Advanced LIGO: a half-time show

(ok ok, a 36% show)

David Shoemaker

Presentation structure

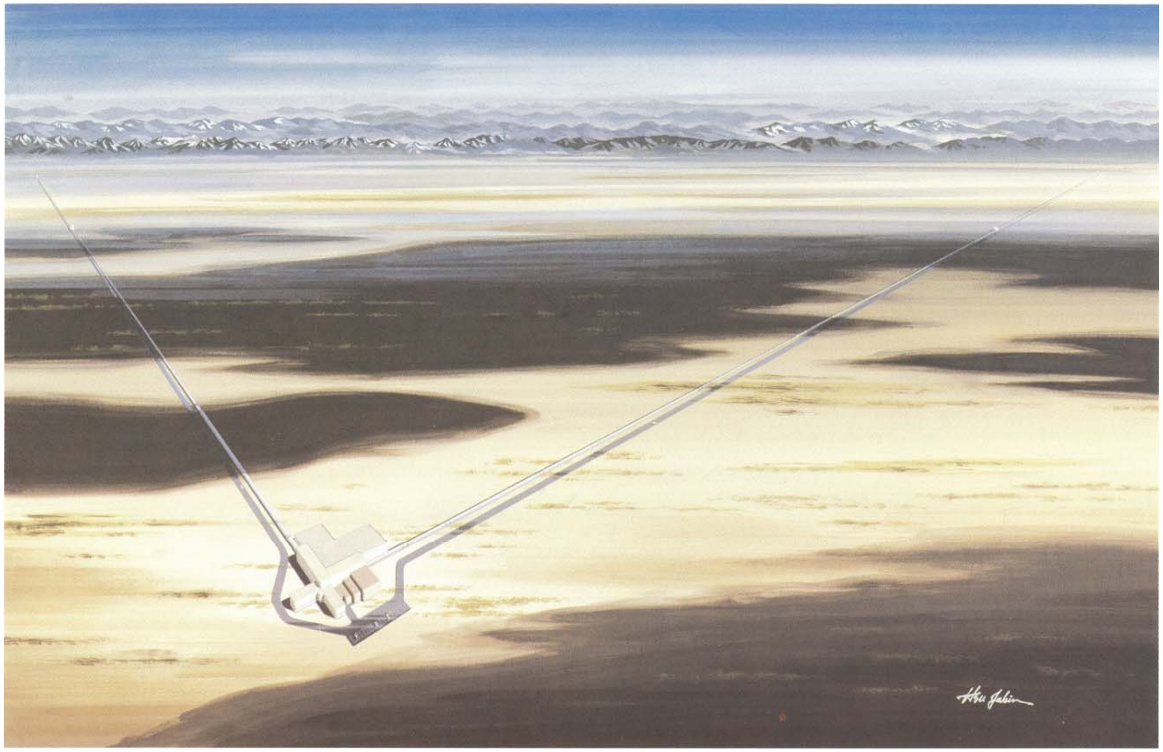
- A very little bit about gravitational waves and their detection, using initial LIGO to set the stage
- Advanced LIGO (aLIGO) Motivation and technical opportunities, constraints
- Snippets of history and chronologies where interleaved
- A description of the Advanced LIGO project structure
- Current project and technical status
- Lessons learned

LIGO: 1989 Proposal to the NSF

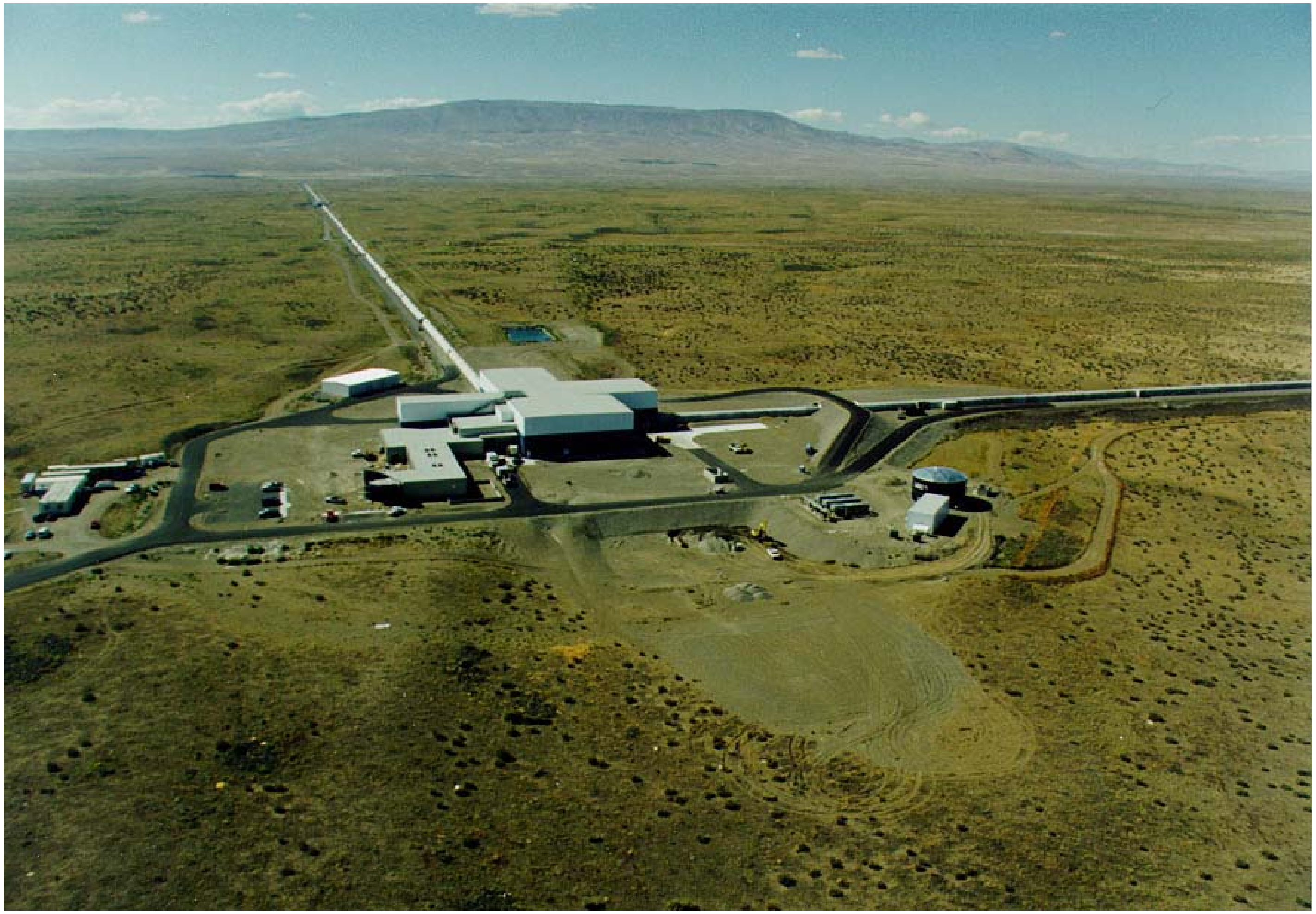
PREFACE

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.

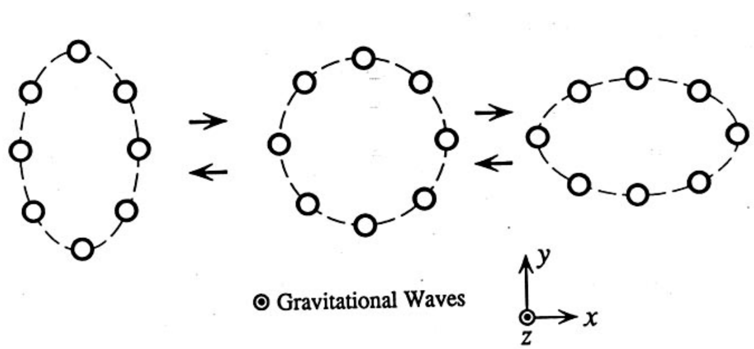


LIGO:
Today, Washington state…



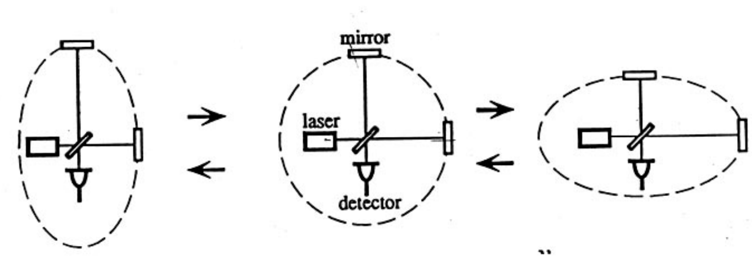
...LIGO in Louisiana

Gravitational Waves



Gravitational waves are "ripples in space-time", quadrupolar distortions of distances between freely falling masses…

…measured in **strain h=ΔL/L.** Michelson-type interferometers can detect these space-time distortions



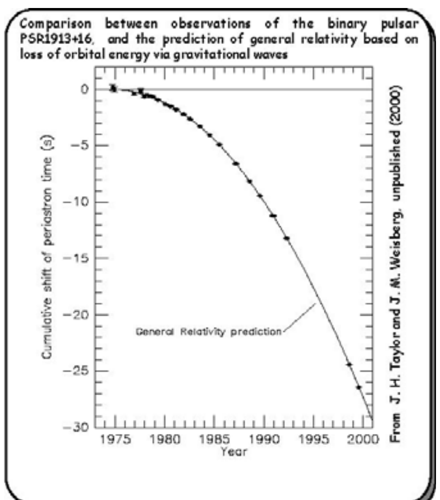
$$h \sim \frac{G\ddot{Q}}{c^4 r} \sim \frac{G(E_{\rm kin}^{\rm non-symm.}/c^2)}{c^2 r}$$

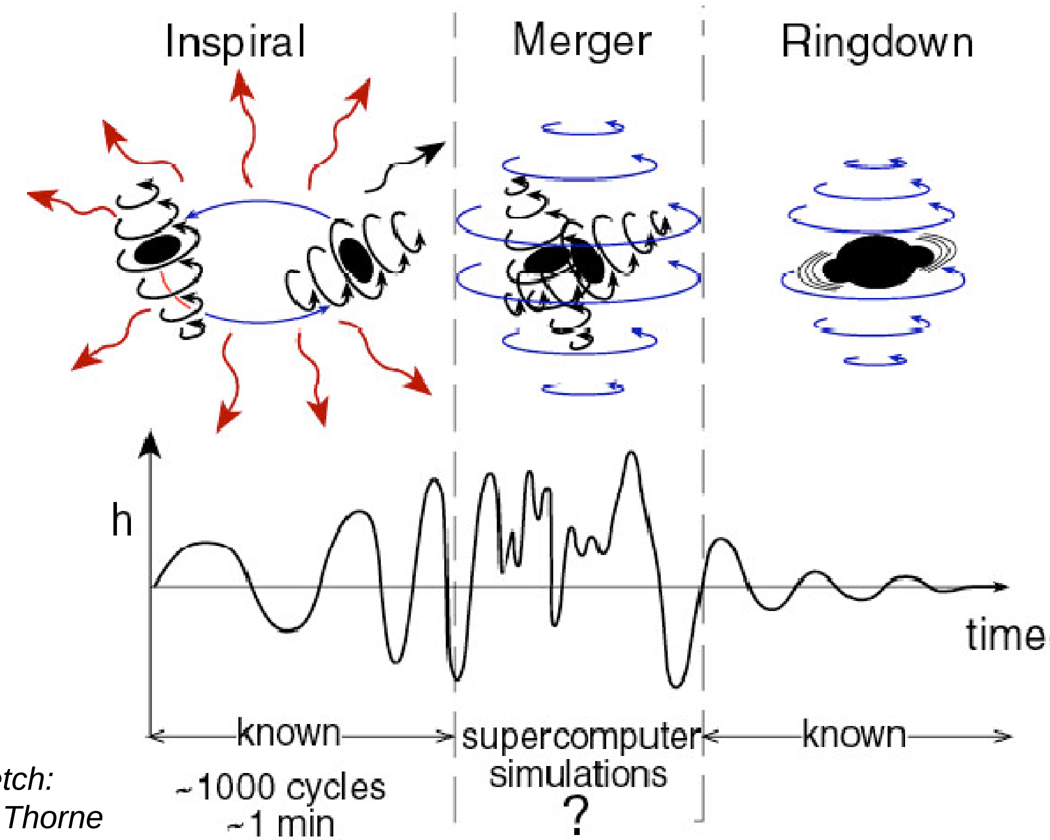
- General Relativity predicts GWs from accelerating masses, but space-time is 'stiff':
  - Only astrophysical-scale masses can make measurable signals
- Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have **h=~ Δ L/L~10^{-21}**

