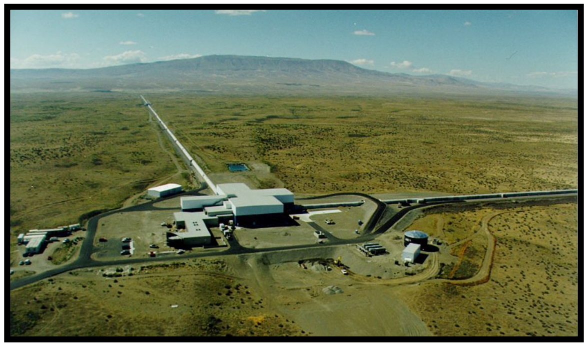
Advanced LIGO:
A second-generation gravitational-wave detector

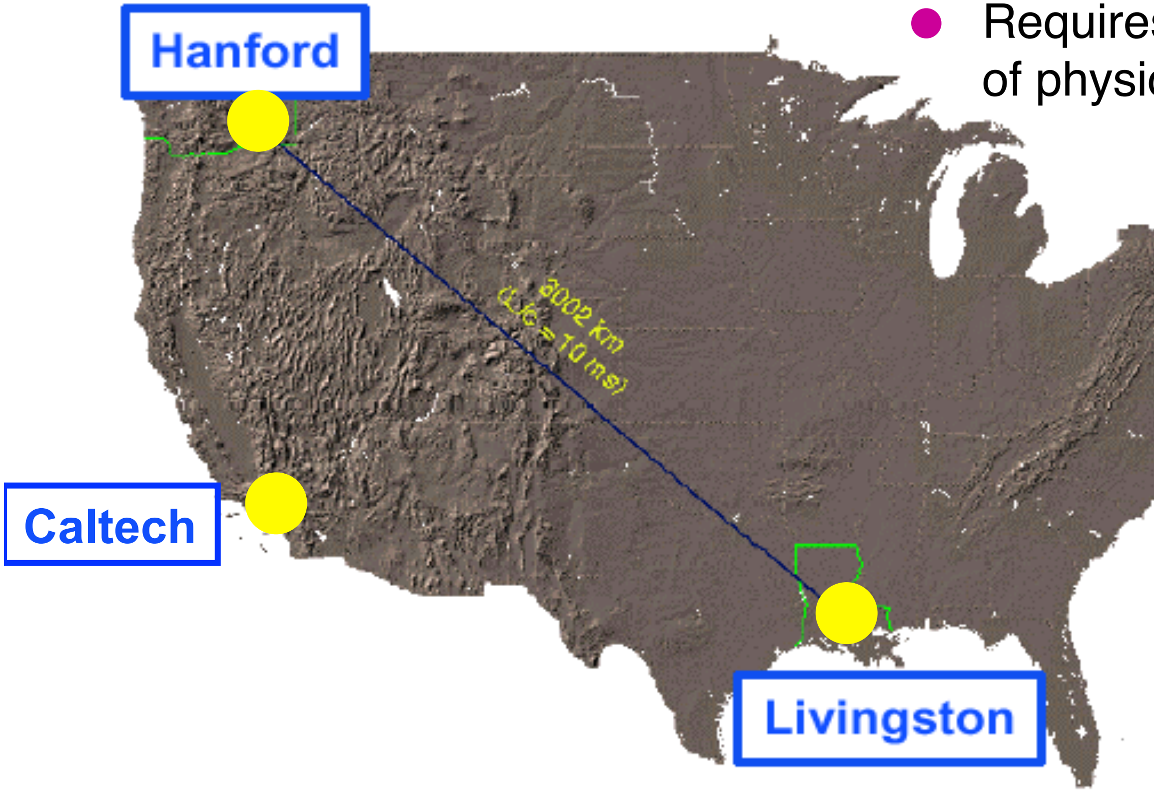
University of Washington
11 July 2013

David Shoemaker
MIT

LIGO Laboratory: two Observatories and Caltech, MIT campuses



- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits

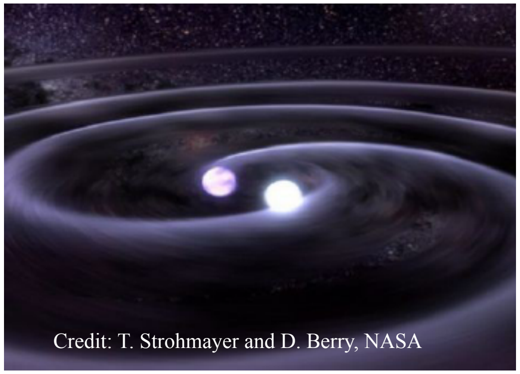


Gravitational Waves – Einstein, 1916

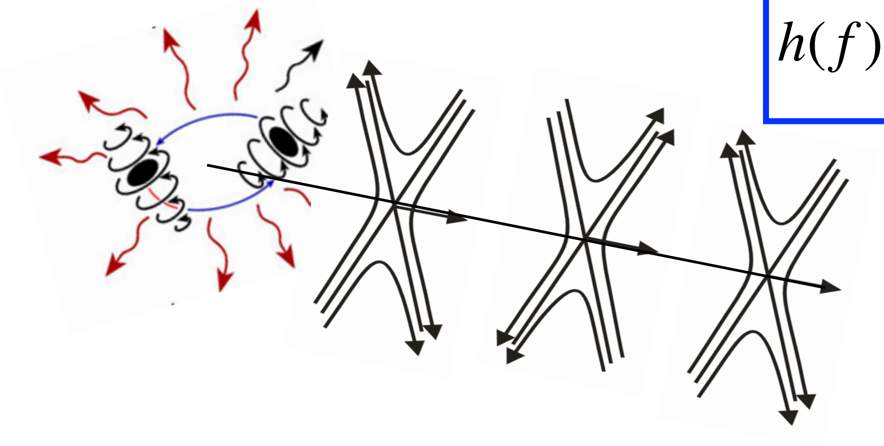
(okok, he got it right in 1918)

- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time (‘ripples’ in space-time)
- Emitted from accelerating mass distributions
  - Generated by the time-dependence of the quadrupole mass moment
  - Practically, need stellar-mass objects moving at speeds approaching the speed of light to make measurable signals

$$\boxed{h(f) = \frac{2\Delta L(f)}{L}}$$



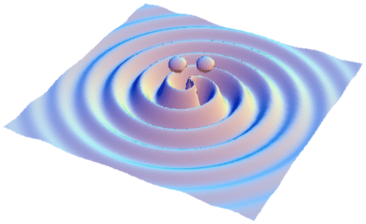
Credit: T. Strohmayer and D. Berry, NASA



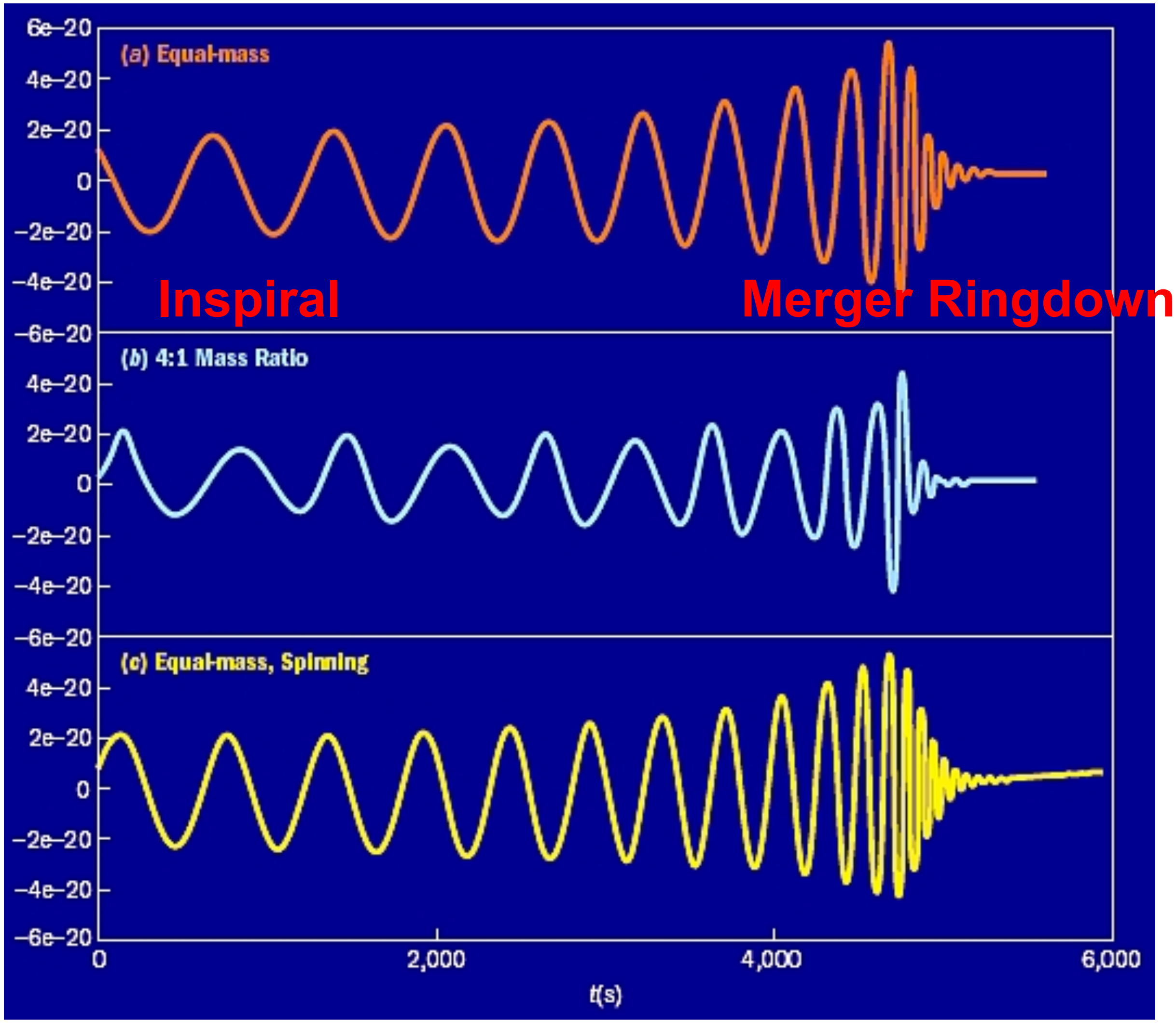
- Are physically manifested as strains **(longer antenna makes bigger signals)**
- A unique means to observe the most violent events in the universe
- …but small signals: coalescing neutron stars in Virgo cluster lead to a strain on earth:

$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad \boxed{h \sim 10^{-21}}$$

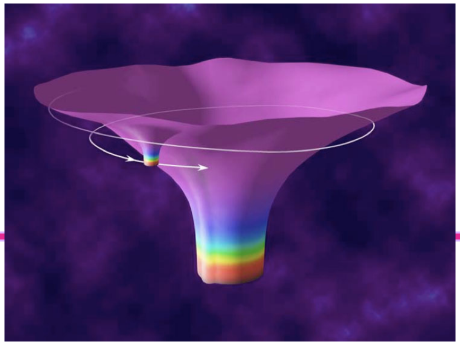
Standard Candle: Compact binary inspiral, merger, ringdown



- This source has the best understood waveform and rate
- There’s a lot of physics and astrophysics in the waveforms!

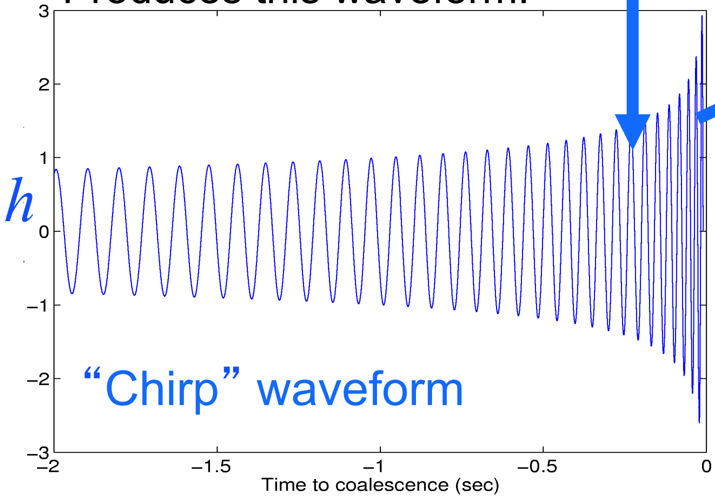


Searches for Binary Mergers

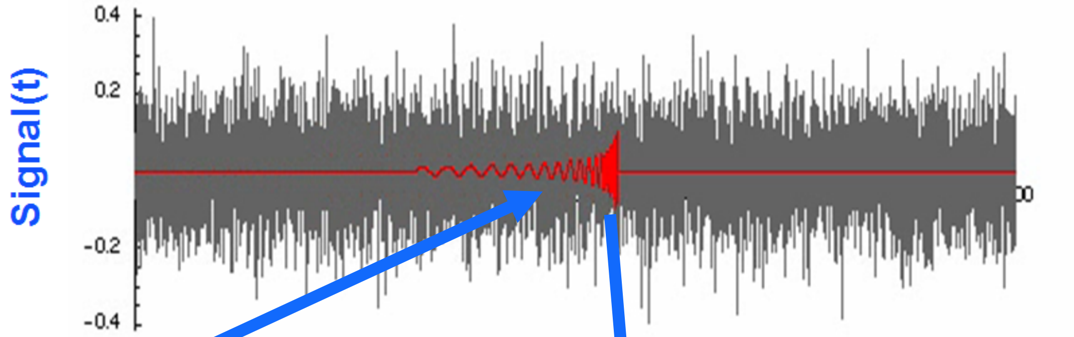


This source:

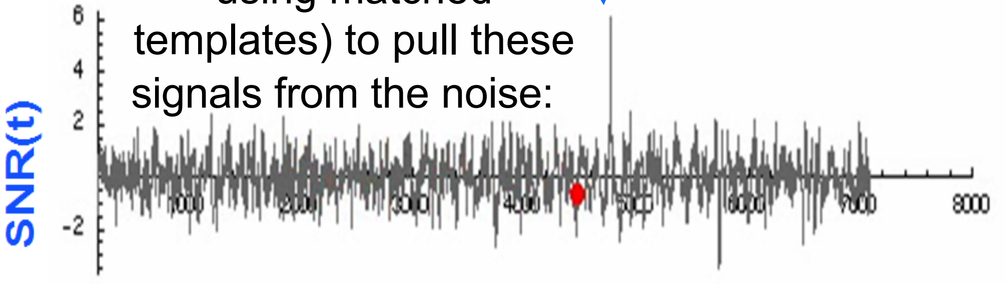
Produces this waveform:



Buried in this noise stream:

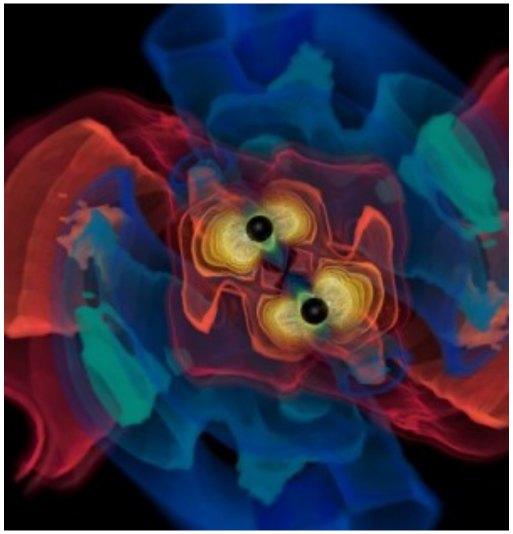


We use different methods (in this case optimal Wiener filtering using matched templates) to pull these signals from the noise:



The problem is that non-astrophysical sources also produces signals (false positives)

Astrophysical Sources of Gravitational Waves

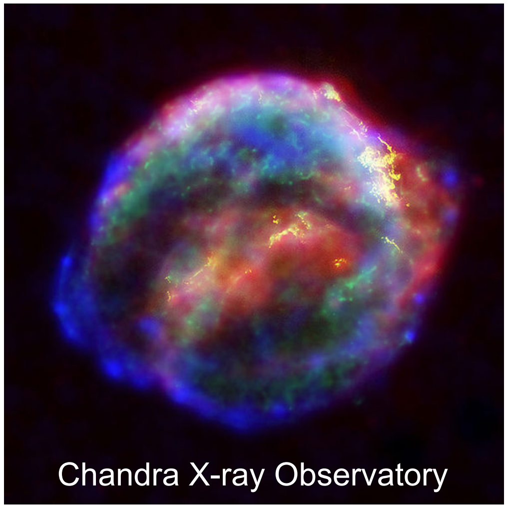


Credit: AEI, CCT, LSU

Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

- (effectively) transient

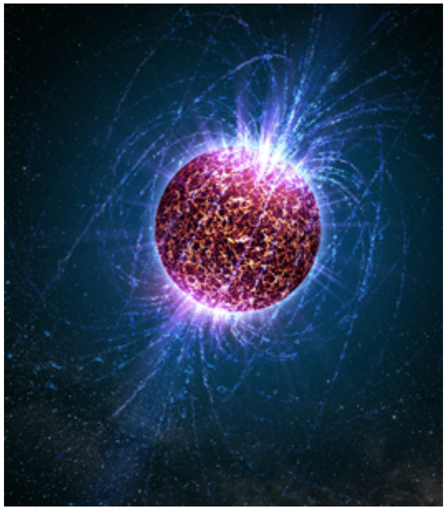


Chandra X-ray Observatory

Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled (‘bursts’), transient

- Cosmic strings, soft gamma repeaters, pulsar glitches also in ‘burst’ class

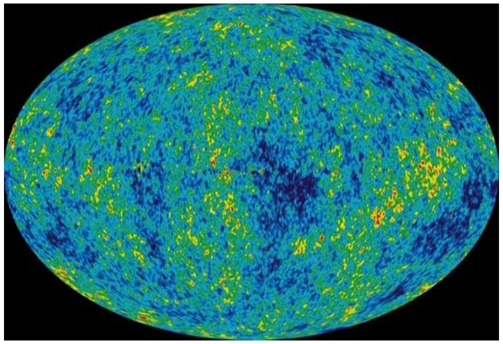


Casey Reed, Penn State

Spinning neutron stars with a mountain

- (effectively) monotonic waveform

- Long duration



NASA/WMAP Science Team

Cosmic Gravitational-wave Background

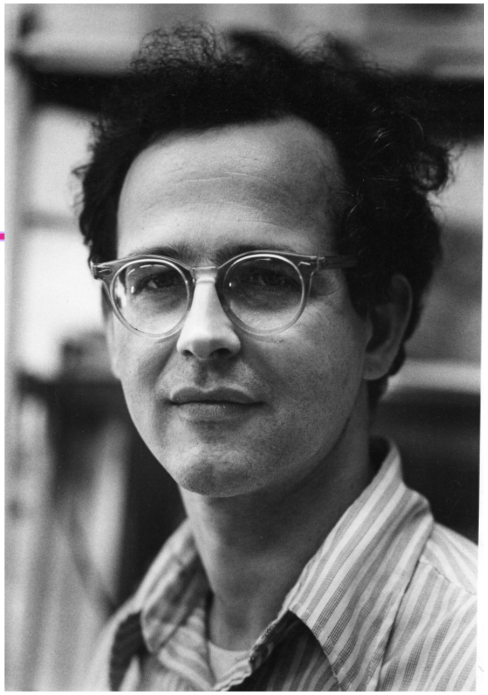
- Residue of the Big Bang, long duration

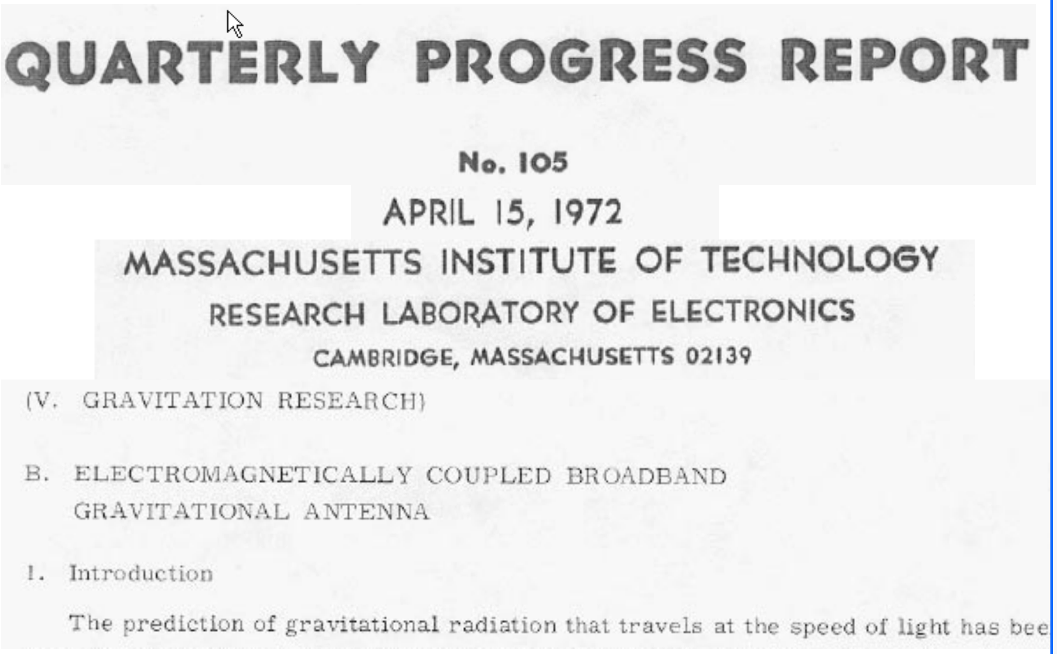
- Long duration, stochastic background

Insights into astrophysics inaccessible to photon and neutrino astronomy, and provides unique test of extreme relativity

How to detect these waves?

