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

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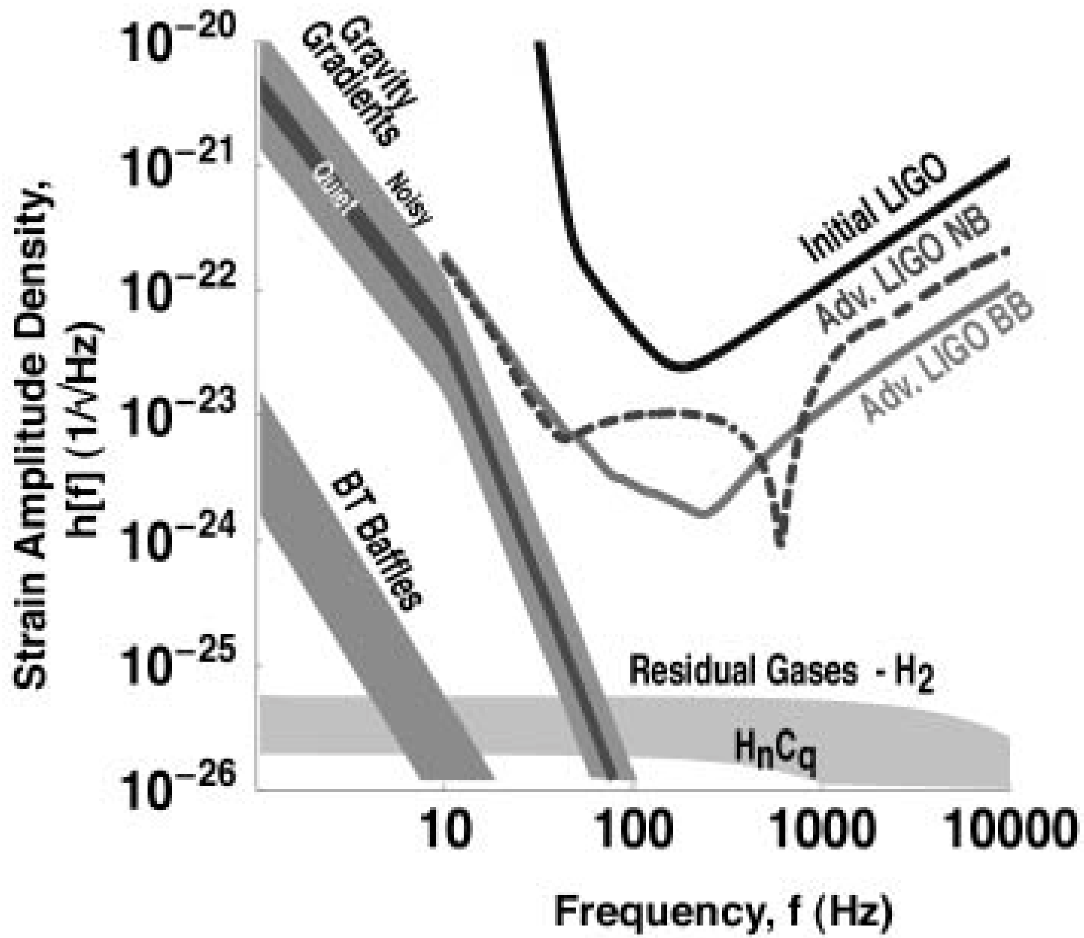
# Program and Mission of the LIGO Laboratory

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

# The Vision for Research and Development in LIGO

- LIGO was conceived as a **program** to detect gravitational waves; From the NSF Review of the LIGO II Conceptual plan (1999): “Since its inception, the LIGO Project was authorized by the NSF to pursue the development of the technology of advanced gravitational wave detectors.”
- LIGO construction was approved to provide an initial set of feasible detectors and a set of facilities capable of supporting much more sensitive detectors
- It was planned that the initial detectors would have a **plausible** chance to make direct detections
- It was planned that more sensitive detectors would be required to enable **confident** detection

