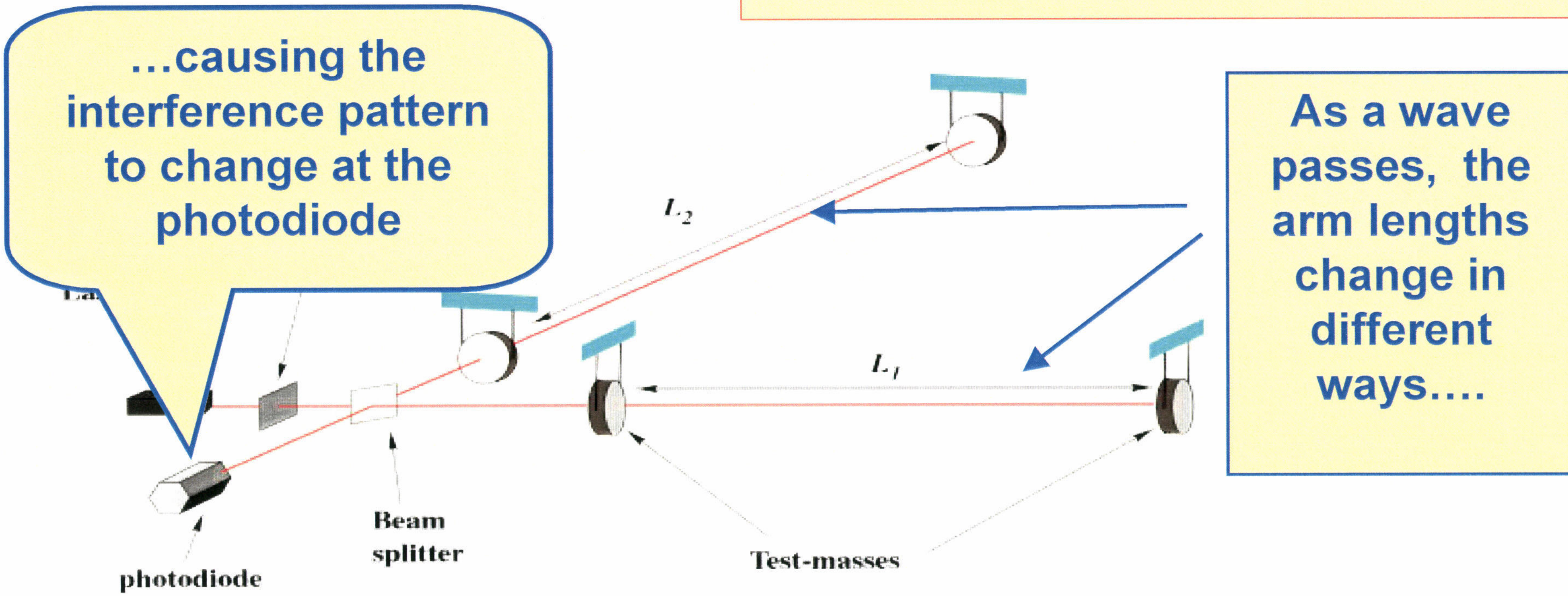


LIGO

Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

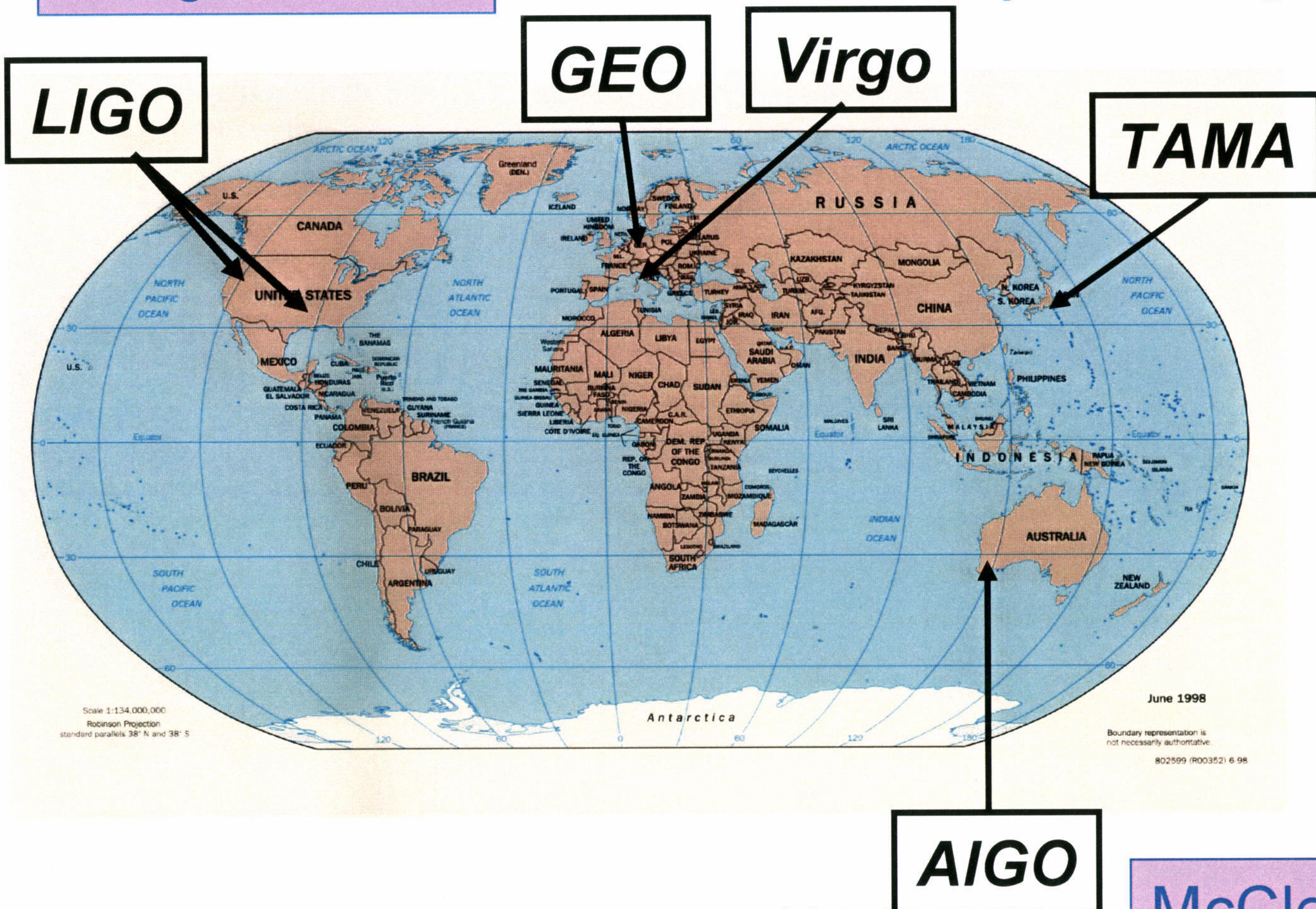
- **Arms in LIGO are 4km**
- **Measure *difference in length to one part in 10^{21} or 10^{-18} meters***



An International Network of Interferometers

Hough, Willke

Simultaneously detect signal (within msec)



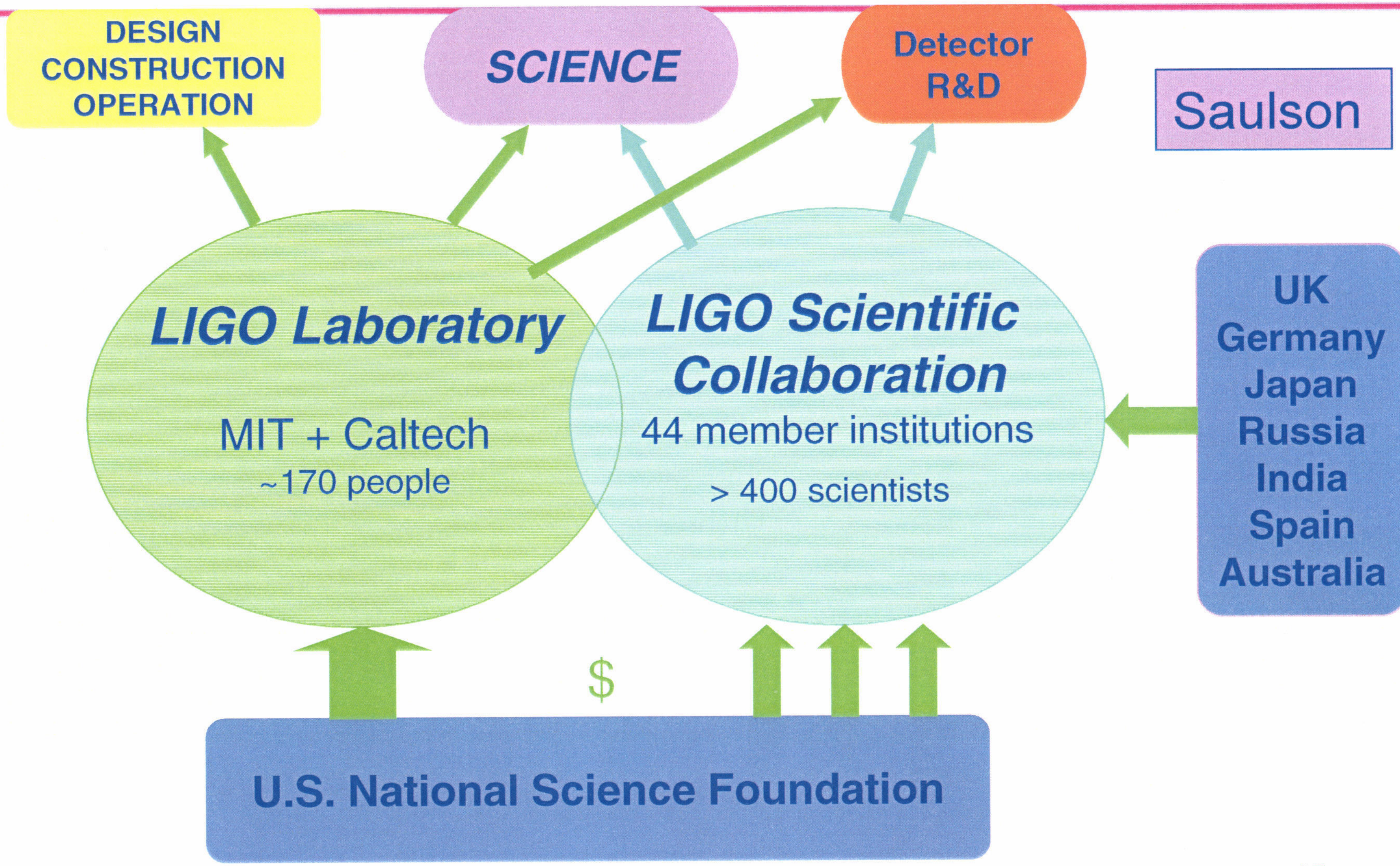
detection confidence

locate the sources

decompose the polarization of gravitational waves

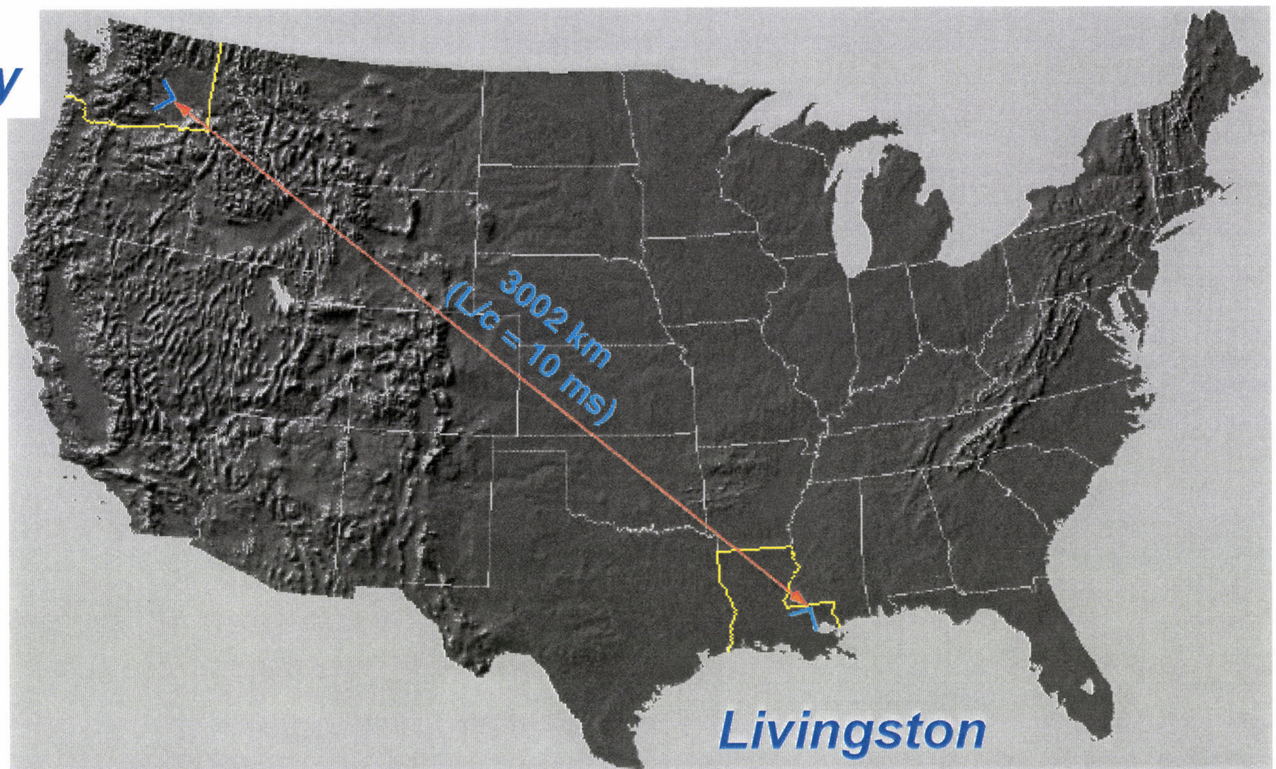
McClelland

LIGO Organization & Support



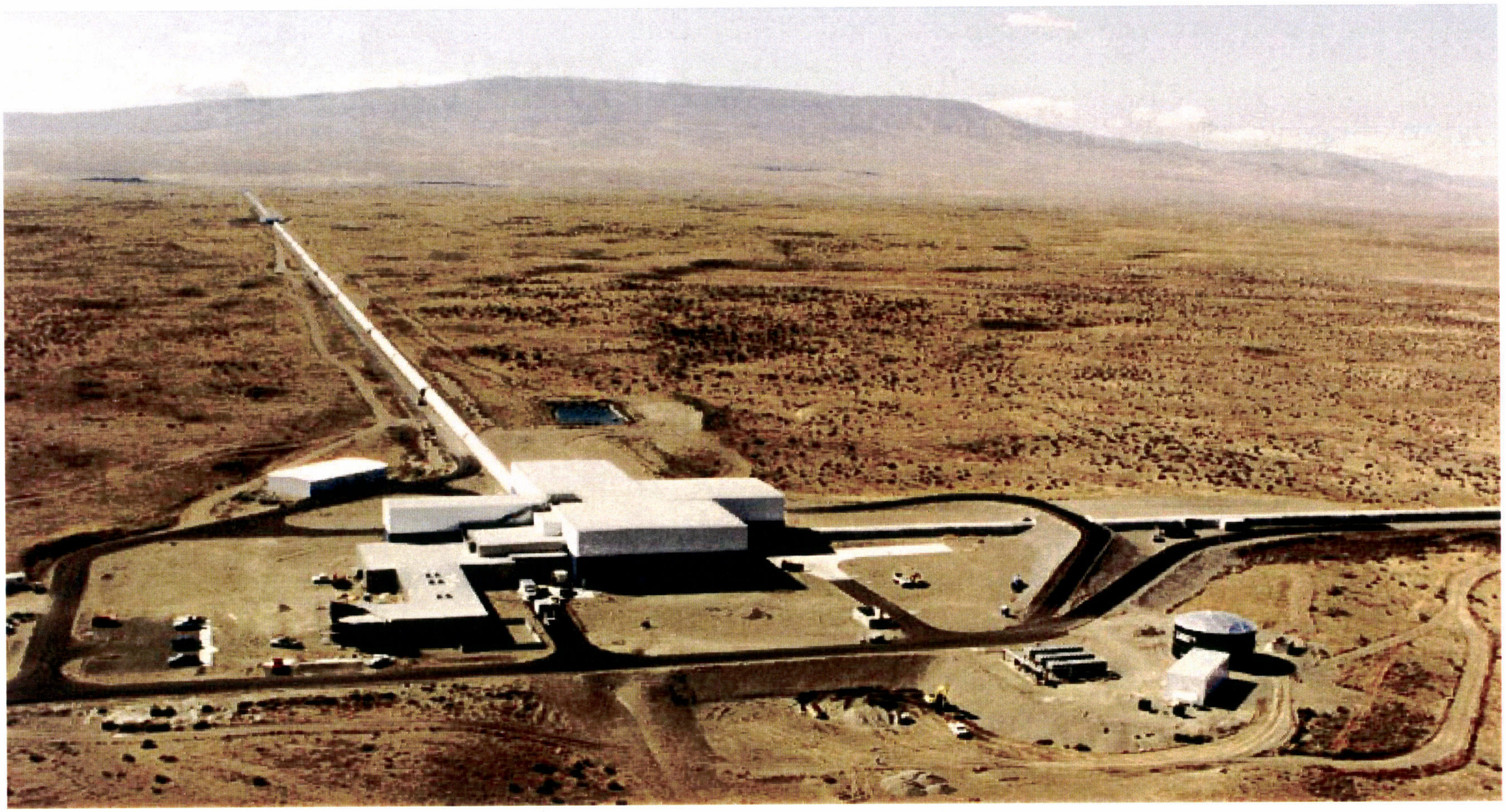
The Laboratory Sites

Laser Interferometer Gravitational-wave Observatory (LIGO)

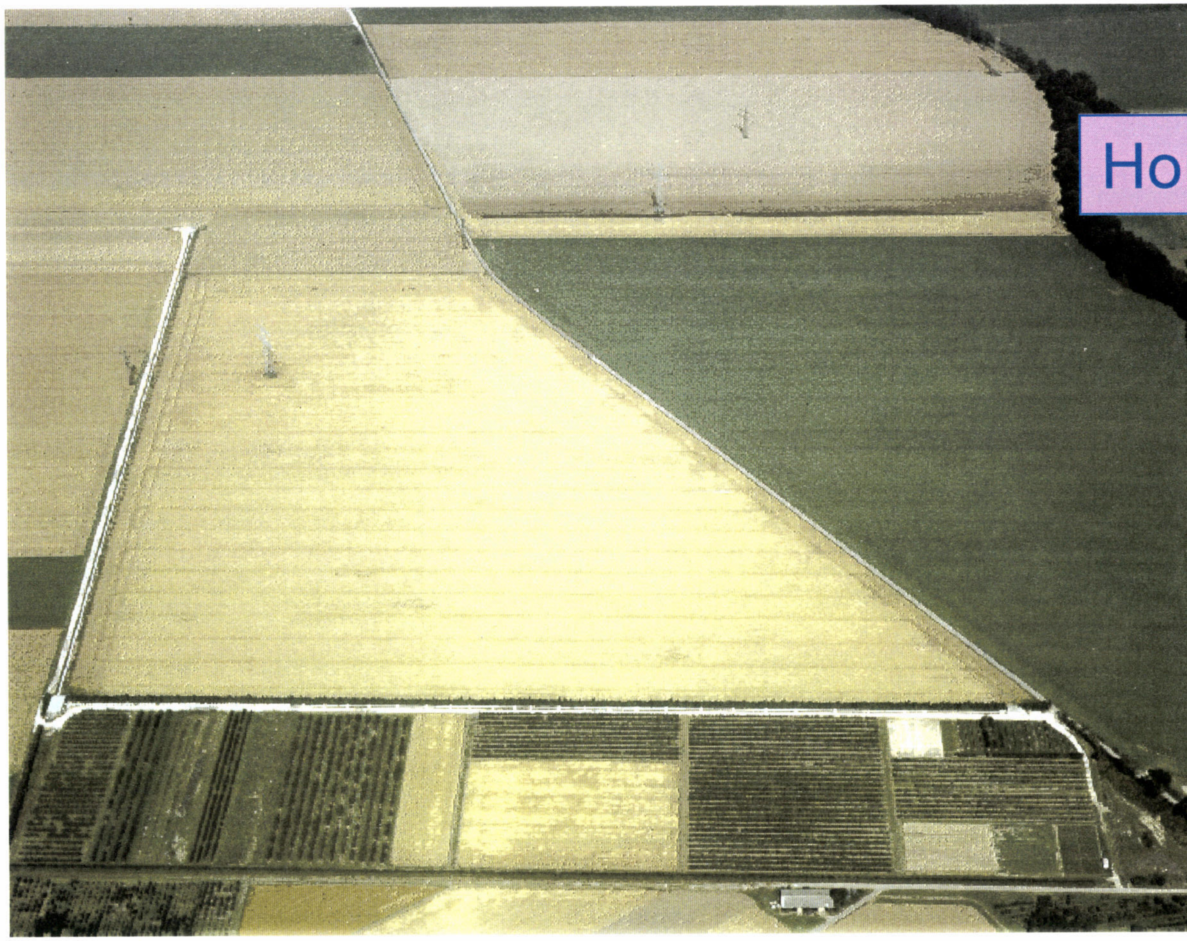


LIGO Livingston Observatory

LIGO Hanford Observatory

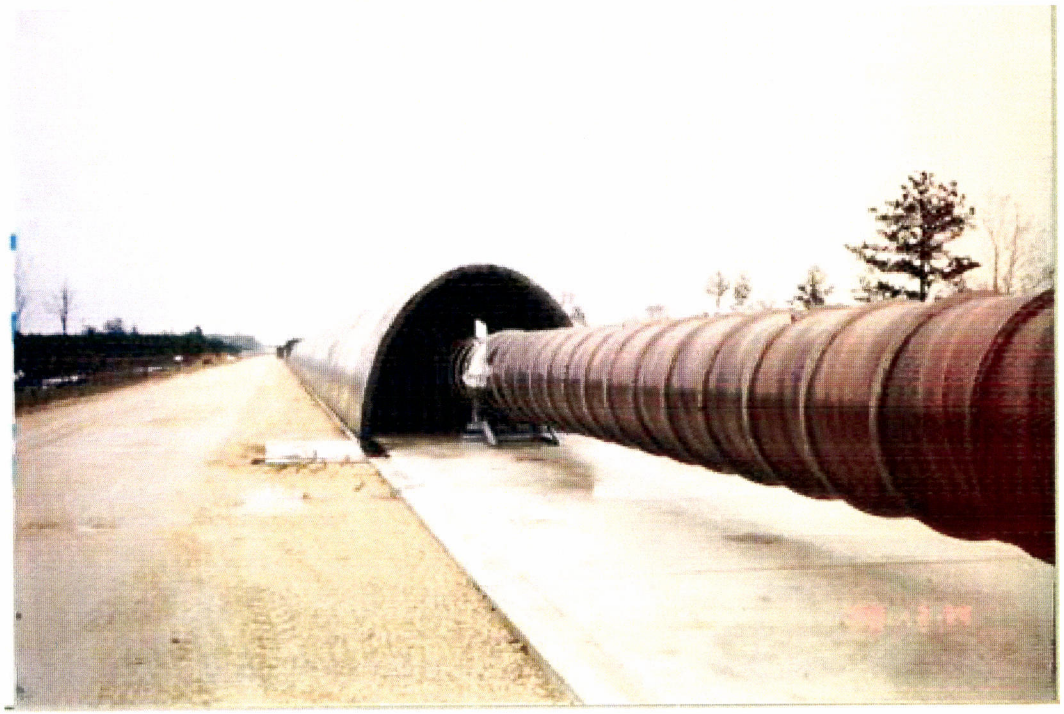


GEO 600



LIGO

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 Vacuum Equipment

LIGO

A LIGO Mirror

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5 x 10^{-7}

Internal mode Q's > 2 x 10^{6}

Polishing

Surface uniformity < 1 nm rms

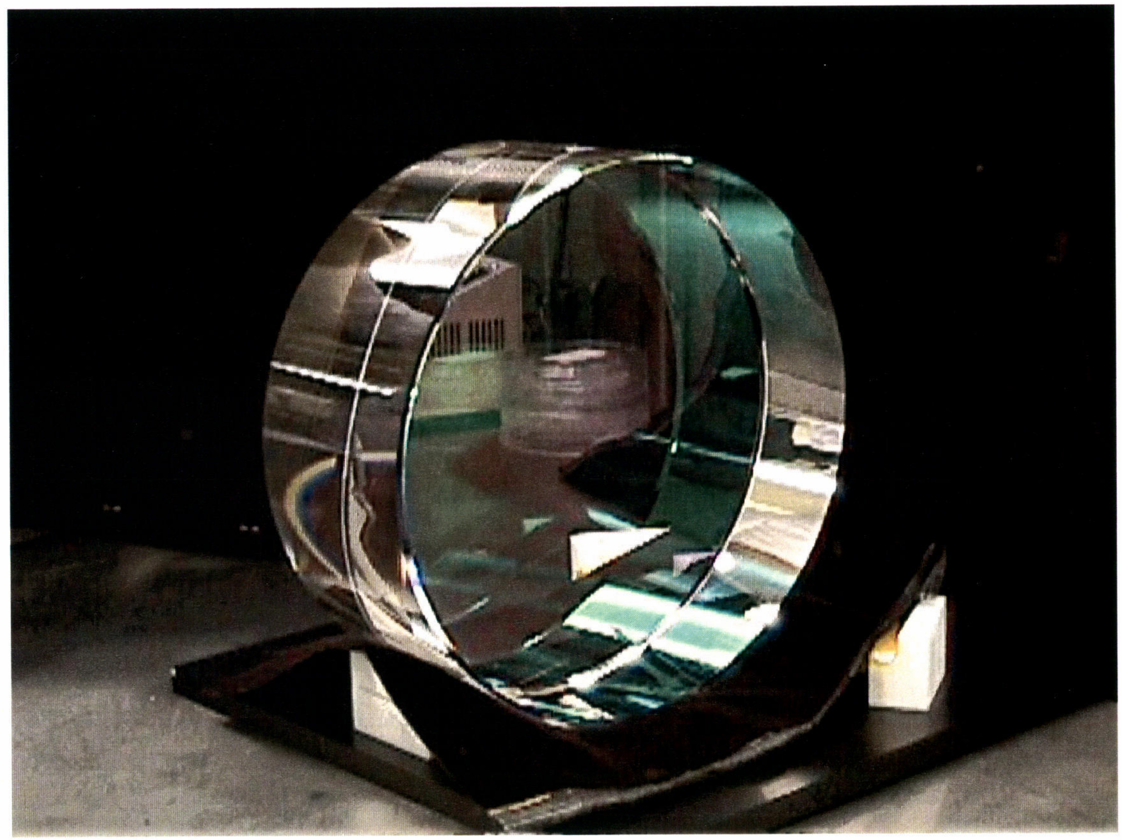
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

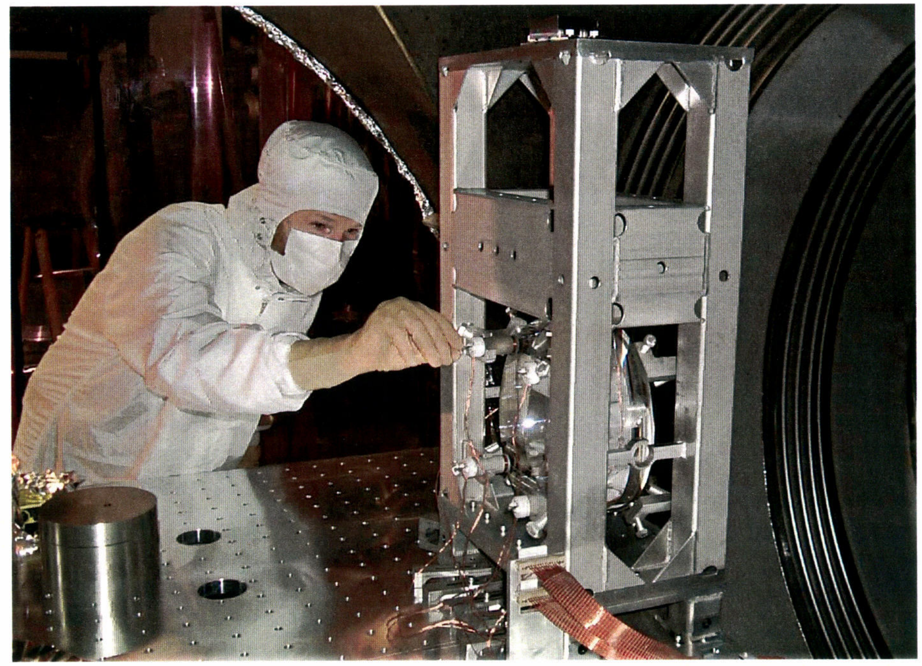
Absorption < 0.5 ppm

Uniformity <10^{-3}



Core Optics

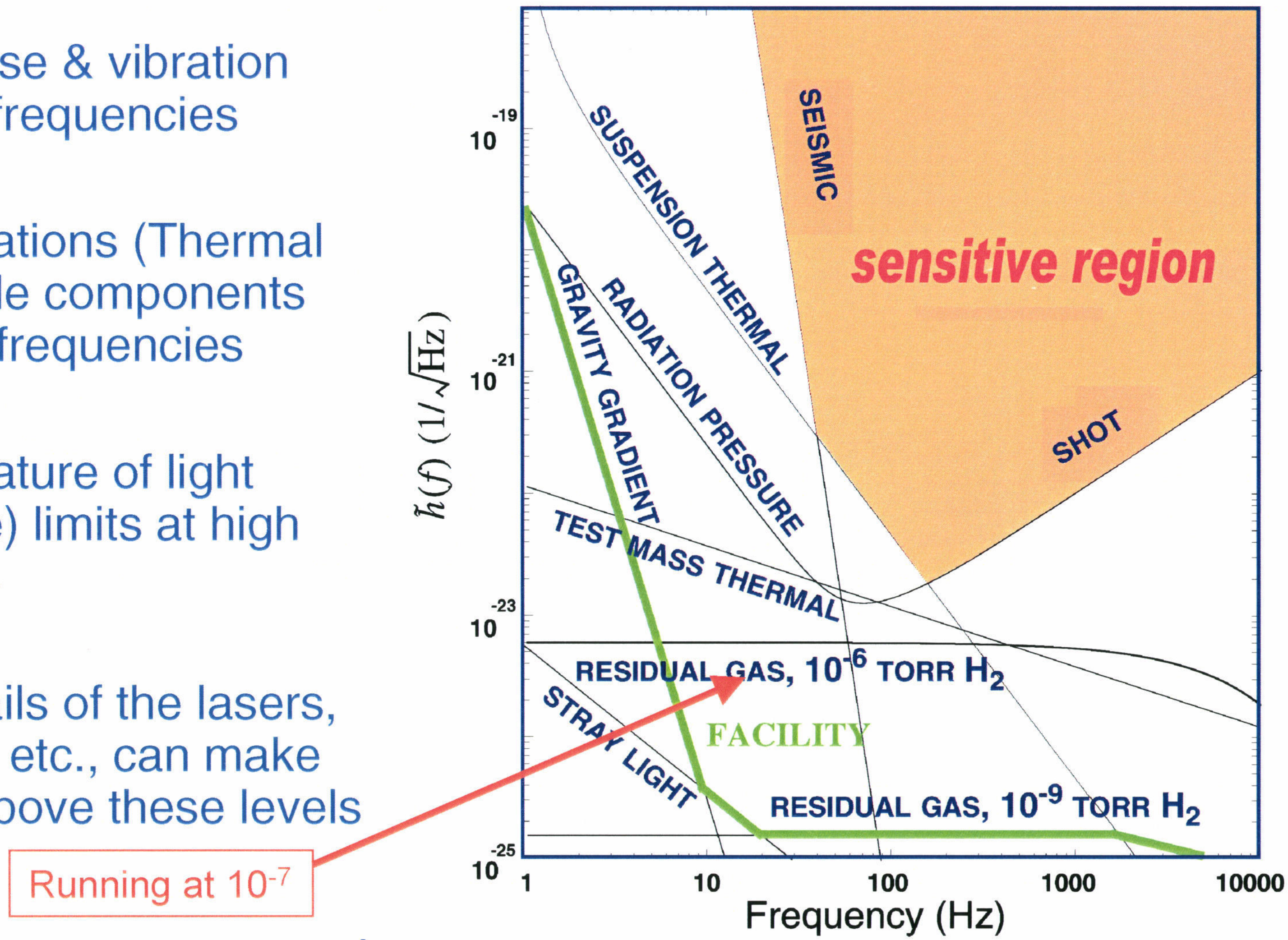
installation and alignment



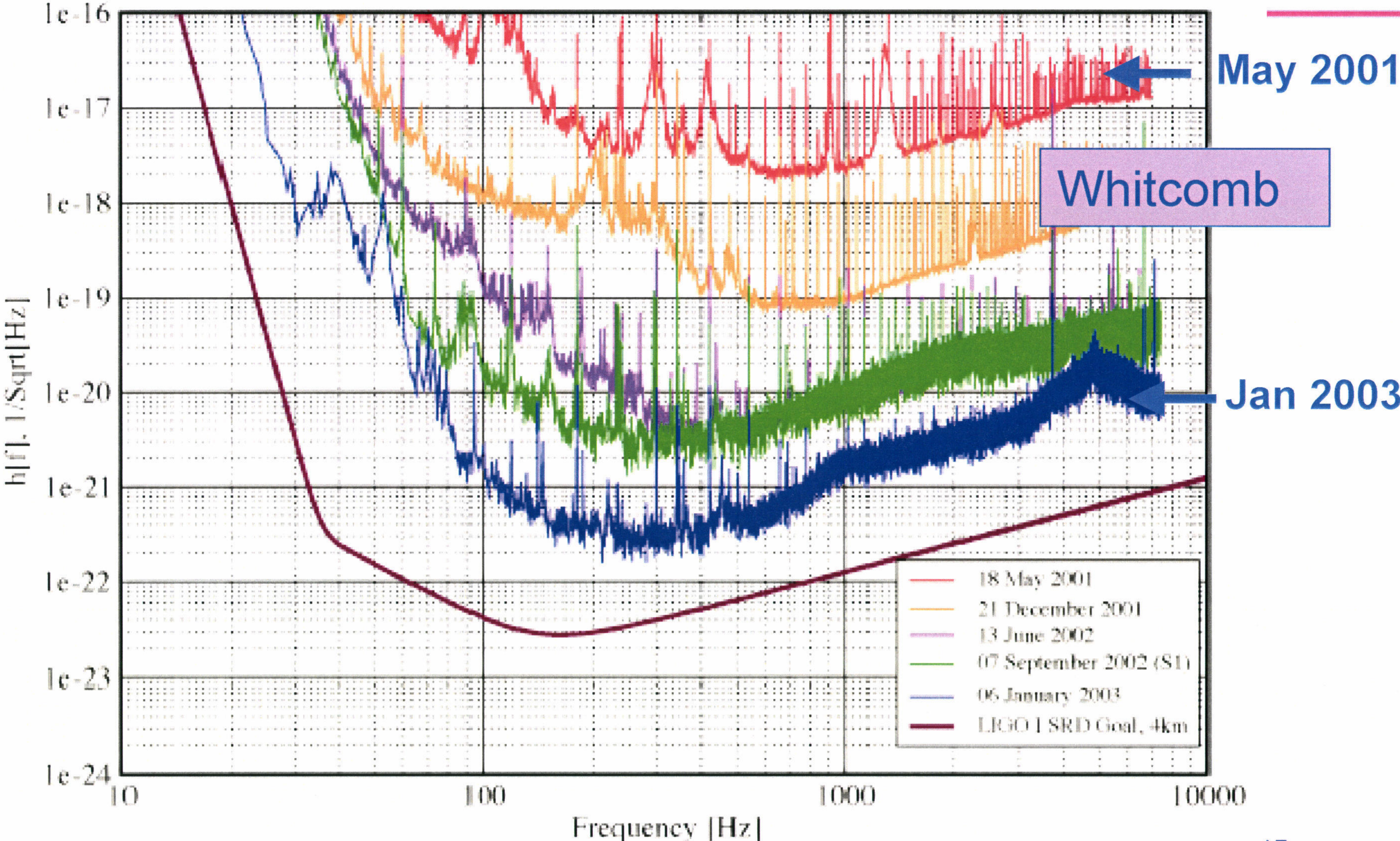
LIGO team now expert in this very demanding work

What Limits Sensitivity of Interferometers?

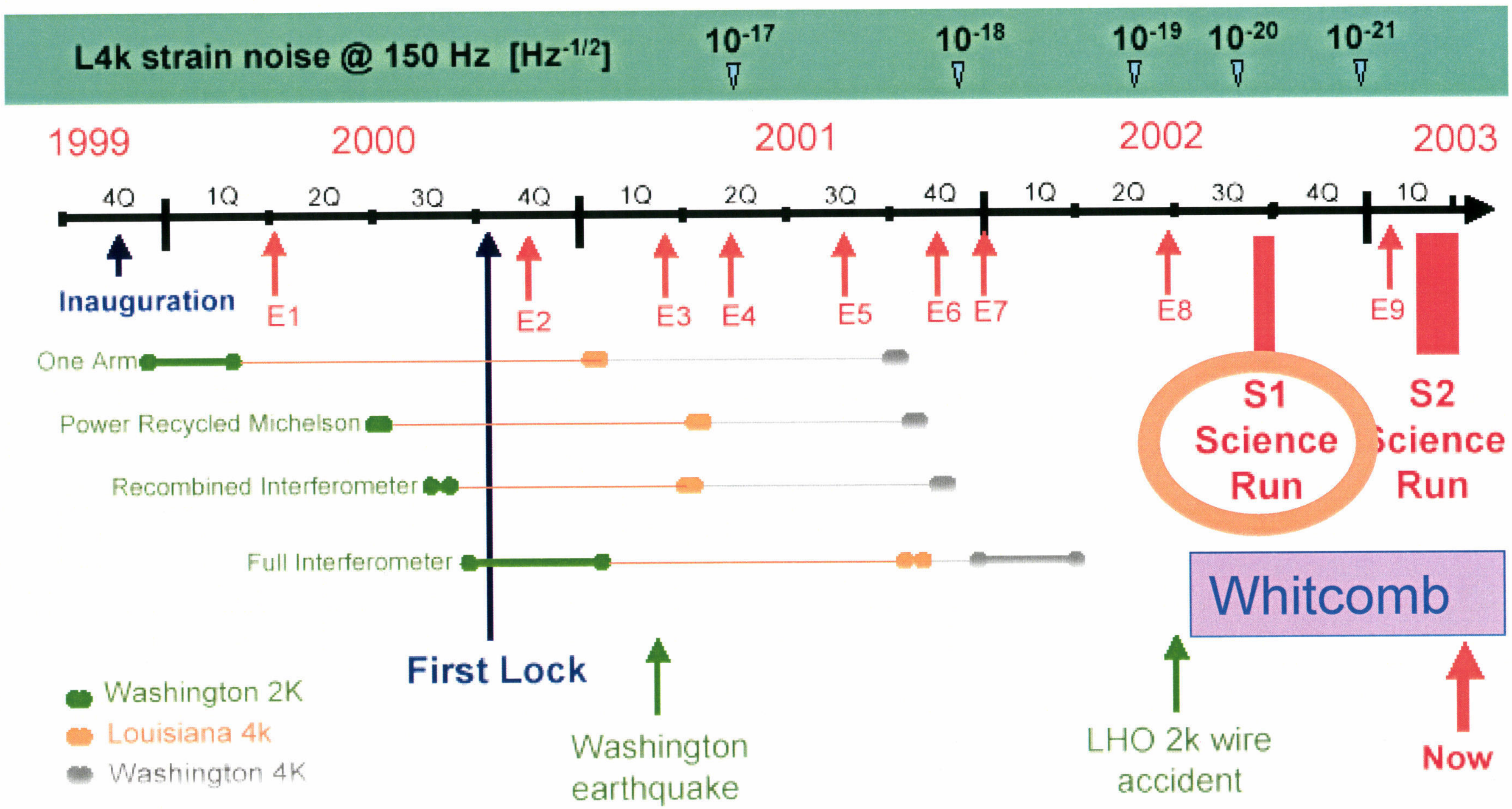
- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



LIGO Sensitivity
Livingston 4km Interferometer



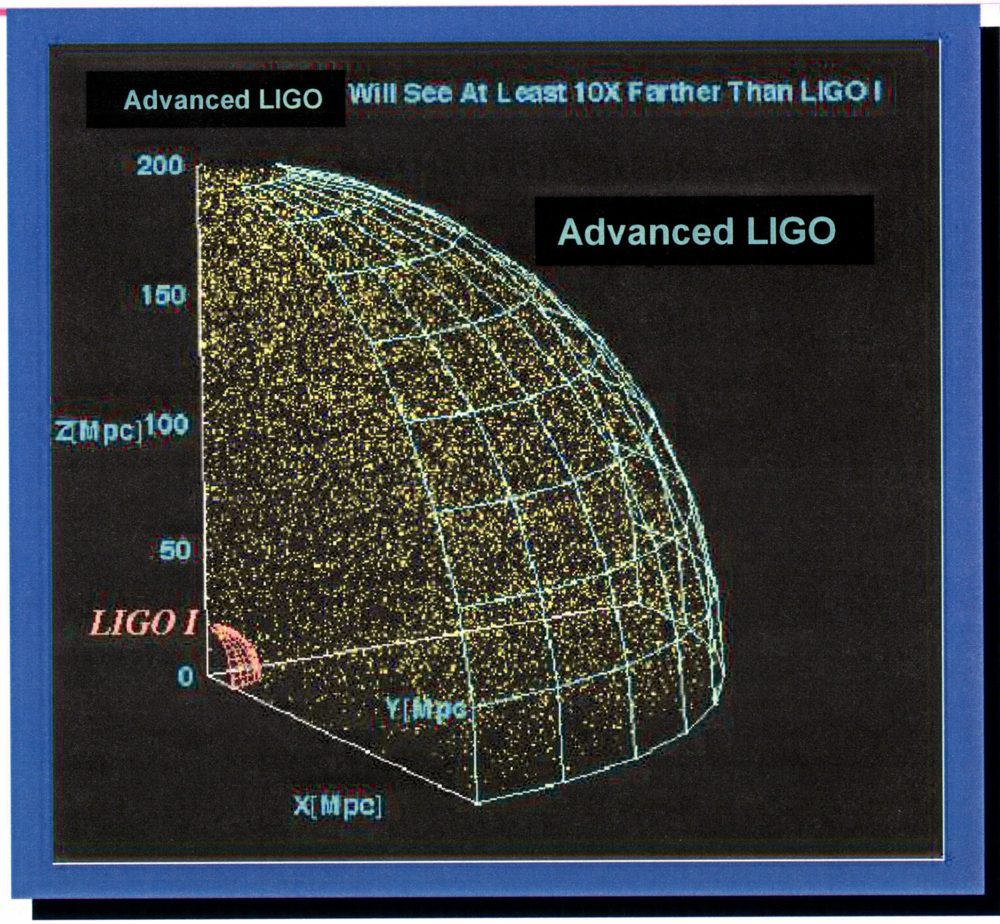
LIGO Commissioning and the First Science Runs



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 $h \sim 10^{-21}$)
2007	Begin ‘advanced’ LIGO installation

Advanced LIGO Reach



Science from a few hours of Advanced LIGO observing should be comparable to 1 year of initial LIGO!

Historical Background

- LIGO was approved for construction of
  - » a platform suitable for successive and additional interferometers
  - » an initial set of interferometers
- 1996 McDaniel report endorsed plans for:
  - » NSF support of an Advanced R&D program to lead to the detectors beyond initial LIGO
  - » formation of a scientific collaboration
    - – LIGO Scientific Collaboration (LSC)
- R&D proposals from LIGO Lab and LSC received late 1996
  - » NSF defined a budget and program in 1998
  - » R&D was organized and initiated in 1997 – 2001 period

Establishing a Supported Development Program

- LSC authored a White Paper on an advanced LIGO detector in 1998 and described a reference concept and R&D program
  - » This was an international R&D program from the start
- LIGO Lab and LSC jointly submitted a revised White Paper and a project conceptual document to NSF in late 1999
  - » Proposed upgrade of 3 interferometers, all 4 km arms, simultaneous installation
  - » Peoples panel endorsed concept and urged support of the development program
  - » NSF decided to support further R&D for Advanced LIGO development

The Current LIGO Laboratory Development Program

- In 2000, LIGO Lab proposed to NSF continuation of LIGO operations and R&D for the period FY2002 – FY2006
  - » Program and budget included support of
    - – Operating initial LIGO
    - – Analyzing data and producing science
    - – Developing Advanced LIGO through Final Design
  - » Permanent LIGO staff scientists and engineers engaged in Advanced LIGO development were to be supported from the basic operating budget
  - » Equipment, fabrications, incremental labor were to be supported from an Advanced R&D budget line

Proposal Budget
LIGO Operations (2002 – 2006)

	FY 2001 ($M)	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)	Total 2002-6 ($M)
Currently funded Operations	22.92	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	2.70	2.77	2.86	2.95	3.04	3.13	14.76
R&D Equipment for LSC Research		3.30	3.84	3.14			10.28
Total Budgets	25.62	34.91	36.21	35.93	33.77	34.74	175.57

FY 2001 currently funded Operations ($19.1M for ten months) is normalized to 12 months and provided for comparison only and is not included in totals.

"Revised" Proposal Budget LIGO Operations (2002-2006)

- $28 million provided for FY 2002 Operations in February and May 2002
  - » Reduced or deferred hiring, Adv R&D, equipment, outreach, etc
- Priority for commissioning and toward LIGO 24x7 Operations
- Full $33 million awarded for FY2003 (6 months late)

	FY 2002 ($M)	FY 2003 ($M)	FY 2004 ($M)	FY 2005 ($M)	FY 2006 ($M)
Operations	$24	$29	$30	$30	$30
Advanced R&D	$4	$4	$3	$3	$3

Funding for LIGO Laboratory Program

- NSF award for continuing LIGO operations is at a level less than requested
- FY2003 appropriations delayed 6 months
- Initial LIGO operations and data analysis/science is highest priority
- Nevertheless, the Advanced LIGO development program has accomplished much of what was proposed
  - » The LSC has been a full partner in all of these activities
  - » Advanced LIGO R&D not run as a firm project though we are ready

A Development Project Across the LSC

Since late 1999, we have planned the Advanced LIGO development program as if it was part of a construction project

- » Work Breakdown Structure
- » Cost estimate
- » Schedule
- » Management structure
- » Requirements documented and systems engineering and modeling
- » Design process established

This "projectized" development program has been operating in a serious collaborative manner across the LSC

- » LSC Working Groups
  - – Advanced detector configurations working group
  - – Core optics working group
  - – Laser working group
  - – Suspensions working group

LIGO

Advanced LIGO Proposal

- R&D through final design and full prototypes now underway
  - » supported by LIGO and partner funds already awarded
  - » a true LSC-wide activity
- Proposal requests funding for the construction
  - » $123 million beginning in 2005
  - » Some early purchases in 2004
- International partners propose support of additional $25.5 million
  - » GEO (UK) - $11.5 million **(approved)** ✓ Hough, Willke
  - » GEO (Germany) - $11.5 million
  - » ACIGA - $2.5 million McClelland

What are we proposing?

- Replace all three interferometers
  - » Provides **sensitive** suite of detectors during "discovery" phase
  - » Versatile and robust during post-detection exploration
- Convert current 2 km interferometer in Hanford to a 4 km interferometer
  - » Emphasis placed upon **sensitivity**
  - » Cost is a fraction of one percent of the project

Shoemaker

Phasing of Interferometer Replacements

- Initial LIGO installation and commissioning taught us many lessons
  » How to effectively use expert teams
  » How to properly phase rework and installation
  » How to interleave installation with early commissioning
  » How to transfer lessons from one interferometer to the others
  » **Properly phasing the work on the three interferometers can optimize the progress**
  » **Complete R&D before final installation**
- Minimizing scientific "down time" is a major goal of the LSC
  » How we accomplish this should be coordinated with the international network of detectors through the Gravitational Wave International Committee
- Installation into LIGO vacuum system should take place after prototype program retires most risk
  » R&D program tests advanced prototypes fully

Phasing Implementation of the 3 Interferometers

- Replacing all 3 interferometers simultaneously
  - » minimizes duration of LIGO down time
  - » very expensive in expert staffing and resulting rework
- Strict serial replacement of 3 interferometers
  - » reduces duplication of skilled teams and tooling
  - » maintains at least one interferometer operating as much as possible
  - » stretches out period before the upgraded set of detectors is available
- Rapid and overlapping phasing of replacement/upgrade ✓
  - » Balances application of skilled teams and resources with scientific imperative to bring set of detectors on line
- International community and scientific review will enable us to further optimize this balance

Buildup of Education and Outreach

- LIGO Lab outreach has been primarily observatory centered
- LIGO Lab renewal called for increased activity
- Supported new effort and formed a strategy and Local Educator's Networks at each observatory
- This process led to a new proposal with partners for a greatly expanded program
  - » Next slide has some details
- NSF is beginning an effort to produce a "half-hour" video on LIGO
- **Advanced LIGO proposal calls for an LSC-wide education and outreach program**

LSC Outreach Program Startup

- FY2004 – Recruit LSC Outreach Director and assistant
- FY2004 – Survey all LSC education and outreach activities and develop a descriptive survey document
- FY2004 – Formation of LSC Educators Advisory Network
- FY2004 – August 2004 LSC meeting hosts an additional two day LSC Outreach Workshop at which all LSC activities are showcased and attendees, including outside consultants and advisory network members participate in design discussions for an enhanced, coordinated LSC program
- FY2005 – LSC Outreach Director develops detailed program plan with review meetings and educators advisory network participation
- FY2005 – March 2005 LSC meeting hosts one day LSC Outreach Workshop to finalize and approve program plan
- FY2005 – Initial elements of the plan implemented
- FY2005 – Supplemental proposals to NSF are submitted as necessary
- FY2006 – Initial operation of the coordinated LSC outreach programs

February 2003 Proposed Education & Outreach Program

- Proposal submitted to NSF Feb. 10 for major enhancement to outreach activity:
  - » Collaboration of Caltech, SUBR, La Board of Regents, Exploratorium of San Francisco
- Construct an educational outreach center on-site at LLO.
- Place hands-on exhibits from Exploratorium in center (with subset at LHO).
- Implement teacher pre-service and in-service training initiative to teach inquiry based science techniques at SUBR – extend to LHO communities
- Use LIGO staff to provide science leadership in selection of exhibits, development of science content in teacher training programs
- La Board of Regents, through La Systemic Initiative with leveraged resources from US Dept of Education LA GEAR UP program, will facilitate teacher training and student visits to outreach center from underserved communities.

Advanced LIGO In Context

- LIGO construction is complete
  - » NSF investment in LIGO now totals about $400 million
  - » Construction cost $292 million
  - » LIGO facilities represent ~ 2/3 of the construction investment and are intended to support successive detectors
- Initial LIGO detectors are operating and have carried out early scientific running
  - » Initial LIGO should accomplish its sensitive observation by late 2006
- Advanced LIGO development is defining the detailed design and retiring risks
- The experienced LIGO team will be ready to install Advanced LIGO in 2007
- Observations for probable gravitational wave detection can commence in 2010

Mission and Strategy

- Observe gravitational waves directly
- Initiate gravitational wave astronomy
- Bring initial LIGO to design sensitivity and observe for one integrated year at that sensitivity
  - » "plausible" chance to detect gravitational waves
- Upgrade detector with a very significant increment in sensitivity
  - » "probable" detection of gravitational waves

Plenary Talks

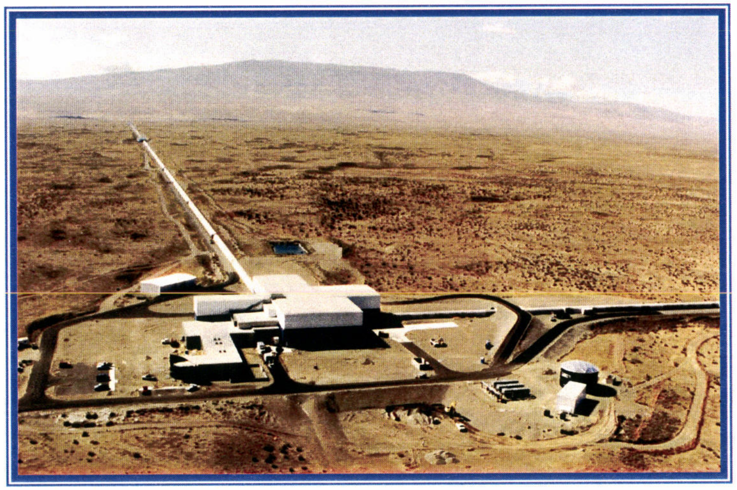
- LIGO Overview – Sanders
- LIGO Commissioning and First Results – Whitcomb
- Astrophysics – Thorne
- Advanced LIGO – Shoemaker
- Cost, Schedule and Management - Sanders

LIGO

Specific Charge

- Is the scientific case for the needed upgrade convincing? Are the scientific requirements achieved in a cost-effective manner?
- Is the specific proposed Advanced Detector upgrade appropriate to accomplish the scientific goals? In particular, is the decision to convert the 2-km Hanford interferometer to a second 4-km interferometer well founded, and will the specific subsystems each meet the required performance specifications?
- Are the requested budget (including contingency) and manpower levels appropriate to carry out the proposed upgrade?
- Are the schedule and milestones achievable with the proposed resources? Does the phasing of the downtime of detectors achieve a proper balance of cost, manpower, and observation time?
- Is the proposed management plan appropriate to oversee the R&D, construction, installation and commissioning of the upgrade?
- Has the issue of cost effectiveness in operating the more complex Advanced LIGO system been addressed?
- Is the proposed education and outreach plan well designed, and are the proposed manpower and funds appropriate to carry it out?

