Advanced LIGO

Daniel Sigg,
for the LIGO Scientific Collaboration

TAUP, University of Washington

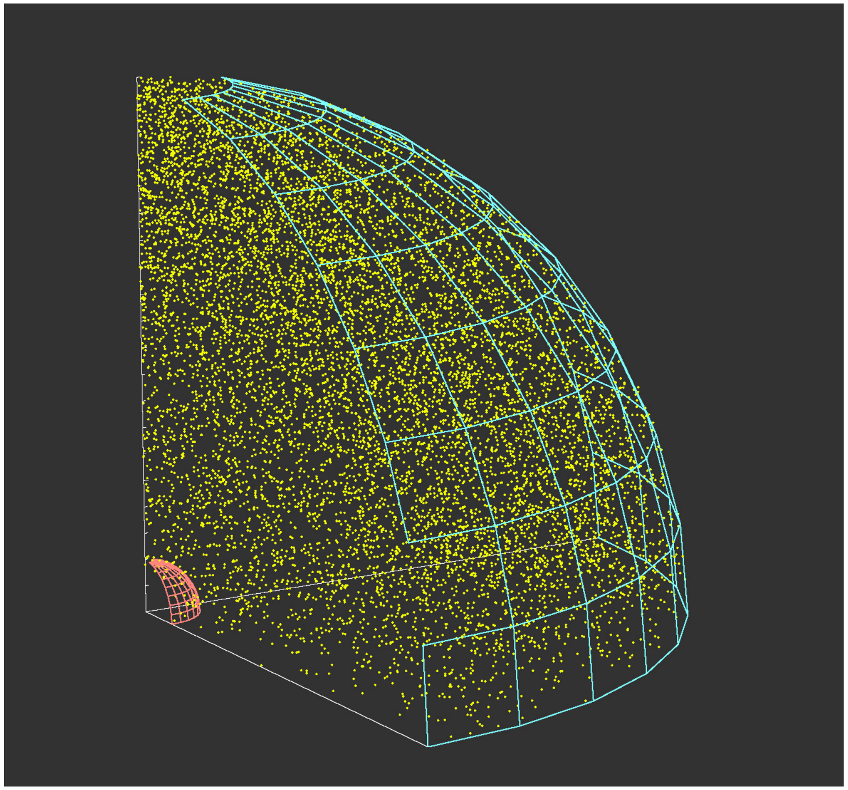
September 8, 2003

G030488-00-M

Advanced LIGO

- LIGO mission: detect gravitational waves and

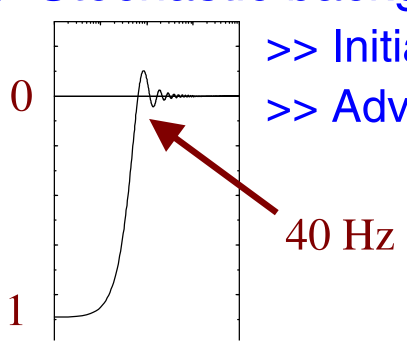
  initiate GW astronomy
- Next detector
  - Should have assured detectability of known sources
  - Should be at the limits of reasonable extrapolations of detector physics and technologies
  - Must be a realizable, practical, reliable instrument
  - Should come into existence neither too early nor too late



→ **Advanced LIGO**

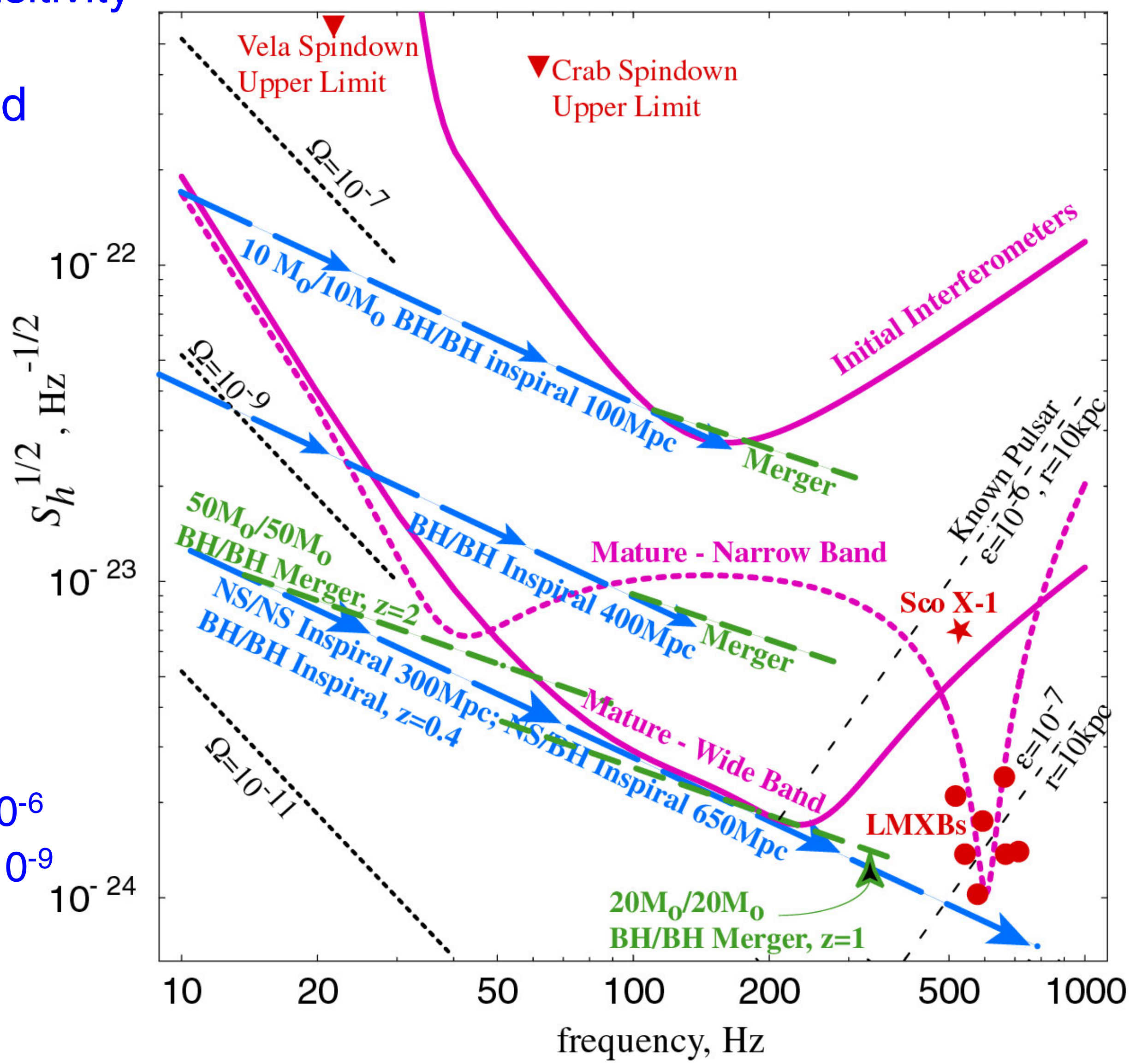
Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - (Reach)[3] = rate
- Factor 4 lower frequency bound
- Factor 100 better narrow-band
- NS Binaries:
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~350 Mpc
- BH Binaries:
  - Initial LIGO: 10 M_o, 100 Mpc
  - Adv LIGO : 50 M_o, z=2
- Known Pulsars:
  - Initial LIGO: $\varepsilon = 3 \times 10^{-6}$
  - Adv LIGO $\varepsilon = 2 \times 10^{-8}$
- Stochastic background:



