Update on Suspension Design for Advanced LIGO

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for the Advanced LIGO Suspensions Group

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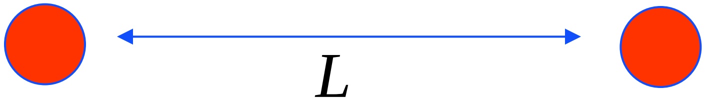
Outline of Talk

- Introduction to gravitational wave detection
- Suspension design for gravitational wave detectors
- Advanced LIGO suspension design
- Conclusion

Gravitational Wave Detection

- Gravitational waves are waves in the curvature of space time.
- We expect a significant flux from astronomical events such as inspiral and merger of neutron stars or black holes, supernova explosions, pulsars.
- We can look for these signals by measuring the time-dependent tidal strain, *h*, in space
- Simplest detector – two free masses a distance *L* apart whose separation is monitored

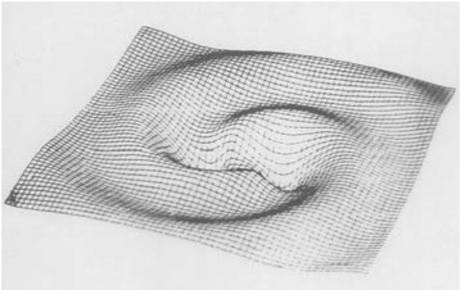


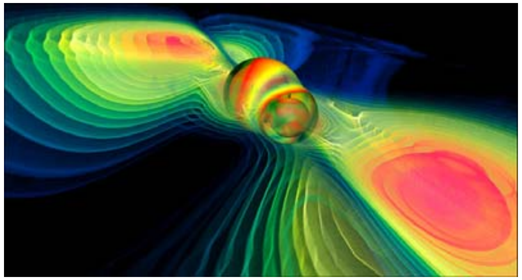
$$\frac{\Delta L}{L} \approx h$$

- Magnitude of *h* for reasonable event rate:

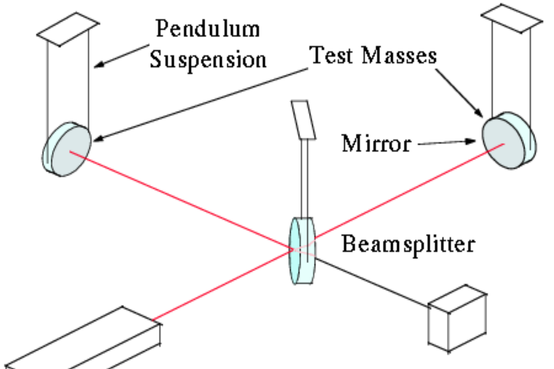
  $h \sim 10^{-22}\text{-}10^{-23}$

- Practical detector: Michelson Interferometer
  - » long baseline interferometry between freely suspended test masses
  - » LIGO: Laser Interferometer Gravitational Wave Observatory