Initial LIGO Commissioning and First Observations



Stan Whitcomb

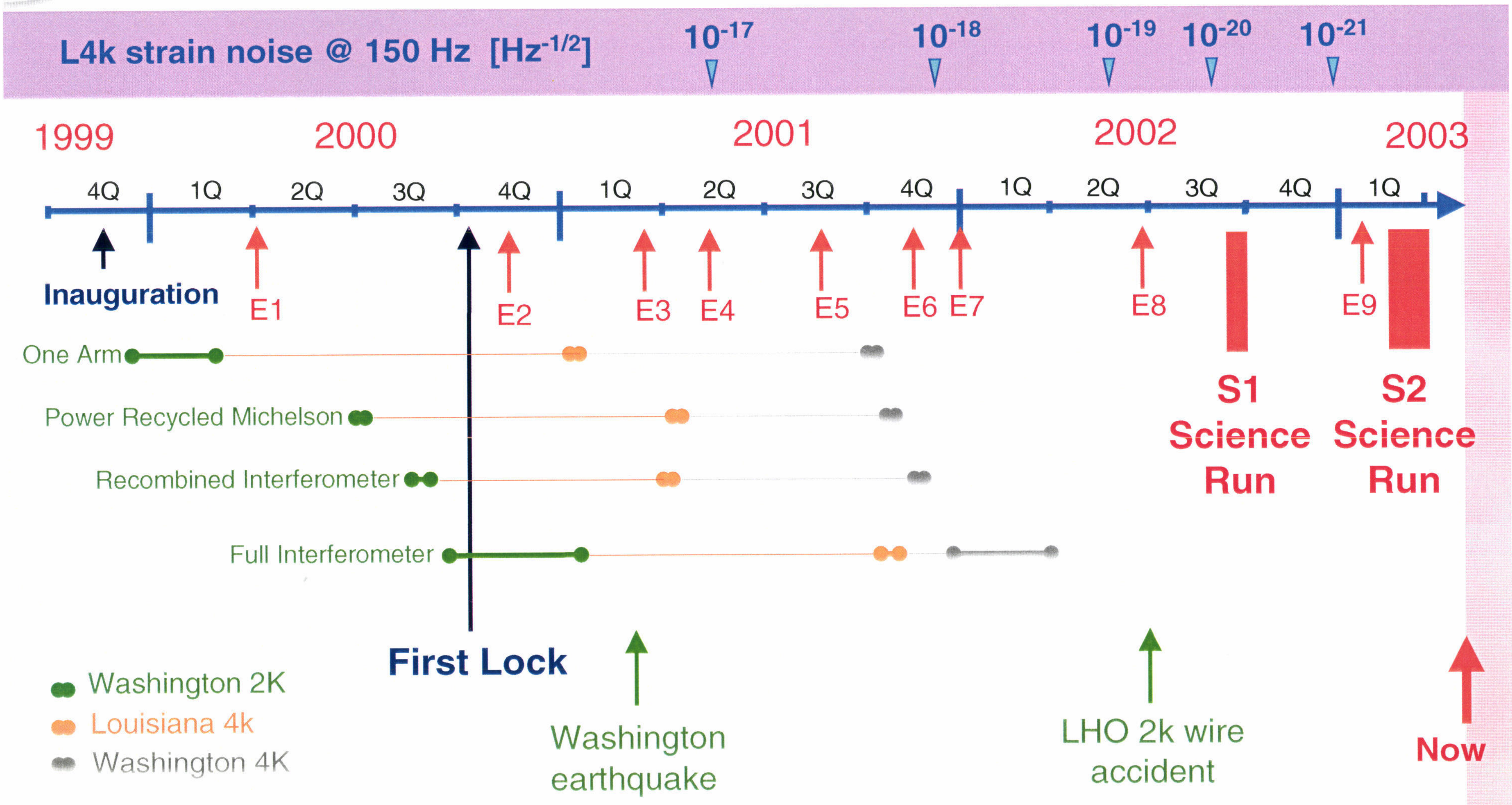
NSF AdvLIGO Review

Caltech

11 June 2003

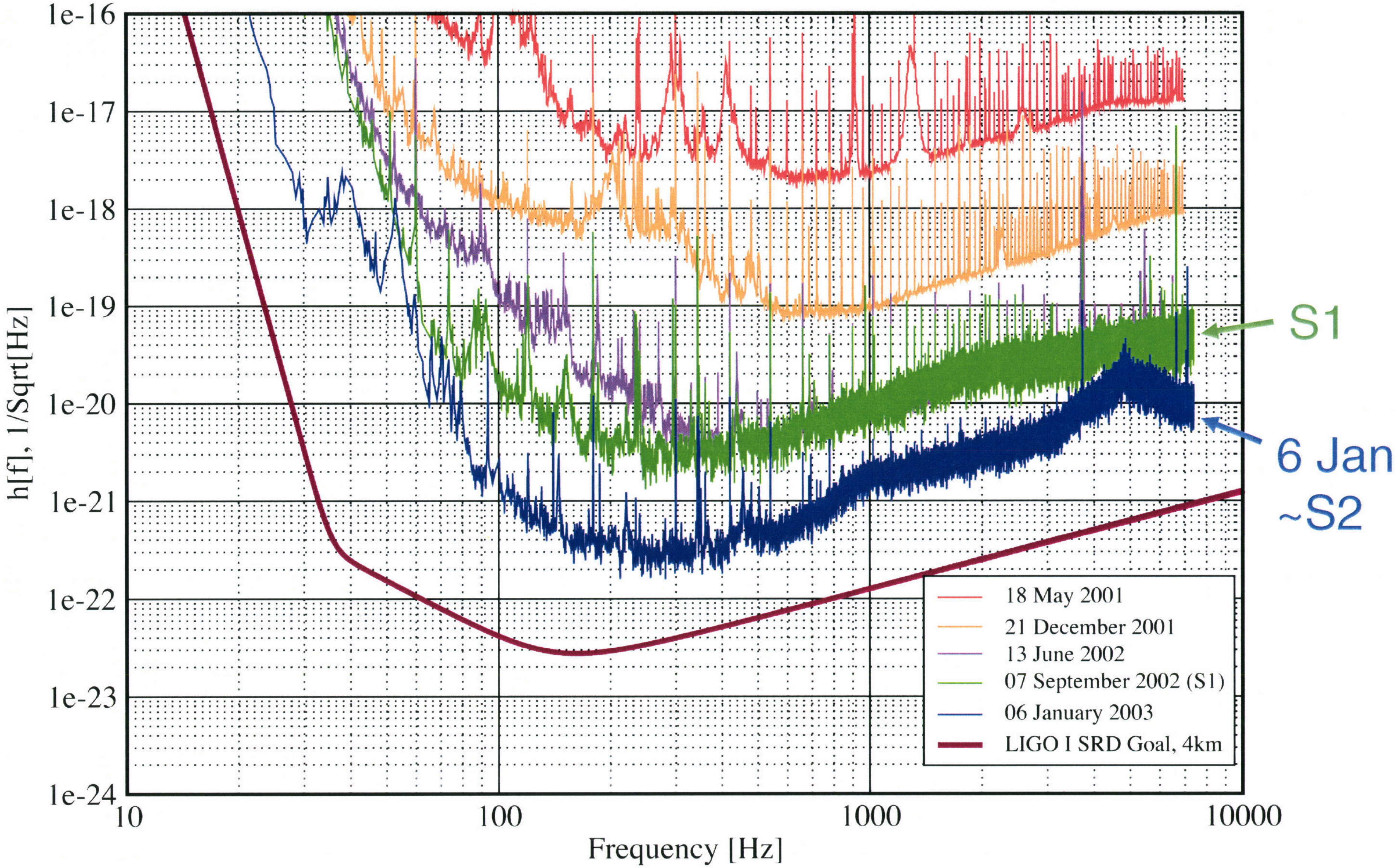
LIGO-G030280-00-D

Commissioning History



Strain Sensitivity for the LLO 4km Interferometer

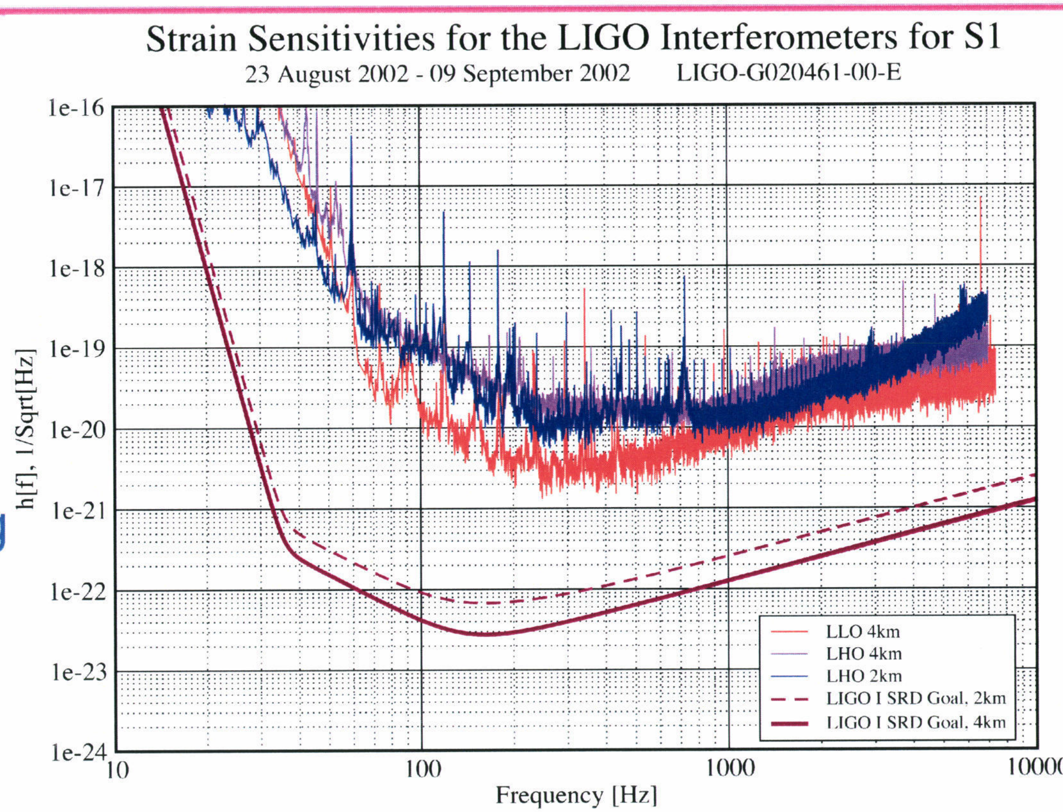
31 January 2003 LIGO-G030014-00-E



LIGO

First Science Run (S1)

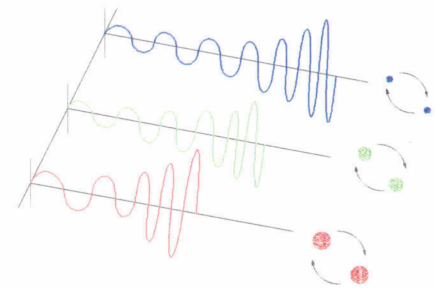
- August 23 - September 9 (~400 hours)
- Three LIGO interferometers, plus GEO (Europe) and TAMA (Japan)
- Hardware reliability good for this stage in the commissioning
  - » Longest locked section for individual interferometer: 21 hrs



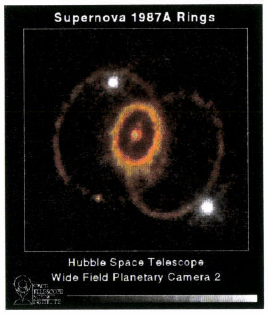
	LLO-4K	LHO-4K	LHO-2K	3x Coinc.
Duty cycle	42%	58%	73%	24%

LIGO Astrophysical Searches with S1 Data

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

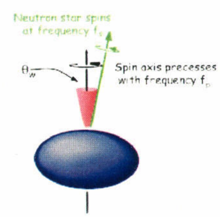


- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagn
  - » prompt alarm

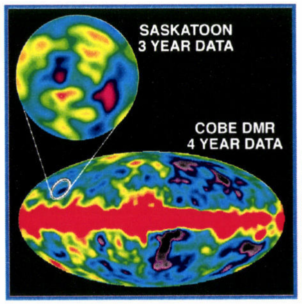


Four papers describing results in final stages of preparation

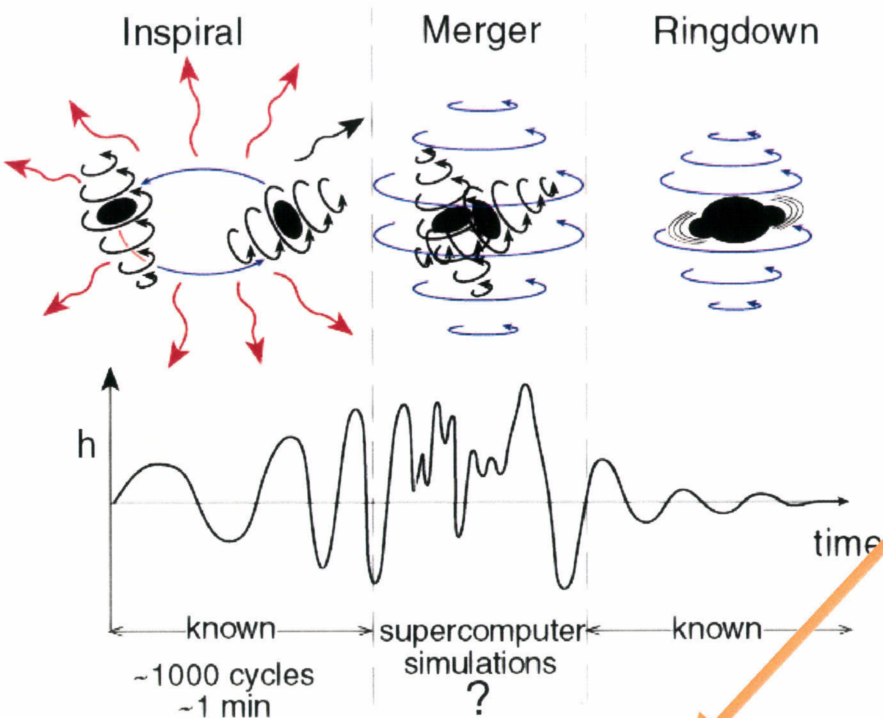
- Pulsars in our
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes



- Cosmological Signals *"stochastic background"*



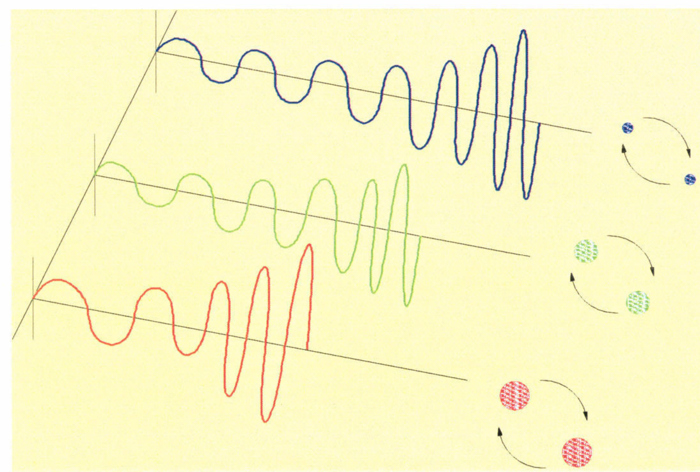
Compact Binary Coalescence



» Search: *matched templates*

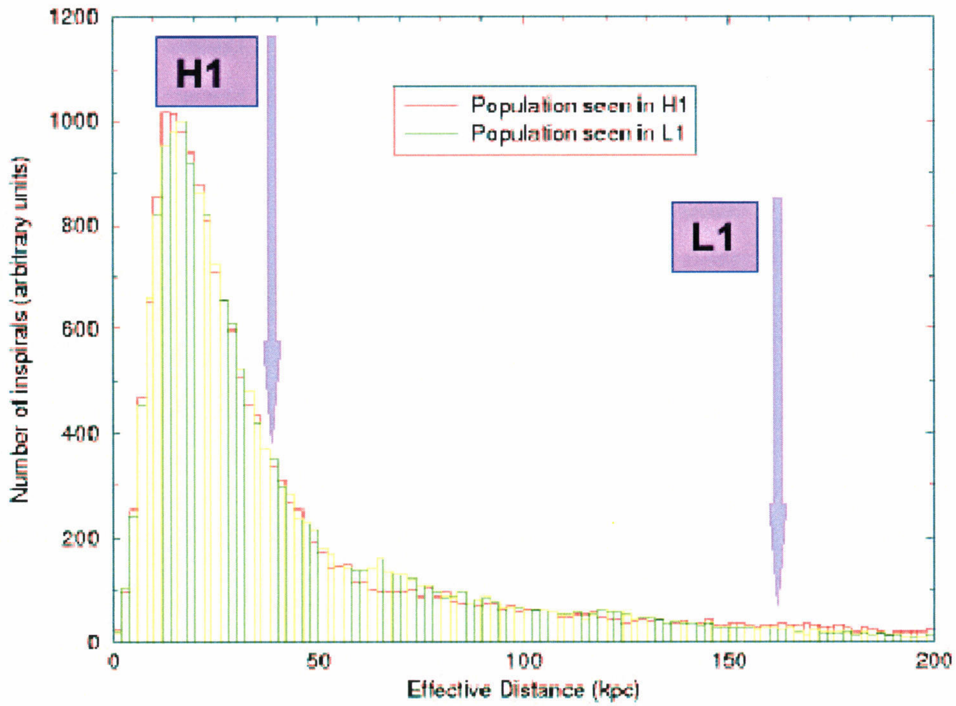
» Neutron Star – Neutron Star
  - **waveforms are well described**

» Black Hole – Black Hole
  - **need better waveforms**



- Discrete set of templates labeled by (m1, m2)
  - » 1.0 Msun < m1, m2 < 3.0 Msun
  - » 2110 templates
  - » At most 3% loss in SNR

Results of S1 Inspiral Search



Simulated Galactic Population

- Population includes Milky Way, LMC and SMC
- LMC and SMC contribute ~12% of Milky Way

LIGO S1 Upper Limit

R < 160 / yr / MWEG

» Japanese TAMA → R < 30,000 / yr / MWEG

» Caltech 40m → R < 4,000 / yr / MWEG

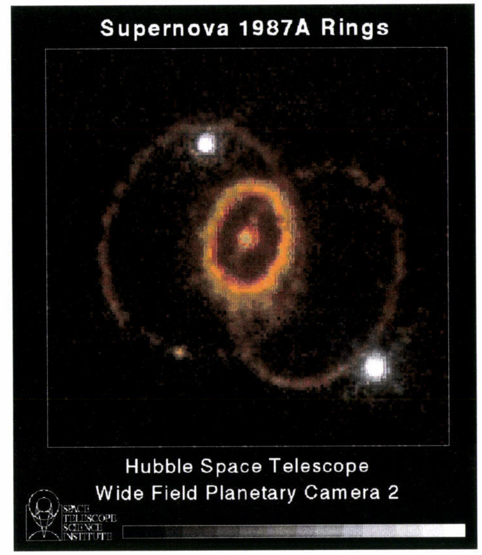
- Theoretical prediction R < 2×10^{-5} / yr / MWEG

Detectable Range for S2 data will reach Andromeda!

LIGO

Burst Sources

- **Known sources -- Supernovae & GRBs**
  » **Coincidence with observed electromagnetic observations.**
    » **No close supernovae occurred during the first science run**
    » **Second science run – We are analyzing the recent very bright and close GRB030329**
    NO RESULT YET



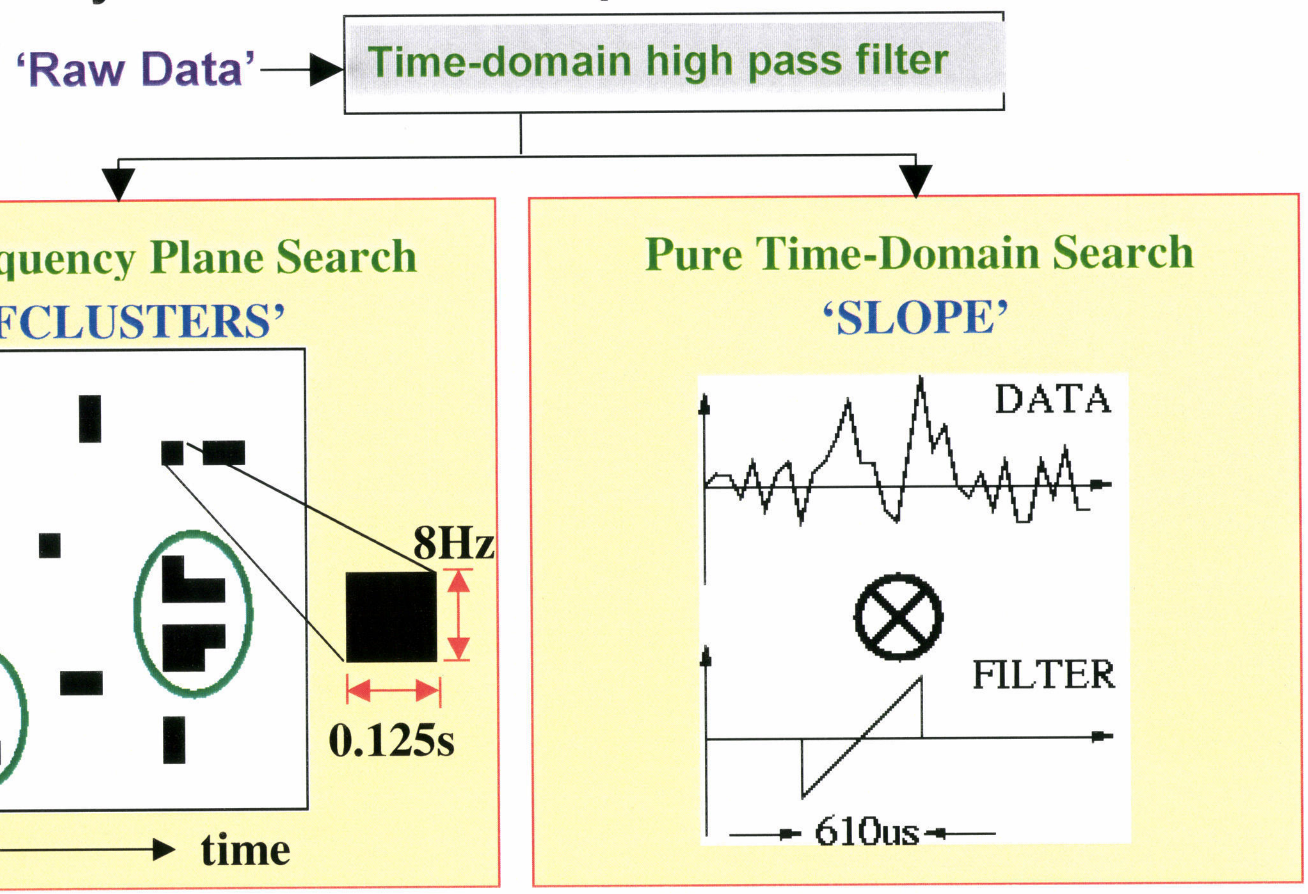
- **Unknown phenomena**
  » **Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).**

S1

'Unmodelled' Burst Search

GOAL search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

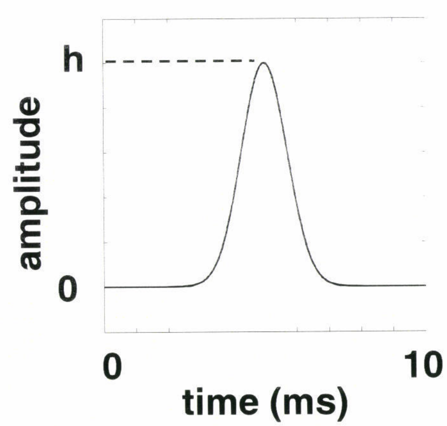
METHODS



Determination of Efficiency

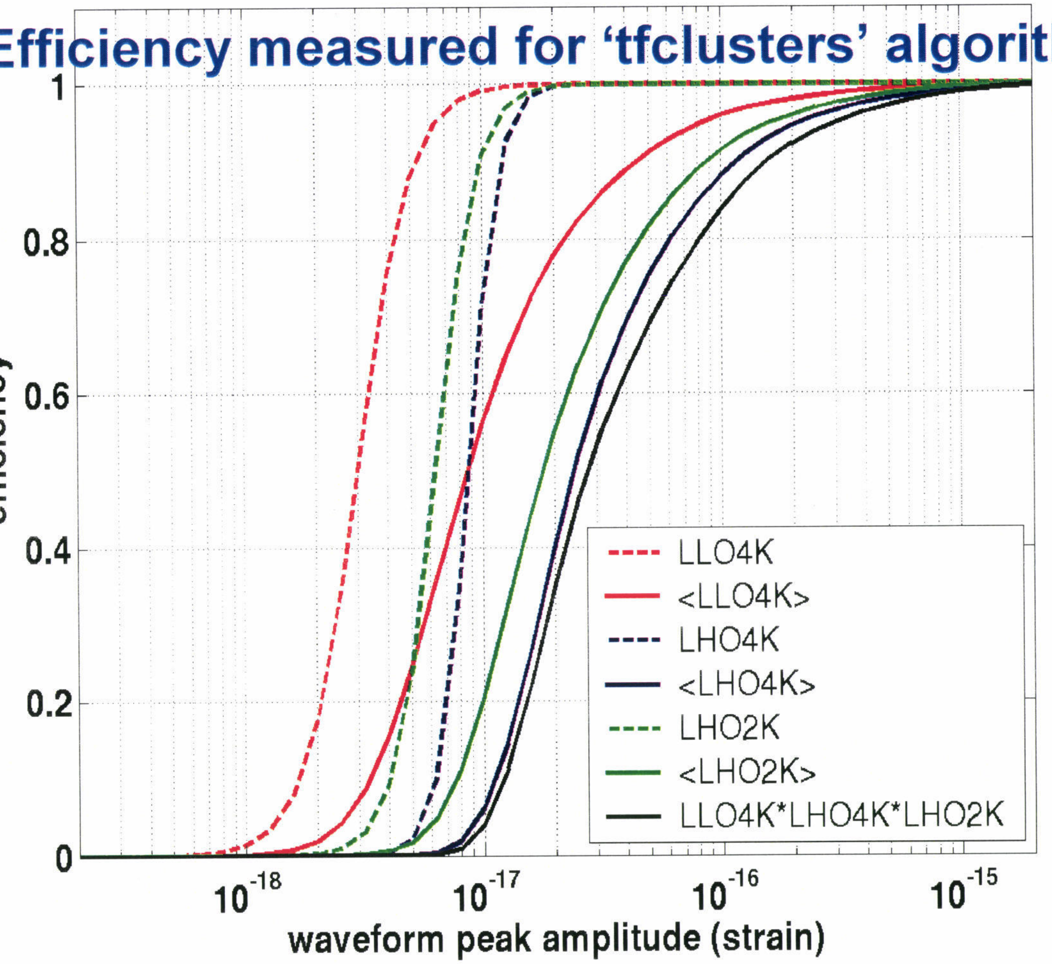
To measure our efficiency, we must pick a waveform.

1ms Gaussian burst



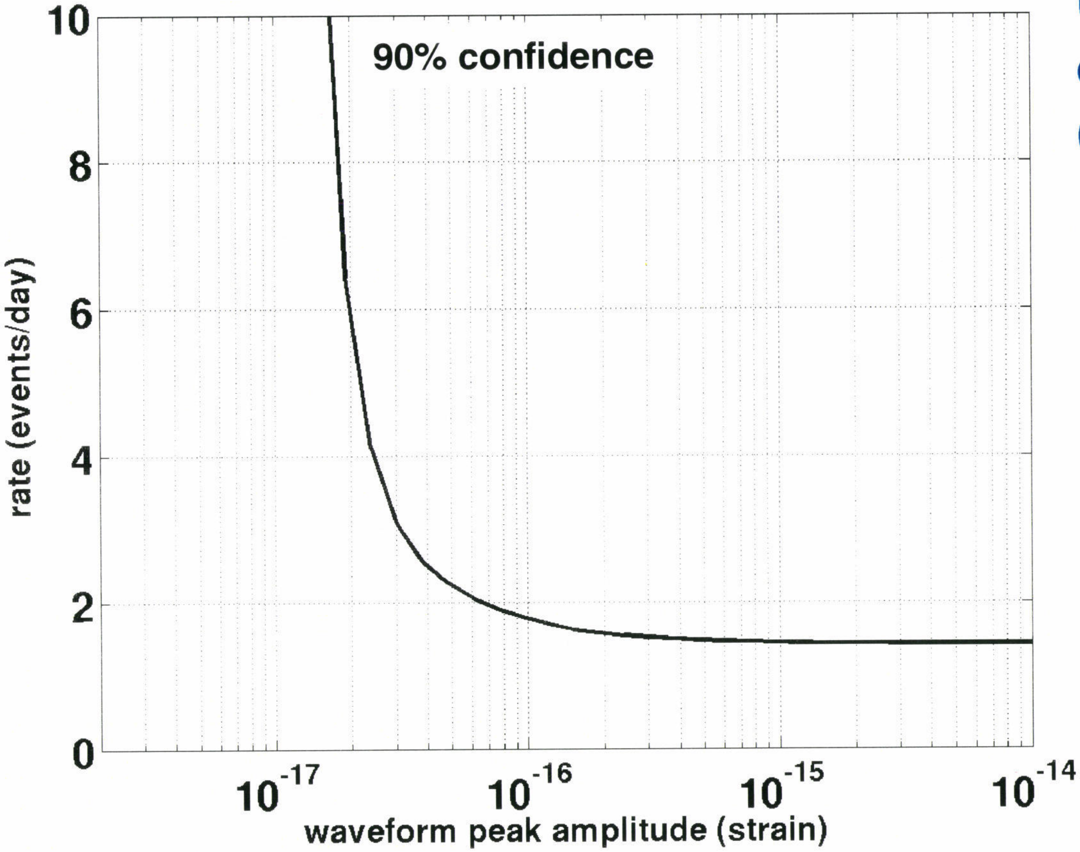
Detector efficiency vs amplitude, average over sources. GA tau=1.0ms

Efficiency measured for 'tfclusters' algorithm



Upper Limit
1ms gaussian bursts

Result is derived using 'TFCLUSTERS' algorithm

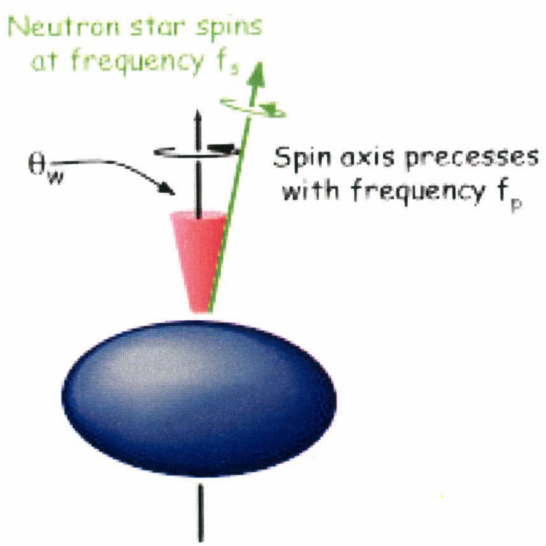


Upper limit in *strain* compared to earlier (cryogenic bar) results:

- **IGEC 2001 combined bar upper limit: < 2 events per day having $h=1x10^{-20}$ per Hz of burst bandwidth. For a 1kHz bandwidth, limit is < 2 events/day at $h=1x10^{-17}$**
- **Astone *et al.* (2002), report a one sigma excess of one event per day at strain level of $h \sim 2x10^{-18}$**

Periodic Sources

- Pulsars in our galaxy:
  - » search for observed neutron stars
  - » all sky search (computing challenge)
  - » r-modes

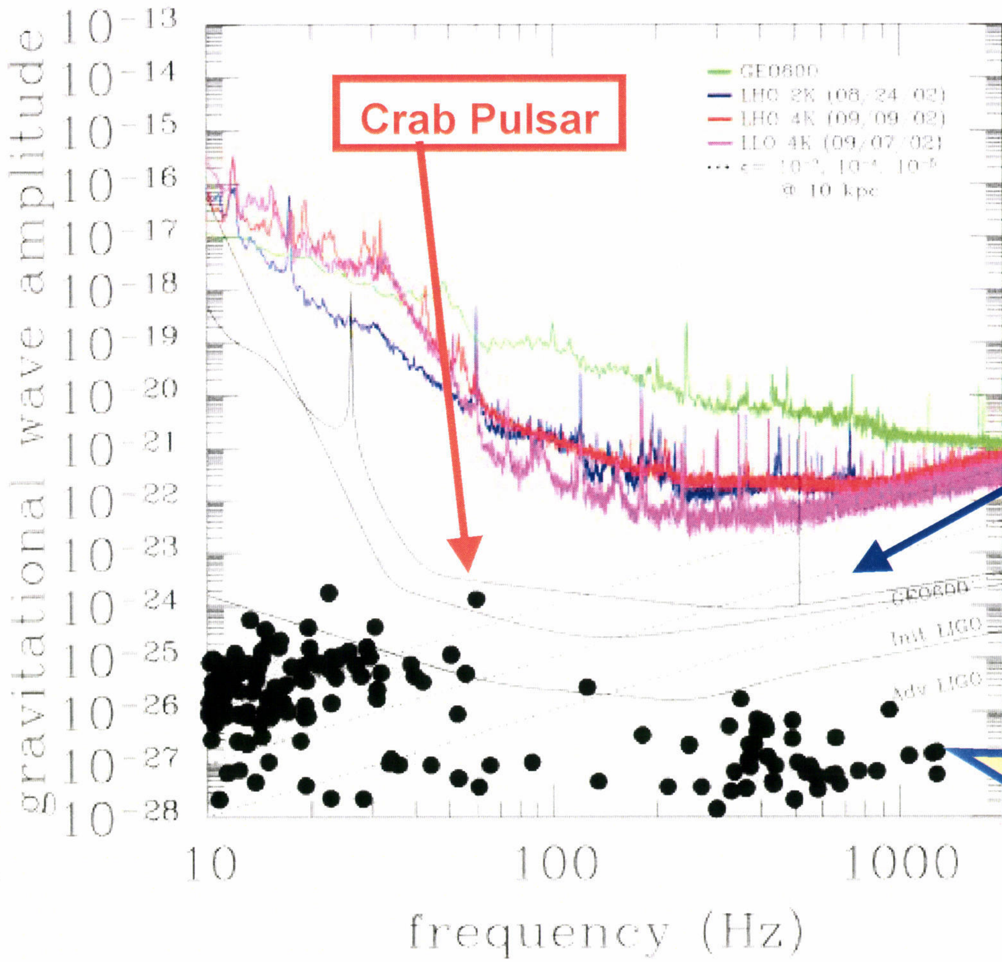


- **Frequency modulation of signal due to Earth's motion**
- **Amplitude modulation due to the detector's antenna pattern.**

Directed Search in S1

NO DETECTION EXPECTED

at present sensitivities



Predicted signal for rotating neutron star with equatorial ellipticity $\varepsilon = \delta I/I$ **:** 10^{-3} **,** 10^{-4} **,** 10^{-5} **@ 8.5 kpc.**

PSR J1939+2134

1283.86 Hz

LIGO

Two Search Methods

Frequency domain

- Best suited for large parameter space searches
- Maximum likelihood detection method + frequentist approach

Time domain

- Best suited to target known objects, even if phase evolution is complicated
- Bayesian approach

First science run --- use both pipelines for the same search for cross-checking and validation

Results: PSR J1939+2134

- No evidence of continuous wave emission from PSR J1939+2134.
- Summary of 95% upper limits on h:

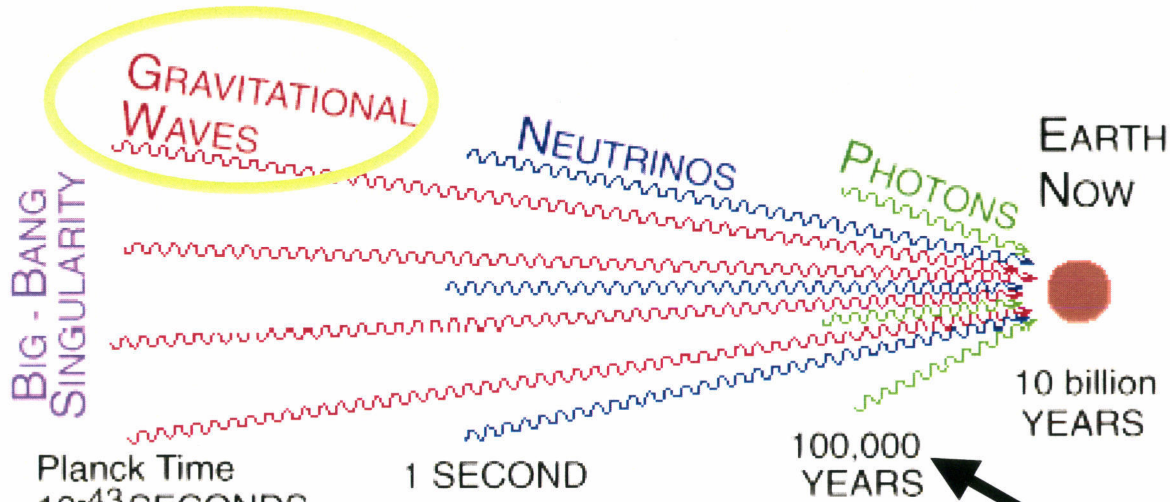
IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.94 \pm 0.12) \times 10^{-21}$	$(2.1 \pm 0.1) \times 10^{-21}$
LLO	$(2.83 \pm 0.31) \times 10^{-22}$	$(1.4 \pm 0.1) \times 10^{-22}$
LHO-2K	$(4.71 \pm 0.50) \times 10^{-22}$	$(2.2 \pm 0.2) \times 10^{-22}$
LHO-4K	$(6.42 \pm 0.72) \times 10^{-22}$	$(2.7 \pm 0.3) \times 10^{-22}$

- **Best previous results for PSR J1939+2134:**

$h_o < 10^{-20}$ (Glasgow, Hough et al., 1983)

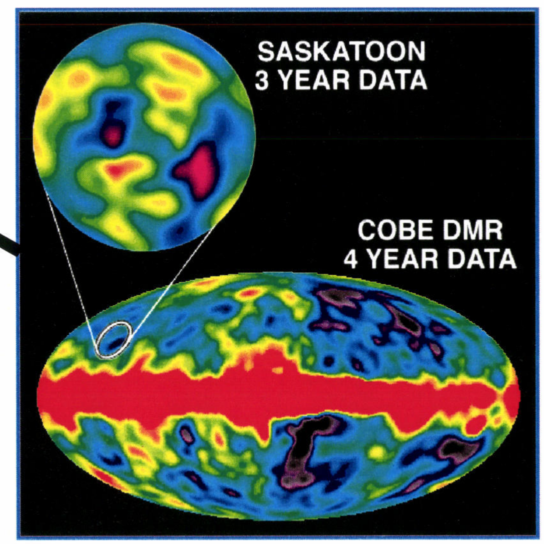
Early Universe
stochastic background

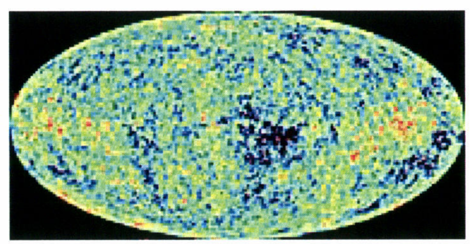
'Murmurs' from the Big Bang



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

Cosmic Microwave background



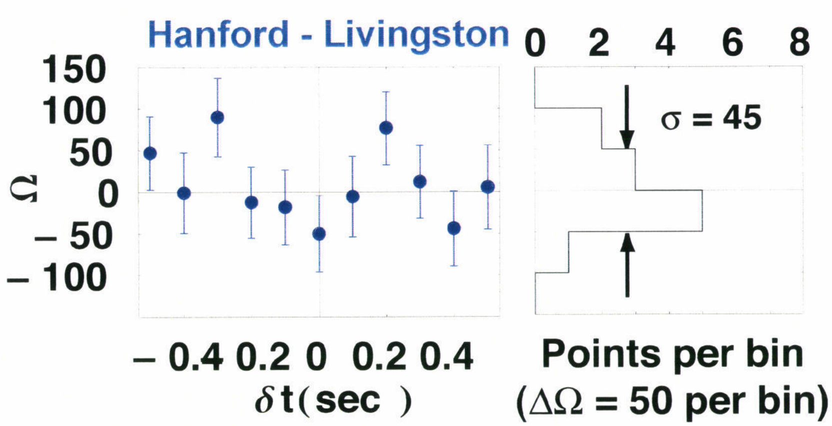

WMAP 2003

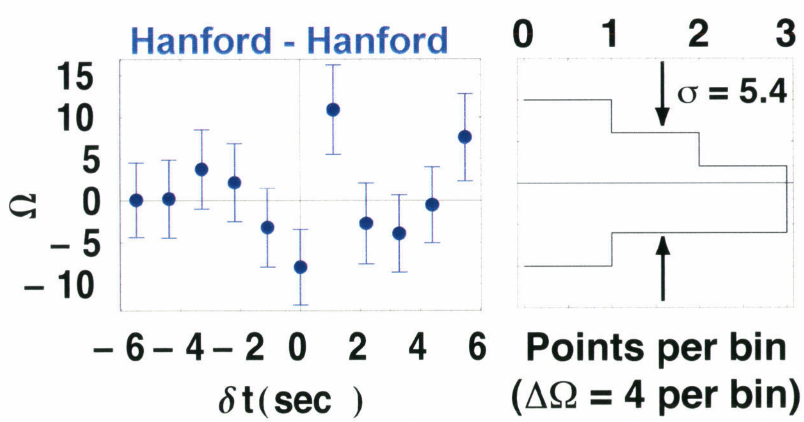
Stochastic Background

- Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)}$$

- Detect by *cross-correlating* output of two GW detectors:



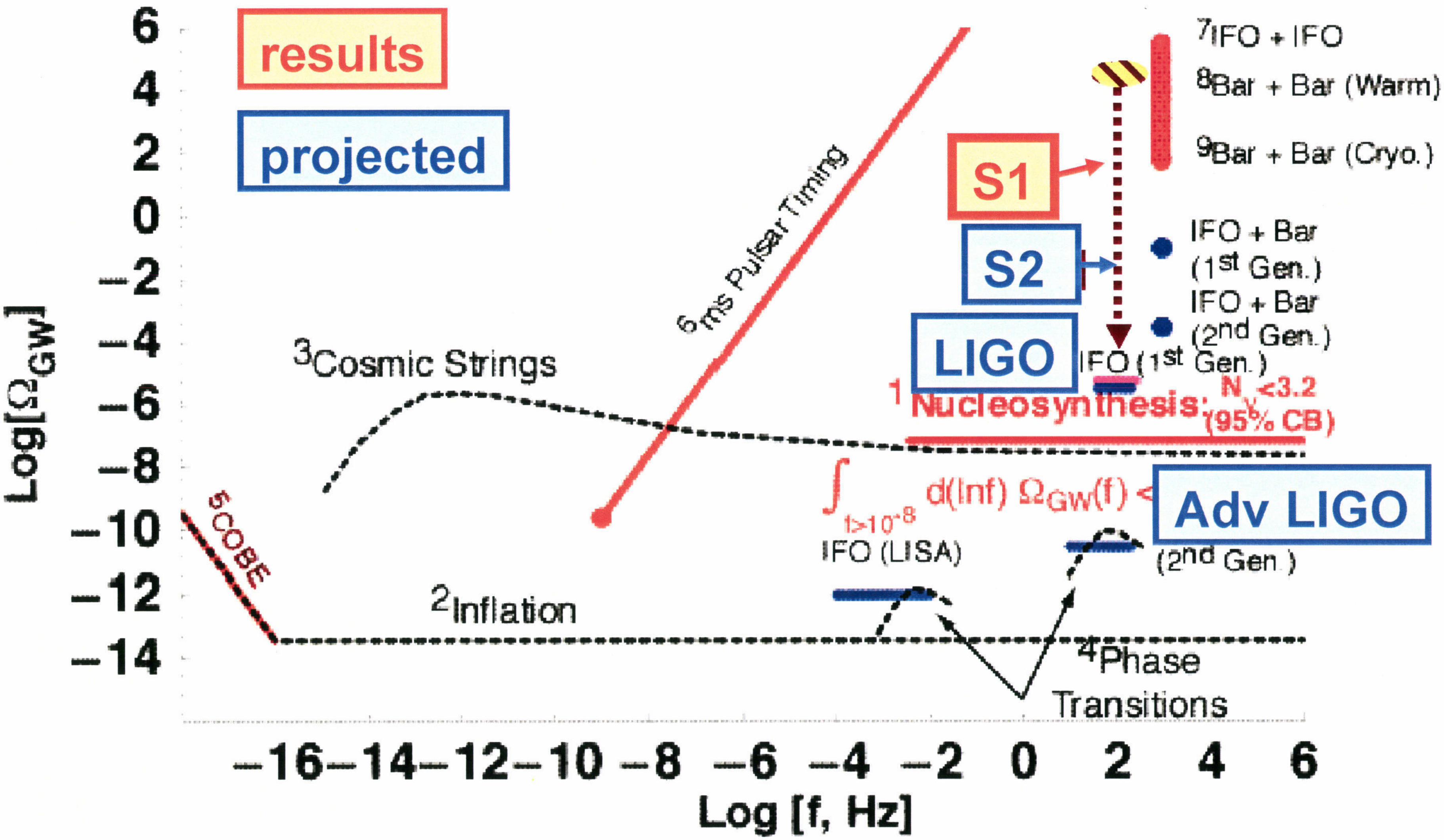


Preliminary Limits: Stochastic Search

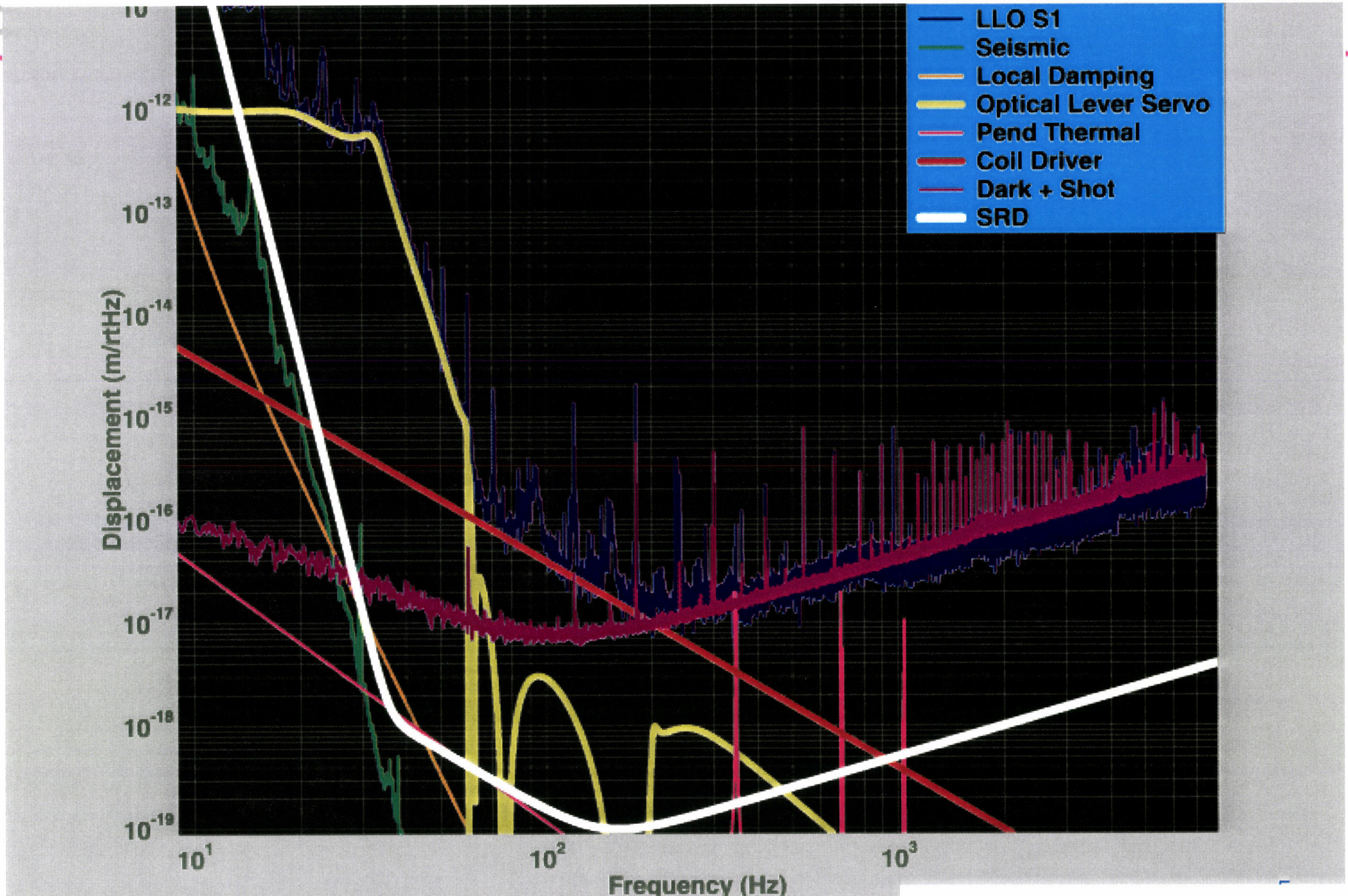
Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 72.4	62.3 hrs
LHO 2km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 23	61.0 hrs

- Non-negligible LHO 4km-2km (H1-H2) instrumental cross-correlation; currently being investigated.
- Previous best upper limits:
  - *Measured:* Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times10^5$
  - *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907Hz) < 60$

Stochastic Background
sensitivities and theory



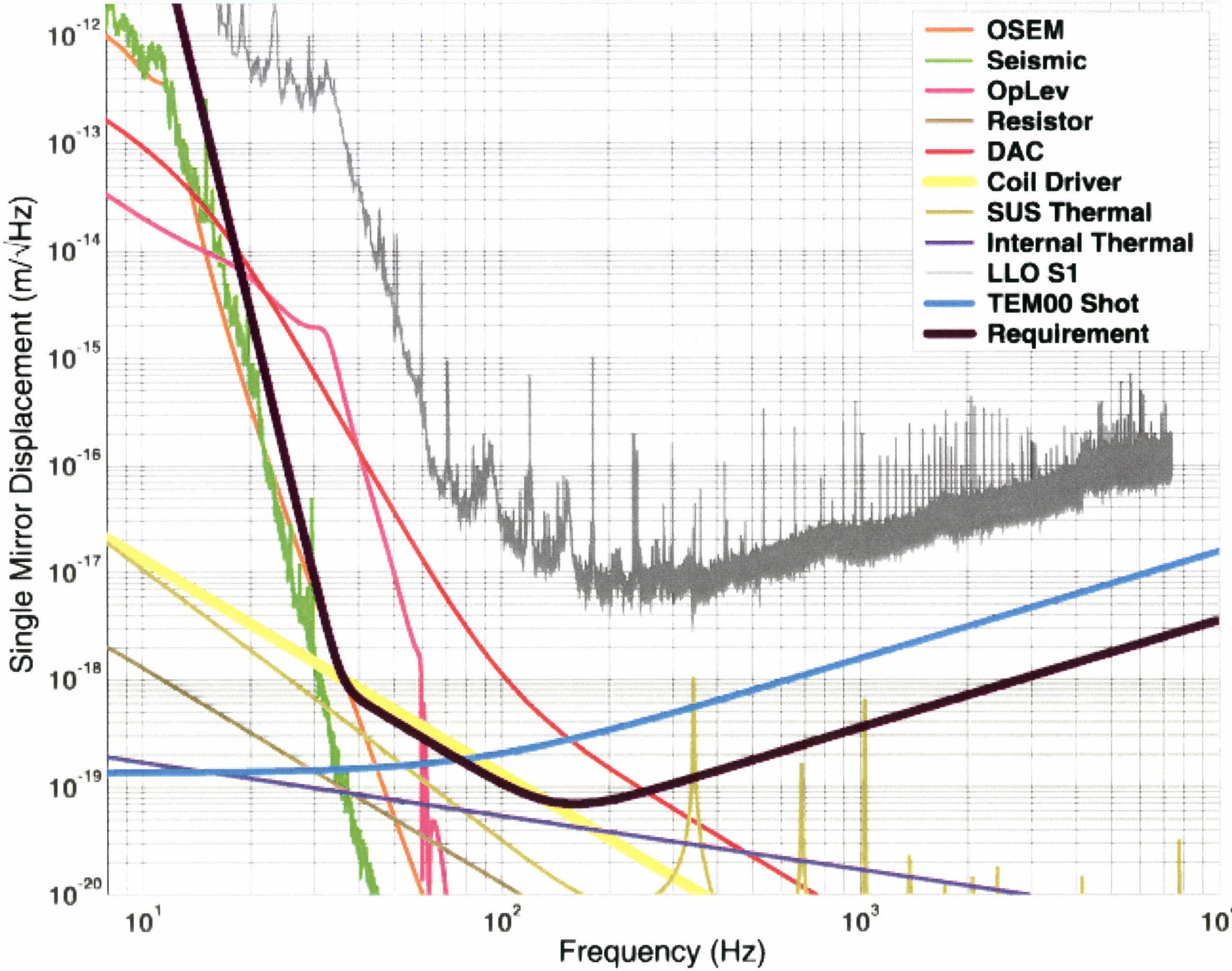
S1 Noise Component Analysis, LLO 4k

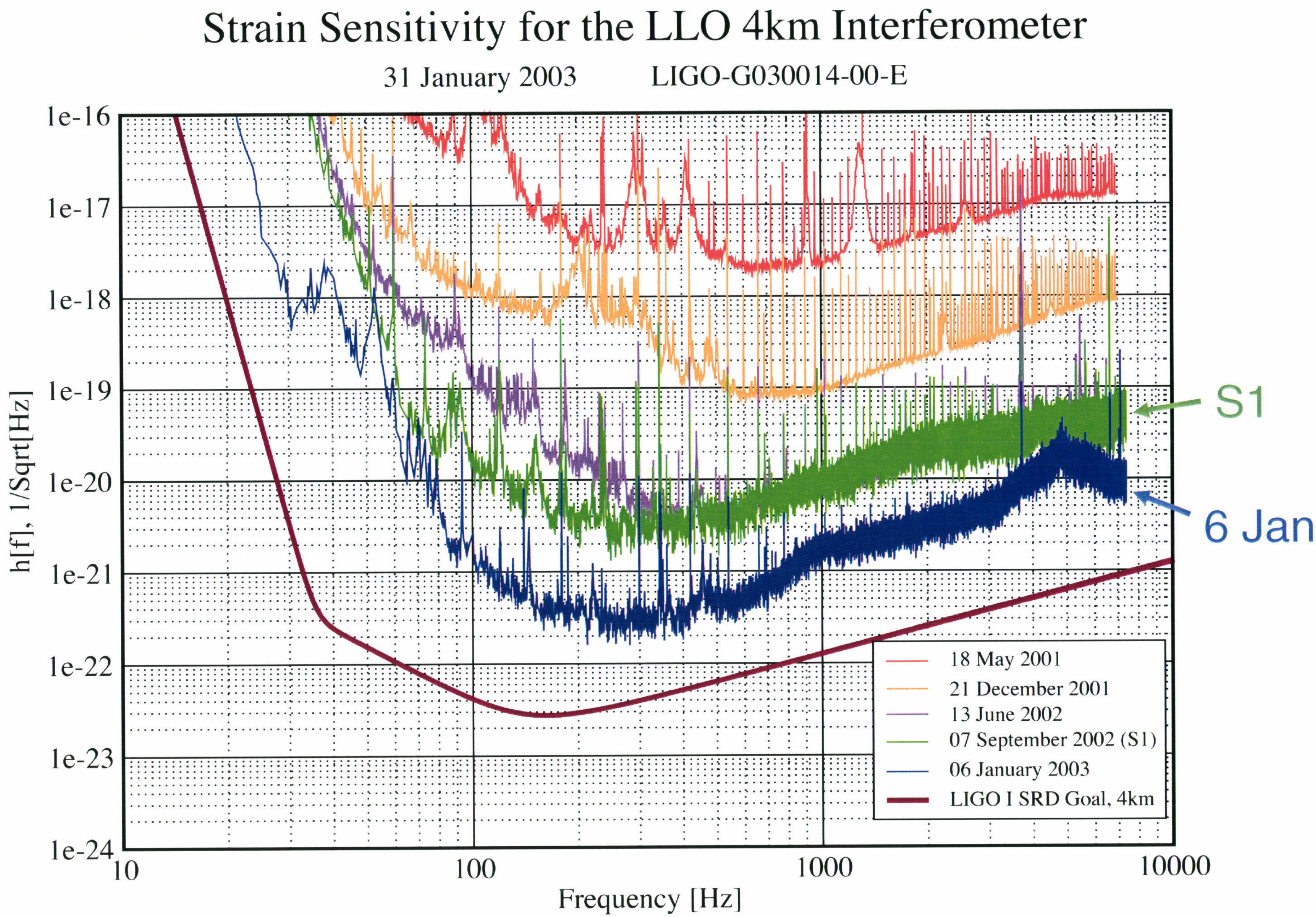


G020482-00-D

Rana Adhikari noise analysis

Estimated Noise Limits for S2 (as planned in October 2002)




Strain Sensitivity for the LLO 4km Interferometer
31 January 2003
LIGO-G030014-00-E
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
18 May 2001
21 December 2001
13 June 2002
07 September 2002 (S1)
06 January 2003
LIGO I SRD Goal, 4km
S1
6 Jan

Changes Between S1 and S2

- Digital Suspensions installed on LHO-2K and LLO-4K
  - New coil drivers & realtime control code for suspensions
  - Lower noise, switchable dynamic range (200 mA acquisition, 5 mA running)
  - Separate DC biases for alignment
  - Better filtering, diagonalization and control/sequencing features
- Optical lever improvements
  - Structural stiffening (designed for thermal/kinematic stability, not low vibration)
  - Improved filtering to take advantage of reduced resonances
  - Pre-ADC "whitening" for improved dynamic reserve
- More Power
  - Enabled by better alignment stability
  - Also required control of "I-phase" photocurrent (overload)
  - Now ~ 1.5 W into mode cleaners, ~ 40 W at beamsplitter (*R*~40)
  - Only 10-20 mA average DC photocurrent at dark ports !! (optics very good)

Second Science Run (S2)

- February 14 – April 14, 2002 (~ 1400 hours)
- Three LIGO interferometers and TAMA (Japan)
- Steady improvement in sensitivity continues
  - » Approximately 10x improvement over S1
- Duty cycle similar to S1
  - » Increased sensitivity did not degrade operation
  - » Longest locked stretch ~ 66 hours (LHO-4K)

	LLO-4K	LHO-4K	LHO-2K	3x Coinc.
Duty cycle (cf. S1)	37% (42%)	74% (58%)	58% (73%)	22% (24%)

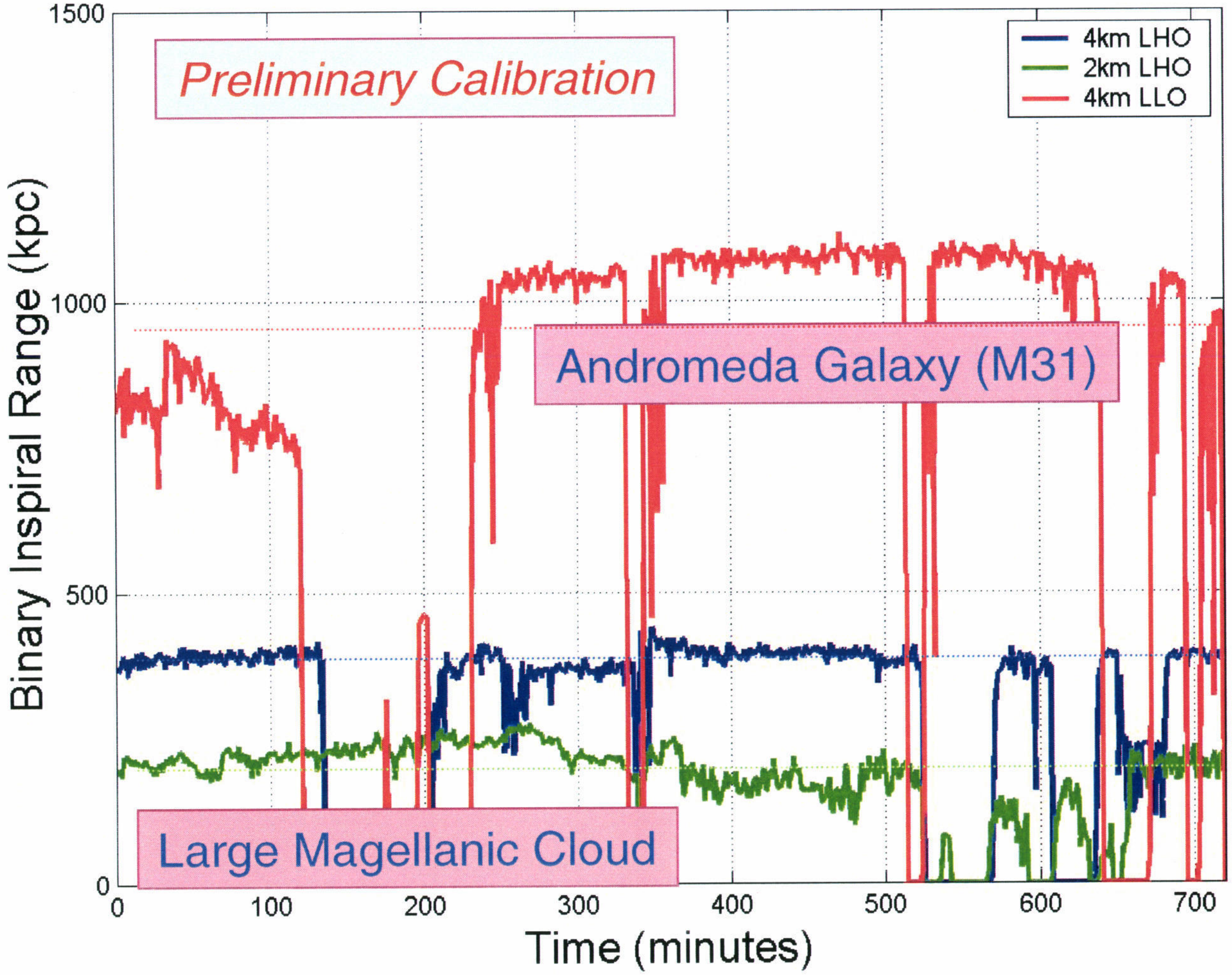
Stability improvements for S2

- Wavefront sensing (WFS) for alignment control
  - » Uses the main laser beam to sense the proper alignment for the suspended optics
  - » Complex! 10 coupled degrees of freedom,
    - – Sensing degrees-of-freedom different from control degrees-of-freedom
- S1:
  - » All interferometers had 2 degrees-of-freedom controlled by WFS
- S2:
  - » LHO-4K: 8 of 10 alignment degrees-of-freedom under feedback control
- Now:
  - » All 10 degrees-of-freedom controlled by WFS

LIGO

Virgo Cluster

S2 Sensitivity and Stability



Major On-going Commissioning Activities

- Seismic retrofit at LLO
- Finish wavefront sensing alignment system
- RFI cleanup, linear power supplies
- Shot noise sensitivity
  - » Thermal lensing
  - » Increase of number of photodiodes
- Acoustic coupling
- Numerous smaller tasks