# LIGO Facilities planned to support detector upgrades



# History of LIGO R&D

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

# Request for LIGO R&D

- This proposal requests funds for the R&D program for Advanced LIGO

1) Continuation of the present R&D funding level ($2.77M in 2002)
2) Increase of funding of R&D engineering support for the Lab and greater LSC ($1.71M in 2002)
3) Funding of 'big ticket' R&D items for the LSC community ($3.30M in 2002)

# Reference Design and the LIGO Scientific Collaboration

- Serious R&D coordination started in 1996, resulting in Reference Design in 1999 in LSC White Paper
- Reference design established through LSC Working Groups, shared research and decision making
- e.g., Seismic Isolation
  - » Key ideas from JILA, Caltech; teams at JILA, Stanford, LSU, MIT, Caltech, LLO, Pisa brought ideas to maturity through prototypes at Caltech and MIT; continued prototyping at Stanford, then MIT
- e.g., Interferometer Configuration
  - » Key ideas from Glasgow, MIT; tabletop experiments in Australia, Caltech, Garching, Univ. Florida to explore different approaches; continued prototyping at Glasgow, then Caltech

# **Major** International Roles in Advanced LIGO

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

# Role of Lab in the LIGO Scientific Collaboration

- Peoples report: Lab should coordinate R&D direction and major investments, provide infrastructure
  - » "…the Panel urges the NSF to take the necessary steps to strengthen the integration of the R&D tasks carried out by the LSC partners into the Lab's planning and reporting process."
- The Lab's plan follows this lead:
  - » all R&D tasks are defined in MOU's with the Laboratory
  - » program is conducted as the early stages of a construction project
  - » systems trades and engineering are carried out by the Lab
  - » the R&D across the LSC is organized with a detailed cost estimate and schedule carried by the Lab
  - » monthly coordinating meetings with LSC working groups are held to monitor progress

# Approach to Interferometer Upgrades

- **substantial** improvements in performance are very inefficient to achieve with incremental upgrades
  - Gravitational wave interferometers are “point” designs
  - lowering one noise floor encounters another
  - changing the performance of one subsystem causes system mismatch with other subsystems
- Installing, and commissioning, an interferometer system is a major effort – typically 1-2 years in duration
  - much of the campaign overhead is encountered even with subsystem upgrades
- Upgrading an interferometer has a high cost in missed scientific opportunity – thus,

**Upgrade must yield a major increase in sensitivity**

# Timing of R&D for interferometer upgrades….

- A 'major increase in sensitivity' requires a major R&D effort on many fronts
- In addition, long-lead items (optics) provide a 2-3 year 'strut' from order to installation
- The LIGO Science Run with the initial detector will be completed 2006
- Now is the appropriate time for a high-level of pre-construction R&D

# …Timing of R&D for interferometer upgrades

- The LSC and Lab submitted a White Paper and a Conceptual Project plan in late 1999; reviewed by the NSF Special Emphasis Panel chaired by John Peoples in Oct 1999
- From the Review report, "The panel recommends….
  - » that the Lab proceed with the preparation of a full proposal for the Preconstruction R&D for LIGO II
  - » that the Lab and the LSC submit an integrated R&D Plan for 2000 and 2001 in order to ensure that the Adv R&D goals are well matched to the Pre-construction R&D plan for 2002 through 2005
  - » that the laboratory be authorized to prepare a complete proposal for the LIGO II Project, including cost and schedule before the end of 2000
  - » that meaningful LIGO I data analyses results be in hand prior to turn off of the LIGO I observing system"