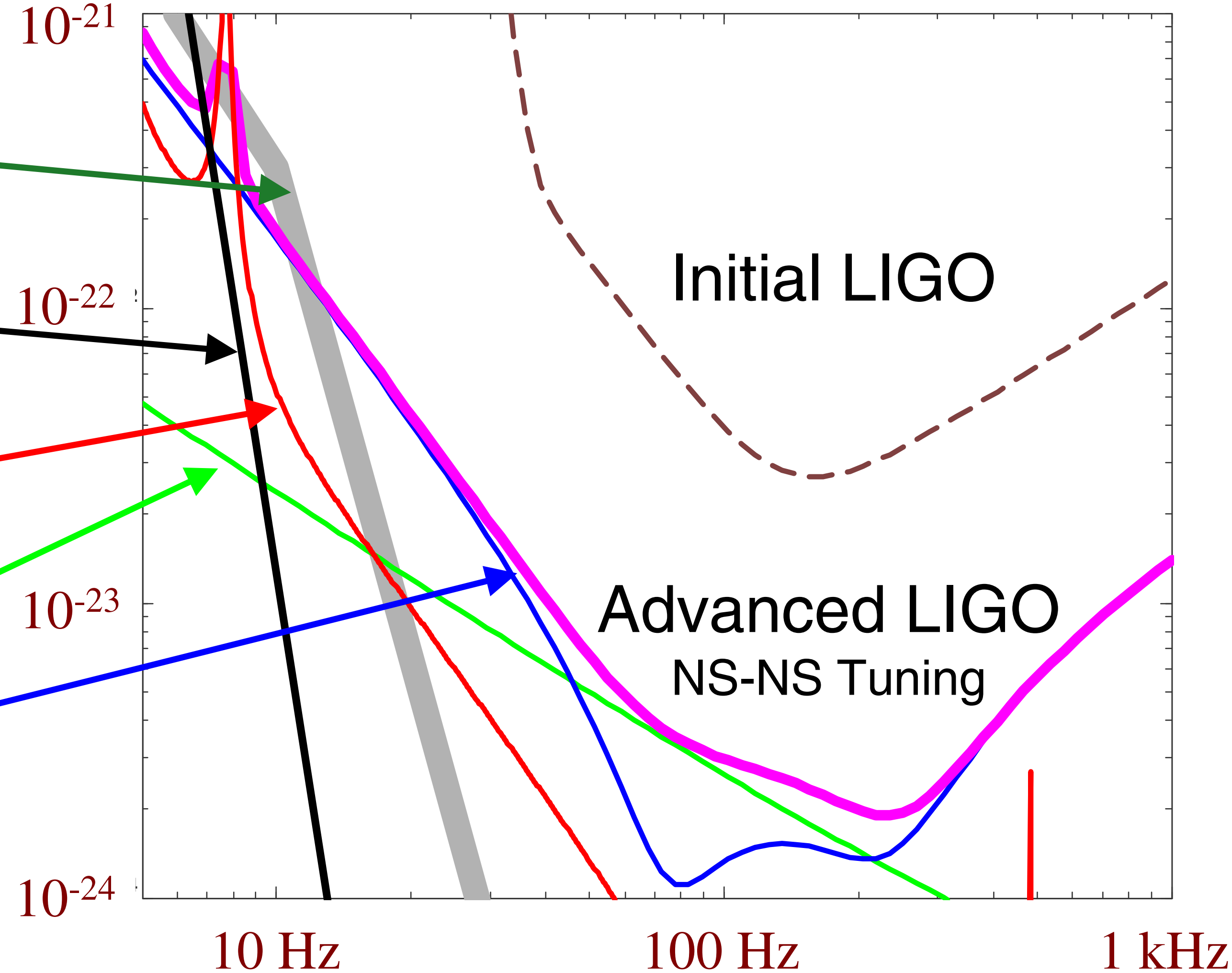
>> Initial LIGO: $\Omega \sim 3 \times 10^{-6}$

