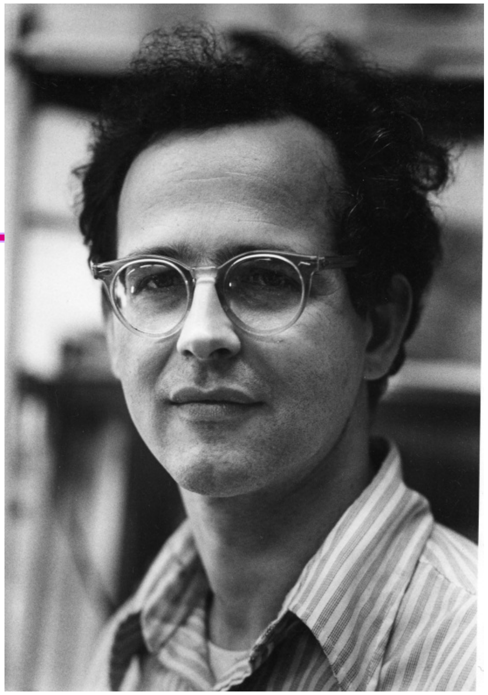
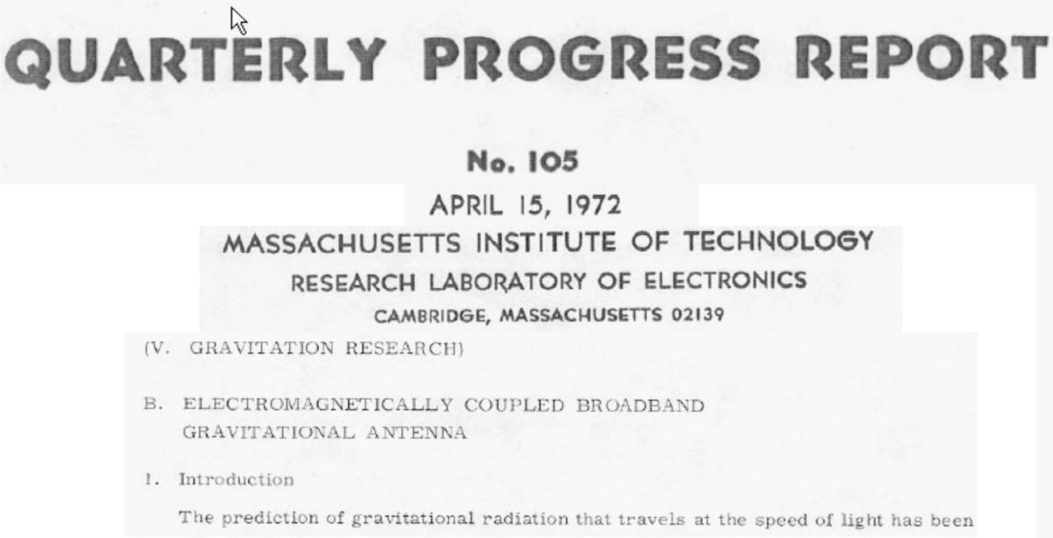
Advanced LIGO

David Shoemaker
For the LIGO Scientific Collaboration

In the beginning

- Rai Weiss of MIT was teaching a course on GR in the late '60s
- Wanted a good homework problem for the students
- Why not ask them to work out how to use laser interferometry to detect gravitational waves?
- …led to the instruction book we have been following ever since





QUARTERLY PROGRESS REPORT

No. 105

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

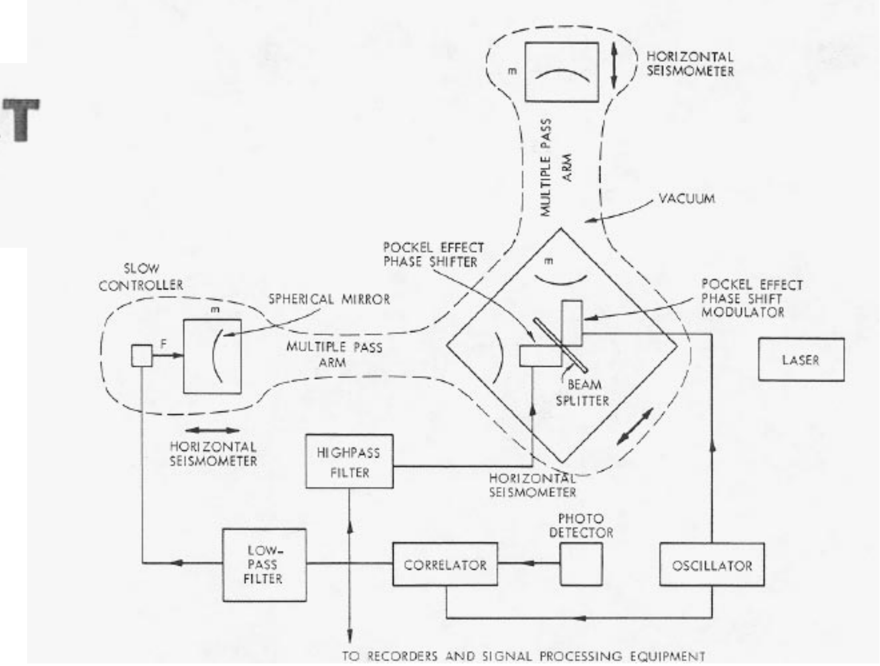
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

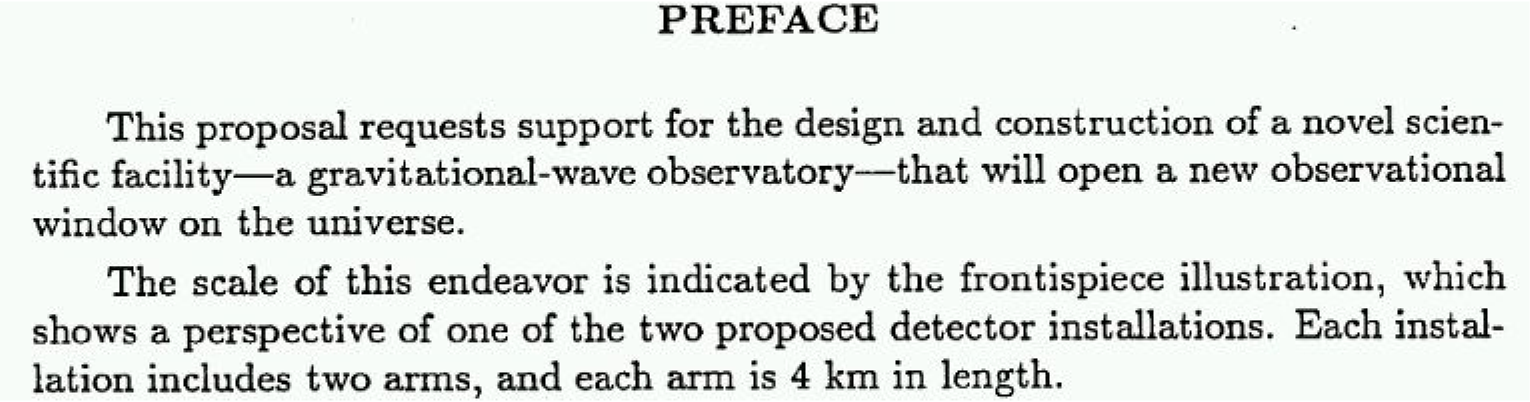
B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

The prediction of gravitational radiation that travels at the speed of light has been



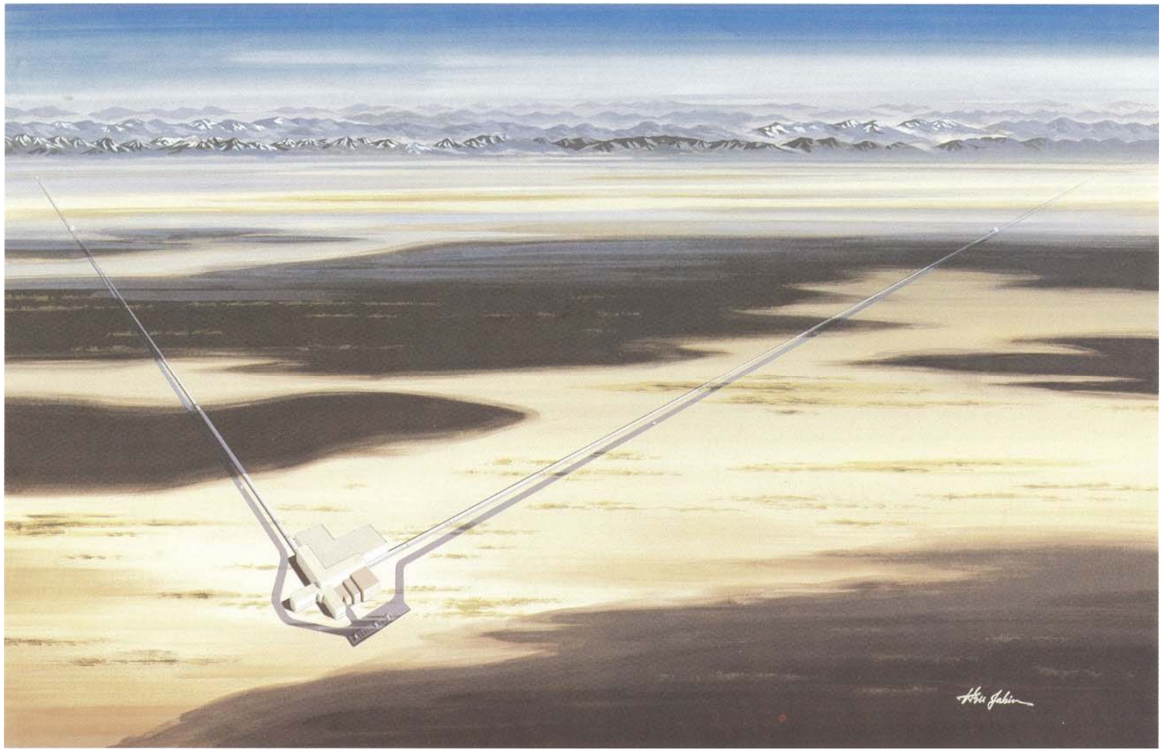
… led to LIGO:
1989 Proposal to the US NSF



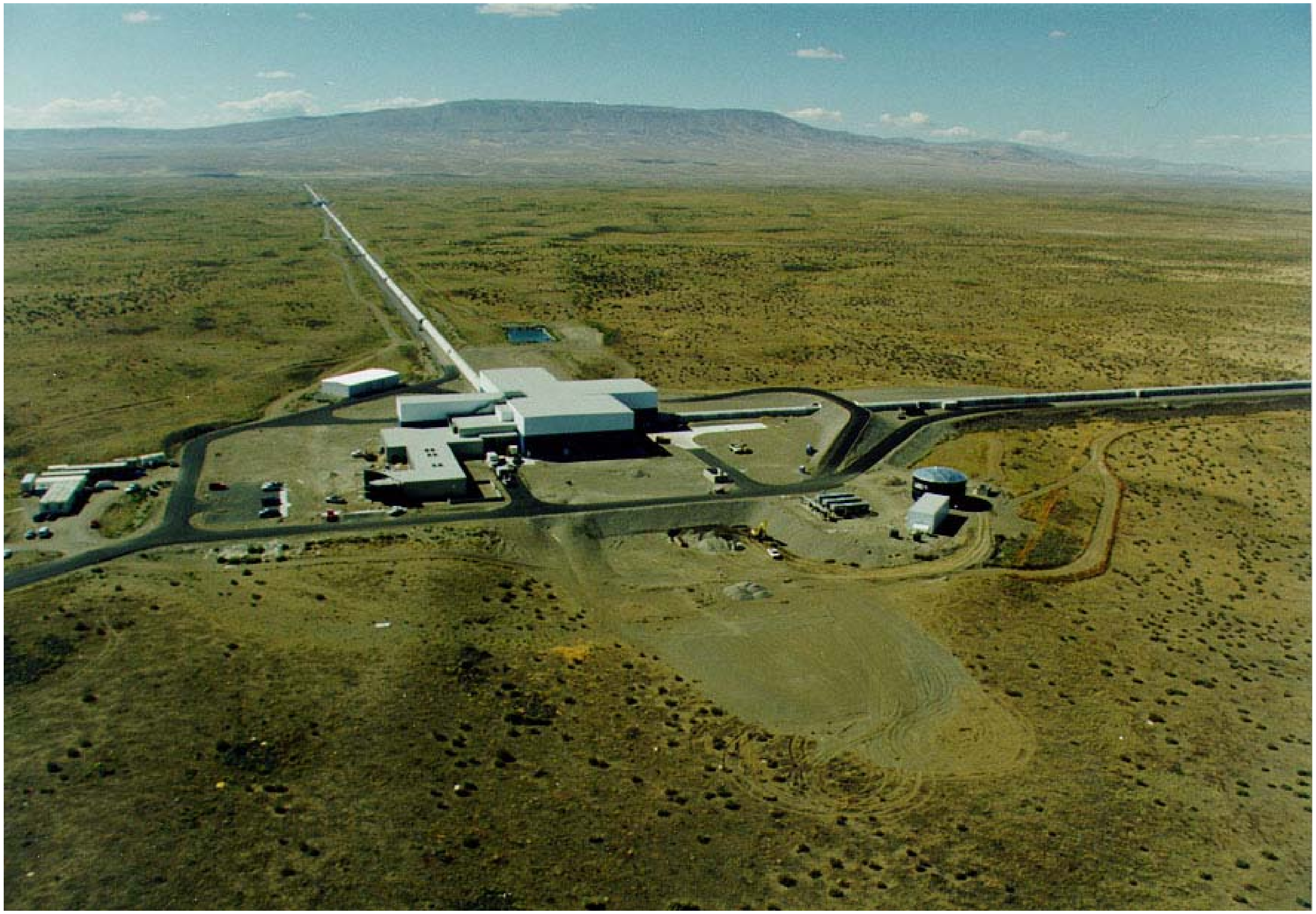
PREFACE

This proposal requests support for the design and construction of a novel scientific facility—a gravitational-wave observatory—that will open a new observational window on the universe.

The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.

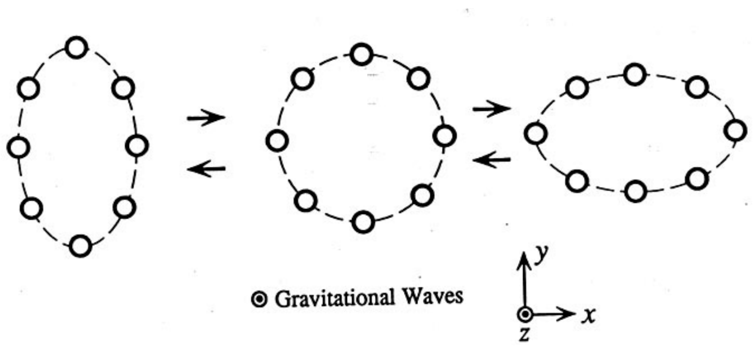


LIGO:
Today, Washington state…



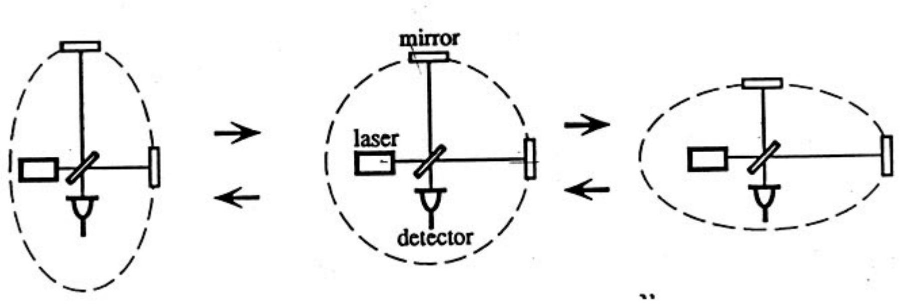
…LIGO in Louisiana

Gravitational Waves



Gravitational waves are perceived as quadrupolar distortions of distances between freely falling masses: “ripples in space-time”

Michelson-type interferometers can detect space-time distortions, measured in “strain” $h = \Delta L/L$.

