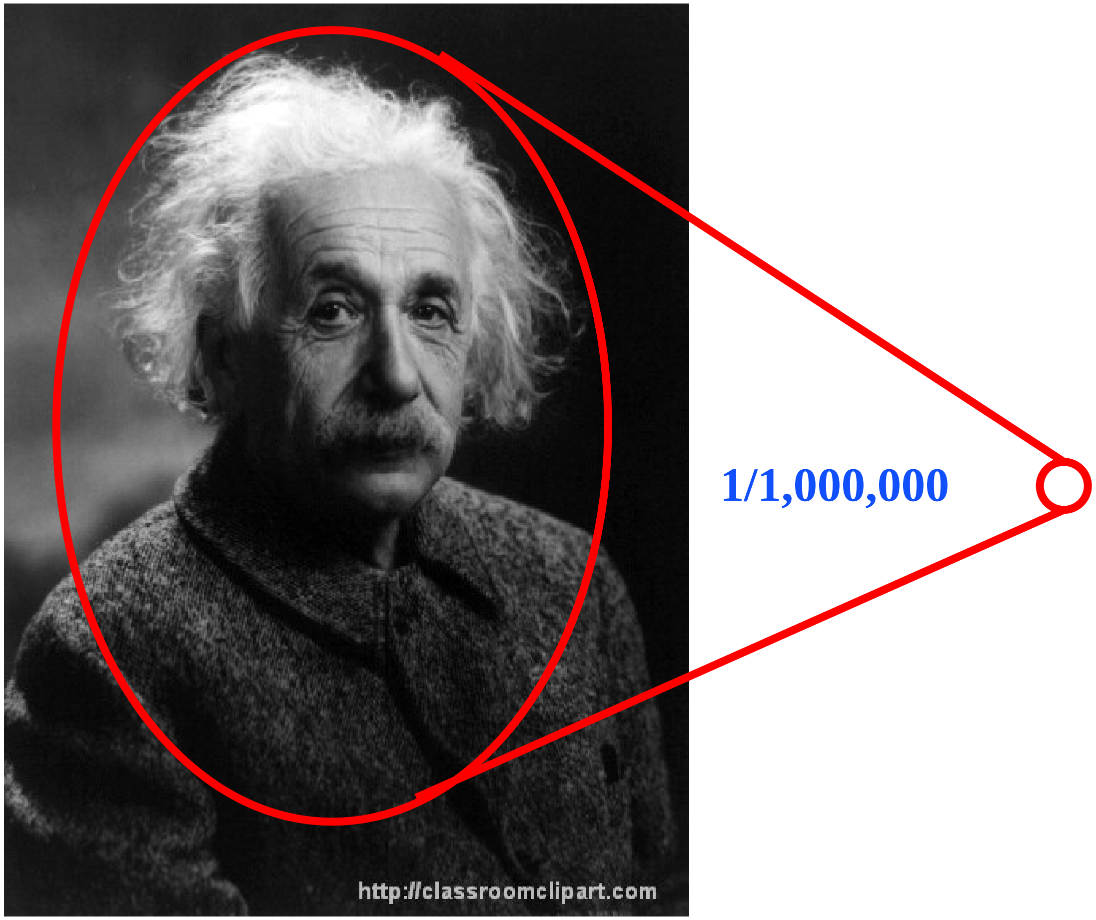
Gravitational Waves & Precision Measurements

Mike Smith

10^{-20} m

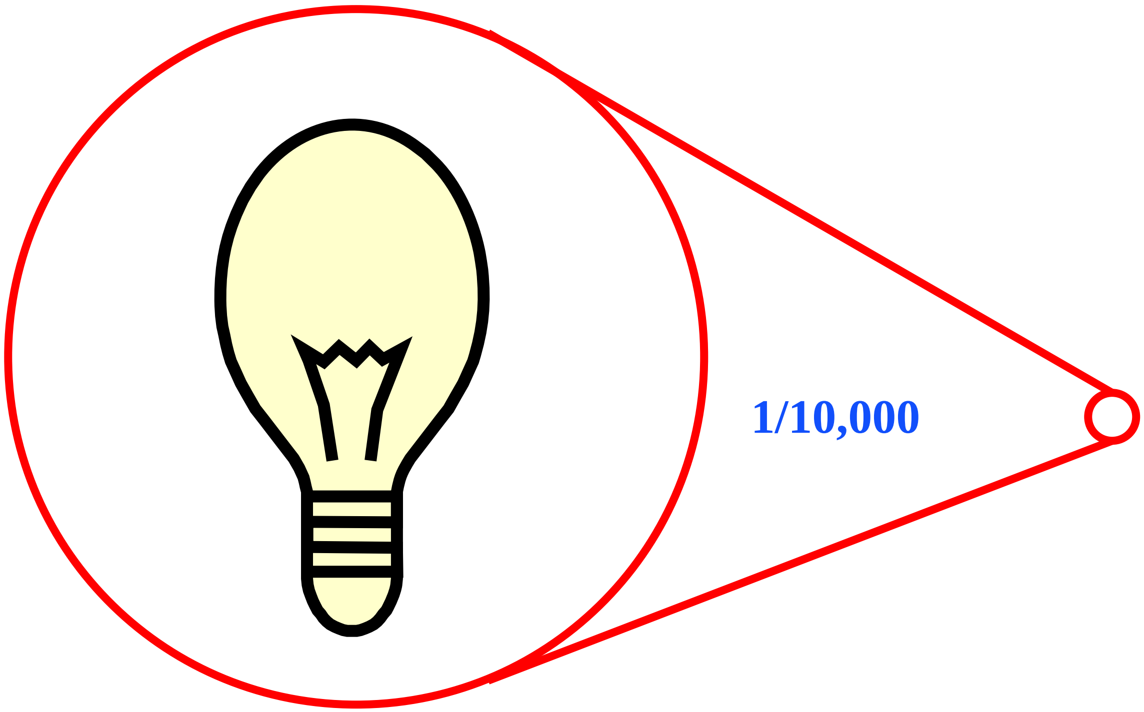
HOW SMALL IS THAT?