>> Adv LIGO: $\Omega \sim 3 \times 10^{-9}$



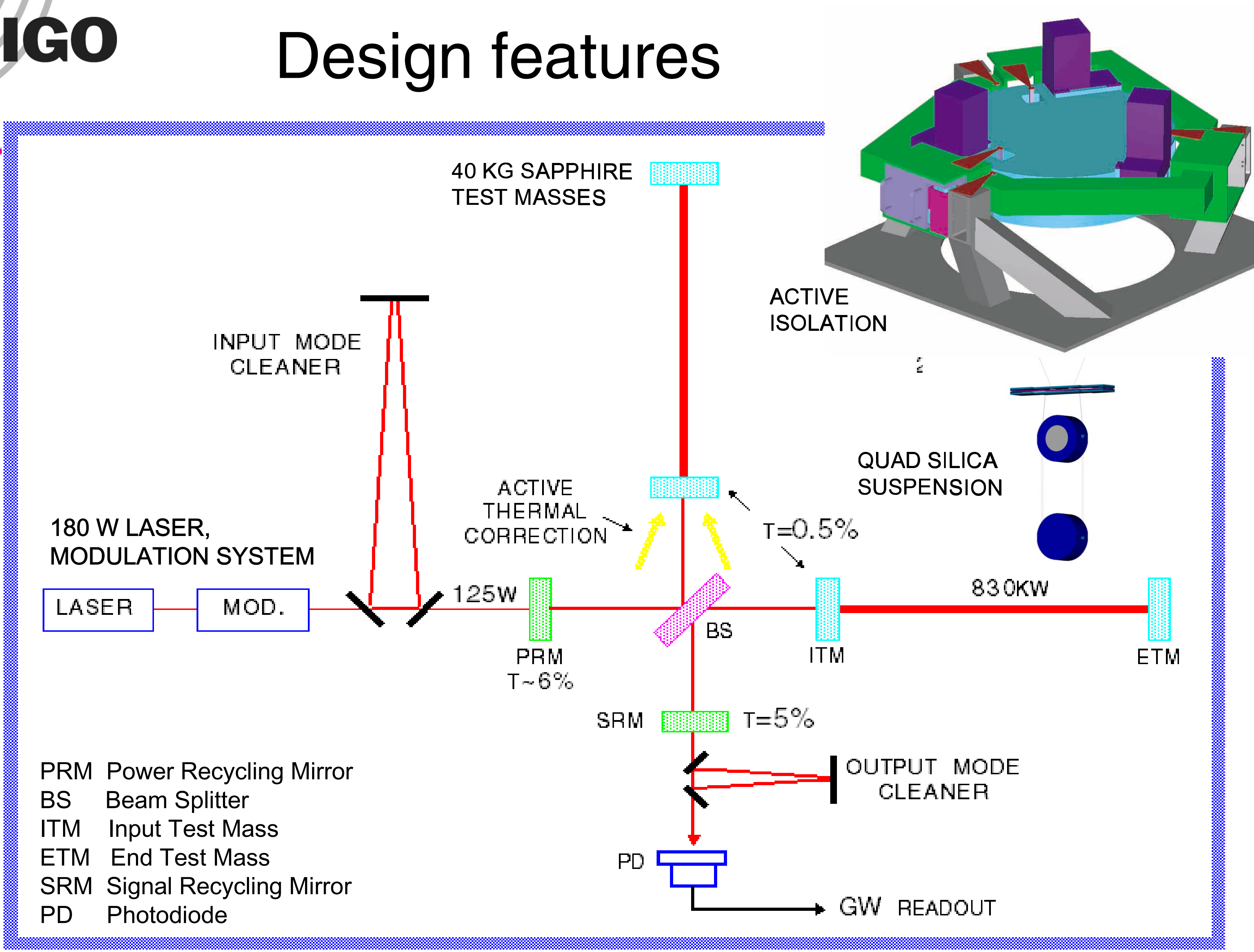
Anatomy of the projected Adv LIGO detector performance

- 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



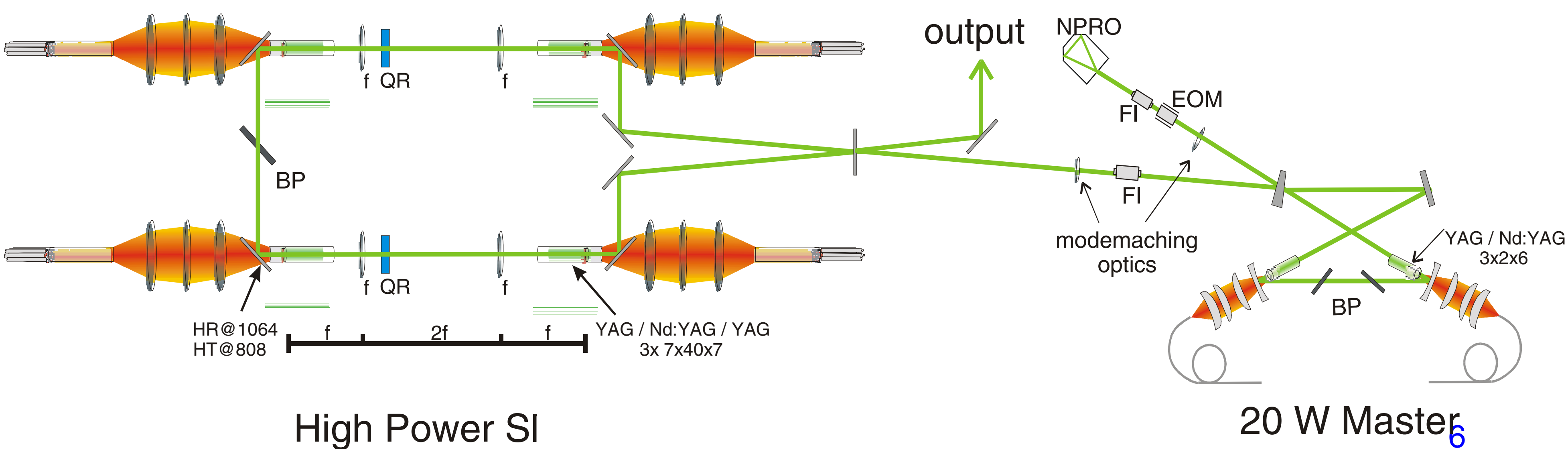
- Advanced LIGO's Fabry-Perot Michelson Interferometer is a platform for currently envisaged enhancements to this detector architecture (e.g., flat-top beams; squeezing; Newtonian background suppression)

