Parts of the path to today's Interferometric Gravitational-Wave detectors

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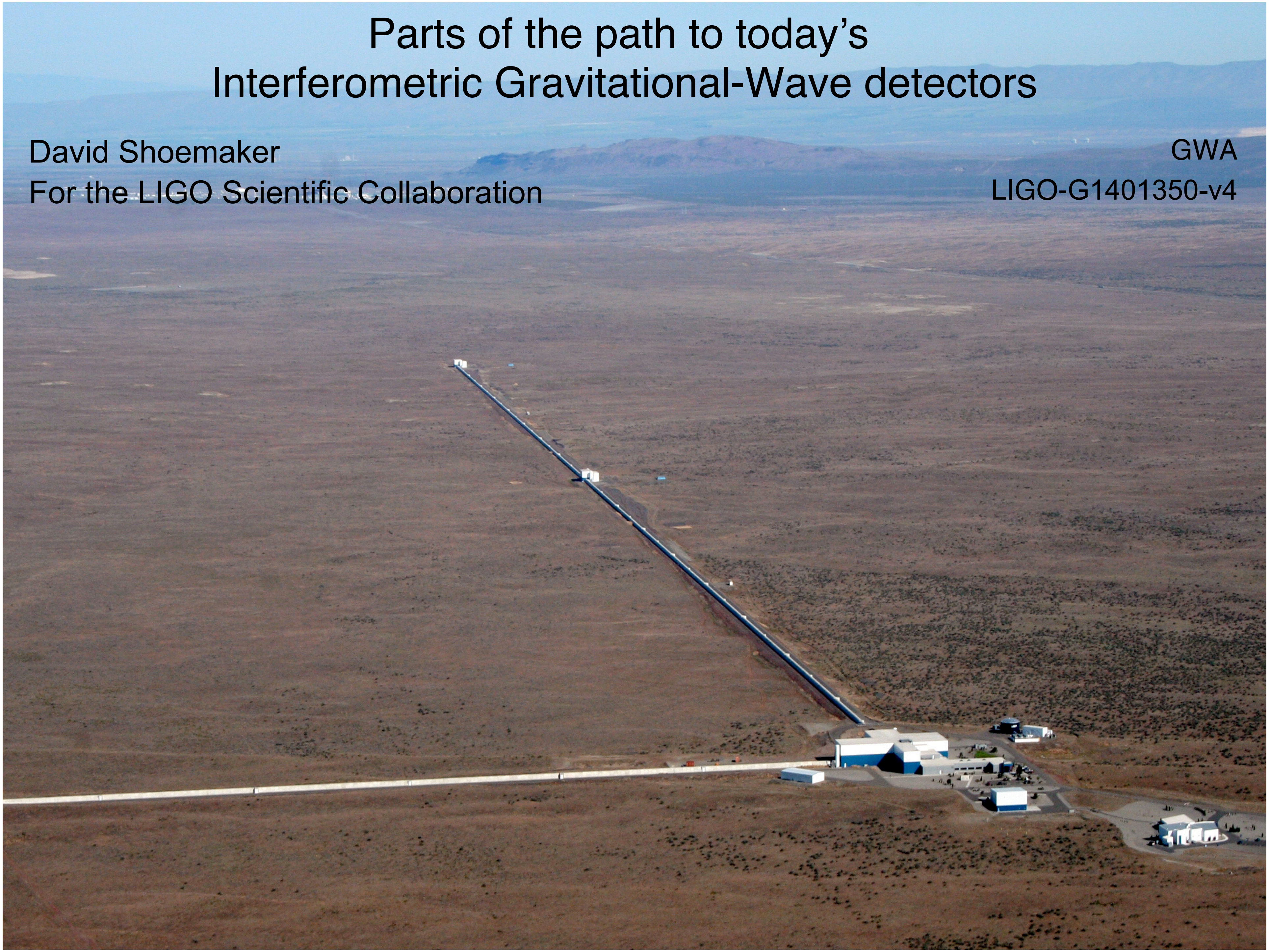
For the LIGO Scientific Collaboration

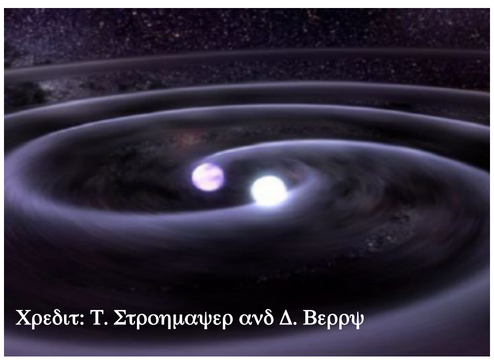
GWA

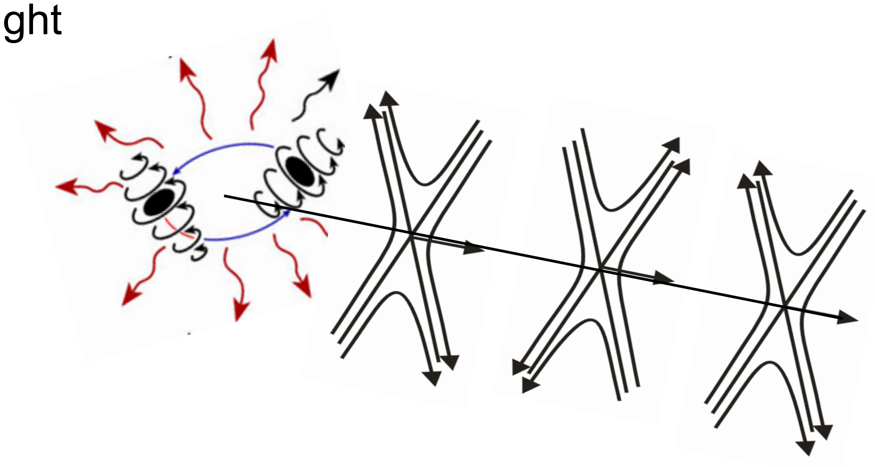
LIGO-G1401350-v4



Gravitational waves

- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time (‘ripples’ in space-time)
- Emissions from rapidly accelerating non-spherical mass distributions
  - Practically, need massive objects moving at speeds approaching the speed of light

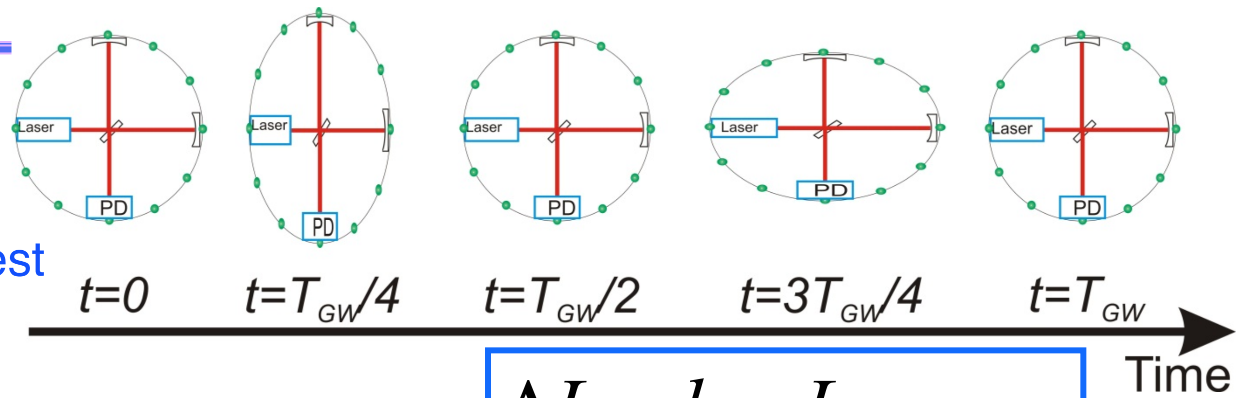




  - According to GR, GWs propagate at the speed of light
  - Quadrupolar radiation; two polarizations: h_+ and h_x
  - **Physically, GWs are strains** → $\boxed{h = \frac{\Delta L}{L}}$
  - **GWs carry direct information about the dynamics of matter**
  - **h is 10^{-21} for a ~monthly signal rate**

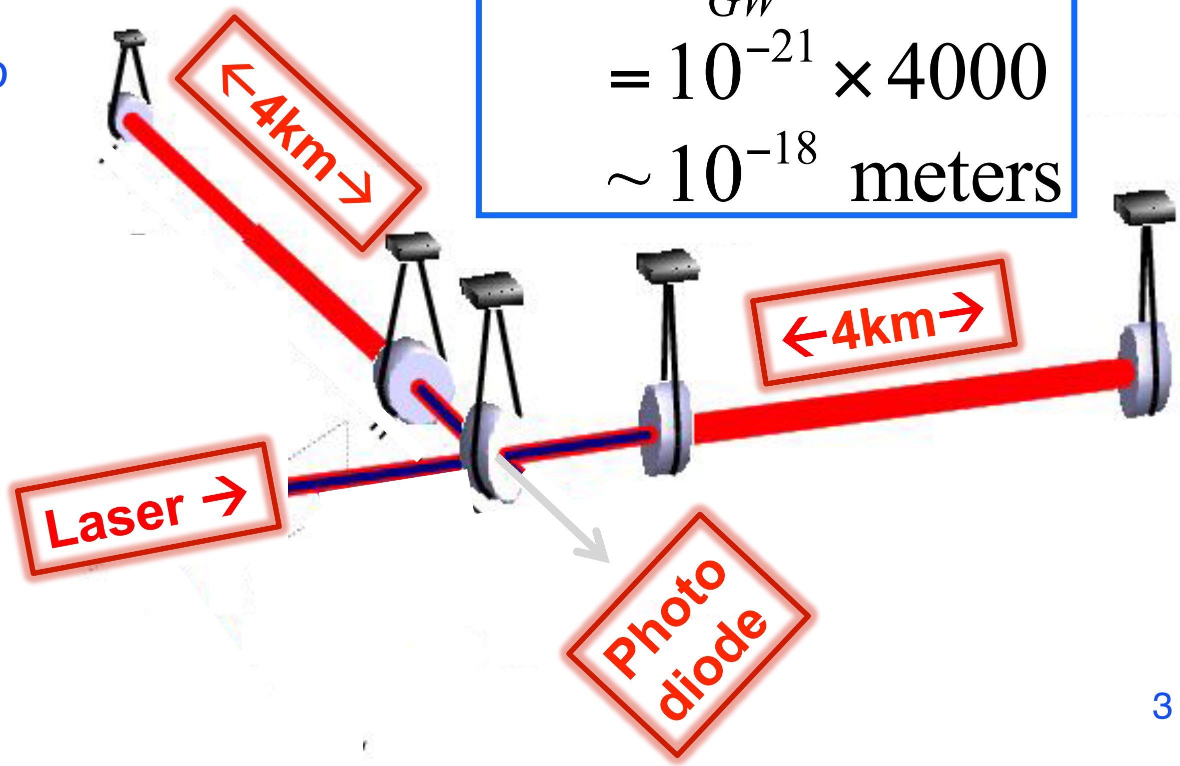
Interferometric Gravitational-wave Detectors

- Enhanced **Michelson interferometers**
- Passing GWs modulate the distance between the end test mass and the beam splitter



- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to GW wavelengths, so longer arms make bigger signals**
  → multi-km installations
- Arm length limited by taxpayer noise….

$$\Delta L = h_{GW} L = 10^{-21} \times 4000 \sim 10^{-18} \text{ meters}$$



The concept

- (At least one) early Gedanken experiment using interferometry to detect GWs:
  - » F.A.E. Pirani, *Acta Phys. Polon*. **15**, 389 (1956)
  - » (predates invention of laser by 4 years!)
- The proposal of using laser interferometry for gravitational-wave detection was first mentioned I believe by Gerstenstein and Pustovoit 1963 Sov. Phys.–JETP 16 433, from the standpoint of a theoretical possibility
- Weber mentioned it in an unpublished laboratory notebook. Worked with Forward, which probably triggered early experiments by Forward – and the first actual interferometer
- (a perfectly good place to apologize to people, places, and ideas that don't show up in this rather narrow 'history')

Forward Interferometer

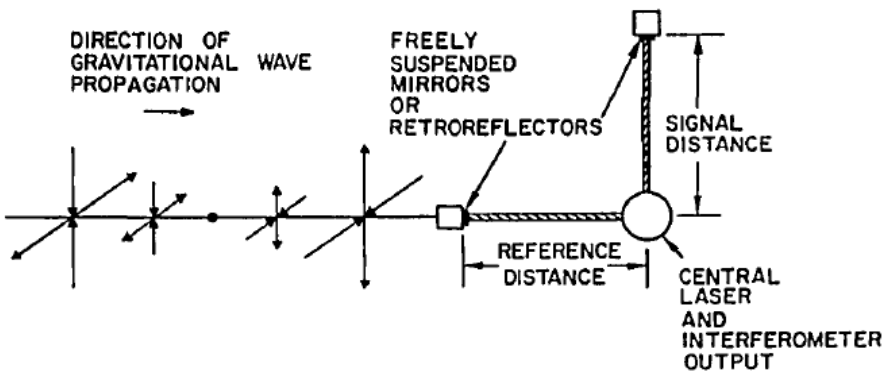


Fig. 1. Right angle interferometer antenna. The reference distance is not changed by gravitational radiation in the direction of propagation shown.