# Advanced LIGO Program Assumption

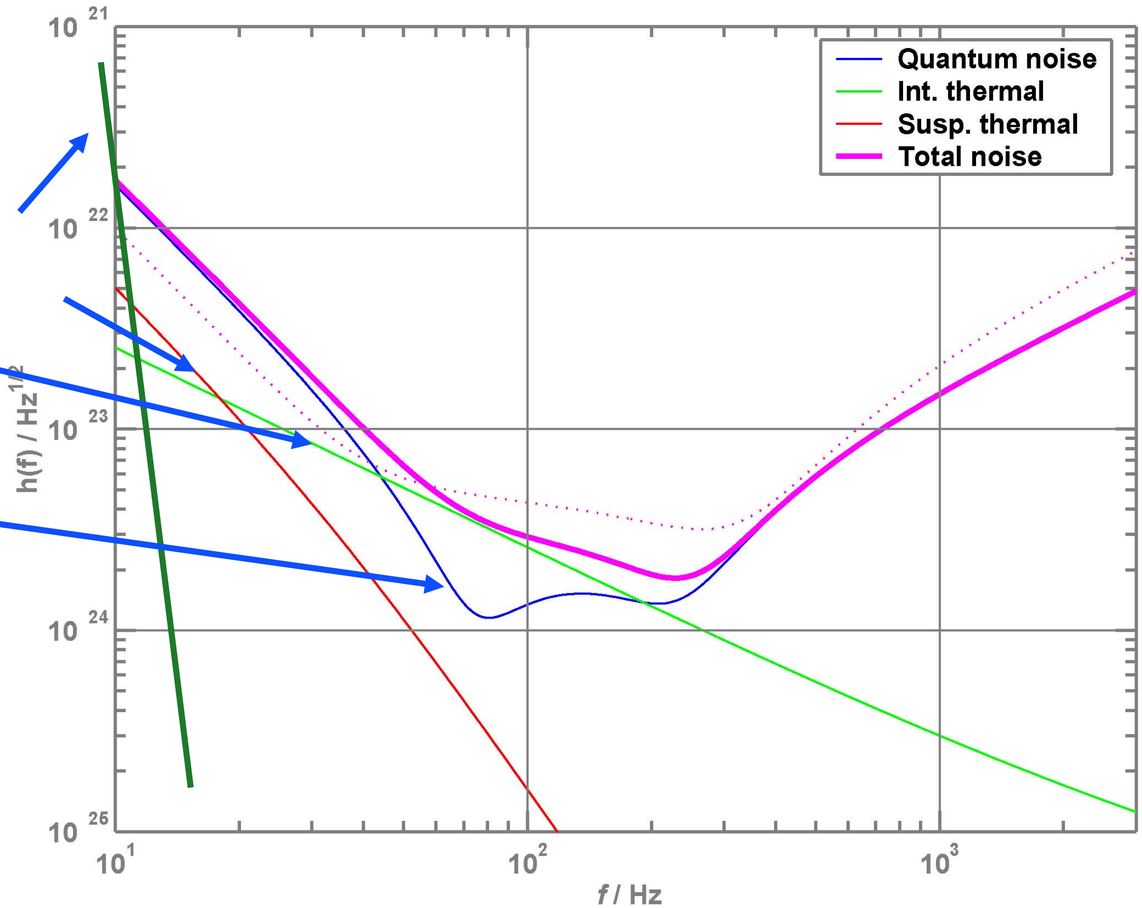
- R&D in progress now
  - » major equipment expenditures in 2001, 2002-2004
- R&D is substantially completed in 2004
  - » some tests are completed in 2005
- Construction funds will be requested for 2004 start
  - » some long lead purchases occur as early as 2003
  - » assembly outside vacuum system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

# The Advanced LIGO Detector concept

- Fabry-Perot Michelson interferometers
- Power recycling AND signal recycling
- 180 W Nd:YAG laser
- possible sapphire core optics
- much better isolation through the use of a fully active seismic isolation system, and a multiple pendulum suspension with silica suspension fibers
- …Estimate that 2.5 hours of operation of Advanced LIGO will be equivalent in observation ‘reach’ to the entire initial LIGO data run

# Anatomy of the projected detector performance

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



# R&D Challenges
## (Quotes from January NSF Review Report)

» Advanced LIGO will require a level of **control system complexity** that considerably exceeds that required for initial LIGO. Recent locking of the Michelson Fabry-Perot 2–km detector at Hanford represents a significant demonstration of a multi-dimensional control system, and builds confidence in the ability of the LIGO team to deal with its even more complex design challenge in advanced LIGO.

» A critical path item for advanced LIGO is a set of **new optics**. Advanced LIGO requires increased size of the test masses, dealing with the absorptivity of optical coatings, and better mechanical Q optimization of the mirrors. This part of the R&D program will require new partnerships with vendors. The availability of increased expertise for the LIGO program, especially in optical materials and system integration in the optics area, is crucial to the success of this effort.