Design features



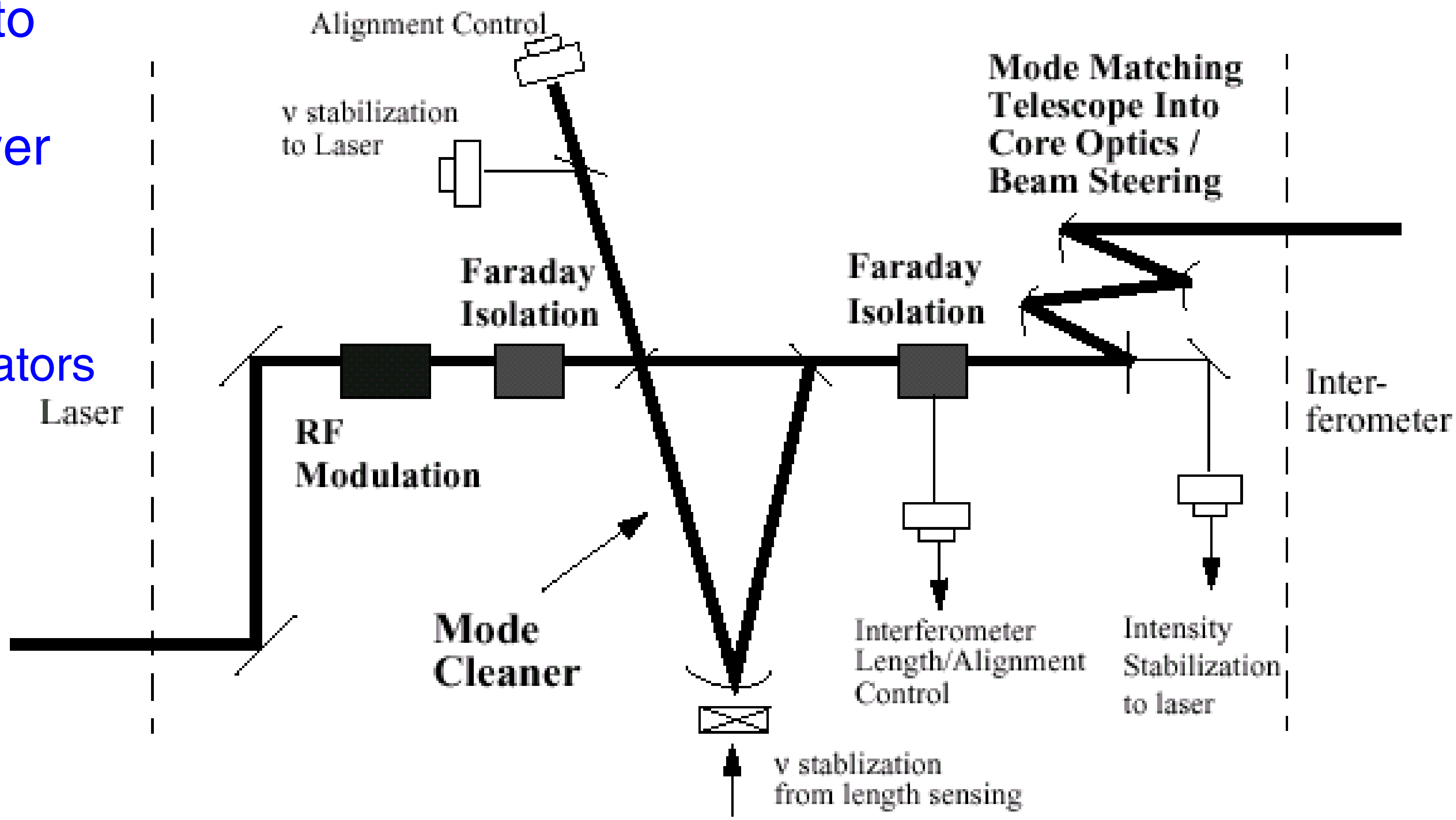
Pre-stabilized Laser

- Require the maximum power compatible with optical materials
  - 180W 1064nm Nd:YAG
  - Baseline design continuing with end-pumped rod oscillator, injection locked to an NPRO
  - 2003: Prototyping well advanced – ½ of Slave system has developed 100 W



Input Optics

- Provides phase modulation for length, angle control (Pound-Drever-Hall)
- Stabilizes beam position, frequency with suspended mode-cleaner cavity
- Intensity stabilization to in-vacuum photodiode,
  2×10^{-9} $\Delta P/P$ at 10 Hz required (1×10^{-8} at 10 Hz demonstrated)
- Design similar to initial LIGO but 20x higher power
- Challenges:
  - Modulators
  - Faraday Isolators



Test Masses / Core Optics

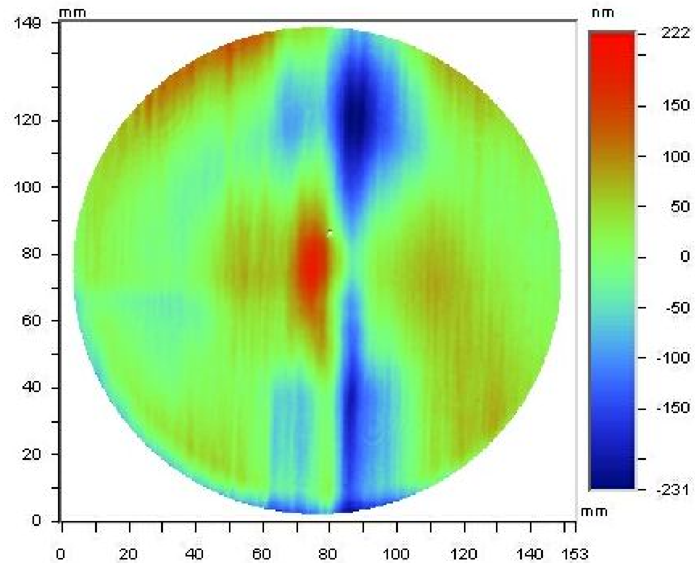
- Absolutely central mechanical *and* optical element in the detector
  - 830 kW; <1ppm loss; <20ppm scatter
  - 2x10^8 Q; 40 kg; 32 cm dia
- Sapphire is the baseline test mass/core optic material; development program underway
- Characterization by very active and broad LSC working group
- Low mechanical loss, high density, high thermal conductivity all desirable attributes of sapphire
- Fused silica remains a viable fallback option

