Advanced LIGO

Gravitational Waves: New Frontier
Seoul, South Korea
16 January 2013

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Advanced LIGO

Goal: open the era of gravitational-wave astronomy through the direct detection of gravitational waves

- Replaces the instruments at the Washington and Louisiana sites
  - ~15 years of R&D and Initial LIGO experience

- Advanced LIGO is designed to increase the distance probed (‘reach’) by ~ 10X
  - Leads to 1000X increase in volume
    → 1000X increase in event rate

- Expect tens of detections per year at design sensitivity
  - 1 aLIGO observational day = a few years of iLIGO

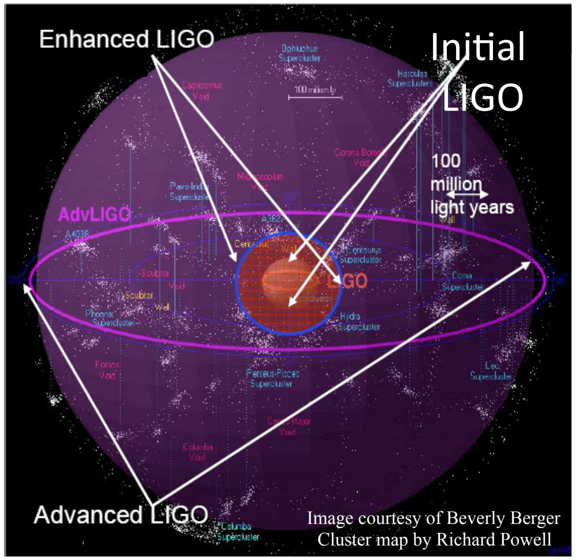


Image courtesy of Beverly Berger
Cluster map by Richard Powell

Advanced LIGO: Philosophy

- Ensure that the second generation of LIGO instruments will have sufficient sensitivity to see gravitational wave sources
  - Sets a minimum bar for sensitivity
- Use the most advanced technology that is sure to deliver a reliable instrument
  - Some neat ideas did not fit in this category
- Provide a base which would allow enhancements, fully exploiting the basic topology
  - Major investment by NSF; needs to have a long lifetime
- Don't repeat errors of initial LIGO!
  - Build full scale prototypes, and where possible use in real instruments
  - Test subcomponents and subsystems rigorously
  - Maintain configuration control on hardware and software
  - Document everything well, and organize it for easy access

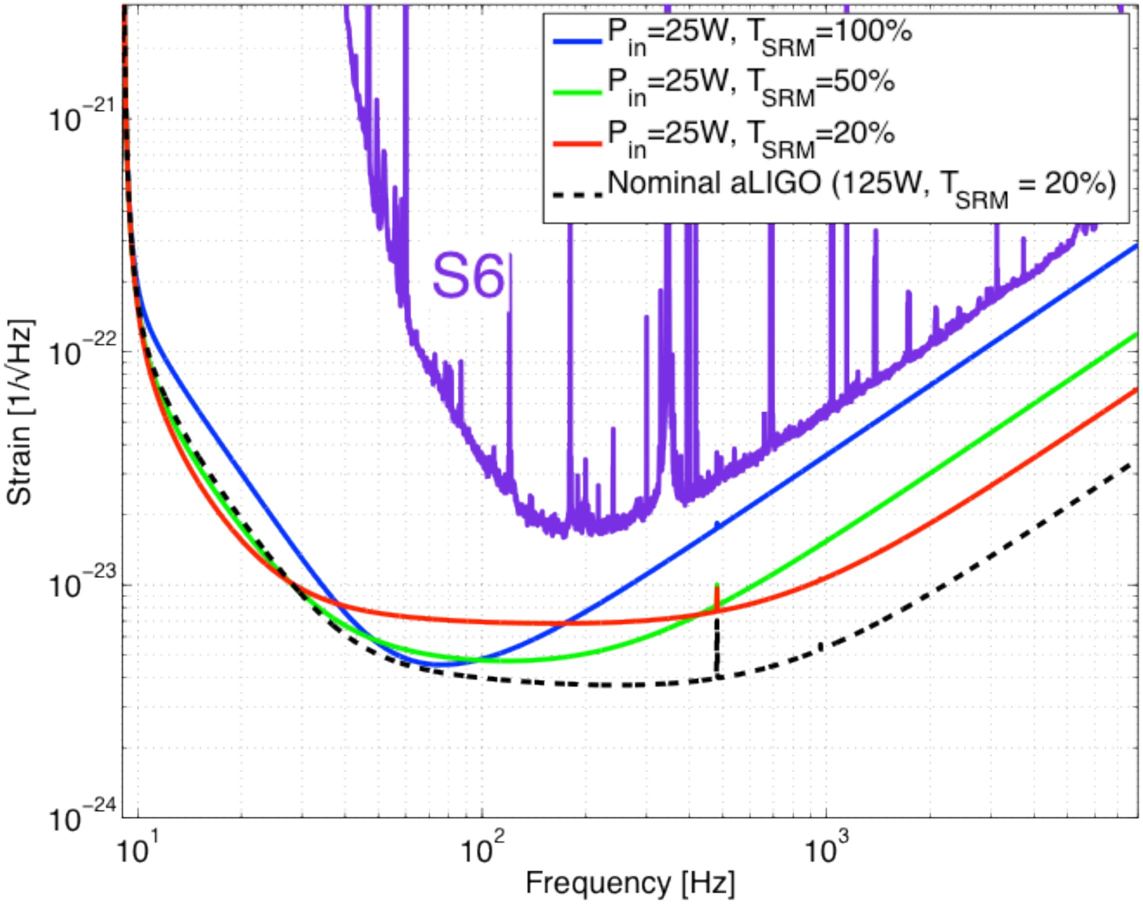
Advanced LIGO: History

- 1990’s: small-scale testing of various ideas to go beyond initial detectors
- 1999: LIGO Scientific Collaboration White Paper describing a range of candidate technologies meriting exploration, but with a potential sensitivity enabled by…:
  - Low-loss monolithic fused silica suspensions
  - Signal-recycled interferometer topologies
- 1999 – 2005: Structured, focused R&D by the community and LIGO Lab, resolving key open design facets:
  - Fused silica or sapphire optics
  - Approach to the high-power laser source
  - Approach to seismic isolation
  - ….and, develop and operate Initial LIGO; learn lessons
- 2005: Leads to a firm design; successful proposal to NSF by the LIGO Lab for $205M USD, plus significant contributions from Max Planck (Germany), STFC (UK), ARC (Australia)

- **2008: The NSF-funded Advanced LIGO Project Starts!**

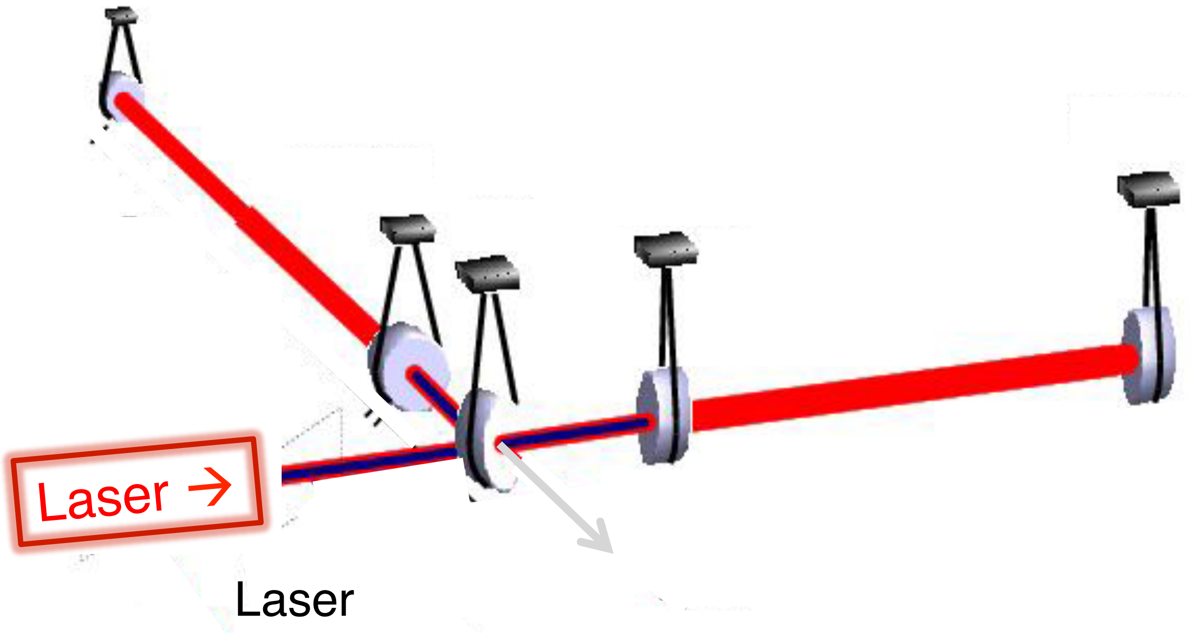
Addressing limits to performance

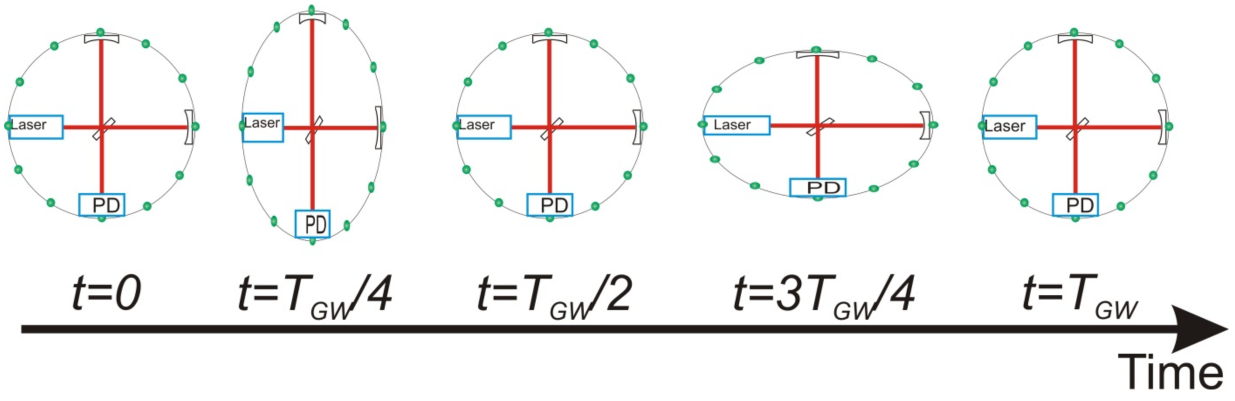
- “Ensure that the second generation of LIGO instruments will have sufficient sensitivity to see gravitational wave sources”
- **What are the basic limits?**