Binary Inspirals

- Early ‘chirp’ and resulting black hole ‘ringing’ are believed to be well known and a good source for detection templates
- Can learn about the complicated GR in the middle…
- Can combine with EM observations to test GR, do cosmology

Credit: Jillian Bornak

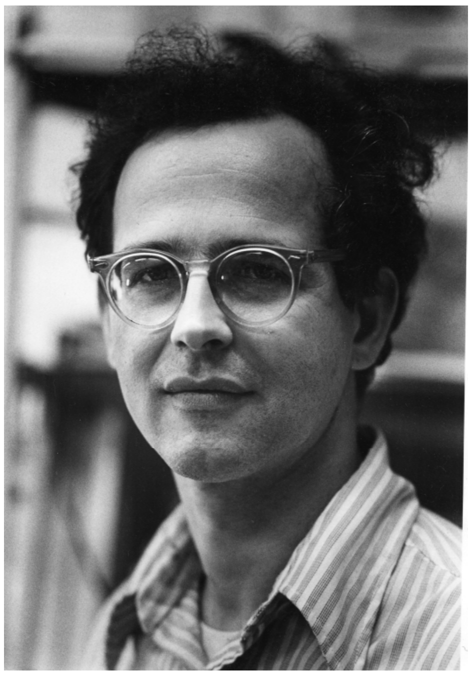




Sketch: Kip Thorne

Interferometry for Gravitational Wave detection

- Rainer Weiss of MIT



QUARTERLY PROGRESS REPORT
APRIL 15, 1972
No. 105

ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

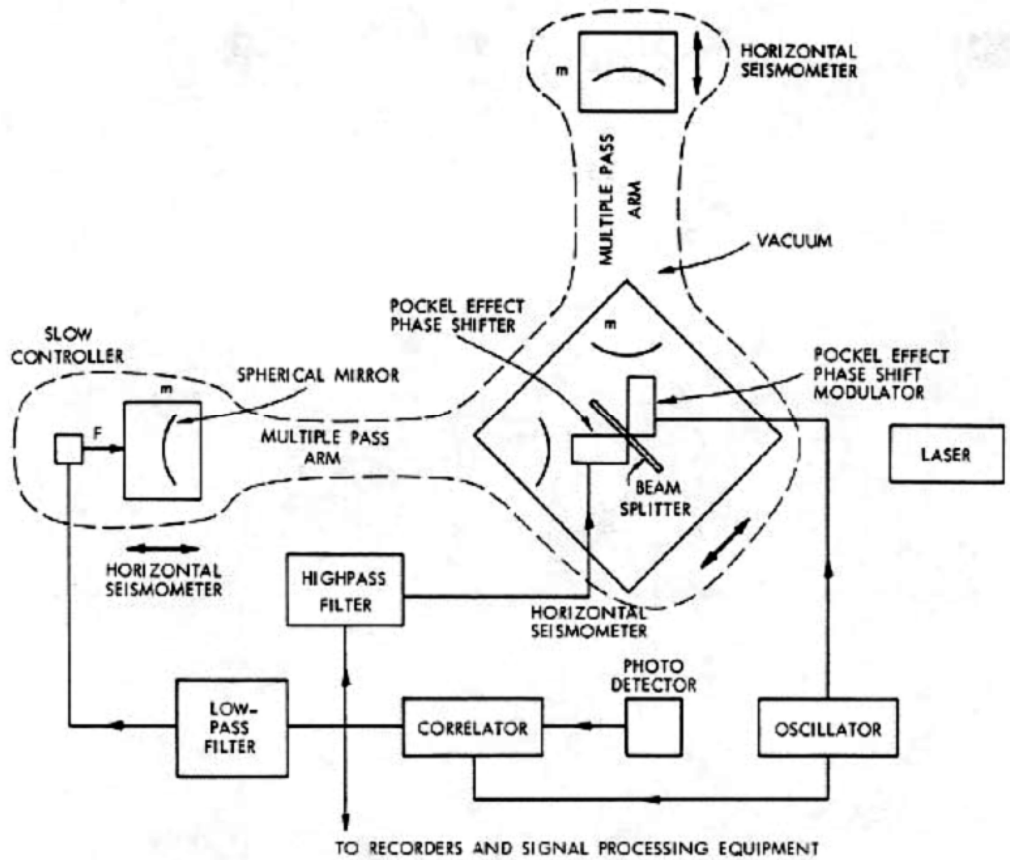


Fig. V-20. Proposed antenna.

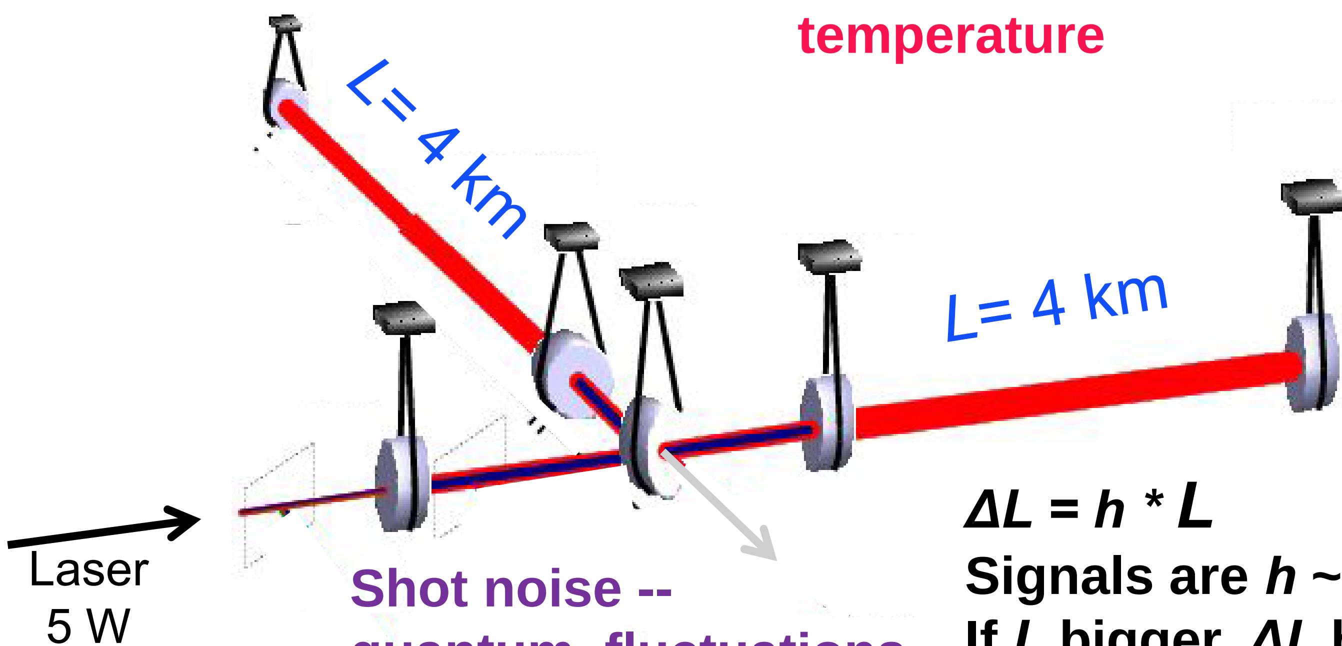
Pause for historical note

- The field of GW detection started out with Joseph Weber
  - » Used instrumented aluminum bars
  - » Thought he saw something, did not really, published, and found himself defending the ‘observation’ with theory that did not hold water – so we are now VERY cautious about what we claim!
- Weiss (and a few others independently) came up with the notion of laser interferometry for GW detection
  - » Intrinsically better – broadband, limits to sensitivity much better
- Started out as tabletop experiments, with groups at MIT, Munich, and then Glasgow; followed by activity at Caltech, Paris, Pisa
  - » Small science culture, some competition, some cooperation
- But the realities of practical instruments drove a move to Big Science…

Practical considerations, big impacts

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

Thermal noise -- vibrations due to finite temperature



Shot noise -- quantum fluctuations in the number of photons detected

$\Delta L = h * L$

Signals are $h \sim 10^{-21}$

If L bigger, ΔL bigger

if have $L \sim 4$ km, then

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

A little more history

- …and the light needs to travel in a vacuum to avoid path length fluctuations…
- So: Two arms, 4 km long, with a 1m diameter beam tube, laid out in a straight line, in a quiet place, with two separated observatories for triangulation and environmental independence….

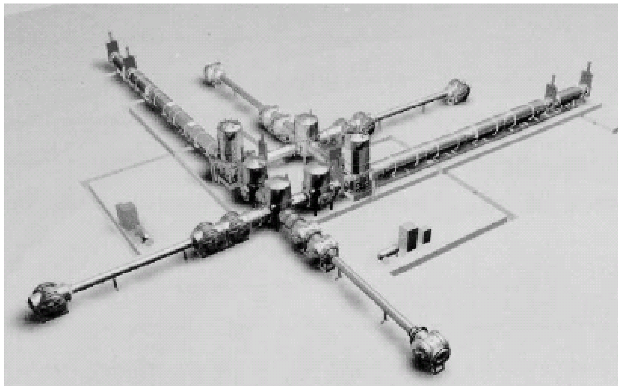
- Weiss saw need to scale up very significantly, the NSF agreed
- Big Science needed
- Most of the original crowd left the scene rather than 'convert'
- Picked up Big Science experienced Management (Gary Sanders and Barry Barish), got real money from the NSF, and got going in mid-'90s

- LIGO came into being.

LIGO Infrastructure: 4km Beam Tube

- 1.2 m diameter
  - Diffraction-limited beam size over 4km sets scale
  - 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
- 10^{-9} torr
- Cover needed (stray bullets….stray cars)

LIGO Infrastructure: Vacuum Equipment



Designed to accommodate sizable Seismic Isolation, and Suspension systems

LIGO Infrastructure: Buildings, Labs, offices

- High bays, extensible to additional interferometers
- HEPA filtered air, temperature and humidity controlled
- Labs, shops, offices, auditorium, outreach center

LIGO Laboratory for Initial LIGO

- The LIGO Laboratory grew to ~180 people through this process, MIT and Caltech as parent institutions
- Caltech as fiduciary responsible to NSF, ~90 persons
  - » Most of the engineering staff
  - » Most administration/bookkeeping/project controls
  - » A core of scientists
- MIT, mostly scientists/students, ~30 persons
- Hanford and Livingston Observatories, ~30 persons each
  - » Some scientists and post-docs
  - » Some engineers
  - » A handful of instrument operators with technical backgrounds

- There were a lot of interested persons outside of the Lab, but no clear-cut way to get involved

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.

Led to the creation of The LIGO Scientific Collaboration (LSC)

- The LSC carries out the scientific program of LIGO – instrument science, data analysis.
- The 3 LIGO interferometers and the GEO600 instrument are analyzed as one data set (also share our data with French-Italian Virgo)
- Approximately 800 members
- ~ 50 institutions including the LIGO Laboratory
- Participation from (at least) Australia, Germany, India, China, Korea, Italy, Hungary Japan, Russia, Spain, the U.K. and the U.S.A.