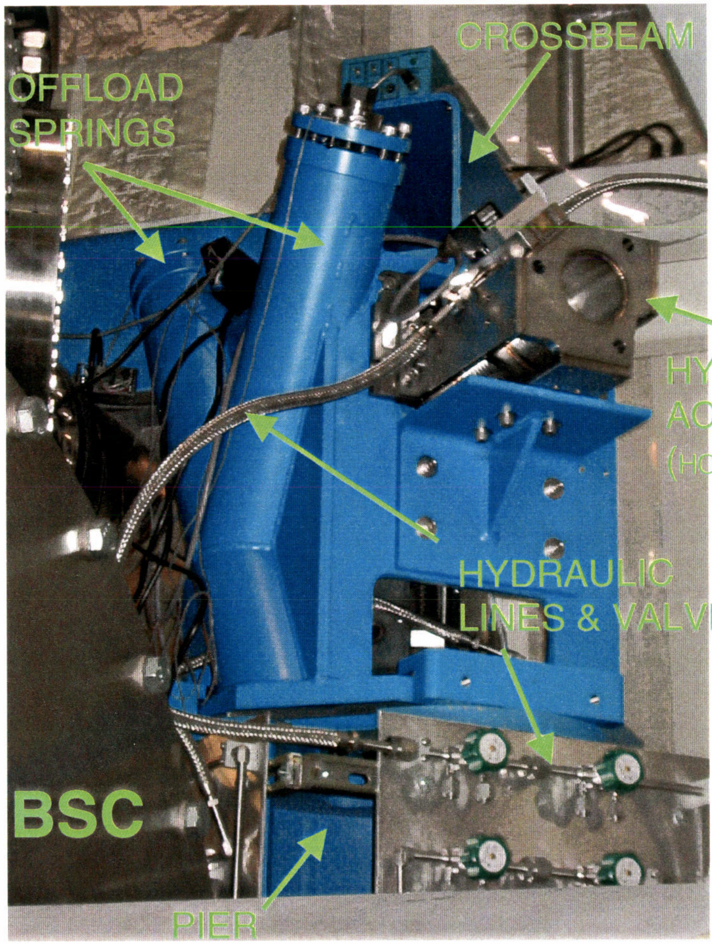
LIGO

Seismic Isolation Upgrade

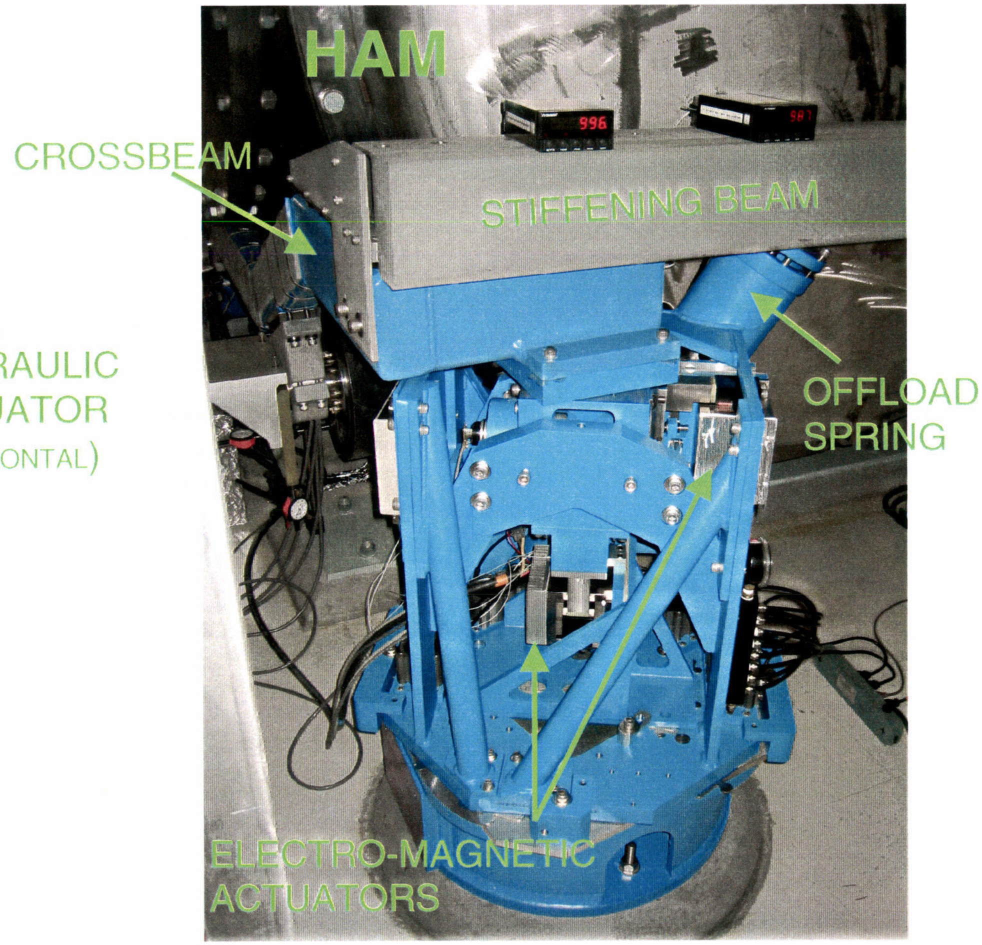
- The Seismic Isolation System at LLO needs to be upgraded
  - » Seismic noise environment much worse below 10 Hz than originally planned (logging largest factor, but also train, other anthropogenic noise)
  - » Plan is to add an active, external pre-isolation (EPI) stage without disturbing the alignment of the installed optics
- Current Plan:
  - » Continue prototype testing at MIT, including testing VME based controls
  - » Review held for 4/18; management decision on how to proceed pending
  - » Order components, fabricate and assemble; fabrication/assembly phase lasts ~5.5 months
  - » Installation starts ~Jan '04 and should complete ~Apr '04

Seismic Isolation Testing at MIT

Hydraulic External Pre-Isolator (HEPI)

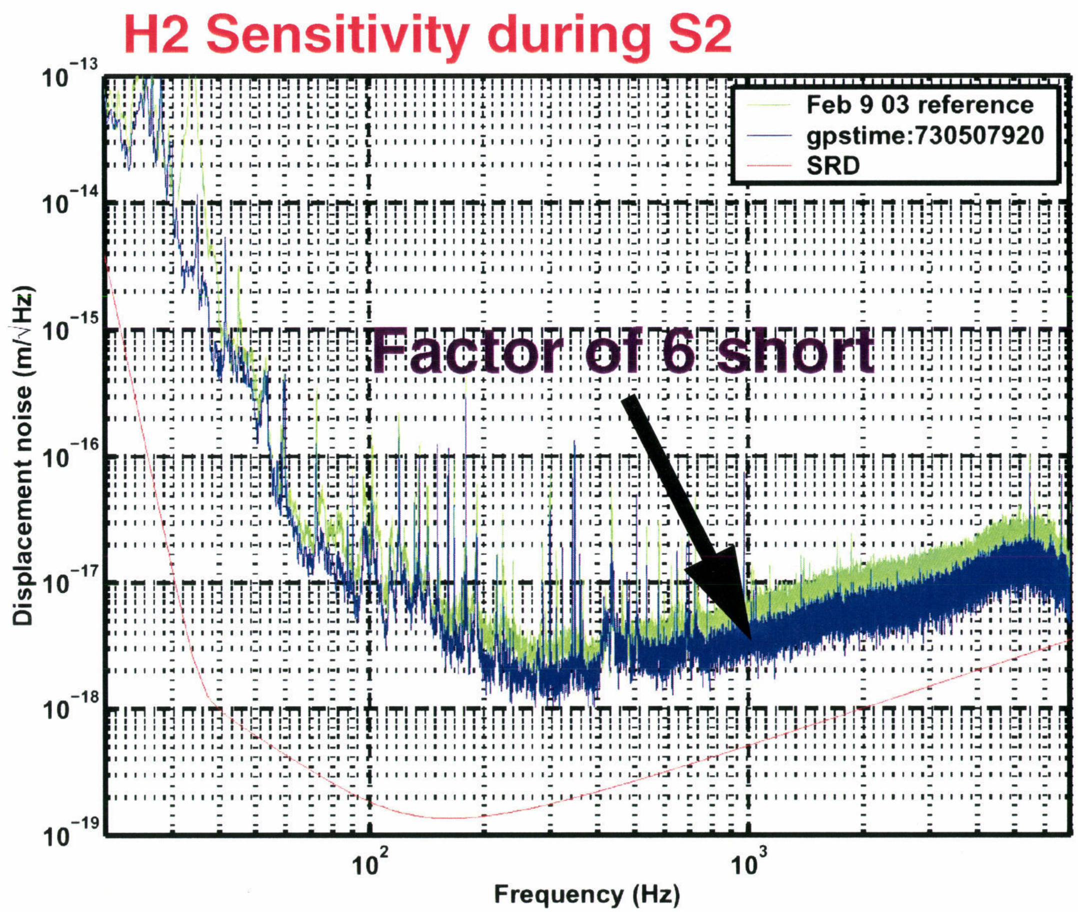


electro-Magnetic External Pre-Isolator (MEPI)



Shot Noise Sensitivity

- Simplistic power calculations suggests factor of ~2 shortfall
  - » 10x increase in laser power would give factor ~3 improvement
- Does not take improved sideband efficiency into account

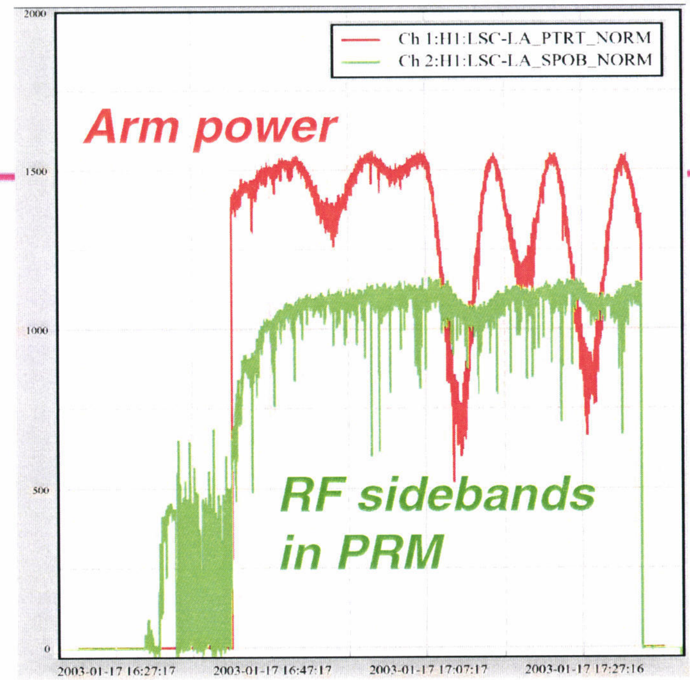


Optical characterization

- Good news: optics quality is (almost all) good
  - » Recycling gain meets or exceeds goals (design was >30)
    - – LLO-4K: Gain of nearly 50 seen, more usually about 45
    - – LHO-4K : Gain of 40-45
  - » Contrast defect meets or exceeds goals (design was $< 10^{-3}$)
    - – LLO-4K : $P_{as}/ P_{bs} = 3 \times 10^{-5}$
    - – LHO-4K : $P_{as}/ P_{bs} = 6 \times 10^{-4}$
  - » LHO-2K: Cause of low recycling gain (20) discovered
    - – Bad AR coating on ITMX, ~~must be~~ has been replaced
- Low RF sideband gain/efficiency
  - » LHO-4K : Sideband power efficiency to AS port: ~6%
  - » Cause: thermal lensing in the ITMs isn't at the design level
  - » Achieving shot noise goal requires that this be fixed

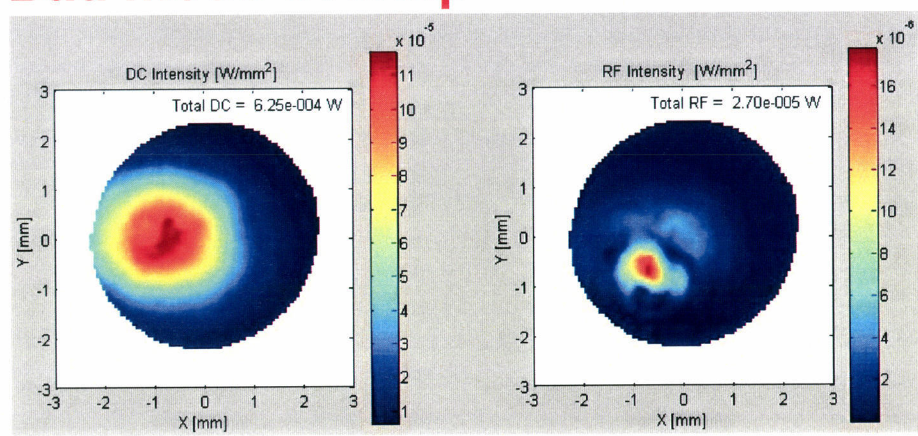
Thermal Lensing

- RF sideband efficiency is low
  - » Power recycling cavity slightly unstable: lack of Input Test Mass (ITM) thermal lens makes $g_1 \cdot g_2 > 1$
  - » Recycling Mirror (RM) curvature relies on point design for thermal lensing
  - » Heating differs from design value
- Possible solutions
  - » Change RM (w/ new radius of curvature); 6 month lead time
  - » Add the missing heat to ITMs with another source (AdvLIGO or GEO technique)
  - » Pursued in parallel with other commissioning activities



ITM Heating

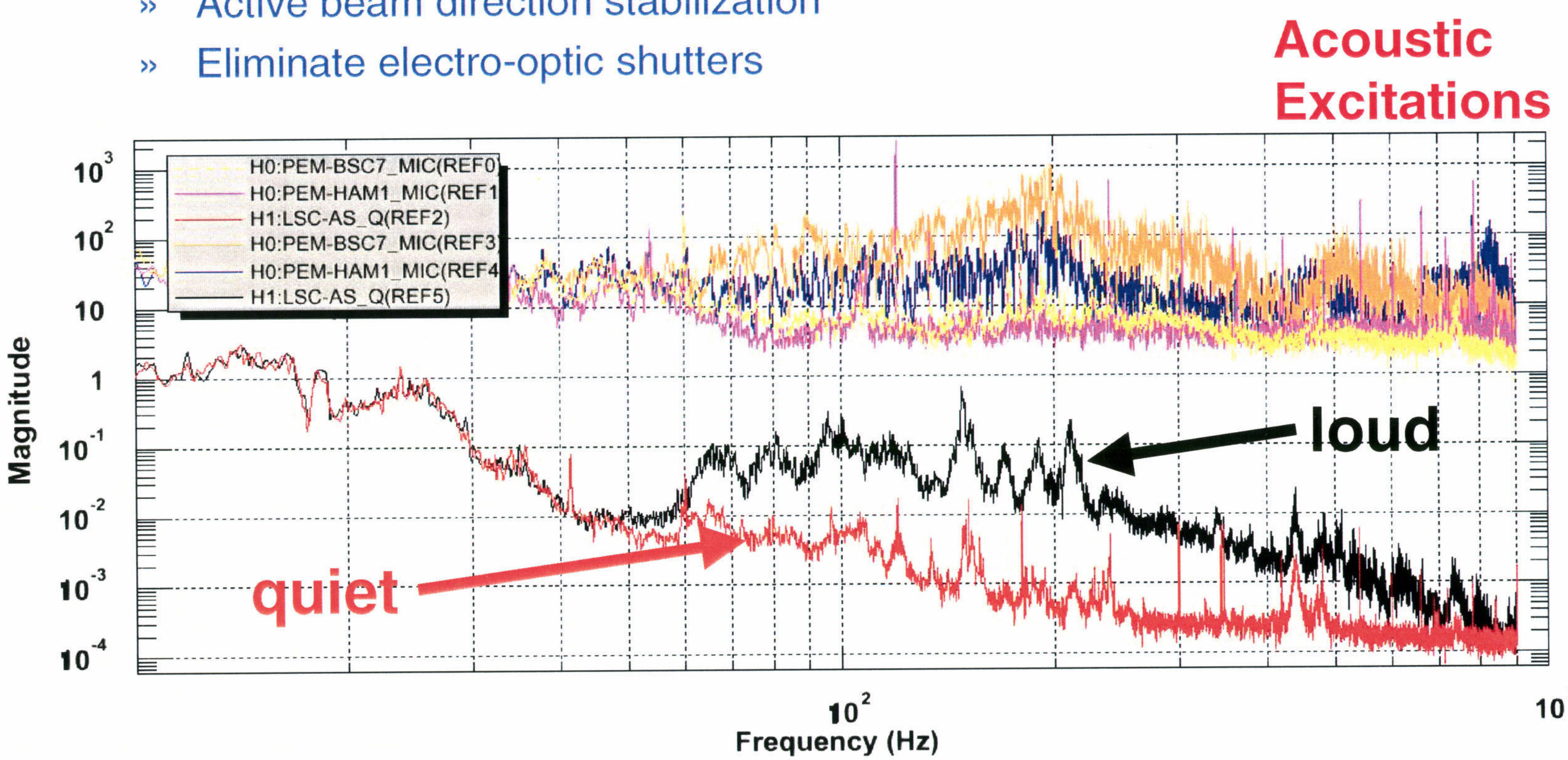
Bad mode overlap



DC (carrier) RF sidebands

Acoustic Peaks: Scattering/clipping

- Peaks occur in 80-1000 Hz band, at 10-100x required level
- Source for LHO correlated noise (stochastic search)
- Investigating:
  - » Acoustic isolation improvements
  - » Modify output periscopes/mirror mounts: stiffer, damped
  - » Active beam direction stabilization
  - » Eliminate electro-optic shutters



LIGO

Summary

- Commissioning of detectors progressing well
  - » Steady progression on all fronts: sensitivity, duty cycle, stability, …
  - » Next Science Run: Nov 2003 – Jan 2004
- First Science analyses underway
  - » S1 results demonstrate analysis techniques, S2 data (and beyond) offer a real possibility to detect gravitational waves
  - » Developing synergy between detector commissioning and data analysis efforts
  - » Four analysis papers (and one instrumental one…) in final stages of preparation
- Design performance (both sensitivity and duty cycle) should be achieved next year
  - » Still a lot to do, but no showstoppers

LIGO

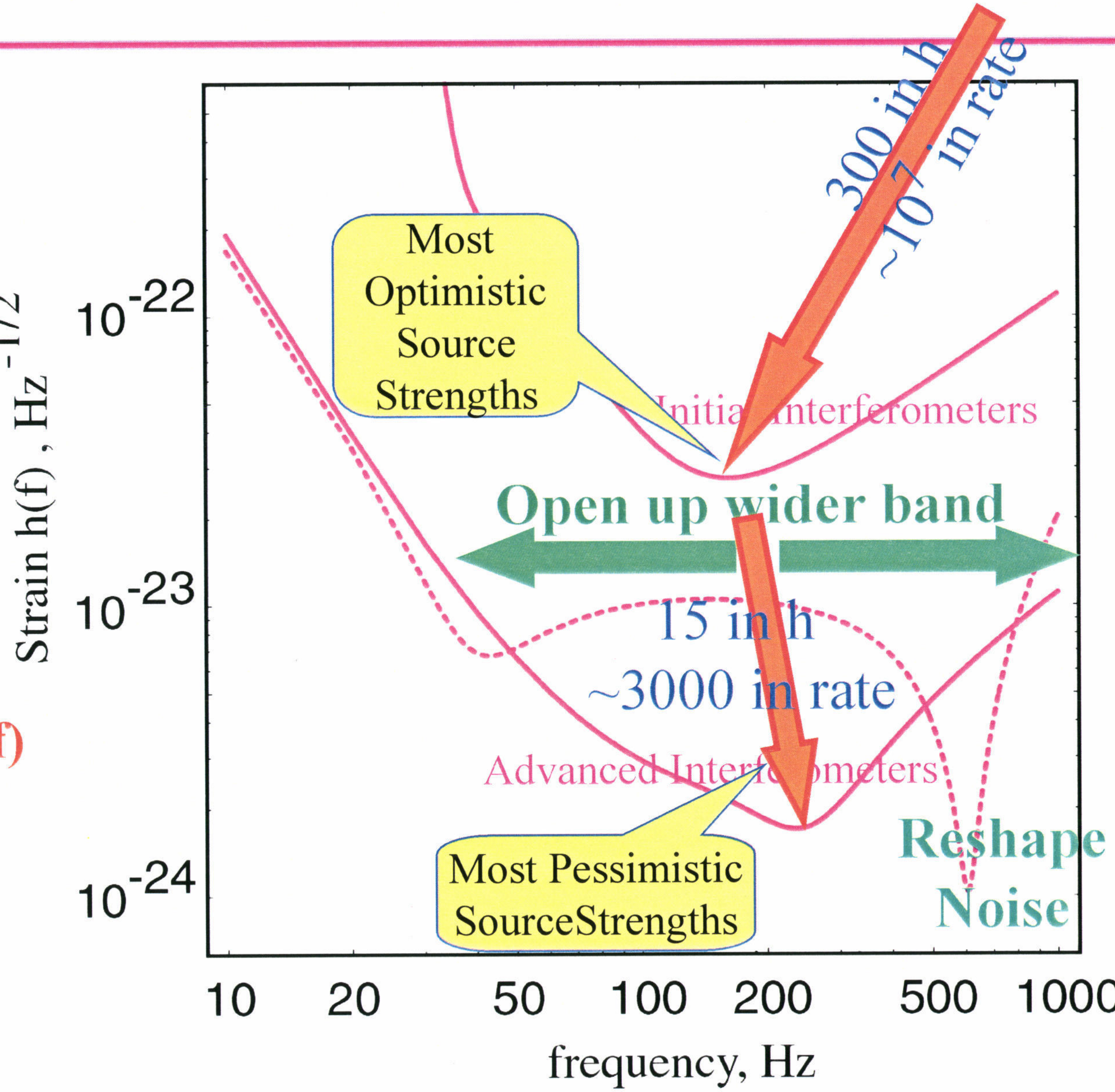
ASTROPHYSICS

Kip S. Thorne
CaRT, California Institute of Technology

NSF Advanced LIGO Review
Pasadena, 11 June 2003

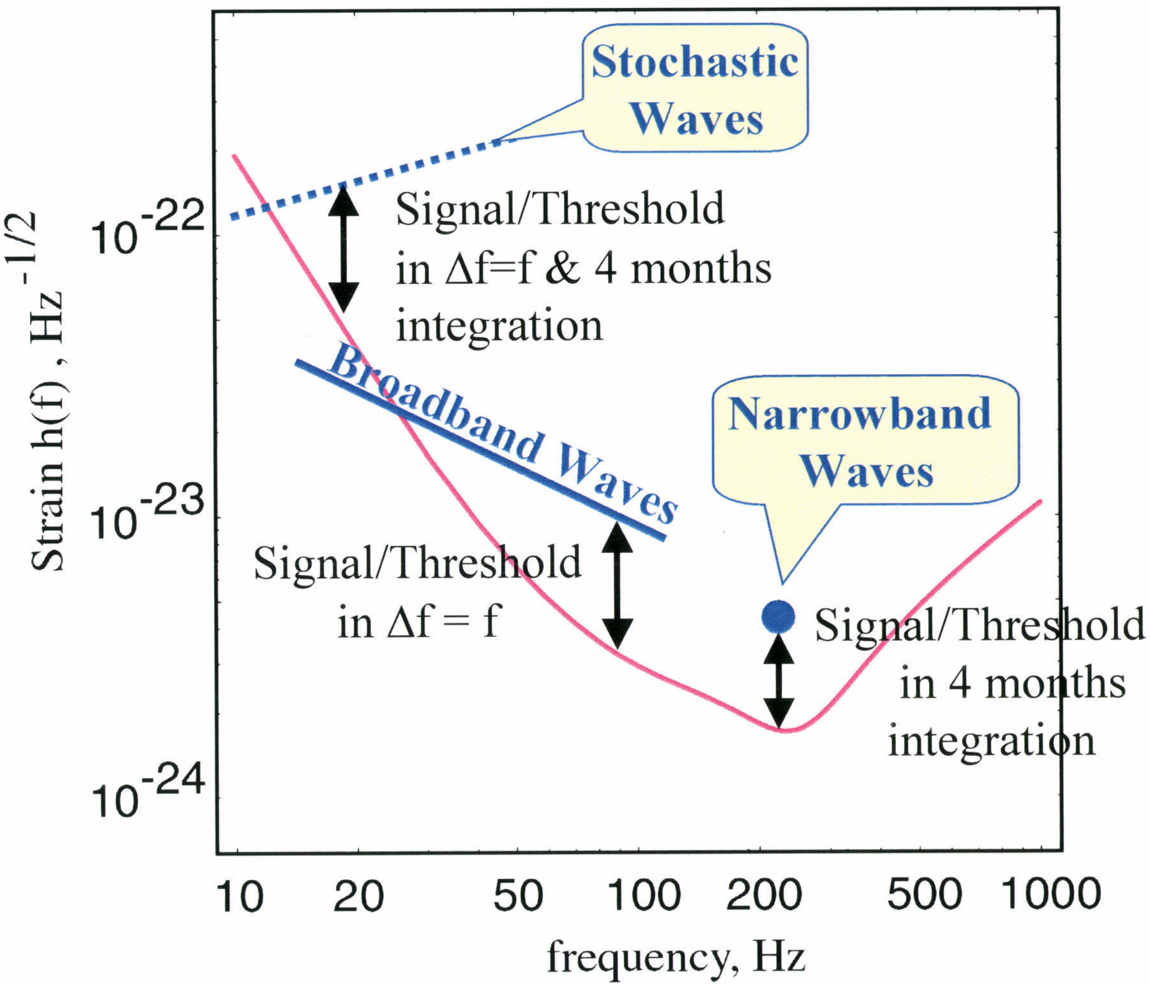
LIGO From Initial Interferometers to Advanced

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



Conventions on Source/Sensitivity Plots

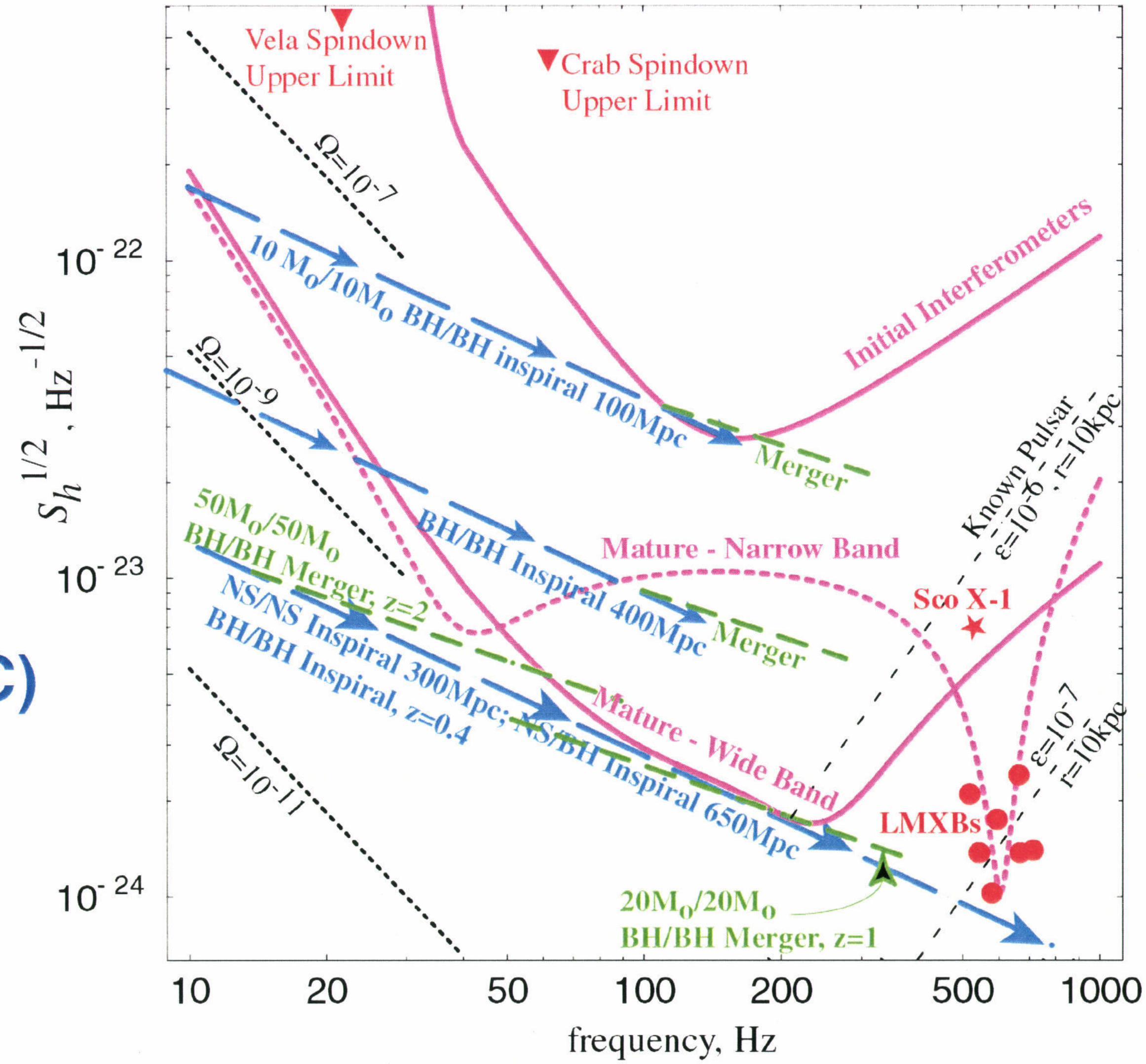
- Assume the best search algorithm now known
- Set Threshold so false alarm probability = 1%
  - » For rare broadband signals: on tail of Gaussian; increase S/T by ~10% ➔ 0.01% false alarm



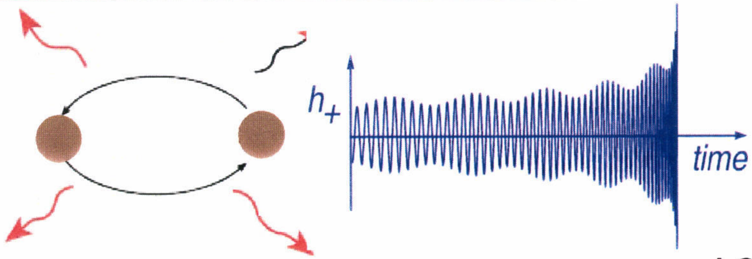
LIGO

Overview of Sources

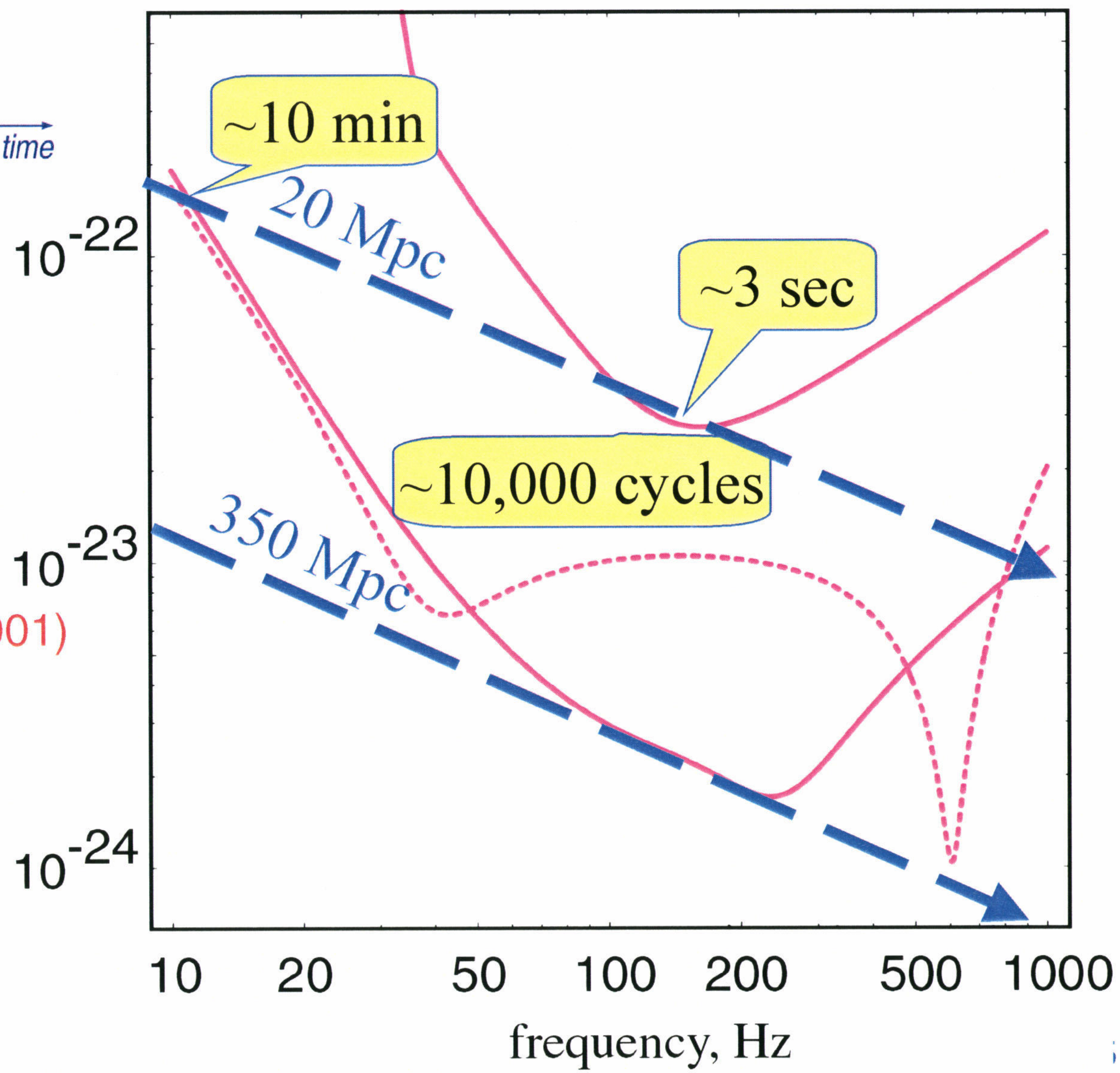
- **Neutron Star & Black Hole Binaries**
  - » inspiral
  - » merger
- **Spinning NS's**
  - » LMXBs
  - » known pulsars
  - » previously unknown
- **NS Birth (SN, AIC)**
  - » tumbling
  - » convection
- **Stochastic background**
  - » big bang
  - » early universe



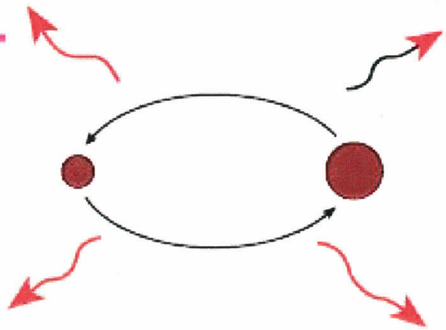
Neutron Star / Neutron Star Inspiral
(our most reliably understood source)

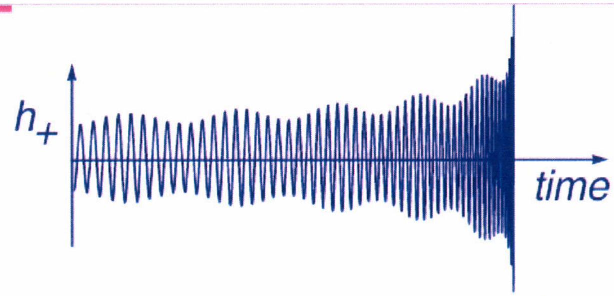


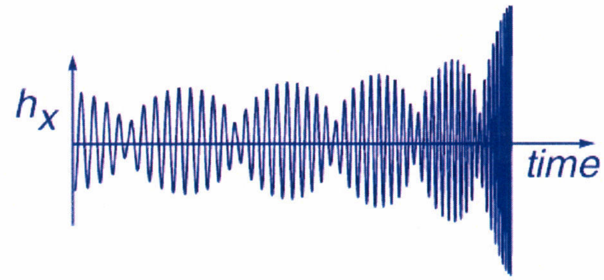
- **1.4 Msun / 1.4 Msun NS/NS Binaries**
- **Event rates**
  - » V. Kalogera, R. Narayan, D. Spergel, J.H. Taylor *Astrophys J,* 556, 340 (2001)
- **Initial IFOs**
  - » Range: 20 Mpc
  - » 1 / 3000 yrs to **1 / 4yrs**
- **Advanced IFOs -**
  - » Range: 350Mpc
  - » **2 / yr to 3 / day**

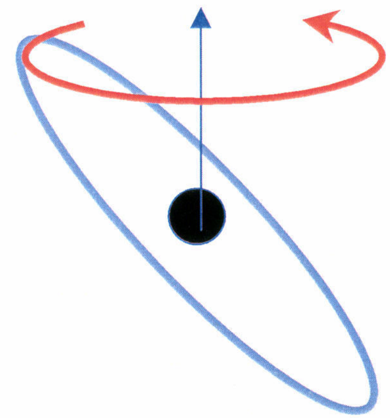


Science From Observed Inspirals: NS/NS, NS/BH, BH/BH





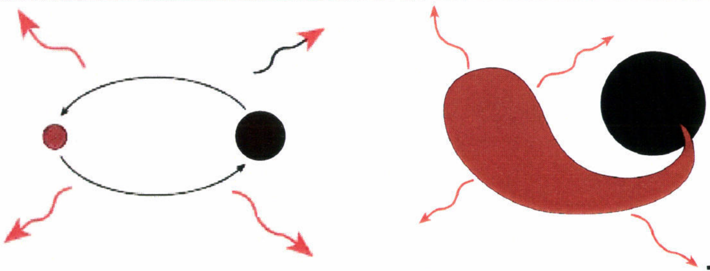




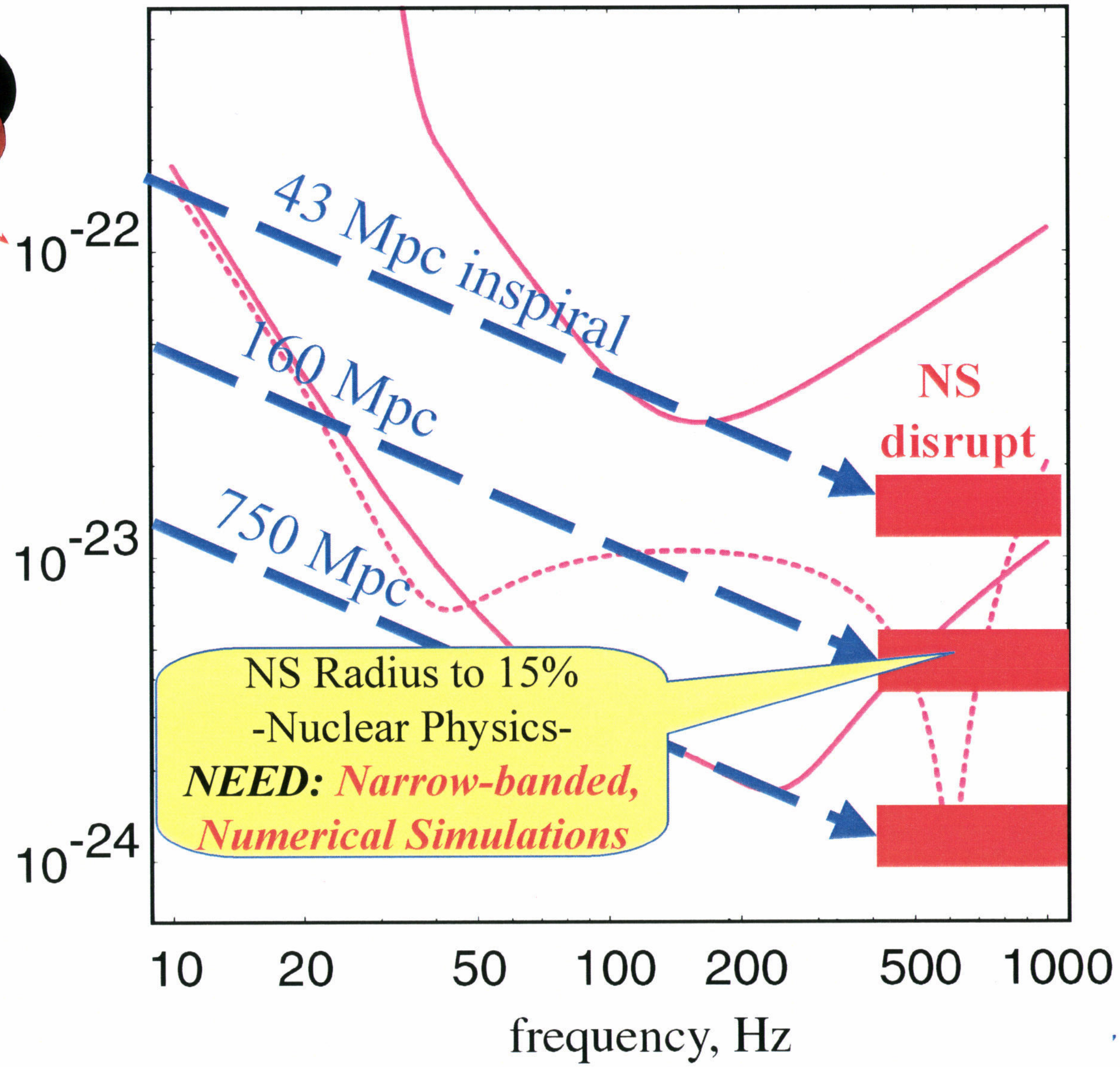
- Relativistic effects are very strong -- e.g.
  - » ***Frame dragging by spins ➔ precession ➔ modulation***
  - » ***Tails of waves modify the inspiral rate***
- Information carried:
  - » ***Masses (a few %), Spins (?few%?), Distance [not redshift!] (~10%), Location on sky (~1 degree)***
    - – $M_{\mathbf{chirp}} = \mu^{3/5} M^{2/5}$ to $\sim 10^{-3}$
- 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}***

LIGO

Neutron Star / Black Hole Inspiral and NS Tidal Disruption



- **1.4Msun / 10 Msun NS/BH Binaries**
- **Event rates**
  - » Population Synthesis [Kalogera's summary]
- **Initial IFOs**
  - » Range: 43 Mpc
  - » 1 / 5000 yrs to **1 / 3yrs**
- **Advanced IFOs**
  - » Range: 750 Mpc
  - » **1 / yr to 4 / day**



Black Hole / Black Hole Inspiral and Merger

10Msun / 10 Msun BH/BH Binaries

Event rates

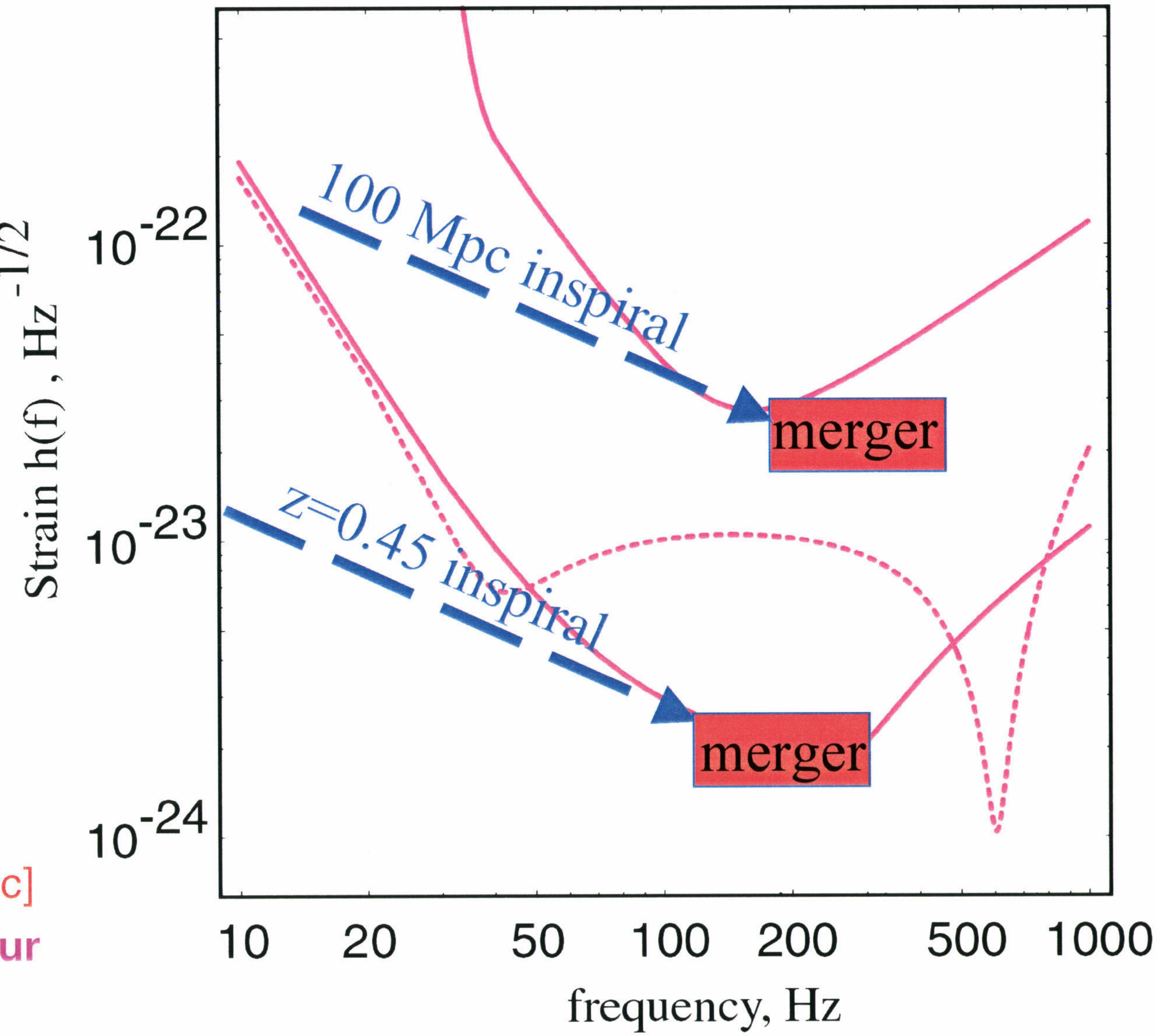
- » Population synthesis [Kalogera's summary]

Initial IFOs

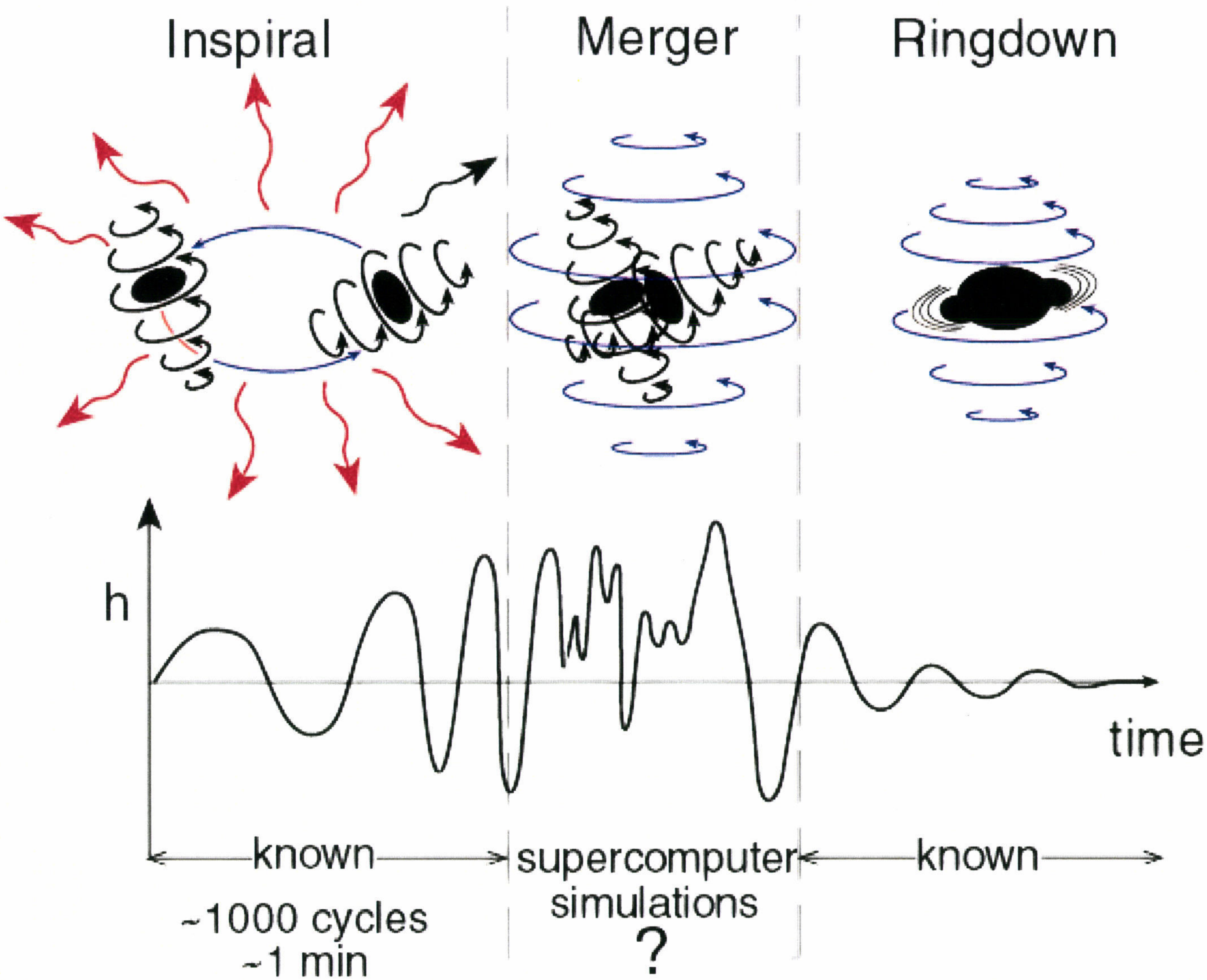
- » Range: 100 Mpc
- » ~1 / 250 yrs to **~2 / yr**

Advanced IFOs -

- » Range: z=0.45 [1.7 Gpc]
- » **~1/ month to ~1 / hour**



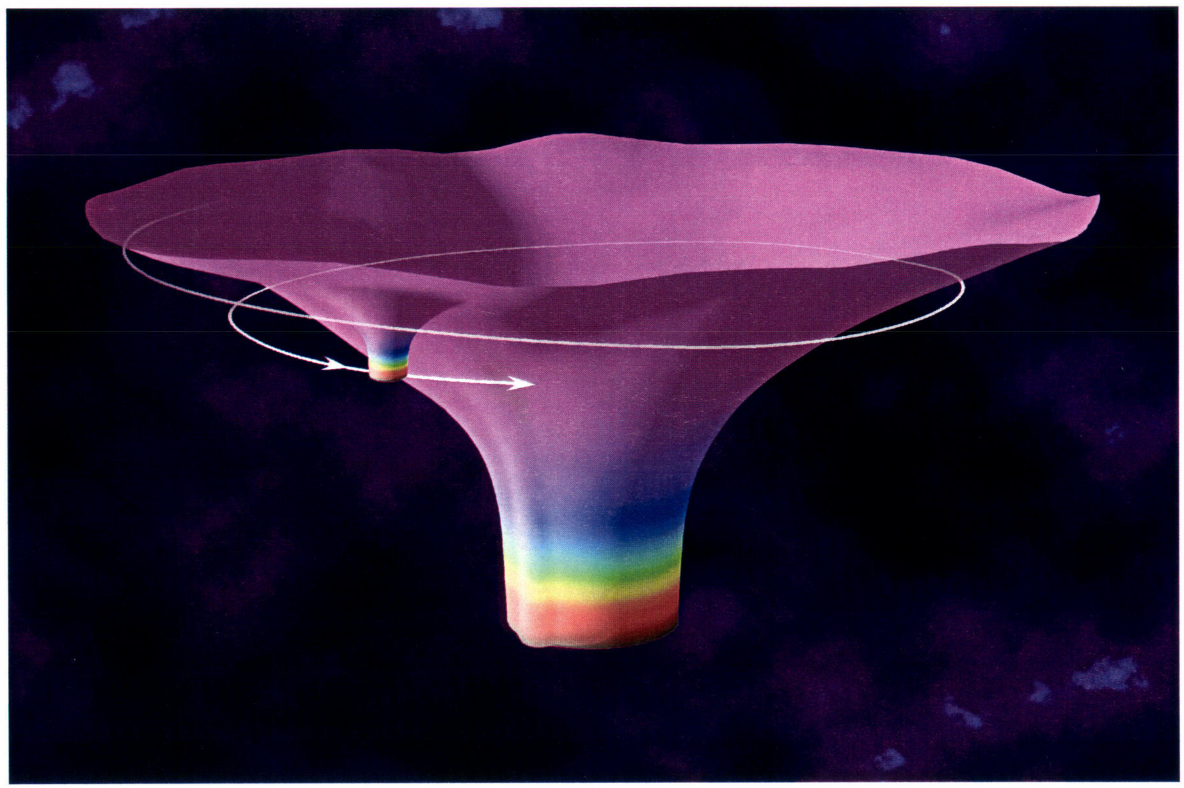
BH/BH Mergers: Exploring the Dynamics of Spacetime Warpage



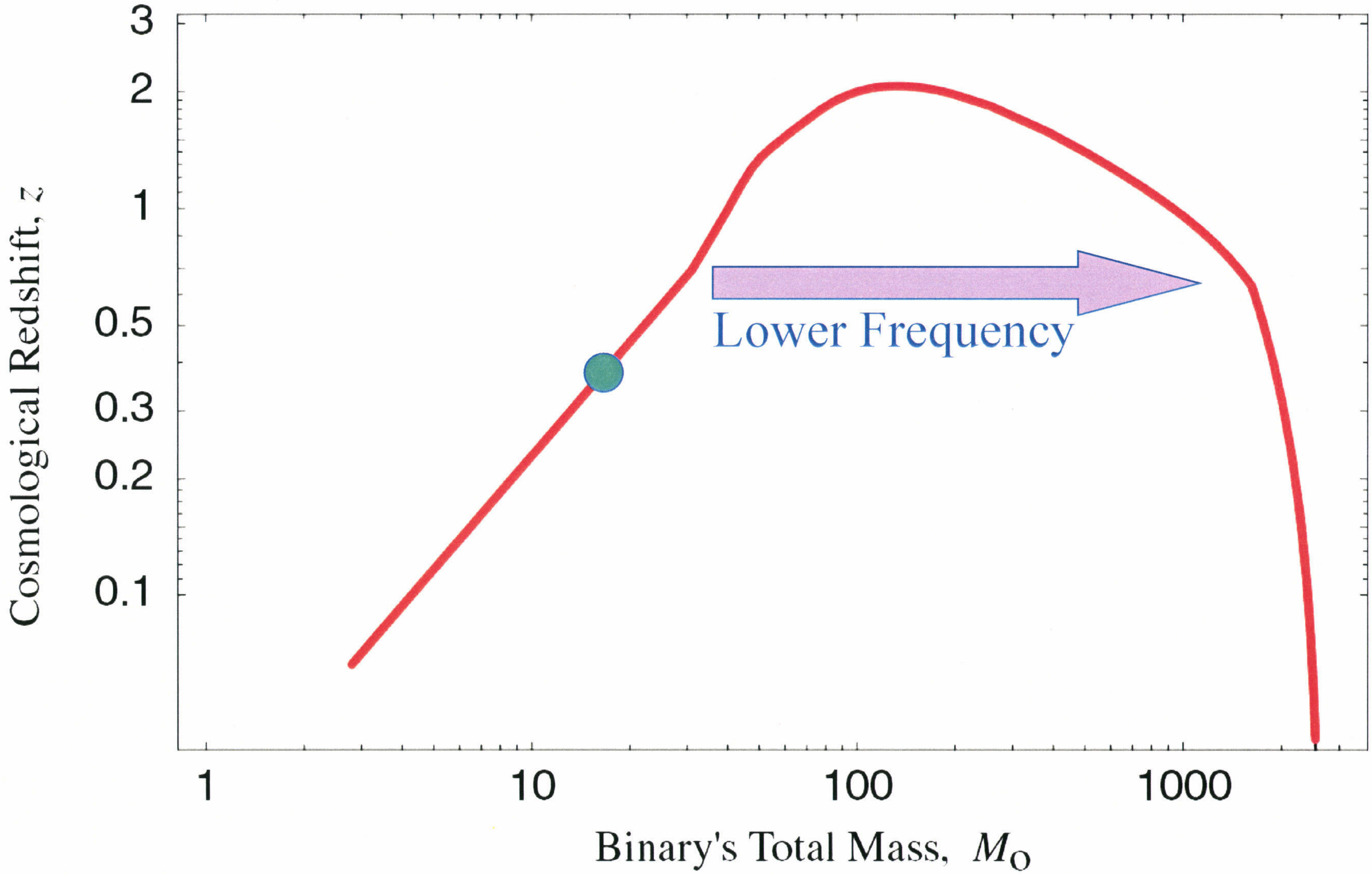
To interpret Observed waves: Compare with Numerical Relativity Simulations

Probing Intermediate Mass BH's with Small BH's

- In globular clusters: BH-BH capture formation, merger, formation, merger, ... in globular clusters ➔ intermediate-mass BH: 100 - 1000 Msun [Cole Miller]
- Plunge of few Msun BH into few ~100 Msun BH
- Ringdown studies: ~ 10 per year with M/m > 60; more for smaller M/m



Massive BH/BH Mergers with Fast Spins - Advanced IFOs



LIGO Spinning NS's: Pulsars in Our Galaxy

NS Ellipticity:

» Crust strength or B strength

$\varepsilon \lesssim 10^{-5}$

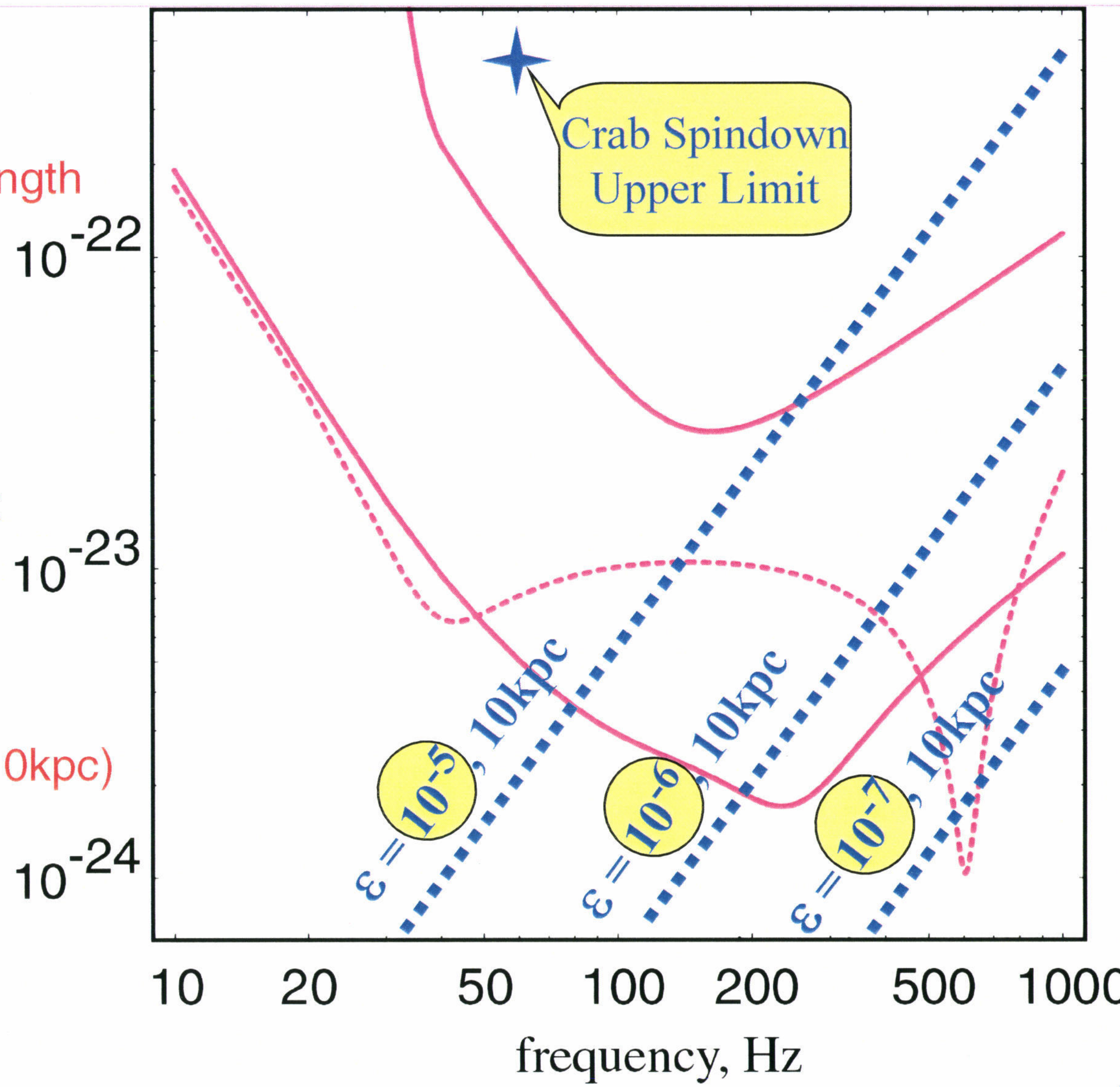
Known Pulsars:

» First Interferometers:

$\varepsilon \gtrsim 3 \times 10^{-6}$ (1000Hz/f) x (distance/10kpc)

» Broadband Advanced

$\varepsilon \gtrsim 5 \times 10^{-7}$ x (distance/10kpc)

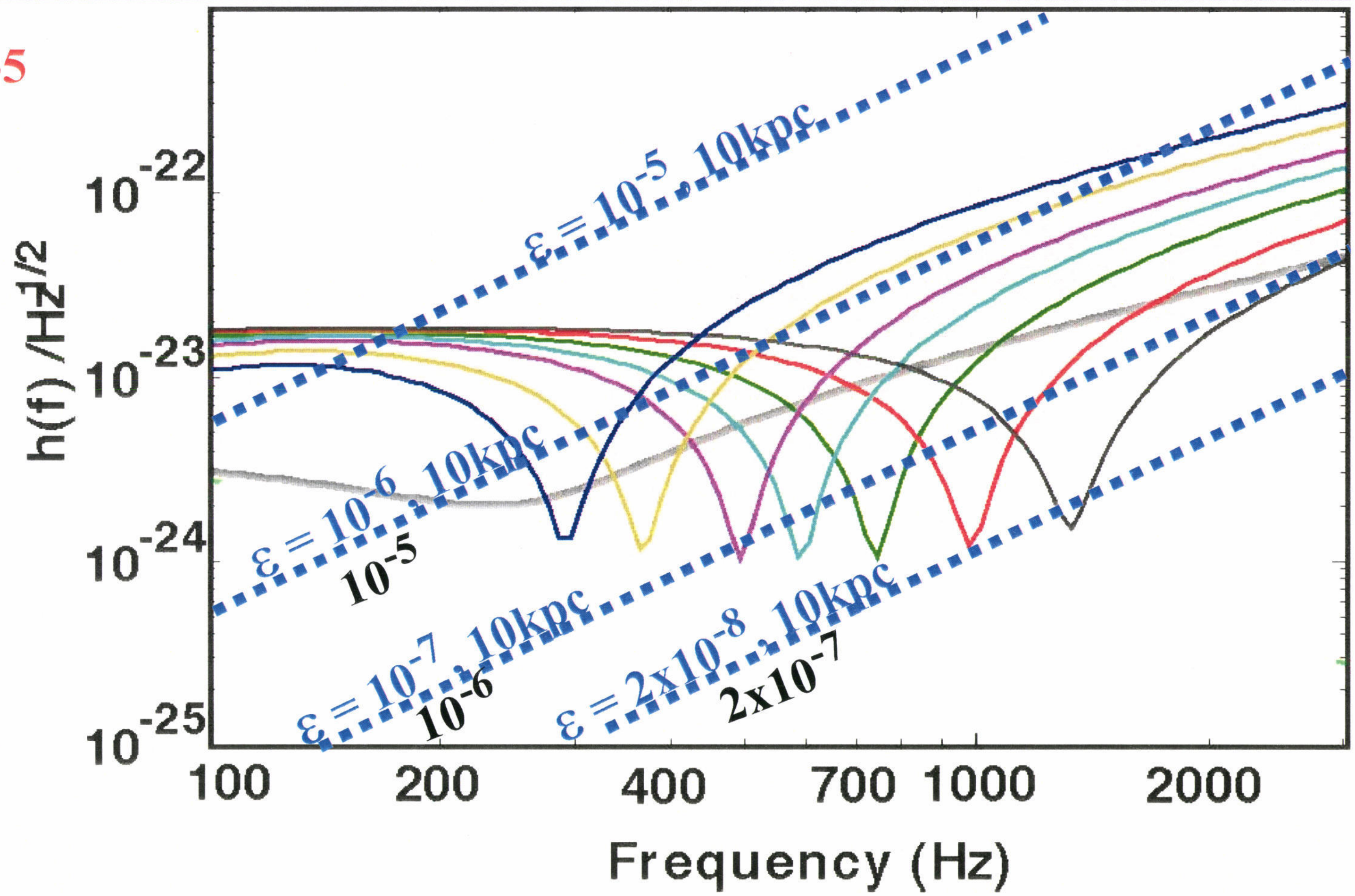


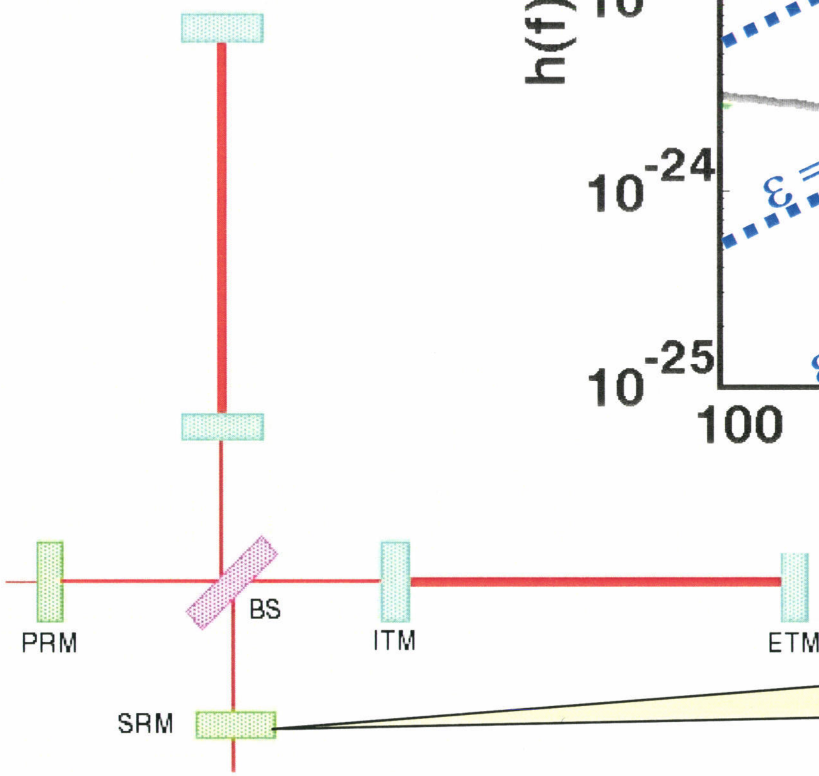
Spinning NS's: Pulsars in Our Galaxy [narrow-banded interferometer]

Plausible: $\varepsilon \lesssim 10^{-5}$

Known Pulsars

Unknown: All Sky search

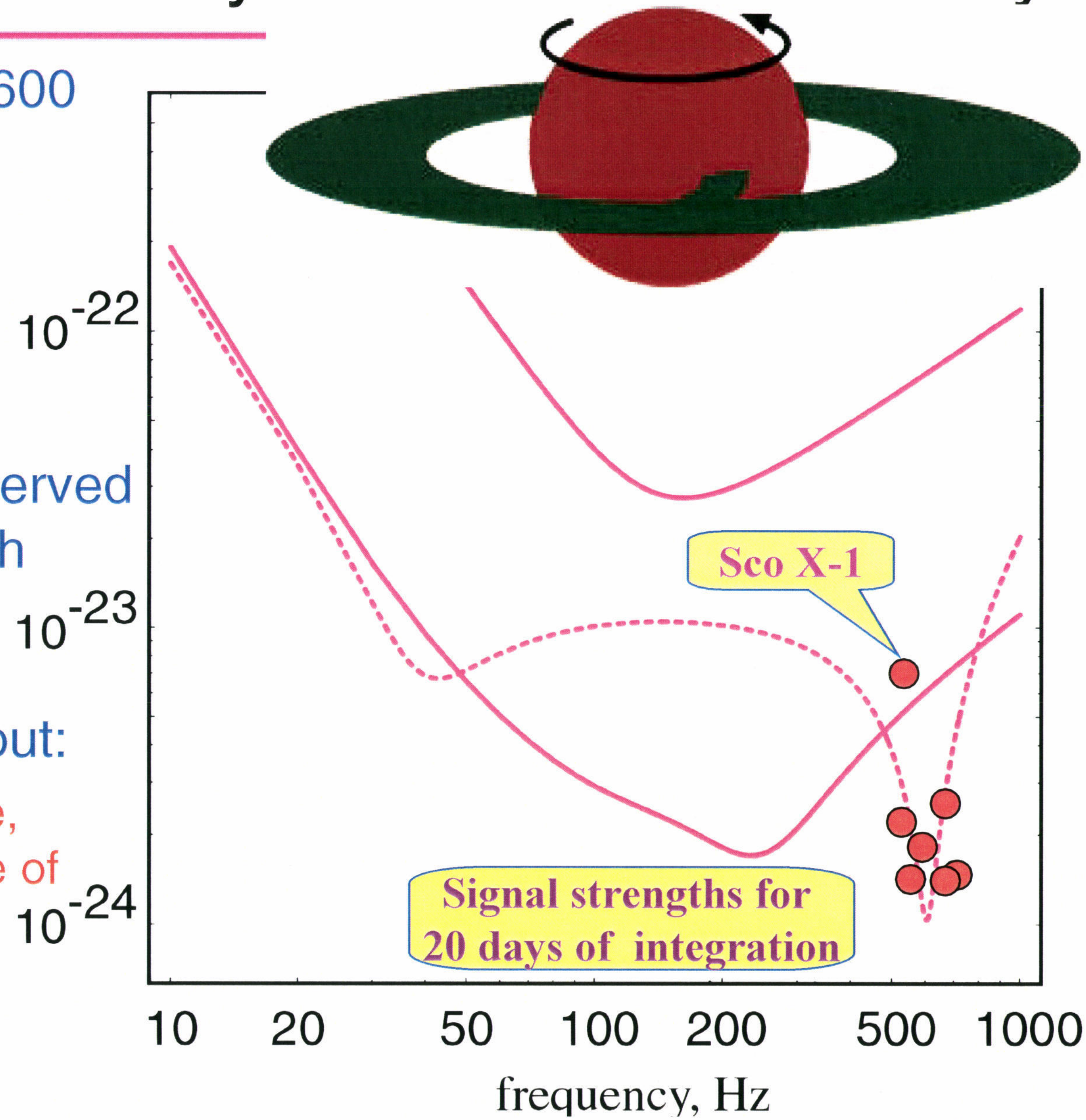




Tune by moving Signal Recycling Mirror

Spinning Neutron Stars: Low-Mass X-Ray Binaries in our Galaxy

- Rotation rates ~250 to ~600 revolutions / sec
  - » Why not faster?
  - » **Bildsten**: Spin-up torque balanced by GW emission torque
- If so, & steady state: observed X-ray flux ➔ GW strength
- Combined GW & EM obs's ➔ information about:
  - » crust strength & structure, temperature dependence of viscosity, ...



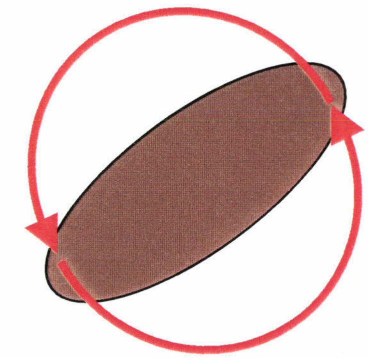
NS Birth: Tumbling Bar; Convection

Born in:

- Supernovae
- Accretion-Induced Collapse of White Dwarfs

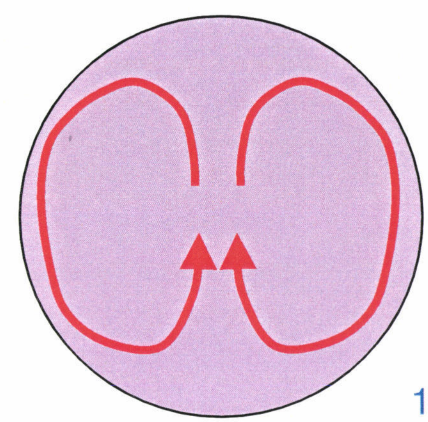
If very fast spin:

- Centrifugal hangup
- **Tumbling bar** - episodic? (for a few sec or min)
- ***If modeling gives enough waveform information,*** detectable to:
  - Initial IFOs: ~5Mpc (M81 group, ~1 supernova/3yr)
  - Advanced IFOs: ~100Mpc (~500 supernovae/yr)



If slow spin:

- **Convection** in first ~1 sec.
- Advanced IFOs: Detectable only in our Galaxy (~1/30yrs)
- GW / neutrino correlations!



LIGO

Complementarity of LIGO & LISA

LIGO

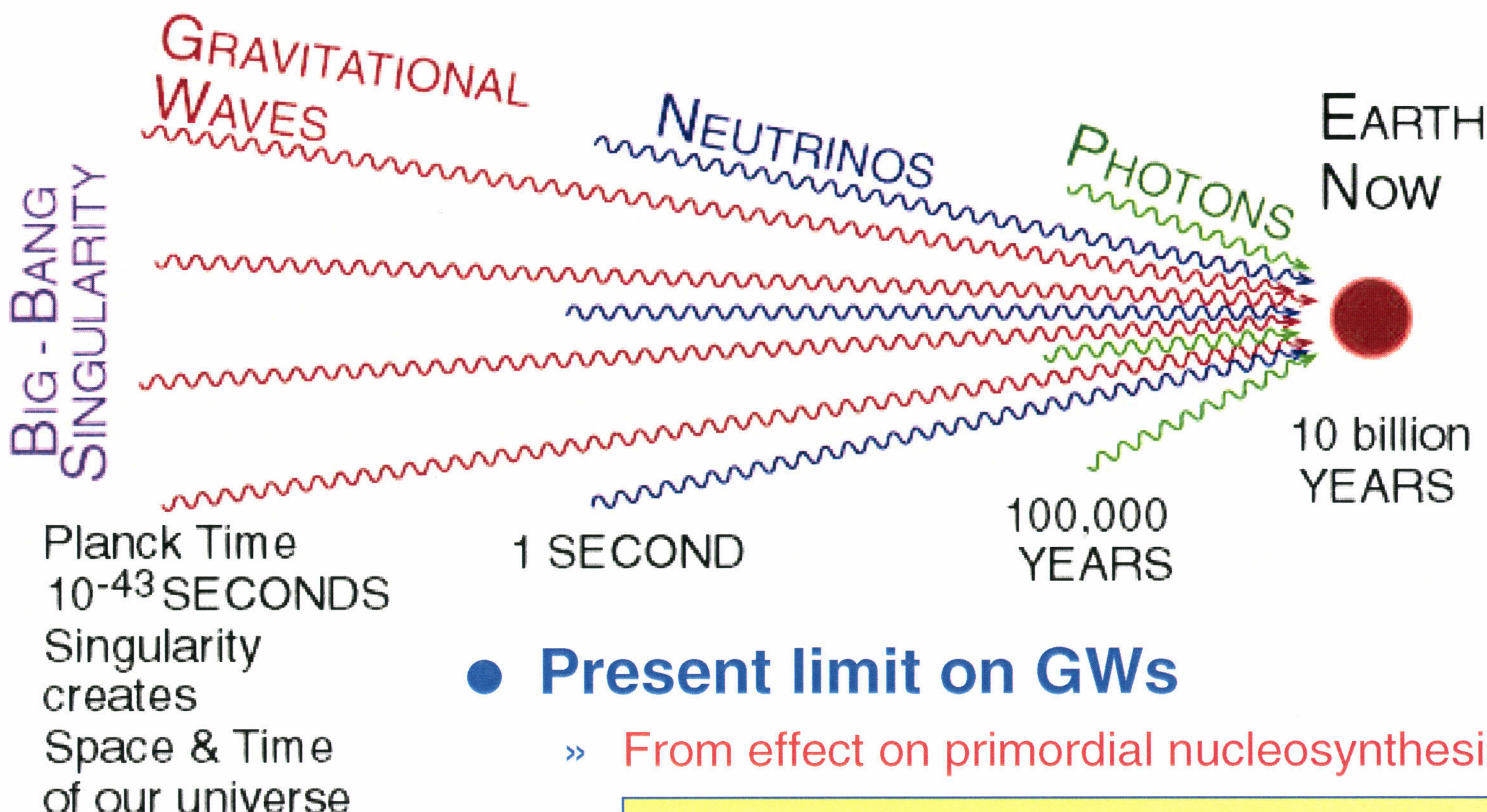
- High-frequency band: ~10Hz to ~1500Hz (analog of optical astronomy)
- Neutron-star studies:
  - » Tidal disruption by BH
  - » Low Mass X-Ray Binaries
  - » Pulsar Spins
- Study stellar mass BH's (~3 Msun to ~1000 Msun)
- Study merger of NS and BH binaries in distant galaxies
- Study early universe at age ~10^{-25} sec (~10^{9} Gev)

LISA

- Low-frequency band: ~0.0001 Hz to ~0.1 Hz (analog of radio astronomy)
- Cannot study neutron star physics
- Study supermassive BH's (~100,000 to 10,000,000 Msun)
- Study White dwarf, NS, and BH binaries in our galaxy, long before merger
- Study early universe at age ~10^{-12} sec (~100 GeV)

Stochastic Background from Very Early Universe

- **GW's are the ideal tool for probing the very early universe -- "messenger" from first one second**



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

Stochastic Background from Very Early Universe

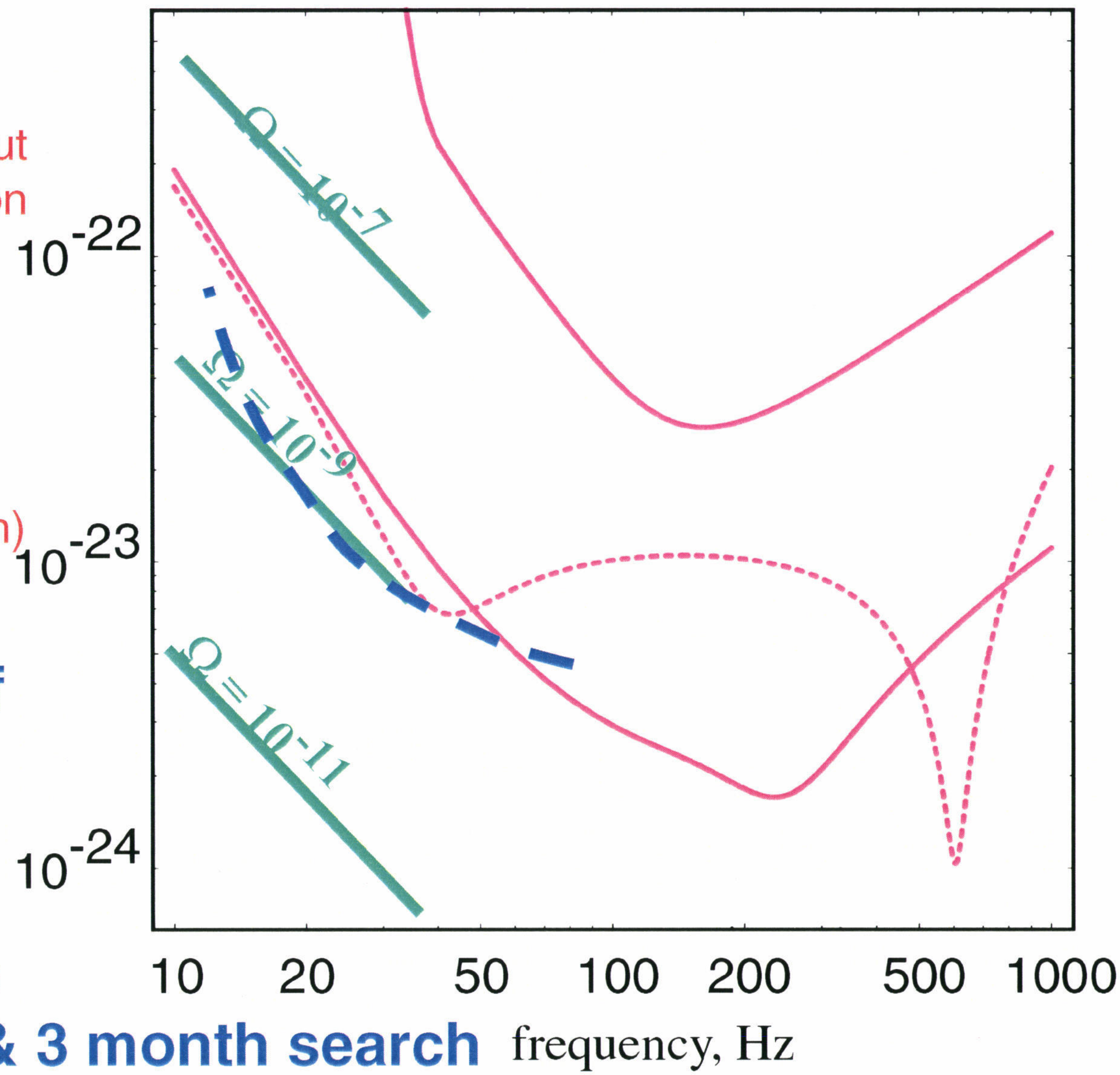
- **Detect by**
  - » cross correlating output of Hanford & Livingston 4km IFOs
- **Good sensitivity requires**
  - » (GW wavelength) $\gtrsim$ **2x**(detector separation)
  - » f $\lesssim$ 40 Hz

Initial IFOs detect if

» $\Omega \gtrsim 10^{-5}$

Advanced IFOs:

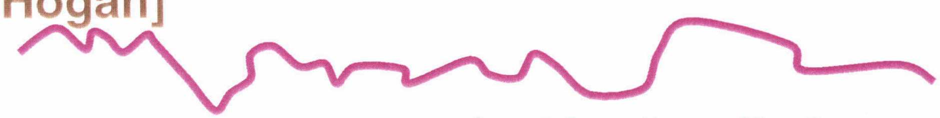
» $\Omega \gtrsim 1\text{x}10^{-9}$ **with reduced power & 3 month search**



LIGO

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

- Waves from **standard inflation**: $\Omega \sim 10^{-15}$: much too weak
- ***BUT:*** Crude **superstring models** of big bang suggest waves *might be strong enough* for detection by Advanced IFOs
- Bursts from **cosmic strings**: possibly detectable by Initial IFOs
- Energetic processes at (universe age) ~ $\mathbf{10^{-25}}$ **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: [C. Hogan]**
    - **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**
    - **If wave energy equilibrates: possibly detectable by initial IFOs**
- Example of hitherto ***UNKNOWN SOURCE***

LIGO

Conclusions

- LIGO's Initial Interferometers bring us into the realm where it is plausible to begin detecting cosmic gravitational waves.
- With LIGO's Advanced Interferometers we can be confident of:
  - » detecting waves from a variety of sources
  - » gaining major new insights into the universe, and into the nature and dynamics of spacetime curvature, that cannot be obtained in any other way

Overview of Advanced LIGO

David Shoemaker

NSF Review of Advanced LIGO

11 June 2003

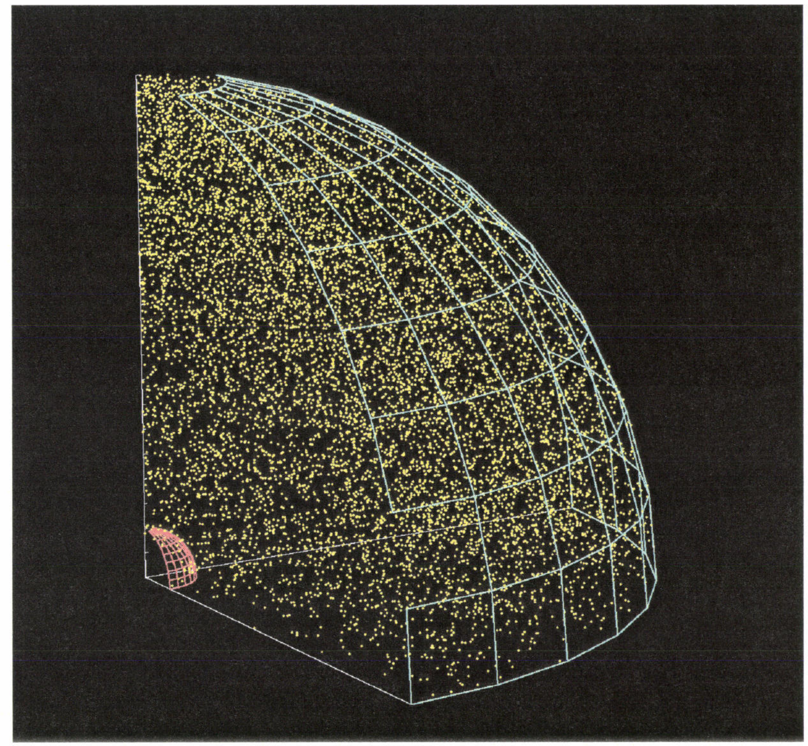
G0300260-00-M

Advanced LIGO

- LIGO mission: detect gravitational waves and

  initiate GW astronomy

- Next detector
  - Should have assured detectability of known sources
  - Should be at the limits of reasonable extrapolations of detector physics and technologies
  - Must be a realizable, practical, reliable instrument
  - Should come into existence neither too early nor too late

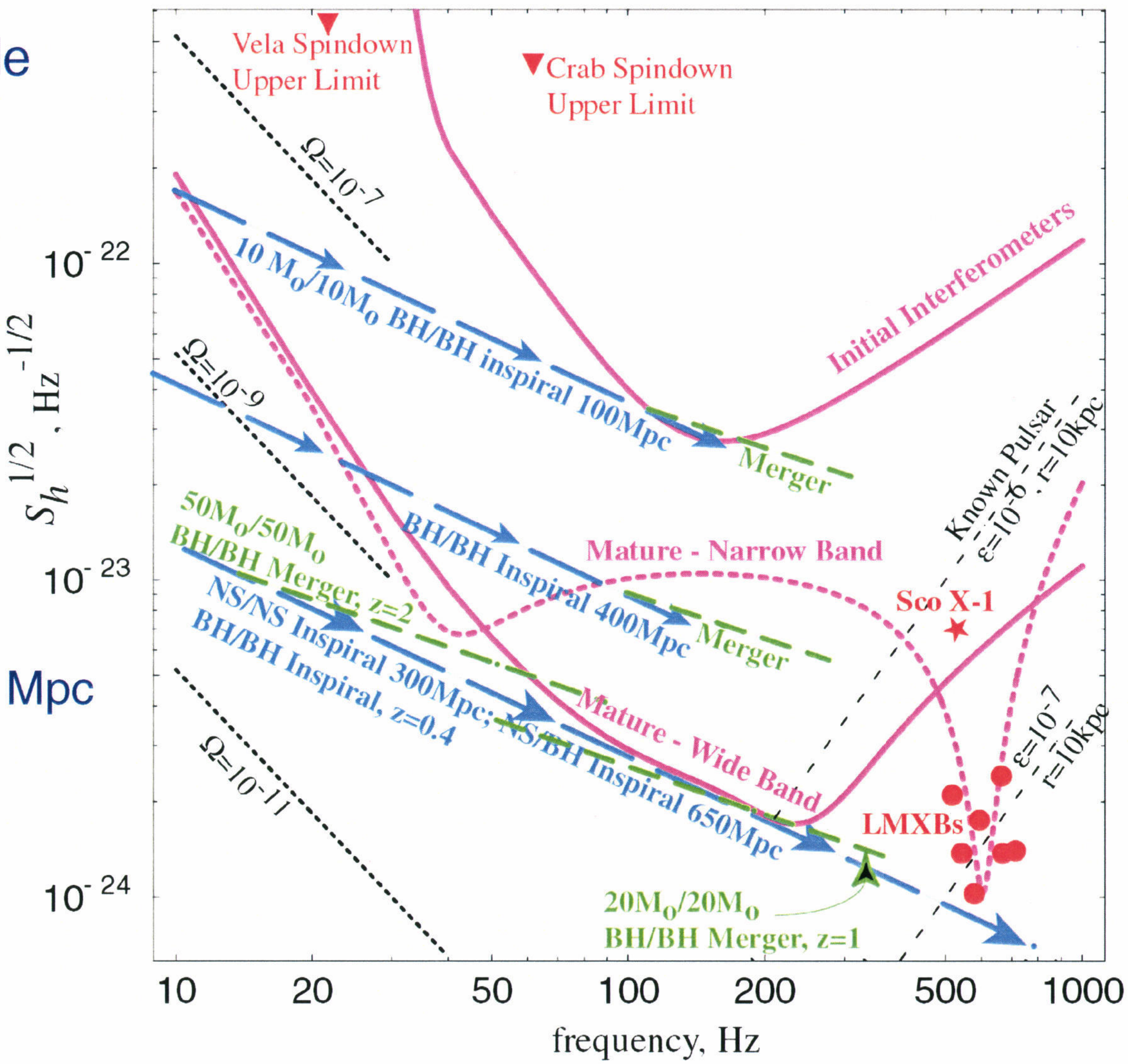


→ **Advanced LIGO**

LIGO

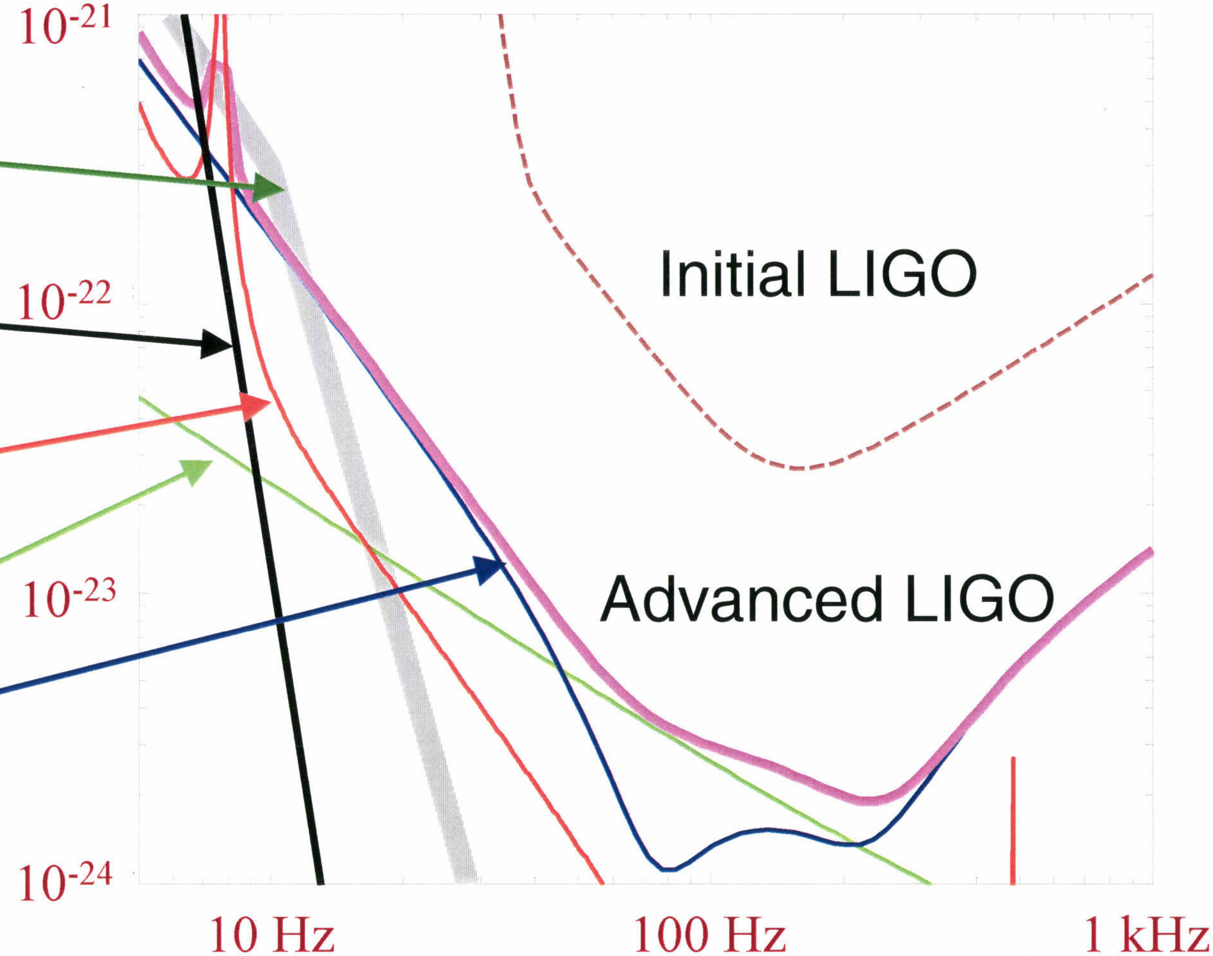
Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - (Reach)^3 = rate
- Factor 4 lower frequency bound
- NS Binaries: for three interferometers,
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~350 Mpc
- BH Binaries:
  - Initial LIGO: 10 M_o, 100 Mpc
  - Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - Initial LIGO: ~3e-6
  - Adv LIGO ~3e-9



Anatomy of the projected Adv LIGO detector performance

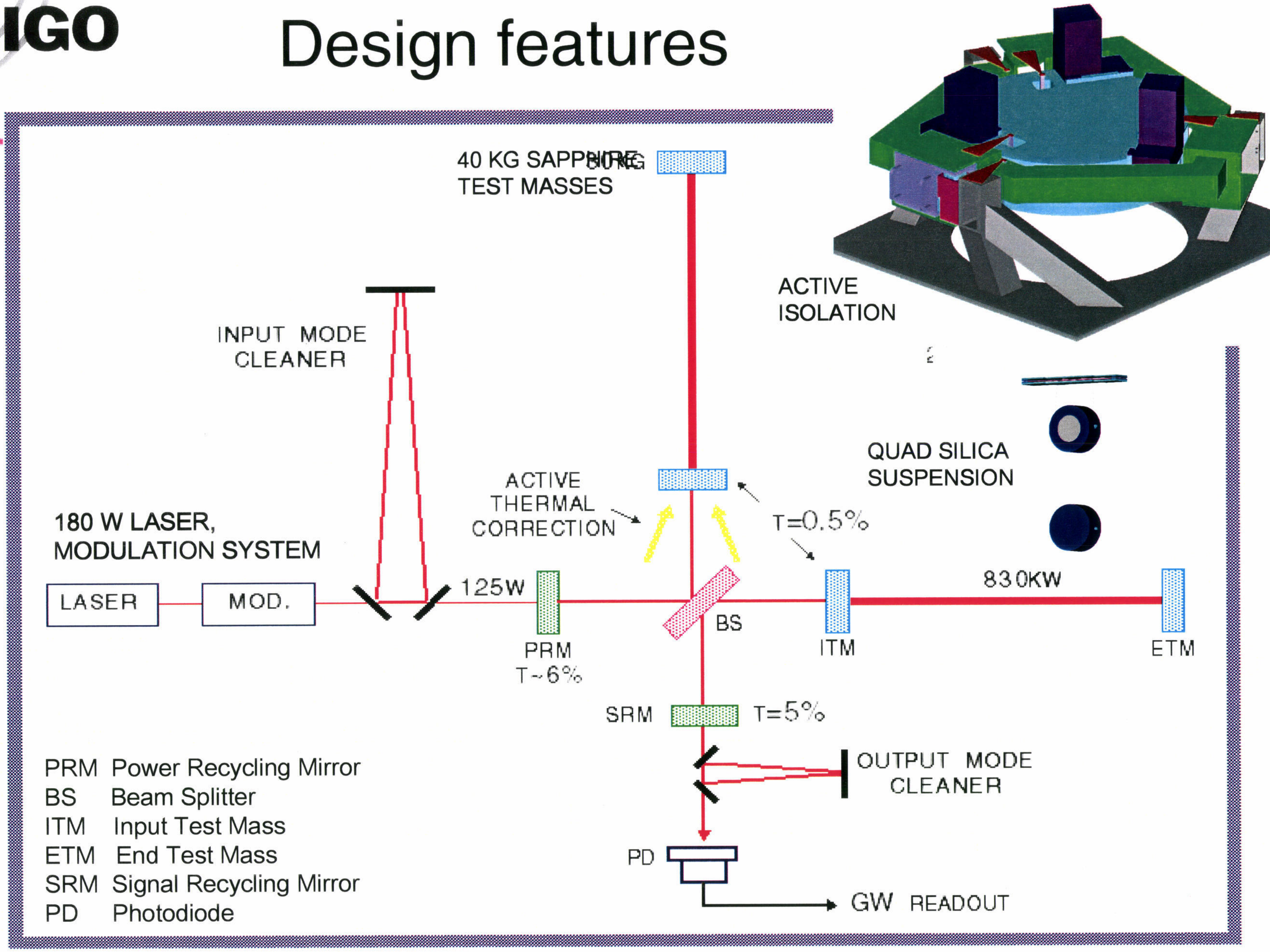
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



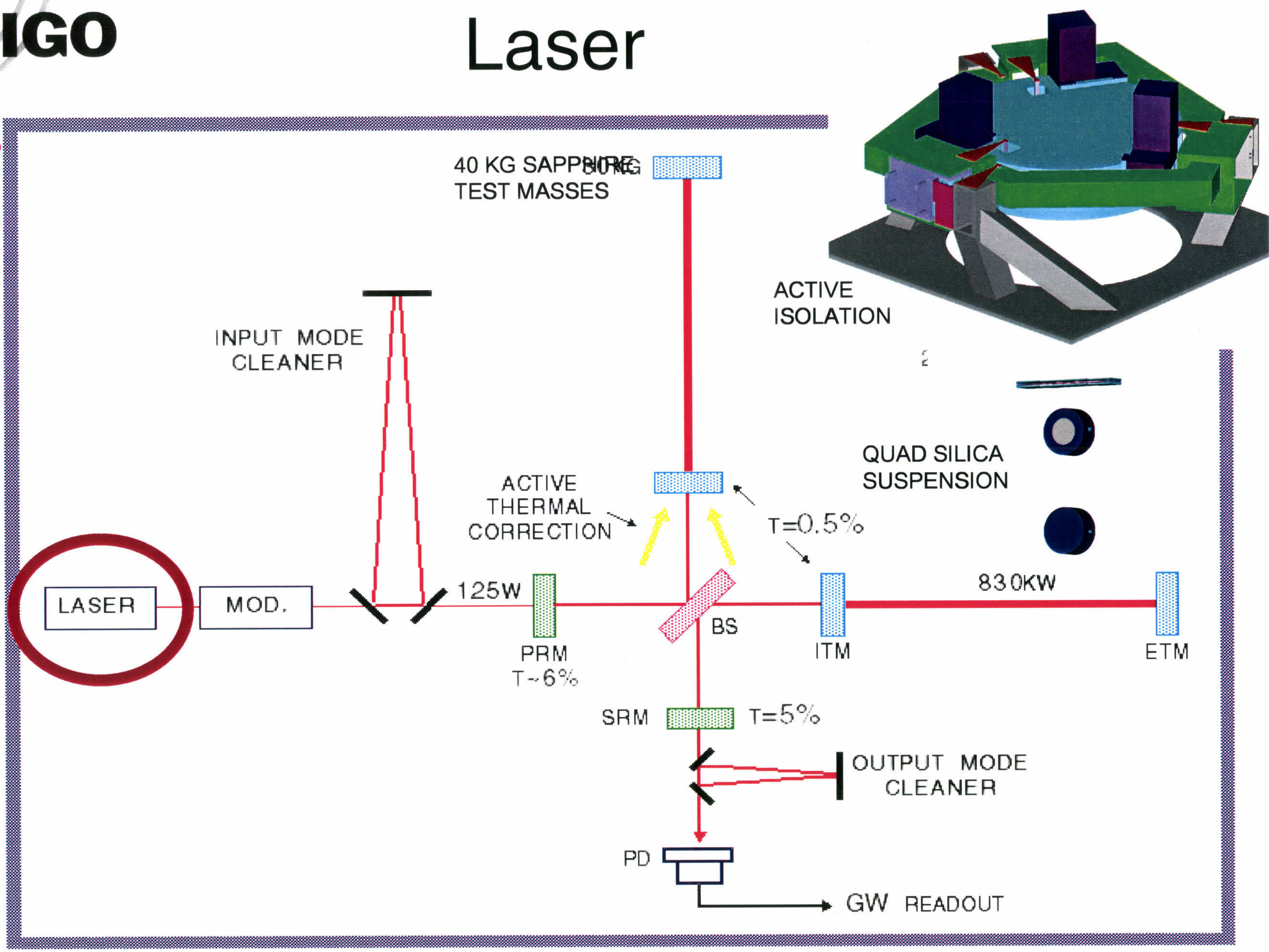
- Advanced LIGO's Fabry-Perot Michelson Interferometer is a platform for all currently envisaged enhancements to this detector architecture

LIGO

Design features



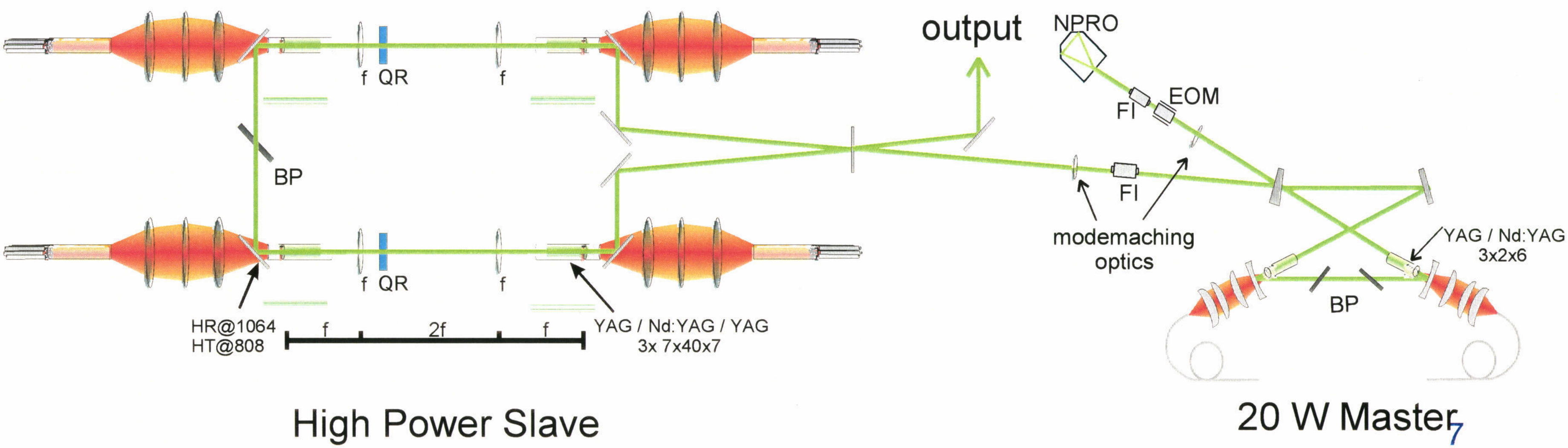
Laser



G0300260-00-M

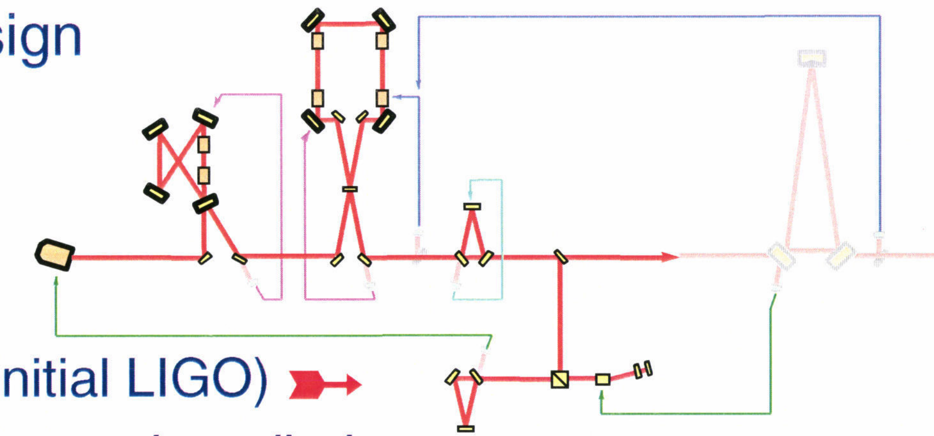
Pre-stabilized Laser

- Require the maximum power compatible with optical materials
  - 1999 White Paper: 180 W at output of laser, leads to 830 kW in cavities
  - Continue with Nd:YAG, 1064 nm
  - 2002: Three approaches studied by LSC collaboration – stable/unstable slab oscillator (Adelaide), slab amplifier (Stanford), end-pumped rod oscillator (Laser Zentrum Hannover (LZH)); evaluation concludes that all three look feasible
  - Choose the end-pumped rod oscillator, injection locked to an NPRO
  - 2003: Prototyping well advanced – ½ of Slave system has developed 87 W



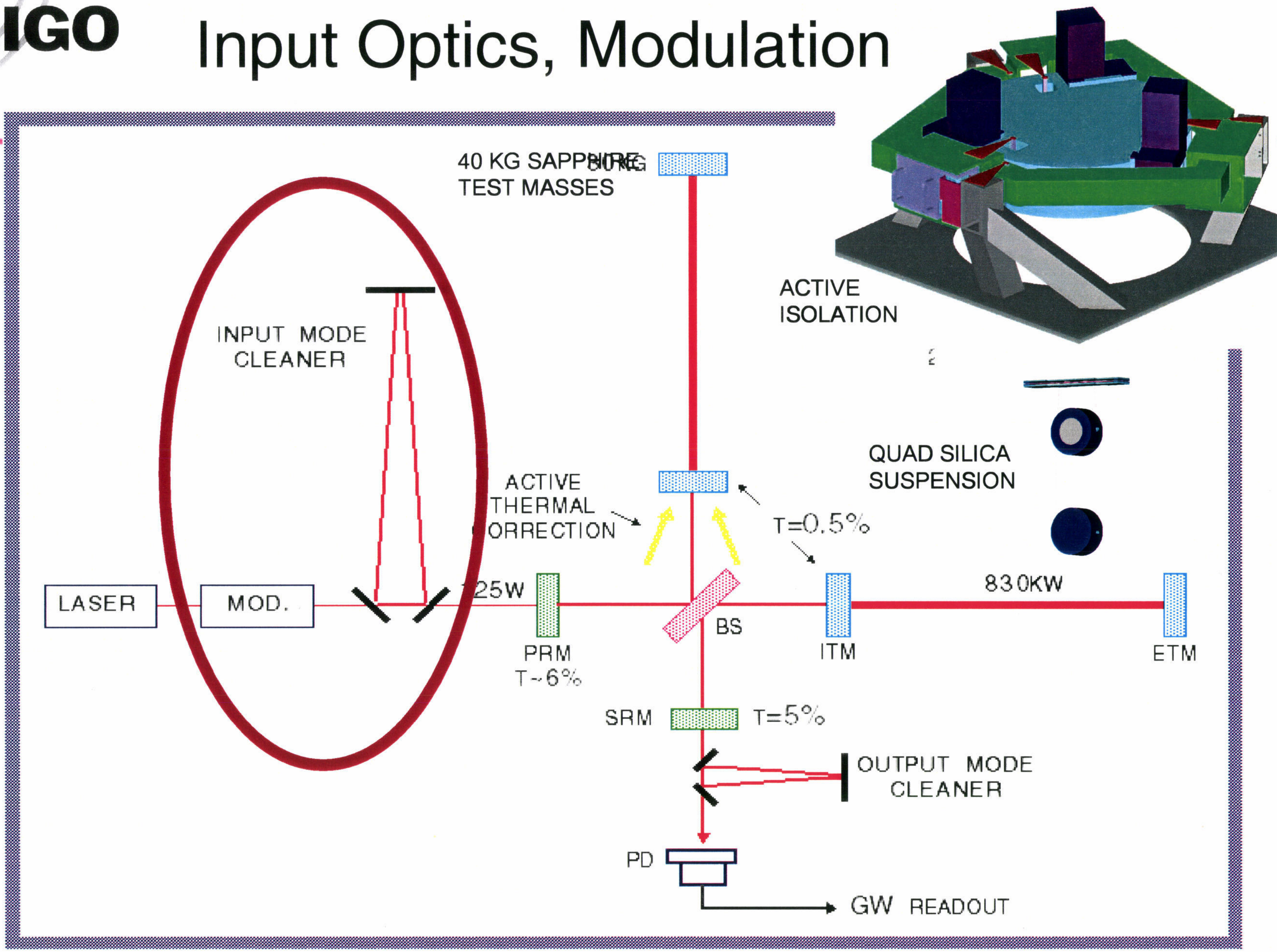
Pre-stabilized laser

- Overall subsystem system design similar to initial LIGO
  - » Frequency stabilization to fixed reference cavity, 10 $Hz/Hz^{1/2}$ at 10 Hz required (10 $Hz/Hz^{1/2}$ at 12 Hz seen in initial LIGO)
  - » Intensity stabilization to in-vacuum photodiode, $2x10^{-9}$ $\Delta P/P$ at 10 Hz required ($1x10^{-8}$ at 10 Hz demonstrated)



- Max Planck Institute, Hannover leading the Pre-stabilized laser development – Willke
  - » Close interaction with Laser Zentrum Hannover
  - » Experience with GEO-600 laser, reliability, packaging
  - » Germany contributing laser to Advanced LIGO

Input Optics, Modulation



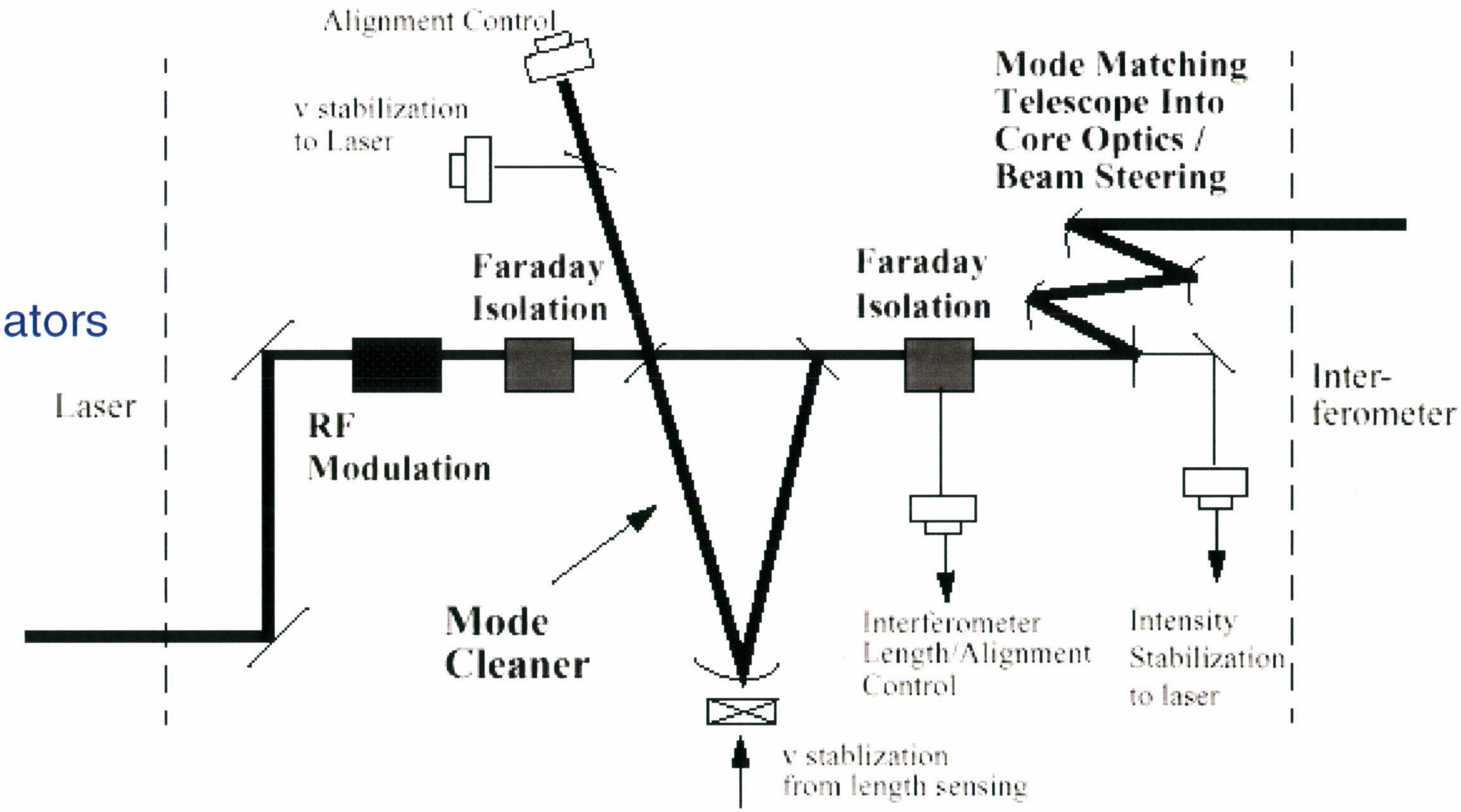
G0300260-00-M

LIGO

Input Optics

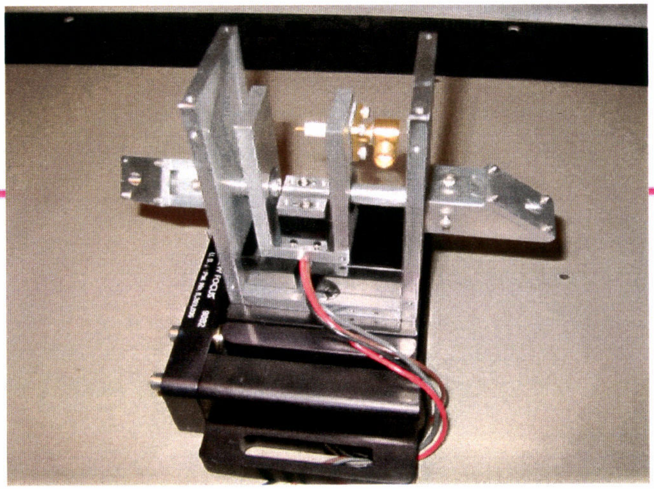
- Provides phase modulation for length, angle control (Pound-Drever-Hall)
- Stabilizes beam position, frequency with suspended mode-cleaner cavity
- Matches into main optics (6 cm beam) with suspended telescope
- 1999 White Paper: Design similar to initial LIGO but 20x higher power

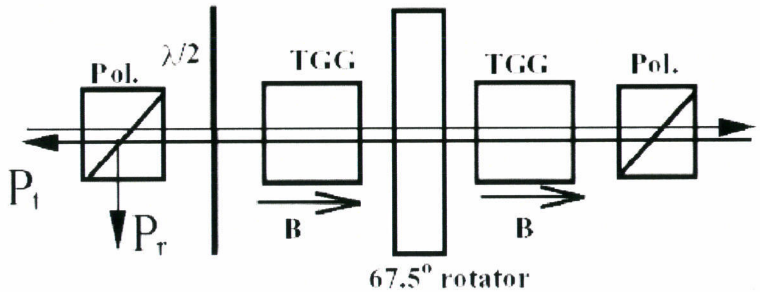
- Challenges:
  » Modulators
  » Faraday Isolators

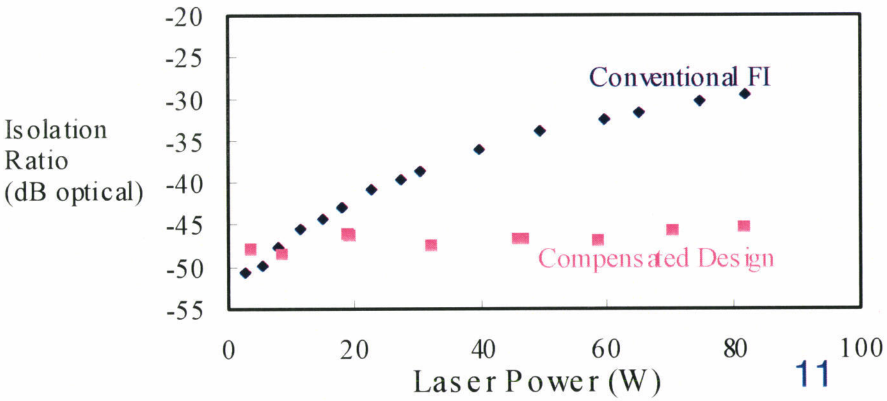


Input Optics

- University of Florida leading development effort -- Reitze
  - » As for initial LIGO
- 2002: High power rubidium tantanyl phosphate (RTP) electro-optic modulator developed
  - » Long-term exposure at Advanced LIGO power densities, with no degradation
- 2003: Faraday isolator from IAP-Nizhny Novgorod
  - » thermal birefringence compensated
  - » Ok to 80 W – more powerful test laser being installed at Livingston

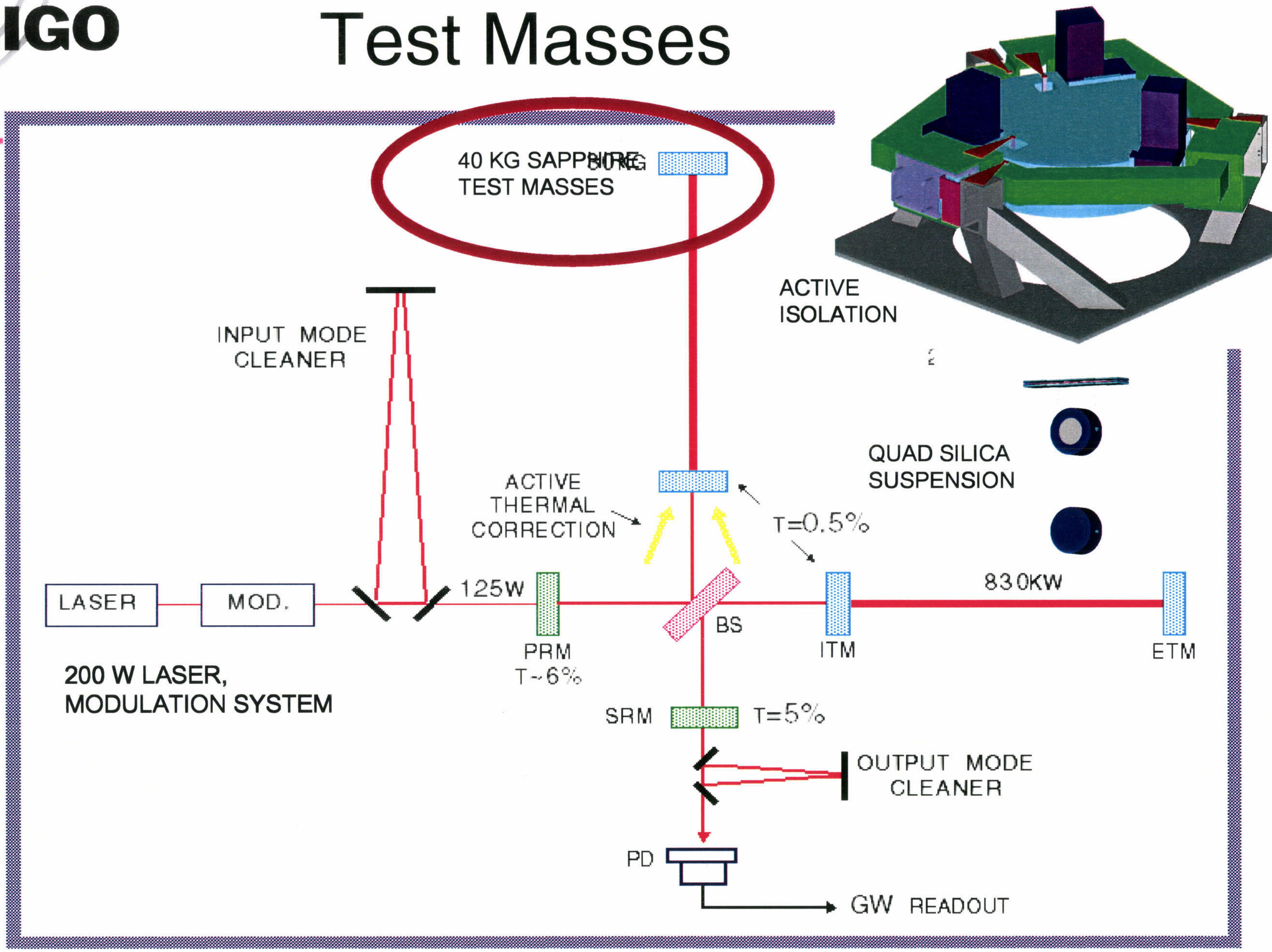






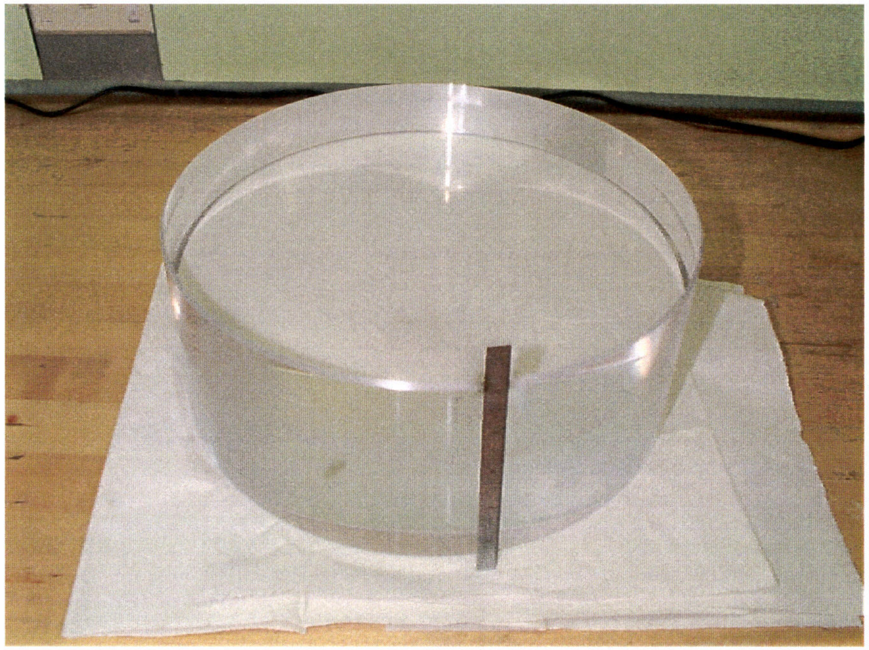
LIGO

Test Masses



Test Masses / Core Optics

- Absolutely central mechanical *and* optical element in the detector
  - » 830 kW; <1ppm loss; <20ppm scatter
  - » $2x10^8$ Q; 40 kg; 32 cm dia
- 1999 White Paper: Sapphire as test mass/core optic material; development program launched
- Low mechanical loss, high density, high thermal conductivity all desirable attributes of sapphire
- Fused silica remains a viable fallback option
- Significant progress in program
  - » Industrial cooperation
  - » Characterization by very active LSC working group