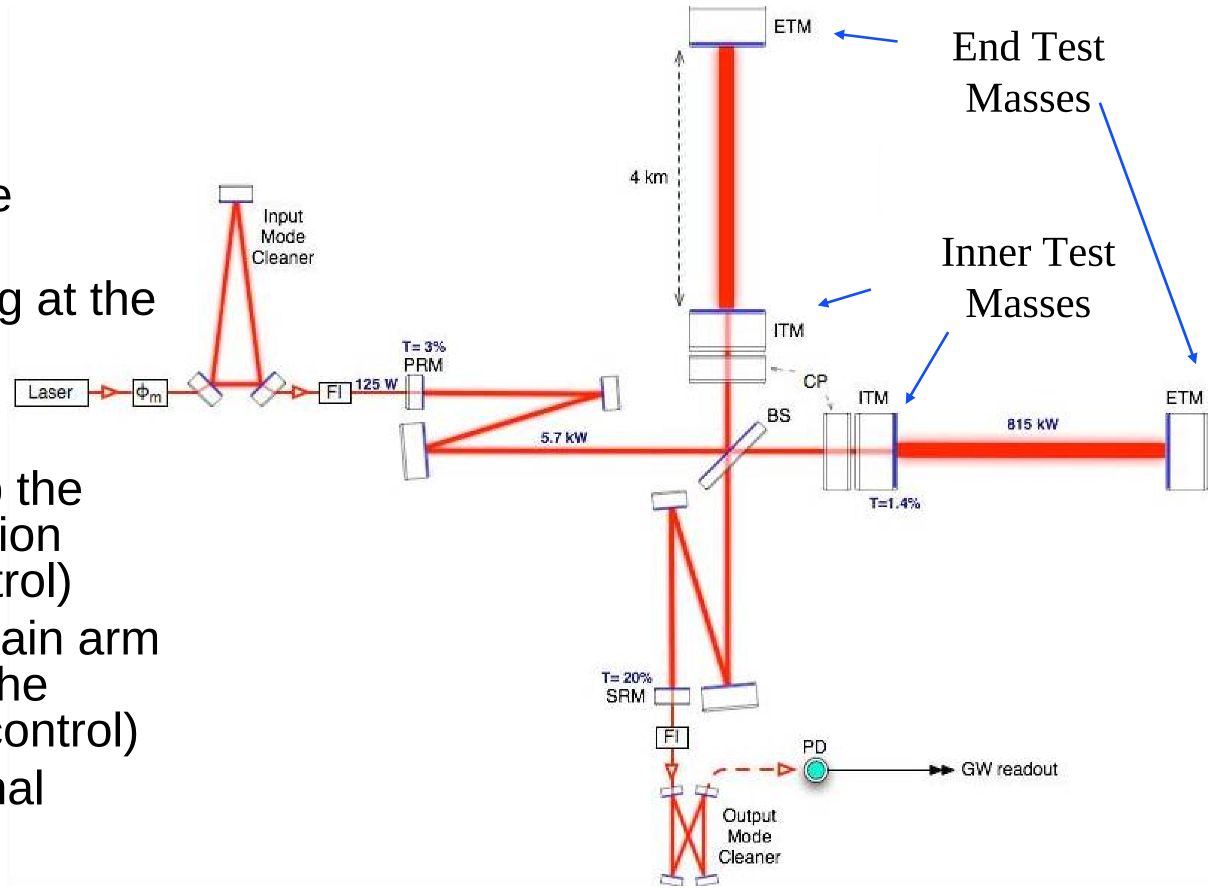
Merger of two black holes (Image: MPI for Gravitational Physics/W.Benger-ZIB)



Suspension Design for Gravitational Wave Detectors

- In principal: long baseline laser interferometry between freely suspended test masses
- Fundamental requirements
  - » support the mirrors to minimise the effects of
    - – thermal noise in the suspensions
    - – seismic noise acting at the support point
- Technical requirements
  - » allow a means to damp the low frequency suspension resonances (local control)
  - » allow a means to maintain arm lengths as required in the interferometer (global control)