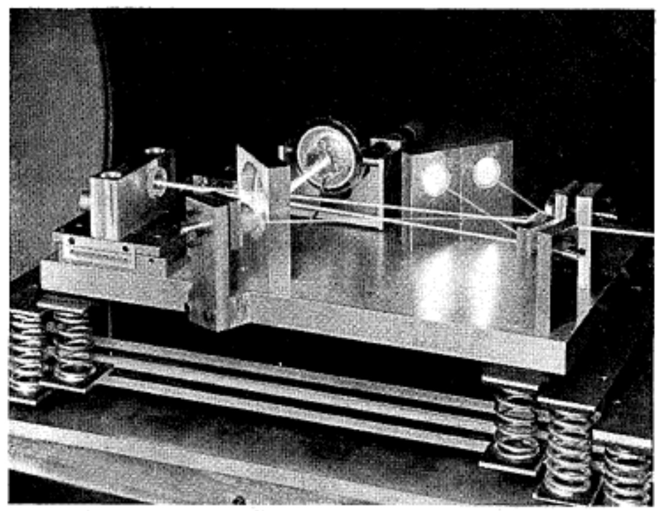


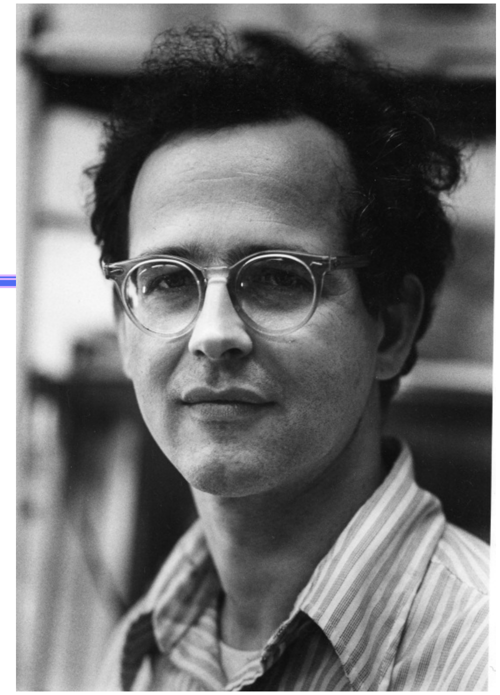
Fig. 4. Photograph of interferometer setup on 3-Hz isolation suspension.

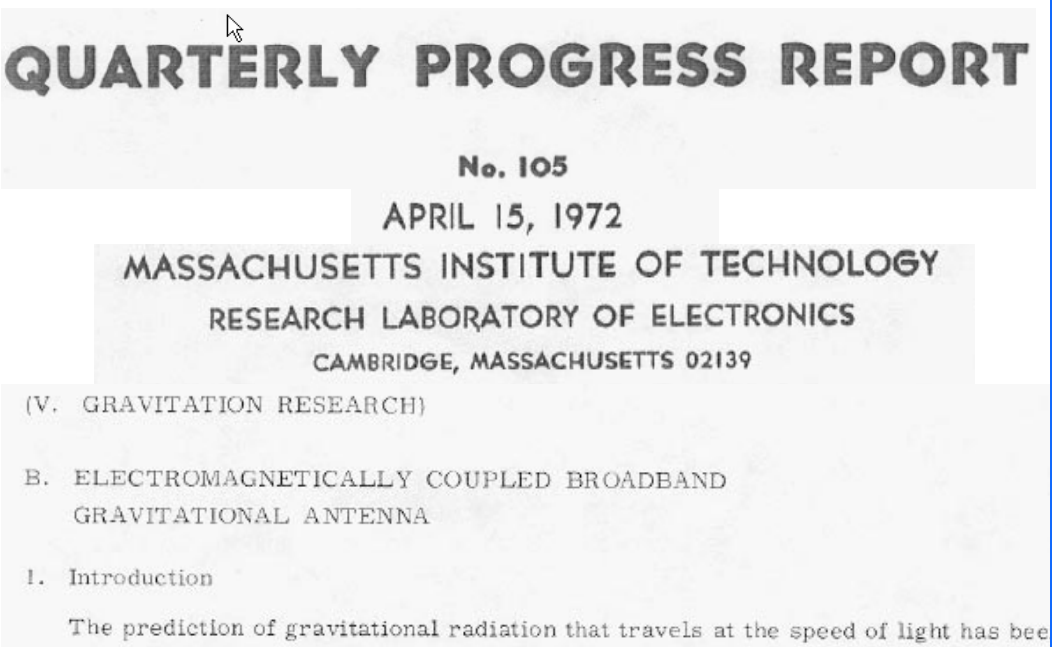
Did not take advantage of the Michelson differential arm sensitivity!

Data Analysis section:
"Calibration of the Ear"

Substantial starting point for the field

- 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?
- Weiss wrote the instruction book we have been following ever since





QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

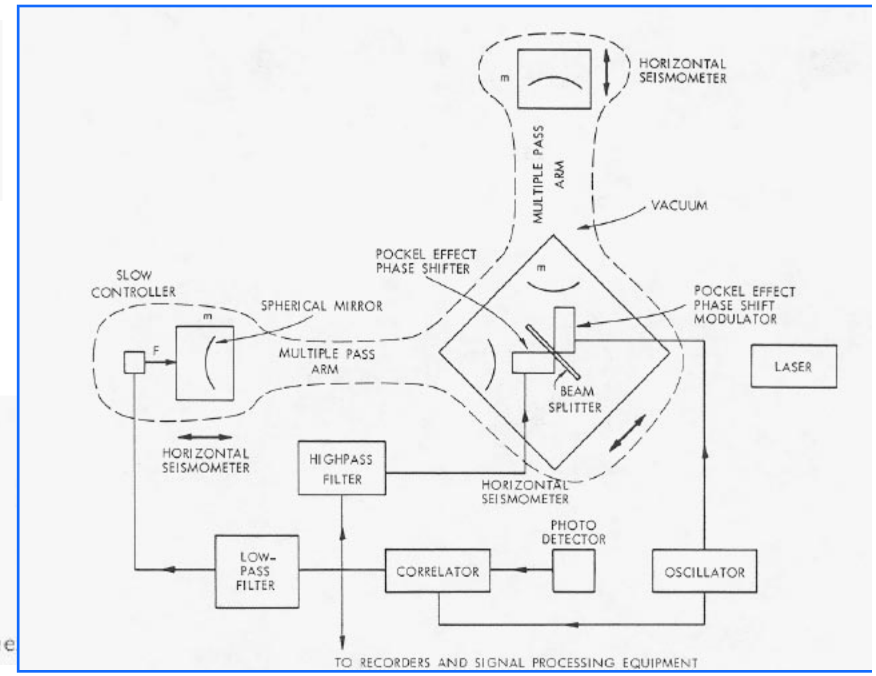
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

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



A few quotes from Weiss' '72 Report

5. Noise Sources in the Antenna

The power spectrum of noise from various sources in an antenna of the design shown in Fig. V-20 is estimated below.

a. Amplitude Noise in the Laser Output Power

The ability to measure the motion of an interferometer fringe is limited by the fluctuations in amplitude of the photo current. A fundamental limit to the amplitude noise in a laser output is the shot noise in the arrival rate of the photons

c. Mechanical Thermal Noise in the Antenna

Mechanical thermal noise enters the antenna in two ways. First, there is thermal motion of the center of mass of the masses on the horizontal suspensions and second, there is thermal excitation of the internal normal modes of the masses about the center of mass.

d. Radiation-Pressure Noise from the Laser Light

Fluctuations in the output power of the laser can drive the suspended masses through the radiation pressure of light.

The epoch of city-states ('70s, '80s)

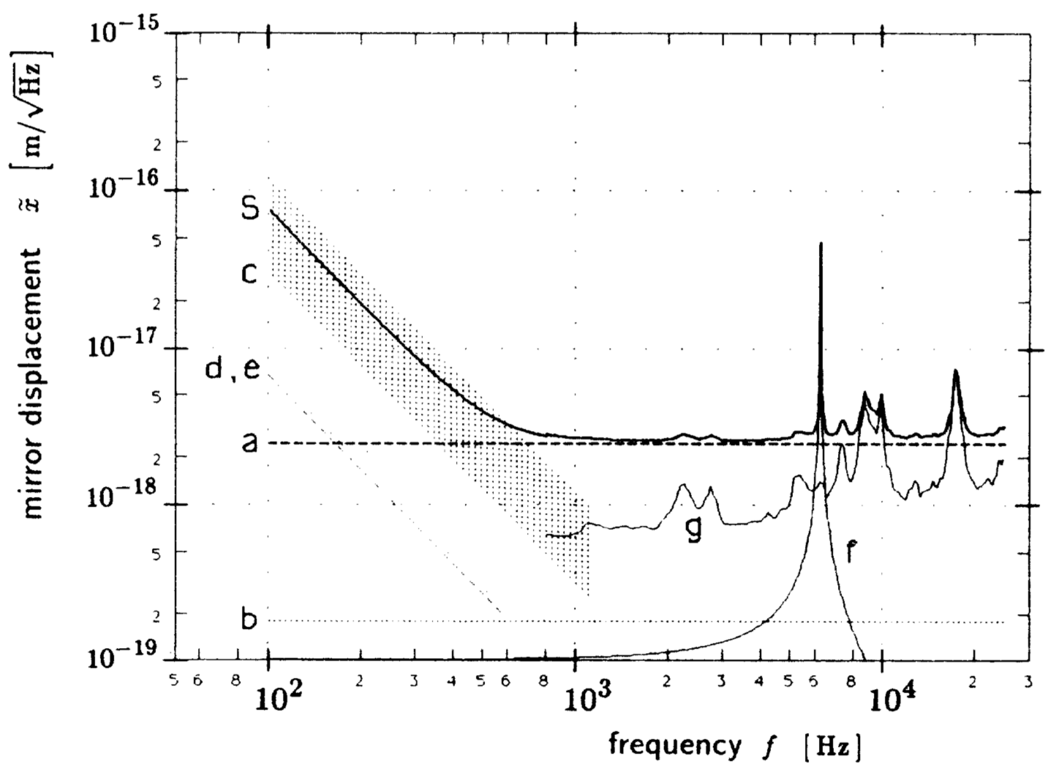
- Weber Bar groups, who both competed with us and developed needed technologies and cultured young scientists in the field
- MIT/Weiss: 1.5m prototype with Delay Lines and electrostatic controls, early active systems, demonstrations of interferometry with FP arms
- Glasgow/Drever/Hough: from Bars to Fabry-Perot cavities, then inspiration in configurations and multiple pendulums
- Caltech/Drever/Whitcomb: the 40m Prototype and position sensing records
- Orsay/Brillet: Diode-pumped Nd:Yag as the right laser
- Pisa/Giazotto: first a high-gain active seismic isolation system, then an about face to the Super Attenuator concept