Interferometric Gravitational-wave Detectors

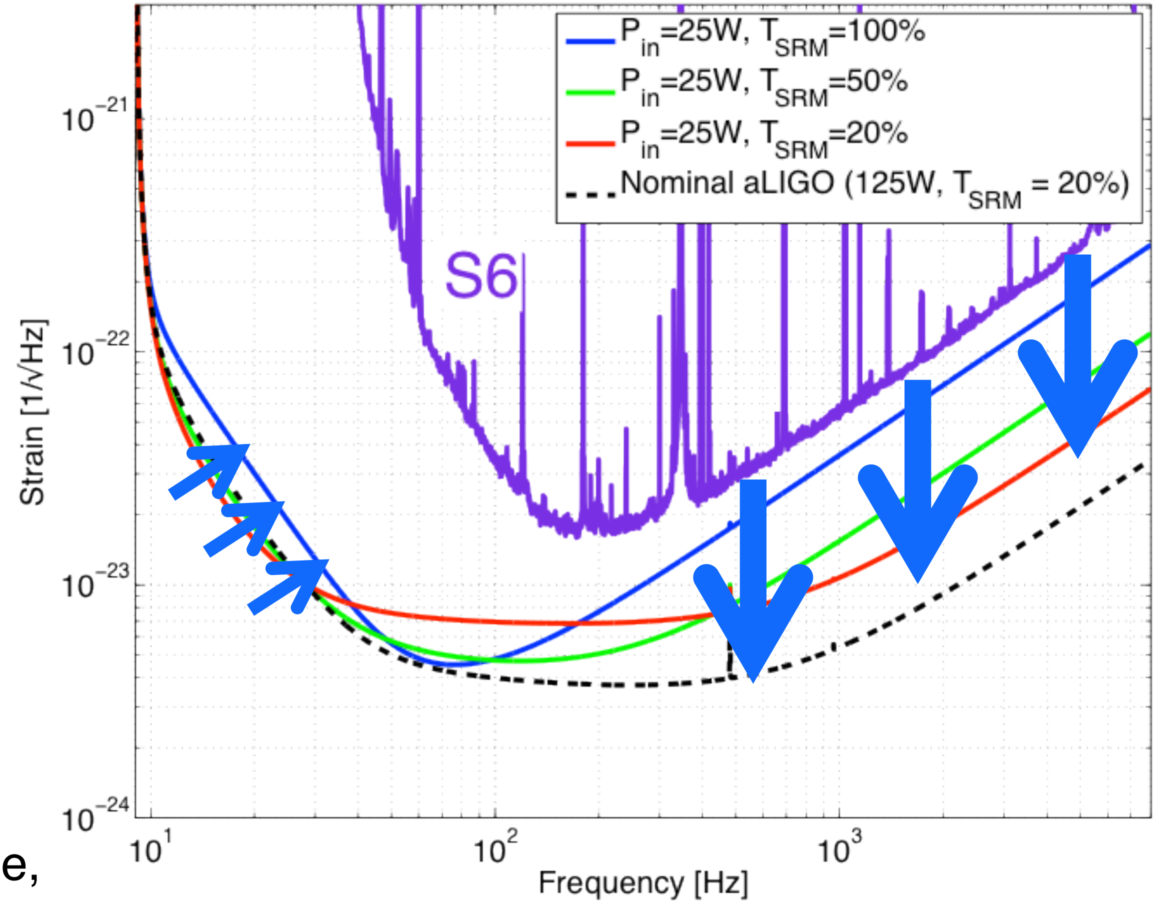
- Enhanced Michelson interferometers
  - » LIGO, Virgo, and GEO600 use variations
- Passing GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- Arms are short compared to GW wavelengths, so longer arms make bigger signals
  → multi-km installations





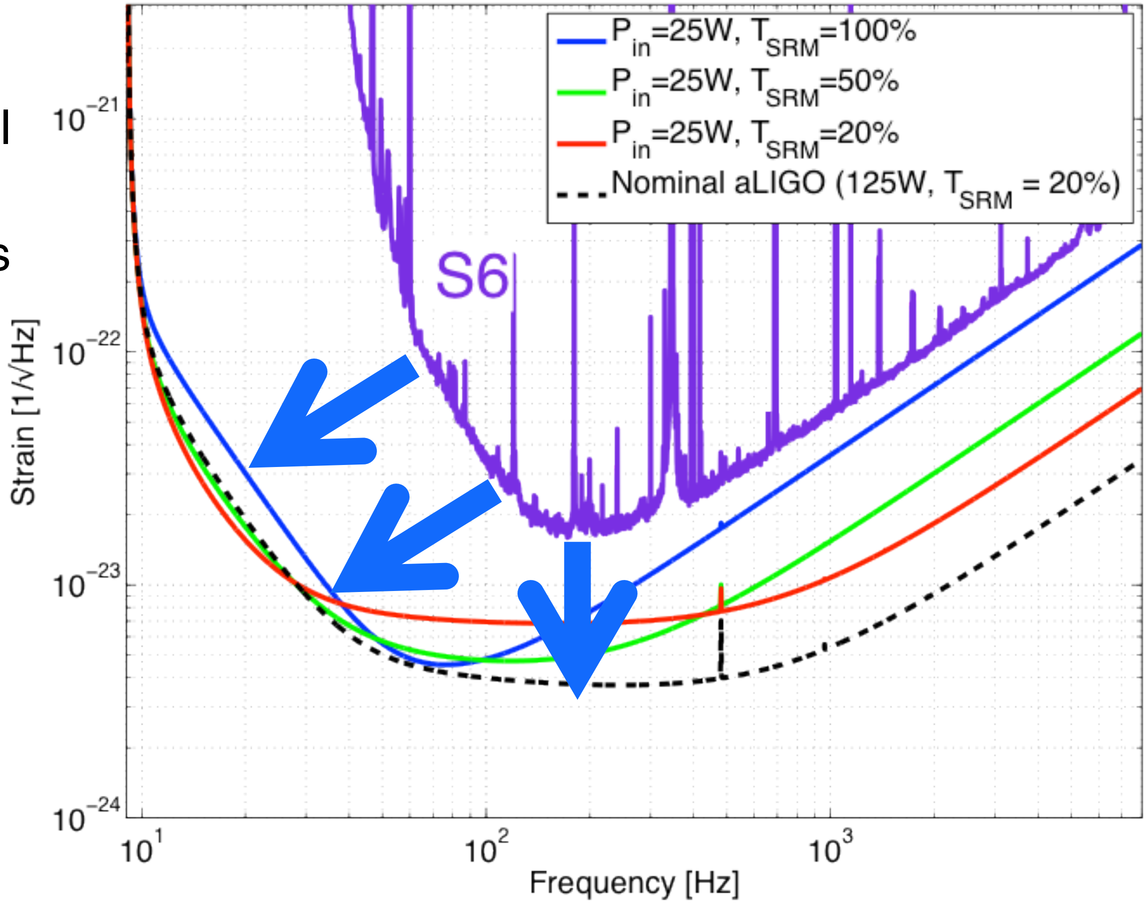
Addressing limits to performance

- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Increases in laser power help, as sqrt(power)
- Resonant cavity for signals helps in managing power, tuning for astrophysics
- 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 source, 40 kg test masses



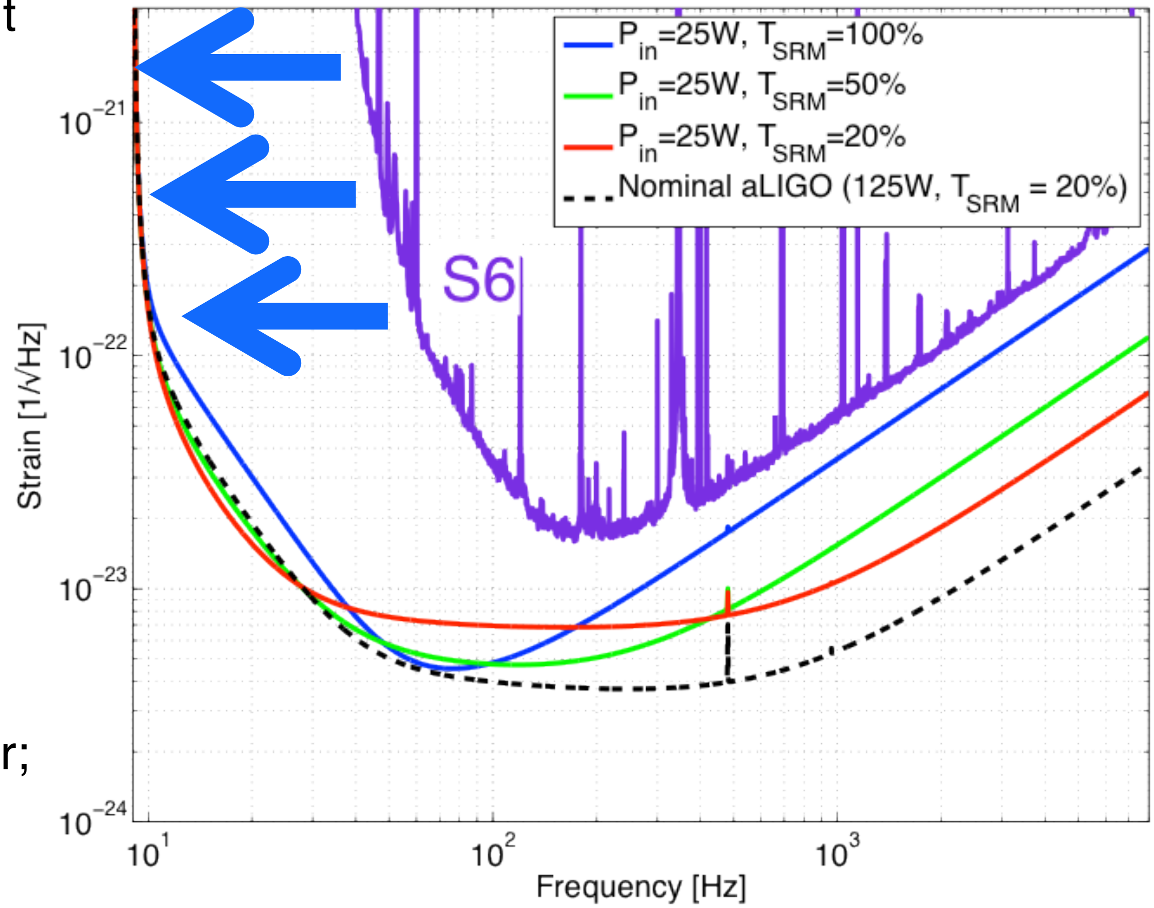
Addressing limits to performance

- **Thermal noise** – keeping 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 in frequency
- Realized in aLIGO with an all fused-silica test mass suspension – *Q*s of order 10^9
- Mirror coatings engineered for low mechanical loss

