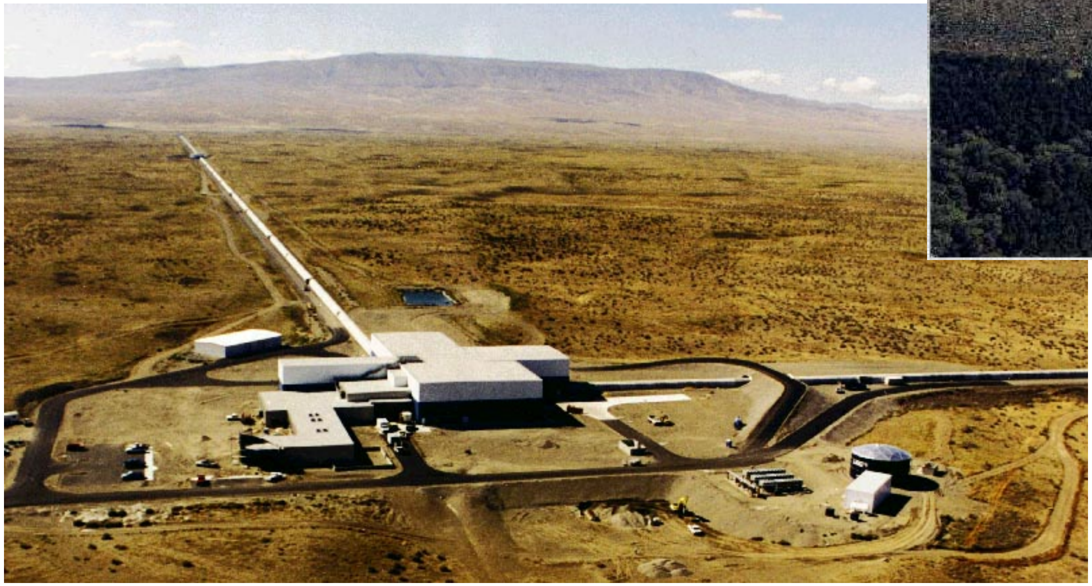
Plans for Advanced LIGO Instruments

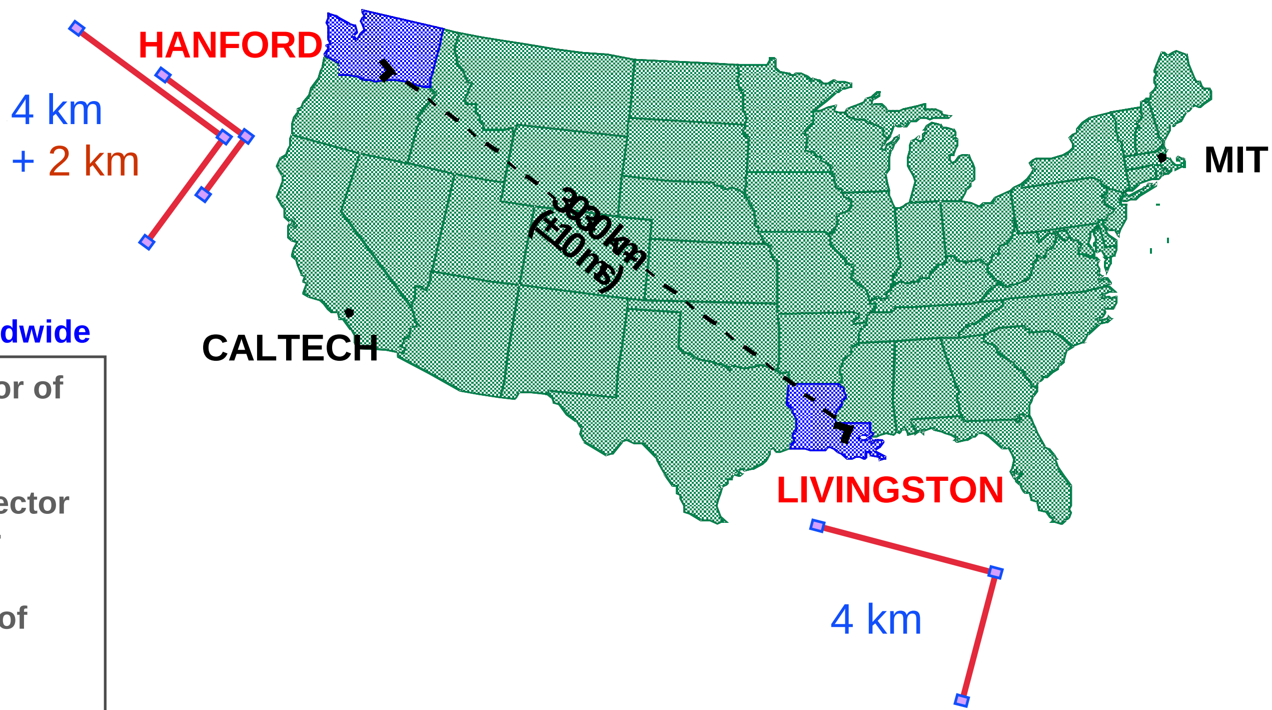
APS Meeting, April 18, 2005



Carol Wilkinson
LIGO Hanford Observatory

Laser **I**nterferometer **G**ravitational-Wave **O**bservatory

- **Consists of 3 Fabry-Perot Michelson Interferometers at two sites**
  3030 km apart, running in coincidence
  » **LIGO Livingston Observatory (LLO)– one with 4K long arms**
  » **LIGO Hanford Observatory (LHO) – one 4K and one 2K**



"Comrades in Arms"

Gravitational Wave Detectors Worldwide

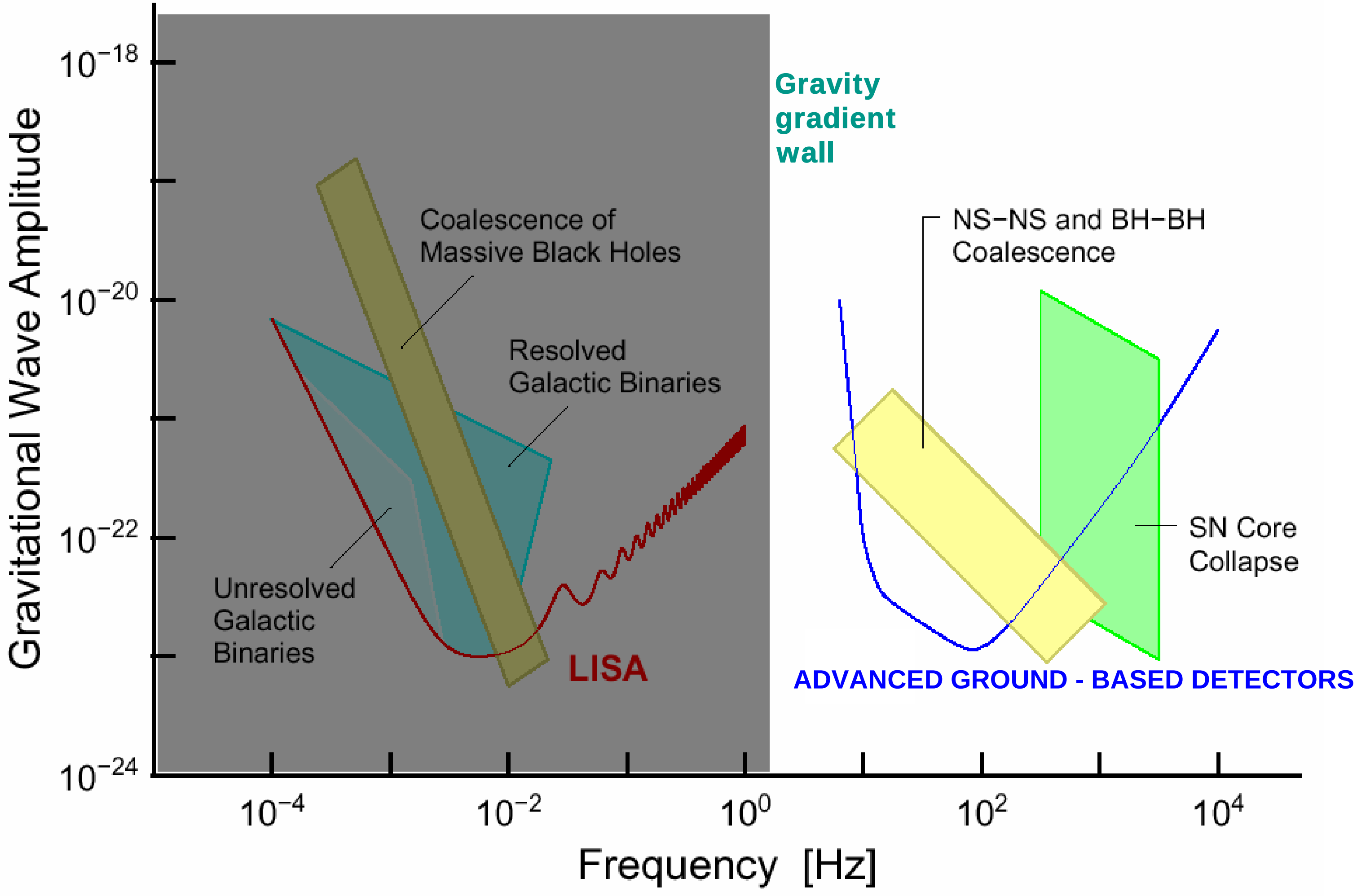
VIRGO (Italy/France) - 1 detector of 3km arm length - Pisa

