LIGO Overview

Gary H Sanders

NSF Review of Advanced LIGO

Caltech, June 11, 2003

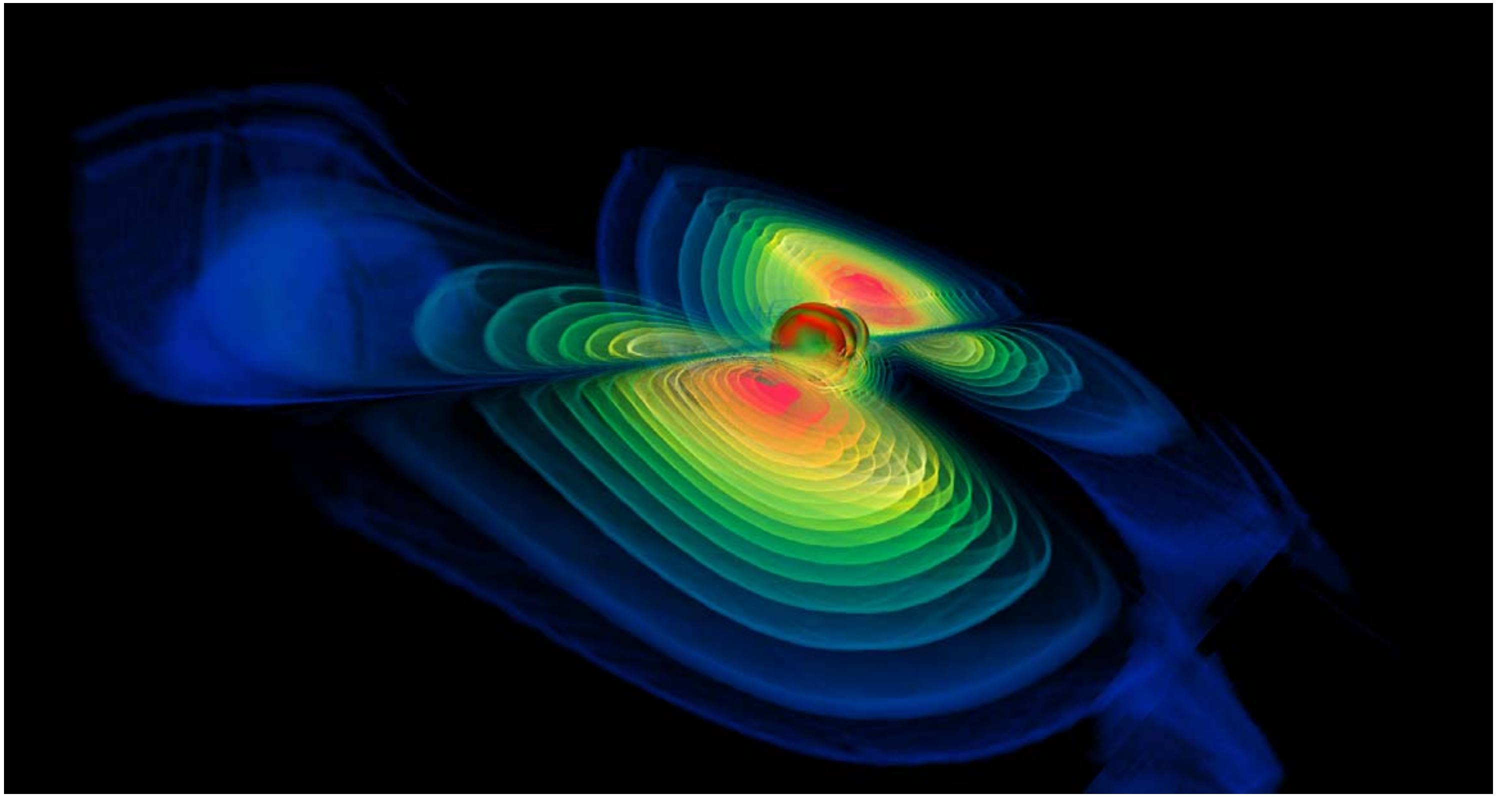
This talk

- 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

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

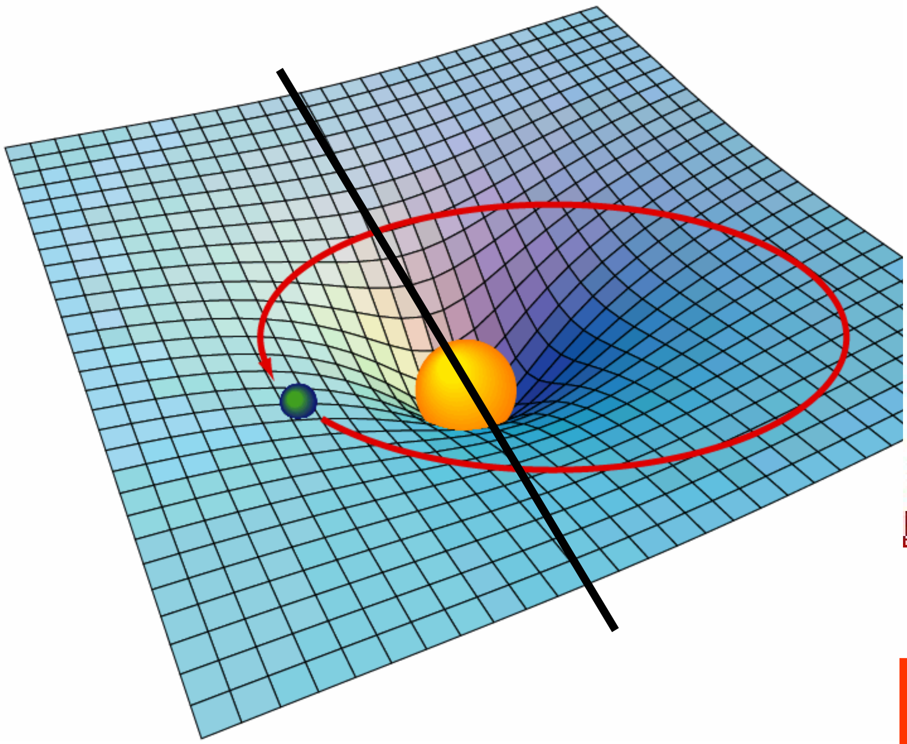
LIGO Overview

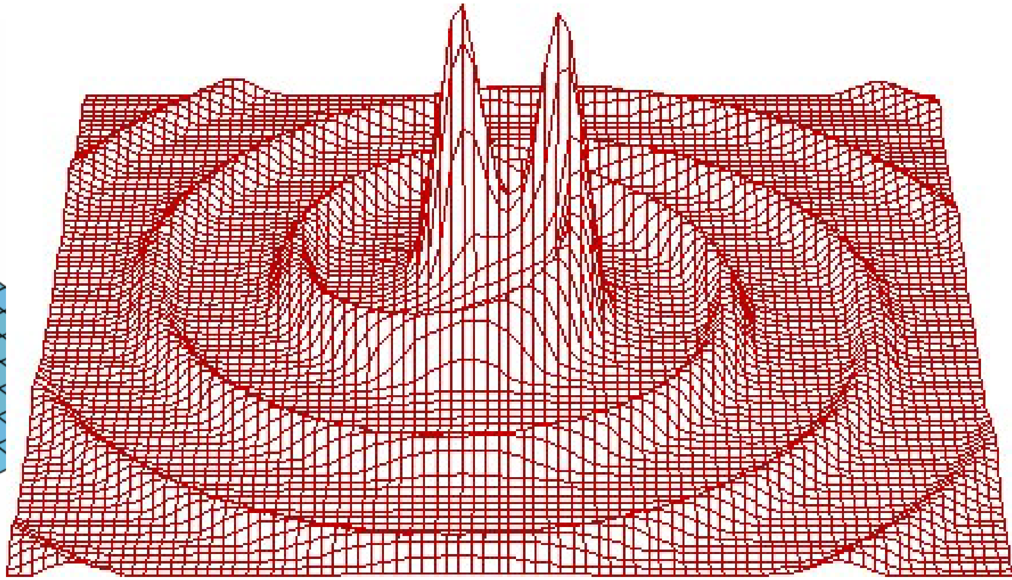


"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)