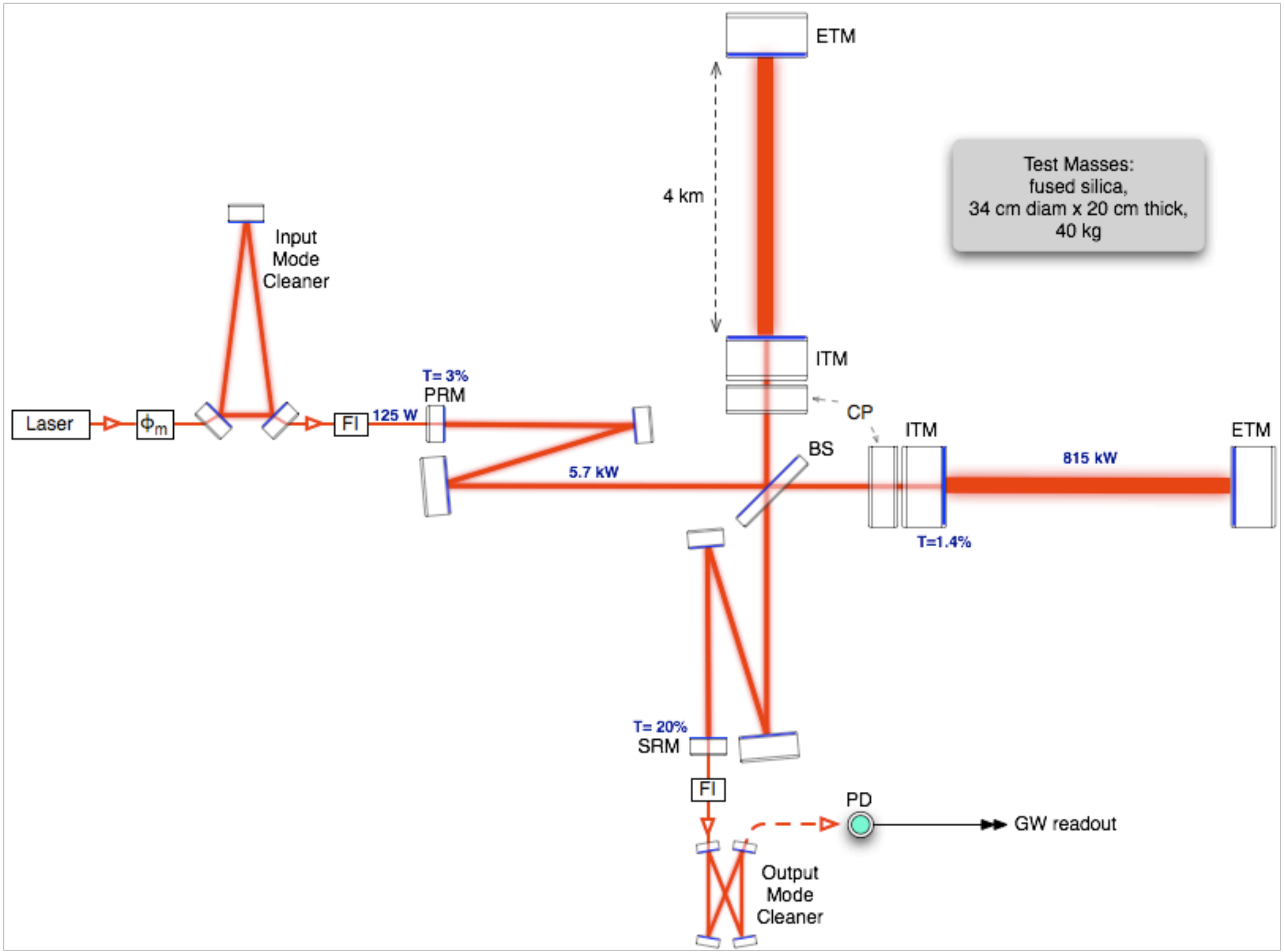


Addressing limits to performance

- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- 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
- Newtownian background – wandering in net gravity vector; a limit in the 10-20 Hz band



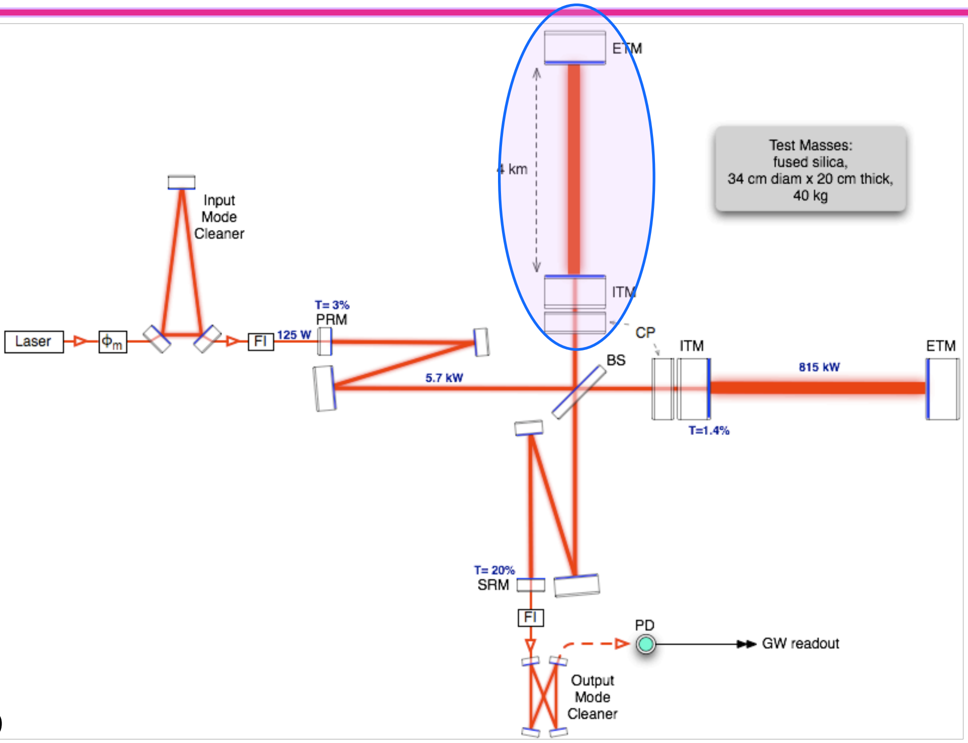
The Design: Optical Configuration



Key Interferometer Features

4km Arm cavity design

- Finesse: 450
  - 2x higher than iLIGO
  - Value involves trade-offs between optical loss, sensitivity to noise in other degrees-of-freedom, and interferometer sensitivity in different modes of operation
- Beam sizes: 6.2 cm on far mirror, 5.3 cm on near mirror
  - Approx. 50% larger than iLIGO, to reduce thermal noise
  - Smaller beam on the ITM to allow smaller optic apertures in the vertex
- Cavities are made to be dichroic
  - Low finesse cavity for 532 nm to aid in lock acquisition



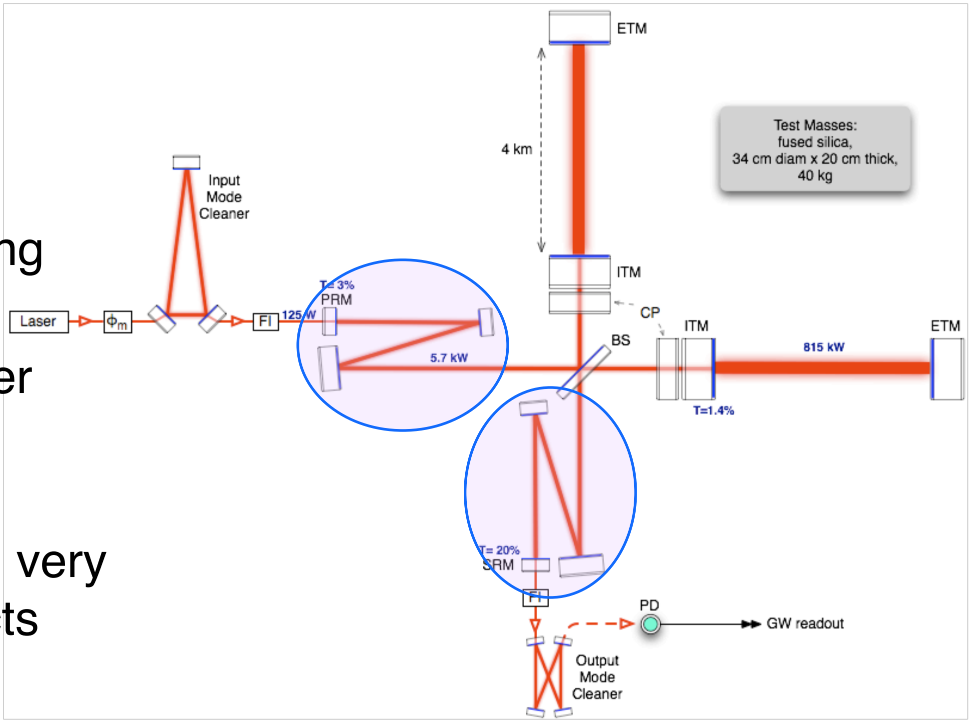
- Near-confocal design

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

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

Key Interferometer Features

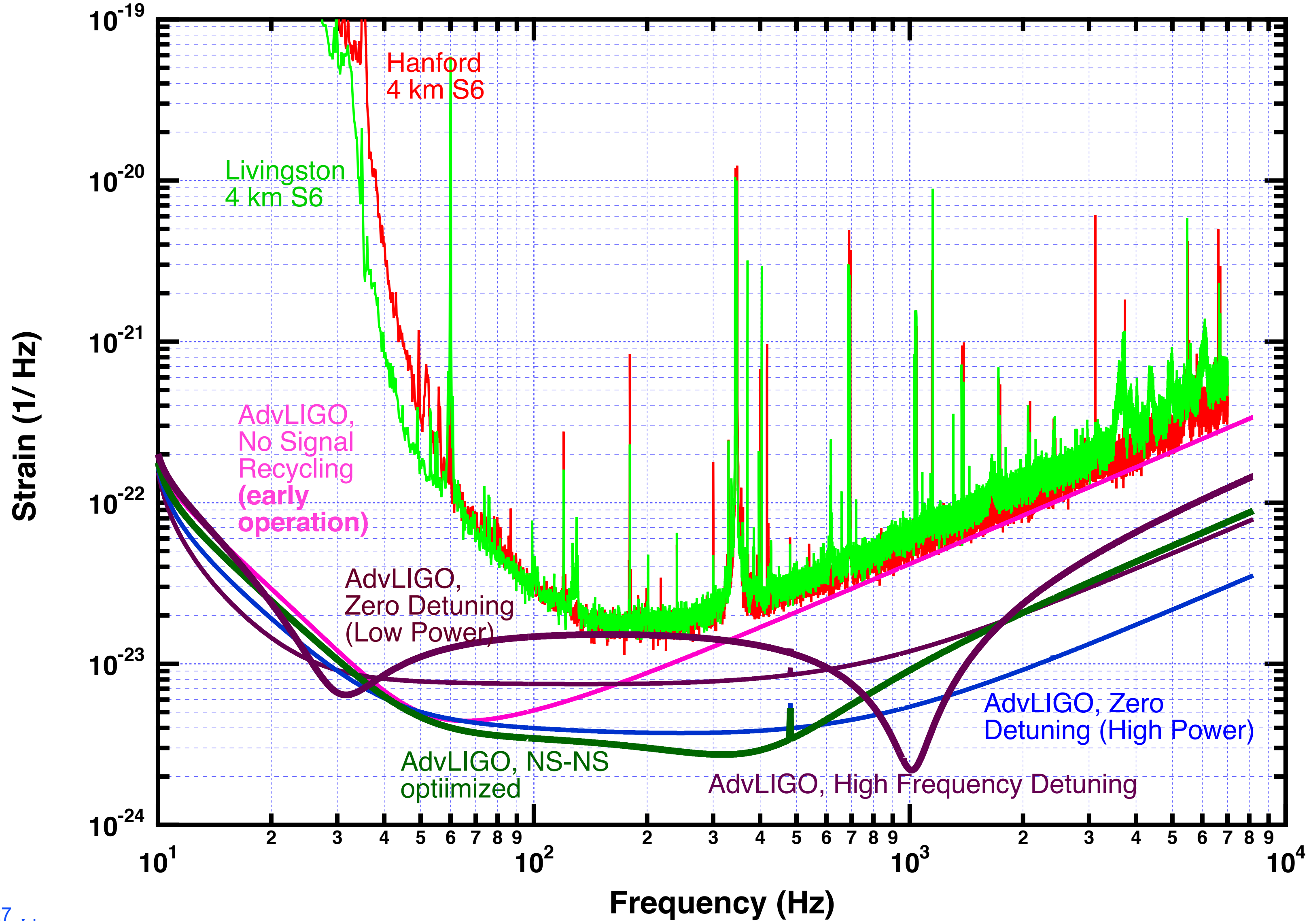
Stable Recycling Cavities



- iLIGO had a marginally stable recycling cavity
  - » Nearly a plane-plane cavity; higher order spatial modes are nearly resonant
  - » Mode quality (& thus optical gain) very sensitive to optic, substrate defects
- Stable geometry for aLIGO
  - » Beam expansion/reduction telescopes are included in the recycling cavities
  - » Higher order spatial modes are suppressed
  - » Configuration is more tolerant to optical distortions