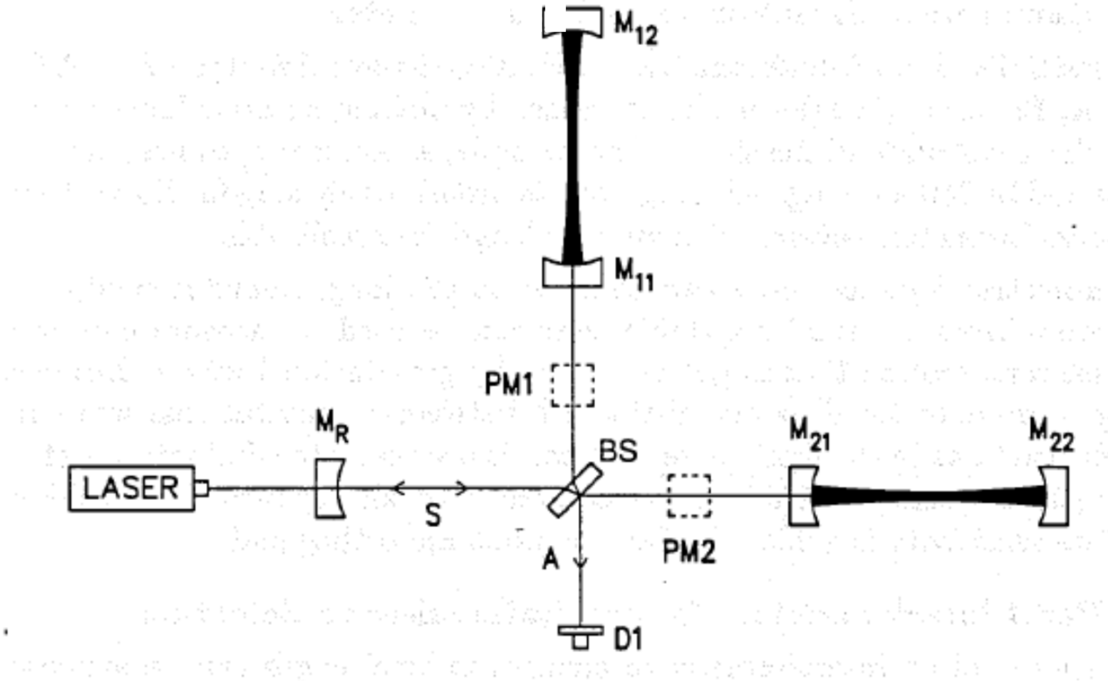


Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h = \sim L/L \sim 10^{-21}$

The Initial LIGO Detector, 1989 Proposal

Basic design notions:

1) Many noise sources are, or look like, mirror motions
2) λ_{GW} ~ 3000 km for ~100 Hz (a technically practical target frequency)
   → realistic antennas are in the short wavelength limit, and longer arms 'amplify' the GW signal, but not most noises
3) Arms can be 'folded' – like putting an inductor in a radio antenna
4) Fringe splitting precision ~ √Power (Poisson statistics)
   → higher laser power is better (…to a point)



The LIGO Detectors: limits and scaling laws

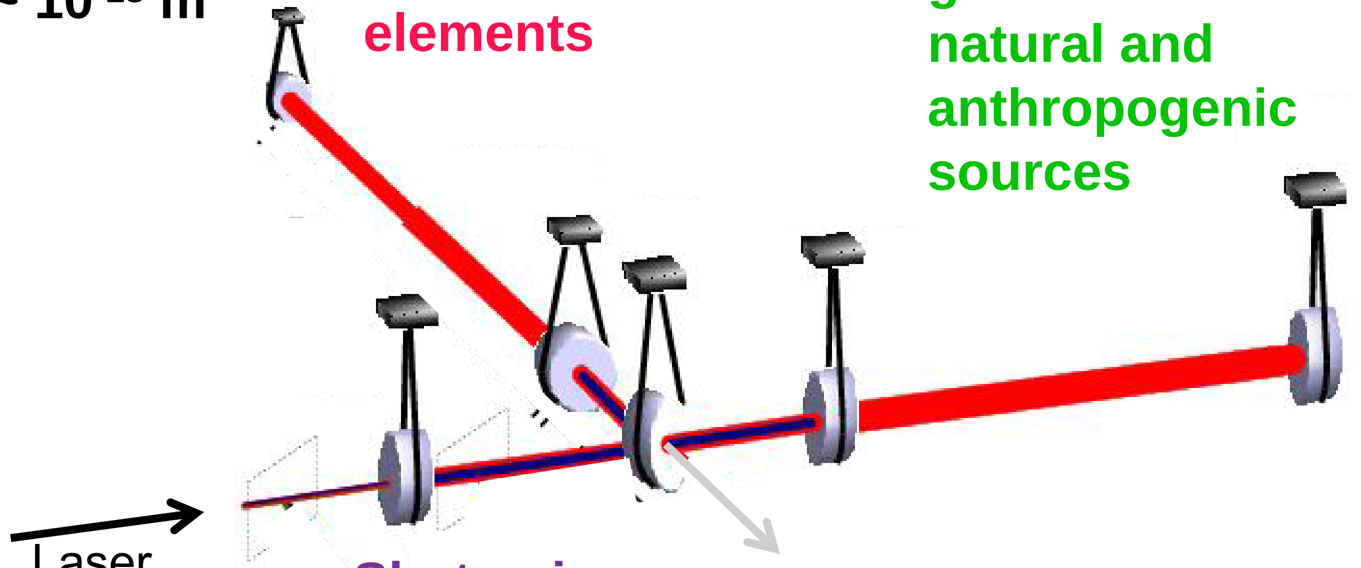
$h = \Delta L/L$

$L \sim 4$ km

We need $h \sim 10^{-21}$

We have $L \sim 4$ km

We see $\Delta L \sim 10^{-18}$ m



Thermal noise -- vibrations due to kT of mechanical elements

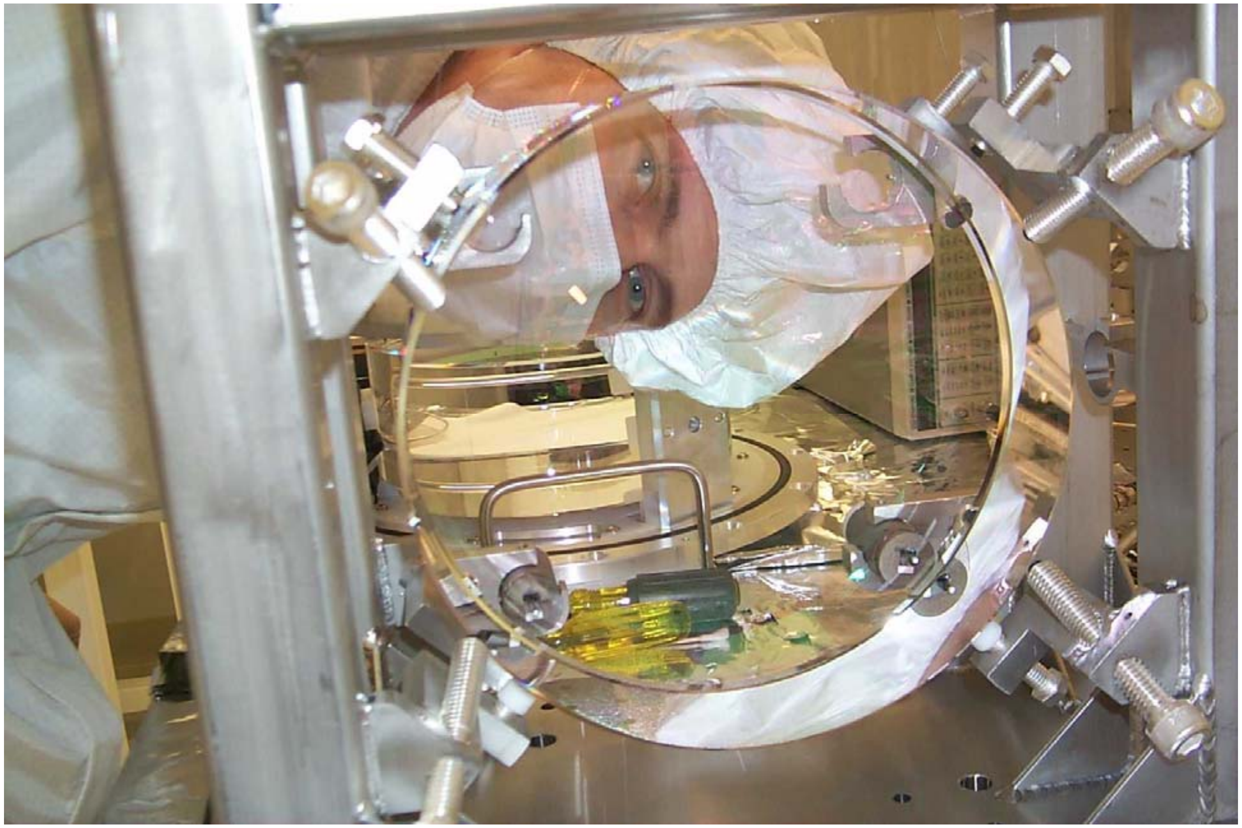
Seismic motion -- ground motion due to natural and anthropogenic sources

Laser
5 W

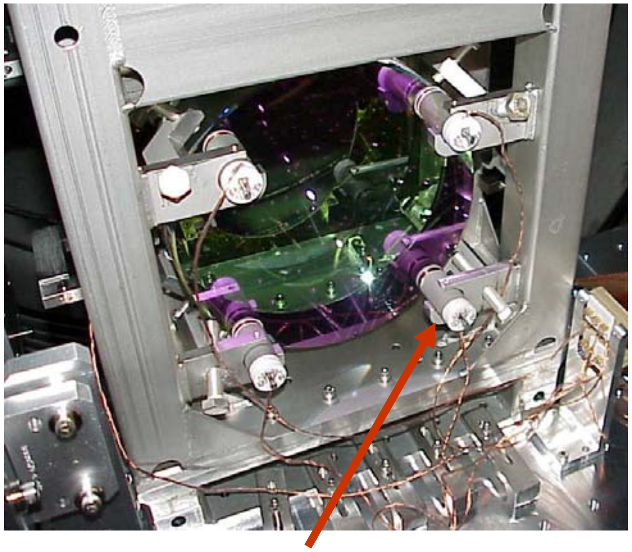
Shot noise -- quantum fluctuations in the rate of photons detected at output

Some initial LIGO hardware: Test Masses

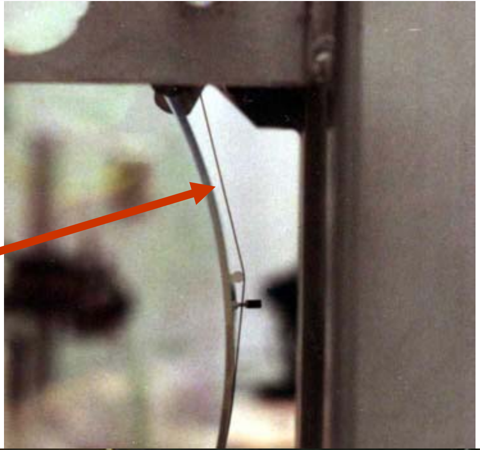
Fused Silica, 10 kg, 25 cm diameter and 10 cm thick
Polished to λ/1000 (1 nm)



Test mass suspensions

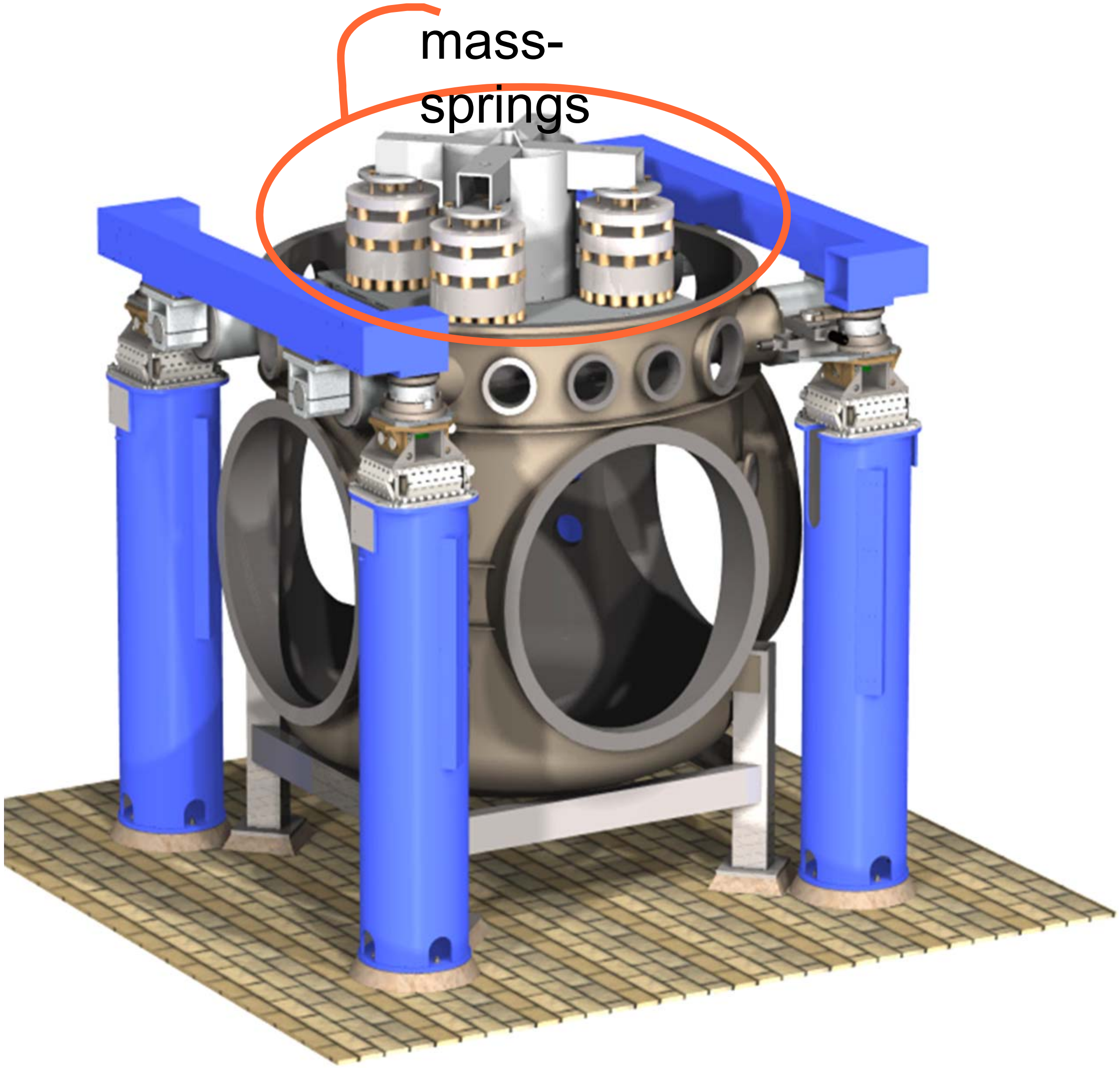


Optics suspended as simple pendulums

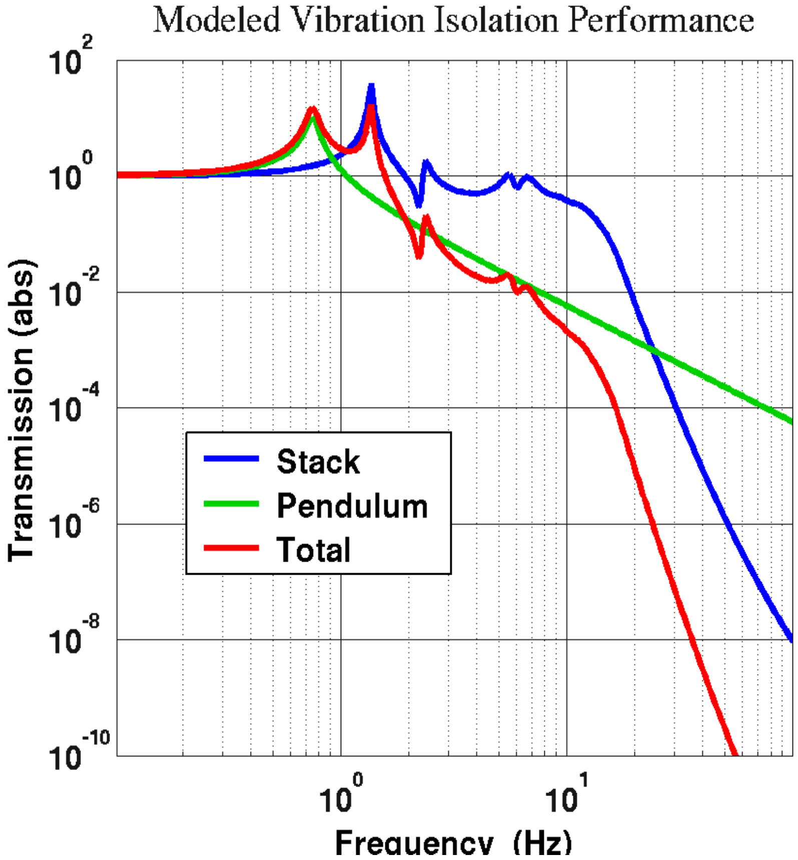


Shadow sensors & voice-coil actuators provide damping and control forces

Initial LIGO: Seismic Isolation



stack of mass-springs

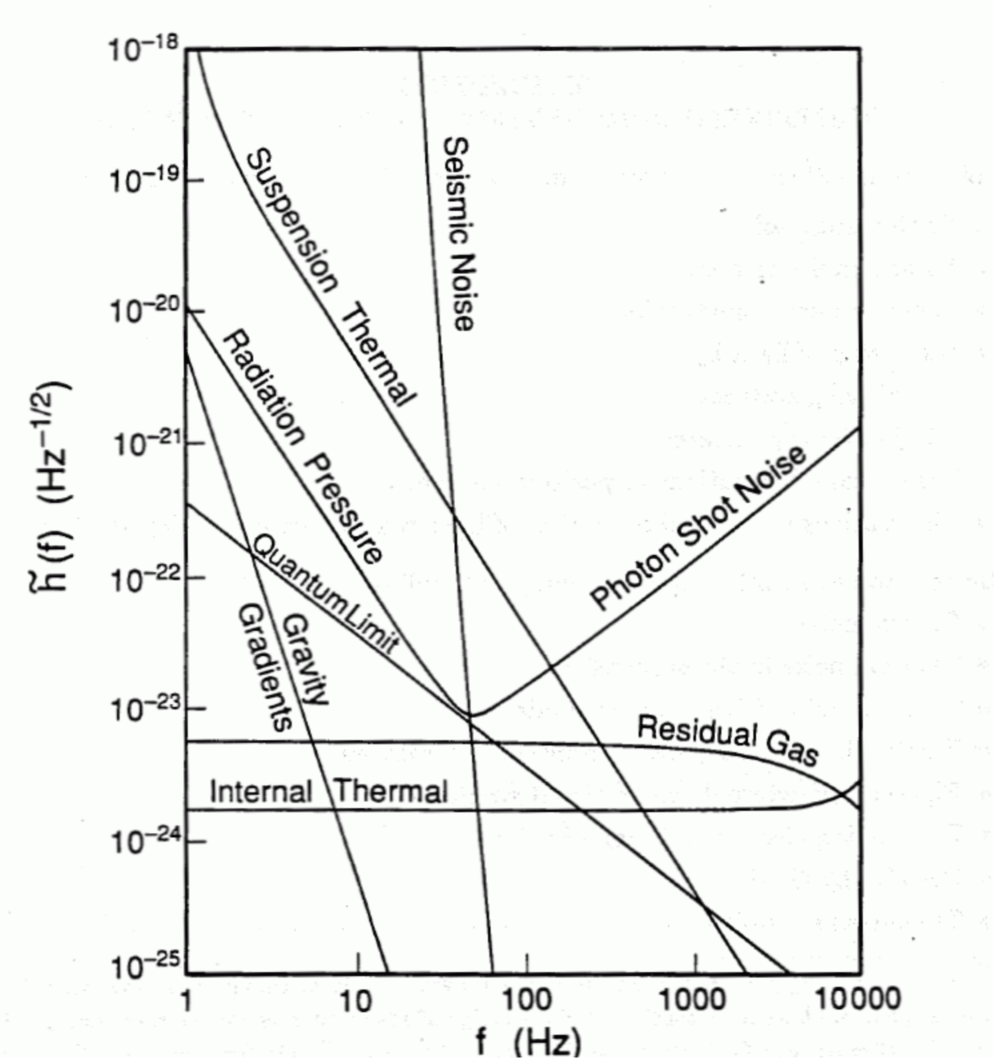


LIGO Vacuum Equipment – designed for several generations

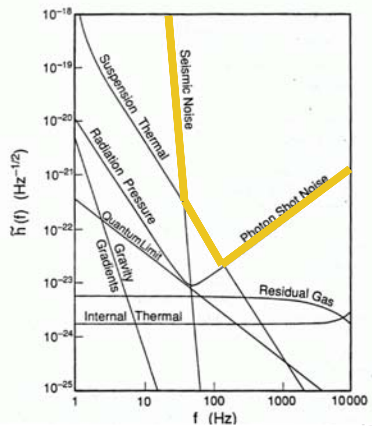
LIGO Beam Tube – designed for several generations