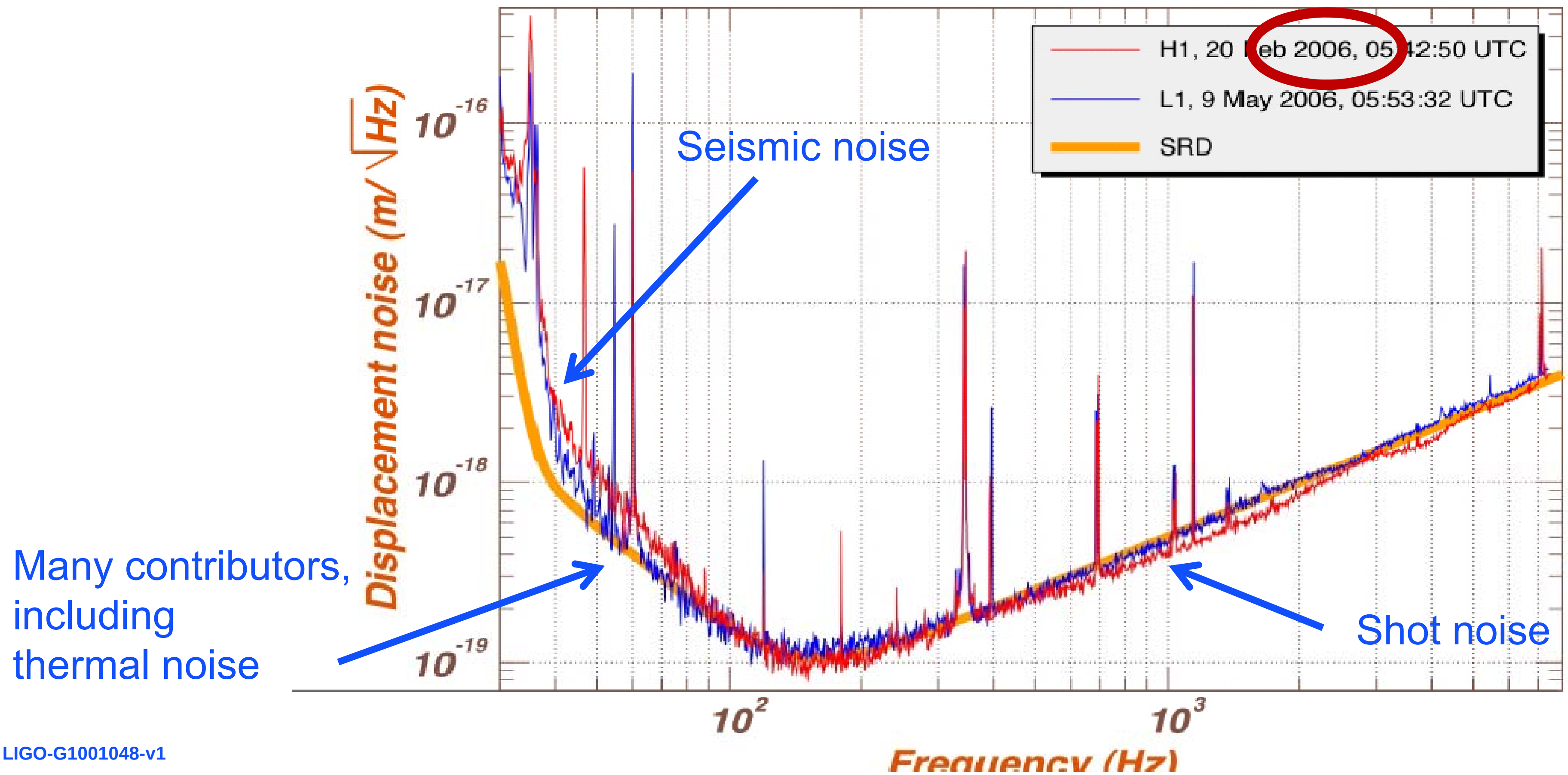
LSC Roles

- Supplies the bulk of the Data Analysis effort, a lot of the computing resources needed
- Was instrumental in undertaking R&D for next-generation instruments and developing a coherent concept
- An Open Collaboration – but with responsibilities and structure
  - » Members perform science observing shifts at observatories
  - » Do service work in reviewing code, outreach, etc.
  - » Obey strict presentation and publication policies
- Provides a vocal, organized lobby with NSF and the greater scientific community
- LSC members not in the Lab are supported by the NSF or by their own countries' science funding, and some are making capital contributions to aLIGO – leverages Lab/NSF funding nicely
- For now, the only way to get LIGO data is to belong to LSC (or VIRGO collaboration)
  - » will change in the 'observation epoch' to fully open data

Initial LIGO sensitivity goal reached

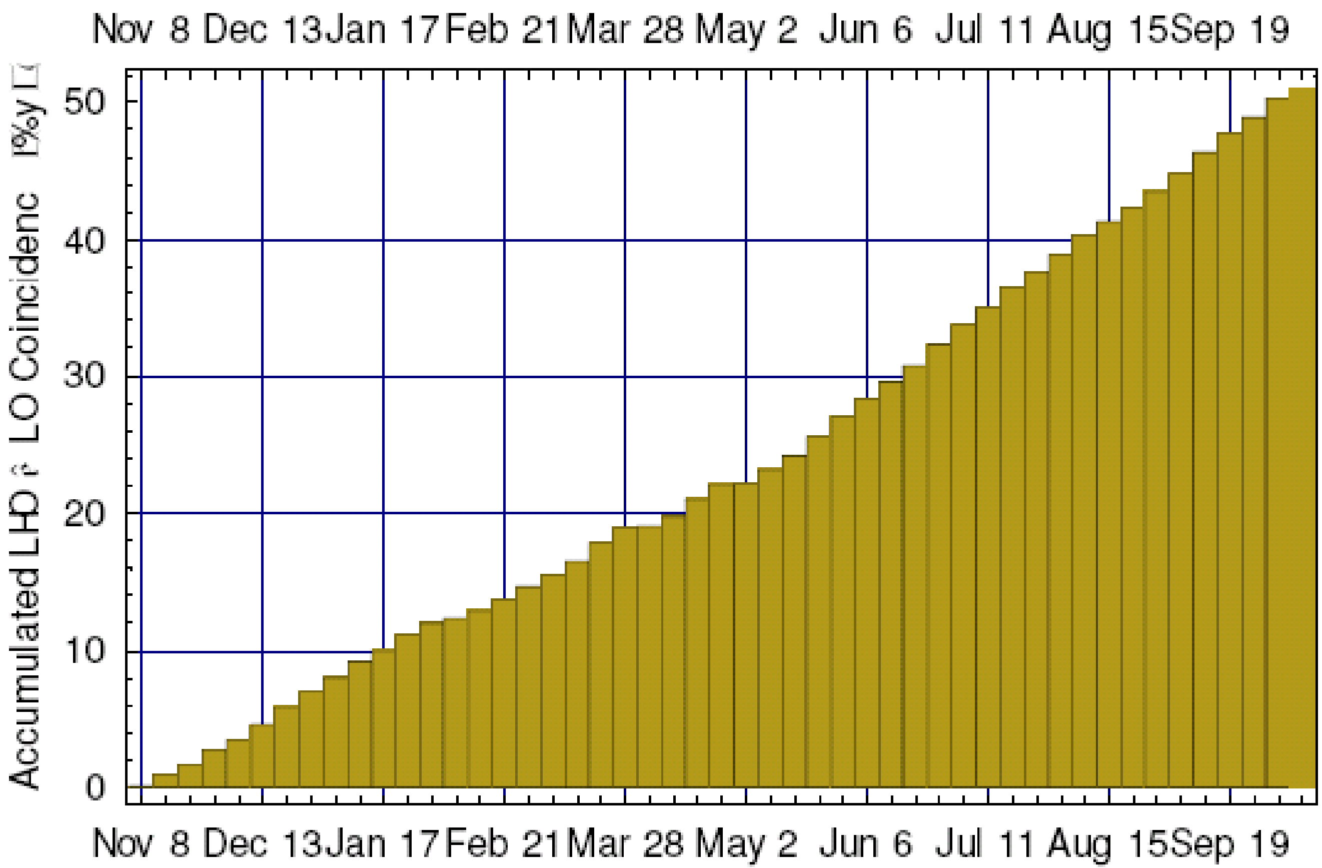
1991: 1st funding
2000: 1st light
2002: 1st run
2005: design sensitivity

- Initial LIGO performance requirement: $h_{RMS} \leq 10^{-21}$ over 100Hz Bandwidth
- Final performance ~ $h_{RMS} \approx 4 \times 10^{-22}$
- **Success! (but it took far longer than we expected)**



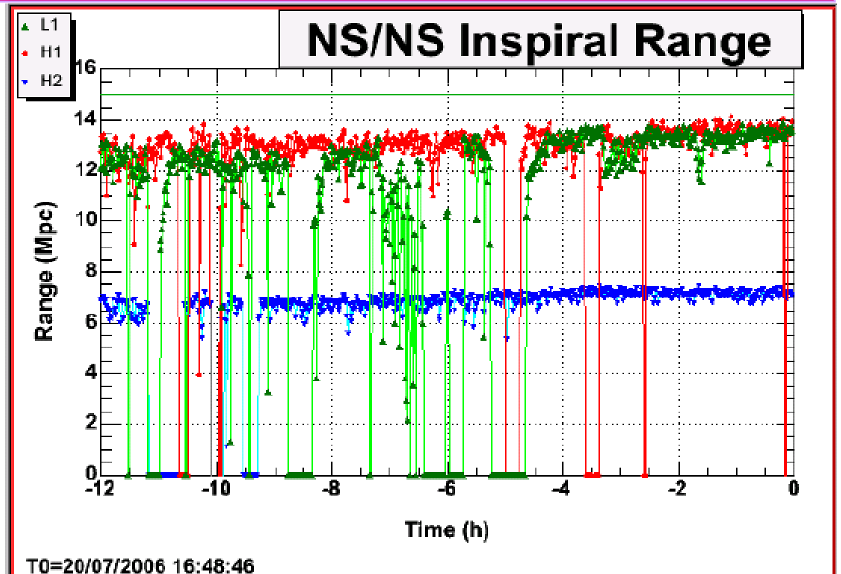
LIGO observed

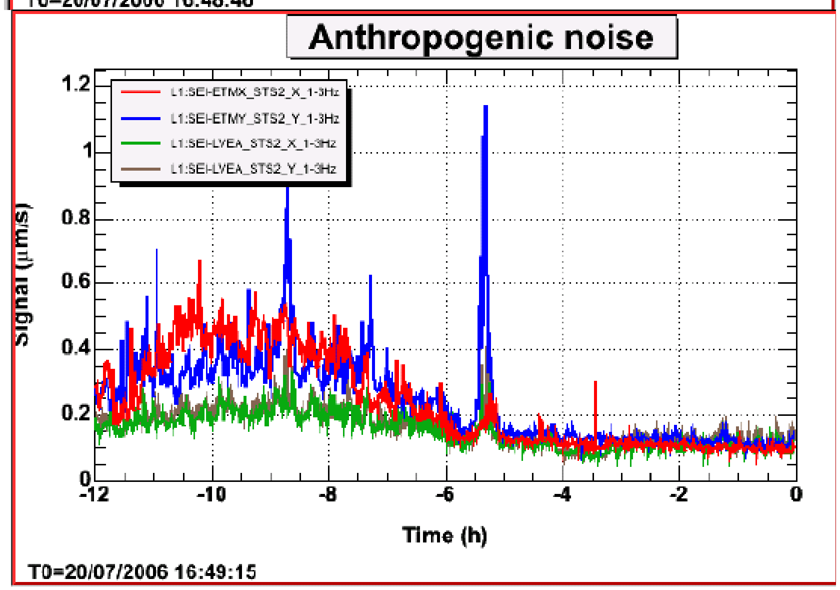
- S5 Science Run to collect one integrated year of data (NSB mandated for Advanced LIGO start) -- ~50% duty cycle, including pauses for tuning and repairs
- S6 'enhanced' Run also recently completed