Gravity as a "Strain" of Flat Space-Time



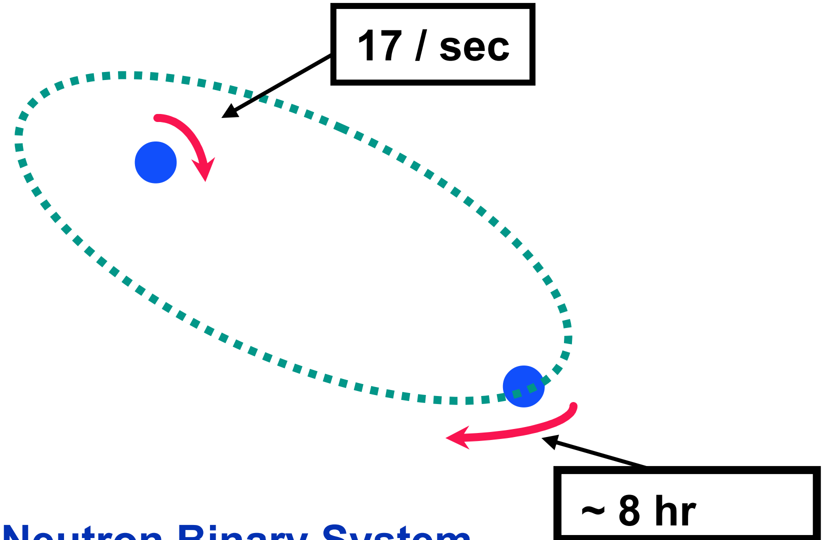


gravitational radiation from binary inspiral of compact objects

Evidence for Gravitational Waves

<u>Neutron Binary System – Hulse & Taylor</u>

PSR 1913 + 16 -- Timing of pulsars



<u>Neutron Binary System</u>

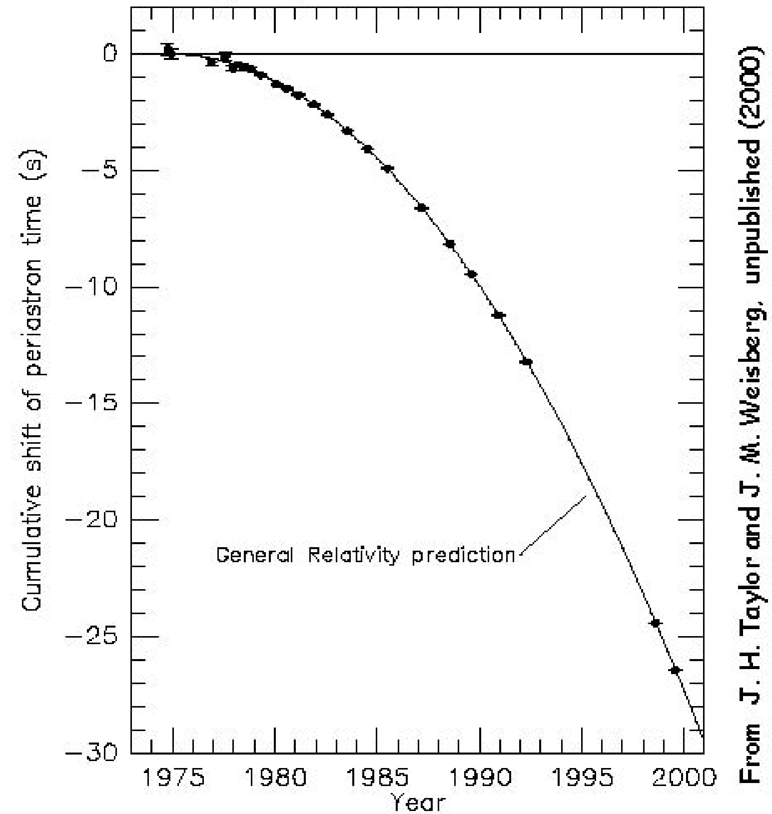
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

<u>Prediction from general relativity</u>

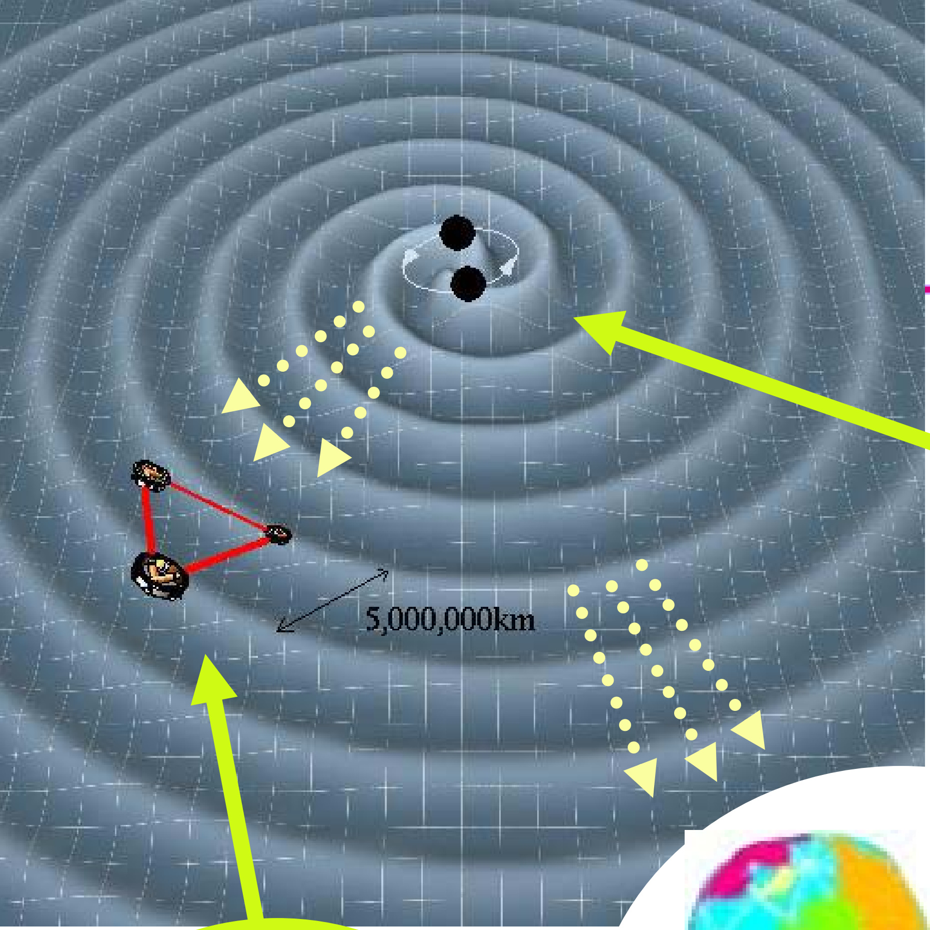
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