GEO 600 (UK/Germany) - 1 detector of 600m arm length - Hannover

TAMA 300 (Japan) - 1 detector of 300m arm length - Tokyo

LISA Space borne detector of 5 x 106km arm length

Gravitational Wave Spectrum



Advanced LIGO Plans and Prospects

➔ Advanced LIGO is the LIGO Lab proposal for the next generation instrument to be installed at the LIGO Observatory

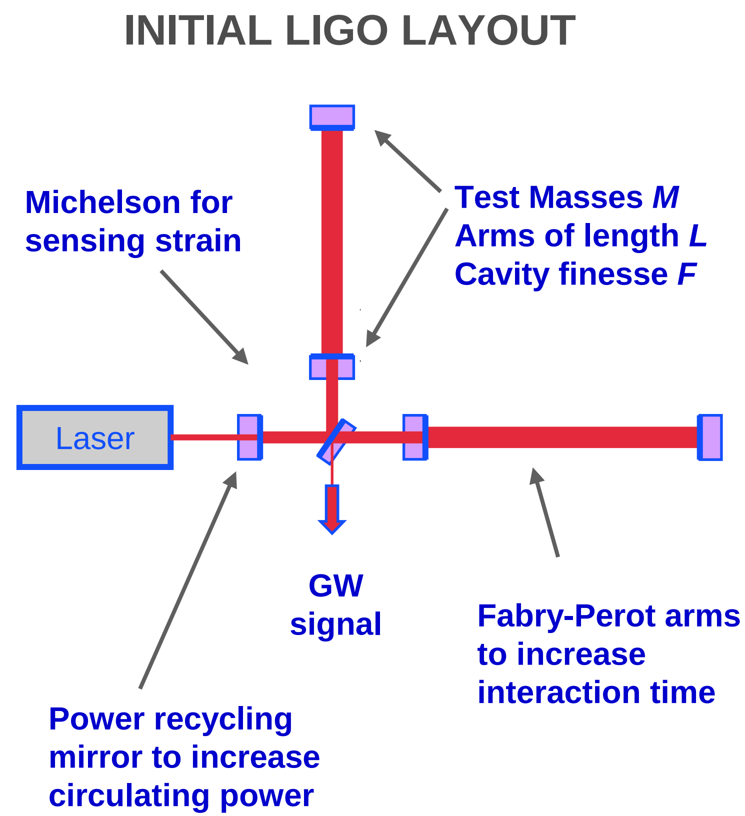
Upgrade all 3 Interferometers and convert Hanford 2K to 4K Interferometer

- **Factor of 10 better amplitude sensitivity**
- **Factor of 4 lower frequency bound**
- **Potential for tunable, narrow band searches**
  - » Change transmission of recycling mirrors by changing mirrors or using tunable transmission mirror

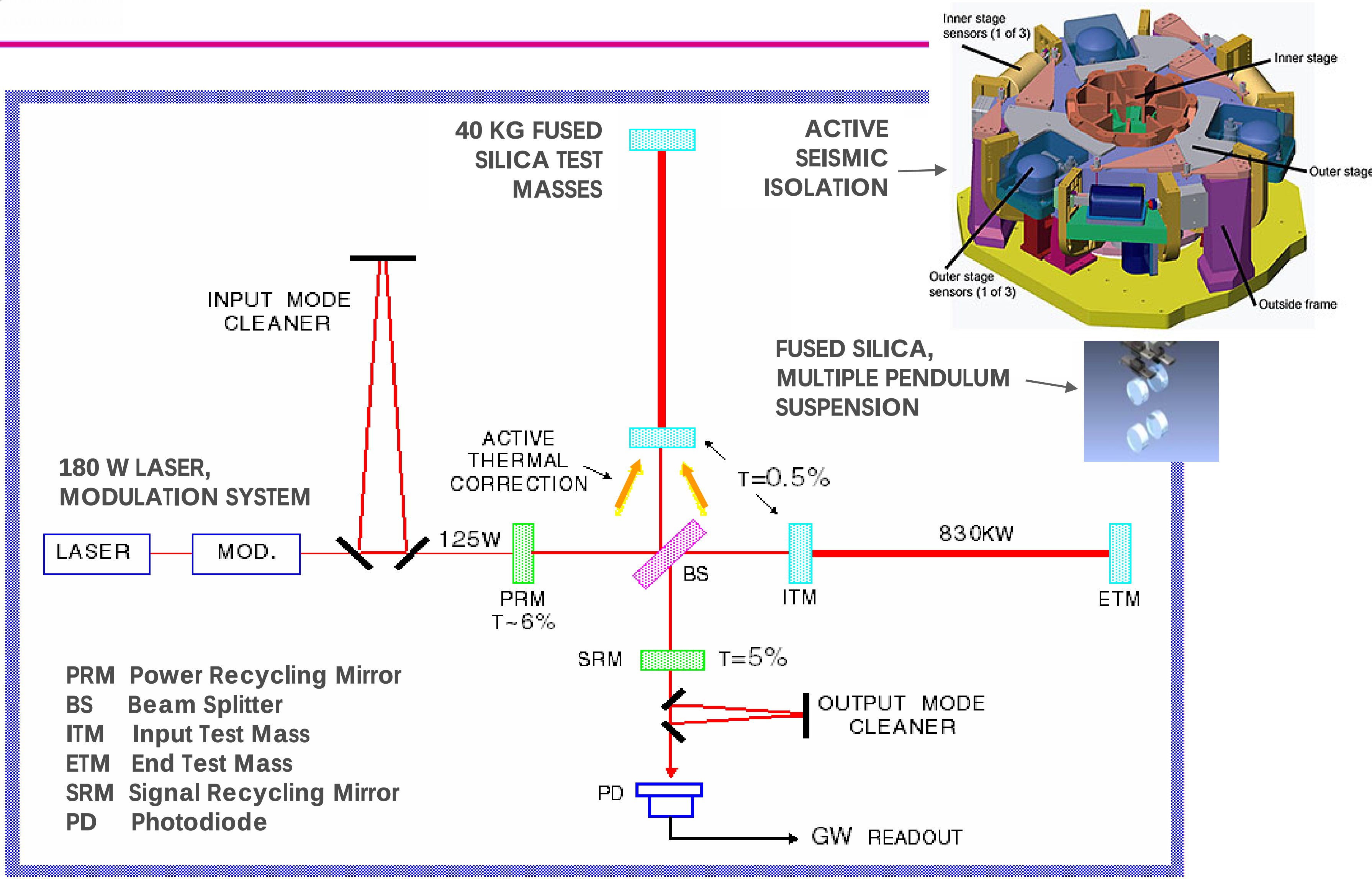
Advanced LIGO Detector Improvements

Retain infrastructure, vacuum chambers, and Initial LIGO layout of power recycled interferometer

- Replace passive seismic isolation with multi-staged system with inertial sensing and feedback control
- Increase number of passive suspension isolation steps and use lower noise activation techniques
- Use lower mechanical-loss materials and construction in suspensions, optical substrates and coatings to reduce thermal noise
- Increase laser power ~20x and reduce optical losses to improve shot noise limits and signal strength
- Add GW signal recycling at output to increase sensitivity and allow narrow band frequency tuning.