Astrophysical interpretation of data

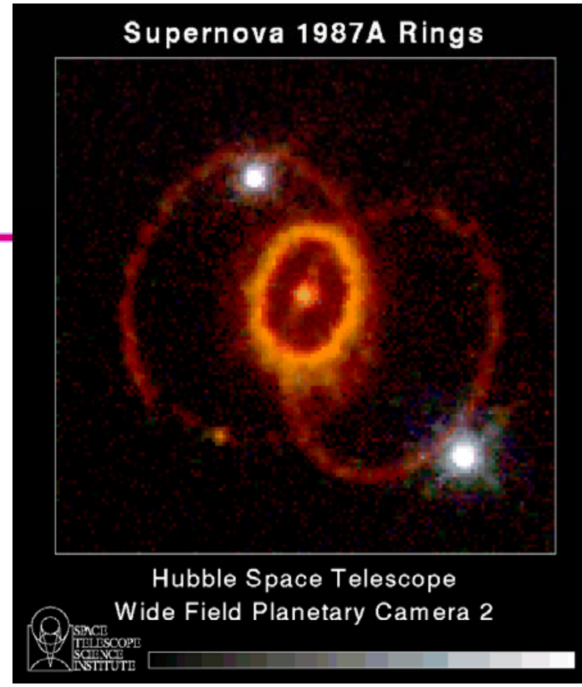
- First effort is to understand instrument and deviations from ideal behavior
  - » Extensive ‘Detector Characterization’ tools and intelligence
- Working groups formed by instrument scientists and analysts, from entire LSC, addressing LIGO and GEO data
- Concentrating on classes of sources:
  - » Bursts, with or without triggers from other observations
  - » Binary inspirals, of various objects
  - » Periodic sources of GWs
  - » Stochastic backgrounds

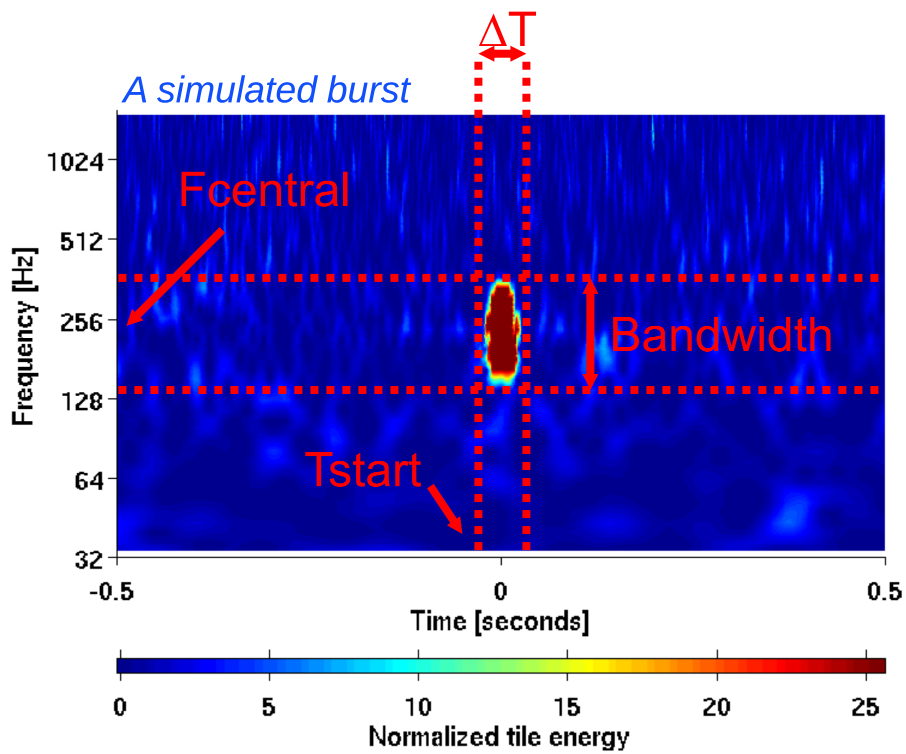




Burst sources

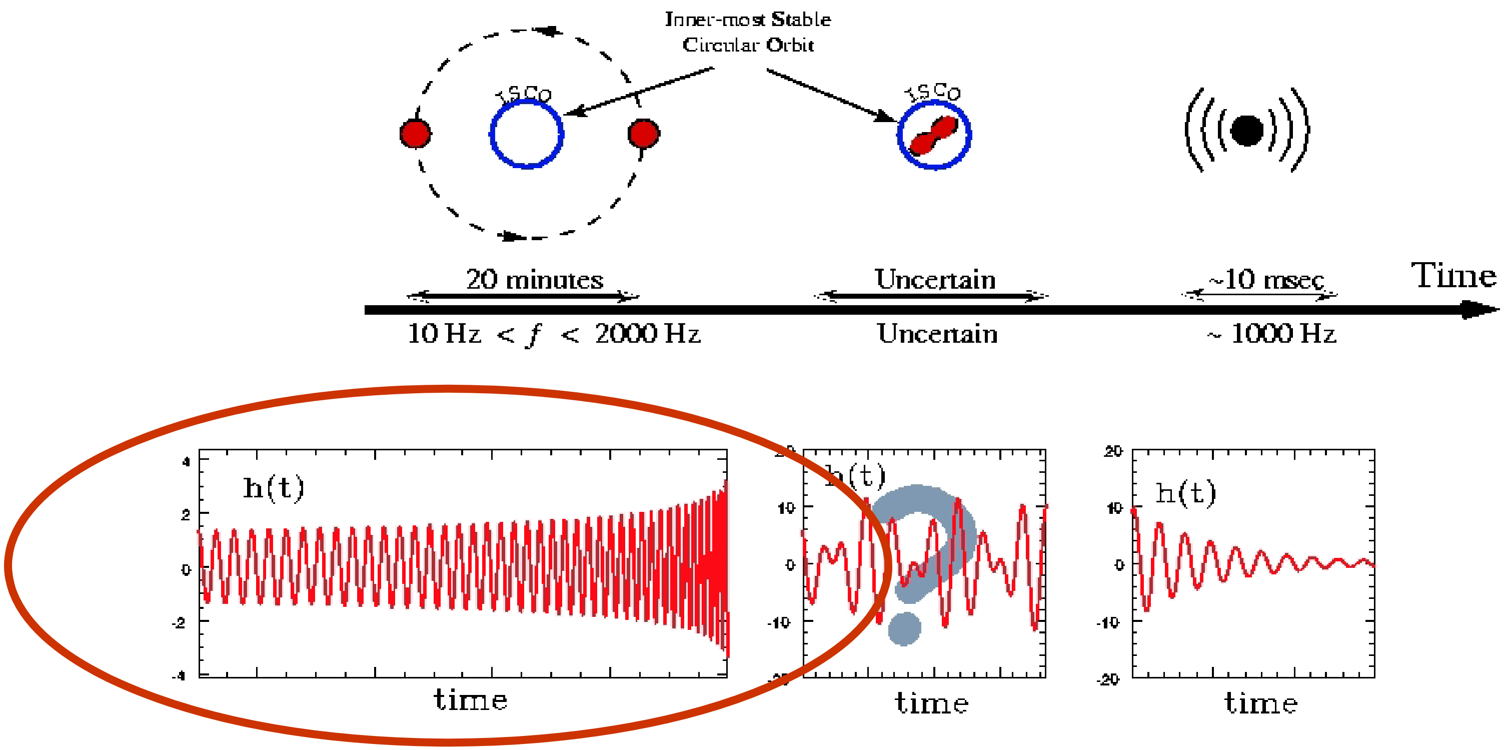
- General un- and ill-defined waveform search
  - » Core-collapse supernovae
  - » Accreting/merging black holes
  - » Gamma-ray burst engines
  - » Kinks/cusps in cosmic strings
  - » …or things we have not yet imagined
- No certain template a priori possible; thus, look for excess of power in instrument
- Require detection in widely separated instruments, time delay consistent with position in sky, and no recognizable instrumental vetoes
- Requires intimate knowledge of instrument behavior!
- Nice also to have a trigger (GRB, neutrino, etc.)



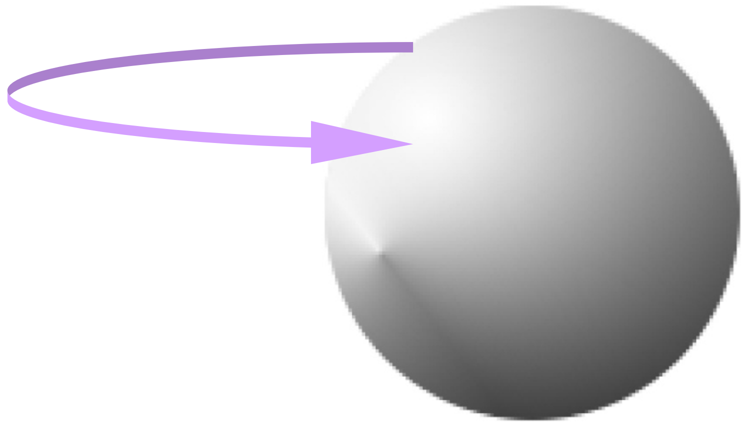


Binary Inspirals

- Neutron star or Black hole binary up to ~70 solar masses
- Template search over best-understood ‘chirp’ section of waveform, gives very good rejection of spuria;
- Can also use GRB as trigger with recent identification with inspirals
- Becomes more complicated with spins….many more templates!



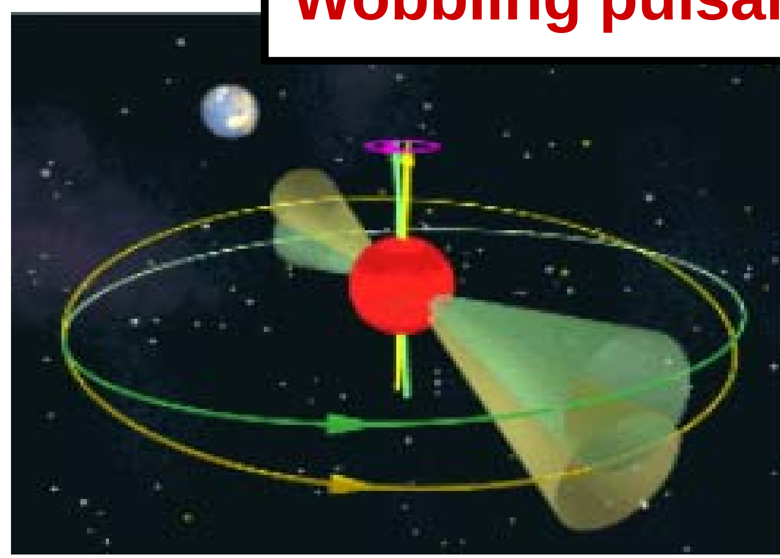
Periodic sources



Bumpy Neutron Star

Low-mass x-ray binary

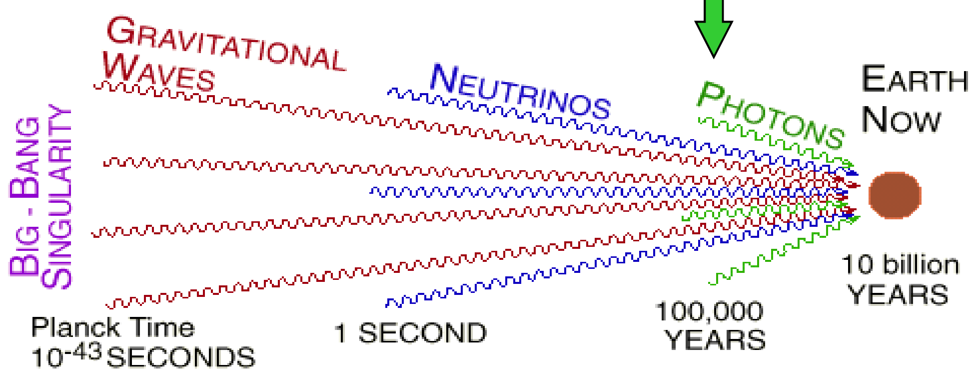
Wobbling pulsars

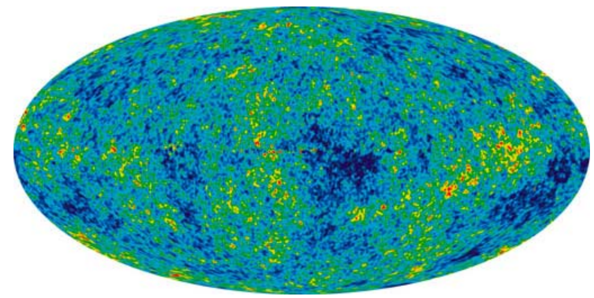


Stochastic sources

cosmic gravitational-wave background (10^{-22}s)