- And one very special case:

Garching Group

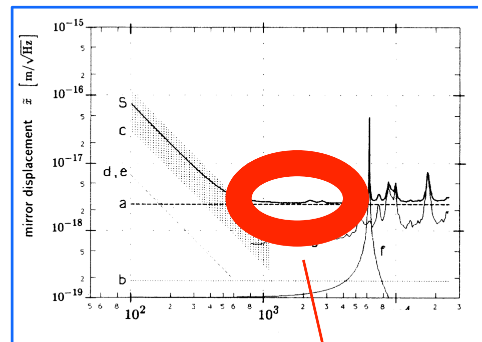
R. Schilling, L. Schnupp, W. Winkler, K. Maischberger, and A. Rüdiger

- Early activity in computer automated analysis of Bubble chamber photographs and 'large scale' data magnetic storage; group led by Billing
  - » Custom hardware and software
- A bold step: Billing Pursued GWs via Weber Bars – in Munich and in Frascati, Italy
- Then, Interest in Interferometers perhaps piqued by Weiss' proposal to NSF
- Core group together for decades, representing a broad range of skills and interests
- Built a series of ever more sensitive prototypes, culminating in the 30m Delay Line system; best understood and most sensitive instrument for many years
- First 'noise budget' that explained observed performance



Garching Group

- Many key discoveries/inventions made at Garching; a few examples…:
  - » Common mode interferometer stabilization – bringing reflected light back into interference with the incoming light – *Almost* power recycling
  - » OSEMs – simple combined shadow sensors and electromagnetic motors for suspended mirror control
  - » Shot noise and the non-stationary aspect of it in modulated systems
    - – Came to light due to the exquisite stability of the instrument, and the dogged determination and 'housewife logic' (her terminology!) of Lise Schnupp
  - » Scattering in delay lines, and means to mitigate through frequency modulation techniques
  - » Optical mode cleaners – cavities used in transmission
  - » Multiple pendulum suspensions
  - » Suspended bare optics to avoid mechanical damping and complexity
  - » Triangular arrangement for multiple interferometers ('*Vorschlag zum Bau…*')
- Group migrated, mostly in spirit, to Hannover, and carries on!



Later Caltech and MIT activities (and here my focus narrows to LIGO…)

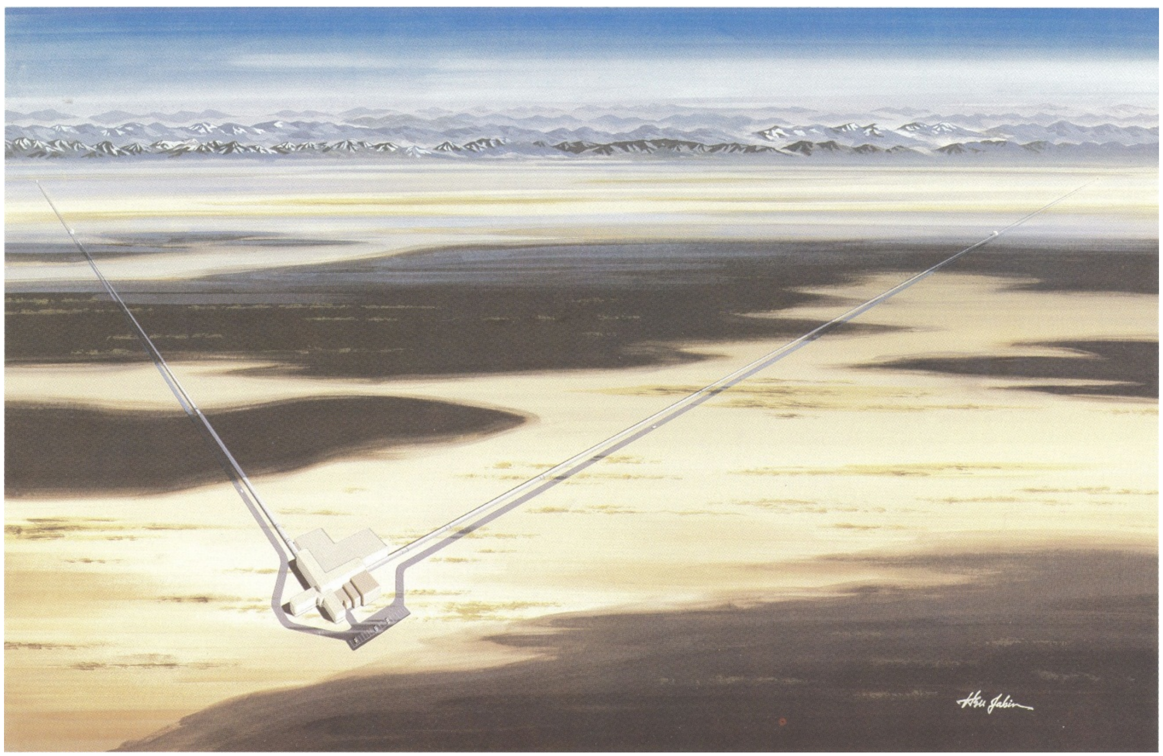
- The worldwide effort to establish a technical path to the required sensitivity gave some confidence that we knew what to build
- Kip Thorne, Rai Weiss, and Ron Drever each had a vision that something great could happen in this field; Kip brought Drever to Caltech to found experimental group
- Rai was certain that a unified proposal from both MIT and Caltech groups would be needed, and worked hard to make that happen
- Caltech provided strong support to the (now named) LIGO Project, with Robbie Vogt as leader
- A great deal of heat and just enough light followed, resulting in…

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.

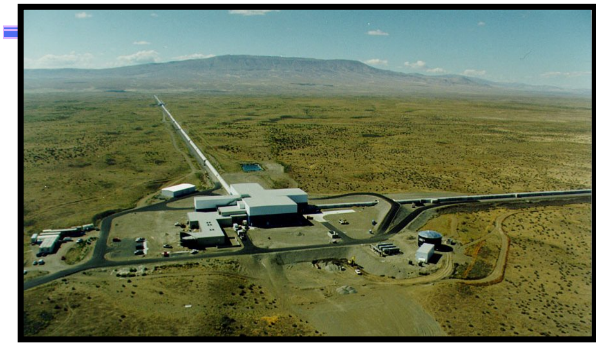
The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.



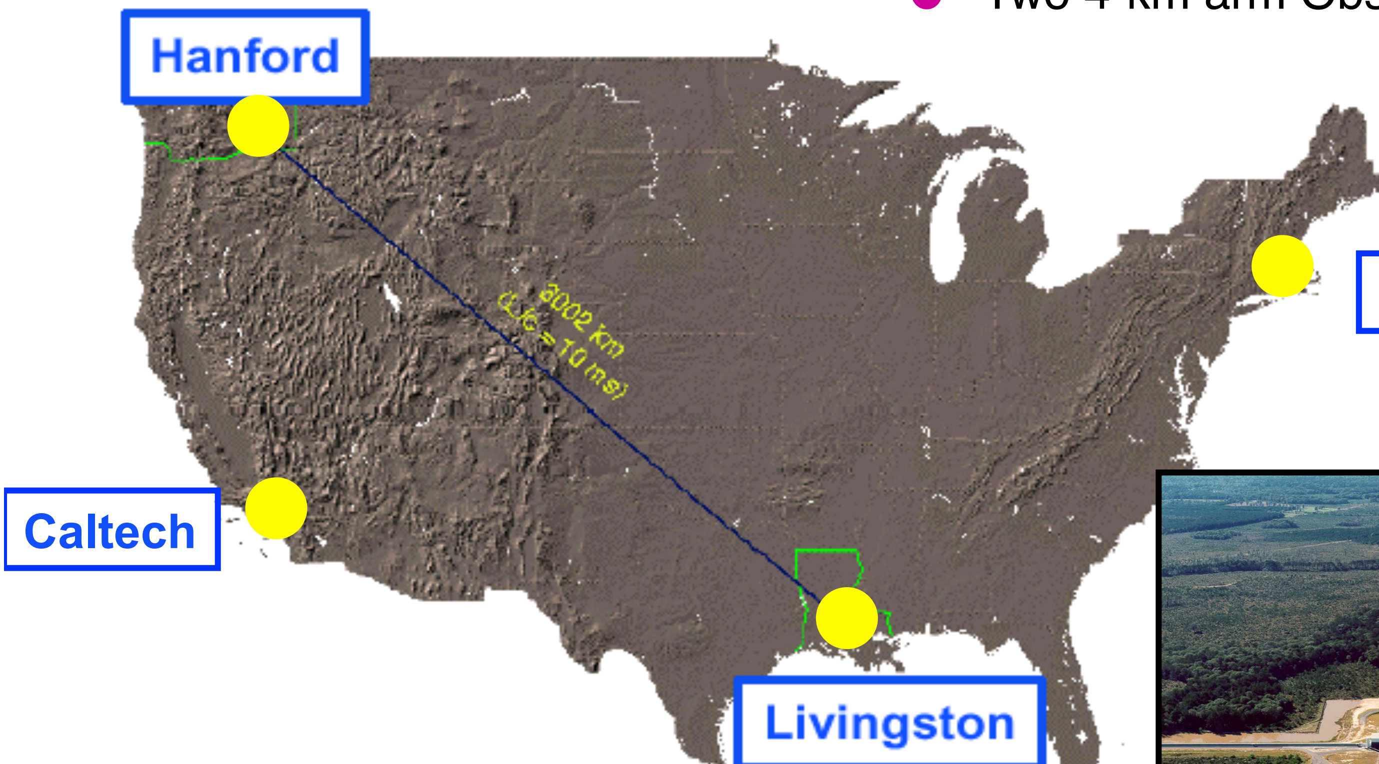
LIGO:
Today, Washington state…

…LIGO in Louisiana

LIGO Laboratory: two Observatories and Caltech, MIT campuses



- Mission: Develop gravitational-wave detectors; Operate them as astrophysical observatories
- Jointly managed by Caltech and MIT
- Two 4-km arm Observatories