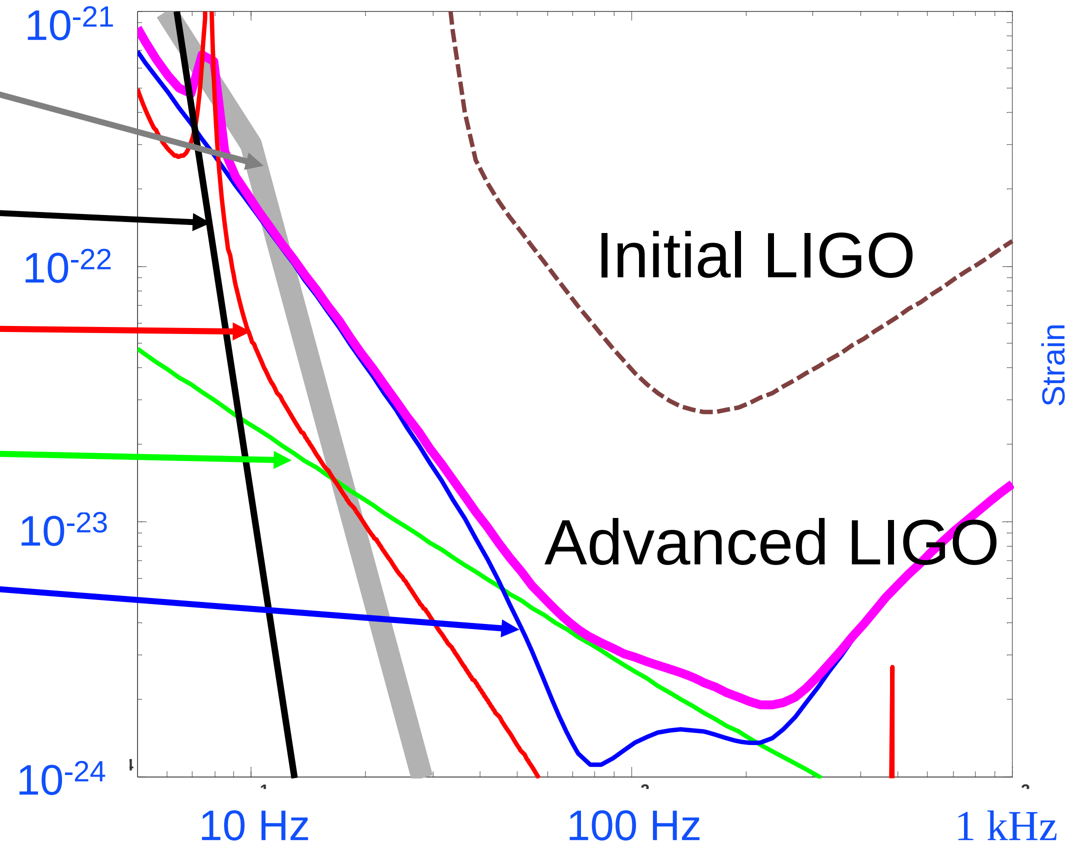


Advanced LIGO Design Features



Projected Adv LIGO Detector Performance

- **Newtonian background, estimate for LIGO sites**
- **Seismic 'cutoff' at 10 Hz**
- **Suspension thermal noise**
- **Test mass thermal noise**
- **Unified quantum noise dominates at most frequencies for full power, broadband tuning**



Advanced LIGO's Fabry-Perot Michelson Interferometer is flexible – can tailor to what we learn before and after we bring it on line, to the limits of this topology and fundamental noise limits.

Active Development and Design Programs

LIGO Lab and members of the LIGO Scientific Collaboration (LSC) are currently developing and designing major subcomponents, with testing of accurate prototypes in context.

Prototype test beds include:

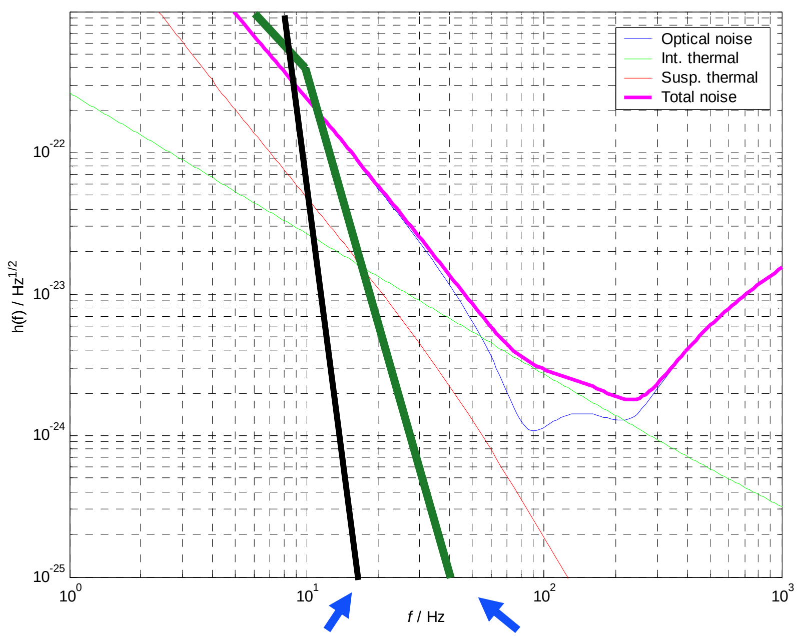
- **Two major LIGO facilities:**
  - **MIT Interferometer facility – full scale tests of seismic isolation, suspensions, laser, mode cleaner**
  - **Caltech 40m Interferometer – sensing/controls tests of readout, engineering model for data acquisition, software**
- **Support from LSC testbeds**
  - **Gingin – thermal compensation**
  - **Glasgow 10m – readout**
  - **Stanford ETF – seismic isolation**
  - **GEO600 – much more than a prototype!**