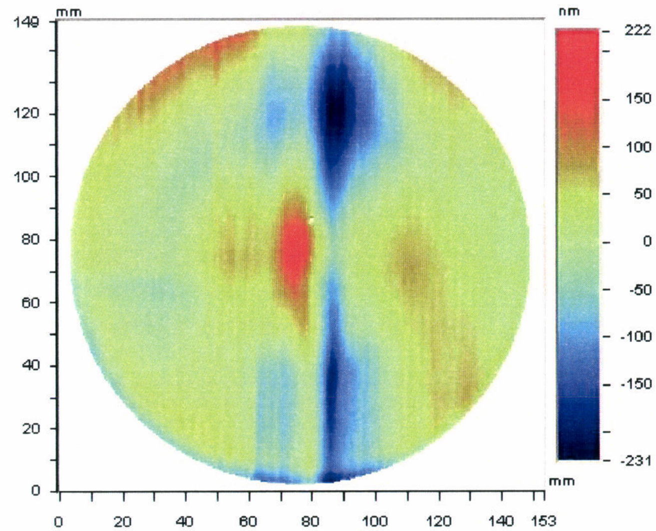


Full-size Advanced LIGO sapphire substrate

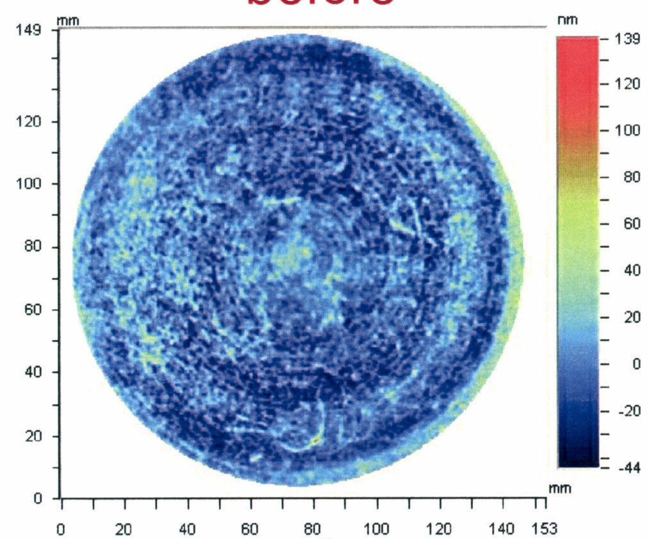
Core Optics

- 2002: Fabrication of Sapphire:
  - » 4 full-size Advanced LIGO boules grown (Crystal Systems); 31.4 x 13 cm; two acquired
- 2003: Mechanical losses: requirement met
  - » recently measured at 200 million (uncoated)
- 2002: Bulk Homogeneity: requirement met
  - » Sapphire as delivered has 50 nm-rms distortion
  - » Goodrich 10 nm-rms compensation polish
- 2001: Polishing technology:
  - » CSIRO has polished a 15 cm diam sapphire piece: 1.0 nm-rms uniformity over central 120 mm (requirement is 0.75 nm)
- 2003: Bulk Absorption:
  - » Uniformity needs work
  - » Average level ~60 ppm, 40 ppm desired
  - » Annealing shown to reduce losses

Compensation Polish

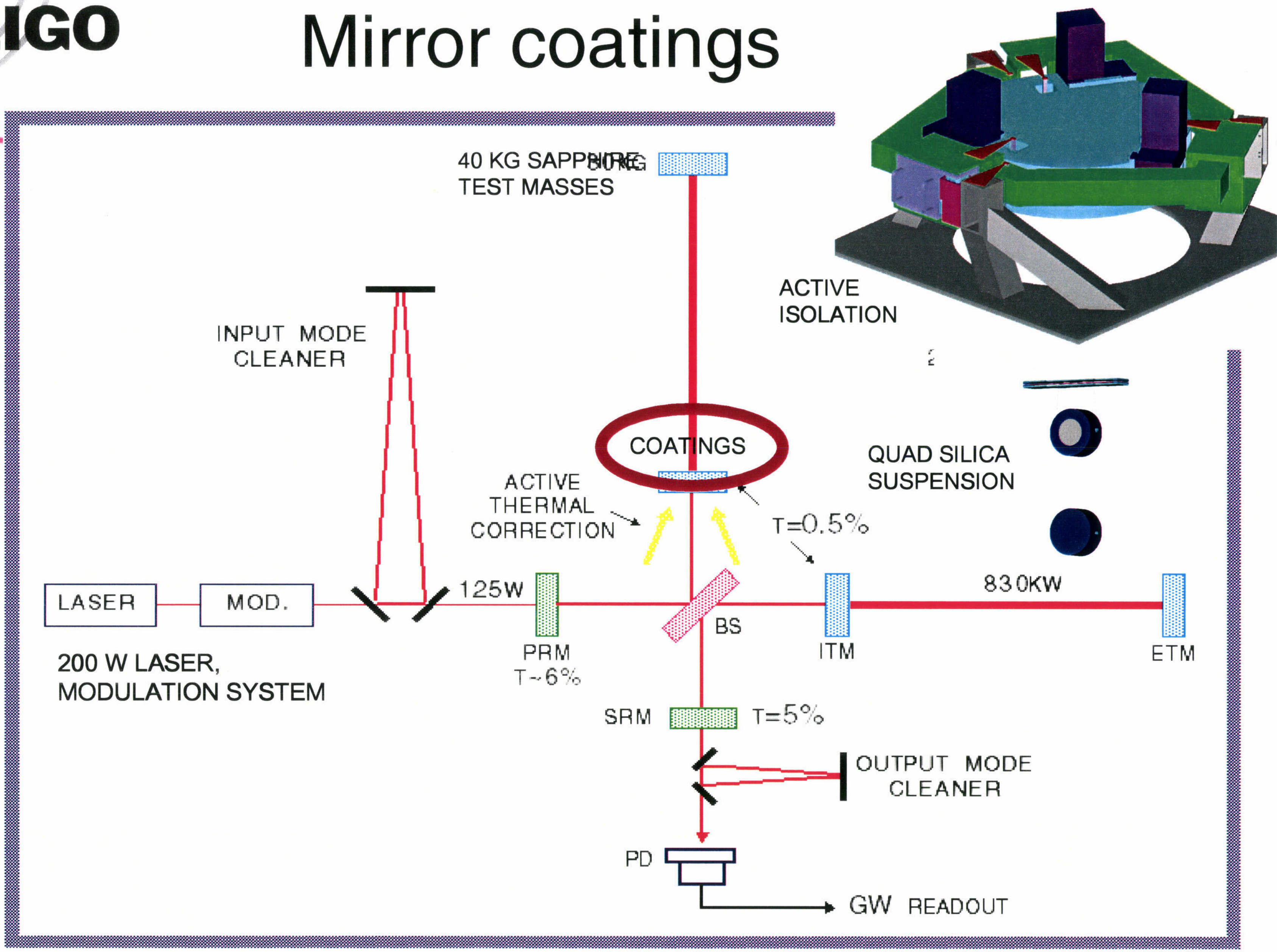


before



after

Mirror coatings



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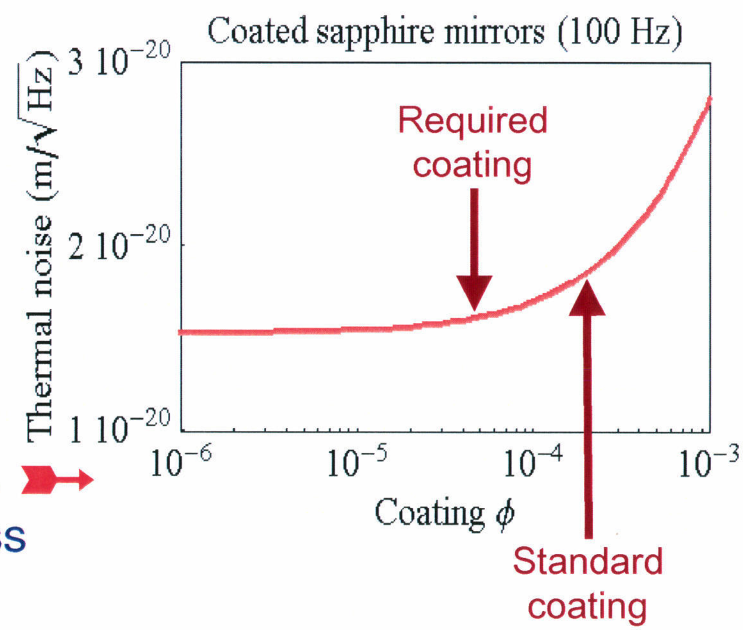
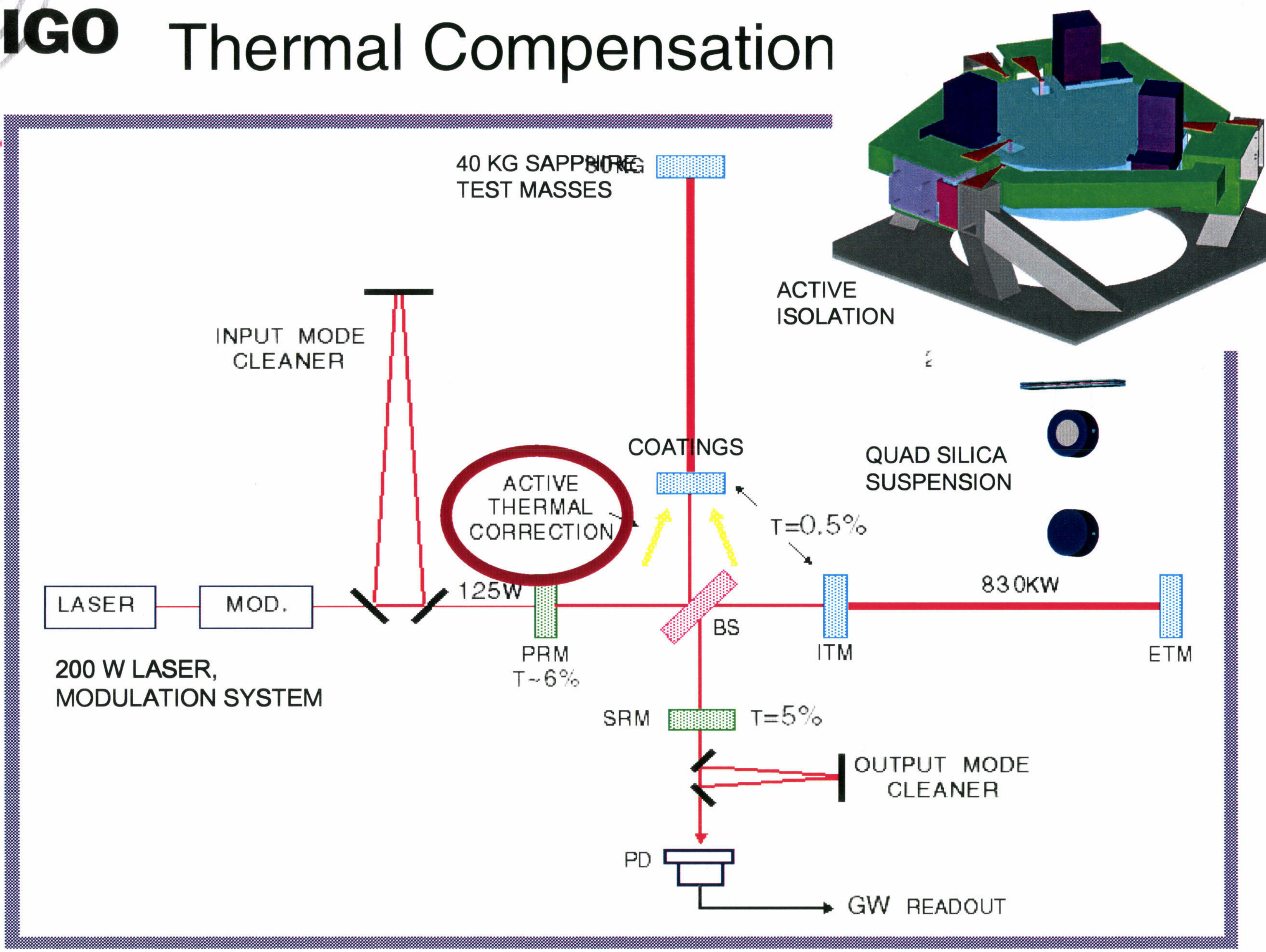
Test Mass Coatings

- Optical absorption (~0.5 ppm), scatter meet requirements for (good) conventional coatings
- R&D mid-2000: Thermal noise due to coating mechanical loss recognized; LSC program put in motion to develop low-loss coatings
  - » Series of coating runs – materials, thickness, annealing, vendors
  - » Measurements on a variety of samples
- 2001: Ta_2O_5 identified as principal source of loss



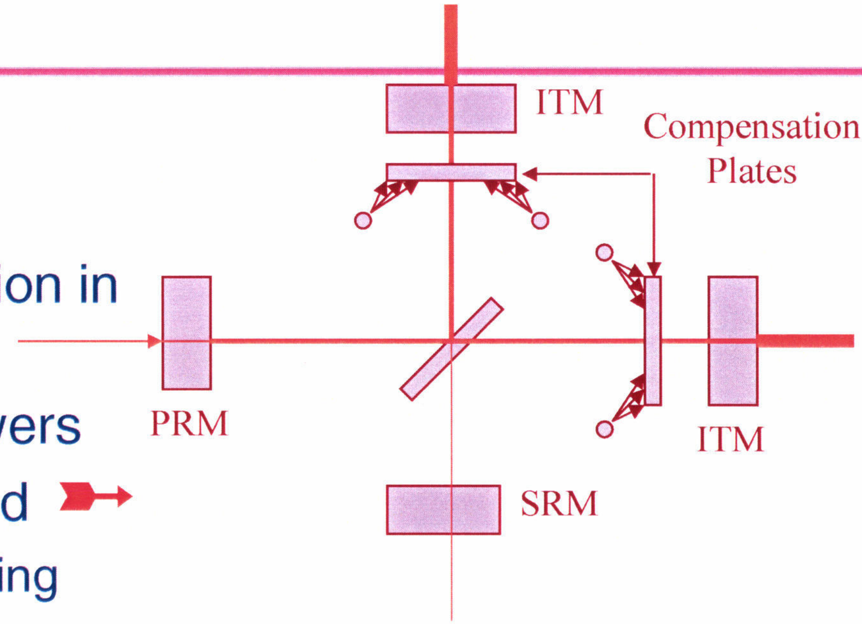
- 2002: Test coatings show somewhat reduced loss
  - » Alumina/Tantala
  - » Doped Silica/Tantala
- Need ~5x reduction in loss to make compromise to performance minimal
- 2003: Expanding the coating development program
  - » RFP out to 5 vendors; expect to select 2
- Direct measurement via special purpose TNI interferometer – lab tour
- First to-be-installed coatings needed in ~2.5 years – sets the time scale

Thermal Compensation

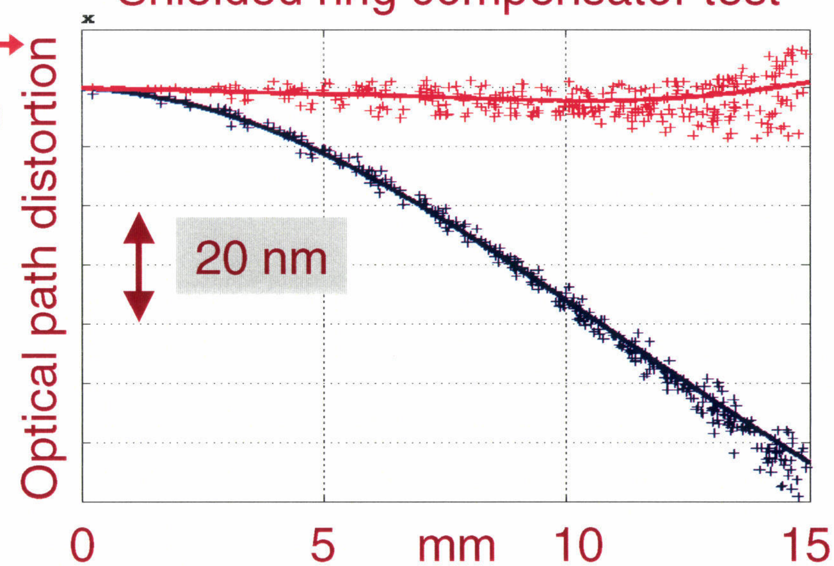


Active Thermal Compensation

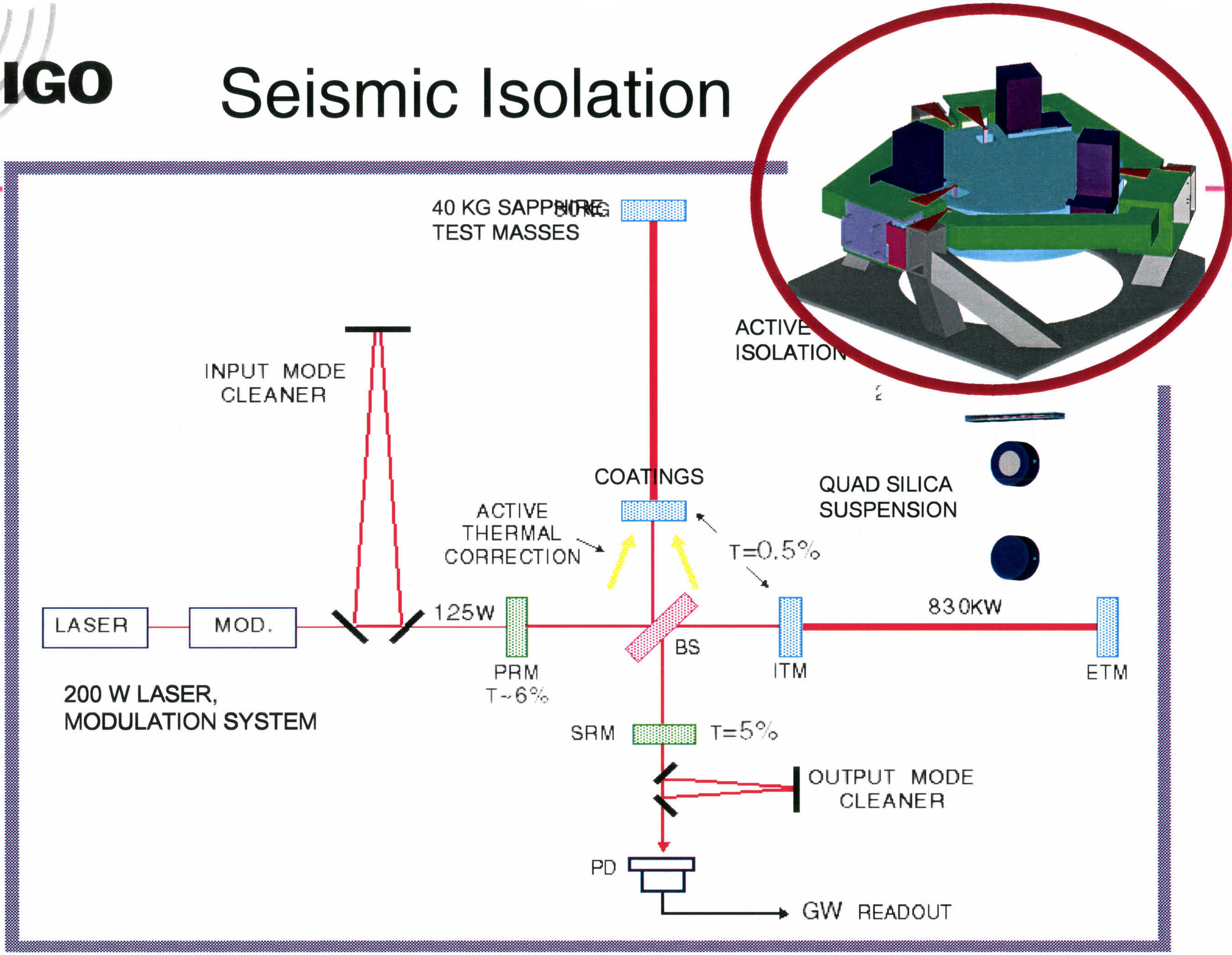
- 1999 White Paper: Need recognized, concept laid out
- Removes excess 'focus' due to absorption in coating, substrate
- Allows optics to be used at all input powers
- 2002: Initial R&D successfully completed
  - » Quasi-static ring-shaped additional heating
  - » Scan to complement irregular absorption
- Sophisticated thermal model ('Melody') developed to calculate needs and solution
- 2003: Gingin facility (ACIGA) readying tests with Lab suspensions, optics
- Application to initial LIGO in preparation



Shielded ring compensator test



Seismic Isolation



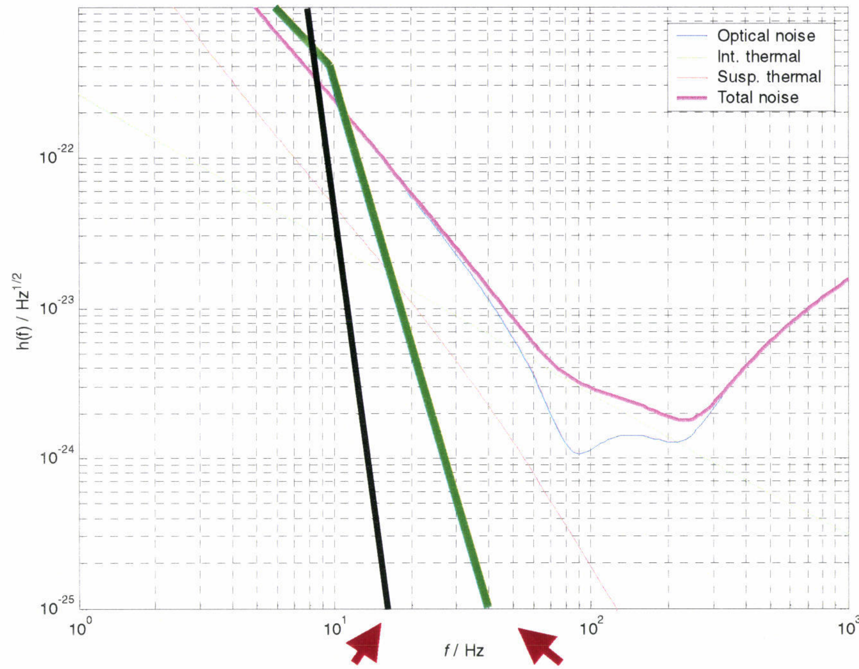
Isolation: Requirements

1999 White Paper: Render seismic noise a negligible limitation to GW searches

- » Newtonian background will dominate for frequencies less than ~15 Hz
- » Suspension and isolation contribute to attenuation

1999 White Paper: Reduce or eliminate actuation on test masses

- » Actuation source of direct noise, also increases thermal noise
- » Acquisition challenge greatly reduced
- » In-lock (detection mode) control system challenge is also reduced



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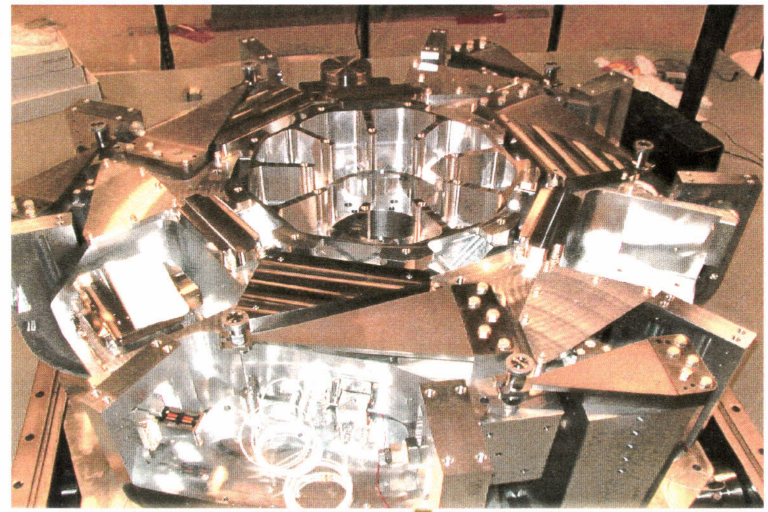
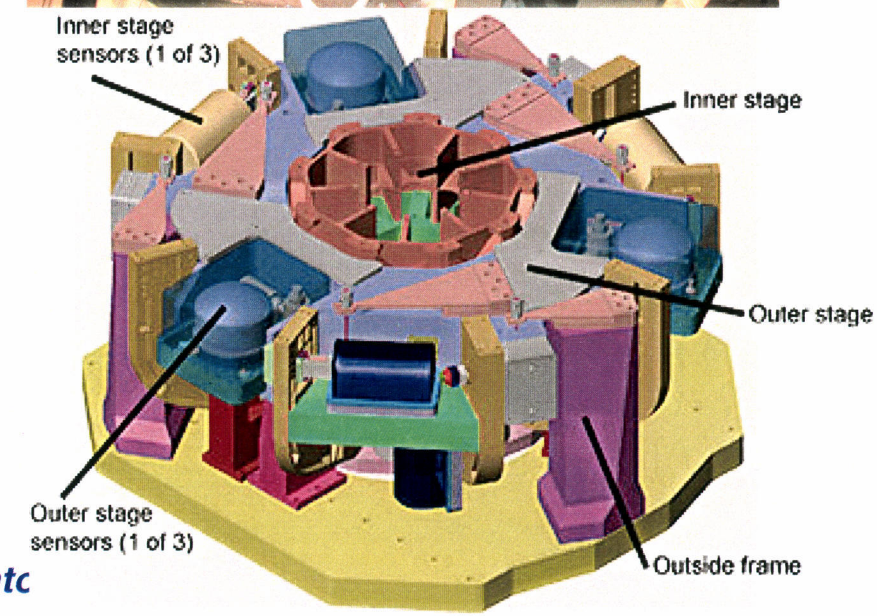
Isolation: Two-stage platform

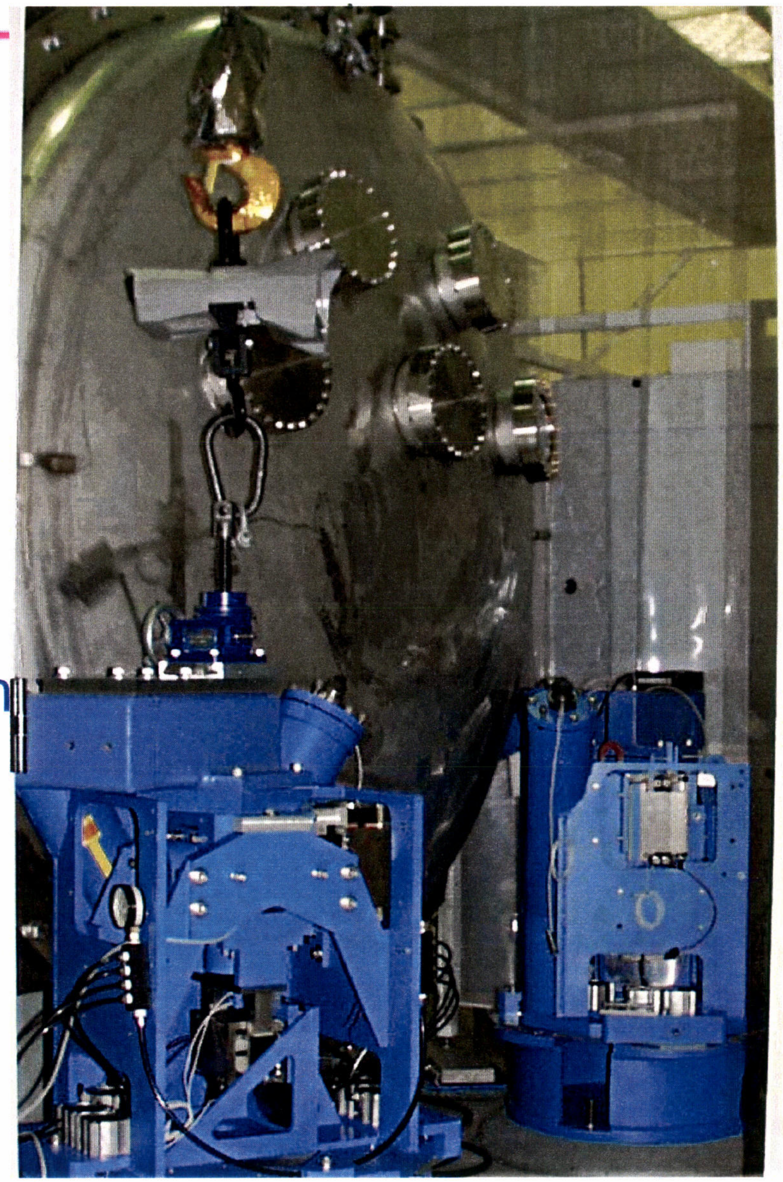
- 2000: Choose an active approach:
  - high-gain servo systems, two stages of 6 degree-of-freedom each
  - Allows extensive tuning of system after installation, operational modes
  - Dynamics decoupled from suspension systems
- Lead at LSU – Giaime
- 2003: Stanford Engineering Test Facility Prototype fabricated
  - Mechanical system complete
  - Instrumentation being installed
  - First measurements indicate excellent actuator – structure alignment
- 2003: RFP for final Prototypes released





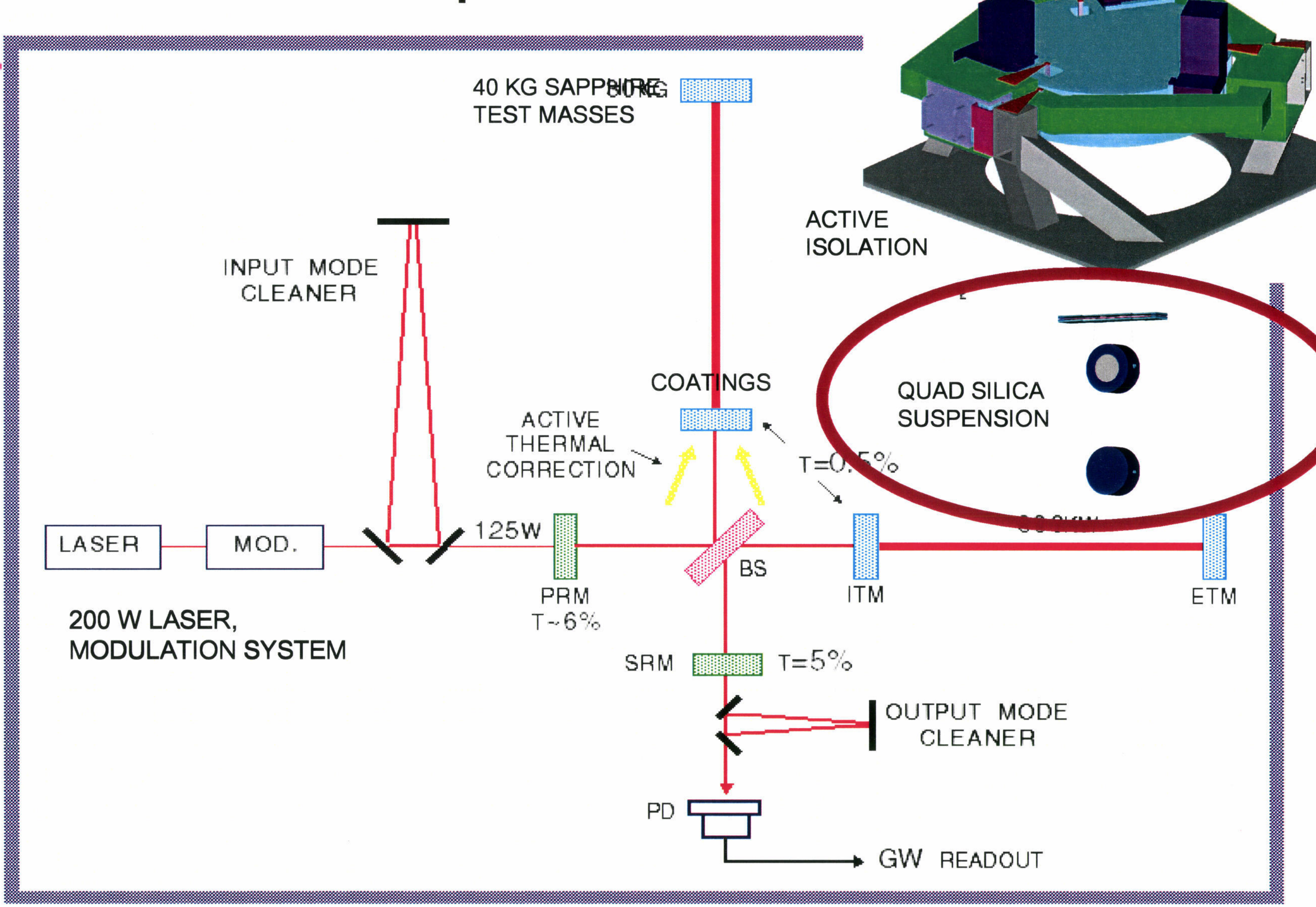
Isolation: Pre-Isolator

- External stage of low-frequency pre-isolation (→ ~1 Hz)
  - Tidal, microseismic peak reduction
  - DC Alignment/position control and offload from the suspensions
  - 1 mm pp range
- Lead at Stanford – Lantz
- 2003: Prototypes in test and evaluation at MIT for early deployment at Livingston in order to reduce the cultural noise impact on initial LIGO
  - System performance exceeds → Advanced LIGO requirements



LIGO

Suspension



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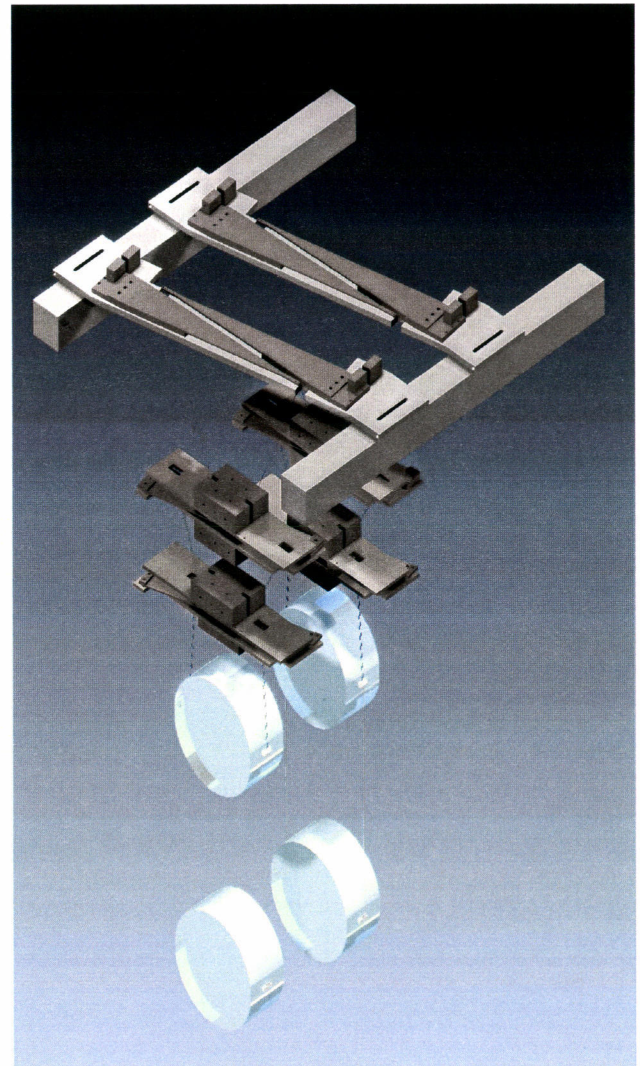
Suspensions: Test Mass Quads

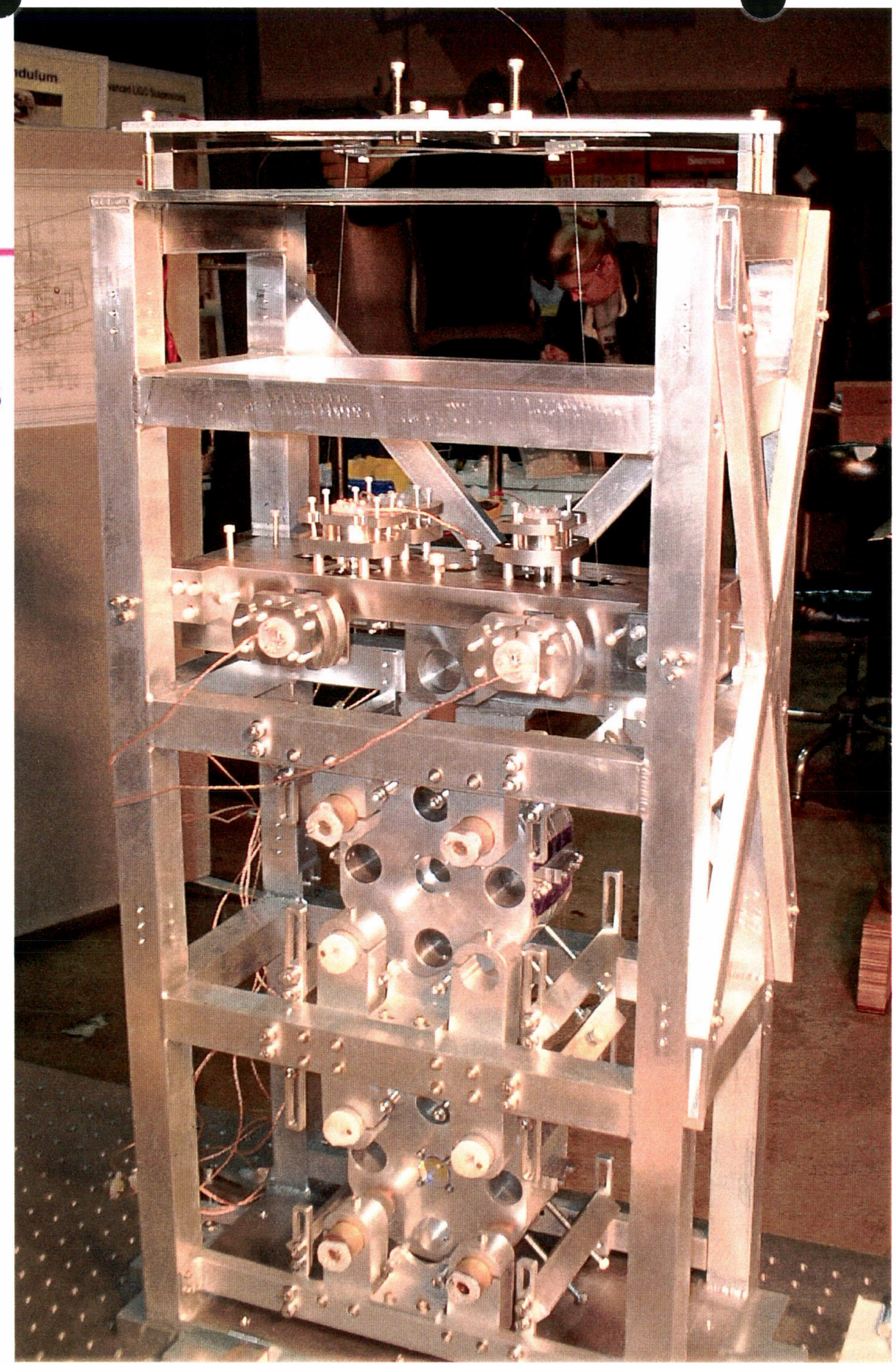
- 1999 White Paper: Adopt GEO600 monolithic suspension assembly
- Requirements:
  - » minimize suspension thermal noise
  - » Complement seismic isolation
  - » Provide actuation hierarchy
- 2000: Quadruple pendulum design chosen
  - » Fused silica fibers, bonded to test mass
  - » Leaf springs (VIRGO origin) for vertical compliance
- Success of GEO600 a significant comfort
  - » 2002: All fused silica suspensions installed
- PPARC funding approved: significant financial, technical contribution; quad suspensions, electronics, and some sapphire substrates
  - » U Glasgow, Birmingham, Rutherford
  - » Quad lead in UK – Cantley, Strain, Hough



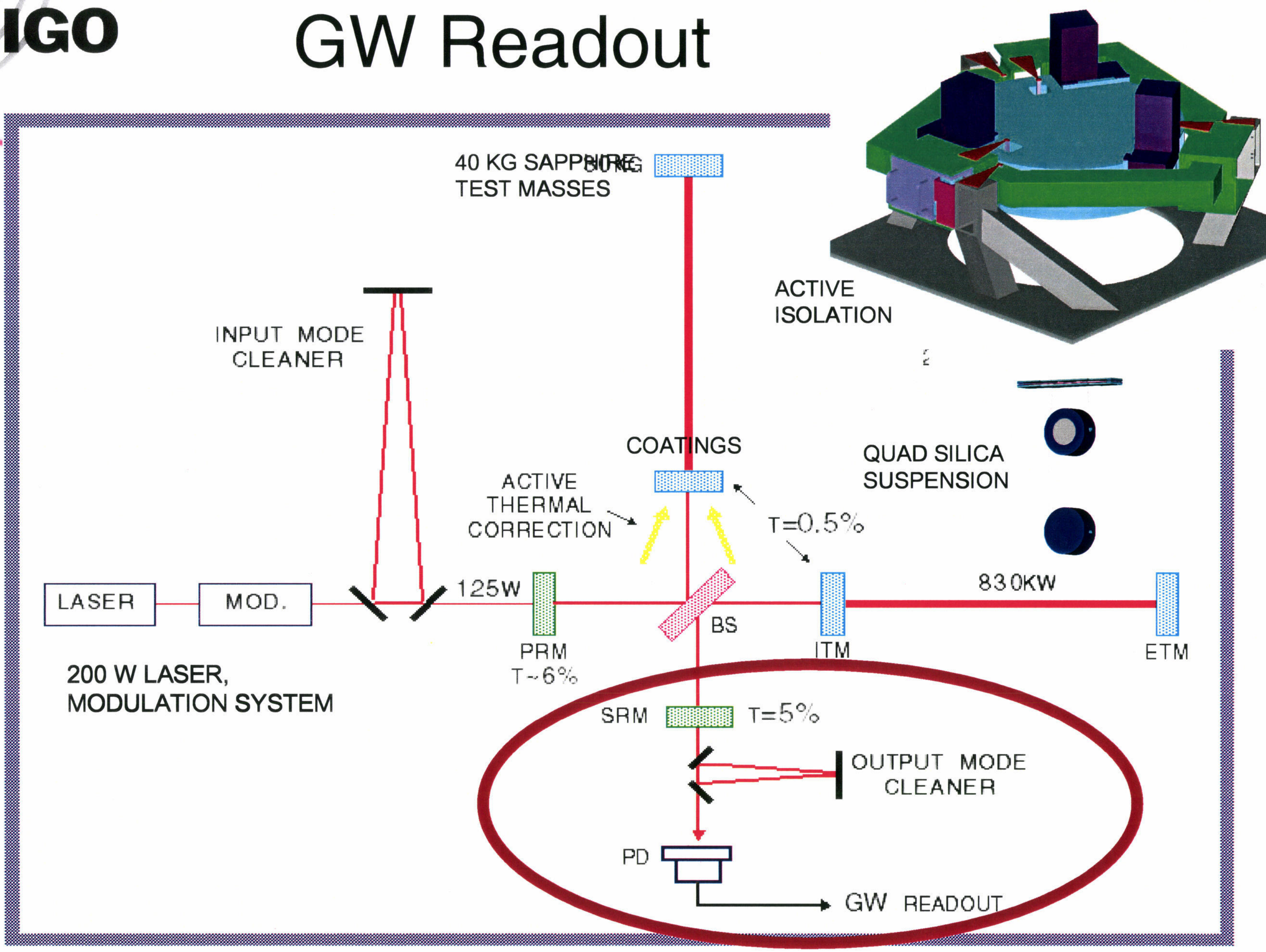
LIGO

Suspensions: Triples

- Triple suspensions for auxiliary optics
  - » Relaxed performance requirements
- Uses same fused-silica design, control hierarchy
- 2003: Prototype of Mode Cleaner triple suspension fabricated -- lab tour
- To be installed in LASTI fall-2003
  - » Fit tests
  - » Controls/actuation testing

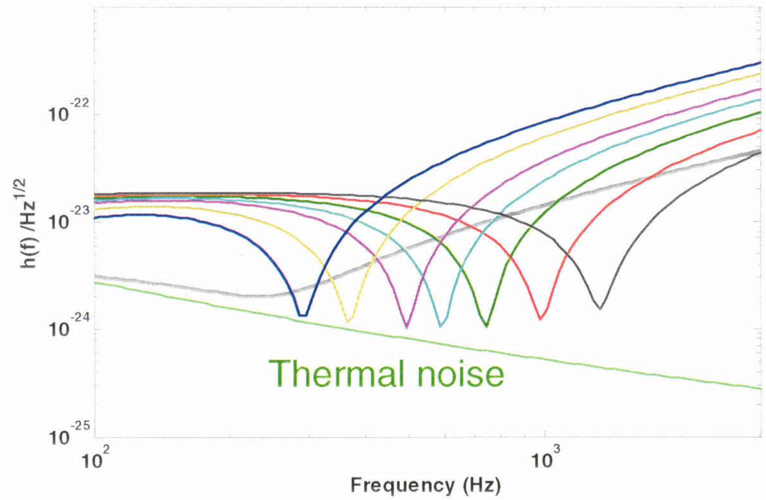


GW Readout


40 KG SAPPHIRE
TEST MASSES
ACTIVE
ISOLATION
INPUT MODE
CLEANER
COATINGS
QUAD SILICA
SUSPENSION
ACTIVE
THERMAL
CORRECTION
T=0.5%
LASER
MOD.
125W
830KW
BS
PRM
T~6%
ITM
ETM
200 W LASER,
MODULATION SYSTEM
SRM
T=5%
OUTPUT MODE
CLEANER
PD
GW READOUT

GW readout, Systems

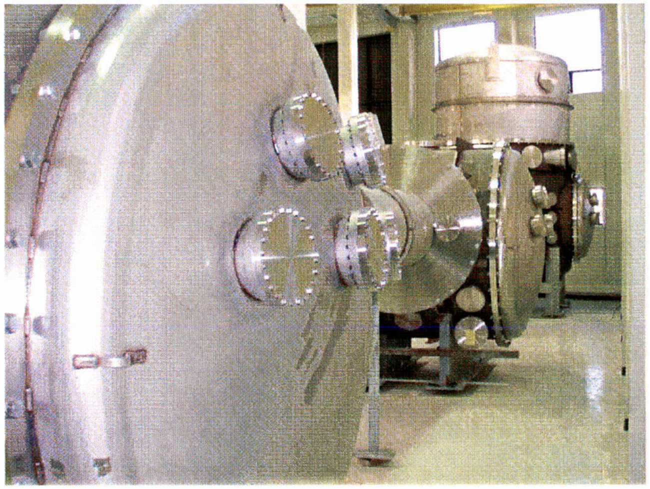
- 1999 White Paper: Signal recycled Michelson Fabry-Perot configuration
  - Offers flexibility in instrument response, optimization for technical noises
  - Can also provide narrowband response
  - Critical advantage: can distribute optical power in interferometer as desired

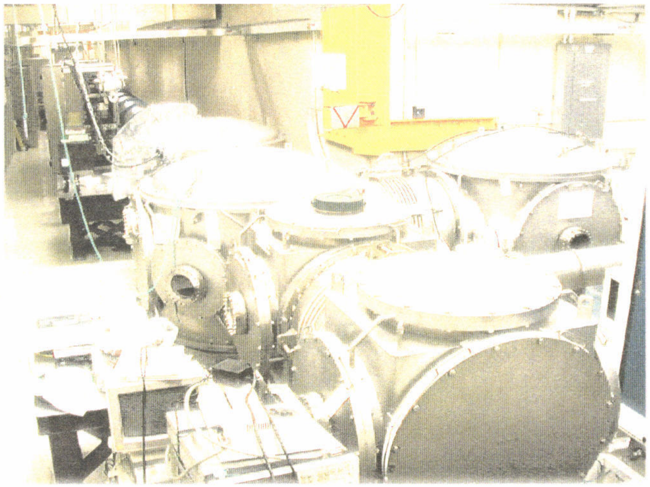


- 2000: Three table-top prototypes give direction for sensing, locking system
- 2003: Glasgow 10m prototype: control matrix elements confirmed
- 2003: Readout choice – DC rather than RF for GW sensing
  - Offset ~ 1 picometer from interferometer dark fringe
  - Best SNR, simplifies laser, photodetection requirements
- Caltech 40m prototype in construction, early testing – lab tour
  - Complete end-to-end test of readout, controls, data acquisition

System testing

- Initial LIGO experience: thorough testing off-site necessary
- Very significant feature in Advanced LIGO plan: testing of accurate prototypes in context
- Two major facilities:
  - » MIT LASTI facility – full scale tests of seismic isolation, suspensions, laser, mode Cleaner
  - » Caltech 40m interferometer – sensing/controls tests of readout, engineering model for data acquisition, software – lab tour
- Support from LSC testbeds
  - » Gingin – thermal compensation
  - » Glasgow 10m – readout
  - » Stanford ETF – seismic isolation
  - » GEO600 – much more than a prototype!