- 1.2 m diameter
  - Multiple beams can be accommodated
  - Optimum also for cost considering pumping
- Aligned to within mm over km (correcting for curvature of the earth)
- Total of 16km fabricated with no leaks
- Cover needed (hunters…)

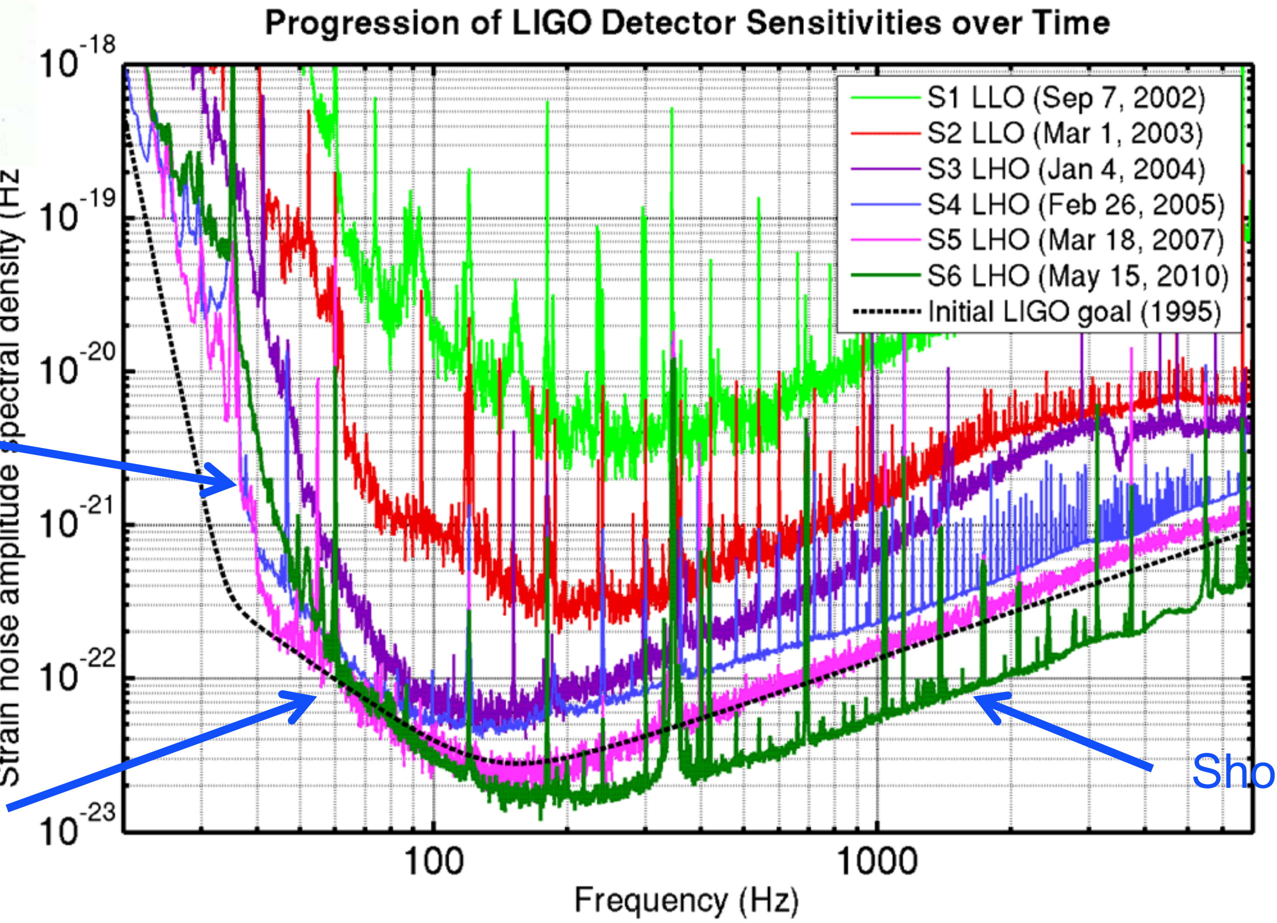
The planned sensitivity of LIGO, 1989 Proposal



The sensitivity of initial LIGO



- Reached the design sensitivity with the initial design
- Understood the performance well
- Made modest changes in the design, achieved yet a better sensitivity ('enhanced LIGO')


Progression of LIGO Detector Sensitivities over Time

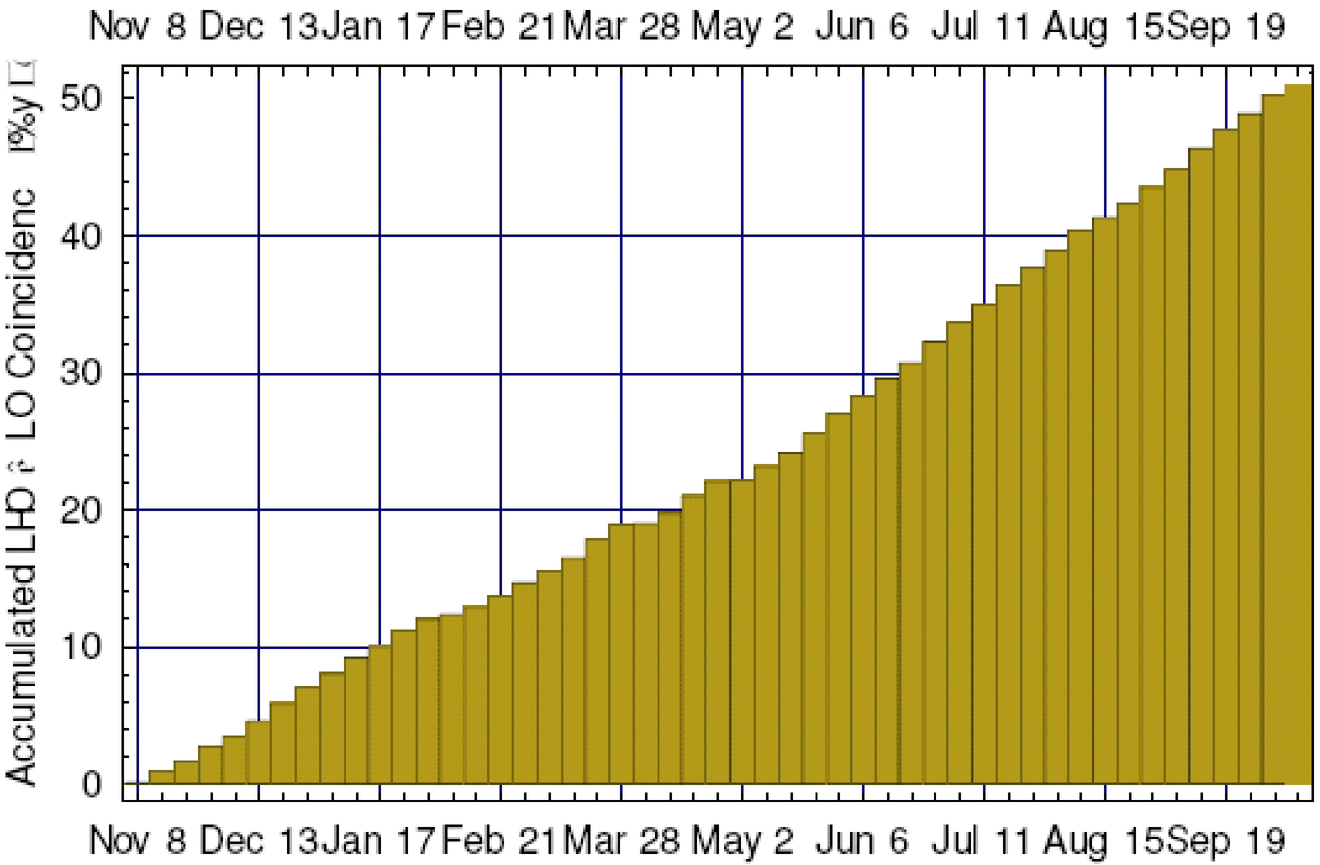
Seismic noise

Thermal noise

Shot noise

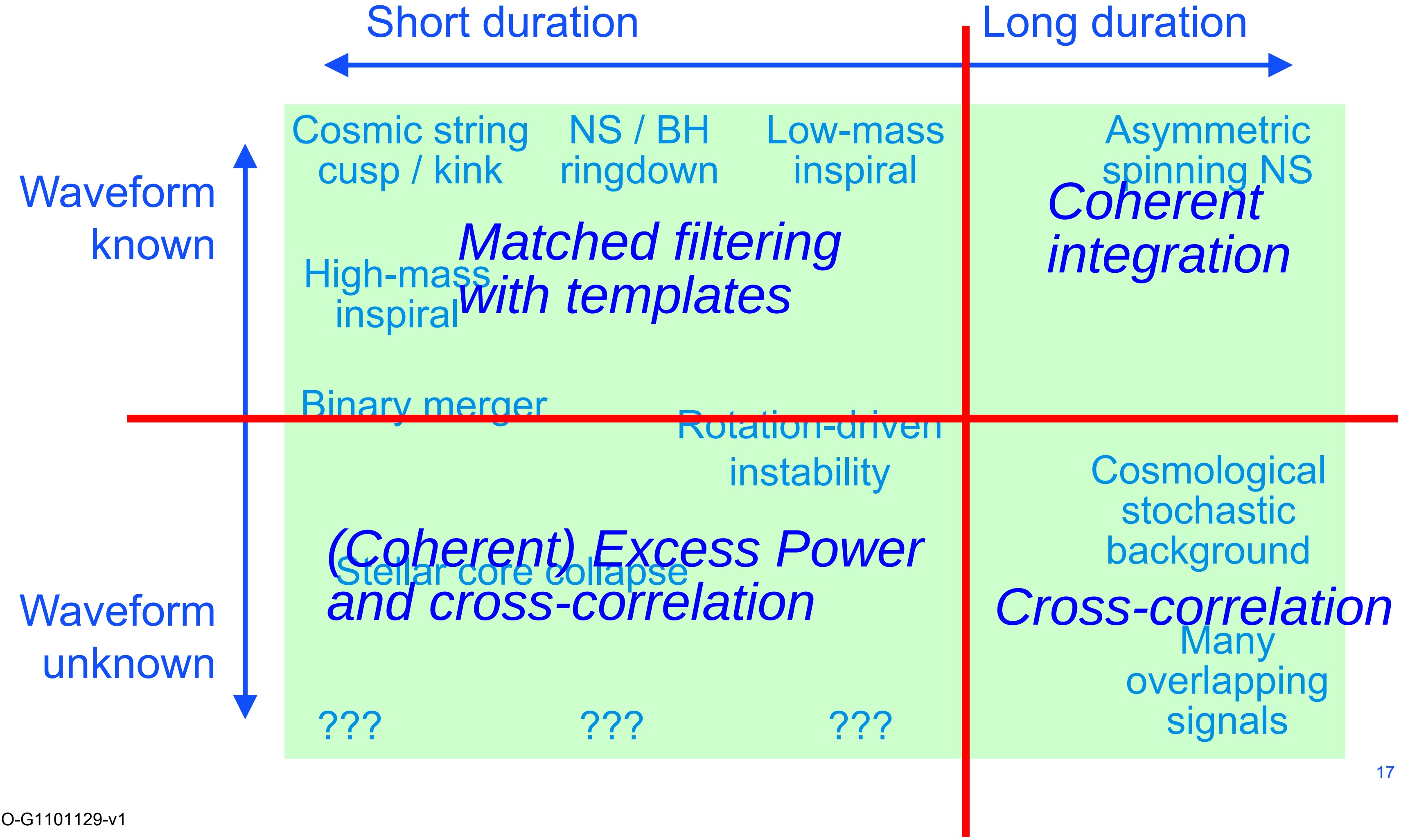
…and so we observed

- Several years of observation, interleaved with improvements
- Joint observation with Virgo



…and we saw no signals…

- A range of potential sources and search techniques used (Peter Shawhan)



Short duration

Long duration

Waveform known

Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

High-mass inspiral

Matched filtering with templates

Asymmetric spinning NS

Coherent integration

Binary merger

Rotation-driven instability

Stellar core collapse

(Coherent) Excess Power and cross-correlation

??? ??? ???

Cosmological stochastic background

Cross-correlation

Many overlapping signals

…and we were not too surprised at that (even if a little disappointed)

- Few sources with known rates – but have some notion for binary inspirals
- For those, some rate estimates for initial LIGO:

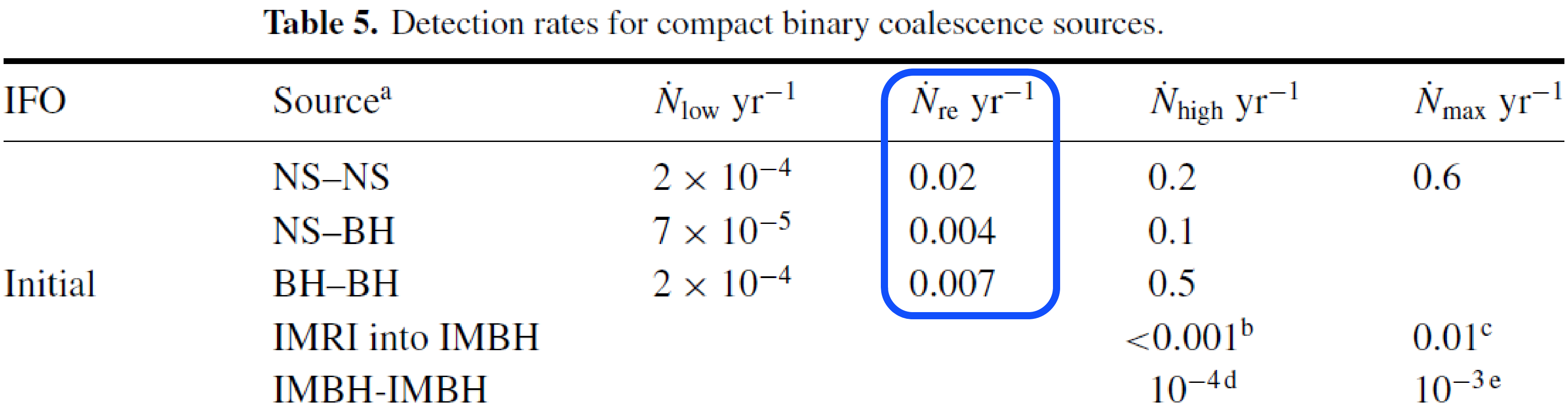


Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{re}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{high}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{max}}\ \mathrm{yr}^{-1}$
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]

- .02 per year….50 years for a reasonable chance of observing an NS-NS inspiral.

Suppose we could do better?