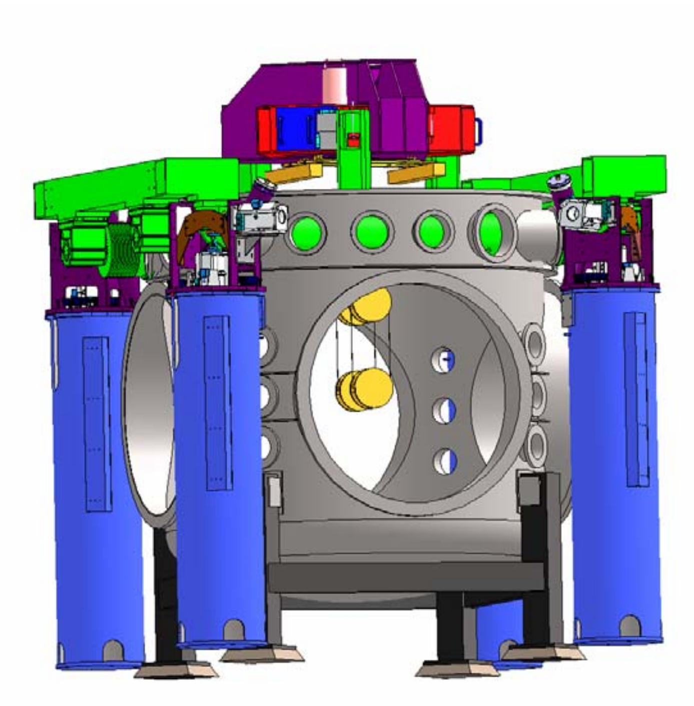
MIT

40 M

Seismic Isolation: Multi-Stage Solution

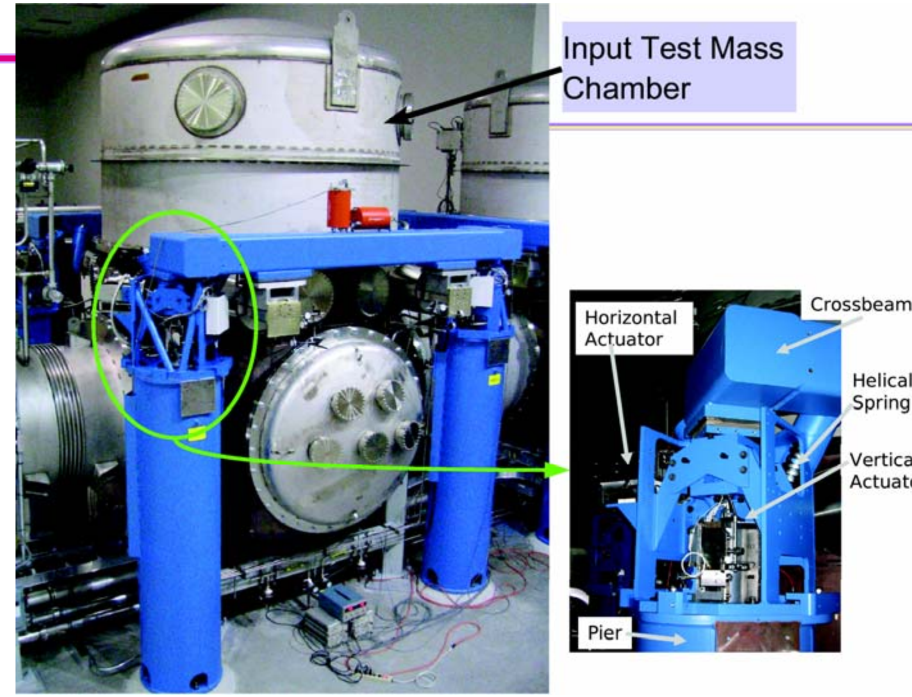
- **Render seismic noise a negligible limitation to GW searches**
  - » Newtonian background will dominate for frequencies less than ~15 Hz
  - » Both suspension and isolation systems contribute to attenuation
- **Reduce actuation forces on test masses**





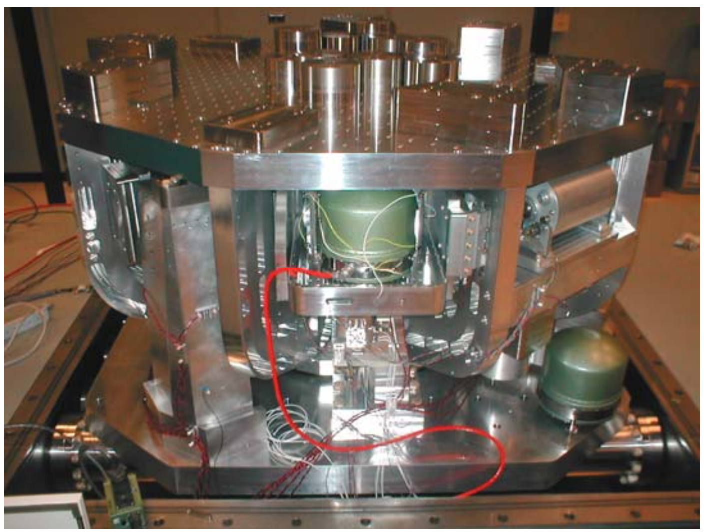
- **Choose an active isolation approach:**
  - » 3 stages of 6 degree-of-freedom each: one external (hydraulic actuation) and two in vacuum
  - » Allows extensive tuning of system after installation, operational modes
- **Increase number of passive isolation stages in suspensions**

Full-Scale Seismic Prototypes & Early Implementation



External pre-isolator installed and operating at Livingston

- Performance meets initial LIGO and exceeds Advanced LIGO requirements



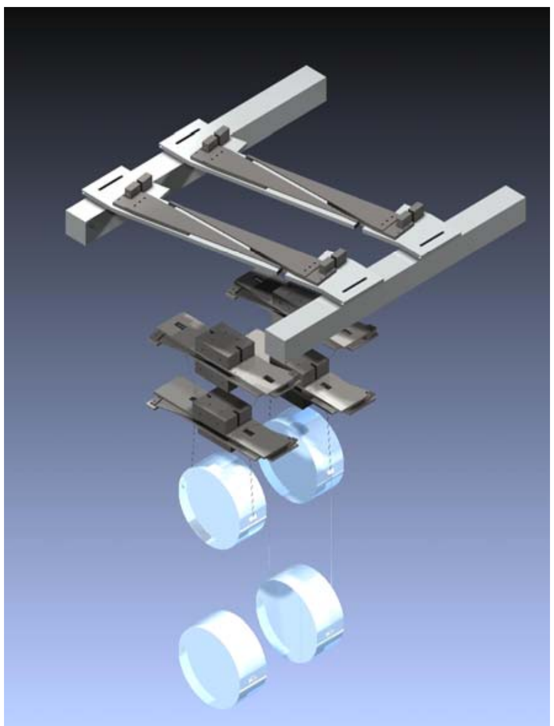
Technology Demonstrator at Stanford in characterization

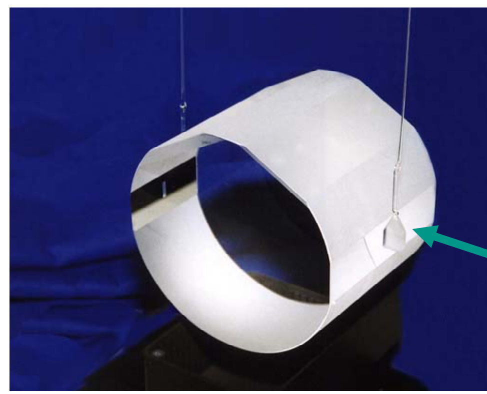
- 1000x Isolation at GW frequencies demonstrated
- 1-10 Hz performance testing in progress

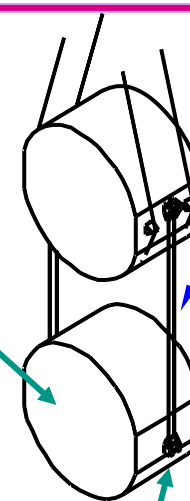
Planned future testing of full scale, integrated seismic isolation and suspensions at MIT's test facility.

Thermal Noise Suppression

- **Minimise thermal noise from pendulum modes and their electronic controls**
  - » Thermally induced motion of the test masses sets the sensitivity limit in the range ~10 — 100 Hz
  - » Required noise level at each of the main optics is 10^{-19} m/√Hz at 10 Hz, falling off at higher frequencies

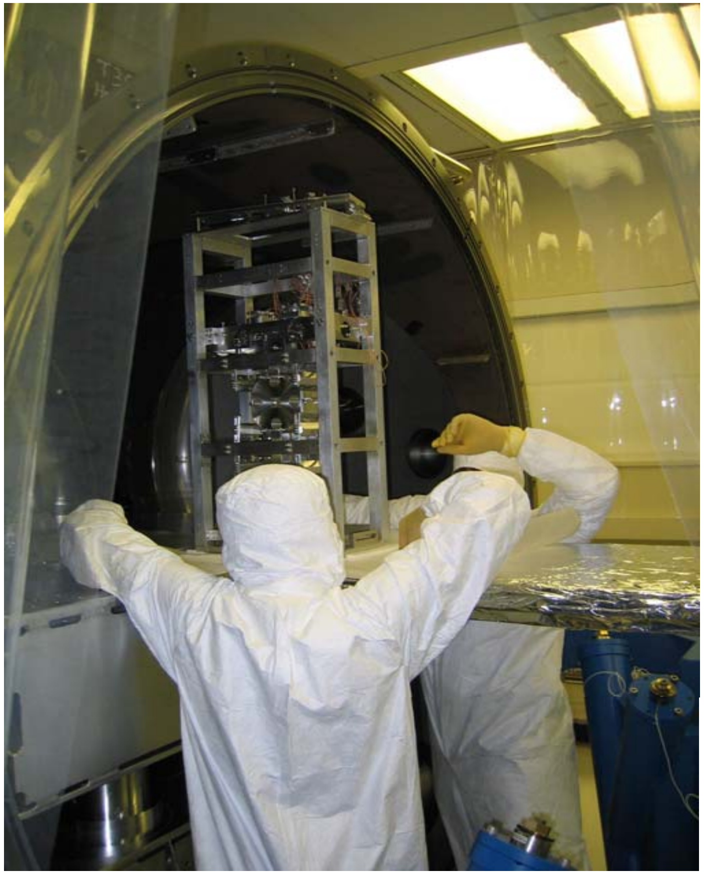






- **Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical optics**
- **Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass**