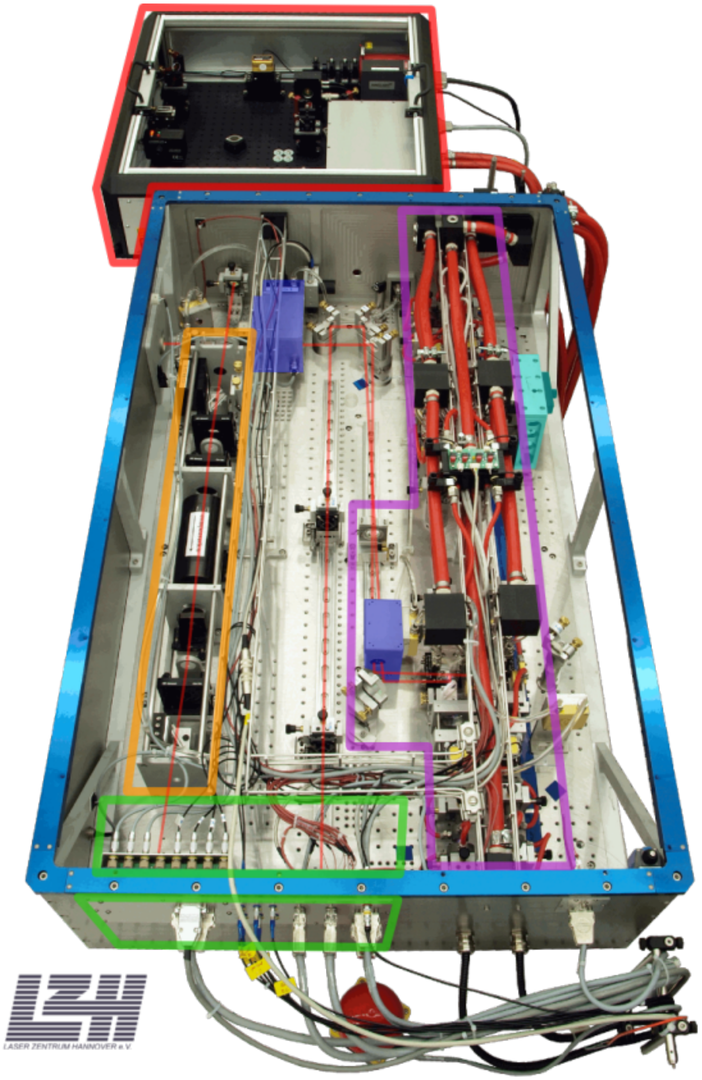
Resulting flexibility in the instrument response

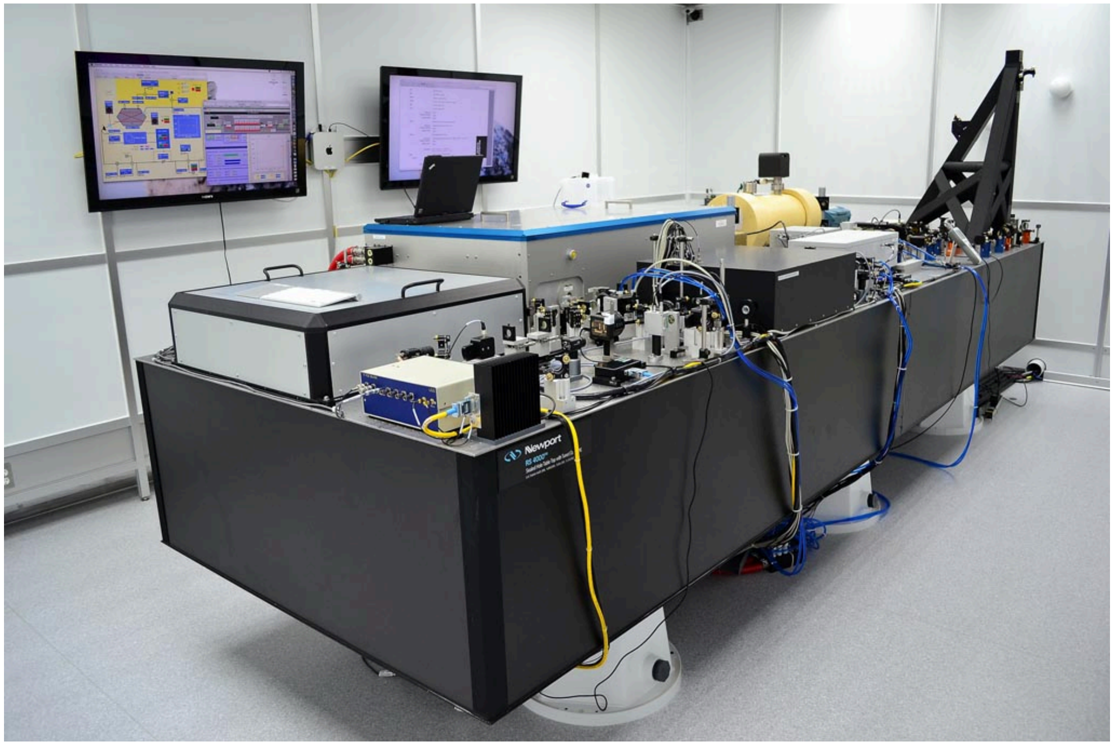
Initial LIGO curves for comparison



A look at the hardware –
with a focus on things unique to Advanced LIGO

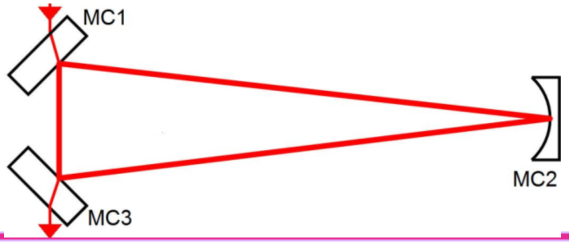
200W Nd:YAG laser, stabilized in power and frequency



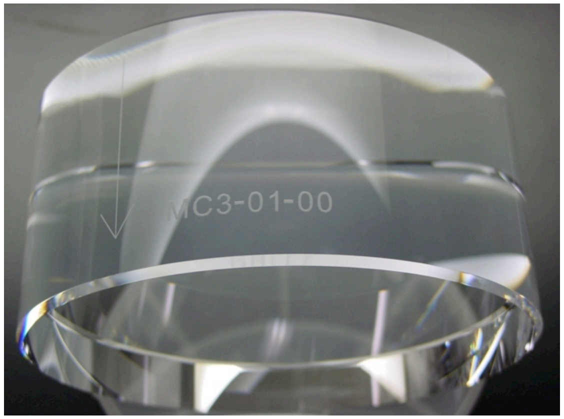


- Designed and contributed by Max Planck Albert Einstein Institute
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Input Mode Cleaner

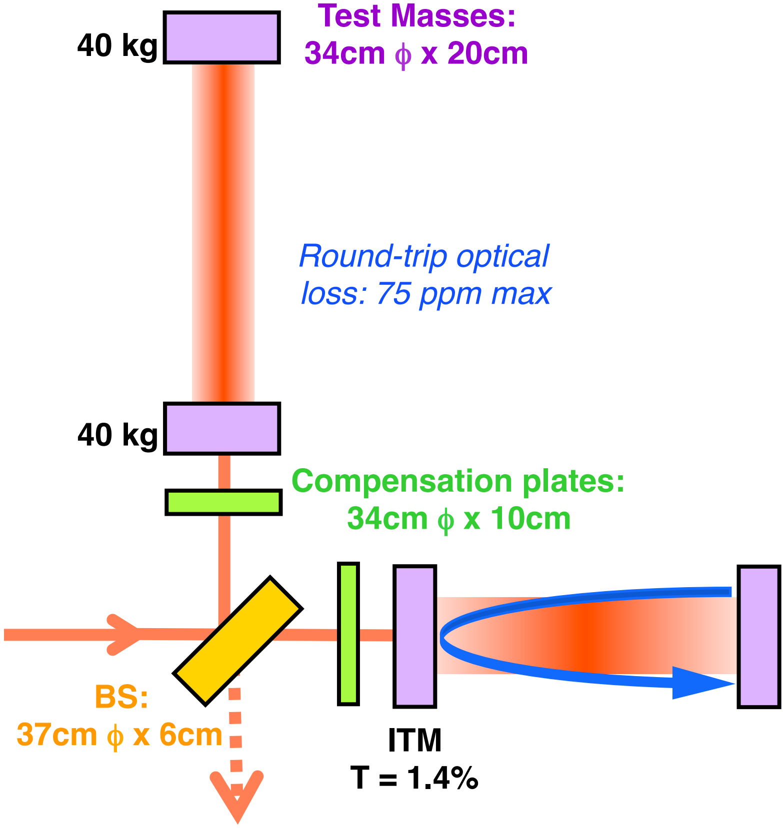


- Triangular ring cavity to stabilize pointing of beam, act as frequency reference
- *L/2* = 16.5 m; Finesse = 520
- Mirrors suspended as 3 pendulums in series for seismic isolation, control
- Mirrors 15 cm diameter x 7.5 cm thick -- 3 kg: 12x heavier than iLIGO, to limit noise due to radiation pressure