- 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

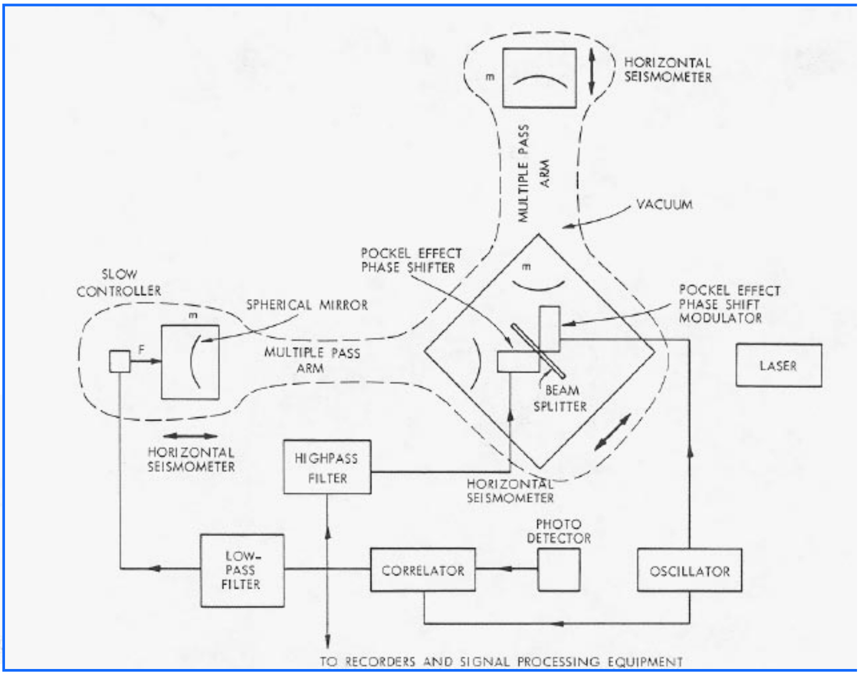
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

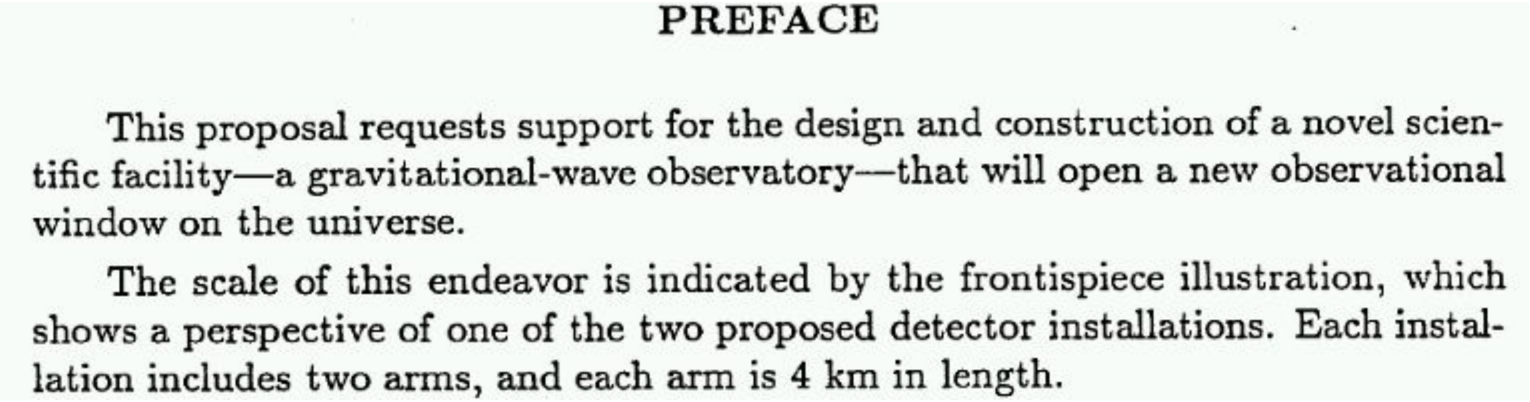
B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

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



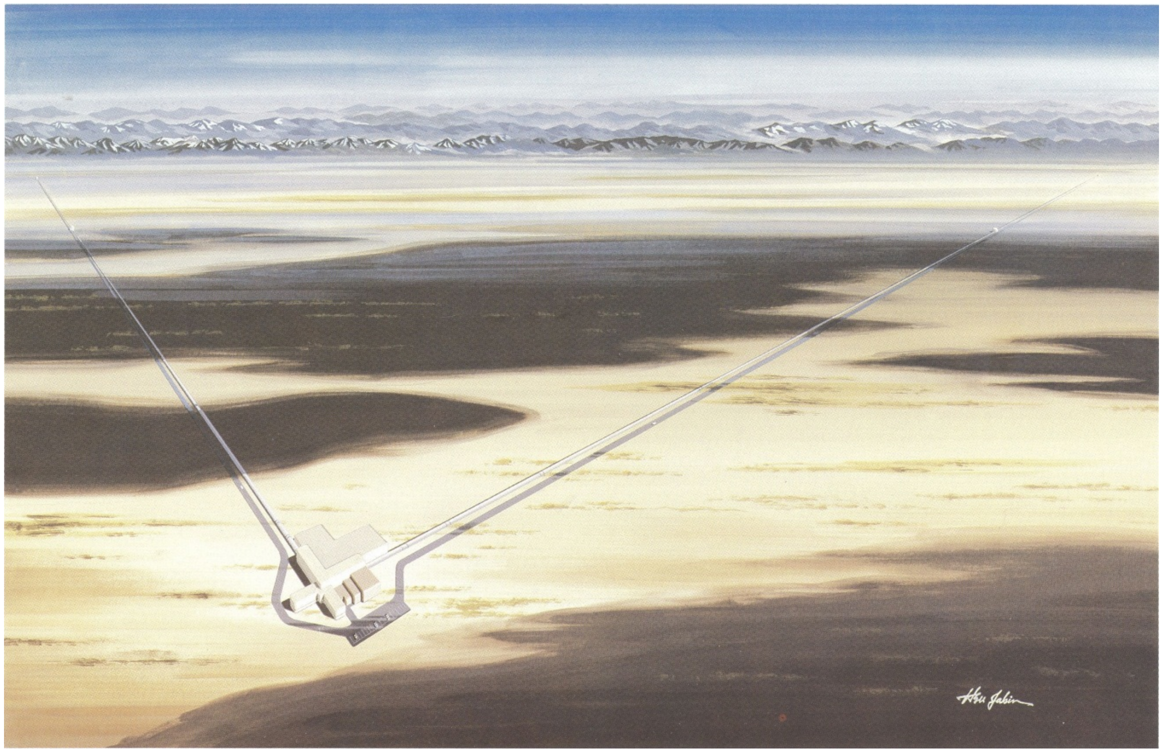
… led to LIGO:
1989 Proposal to the US NSF



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.

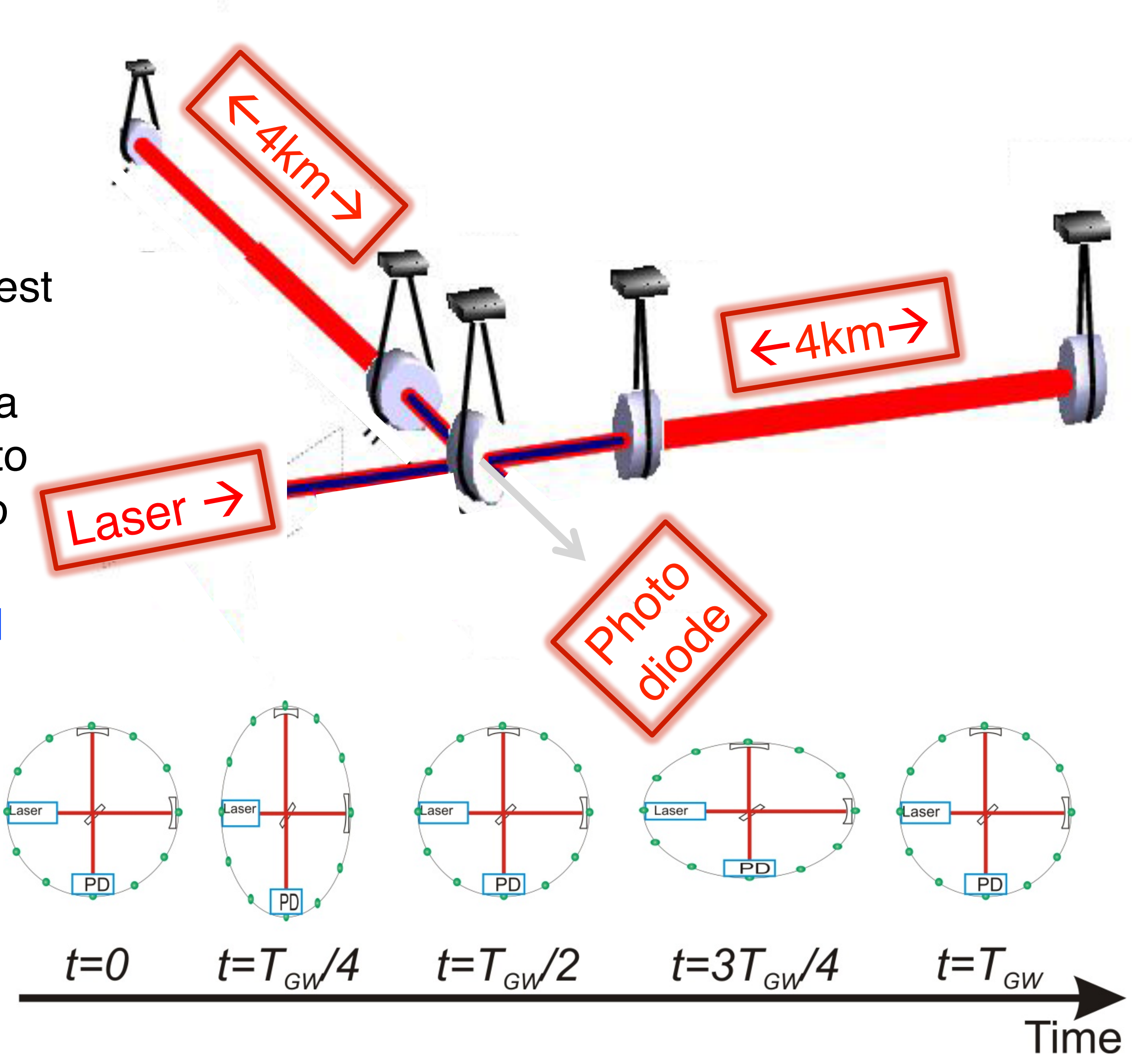


LIGO:
Today, Washington state…

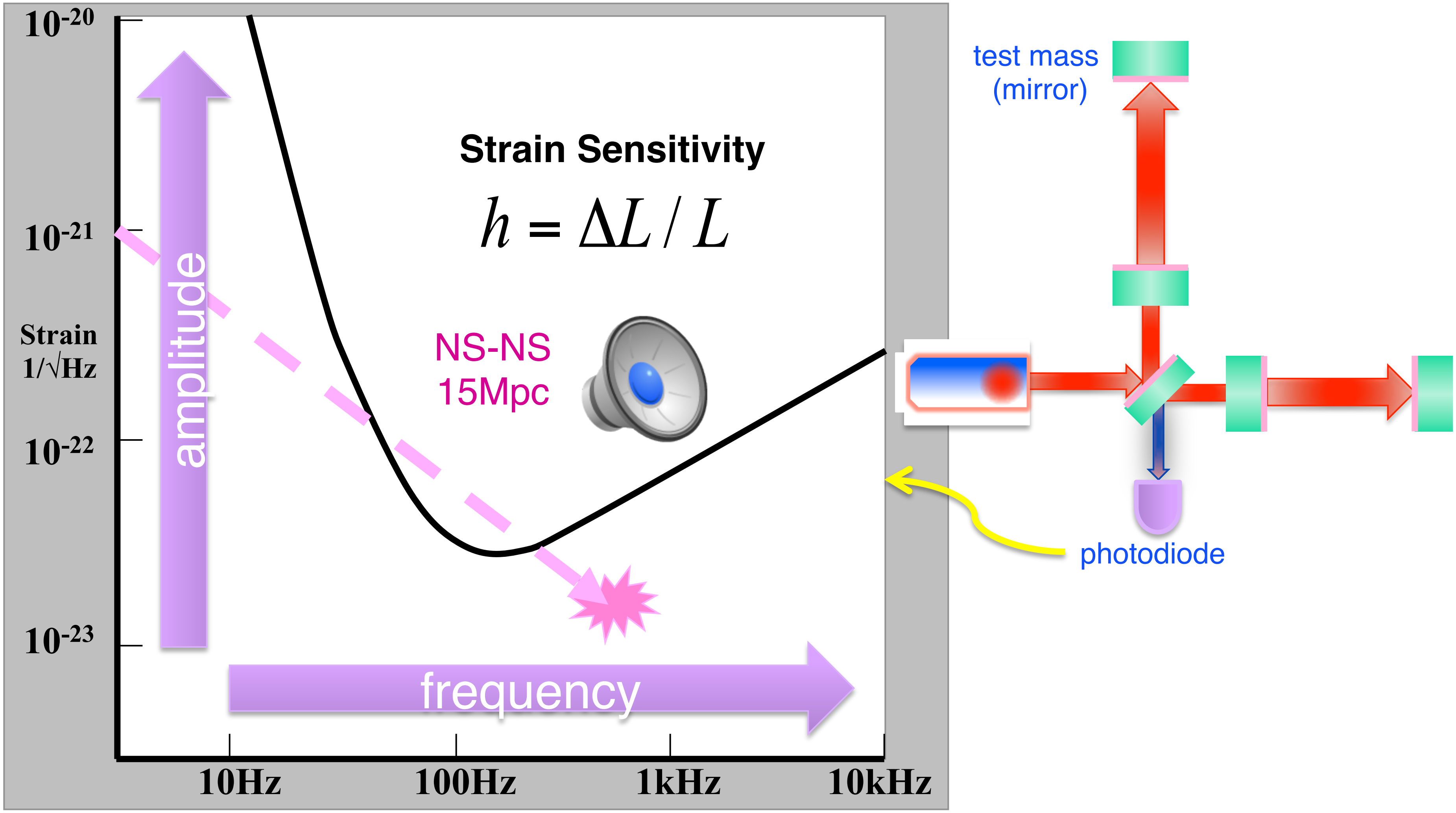
…LIGO in Louisiana

Interferometric Gravitational-wave Detectors

- Enhanced **Michelson interferometers**
  - LIGO, Virgo, and GEO600 use variations
- 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
- Length limited by taxpayer noise….



What does an inspiral sound like? For Initial LIGO, two Neutron Stars in an inspiral at 15 Mpc distance….:

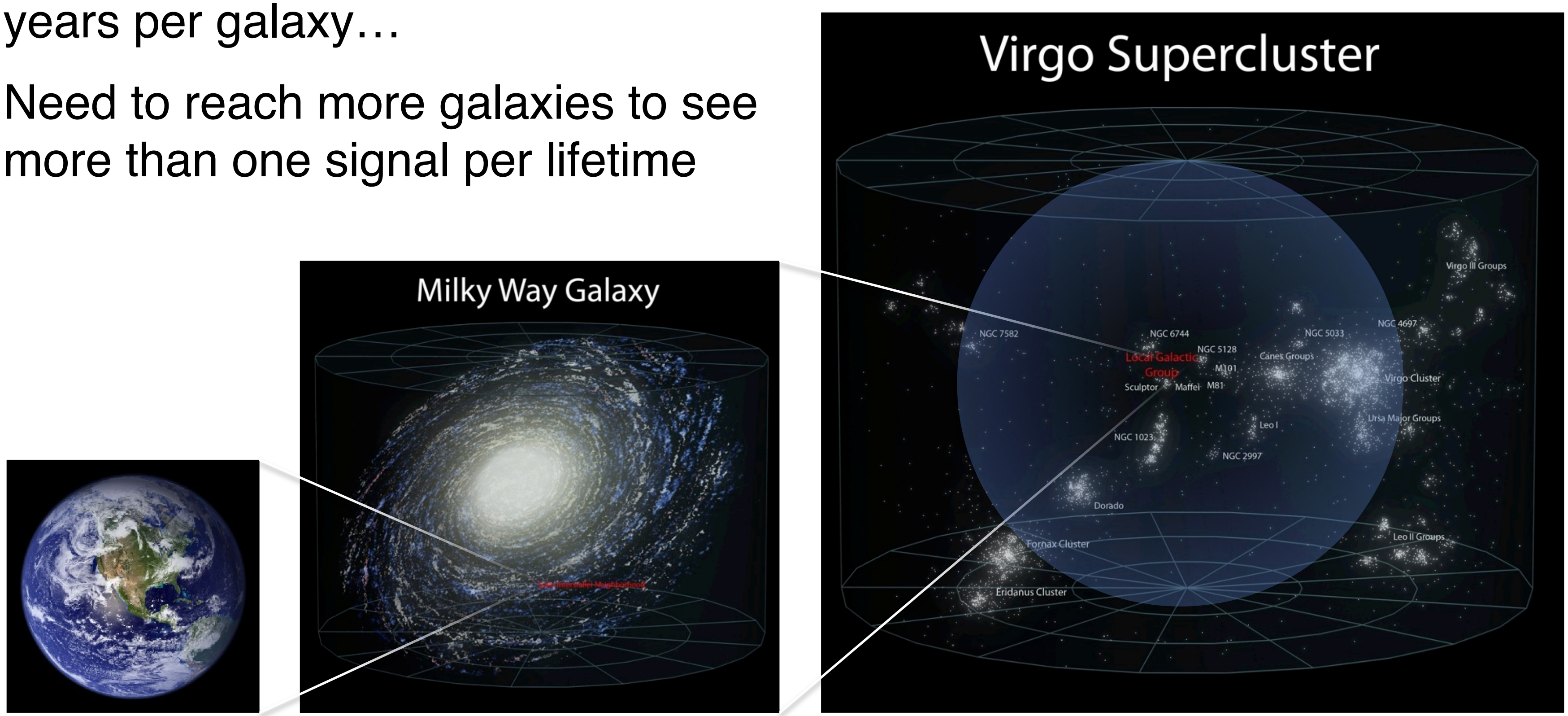


M. Evans

No Detections Yet…
Why not?