Full-size Advanced LIGO sapphire substrate

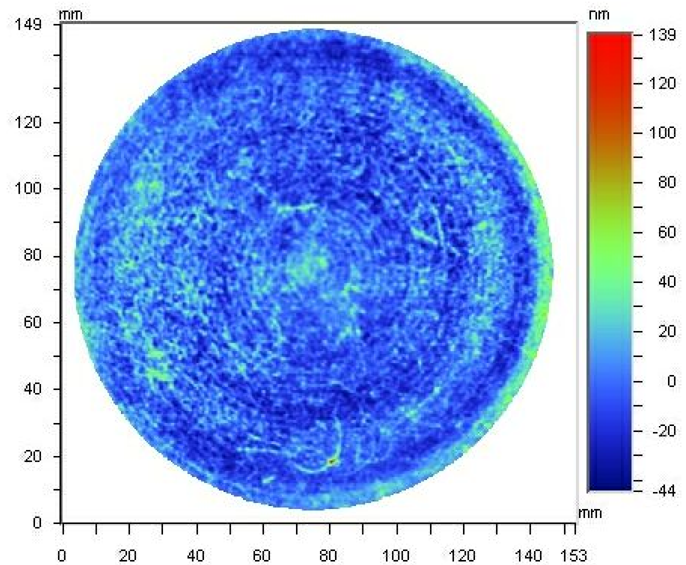
Core Optics

- Fabrication of Sapphire:
  - 4 full-size Advanced LIGO boules grown (Crystal Systems); 31.4 x 13 cm; two acquired
- Mechanical losses: requirement met
  - recently measured at 200 million (uncoated)
- Bulk Homogeneity: requirement met
  - Sapphire as delivered has 50 nm-rms distortion
  - Goodrich 10 nm-rms compensation polish
- Polishing technology:
  - CSIRO has polished a 15 cm diam sapphire piece: 1.0 nm-rms uniformity over central 120 mm (requirement is 0.75 nm)
- Bulk Absorption:
  - Uniformity needs work
  - Average level ~60 ppm, 40 ppm desired
  - Annealing shown to reduce losses

Compensation Polish



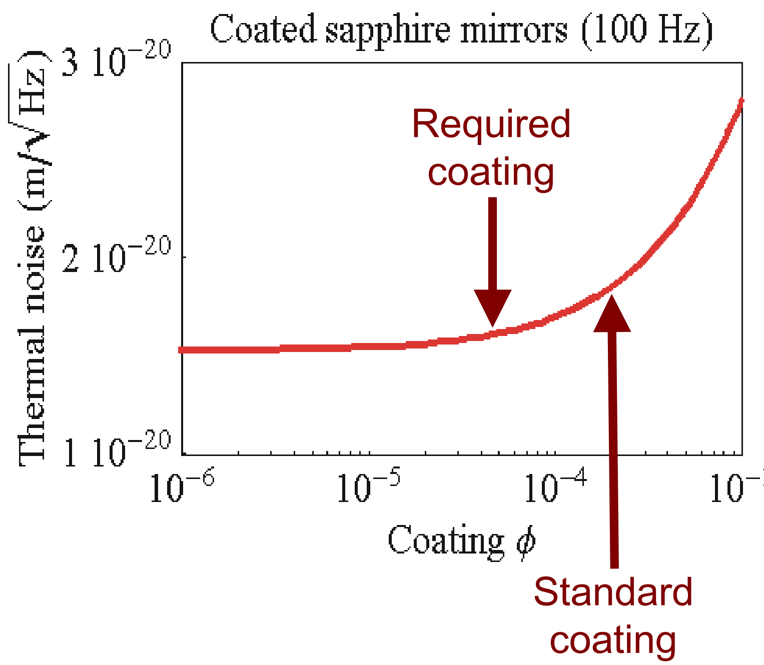
before



after

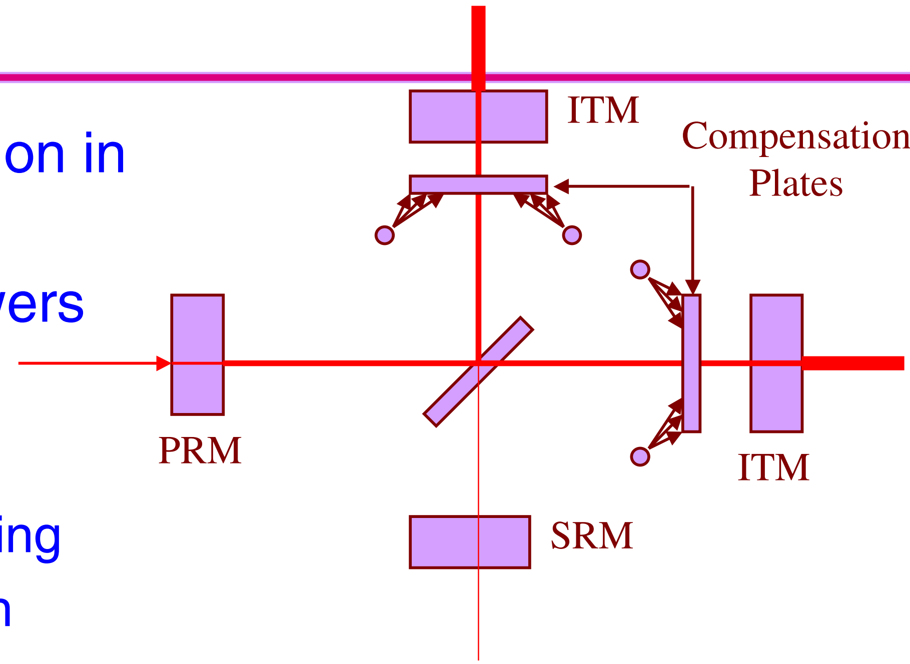
Test Mass Coatings

- Optical absorption (~0.5 ppm), scatter meet requirements for (good) conventional coatings
- Thermal noise due to coating mechanical loss recognized; program put in motion to develop low-loss coatings
- Ta_2O_5 identified as principal source of loss
- Test coatings show somewhat reduced loss
  - Alumina/Tantala
  - Doped Silica/Tantala
- Need ~5x reduction in loss to make compromise to performance minimal
- Expanding the coating development program
- First to-be-installed coatings needed in ~2.5 years – sets the time scale

