Laser Interferometers for Gravitational-Wave Detection

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31 May 2012

LIGO-G1200580

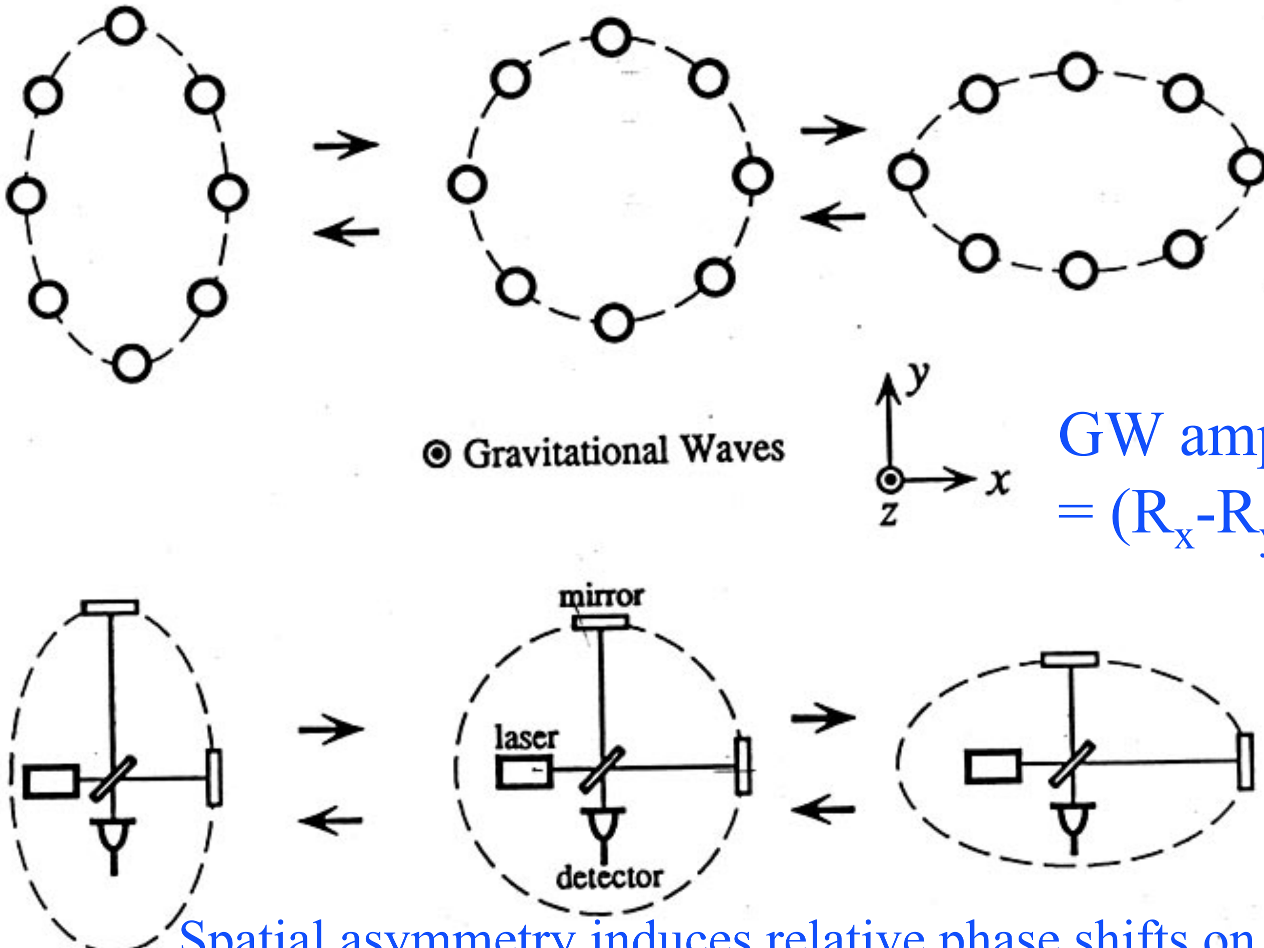
Outline

- Basic idea
- Some numbers
- What do generic detectors look like and how do they work?
- Kilometer-scale terrestrial detectors:
  » First generation: Initial LIGO detectors and the worldwide network
  » Second generation: Advanced LIGO
  » R&D toward enhanced and third generation detectors

References

- Rep. Prog. Phys. 72 (2009) 076901 (arXiv:0711.3041) - LIGO: The Laser Interferometer Gravitational-Wave Observatory
- Nucl. Instrum. Meth. A624 (2010) 223 (arXiv:1007.397 - Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run

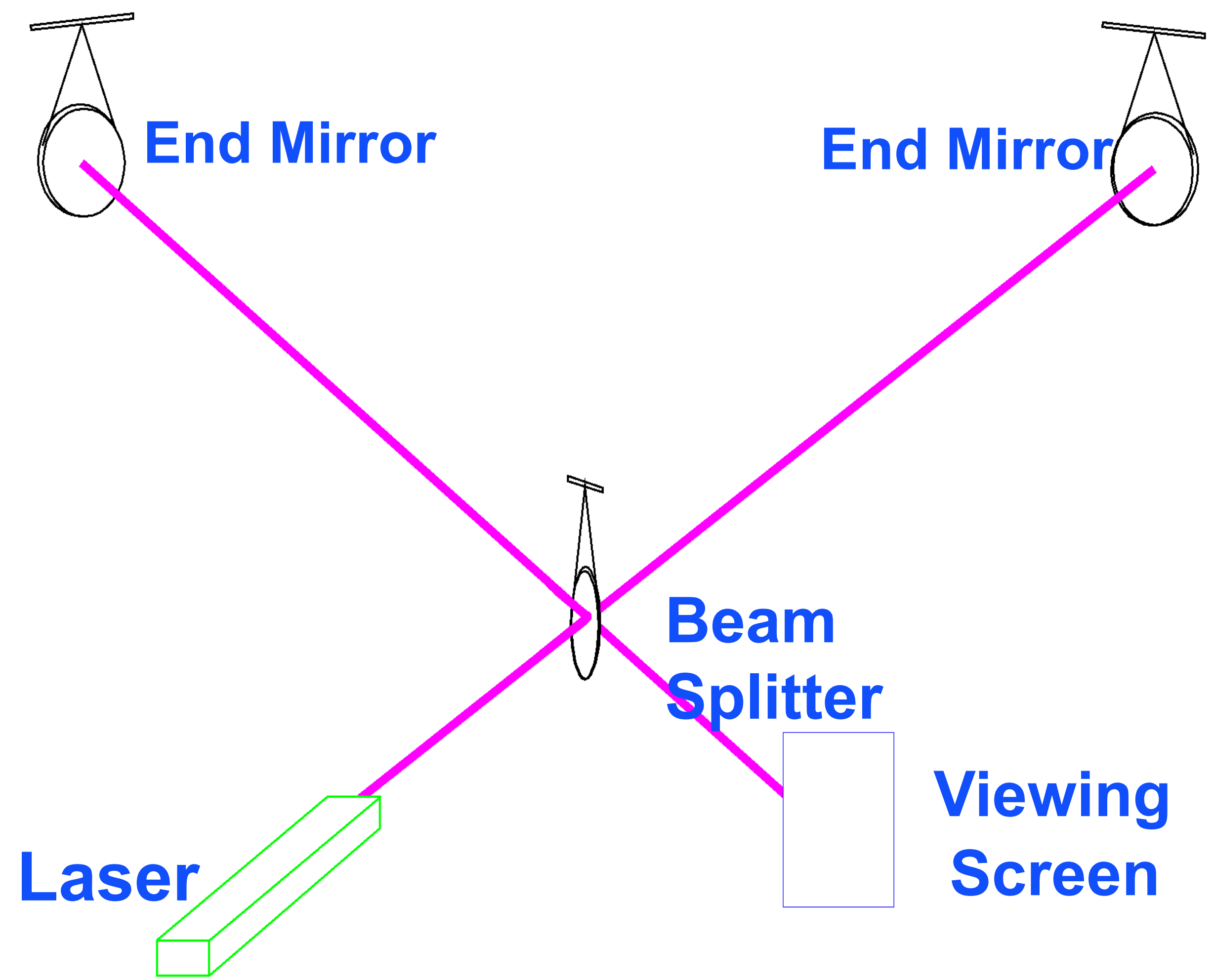
Basic idea for a laser interferometer GW detector



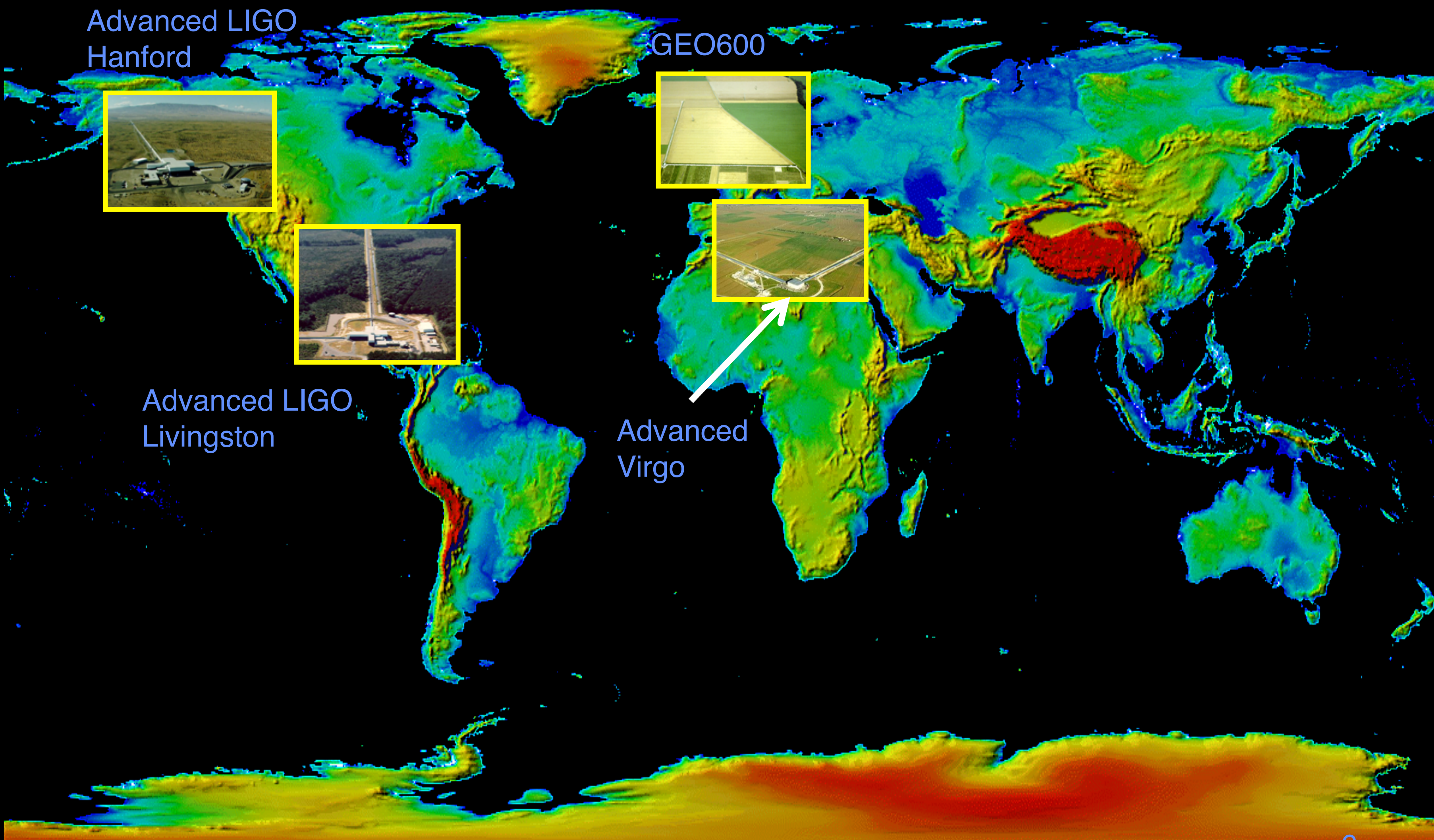
GW amplitude h $= (R_x - R_y)/R$

Spatial asymmetry induces relative phase shifts on light in arms

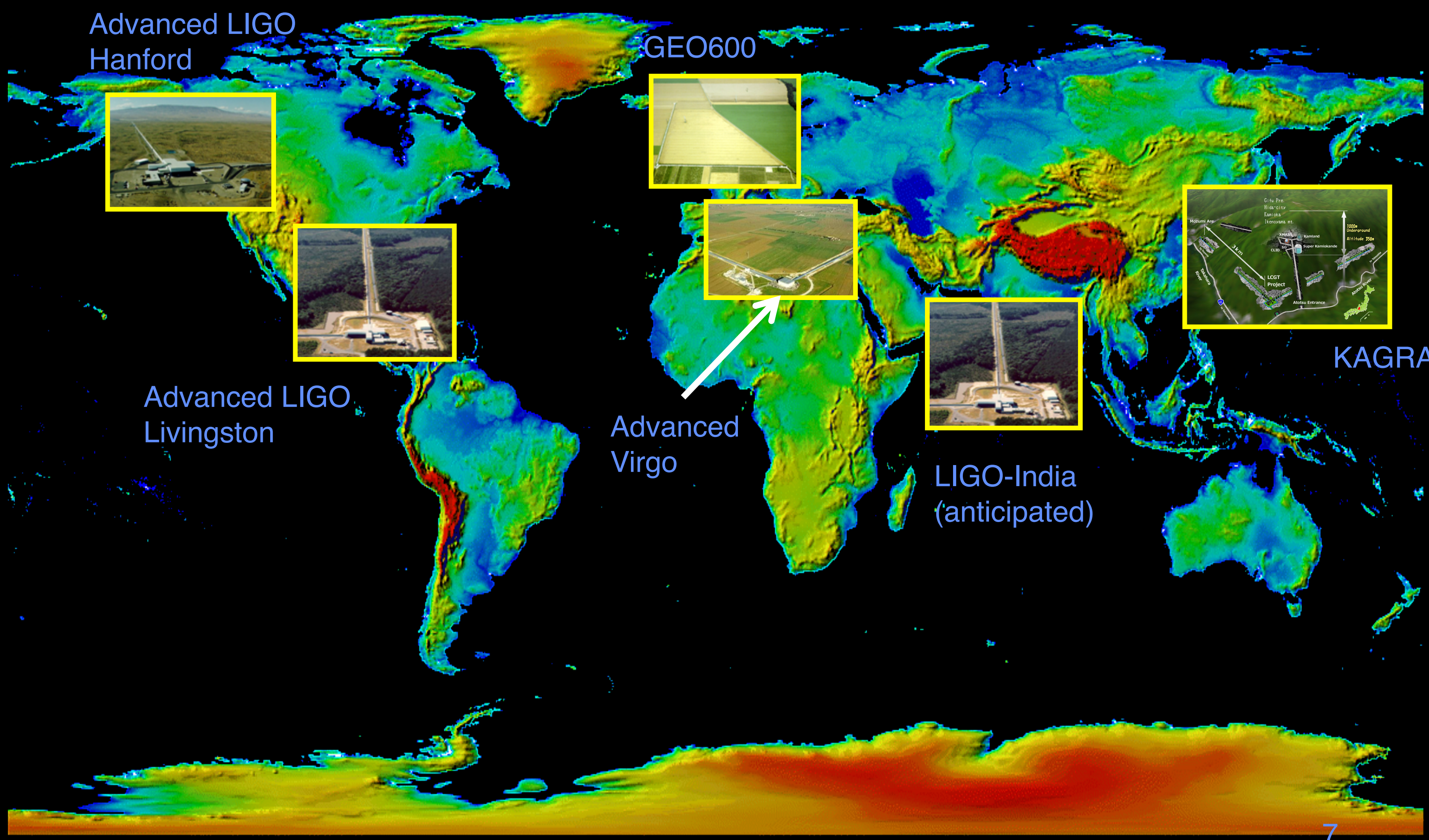
Terrestrial interferometers need to counter Earth's gravity