# R&D Challenges
## (Quotes from January NSF Review Report)

» The requirement for stable, single-mode, **80 - 180 W lasers** for advanced LIGO represents a significant challenge to the state-of-the-art. Attention should be given to the tradeoffs between a potentially more reliable but lower power laser system (or a phased-locked ensemble of lower power laser systems), and the potentially increased high-frequency performance of the detector at higher power.

» Higher average power on the input optics of advanced LIGO presents a challenge to the current technology of crystal **modulators and isolators**. An aggressive testing program will be required to understand the limitations and  potential of these important optical elements.

# R&D Challenges
## (Quotes from January NSF Review Report)

» **Forces exerted on the mirrors due to the higher average power** stored in advanced LIGO cavities may introduce alignment instabilities. The planned inclusion of these effects in the end-to-end model and the planned testing program are essential elements of the program.

» Success of advanced LIGO will be (in part) measured by its uptime. The **reliability of the in-vacuum components** (such as the active seismic isolation system) is crucial, and design for reliability should be kept at the forefront of the R&D effort.

» **Suspension of test masses by [fused silica] ribbons** represents a novel solution to test mass suspension noise. However, effects such as creep (leading to potential excess noise) in the expected load regime, should be carefully evaluated.

# R&D Program Approach to Risk Reduction

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

# The R&D Program Budget

- Most work supports Advanced LIGO realization, both science ('R&D') and engineering ('Ops')
- Some far reaching research
- All work highly collaborative, coordinated with and supportive of the LSC at large
- Three budgetary elements, each with a distinct role:

1) Research and Development activities *per se*
2) Engineering, infrastructure, and some senior effort supported from Lab Operations
3) Big ticket equipment items for LSC program in Lab proposal

# 1) R&D Effort: Subsystem science
## (snapshot 2002)

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

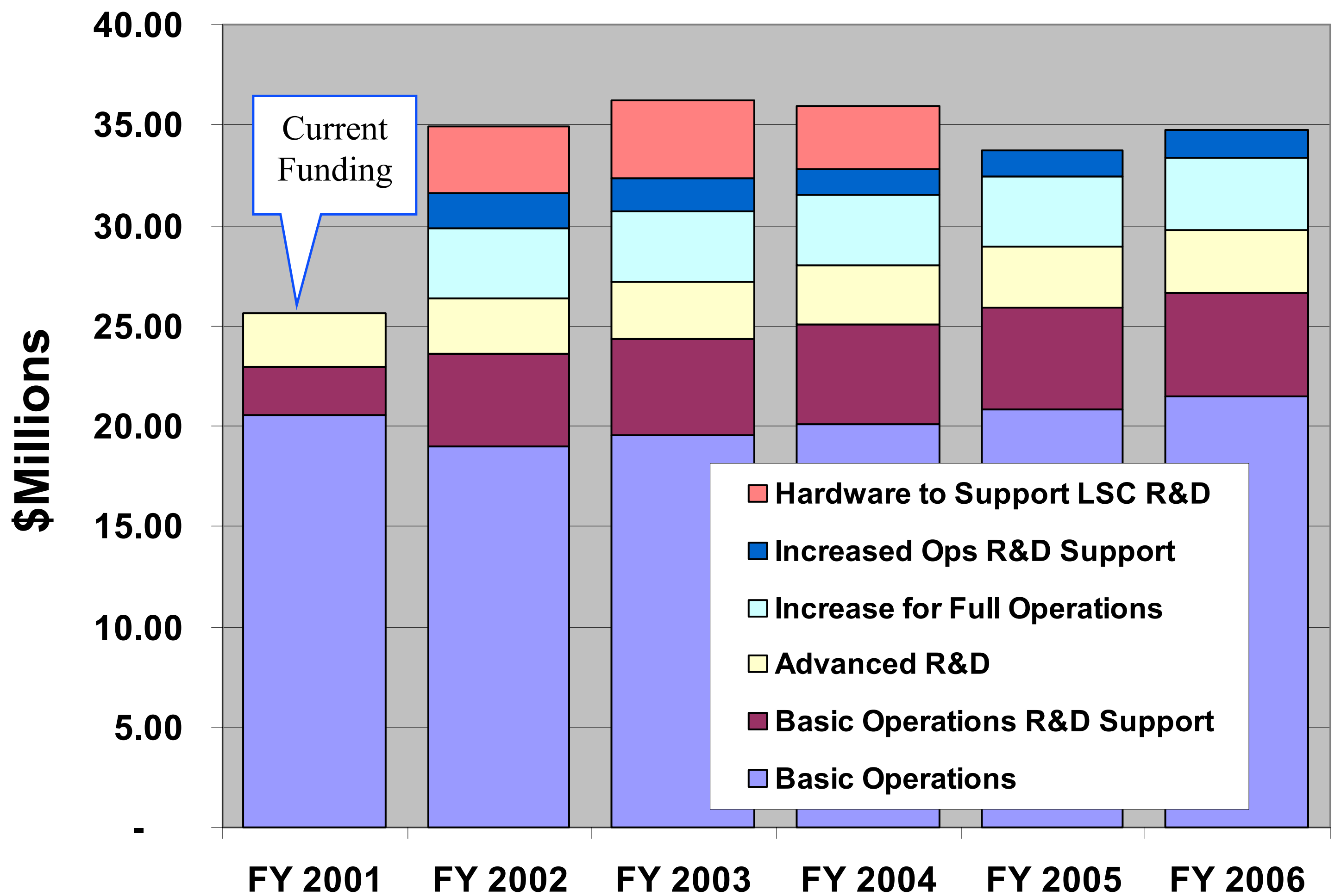
# 2) Increased Staffing in Ops to Support R&D and Modeling