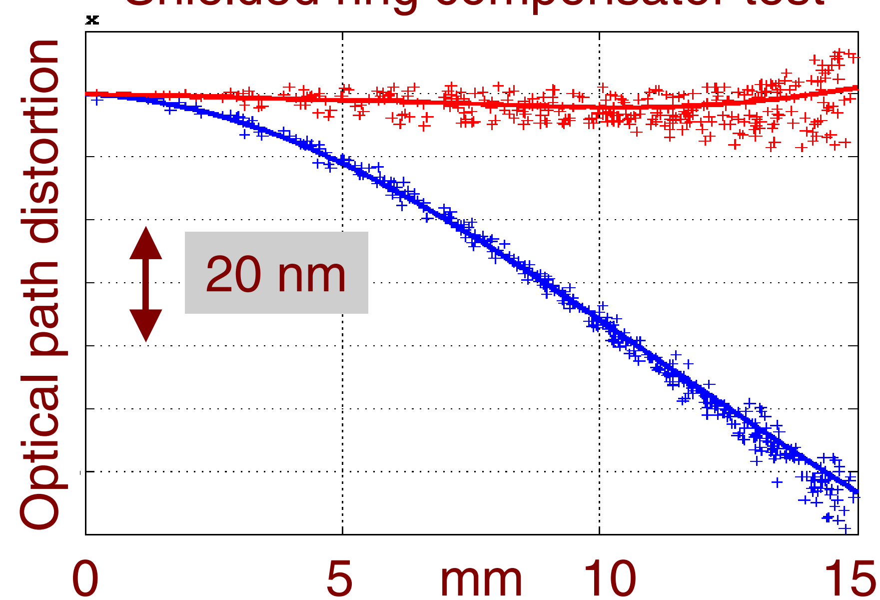


Active Thermal Compensation

- Removes excess 'focus' due to absorption in coating, substrate
- Allows optics to be used at all input powers
- Initial R&D successfully completed
  - Ryan Lawrence MIT PhD thesis
  - Quasi-static ring-shaped additional heating
  - Scan to complement irregular absorption
- Sophisticated thermal model ('Melody') developed to calculate needs and solution
- Gingin facility (ACIGA) readying tests with Lab suspensions, optics
- Application to initial LIGO in preparation

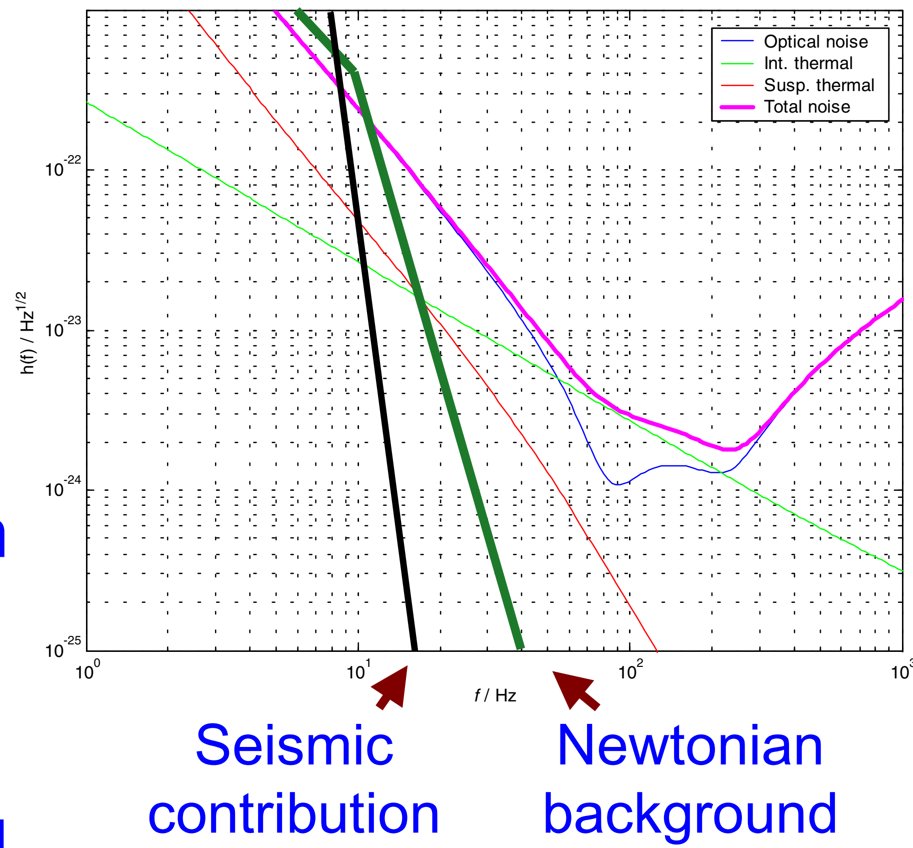


Shielded ring compensator test



Isolation: Requirements

- Render seismic noise a negligible limitation to GW searches
  - Newtonian background will dominate for frequencies less than ~15 Hz
  - Suspension and isolation contribute to attenuation
- Reduce or eliminate actuation on test masses
  - Actuation source of direct noise, also increases thermal noise
  - Acquisition challenge greatly reduced
  - In-lock (detection mode) control system challenge is also reduced