- Really need an 'Advanced' detector with about a factor of 10 greater sensitivity, broader bandwidth –
- Since gravitational waves are an amplitude phenomenon, x1000 more volume searched, plus yet greater reach due to bandwidth:

IFO	Source[a]	$\dot{N}_{\mathrm{low}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{re}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{high}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{max}}\ \mathrm{yr}^{-1}$
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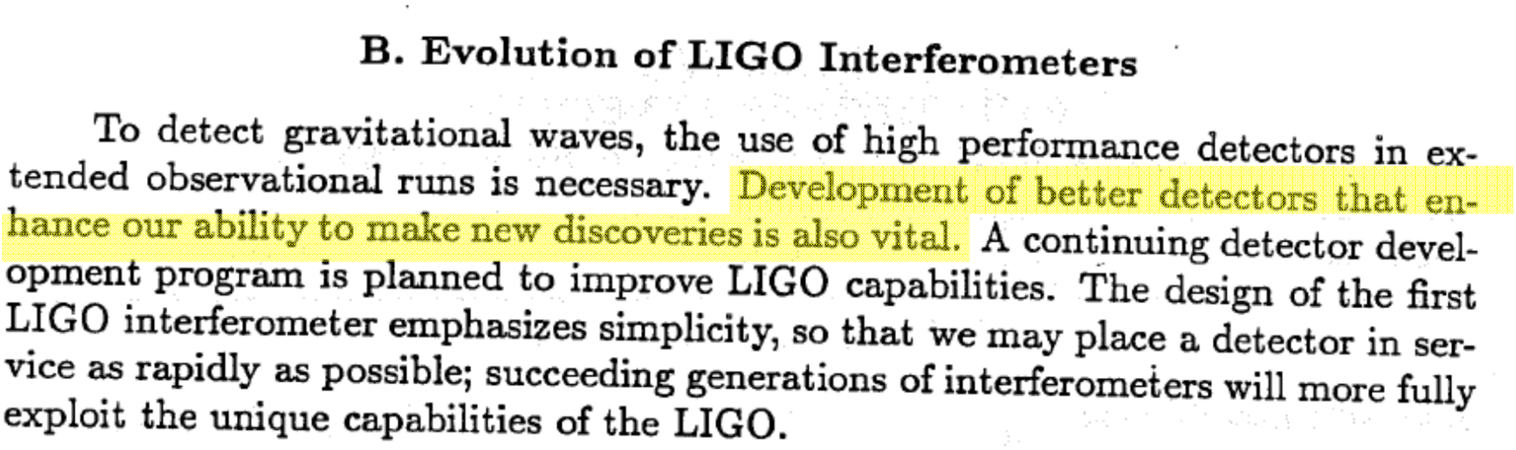
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

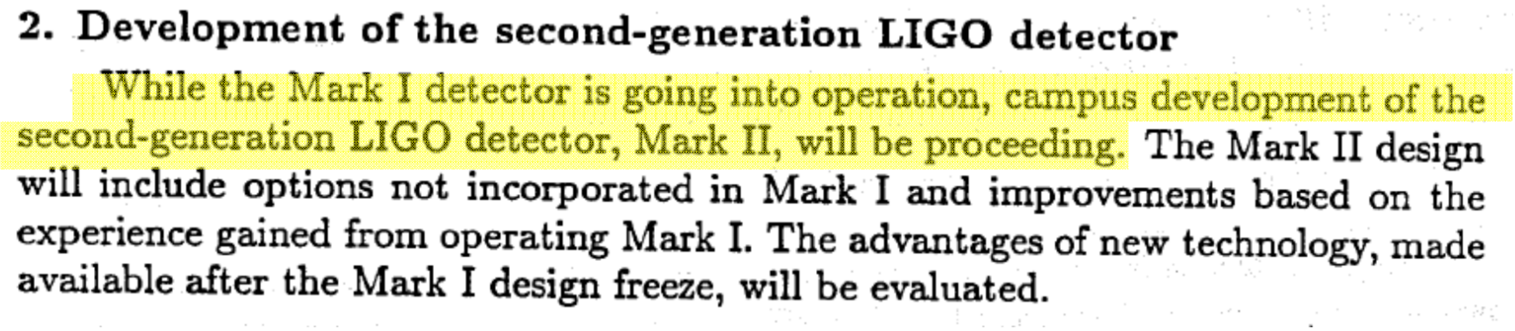
- At ~40 events per year, the rate is much more attractive!

Advanced LIGO: 1989 Proposal



B. Evolution of LIGO Interferometers

To detect gravitational waves, the use of high performance detectors in extended observational runs is necessary. Development of better detectors that enhance our ability to make new discoveries is also vital. A continuing detector development program is planned to improve LIGO capabilities. The design of the first LIGO interferometer emphasizes simplicity, so that we may place a detector in service as rapidly as possible; succeeding generations of interferometers will more fully exploit the unique capabilities of the LIGO.

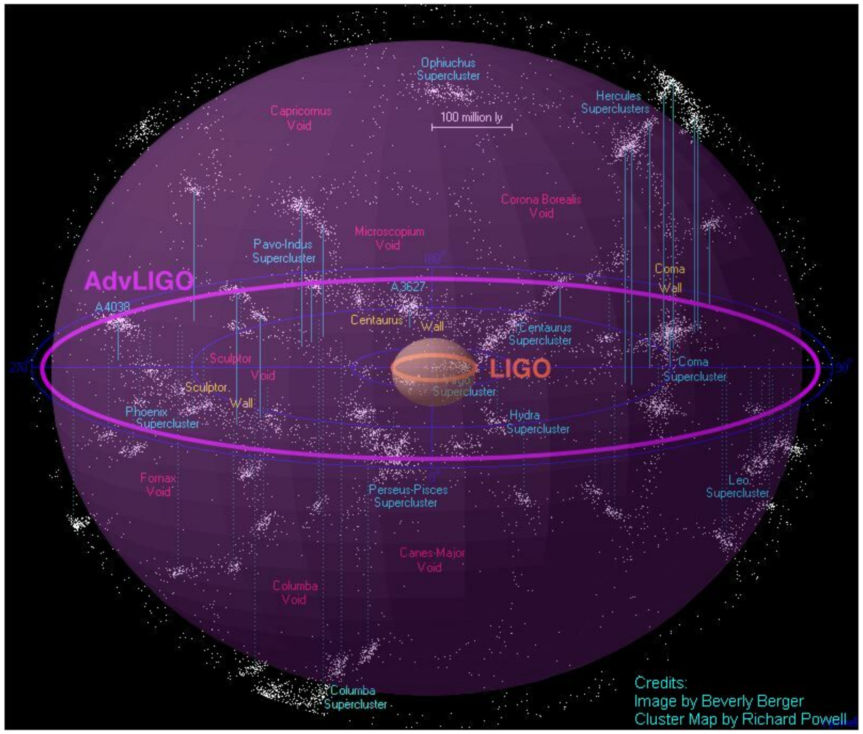


2. Development of the second-generation LIGO detector

While the Mark I detector is going into operation, campus development of the second-generation LIGO detector, Mark II, will be proceeding. The Mark II design will include options not incorporated in Mark I and improvements based on the experience gained from operating Mark I. The advantages of new technology, made available after the Mark I design freeze, will be evaluated.

Advanced LIGO

- At the limit of today’s technology
- Delivers the factor of 10 in sensitivity, thus a factor of 1000 in rate
- …a year of observation with initial LIGO is equivalent to just several hours of observation with Advanced LIGO



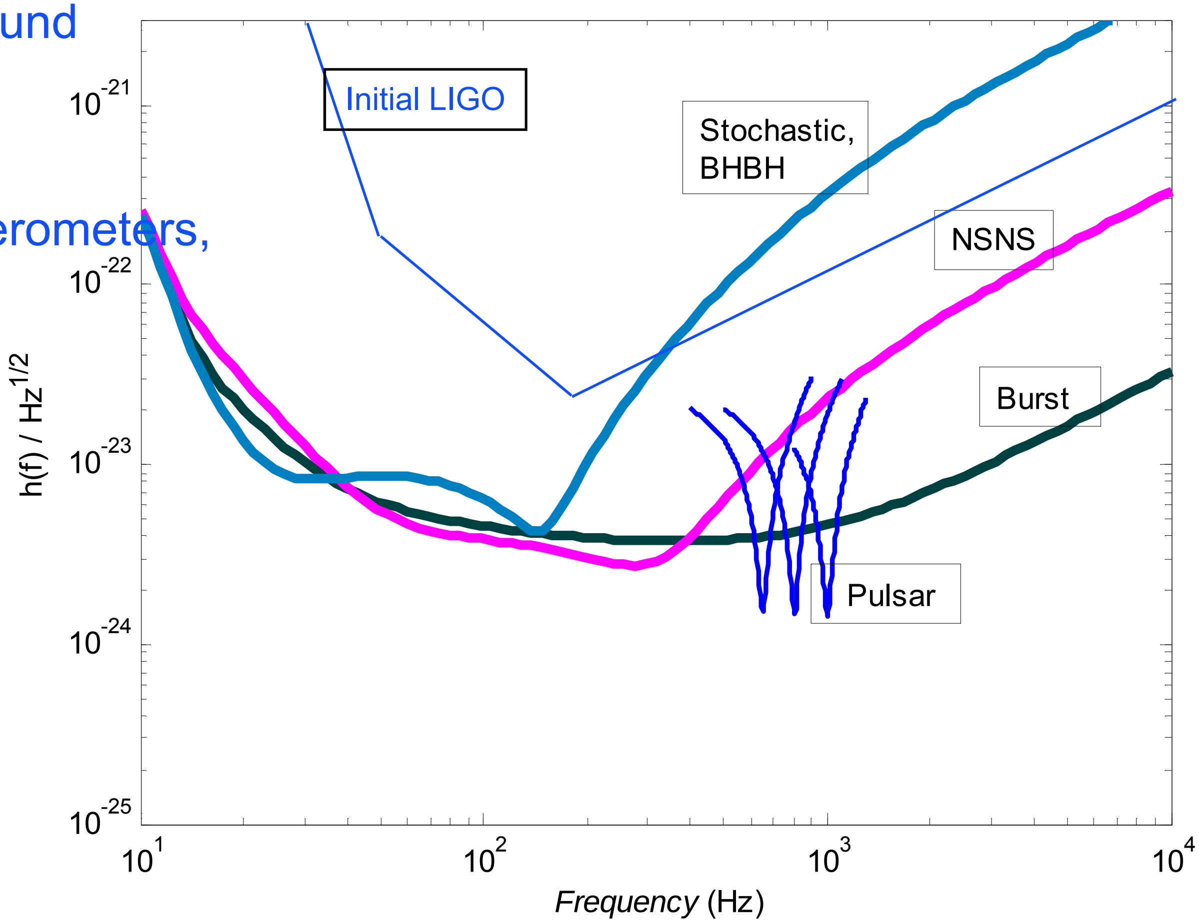
Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

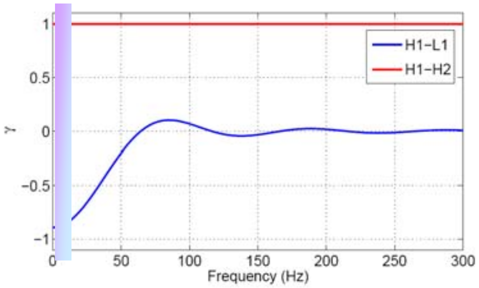
Advanced LIGO sensitivity

- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- Tunable for various sources

- NS Binaries: for three interferometers,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~445 Mpc

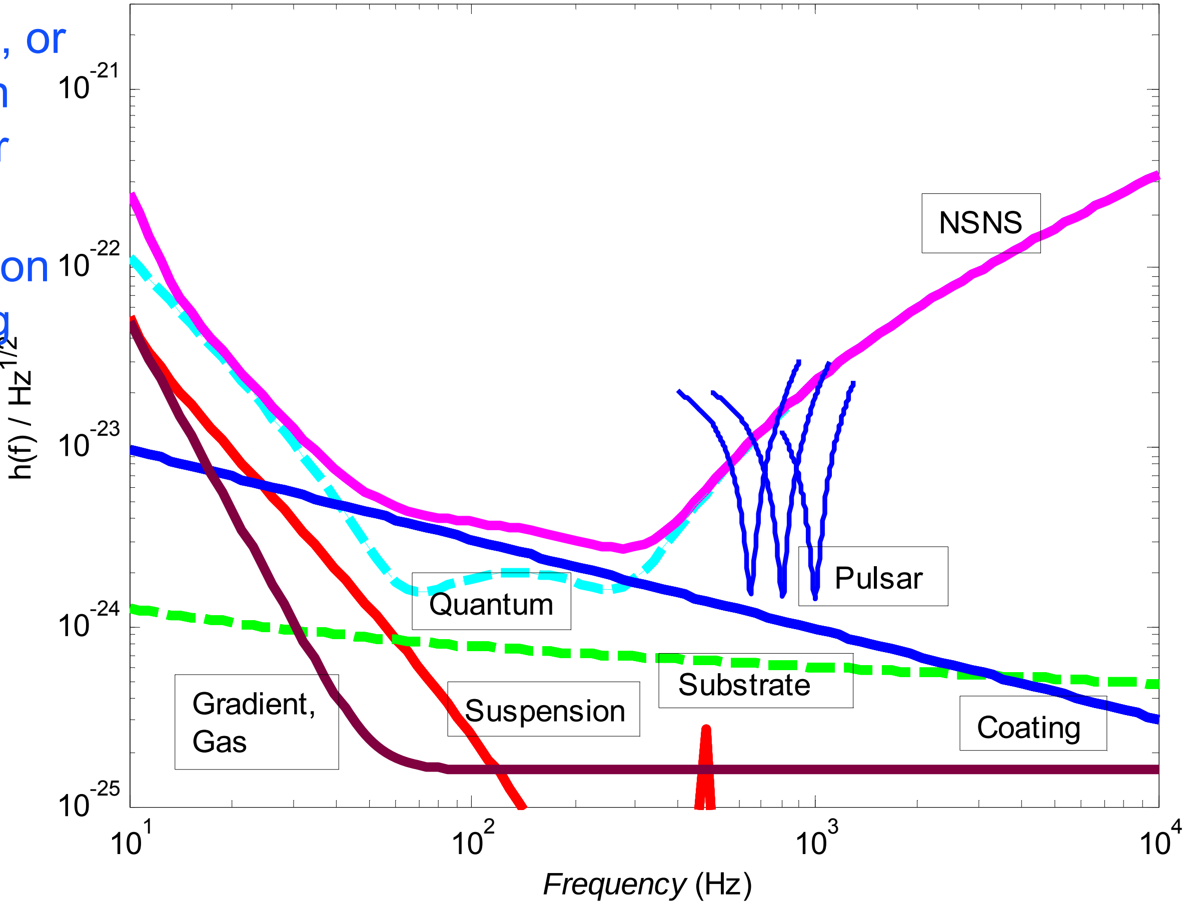
- Stochastic background:
  - » Initial LIGO: ~3e-6
  - » Adv LIGO ~3e-9 (due to improved overlap)





More on sensitivity

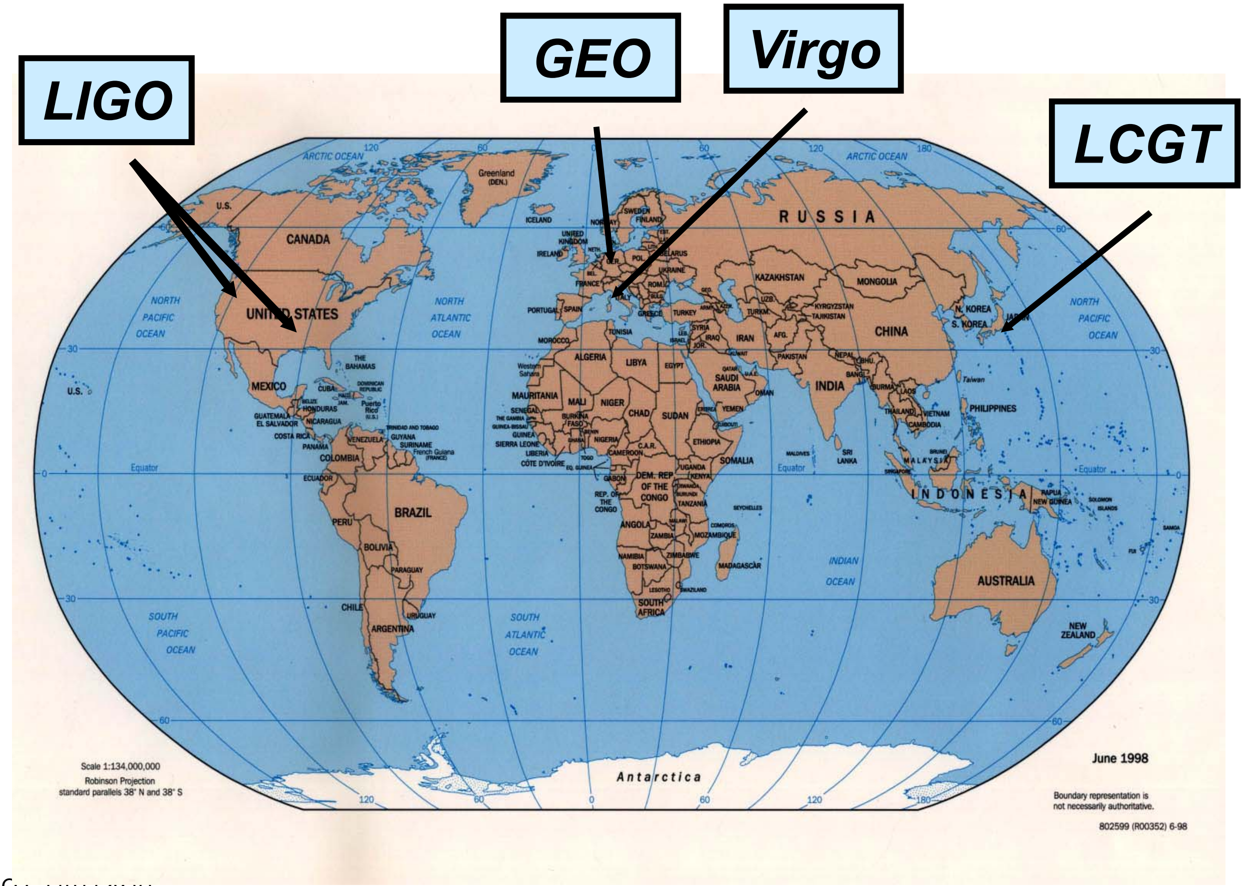
- Mid-band performance limited by Coating thermal noise – a clear opportunity for further development, but present coating satisfactory
- Low-frequency performance limited by suspension thermal noise, gravity gradients
- Performance at other frequencies limited by quantum noise (shot, or photon pressure); have chosen maximum practical laser power
- Most curves available on short time scale through a combination of signal recycling mirror tuning (sub-wavelength motions) and changes in laser power
- To change to 'Pulsar' tuning requires a change in signal recycling mirror transmission – several weeks to several days (practice) of reconfiguration (but then seconds to change center frequency)



Astrophysics with Advanced detectors

(lots borrowed from Alan Weinstein and other colleagues!)