- First generation detectors reached about 100 galaxies
- Events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see more than one signal per lifetime

(considering NS-NS mergers)

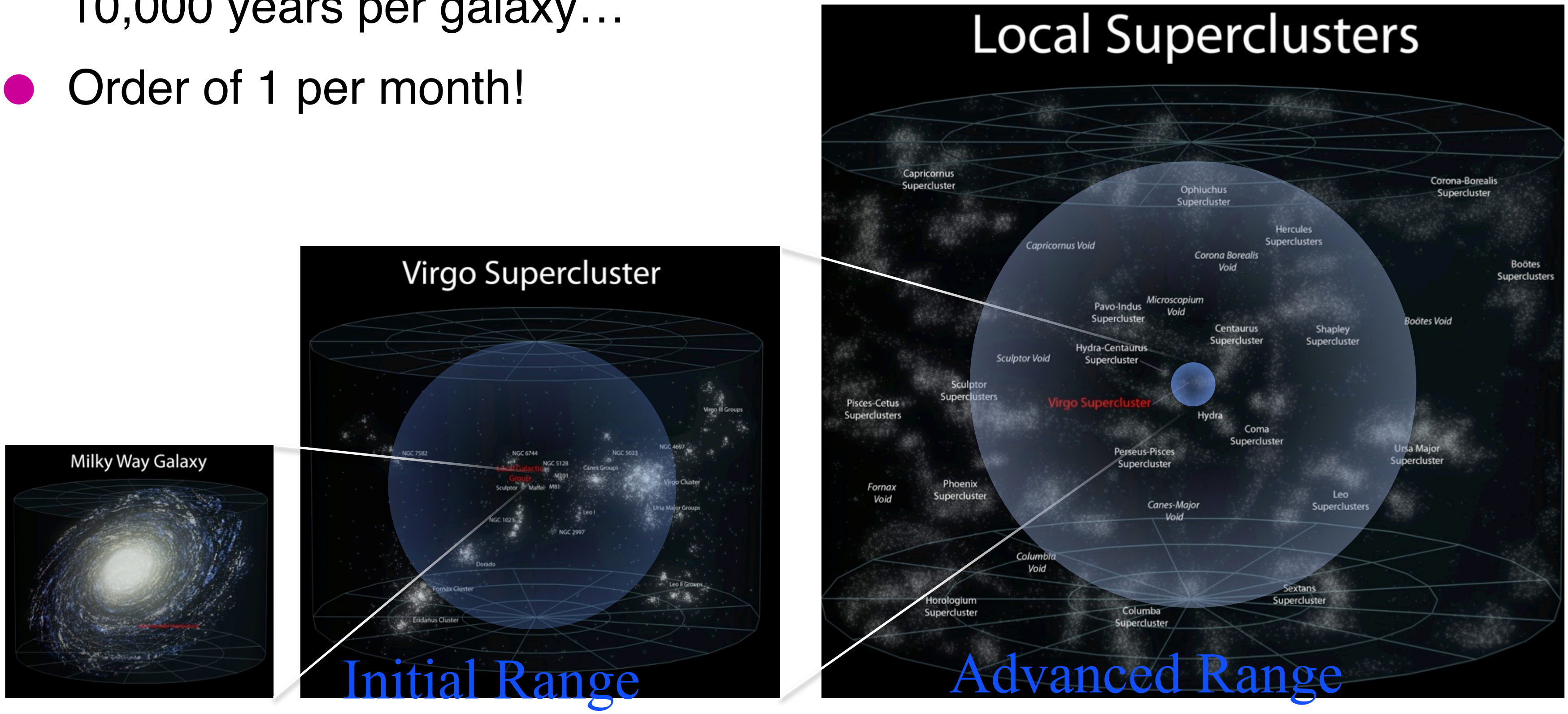


M. Evans

Advanced Sensitivity:
10x More Range makes a qualitative difference

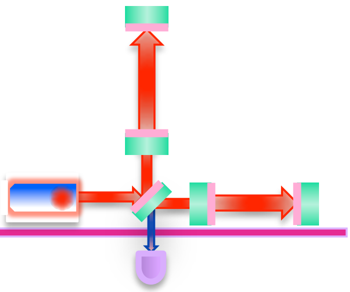
- Advanced detectors will reach about 100,000 galaxies
- Events happen once every 10,000 years per galaxy…
- Order of 1 per month!

- Advanced LIGO concept ~1999
- Project start 2008, $205M NSF
- Completion 2015, tuning follows

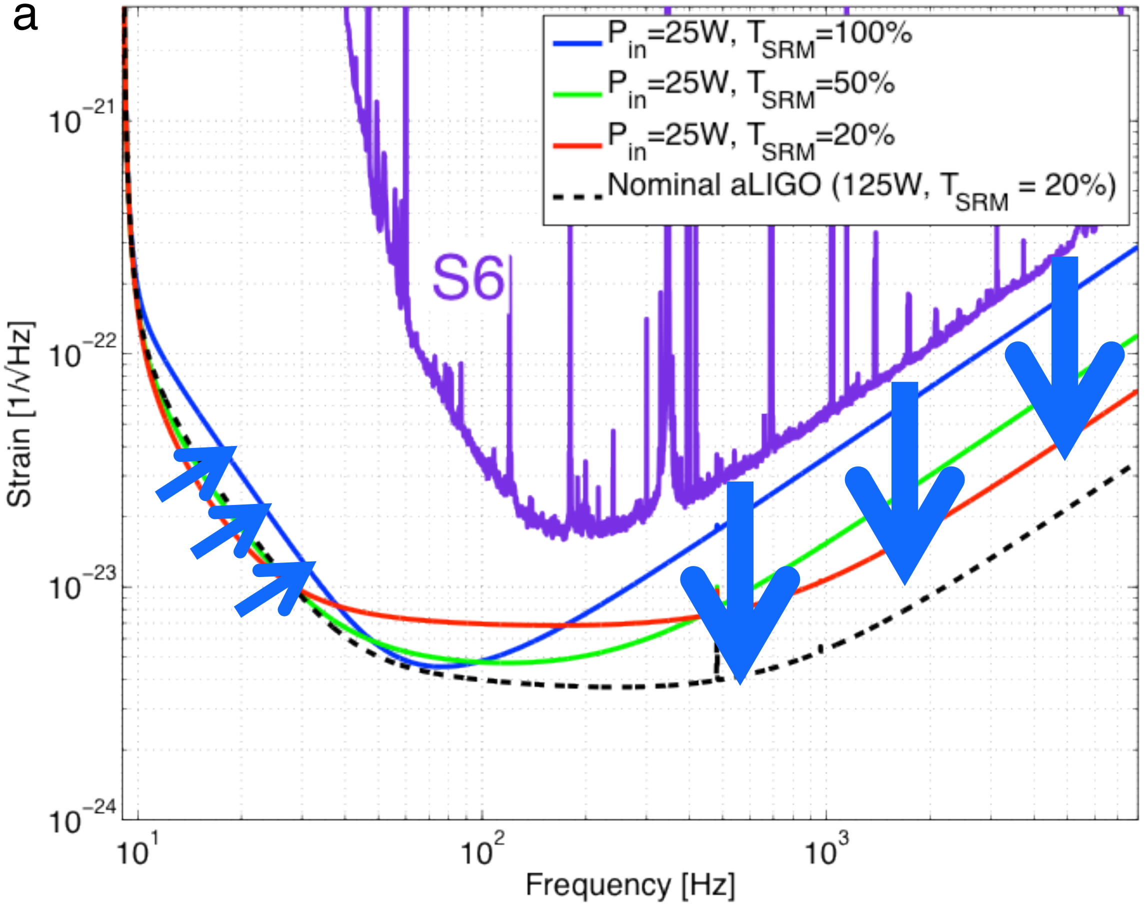


M. Evans

How to get there:
Addressing limits to performance

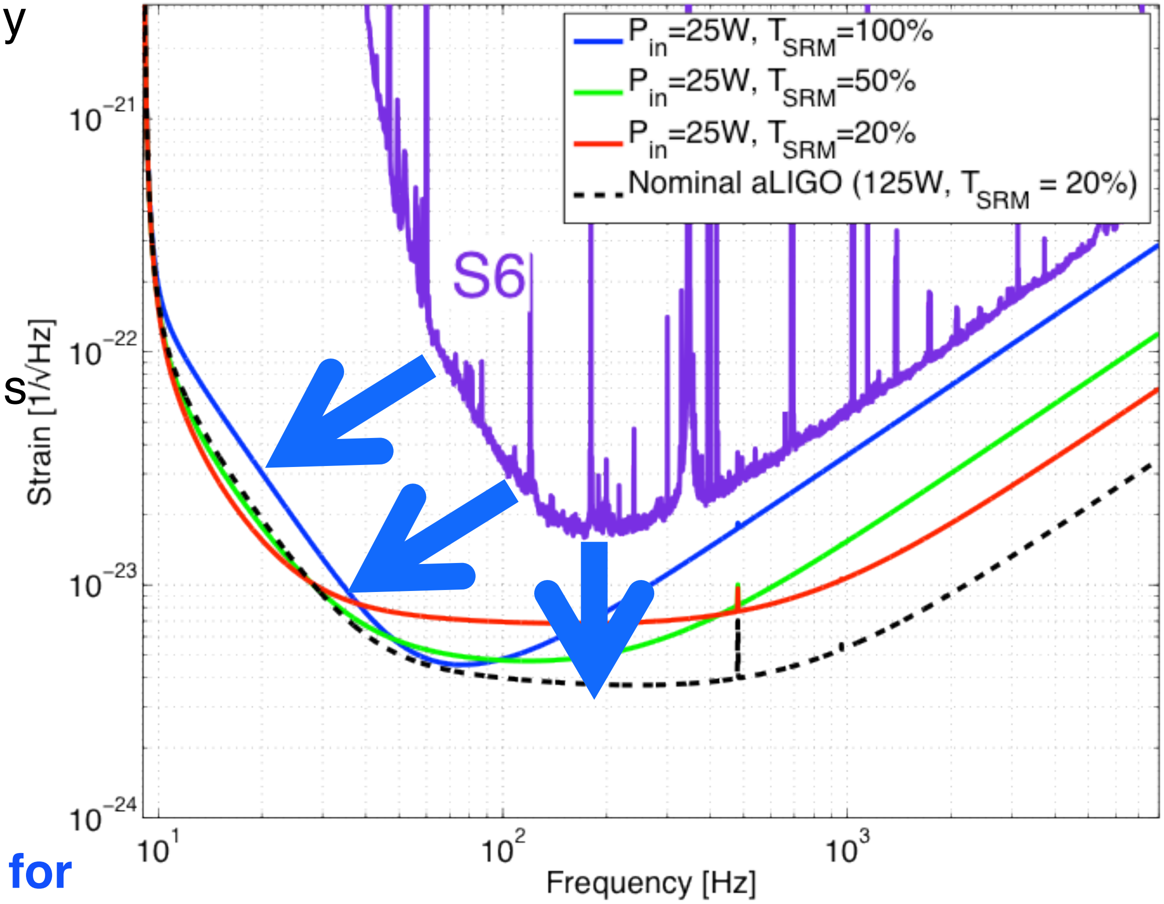


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses!
- ‘Standard Quantum Limit’
- Advanced LIGO reaches this limit with its **200W laser, 40 kg test masses**



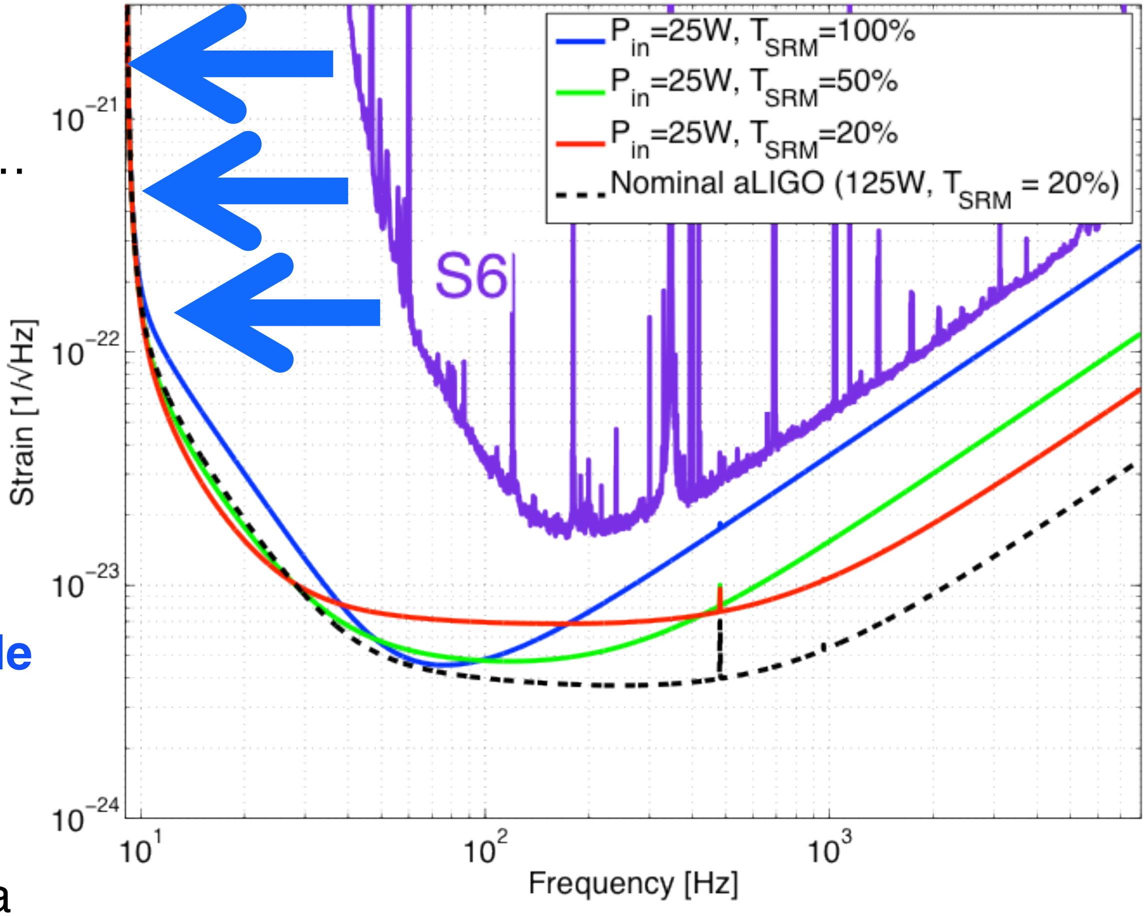
Addressing limits to performance

- **Thermal noise** – kT of energy per mechanical mode
- Wish to keep the motion of components due to thermal energy below the level which masks GW
- Low mechanical loss materials gather this motion into a narrow peak at resonant frequencies of system
- Realized in aLIGO with an all **fused-silica test mass suspension** – *Q* of order 10^9
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**

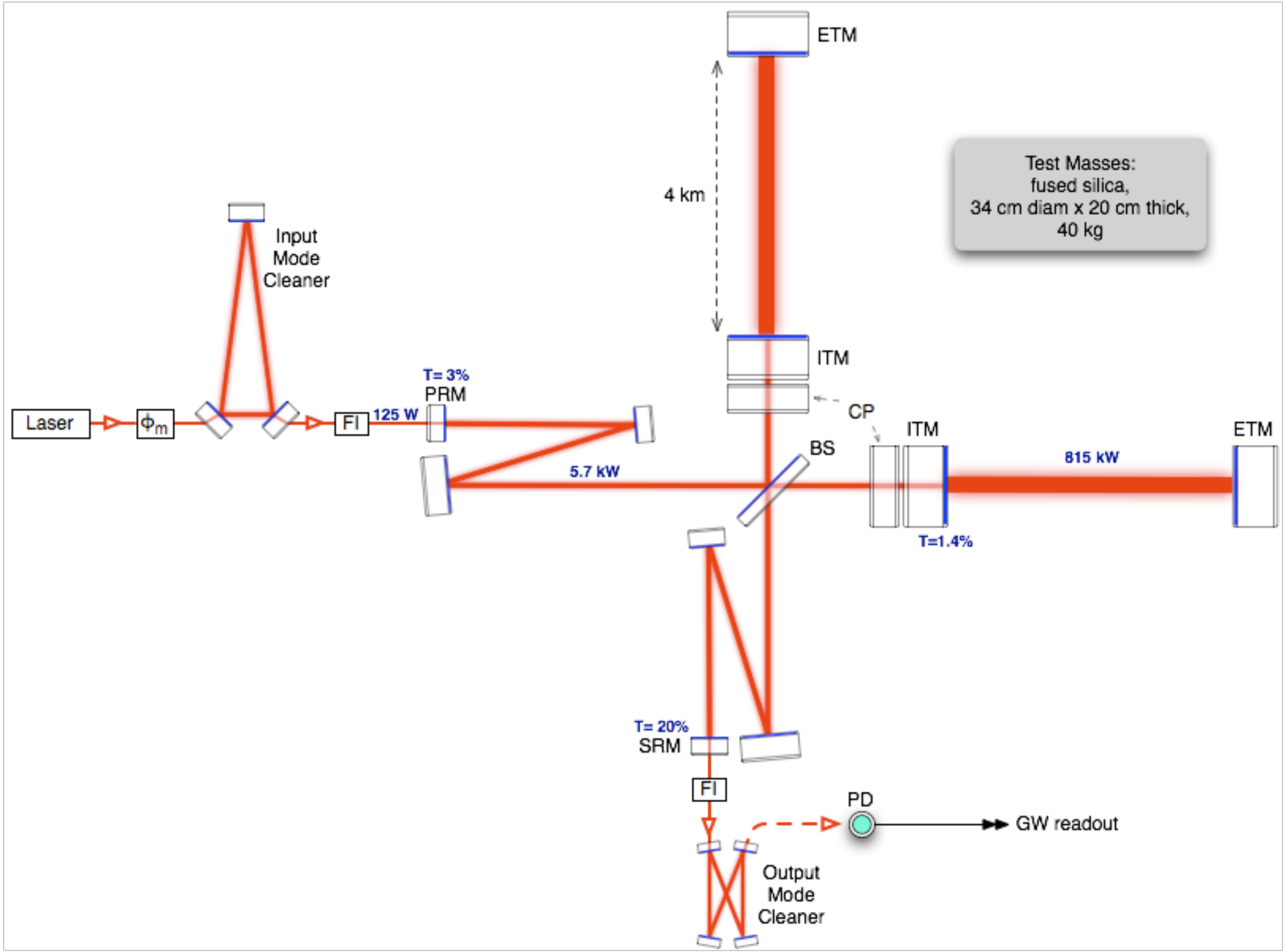


Addressing limits to performance

- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Motion from waves on coasts… and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Ultimate limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band