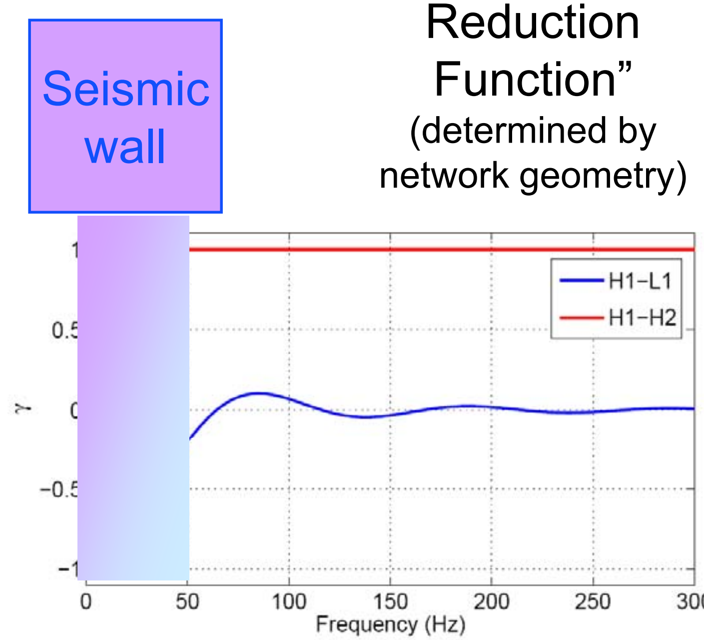
cosmic microwave background (10^{+12}s)





- Cosmological background from Big Bang (analog of CMB) most exciting potential origin, but not likely at a detectable level
- …or, Astrophysical backgrounds due to unresolved individual sources
- All-sky technique: cross-correlate data streams; observatory separation and instrument response imposes constraints

"Overlap Reduction Function" (determined by network geometry)



No signals identified so far.

(there remain data to analyze)

…motivation for Advanced LIGO

- Rate estimates for initial LIGO, while very uncertain, were very low
- Source with best rate estimate (Neutron star binary inspirals) estimated at 1 detectable event per 50 years, plus or minus a power of ten
- We, and the NSF, knew from the start that a more sensitive detector would be needed; infrastructure was planned for it
- R&D in parallel with the initial detector development offered some specific technology paths
- A key question was when to move from R&D to a proposal
- Triggers:
  - » Technical success with the initial LIGO detectors
  - » A community to support both instrument science and data analysis
  - » A mature analysis approach, and an honest search for signals
  - » Technical readiness of a significantly better instrument design

A pause for an Advanced LIGO pre-project chronology

1997-1998

- Jan 1997: First meetings of the community (Aspen Center for Physics) with the objective of coordinating research: sharing of potential technologies, trades within technical domains

- August 1997: First LIGO Scientific Collaboration (LSC) meeting; the community signs up to concept of a constrained focused research program for the greater good.

- March 1998: Some initial concepts of the upgrade floated, small changes to initial LIGO mechanical infrastructure – not yet the vision of complete instrument change; memoranda of understanding (MoU) drafted between the LIGO Laboratory and the LIGO Scientific Collaboration member groups to determine research foci in discussion

1999

- May 99: Key technical element: improved suspension thermal noise estimates, at LSC technical summit; establishment of the noise model and likely limits to performance
- July 99: Consensus on target sensitivity, all LSC input gathered to form plan; moment that the final scope becomes clear
- Sept 1999: LSC white paper completed: First definition of approach, commitments from groups to work through designs and do prototype tests; formalization of LSC input to NSF on what LSC wants to do

2000-2001

- March 2000: Project book assembled, upgrade scenario firm, costs estimated
- August 2000: Projectification: management and professional cost/schedule person/tool applied to estimate costs. Interviews with scientists, mostly with initial LIGO experience in estimating; discussions with NSF on scope, timing of upgrade; tight synchronization of NSF-supported research and the AdvLIGO concept
- August 2001: Naming of Advanced LIGO (instead of LIGO II); plan for taking R&D activities through final design under Operations funding

2002-2003

- March 2002: Cost estimating; refinement of design concepts; concepts sufficiently settled such that discussion in LSC from this point onward is on technical progress, not community building or consensus

- August 2002: Discussion in Lab on timing of proposal – guesses on initial LIGO commissioning and thus astrophysics observation roadmap; readiness of technical elements; readiness/availability of staff; readiness of NSF/funding situation. Concerns about distracting from commissioning of proposal preparation.

- Feb 2003: Proposal submitted; installation planned to start in 2007

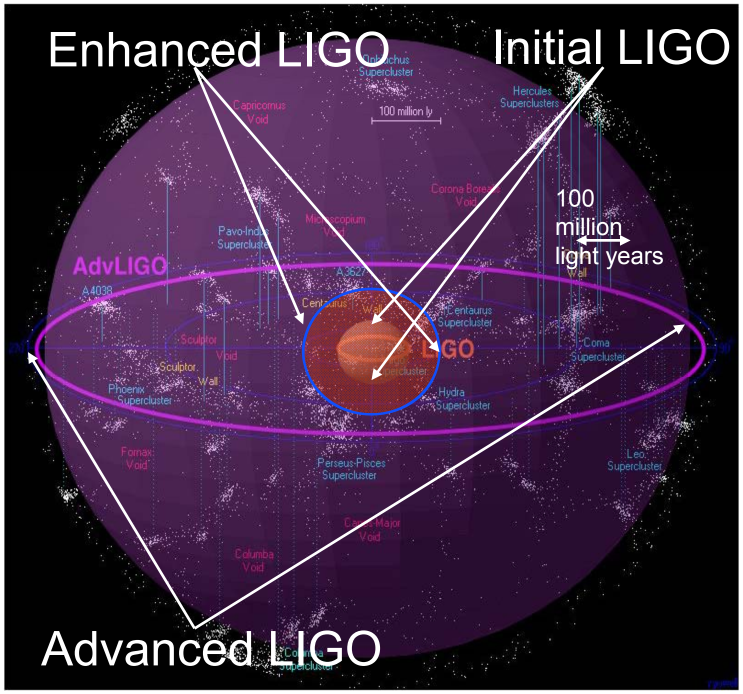
- June 2003: first NSF review and detailed feedback; Advanced LIGO organization takes form, leader named

2004-2008

- Oct 2004: NSB endorsement of proposal; engineering starts in earnest
- 2005: Cost/Schedule/Risk; growing project management structure, discipline; subsystem preliminary design reviews start
- June 2006: Baseline review
- June 2007: Baseline update review
- **April 1** (yes) **2008: Project Start**
  - » A bit more than 10 years after inception
  - » 5 years after proposal first submitted
  - » All that time put to good use in improving technical definition, testing prototypes, building project office, spinning up team

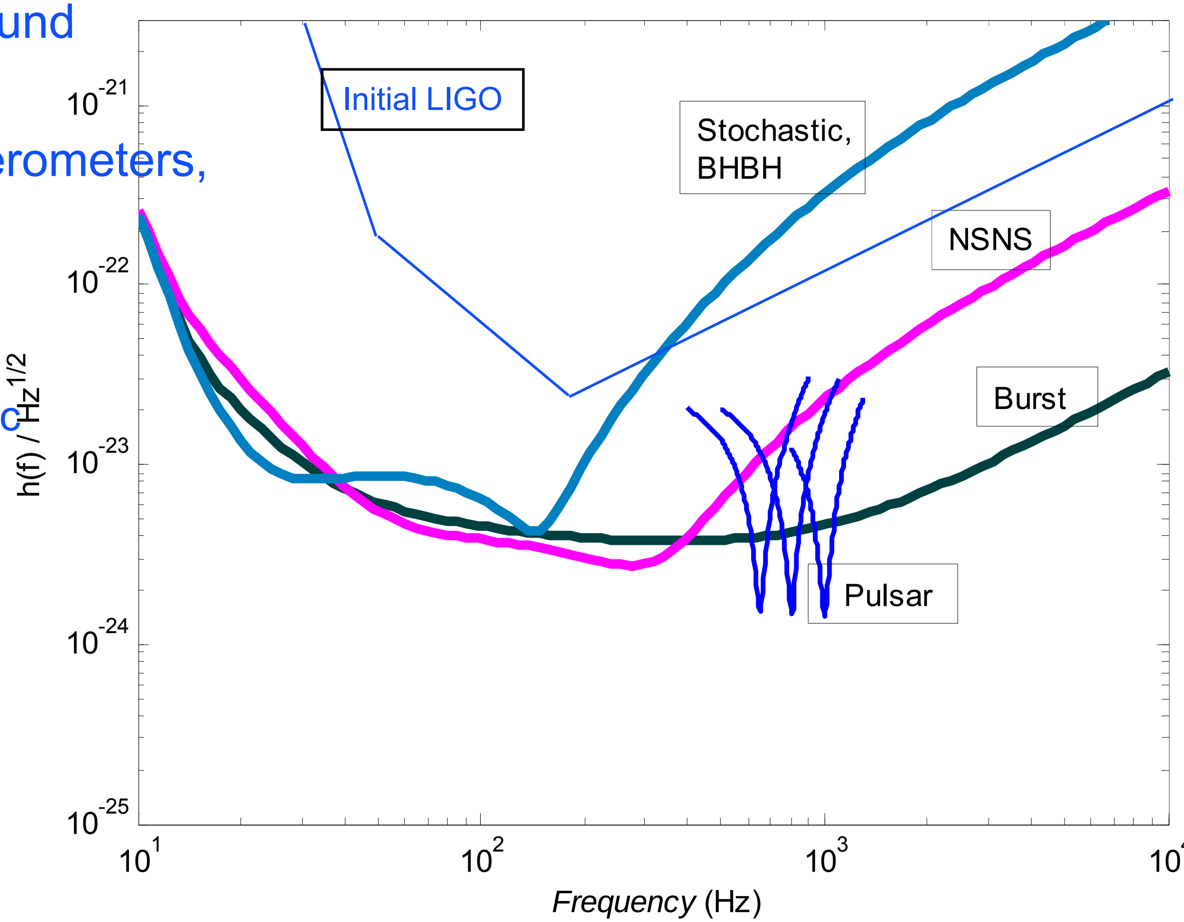
Advanced LIGO

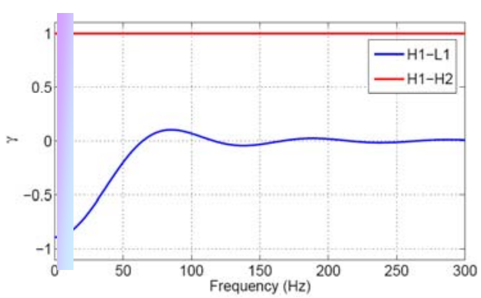
- Factor of 10 greater sensitivity than initial LIGO
- Factor 4 lower start to sensitive frequency range
  - » ~10 Hz instead of ~40 Hz
  - » More massive astrophysical systems, greater reach, longer observation of inspirals
- Intended to start gravitational-wave astronomy
- Frequent detections expected – exact rates to be determined, of course
  - » Most likely rate for NS-NS inspirals observed: ~40/year