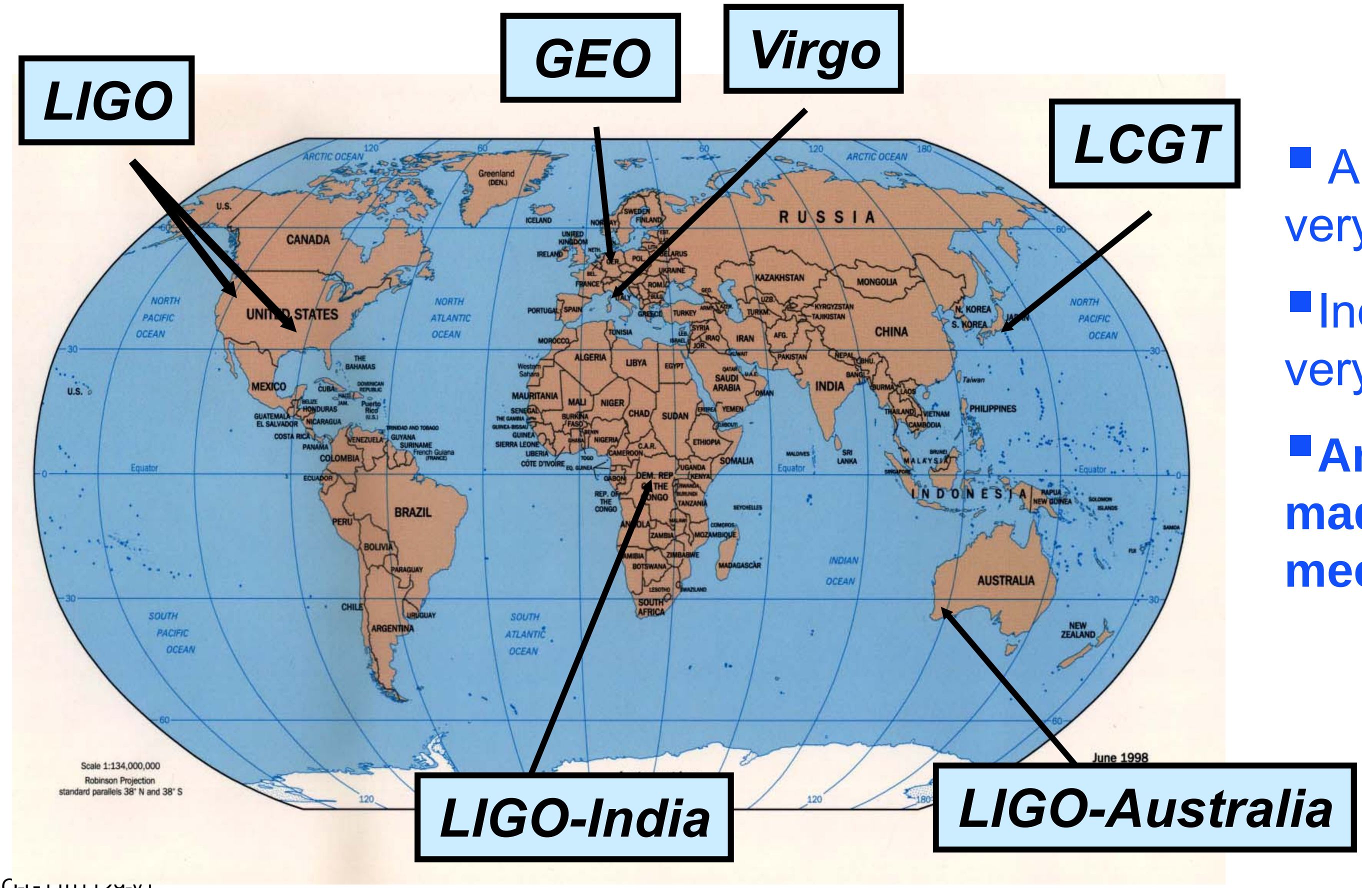
- It takes a Network (to paraphrase Hillary Clinton)
- All detectors need to be of similar sensitivity
- Have a great handful of next-gen detectors in construction



- detection confidence
- locate the sources
- decompose the polarization of gravitational waves
- verify light speed propagation
- **…note, however, all these detectors are in a plane…**

The third Advanced LIGO interferometer

- Baseline was (as for initial LIGO) 2 interferometers at Hanford
- Started working last year to find a better location for the 3rd aLIGO instrument
- Strong interest from the NSF, as well as potential host countries

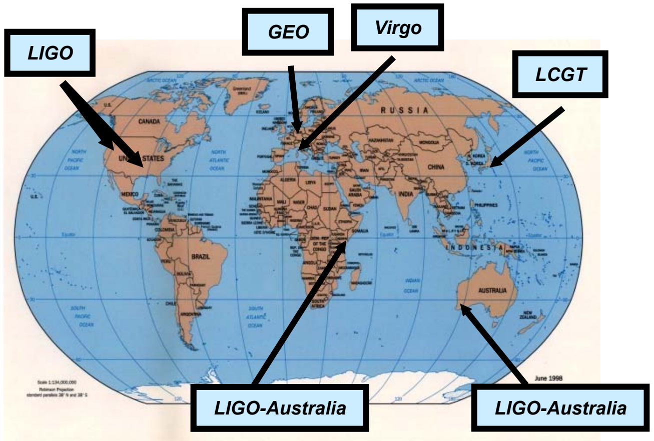


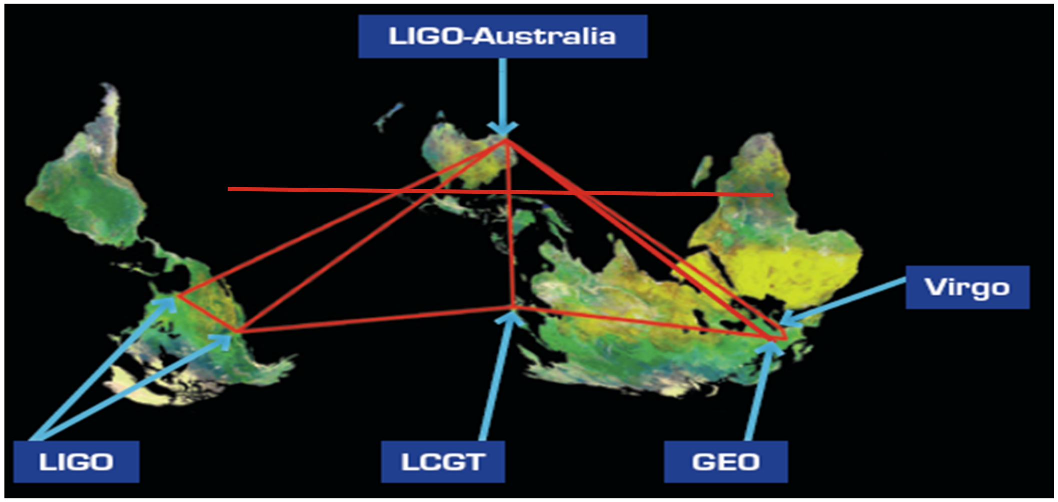
- Australia would be one very good placement
- India would also work very well
- **Any decision must be made by March 2012 to meet aLIGO's timing**

Reliable sky localization

Pointing resolution is good for sources away from plane of three detectors; not as good in the plane.

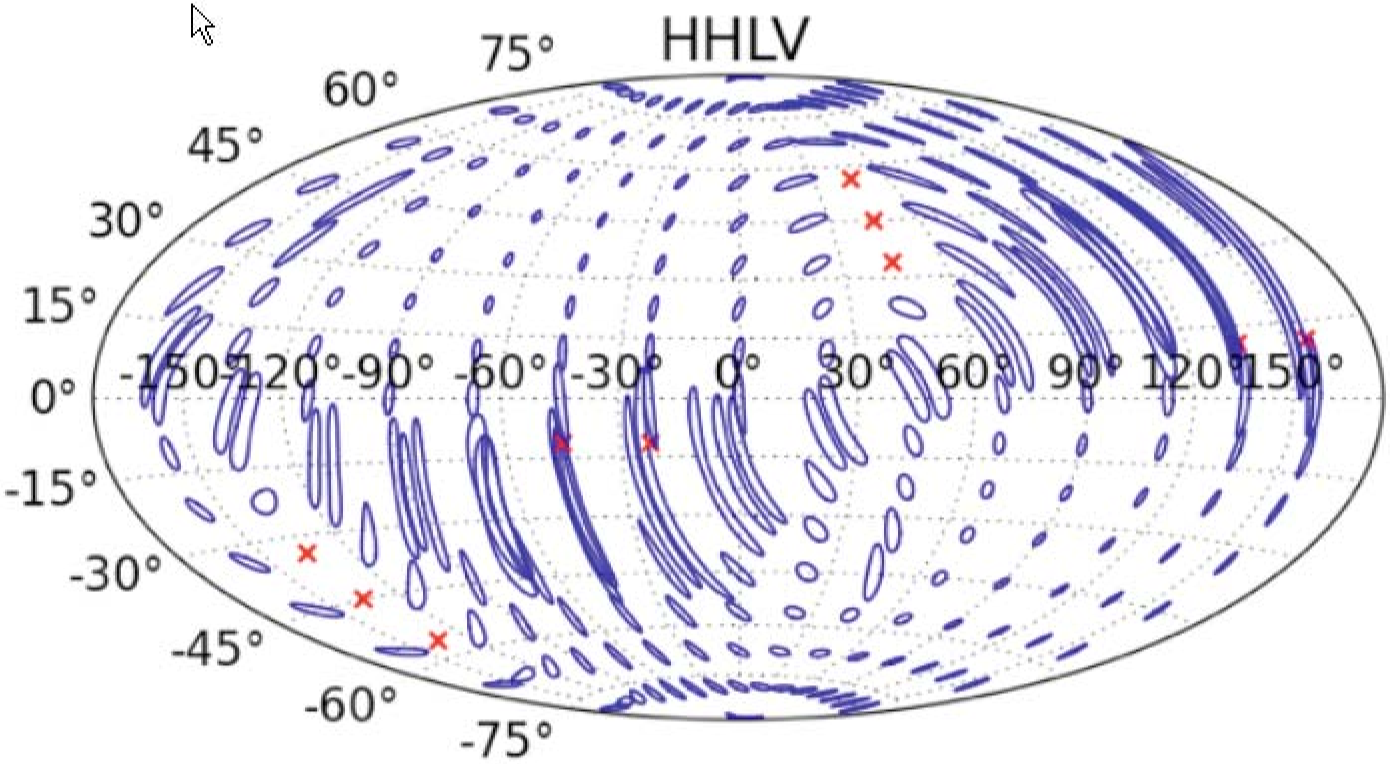
- A global *tetrahedron* can triangulate in all directions.
- Data from all detectors will be analyzed as from a single global network
- Other benefits of network--- determination of polarization of GW, waveform extraction, better duty cycle, …
- A continental-scale tetrahedron of (laser-interferometric) detectors, to locate sources in the sky via GW interferometry.





Sky Localization Error Ellipses

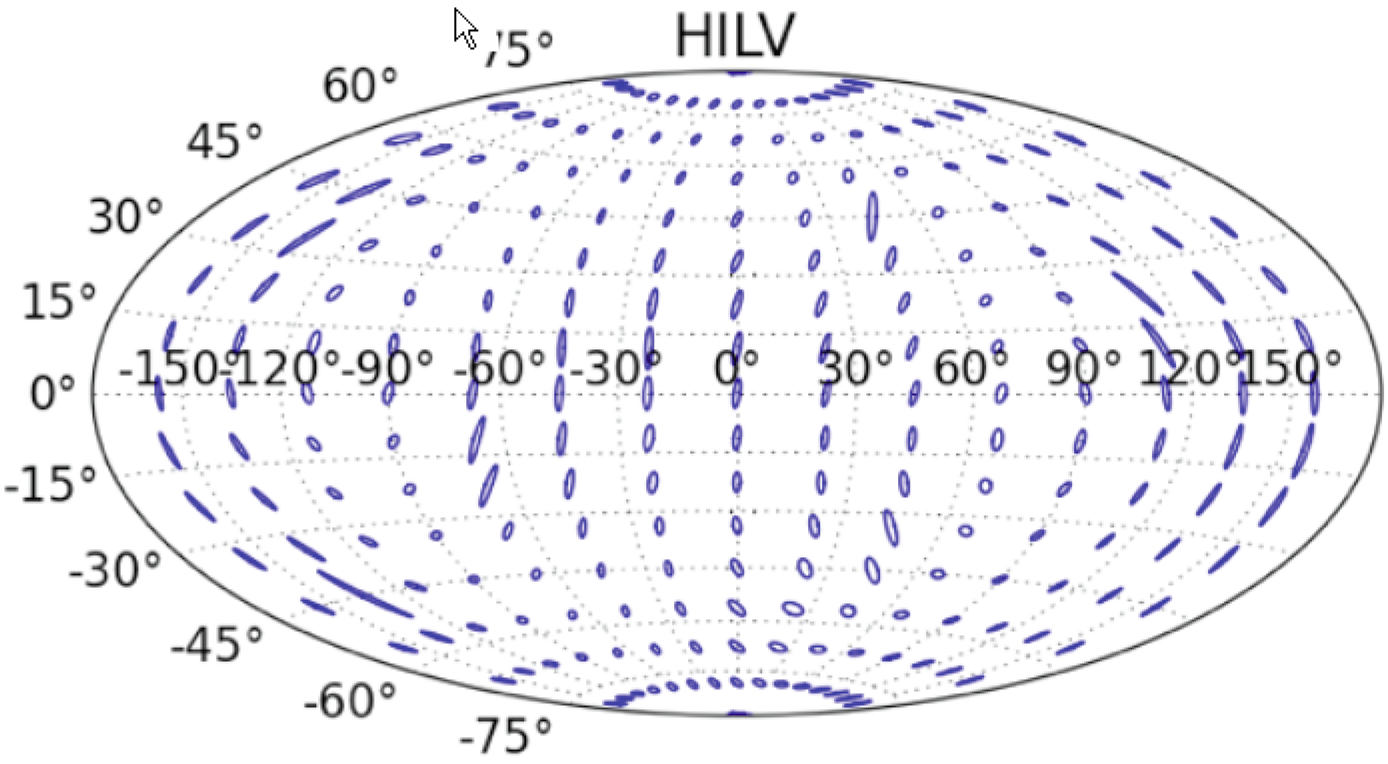
- If we leave the 3rd interferometer at Hanford,
- for the restricted network of LIGO only interferometers