<u>Emission of gravitational waves</u>

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



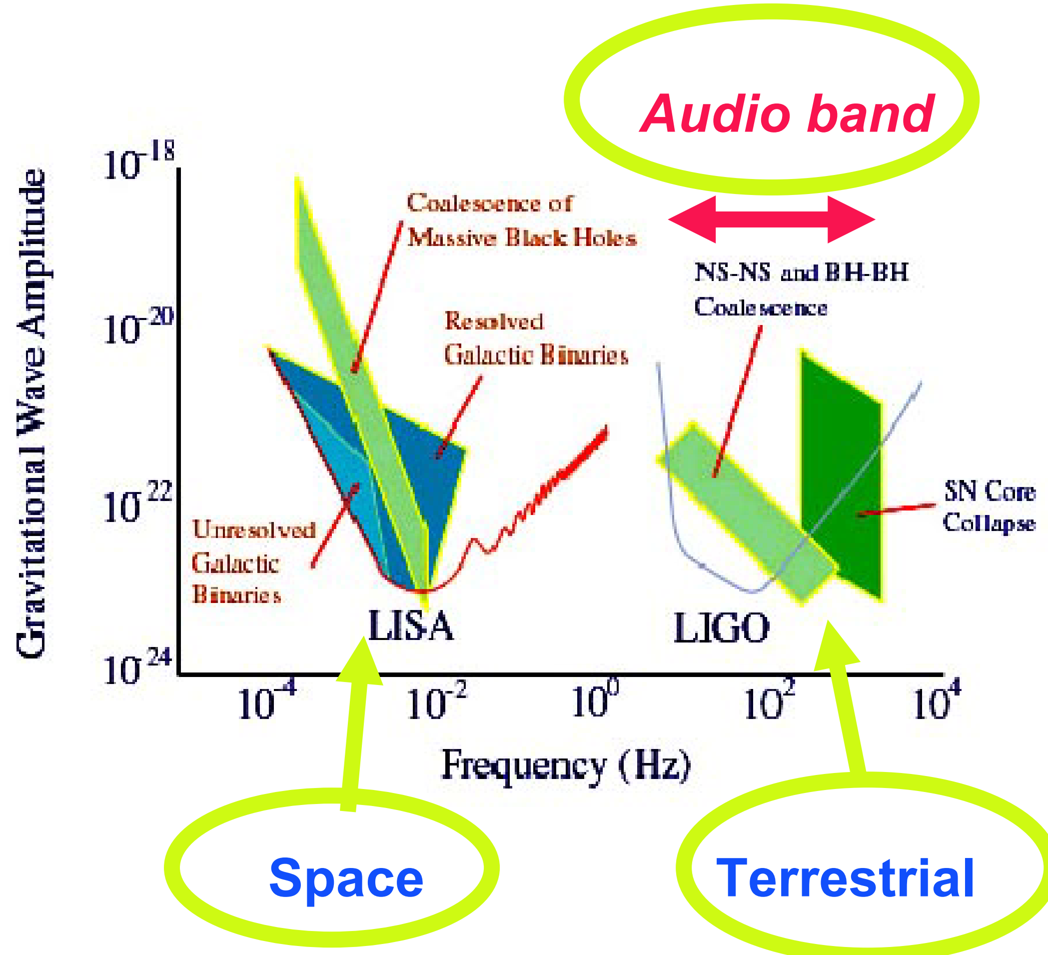
Gravitational Wave Astrophysical Source

Detectors in space
LISA

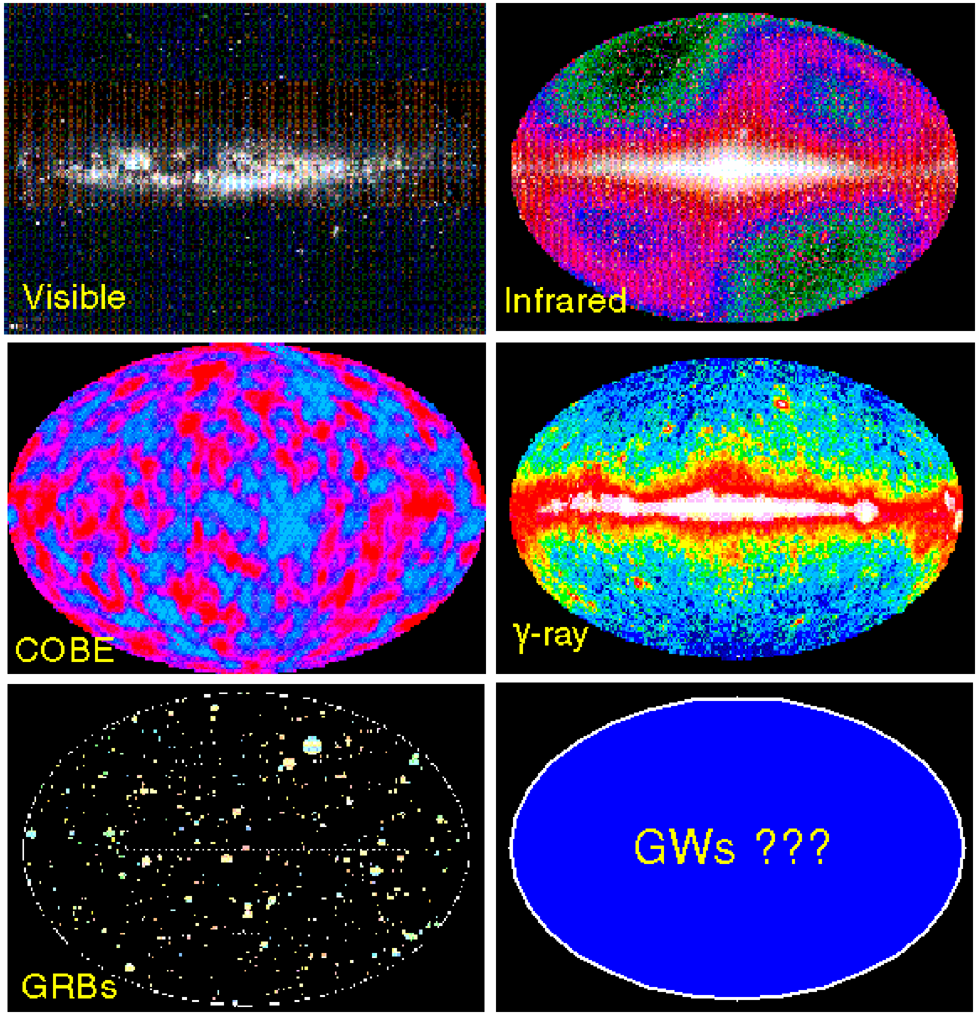
Terrestrial detectors
LIGO, GEO, TAMA, Virgo

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)



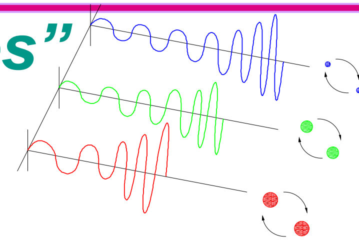
A New Window on the Universe



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

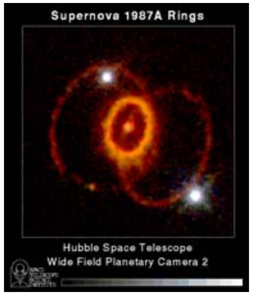
Astrophysical Sources of Gravitational Waves

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

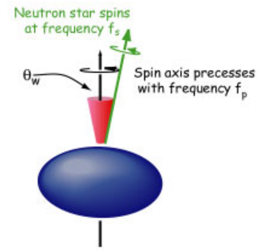


Thorne

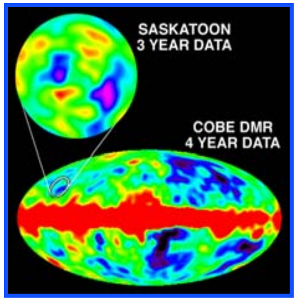
- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » Challenge to search for untriggered bursts