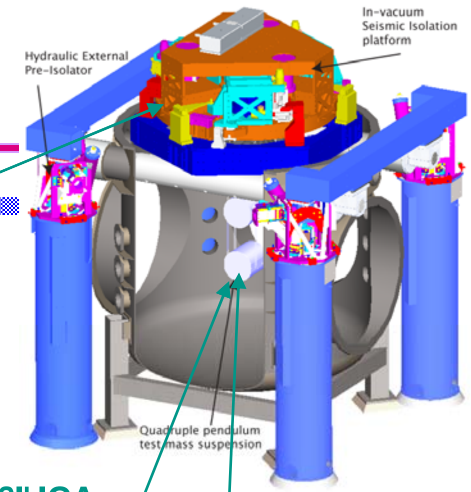
Advanced LIGO sensitivity

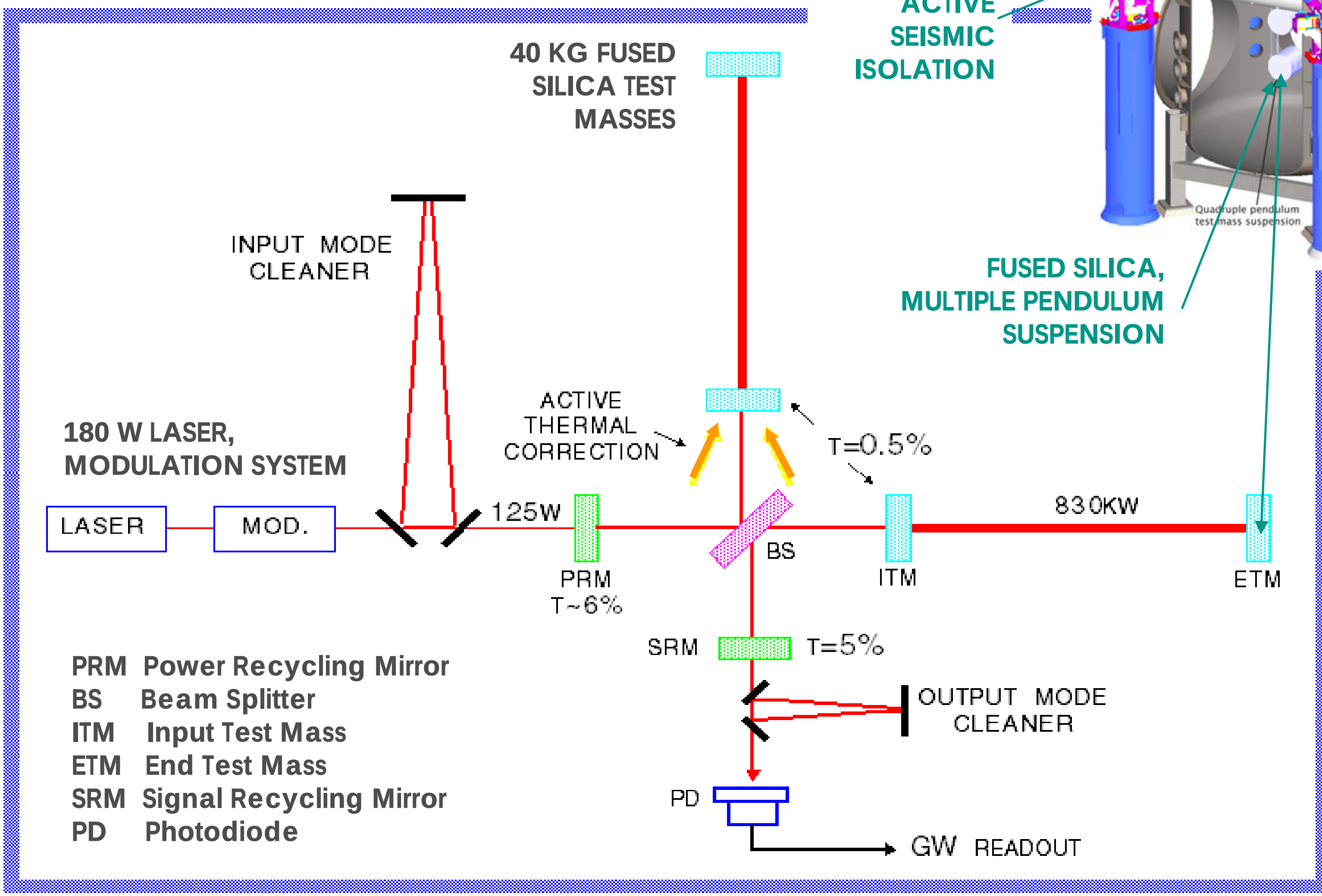
- Factor 10 better amplitude sensitivity
  - » $(\text{Reach})^3$ = rate
- Factor 4 lower frequency bound
- Tunable for various sources
- NS Binaries: for three interferometers,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~300 Mpc
- BH Binaries:
  - » Initial LIGO: 10 M_o, 100 Mpc
  - » Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - » Initial LIGO: ~3e-6
  - » Adv LIGO ~3e-9 (due to improved overlap)



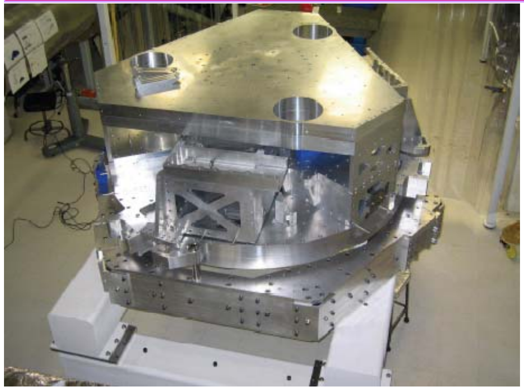


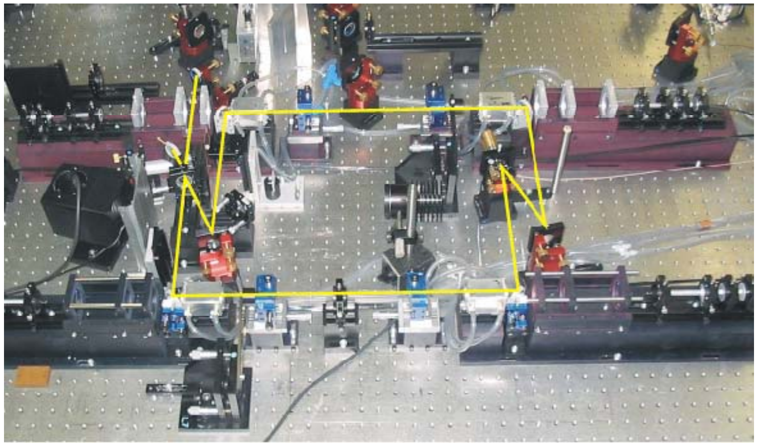
Advanced LIGO Design Features

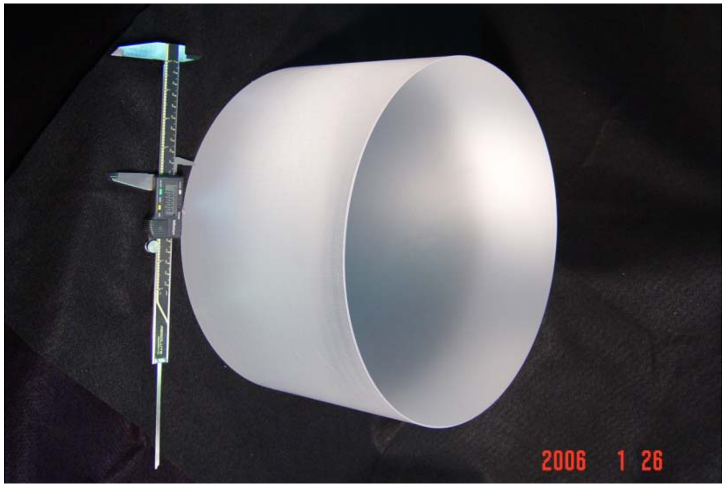




Advanced LIGO equipment







aLIGO technical status

- Baseline design has remained very stable – helps manage costs and schedules
- Projected ultimate sensitivity has bounced up and down by 10% as models are refined, components characterized, but always factor ~3x better than requirement
- Some scope creep due to increasing cleverness, some scope creep due to design difficulties
- Development up to Final Design Review is formally ‘Pre-Project’
  - » Only one subsystem has remaining design work: Auxiliary Optics
  - » A catch-all of baffles, relay telescopes, thermal compensation systems
- Production underway for most all subsystems
- Small to moderate technical problems, bad welds, poor cleaning, sloppy testing protocols, disorganized teams…nothing dramatic.

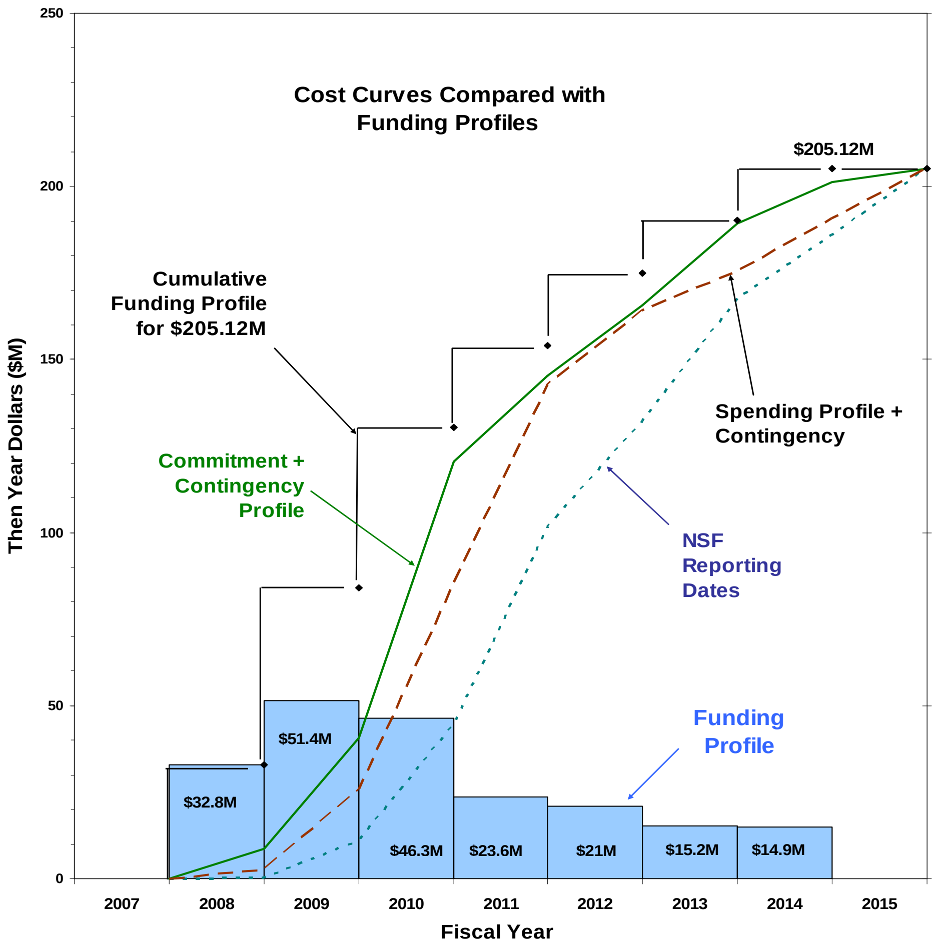
Project Stuff

30,000 feet

- Scope
  - » Replace/Upgrade all detector components for 3 Interferometers
  - » Procurement, Installation, Commissioning to Acceptance
  - » Acceptance criterion - 2 hours locked
- Cost
  - » NSF funded - \$205.12M
  - » UK funded - ~\$7.8M (total with design ~\$14M)
  - » Germany funded - ~\$8.9M (total with design ~\$14M)
  - » Australia funded - ~\$1M pending (total with design \$1.7M)
- Baseline Time Frame
  - » Seven years with schedule contingency: April 2008 - March 2015
  - » Detector Acceptance dates Nov 2014 (includes contingency use)
  - » Data analysis and storage computers / project end – March 2015
- Staffing
  - » ~500 FTE-yrs total
  - » 95% are already at LIGO – existing LIGO operations staff plus uniquely aLIGO hires