- Einstein
- 1 meter



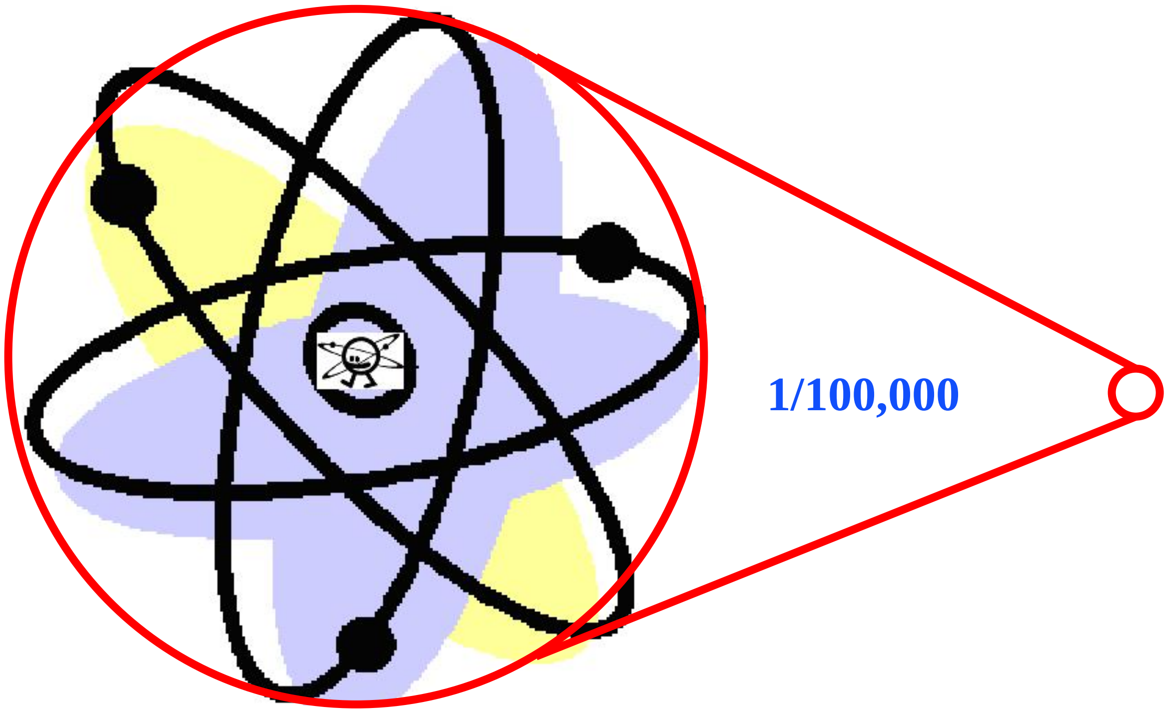
1,000,000 smaller

- Wavelength of light
- 10^{-6} meters



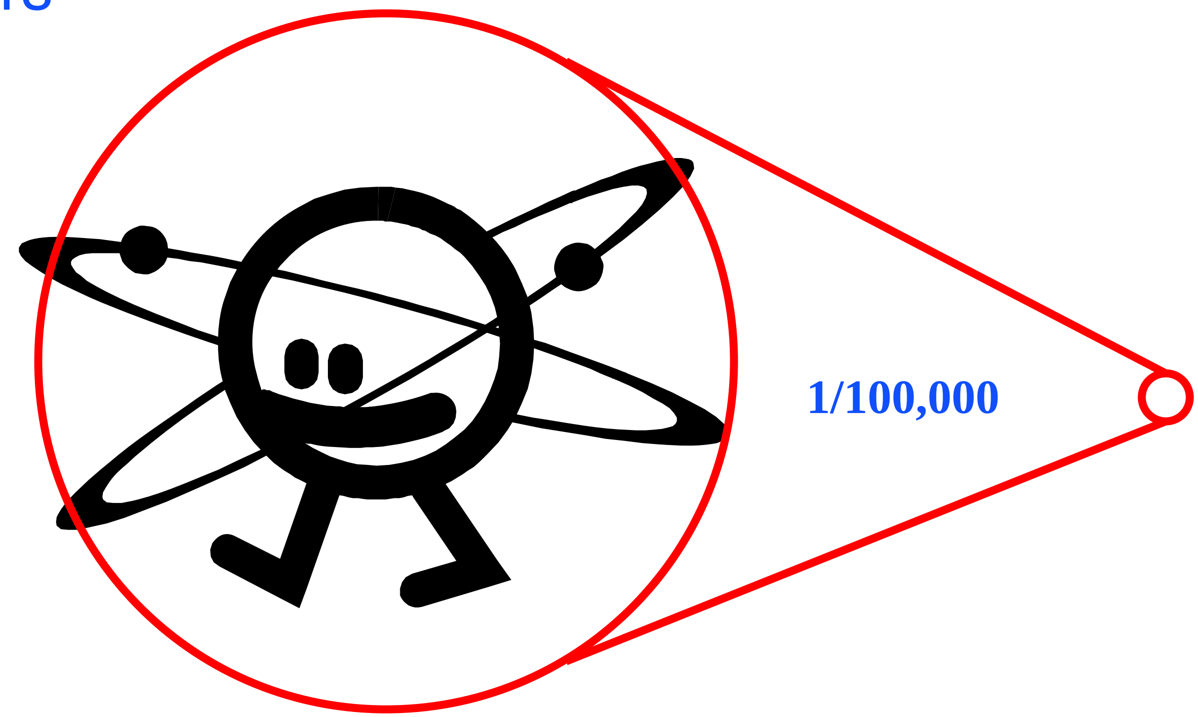
10,000 smaller

- Atom
- 10^{-10} meters

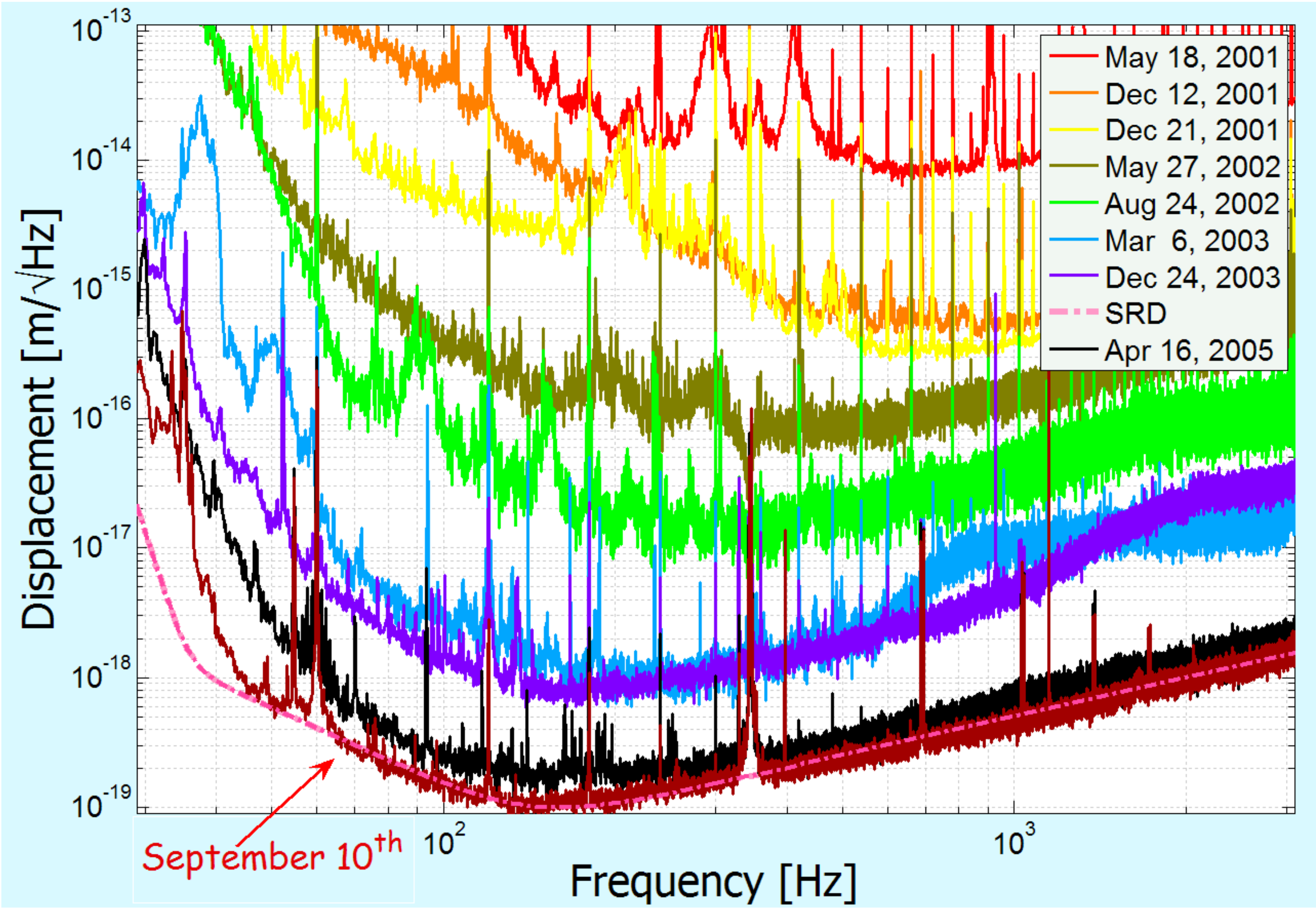


100,000 smaller

- Nucleus of hydrogen atom
- 10^{-15} meters

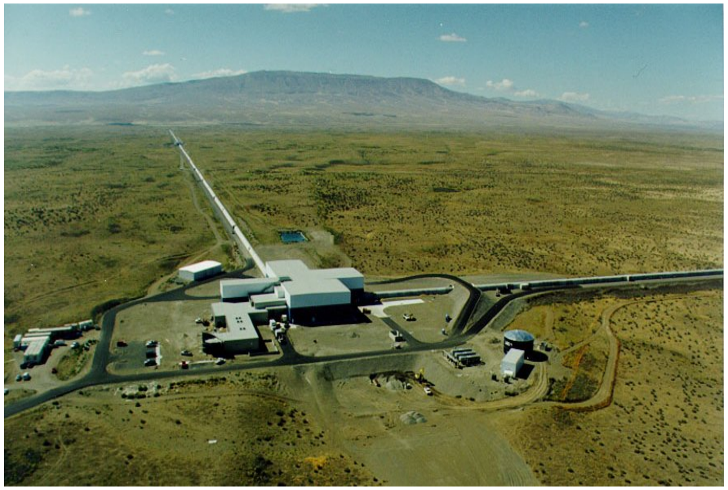


100,000 smaller than the proton
10^{-20} meters



LIGO Observatories

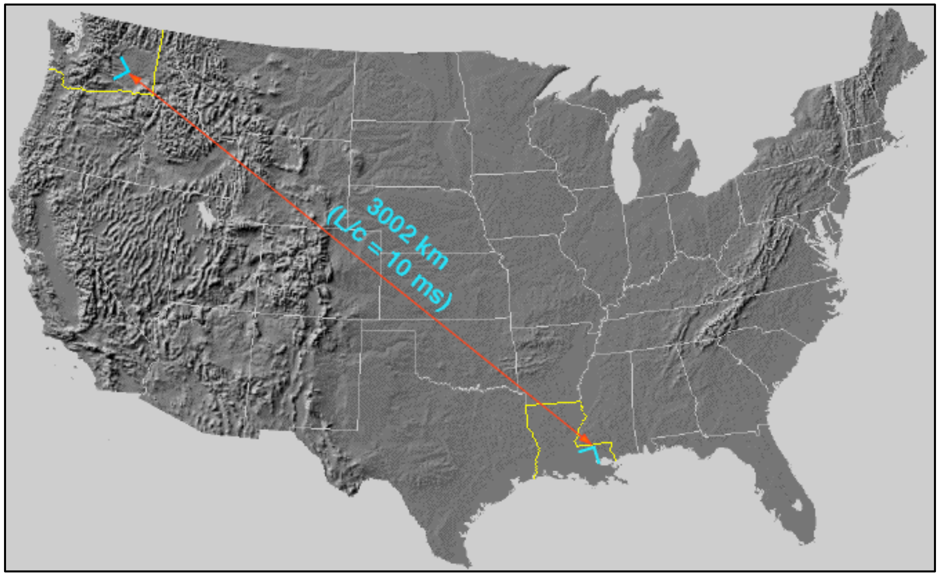
Hanford Nuclear Reservation, Eastern WA (H1 4km, H2 2km)



- Interferometers are aligned to be as close to parallel to each other as possible

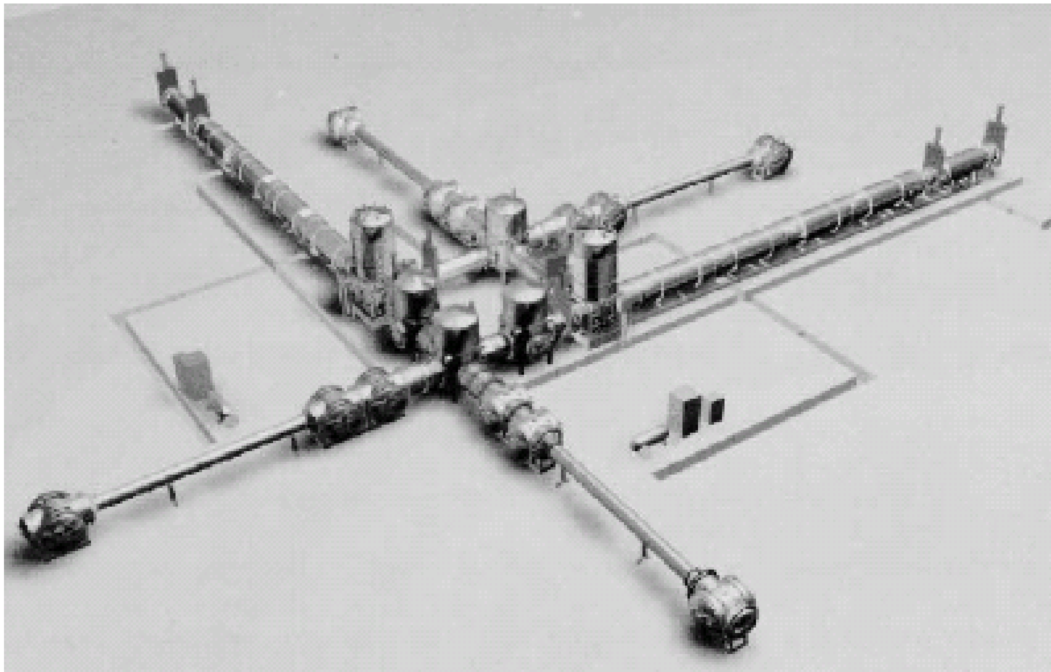
- Observing signals in coincidence increases the detection confidence

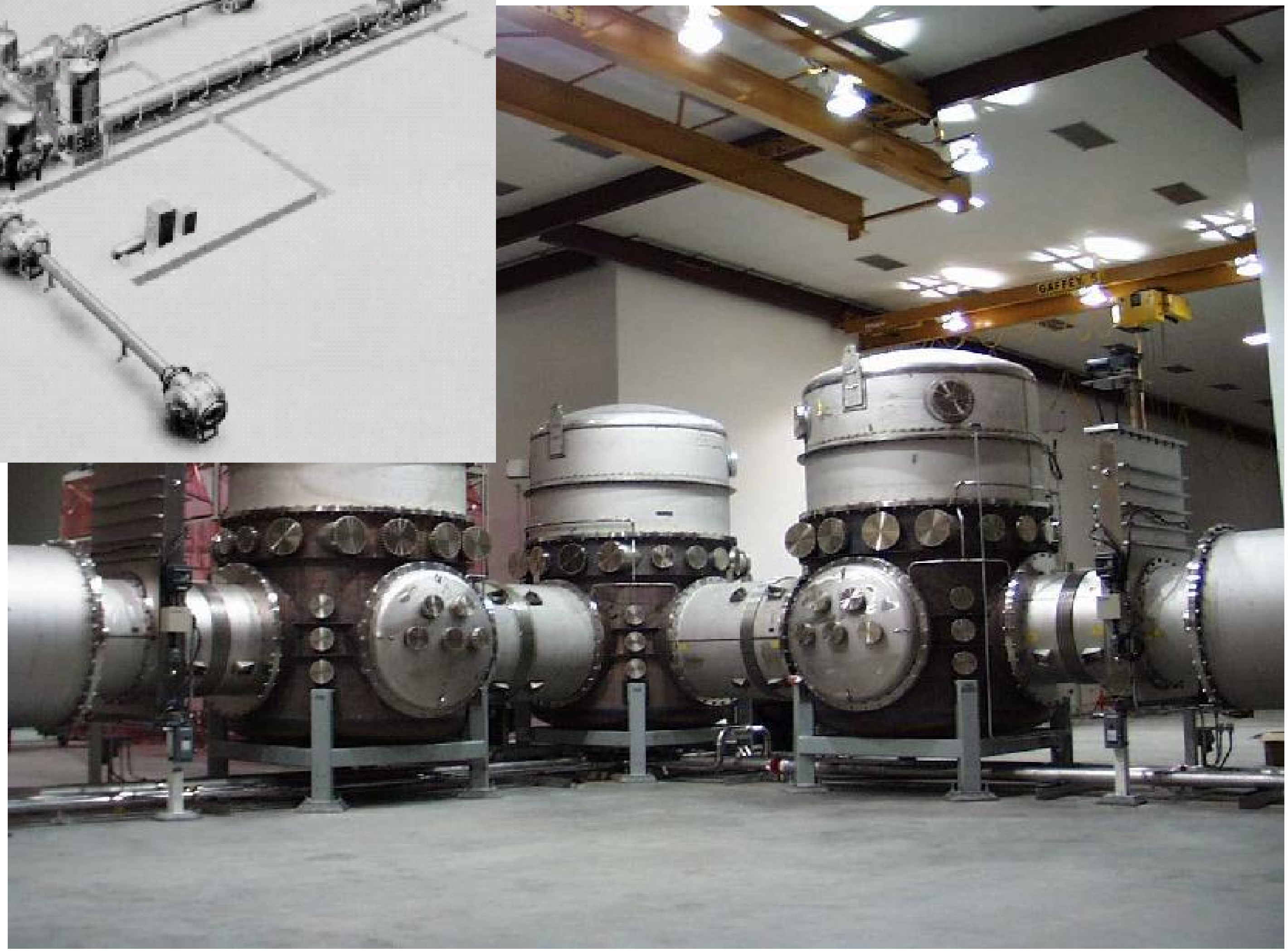
- Determine source location on the sky, propagation speed and polarization of the gravity wave



Livingston, LA (L1 4km)

Vacuum Equipment





G1000029

LIGO Beam Tube

- 1.2 m diameter stainless tubing, pumps only every 2 km

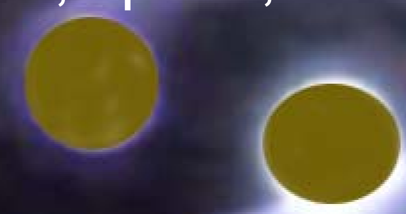
- Aligned to within mm over km (corrected for curvature of the earth)

- Total of 16km fabricated with no leaks

- Cover needed (stray bullets, stray cars…)

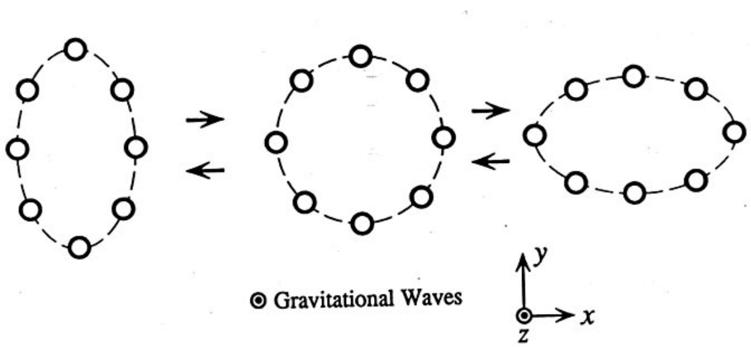
What and why?