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

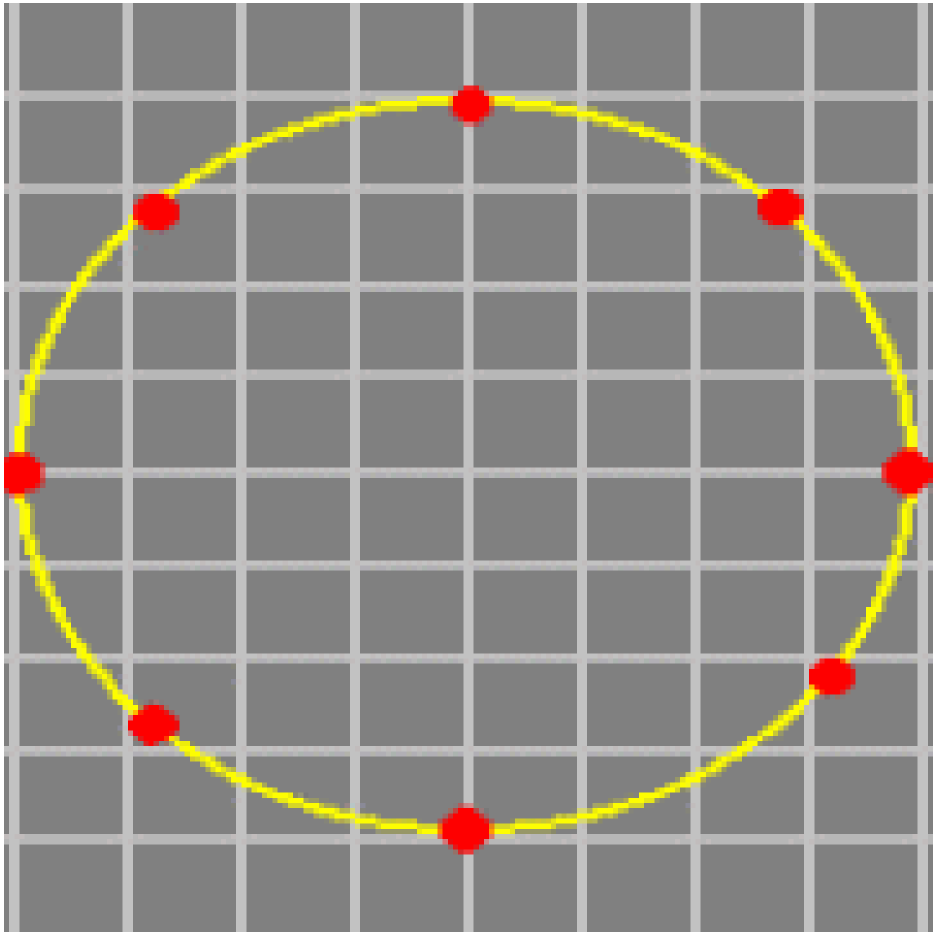


- Cosmological Signals *"stochastic background"*



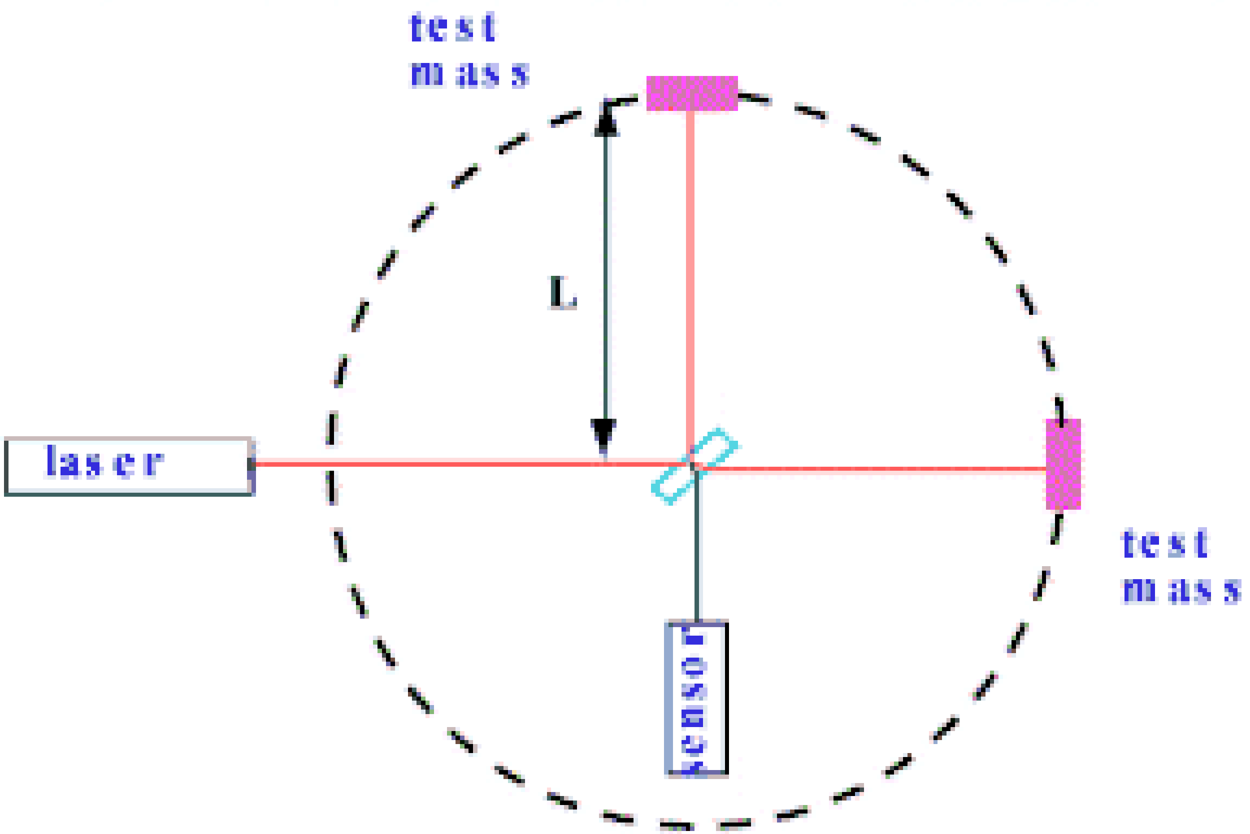
Detecting a passing wave ….

Free masses



Detecting a passing wave ….