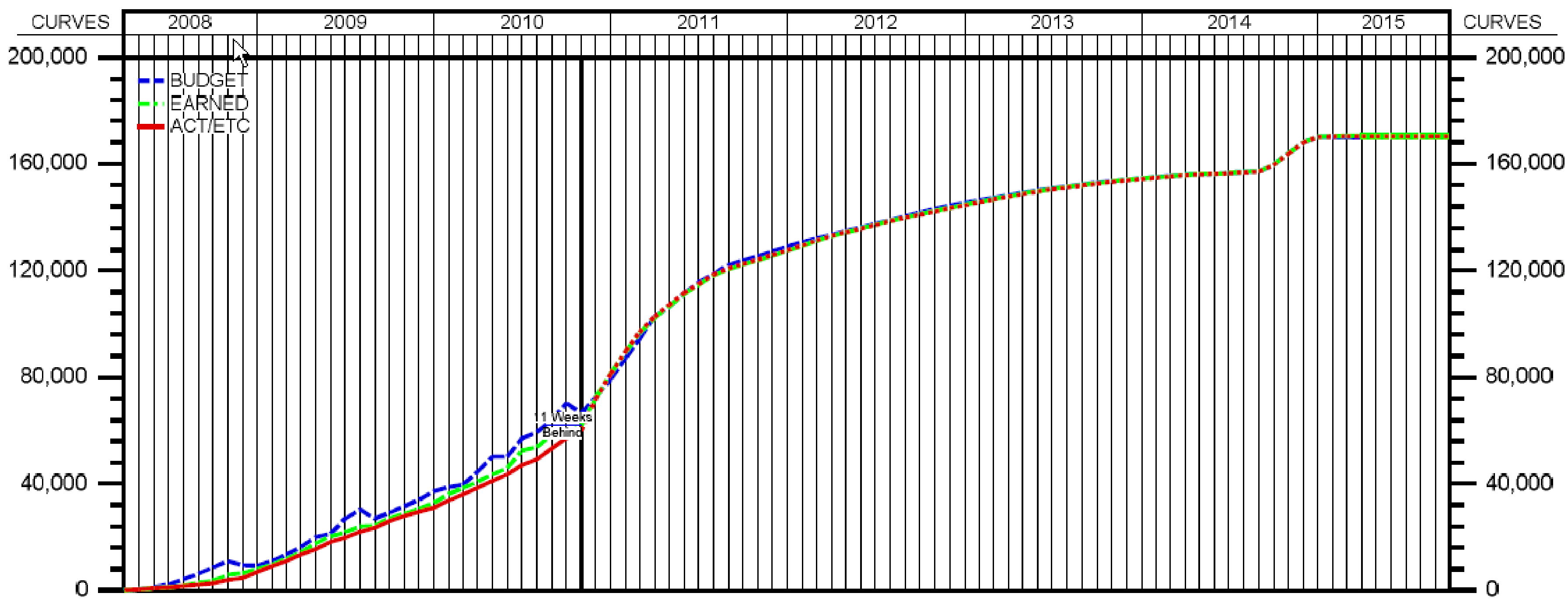
Funding, spending

- Front loaded funding curve allows for baseline activities, contingency usage, and some year-end carryover (continuing resolutions…)
- NSF shifted funding from late in project to FY2011, at our request, to allow flexibility in planning
- Helpful with our accelerated installation/integration plan
- Contingency currently at ~30% of ETC, from initial ~23%
  - » Have had good luck with vendors
  - » Have not had big problems to solve…yet
  - » ….expect to use this up in installation/integration!

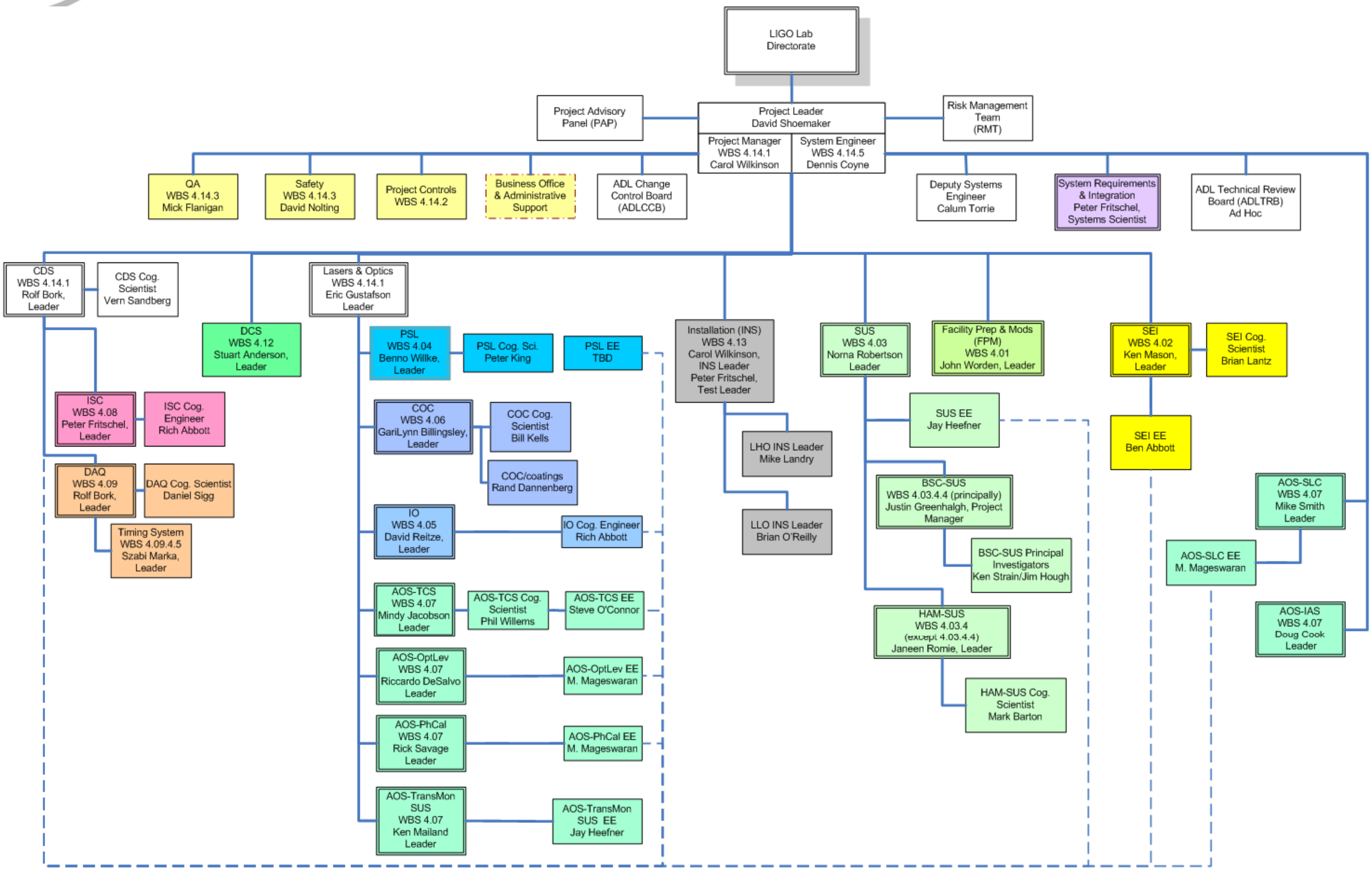


Schedule

- Project is 36% complete against the planned 39% complete (end October'10)
  - » Reflects NSF-approved replanning to move from 'early dates' to 'most likely dates'; breaking up monolithic 'done' into more realistic due dates
  - » Schedule float used; no schedule contingency used to date (ahead of all NSF milestones)



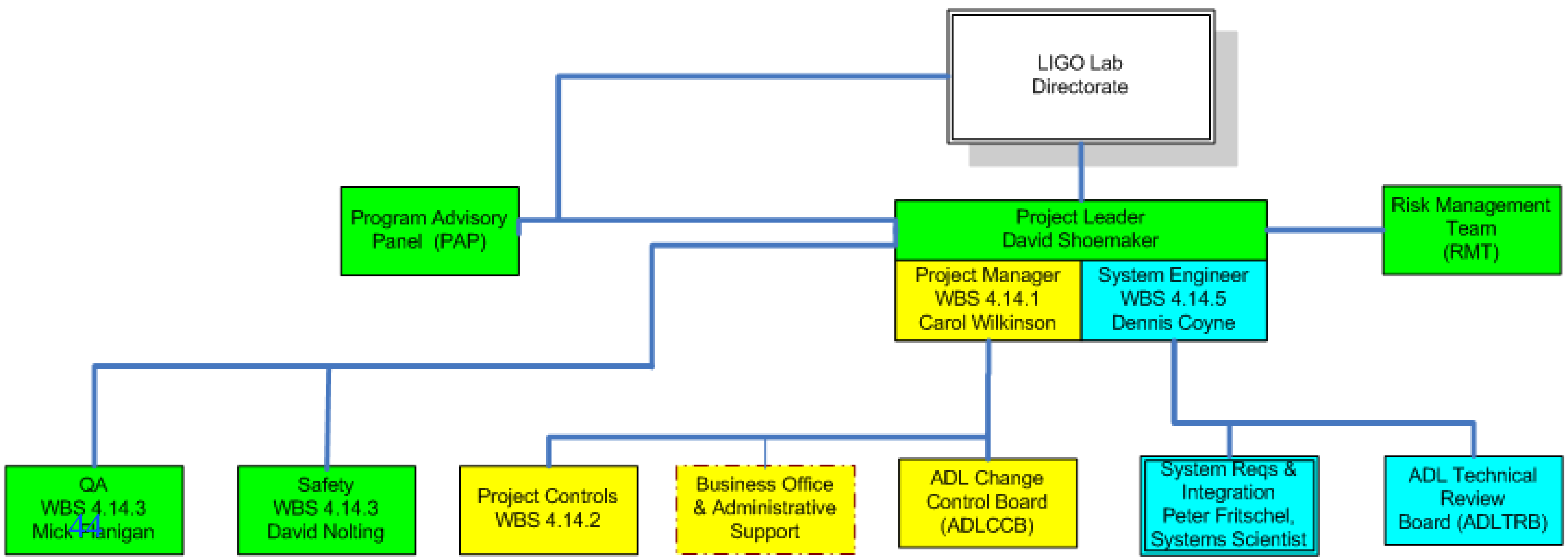
Advanced LIGO Organization



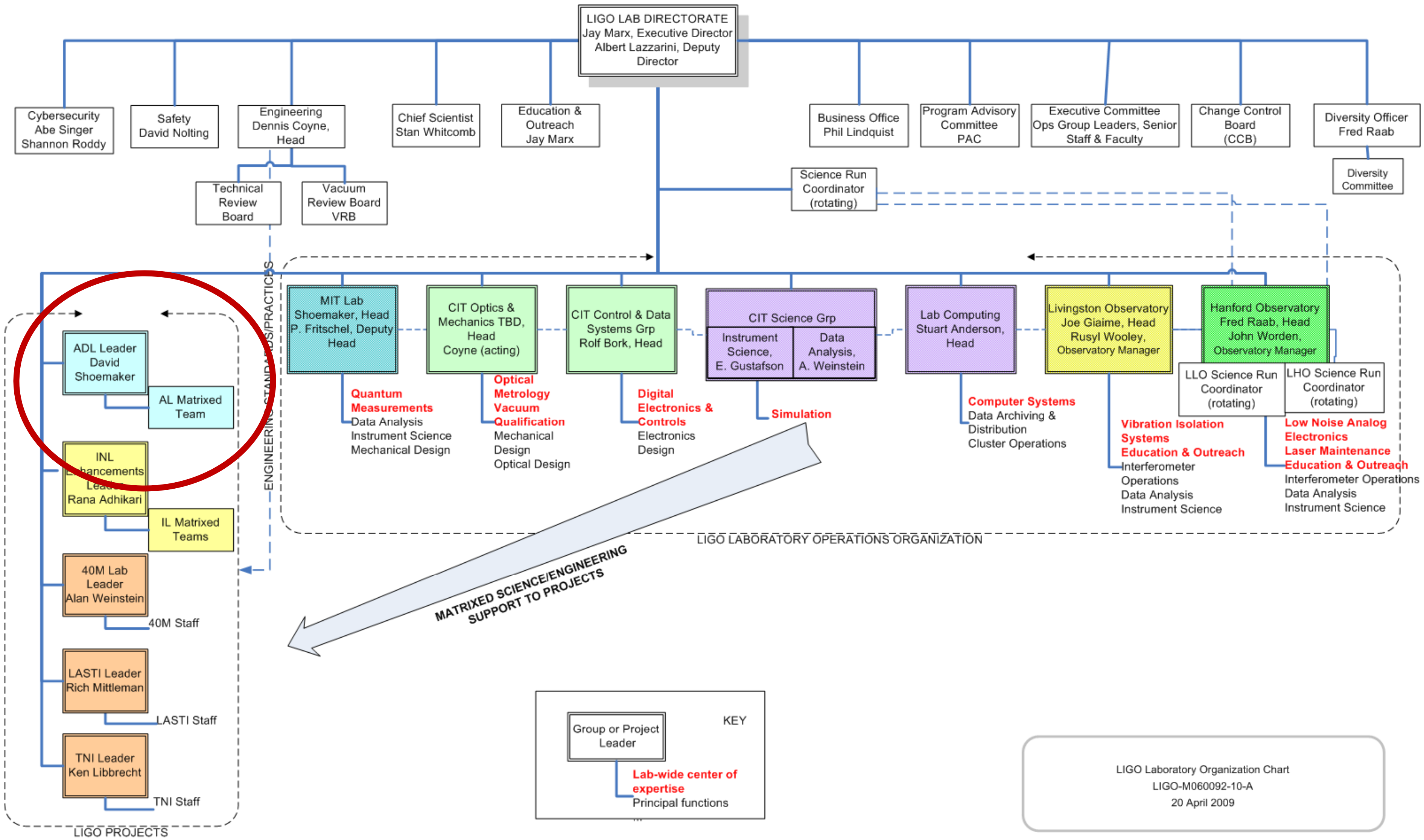
Advanced LIGO Project Organization
LIGO-M070069-v7
6 April 2010