Test Masses

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



40 kg

Test Masses:
34cm ϕ x 20cm

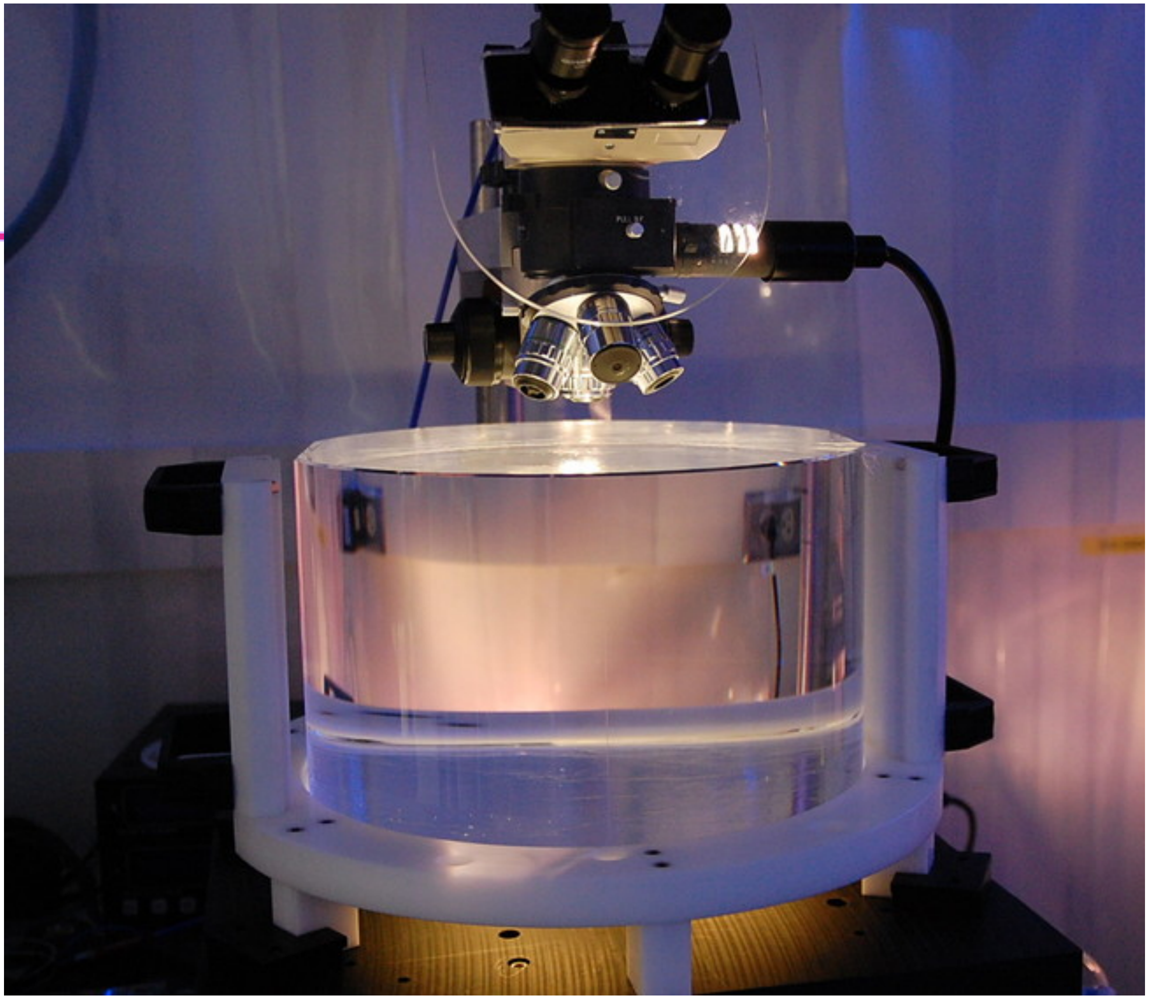
Round-trip optical loss: 75 ppm max

40 kg

Compensation plates:
34cm ϕ x 10cm

BS:
37cm ϕ x 6cm

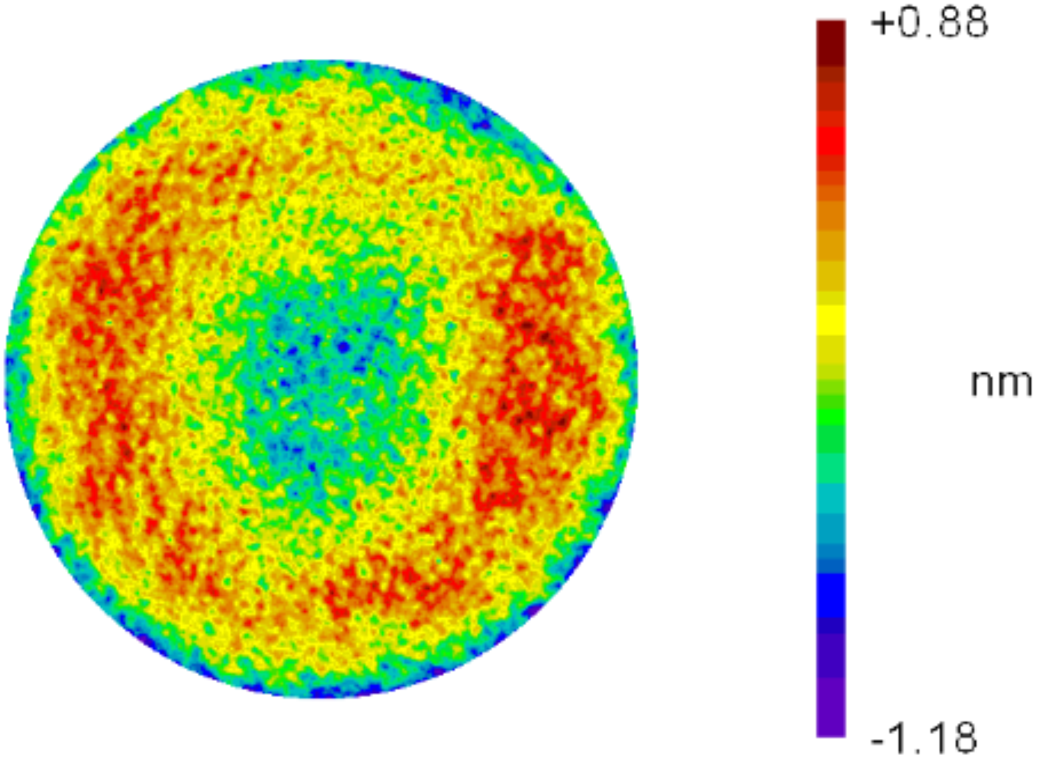
ITM
T = 1.4%



- 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

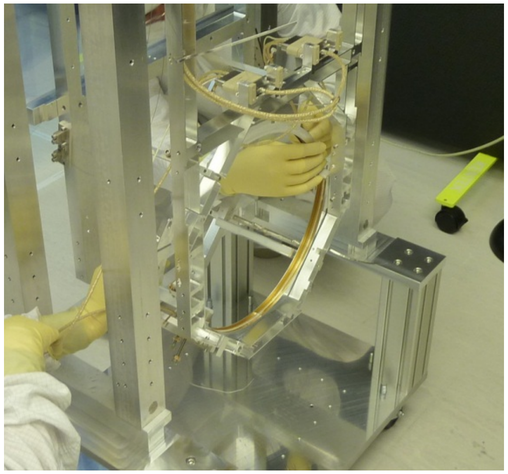
- Heraeus substrates: low absorption, excellent homogeneity, stability under annealing
- Superpolished; then, cycle of precision metrology and ion-beam milling to correct errors; surface is as good as 0.08 nm RMS over 300 mm aperture (Tinsley)
- Ion-beam assisted sputtered coatings, ~0.6 ppm/bounce absorption, and showing 0.31 nm RMS over 300 mm aperture (LMA Lyon)
- Meets requirements of projected 75 ppm round-trip loss in 4km cavity

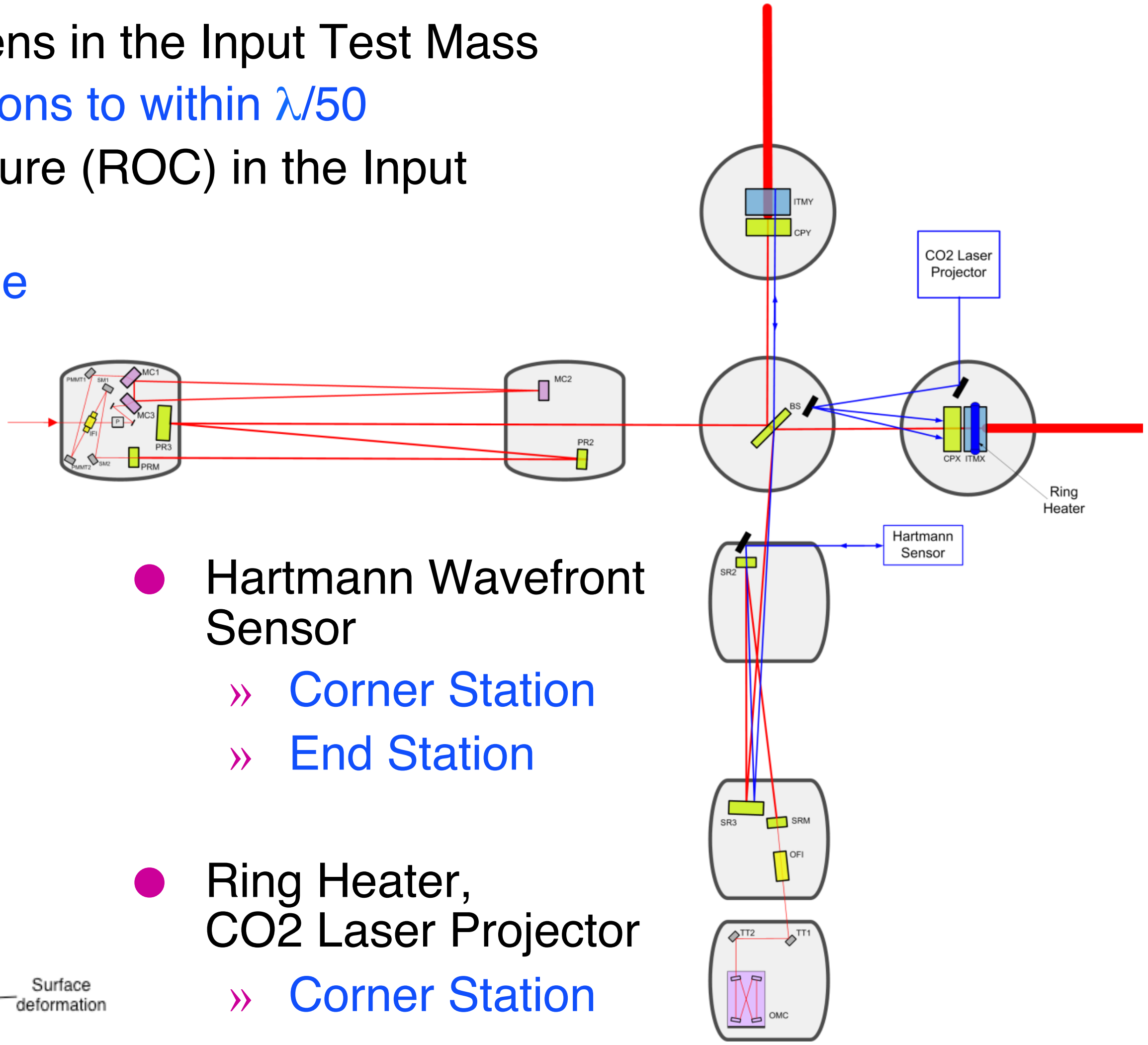


Compensation of focus induced by laser-induced substrate heating

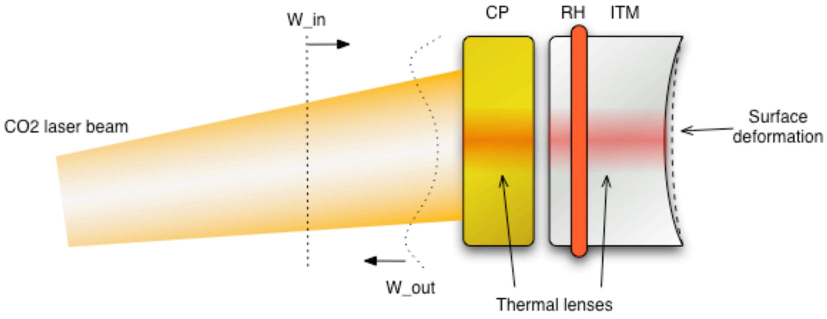
Elements contributed by Australian consortium

- Measure & Control thermal lens in the Input Test Mass
  - » Maintain thermal aberrations to within $\lambda/50$
- Control the Radius Of Curvature (ROC) in the Input and End Test Masses
  - » Provide 35 km ROC range