Interferometer

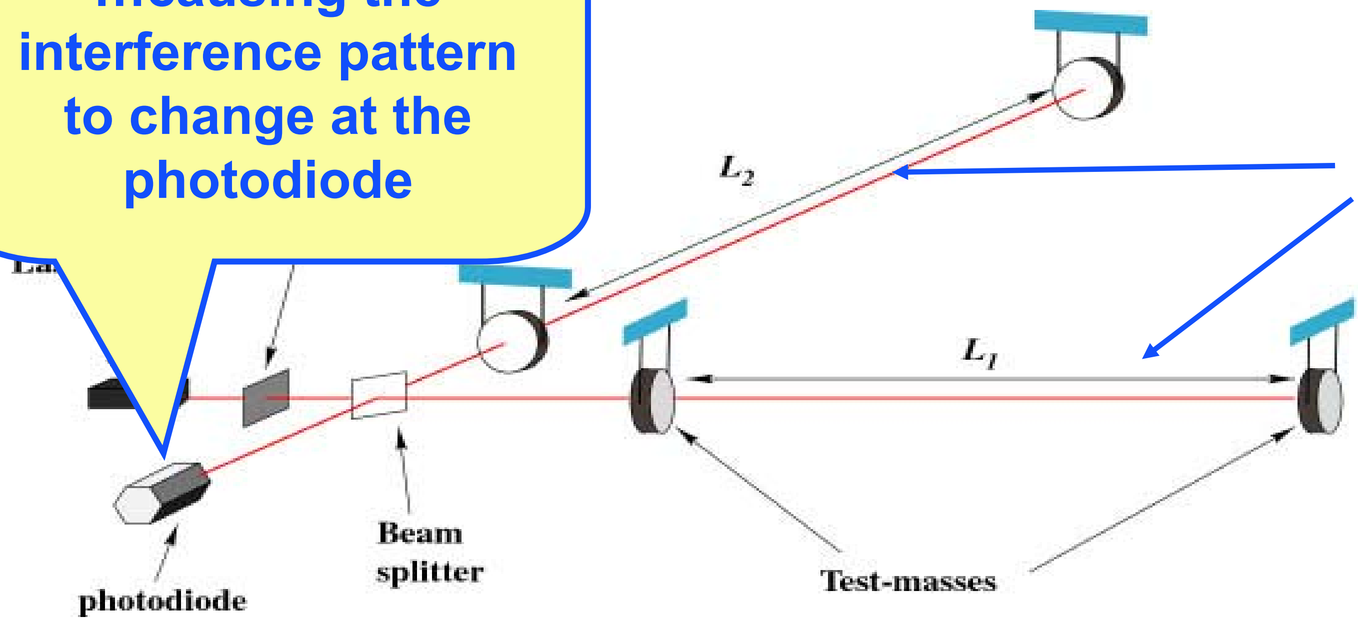


Interferometer Concept

- 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***

…causing the interference pattern to change at the photodiode

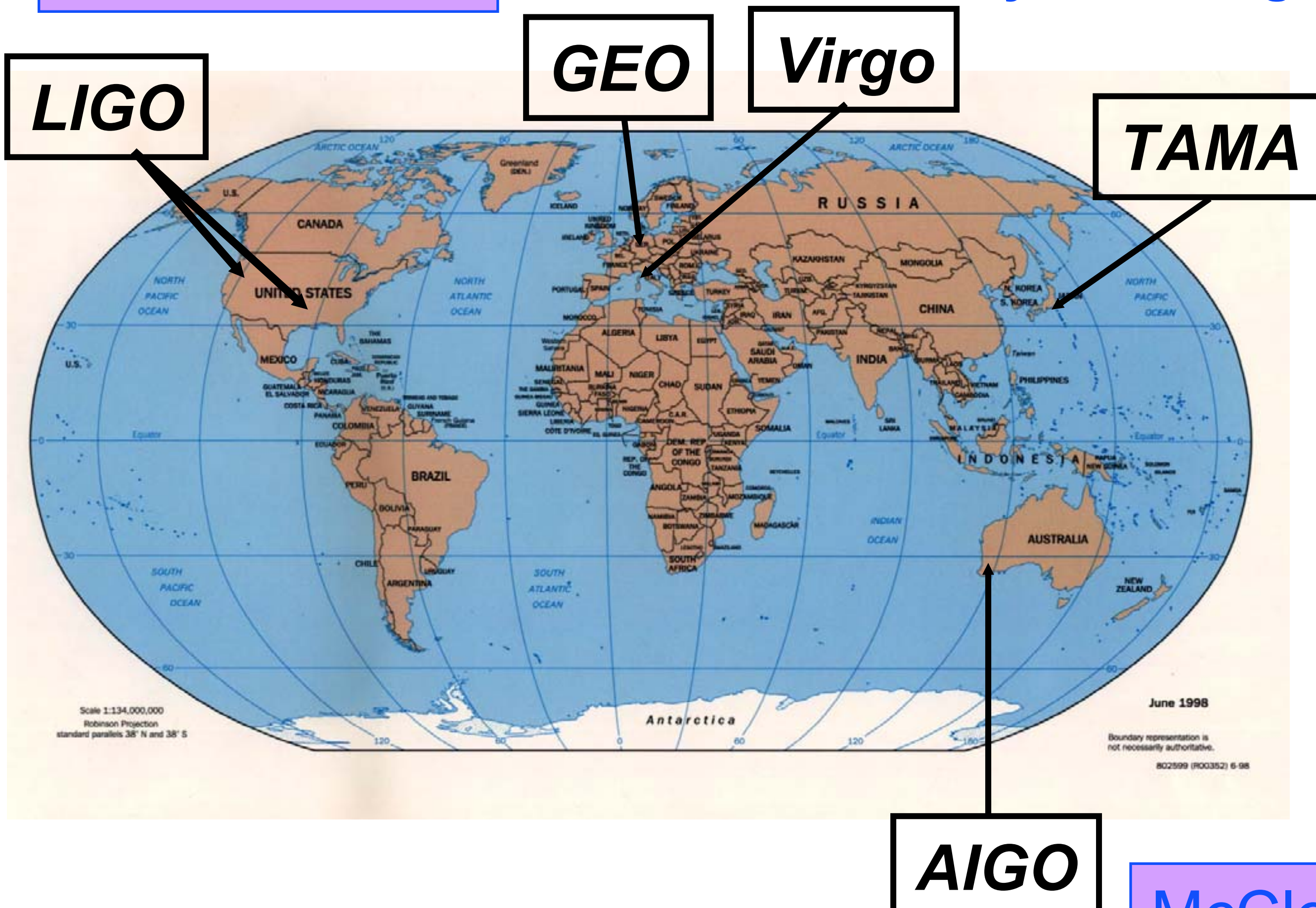


As a wave passes, the arm lengths change in different ways….

An International Network of Interferometers

Hough, Willke

Simultaneously detect signal (within msec)