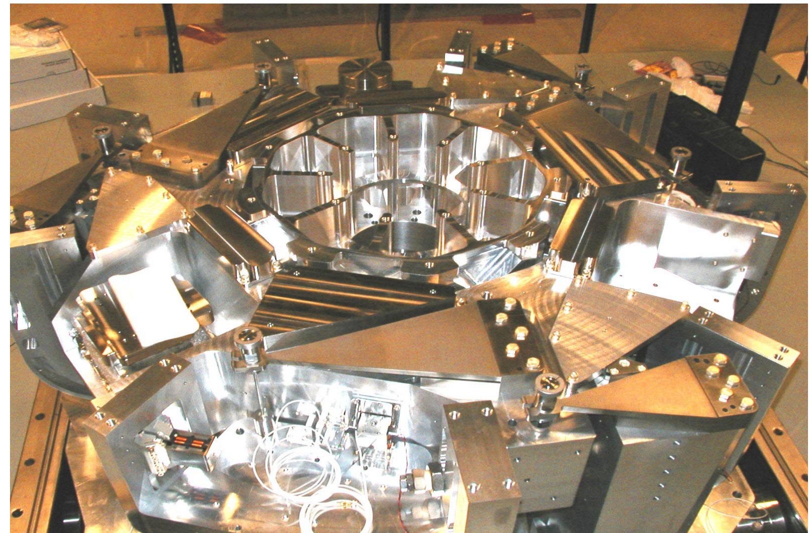


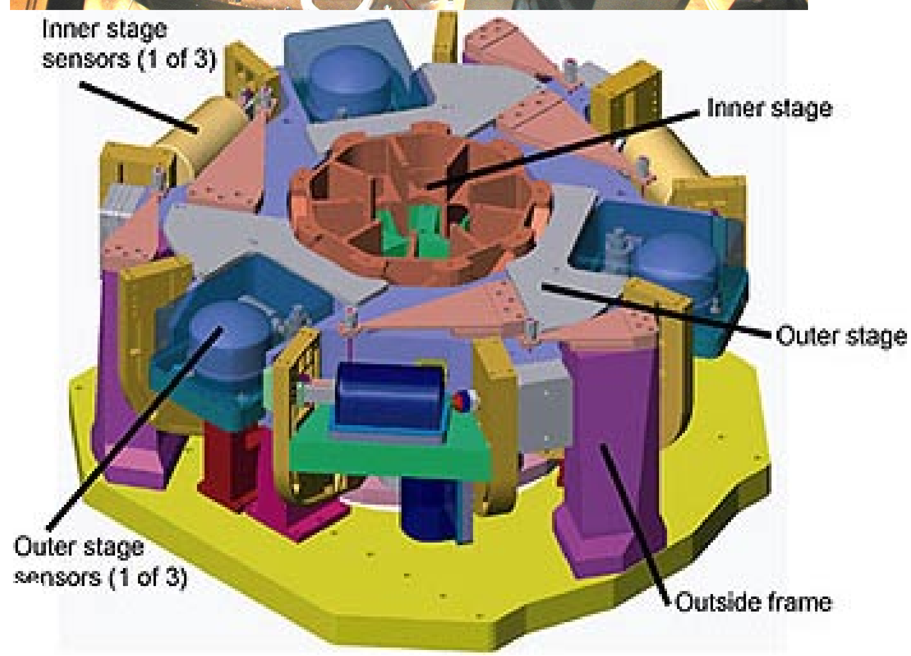
Isolation: Pre-Isolator

- External stage of low-frequency pre-isolation (→ ~1 Hz)
  - Tidal, microseismic peak reduction
  - DC Alignment/position control and offload from the suspensions
  - 1 mm pp range
- Lead at Stanford
- Prototypes in test and evaluation at MIT for early deployment at Livingston in order to reduce the cultural noise impact on initial LIGO
  - System performance exceeds Advanced LIGO requirements

Isolation: Two-stage platform

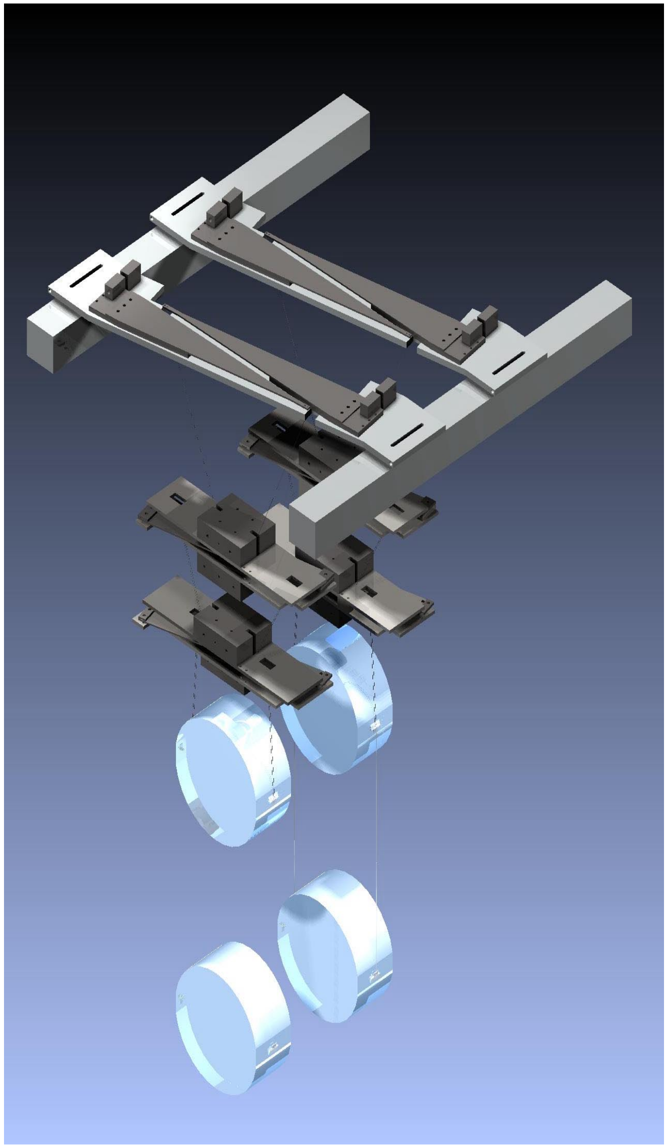
- Choose an active approach:
  - high-gain servo systems, two stages of 6 degree-of-freedom each
  - Allows extensive tuning of system after installation, operational modes
  - Dynamics decoupled from suspension systems
- Lead at LSU
- Stanford Engineering Test Facility Prototype fabricated
  - Mechanical system complete
  - Instrumentation being installed
  - First measurements indicate excellent actuator – structure alignment