The Advanced Ground-based GW Detector Network in 2015



The Advanced Ground-based GW Detector Network in 2020



Issues to address in 1989 proposal to build a gravitational wave detector

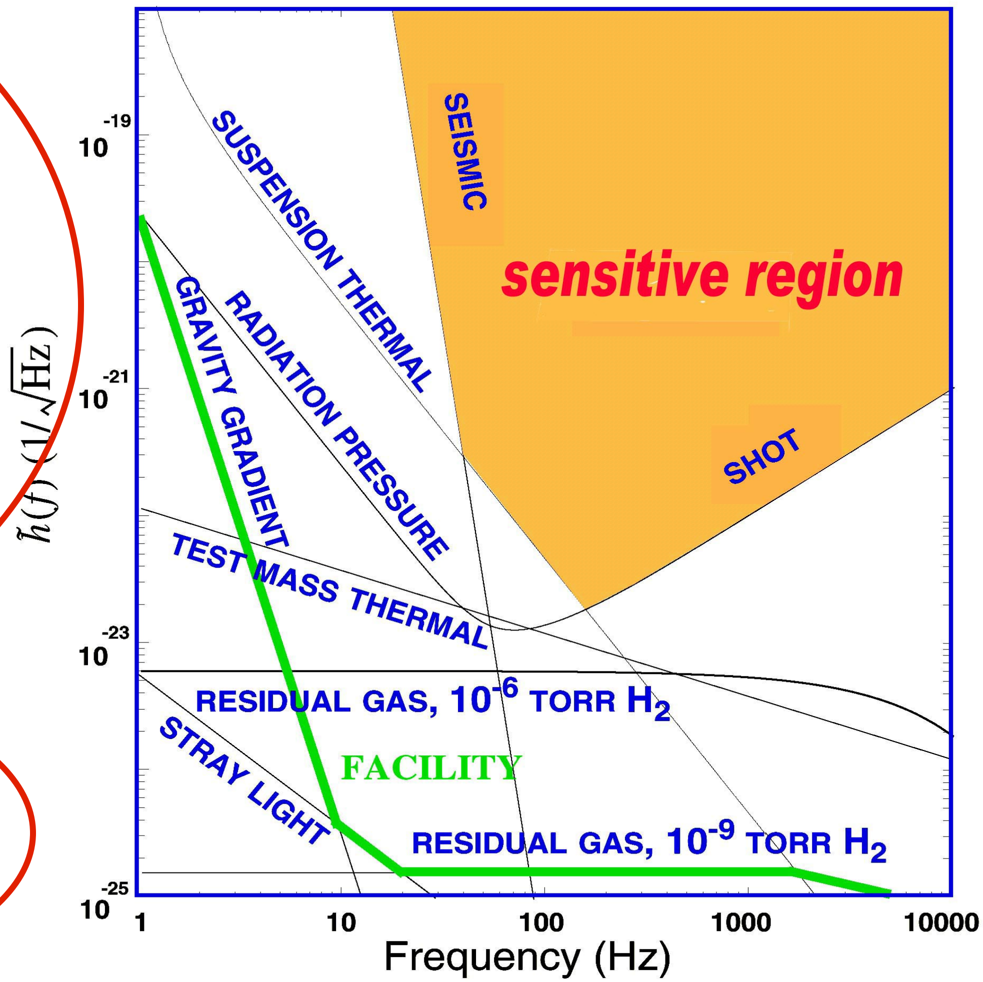
- Signal has never been detected directly; source strengths or source populations range from “not well” to “poorly” known
- Simple arguments indicate the need to cover a space-time volume from billions to a trillion times larger than previous detector searches
- Need to scale up size 100-fold from largest existing devices and push frontier of measurement science, but no law of physics prevents it
- In 1989, current or close-to-hand technology not sufficiently sensitive to guarantee detections
- Very expensive: failure is not a viable option
- Strategy: build initial generation of km-scale detectors (iLIGO and Virgo) to serve as pathfinders and conduct searches, while pushing R&D toward advanced detectors (Advanced LIGO & Advanced Virgo) capable of routine detections

What Limits Sensitivity of Interferometers?

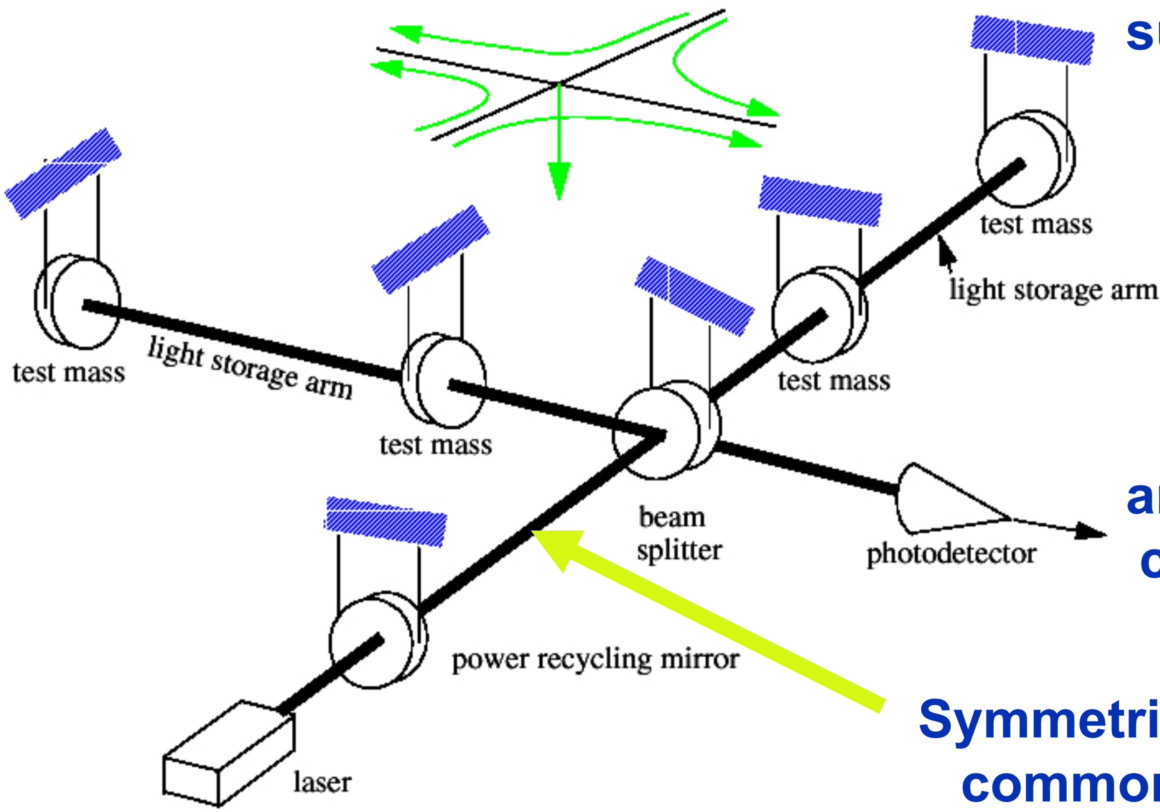
DESIGN

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

COMMISSIONING



Initial LIGO: Power-recycled Fabry-Perot-Michelson



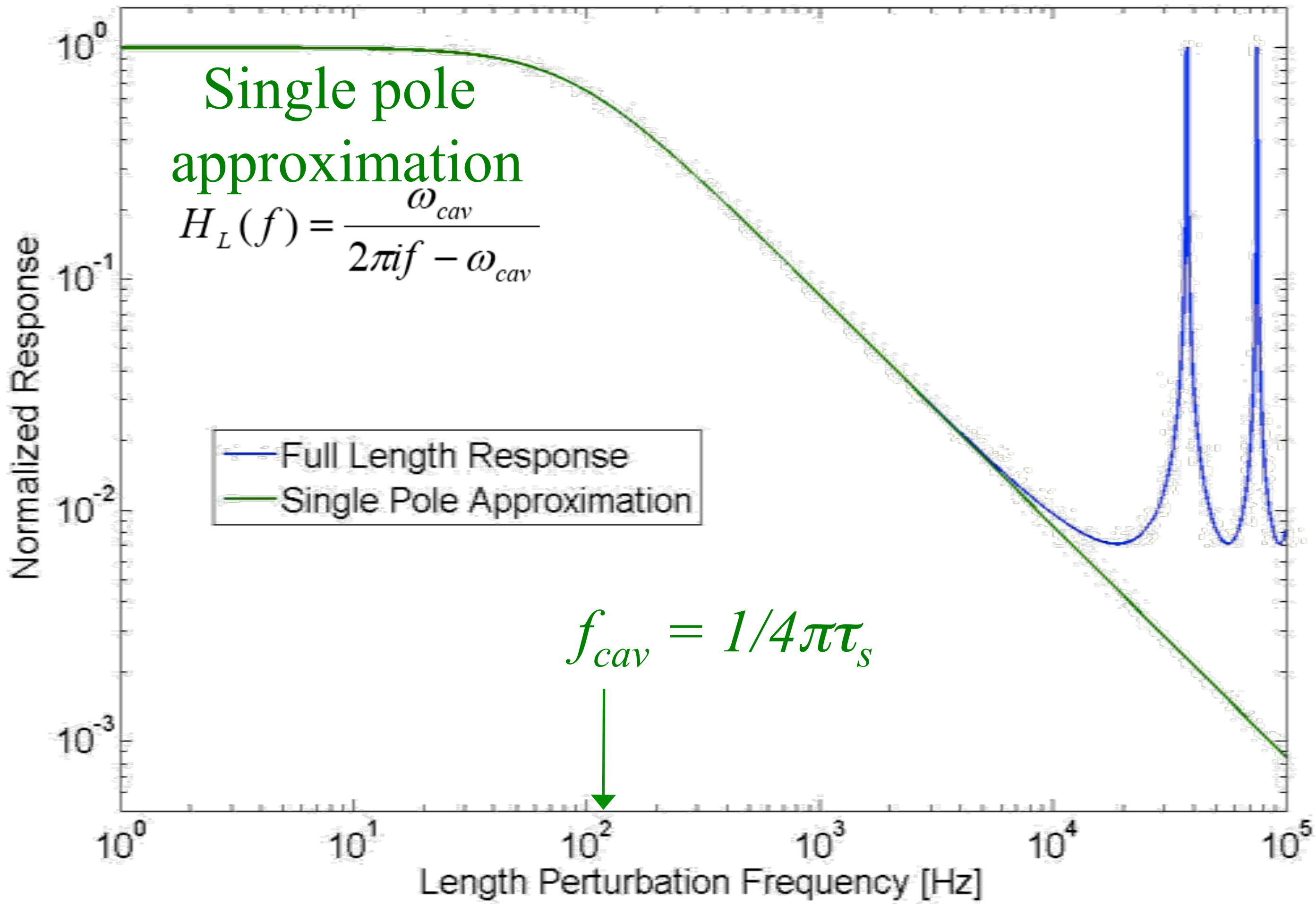
suspended mirrors mark inertial frames

antisymmetric port carries GW signal

Symmetric port carries common-mode info

Intrinsically broad band and size-limited by speed of light.

Sensing as a function of frequency



Initial or 1st-Generation Detectors

Some of the technical challenges for initial detector design and commissioning

- ✓ Typical Strains < 10^{-21} at Earth ~ a hair's width over 4 light years
- ✓ Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- ✓ Control km-scale arm lengths to 10^{-13} meters RMS
- ✓ Detect optical phase changes of ~ 10^{-10} radians
- ✓ Hold mirror alignments to 10^{-8} radians
- ✓ Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- Do all of the above 7x24x365

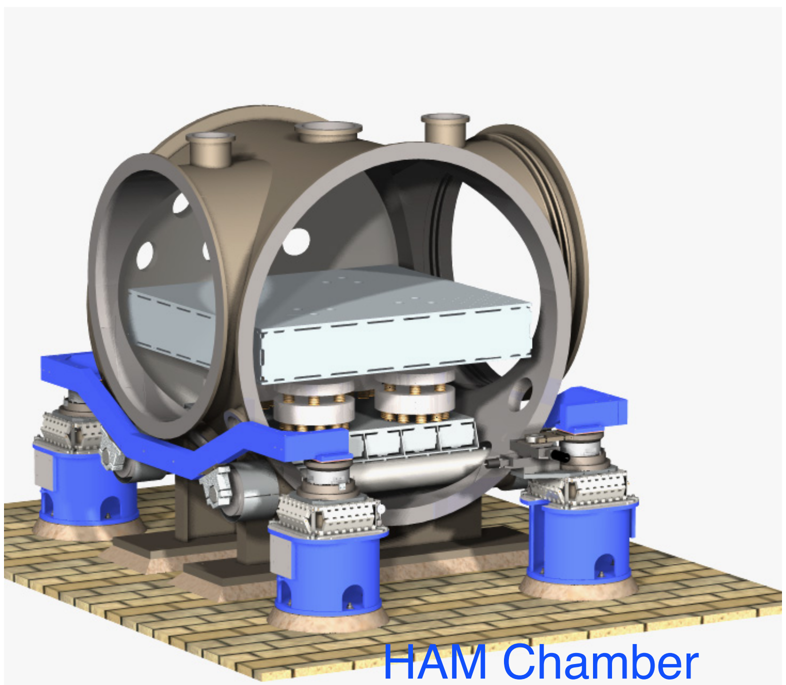
✓ LIGO S5 science run 14Nov05 to 30Sep07
VSR1 science run 18May07 to 30Sep07

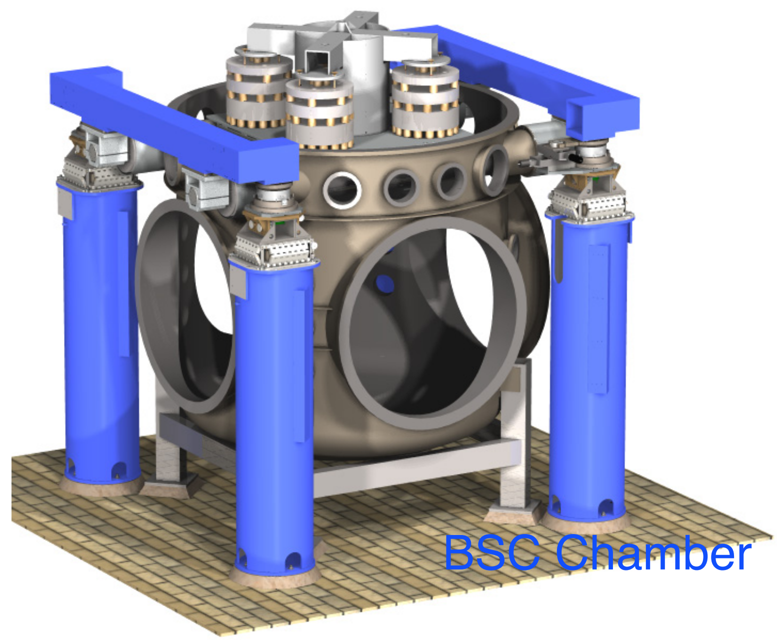
Seismic Isolation

- Strategy is to use cascades of passive springs, pendula, and active controls to approximate a “brick-wall” mechanical filter
- There is some effective frequency, f_{low}, below which seismic and other vibrations will dominate and above which external vibrations have little or no effect
  - » ~ 40 Hz for iLIGO; ~10 Hz for Virgo
  - » ~ 10 Hz for Advanced LIGO and Virgo
- Below f_{low} a control system must actively “zig” the mirrors just enough to cancel any “zag” of the lab, so the mirror remains motionless in space
- Strength of controls is limited to prevent injection of electronic noise above f_{low}
- Saturation of the control signal will occur above some threshold level of external vibration

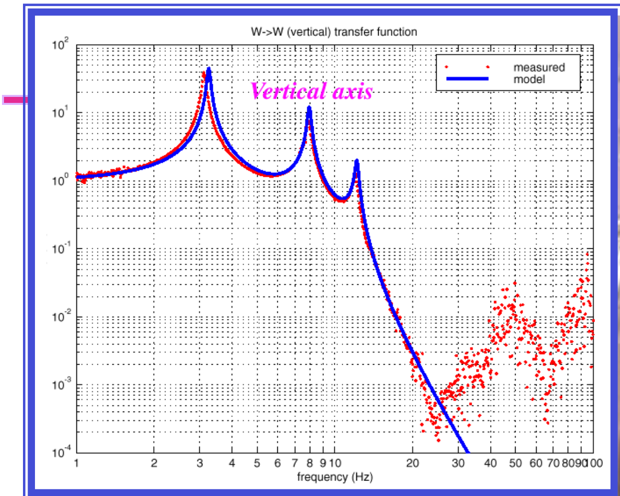
Initial LIGO Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Little or no attenuation below 10Hz
» Large range actuation for initial alignment and drift compensation
» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