Thermal Noise Suppression

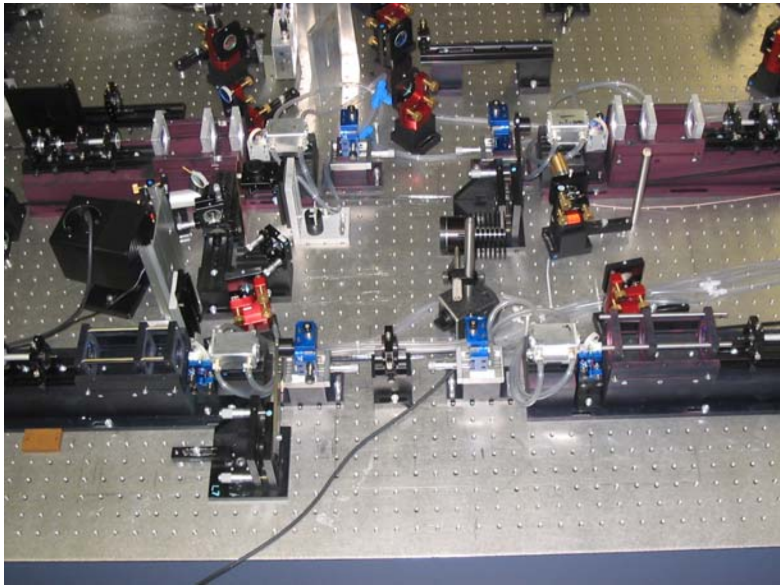


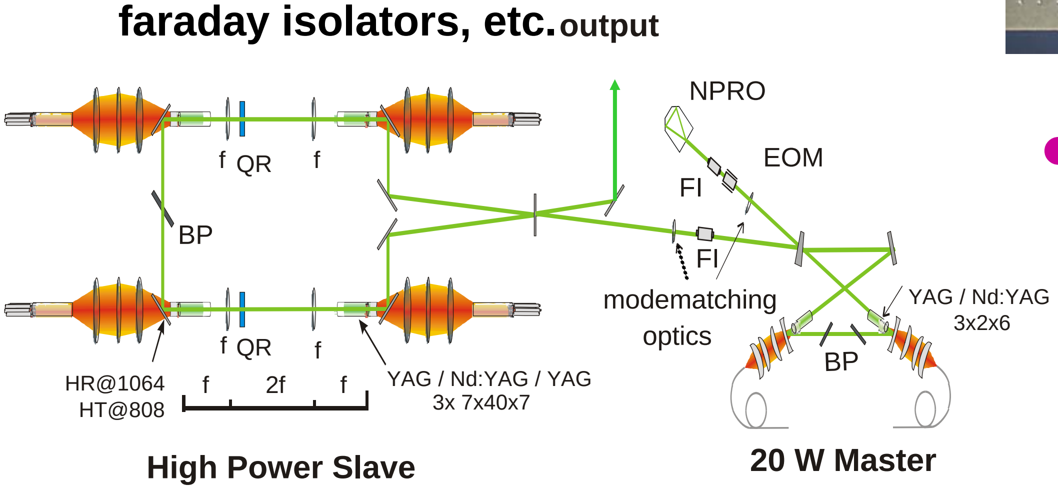
- Reduce mechanical loss from optics by choosing low loss materials
- Recent selection of fused silica for test masses (40 kg, 32 cm dia.)
- Development program underway for suitable coatings with low optical and mechanical losses
  - » Achieved 3.2 10^{-4} for loss goal of 5 10^{-5}

- Stand-alone testing and testing of suspensions coupled with active seismic isolation stages.

Shot Noise Limits

- **Increase laser power to lower shot noise**
  - » **Require TEM00, stability in frequency and intensity**
  - » **Significant motion due to photon pressure – quantum limited**
  - » **~180 W input power is practical limit**
- **Increased laser power (~0.8MW in FP cavities) leads to increased requirements on many components**
  - » **Photo-diodes, optical absorption, thermal lensing compensation, modulators and faraday isolators, etc.**

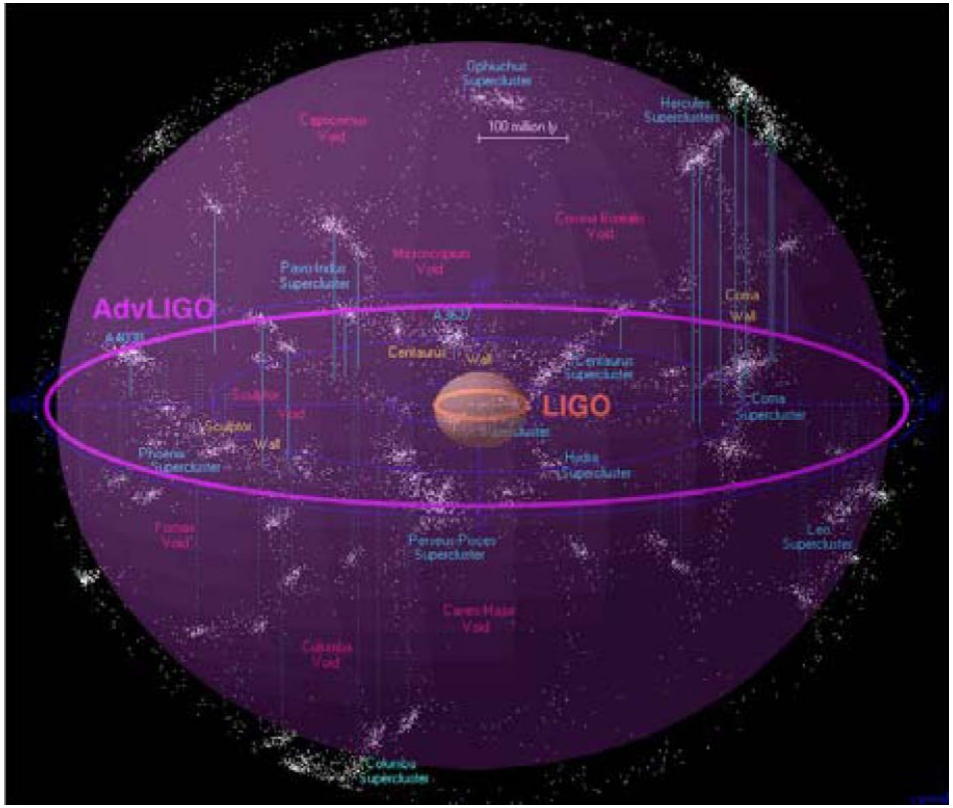




- **Full injection locked master-slave system running, 200 W, linear polarization, single frequency, many hours of continuous operation**

Advanced LIGO Project Funding Status

- **NSB endorsed the Advanced LIGO construction proposal (Oct ’04)**
  - » Contingent upon an integrated year of observation with Initial LIGO
- **NSF & Presidential Out-year Budget includes Advanced LIGO!**
  - » One of 3 proposed new starts next 3 years
  - » NSF proposed FY08 funding start (FY07 start is a possibility)
- **AEI Budget will include Adv. LIGO**
  - » Presidential Board of Max Planck Society endorsed AEI plans for material contribution; funding levels being determined
- **PPARC Funding already available**
  - » UK Adv. LIGO material contribution funded. In development phase.
- **LIGO/LSC Development & Planning:**
  - » Research, Design & Development phase in progress



Sky map showing locations of superclusters, walls, and voids of galaxies within about 500 million light years. Superimposed circles show the range of LIGO (orange inner circle) and the 10 times larger range of AdvLIGO (purple outer circle). The milky way is at the center in this representation. *Credit: the underlying black and white image with names of clusters and voids is by Richard Powell; the superimposed color circles were added by Beverly Berger, Division of Physics, NSF.*