- Gravitational waves are ripples in space-time – stretching and compressing space itself
- A good source: two stars orbiting around each other near the speed of light (a ‘neutron star binary’)
- Signal carries information about **very** extreme conditions of matter, space, and gravitation



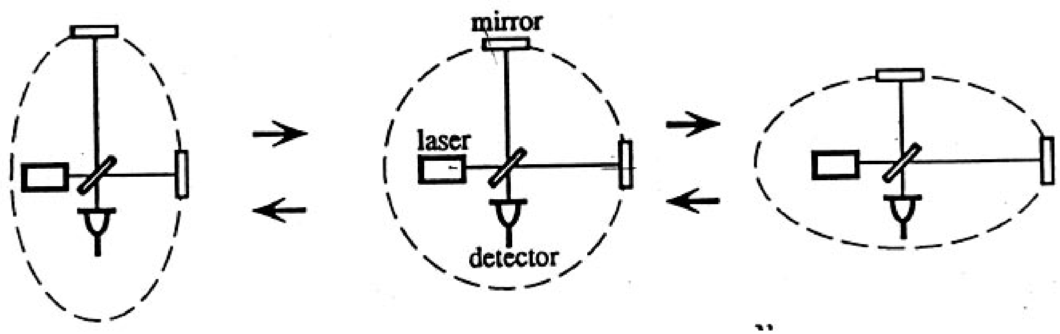
- It’s a brand new way of seeing the Universe
- Will help to understand black holes and other exotic phenomena
- Will be used with other astronomical tools – Optical and radio telescopes, neutrino and gamma ray detectors – to build a more complete picture of what’s out there

How to detect them?



Passing wave distorts space – changes distances along vertical and horizontal paths

Michelson interferometers can measure these distortions by comparing light along two arms at right angles



Longer arms → bigger signals (like radio waves), but still very very small length changes:
0.0000000000000000001 inch (ouch)
over 2.5 miles for the strongest sources
-- a strain sensitivity of one part in 10^{21}

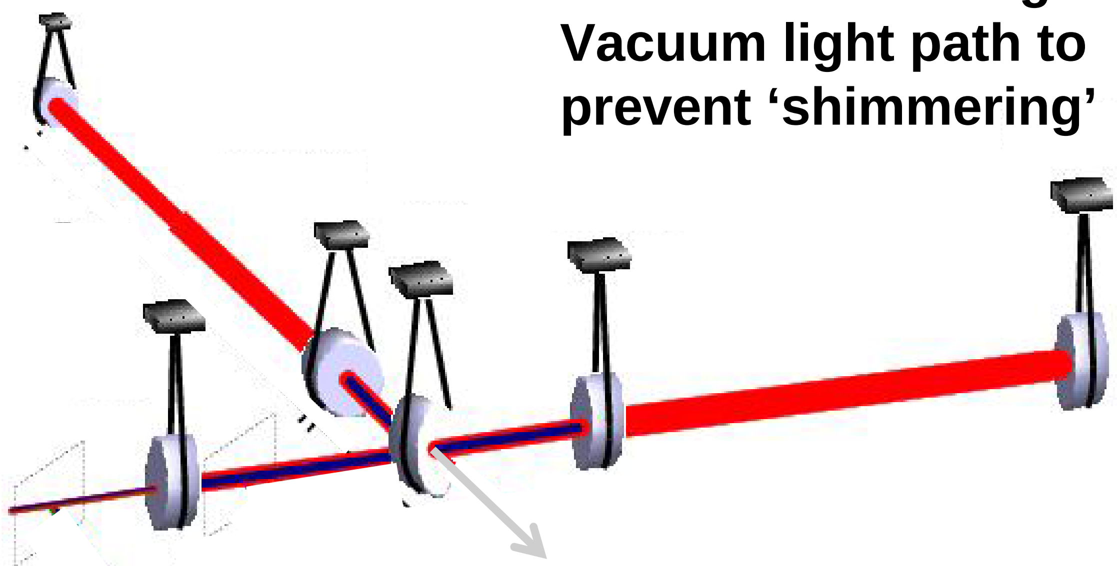
LIGO: a precision instrument
Opto/Mechanical Engineer's dream

Superb optics to minimize light loss

Seismic isolation and Suspension to ensure that only GWs move the test masses

4km arms for a larger signal
Vacuum light path to prevent 'shimmering'

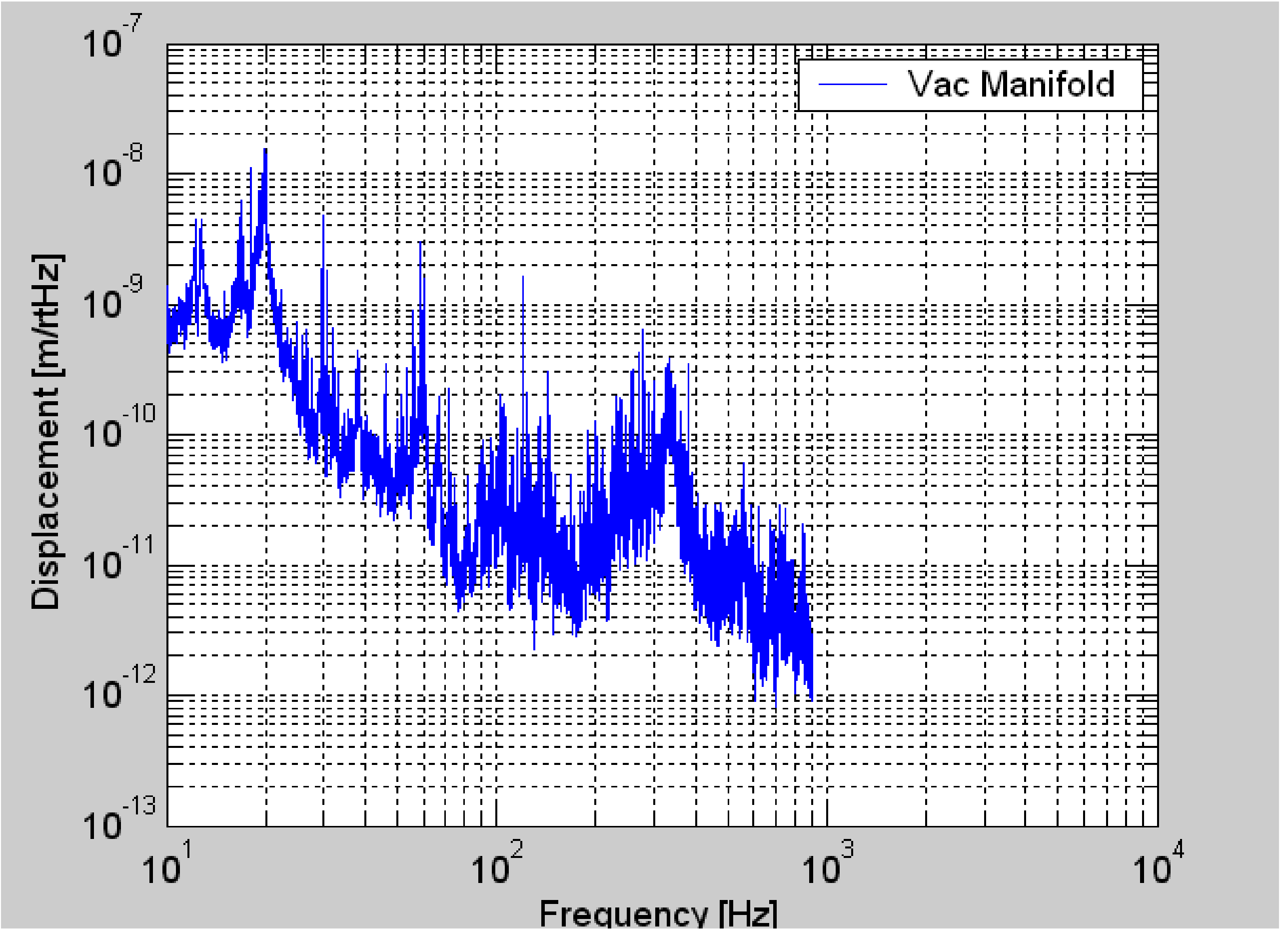
Powerful, stable laser to make distance measurement precise



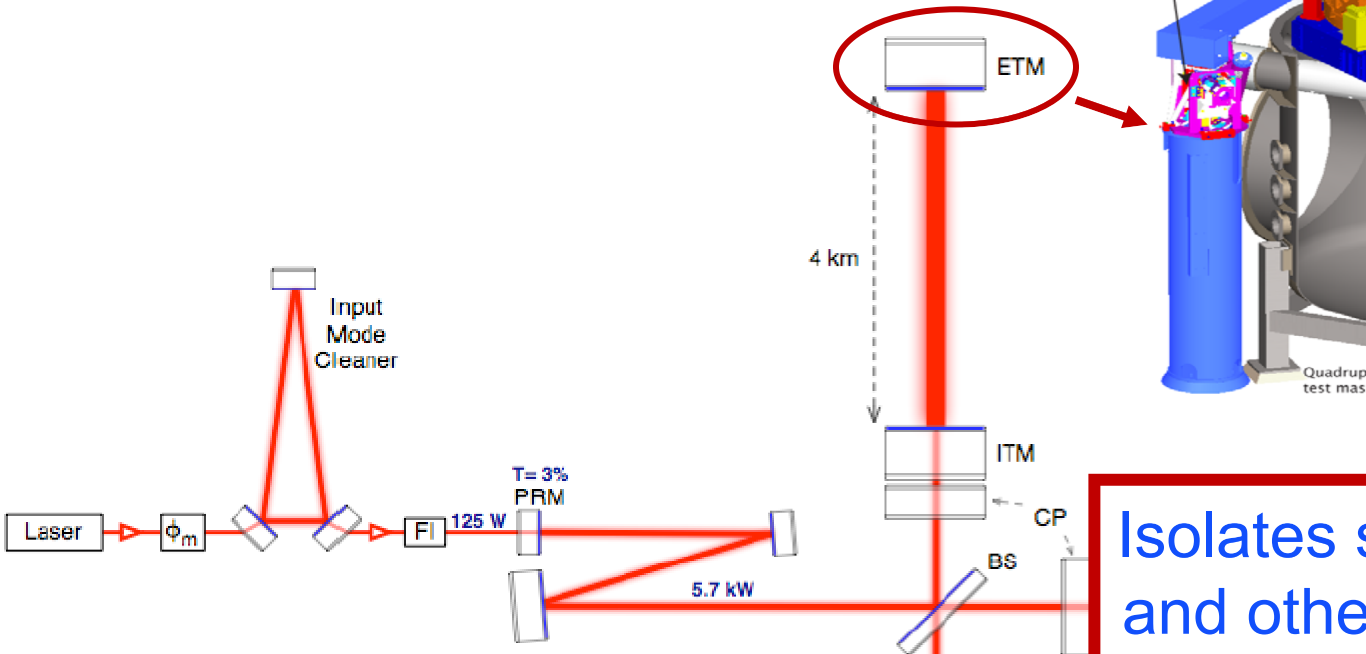
Laser

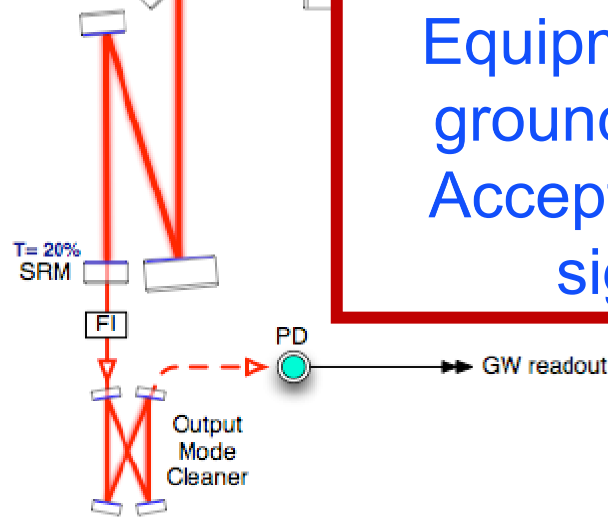
Sensors and control systems to hold optics to the right position