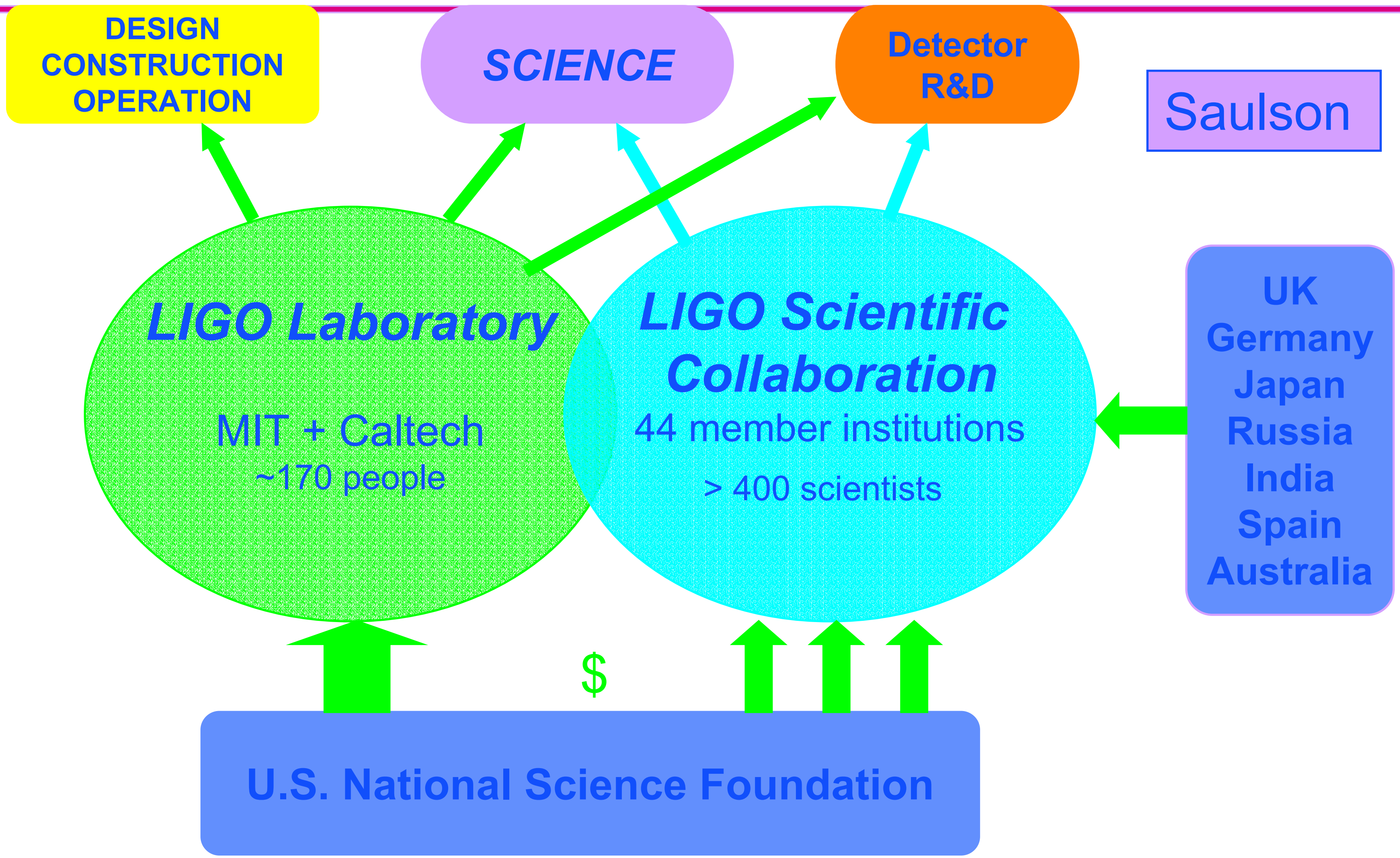
detection confidence

locate the sources

decompose the polarization of gravitational waves

McClelland

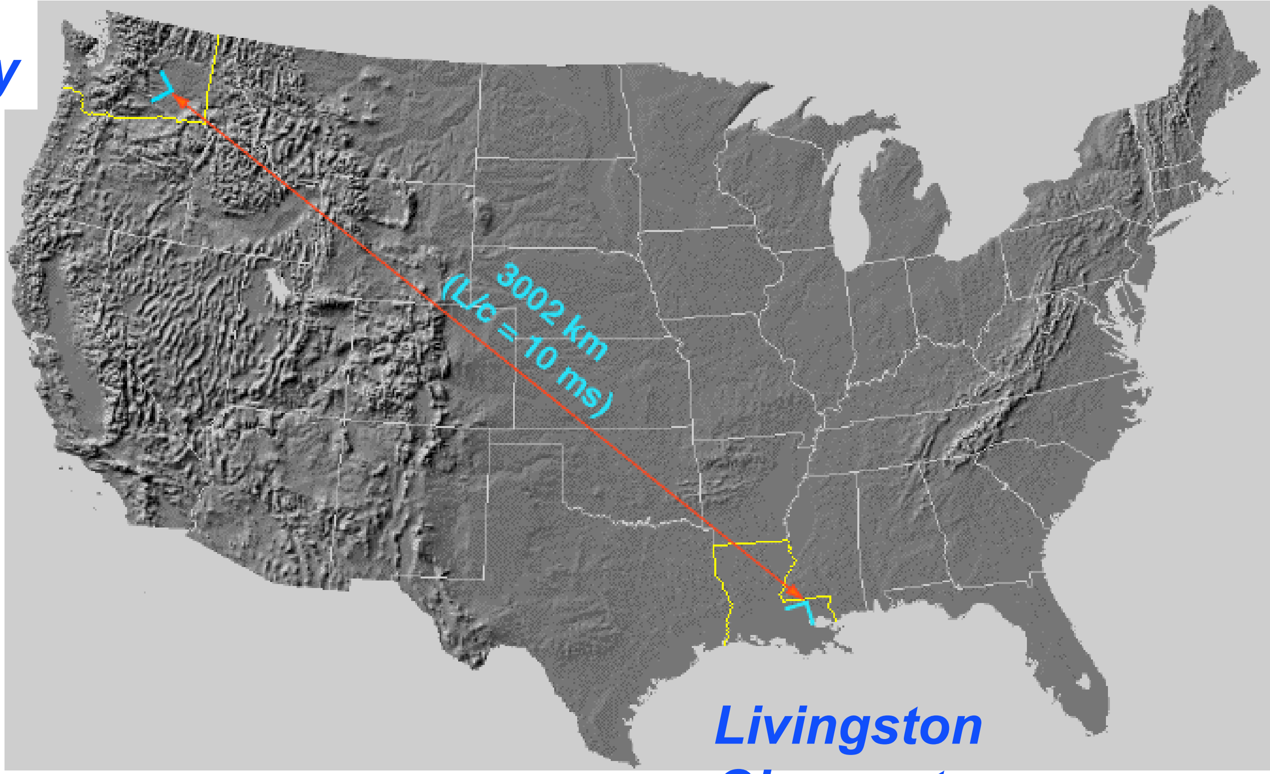
LIGO Organization & Support



The Laboratory Sites

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford Observatory

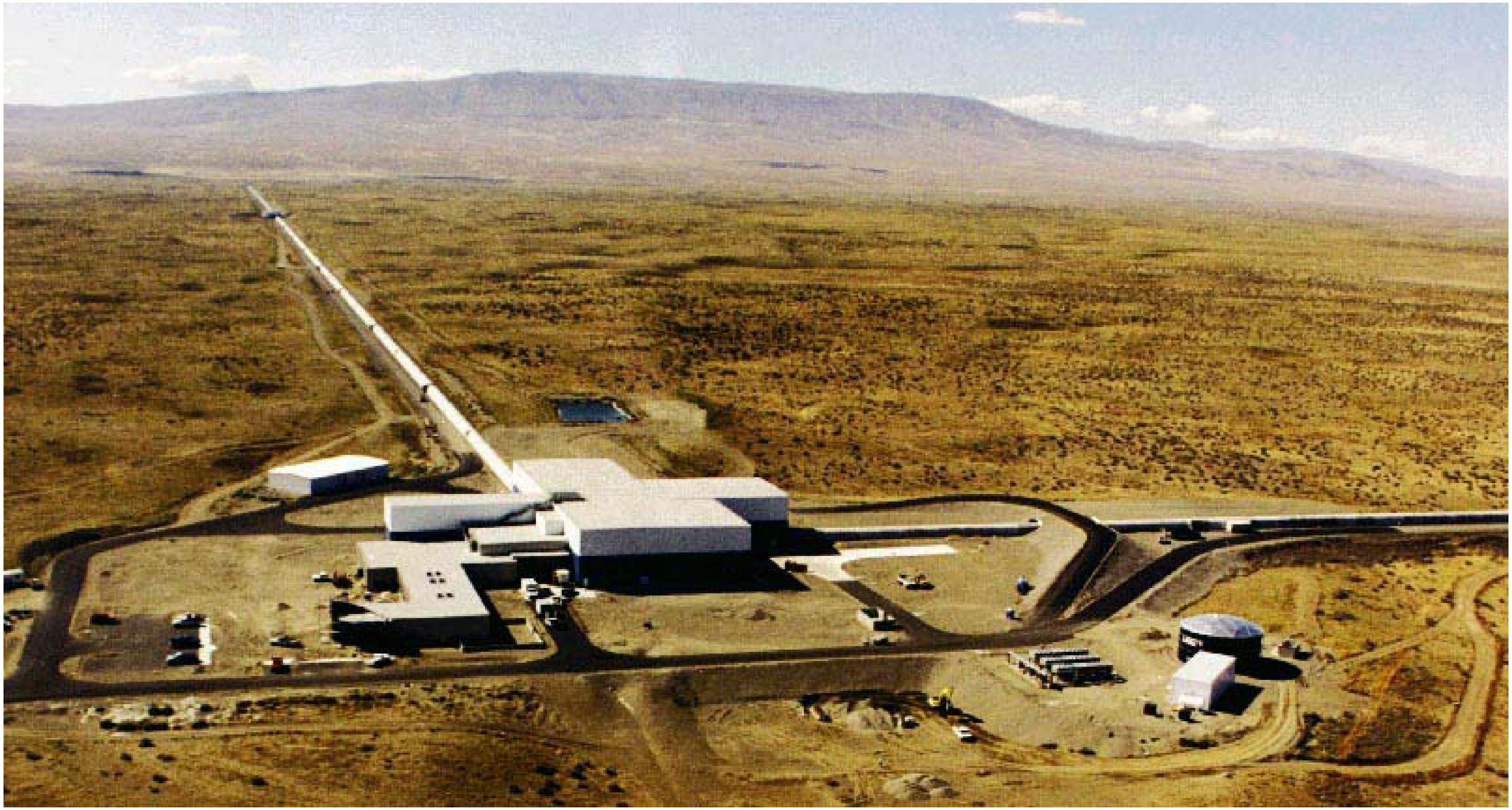


Livingston Observatory

LIGO

LIGO Livingston Observatory

LIGO Hanford Observatory



GEO 600

Hough, Willke

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

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

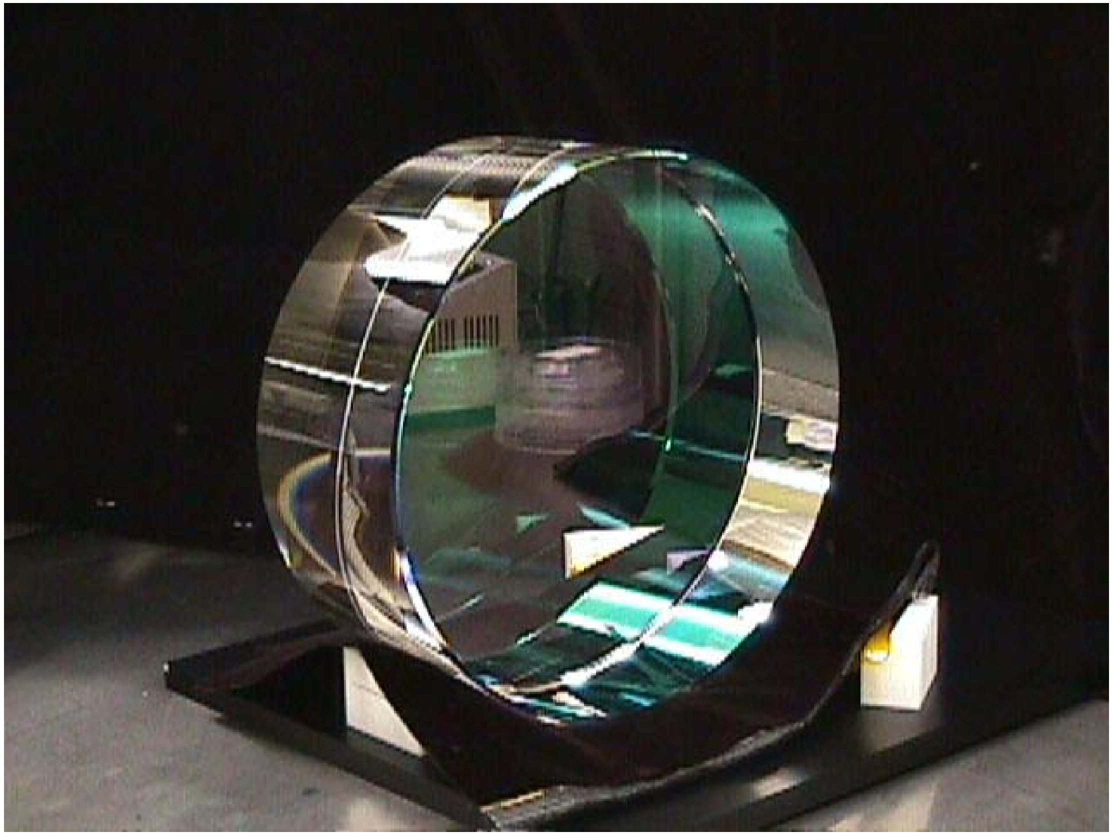
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption < 0.5 ppm