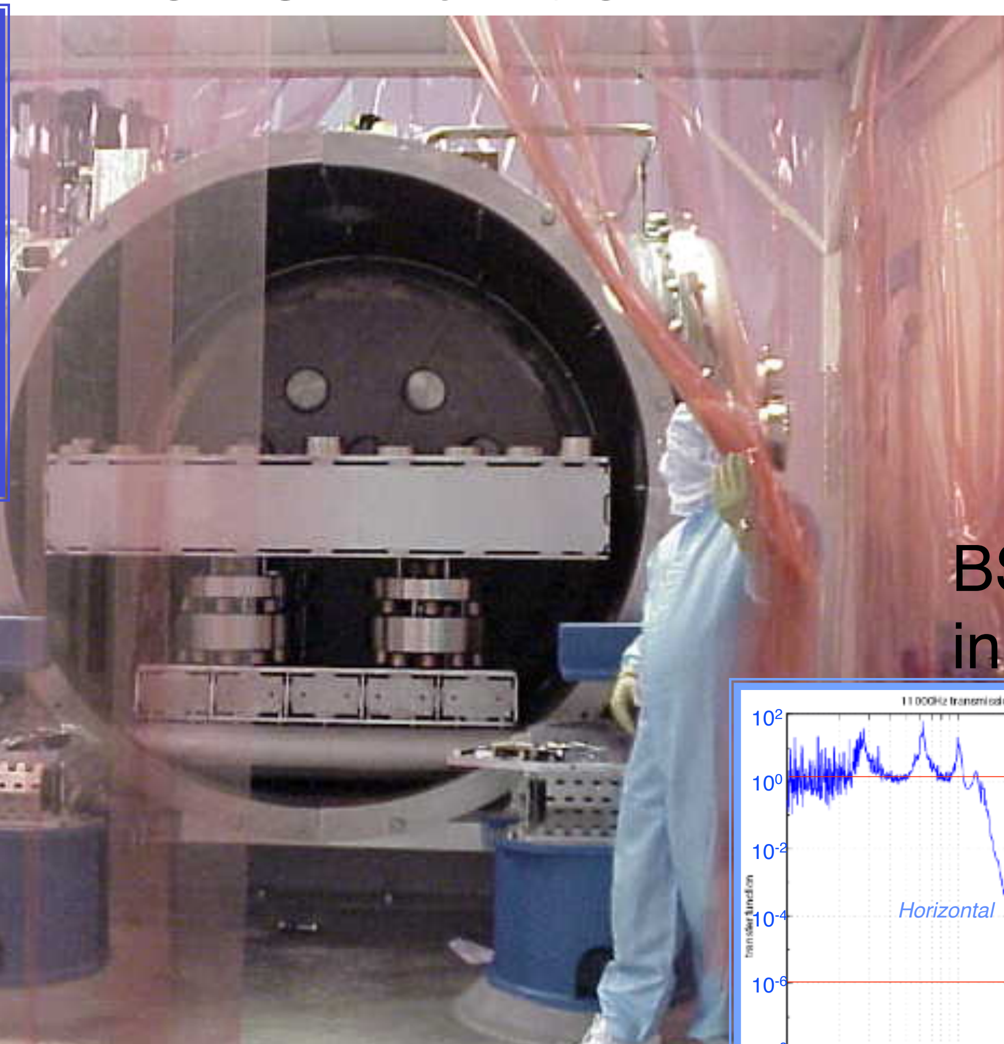




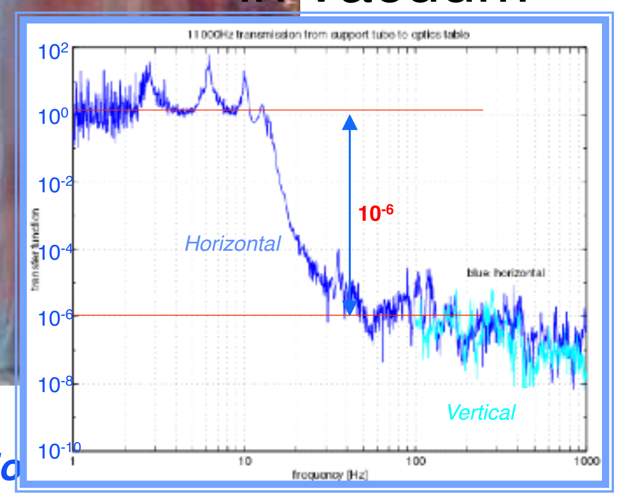
Seismic System Performance



HAM stack in air

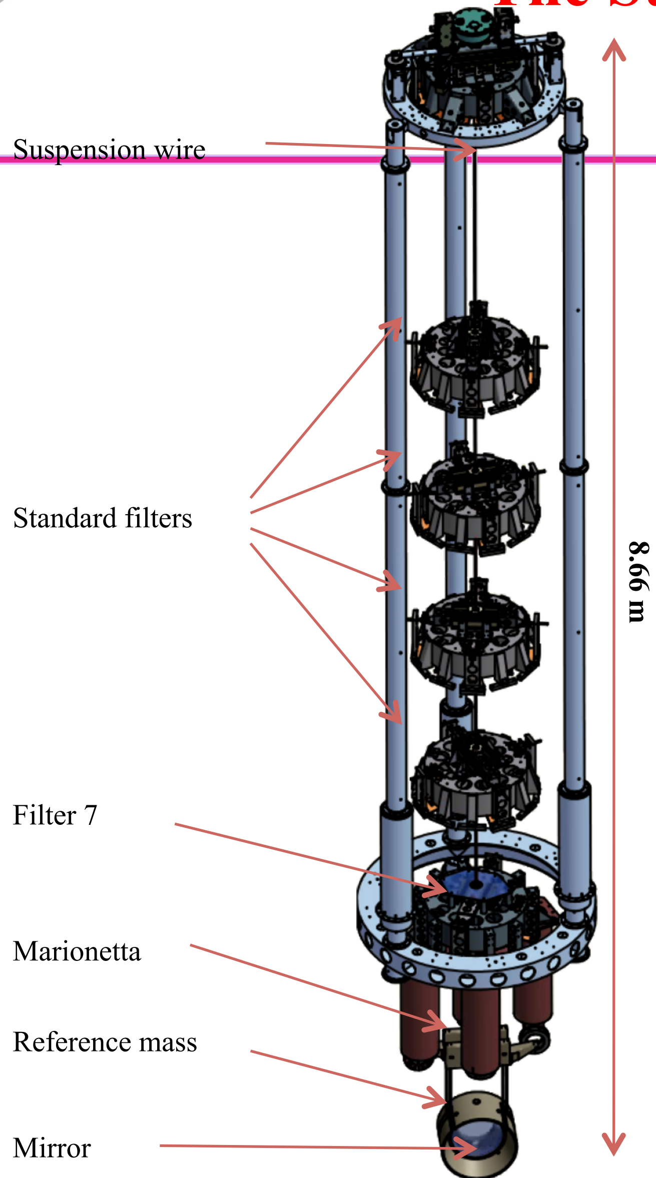


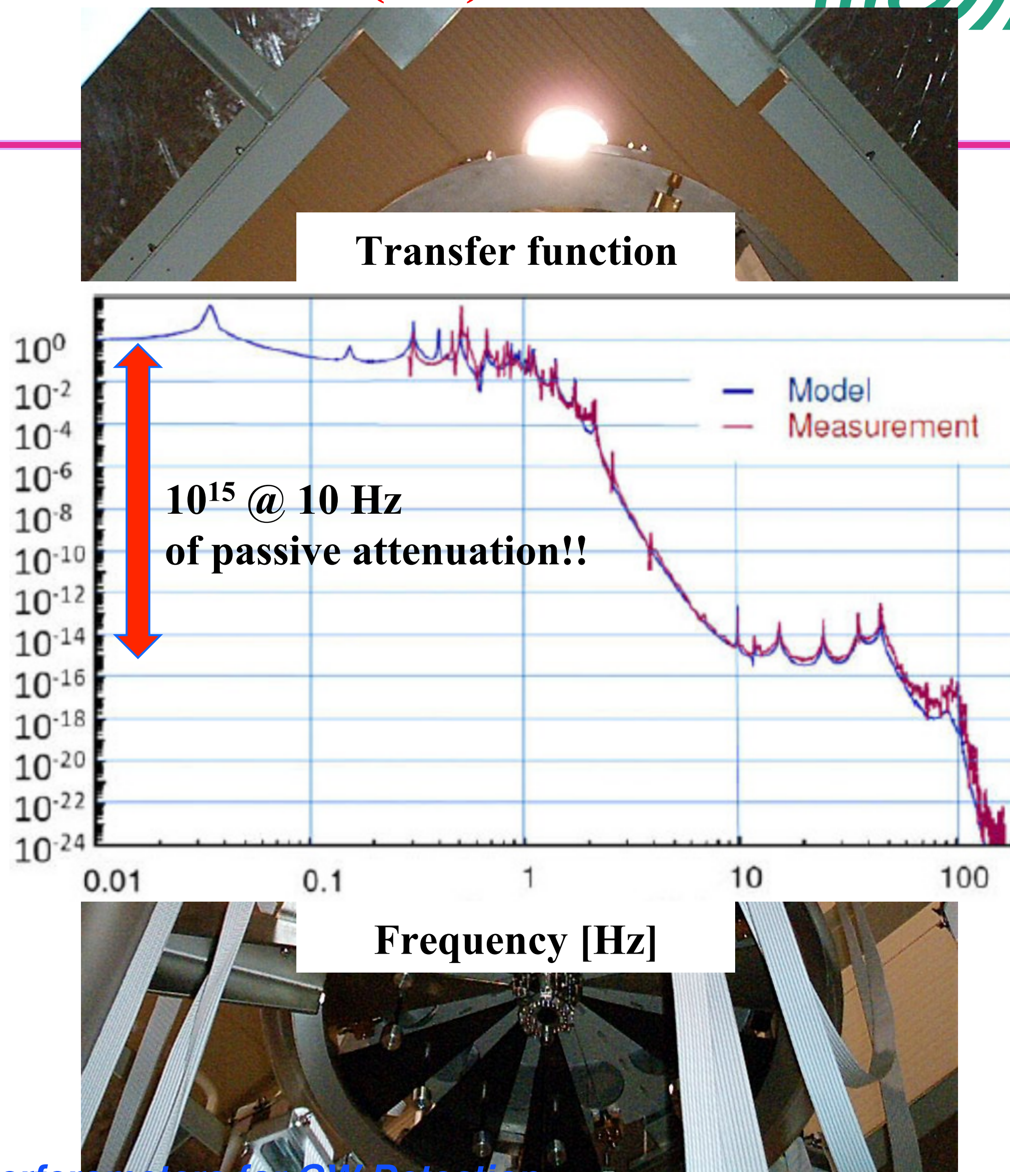
BSC stack in vacuum



VIRGO

The Superattenuator (SA)

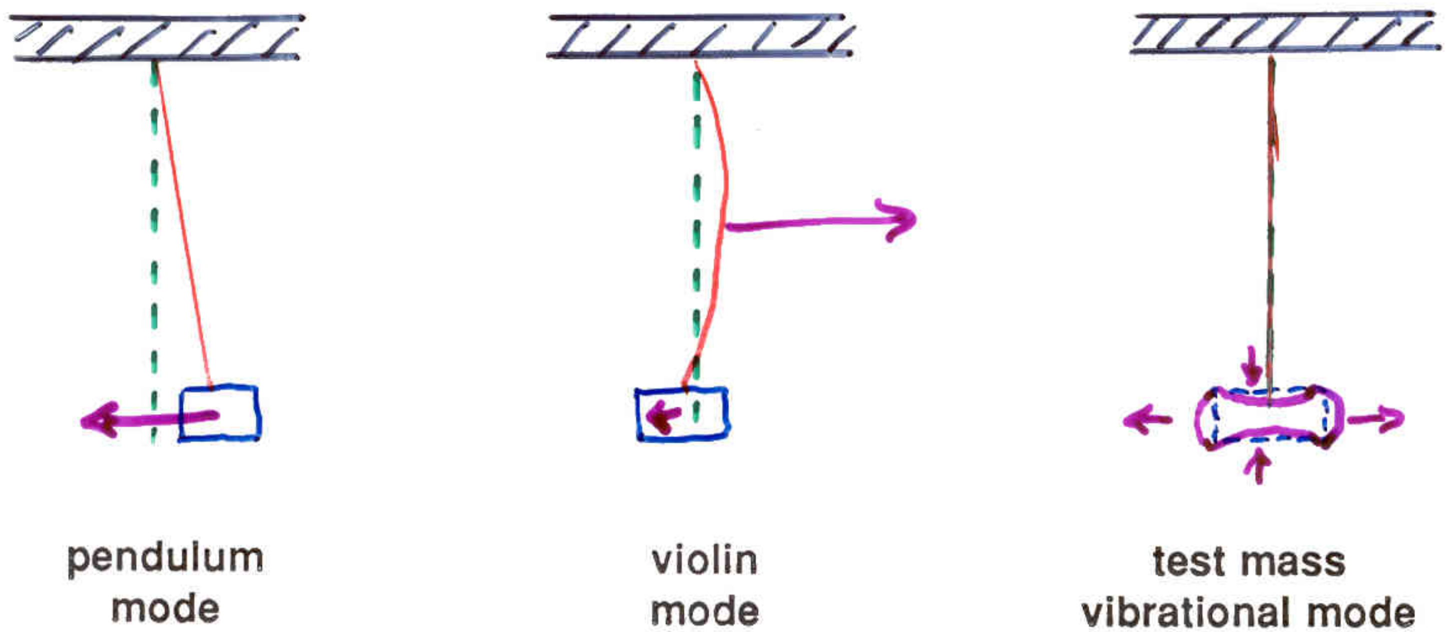




Thermal noise

- Atom in a solid at room temperature moves of order a tenth of an atomic diameter, whereas required mirror resolution is of order a billionth of an atomic diameter
- Strategy is not to measure where a particular atom is, but to average over as many atoms as possible; variance of this average over the the mirror surface is known at thermal noise
- To reduce thermal noise:
  - » Design mechanical resonances out of the “signal band “ of the detector
  - » Maximize Q to draw as much of kT of energy into a narrow resonance, thus depleting energy in the wings of the resonances
- Major contributors are due to motions of atoms in the mirrors, atoms in the suspension wires, possibly residual gas atoms

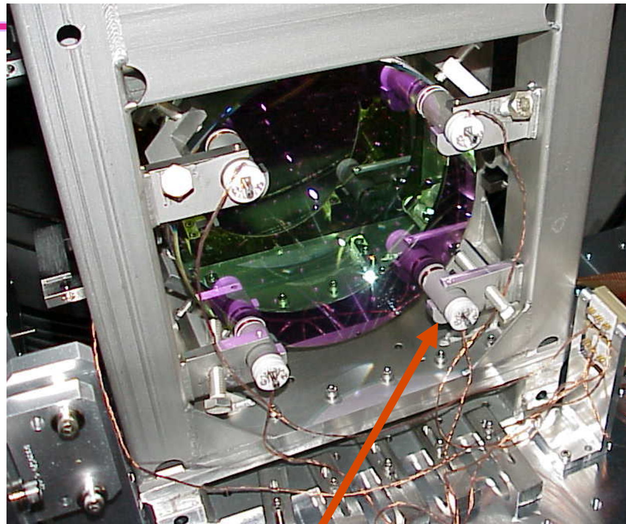
Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



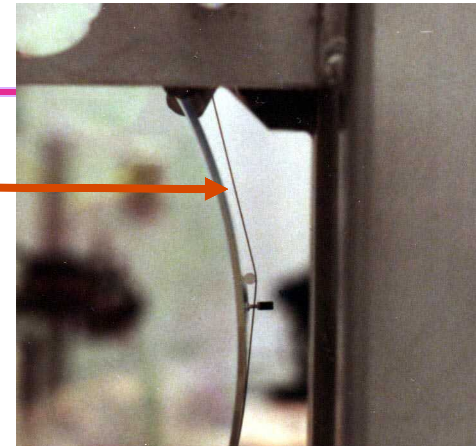
$x_{rms} \approx 10^{-11}$ m	$x_{rms} \approx 2\times10^{-17}$ m	$x_{rms} \approx 5\times10^{-16}$ m
f < 1 Hz	f ~ 350 Hz	f ≥ 10 kHz

Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

Initial LIGO Suspension and Control



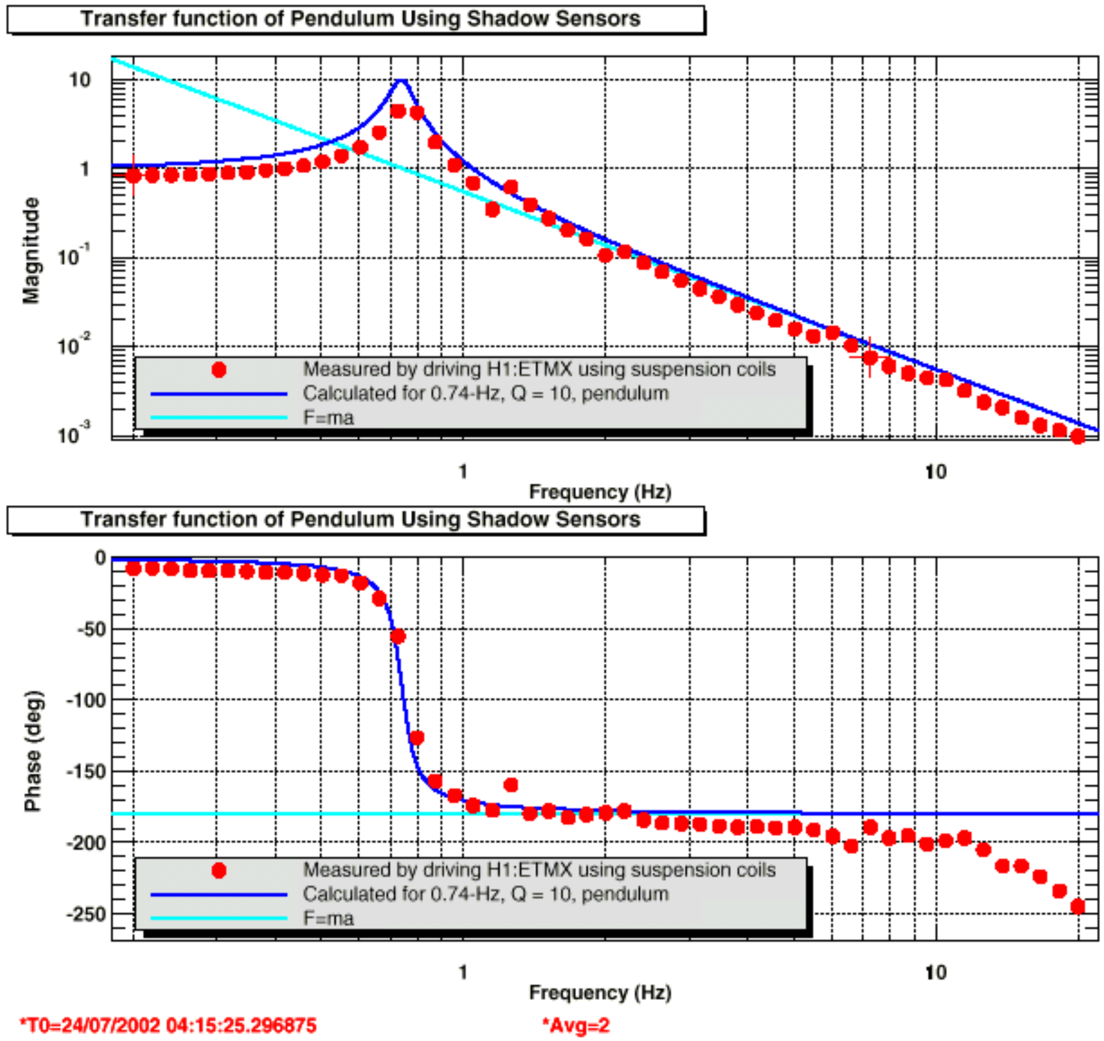
Optics suspended as simple pendulums



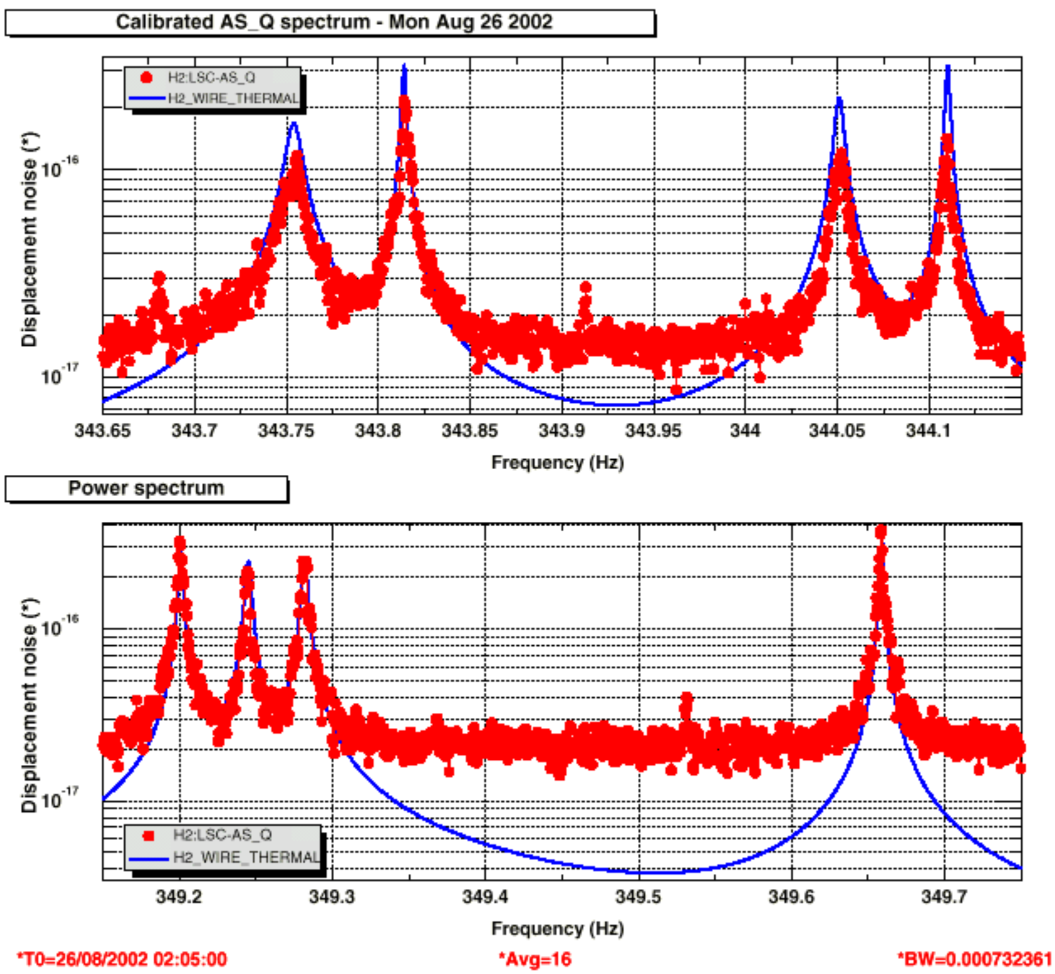
Local sensors/actuators provide damping and control forces

Mirror is balanced on 0.25-mm diameter wire to 1/100th degree of arc

Suspended Mirror Approximates a Free Mass Above Resonance

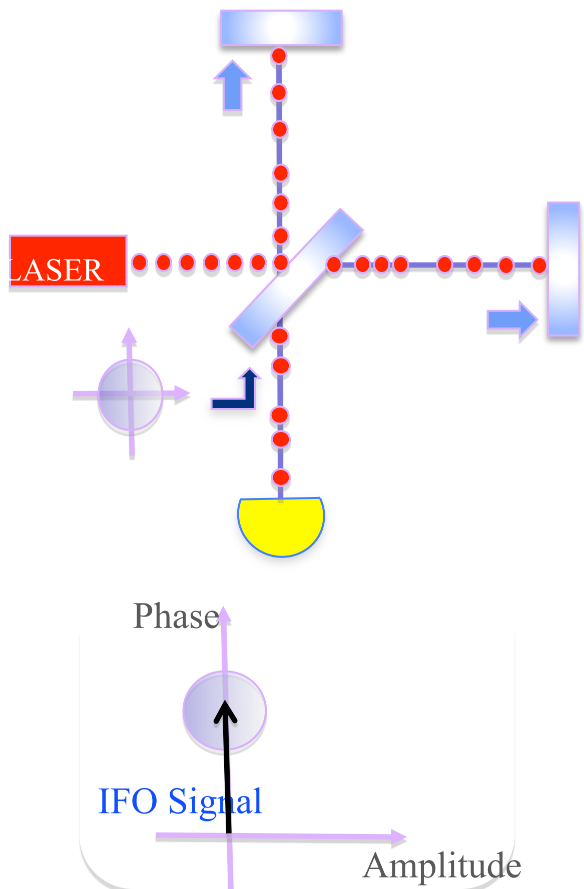


Thermal Noise Observed in 1st Violins on H2, L1 During S1



Almost good enough for tracking calibration.

Quantum Noise and Vacuum



- ✧ Quantum noise is produced by vacuum fluctuations entering the open ports
- ✧ Vacuum fluctuations have equal uncertainty in phase and amplitude:
  - ❖ Phase: Shot-Noise (photon counting noise)
  - ❖ Amplitude: Radiation Pressure Noise (back-action)

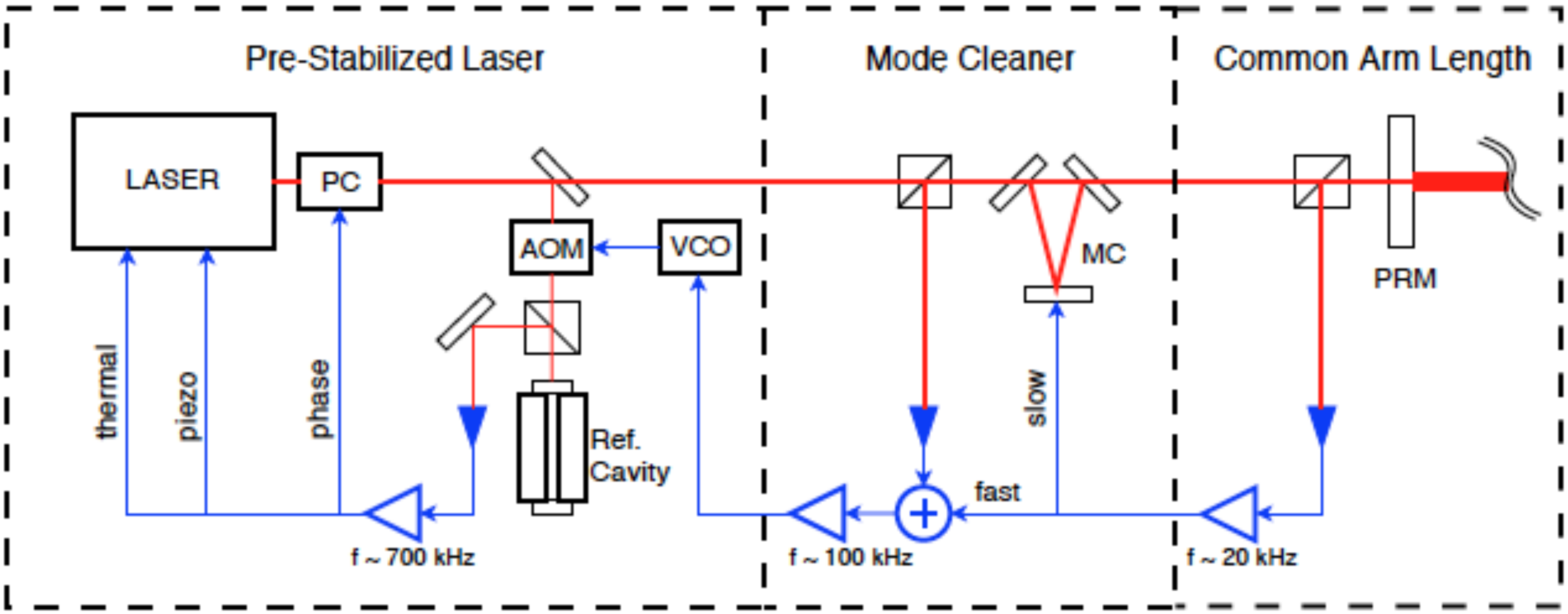
Shot-noise-equivalent strain

$$\tilde{h}(f) = \sqrt{\frac{\pi \hbar \lambda}{\eta P_{\mathrm{BS}} c}} \frac{\sqrt{1 + (4\pi f \tau_{\mathrm{s}})^2}}{4\pi \tau_{\mathrm{s}}}$$