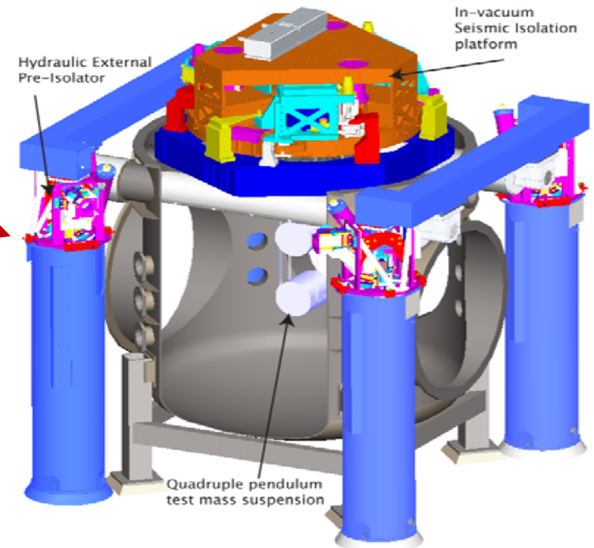
Seismic Motion Of
Vacuum Chamber Walls, m/rtHz



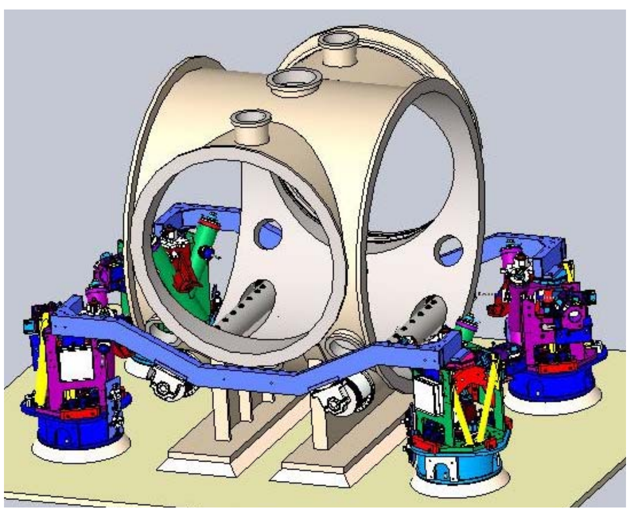
Seismic Isolation



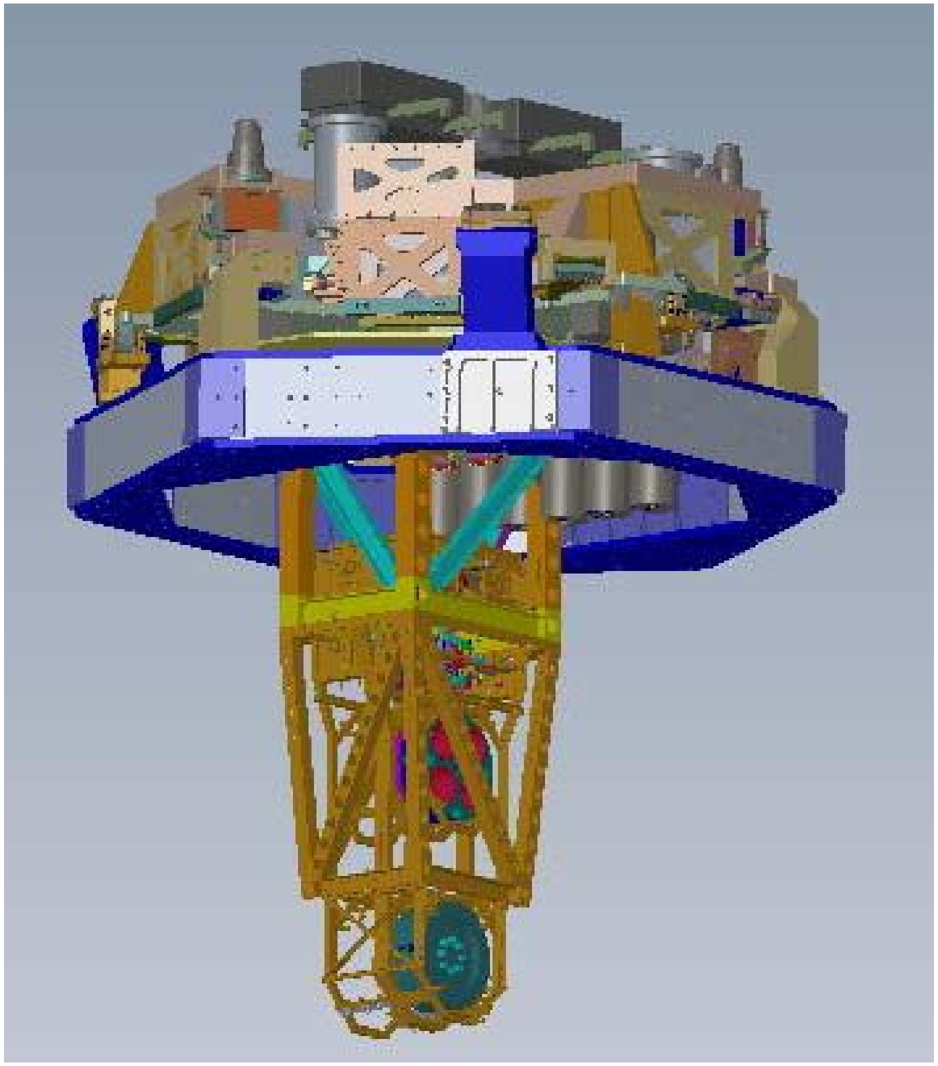




Isolates suspensions and other in-vacuum Equipment from ground motion; Accepts control signals