Scope of proposal

- Upgrade of the detector
  - » All interferometer subsystems
  - » Data acquisition and control infrastructure
- Upgrade of the laboratory data analysis system
  - » Observatory on-line analysis
  - » Caltech and MIT campus off-line analysis and archive
- Virtually no changes in the infrastructure
  - » Buildings, foundations, services, 4km arms unchanged
  - » Present vacuum quality suffices for Advanced LIGO – 10^{-7} torr
  - » Move 2km test mass chambers to 4km point at Hanford
  - » Replacement of ~15m long spool piece in vacuum equipment

Upgrade of all three interferometers

- In discovery phase, tune all three to broadband curve
  - » 3 interferometers nearly doubles the event rate over 2 interferometers
  - » Improves non-Gaussian statistics
  - » Commissioning on other LHO IFO while observing with LHO-LLO pair
- In observation phase, the same IFO configuration can be tuned to increase low or high frequency sensitivity
  - » sub-micron shift in the operating point of one mirror suffices
  - » third IFO could e.g.,
    - – observe with a narrow-band VIRGO
    - – focus alone on a known-frequency periodic source
    - – focus on a narrow frequency band associated with a coalescence, or BH ringing of an inspiral detected by other two IFOs

LIGO

Reference design

- Baseline is to upgrade the 3rd interferometer from 2km to 4km
  - » Cost is modest and sensitivity gain supports discovery
  - » Will certainly want maximum sensitivity later
- Baseline is a nearly simultaneous upgrade of both sites
  - » Could stagger quite significantly to maintain the network – with an equally significant delay in completion and coincidence observations by the two LIGO sites
- Baseline is to employ Sapphire as the test mass material
  - » Fused silica a strong fallback

Timing of Advanced LIGO

- Direct observation of gravitational waves is a compelling scientific goal, and Advanced LIGO will be a crucial element
  - » Revolutionary increase in sensitivity over first generation instruments
  - » Strong astrophysical support for Advanced LIGO signal strengths
- Delaying Advanced LIGO likely to create a significant gap in the field – at least in the US
  - » Can lose the team of instrument scientists
  - » Running costs of an over-exploited instrument represents lost opportunity
- Our LSC-wide R&D program is in concerted motion
  - » Appears possible to meet program goals
- We are well prepared
  - » Reference design well established, confirmation growing through R&D
- Timely for International partners that we move forward now

Baseline plan

- Initial LIGO Observation at design sensitivity 2004 – 2006
  - » Significant observation within LIGO Observatory
  - » Significant networked observation with GEO, VIRGO, TAMA
- Structured R&D program to develop technologies
  - » Conceptual design developed by LSC in 1998
  - » Cooperative Agreement carries R&D to Final Design
- Now: This proposal is for fabrication, installation
- Long-lead purchases planned for 2004, real start 2005
  - » Sapphire Test Mass material, seismic isolation fabrication
  - » Prepare a 'stock' of equipment for minimum downtime, rapid installation
- Start installation in 2007
  - » Baseline is a staggered installation, Livingston and then Hanford
- Coincident observations by 2010

LIGO

Advanced LIGO

- Initial instruments, data establishing the field of interferometric GW detection
- Advanced LIGO promises exciting astrophysics
- Substantial progress in R&D, design
- Still a few good problems to solve
- A broad community effort, international support
- Ready to make transition from R&D to Project

- Advanced LIGO can lead the field to maturity

G0300260-00-M

LIGO

Advanced LIGO Cost, Schedule and Management

Gary H Sanders

NSF Review of Advanced LIGO

Caltech, June 11, 2003

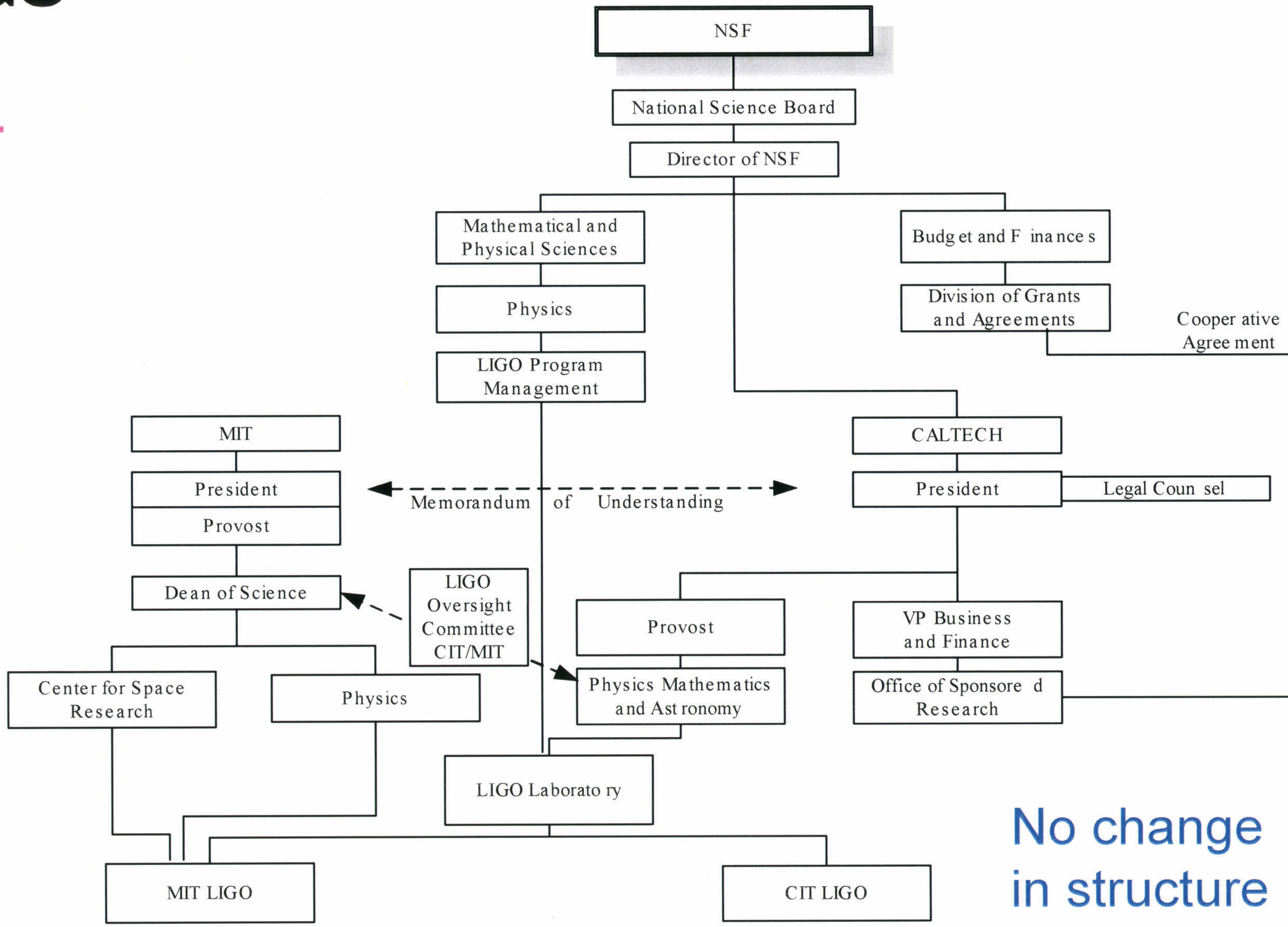
LIGO-G030251-01-M

Main Points

- **Experienced LIGO Lab team** has planned and estimated Advanced LIGO with the LSC
- LIGO Lab and LSC have formed a strong partnership
- Design and development process is already underway in a “project” setting
- Most of the elements of a formal project are in place
- Costs are estimated in detail
- Schedule planning is thorough and will support definition of the final negotiated project
- Performance measurement infrastructure is in place
- International partnerships are already being exercised
- Project Management Plan can be made definitive when financial commitments are complete

LIGO

Organization

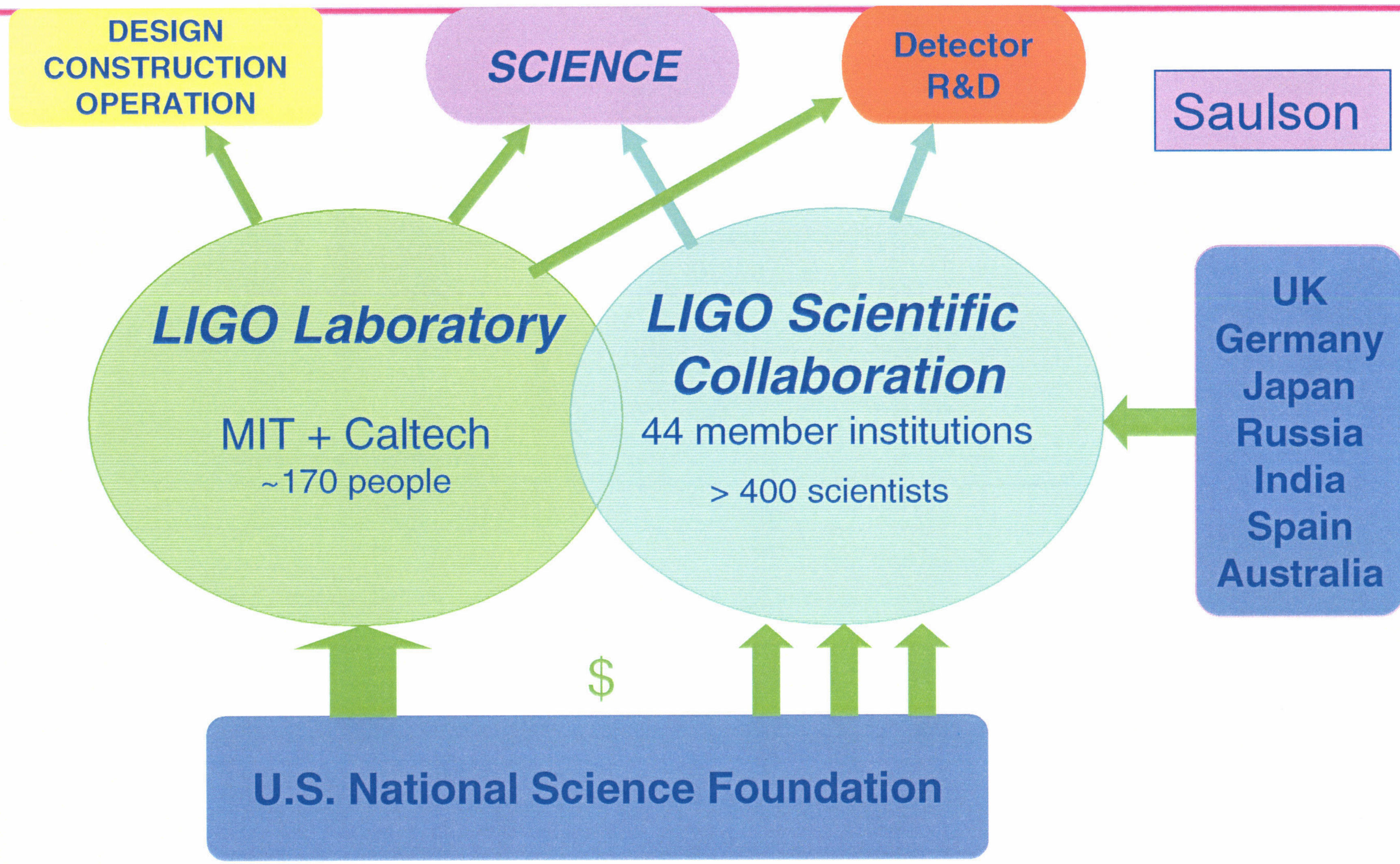


No change in structure required

A Development Project Across the LSC

- Since late 1999, we have planned the Advanced LIGO development program as if it was part of a construction project
  - » Work Breakdown Structure
  - » Cost estimate
  - » Schedule
  - » Management structure
  - » Requirements documented and systems engineering and modeling
  - » Design process established
- This "projectized" development program has been operating in a serious **collaborative** manner across the LSC
  - » LSC Working Groups
    - – Advanced detector configurations working group
    - – Core optics working group
    - – Laser working group
    - – Suspensions working group

LIGO Organization & Support



LIGO

LSC "Project" Participation

- Lab and LSC scientists/engineers share in leadership roles in the project
- LSC working groups already coordinate progress in monthly meetings and at LSC face-to-face meetings
- LSC Executive Committee involved in discussions of all major design choices and decisions
- Advanced LIGO has become a shared Lab/LSC project

Advanced LIGO Resource Model

- Current FY2002 – FY2006 Cooperative Agreement
  - » LIGO Lab **operating** resources provide staff and support for Advanced LIGO development through Final Design/prototype stage
  - » LIGO Lab **R&D** resources support Advanced LIGO equipment, procurements, incremental staff
- This request supports fabrication and construction, and very little incremental staff for construction and installation
  - » From MREFC or R&RA NSF accounts as NSF determines
- We assume LIGO Lab renewal Cooperative Agreement FY2007 – FY2011 supports staff and infrastructure support for fabrication, construction, installation, commissioning of Advanced LIGO
- LSC/international partner resources support their development programs
- International partner capital budgets support portions of the fabrication, construction, installation
- All of these elements are properly included in the plan shown at this review

LIGO

Work Breakdown Structure (WBS)

Advanced LIGO WBS

- 1.0 Initial LIGO Construction
- 2.0 LIGO Laboratory Operations
- 3.0 LIGO Laboratory Advanced R&D
- 4.0. Advanced LIGO Project (Advanced LIGO)
  - » 4.1. Facility Modifications (FAC)
  - » 4.2. Seismic Isolation Subsystem (SEI)
  - » 4.3. Suspension Subsystem (SUS)
  - » 4.4 Prestabilized Laser Subsystem (PSL)
  - » 4.5. Input Optics Subsystem (IO)
  - » 4.6. Core Optics Components (COC)
  - » 4.7. Auxiliary Optics Subsystem (AOS)
  - » 4.8. Interferometer Sensing and Controls Subsystem (ISC)
  - » 4.9. Data Acquisition, Diagnostics, Network & Supervisory Control (DAQ)
  - » 4.10. Support Equipment (SUP)
  - » 4.11. Advanced LIGO Construction Project Research and Development (R&D)
  - » 4.12. Data Analysis and Computing Subsystem (COMP)
  - » 4.13. Installation and Commissioning Task (INS)
  - » 4.14. Project Management (PM)

Based upon existing LIGO Laboratory WBS/account structure

LIGO.2 LIGO Laboratory Operations

LIGO.2.01 Laboratory Caltech Site Operations

- LIGO.2.01.1 Director's Office (DIR)
- LIGO.2.01.2 Business Office (BUS)
- LIGO.2.01.3 Technical and Engineering Support (TEC)
- LIGO.2.01.4 Detector Support (DET)
- LIGO.2.01.5 Data Analysis and Computing (COMP)
  - LIGO.2.01.5.1 Data Analysis (REC)
  - LIGO.2.01.5.2 Modeling & Simulation (REC)
  - LIGO.2.01.5.3 Data Analysis - General Comp
- LIGO.2.01.6 Campus Research Facilities (CAM)
  - LIGO.2.01.6.1 40 Meter Interferometer Upgrade
    - LIGO.2.01.6.1.1 FAC
      - LIGO.2.01.6.1.1.1 Lab Expansion
      - LIGO.2.01.6.1.1.2 Vacuum Envelope
      - LIGO.2.01.6.1.1.3 Vacuum Controls
    - LIGO.2.01.6.1.2 SEI
      - LIGO.2.01.6.1.2.1 Output Chamber Stack
      - LIGO.2.01.6.1.2.2 Cavity Optics Isolation
      - LIGO.2.01.6.1.2.3 Open
      - LIGO.2.01.6.1.2.4 Active Isolators
    - LIGO.2.01.6.1.3 SUS
      - LIGO.2.01.6.1.3.1 Large Optic Suspensions
      - LIGO.2.01.6.1.3.2 Small Optic Suspensions
    - LIGO.2.01.6.1.4 PSL
      - LIGO.2.01.6.1.4.1 Laser
      - LIGO.2.01.6.1.4.2 PSL

LIGO.4 Advanced LIGO Construction

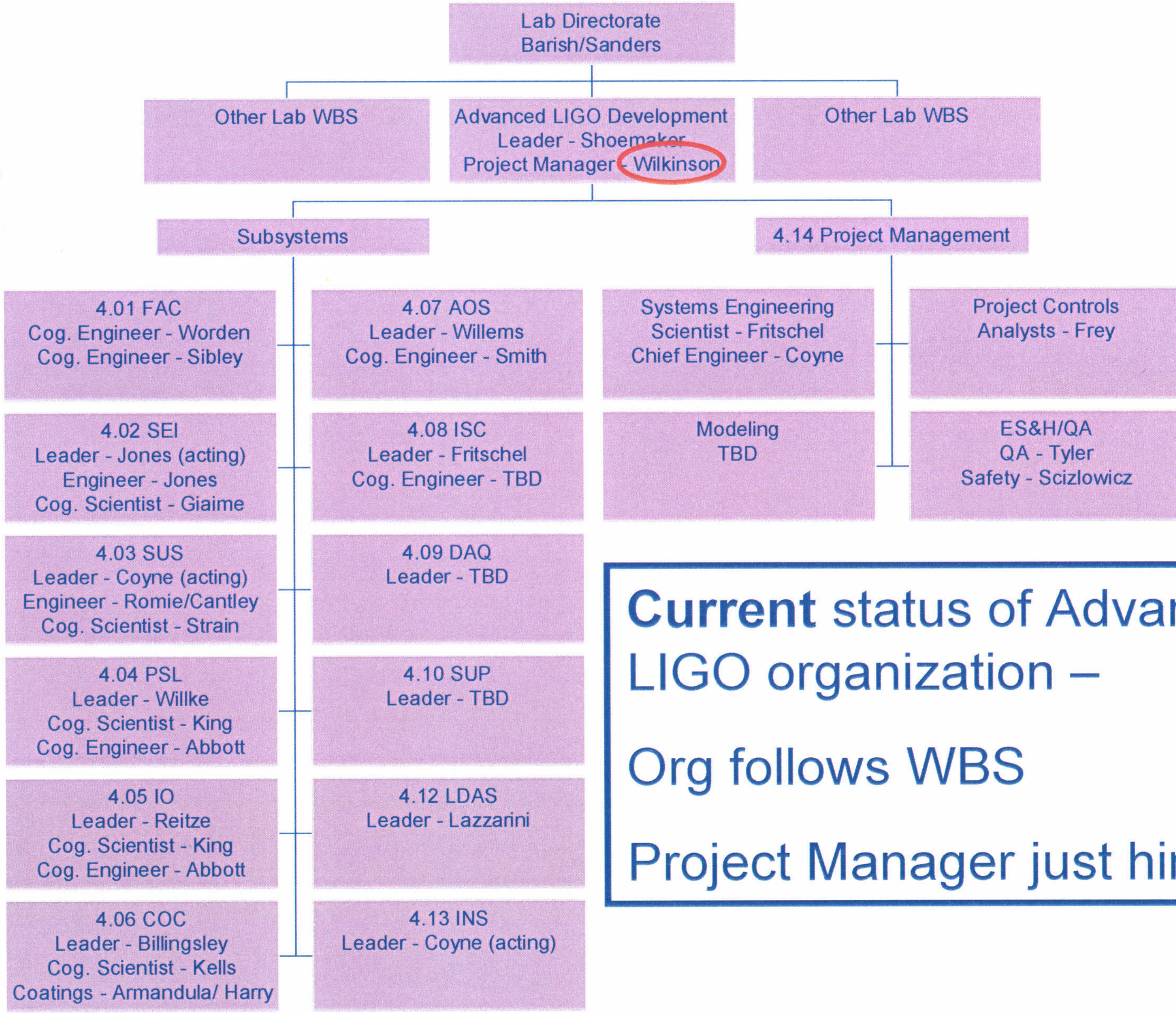
LIGO.4.01 Facility Modifications (FAC)

- LIGO.4.01.1 FAC Vacuum Equipment
  - LIGO.4.01.1.1 2K to 4K Conversion
  - LIGO.4.01.1.2 Clean Room Systems
  - LIGO.4.01.1.3 Vacuum Equipment Bakeout and Preparation
- LIGO.4.01.2 FAC Beam Tube
- LIGO.4.01.3 FAC Conventional Facilities
  - LIGO.4.01.3.1 Livingston Staging Building
  - LIGO.4.01.3.2 Staging Building Cranes

LIGO.4.02 Seismic Isolation (SEI)

- LIGO.4.02.1 SEI Subsystem Management
- LIGO.4.02.2 SEI R&D
  - LIGO.4.02.2.1 Seismic Isolation R&D - Caltech (SEI)
  - LIGO.4.02.2.2 Stochastic Noise R&D - MIT (STO)
  - LIGO.4.02.2.3 Seismic Isolation R&D - LSU
  - LIGO.4.02.2.4 Seismic Isolation R&D - Stanford
  - LIGO.4.02.2.5 Seismic Isolation R&D - JILA
- LIGO.4.02.3 SEI Design
  - LIGO.4.02.3.1 SEI Conceptual Design/Requirements
  - LIGO.4.02.3.2 SEI Preliminary Design
    - LIGO.4.02.3.2.1 ETF Prototype Unit
      - LIGO.4.02.3.2.1.1 Design
        - LIGO.4.02.3.2.1.1.1 Requirements Definition
        - LIGO.4.02.3.2.1.1.2 Mechanical Design
        - LIGO.4.02.3.2.1.1.3 Electrical Design

LIGO



Current status of Advanced LIGO organization –

Org follows WBS

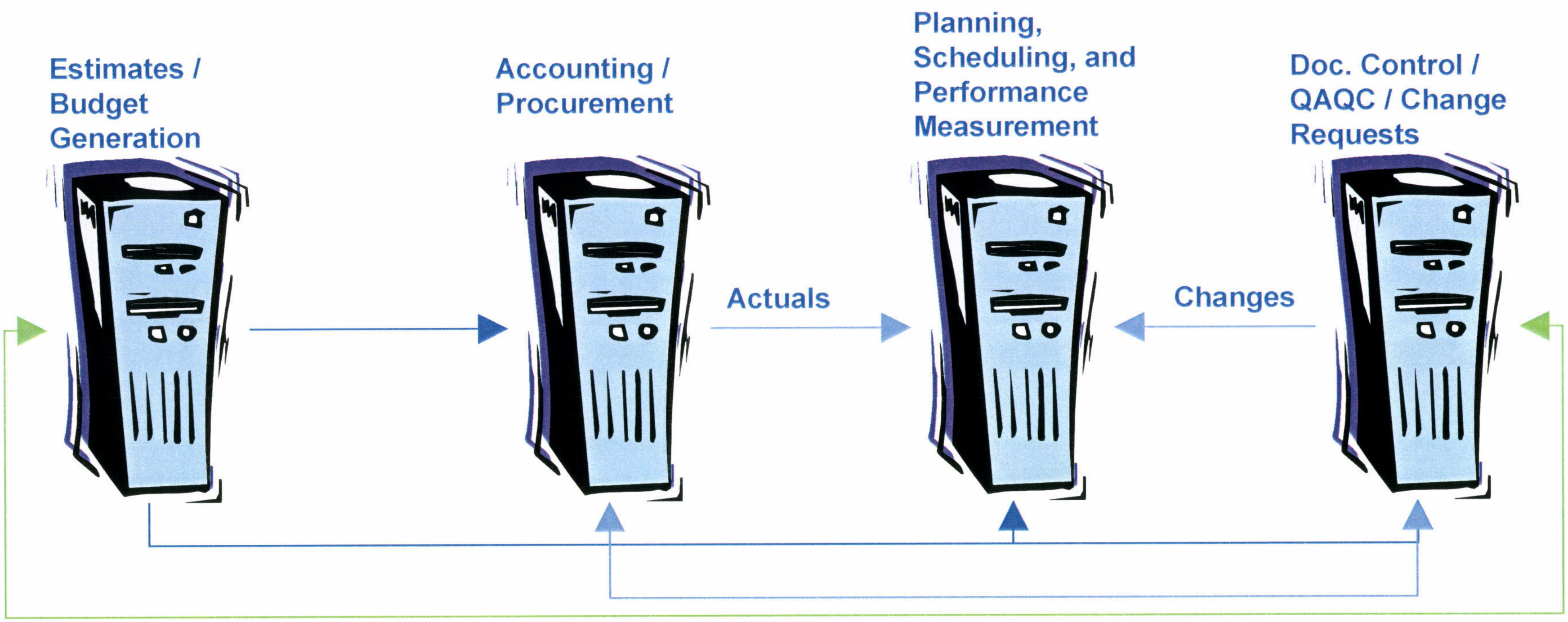
Project Manager just hired

LIGO

Project Planning

Basic Elements of Project Planning Are in Place

- Elements of the PMCS (EVMS)



Cost Estimate

Estimates Performed To a Standard

- Guidance provided to estimators on
  - Basis of Estimate (BOE)
  - Work Breakdown Structure (WBS)
  - Costing Methodology
  - Cost Database
  - Collection of Information
  - Confidence of Cost Estimate
  - Cost Book
  - Schedule Integration
  - Direct Labor Rates
  - Contract Labor
  - Risk Analysis
  - Risk Assessment Methodology
  - Escalation

Advanced LIGO

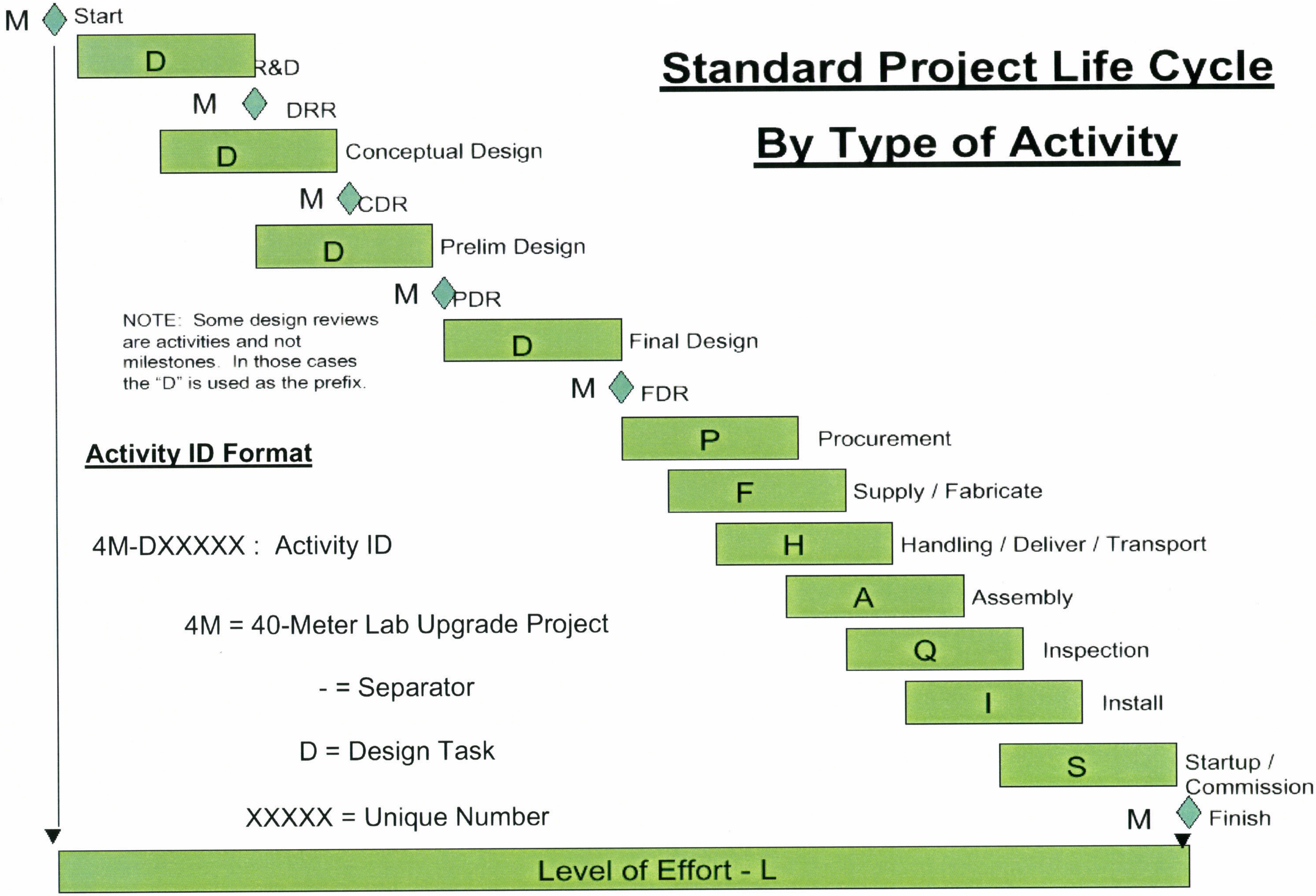
COST ESTIMATING PLAN (CEP)

May 23, 2003

LIGO-M990310-05-M

Standard Project Life Cycle

By Type of Activity



Activity ID Format

4M-DXXXXX : Activity ID

4M = 40-Meter Lab Upgrade Project

- = Separator

D = Design Task

XXXXX = Unique Number

Advanced LIGO					
09-40111-12	2K to 4K Conversion	CAP	LIGO.00009	40111	NSFLIGO.000012
09-40112-12	Clean Room Systems	CAP	LIGO.00009	40112	NSFLIGO.000012
09-40113-12	Vacuum Equipment Bakeout and Preparation	CAP	LIGO.00009	40113	NSFLIGO.000012
09-4012-12	FAC Beam Tube	CAP	LIGO.00009	4012	NSFLIGO.000012
09-40131-12	Livingston Staging Building	CAP	LIGO.00009	40131	NSFLIGO.000012
09-40132-12	Staging Building Cranes	CAP	LIGO.00009	40132	NSFLIGO.000012
09-4021-12	SEI Subsystem Management	ON	LIGO.00009	4021	NSFLIGO.000012

LIGO.4 Advanced LIGO Construction

- **LIGO.4.01 Facility Modifications (FAC)**
  - **LIGO.4.01.1 FAC Vacuum Equipment**
    - **LIGO.4.01.1.1 2K to 4K Conversion**
    - **LIGO.4.01.1.2 Clean Room Systems**
    - **LIGO.4.01.1.3 Vacuum Equipment Bakeout and Preparation**
  - **LIGO.4.01.2 FAC Beam Tube**
  - **LIGO.4.01.3 FAC Conventional Facilities**
    - **LIGO.4.01.3.1 Livingston Staging Building**
    - **LIGO.4.01.3.2 Staging Building Cranes**
- **LIGO.4.02 Seismic Isolation (SEI)**
  - **LIGO.4.02.1 SEI Subsystem Management**

Note: the value “40111” is common.

Print

Resouce Pool -

Status: Known Status

Discipline: Engineer

NSF Code: NSF Code B2

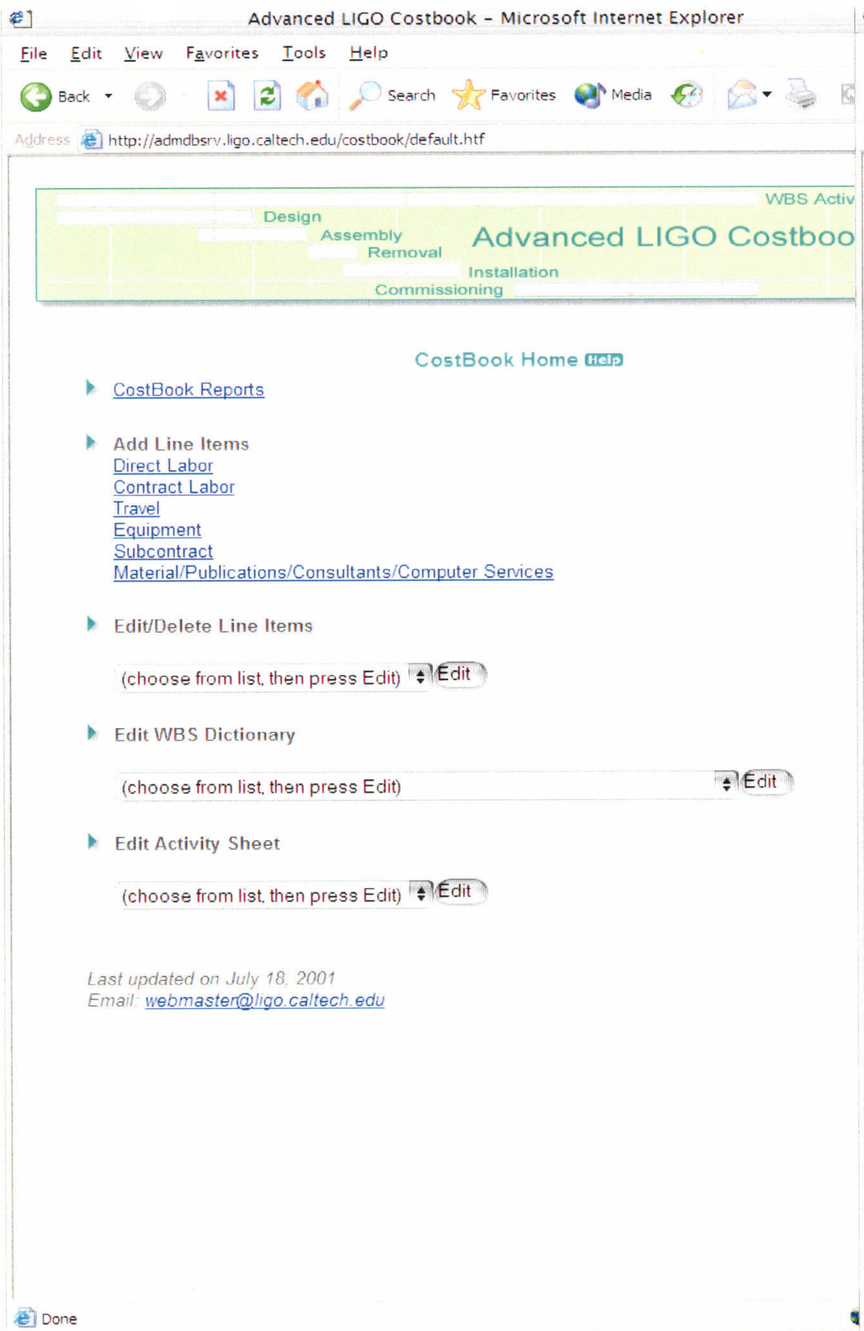
Organization: Caltech

NAME	RES ID	Relation to Proj.	Percentage Availability
Abbott, Richard	ENB2CT02	LIGO Lab	100.00%
Armandula, Helena	ENB2CT04	LIGO Lab	100.00%
Barnes, Maria	ENB2CT08	LIGO Lab	100.00%
Billingsly, Garilynn	ENB2CT10	LIGO Lab	100.00%
Ding, Hongyu	ENB2CT14	LIGO Lab	100.00%
Duncan, Kris	ENB2CT16	LIGO Lab	100.00%
Eherns, Philip	ENB2CT18	LIGO Lab	100.00%
Frey, Thomas	ENB2CT55	LIGO Lab	100.00%
Hu, Grace	ENB2CT58	LIGO Lab	100.00%

Thursday, July 13, 2000 **Page 2 of 22**

This value is used as a unique resource ID and populates the resource dictionary for planning.

This value is used as a FTE value for making head counts and evaluating resource usage.



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WBS Activ
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Assembly
Removal
Advanced LIGO Costboo
Installation
Commissioning
CostBook Home Help
CostBook Reports
Add Line Items
Direct Labor
Contract Labor
Travel
Equipment
Subcontract
Material/Publications/Consultants/Computer Services
Edit/Delete Line Items
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Edit WBS Dictionary
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Last updated on July 18, 2001
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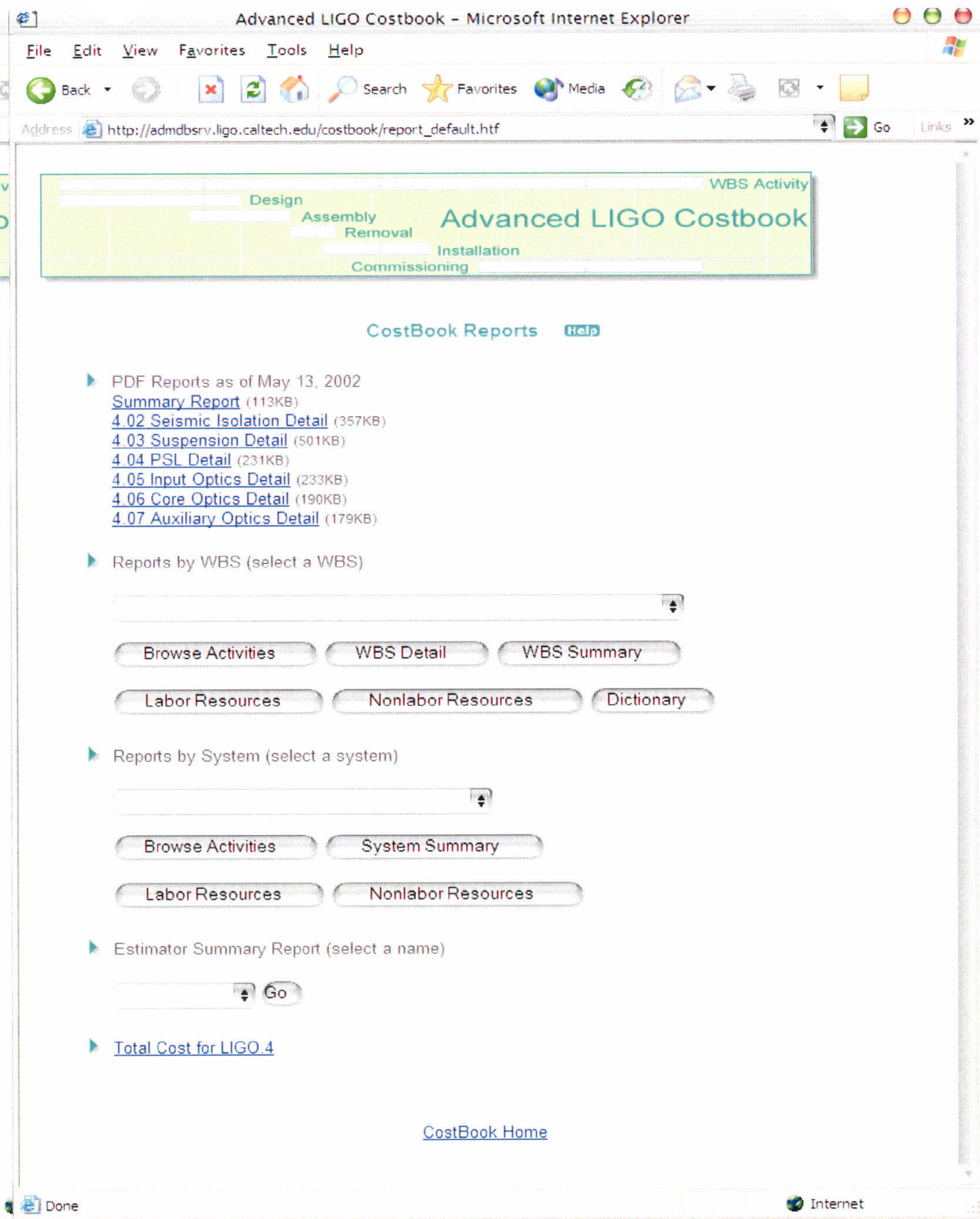

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WBS Activity
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Removal
Advanced LIGO Costbook
Installation
Commissioning
CostBook Reports Help
PDF Reports as of May 13, 2002
Summary Report (113KB)
4.02 Seismic Isolation Detail (357KB)
4.03 Suspension Detail (501KB)
4.04 PSL Detail (231KB)
4.05 Input Optics Detail (233KB)
4.06 Core Optics Detail (190KB)
4.07 Auxiliary Optics Detail (179KB)
Reports by WBS (select a WBS)
Browse Activities
WBS Detail
WBS Summary
Labor Resources
Nonlabor Resources
Dictionary
Reports by System (select a system)
Browse Activities
System Summary
Labor Resources
Nonlabor Resources
Estimator Summary Report (select a name)
Go
Total Cost for LIGO 4
CostBook Home
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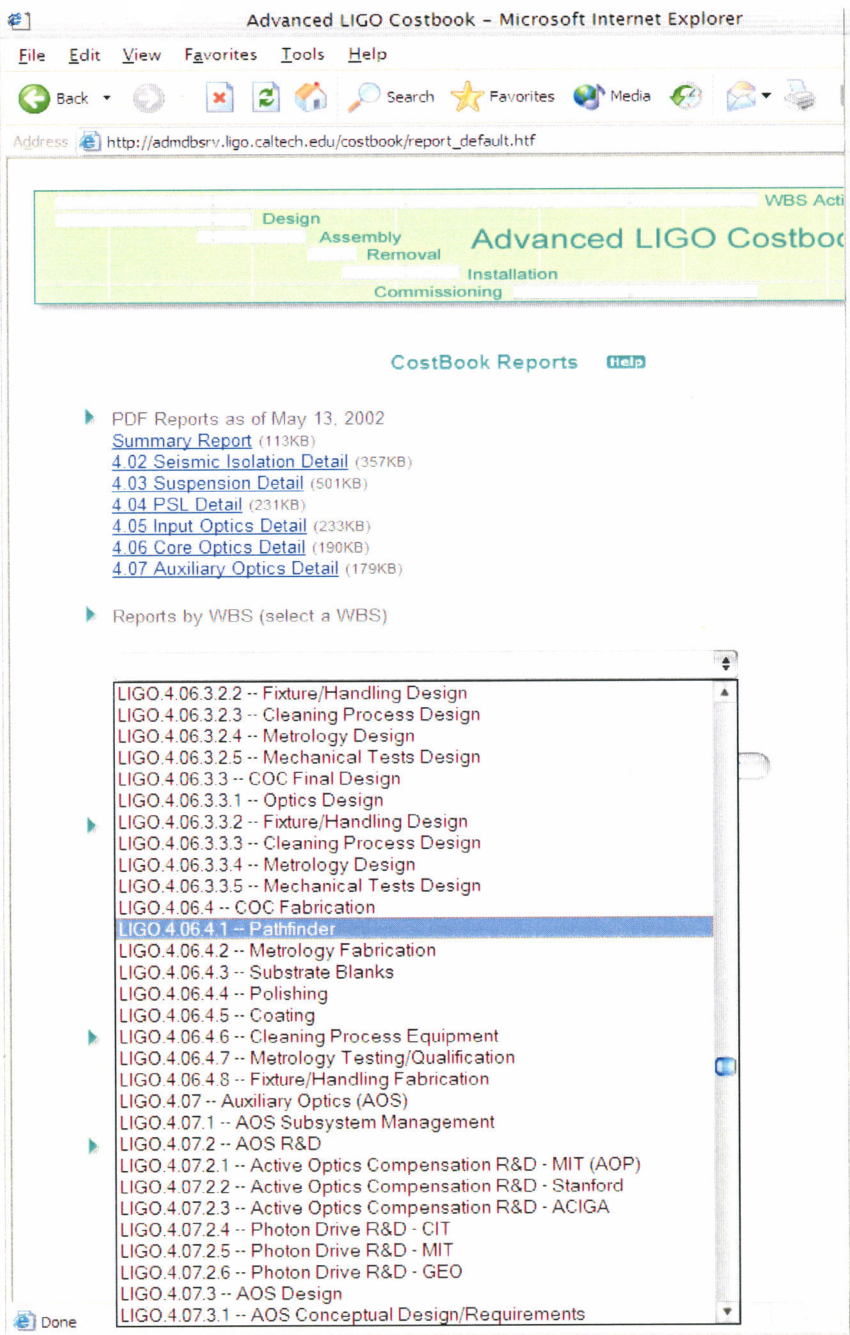
Internet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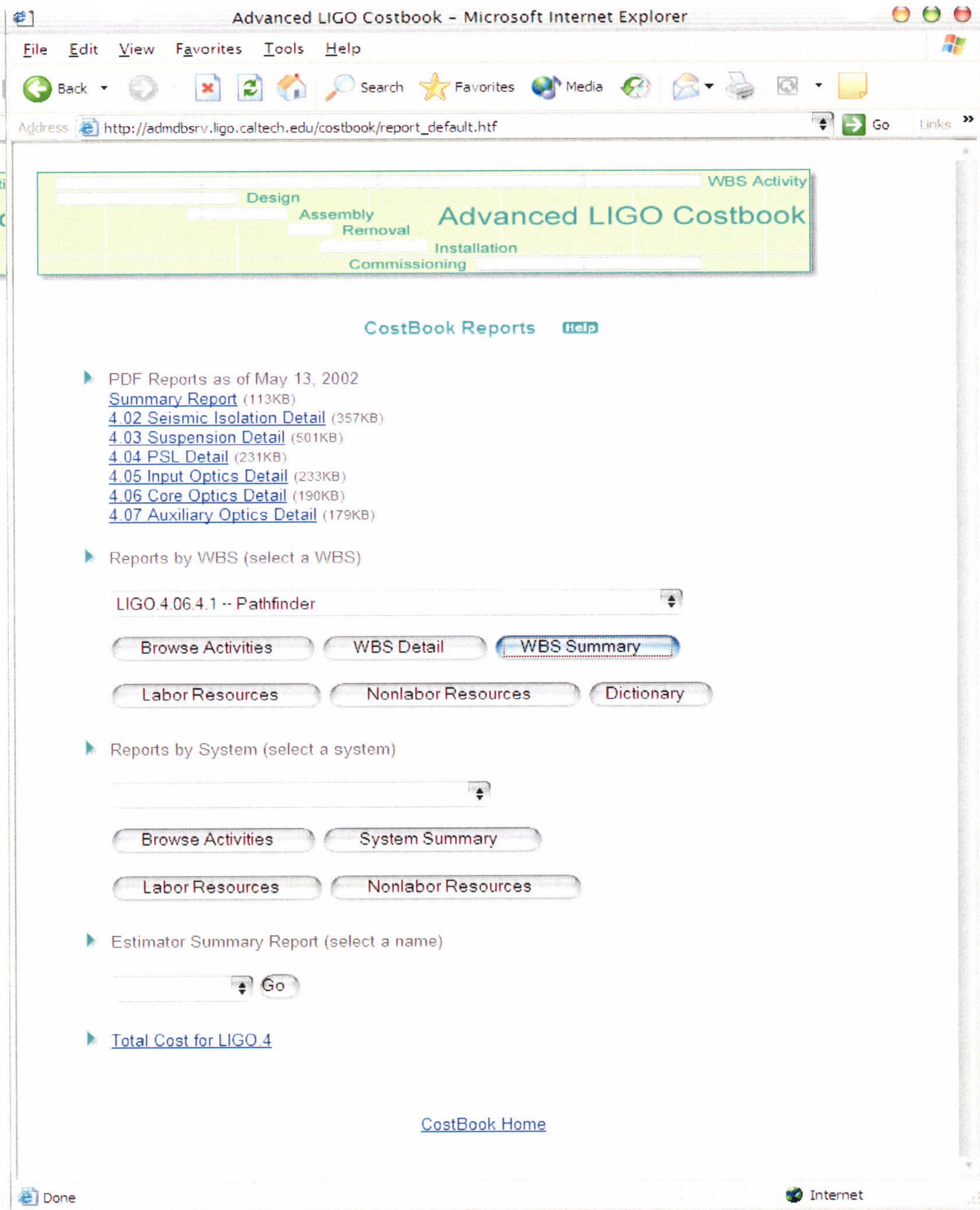
4.06 Core Optics Detail (190KB)
4.07 Auxiliary Optics Detail (179KB)
Reports by WBS (select a WBS)
LIGO.4.06.3.2.2 -- Fixture/Handling Design
LIGO.4.06.3.2.3 -- Cleaning Process Design
LIGO.4.06.3.2.4 -- Metrology Design
LIGO.4.06.3.2.5 -- Mechanical Tests Design
LIGO.4.06.3.3 -- COC Final Design
LIGO.4.06.3.3.1 -- Optics Design
LIGO.4.06.3.3.2 -- Fixture/Handling Design
LIGO.4.06.3.3.3 -- Cleaning Process Design
LIGO.4.06.3.3.4 -- Metrology Design
LIGO.4.06.3.3.5 -- Mechanical Tests Design
LIGO.4.06.4 -- COC Fabrication
LIGO.4.06.4.1 -- Pathfinder
LIGO.4.06.4.2 -- Metrology Fabrication
LIGO.4.06.4.3 -- Substrate Blanks
LIGO.4.06.4.4 -- Polishing
LIGO.4.06.4.5 -- Coating
LIGO.4.06.4.6 -- Cleaning Process Equipment
LIGO.4.06.4.7 -- Metrology Testing/Qualification
LIGO.4.06.4.8 -- Fixture/Handling Fabrication
LIGO.4.07 -- Auxiliary Optics (AOS)
LIGO.4.07.1 -- AOS Subsystem Management
LIGO.4.07.2 -- AOS R&D
LIGO.4.07.2.1 -- Active Optics Compensation R&D - MIT (AOP)
LIGO.4.07.2.2 -- Active Optics Compensation R&D - Stanford
LIGO.4.07.2.3 -- Active Optics Compensation R&D - ACIGA
LIGO.4.07.2.4 -- Photon Drive R&D - CIT
LIGO.4.07.2.5 -- Photon Drive R&D - MIT
LIGO.4.07.2.6 -- Photon Drive R&D - GEO
LIGO.4.07.3 -- AOS Design
LIGO.4.07.3.1 -- AOS Conceptual Design/Requirements
Done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4.05 Input Optics Detail (233KB)
4.06 Core Optics Detail (190KB)
4.07 Auxiliary Optics Detail (179KB)
Reports by WBS (select a WBS)
LIGO.4.06.4.1 -- Pathfinder
Browse Activities
WBS Detail
WBS Summary
Labor Resources
Nonlabor Resources
Dictionary
Reports by System (select a system)
Browse Activities
System Summary
Labor Resources
Nonlabor Resources
Estimator Summary Report (select a name)
Go
Total Cost for LIGO.4
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LIGO II CostBook Activity Sheet Summary for a WBS - Microsoft Internet Explorer

http://admdbsrv.ligo.caltech.edu/costbook/report_wbsSummary.htf?rtype=wbs&callingform=sum&wbs

CostBook Activity Sheet Summary

for WBS Number LIGO.4.06.4.1 -- Pathfinder

(Amounts Include Staff Benefits, GRA Benefits, and Indirect Cost)

WBSNo: LIGO.4.06.4.1 - Pathfinder

COF40641A - EST: Pathfinder SPF	$490,276.25
COF40641B - EST: Pathfinder LPF	$833,015.50
WBS Total:	**$1,323,291.75**
Report Total:	**$1,323,291.75**
Report Contingency at 63.40%:	$839,007.79
Total Plus Contingency:	$2,162,299.54

Done — Internet

LIGO II Costbook Activity Sheet Detail - Microsoft Internet Explorer

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Address http://admdbsrv.ligo.caltech.edu/costbook/report_sheetDetail.htf?sheet=COF40641A&wbsstring=LIGO.4.06.4.1%2APathfinder&type=wbs&callingform=sum

Costbook Activity Sheet Detail

WBSNo:LIGO.4.06.4.1 - Pathfinder
Activity:COF40641A - EST: Pathfinder SPF
Duration:365 days
Estimator:G. Billingsley on 05/02/2001

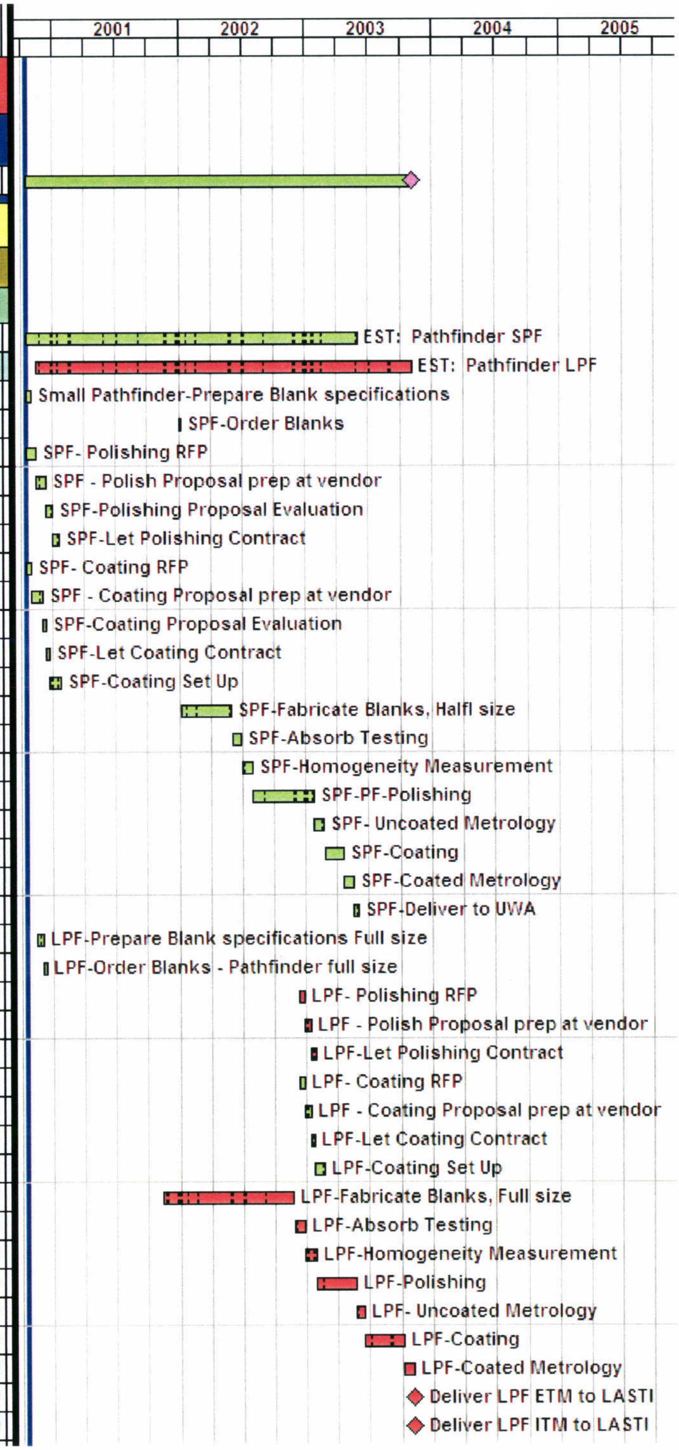
Item Code	Cost Category	Resource	Description	Comments or Vendor	Cost Basis	Cost Code	Quantity	Unit Cost	Item Amount
B2	Labor	EN	Engineer		EE	12-40641-14 CP	507	$45.00	$22,815.00
B2	Labor	OT	Other		EE	12-40641-14 CP	179	$50.00	$8,950.00
B2	Labor	SC	Scientist		EE	12-40641-14 CP	108	$40.00	$4,320.00
D2	Equip.	D2	Small Pathfinder blank cost - rollup of 6		HD	12-40641-14 CP	1	$43,010.00	$43,010.00
E1	Int Travel	E1	Deliver Mirrors to UWA, review specifications		HD	12-40641-14 CP	1	$2,075.00	$2,075.00
G5	Contract	G5	Coat 5 types of mirrors	? Virgo-Lyon	EE	12-40641-14 CP	1	$200,000.00	$200,000.00
G5	Contract	G5	Polish 3 Mode cleaner mirrors	Wave Precision	VQ	12-40641-14 CP	1	$68,445.00	$68,445.00
G5	Contract	G5	polish 3 optics	CSIRO	VQ	12-40641-14 CP	1	$129,640.00	$129,640.00
G5	Contract	G5	Shipping	Time Trax	HD	12-40641-14 CP	1	$2,000.00	$2,000.00

Subtotal:	**$481,255.00**
Staff Benefits:	**$9,021.25**
GRA Benefits:	**$0.00**
Indirect Cost:	**$0.00**
Total Cost:	**$490,276.25**
(Cost: 6x1.00% + Sched: 4x1.00% + Tech: 8x4.00%) Contingency @ 42.00%:	**$205,916.02**
Cost Plus Contingency:	**$696,192.27**

Return to WBS Summary page

Done Internet

Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Late Start	Late Finish	Total Float	Budgeted Cost
LIGO								
LIGO.4 Advanced LIGO Construction								
Subtotal		762	18OCT00	03NOV03	12OCT01	20MAR07	841	2,162,299.54
LIGO.4.06 Core Optics Components (COC)								
LIGO.4.06.4 COC Fabrication								
LIGO.4.06.4.1 Pathfinder								
CO-F40641A	EST: Pathfinder SPF	654*	18OCT00	02JUN03	29SEP05	20MAR07	949	696,192.27
CO-F40641B	EST: Pathfinder LPF	742*	15NOV00	03NOV03	12OCT01	03NOV03	0	1,466,107.27
CO-D50540	Small Pathfinder-Prepare Blank specifications	10	18OCT00	31OCT00	29SEP05	12OCT05	1,238	0.00
CO-P50550	SPF-Order Blanks	5	02JAN02*	08JAN02	13OCT05	19OCT05	949	0.00
CO-P50560	SPF- Polishing RFP	20	18OCT00	14NOV00	21FEB06	20MAR06	1,333	0.00
CO-P50570	SPF - Polish Proposal prep at vendor	20	15NOV00	14DEC00	21MAR06	17APR06	1,333	0.00
CO-P50580	SPF-Polishing Proposal Evaluation	10	15DEC00	02JAN01	18APR06	01MAY06	1,333	0.00
CO-P50590	SPF-Let Polishing Contract	10	03JAN01	17JAN01	02MAY06	15MAY06	1,333	0.00
CO-P50600	SPF- Coating RFP	10	18OCT00	31OCT00	31AUG06	14SEP06	1,468	0.00
CO-P50610	SPF - Coating Proposal prep at vendor	20	01NOV00	30NOV00	15SEP06	12OCT06	1,468	0.00
CO-P50620	SPF-Coating Proposal Evaluation	10	01DEC00	14DEC00	13OCT06	26OCT06	1,468	0.00
CO-P50630	SPF-Let Coating Contract	5	15DEC00	21DEC00	27OCT06	02NOV06	1,468	0.00
CO-T50640	SPF-Coating Set Up	20	22DEC00	24JAN01	03NOV06	04DEC06	1,468	0.00
CO-F50650	SPF-Fabricate Blanks, Halfl size	100	09JAN02	31MAY02	20OCT05	20MAR06	949	0.00
CO-Q50660	SPF-Absorb Testing	20	03JUN02	28JUN02	21MAR06	17APR06	949	0.00
CO-Q50670	SPF-Homogeneity Measurement	20	01JUL02	29JUL02	18APR06	15MAY06	949	0.00
CO-F50680	SPF-PF-Polishing	120	30JUL02	23JAN03	16MAY06	02NOV06	949	0.00
CO-Q50690	SPF- Uncoated Metrology	20	24JAN03	21FEB03	03NOV06	04DEC06	949	0.00
CO-T50700	SPF-Coating	40	24FEB03	18APR03	05DEC06	05FEB07	949	0.00
CO-Q50710	SPF-Coated Metrology	20	21APR03	16MAY03	06FEB07	06MAR07	949	0.00
CO-H50720	SPF-Deliver to UWA	10	19MAY03	02JUN03	07MAR07	20MAR07	949	0.00
CO-D50740	LPF-Prepare Blank specifications Full size	10	15NOV00	30NOV00	12OCT01	25OCT01	227	0.00
CO-P50750	LPF-Order Blanks - Pathfinder full size	10	01DEC00	14DEC00	26OCT01	08NOV01	227	0.00
CO-P50760	LPF- Polishing RFP	10	11DEC02	26DEC02	11DEC02	26DEC02	0	0.00
CO-P50770	LPF - Polish Proposal prep at vendor	10	27DEC02	13JAN03	27DEC02	13JAN03	0	0.00
CO-P50780	LPF-Let Polishing Contract	10	14JAN03	28JAN03	14JAN03	28JAN03	0	0.00
CO-P50790	LPF- Coating RFP	10	11DEC02	26DEC02	10APR03	23APR03	80	0.00
CO-P50800	LPF - Coating Proposal prep at vendor	10	27DEC02	13JAN03	24APR03	07MAY03	80	0.00
CO-P50810	LPF-Let Coating Contract	5	14JAN03	21JAN03	08MAY03	14MAY03	80	0.00
CO-T50820	LPF-Coating Set Up	20	22JAN03	19FEB03	15MAY03	12JUN03	80	0.00
CO-F50830	LPF-Fabricate Blanks, Full size	260	09NOV01*	22NOV02	09NOV01	22NOV02	0	0.00
CO-Q50840	LPF-Absorb Testing	20	25NOV02	26DEC02	25NOV02	26DEC02	0	0.00
CO-Q50850	LPF-Homogeneity Measurement	20	27DEC02	28JAN03	27DEC02	28JAN03	0	0.00
CO-F50860	LPF-Polishing	80	29JAN03	21MAY03	29JAN03	21MAY03	0	0.00
CO-Q50870	LPF- Uncoated Metrology	15	22MAY03	12JUN03	22MAY03	12JUN03	0	0.00
CO-F50880	LPF-Coating	80	13JUN03	06OCT03	13JUN03	06OCT03	0	0.00
CO-Q50890	LPF-Coated Metrology	20	07OCT03	03NOV03	07OCT03	03NOV03	0	0.00
CO-H50900	Deliver LPF ETM to LASTI	0		03NOV03		03NOV03	0	0.00
CO-H50930	Deliver LPF ITM to LASTI	0		03NOV03		03NOV03	0	0.00



LIGO

Cost

D2*

Resource	D2*	E1*	EN*	G5*	OT*	SC*	Z-RISK	Z-RISK	Z-RISK	Z-RISK
Cost Acct/Category	12-40641-14E	12-40641-14I	12-40641-14L	12-40641-14C	12-40641-14L	12-40641-14L	12-40641-14C	12-40641-14E	12-40641-14I	12-40641-14L
Driving	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Curve										
Budgeted cost	43010.00	2075.00	28518.75	400085.00	11187.50	5400.00	168035.70	18064.20	871.50	18944.62
Actual this period	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Actual to date	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Percent expended	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Percent complete										
Earned value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost to complete	43010.00	2075.00	28518.75	400085.00	11187.50	5400.00	168035.70	18064.20	871.50	18944.62
At completion	43010.00	2075.00	28518.75	400085.00	11187.50	5400.00	168035.70	18064.20	871.50	18944.62
Variance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Budget Summary

D2*

Resource	Cost Acct/Category	Driving	Curve
D2*	12-40641-14E	☐	
E1*	12-40641-14I	☐	
EN*	12-40641-14L	☐	
G5*	12-40641-14C	☐	

	Units	Cost	Total Units	Total Cost
Units per day	0.00			
Res Lag/Duration	0			
% Complete/Expended		0.0	0.0	0.0
Budgeted amount	1.00	43010.00	800.00	696192.27
Planned value	0.00	0.00	0.00	0.00
Earned value	0.00	0.00	0.00	0.00
Actual to date	0.00	0.00	0.00	0.00
To complete	1.00	43010.00	800.00	696192.27
At completion	1.00	43010.00	800.00	696192.27
Variance	0.00	0.00	0.00	0.00

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO 4.06.4.1
WBS Description	Pathfinder
Activity	COF40641A
Description	EST: Pathfinder SPF
Location	Capital Project
Cost Code	12-40641-14

Duration	365 days
Estimated By	G. Billingsley
Last Modified On	07/12/2001

Line	NSF Item Code	Cost Category	LIGO Resource Code	Description	Estimator Comments or Vendor	Cost Basis	Quantity (Hrs/Ea)	Direct Labor (AA, B1-B6) Unit Cost	Direct Labor Total ($)	Contract Labor (G5) Unit Cost	Contract Labor Total ($)	Equipment (D1,D2) Unit Cost ($)	Equipment Total ($)	Travel (E1,E2) Unit Cost ($)	Travel Total ($)	Material (G1-G4) Unit Cost ($)	Material Total ($)	Subcontracts (G5) Unit Cost ($)	Subcontracts Total ($)	Total Cost ($)	Reference
1	B2	Labor	EN	Engineer		EE	507	45	22,815											22,815	[illegible]
2	B2	Labor	OT	Other		EE	179	50	8,950											8,950	[illegible]
3	B2	Labor	SC	Scientist		EE	108	40	4,320											4,320	[illegible]
4	D2	Equip.	D2	Small Pathfinder blank cost - rollup of 6		HD	1					13,010	13,010							13,010	[illegible]
5	E1	Int Travel	E1	Deliver Mirrors to UWA, review specifications		HD	1							2,075	2,075					2,075	[illegible]
6	G5	Contract	G5	polish 2 optics	CSIRO	VQ	1											129,640	129,640	129,640	[illegible]
7	G5	Contract	G5	Polish 3 Mode cleaner mirrors	Wave Precision	VQ	1											68,445	68,445	68,445	[illegible]
8	G5	Contract	G5	Shipping	Time Trax	HD	1											2,000	2,000	2,000	
9	G5	Contract	G5	Coat 5 types of mirrors	Virgo Lyon	EE	1											200,000	200,000	200,000	
				Subtotal COF40641A EST: Pathfinder SPF					36,085		400,085		13,010		2,075				400,085	481,255	

Staff Benefits at 25.00%	9,021
(G6) GRA Benefits at 58.00%	0
Indirect Cost at 0.00%	0
Total Cost	490,276
Contingency at 42.00%	205,916
Cost Plus Contingency	696,192

Labor Summary (Direct Labor plus Contract Labor)

	AA Key/Fac	B1 PostDoc	B2 Mgmt	B2 SrSci	B2 Sci	B2 SrEngr	B2 Engr	B2 Tech	B2 Other	B2 Total	B3 Grad	B4 UGrad	B5 Admin
Hours					108		507		179	794			
Person Years					0.1		0.3		0.1	0.4			

Risk Factors		Risk Multipliers
Technical	8	1.00%
Cost	6	1.00%
Schedule	1	1.00%

Calculated Contingency	42.00%
Estimator Override	

WBS Definition

In addition to serving as a summary WBS element for all COC fabrication other than the fabrication associated with the R&D elements, the Pathfinder-II effort is also covered under this WBS element. The purpose of the Pathfinder-II program is to demonstrate the ability of industrial partners to achieve the requirements for:

- Sapphire Blanks in the large sizes required for LIGO-II with required homogeneity and low bulk absorption at 1064 microns. Although sapphire material development is covered under WBS elements 0.1.6.2.2 and 0.1.6.2.4 these efforts are focused on small samples and enabling research to be able to attempt production of large blanks meeting LIGO-II requirements. The cost for the large scale blanks is to be covered under this WBS element, as a proof of capability and the first step in the Pathfinder program.
- Sapphire polishing to the LIGO-II surface figure and micro-smoothness requirements in the large sizes required. Initially polishing will be attempted on small samples of sapphire, provided by WBS elements 0.1.6.2.2 and 0.1.6.2.4. Later the full scale blanks procured under this WBS element, will be polished to demonstrate the capability meet LIGO-II requirements on full scale optics.
- Coating on large diameter optics to equal or better than the LIGO-I requirement for absorption in the high-reflectance coatings. The purpose of this WBS element is the qualification of a new coating vendor and possibly a new coating prescription (for lower absorption) at full scale size, whether on fused silica or sapphire. The small scale coating research (WBS element 0.1.6.2.1) is to define a suitable coating for sapphire substrates and a coating prescription for a lower absorption high reflectance coating on fused silica. The results of this small scale coating research are applied under this WBS element at full scale in a production facility.