The Design: Optical Configuration

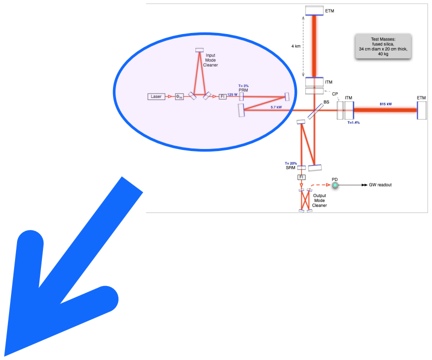


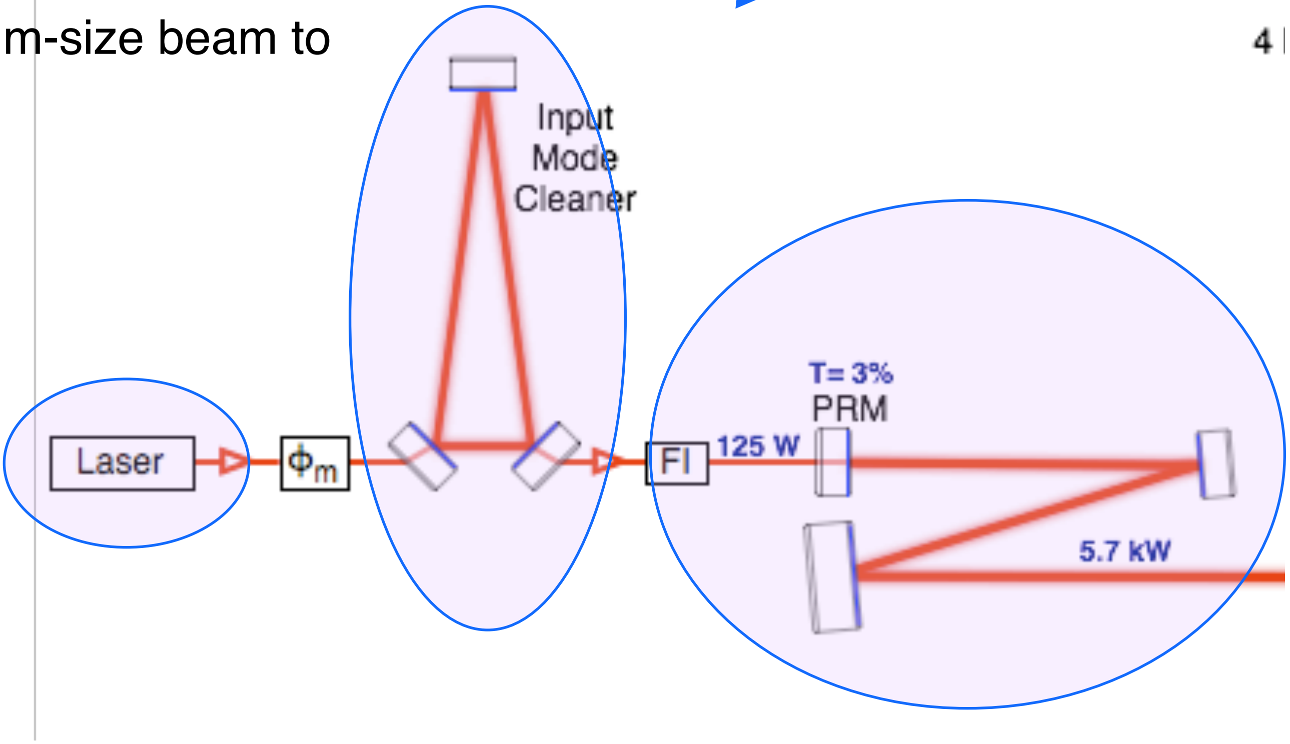
Test Masses:
fused silica,
34 cm diam x 20 cm thick,
40 kg

Key Interferometer Features

Laser light source

- High power to reduce the photon shot noise – 200 W, CW Nd:YAG 1.06 µm
- Frequency stabilized to a 15-meter triangular reference cavity which also stabilizes the pointing of the light
- Mode-matched from mm-size beam to the 4km arm cavities

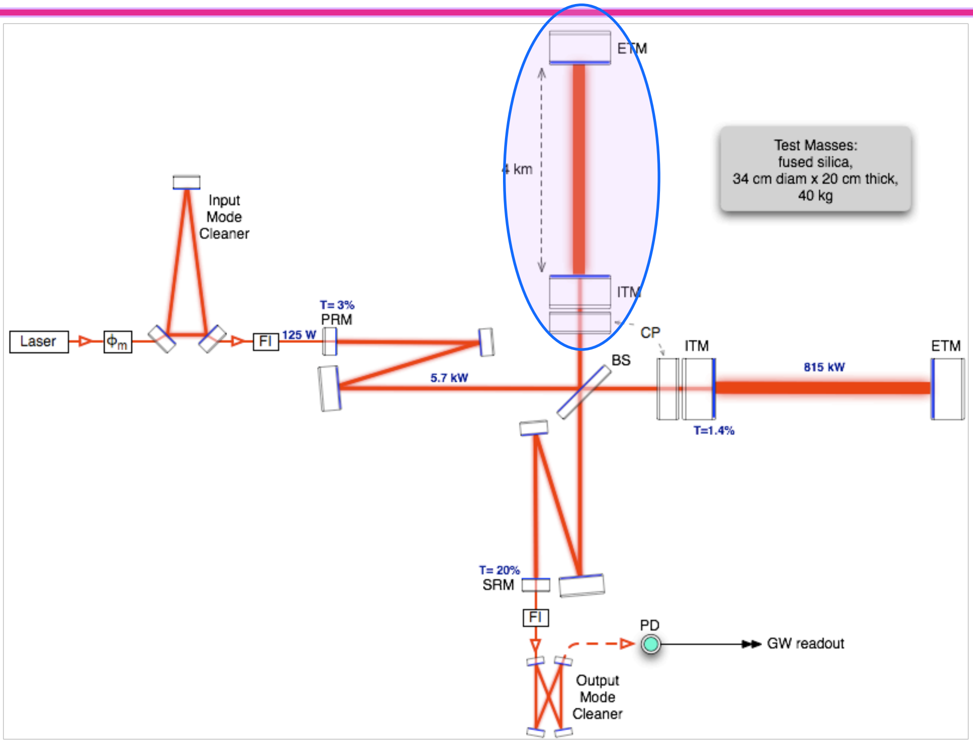




Key Interferometer Features

4km Arm cavity design

- Stores light for longer interaction with GWs, increases phase shift on reflection
  - Very low optical loss, $\mathcal{F} = 450$
  - Light stored for ~4 msec
- Beam sizes: 6.2 cm on far mirror, 5.3 cm on near mirror
  - Diffraction limited beam size for 1.06 micron laser light
- Requires extremely well-figured mirrors, held in alignment and position with control systems



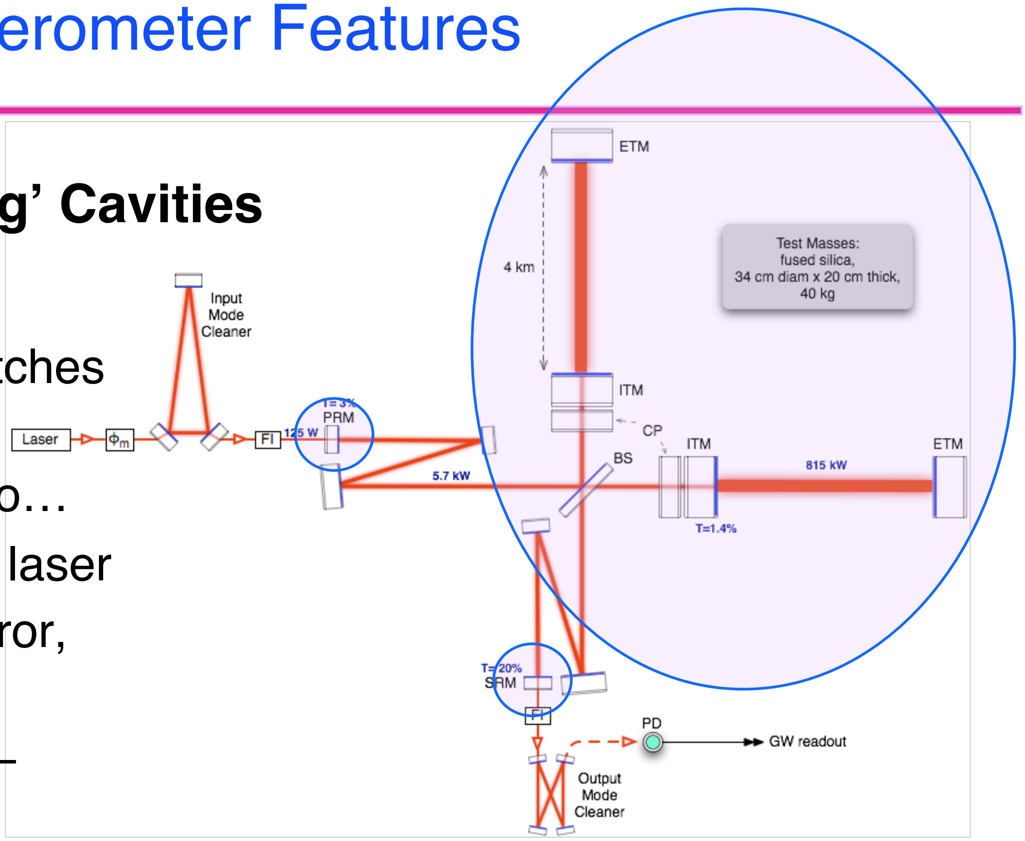
- Near-confocal design

$$R_{ITM}, R_{ETM} \approx L$$

  - Gives better angular stability than the near flat-flat case (torques from off-center beams)

Key Interferometer Features

‘Recycling’ Cavities

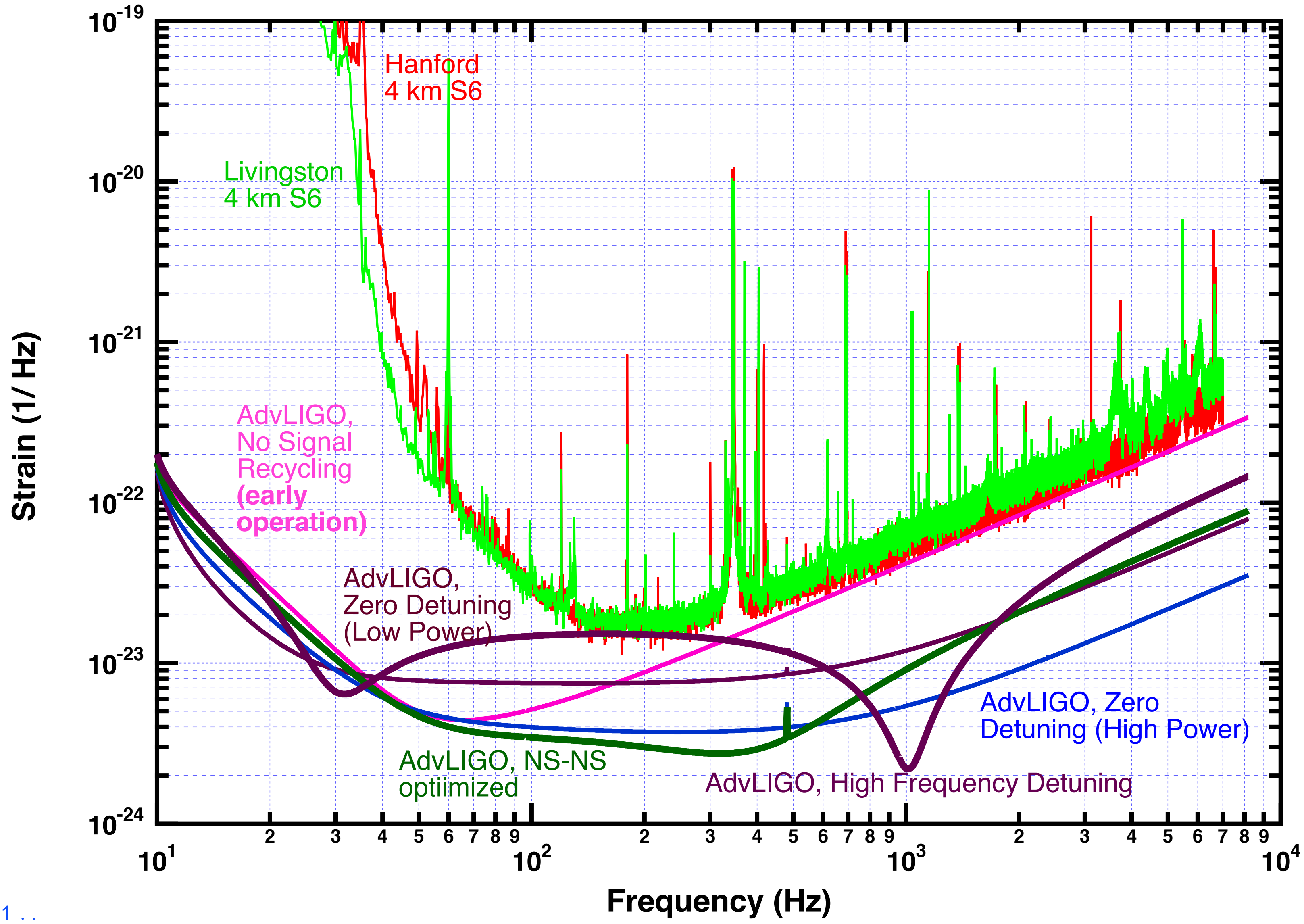


- Input recycling mirror impedance-matches the laser light to the optical losses
  - Michelson held on ‘dark fringe’, so…
  - Most light reflected back towards laser
- Form resonant cavity of recycling mirror, and lossy interferometer ‘mirror’
- Increases circulating power by ~50x – from 125W to 5.7 kW

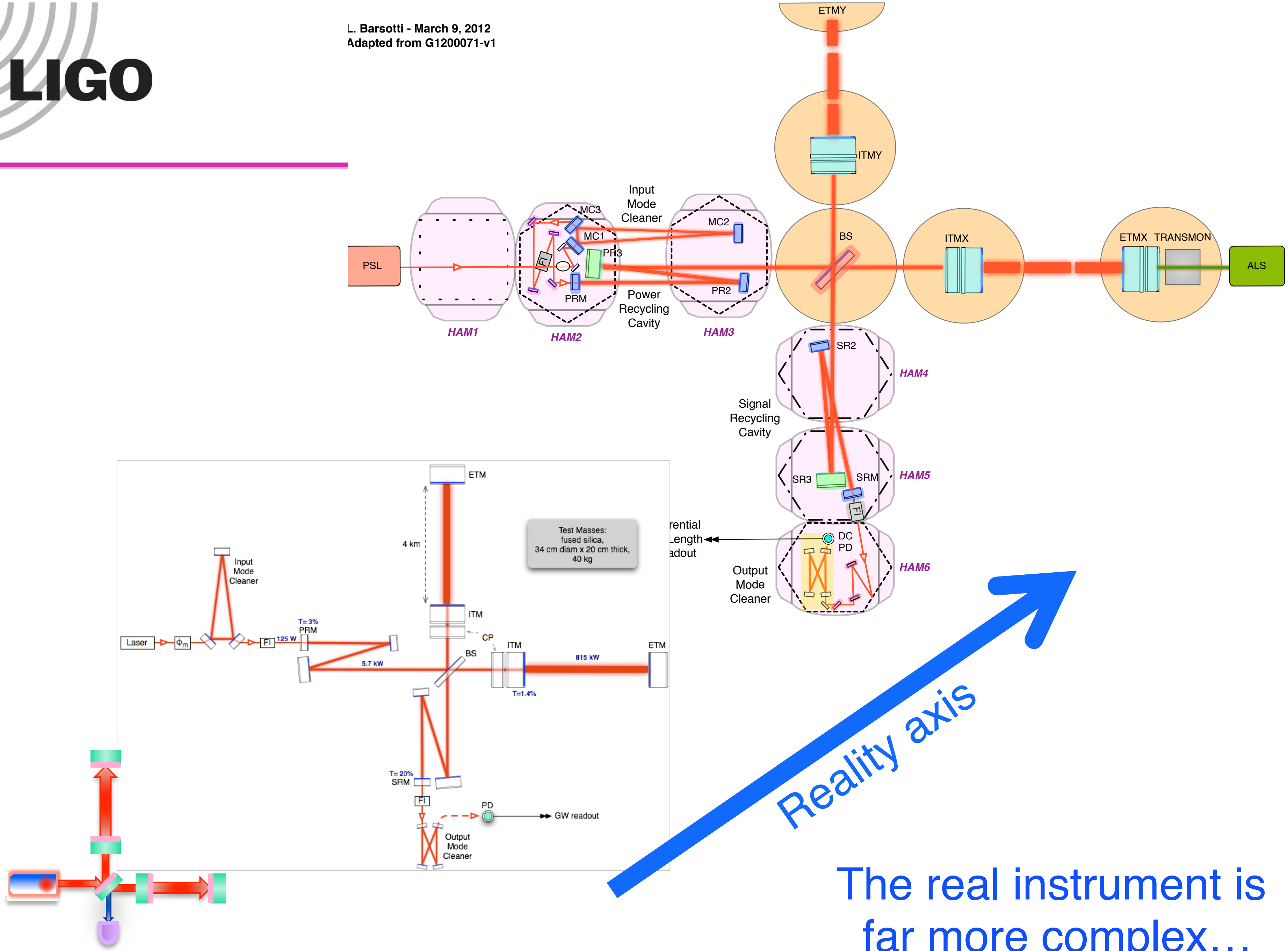
- Signal recycling mirror similarly forms cavity for gravitationally-induced sidebands on the light – allows tuning of instrument response