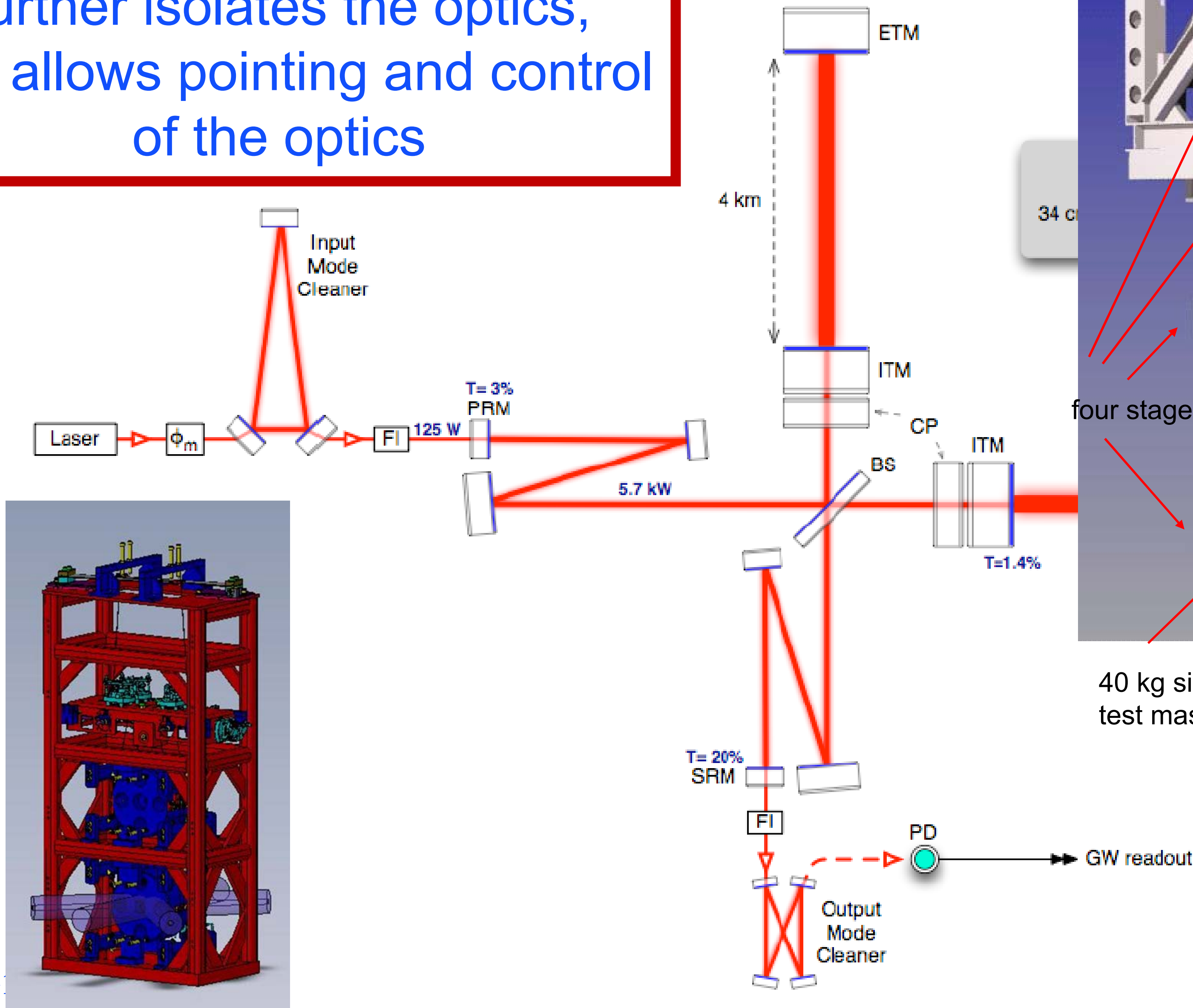


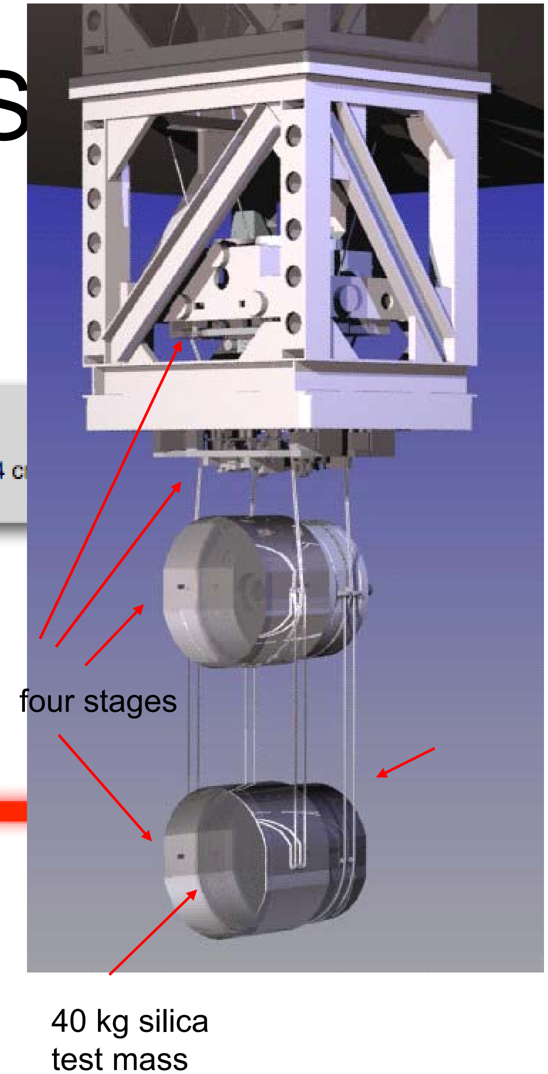
Quadruple Mirror Suspension



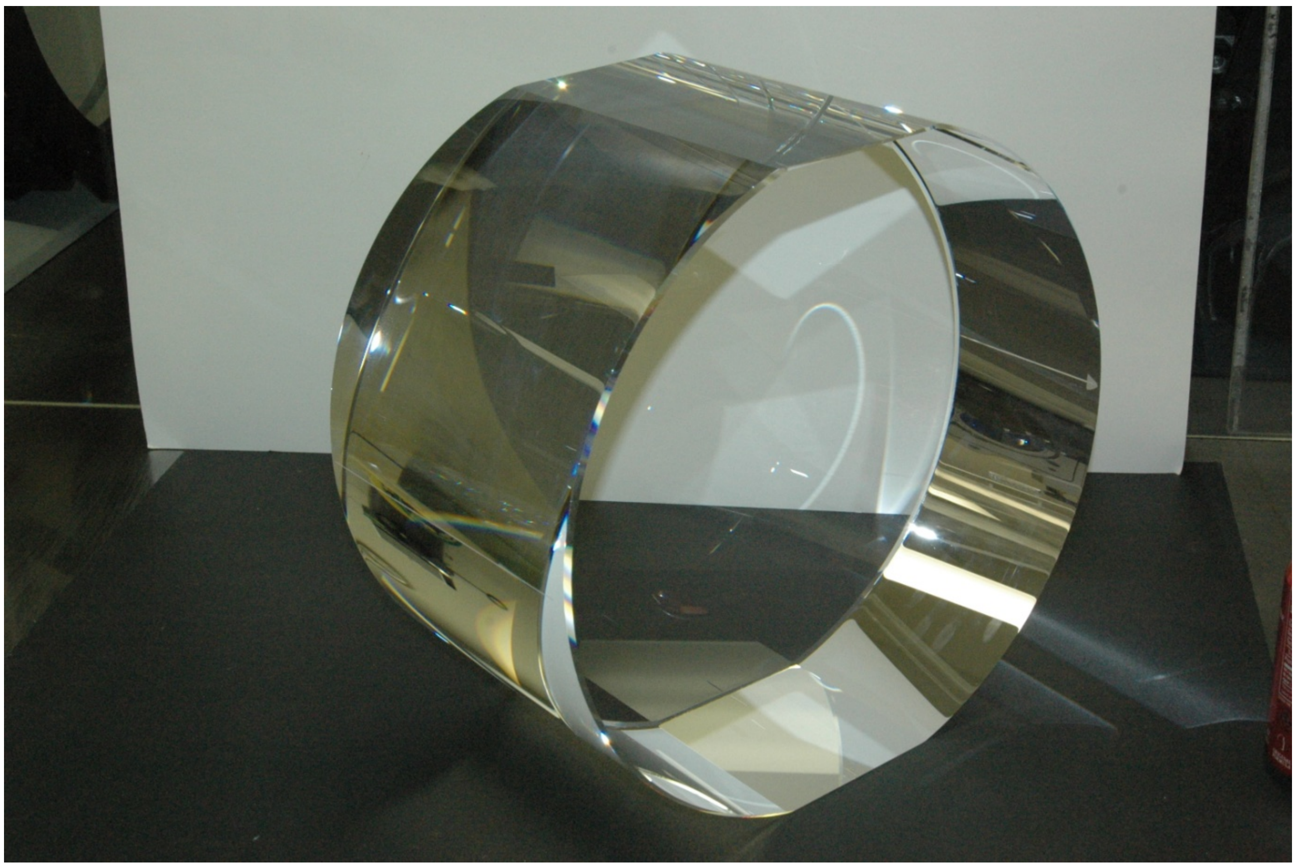
Suspensions (SUS

Further isolates the optics, and allows pointing and control of the optics





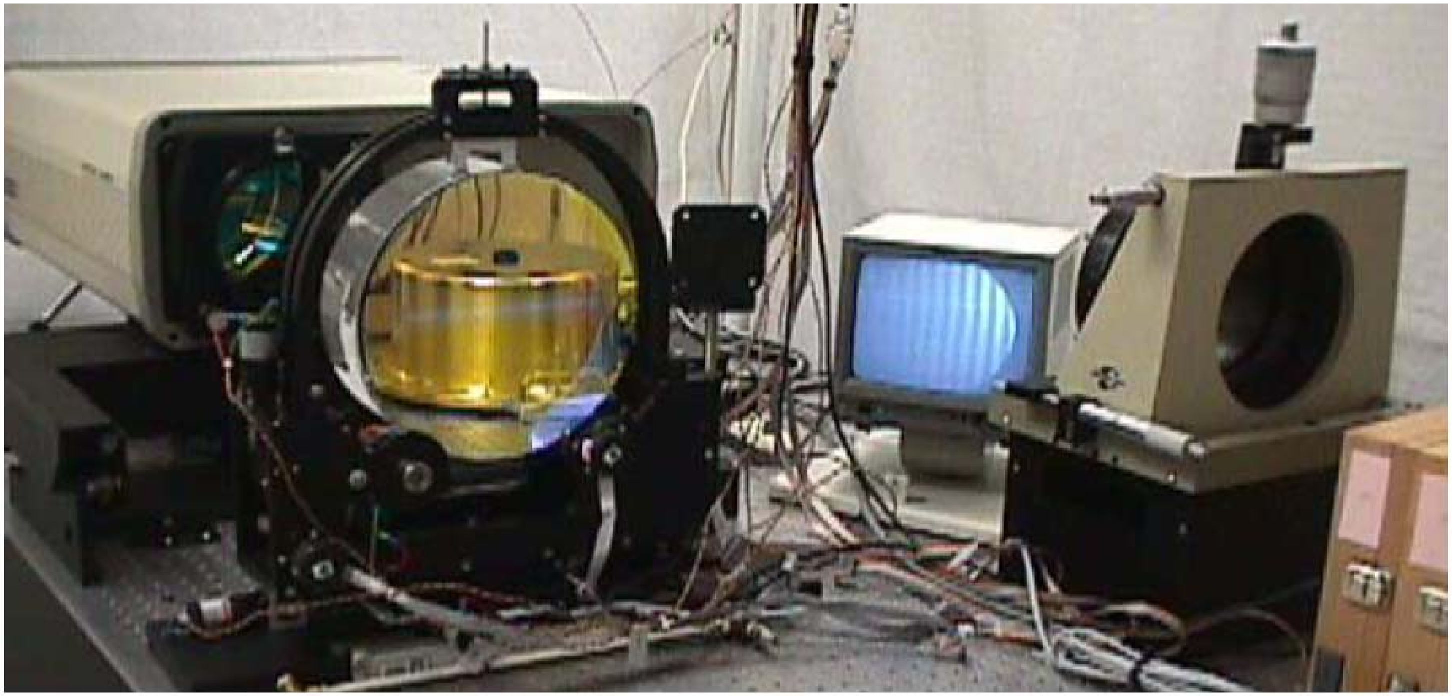
Super Polished Fused Silica Mirrors



Metrology of LIGO Optics using Fizeau Interferometry

σ_{rms} < 0.8 nm over the central 80 mm dia

Surface height repeatability	< 5 nm
Accuracy	< 10 nm

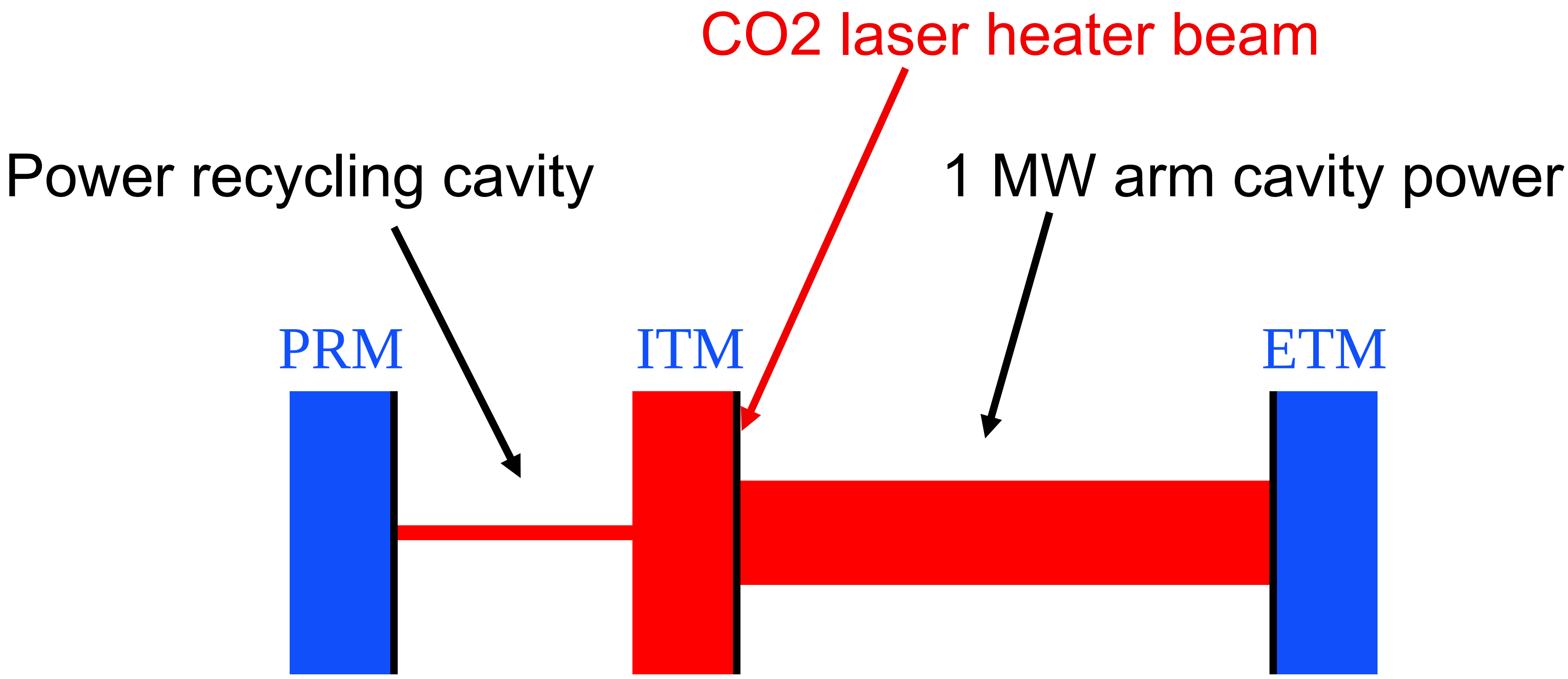


Low Noise Coatings

- Thermal Noise

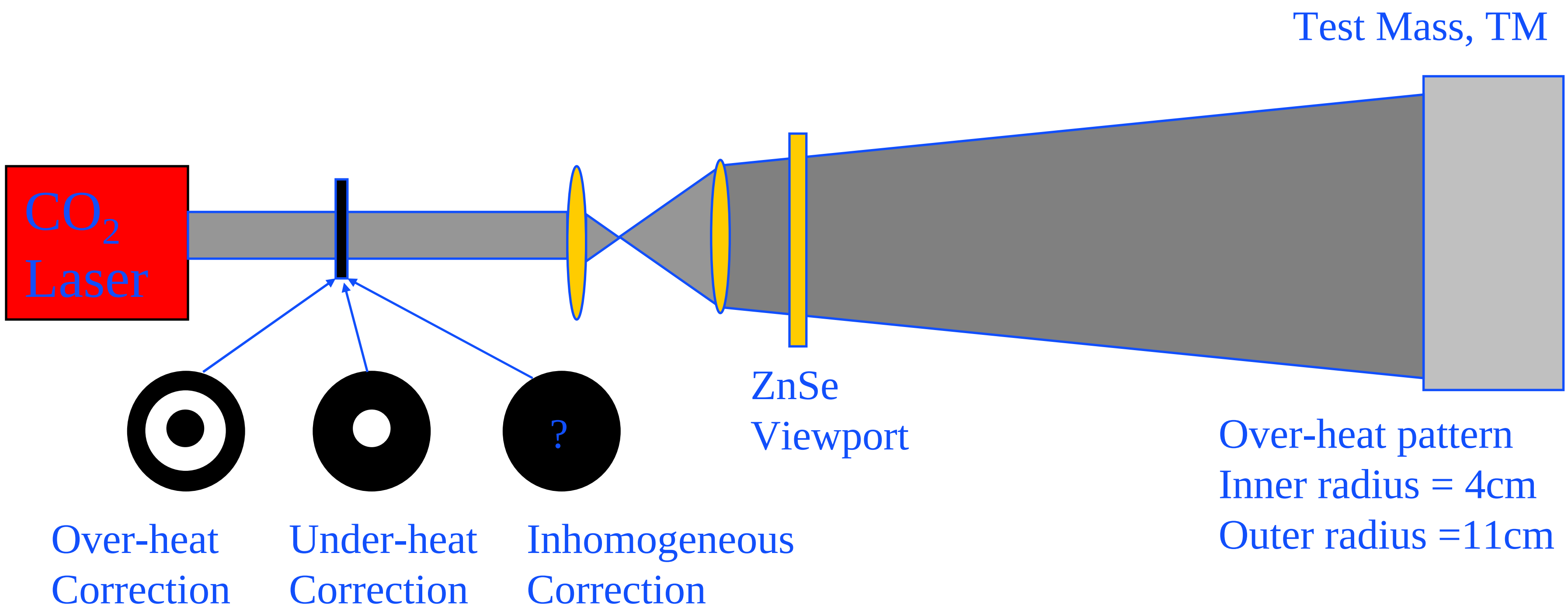
thermal fluctuations of a system (atomic motion in this case) results in energy losses for any forced motion *of* the system, or forced motion *through* the system. Turning this around, if there is more mechanical loss (lower Q, higher φ), there must be more statistical fluctuation from the thermally activated motion of atoms, resulting in displacement of the mirror surfaces, and therefore, more *noise*. “fluctuation-dissipation”