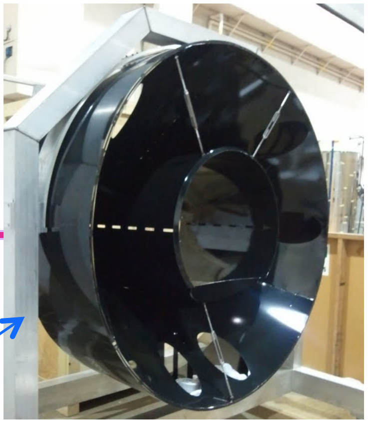


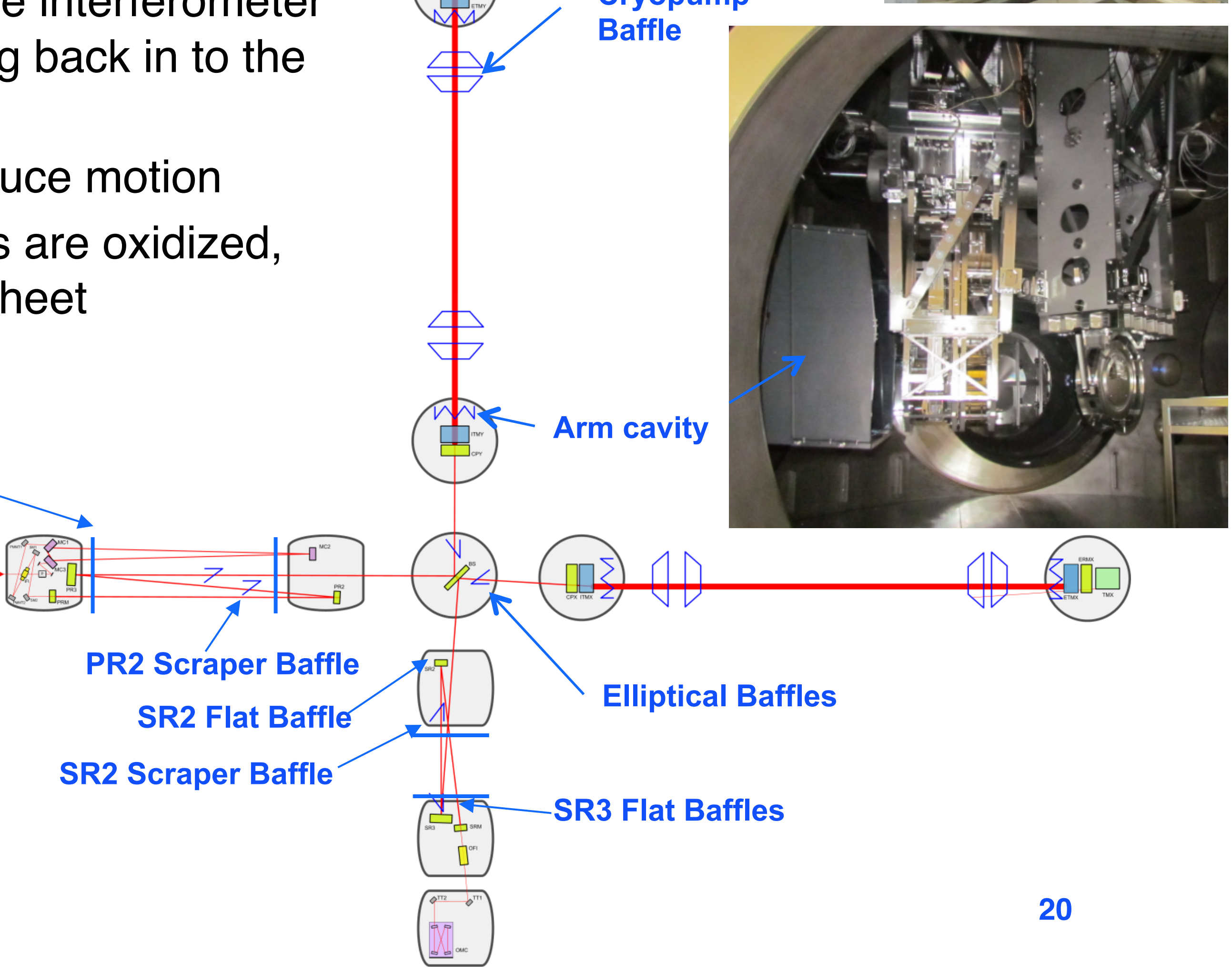
- Hartmann Wavefront Sensor
  - » Corner Station
  - » End Station
- Ring Heater, CO2 Laser Projector
  - » Corner Station



Stray Light Control

- Ensure that phase noise due to scattered light does not compromise interferometer performance by scattering back in to the beam
- Baffles suspended to reduce motion
- All baffles & beam dumps are oxidized, polished stainless steel sheet