Uniformity <10^{-3}



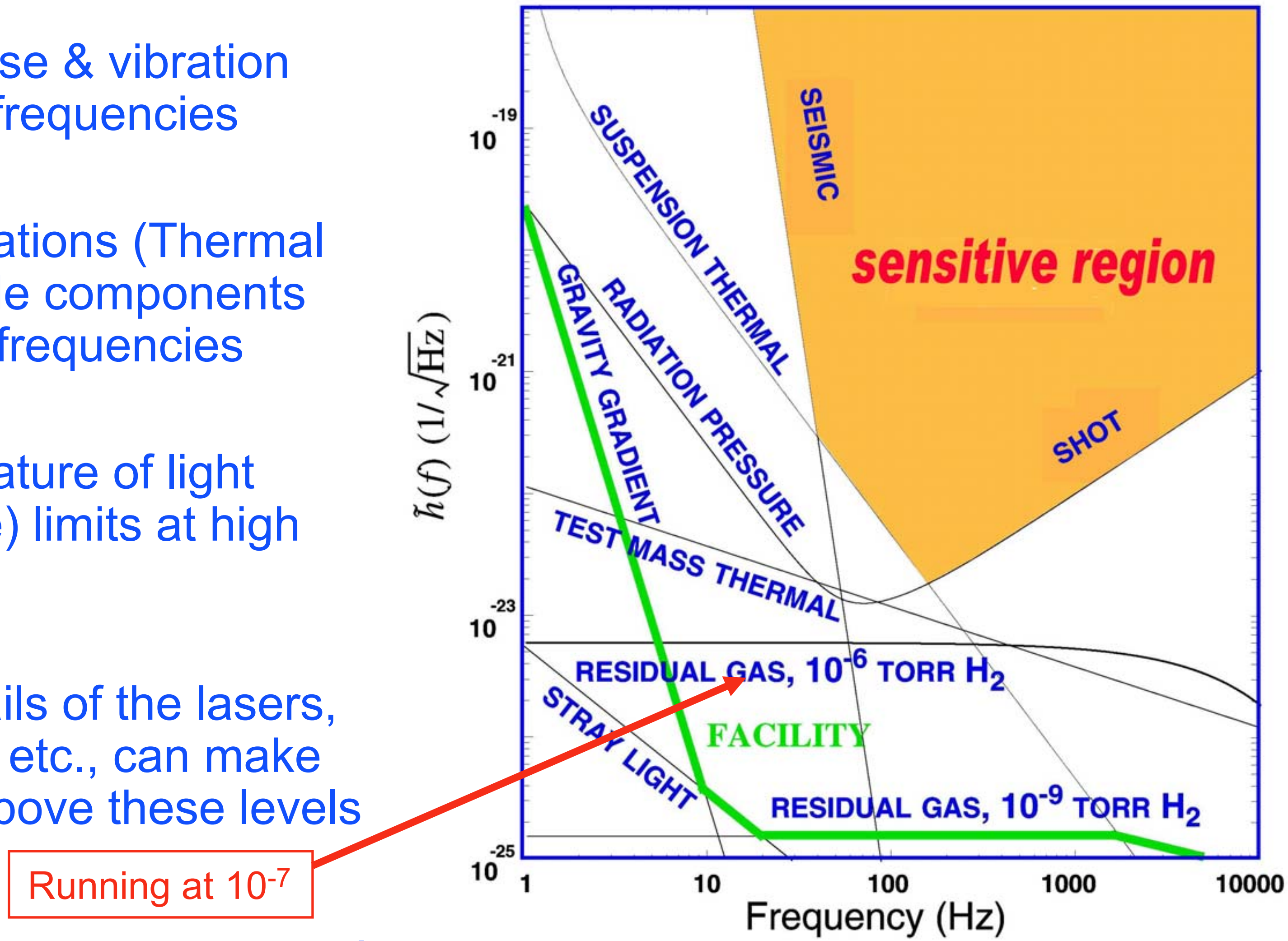
Core Optics

installation and alignment

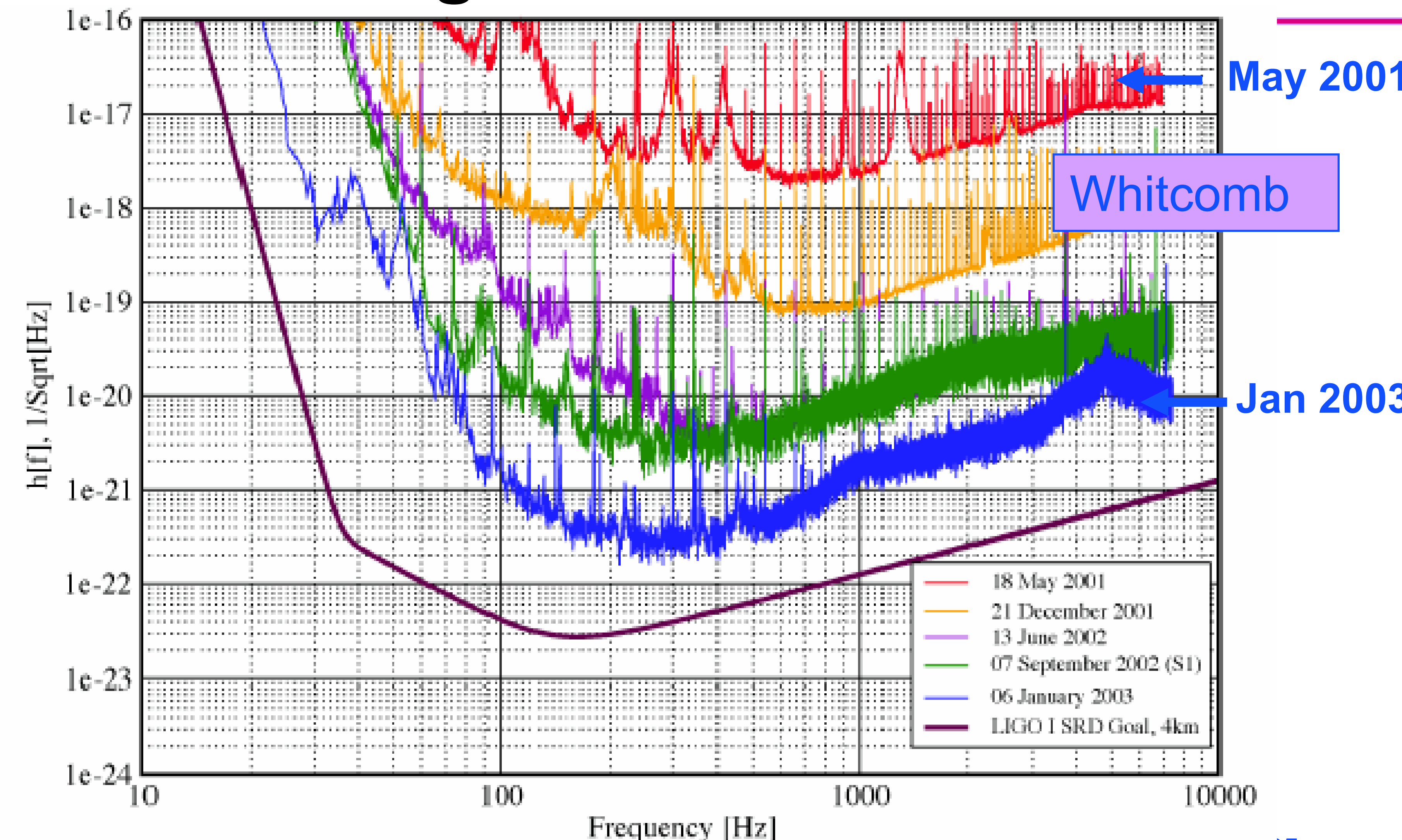
LIGO team now expert in this very demanding work

What Limits Sensitivity of Interferometers?