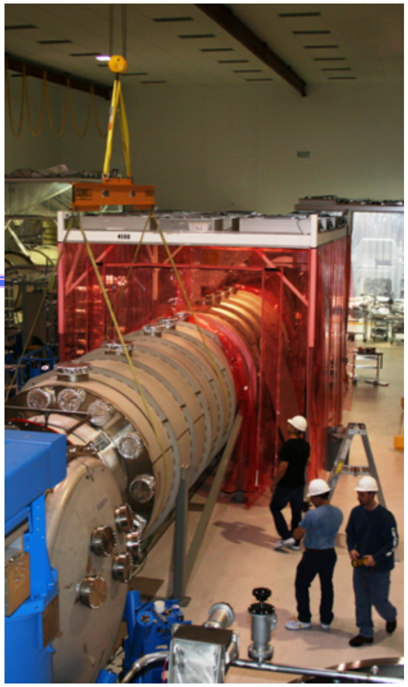


Initial LIGO Chronology

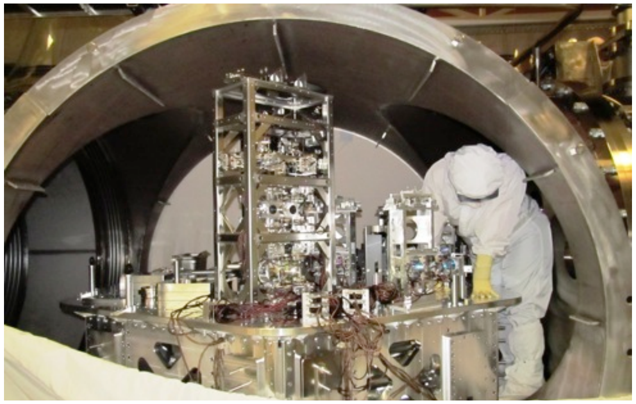
- 1985 (or so): Conceptual Design well formed
- 1989 : Construction proposal for LIGO submitted to the NSF
- 1992: NSF selects LIGO sites: Hanford, Wash., and Livingston, La.
- 1994: Groundbreaking at Hanford site
- 2000: Achieved “first lock” on Hanford 2-km interferometer
- 2002: First scientific operation of all three interferometers in S1 run
- 2005: Design sensitivity reached
- **…so about 20 years from a conceptual design to two Observatories, instruments, commissioning to design sensitivity**

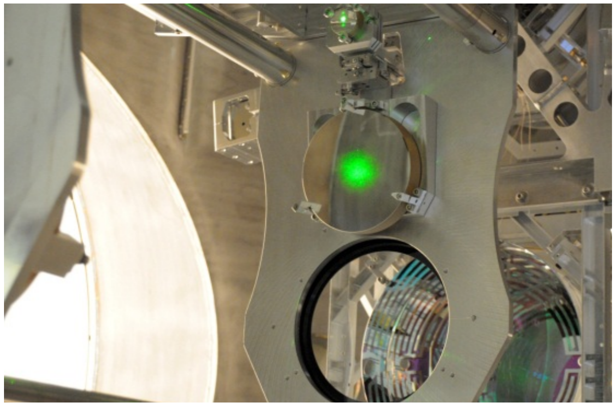
- 2007: Science run of one year integrated quality data at design sensitivity completed (“S5”)
  - » Upper limits and interesting non-detections; no detections
- 2010: Initial LIGO starts to be disassembled at Livingston, to enable…

Advanced LIGO



- Advanced LIGO is a complete redesign and rebuild of the LIGO interferometers
  - » 10x more sensitive, 1000x more of the universe probed
- Advanced LIGO funded April 2008
  - » $205.1M in funding from NSF; capital contributions from partners in UK, Germany, and Australia totaling $30M
- Three 4 km long interferometers built
  - » One for Hanford, one for Livingston, one for future installation in India
- Construction by LIGO Laboratory with participation by member groups of the LIGO Scientific Collaboration
- **On schedule and on budget to complete in March 2015**



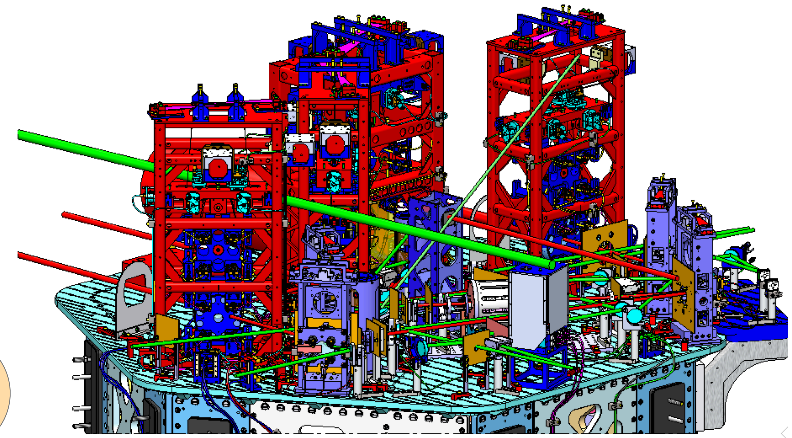


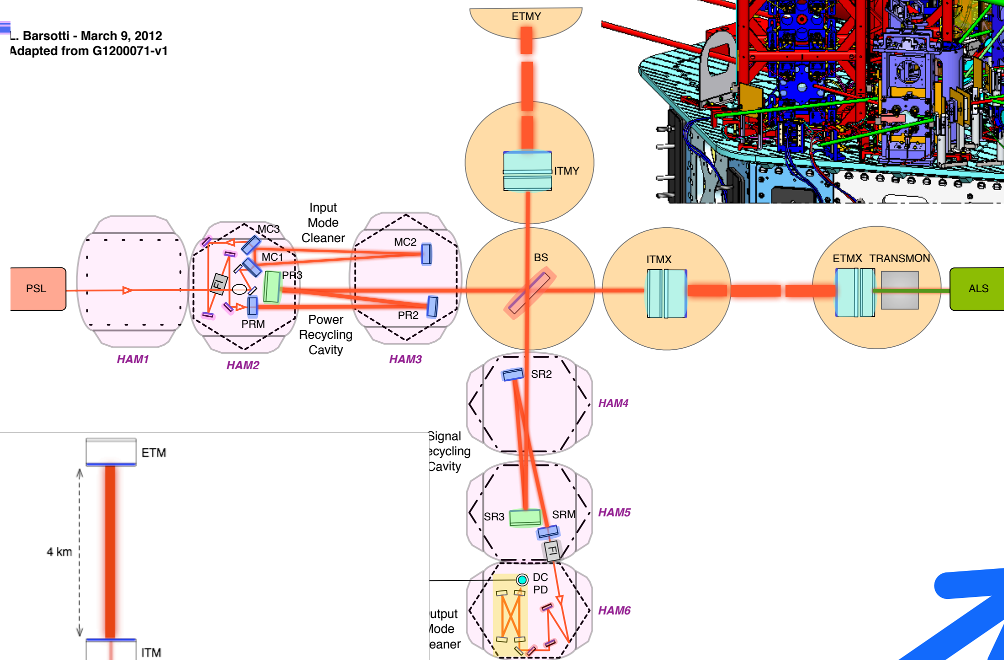
Chronology of aLIGO (as far as it goes…)

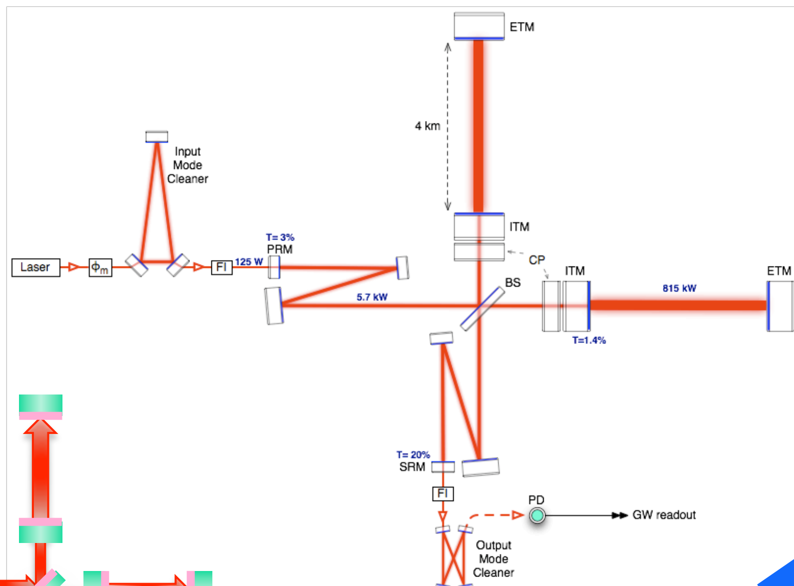
- **aLIGO's path through the decades:**
- 1990-2000: R&D, meetings like this one
- 1999: White Paper with conceptual design
- 2000-2004: Prototyping, modeling, applying (Note: this how where the LIGO Scientific Collaboration took form, to focus the community – City-States morph into Unions of LIGO, GEO, Virgo, KAGRA, ACIGA)
- 2006: Funding for 2008 start
- 2005-2008: Engineering, 1st articles, procurements
- 2008-2012: Building, de-installing, cleaning, installing
- 2013-2015: Installing, testing, documenting
- 2015→ Astrophysics

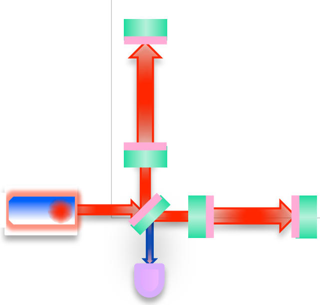
- **So, about 20 years from ripe R&D to fruition…**
  - » **(similar to Initial LIGO)**
  - » **Sobering for the next generation – need the conceptual design soon!**

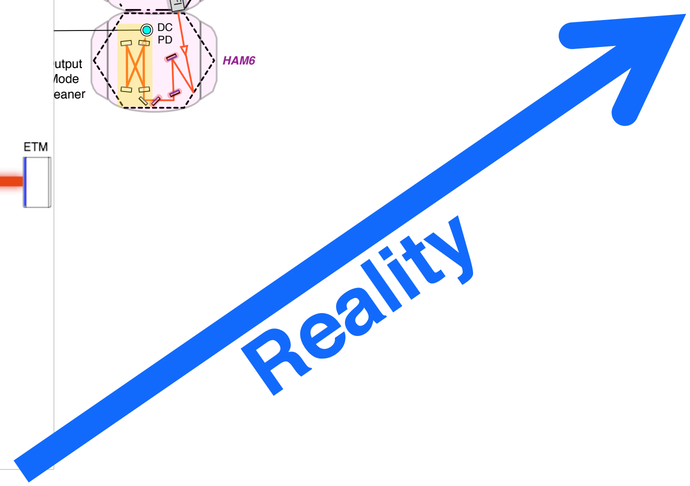
aLIGO is more complex than Initial LIGO…