- Increased staff in the Technical and Engineering Support and Detector Support Groups to perform Advanced LIGO R&D engineering  $921k
- Increment for engineering and technician labor (4 FTEs) in Livingston to support the Seismic Isolation LSC team (2 years, non-recurring) $506k
- Increased staff for Modeling and Simulation (end-to-end model) $282k

# 3) R&D Equipment in Support of LSC Research Program

- Equipment costs for the development of advanced seismic isolation prototypes. $934k
- Equipment costs for the development of multiple pendulum, fused silica fiber suspension prototypes. $2,257k
- Materials and manufacturing subcontracts to support the development of sapphire test masses and high Q test mass materials and coatings research. 5,585k
- Investment and non-recurring engineering costs for a large coating chamber and its commissioning. $1,500k
  - » study of coating strategy in progress

# LIGO Budget Proposal…




FY 2001 funding normalized to 12 months shown for comparison

# …LIGO Budget Proposal

| | 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.

# Isolation Research

(STO, SUS, TNI, SEI)

FY02

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

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

# Lasers & Optics Research

(LAS, OPT, IOS, AOS)

FY02

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

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

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

FY02

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

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

# Total LIGO Laboratory R&D

FY02

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

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

# …Advanced LIGO Chronology

- The proposal under review lays the path for installing advanced interferometers beginning in early 2006
  - » when LIGO Science Run I is producing published results
  - » Coordinated shutdowns with other detectors worldwide

Commissioning, then observation, starting in 2007-2008

# R&D for Advanced LIGO
## (Quotes from January NSF Review Report)

- The proposal for research and development regarding an advanced LIGO detector contains a set of **significant technical challenges** that, if met, will provide a design for a gravitational wave detector that should be **capable of yielding extremely exciting science**.

- We believe that the **LIGO Laboratory, in consort with the LSC, is capable of carrying out, and is ready to carry out, the R&D program** described in the proposal.

# R&D for Advanced LIGO
## (Quotes from January NSF Review Report)

- The review panel finds that the proposed **balance between operation of initial LIGO and R&D on advanced LIGO**, as described during the review, is **appropriate for optimizing the probability of programmatic success**.

- The Panel did not validate budgetary items in detail. However, the Panel notes that **the total request, the continuity** of the funding request, the clarification of R&D costs actually contained within "operations manpower," **and the proposed balance between operation of initial LIGO and R&D on advanced LIGO** as described during the review, seem appropriate for **optimizing the probability of programmatic success**.