I Mega Watt Arm Power Distorts the Cavity Mirrors



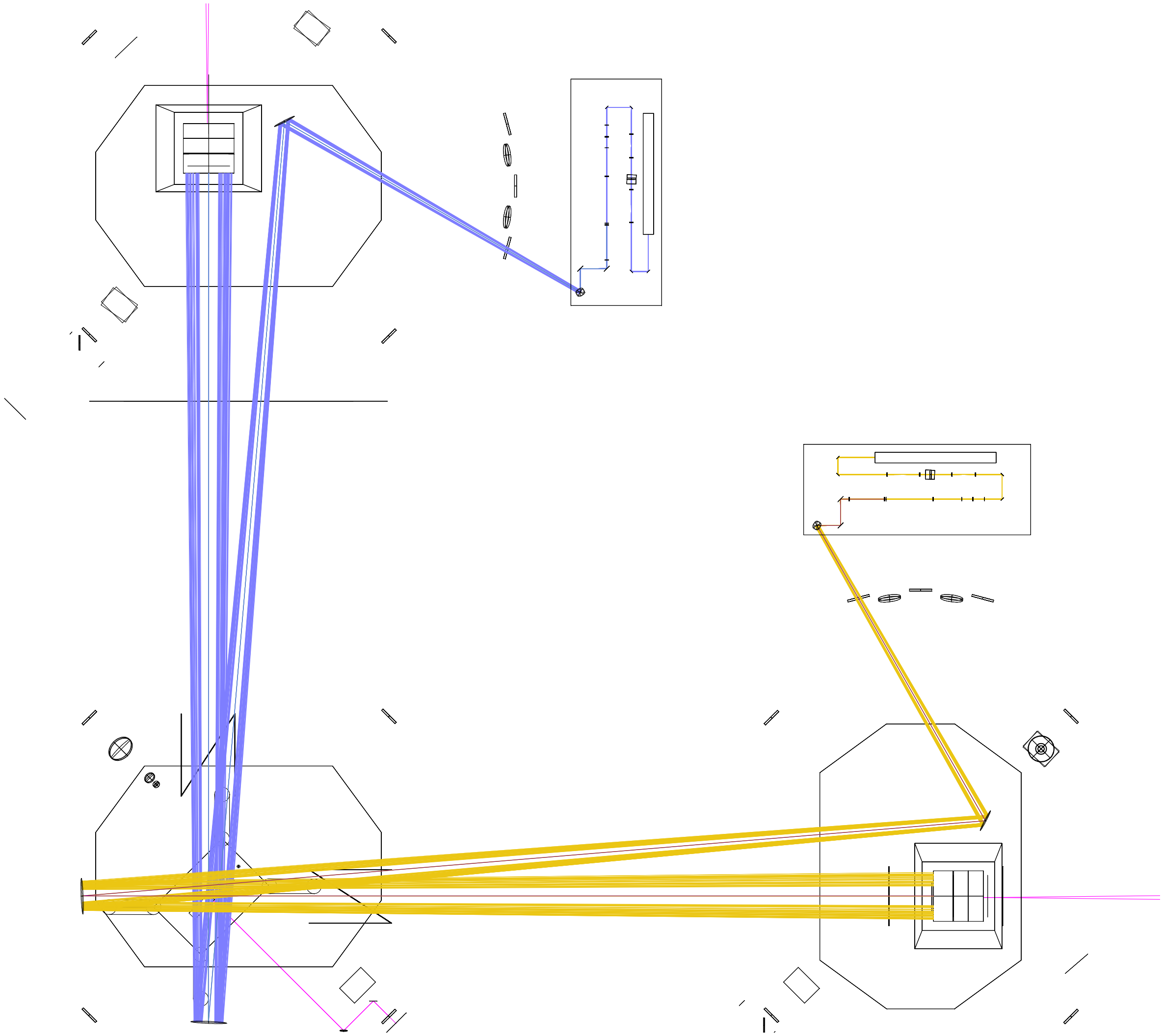
Add heat to erase the thermal gradient in the ITM, leaving a uniformly hot, flat temperature profile mirror. **Use ring heater around ITM and ETM to change radius of curvature**

LIGO CO_2 Laser Thermal Compensator

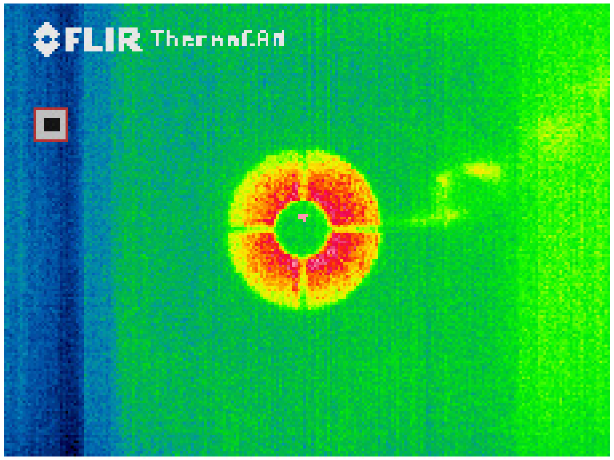


- Heating the TM limits the effect of diffraction spreading of cavity beam
- Modeling suggests a centering tolerance of 10 mm is required

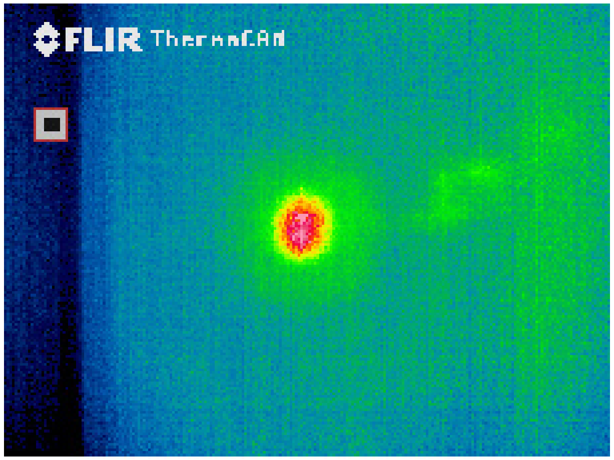
CO2 Laser Heater



Mirror Heating Patterns



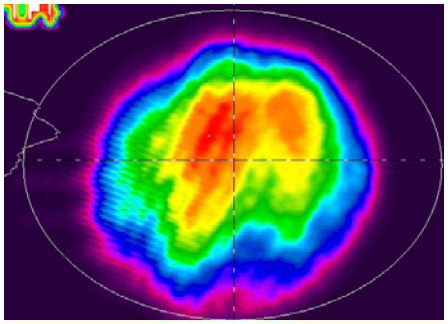
Annulus Mask



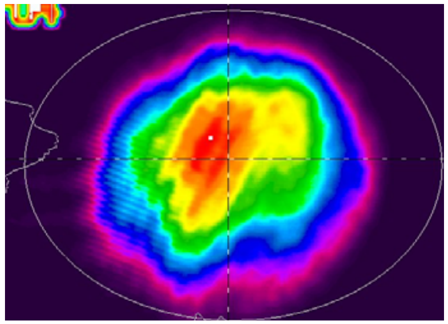
Central Heat Mask

- Annular and Central heating patterns used in Initial LIGO

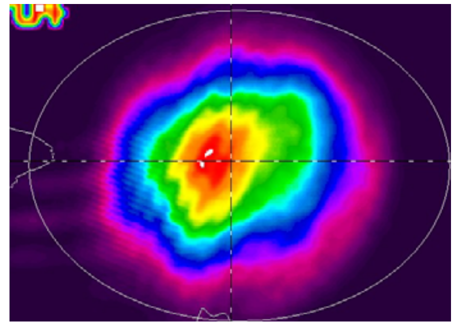
Heating ITM: Power-Recycled Michelson Heterodyne detection between PR beam and ARM beam