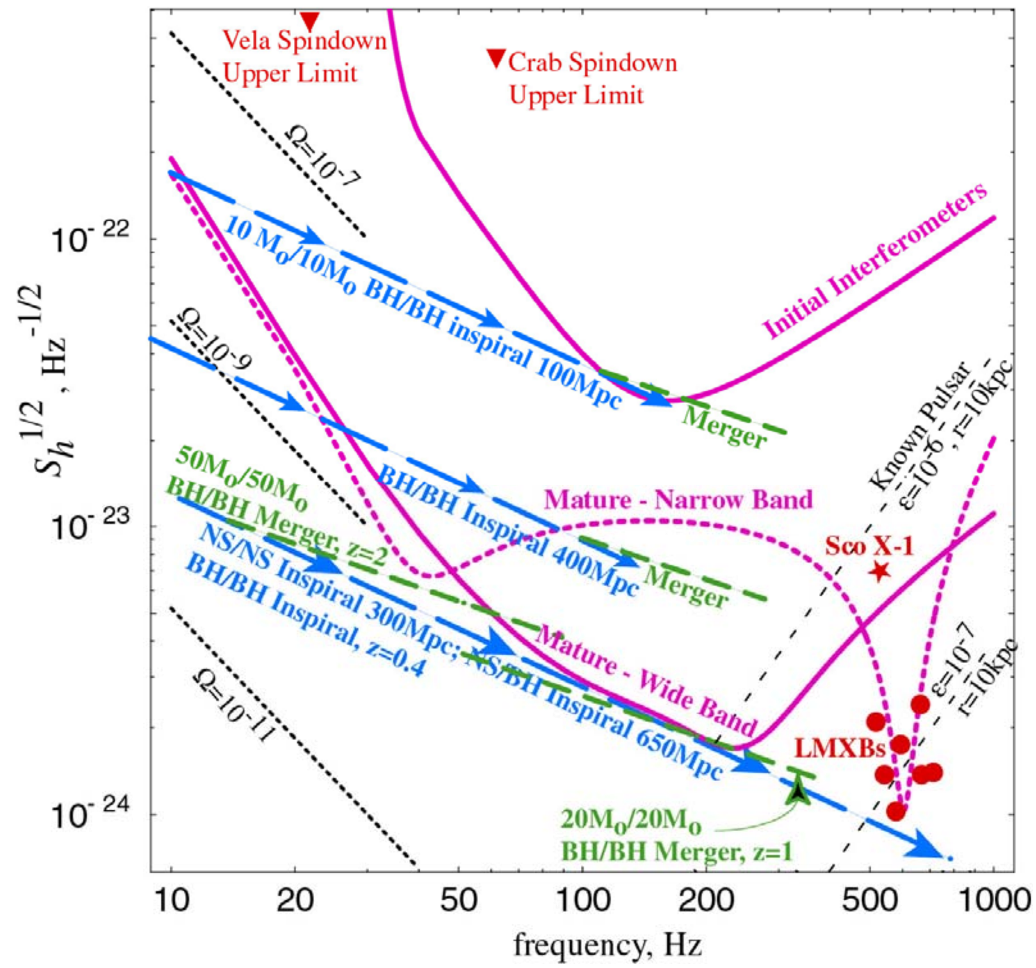
Overall Projected Cost and Schedule

- **Request for NSF construction funding ~$185M**
  - » **Final cost and schedule under development. Review expected ~mid-2006**
- **International partners contribute potential additional $25.5M (includes development as well as construction)**
  - » **UK (PPARC) - approved and funded**
  - » **Germany (MPS) - endorsed; funding levels being determined**
  - » **Australia (ARC + other) - proposed**
- **Development Schedule *(Contingent on present RD&D budgets as well as funding start date)***
  - » **Major subsystems in preliminary design and prototype testing phase**
  - » **Expect to have final designs, excluding just-in-time components, by proposed NSF MREF funding date FY2008.**
- **Construction Schedule *(Following Presidential Out-year Budget recommendations)***
  - » **Start fabrication in FY2008 when funds available.**
  - » **Shutdown Livingston in FY10, but continue Hanford operations**
  - » **Shutdown Hanford in FY11.**
  - » **Schedule installation work to minimize downtime and make effective use of "specialized" work force.**
  - » **Resume coincidental observations in FY13 (caveat: see first bullet)**

Advanced vs. Initial LIGO Astrophysical Reach

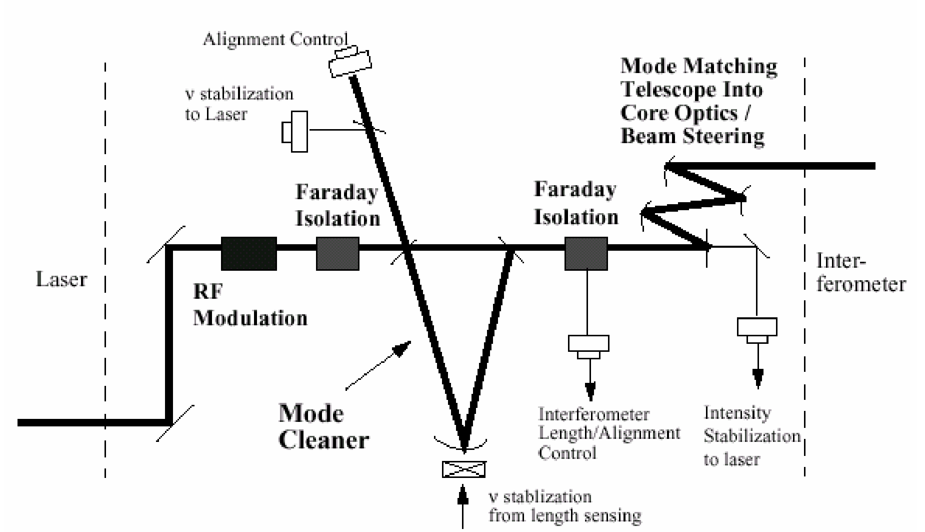
Upgrade all 3 Interferometers and convert Hanford 2K to 4K Interferometer

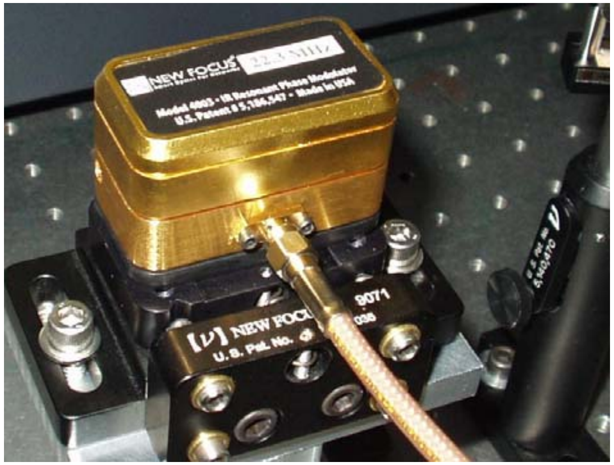
- **Factor of 10 better amplitude sensitivity**
- **Factor of 4 lower frequency bound**
- **Potential for tunable, narrow band searches**
  - » Change transmission of recycling mirrors by changing mirrors or using tunable transmission mirror



Input Optics and Modulation

- **Design similar to initial LIGO but 20x higher power**
  - » Provides phase modulation for length, angle control (Pound-Drever-Hall)
  - » Stabilizes beam position, frequency with suspended mode-cleaner cavity
  - » Matches into main optics (6 cm beam) with suspended telescope
- **University of Florida leading development**
  - » As for initial LIGO
- **Testing at LLO High-Power Laser Facility**
  - » Lab acquisition of 100W test laser, high-power test lab at Livingston
  - » 90W, 700 micron dia beam in RTP – full power for likely configuration