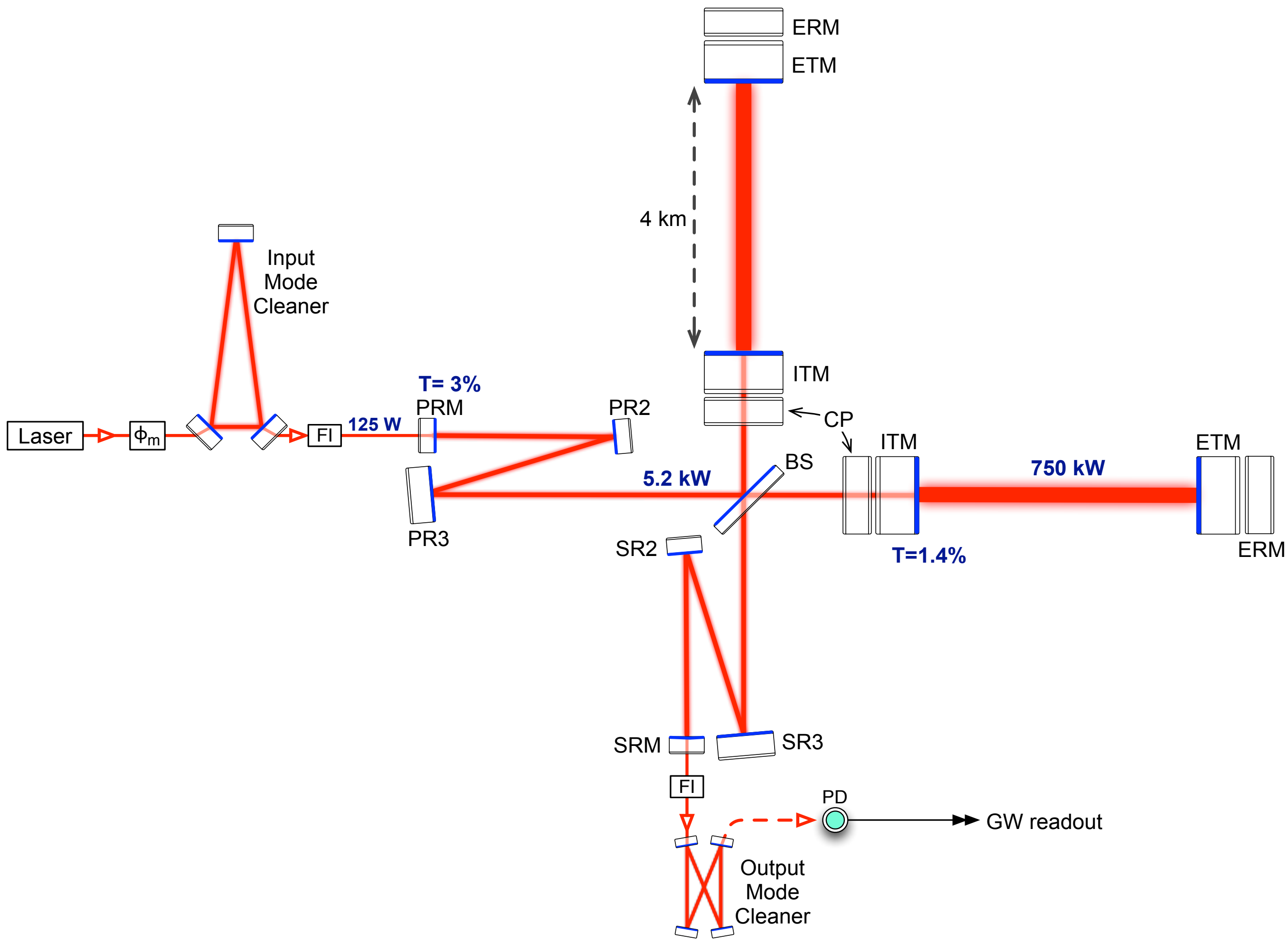








aLIGO system layout

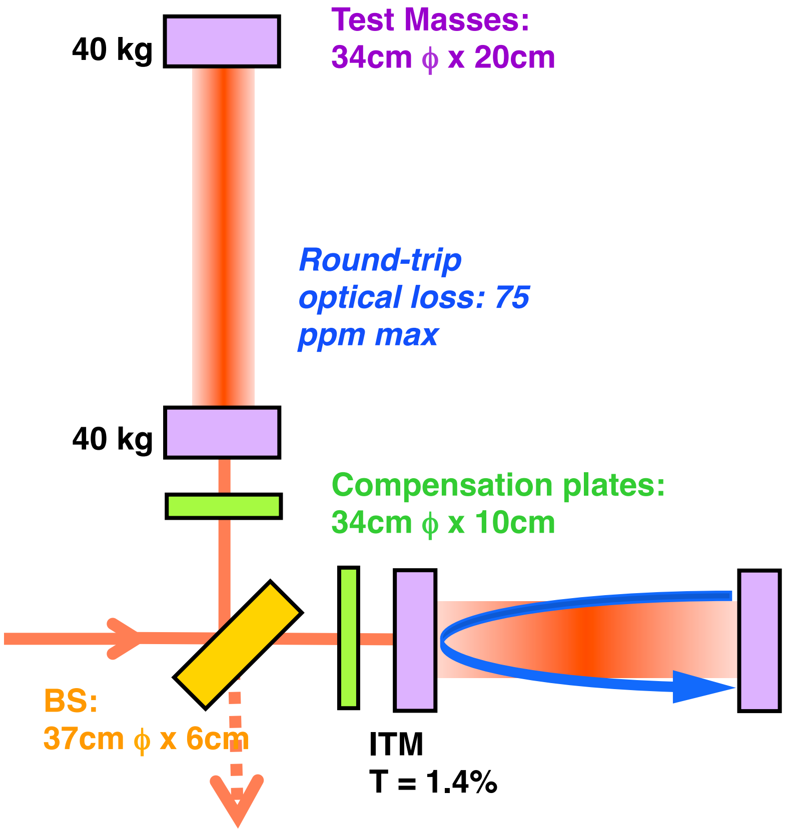


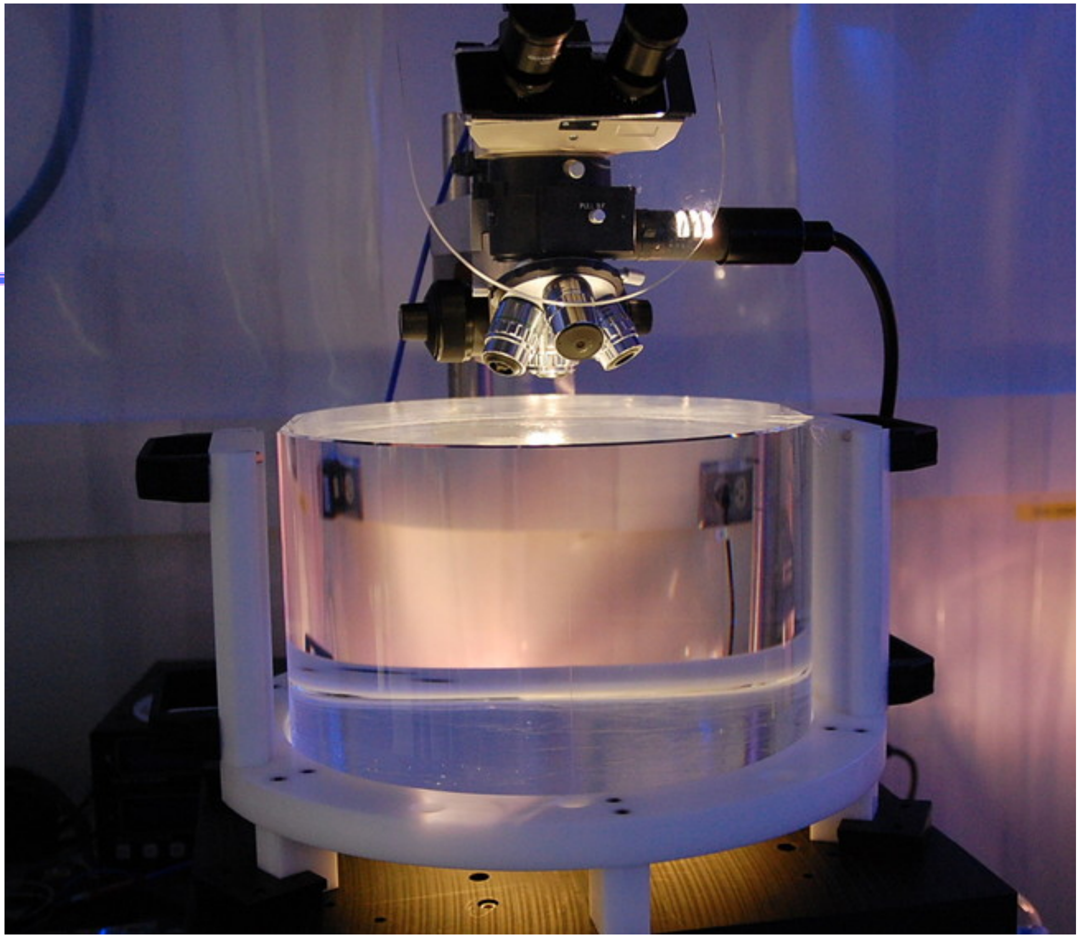
Design drivers

- Long arms and extreme interferometry lead to many design impacts
- World's biggest UHV vacuum system, straighter than earth's curvature
- Optics size – 1064 nm over 4km requires beam spots of ~12 cm, 34cm optics
- Readout requirements of one part in 10^{10} of a fringe requires 200W CW Nd:YAG lasers, stabilized in frequency, intensity, and pointing; boosted to ~1 MW with optical resonant cavities
- Pointing and control requirements – hold 4km cavities on resonance to 10^{-15} m; point optics with microradian RMS motion; 5 coupled cavities, 21 coupled DOF
- Suppress seismic and anthropogenic noise input; another 18×5 + 12×5 MIMO

LIGO Test Masses

- Both the physical test mass – a free point in space-time – and a crucial optical element
- Requires the state of the art in substrates, polishing, coating

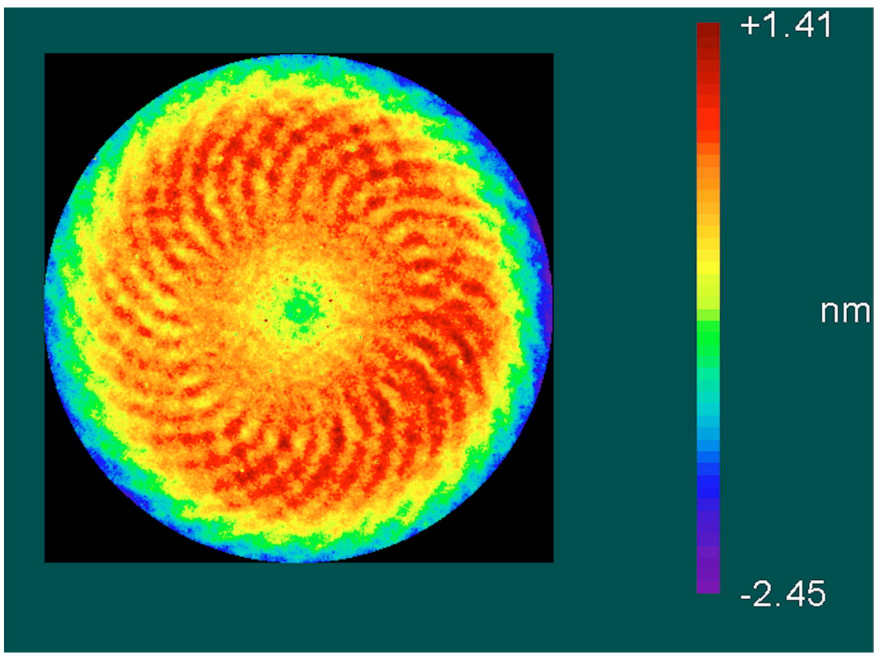


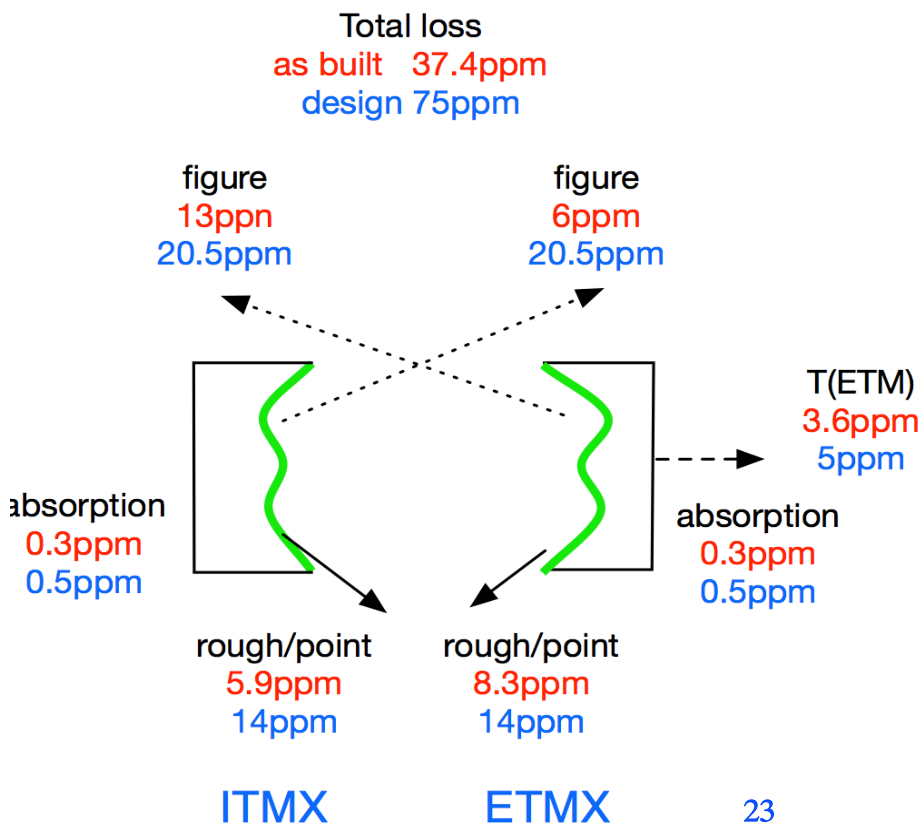


- Half-nm flatness over 300mm diameter
- 0.5 ppm absorption at 1064nm
- Coating specs for 1064 and 532 nm
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency

Coated Test mass Optics figure

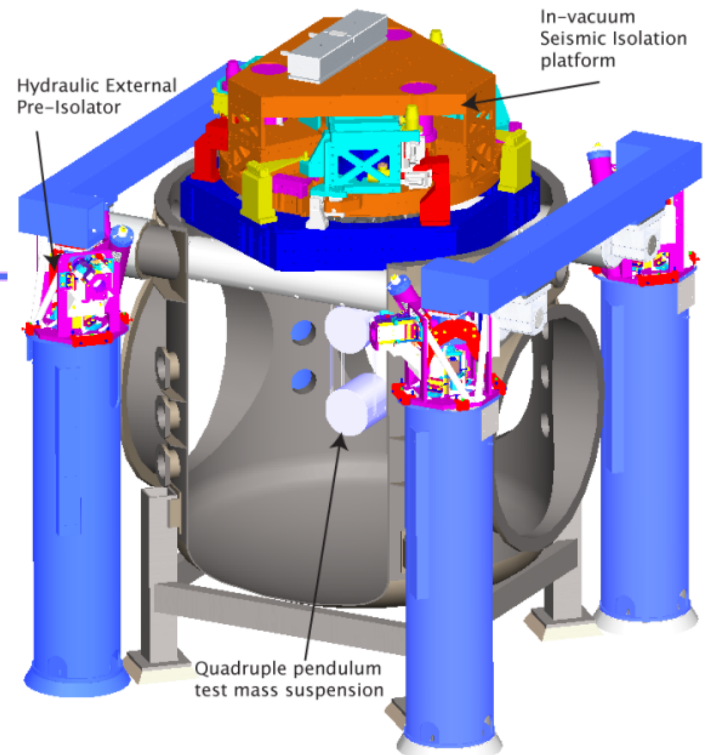
- In-house metrology on 300 mm diameter shows 0.66 nm RMS
  - » Substrate is <0.2 nm RMS – Ion Beam milling
  - » Note spiral from planetary system; about 0.2 nm pk-pk
- Measurements of as-built mirrors show results are better than requirements! (but then dust pulls the complete cavity loss back up to 80 ppm…)



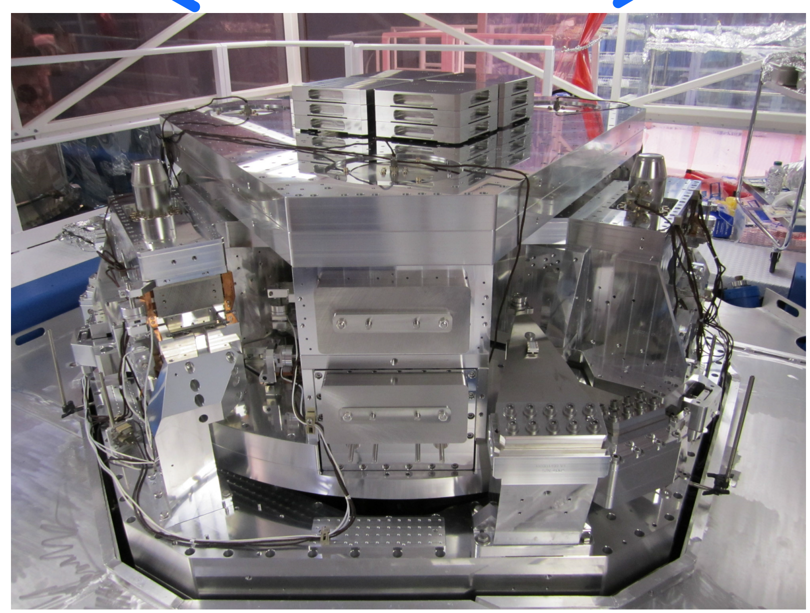


Seismic Isolation: Multi-Stage Solution

- Objectives:
  - » Render seismic noise a negligible limitation to GW searches
  - » Reduce actuation forces on test masses
- Both suspension and seismic isolation systems contribute to attenuation
- Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :
  - » 1) Hydraulic External Pre-Isolation
  - » 2) Two Active Stages of Internal Seismic Isolation
- Low noise sensors (position, velocity, acceleration) are combined, passed through a servo amplifier, and delivered to the optimal actuator as a function of frequency to hold platform and 1-ton payload still in inertial space
- At 10Hz: 10^{-12} m/rHz and -80 dB transmissibility

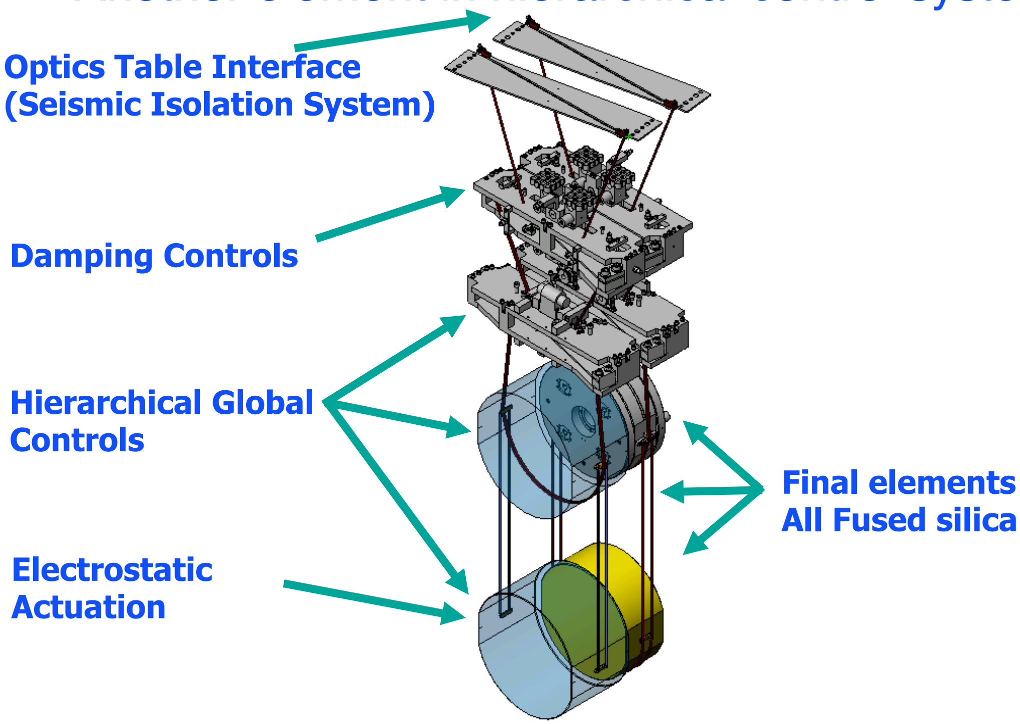


~2m



Test Mass Quadruple Pendulum suspension (GEO)

- Quadruple pendulum suspensions for the test masses; second 'reaction' mass to give quiet point from which to push
- Create quasi-monolithic pendulums using fused silica fibers to suspend 40 kg test mass
  - VERY Low thermal noise! $Q = 10^9$
- Another element in hierarchical control system

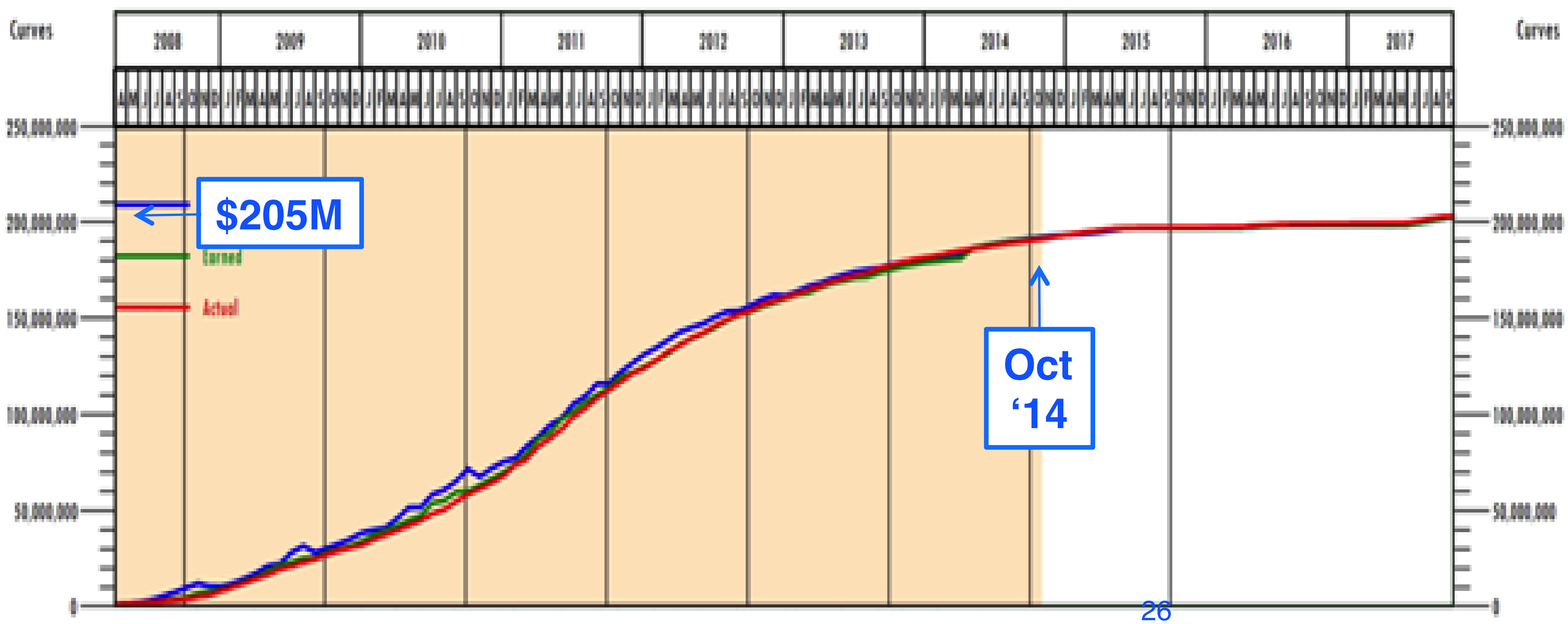


LIGO

Advanced LIGO Project Status

- The Project is 94% complete (earned value); H1 97%, L1 99.7% complete
- All funds received from NSF, all in-kind contributions made; $12M remaining planned cost (mostly computing), plus $3.7M contingency for surprises

- Project now extends to 2017 for Computing activities, but all else end-March 2015



Hanford installation complete

- Now under vacuum at all stations. Dual-recycled Michelson test underway; arms lockable with green Arm Length Stabilization, working toward full lock
- Accomplished with huge help from LLO, CIT, MIT, LSC
- Next: installation acceptance, and get to two-hour-lock milestone
- Also, responsibility for 3rd ifo (India) is at Hanford – non-trivial task.