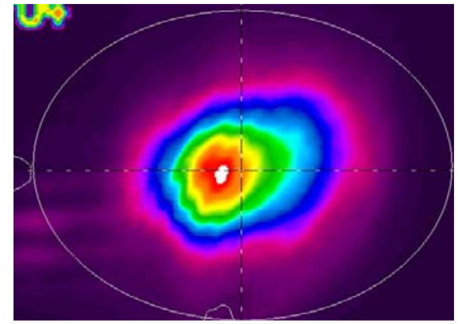
No Heating



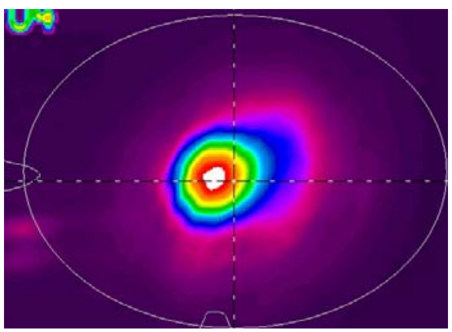
30 mW



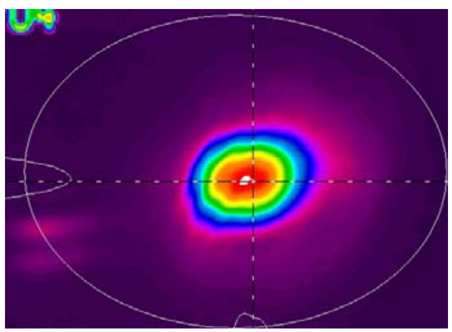
60 mW



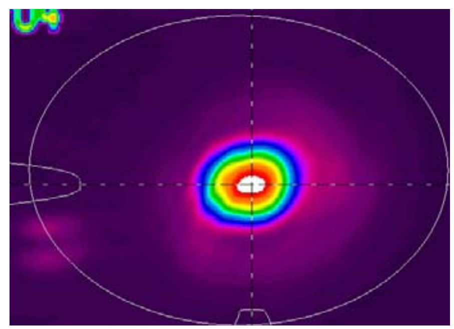
90 mW



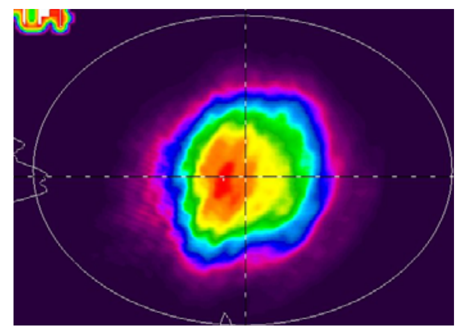
120 mW



150 mW



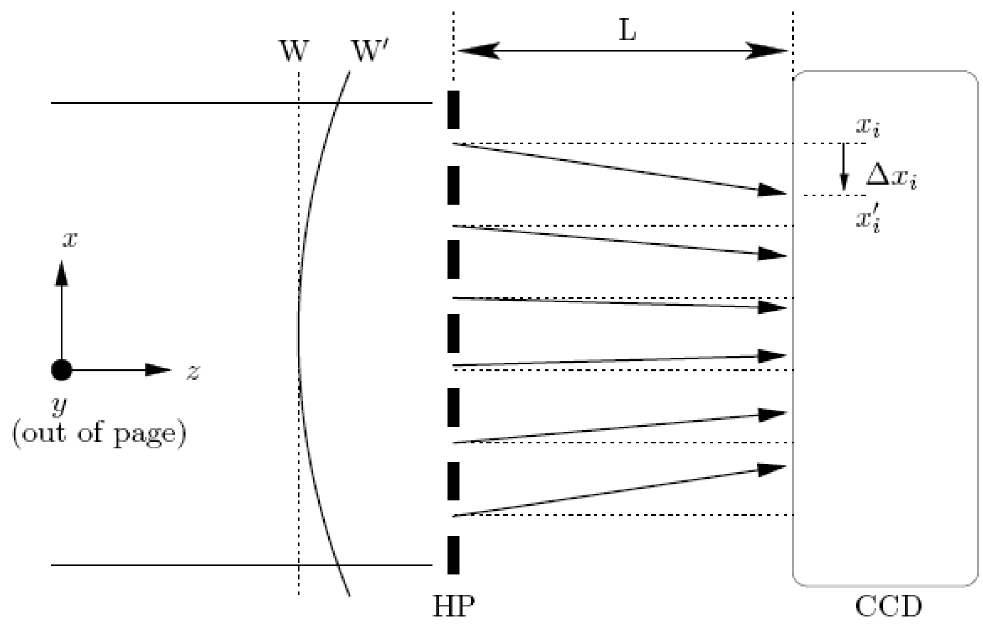
180 mW



Arm Carrier

Hartmann Sensor to Measure Wavefront Correction

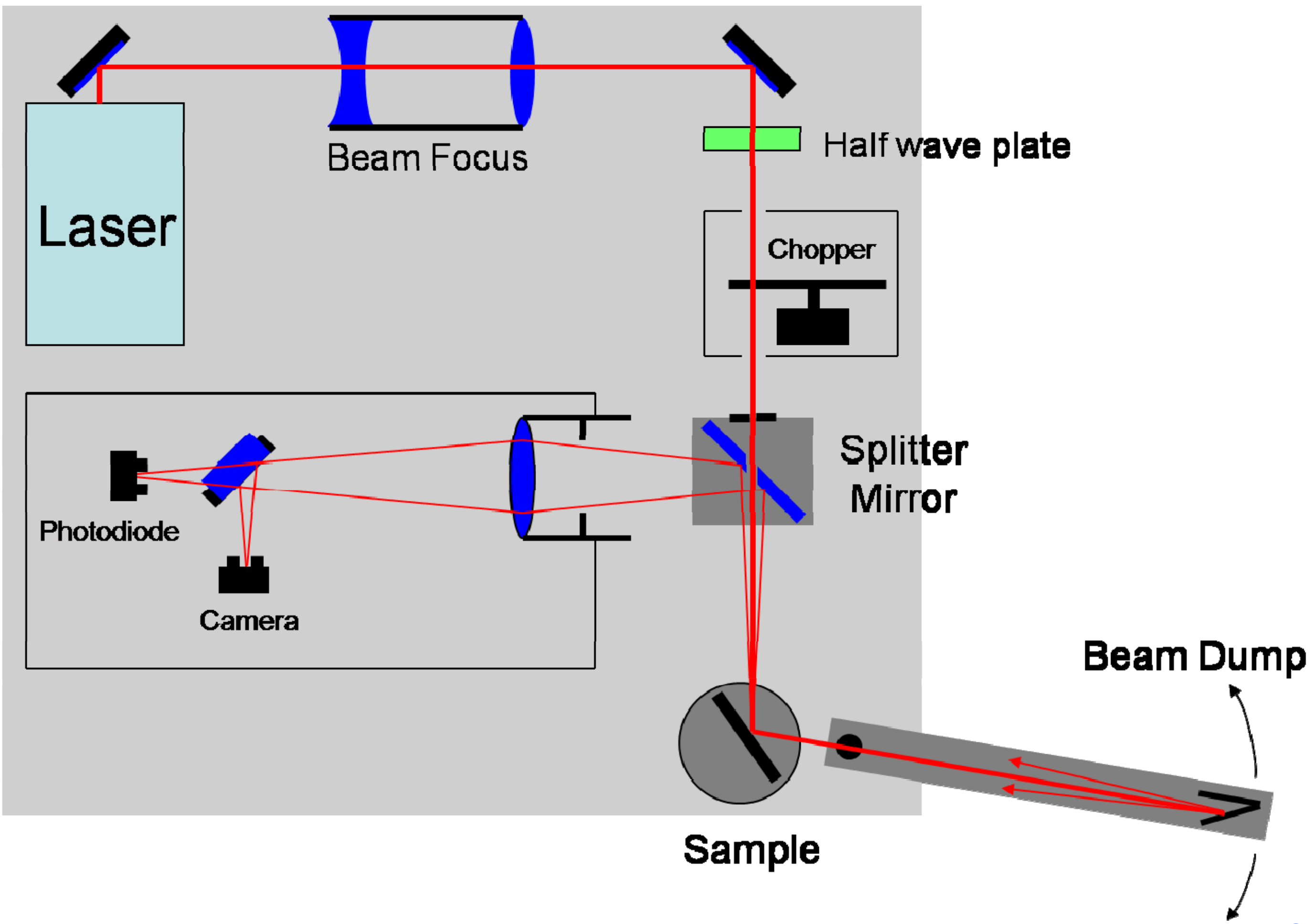
Hartmann sensor has a shot-to-shot reproducibility of λ/580 at 635 nm, which can be improved to λ/16000 precision with averaging, and with an overall accuracy of λ/6800.



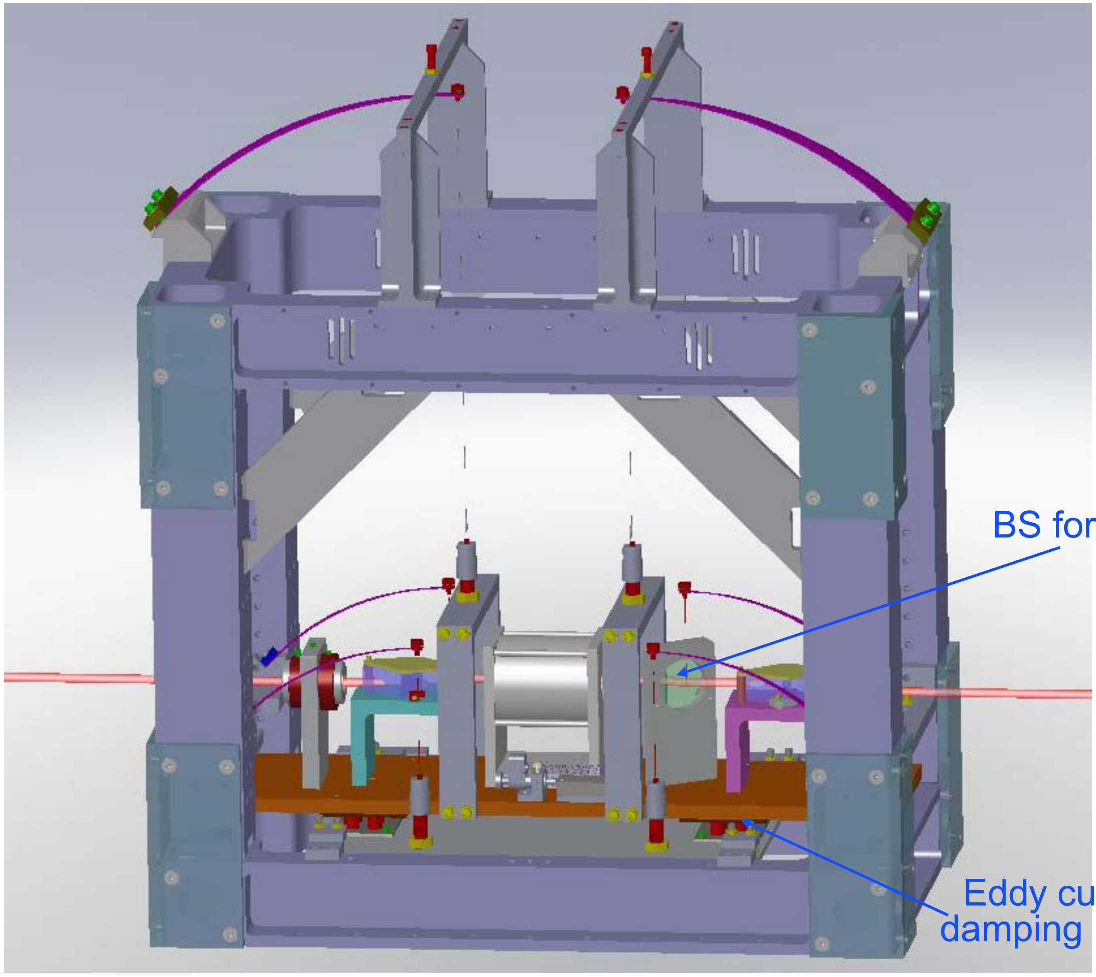
Scattered Light: Apparent Displacement Noise

- Min Gravity Wave Signal: $V_{signal} := DARM \cdot L \cdot h_{min} \cdot \sqrt{P_0}$
- Scattered Light:
  - Noise $V_{noise} := SNXXX \cdot \delta_{SN} \cdot \sqrt{P_{SNi}}$
  - Phase Shift due to motion of surface $\delta_{SNi} := \frac{4 \cdot \pi \cdot x_s}{\lambda}$
- Requirement: $SNXXX \cdot \delta_{SN} \cdot \sqrt{P_{SNi}} < \frac{1}{10} \cdot DARM \cdot L \cdot h_{min.} \cdot \sqrt{P_0}$
- Scattered Light Power: $P_{SNi} := P_{in} \cdot BRDF \cdot \Delta\Omega \cdot \frac{w_{IFO}^2}{w_{SN}^2} \cdot T$