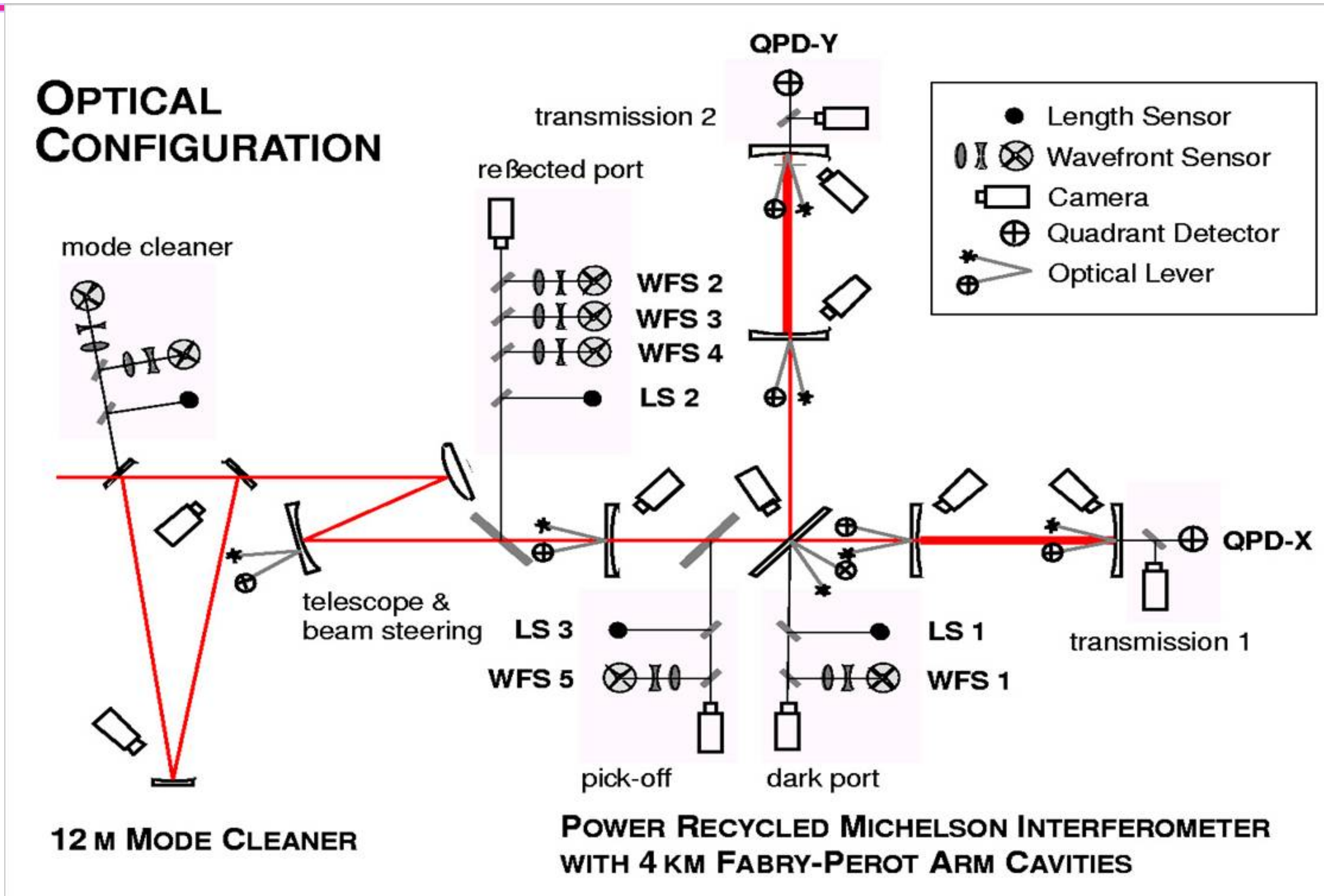
Power at beam splitter

Fabry-Perot storage time

Frequency Stabilization Scheme



Closer look - more lasers and optics



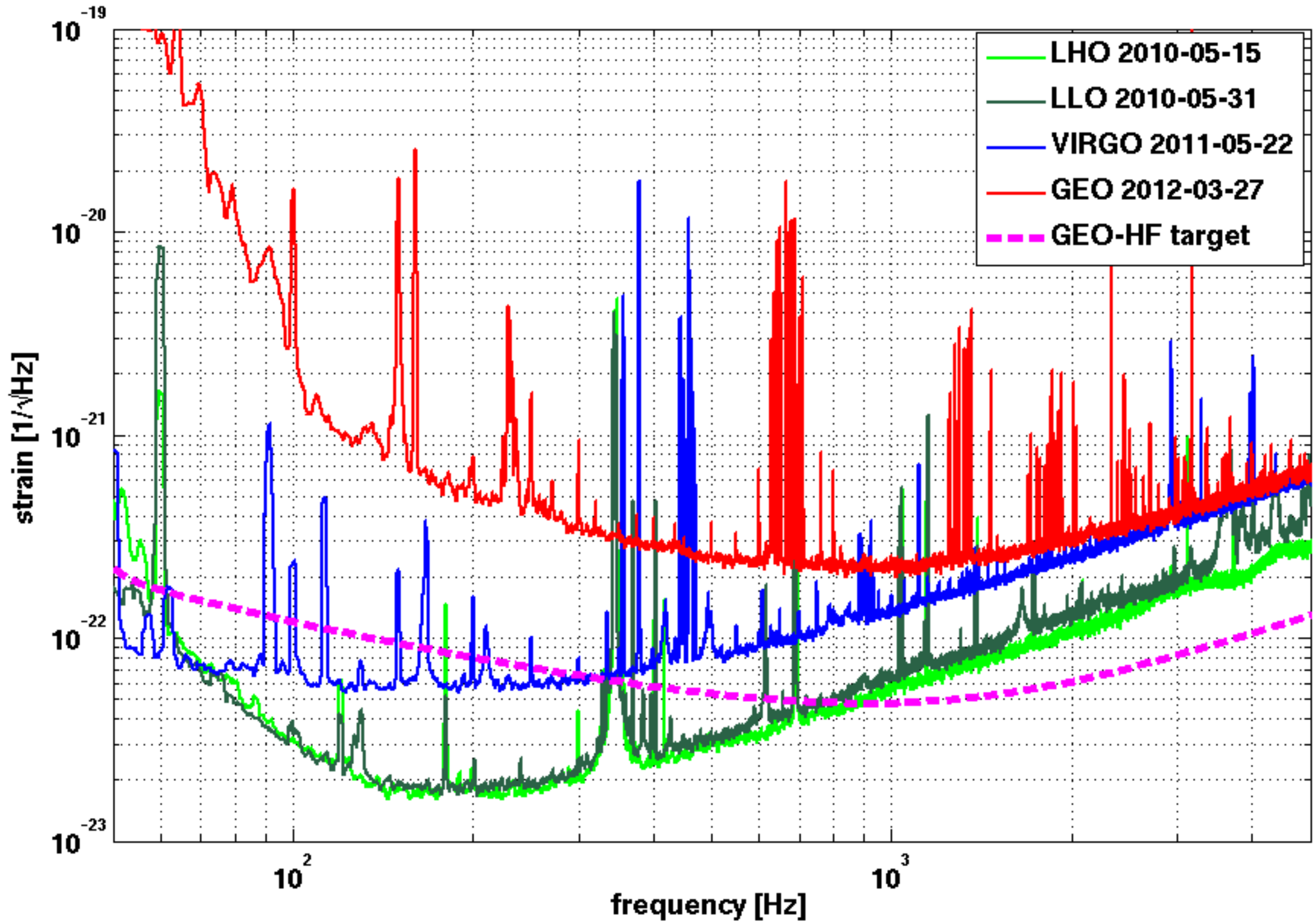
Feedback & Control for Mirrors and Light

- Damp suspended mirrors to vibration-isolated tables
  - » 14 mirrors × (pos, pit, yaw, side) = 56 loops
- Damp mirror angles to lab floor using optical levers
  - » 7 mirrors × (pit, yaw) = 14 loops
- Pre-stabilized laser
  - » (frequency, intensity, pre-mode-cleaner) = 3 loops
- Cavity length control
  - » (mode-cleaner, common-mode frequency, common-arm, differential arm, michelson, power-recycling) = 6 loops
- Wave-front sensing/control
  - » 7 mirrors × (pit, yaw) = 14 loops
- Beam-centering control
  - » 2 arms × (pit, yaw) = 4 loops

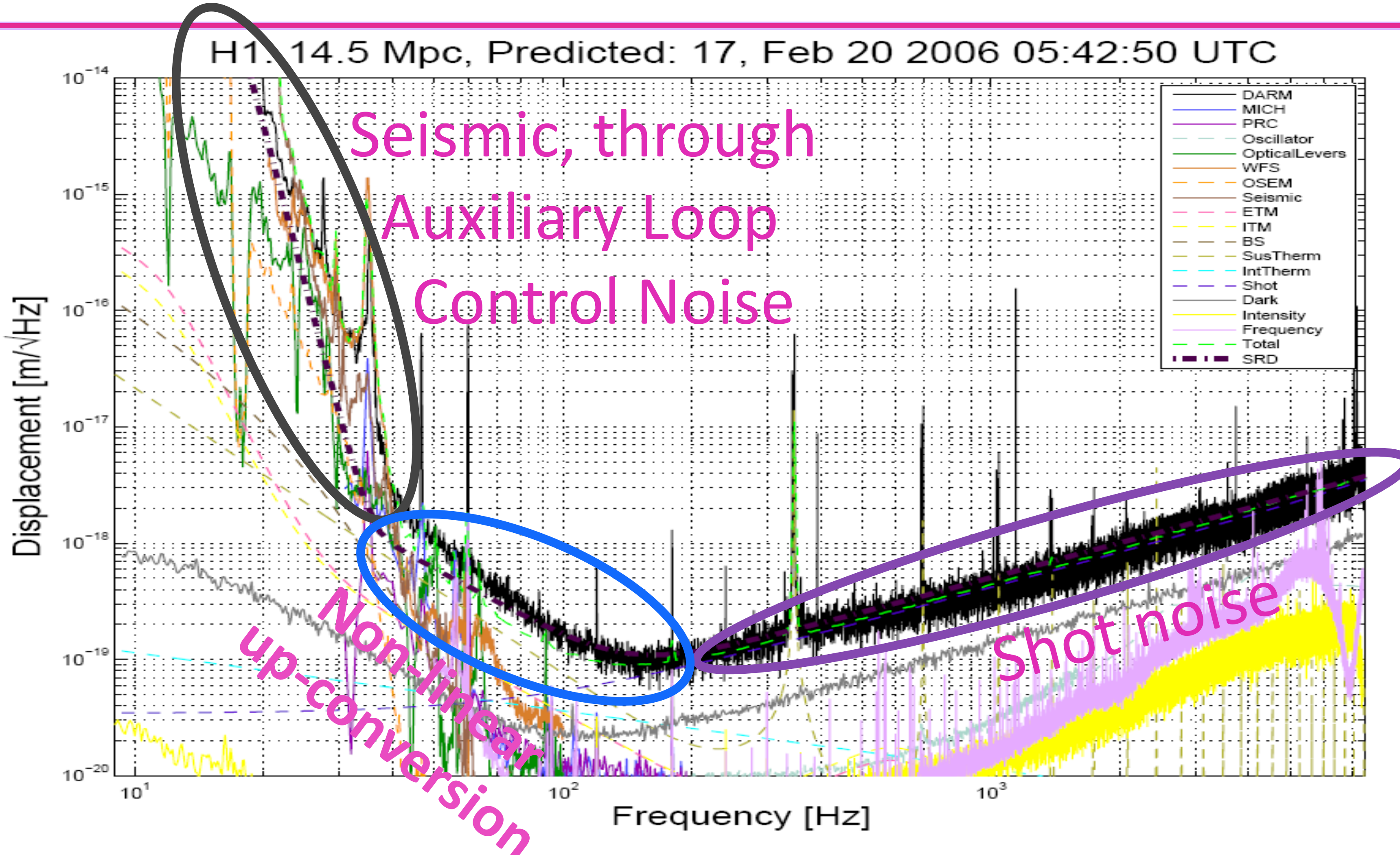
Controls require calibrations

- Tidal calibration – Earth tide is calculable and measureable on actuators
- “Electromagnetic” calibration – inject currents into voice-coil actuators; compare operating currents and fringe-hopping currents
- Laser frequency calibration – change laser frequency and measure corresponding voice-coil actuator correction current
- Ponderomotive calibration – modulate power of a low-power auxiliary laser reflected off the end mirrors

Sensitivity of Initial Generation Detectors



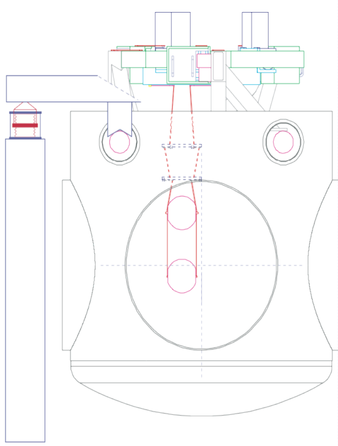
S5 Noise Analysis



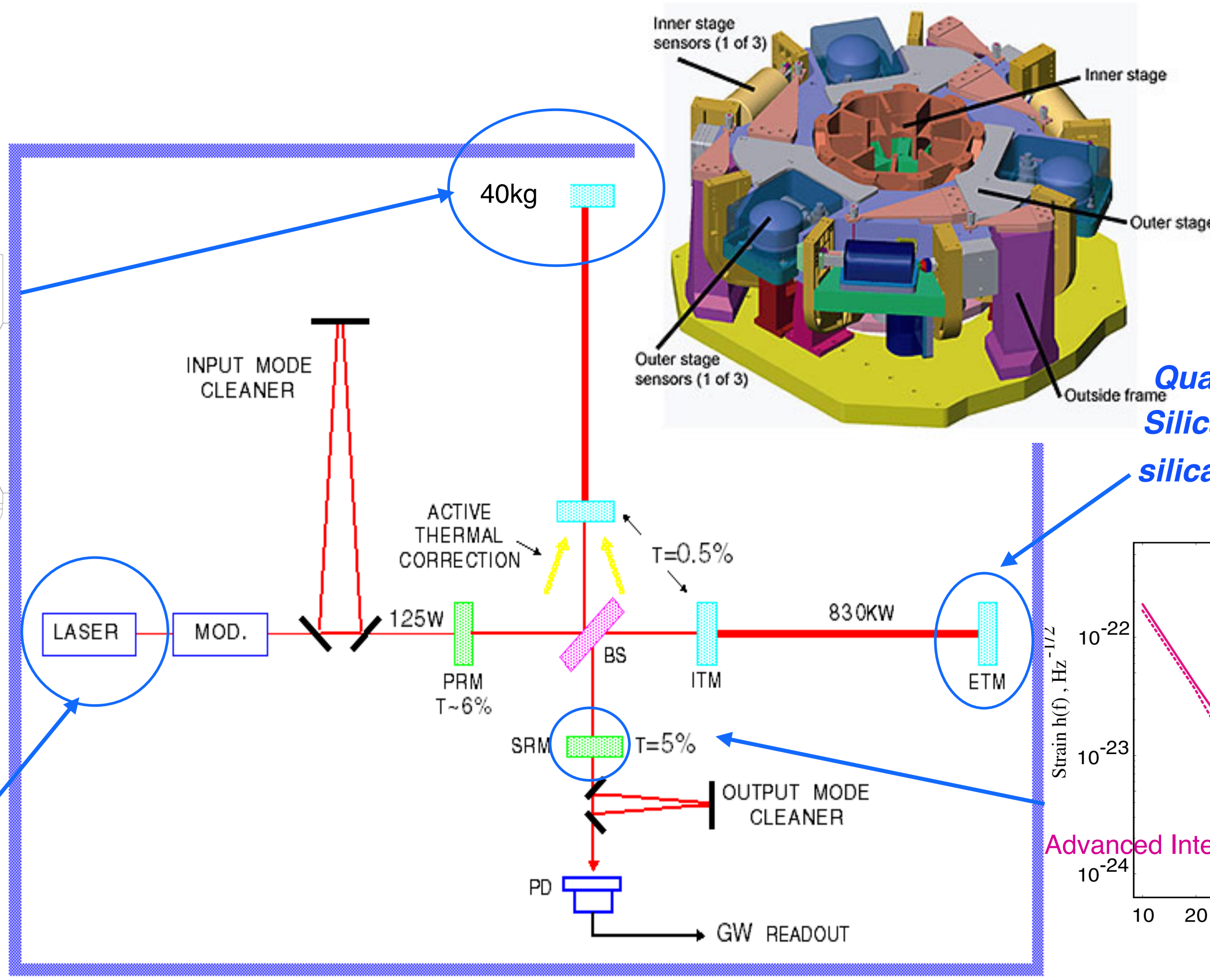
Advanced or 2nd-Generation Detectors

Advanced LIGO construction (aLIGO) started 1Apr2008

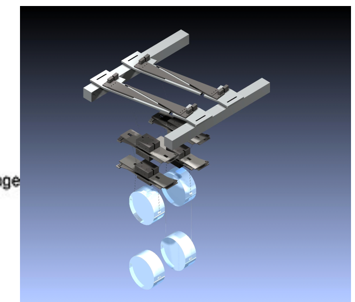
Major technological differences between LIGO and Advanced LIGO



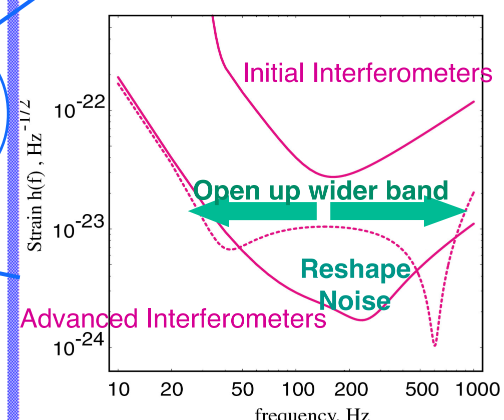
Active vibration isolation systems



High power laser (180W)