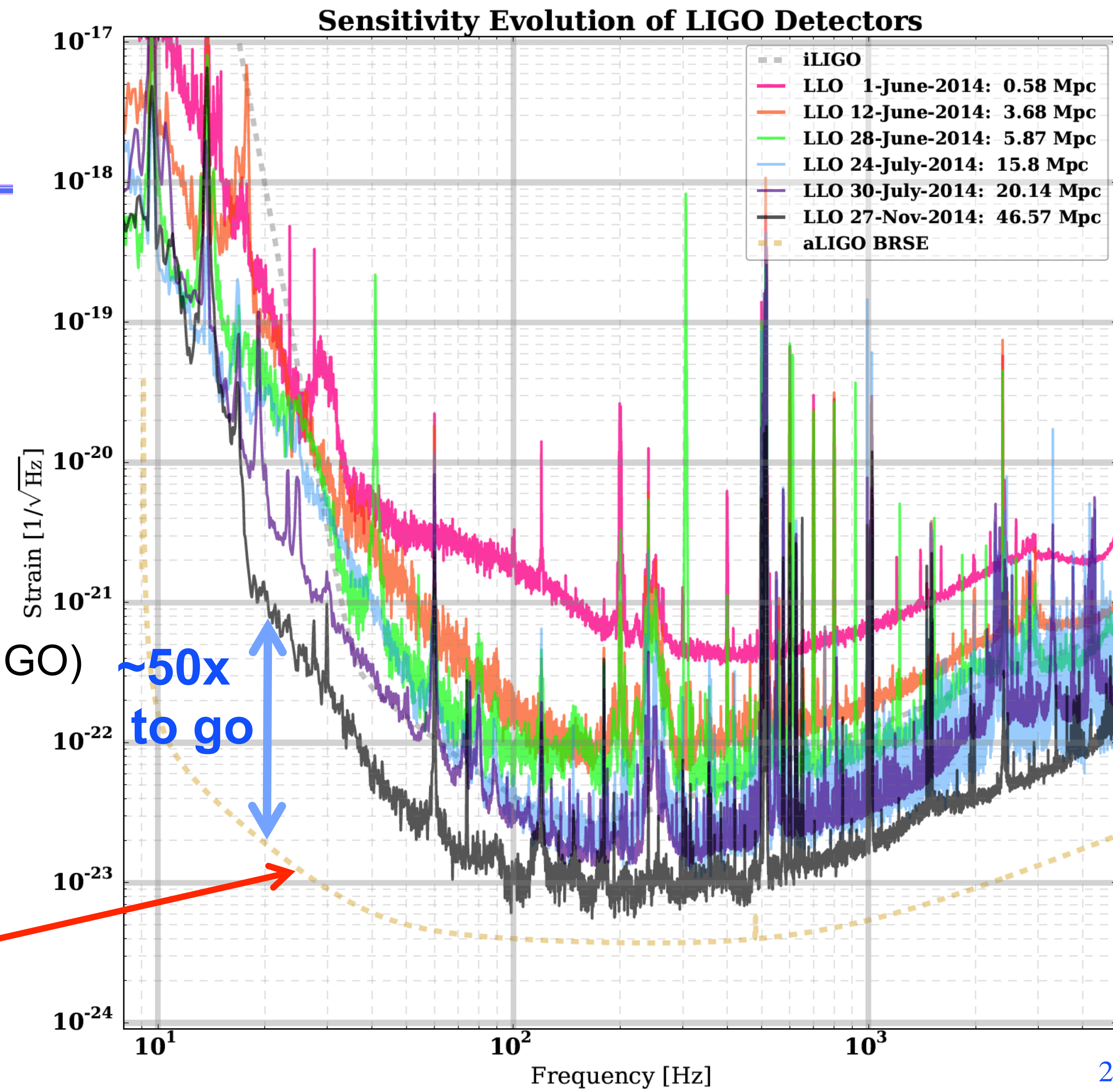
Livingston Project scope finished

- **The full interferometer lock was achieved on May 26, 2014**
- **L1 formally met the aLIGO goal of a 2h stable lock**
- The IFO has been locked for as long as 7.5h
- Initial alignment and the lock acquisition are mostly automated
- Currently recovering from some in-vacuum work
- (Need to complete System Acceptance/documentation)

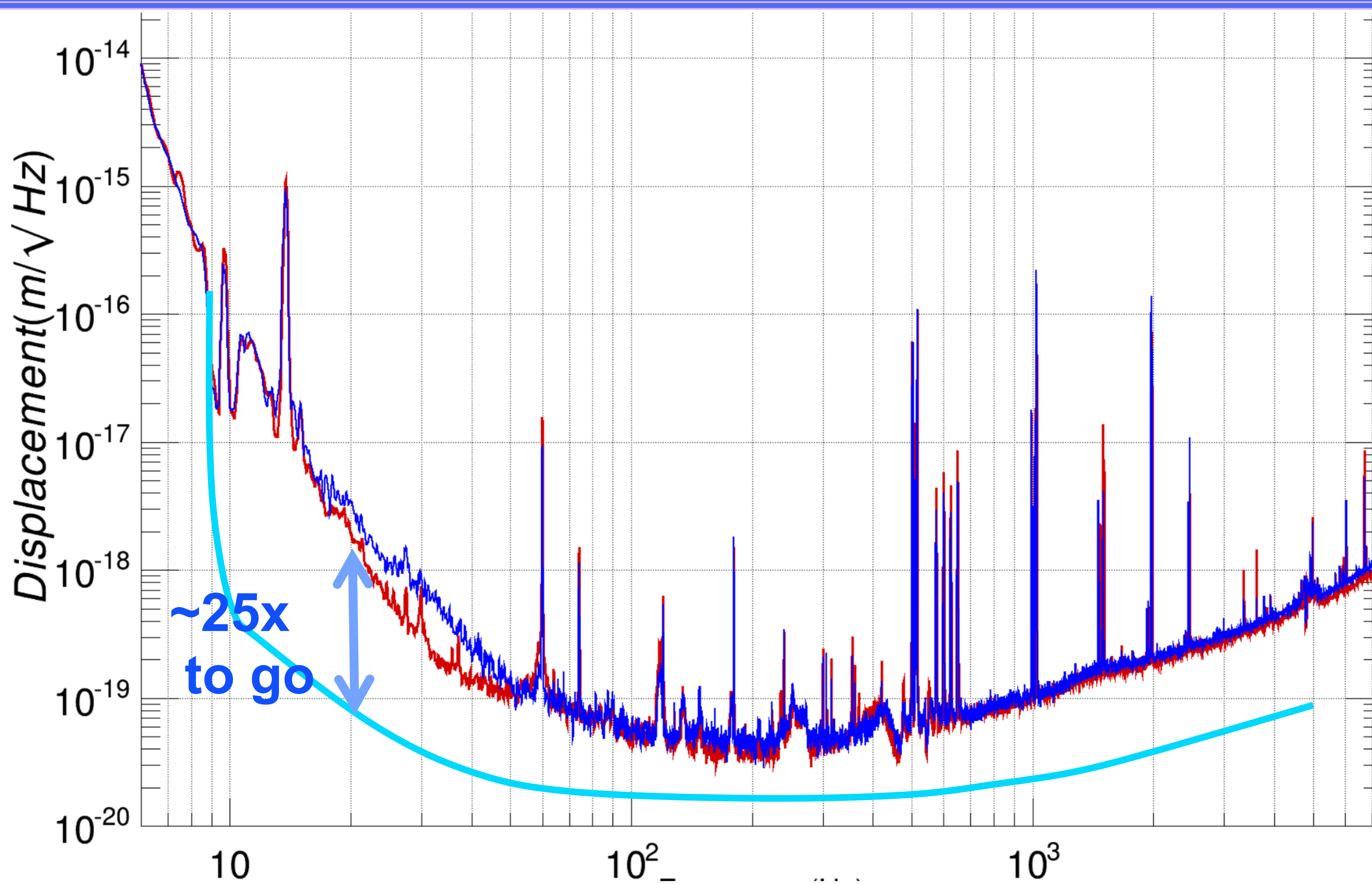
Progression of sensitivity through commissioning

Currently ~47 Mpc range for NS-NS inspiral, SNR 8 (2.6x better than iLIGO)

Goal at full power and completed commissioning

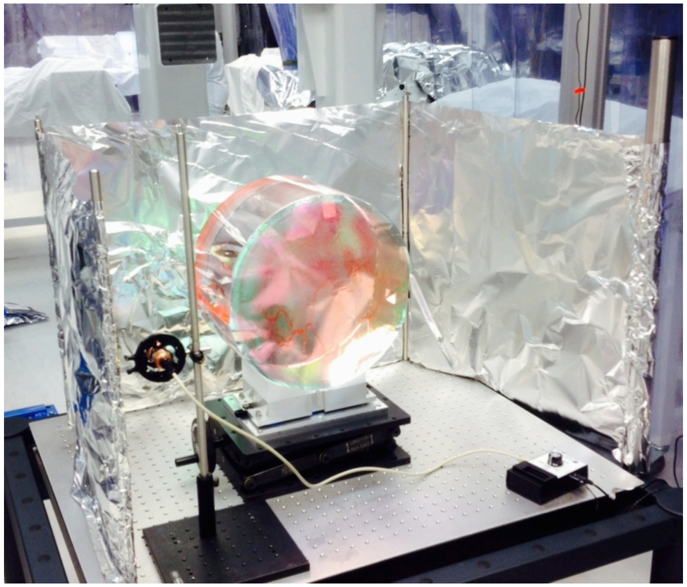


...and another factor of 2 improvement at low frequencies about 6 hours ago...