Manifold/ Cryopump Baffle

Arm cavity

Modecleaner Tube Baffle

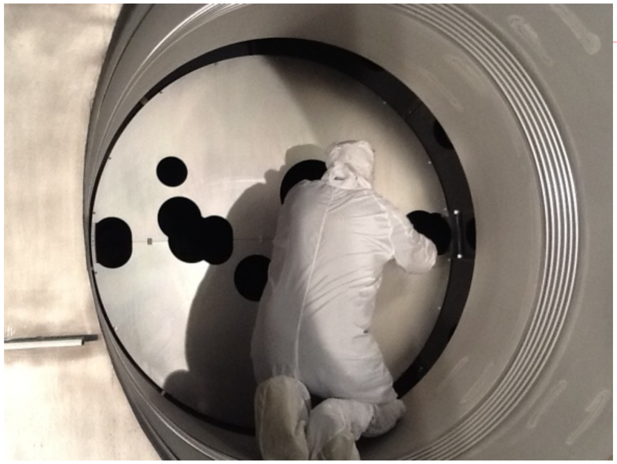
PR2 Scraper Baffle

SR2 Flat Baffle

SR2 Scraper Baffle

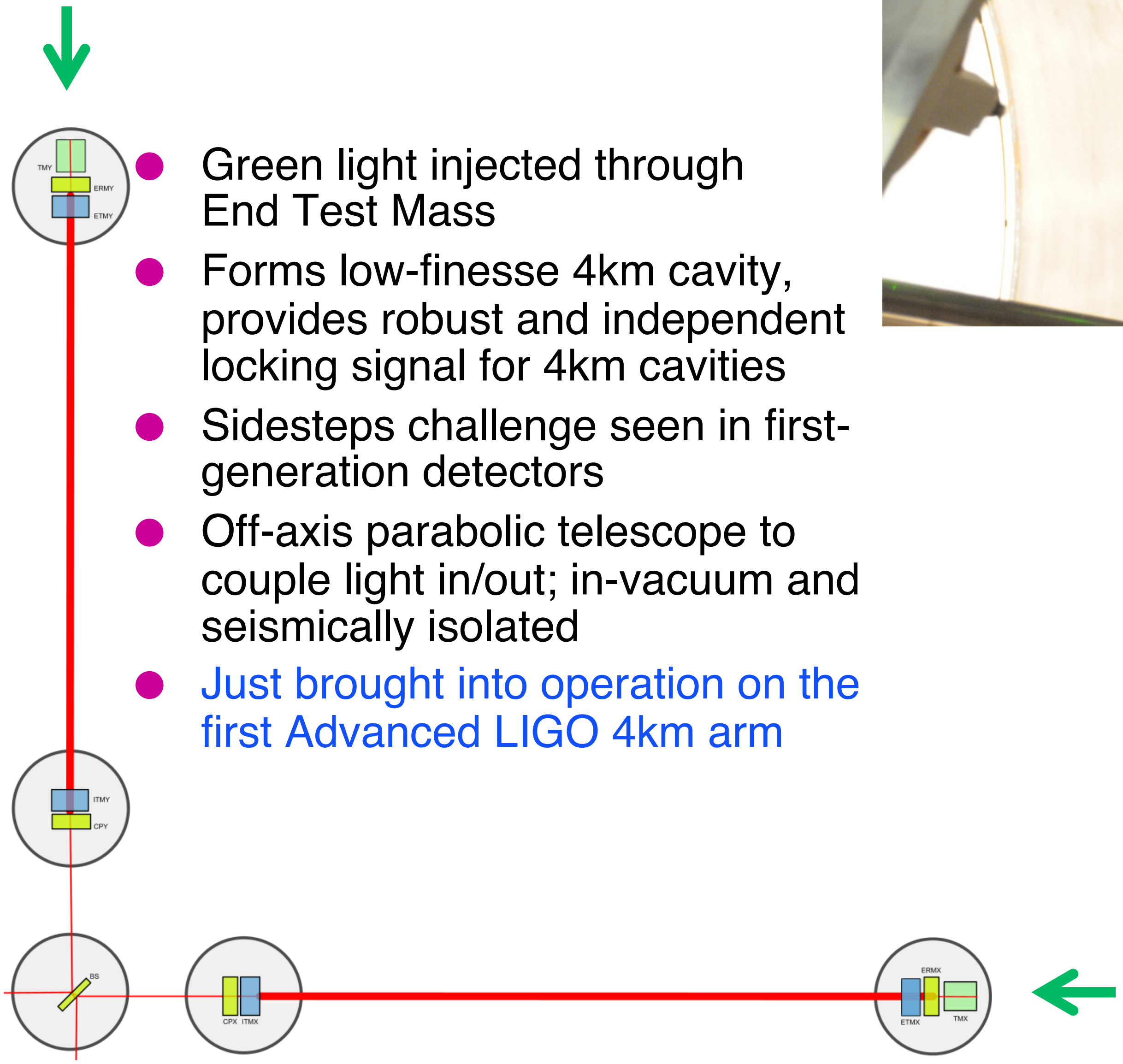
Elliptical Baffles

SR3 Flat Baffles

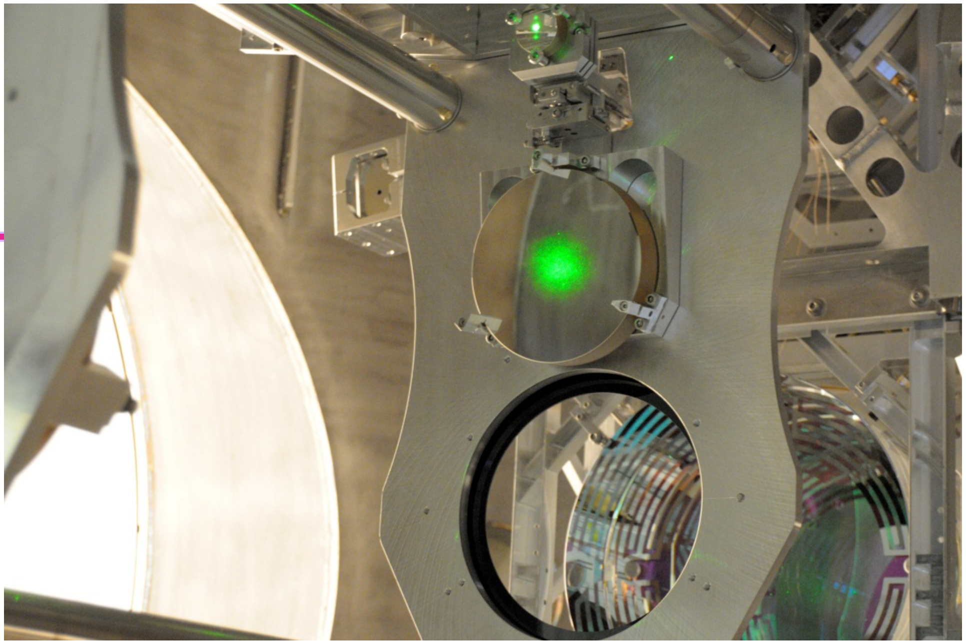


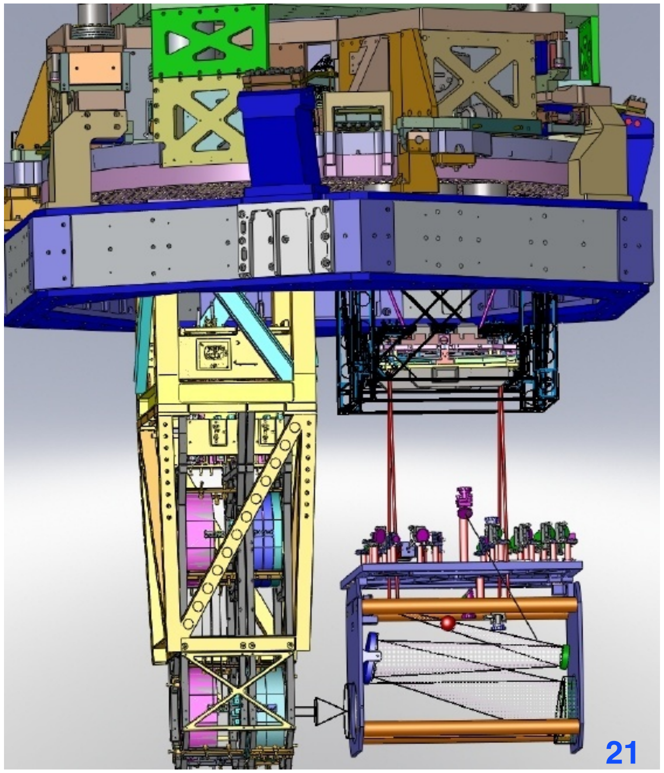
Pre-Lock Arm Length Stabilization

Contributed by Australian consortium



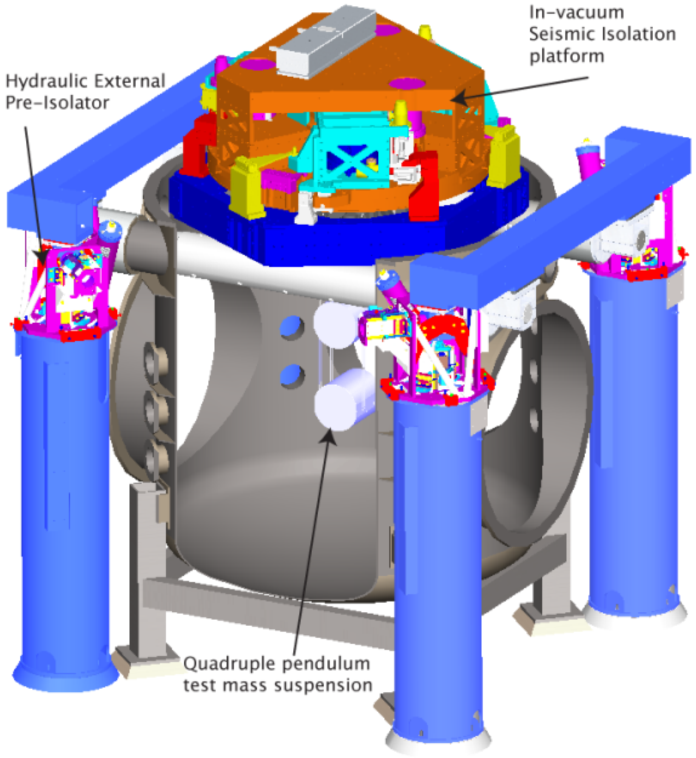
- Green light injected through End Test Mass
- Forms low-finesse 4km cavity, provides robust and independent locking signal for 4km cavities
- Sidesteps challenge seen in first-generation detectors
- Off-axis parabolic telescope to couple light in/out; in-vacuum and seismically isolated
- Just brought into operation on the first Advanced LIGO 4km arm



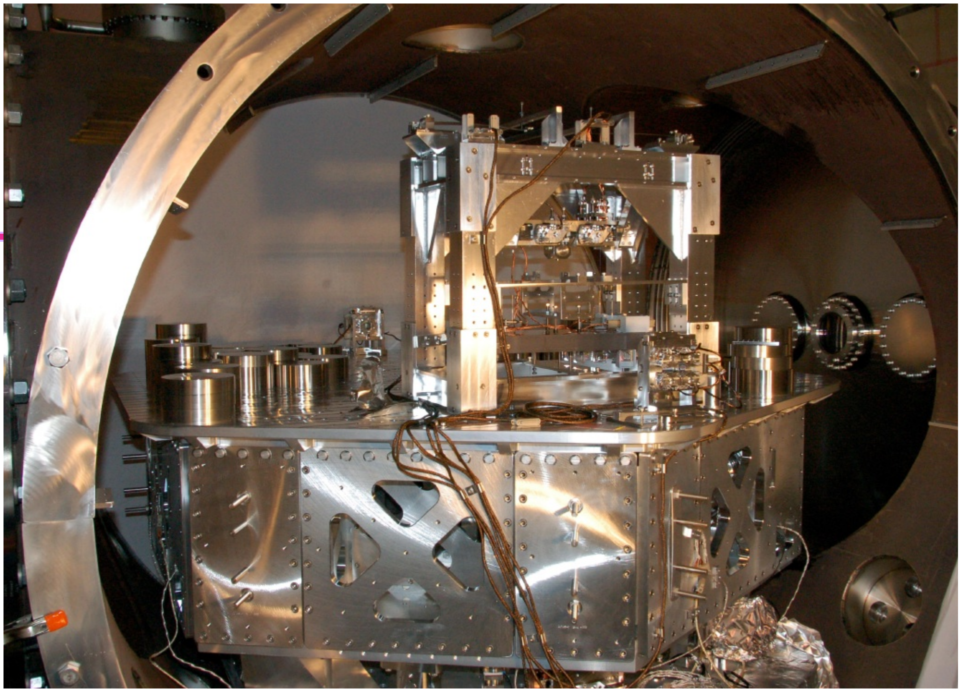


Seismic Isolation: Multi-Stage Solution

- 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
- Increase number of passive isolation stages in suspensions
  - From single suspensions ($1/f^2$) in initial LIGO to quadruple suspensions ($1/f^8$) for aLIGO



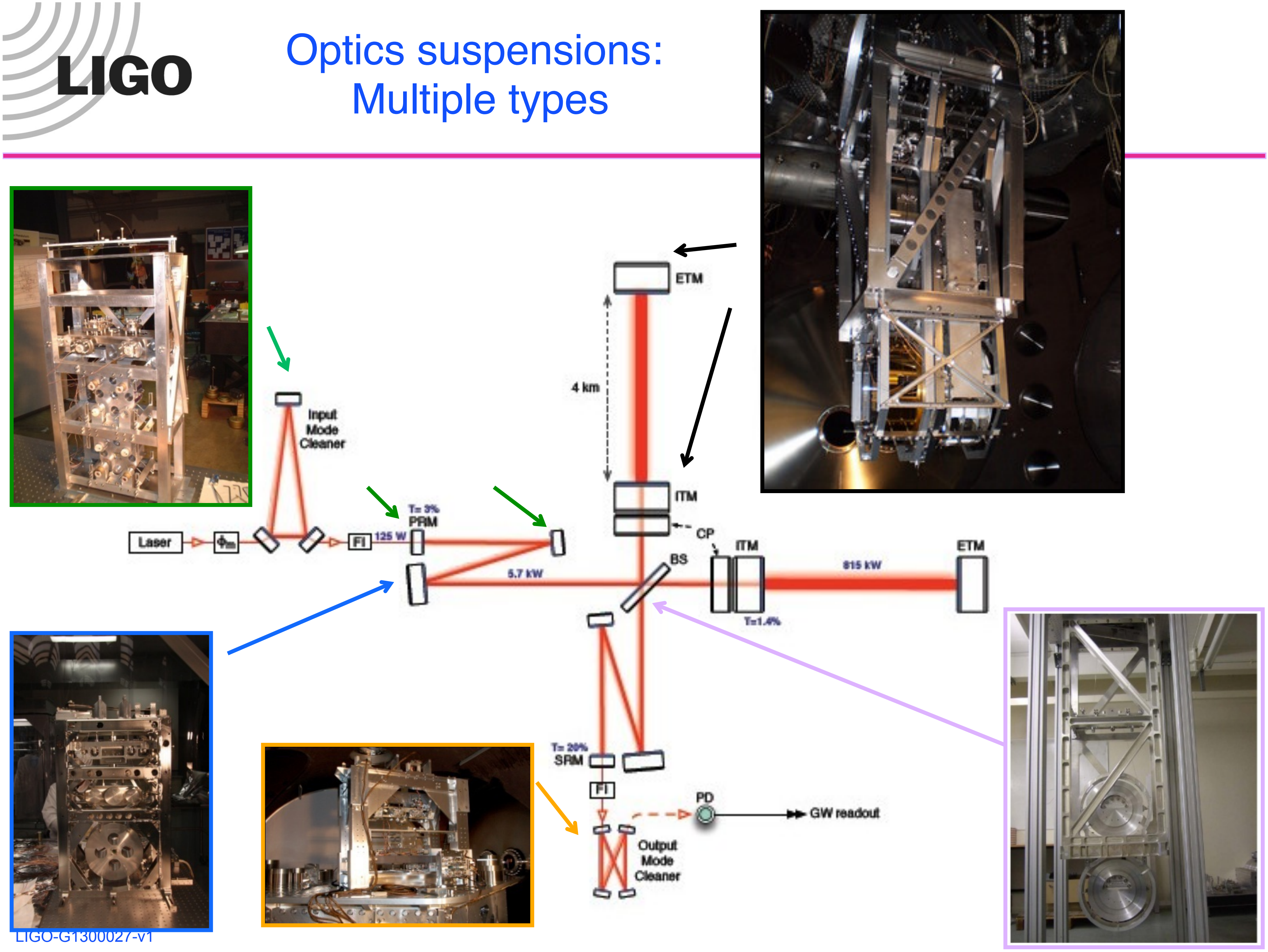
Seismic Isolation: two models



- 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.

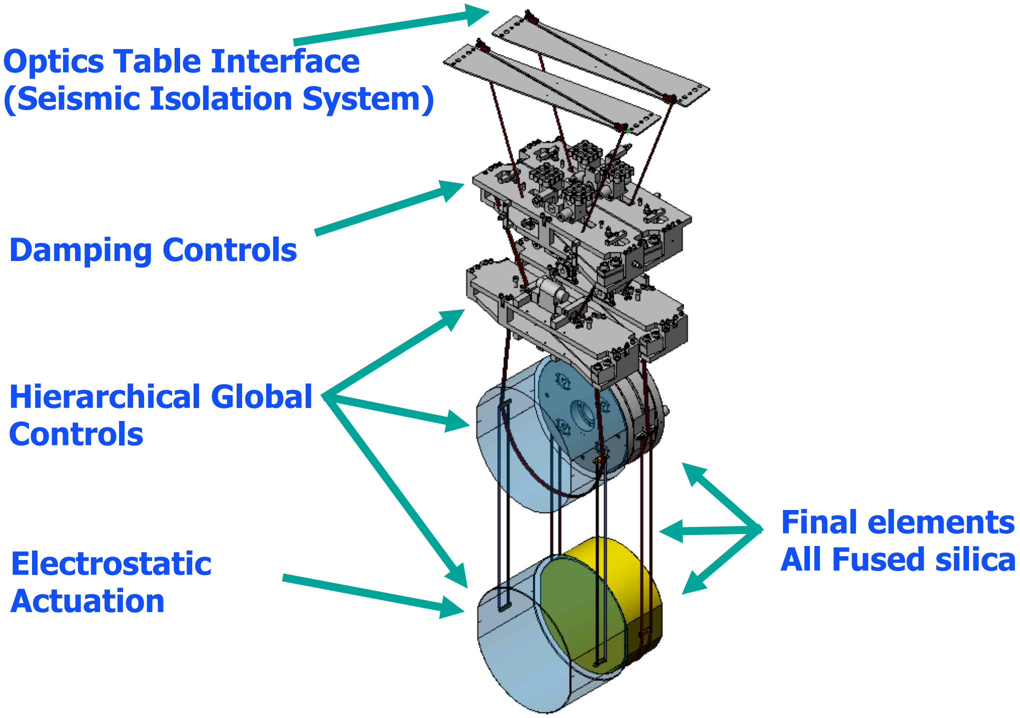
Optics suspensions: Multiple types



Test Mass Quadruple Pendulum suspension

Contributed by UK consortium

- 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
- Another element in hierarchical control system


Optics Table Interface (Seismic Isolation System)