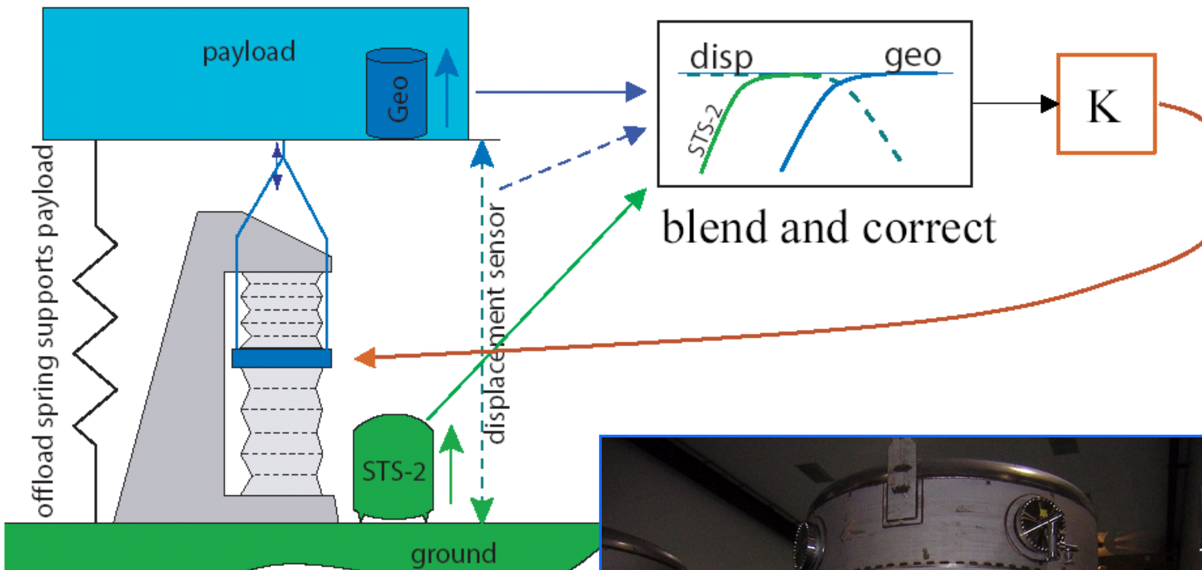


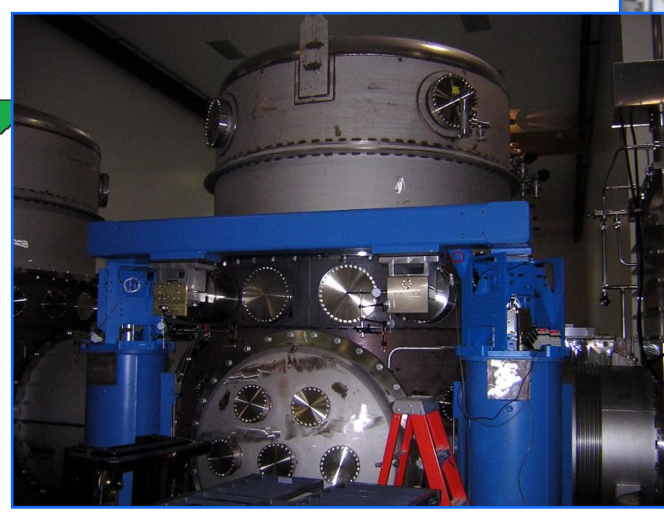
Quadruple pendulum: Silica optics, welded to silica suspension fibers



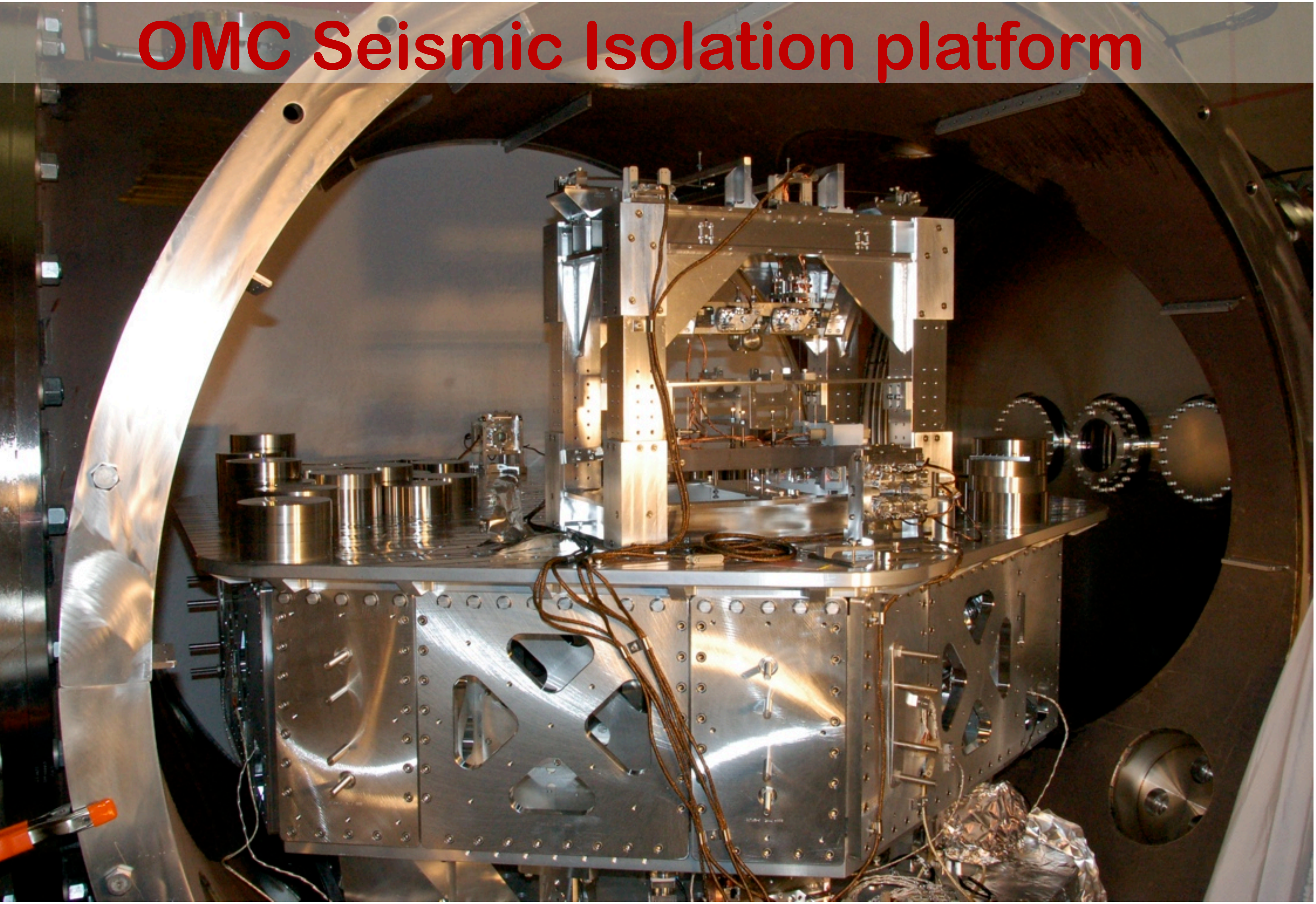
Advanced interferometry Signal recycling