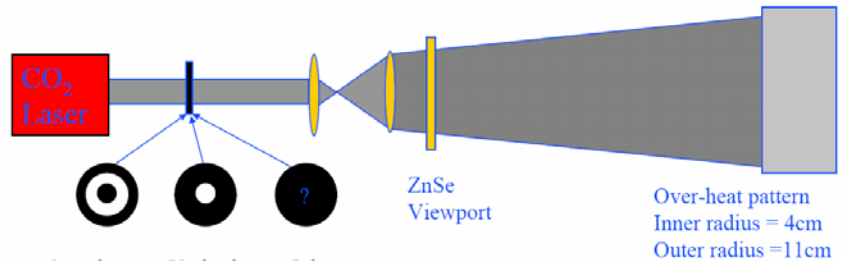


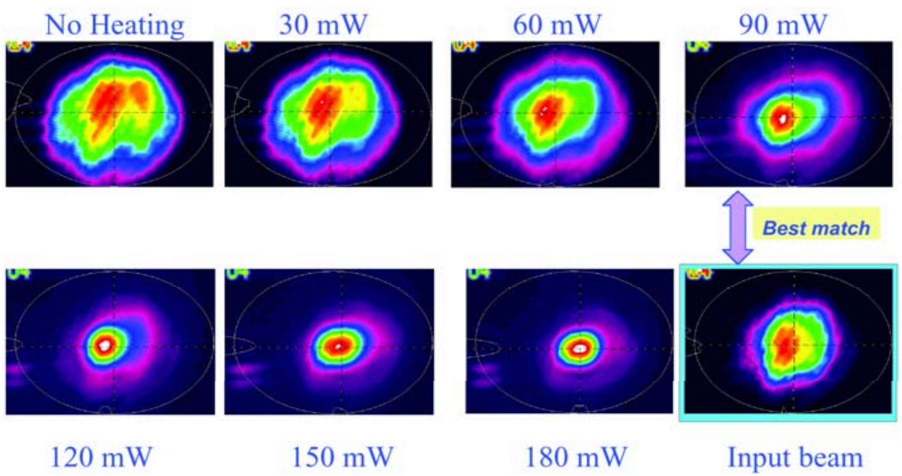


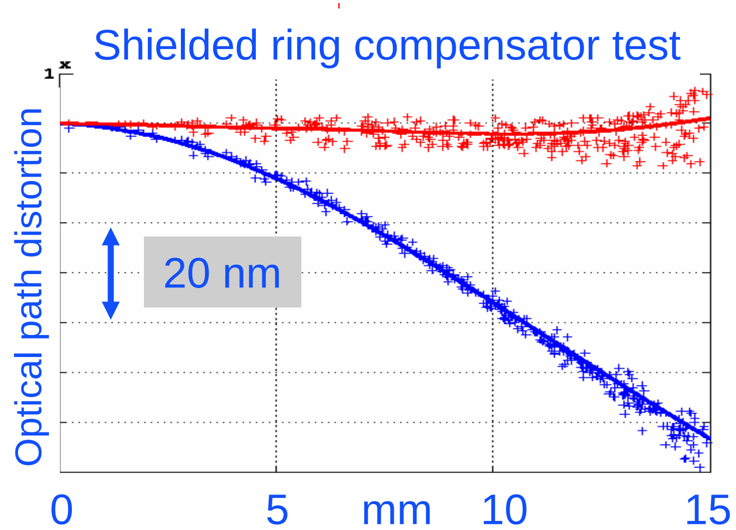
What is this? FI?

Active Thermal Compensation

- Removes excess 'focus' due to absorption in coating, substrate
- Allows optics to be used at all input powers
- Sophisticated thermal model ('Melody') developed to calculate needs and solution





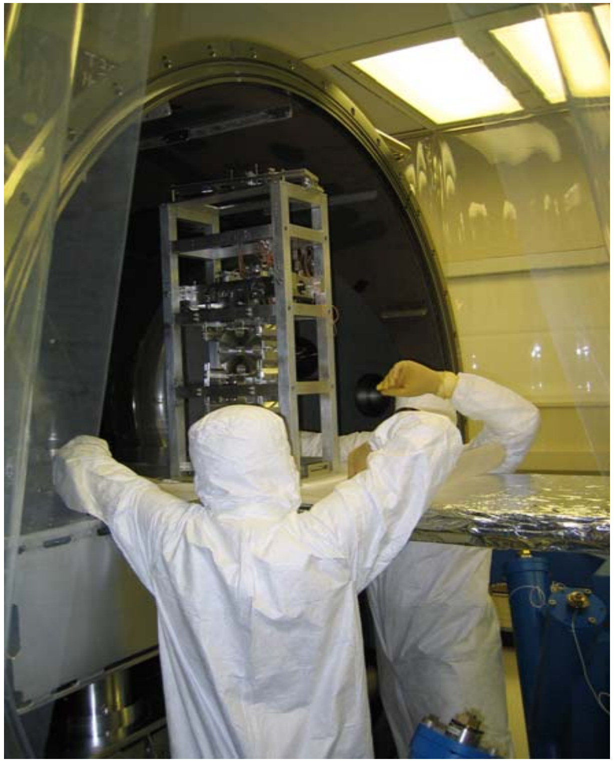


- Successful application to initial LIGO using new 'staring' approach
- Modeling, investigating effect on sidebands and point absorbers

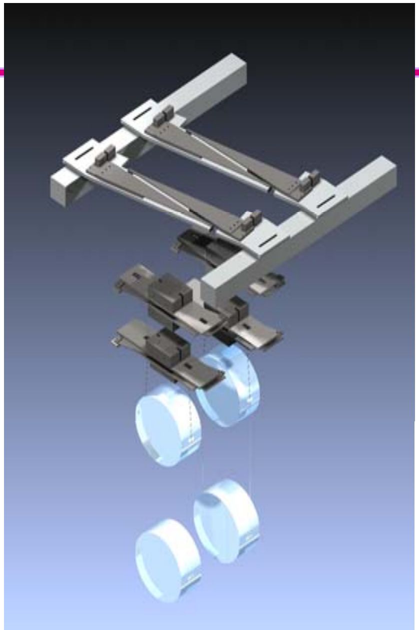
Thermal Noise Suppression

- **Reduce core optics and suspension thermal noise: complement seismic noise system.**
  - » Chose low loss materials and techniques

Triple pendulum suspension testing at MIT facility



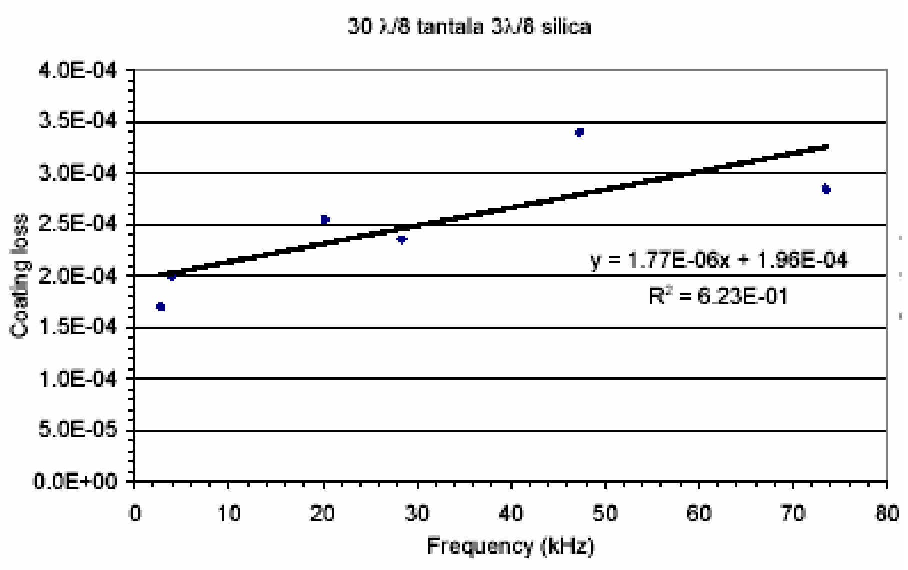
Quad pendulum

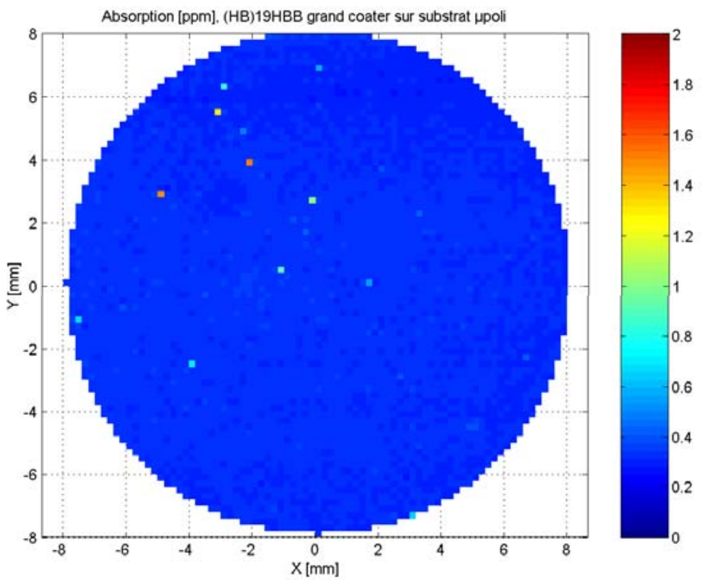


- **Suspensions**
  - » Adopt successful GEO600 and VIRGO designs
  - » Quadruple pendulum design chosen for test masses; triple pendulum for other core optics
  - » Fused silica fibers, bonded to test mass
  - » Leaf springs (VIRGO origin) for vertical compliance
  - » Quad leader and funding in UK: Rutherford, U Glasgow, Birmingham
  - » Triple pendulum leader at Caltech