Basis of Estimate

Based on Material costs quoted by vendors as follows:

10 Kg sapphire masses 2 ITMs, 1ITM spares, $97,980 ea.

2 ETMs, 1 ETM spare $97,980 ea.

Grade 0AA fused silica 1 PRM and 2 spares at $22,076 ea.

1 SRM and 2 spares at $22,076 ea.

Grade 311 SV fused silica

1 BS and 2 spares at $112,291 ea.

Travel:
Assume 2 trips to 311SV vendor (Germany)

Assume 1 trip to 0AA vendor (NY)

Assume 2 trips to Sapphire vendor (Boston)

Shipping:

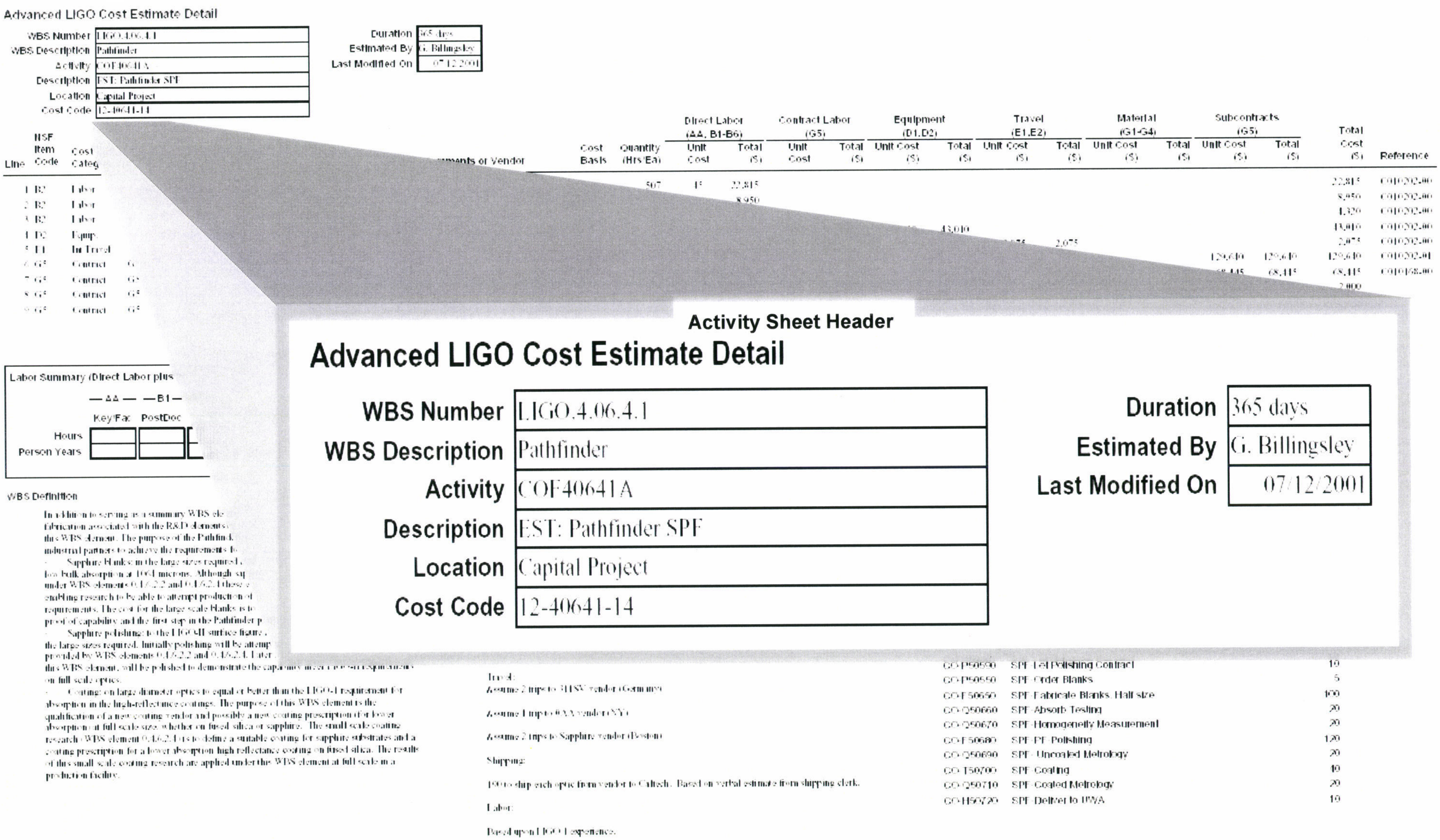
100 to ship each optic from vendor to Caltech. Based on verbal estimate from shipping clerk.

Labor:

Based upon LIGO I experience.

Task List

Task No	Description	Duration
CO-P50560	SPF - Polishing RFP	20
CO-P50600	SPF - Coating RFP	10
CO-D50540	Small Pathfinder-Prepare Blank specifications	10
CO-P50610	SPF - Coating Proposal prep at vendor	20
CO-P50570	SPF - Polish Proposal prep at vendor	20
CO-P50620	SPF-Coating Proposal Evaluation	10
CO-P50580	SPF-Polishing Proposal Evaluation	10
CO-P50630	SPF-Let Coating Contract	5
CO-T50640	SPF-Coating Set Up	20
CO-P50590	SPF-Let Polishing Contract	10
CO-P50550	SPF-Order Blanks	5
CO-F50650	SPF-Fabricate Blanks, Half size	100
CO-Q50660	SPF-Absorb Testing	20
CO-Q50670	SPF-Homogeneity Measurement	20
CO-F50680	SPF-PF-Polishing	120
CO-Q50690	SPF- Uncoated Metrology	20
CO-T50700	SPF-Coating	10
CO-Q50710	SPF-Coated Metrology	20
CO-H50720	SPF-Deliver to UWA	10


Advanced LIGO Cost Estimate Detail
Activity Sheet Header
Advanced LIGO Cost Estimate Detail
WBS Number
LIGO.4.06.4.1
WBS Description
Pathfinder
Activity
COF40641A
Description
EST: Pathfinder SPF
Location
Capital Project
Cost Code
12-40641-14
Duration
365 days
Estimated By
G. Billingsley
Last Modified On
07/12/2001
Direct Labor (AA, B1-B6)
Contract Labor (G5)
Equipment (D1,D2)
Travel (E1,E2)
Material (G1-G4)
Subcontracts (G5)
Total Cost ($)
Reference
Labor Summary (Direct Labor plus
WBS Definition

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO.4.06.4.1	Duration	365 days
WBS Description	Pathfinder	Estimated By	G. Billingsley
Activity	COF4064IA	Last Modified On	07/12/2001
Description	EST: Pathfinder SPF		
Location	Capital Project		
Cost Code	12-40641-14		

Staff Benefits at 25.00%

(G6) GRA Benefits at 58.00%

Indirect Cost at 0.00%

Total Cost

Labor Summary

Hours

Person Years

WBS Definition

Activity Sheet Takeoff Area

Line	NSF Item Code	Cost Category	LIGO Resource Code	Description	Estimator Comments or Vendor	Cost Basis	Quantity (Hrs/Ea)
1	B2	Labor	EN	Engineer		EE	507
2	B2	Labor	OT	Other		EE	179
3	B2	Labor	SC	Scientist		EE	108
4	D2	Equip.	D2	Small Pathfinder blank cost - rollup of 6		HD	1
5	E1	Int Travel	E1	Deliver Mirrors to UWA, review specifications		HD	1
6	G5	Contract	G5	polish 3 optics	CSIRO	VQ	1
7	G5	Contract	G5	Polish 3 Mode cleaner mirrors	Wave Precision	VQ	1
8	G5	Contract	G5	Shipping	Time Trax	HD	1
9	G5	Contract	G5	Coat 5 types of mirrors	? Virgo-Lyon	EE	1

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO.4.06.4.1
WBS Description	Pathfinder
Activity	COF40641A
Description	EST: Pathfinder SPF
Location	Capital Project
Cost Code	12-40641-14
Duration	365 days
Estimated By	G. Billingsley
Last Modified On	07/12/2001

Subtotal COF40641A EST: Path...

Labor Summary (Direct Labor plus Contract Labor)

WBS Definition

Cost Extension Area

Direct Labor (AA, B1-B6) Unit Cost	Direct Labor Total ($)	Contract Labor (G5) Unit Cost	Contract Labor Total ($)	Equipment (D1,D2) Unit Cost ($)	Equipment Total ($)	Travel (E1,E2) Unit Cost ($)	Travel Total ($)	Material (G1-G4) Unit Cost ($)	Material Total ($)	Subcontracts (G5) Unit Cost ($)	Subcontracts Total ($)	Total Cost ($)	Reference
45	22,815											22,815	C010202-00
50	8,950											8,950	C010202-00
40	4,320											4,320	C010202-00
				43,010	43,010							43,010	C010202-00
						2,075	2,075					2,075	C010202-00
										129,640	129,640	129,640	C010202-01
										68,445	68,445	68,445	C010168-00
										2,000	2,000	2,000	
										200,000	200,000	200,000	
	36,085		400,085		43,010		2,075				400,085	481,255	

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO.4.06.4.1	Duration	365 days
WBS Description	Pathfinder	Estimated By	G. Billingsley
Activity	COF40641A	Last Modified On	07/12/2001
Description	EST: Pathfinder SPF		
Location	Capital Project		
Cost Code	12-40641-14		

Line	NSF Item Code	Cost Category	LIGO Resource Code	Description	Estimator Comments or Vendor	Cost Basis	Quantity (Hrs/Ea)	Direct Labor (AA, B1-B6) Unit Cost	Direct Labor Total ($)	Contract Labor (G5) Unit Cost	Contract Labor Total ($)	Equipment (D1,D2) Unit Cost ($)	Equipment Total ($)	Travel (E1,E2) Unit Cost ($)	Travel Total ($)	Material (G1-G4) Unit Cost ($)	Material Total ($)	Subcontracts (G5) Unit Cost ($)	Subcontracts Total ($)	Total Cost ($)	Reference
1	B2	Labor	EN	Engineer		EE	507	45	22,815											22,815	C0102202-00
2	B2	Labor	OT	Other		EE	179	50	8,950											8,950	C0102202-00
3	B2	Labor	SC	Scientist		EE	108	40	1,320											1,320	C0102202-00
4	D2	Equip.	D2	Small Pathfinder Blank cost - rollup of 6		HD	1					13,010	13,010							13,010	C0102202-00
5	E1	Int Travel	E1	Deliver Mirrors to UWA, review specifications		HD	1							2,075	2,075					2,075	C0102202-00
6	G5	Contract	G5	polish 3 optics	CSIRO	VQ	1											129,640	129,640	129,640	C0102202-01
7	G5	Contract	G5	Polish 3 Mode cleaner mirrors	Wave Precision	VQ	1											68,115	68,115	68,115	C0101168-00
8	G5	Contract	G5	Shipping	Time Trax	HD	1											2,000	2,000	2,000	
9	G5	Contract	G5	Coat 5 types of mirrors	2 Vires Lyon	EE	1											200,000	200,000	200,000	
				Subtotal COF40641A EST: Pathfinder SPF					36,085		100,085		13,010		2,075				400,085	481,255	

Staff Benefits at 25.00% 9,021

(G6) GRA Benefits 0

0

400,276

205,916

696,192

Labor Summary (Direct Labor plus Contract Labor)

	AA Key/Fac	B1 PostDoc	B2 Mgmt	B2 SrSci	B2 Sci	B2 SrEngr	B2 Engr	B2 Tech	B2 Other	B2 Total	B3 Grad	B4 UGrad	B5 Admin
Hours					108		507		179	794			
Person Years					0.1		0.3		0.1	0.4			

Risk Factors Risk Multipliers

Technical 8

WBS Definition

In addition to serving as a summary WBS element for all COC fabrication ... fabrication associated with the R&D elements), the ... this WBS element. The purpose of ... industrial ...

Duration

20
10
10
20
20
10
10
5
20
10
5
100
20
20
120
20
10
20
10

Risk and Cost Totals

Staff Benefits at	25.00%	9,021
(G6) GRA Benefits at	58.00%	0
Indirect Cost at	0.00%	0
Total Cost		490,276
Contingency at	42.00%	205,916
Cost Plus Contingency		696,192

Risk Factors		Risk Multipliers
Technical	8	4.00%
Cost	6	1.00%
Schedule	4	1.00%

Calculated Contingency	42.00%
Estimator Override	

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO.4.06.4.1	Duration	365 days
WBS Description	Pathfinder	Estimated By	G. Billingsley
Activity	COF40641A	Last Modified On	07/12/2001
Description	EST: Pathfinder SPF		
Location	Capital Project		
Cost Code	12-40641-11		

Line	NSF Item Code	Cost Category	LIGO Resource Code	Description	Estimator Comments or Vendor	Cost Basis	Quantity (Hrs/Ea)	Direct Labor (AA, B1-B6) Unit Cost	Direct Labor Total ($)	Contract Labor (G5) Unit Cost	Contract Labor Total ($)	Equipment (D1,D2) Unit Cost ($)	Equipment Total ($)	Travel (E1,E2) Unit Cost ($)	Travel Total ($)	Material (G1-G4) Unit Cost ($)	Material Total ($)	Subcontracts (G5) Unit Cost ($)	Subcontracts Total ($)	Total Cost ($)	Reference
1	B2	Labor	EN	Engineer		FF	507	45	22,815											22,815	C010202-00
2	B2	Labor	OT	Other		FF	179	50	8,950											8,950	C010202-00
3	B2	Labor	SC	Scientist		FF	108	[illegible]	1,320											1,320	C010202-00
4	D2	Equip.	D2	Small Pathfinder blank cost - rollup of 6		HD	1					13,010	13,010							13,010	C010202-00
5	E1	Int Travel	E1	Deliver Mirrors to UWA, review specifications		HD	1							2,075	2,075					2,075	C010202-00
6	G5	Contract	G5	polish 3 optics	CSIRO	VQ	1											129,640	129,640	129,640	C010202-01
7	G5	Contract	G5	Polish 3 Mode cleaner mirrors	Wave Precision	VQ	1											68,415	68,415	68,415	C010168-00
8	G5	Contract	G5	Shipping	Time Trax	HD	1											2,000	2,000	2,000	
9	G5	Contract	G5	Coat 5 types of mirrors	Virgo Lyon	FF	1											200,000	200,000	200,000	
				Subtotal COF40641A EST: Pathfinder SPF					30,085		400,085		13,010		2,075				400,085	481,255	

Staff Benefits at	25.00%	9,021
(G6) GRA Benefits at	58.00%	0
Indirect Cost at	0.00%	0
Total Cost		490,276
Contingency at	42.00%	205,916
Cost Plus Contingency		696,192

Risk Factors: Technical, Cost — Risk Multipliers — Calculated Contingency 42.00% — Estimator Override

WBS Definition

Task List

Labor Summary (FTEs)

Labor Summary (Direct Labor plus Contract Labor)

	AA	B1	B2								B3	B4	B5
	Key/Fac	PostDoc	Mgmt	SrSci	Sci	SrEngr	Engr	Tech	Other	Total	Grad	UGrad	Admin
Hours					108		507		179	794			
Person Years					0.1		0.3		0.1	0.4			

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO.4.06.4.1
WBS Description	Pathfinder
Activity	COF4064IA
Description	FST: Pathfinder SPF
Location	Capital Project
Cost Code	12-40641-11

Duration	365 dys
Estimated By	G. Billingsley
Last Modified On	07/12/2001

Line	NSF Item Code	Cost Category	LIGO Resource Code	Description	Estimator Comments or Vendor	Cost Basis	Quantity (Hrs/Ea)	Direct Labor (AA, B1-B6) Unit Cost	Direct Labor Total ($)	Contract Labor (G5) Unit Cost	Contract Labor Total ($)	Equipment (D1,D2) Unit Cost ($)	Equipment Total ($)	Travel (E1,E2) Unit Cost ($)	Travel Total ($)	Material (G1-G4) Unit Cost ($)	Material Total ($)	Subcontracts (G5) Unit Cost ($)	Subcontracts Total ($)	Total Cost ($)	Reference
1	B2	Labor	EN	Engineer		EE	507	45	22,815											22,815	C010202-00
2	B2	Labor	OT	Other		EE	179	50	8,950											8,950	C010202-00
3	B2	Labor	SC	Scientist		EE	108	10	1,320											1,320	C010202-00
4	D2	Equip.	D2	Small Pathfinder Blank cost - rollup of 6		HD	1					13,010	13,010							13,010	C010202-00
5	E1	Int Travel	E1	Deliver Mirrors to UWA, review specificati[illegible]																2,075	C010202-00
6	G5	Contract	G5	polish 3 optics																129,640	C010202-01
7	G5	Contract	G5	Polish 3 Mode cleaner mirrors																68,115	C010168-00
8	G5	Contract	G5	Shipping																2,000	
9	G5	Contract	G5	Coat 5 types of mirrors																200,000	
				Subtotal																481,255	
																				9,021	
																				0	
																				0	
																				490,276	
																				205,916	
																				696,192	

Labor Summary (Direct Labor plus Contract Labor)

	AA Key/Fac	B1 PostDoc	Mgmt	SrS
Hours				
Person Years				

WBS Definition

Duration
20
10
10
20
20
10
10
5
20
10
5
100
20
20
120
20
10
20
10

WBS Definition

In addition to serving as a summary WBS element for all COC fabrication (other than the fabrication associated with the R&D elements), the Pathfinder-II effort is also covered under this WBS element. The purpose of the Pathfinder-II program is to demonstrate the ability of industrial partners to achieve the requirements for:

- Sapphire blanks: in the large sizes required for LIGO-II with required homogeneity and low bulk absorption at 1064 microns. Although sapphire material development is covered under WBS elements 0.4.6.2.2 and 0.4.6.2.4 these efforts are focused on small samples and enabling research to be able to attempt production of large blanks meeting LIGO-II requirements. The cost for the large scale blanks is to be covered under this WBS element, as a proof of capability and the first step in the Pathfinder program.
- Sapphire polishing: to the LIGO-II surface figure and micro-smoothness requirements in the large sizes required. Initially polishing will be attempted on small samples of sapphire, provided by WBS elements 0.4.6.2.2 and 0.4.6.2.4. Later the full scale blanks procured under this WBS element, will be polished to demonstrate the capability meet LIGO-II requirements on full scale optics.
- Coating: on large diameter optics to equal or better than the LIGO-I requirement for absorption in the high-reflectance coatings. The purpose of this WBS element is the qualification of a new coating vendor and possibly a new coating prescription (for lower absorption) at full scale size, whether on fused silica or sapphire. The small scale coating research (WBS element 0.4.6.2.4) is to define a suitable coating for sapphire substrates and a coating prescription for a lower absorption high reflectance coating on fused silica. The results of this small scale coating research are applied under this WBS element at full scale in a production facility.

Advanced LIGO Cost Estimate Detail

WBS Number	LIGO.4.06.4.1
WBS Description	Pathfinder
Activity	COE406.41A
Description	FSE: Pathfinder SPF
Location	Capital Project
Cost Code	12-40641-14

Duration	365 days
Estimated By	G. Billingsley
Last Modified On	07/12/2001

Line | NSF Item Code | Cost Category | LIGO Resource Code | Description | Estimator Comments or Vendor | Cost Basis | Quantity (Hrs/Ea) | Direct Labor (AA, B1-B6) | Contract Labor (G5) | Equipment (D1, D2) | Travel (E1, E2) | Material (G1-G4) | Subcontracts (G5) | Total Cost ($) | Reference

Staff Benefits at 25.00%

(G6) GRA Benefits at 58.00%

Indirect Cost at 0.00%

Total Cost

Contingency at 42.00%

Cost Plus Contingency

Labor Summary (Direct Labor plus Contract Labor)

Hours

Person Years

WBS Definition

Duration

Basis of Estimate

Based on Material costs quoted by vendors as follows:

40 Kg sapphire masses 2 ITMs, 4ITM spares, $97,986 ea.

2 ETMs, 4 ETM spares $97,986 ea

Grade 0AA fused silica1 PRM and 2 spares at $22,076 ea

1 SRM and 2 spares at $22,076 ea

Grade 311 SV fused silica

1 BS and 2 spares at $142,291 ea

Travel:
Assume 2 trips to 311SV vendor (Germany)

Assume 1 trip to 0AA vendor (NY)

Assume 2 trips to Sapphire vendor (Boston)

Shipping:

190 to ship each optic from vendor to Caltech. Based on verbal estimate from shipping clerk.

Labor:

Based upon LIGO 1 experience.

Advanced LIGO Cost Estimate Detail

WBS Number: [illegible]
WBS Description: Pathfinder
Activity: [illegible]
Description: [illegible]
Location: Capital Project
Cost Code: [illegible]

Duration: [illegible]
Estimated By: [illegible]
Last Modified On: [illegible]

Task List

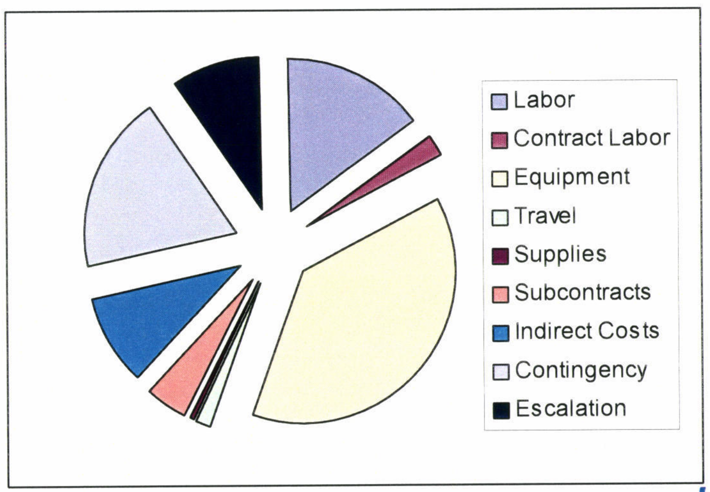
Task No	Description	Duration
CO-P50560	SPF- Polishing RFP	20
CO-P50600	SPF- Coating RFP	10
CO-D50540	Small Pathfinder-Prepare Blank specifications	10
CO-P50610	SPF - Coating Proposal prep at vendor	20
CO-P50570	SPF - Polish Proposal prep at vendor	20
CO-P50620	SPF-Coating Proposal Evaluation	10
CO-P50580	SPF-Polishing Proposal Evaluation	10
CO-P50630	SPF-Let Coating Contract	5
CO-T50640	SPF-Coating Set Up	20
CO-P50590	SPF-Let Polishing Contract	10
CO-P50550	SPF-Order Blanks	5
CO-F50650	SPF-Fabricate Blanks, Half size	100
CO-Q50660	SPF-Absorb Testing	20
CO-Q50670	SPF-Homogeneity Measurement	20
CO-F50680	SPF-PF-Polishing	120
CO-Q50690	SPF- Uncoated Metrology	20
CO-T50700	SPF-Coating	40
CO-Q50710	SPF-Coated Metrology	20
CO-H50720	SPF-Deliver to UWA	10

Summary (Base Year Estimate)

Advanced LIGO Cost Estimate Summary

WBS LIGO.4 Advanced LIGO

WBSNo	Description	Direct Labor Hours	Direct Labor Total ($)	Contract Labor Hours	Contract Labor Total ($)	Equipment Total ($)	Travel Cost ($)	Material Total ($)	Subcontracts Total ($)	Indirect Cost ($)	SubTotal Cost ($)	Contingency %	Contingency ($)	Total Cost ($)
LIGO.4.01	Facility Modifications (FAC)	2,432	197,631			1,404,640			1,774,283	51,384	3,427,938	22.00%	754,146	4,182,085
LIGO.4.02	Seismic Isolation (SEI)	46,875	2,118,156			31,515,198	157,200		60,000	1,308,419	35,158,973	26.09%	9,172,353	44,331,327
LIGO.4.03	Suspension (SUS)	124,250	5,321,805			19,770,570	743,300	27,500	694,400	4,195,632	30,753,207	27.12%	8,340,631	39,093,838
LIGO.4.04	Prestabilized Laser (PSL)	41,520	2,572,135			8,894,894	250,000		128,000	2,316,728	14,161,757	22.00%	3,115,553	17,277,310
LIGO.4.05	Input Optics (IO)	16,768	779,919			1,627,044	60,450		766,711	564,370	3,798,493	27.41%	1,041,280	4,839,773
LIGO.4.06	Core Optics Components (COC)	20,898	900,646			6,205,533	186,550		5,876,029	674,061	13,842,819	43.91%	6,078,011	19,920,830
LIGO.4.07	Auxiliary Optics (AOS)	94,472	3,830,860			3,114,360	393,050	1,091,360	991,051	2,483,390	11,904,070	26.55%	3,160,863	15,064,932
LIGO.4.08	Interferometer Sensing and Control (ISC)	78,290	3,018,284			4,740,065	52,000			1,895,493	9,705,841	32.00%	3,105,869	12,811,710
LIGO.4.09	Data Acq., Diags., Network & Supervisory Ctrl (	33,836	2,463,483			3,080,500	225,000			1,737,229	7,506,212	22.00%	1,651,367	9,157,578
LIGO.4.10	Support Equipment (SUP)					1,185,771				0	1,185,771	26.50%	314,229	1,500,000
LIGO.4.12	LIGO Data Analysis System (LDAS)	52,952	2,294,153			6,657,000	20,000			1,434,775	10,405,928	20.00%	2,081,186	12,487,114
LIGO.4.13	Installation (INS)	232,289	10,855,243	51,732	2,069,280	1,730,000	1,175,000			3,963,300	20,351,529	22.00%	4,477,336	24,828,865
LIGO.4.14	Project Management (PM)	27,540	1,680,682	39,730	2,387,322		37,400			2,944,988	7,694,969	22.00%	1,692,893	9,387,862
		772,122	36,032,997	91,462	4,456,602	89,925,574	3,299,950	1,118,860	10,290,473	23,569,770	169,897,507	26.48%	44,985,718	214,883,225

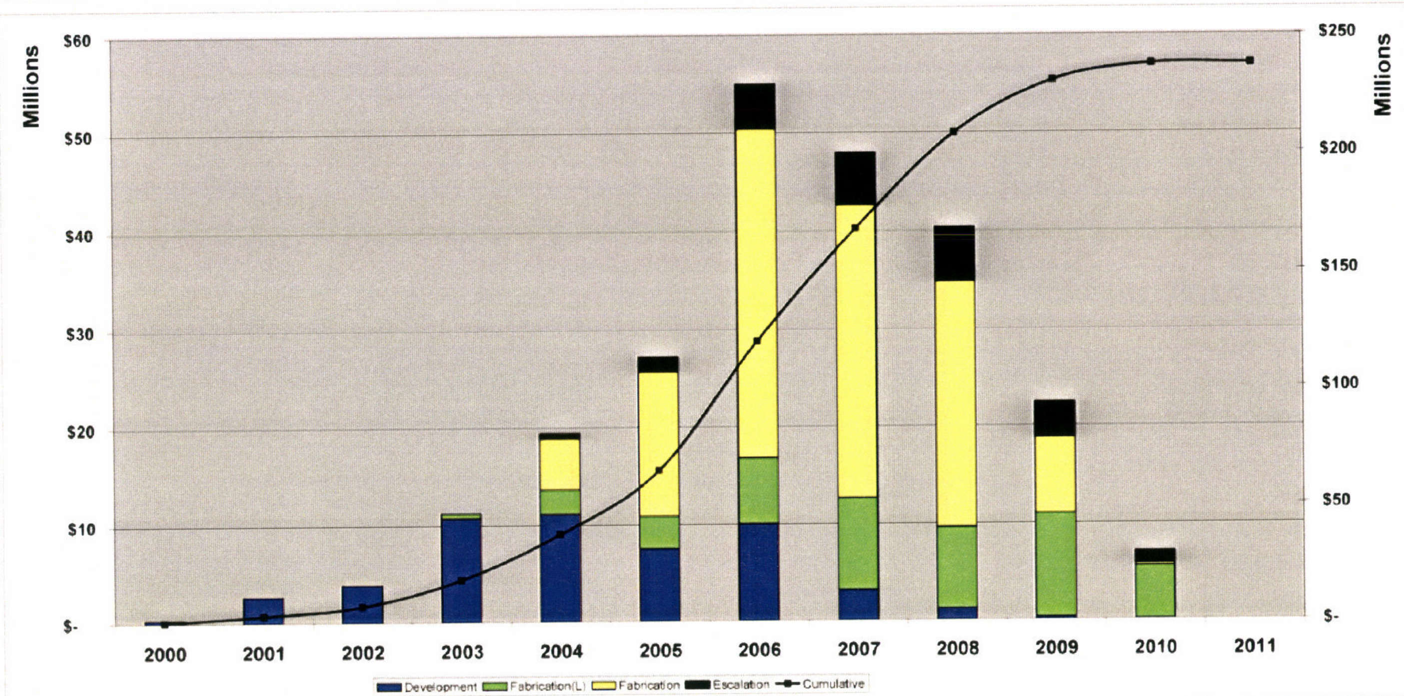


LIGO

Total Cost Profile

Profile Data

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL	Total Cbook
Development	$ 342,211	$ 2,698,581	$ 3,890,989	$ 10,695,029	$ 11,113,229	$ 7,475,468	$ 10,020,353	$ 3,138,804	$ 1,149,818	$ 259,607	$ 71,316	$ -	$ 50,855,405	
Fabrication(L)	$ -	$ -	$ -	$ 535,487	$ 2,496,496	$ 3,333,760	$ 6,737,831	$ 9,471,502	$ 8,416,473	$ 10,682,198	$ 5,406,090	$ -	$ 47,079,837	
Fabrication	$ -	$ -	$ -	$ 4,249	$ 5,233,581	$ 14,827,432	$ 33,589,385	$ 29,968,068	$ 25,227,342	$ 7,841,298	$ 256,695	$ -	$ 116,948,050	$ 214,883,292
Escalation	$ -	$ -	$ -	$ -	$ 565,299	$ 1,561,273	$ 4,668,579	$ 5,343,961	$ 5,541,724	$ 3,644,904	$ 1,318,120	$ -	$ 22,643,860	
Cumulative	**$ 342,211**	**$ 3,040,792**	**$ 6,931,781**	**$ 18,166,546**	**$ 37,575,151**	**$ 64,773,084**	**$ 119,789,232**	**$ 167,711,567**	**$ 208,046,924**	**$ 230,474,931**	**$ 237,527,152**	**$ 237,527,152**	**$ 237,527,152**	



Escalated CB	**$237,527,152**
ACIGA	($2,101,371)
UG (Pparc)	($12,388,443)
Albert Einstein Institute	($13,283,883)
GEO - SUS PD	($724,536)
Subtotal	**$209,028,918**
Ops covers Development	($53,217,070)
Ops covers Fab Labor	($53,827,443)
Collaborator Labor Above	$8,703,117
Collaborator Dev Non-Labor	$1,449,479
New Labor	$11,176,839
Forecast of Request	**$123,313,839**

NOTES

1. Included in the collaborator amounts are $8,703,117 in labor and $1,449,479 in non-labor through development. This is added back in after deduction of the operations contribution for Development and Fab Labor.

2. New Labor included in the request is based upon identifying new labor specifically for Adv. LIGO as contract labor. (See Cost Book Summary)

IFO	As Spent	Base Year
IFO 01	$ 133,697,288	$ 123,485,780
IFO 02	$ 53,200,505	$ 47,079,045
IFO 03	$ 50,629,352	$ 44,318,459
Grand Total	**$ 237,527,145**	**$ 214,883,284**

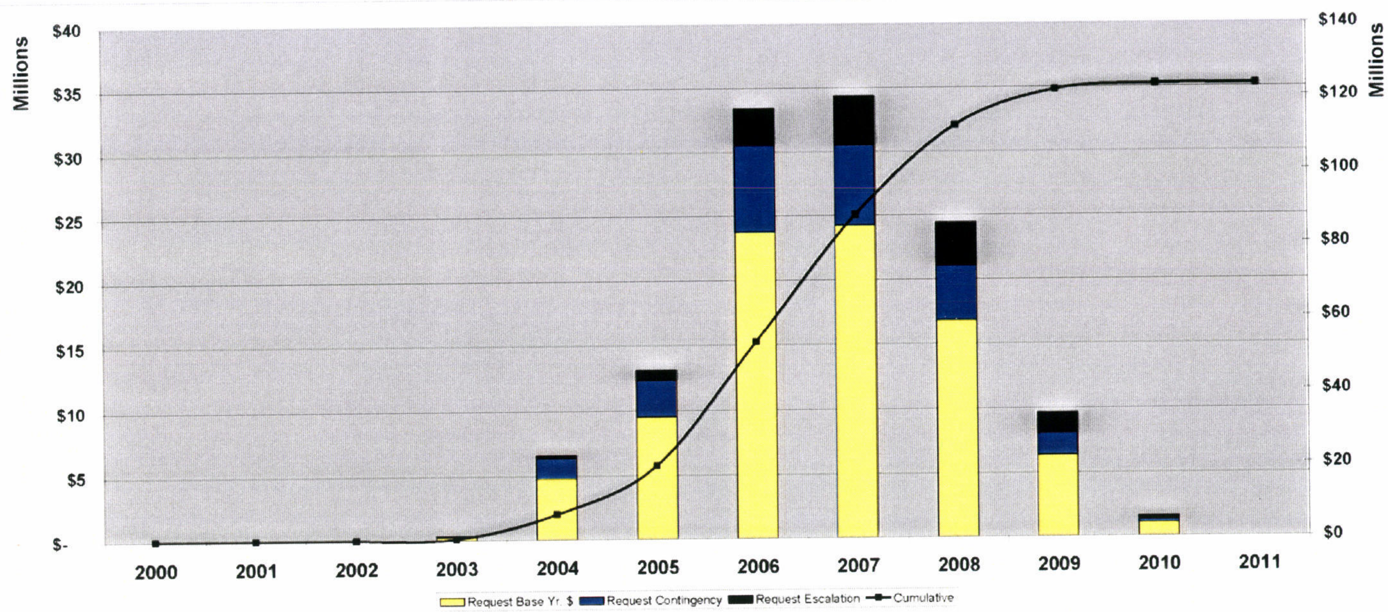
As Spent Matrix

Phase		Sub System AOS	COC	COMP	DAQ	FAC	INS	IO	ISC	PSL	SEI	SUS	PM	SUP	Grand Total	
Ops / R&D		$5,644,751	$2,864,716	$2,065,813	$3,494,185	$0	$595,061	$1,256,893	$6,333,844	$8,103,019	$6,378,870	$14,118,250	$0	$0	$50,855,402	
MRE	*Labor*	$2,780,593	$820,848	$2,432,903	$2,062,914	$303,801	$20,345,103	$625,123	$2,220,903	$1,340,224	$1,179,397	$3,654,087	$9,313,945	$0	$47,079,841	**Cost Book Total $214,883,284**
	Non Labor	$6,639,587	$16,235,268	$7,988,400	$3,600,464	$3,878,286	$3,888,696	$2,957,759	$4,257,000	$7,834,077	$36,773,074	$21,321,511	$73,919	$1,500,000	$116,948,041	
Escalation		$1,231,778	$1,167,580	$1,877,977	$761,922	$441,209	$4,132,071	$473,183	$1,875,595	$964,573	$4,157,146	$4,689,299	$683,263	$188,263	$22,643,858	
Subtotal		$16,296,709	$21,088,412	$14,365,093	$9,919,485	$4,623,296	$28,960,931	$5,312,958	$14,687,342	$18,241,893	$48,488,487	$43,783,147	$10,071,127	$1,688,263	$237,527,142	
GEO												($722,100)			($722,100)	
U. Glasgow			($560,480)				($192,196)					($1,530,970)			($2,283,646)	
U. Birmingham							($287,667)					($2,185,344)			($2,473,011)	
Rutherford							($388,913)					($5,709,740)			($6,098,653)	
Albert Einstein Institute										($12,435,506)					($12,435,506)	
ACIGA		($1,934,190)													($1,934,190)	**Collaborator Total ($28,498,234)**
Escalation		($167,181)	($24,608)				($141,757)			($848,377)		($1,369,205)			($2,551,128)	
Sutotal		$14,195,337	$20,503,324	$14,365,093	$9,919,485	$4,623,296	$27,950,398	$5,312,958	$14,687,342	$4,958,010	$48,488,487	$32,265,788	$10,071,127	$1,688,263	$209,028,909	

Request Profile

Request Profile As Spent Data

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL
Total As-Spent	$ 342,211	$ 2,698,581	$ 3,890,989	$ 11,234,765	$ 19,408,605	$ 27,197,933	$ 55,016,148	$ 47,922,335	$ 40,335,357	$ 22,428,007	$ 7,052,221	$ -	$ 237,527,152
Contribution from Ops	($ (342,211)	($ (2,698,581)	($ (3,890,989)	($ (10,886,004)	($ (12,557,909)	($ (9,969,589)	($ (16,526,611)	($ (11,639,914)	($ (10,124,126)	($ (11,716,137)	($ (5,515,603)	$ -	($ (95,867,674)
Collaborators	$ -	$ -	$ -	$ -	($ (317,512)	($ (4,140,055)	($ (5,073,644)	($ (1,929,845)	($ (5,763,453)	($ (1,121,133)	$ -	$ -	($ (18,345,641)
Request Amount	$ -	$ -	$ -	$ 348,761	$ 6,533,184	$ 13,088,288	$ 33,415,893	$ 34,352,576	$ 24,447,778	$ 9,590,738	$ 1,536,618	$ -	$ 123,313,836
Cumulative	$ -	$ -	$ -	$ 348,761	$ 6,881,945	$ 19,970,233	$ 53,386,126	$ 87,738,703	$ 112,186,481	$ 121,777,218	$ 123,313,836	$ 123,313,836	



Escalated CB	**$237,527,152**
ACIGA	($2,101,371)
UG (Pparc)	($12,368,443)
Albert Einstein Institute	($13,283,883)
GEO - SUS PD	($724,536)
Subtotal	**$209,028,918**
Ops covers Development	($53,217,070)
Ops covers Fab Labor	($53,827,443)
Collaborator Labor Above	$8,703,117
Collaborator Dev Non-Labor	$1,449,479
New Labor	$11,176,839
Forecast of Request	**$123,313,839**

NOTES:

1. Included in the collaborator amounts are $8,703,117 in labor and $1,449,479 in non-labor through development. This is added back in after deduction of the operations contribution for Development and Fab Labor.

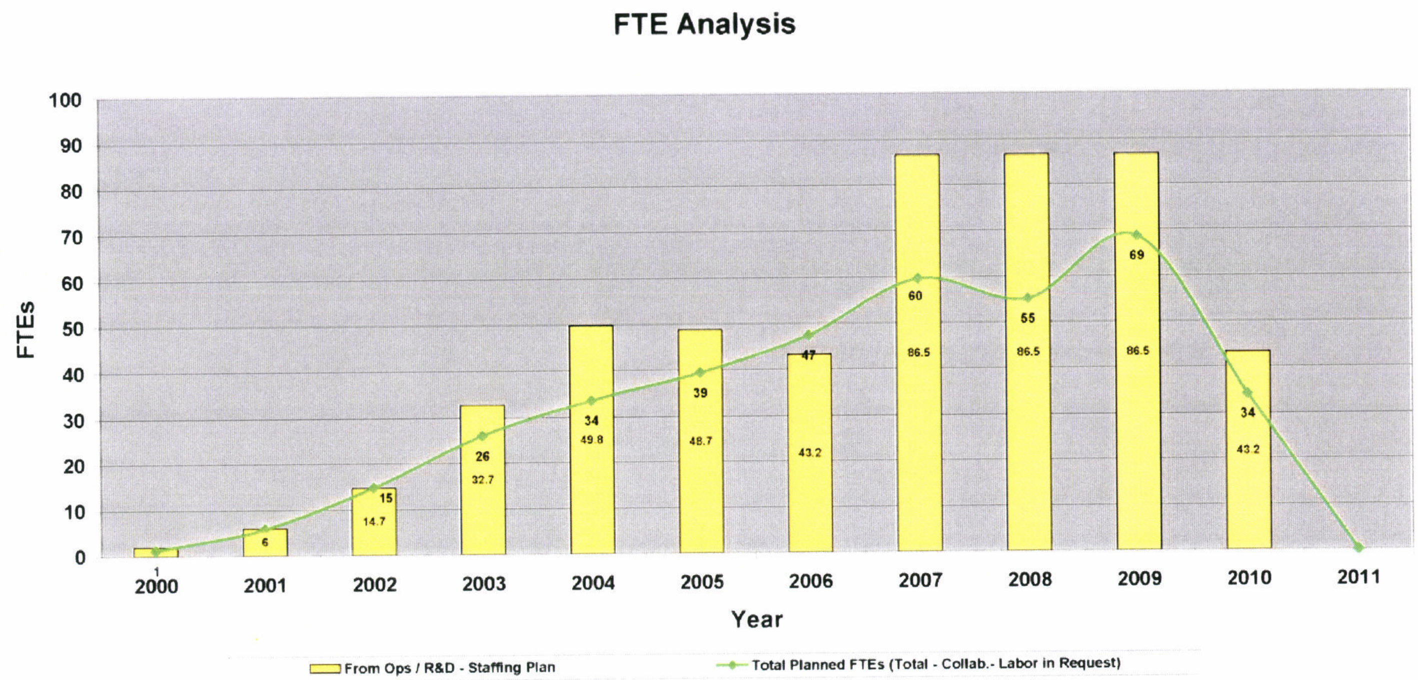
2. New Labor included in the request is based upon identifying new labor specifically for Adv LIGO as contract labor. (See Cost Book Summary)

IFO	As Spent	Collaborators
IFO 01	$ 54,187,315	$ (6,973,348)
IFO 02	$ 35,600,787	$ (5,623,326)
IFO 03	$ 33,525,733	$ (5,748,963)
Grand Total	$ 123,313,835	$ (18,345,638)

Request Profile Base Yr. Adding Contingency and Escalation

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	TOTAL	
Total Base Yr. $	$ 296,534	$ 2,138,363	$ 2,899,984	$ 8,689,884	$ 14,393,023	$ 19,978,696	$ 39,085,621	$ 33,598,086	$ 27,706,616	$ 14,776,784	$ 4,524,967	$ -	$ 168,088,558	Cost Book Check
Total Contingency	$ 45,677	$ 560,218	$ 991,005	$ 2,544,881	$ 4,450,283	$ 5,657,964	$ 11,261,948	$ 8,980,288	$ 7,087,017	$ 4,006,319	$ 1,209,134	$ -	$ 46,794,734	$214,883,292
Request Base Yr. $	$ -	$ -	$ -	$ 285,870	$ 4,755,661	$ 9,484,721	$ 23,754,959	$ 24,241,710	$ 16,814,271	$ 6,318,009	$ 1,024,107	$ -	$ 86,679,308	Percentage Contingency
Request Contingency	$ -	$ -	$ -	$ 62,891	$ 1,587,236	$ 2,852,246	$ 6,825,317	$ 6,280,109	$ 4,274,597	$ 1,714,083	$ 225,304	$ -	$ 23,821,783	27.48%
Request Escalation	$ -	$ -	$ -	$ -	$ 190,287	$ 751,321	$ 2,835,617	$ 3,830,757	$ 3,358,910	$ 1,558,646	$ 287,207	$ -	$ 12,812,745	
Cumulative	$ -	$ -	$ -	$ 348,761	$ 6,881,945	$ 19,970,233	$ 53,386,126	$ 87,738,703	$ 112,186,481	$ 121,777,218	$ 123,313,836	$ 123,313,836	$ 123,313,836	

Bottom Up and Top Down Staffing Model



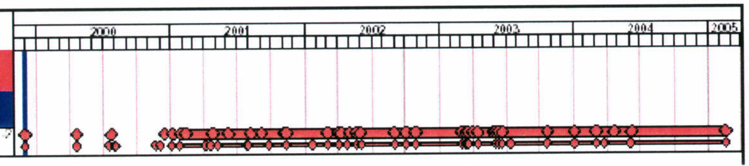
FTE Summary Graph Area	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Total FTEs 1800 Hrs / Yr	2	9	16	32	45	50	65	74	66	80	41	0
From Ops / R&D - Staffing Plan	2	6	14.7	32.7	49.8	48.7	43.2	86.5	86.5	86.5	43.2	0
Collaborators	-0.72	-2.70	-1.34	-5.04	-5.77	-4.97	-10.68	-3.13	-4.85	-2.86	-0.13	0.00
Labor Included in the Request Amount	0.00	0.00	0.00	-1.27	-5.22	-5.20	-6.80	-11.29	-5.93	-8.04	-7.06	0.00
Total Planned FTEs (Total - Collab.- Labor in Request)	1	6	15	26	34	39	47	60	55	69	34	0

Ttl Hours Less Collaborators and Request	694429
Total Hours Staffing Plan	899640

Schedule

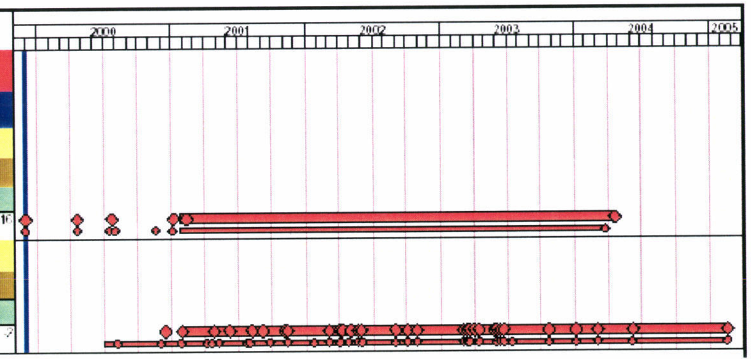
Level 1

Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	% Comp		Late Start	Late Finish	Total Float		Baseline Variance Early Finish
LIGO												
+ LIGO.2 LIGO Laboratory Operations												
		0	1,023		17FEB05	20			15FEB05	-2		-2



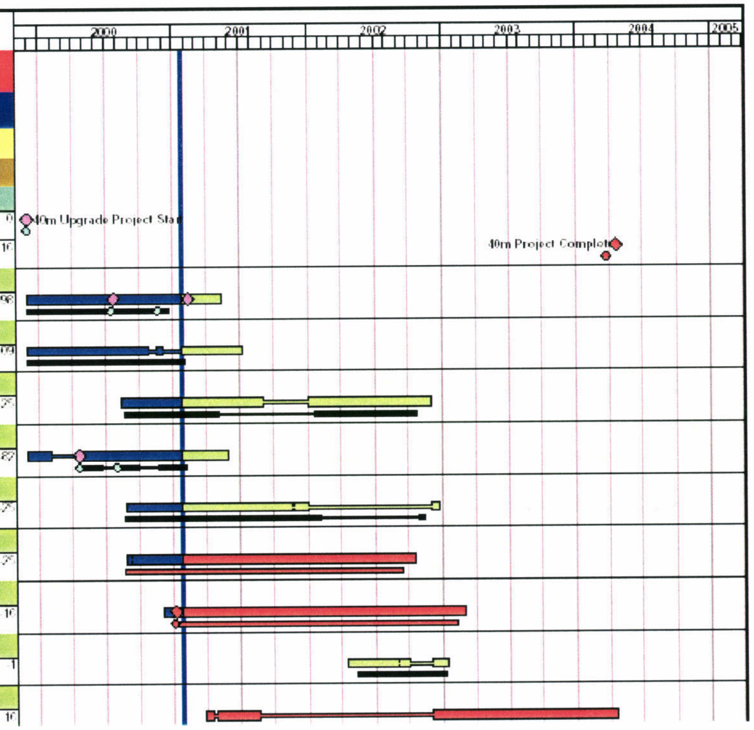
Level 2

Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	% Comp		Late Start	Late Finish	Total Float		Baseline Variance Early Finish
LIGO												
LIGO.2 LIGO Laboratory Operations												
LIGO.2.01 Laboratory Caltech Site Operations												
LIGO.2.01.6 Campus Research Facilities (CAM)												
+ LIGO.2.01.6.1 40 Meter Interferometer Upgrade												
		0	814		19APR04	29			12APR04	-5		-16
LIGO.2.04 MIT Site Operations												
LIGO.2.04.6 MIT Campus Research (LASTI)												
+ LIGO.2.04.6.1 LASTI Upgrade												
		0	1,023		17FEB05	5			15FEB05	-2		-2



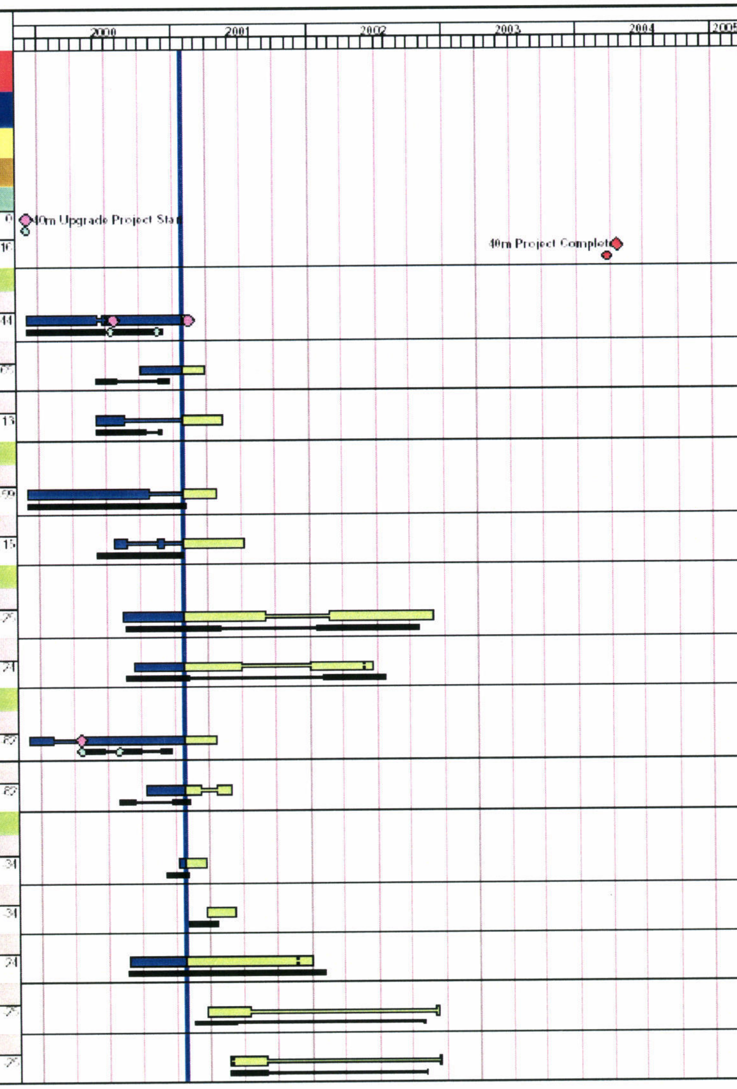
Level 3

Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	% Comp		Late Start	Late Finish	Total Float		Baseline Variance Early Finish
LIGO												
LIGO.2 LIGO Laboratory Operations												
LIGO.2.01 Laboratory Caltech Site Operations												
LIGO.2.01.6 Campus Research Facilities (CAM)												
LIGO.2.01.6.1 40 Meter Interferometer Upgrade												
4M-M00010	40m Upgrade Project Start	0	0	01DEC99A		100		01DEC99A				0
4M-M99999	40m Project Complete	0	0		19APR04	0			12APR04*	-5		-16
+ LIGO.2.01.6.1.1 FAC												
		363	75	01DEC99A	10MAY01	69		01DEC99A	29APR03	494		-98
+ LIGO.2.01.6.1.2 SEI												
		403	115	01DEC99A	09JUL01	78		01DEC99A	18MAR03	424		-109
+ LIGO.2.01.6.1.3 SUS												
		581	469	14AUG00A	03DEC02	23		14AUG00A	04FEB03	40		-25
+ LIGO.2.01.6.1.4 PSL												
		377	89	01DEC99A	31MAY01	63		01DEC99A	25FEB03	435		-82
+ LIGO.2.01.6.1.5 IO												
		588	481	24AUG00A	27DEC02	21		24AUG00A	28JAN03	20		-25
+ LIGO.2.01.6.1.6 COC												
		542	439	25AUG00A	18OCT02	13		25AUG00A	18OCT02	0		-25
+ LIGO.2.01.6.1.7 AOS												
		585	529	01DEC00A	04MAR03	2		01DEC00A	25FEB03	-5		-16
+ LIGO.2.01.6.1.8 ISC												
		187	187	15APR02	13JAN03	0		27JUN02	28JAN03	10		-1
+ LIGO.2.01.6.1.B Experiments												
		772	772	27MAR01	19APR04	0		05FEB03	12APR04	-5		-16



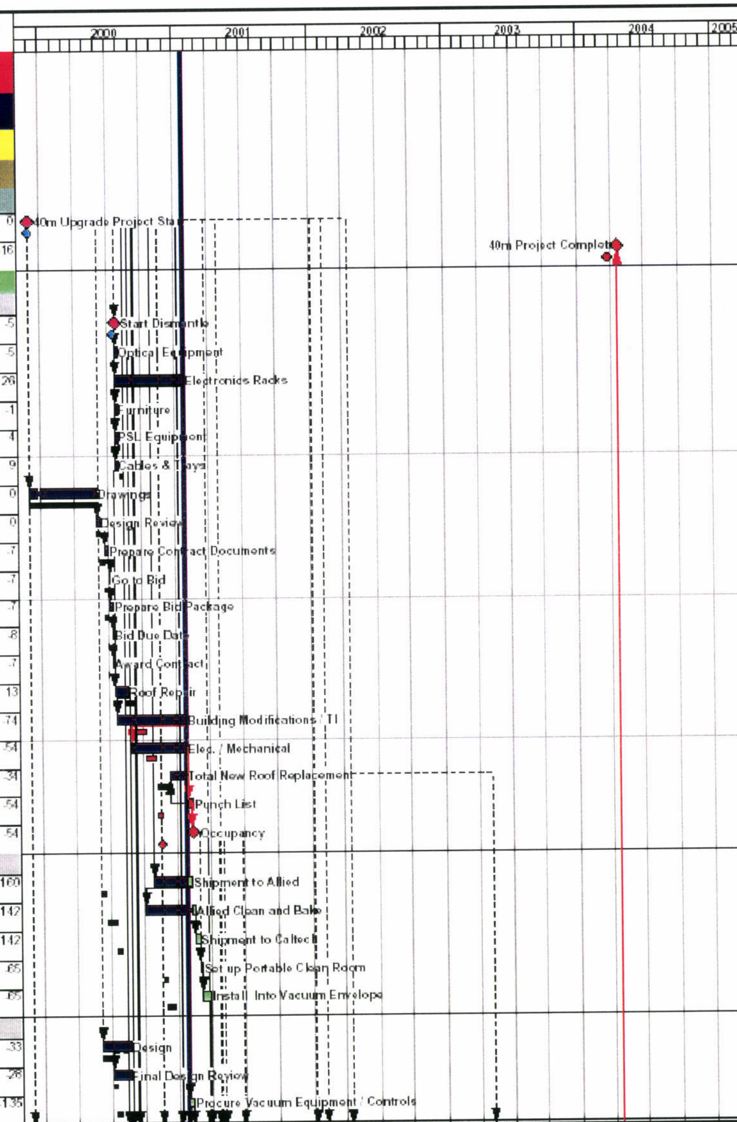
Level 4

Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	% Comp	Late Start	Late Finish	Total Float	Baseline Variance Early Finish
LIGO										
LIGO.2 LIGO Laboratory Operations										
LIGO.2.01 Laboratory Caltech Site Operations										
LIGO.2.01.6 Campus Research Facilities (CAM)										
LIGO.2.01.6.1 40 Meter Interferometer Upgrade										
4M-M00010	40m Upgrade Project Start	0	0	01DEC99A		100	01DEC99A			0
4M-M99999	40m Project Complete	0	0		19APR04	0		12APR04*	-5	16
LIGO.2.01.6.1.1 FAC										
+ LIGO.2.01.6.1.1.1 Lab Expansion		299	11	01DEC99A	09FEB01	96	01DEC99A	29APR03	558	44
+ LIGO.2.01.6.1.1.2 Vacuum Envelope		117	12	05OCT00A	26MAR01	30	05OCT00A	18MAR03	497	62
+ LIGO.2.01.6.1.1.3 Vacuum Controls		235	75	05JUN00A	10MAY01	25	05JUN00A	18MAR03	464	113
LIGO.2.01.6.1.2 SEI										
+ LIGO.2.01.6.1.2.1 Output Chamber Stack		353	65	01DEC99A	26APR01	93	01DEC99A	18MAR03	471	59
+ LIGO.2.01.6.1.2.2 Cavity Optics Isolation		242	115	22JUL00A	09JUL01	18	22JUL00A	18MAR03	421	115
LIGO.2.01.6.1.3 SUS										
+ LIGO.2.01.6.1.3.1 Large Optic Suspensions		581	469	14AUG00A	03DEC02	17	14AUG00A	04FEB03	40	25
+ LIGO.2.01.6.1.3.2 Small Optic Suspensions		448	355	11SEP00A	20JUN02	34	11SEP00A	04FEB03	154	24
LIGO.2.01.6.1.4 PSL										
+ LIGO.2.01.6.1.4.1 Laser		317	59	01DEC99A	18APR01	70	01DEC99A	18FEB03	400	62
+ LIGO.2.01.6.1.4.2 PSL		158	89	13OCT00A	31MAY01	1	13OCT00A	25FEB03	435	62
LIGO.2.01.6.1.5 IO										
+ LIGO.2.01.6.1.5.1 IO Design		54	40	05JAN01A	22MAR01	5	05JAN01A	26JUN02	319	34
+ LIGO.2.01.6.1.5.2 Input Mode Cleaner PO Beams		55	55	23MAR01	08JUN01	0	11OCT02	06JAN03	394	34
+ LIGO.2.01.6.1.5.3 Optics		341	237	24AUG00A	03JAN02	35	24AUG00A	12AUG02	154	24
+ LIGO.2.01.6.1.5.4 Mode Matching Telescope		434	434	23MAR01	10DEC02	0	09SEP02	13JAN03	20	25
+ LIGO.2.01.6.1.5.5 Faraday Isolator		397	397	22MAY01	17DEC02	0	07OCT02	28JAN03	25	25