Active Hydraulic External Pre-Isolators

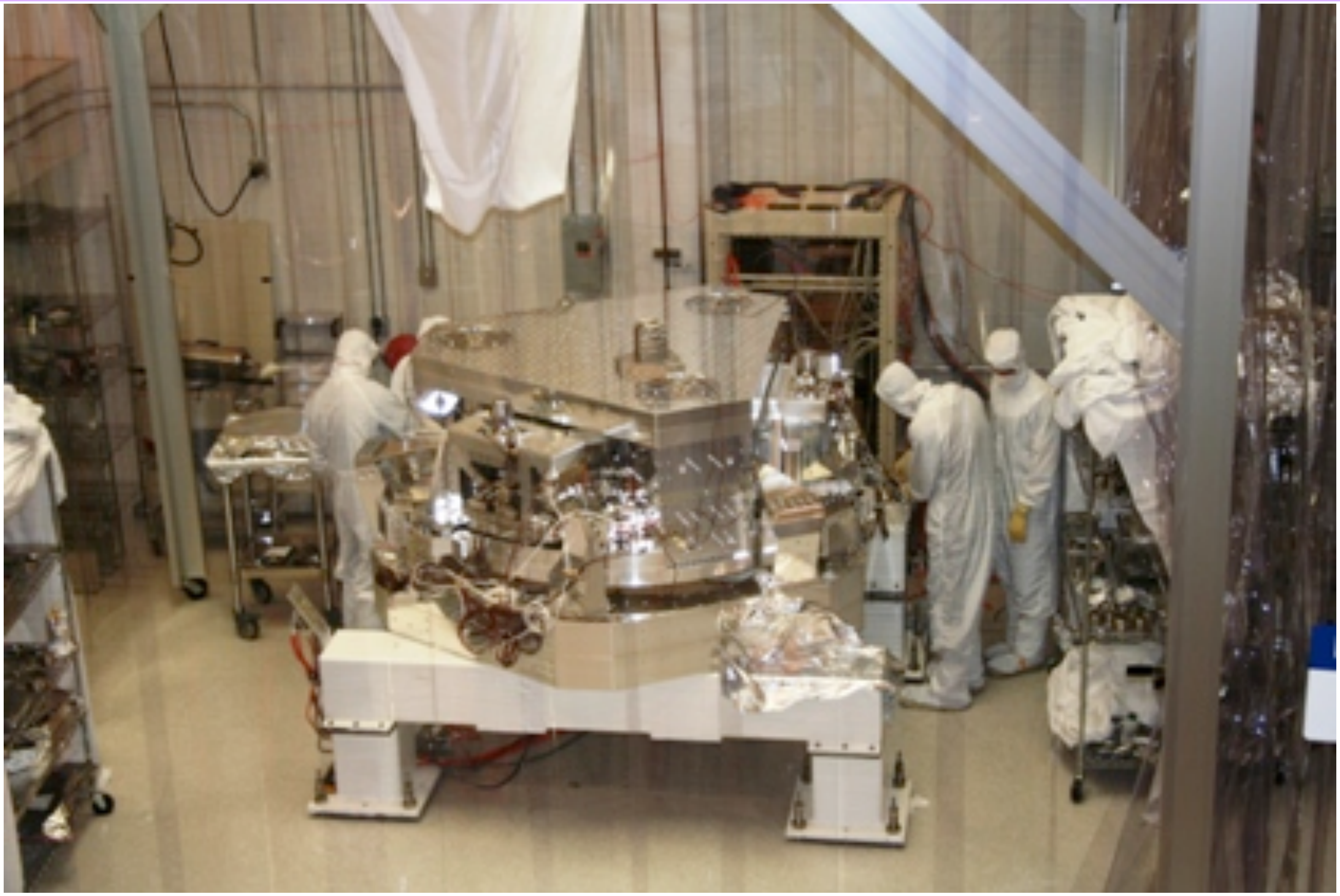




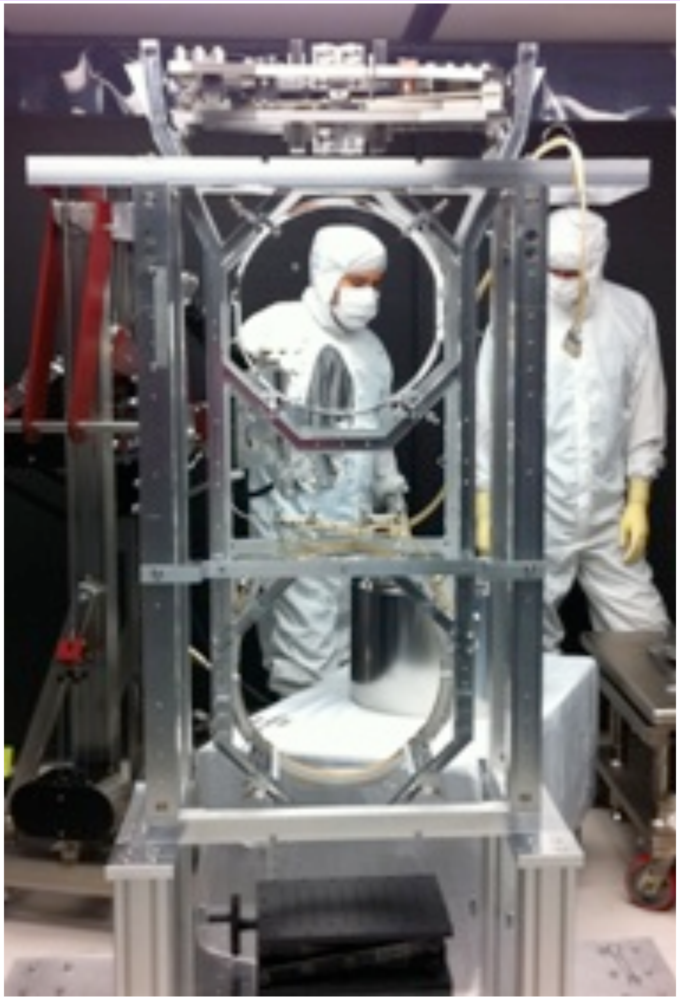
OMC Seismic Isolation platform

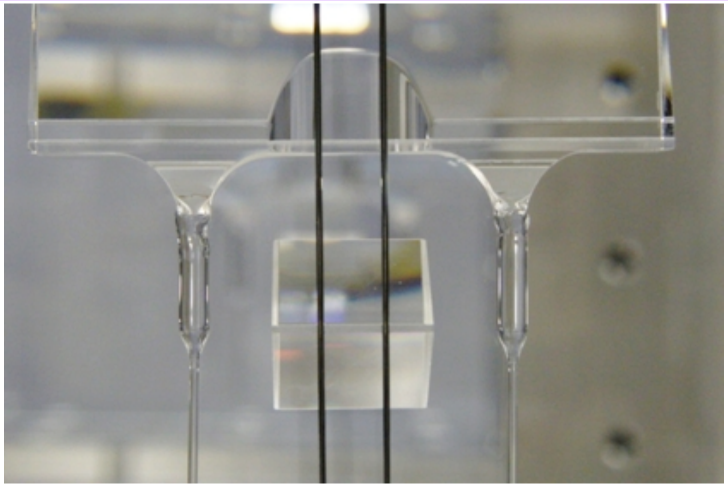


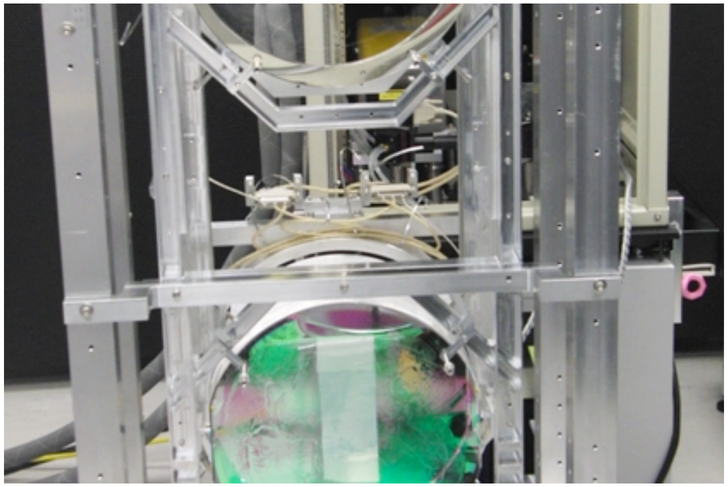
BSC Internal Seismic Isolator



Adv. LIGO Monolithic Suspension







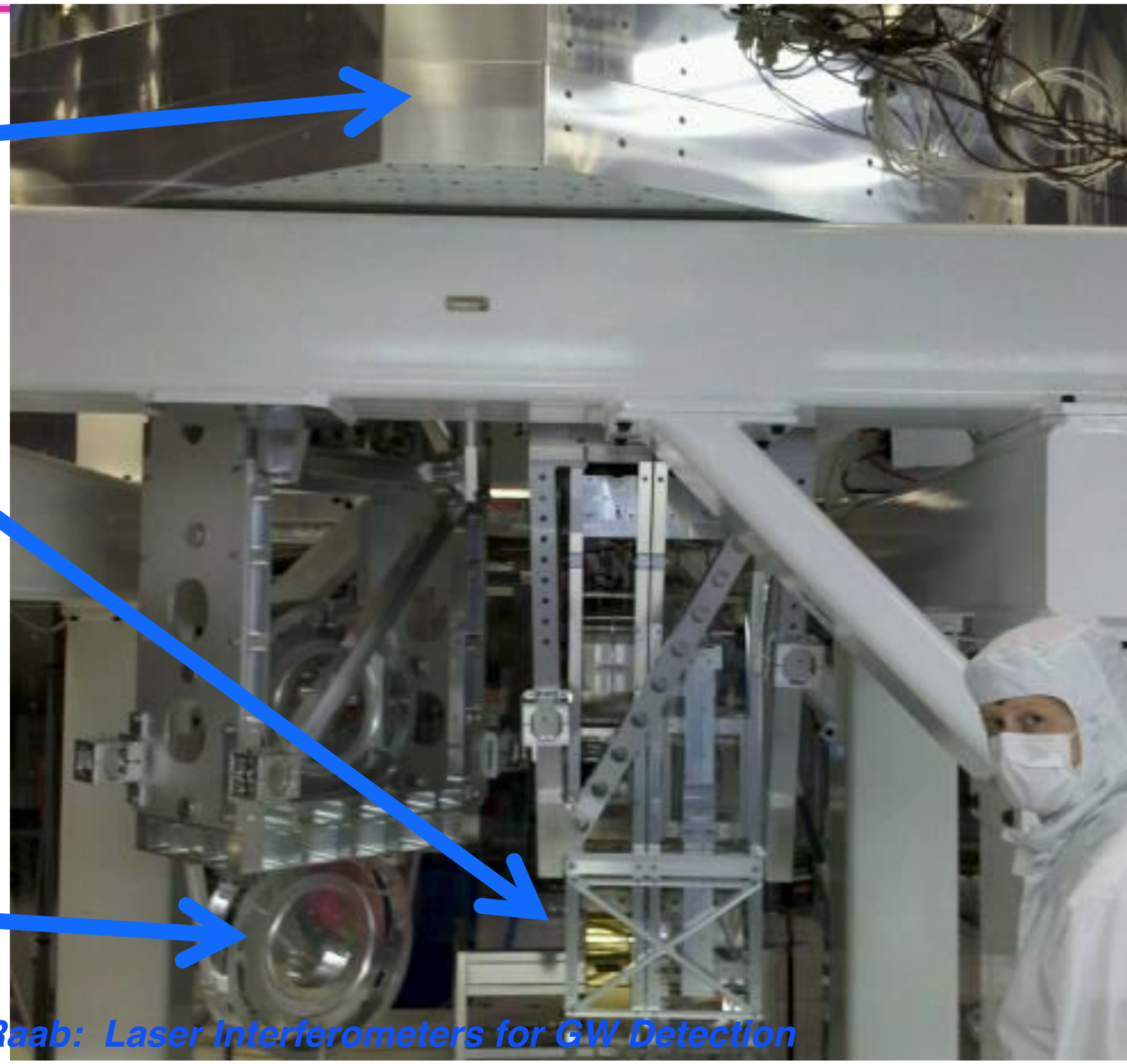
aLIGO installation in progress

Putting it together: Seismic & Suspension & Optics

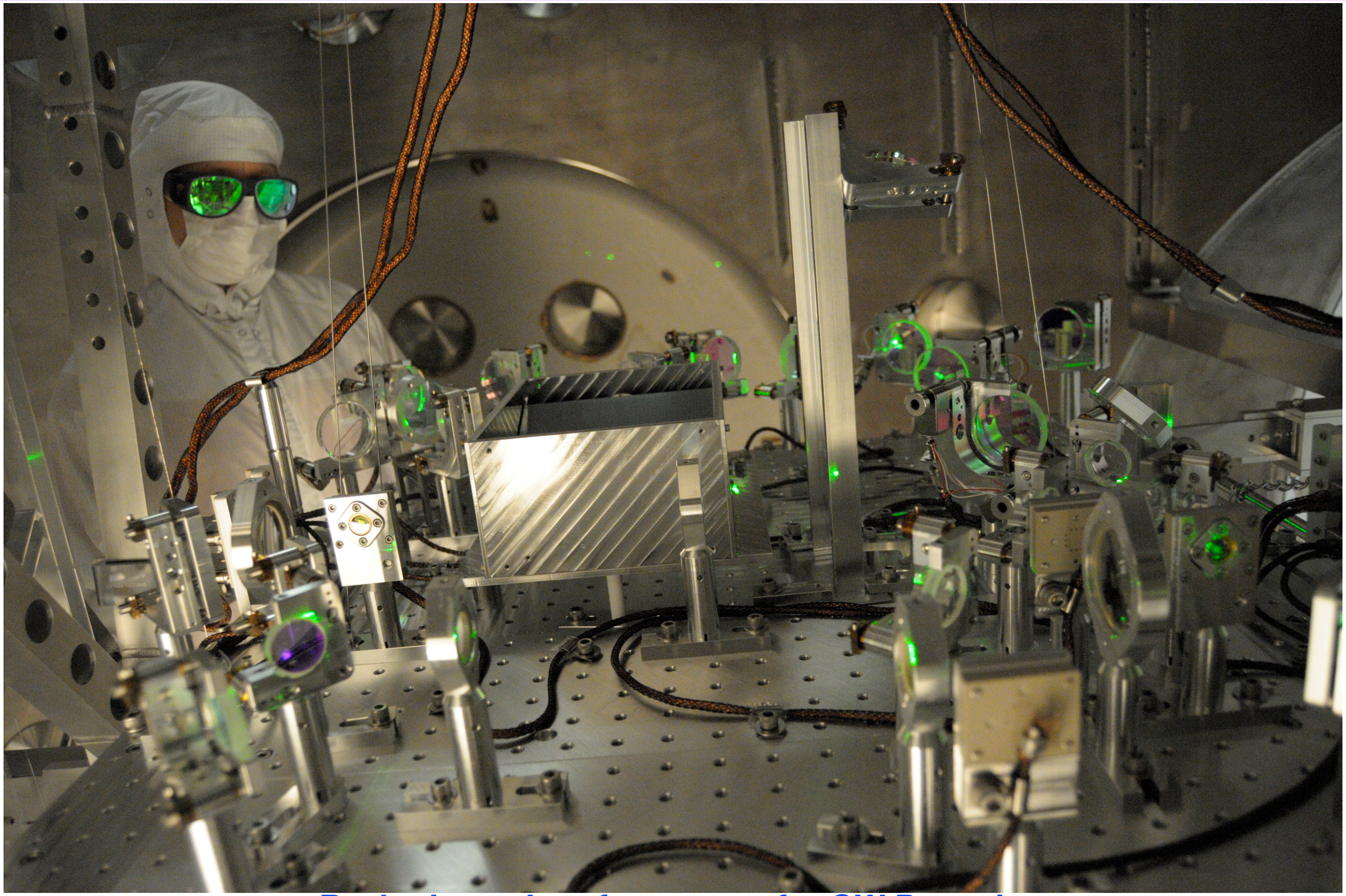
Seismic isolation

Test mass suspension

Folding mirror suspension

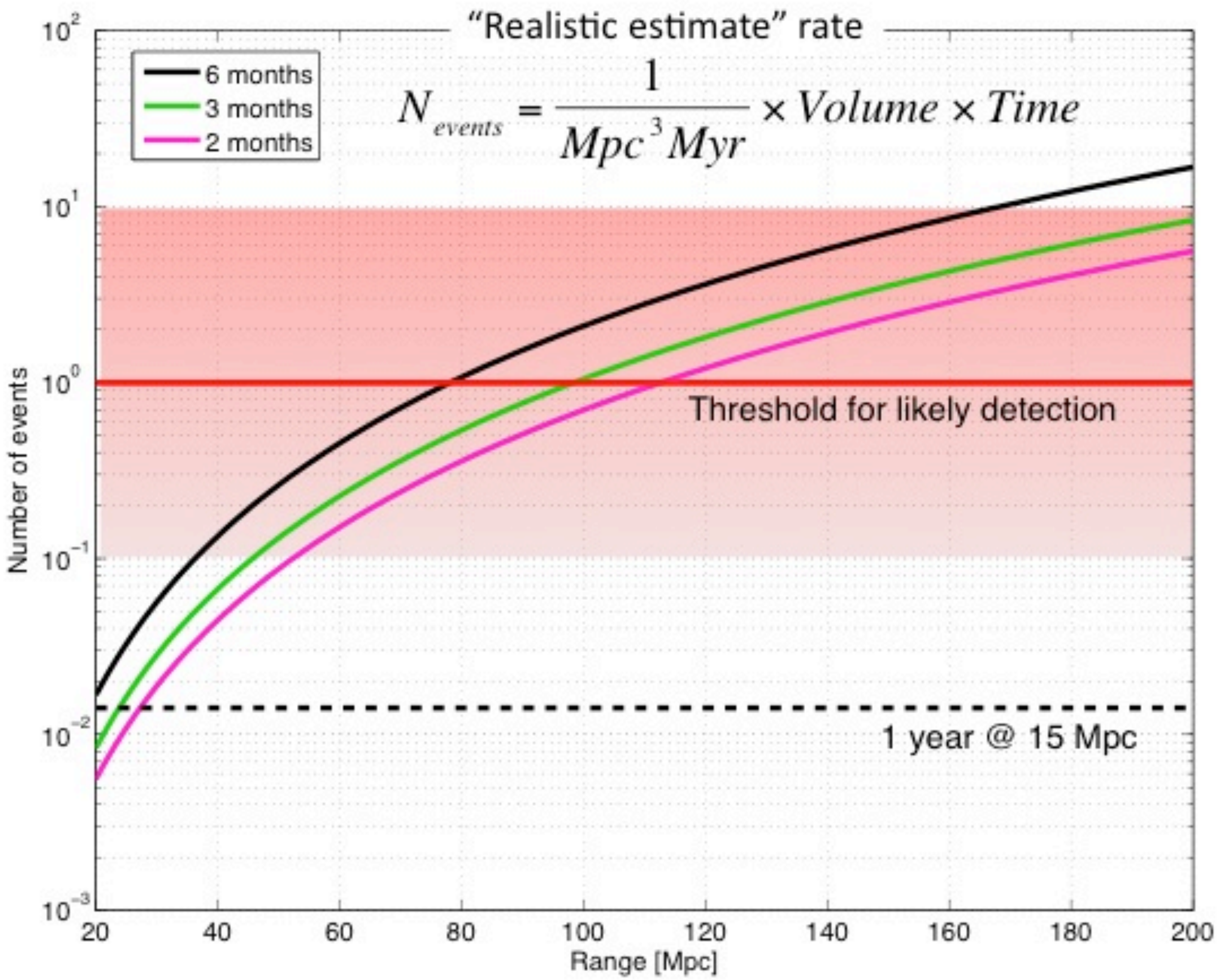


Lock Acquisition: Arm Locking Subsystem

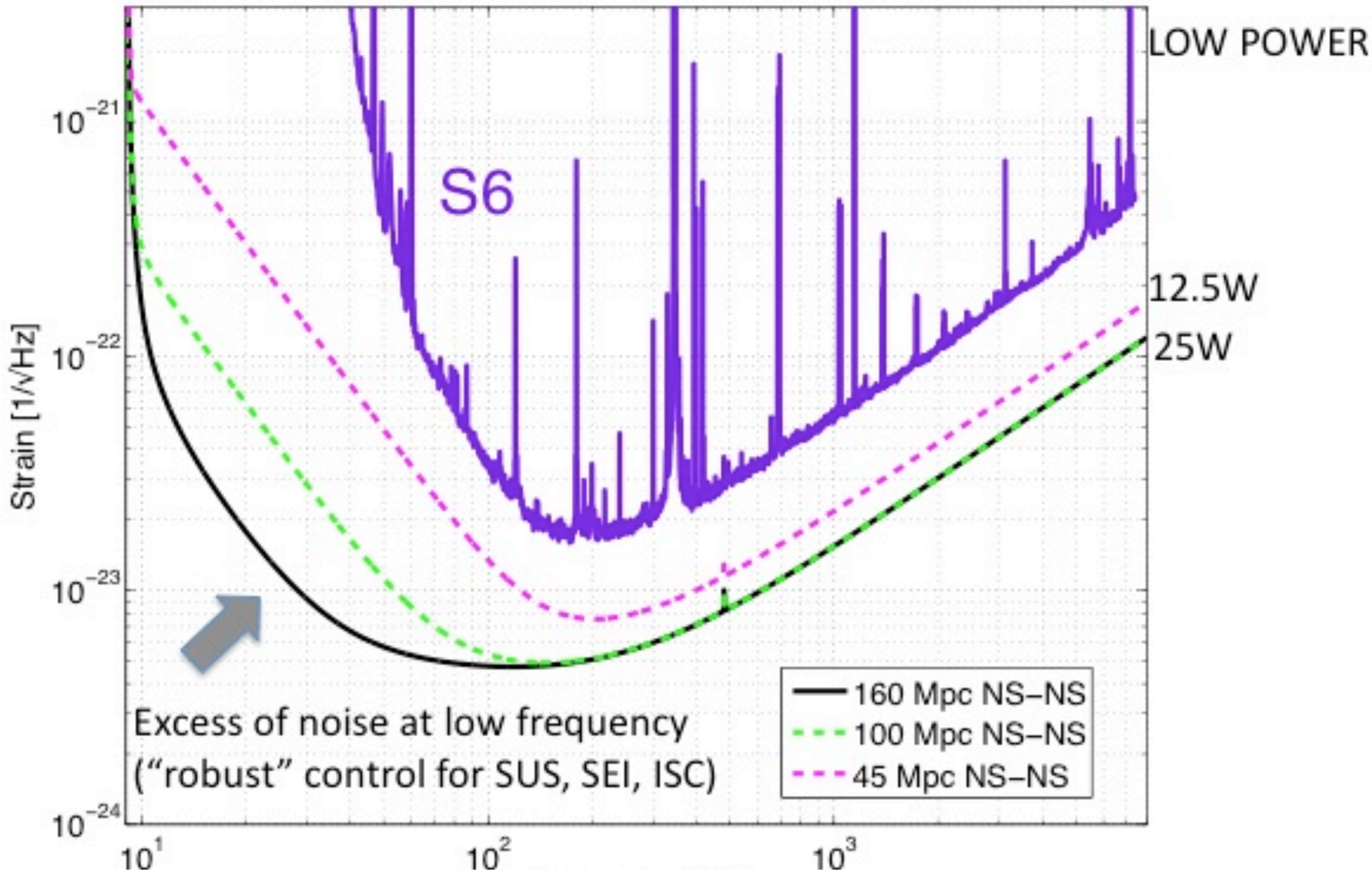


aLIGO Pre-stabilized laser

Criteria for early science runs



A Plausible Path to Early Science Running



R&D for enhancements and 3rd generation detectors

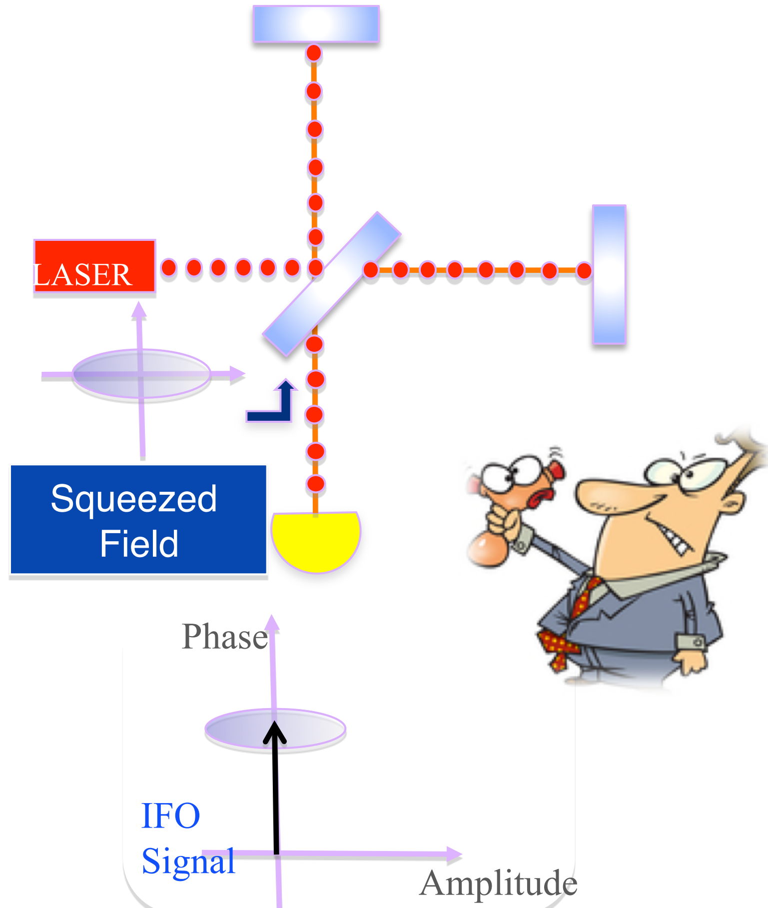
- Vacuum squeezing
- Subtraction of Newtonian noise
- Higher precision sensors of vibration & rotation
- Low-mechanical-loss mirror coatings
- Cryogenic mirror suspensions
- New interferometers with 1.5-micron lasers and silicon mirrors and beam splitters
- Ideas not yet invented