Damping Controls

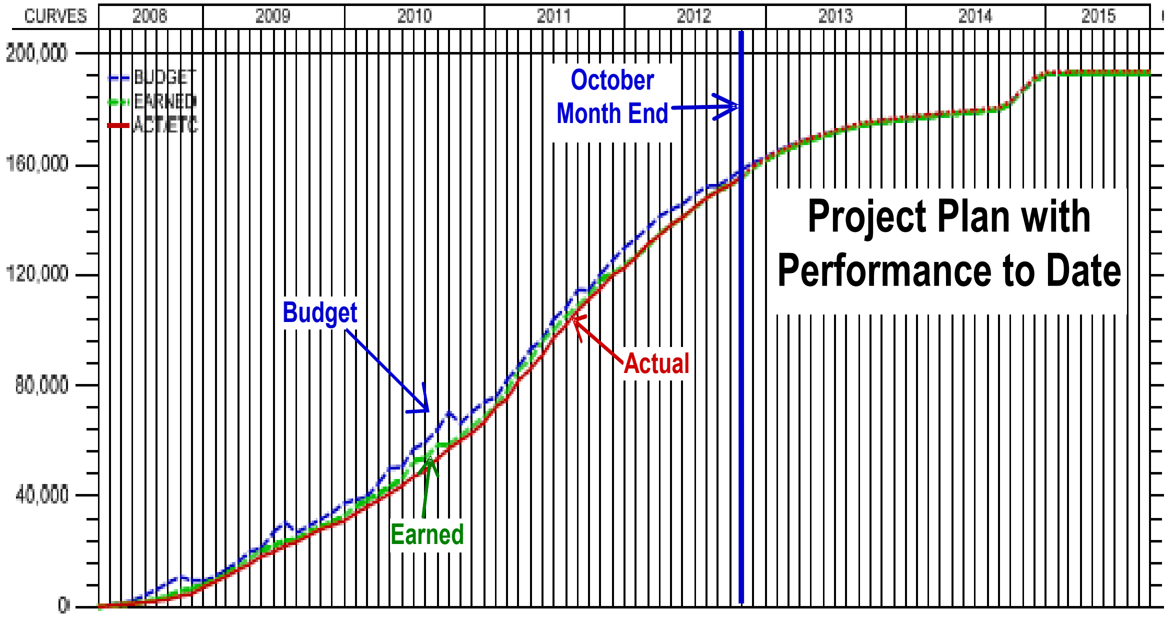
Hierarchical Global Controls

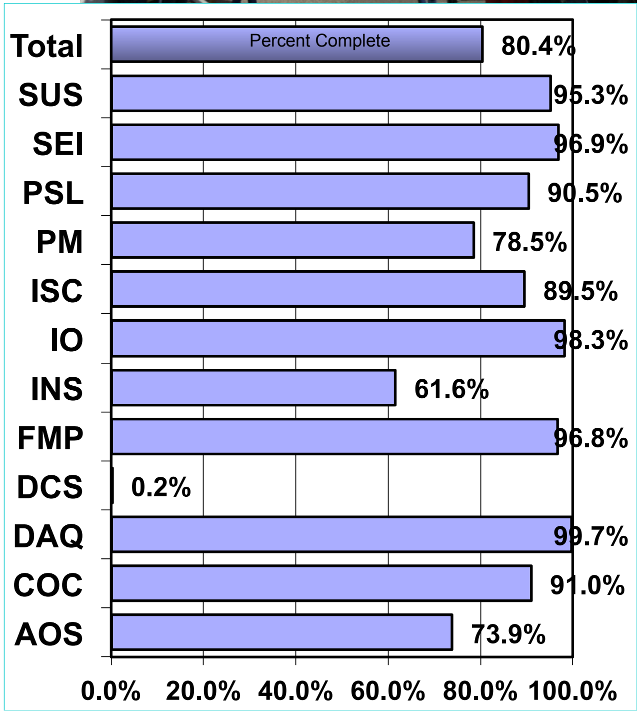
Electrostatic Actuation

Final elements All Fused silica

Where are we?

- All designs are complete, all major items procured
- ~90% of the subsystem work is completed
- The installation phase is more than half completed
  ….and parts all fit and work together, happily
- The ‘integrated testing’ of many components together is well underway
- **First 4km aLIGO cavity locked, tested at Hanford**
- **First suspended mode cleaner, tested at Livingston**

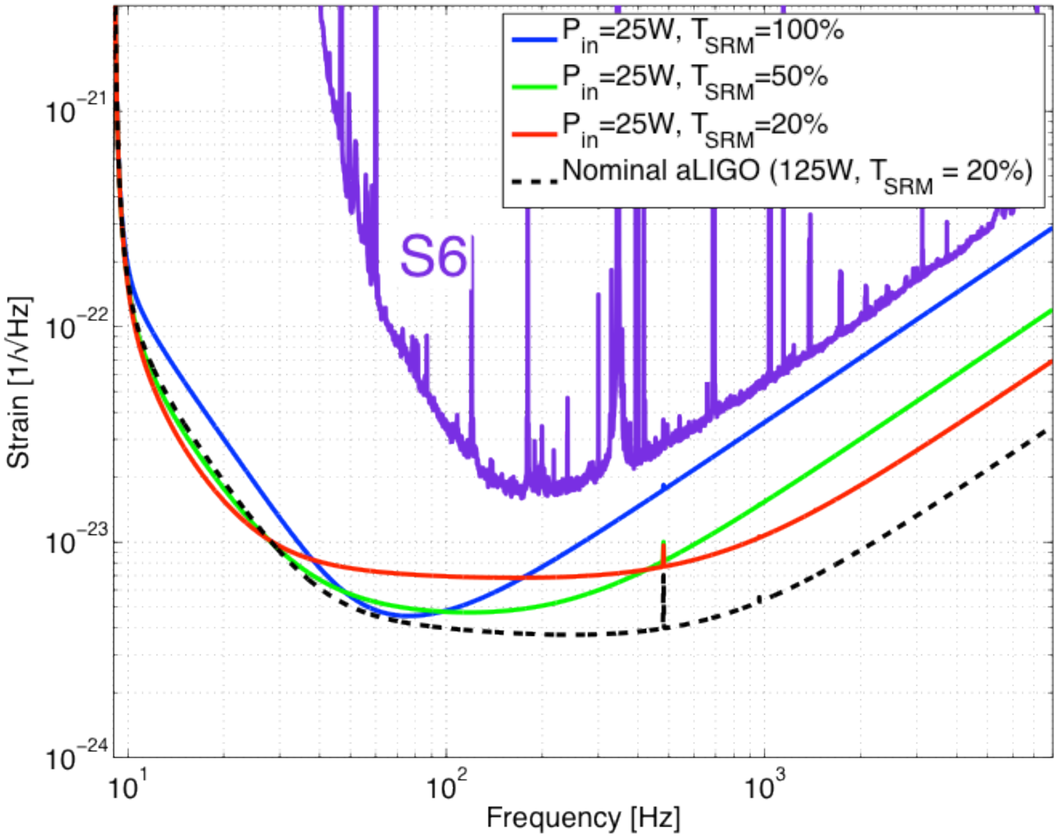




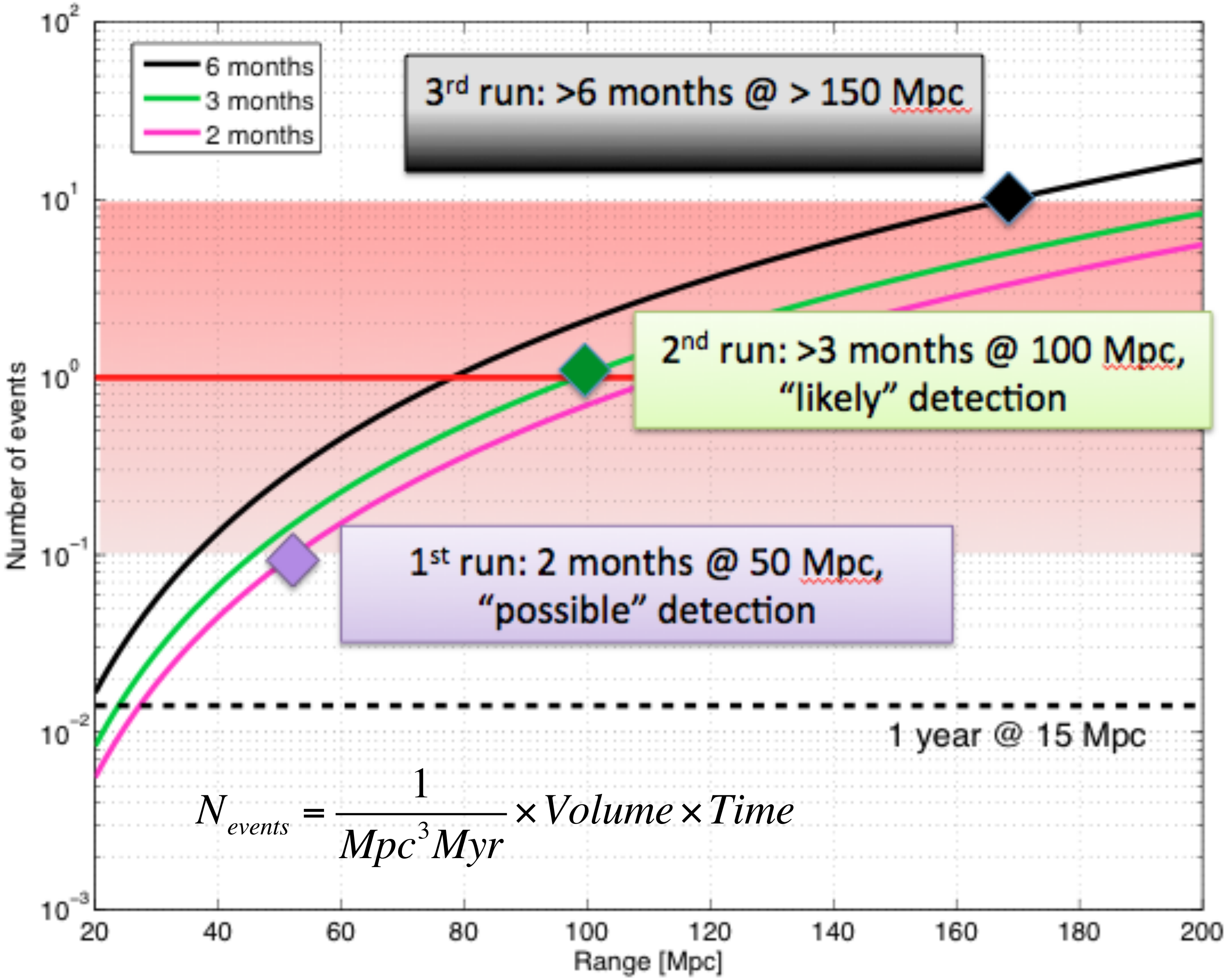
And after the Project: Tuning for Astrophysics, and Observation

- 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
  - Probably no signal recycling
- 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



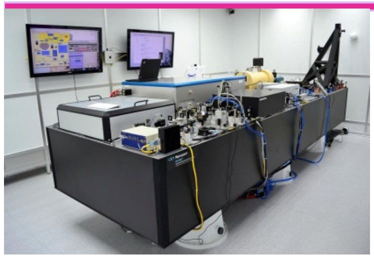
3rd run: >6 months @ > 150 Mpc

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

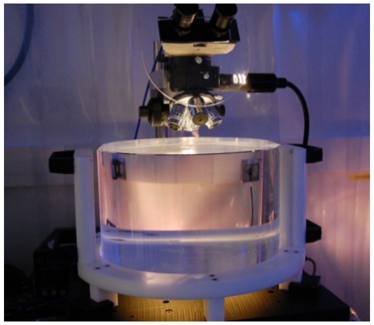
1st run: 2 months @ 50 Mpc, "possible" detection

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

The 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 2014
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy



Planning on a first observation ‘run’ as early as 2015