Optical Coatings

- **Optical Properties**
  - » Require low average absorption (0.5 ppm) to limit thermal distortion
  - » Require freedom from point absorbers to limit inhomogeneous distortion
  - » Maps of low-absorption coatings measured give average 0.32 ppm

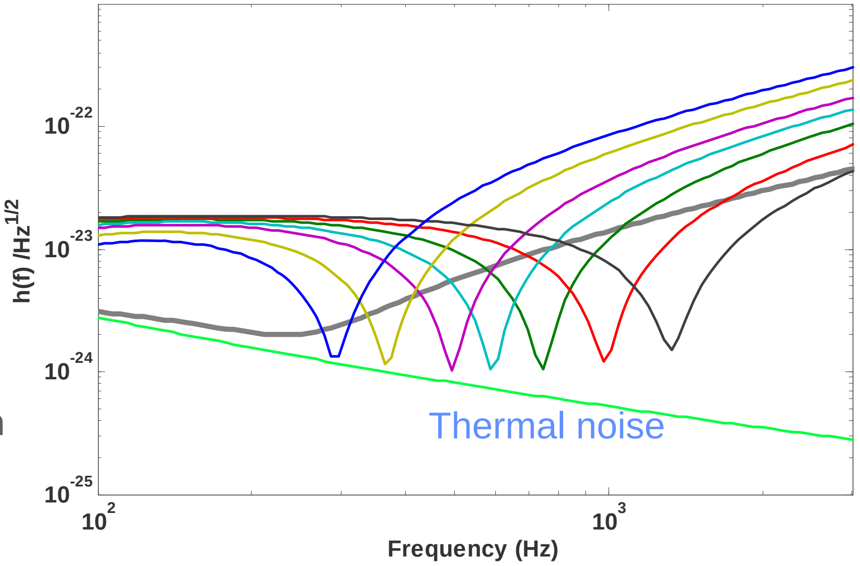


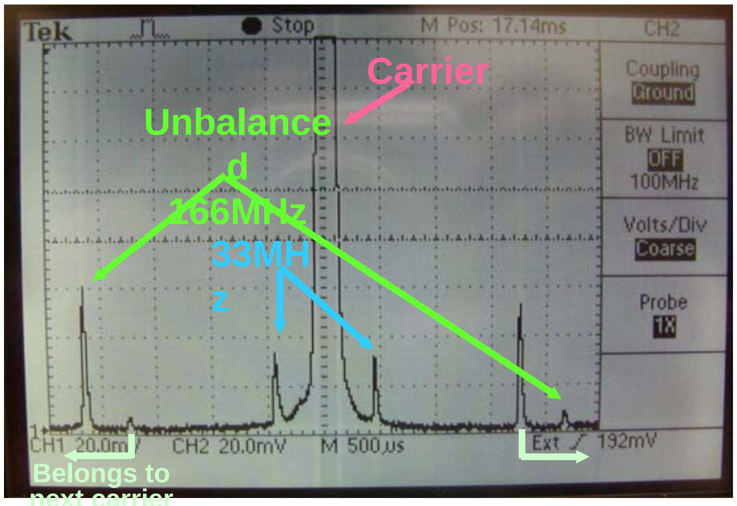


- **Thermal Properties**
  - » Evidence of frequency dependence of coating mechanical loss lower at lower (GW) frequencies
  - » Continuing research on dopants and processing for incremental approach from 3.2 10^{-4} to

GW Readout, Systems

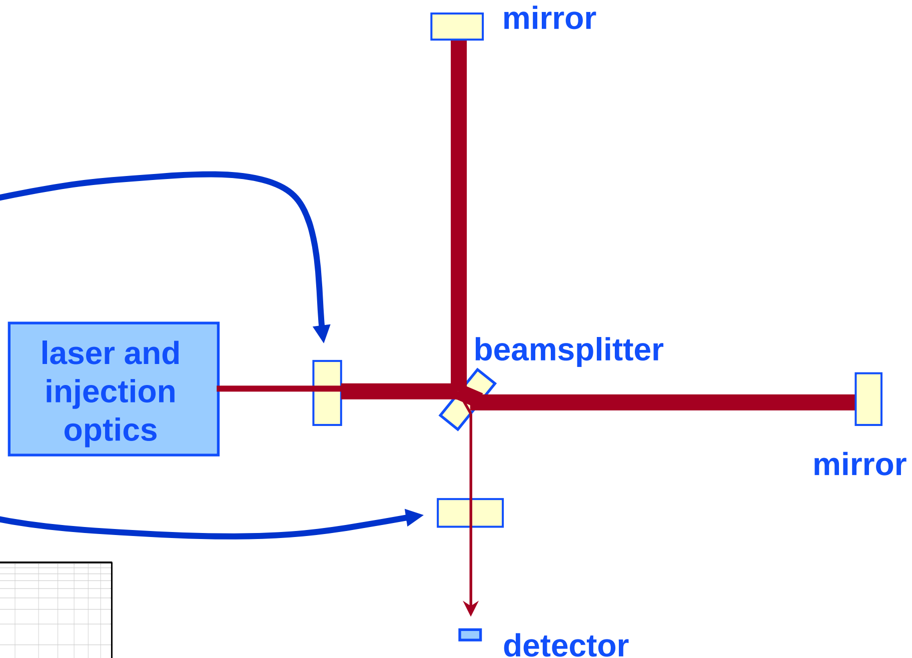
- **Signal recycled Michelson with Fabry-Perot configuration**
  - » Offers resonance for signal frequencies
  - » Can also provide narrowband response
- **DC rather than RF for GW sensing**
  - » Best SNR, simplifies laser, photo-detection requirements
- **Caltech 40m prototype giving guidance to design**
  - » Exploring modulation techniques; adoption of Mach-Zehnder design to avoid 'sidebands on sidebands'
  - » Off-resonance arm lock with Dual-recycled Michelson



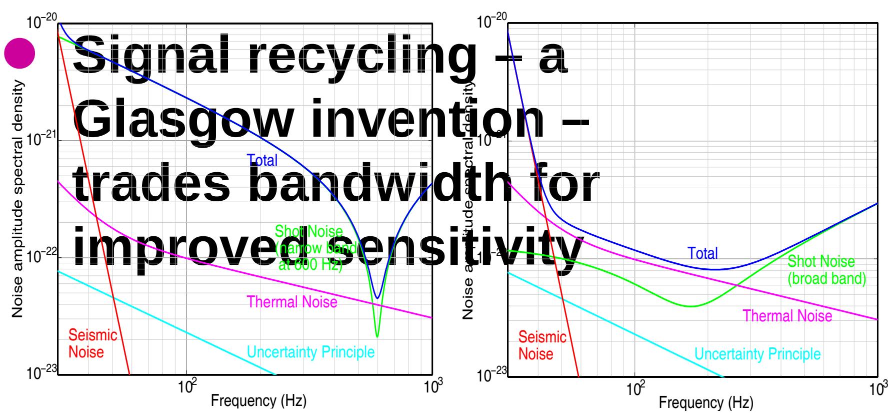


Advanced interferometry

- One of the fundamental limits to interferometer sensitivity is photon shot noise
- Power recycling effectively increases the laser power



- Signal recycling – a Glasgow invention – trades bandwidth for improved sensitivity



- With signal recycling the frequency and bandwidth of the optimum sensitivity are easily adjustable