Resulting flexibility in the instrument response

Initial LIGO curves for comparison



L. Barsotti - March 9, 2012
Adapted from G1200071-v1



Reality axis

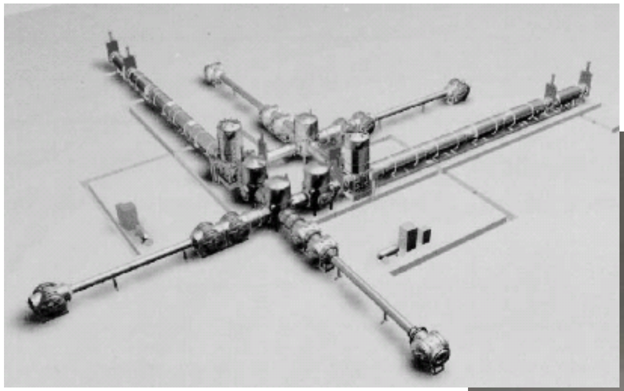
photodiode

The real instrument is far more complex…

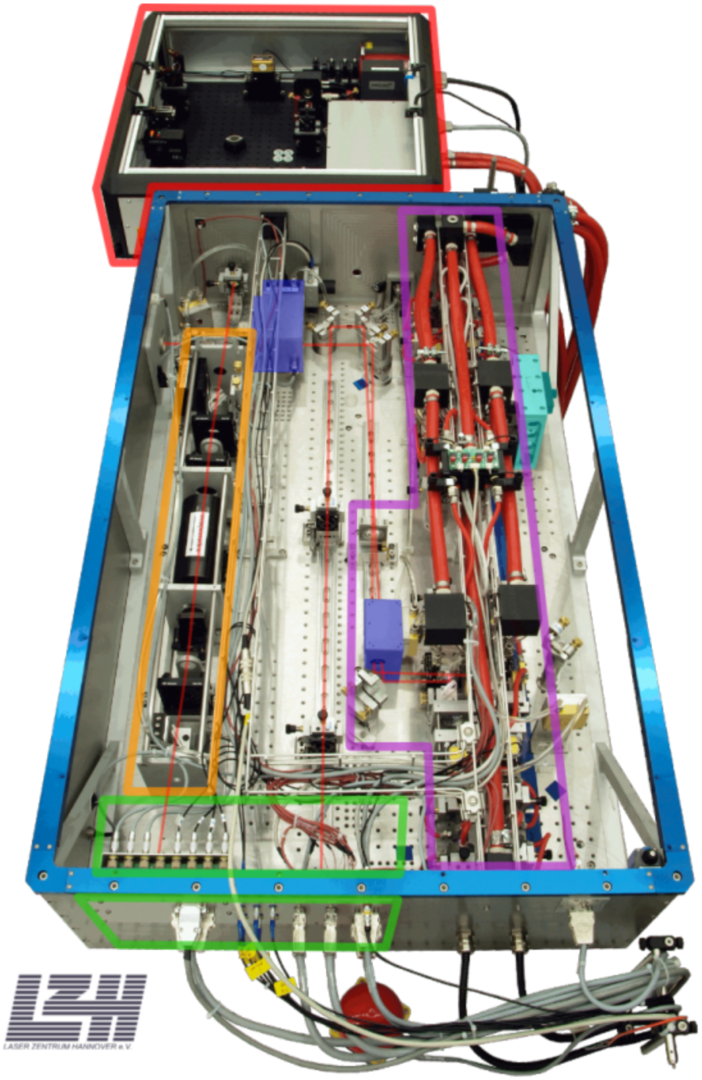
4km Beam Tubes

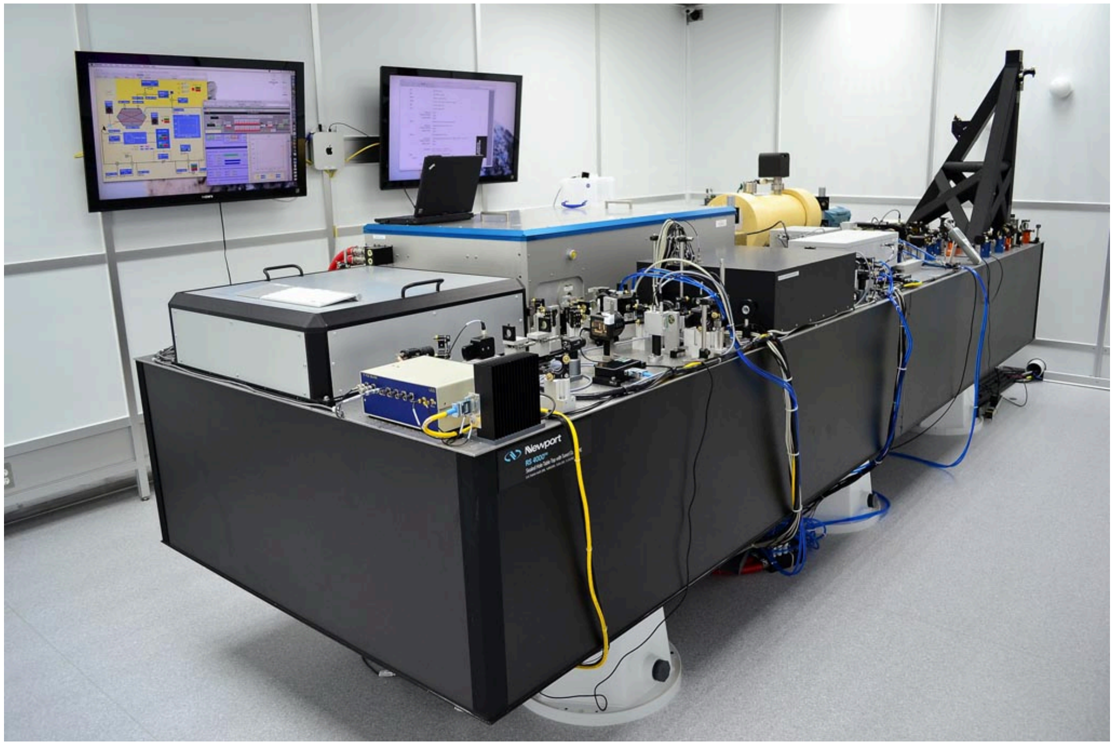
- Light must travel in an excellent vacuum
  - Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - 1.2 m diameter – avoid scattering against walls
- Cover over the tube – hunters' bullets and the stray car
- Tube is straight to a fraction of a cm…not like the earth's curved surface

LIGO Vacuum Equipment – designed for several generations of instruments



200W Nd:YAG laser, stabilized in power and frequency

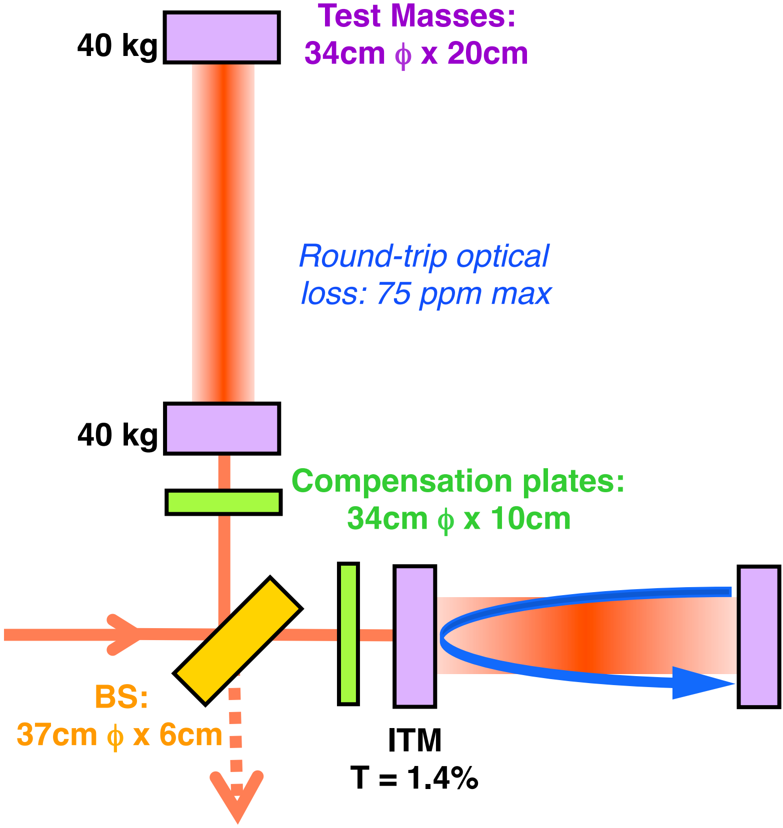


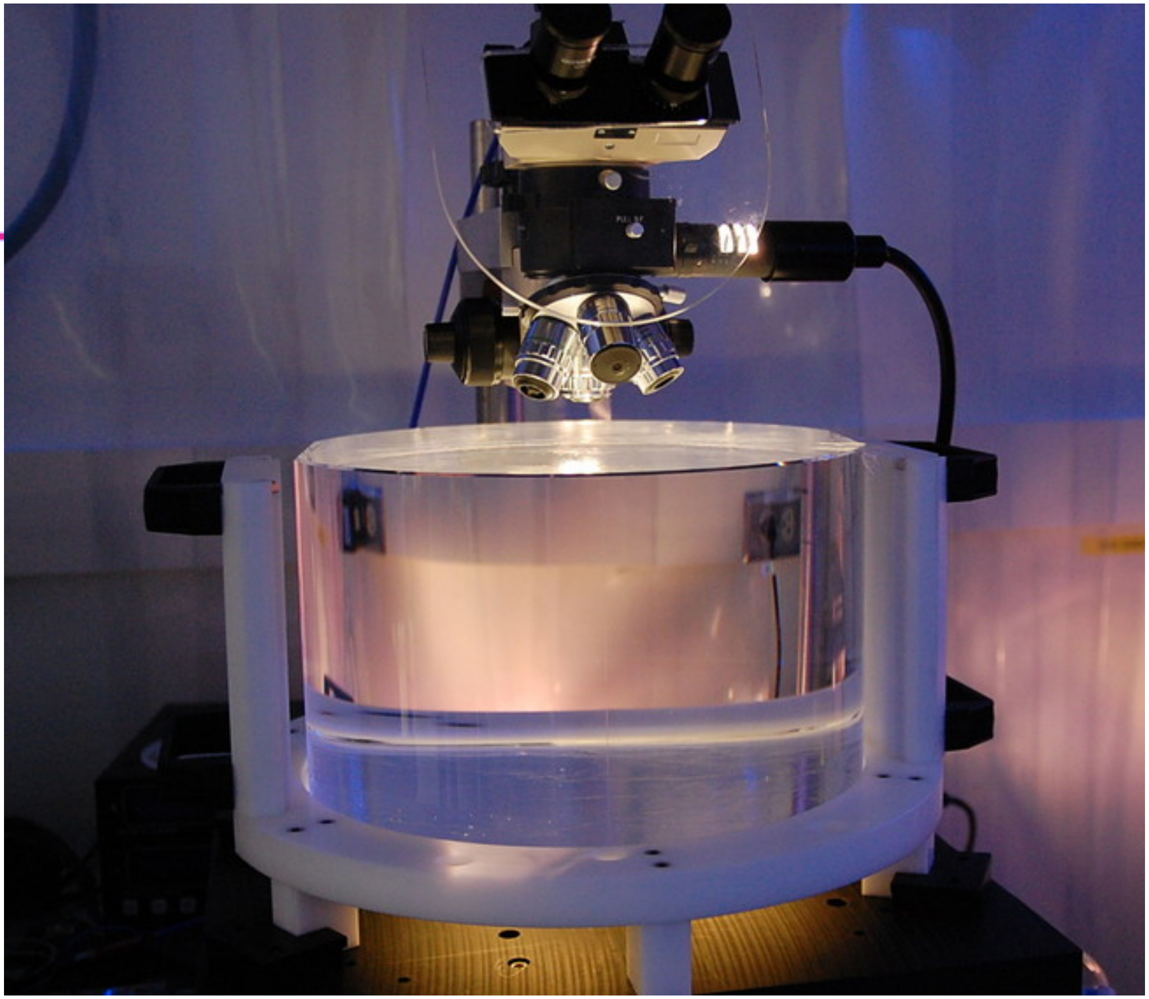


- Designed and contributed by Max Planck Albert Einstein Institute
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Test Masses

- Requires the state of the art in substrates and polishing
- Pushes the art for coating!

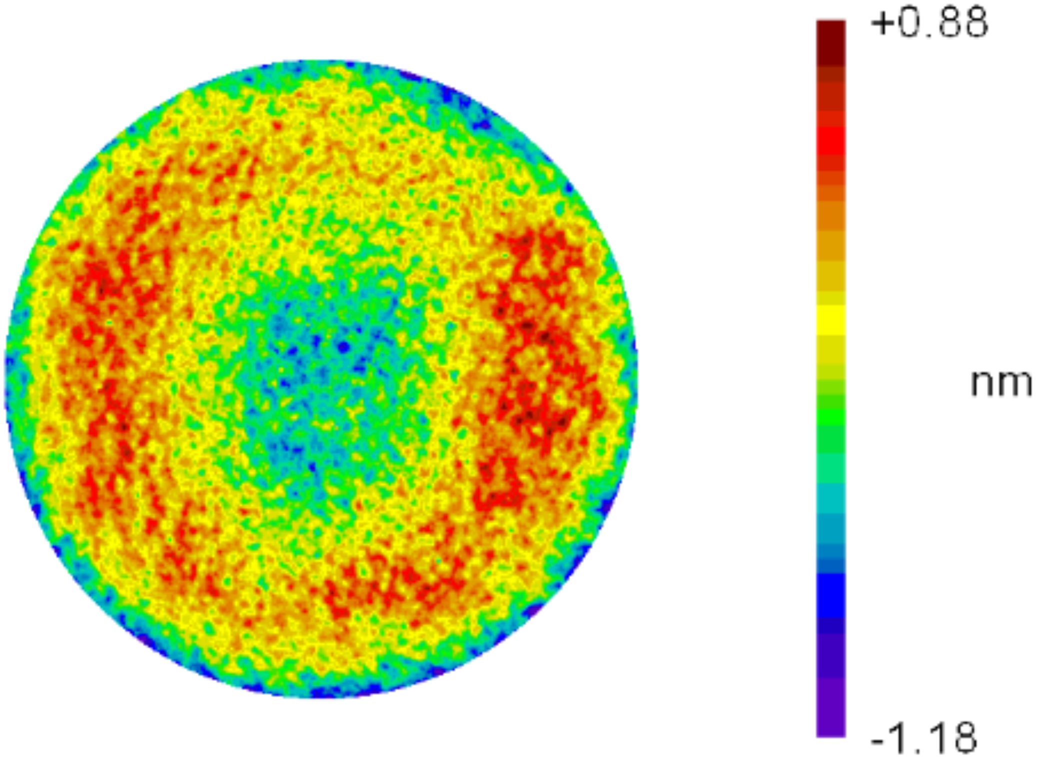




- Both the physical test mass, a free point in space-time, and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

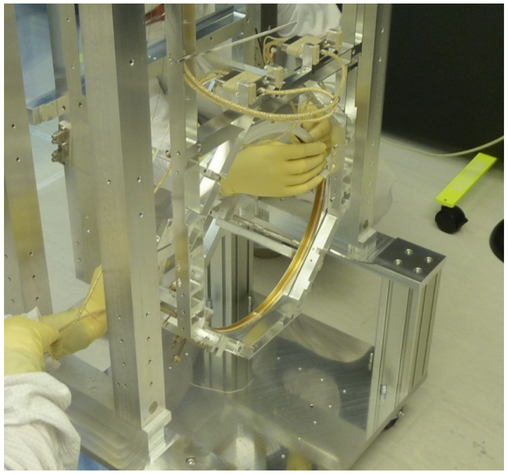
Test Mass Polishing, Coating

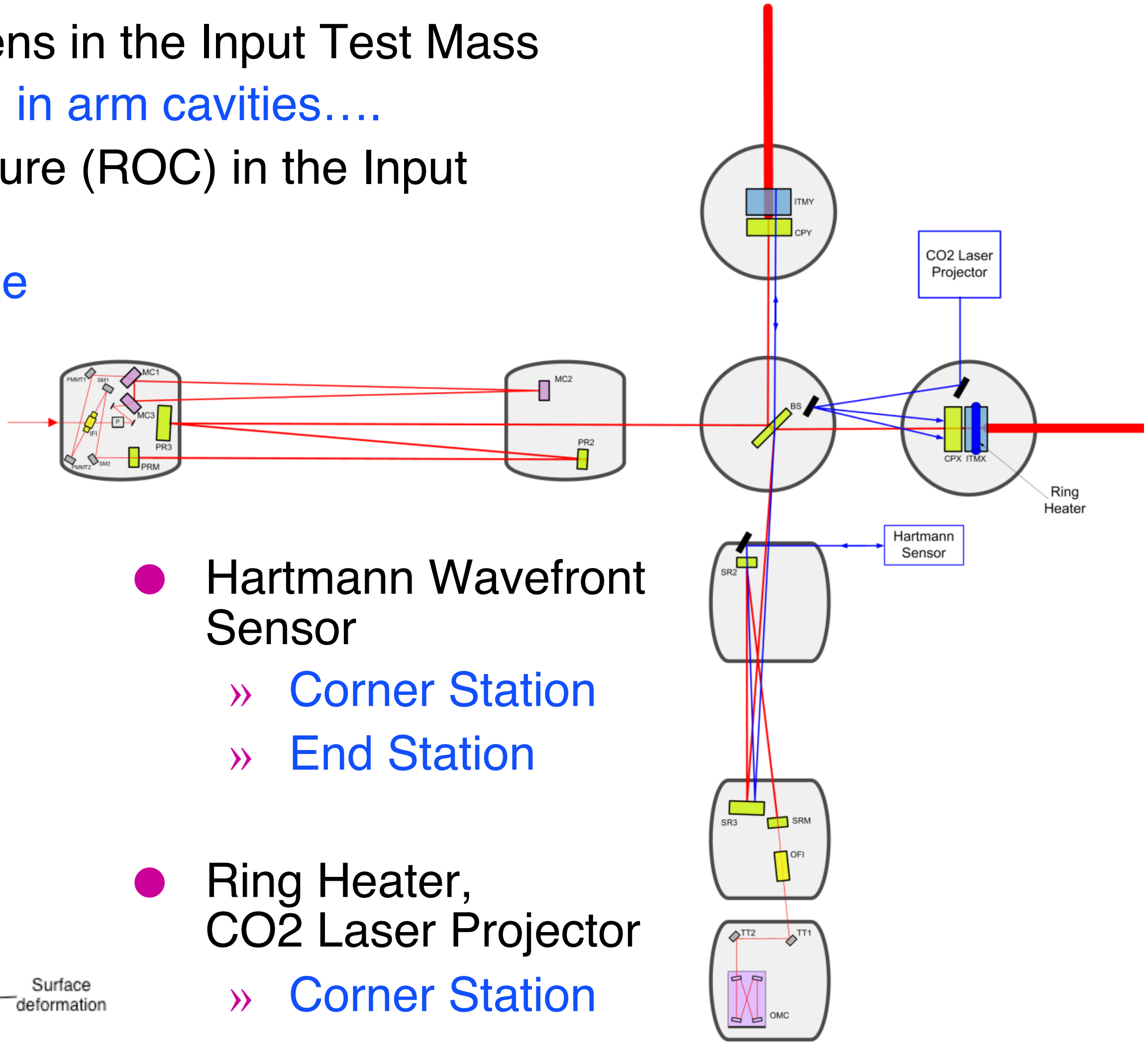
- Heraeus substrates: low absorption, excellent homogeneity, stability under annealing
- Superpolished; then, cycle of precision metrology and ion-beam milling to correct errors; surface is flat to < 1/10 nm RMS over 300 mm aperture (Tinsley)
- Ion-beam assisted sputtered coatings, ~0.6 ppm/bounce absorption, and showing 0.31 nm RMS over 300 mm aperture (LMA Lyon)
- Meets requirements of projected 75 ppm round-trip loss in 4km cavity