Level 5

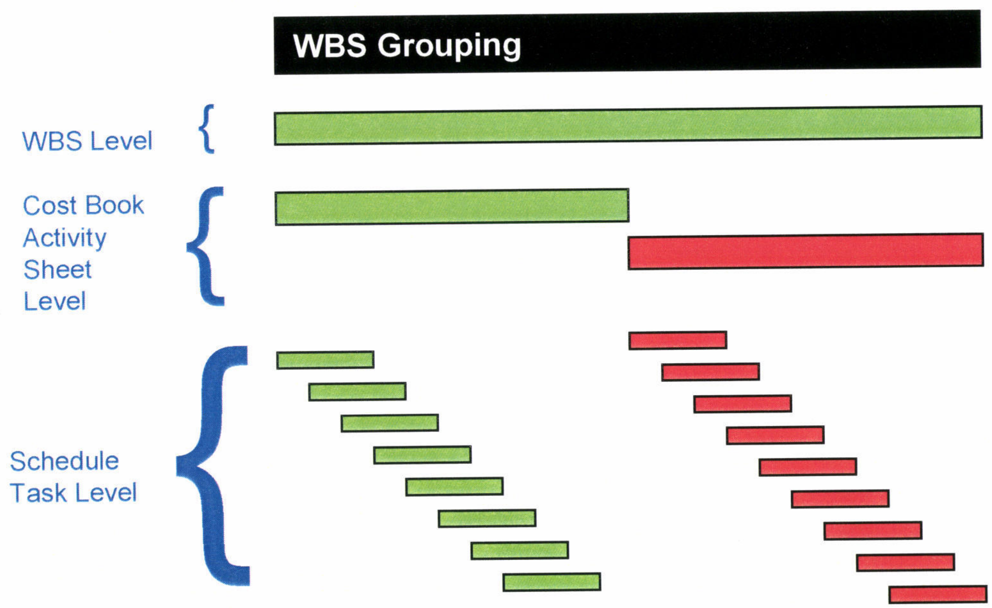
Activity ID	Activity Description	Orig Dur	Rem Dur	Early Start	Early Finish	% Comp	Late Start	Late Finish	Total Float	Baseline Variance Early Finish
LIGO										
LIGO.2 LIGO Laboratory Operations										
LIGO.2.01 Laboratory Caltech Site Operations										
LIGO.2.01.6 Campus Research Facilities (CAM)										
LIGO.2.01.6.1 40 Meter Interferometer Upgrade										
4M-M00010	40m Upgrade Project Start	0	0	01DEC99A		100	01DEC99A			0
4M-M99999	40m Project Complete	0	0		19APR04	0		12APR04*	-5	-16
LIGO.2.01.6.1.1 FAC										
LIGO.2.01.6.1.1.1 Lab Expansion										
4M-M00020	Start Dismantle	0	0	24JUL00A		100	24JUL00A			-5
4M-T00030	Optical Equipment	5	0	24JUL00A	28JUL00A	100	24JUL00A	28JUL00A		-5
4M-T00040	Electronics Racks	2	1	24JUL00A	26JAN01	50	24JUL00A	03NOV00	-54	-126
4M-T00050	Furniture	2	0	24JUL00A	28JUL00A	100	24JUL00A	28JUL00A		-1
4M-T00060	PSL Equipment	5	0	24JUL00A	28JUL00A	100	24JUL00A	28JUL00A		4
4M-T00070	Cables & Trays	5	0	24JUL00A	28JUL00A	100	24JUL00A	28JUL00A		9
4M-D00090	Drawings	126*	0*	01DEC99A	31MAY00A	100	01DEC99A	31MAY00A		0
4M-D00100	Design Review	5	0	01JUN00A	07JUN00A	100	01JUN00A	07JUN00A		0
4M-P00110	Prepare Contract Documents	10	0	19JUN00A	30JUN00A	100	19JUN00A	30JUN00A		-7
4M-P00120	Go to Bid	1	0	05JUL00A	05JUL00A	100	05JUL00A	05JUL00A		-7
4M-P00130	Prepare Bid Package	4	0	06JUL00A	11JUL00A	100	06JUL00A	11JUL00A		-7
4M-M00140	Bid Due Date	0	0	12JUL00A	12JUL00A	100	12JUL00A	12JUL00A		-8
4M-P00150	Award Contract	1	0	12JUL00A	12JUL00A	100	12JUL00A	12JUL00A		-7
4M-C00160	Roof Repair	20	0	17JUL00A	21AUG00A	100	17JUL00A	21AUG00A		13
4M-C00170	Building Modifications / TI	20	0	24JUL00A	26JAN01	98	24JUL00A	03NOV00	-54	-74
4M-C00180	Elec. / Mechanical	20	0	29AUG00A	26JAN01	99	29AUG00A	03NOV00	-54	-54
4M-C00190	Total New Roof Replacement	20	0	10DEC00A	26JAN01	99	10DEC00A	29APR03	568	-34
4M-Q00190	Punch List	10	10	29JAN01	09FEB01	0	06NOV00	17NOV00	-54	-54
4M-M00200	Occupancy	0	0		09FEB01	0		17NOV00*	-54	-54
LIGO.2.01.6.1.1.2 Vacuum Envelope										
4M-H00230	Shipment to Allied	10	10	27OCT00A	08FEB01	0	27OCT00A	31JAN03	497	-160
4M-F00240	Allied Clean and Bake	20	2	05OCT00A	12FEB01	90	05OCT00A	04FEB03	497	-142
4M-H00250	Shipment to Caltech	10	10	13FEB01	26FEB01	0	05FEB03	18FEB03	497	-142
4M-T00260	Set up Portable Clean Room	5	5	27FEB01	05MAR01	0	19FEB03	25FEB03	497	-65
4M-I00270	Install Into Vacuum Envelope	15	15	06MAR01	26MAR01	0	26FEB03	18MAR03	497	-65
LIGO.2.01.6.1.1.3 Vacuum Controls										
4M-D00340	Design	20	0	05JUN00A	18AUG00A	100	05JUN00A	18AUG00A		-33
4M-D00350	Final Design Review	5	0	05JUL00A	18AUG00A	100	05JUL00A	18AUG00A		-28
4M-P00360	Procure Vacuum Equipment / Controls	10	10	26JAN01	08FEB01	0	27NOV02	10DEC02	464	-135



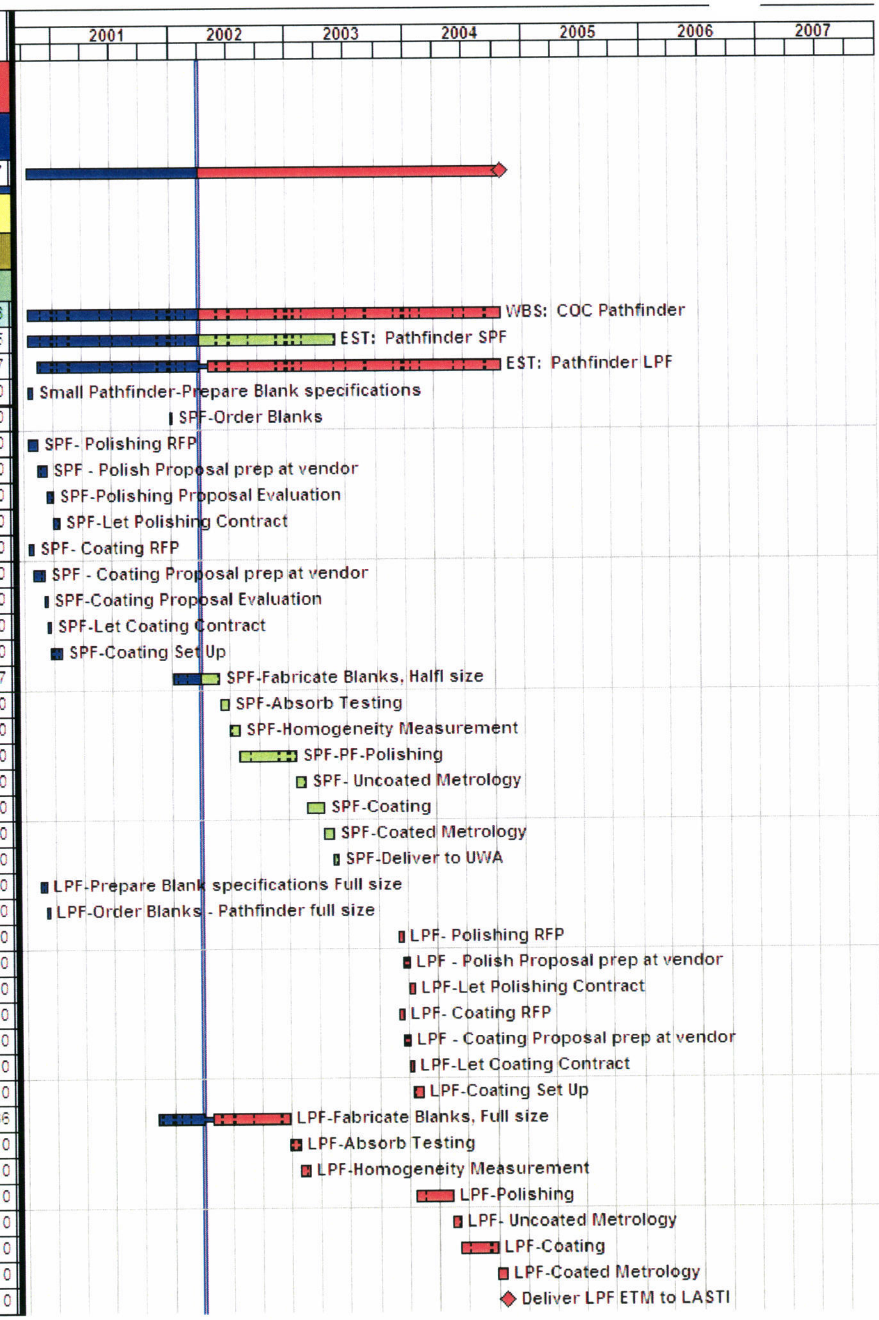
Performance Measurement

Planning for Performance Measurement

- At what level do you cost load the schedule?
  - WBS Level is where we collect actual cost.
  - Cost Book Activity Sheet is where we load the estimate.
  - Schedule Activity level is where we measure progress that determines the earned value.
- Performance Evaluation is executed at the rollup level for the WBS.
  - BCWS – baseline plan
  - BCWP - performance
  - ACWP – actual costs
  - Schedule Variance
  - Cost Variance



Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Total Float	Budgeted Cost	% Comp
LIGO							
LIGO.4 Advanced LIGO Construction							
Subtotal		1,006	18OCT00A	25OCT04	0	2,162,299.54	37
LIGO.4.06 Core Optics Components (COC)							
LIGO.4.06.4 COC Fabrication							
LIGO.4.06.4.1 Pathfinder							
CO-W40641	WBS: COC Pathfinder	1,006	18OCT00A	25OCT04	0	0.00	36
CO-F40641A	EST: Pathfinder SPF	654*	18OCT00A	02JUN03	108	696,192.27	55
CO-F40641B	EST: Pathfinder LPF	986*	15NOV00A	25OCT04	-244	1,466,107.27	37
CO-D50540	Small Pathfinder-Prepare Blank specifications	10	18OCT00A	31OCT00A		0.00	100
CO-P50550	SPF-Order Blanks	5	02JAN02A	08JAN02A		0.00	100
CO-P50560	SPF- Polishing RFP	20	18OCT00A	14NOV00A		0.00	100
CO-P50570	SPF - Polish Proposal prep at vendor	20	15NOV00A	14DEC00A		0.00	100
CO-P50580	SPF-Polishing Proposal Evaluation	10	15DEC00A	02JAN01A		0.00	100
CO-P50590	SPF-Let Polishing Contract	10	03JAN01A	17JAN01A		0.00	100
CO-P50600	SPF- Coating RFP	10	18OCT00A	31OCT00A		0.00	100
CO-P50610	SPF - Coating Proposal prep at vendor	20	01NOV00A	30NOV00A		0.00	100
CO-P50620	SPF-Coating Proposal Evaluation	10	01DEC00A	14DEC00A		0.00	100
CO-P50630	SPF-Let Coating Contract	5	15DEC00A	21DEC00A		0.00	100
CO-T50640	SPF-Coating Set Up	20	22DEC00A	24JAN01A		0.00	100
CO-F50650	SPF-Fabricate Blanks, Halfl size	100	09JAN02A	31MAY02	108	0.00	57
CO-Q50660	SPF-Absorb Testing	20	03JUN02	28JUN02	108	0.00	0
CO-Q50670	SPF-Homogeneity Measurement	20	01JUL02	29JUL02	108	0.00	0
CO-F50680	SPF-PF-Polishing	120	30JUL02	23JAN03	108	0.00	0
CO-Q50690	SPF- Uncoated Metrology	20	24JAN03	21FEB03	108	0.00	0
CO-T50700	SPF-Coating	40	24FEB03	18APR03	108	0.00	0
CO-Q50710	SPF-Coated Metrology	20	21APR03	16MAY03	108	0.00	0
CO-H50720	SPF-Deliver to UWA	10	19MAY03	02JUN03	108	0.00	0
CO-D50740	LPF-Prepare Blank specifications Full size	10	15NOV00A	30NOV00A		0.00	100
CO-P50750	LPF-Order Blanks - Pathfinder full size	10	01DEC00A	14DEC00A		0.00	100
CO-P50760	LPF- Polishing RFP	10	03DEC03	16DEC03	-244	0.00	0
CO-P50770	LPF - Polish Proposal prep at vendor	10	17DEC03	05JAN04	-244	0.00	0
CO-P50780	LPF-Let Polishing Contract	10	06JAN04	20JAN04	-244	0.00	0
CO-P50790	LPF- Coating RFP	10	03DEC03	16DEC03	-164	0.00	0
CO-P50800	LPF - Coating Proposal prep at vendor	10	17DEC03	05JAN04	-164	0.00	0
CO-P50810	LPF-Let Coating Contract	5	06JAN04	12JAN04	-164	0.00	0
CO-T50820	LPF-Coating Set Up	20	13JAN04	10FEB04	-164	0.00	0
CO-F50830	LPF-Fabricate Blanks, Full size	260	09NOV01A	26DEC02	-20	0.00	36
CO-Q50840	LPF-Absorb Testing	20	27DEC02	28JAN03	-20	0.00	0
CO-Q50850	LPF-Homogeneity Measurement	20	29JAN03	26FEB03	-20	0.00	0
CO-F50860	LPF-Polishing	80	21JAN04	12MAY04	-244	0.00	0
CO-Q50870	LPF- Uncoated Metrology	15	13MAY04	03JUN04	-244	0.00	0
CO-F50880	LPF-Coating	80	04JUN04	27SEP04	-244	0.00	0
CO-Q50890	LPF-Coated Metrology	20	28SEP04	25OCT04	-244	0.00	0
CO-H50900	Deliver LPF ETM to LASTI	0		25OCT04	-244	0.00	0



Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Total Float	Budgeted Cost	% Comp	R/C % Expended	Cost to Date (ACWP)	Planned value cost (BCWS)	Earned value cost (BCWP)	Cost at Completion	Sched Var (BCWP - BCWS)	Cost Variance (BCWP - ACWP)
LIGO														
LIGO.4 Advanced LIGO Construction														
Subtotal		1,006	18OCT00A	25OCT04	0	2,162,299.54	37	69	1,500,000.00	1,058,066.66	920,893.41	2,162,299.54	-137,173.25	-579,106.59
LIGO.4.06 Core Optics Components (COC)														
LIGO.4.06.4 COC Fabrication														
LIGO.4.06.4.1 Pathfinder														
CO-W40641	WBS: COC Pathfinder	1,006	18OCT00A	25OCT04	0	0.00	36	0	1,500,000.00	0.00	0.00	2,162,299.54	0.00	-1,500,000.00
CO-F40641A	EST: Pathfinder SPF	654*	18OCT00A	02JUN03	108	696,192.27	55	0	0.00	384,289.61	384,298.14	0.00	8.53	384,298.14
CO-F40641B	EST: Pathfinder LPF	986*	15NOV00A	25OCT04	-244	1,466,107.27	37	0	0.00	673,777.05	536,595.27	0.00	-137,181.78	536,595.27
CO-D50540	Small Pathfinder-Prepare Blank specifications	10	18OCT00A	31OCT00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50550	SPF-Order Blanks	5	02JAN02A	08JAN02A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50560	SPF- Polishing RFP	20	18OCT00A	14NOV00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50570	SPF - Polish Proposal prep at vendor	20	15NOV00A	14DEC00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50580	SPF-Polishing Proposal Evaluation	10	15DEC00A	02JAN01A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50590	SPF-Let Polishing Contract	10	03JAN01A	17JAN01A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50600	SPF- Coating RFP	10	18OCT00A	31OCT00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50610	SPF - Coating Proposal prep at vendor	20	01NOV00A	30NOV00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50620	SPF-Coating Proposal Evaluation	10	01DEC00A	14DEC00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50630	SPF-Let Coating Contract	5	15DEC00A	21DEC00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-T50640	SPF-Coating Set Up	20	22DEC00A	24JAN01A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-F50650	SPF-Fabricate Blanks, Halfl size	100	09JAN02A	31MAY02	108	0.00	57	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50660	SPF-Absorb Testing	20	03JUN02	28JUN02	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50670	SPF-Homogeneity Measurement	20	01JUL02	29JUL02	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-F50680	SPF-PF-Polishing	120	30JUL02	23JAN03	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50690	SPF- Uncoated Metrology	20	24JAN03	21FEB03	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-T50700	SPF-Coating	40	24FEB03	18APR03	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50710	SPF-Coated Metrology	20	21APR03	16MAY03	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-H50720	SPF-Deliver to UWA	10	19MAY03	02JUN03	108	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-D50740	LPF-Prepare Blank specifications Full size	10	15NOV00A	30NOV00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50750	LPF-Order Blanks - Pathfinder full size	10	01DEC00A	14DEC00A		0.00	100	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50760	LPF- Polishing RFP	10	03DEC03	16DEC03	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50770	LPF - Polish Proposal prep at vendor	10	17DEC03	05JAN04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50780	LPF-Let Polishing Contract	10	06JAN04	20JAN04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50790	LPF- Coating RFP	10	03DEC03	16DEC03	-164	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50800	LPF - Coating Proposal prep at vendor	10	17DEC03	05JAN04	-164	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-P50810	LPF-Let Coating Contract	5	06JAN04	12JAN04	-164	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-T50820	LPF-Coating Set Up	20	13JAN04	10FEB04	-164	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-F50830	LPF-Fabricate Blanks, Full size	260	09NOV01A	26DEC02	-20	0.00	36	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50840	LPF-Absorb Testing	20	27DEC02	28JAN03	-20	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50850	LPF-Homogeneity Measurement	20	29JAN03	26FEB03	-20	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-F50860	LPF-Polishing	80	21JAN04	12MAY04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50870	LPF- Uncoated Metrology	15	13MAY04	03JUN04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-F50880	LPF-Coating	80	04JUN04	27SEP04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-Q50890	LPF-Coated Metrology	20	28SEP04	25OCT04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00
CO-H50900	Deliver LPF ETM to LASTI	0		25OCT04	-244	0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00

LIGO

LIGO.4 Advanced LIGO Construction

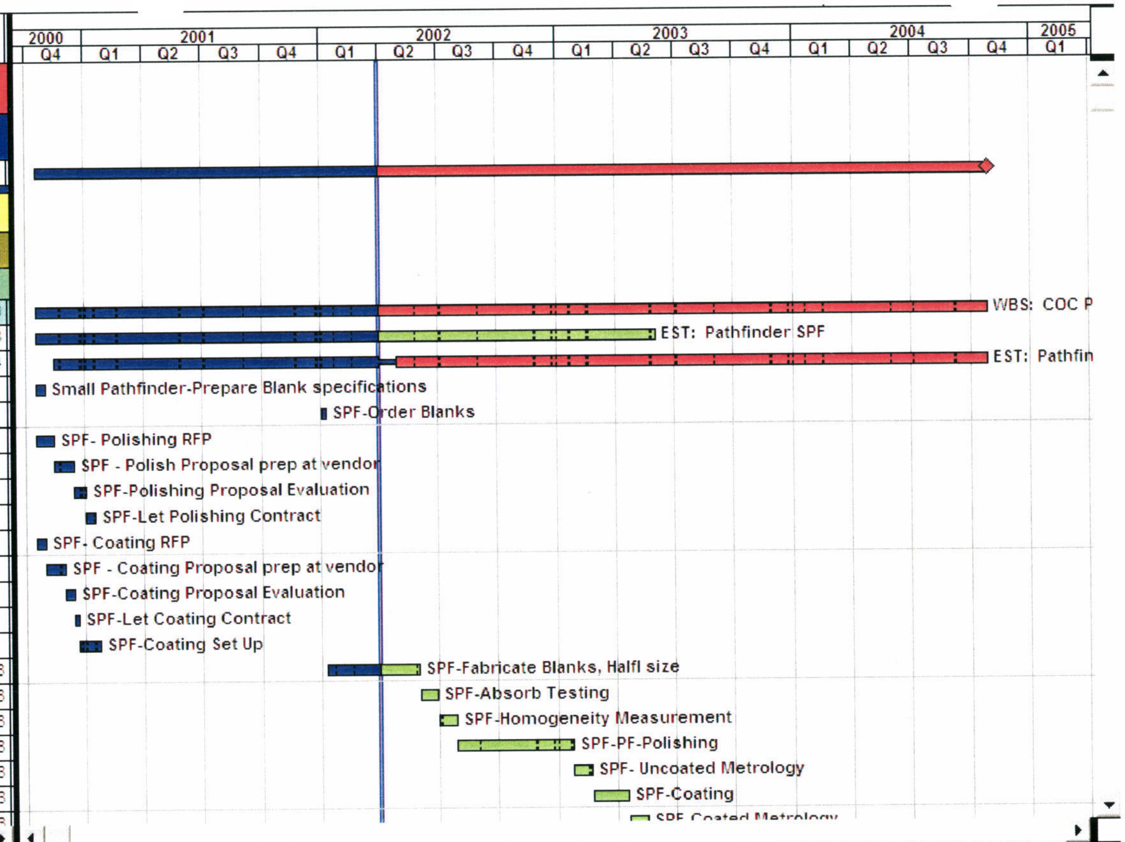
Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Total Float
Subtotal		1,006	18OCT00A	25OCT04	0

LIGO.4.06 Core Optics Components (COC)

LIGO.4.06.4 COC Fabrication

LIGO.4.06.4.1 Pathfinder

Activity ID	Activity Description	Orig Dur	Early Start	Early Finish	Total Float
CO-W40641	WBS: COC Pathfinder	1,006	18OCT00A	25OCT04	0
CO-F40641A	EST: Pathfinder SPF	654*	18OCT00A	02JUN03	108
CO-F40641B	EST: Pathfinder LPF	986*	15NOV00A	25OCT04	-244
CO-D50540	Small Pathfinder-Prepare Blank specifications	10	18OCT00A	31OCT00A	
CO-P50550	SPF-Order Blanks	5	02JAN02A	08JAN02A	
CO-P50560	SPF- Polishing RFP	20	18OCT00A	14NOV00A	
CO-P50570	SPF - Polish Proposal prep at vendor	20	15NOV00A	14DEC00A	
CO-P50580	SPF-Polishing Proposal Evaluation	10	15DEC00A	02JAN01A	
CO-P50590	SPF-Let Polishing Contract	10	03JAN01A	17JAN01A	
CO-P50600	SPF- Coating RFP	10	18OCT00A	31OCT00A	
CO-P50610	SPF - Coating Proposal prep at vendor	20	01NOV00A	30NOV00A	
CO-P50620	SPF-Coating Proposal Evaluation	10	01DEC00A	14DEC00A	
CO-P50630	SPF-Let Coating Contract	5	15DEC00A	21DEC00A	
CO-T50640	SPF-Coating Set Up	20	22DEC00A	24JAN01A	
CO-F50650	SPF-Fabricate Blanks, Halfl size	100	09JAN02A	31MAY02	108
CO-Q50660	SPF-Absorb Testing	20	03JUN02	28JUN02	108
CO-Q50670	SPF-Homogeneity Measurement	20	01JUL02	29JUL02	108
CO-F50680	SPF-PF-Polishing	120	30JUL02	23JAN03	108
CO-Q50690	SPF- Uncoated Metrology	20	24JAN03	21FEB03	108
CO-T50700	SPF-Coating	40	24FEB03	18APR03	108
CO-Q50710	SPF-Coated Metrology	20	21APR03	16MAY03	108

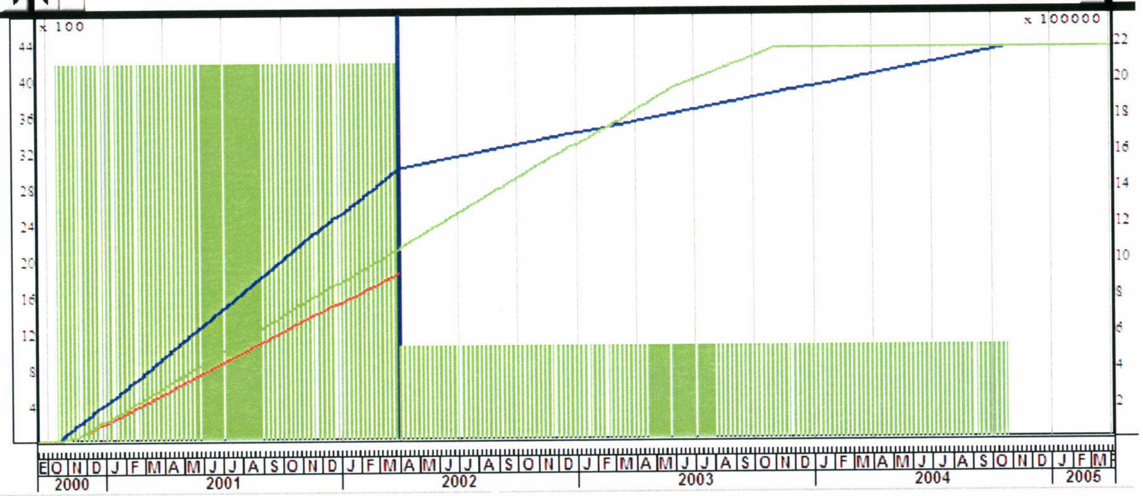


Resource Profile / Table

Select... | Display...

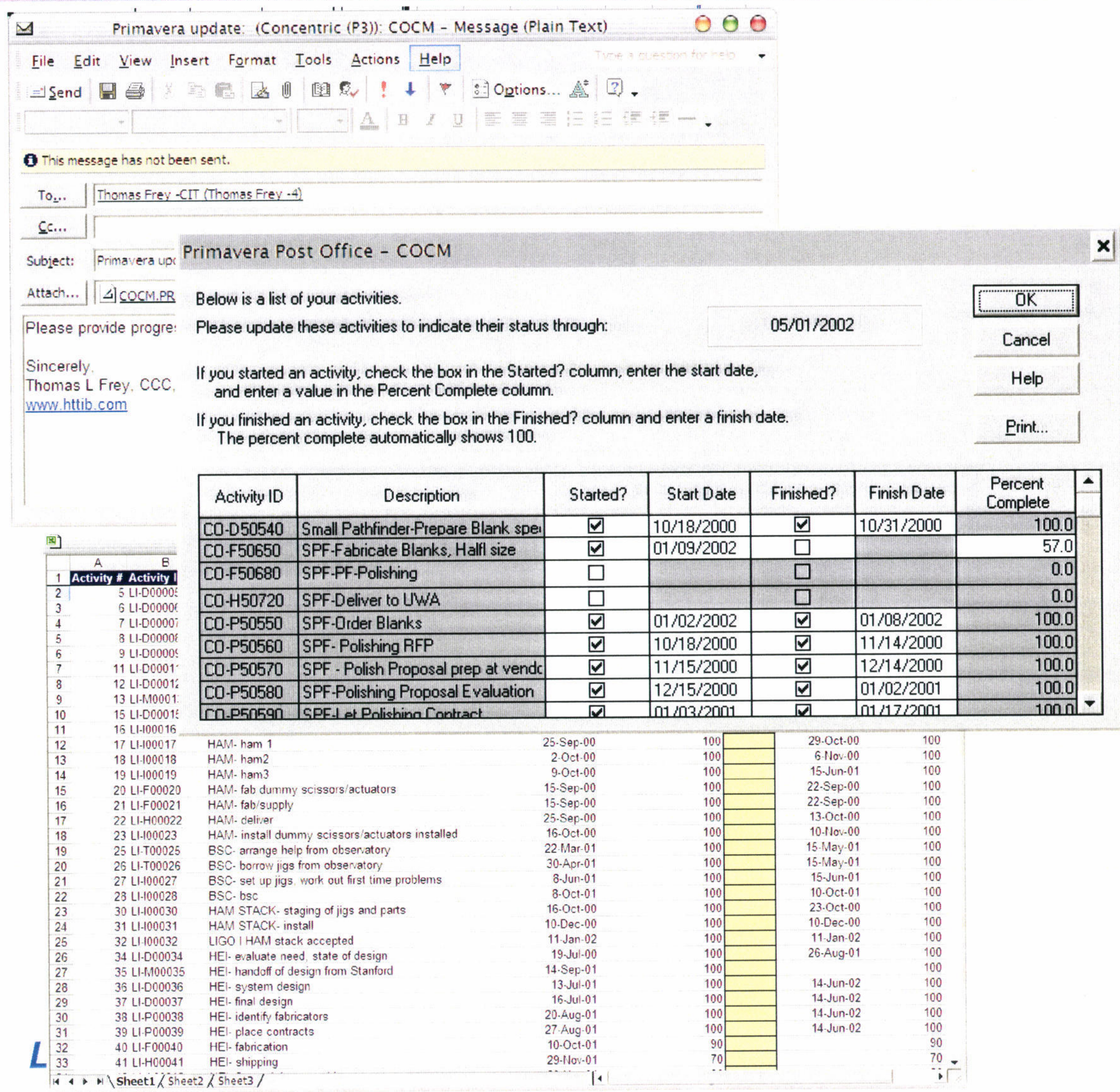
Resources: Total

Previous | Next



Progress Data Collection

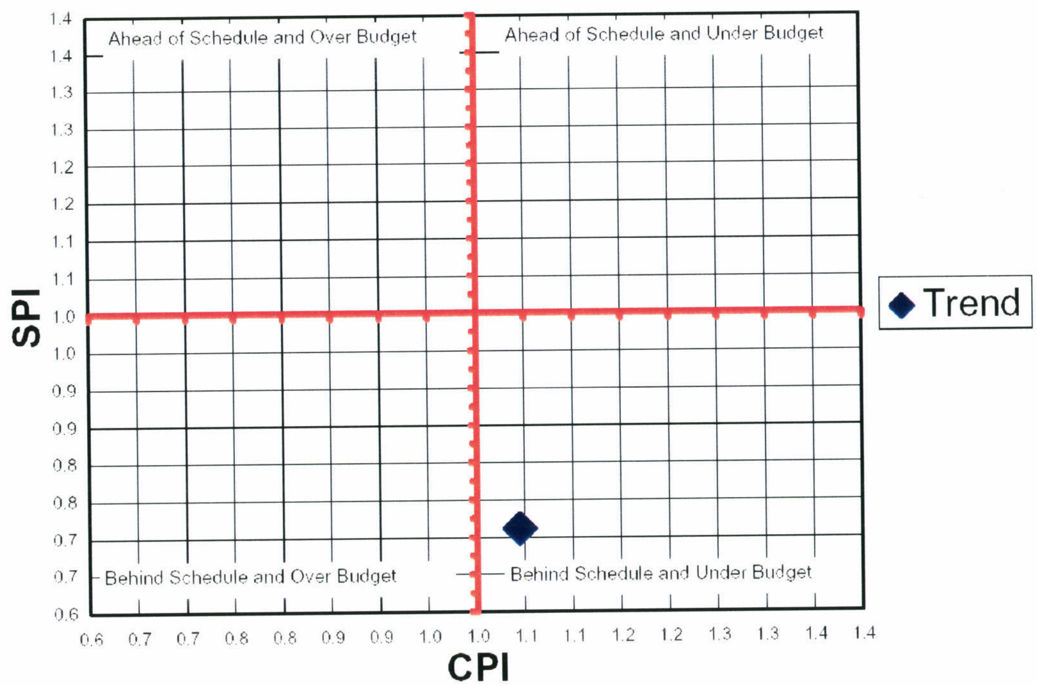
- Primavera Project Planner Post Office.
  - » A built in feature within the application creates a mail attachment that contains the activities to be updated.
- Excel spreadsheets can be easily imported.



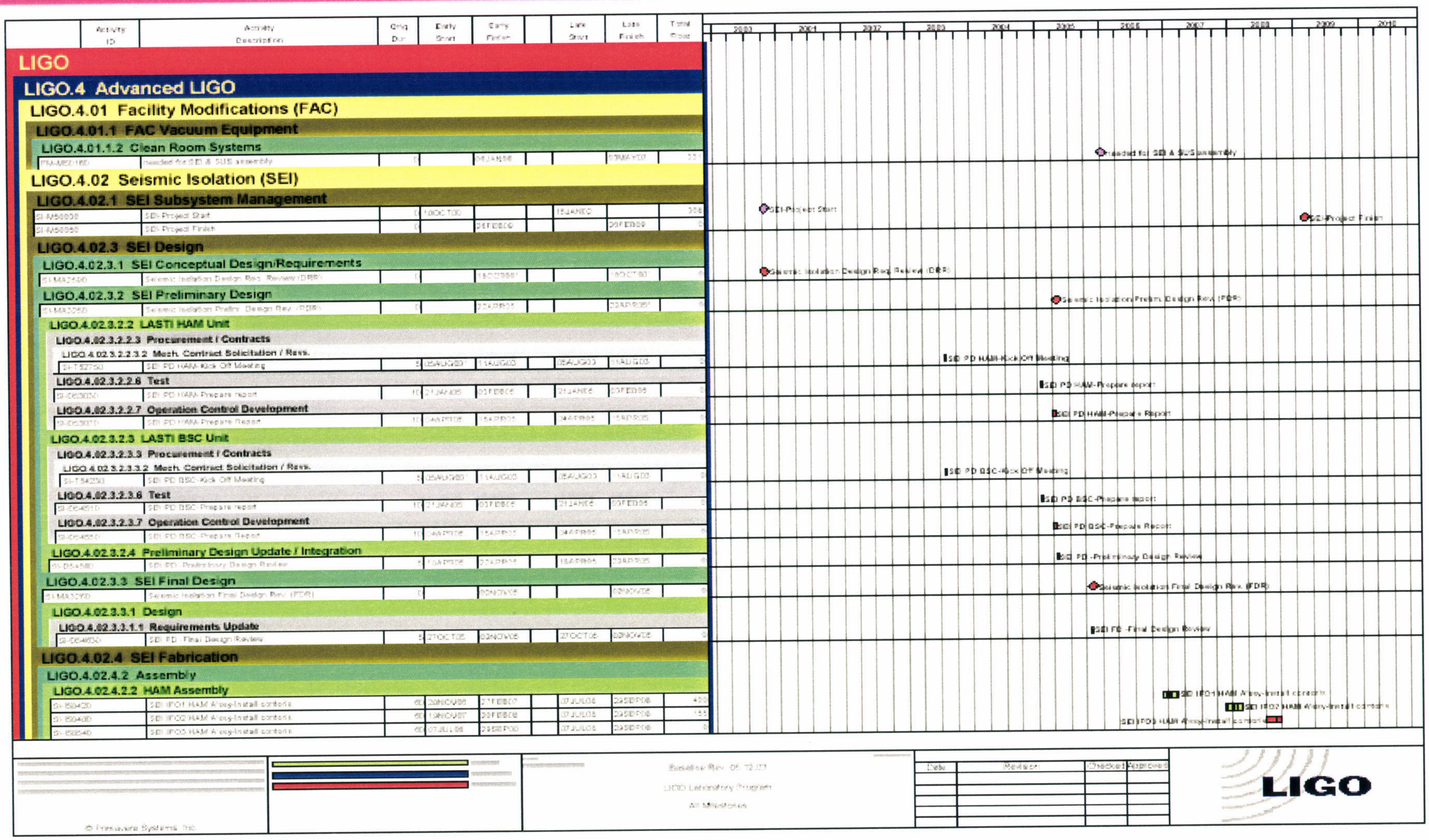
Caltech LIGO II	PRIMAVERA PROJECT PLANNER	Installation
REPORT DATE 06JUL00 RUN NO. 108 15:51	Earned Value Report - Cost Summary by Acct.	START DATE 01DEC99 FIN DATE 23DEC02
Earned Value Report - Cost Summary by Acct.		DATA DATE 30DEC00 PAGE NO. 1

COST ACCOUNT	PCT COM	CUMULATIV ACWP	CUMULATIV BCWP	CUMULATIV BCWS	COST VARIANCE	SCHEDULE VARIANCE	BUDGETED COST	COST AT COMPLETIO	CAC VARIANCE
07-4131-04	100	75000	90000	90000	15000	0	90000	75000	15000
07-4133-04	37	235250	238125	385938	2875	-147812	637500	735150	-97650
07-4134-04	39	234375	234375	435385	0	-201010	600000	837000	-237000
07-4135-04	0	0	0	0	0	0	225000	225000	0
07-4136-04	69	392000	416250	464423	24250	-48173	600000	850000	-250000
07-4137-04	0	0	0	0	0	0	112500	112500	0
		936625	**978750**	**1375745**	**42125**	**-396995**	**2265000**	**2834650**	**-569650**

Trend Analysis LIGO II Model



Milestone Model



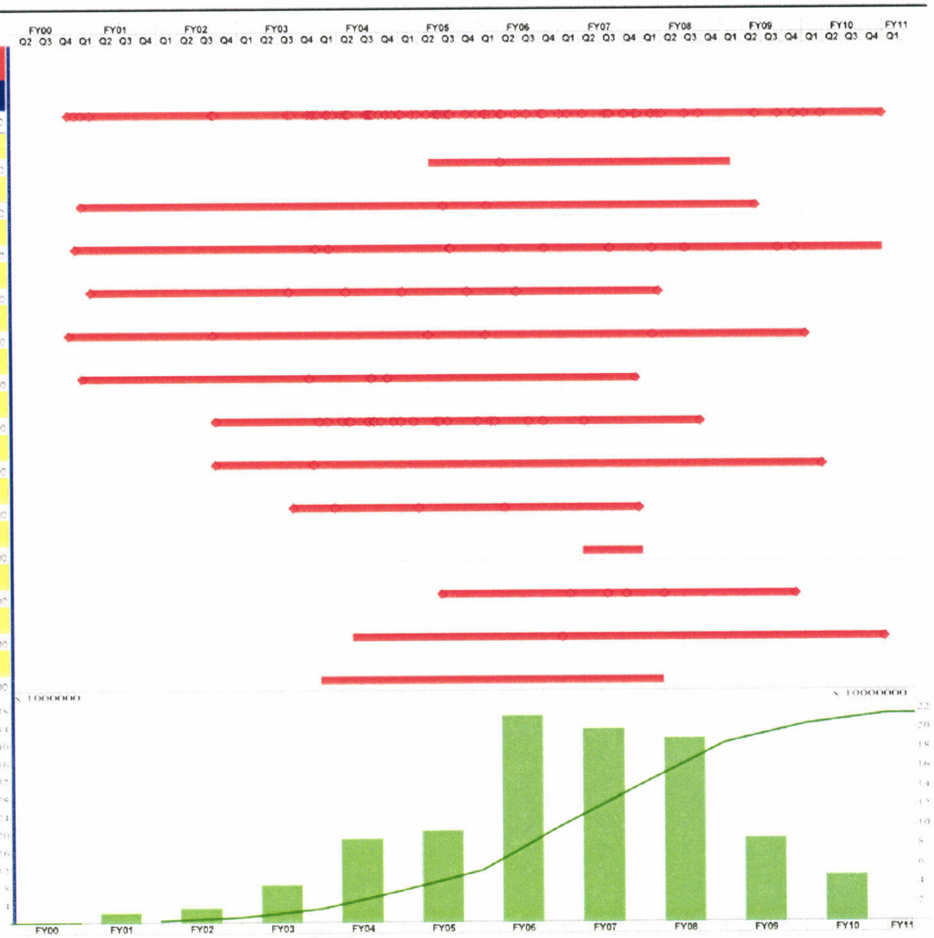
LIGO

Major Milestones

Milestone	Date at End of Quarter Per Calendar Year
NSF Early Funding for Core Optics Available	5 Apr 2004
NSF Funding for Advanced LIGO Construction Available	4 Apr 2005
Installation begins at Livingston	8 Mar 2007
Installation begins at Hanford	15 Nov 2007
Commissioning begins at Livingston	15 Jun 2009
Commissioning begins at Hanford	30 Sep 2009
Livingston Operational	6 Jan 2010
Hanford Operational	22 Sep 2010

LIGO

	Orig Dur	Early Start	Early Finish	Budgeted Cost
LIGO				
LIGO.4 Advanced LIGO				
Subtotal	2,524	21AUG00	22SEP10	214,883,284.00
+ LIGO.4.01 Facility Modifications (FAC)	935	18FEB05	10NOV08	4,182,087.00
+ LIGO.4.02 Seismic Isolation (SEI)	2,088	18OCT00	26FEB09	44,331,341.00
+ LIGO.4.03 Suspension (SUS)	2,503	20SEP00	22SEP10	30,093,848.00
+ LIGO.4.04 Prestabilized Laser (PSL)	1,763	28NOV00	13DEC07	17,277,320.00
+ LIGO.4.05 Input Optics (IO)	2,286	21AUG00	08OCT09	4,839,775.00
+ LIGO.4.06 Core Optics Components (COC)	1,718	18OCT00	30AUG07	19,920,832.00
+ LIGO.4.07 Auxiliary Optics (AOS)	1,502	17JUN02	17JUN08	15,064,931.00
+ LIGO.4.08 Interferometer Sensing and Control (ISC)	1,881	17JUN02	21DEC09	12,811,747.00
+ LIGO.4.09 Data Acq., Diag., Network & Supervisory Control	1,075	02JUN03	14SEP07	9,157,563.00
+ LIGO.4.10 Support Equipment (SUP)	189	02JAN07	28SEP07	1,500,000.00
+ LIGO.4.12 LIGO Data Analysis System (LDAS)	1,097	01APR05	18AUG09	12,487,115.00
+ LIGO.4.13 Installation (INS)	1,649	24FEB04	22SEP10	24,828,860.00
+ LIGO.4.14 Project Management (PM)	1,061	01OCT03	28DEC07	9,387,864.00



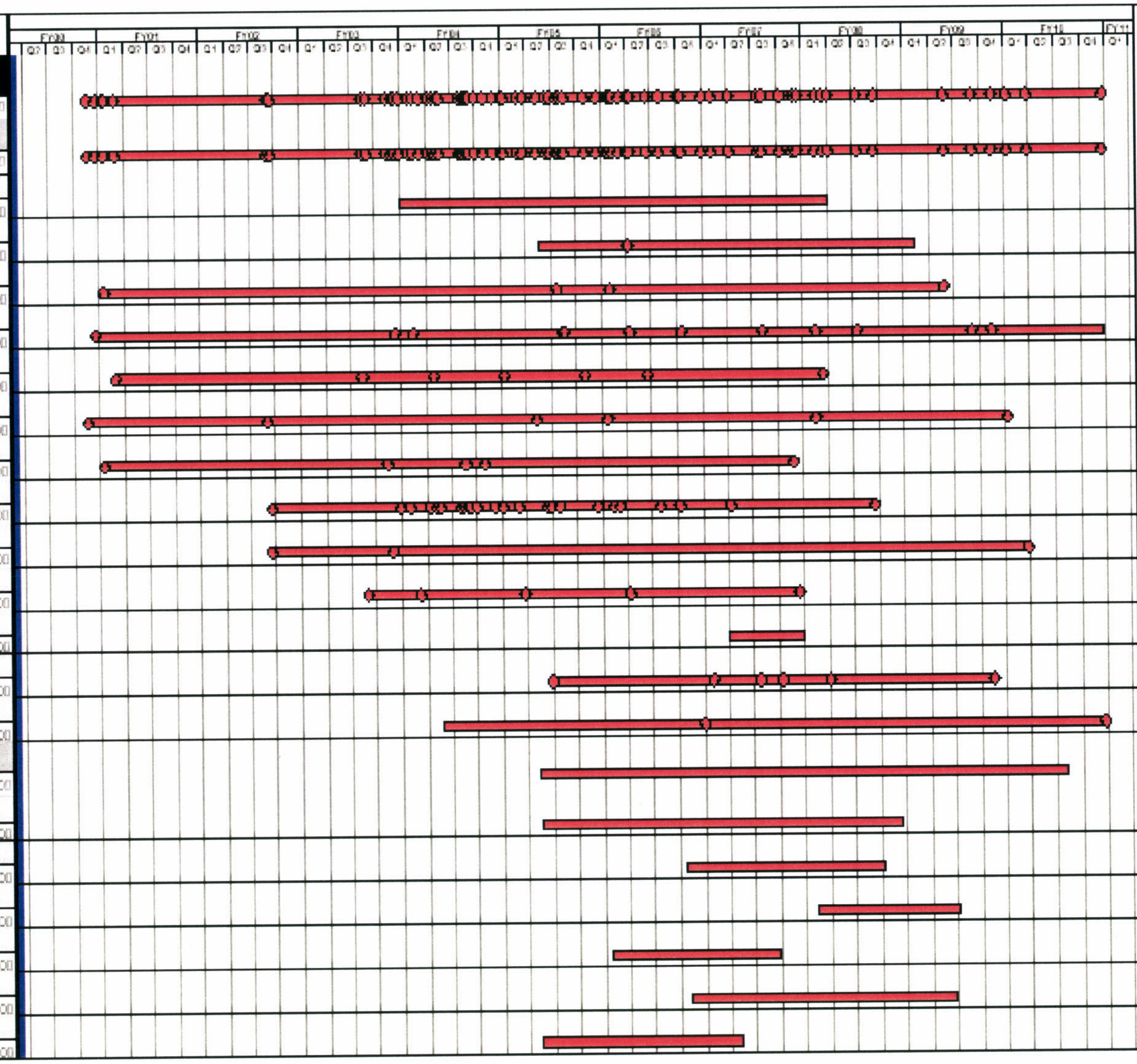
Baseline Rev. 05.22.03

LIGO Laboratory Program

Adv. LIGO Summary

LIGO Laboratory Program

	Orig Dur	Early Start	Early Finish	Budgeted Cost
Total	2,524	21AUG00	22SEP10	214,883,284.00
IFO 01				
Subtotal	2,524	21AUG00	22SEP10	123,485,780.00
+ Project Management	1,061	01OCT03	28DEC07	9,387,884.00
+ Facility Modifications	935	18FEB05	10NOV08	1,682,888.00
+ Seismic Isolation	2,088	18OCT00	26FEB09	17,509,723.00
+ Suspension	2,503	20SEP00	22SEP10	23,202,228.00
+ Prestabilized Laser	1,763	28NOV00	13DEC07	11,621,440.00
+ Input Optics	2,286	21AUG00	08OCT09	2,641,357.00
+ Core Optics	1,718	18OCT00	30AUG07	12,512,419.00
+ Auxiliary Optics	1,502	17JUN02	17JUN08	9,128,011.00
+ Interferometer Sensing and Control	1,881	17JUN02	21DEC09	8,493,145.00
+ Data Acquisition and Diagnostics	1,075	02JUN03	14SEP07	5,426,711.00
+ Support Equipment	189	02JAN07	28SEP07	1,500,000.00
+ Computing and Data Analysis	1,097	01APR05	18AUG09	10,055,452.00
+ Installation	1,649	24FEB04	22SEP10	10,324,445.00
IFO 02				
Subtotal	1,309	11FEB05	06MAY10	47,079,045.00
+ Facility Modifications	895	18FEB05	15SEP08	1,332,408.00
+ Seismic Isolation	490	27JUL06	11JUL08	13,461,898.00
+ Suspension	360	12NOV07	08APR09	8,332,580.00
+ Prestabilized Laser	413	28OCT05	22JUN07	2,831,840.00
+ Input Optics	655	07AUG06	23MAR09	1,104,875.00
+ Core Optics	497	11FEB05	07FEB07	3,080,487.00



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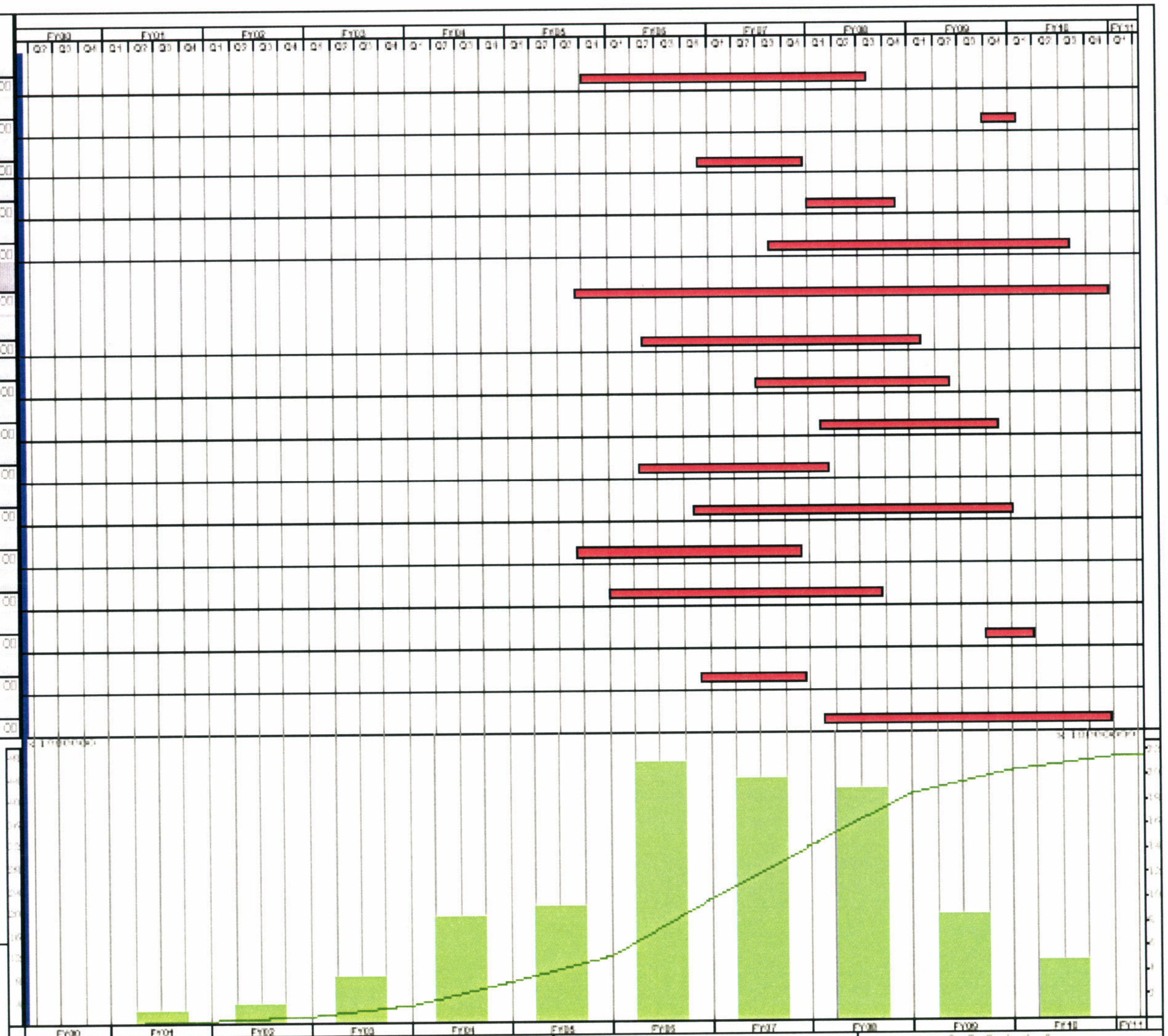
LIGO Laboratory Program

Adv. LIGO Summary by IFO

LIGO

	Orig Dur	Early Start	Early Finish	Budgeted Cost
+ Auxiliary Optics	708	06JUL05	06MAY08	3,143,895.00
+ Interferometer Sensing and Control	90	24JUN09	29OCT09	2,159,301.00
+ Data Acquisition and Diagnostics	261	30AUG06	14SEP07	1,832,528.00
+ Computing and Data Analysis	220	01OCT07	15AUG08	2,431,864.00
+ Installation	750	08MAY07	06MAY10	7,297,803.00
IFO 03				
Subtotal	1,335	07JUN05	23SEP10	44,318,459.00
+ Facility Modifications	698	01FEB06	10NOV08	1,168,891.00
+ Seismic Isolation	485	21MAR07	28FEB09	13,359,922.00
+ Suspension	440	12NOV07	17AUG09	7,559,040.00
+ Prestabilized Laser	473	27JAN06	13DEC07	2,824,040.00
+ Input Optics	795	07AUG06	08OCT09	1,093,543.00
+ Core Optics	580	07JUN05	30AUG07	4,327,929.00
+ Auxiliary Optics	673	06OCT05	17JUN08	2,793,055.00
+ Interferometer Sensing and Control	125	24JUN09	21DEC09	2,159,301.00
+ Data Acquisition and Diagnostics	261	30AUG06	14SEP07	1,798,308.00
+ Installation	710	19NOV07	22SEP10	7,238,812.00



LIGO

LIGO

Support of PPARC Proposal

Real World Example – PPARC Proposal Support

Advanced LIGO Cost Estimate Summary (UG, UB, RAL)

WBS LIGO.4 Advanced LIGO Construction

WBSNo	Description	Direct Labor Hours	Direct Labor Total ($)	Contract Labor Hours	Contract Labor Total ($)	Equipment Total ($)	Travel Cost ($)	Material Total ($)	Subcontracts Total ($)	Indirect Cost ($)	SubTotal Cost ($)	Contingency %	Contingency ($)	Total Cost ($)
LIGO.4 03	Suspension (SUS)	20 257	989 463			4 925 450	202.700		300 000	521.528	6 939.140	24 89%	1.726.910	8.666.050
LIGO.4 06	Core Optics Components (COC)					391 944				0	391.944	43 00%	168.536	560.480
LIGO.4 13	Installation (INS)	3 840	209 500				396.000			157.430	762.930	5 00%	38.146	801.076
		24 097	1.198 963			5 317.394	598.700		300 000	678.958	8 094.014	23 89%	1.933.592	10.027.606

Advanced LIGO Cost Estimate Detail (UG, UB, RAL)

WBS Number	LIGO 4 03 1
WBS Description	SUS Subsystem Management
Activity	SUL50030B
Description	SUS-Sub System Management (UG, UB, RAL
Location	Capital Project
Cost Code	12 4031 14

Duration	1215 days
Estimated By	T. Frey
Last Modified On	06/15/2002

Line	NSF Item Code	Cost Category	LIGO Resource Code	Description	Estimator Comments or Vendor	Cost Basis	Quantity (Hrs Ea)	Direct Labor (AA, B1-B6) Unit Cost	Direct Labor Total ($)	Contract Labor (G5) Unit Cost	Contract Labor Total ($)	Equipment (D1,D2) Unit Cost ($)	Equipment Total ($)	Travel (E1,E2) Unit Cost ($)	Travel Total ($)	Material (G1-G4) Unit Cost ($)	Material Total ($)	Subcontracts (G5) Unit Cost ($)	Subcontracts Total ($)	Total Cost ($)	Reference
1	B2	Labor	SE	Senior Engineer		HD	1500	79	118.500											118.500	
2	E1	Int Travel	E1	Travel Budget for Subsystem Mgmt	10 Trips / 1 week	HD	10							3.000	30.000					30.000	
				Subtotal SUL50030B SUS-Sub System Management (UG, UB.					118.500						30.000					118.500	

Staff Benefits at	0.00%	0
(G6) GRA Benefits at	0.00%	0
Indirect Cost at	0.00%	0
Total Cost		118.500
Contingency at	10.00%	11.850
Cost Plus Contingency		163.350

Labor Summary (Direct Labor plus Contract Labor)

	AA Key/Fac	B1 PostDoc	B2 Mgmt	B2 SrSci	B2 Sci	B2 SrEngr	B2 Engr	B2 Tech	B2 Other	B2 Total	B3 Grad	B4 UGrad	B5 Admin
Hours						1500				1500			
Person Years						0.8				0.8			

Risk Factors		Risk Multipliers
Technical	3	2.00%
Cost	2	1.00%
Schedule	2	1.00%

Calculated Contingency: 10.00%
Estimator Override:

WBS Definition

Technical management of the subsystem is covered in this WBS element. This is a level of effort task (the level may vary according to the development phase).

Basis of Estimate

Labor: Hours estimated based on historical data.

Travel: Estimated based on historical data.

Task List

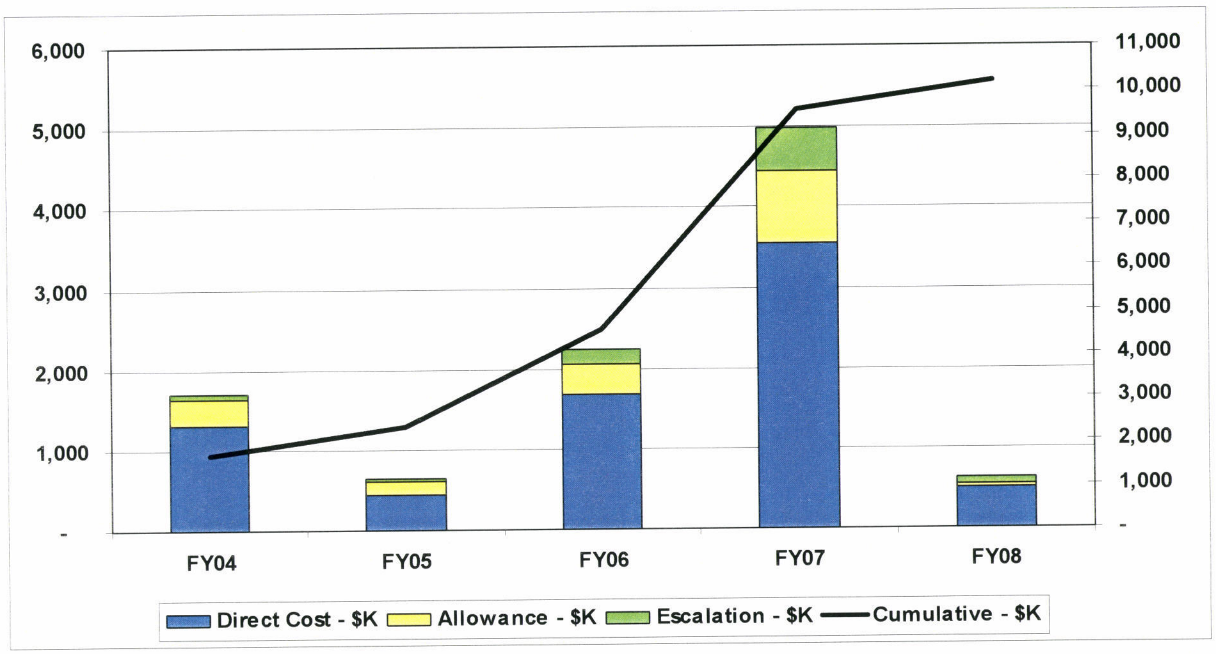
Task No	Description	Duration
SUL50030	SUS Sub System Management	1215

PPARC Proposal Example

- Using the schedule, we coded the tasks that represent the collaborator's scope.
- Using the cost book Access database, we cost loaded the schedule and generated cost profiles.

PPARC Proposal Example

- Using the cost loaded schedule, we exported the cost profile data to a spread sheet in base year dollars.
- Using MS Excel, we generated a cost profile by GB Fiscal Years and applied an escalation rate.



LIGO

Partners and Management

LIGO

Partners and Management

- Principal fiduciary management will come from the LIGO Laboratory
- Advanced LIGO will be implemented with full LSC participation
- Capital partners (UK GEO, German GEO, ACIGA) will have a role in the project management
  - » Possible Institutional Board
  - » Details to be worked out as commitments defined
  - » Discussions between LIGO Lab and UK GEO/PPARC regarding nature and level of formal agreement
- Basic project management methods will follow the LIGO model

LIGO

Summary

- **Experienced LIGO Lab team** has planned and estimated Advanced LIGO
- LIGO Lab and LSC have formed a strong partnership
- Design and development process is already underway in a "project" setting
- Most of the elements of a formal project are in place
- Costs are estimated in detail
- Schedule planning is thorough and will support definition of the final negotiated project
- Performance measurement infrastructure is in place
- International partnerships are already being exercised
- Project Management Plan can be made definitive when financial commitments are complete

Advanced LIGO In Context

- LIGO construction is complete
  - » NSF investment in LIGO now totals about $400 million
  - » Construction cost $292 million
  - » LIGO facilities represent ~ 2/3 of the construction investment and are intended to support successive detectors
- Initial LIGO detectors are operating and have carried out early scientific running
  - » Initial LIGO should accomplish its sensitive observation goal by late 2006
- Advanced LIGO development is defining the detailed design and retiring risks
- The experienced LIGO team will be ready to install Advanced LIGO in 2007
- Observations for probable gravitational wave detection can commence in 2010