Fairhurst 2011

Sky Localization Error Ellipses

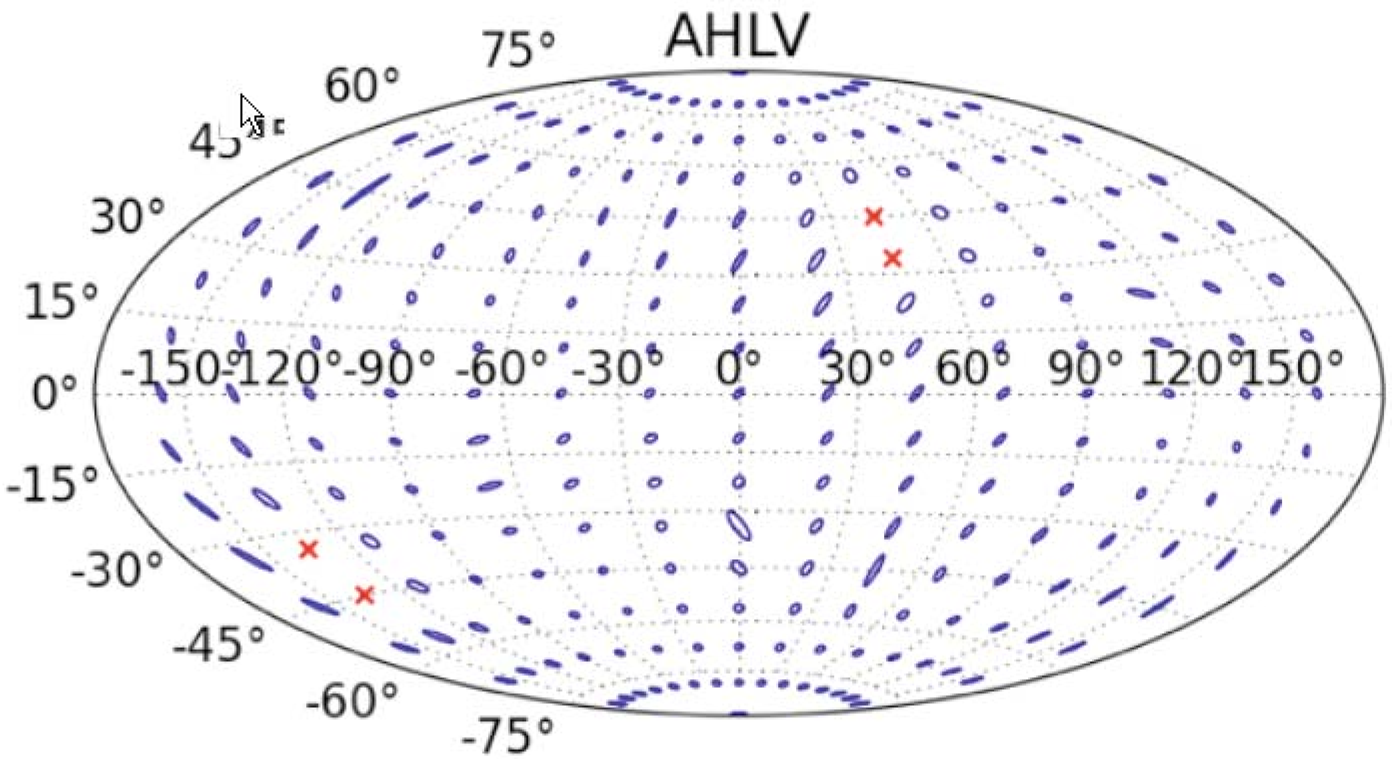
- For the 3rd interferometer in India



Fairhurst 2011

Sky Localization Error Ellipses

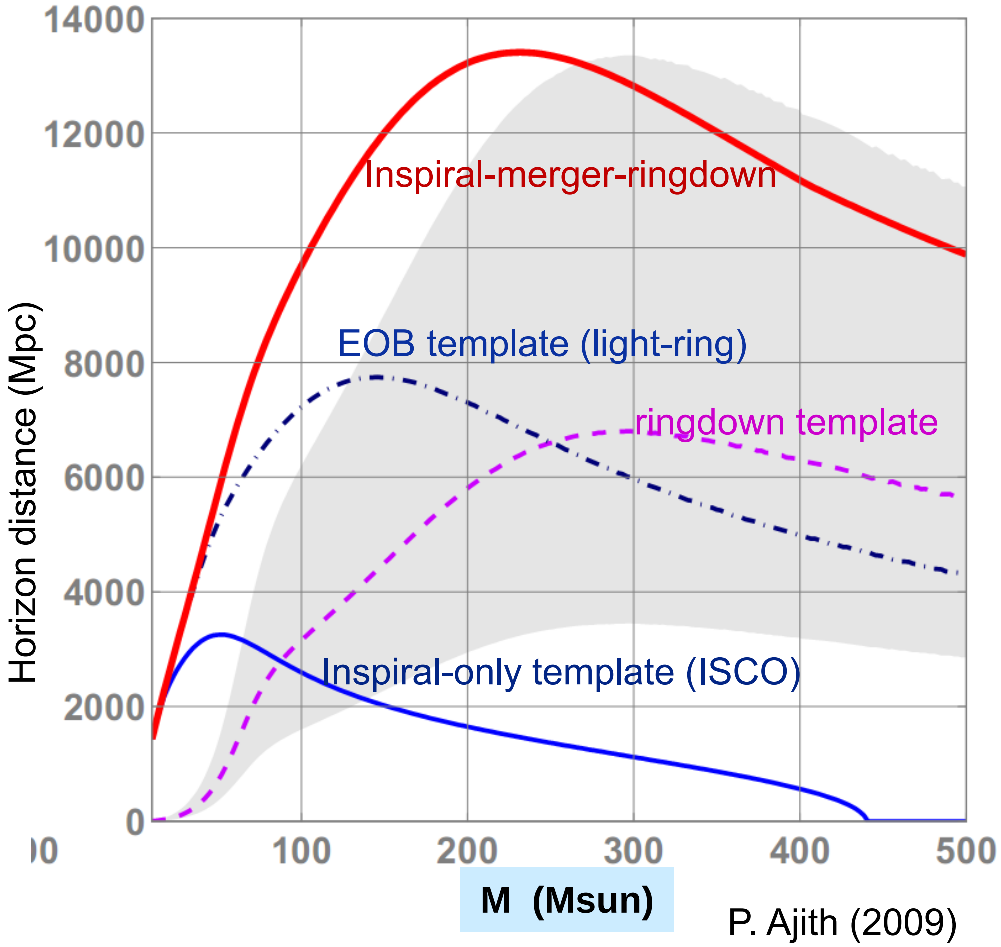
- For the 3rd interferometer in Australia



Fairhurst 2011

Horizon distance for compact binary mergers

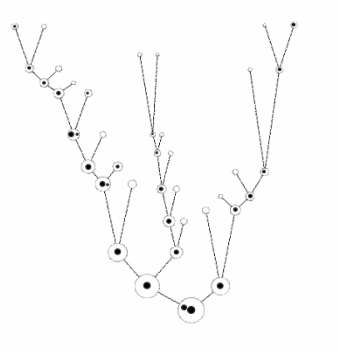
- Horizon distance: Distance in Mpc at which one Advanced LIGO detector can see an optimally-located, optimally oriented binary merger with an SNR=8, as a function of total mass.
- Averaging over sky location and orientation degrades this by ~2.26.
- Important to use the right templates, including IMR, and spin effects!
- The combination of the detector, and the right templates, allows the 'reach' and anticipated rate
- Need strong coupling between experimentalists and source modelers!



P. Ajith (2009)

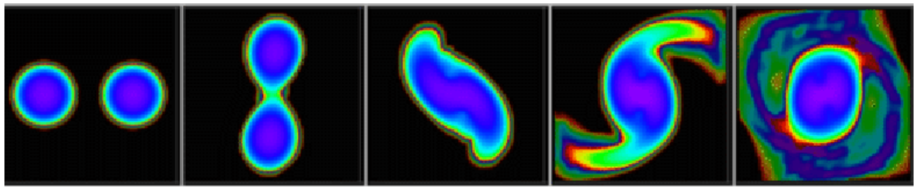
Astrophysical science
with binary mergers

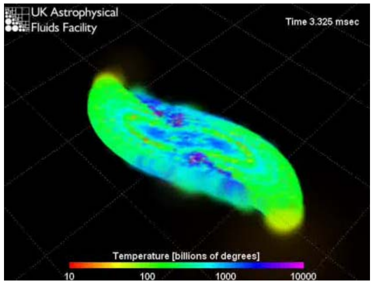
- Merger rates as function of mass, mass ratio, spin
  - » Establish existence of black hole binaries
  - » Neutron star mass distribution
  - » Black hole number, mass, spin and location distribution
  - » Search for intermediate-mass black holes
- Inform / constrain astrophysical source distribution models
  - » Extract population synthesis model parameters.
  - » Binary formation and evolution history
  - » Explore hierarchical merger scenarios
- Study matter effects in waveform: tidal disruption, NS EOS.

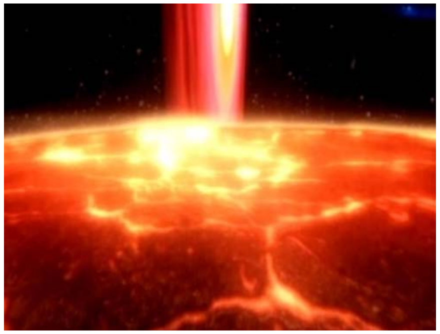


ciera.northwestern.edu/rasio

• Neutron star – neutron star (Centrella et al.)



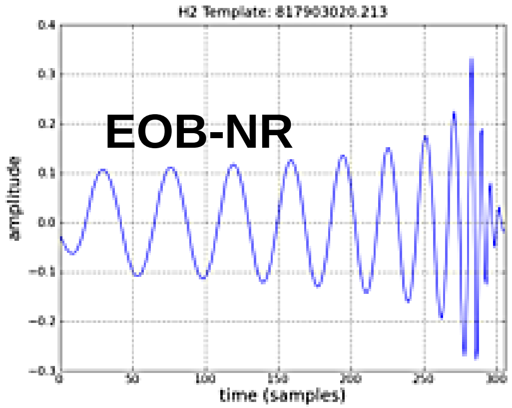




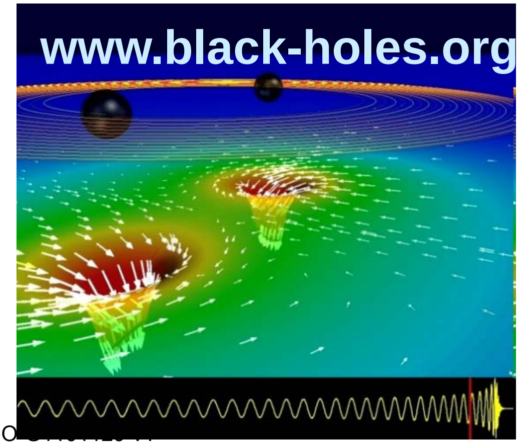
Testing GR with mergers

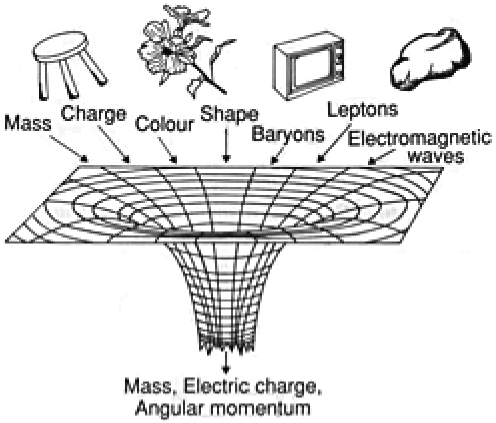
- Test post-Newtonian expansion of inspiral phase.

$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5}\left(1 + \sum_{k=2}^{7} v^k \psi_k\right).$$



- Test Numerical Relativity waveform prediction for merger phase.
- Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.

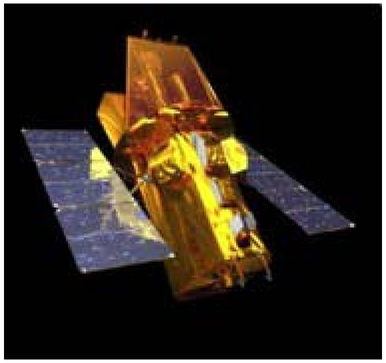




nonlocal.com/hbar/blackholes.html

Multi-messenger astrophysics

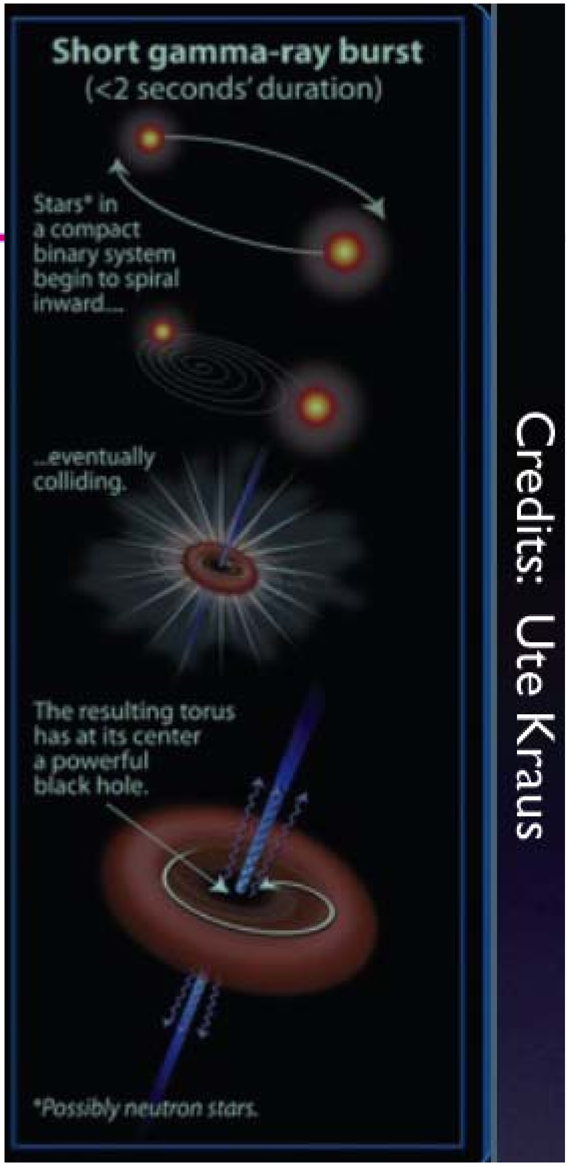
- connecting different observations of the same astrophysical event or system
  - » Gamma-Ray transients (GRBs, SGRs)
  - » Optical transients
  - » Neutrino Events
  - » Radio transients
  - » X-ray transients
  - » ...
- Correlation in time and direction, targeted analysis
- Information on source properties
- Increased confidence in detection of gravitational waves



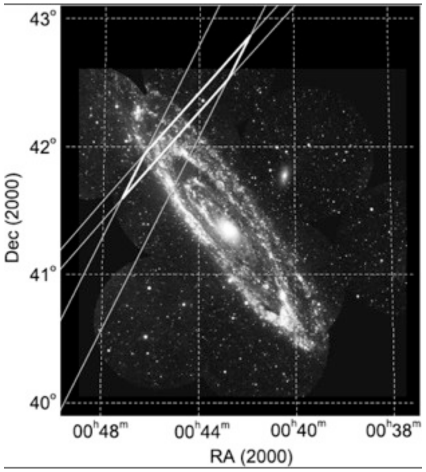
- Ground- and space-based telescopes, satellites, particle detectors all are potential partners for triggers to or from GW detectors

One example: Gamma-ray bursts

- Best guess is that short GRBs are due to binary mergers
  - » Correlated detection will give direct evidence of engine mechanism
  - » Measure component masses and spins in NS-NS/ NS-BH
  - » constrain NS equations of state
  - » test general relativity in the strong-field regime
  - » calibration-free luminosity distance (Hubble expansion, dark energy)



Credits: Ute Kraus

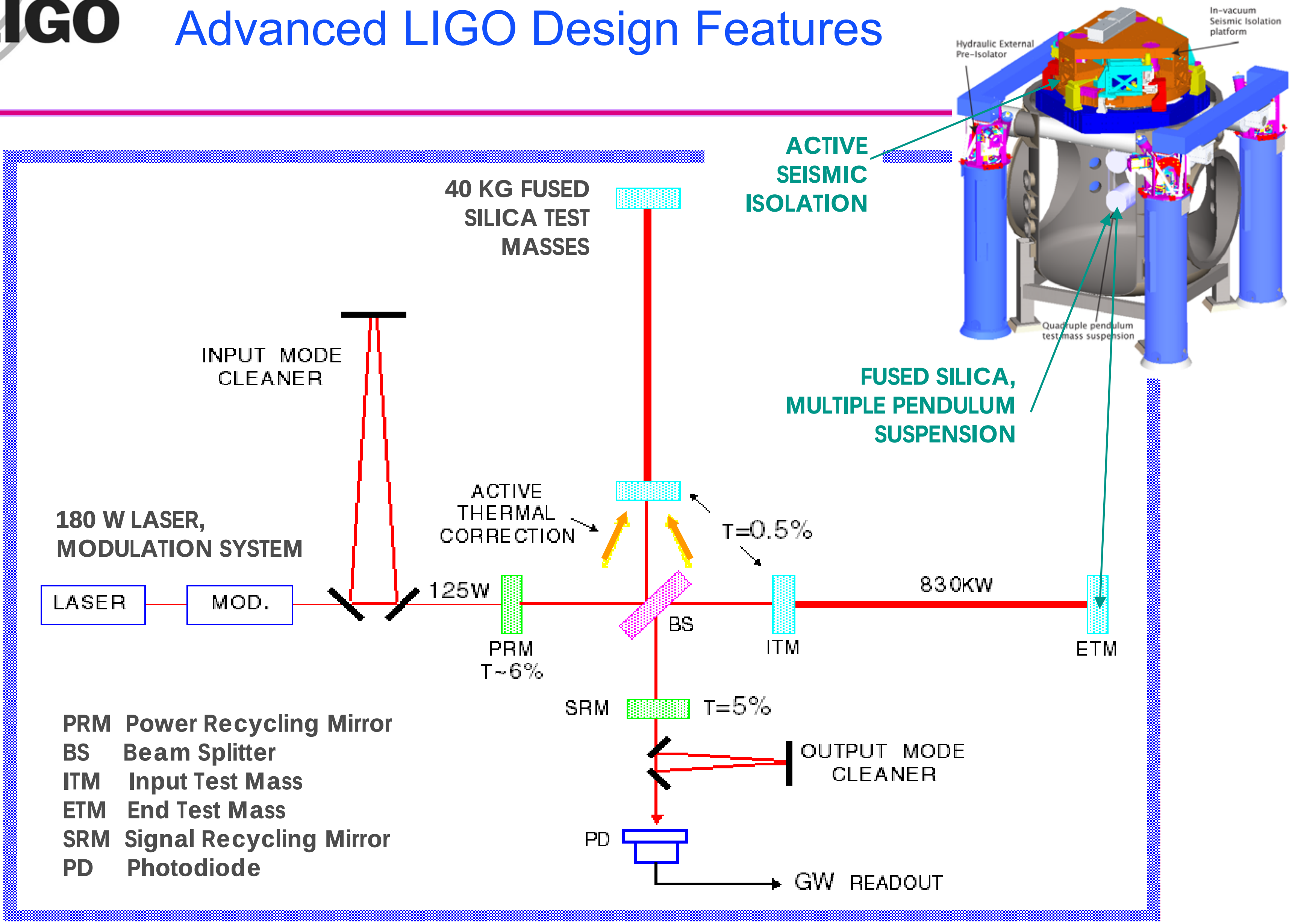


- Unknowns –
  What GW waveform?
  Timing of GW w.r.t. GRB?
- For GRB 070201, Initial LIGO could exclude compact binary coalescence progenitor in M31 with more than 99%CL

The Instrument Scientist's perspective

- The 'advanced' detectors have a high probability of making detections on a ~weekly basis
  - » No detections after an extended full-sensitivity observation would lead to some hard questions…
- Enough signals will be seen to make interesting statistical inferences about populations
- Some signals will be seen with a range of instruments in coincidence, allowing substantial information to be extracted about individual systems
- We can expect that GWs will become an integrated element in the astrophysicists' toolbox, and that's quite neat!
- Very high SNR events will be very rare
  - » some of the precision astrophysics we dream of for 3rd generation instruments and LISA is possible, but we need to press on improving our instruments
- …so, let's get back to instruments!