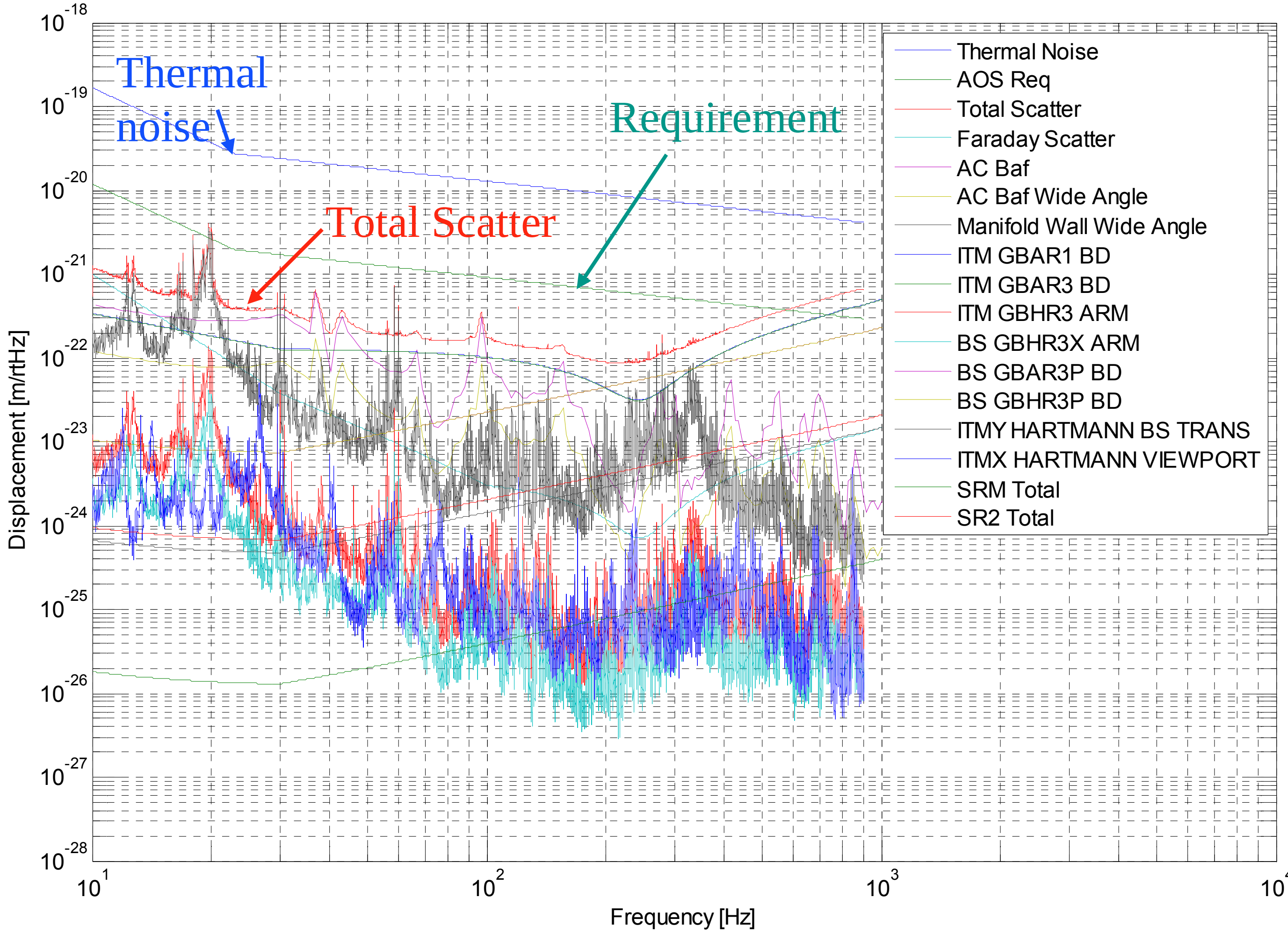
Measuring BRDF

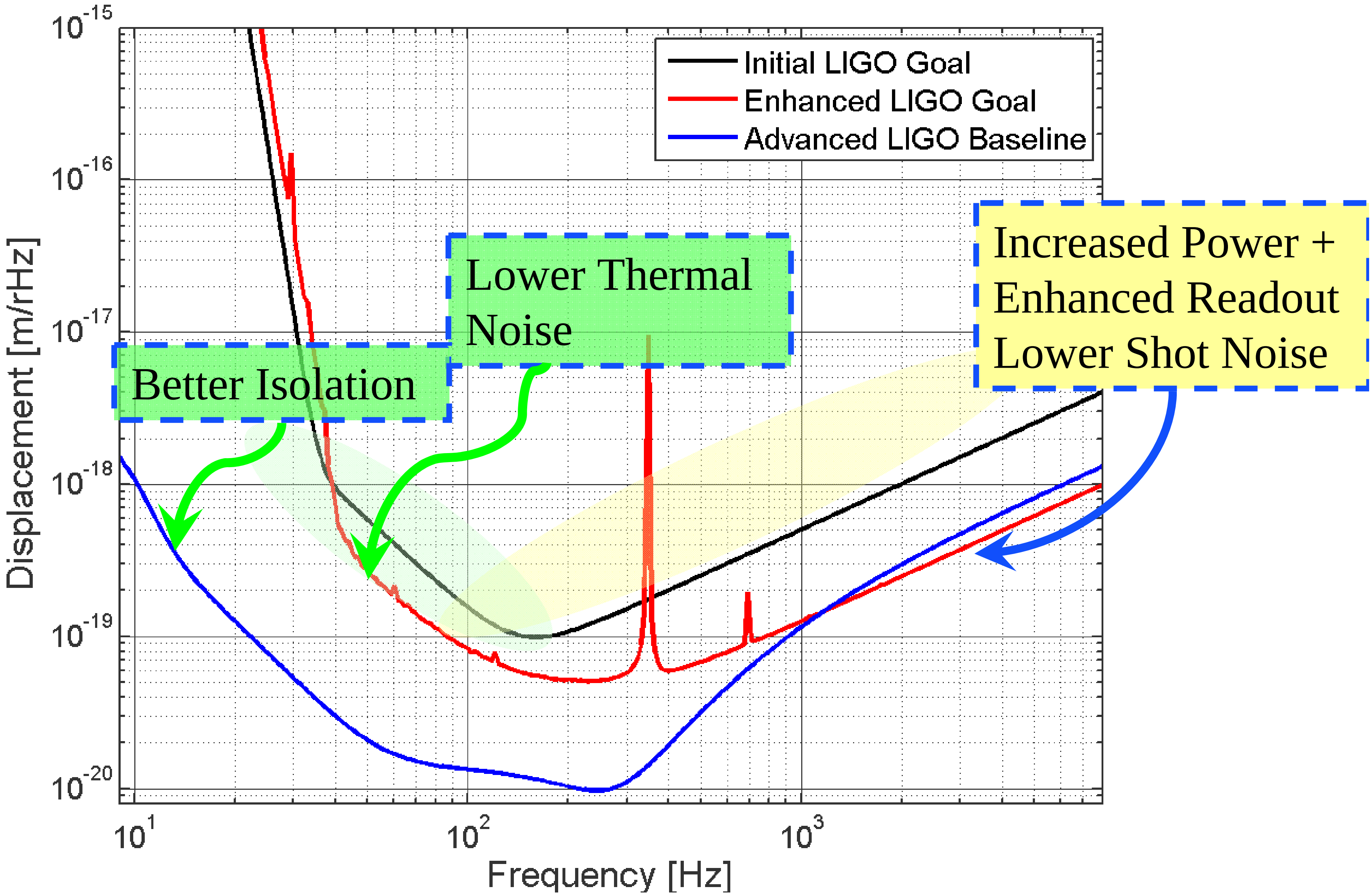


Scattered Light Control
Suspended Output Faraday Isolator



Putting It All Together
Scattered Light Meets Requirement!!

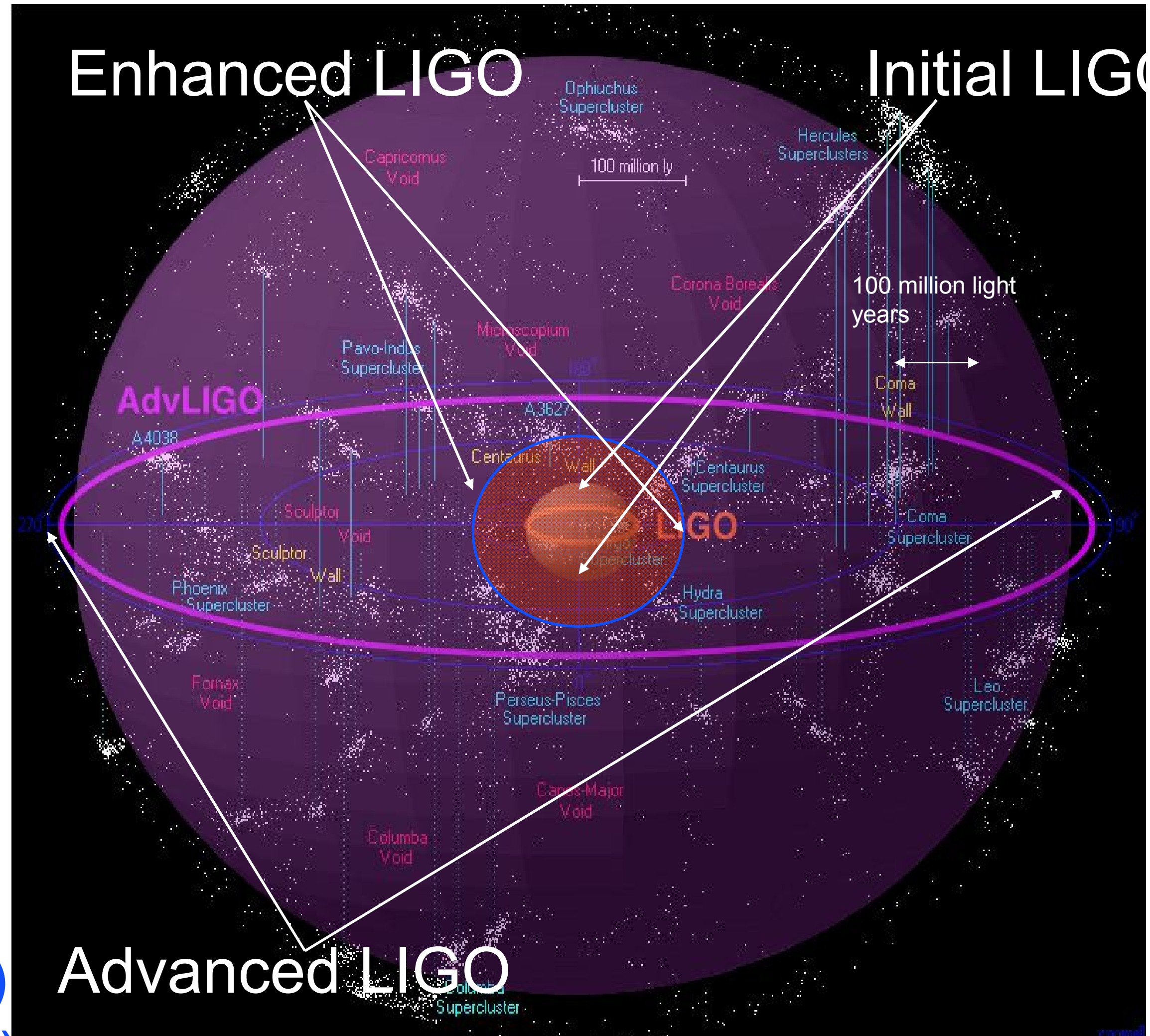




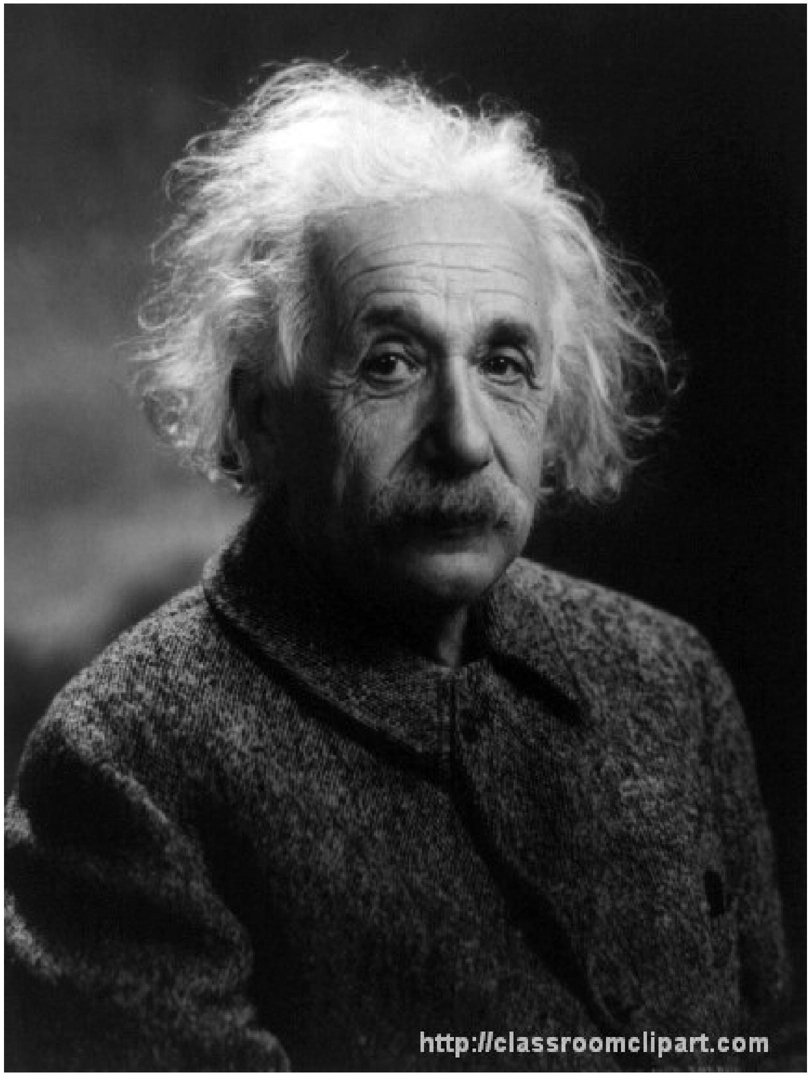
Initial LIGO Goal
Enhanced LIGO Goal
Advanced LIGO Baseline
Better Isolation
Lower Thermal Noise
Increased Power + Enhanced Readout Lower Shot Noise
Displacement [m/rHz]
Frequency [Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}

Advanced LIGO

- Factor 10 improvement in sensitivity
- Better low frequency response
- Reach 1000 times more sources
- Signal predictions from ~1 per 10 years (iLIGO) to **~1 per week** (aLIGO)



Is He Right?



Acknowledgement

- United States National Science Foundation
- Contributions by LIGO-VIRGO Collaboration