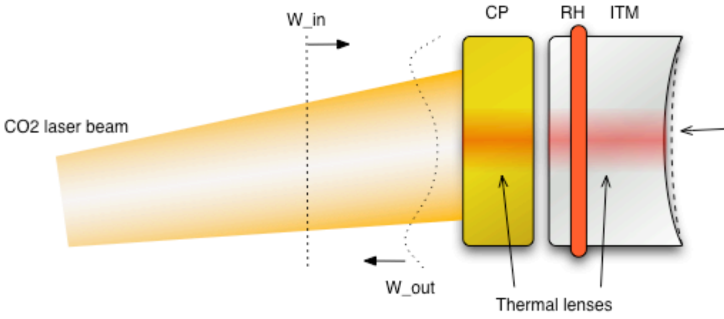
Compensation of focus induced by laser-induced substrate heating

- Measure & Control thermal lens in the Input Test Mass
  - » ~1 MW of light circulating in arm cavities….
- Control the Radius Of Curvature (ROC) in the Input and End Test Masses
  - » Provide 35 km ROC range

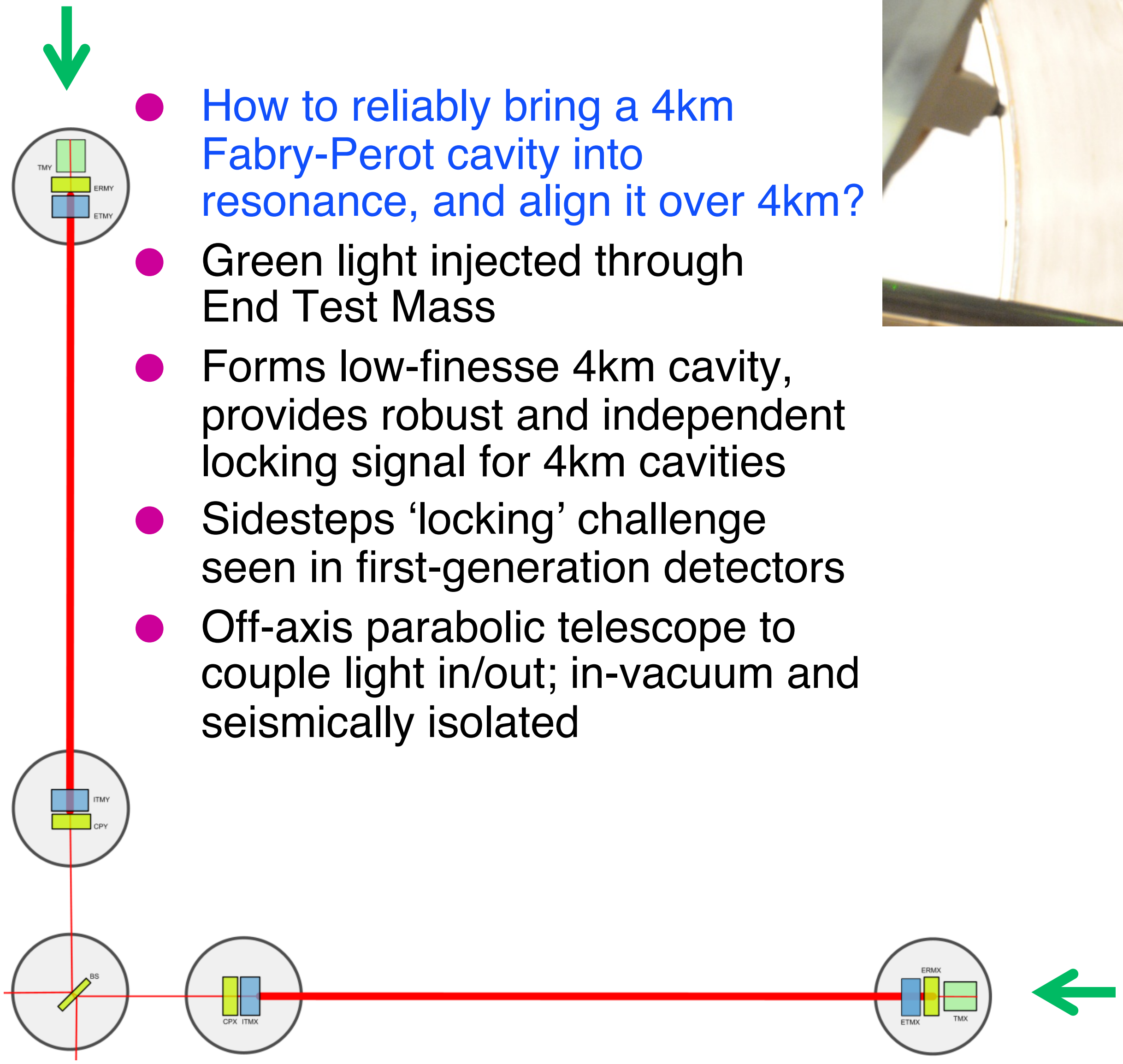




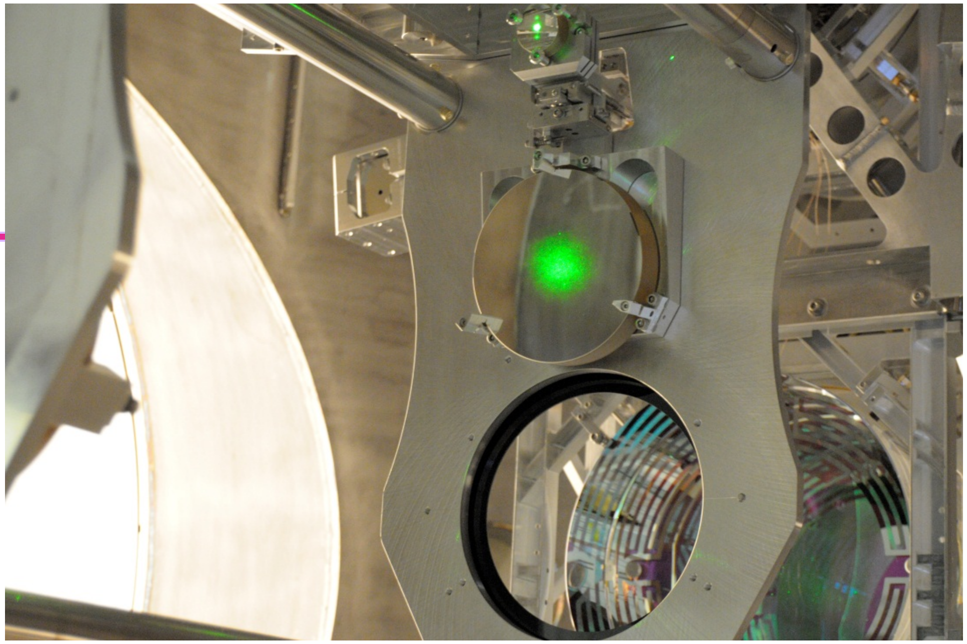
- Hartmann Wavefront Sensor
  - » Corner Station
  - » End Station
- Ring Heater, CO2 Laser Projector
  - » Corner Station

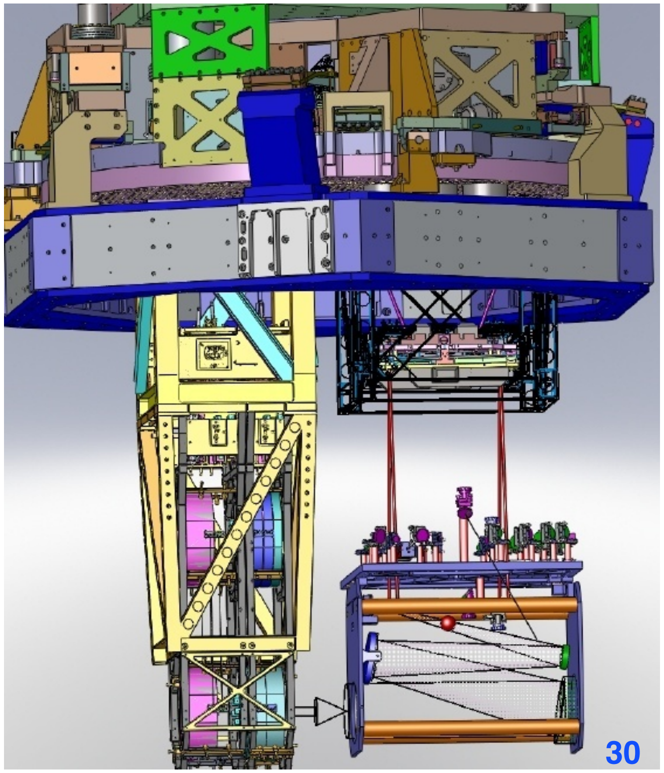


Pre-Lock Arm Length Stabilization



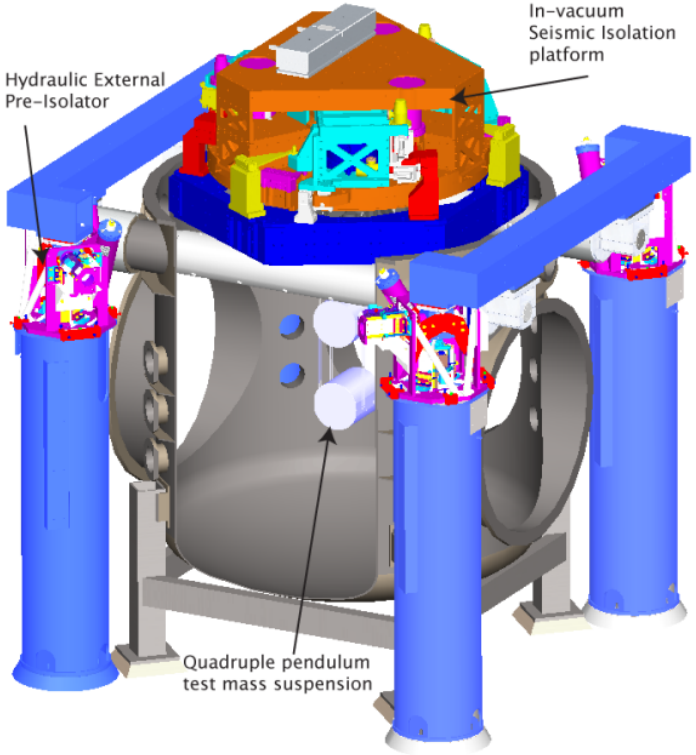
- How to reliably bring a 4km Fabry-Perot cavity into resonance, and align it over 4km?
- Green light injected through End Test Mass
- Forms low-finesse 4km cavity, provides robust and independent locking signal for 4km cavities
- Sidesteps ‘locking’ challenge seen in first-generation detectors
- Off-axis parabolic telescope to couple light in/out; in-vacuum and seismically isolated



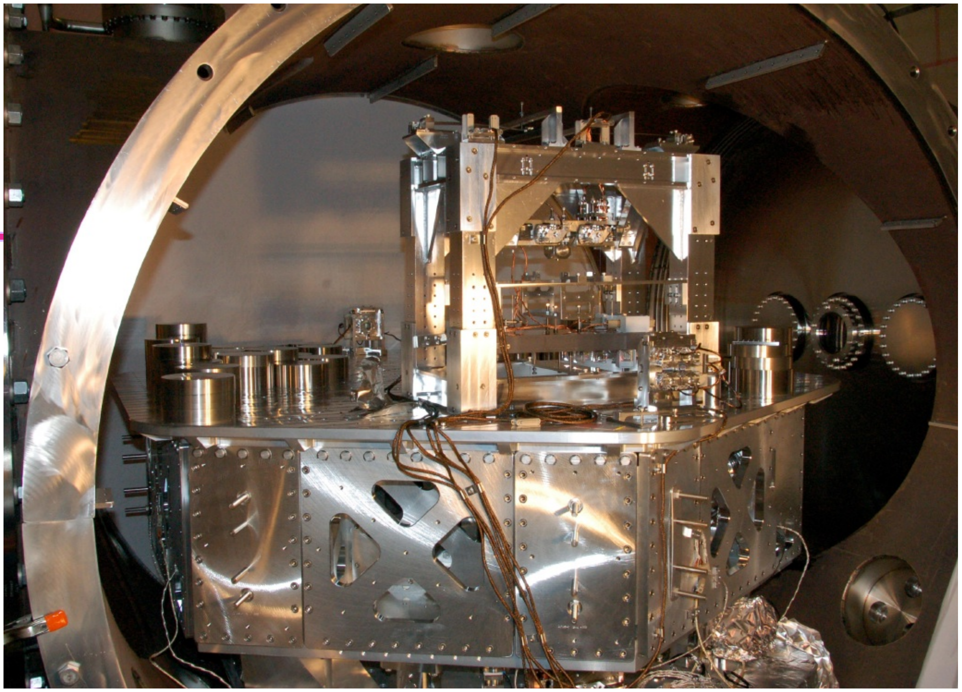


Seismic Isolation: Multi-Stage Solution

- 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 still in inertial space



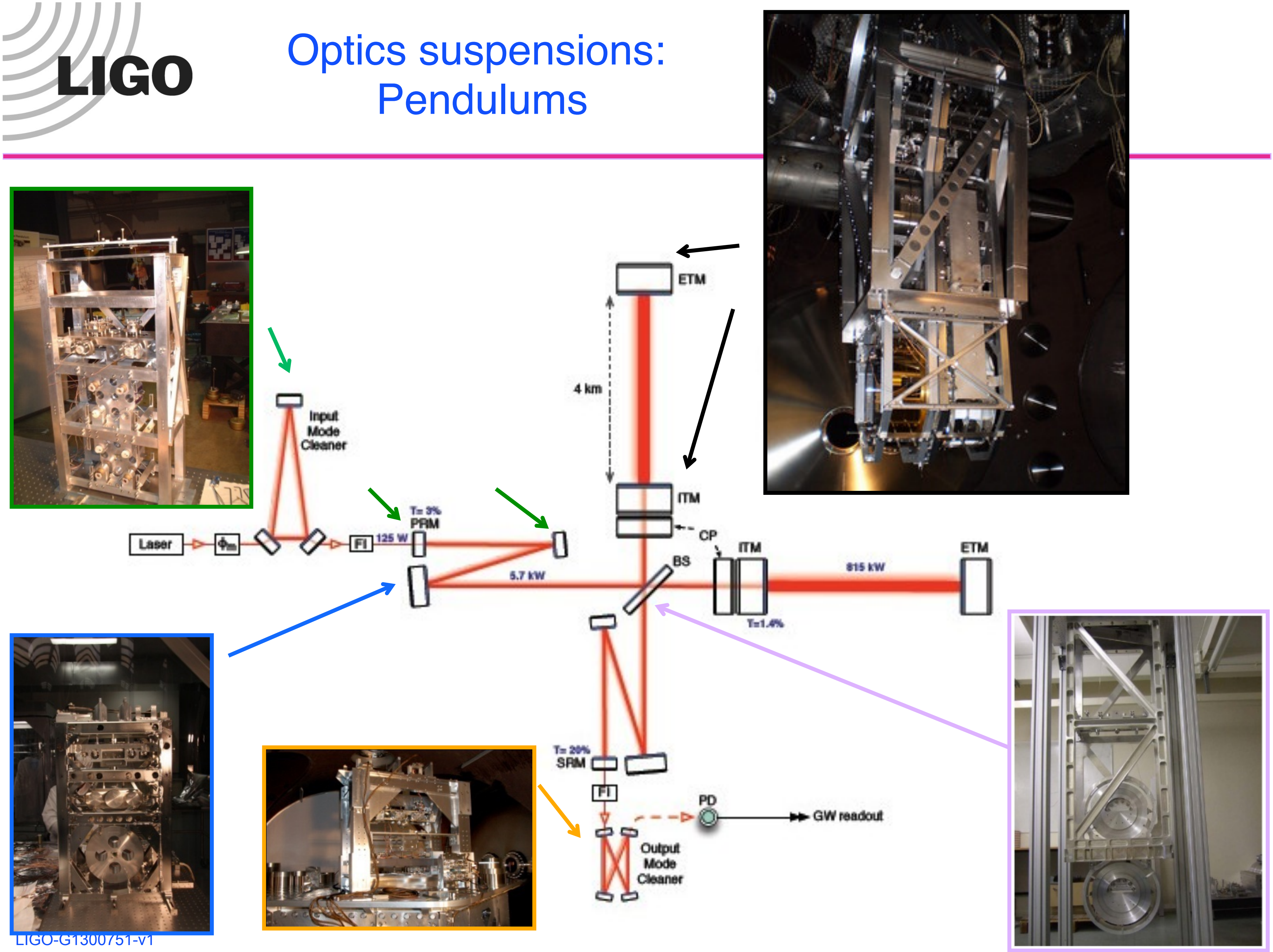
Seismic Isolation: two models



- Sensors are capacitive for ‘DC’, and seismometers to sense acceleration
- Electromagnetic motors for actuation
- Control system is digital, and fully multiple- input multiple-output to optimize for complex figures of merit
- **Type I**: Single stage (6 DOF) isolator

- **Type II:** Two-stage system, each with 6 DOF measured and actuated upon – 18 DOF including hydraulic pre-actuator!
- Suspensions, baffles, etc. hung from quiet optical table
- Part of a hierarchical control system, with distribution of forces for best performance
- Provides a quiet versatile optical table; can carry multiple suspensions, baffles, detectors, etc.