Scariest Technical Challenge of the moment: Electrostatic Charging

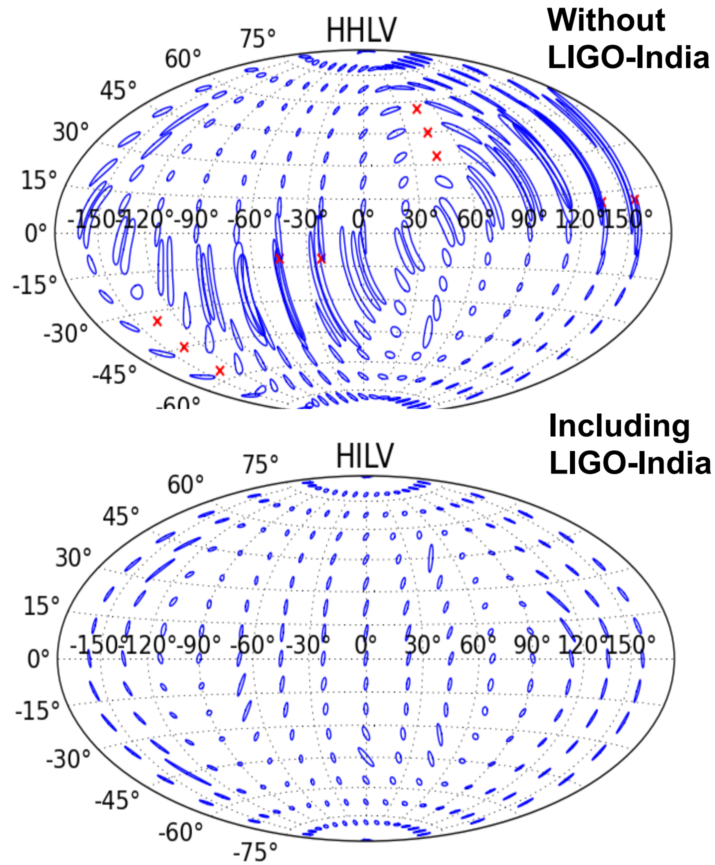
- Evidence at both sites of electrostatic (but time varying) charge on test masses
- Creates problems for electrostatic actuation AND is a possible noise source
- Investigating ion pumps as potential source – looking likely
  - » Looking at shielding from pumps – direct ion flow, x-ray produced remote ions; not easy
  - » …and considering getter pumps
- Rai Weiss ionizer allows adjustment of charge; making enough for all test masses, but invasive – need to let in some gas, then pump again
- **Future interferometers must put this in the planning – problem more severe with lower frequency and better sensitivity**
- (and: it was mentioned in Weiss' 1972 Report)



LIGO-India

- Plan to take the 3rd aLIGO instrument – originally destined for Hanford as a 2nd instrument there – and install in India
- Status
  - » LIGO-India identified by Indian Government as a Mega-science Project for 2012-2026 period
  - » Indian Cabinet level approval expected in November 2014 – signed note traveling to Cabinet as we speak
  - » Should have happened in late 2013, stalled for one year due to complications with data sharing and change of government in India
  - » Site selection process nearly complete
  - » Requires NSF approval of transfer of Ifo
  - » Current schedule has Observations beginning in 2022

Localizing GW events



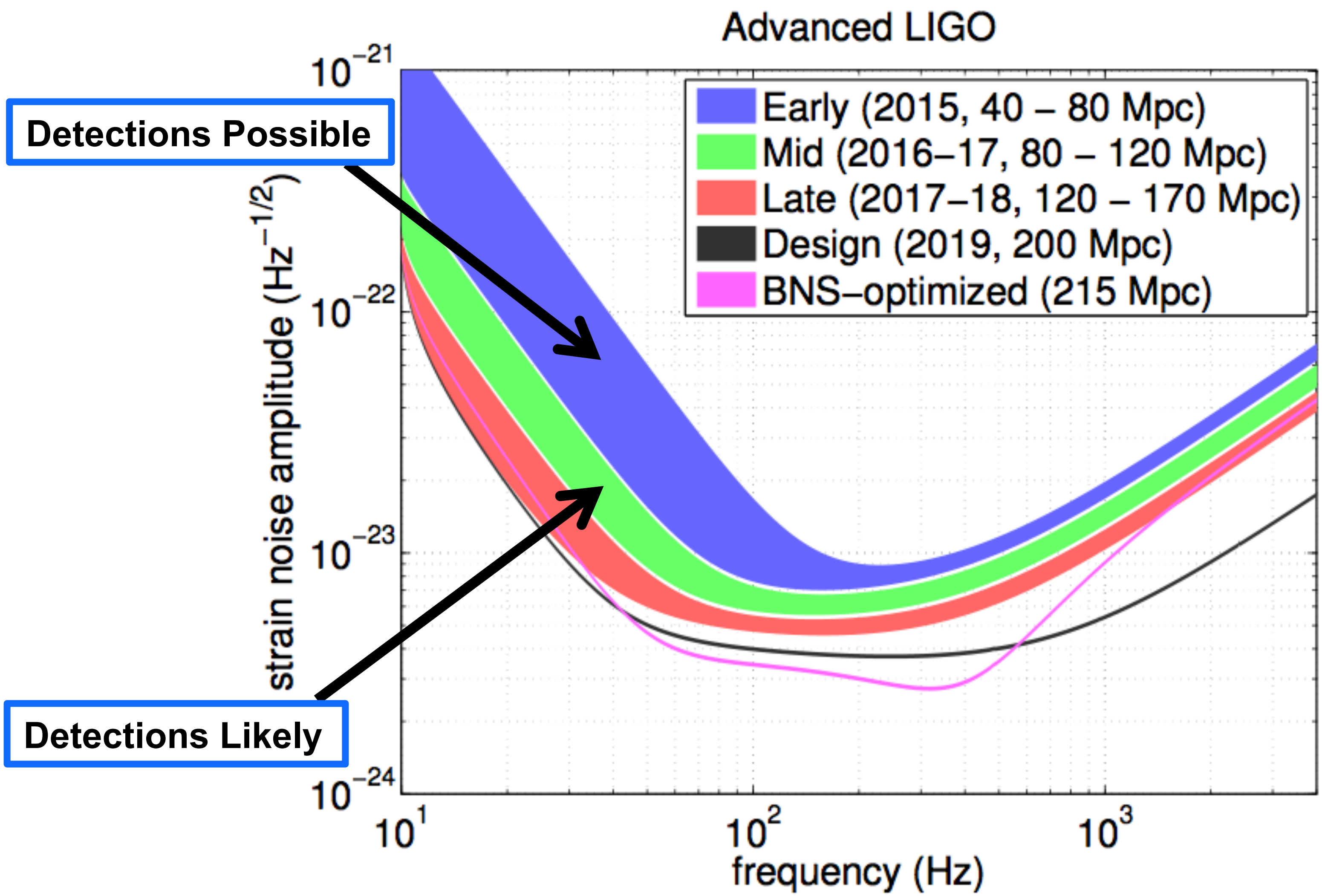
What remains for the Project *per se*?

- **Internal Reviews:** The Systems group spearheading a series of parallel/series reviews to accept subsystems, installations and ultimately the interferometers as whole devices
- *Subsystem* Acceptance Reviews
- *Installation* Acceptance Reviews
- *System* Acceptance Reviews

- **Computing:** In a change of plans, we will present yearly a plan to the NSF which will have in-house computing AND use of ‘shared resources’

- **Champagne**: In March 2015.

A look at the near future of Observations – when do we think we can see something?



What lessons learned?

Things we did well:

- Full-scale mechanical and optics prototypes, installed and tested in exact copies of the infrastructure
- Scaled interferometry testbeds, using acquisition, control, code of final system
- Deep testing for both performance and robustness at all scales of integration
- Documentation of designs, testing, and operations/maintenance
  - » (or will have done well once finished…)
- Systems Engineering; flow-down of requirements, establishment of standards; pool of resources to solve subsystem problems (e.g., FEA)
- Guardian sequencing system for locking/changing state – started late but caught up quickly; absolutely necessary for a device of this complexity

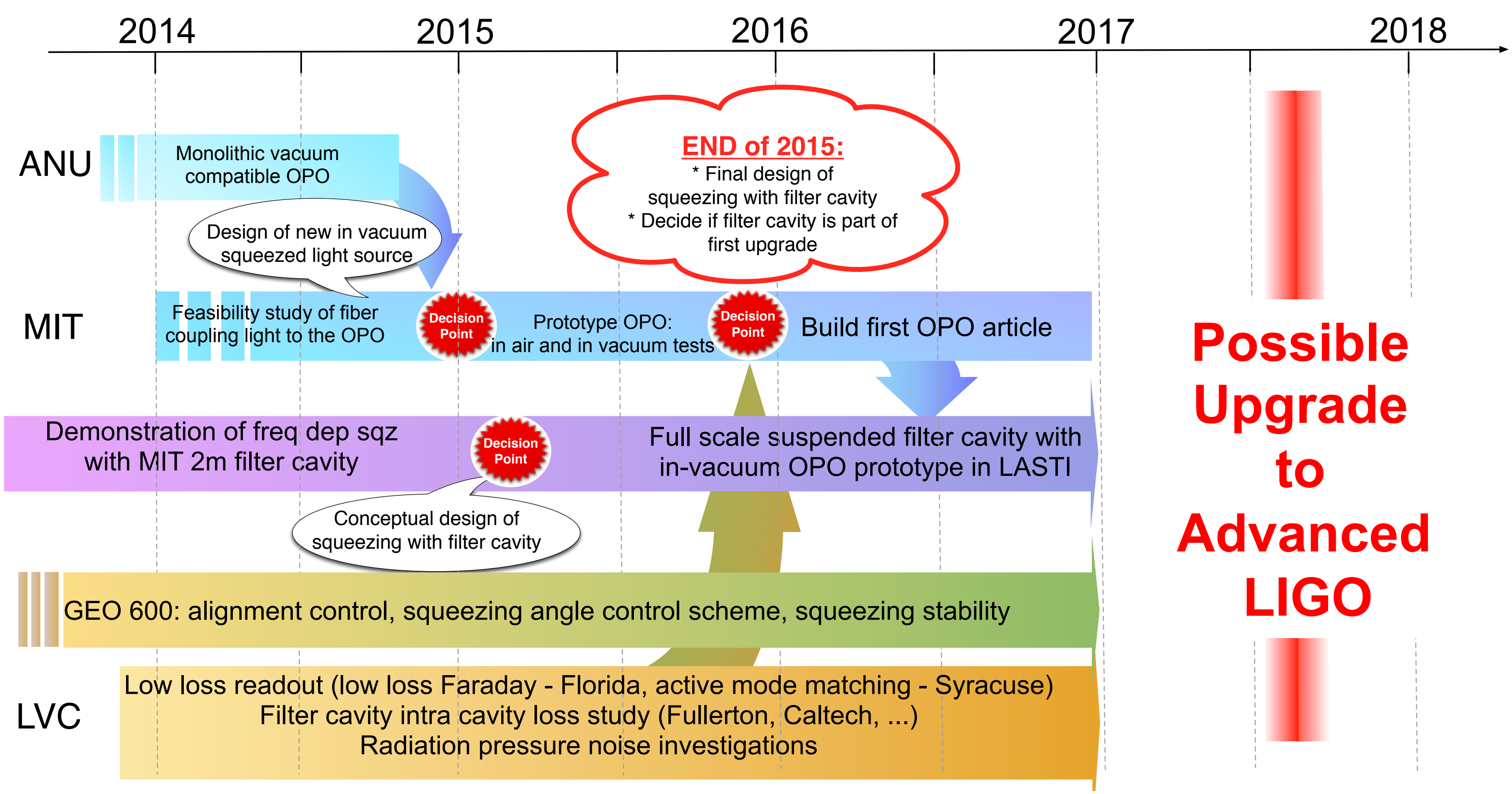
What lessons learned?

Things we did less well:

- Overall Labor estimates (design, engineering, vendor oversight, cleaning, assembly, test, installation, documentation) – aLIGO underestimated the need by a factor 2
- Drastically underestimated the technical scope of ‘Auxiliary Optics’ – thermal compensation, scattered light, optical levers, photon calibration
  - » All these worked (or will work!) out well in the end we believe
- Drastically underestimated cost, labor, complexity, difficulty of contamination control, and still not happy with where we are and with our techniques
- Some subsystems did not get the QA they should have
  - » Some in-house activities got less scrutiny
  - » Some vendors were delivering equipment too specialized for QA staff, so scientists stepped in as QA officers…not so good
  - » More QA staff, and more rigorous rules for QA activities

Incremental upgrades in planning

- Frequency dependent Squeezing is an obvious option for aLIGO
- Question will be if we try to use it instead of full power or after full power



LIGO

The Last Page

- Significant milestones were recently obtained at both sites
  - 2h lock requirements fulfilled at LLO
  - In-vacuum installation complete at LHO
- At LLO, LSC participation in commissioning activities starting
- At LHO, focus on integrated testing and 3IFO
- Acceptance reviews in parallel
- Work to do, but…
- The light at the end of the 4km tunnel can be seen!
- **Goal: deliver detections for the 100th anniversary – 2016 – of Einstein's paper on GWs**