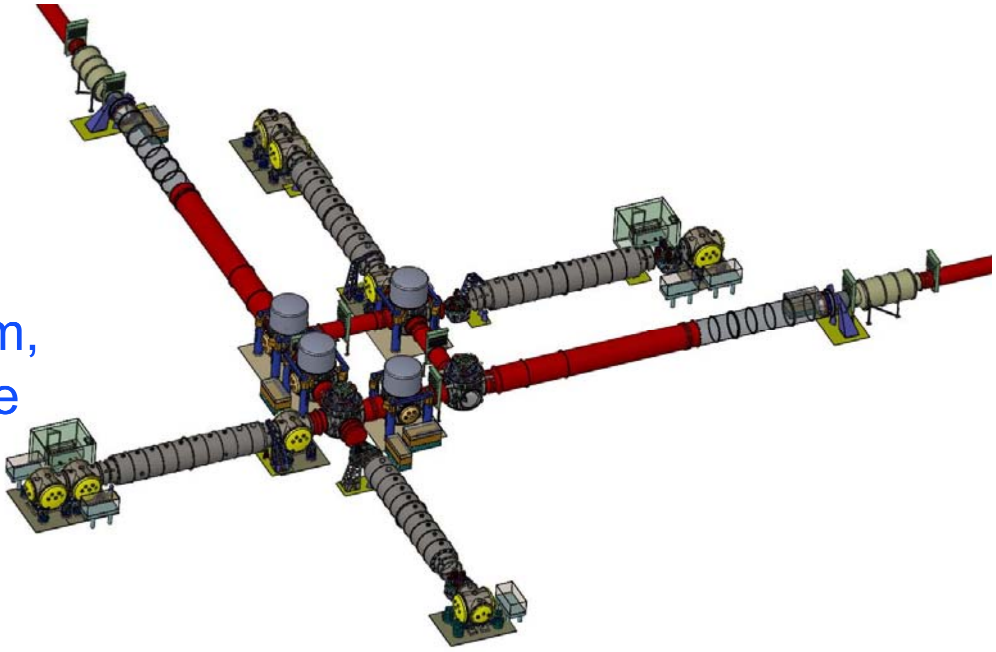
Advanced LIGO Design Features



PRM	**Power Recycling Mirror**
BS	**Beam Splitter**
ITM	**Input Test Mass**
ETM	**End Test Mass**
SRM	**Signal Recycling Mirror**
PD	**Photodiode**

Advanced LIGO Scope

- Re-use of 99% of vacuum system, buildings, technical infrastructure
- Replacement of virtually all initial LIGO detector components
  - » Re-use of a small quantity of technical components – some eLIGO ‘prototypes’ promoted



- Three interferometers, as for Initial LIGO
  - » Can be all identical, or may choose to make one narrow-band at startup – requires exchange of one mirror
- All three interferometers 4km in length
  - » For initial LIGO, one of the two instruments at Hanford is 2km

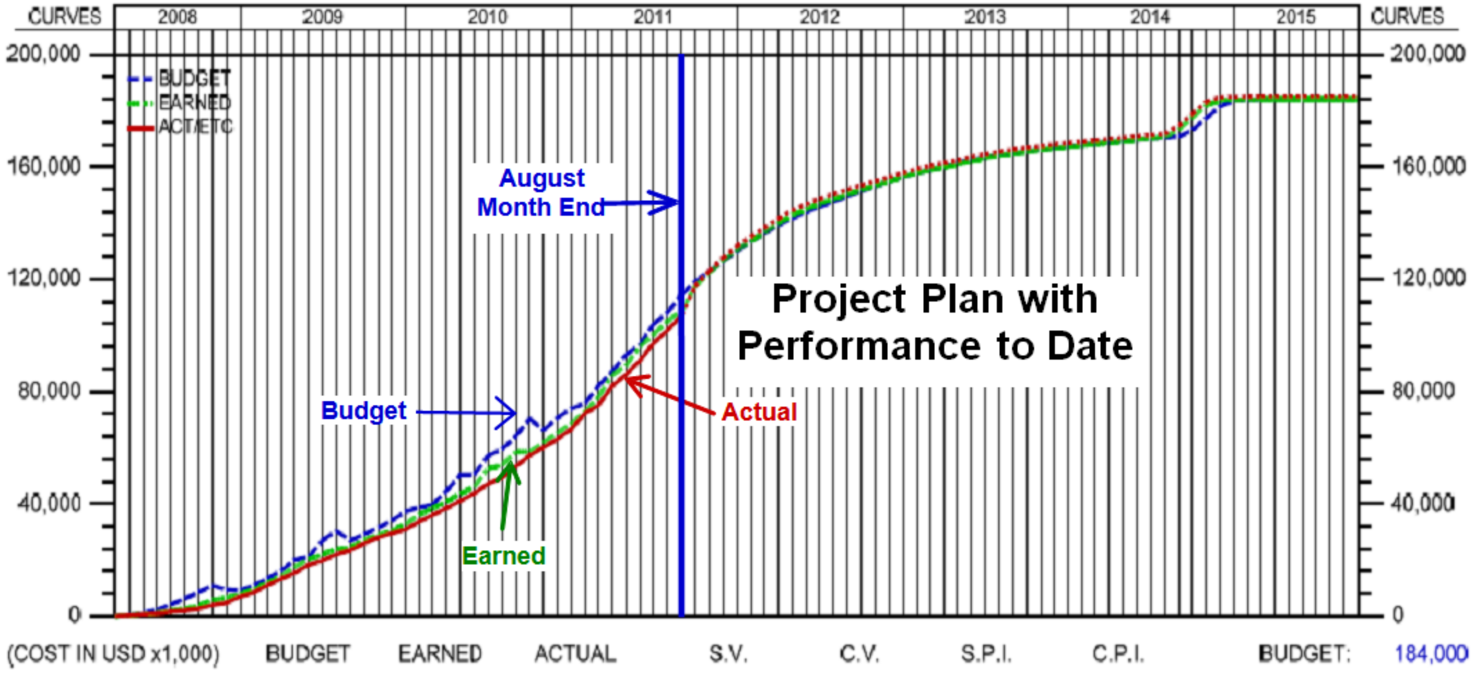
Advanced LIGO Support

- NSF-supported (~$205M MREFC phase)
  - Caltech as awardee, MIT and Caltech sharing responsibility institutionally, organizationally, scientifically, and technically
  - Several US Labs supported on subcontracts from LIGO Lab in Project phase (all US-supported aLIGO work to be on aLIGO MREFC)
  - **The NSF has been a remarkable reliable partner for us!**

- Foreign contributions – from experienced collaborators
  - Germany – Pre-stabilized laser (value ~$14M incl. development);
  - United Kingdom – Test mass suspensions and some test mass optics (value ~$14M incl. development);
  - Australia – wavefront sensors, optics, and suspensions (value ~$1.7M incl. development)

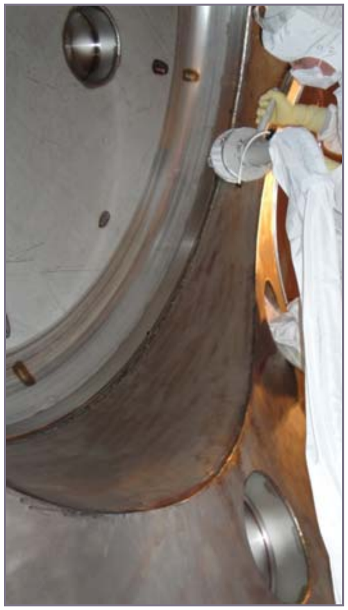
aLIGO Project Metrics

- We have our full funding from the NSF to the close of FY2011 ($154M of $205)
  - » Have committed $130M, with $107M spent.
- The project is 59% complete end August (was 27% in June'10)
- The remaining cost contingency is $21M
- Have 5 months (of initial 7) of remaining schedule contingency


Project Plan with Performance to Date

Facility Modifications

- Larger tubes in the corner stations installed at Livingston, spool additions to move the chambers from 2k to 4k installed at LHO



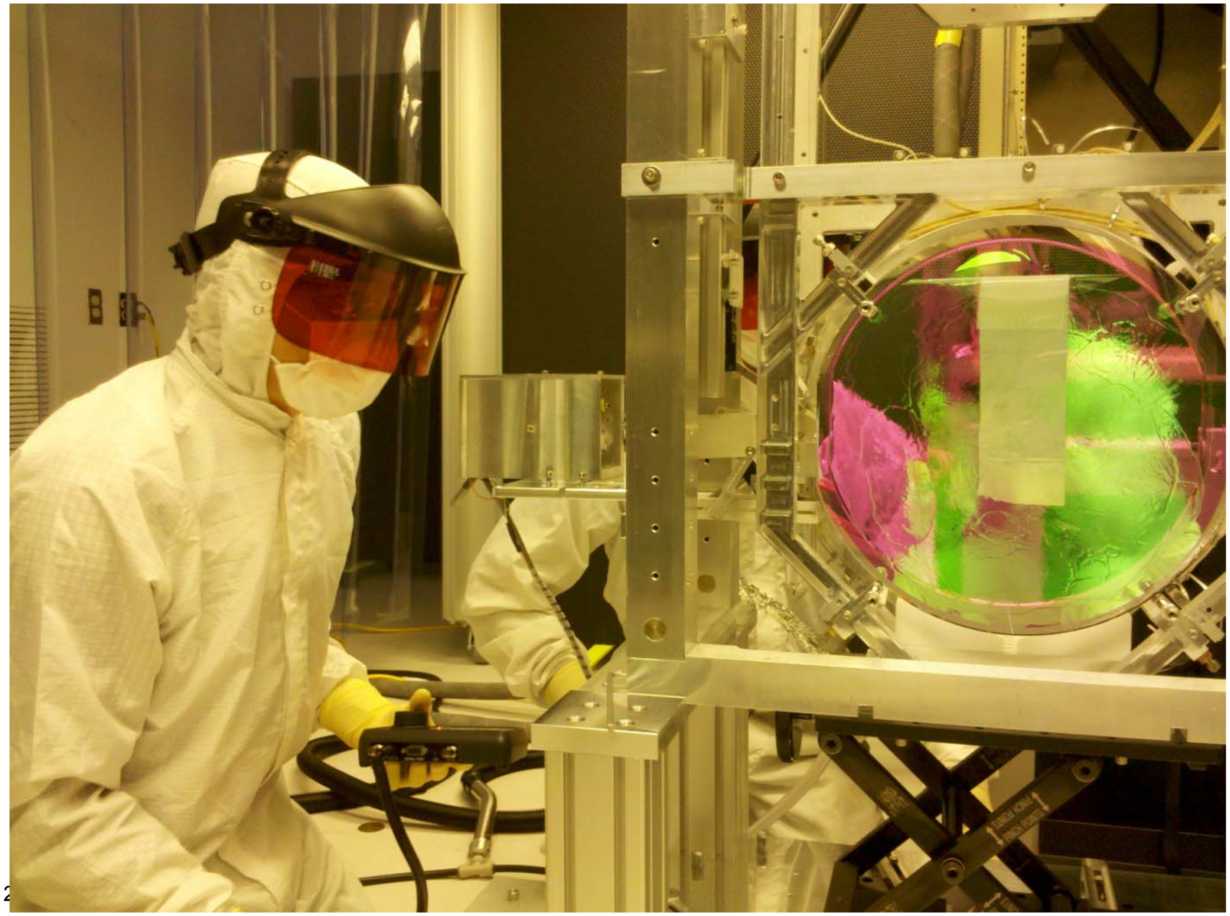
In-chamber cleaning is now routine; requires constant flow of degreased pneumatic tools, but appears to be feasible

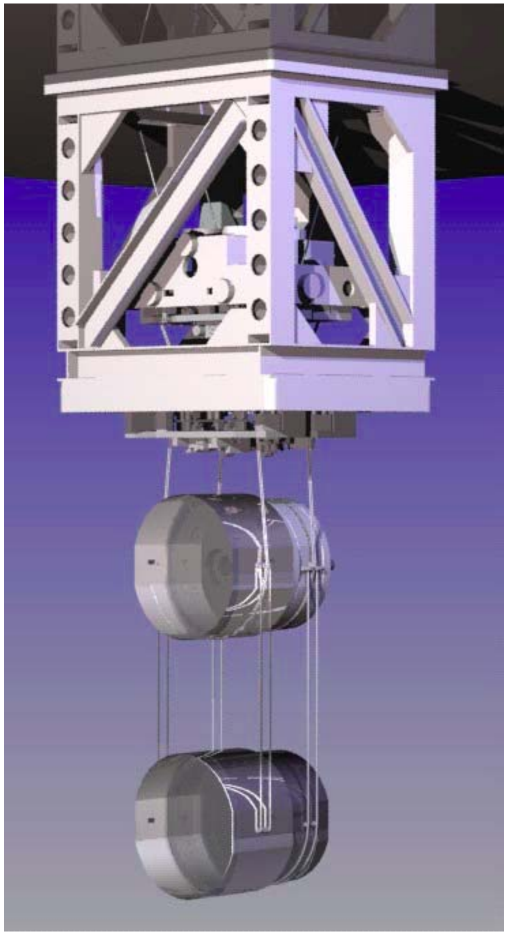
Seismic Isolation

- Our largest subsystem, ~85% complete
- Uses active servo technology to hold the optics table still in inertial space
- Advantage of multiple payloads, but payloads must be ‘stiff’

First production all-fused-silica suspension assembled last week!

- Much like Virgo final suspension stage
- Prototypes seem ok for mechanical Q, robustness
- Have yet to place the suspension in the vacuum chambers….





UK test mass suspensions: all parts delivered, in assembly, testing

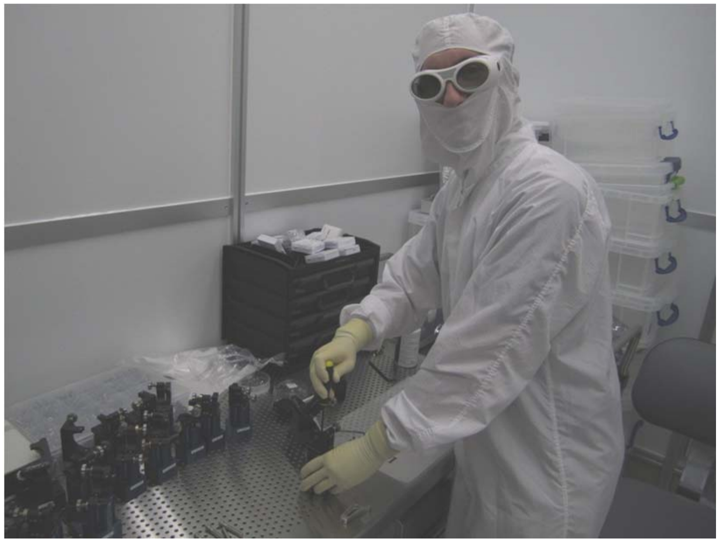
- Most of the Quadruple suspensions assembled
- **The first suspension has been 'mated' to the first seismic isolator – the first significant 'integration'**

Pre-stabilized laser

- Contributed by the Max Planck Albert Einstein Institute (AEI)
- The first Observatory Laser, at Livingston, is installed, tested, and accepted for this phase of installation
- The second is at Hanford and will be installed/tested in October

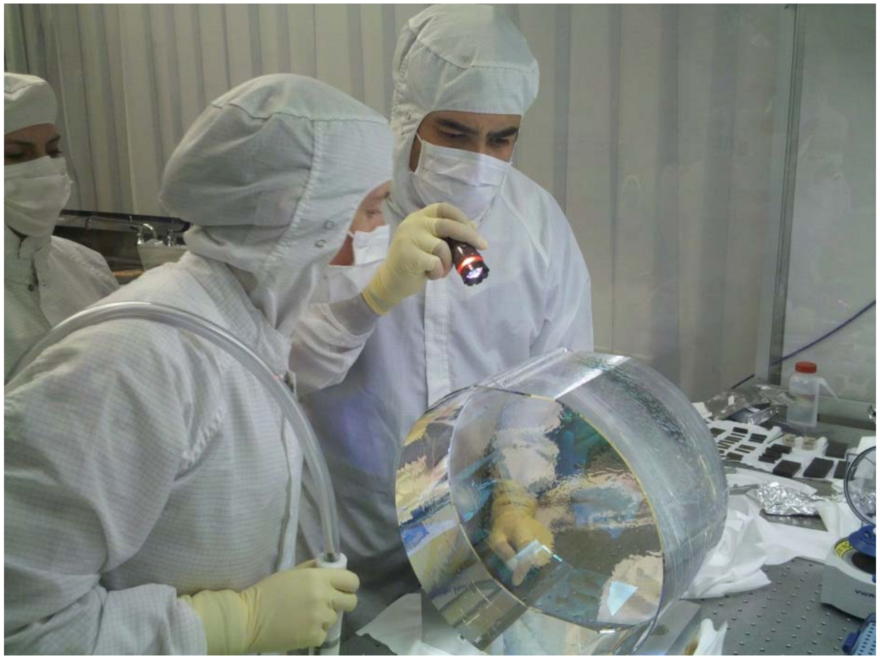
Input Optics (IO)