Advanced LIGO Management

- Activities/People reporting to Advanced LIGO Leader: Project Advisory Panel, QA, Safety, Risk Management Team, Project Manager, System Engineer
- …to Project Manager: Subsystems;   Project Controls, Business Office, Change Control Board
- …to System Engineer: Systems group, Technical Review Board
- Top management talks every day (pairs/trios/quads – with Systems scientist)



aLIGO in the context of the LIGOLab



Safety

- I always thought safety was boring. No longer.
- The consequences of accidents for individuals, and the Project, are just too important
- It is part of every Advanced LIGO design
- It is part of every Advanced LIGO process

Risk Management

- Risk managed through Risk Register and Plan
- Monthly review with Eng/Sci leads; maintained by Project Leader
- Useful both for communicating risks and mitigations to NSF, but also as a reminder of what to worry about, what target of opportunity available when e.g., encountering schedule delays elsewhere

				Initial Risk Evaluation								Residual Risk Evaluation							
					Consequence								Consequence						
Risk ID	Risk Contri-butor	Risk Event	Affected System or WBS Level	Prob-ability	Cost	Sched-ule	Perform	Scope	Risk Score	Major Threat List	Completed Mitigation Actions	Prob-ability	Cost	Sched-ule	Perform	Scope	Resi-dual Risk Score	Major Threat List	Open Mitigation Actions
RR-001	P. Willems	If Test masses require aggressive thermal compensation for arm mode control, additional cost and schedule delay may occur.	AOS	1	2	3	2	2	Low	N	Include purchase of additional Hartmann sensors for permanent installation on test masses in plan	1	1	1	1		Low	N	Accept Risk
RR-002	P. Willems	If thermal lensing is both highly inhomogeneous and rapidly varying, then scanning laser compensation is required	AOS	1	2	4	3	2	Low	N	Maintain R&D backup plan for scanning laser compensation	1	2	2	2	2	Low	N	Continue to develop plan; mplement R&D backup plan for scanning laser compensation
RR-003	P. Willems	If thermal compensators inject noise into system, power stability for heater and laser will be required.	AOS	3	2	3	2	2	Med	N	Have backup plan to enhance power stability of ring heater and laser.	3	2	2	2	2	Med	N	Implement backup plan to enhance power stability of ring heater and laser.
RR-004	P. Willems	If thermal compensator sensors inject noise into system, power stability of sensor lasers will need enhancement.	AOS	1	2	2	3	1	Low	N	Have backup plan to enhance power stability of sensor lasers.	1	2	2	3	1	Low	N	Implement backup plan to enhance power stability of sensor lasers.
RR-005	P. Willems	If thermal compensation sensors inadequately sensitive, performance will be degraded.	AOS	2	2	3	2	1	Med	N	Added to baseline: multiplicity of installed TCS sensors	2	1	1	1	1	Low	N	Accept Risk
RR-006	M. Smith	If optical spring effect in RSE is ignored in calculating the scattered light noise, then ADLIGO may not meet SRD	AOS	2	1	3	3	2	Med	Y	Models do not indicate a problem	1	1	1	1	1	Low	R	
RR-007	M. Smith	If the sole-source vendor for expensive, long lead time, off-axis parabolic mirrors is unable to produce the PO telescope mirrors, the cost and schedule would be impacted	AOS	2	3	5	5	5	Med	Y	Risk retired: Stable recycling design eliminated PO mirrors.	0	0	0	0	0	Low	R	Risk retired: Stable recycling design eliminated PO mirrors.
RR-008	D. Shoemaker	Unanticipated scattering or 'ghost beam' path found once system assembled	AOS	2	2	4	2	1	Med	N	eLIGO has improved baffling design/implementation, demonstrated to be successful, and consistent with AdL designs	2	2	4	2	1	Med	N	Complete AOS SLC design reviews
RR-009	P. Willems	If core optic or coating absorption is too large, the thermal lens at full power will be larger than TCS can compensate, reducing sensitivity or forcing Advanced	AOS COC	3	2	3	4	3	High	Y	TCS designed with 2x power margin; higher powers possible with incremental changes. Cleaning procedure sketched out for core optics in place; suspension etc. compatible. Optics reliably coated with acceptable	2	2	3	4	3	Med	N	Detail the cleaning procedure in situ for core optics. Test at LASTI. Check status 1-Dec-09

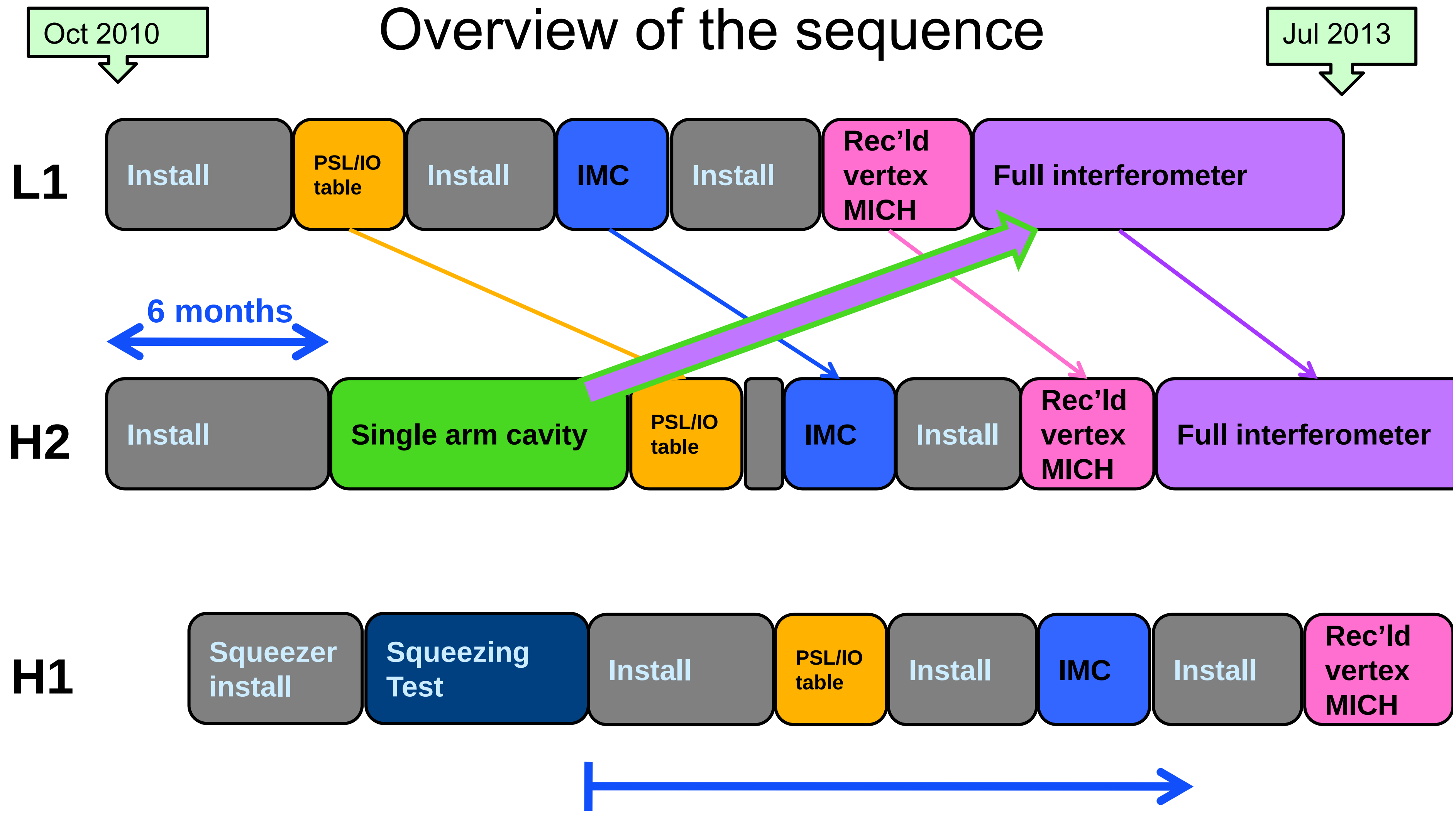
Recent phase transition

- Original plan called for staged shutdown of one Observatory in ~2011, then the other in ~2012
- 'Cost function' was to maximize length of initial LIGO science run
- After considerable discussion with LSC, NSF, Lab, we revised the plan to accelerate shutdown
  - » gives more time to integrate subsystems, perform orderly commissioning – generally to deal with surprises
- Initial LIGO observing had continued in parallel with the aLIGO Project until 20 October 2010

- **Observatories now handed off to aLIGO**
- Currently removing initial LIGO equipment
- Follow with a scrub of our UHV system
- Then bit by bit installation

Installation/integration dance

Overview of the sequence



Things that worked really well

- Structured R&D
  - » Set top level goals early; partition into subsystems; start to set up interfaces (but remain flexible for new developments)
- Creation and exploitation of a collaboration with commitments
  - » Funding agency "complicity" – interest in having feedback from Lab on the top priorities to move field forward
- Robust and honest cost estimates
  - » (also fell on the right sides of the economic slowdown…)
- Close coordination with NSF program managers
  - » Weekly calls of aLIGO/LIGO management with NSF, rain or shine
  - » Frank discussion of what's working and what's not
- The Sanders-style project management approach

Things to watch out for

- Competition for resources Operations/Project
  - » Our most skilled assembly technicians are also our machine Operators; Scientists obligated to fill observing shifts
  - » When the Observing machine breaks, the 'A' team is called
  - » Separate, constrained funding, but just one team
- Geographical dispersion of teams
  - » MIT and Caltech, Livingston and Hanford, Stanford, Columbia, U. Florida
  - » UK, Germany, Australia
  - » Top management lives in three different places!
- Being too optimistic about design time/difficulties
  - » Despite increases from engineering/scientific estimates, we were ~20% too low in staffing, and consequently late on internal schedules

More things to watch out for

- Small university purchasing departments
  - » Throughput
  - » Readiness/ability to comply with funding agencies increasing need for formality
  - » Willingness to give direct access to University financial systems
- Assigning organizational responsibilities
- Cultural differences
- Coordinating contributed resources with directly reporting resources

The last page, at last

- Substantially into the 'matter dominated' universe
  - » Stuff is piling up – what more could I ask for?
  - » Actually tearing into the vacuum system!
- Project machinery working well
- Technical baseline in very good shape; extensive experience with prototypes, and eLIGO installation, and commissioning of elements
- Procurement costs are well in line with (or below) cost estimates, covering metal, machining, optics from US and EU suppliers
- Schedule variance being addressed through technical hires
- Deliverables arriving at Observatories, assembly started, working through startup transients
- Project well staffed with an experienced and enthusiastic team
- **The start of installation is exciting!**
  - » And a bit stressful.