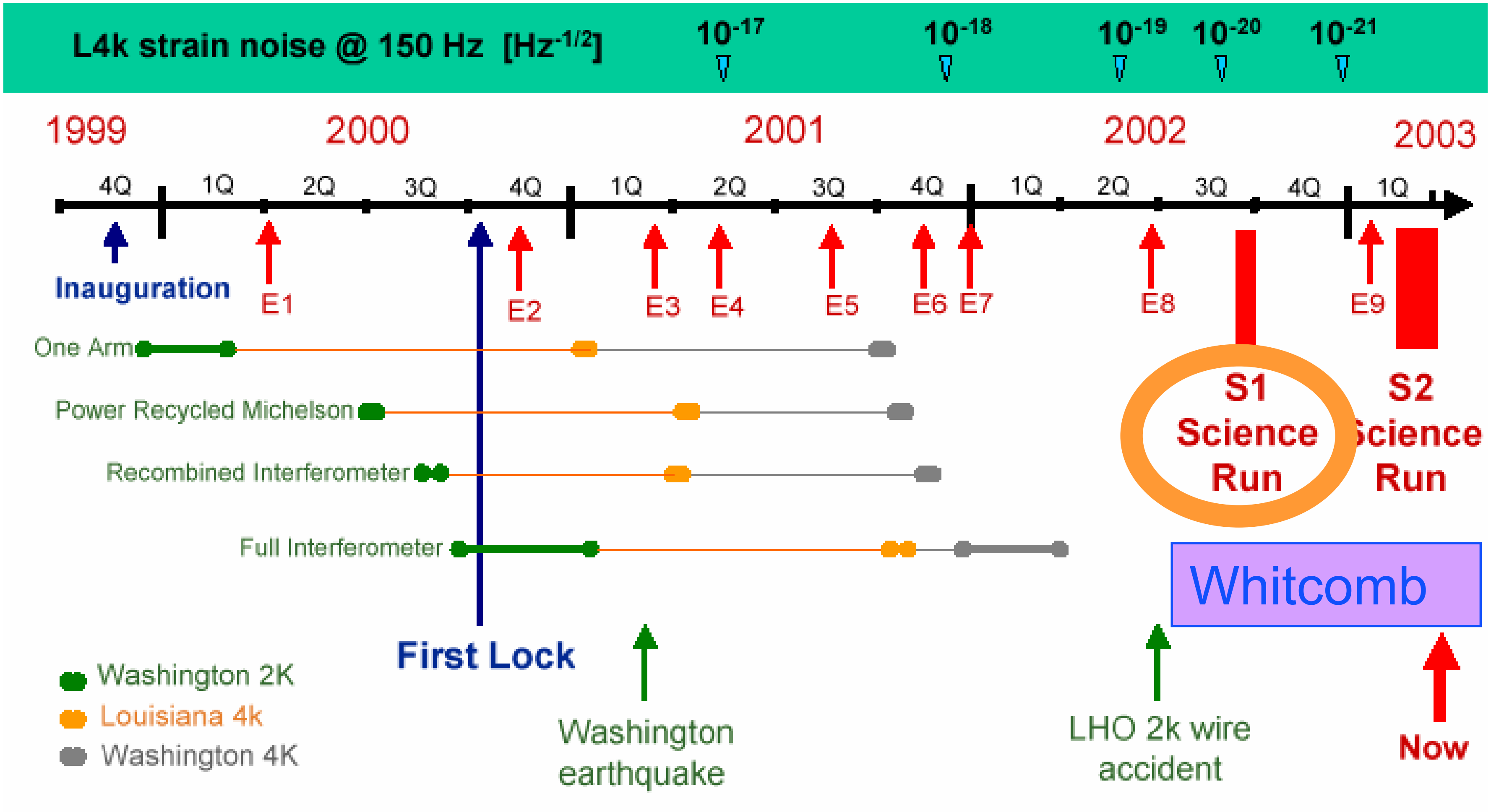
- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



LIGO Sensitivity
Livingston 4km Interferometer



Commissioning and the First Science Runs



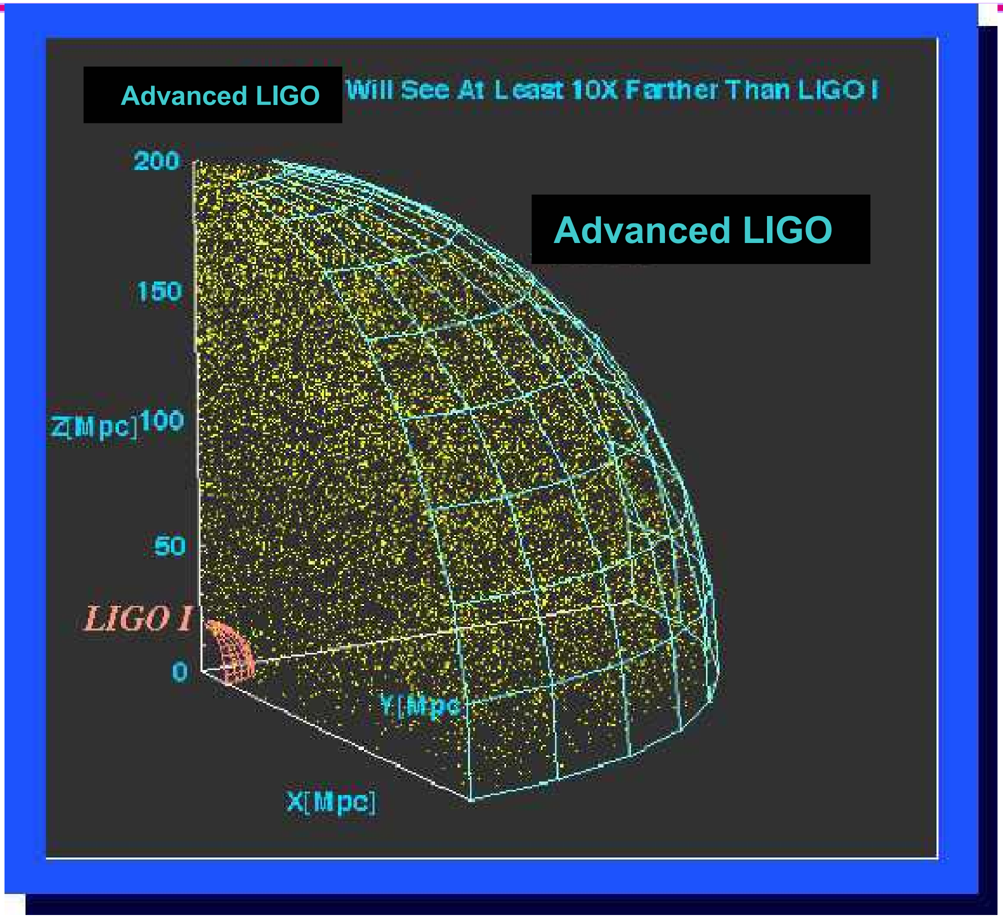
LIGO Plans

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	

LIGO-G010036-00-M 6

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

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)** ✓
  - » GEO (Germany) - $11.5 million
  - » ACIGA - $2.5 million

Hough, Willke

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**

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.

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

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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

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?