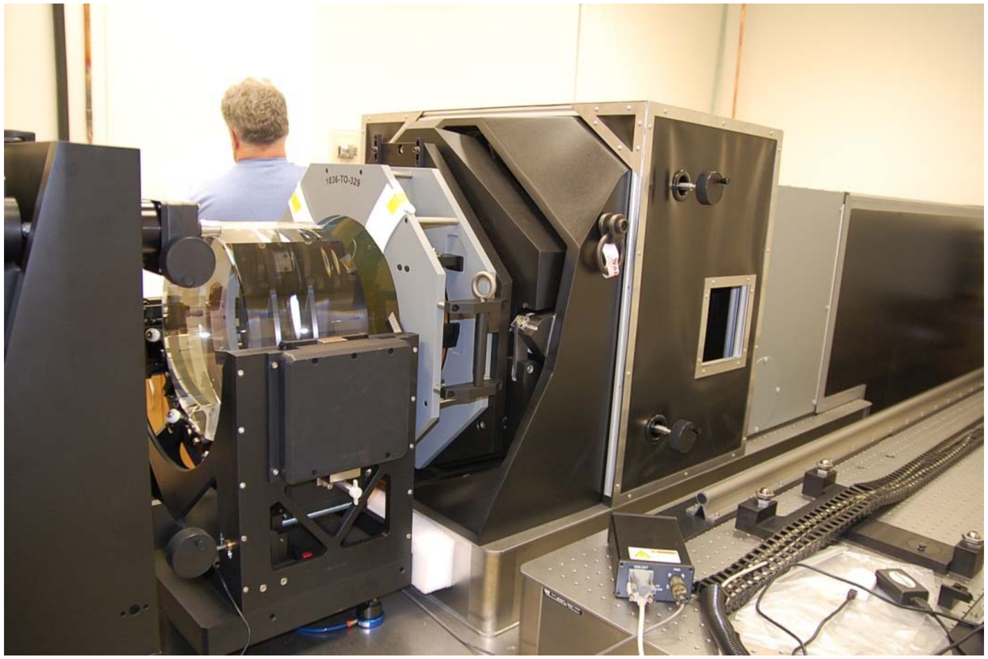
- The University of Florida carries the responsibility for this subsystem under subcontract (as it did for initial LIGO).
- Optics largely procured, fabricated, characterized
- LLO out-of-vacuum components mounted on shared table with the Laser, in testing



Core Optics Components (COC)

- All originally planned substrates received and polished
- 40kg, 32 cm, polished to sub-nm precision! (ion beam milling)
- Coatings (temporary…) on end and input test masses for first integration testing (working closely with LMA Lyon for further development)
- Will swap out later, but can get the value from the integration test with presently available optics





Installation

- Observatories handed off to aLIGO in October 2010 – much earlier than original plan, to allow earlier partial integrated testing
- Two initial LIGO interferometers (L1, H2) removed, H1 in use for tests of squeezed light

- The Electronics building at Hanford was placed on its foundation

Installation

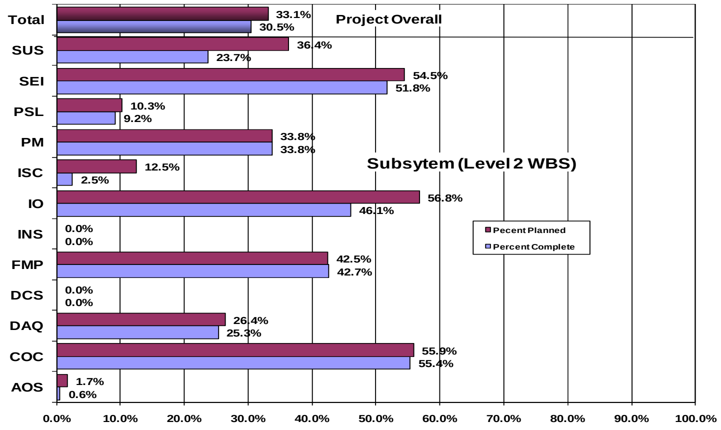
- The Hanford mid-station test mass chambers were uninstalled and transported to the end station; the replacement spool pieces were installed and leak checked, and the system is again at vacuum
- Making all instruments 4km long

Installation

- Removal of one of the initial LIGO Input Optics beam tubes; the replacement tube is larger in diameter, allowing a more flexible optical layout of beams in the mode cleaner.

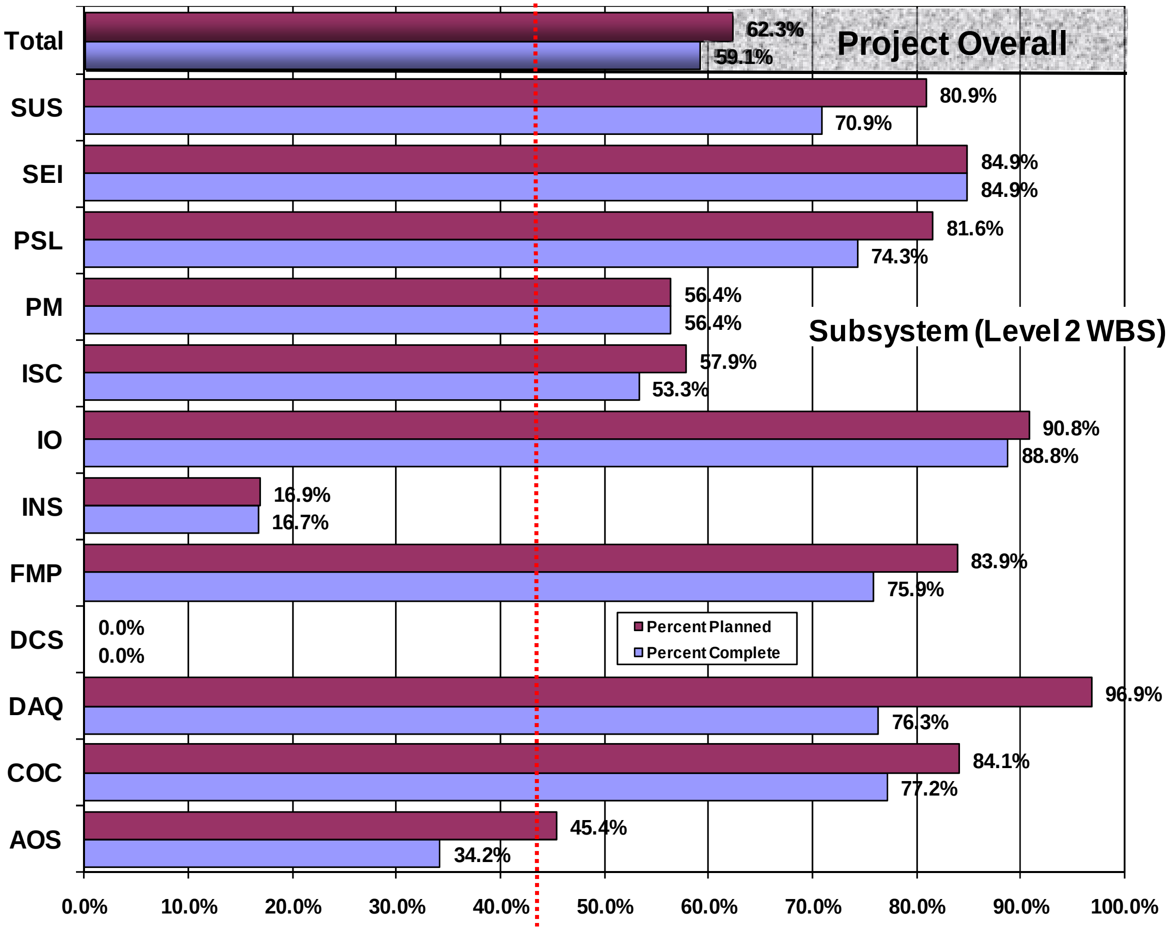
- Vacuum chambers were moved at both LHO and LLO to their new Advanced LIGO positions.

How far along are we?



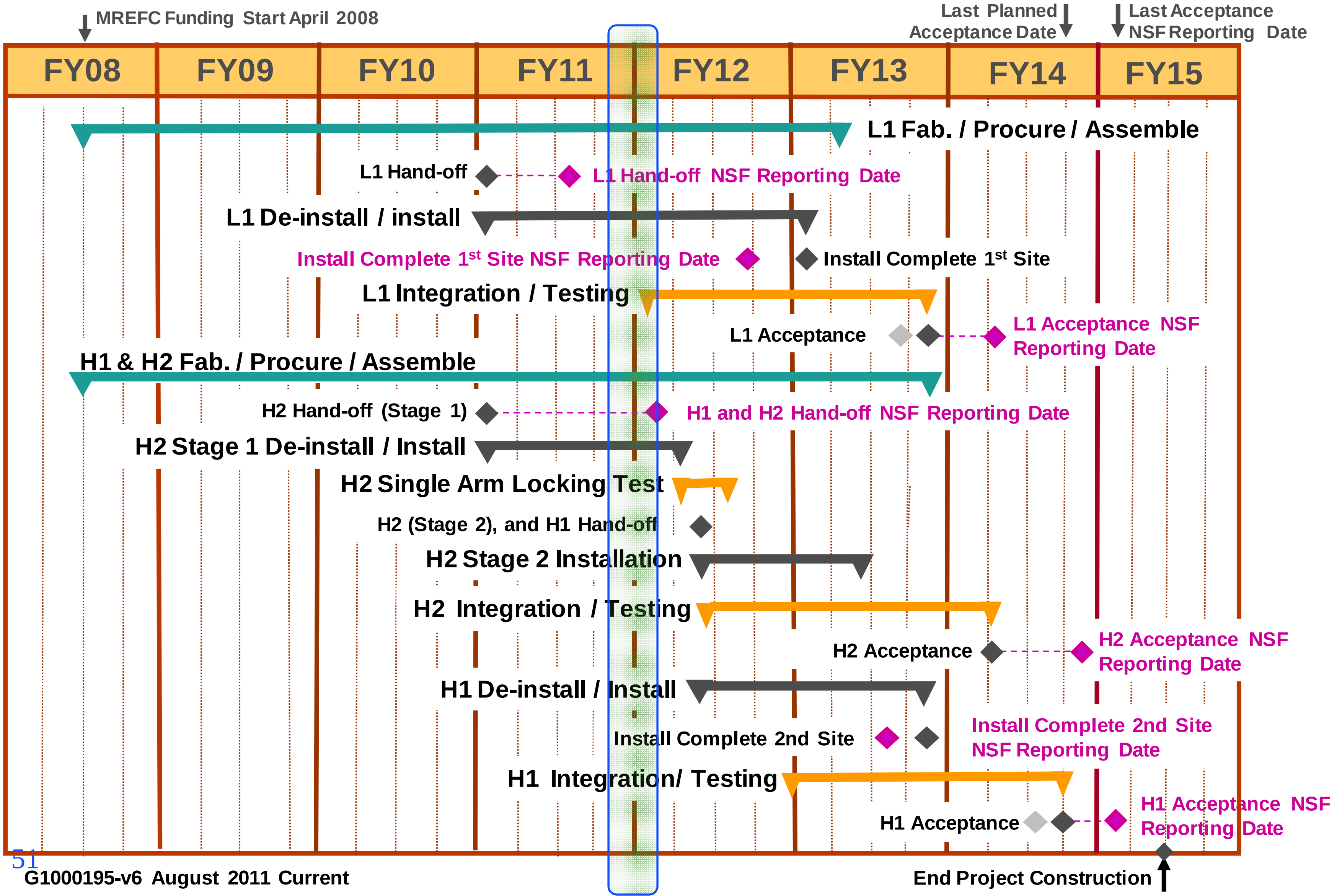
June’10

Aug 2011



- All subsystems >50% complete (except AOS…)
- Data Analysis and Storage Computers (DCS) are just in time at end of construction.

Overall Advanced LIGO Schedule



MREFC Funding Start April 2008

Last Planned Acceptance Date

Last Acceptance NSF Reporting Date

FY08 FY09 FY10 FY11 FY12 FY13 FY14 FY15

L1 Fab. / Procure / Assemble

L1 Hand-off

L1 Hand-off NSF Reporting Date

L1 De-install / install

Install Complete 1st Site NSF Reporting Date

Install Complete 1st Site

L1 Integration / Testing

L1 Acceptance

L1 Acceptance NSF Reporting Date

H1 & H2 Fab. / Procure / Assemble

H2 Hand-off (Stage 1)

H1 and H2 Hand-off NSF Reporting Date

H2 Stage 1 De-install / Install

H2 Single Arm Locking Test

H2 (Stage 2), and H1 Hand-off

H2 Stage 2 Installation

H2 Integration / Testing

H2 Acceptance

H2 Acceptance NSF Reporting Date

H1 De-install / Install

Install Complete 2nd Site

Install Complete 2nd Site NSF Reporting Date

H1 Integration/ Testing

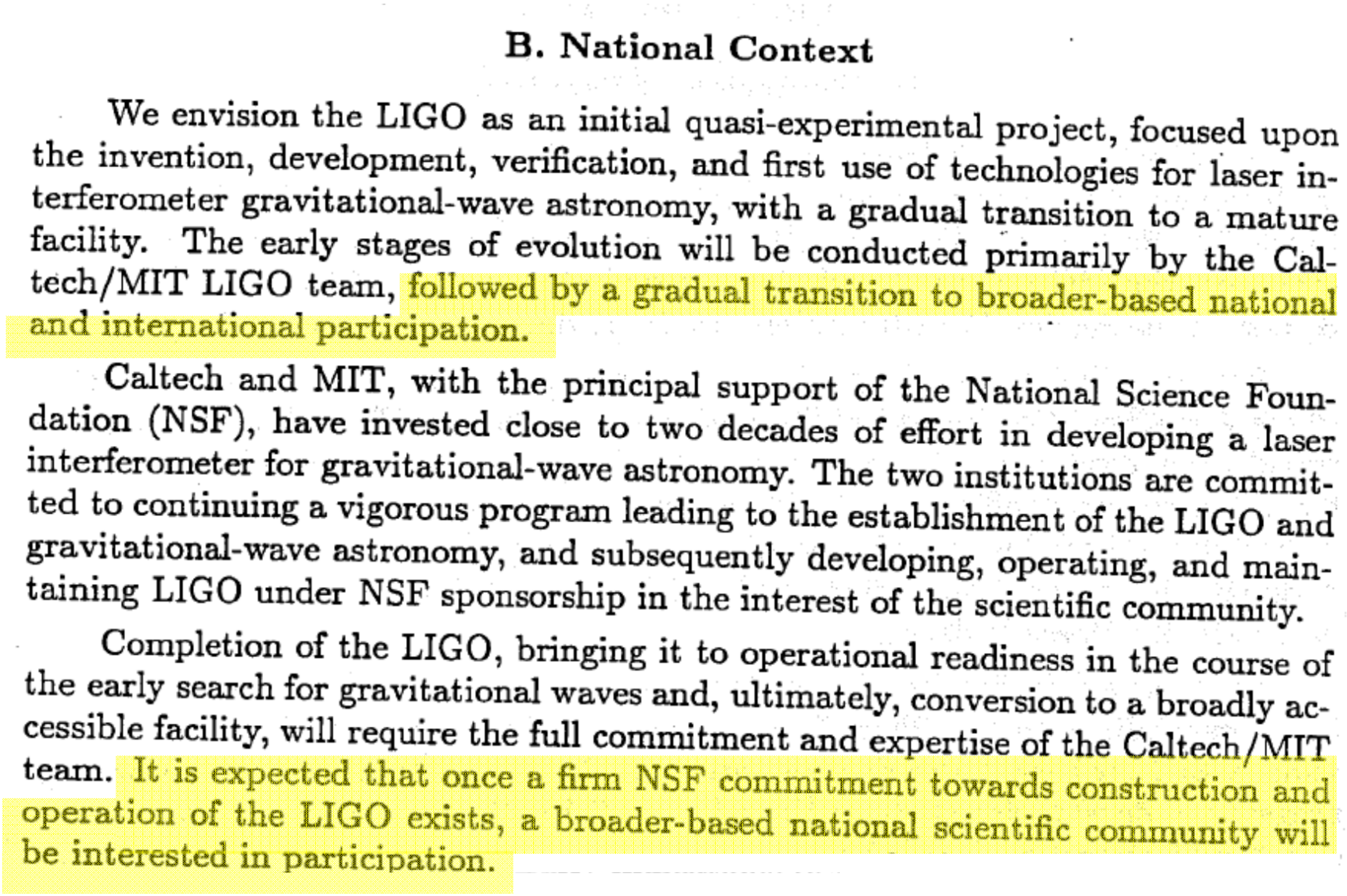
H1 Acceptance

H1 Acceptance NSF Reporting Date

End Project Construction

G1000195-v6 August 2011 Current

LIGO in the larger context, 1989 Proposal



B. National Context

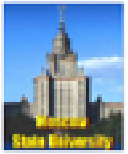
We envision the LIGO as an initial quasi-experimental project, focused upon the invention, development, verification, and first use of technologies for laser interferometer gravitational-wave astronomy, with a gradual transition to a mature facility. The early stages of evolution will be conducted primarily by the Caltech/MIT LIGO team, followed by a gradual transition to broader-based national and international participation.

Caltech and MIT, with the principal support of the National Science Foundation (NSF), have invested close to two decades of effort in developing a laser interferometer for gravitational-wave astronomy. The two institutions are committed to continuing a vigorous program leading to the establishment of the LIGO and gravitational-wave astronomy, and subsequently developing, operating, and maintaining LIGO under NSF sponsorship in the interest of the scientific community.

Completion of the LIGO, bringing it to operational readiness in the course of the early search for gravitational waves and, ultimately, conversion to a broadly accessible facility, will require the full commitment and expertise of the Caltech/MIT team. It is expected that once a firm NSF commitment towards construction and operation of the LIGO exists, a broader-based national scientific community will be interested in participation.

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- CSU Fullerton
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics



- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Tsinghua University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

The Last Page

- US Observatories established with the reliable and enthusiastic support of the National Science Foundation
- Initial instruments worked pretty well, but...no signals.
- There is a range of anticipated astrophysics accessible to the next generation of instruments, especially in concert with other instruments
  - » and some surprises waiting for us, I hope
- The Advanced LIGO detectors are coming along nicely
  - » …but we can be sure there will be more surprises there too before we are done…
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy
- It's a nice place to live!