Squeezing the vacuum

✧ Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures

✧ Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one

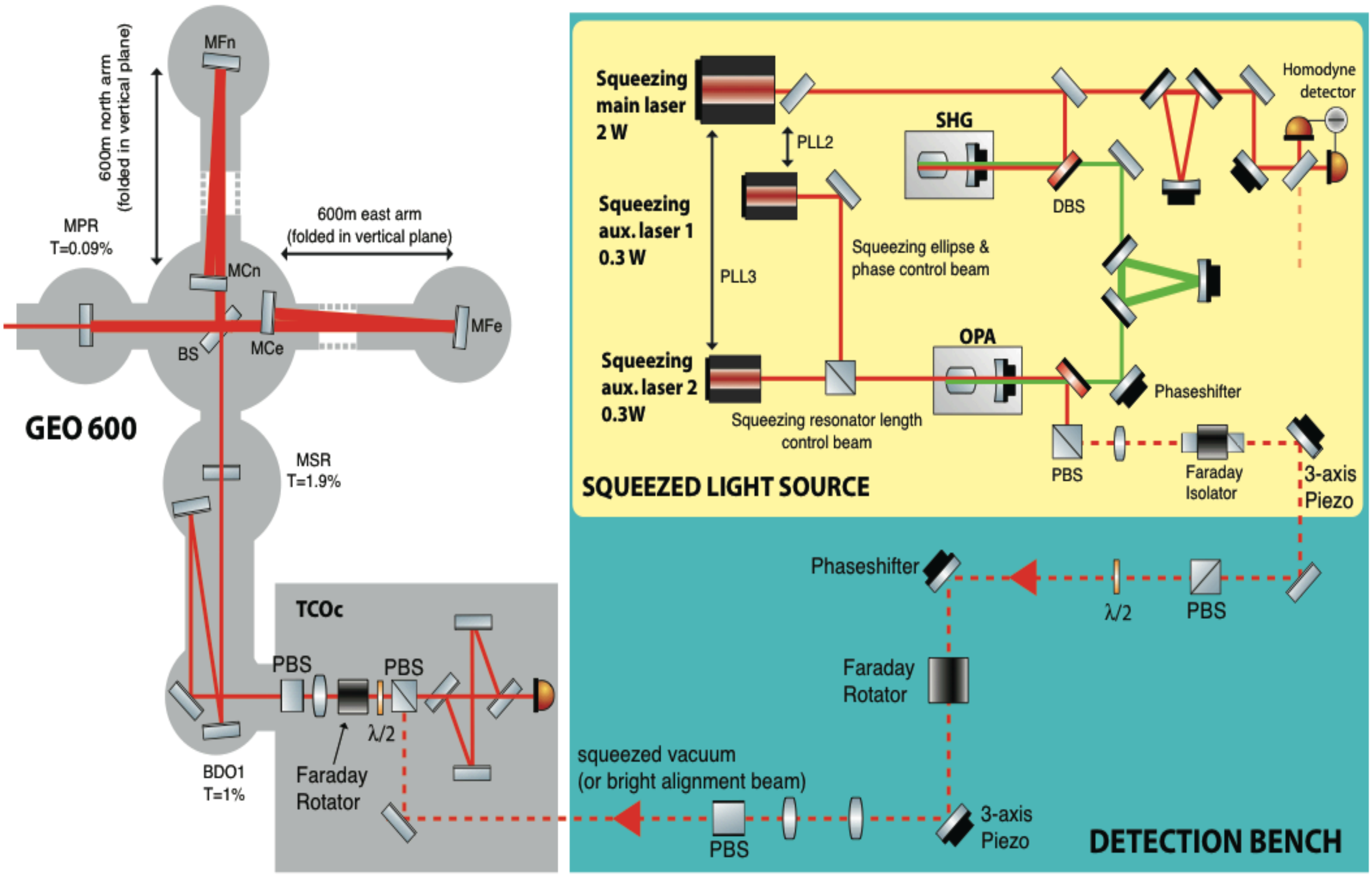
✧ One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)



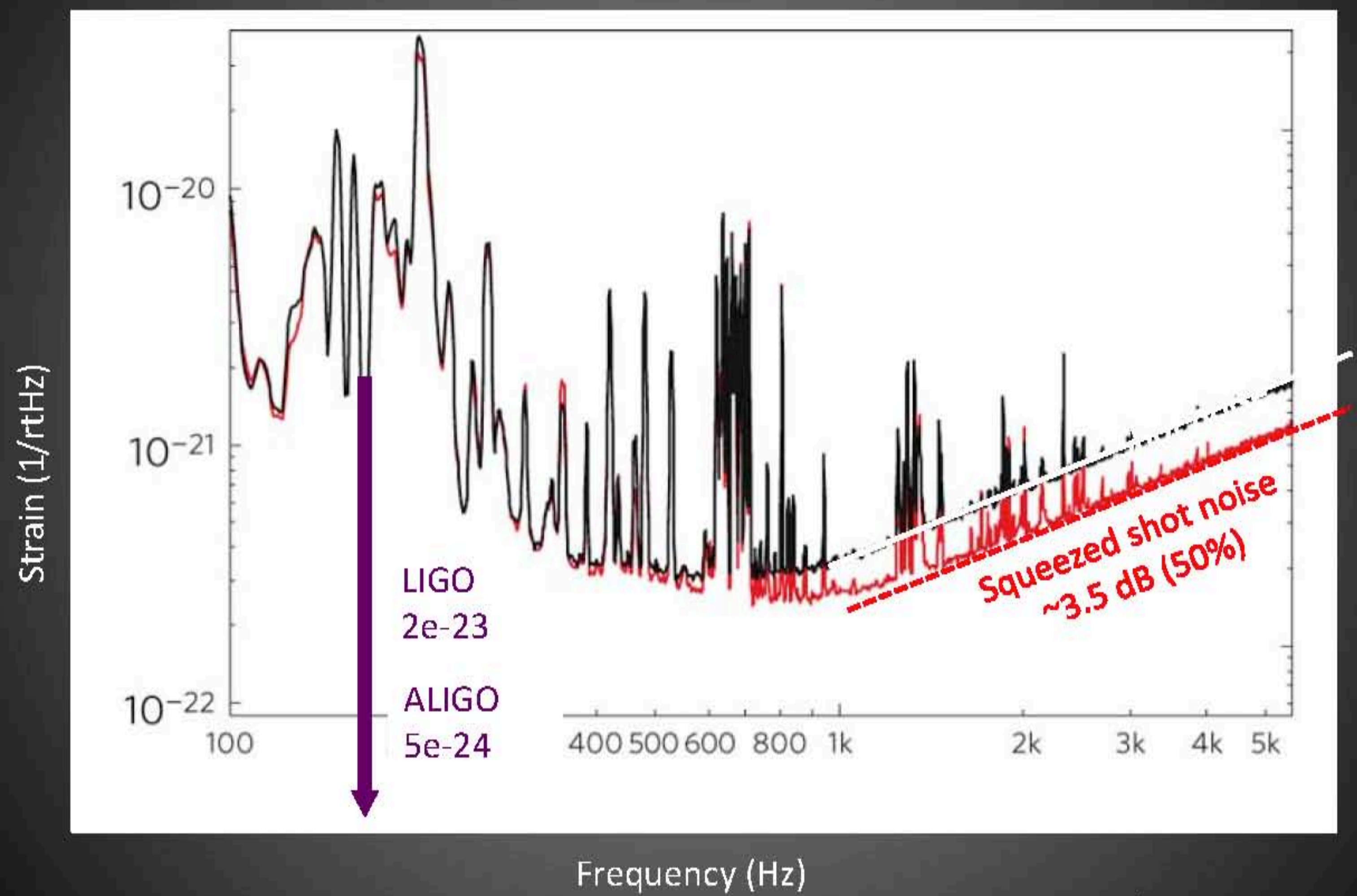
Vacuum squeezing tests at scale

- International collaboration among labs in Australia, Germany and USA to convert quantum-optics toys to tools that enhance sensitivity of working instruments
- GEO Squeezing experiment to investigate robustness of squeezing to enhance sensitivity
- H1 Squeezing experiment to investigate possible technical impairments at low frequencies due to injection of vacuum squeezing

GEO Squeezing

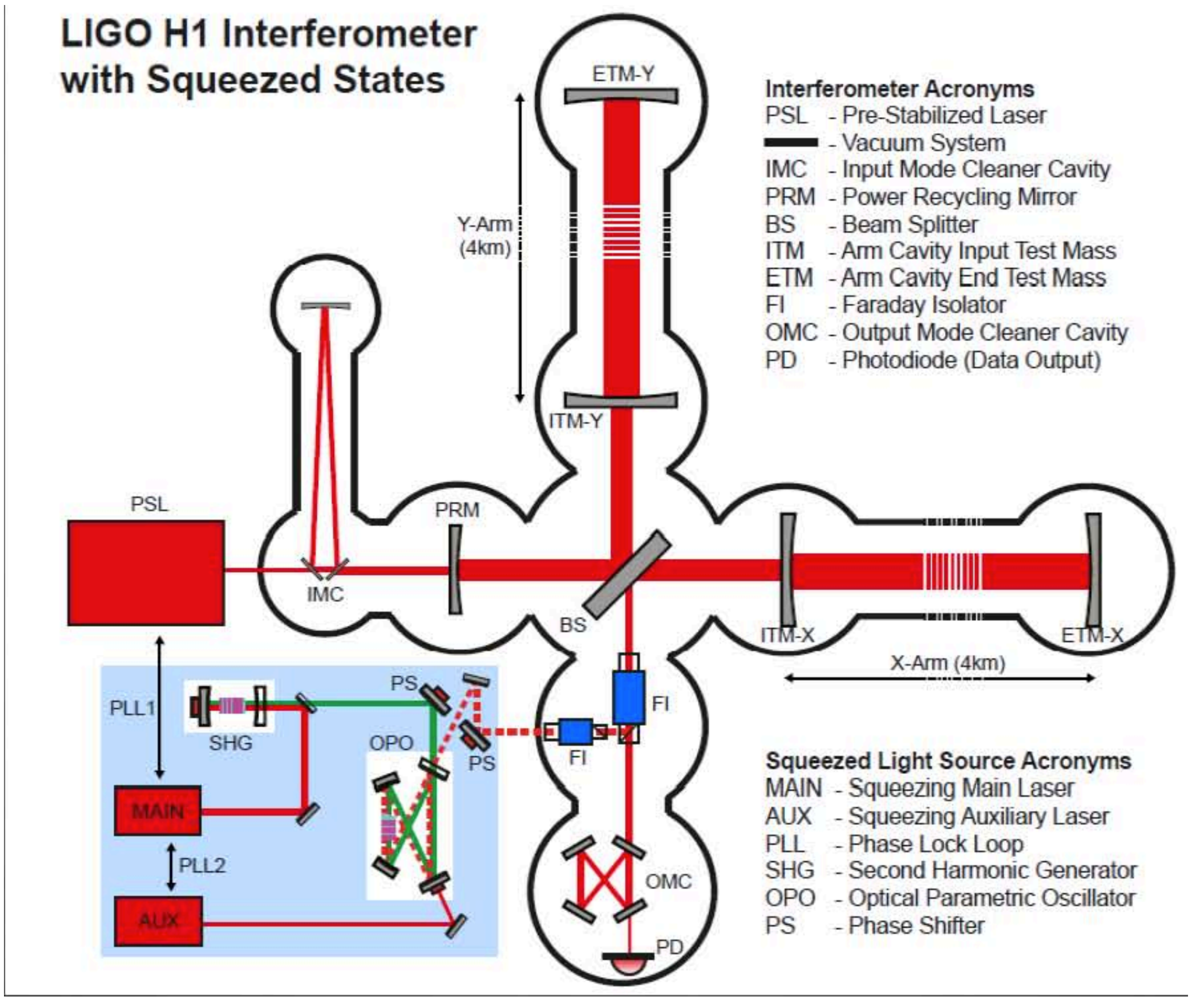


Squeezing Enhancement in GEO600



Nat Phys, Sept 2011

Squeezing test on iLIGO H1: low-frequency consequences?

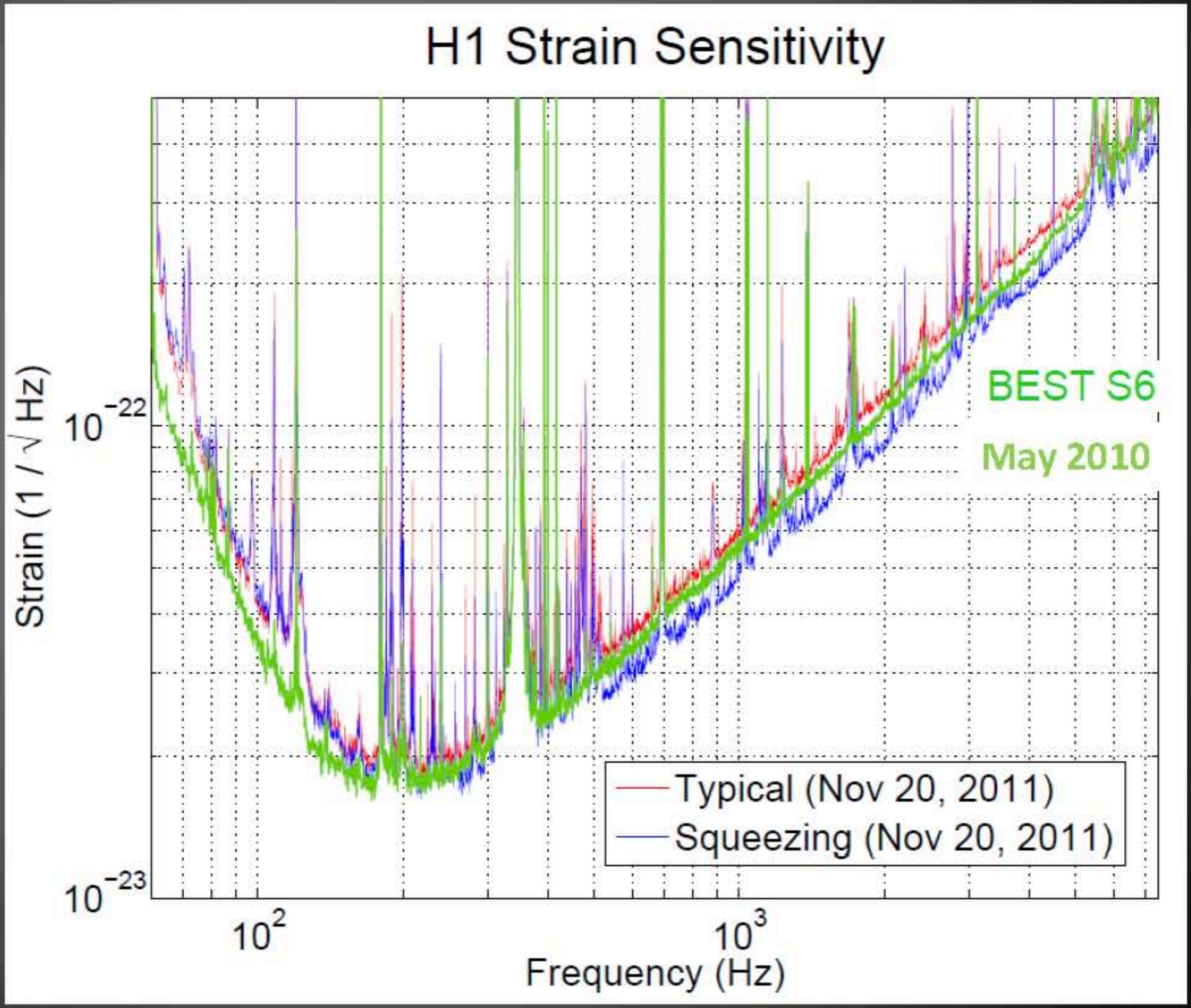


Results

Squeezing does not add noise at any frequency

Inspiral Range improved by 1Mpc

Best broadband sensitivity achieved so far



Summary

- Initial or 1st Generation Detectors were pathfinders that made the transition from laboratory-scale “thesis projects” and prototypes to kilometer-scale operating facilities
- Advanced or 2nd Generation Detectors will go on line by 2015 and usher in the age of Gravitational-Wave Astronomy
- Plenty of opportunities for instrumentalists to advance the sensitivity and robustness of these machines

It's never as easy as it looks…