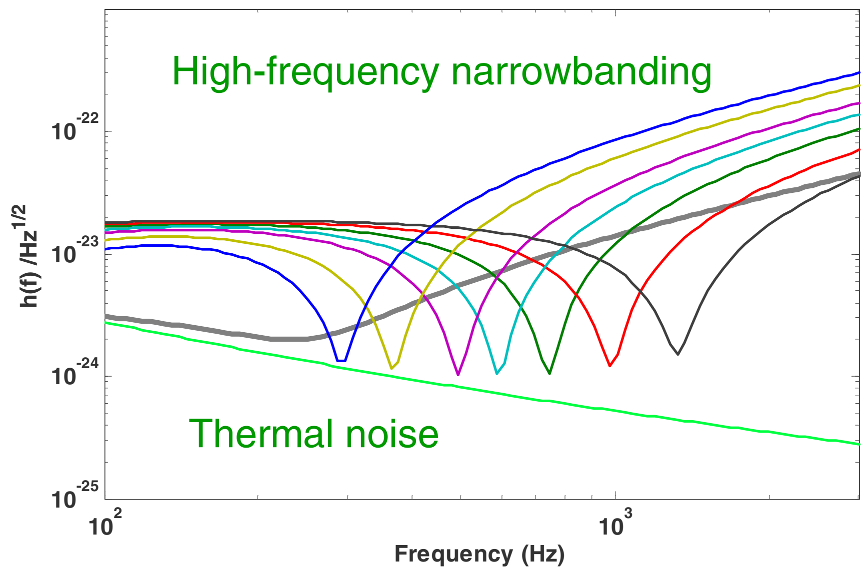
Suspensions: Test Mass Quads

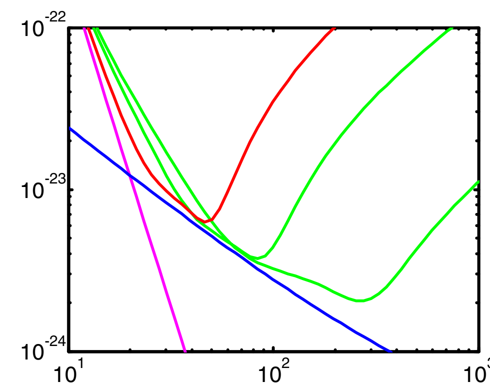
- Adopt GEO600 monolithic suspension assembly
- Requirements:
  - minimize suspension thermal noise
  - Complement seismic isolation
  - Provide actuation hierarchy
- Quadruple pendulum design chosen
  - Fused silica fibers, bonded to test mass
  - Leaf springs (VIRGO origin) for vertical compliance
- Success of GEO600 a significant comfort
  - 2002: All fused silica suspensions installed
- PPARC funding approved: significant financial, technical contribution; quad suspensions, electronics, and some sapphire substrates
  - U Glasgow, Birmingham, Rutherford
  - Quad lead in UK



GW readout, Systems

- Signal recycled Michelson Fabry-Perot
  - Offers flexibility in instrument response, optimization for technical noises, sources
  - Can also provide narrowband response – ~10^{-24}/$Hz^{1/2}$ up to ~2 kHz
  - Critical advantage: can distribute optical power in interferometer as desired
- Three table-top prototypes give direction for sensing, locking system
- Glasgow 10m prototype: control matrix elements confirmed
- Readout choice – DC rather than RF for GW sensing
  - Offset ~ 1 picometer from interferometer dark fringe
  - Best SNR, simplifies laser, photodetection requirements
- Caltech 40m prototype in construction, early testing
  - Complete end-to-end test of readout, controls, data acquisition





Low-frequency optimization

Upgrade of all three interferometers

- In discovery phase, tune all three to broadband curve
  - 3 interferometers nearly doubles the event rate over 2 interferometers
  - Improves non-Gaussian statistics
  - Commissioning on other LHO IFO while observing with LHO-LLO pair
- In observation phase, the same IFO configuration can be tuned to increase low or high frequency sensitivity
  - sub-micron shift in the operating point of one mirror suffices
  - third IFO could e.g.,
    - observe with a narrow-band VIRGO
    - focus alone on a known-frequency periodic source
    - focus on a narrow frequency band associated with a coalescence, or BH ringing of an inspiral detected by other two IFOs

Baseline plan

- Initial LIGO Observation at design sensitivity 2004 – 2006
  - Significant observation within LIGO Observatory
  - Significant networked observation with GEO, VIRGO, TAMA
- Structured R&D program to develop technologies
  - Conceptual design developed by LSC in 1998
  - Cooperative Agreement carries R&D to Final Design
  - Now: Proposal is for fabrication, installation positively reviewed
    "…process leading to construction should proceed"
- Proposed start 2005
  - Sapphire Test Mass material, seismic isolation fabrication
  - Prepare a 'stock' of equipment for minimum downtime, rapid installation
- Start installation in 2007
  - Baseline is a staggered installation, Livingston and then Hanford
- Coincident observations by 2010
- Optimism for networked observation with other '2nd generation' instruments

LIGO

Advanced LIGO

- Initial instruments, data helping to establish the field of interferometric GW detection
- Advanced LIGO promises exciting astrophysics
- Substantial progress in R&D, design
- Still a few good problems to solve
- A broad community effort, international support
- Advanced LIGO will play an important role in leading the field to maturity