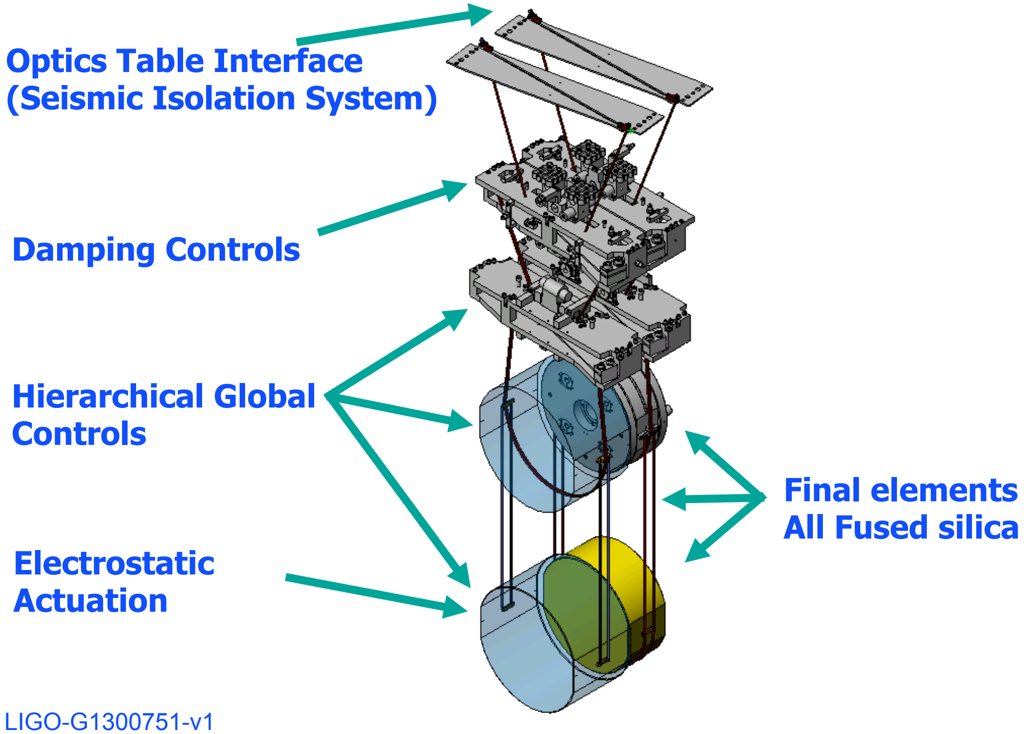
Optics suspensions: Pendulums



Test Mass Quadruple Pendulum suspension

a UK contribution

- Choose quadruple pendulum suspensions for the main optics; 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!
- Another element in hierarchical control system



Optics Table Interface (Seismic Isolation System)

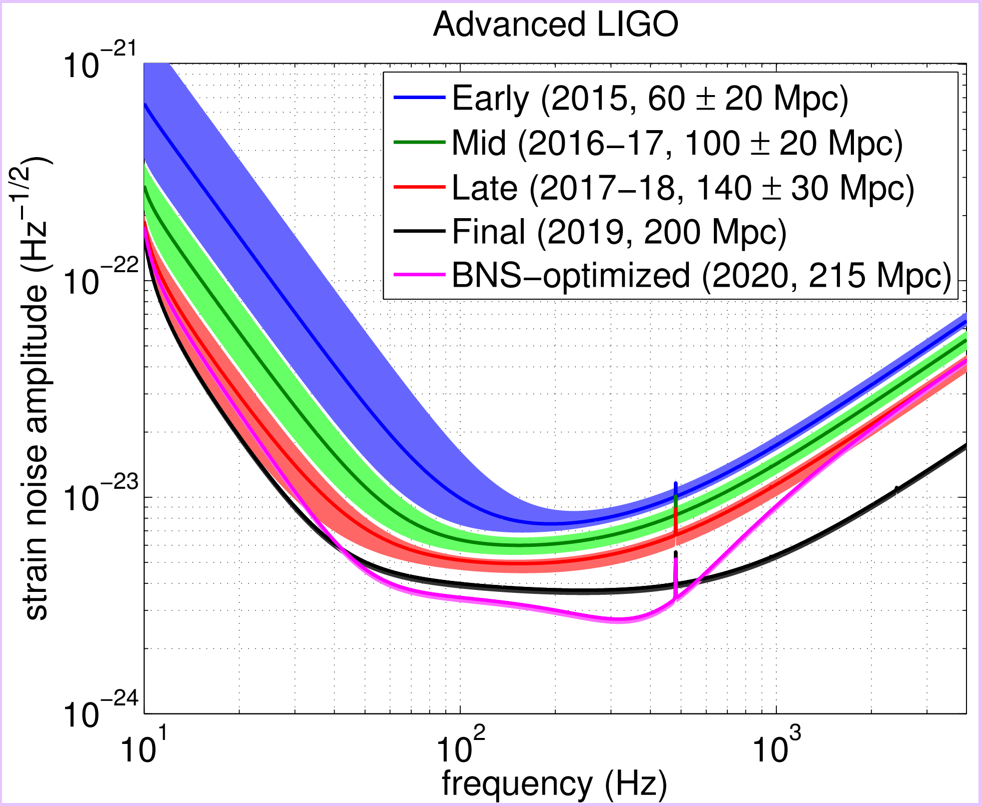
Damping Controls

Hierarchical Global Controls

Electrostatic Actuation

Final elements All Fused silica

Getting from parts to a complete instrument: **We want a scientifically interesting sensitivity as soon as possible**



http://arxiv.org/abs/1304.0670

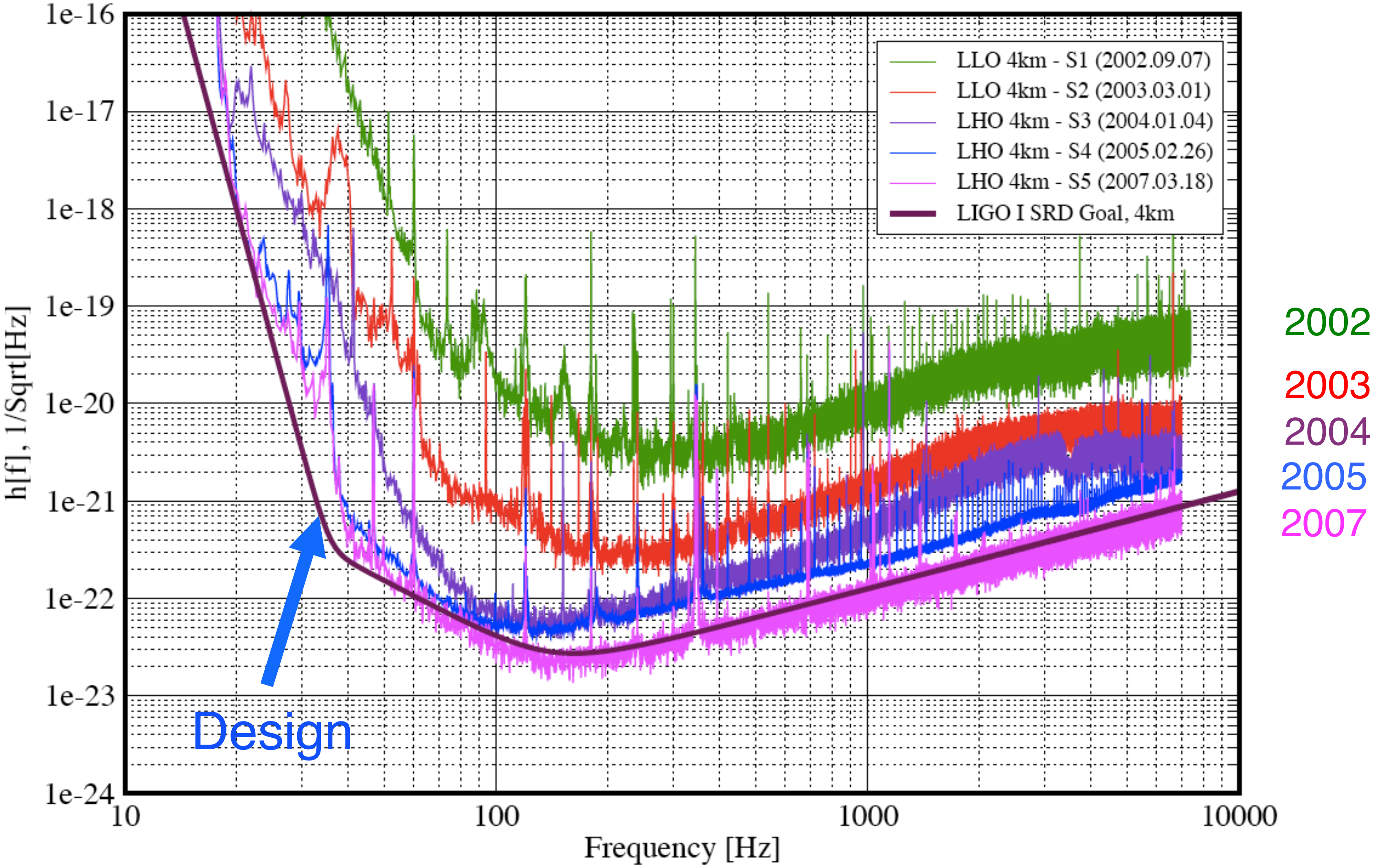
TENTATIVE TIMELINE:

- Complete integration by 2014 (interferometer “locked”)
- “Early” Science Run in 2015 (~60 Mpc)
- Within a factor of 2 of design sensitivity by 2016 (~100 Mpc)

…Does it seem slow?

A few slides from Lisa Barsotti

It actually took longer the first time.
Initial LIGO: first lock in 2000 – **7 years to reach goal**



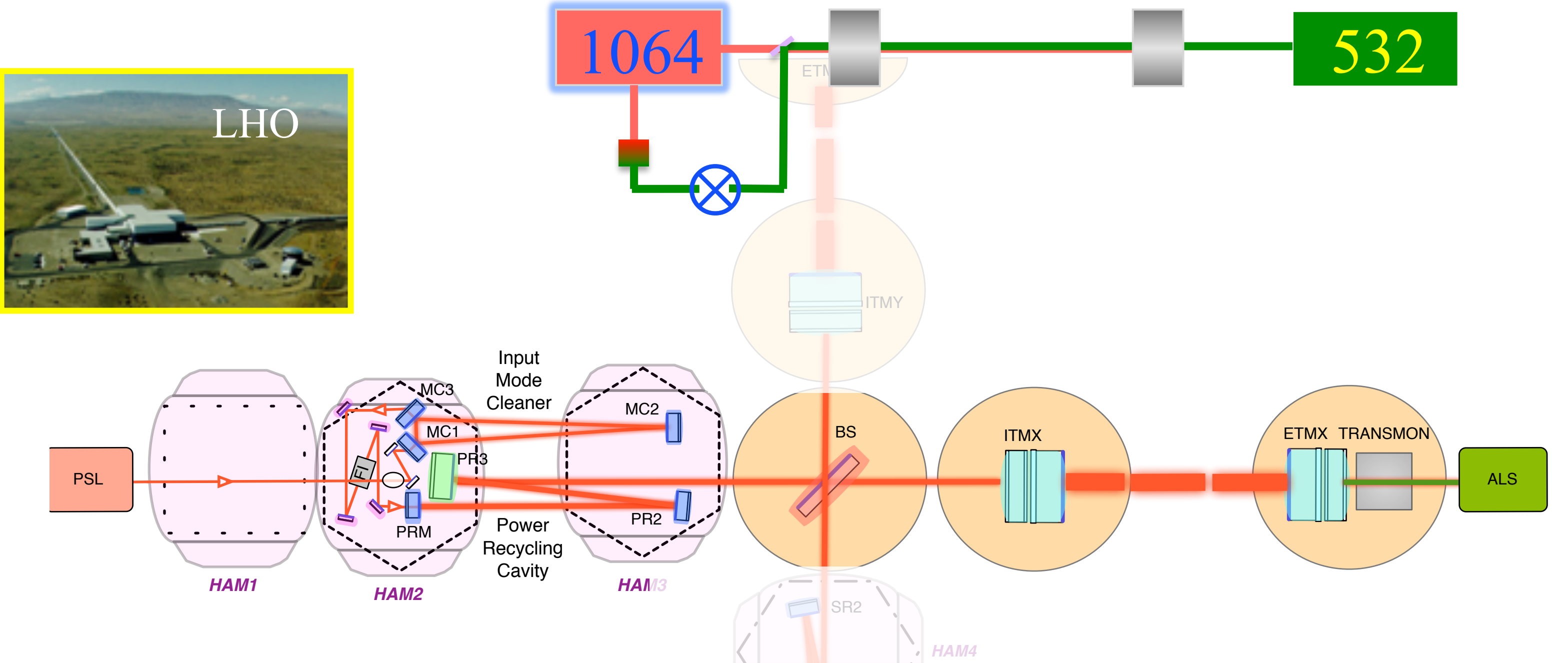
How to proceed faster?
Advanced LIGO Installation and Commissioning Strategy

- ✧Extensive "standalone" testing before installation
- ✧Installation of "new" things as soon as possible
- ✧Configurations of increased complexity
- ✧Parallel, *complementary* effort between Hanford and Livingston
- ✧Better design and engineering informed by LIGO, more experienced staff

It works!

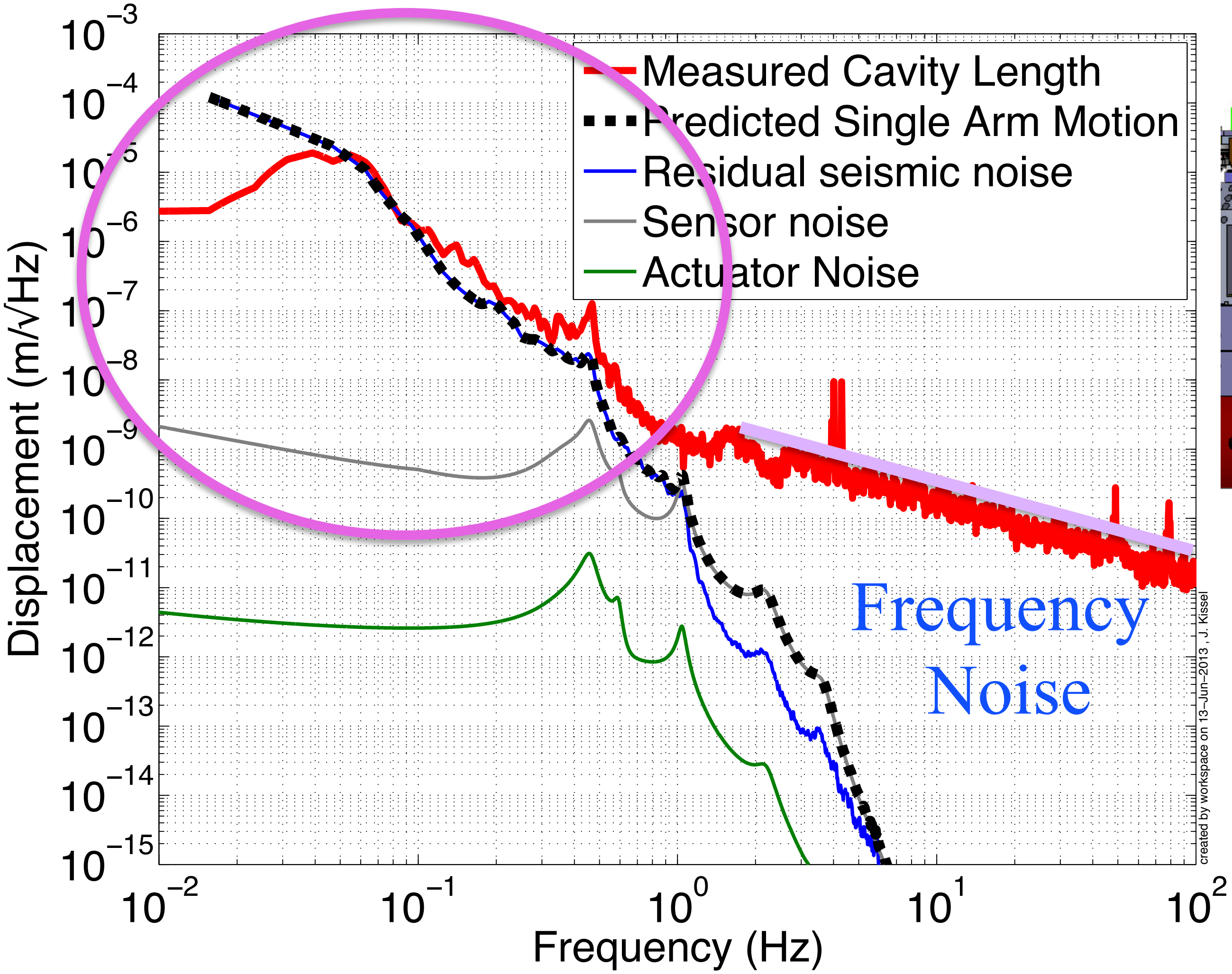
It took 4 months to lock the input mode cleaner cavity in initial LIGO,
it took less than 1 week in Advanced LIGO (the first time at Livingston),
1 day the second time at Hanford

“Half Interferometer” in progress @ Hanford (now one arm, in the fall the other)

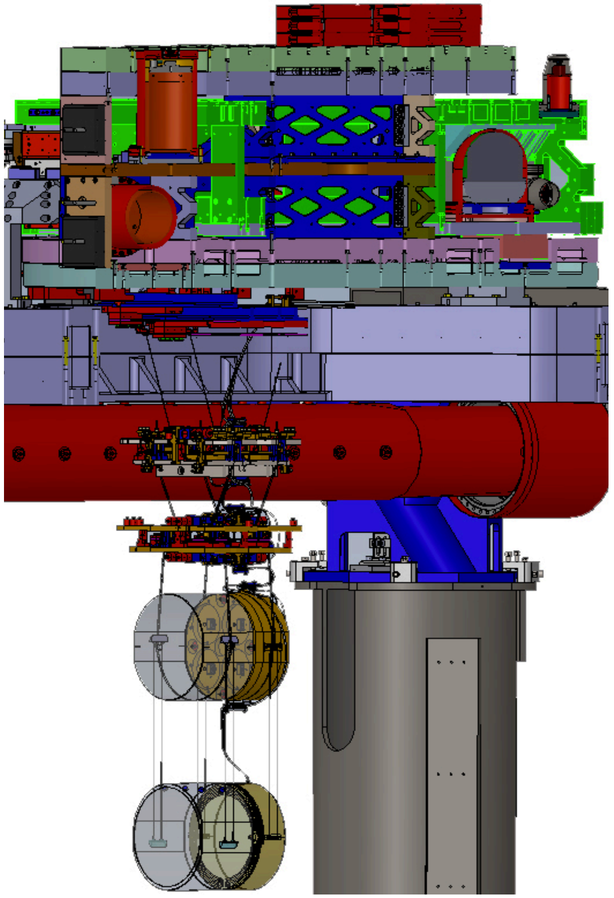


✓Auxiliary green laser to initially stabilize the arm cavity length
✓1.06 micron detection light held precisely on, or off resonance
✓First measurement of arm cavity motion

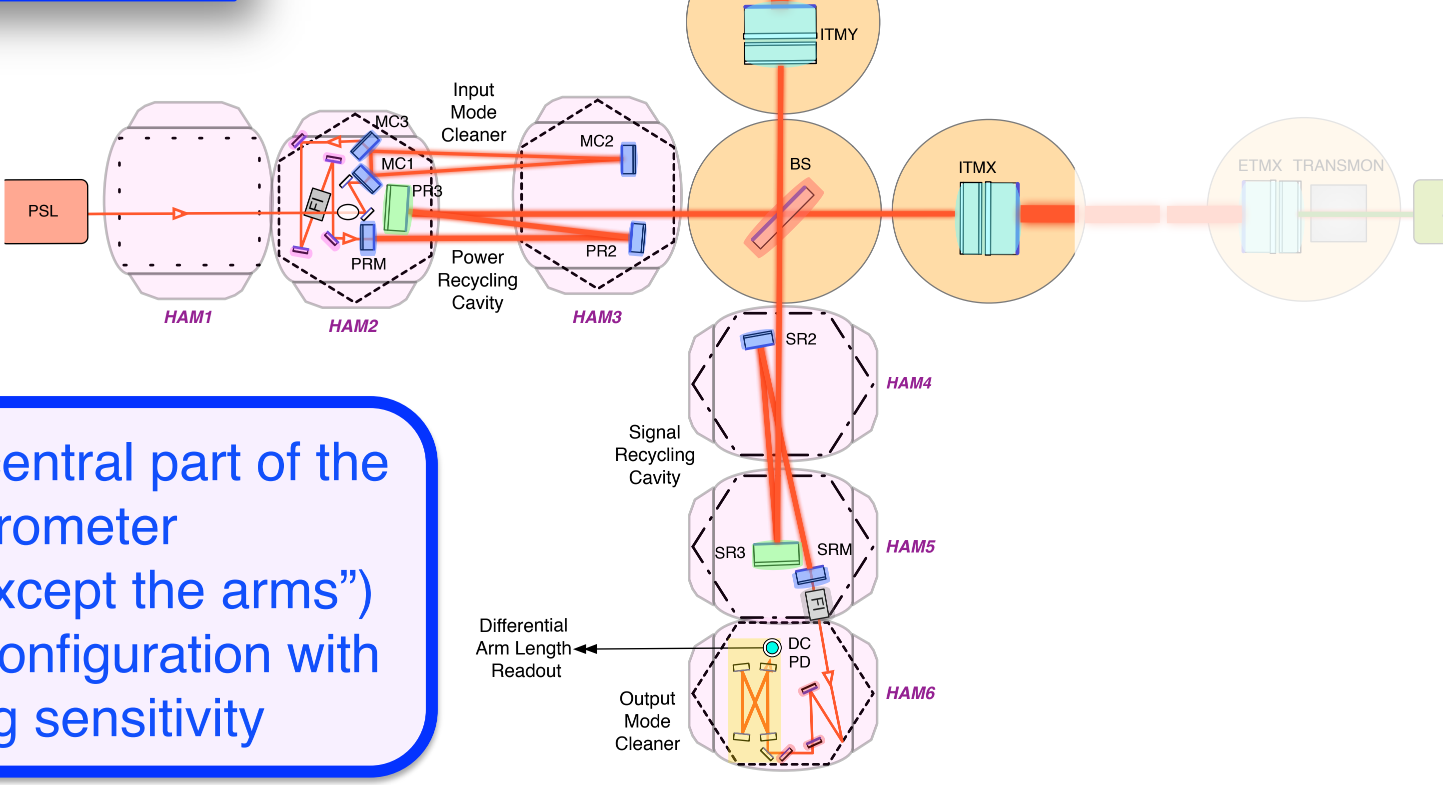
Cavity motion in good agreement with model (Jeff Kissel, MIT)



Frequency Noise

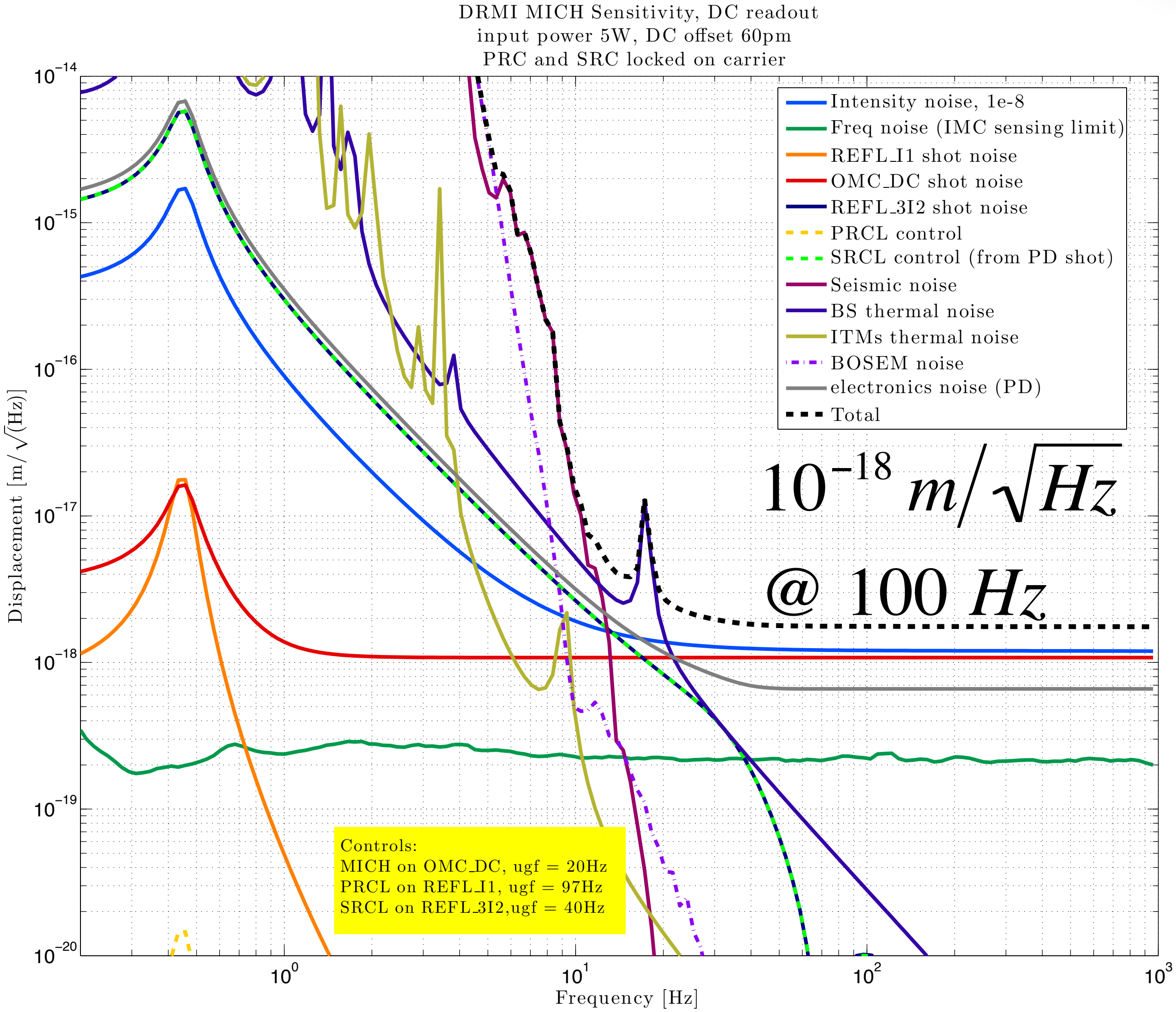


“Short” Interferometer in progress @ Livingston (Dual Recycled Michelson Interferometer)



- ✓ Lock of the central part of the interferometer (“everything except the arms”)
- ✓ Will be first configuration with interesting sensitivity

DRMI Noise Budget Model
(Anamaria Effler, LSU-LIGO Livingston)


DRMI MICH Sensitivity, DC readout
input power 5W, DC offset 60pm
PRC and SRC locked on carrier

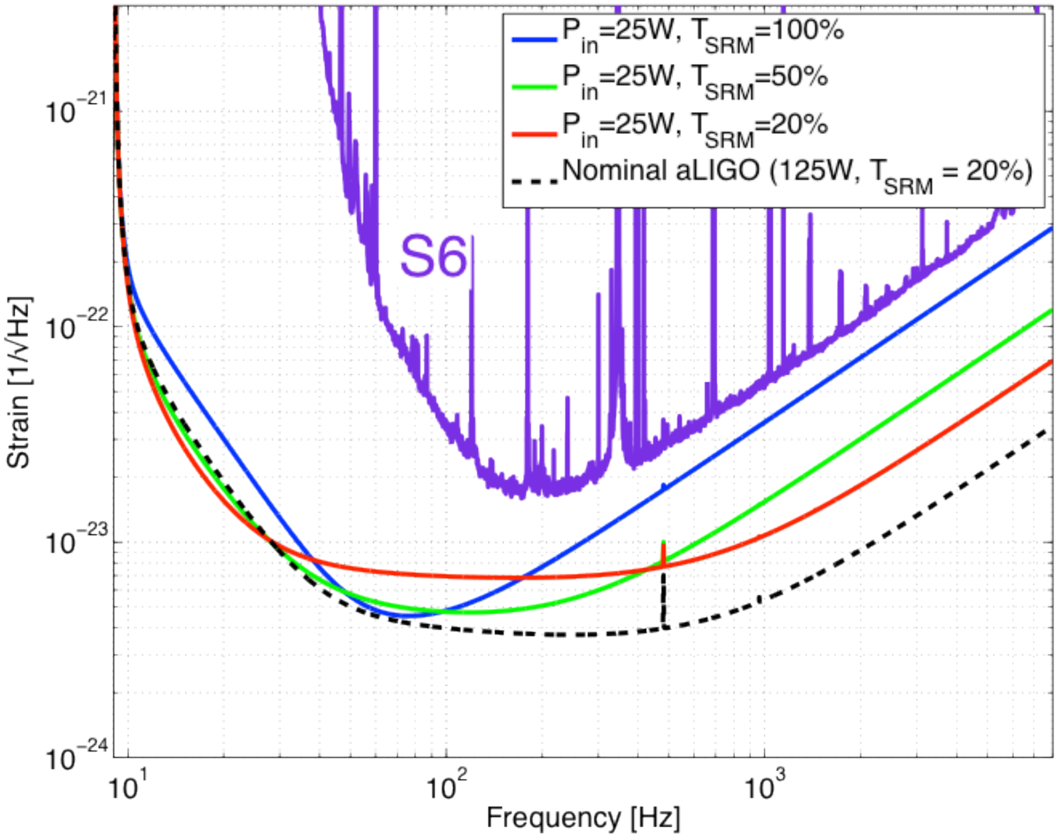
$10^{-18}\ m/\sqrt{Hz}$

@ 100 Hz

Controls:
MICH on OMC_DC, ugf = 20Hz
PRCL on REFL_I1, ugf = 97Hz
SRCL on REFL_3I2,ugf = 40Hz

And after the Project *per se*: Tuning for Astrophysics, and Observation

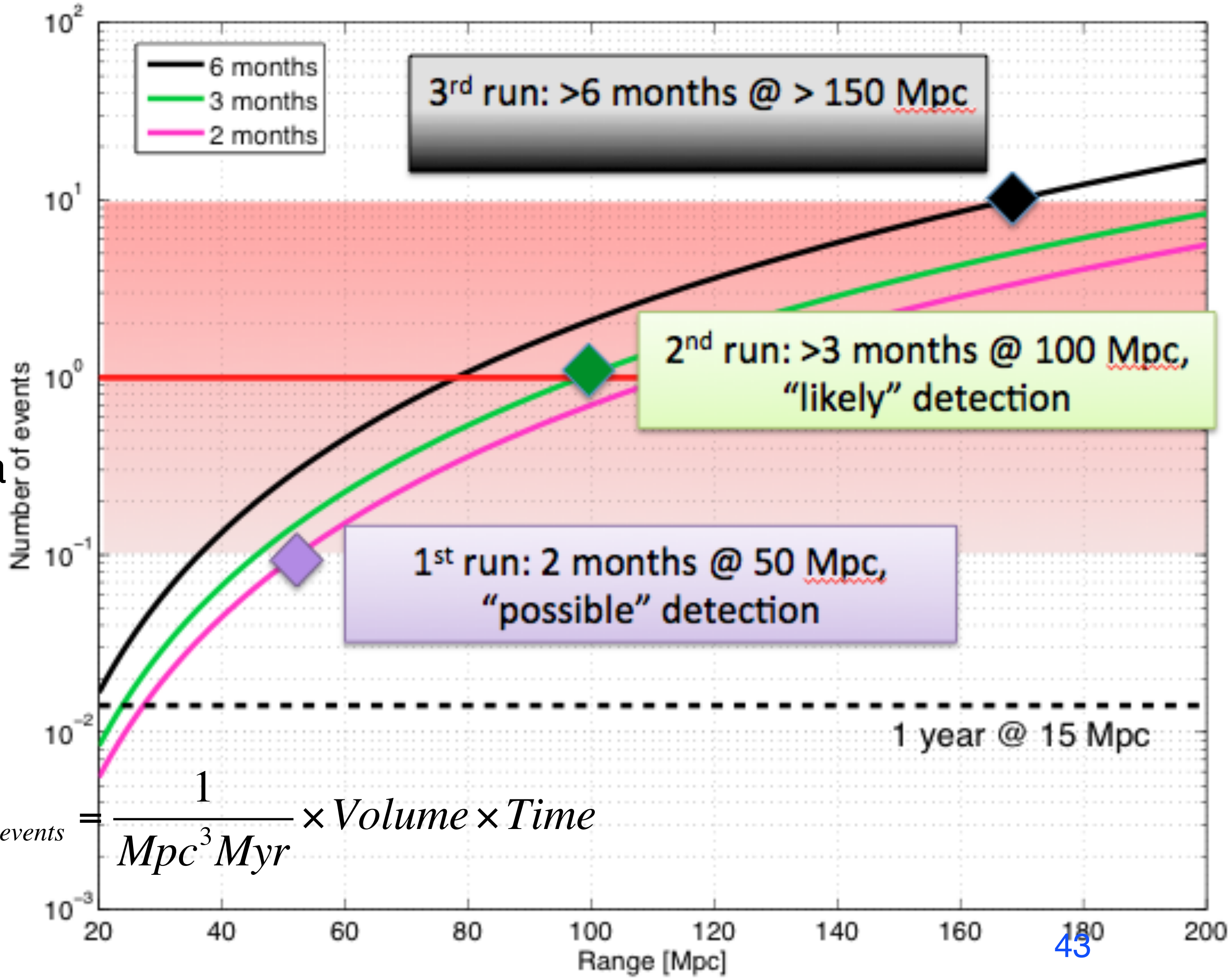
- Transition from Project back to Lab/ collaboration after two-hour lock
  - Planned for 2014
- First work with low laser power
  - No heating problems
  - No optically-driven torques
  - Focus on low frequencies
- Ideal for first astrophysics as well
  - Standard candles are binary neutron stars
  - Most SNR in the 20-200 Hz region
- Focus later on high power, high frequency range



Current guess for sensitivity evolution, observation

- Vertical scale is the number of binary inspirals detected
- Rates based on population synthesis, realistic but uncertain
- LIGO Scientific Collaboration (LSC) preparing for the data analysis challenge
- Close collaboration with Virgo
- **Early detection looks feasible**

- arXiv:1304.0670, arXiv:1003.2480



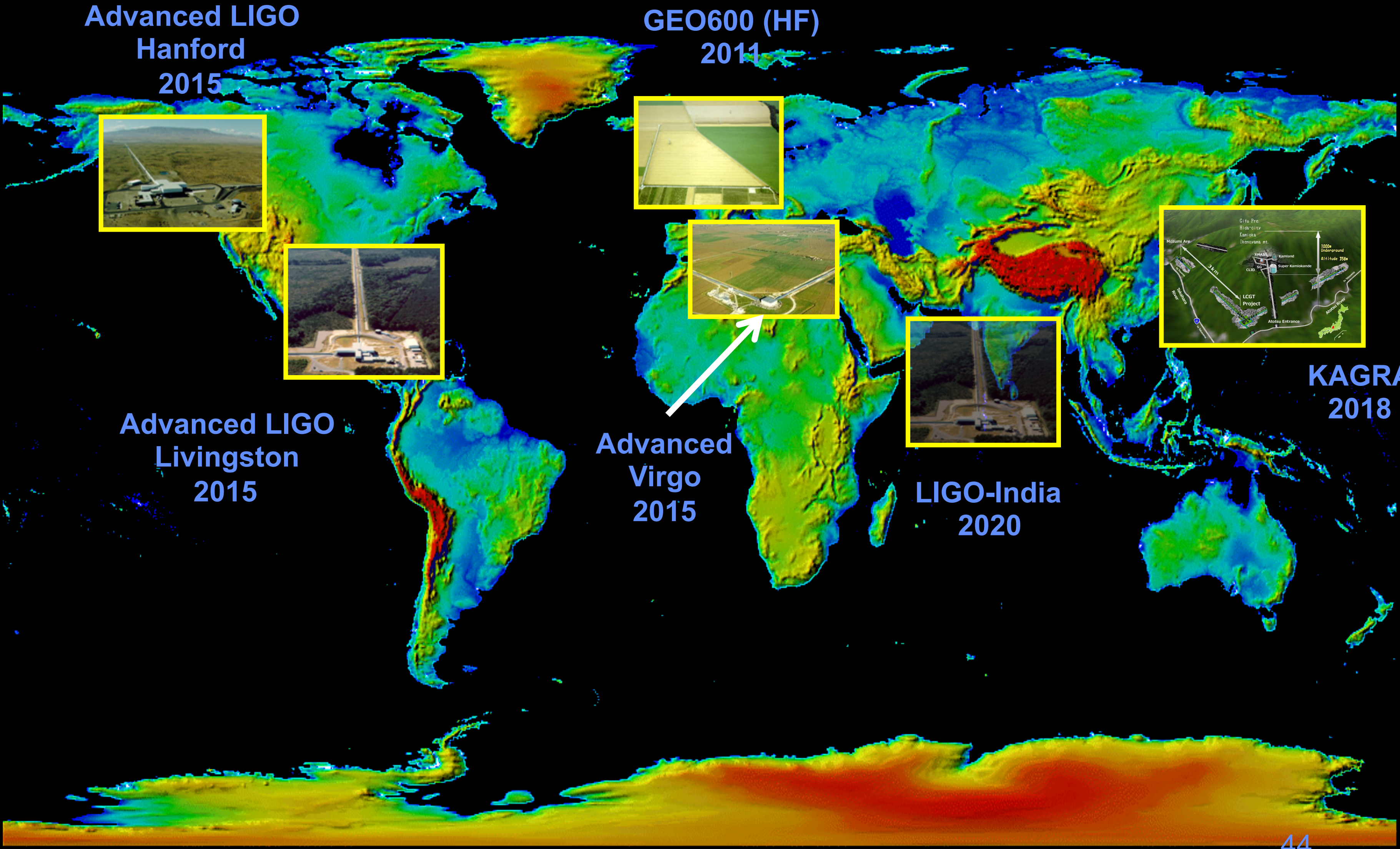
3rd run: >6 months @ > 150 Mpc

2nd run: >3 months @ 100 Mpc, “likely” detection

1st run: 2 months @ 50 Mpc, “possible” detection

$$N_{events} = \frac{1}{Mpc^{3}Myr} \times Volume \times Time$$

The advanced GW detector network



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

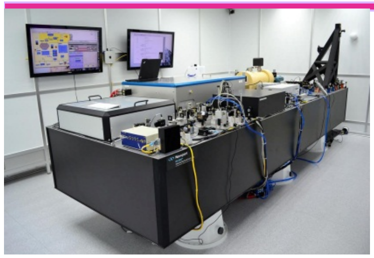
KAGRA
2018

Advanced LIGO
Livingston
2015

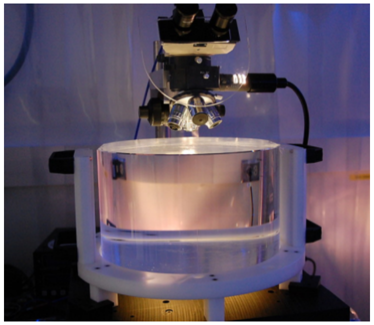
Advanced
Virgo
2015

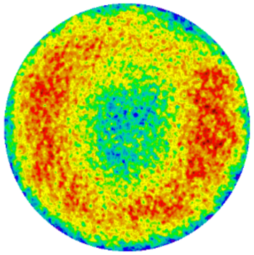
LIGO-India
2020

The Last Page



- The next generation of gravitational-wave detectors will have the sensitivity to make frequent detections
- The Advanced LIGO detectors are coming along well, planned to complete in 2015
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy





Goal: Direct Detection 100 years after Einstein's paper on GWs