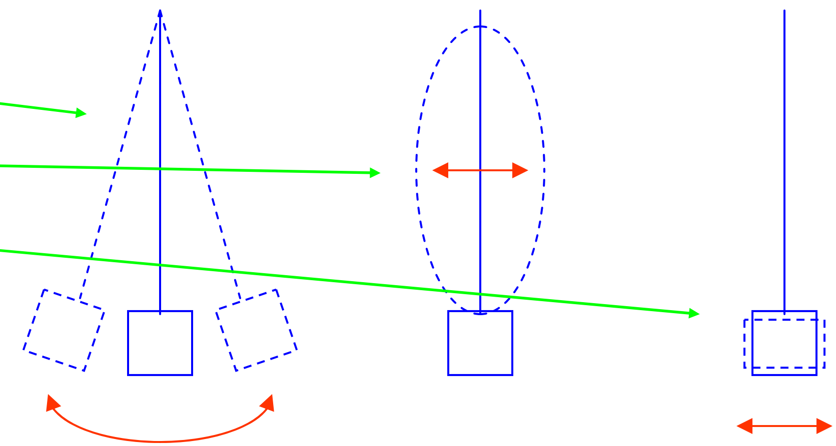
    without adding additional noise

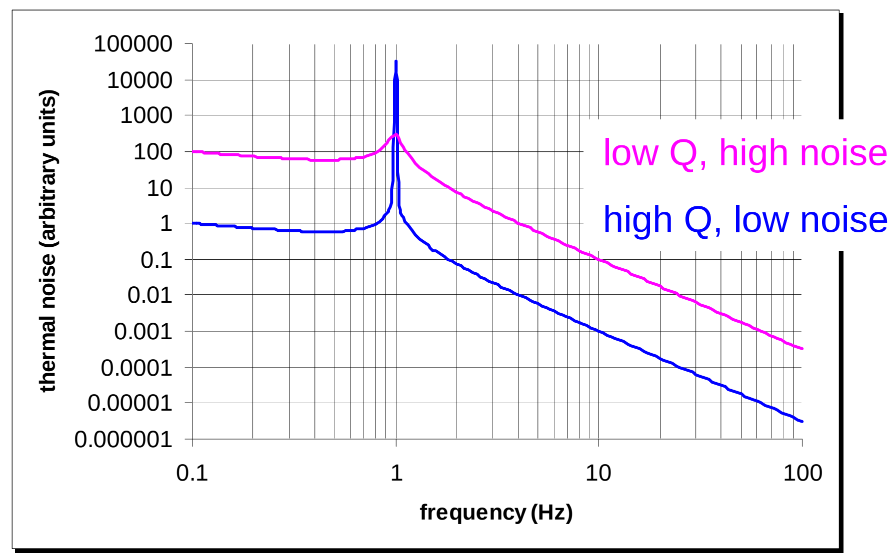


advancedligo

Thermal Noise

- Thermally excited vibrations of
  - » suspension pendulum modes
  - » suspension violin modes
  - » mirror substrates + coatings
- Use fluctuation-dissipation theorem to estimate magnitude of motion
- To minimise:
  - » use low loss (high quality factor, Q) materials for mirror and suspension – gives low thermal noise off resonance -*silica* is a good choice
    - – *silica fibre loss angle ~ 2e-7, c.f. steel wire ~2e-4*
    - – *breaking stress can be larger than steel*
  - » use thin, long fibres to reduce effect of losses from bending





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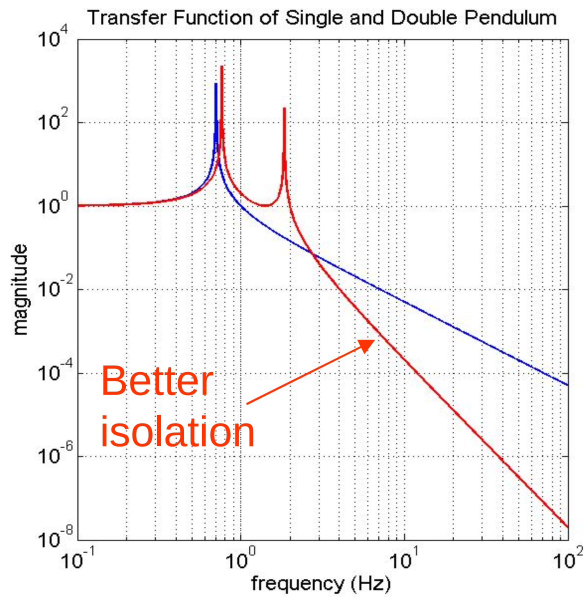
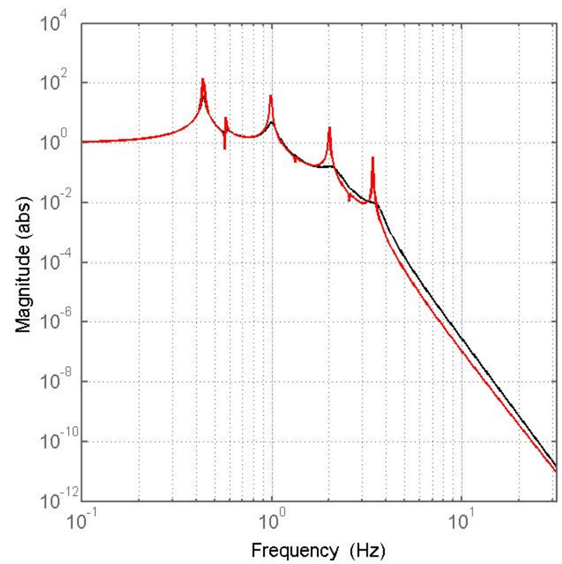
Seismic Noise

- Seismic noise limits sensitivity at low frequencies - "seismic wall"
- Typical seismic noise at quiet site at 10 Hz is ~ few x 10^{-10} m/√Hz
  - » many orders of magnitude above target noise level
- Solution - use multiple stages of isolation
- Isolation required in vertical direction as well as horizontal due to cross-coupling



Advantage of double over single pendulum, same overall length

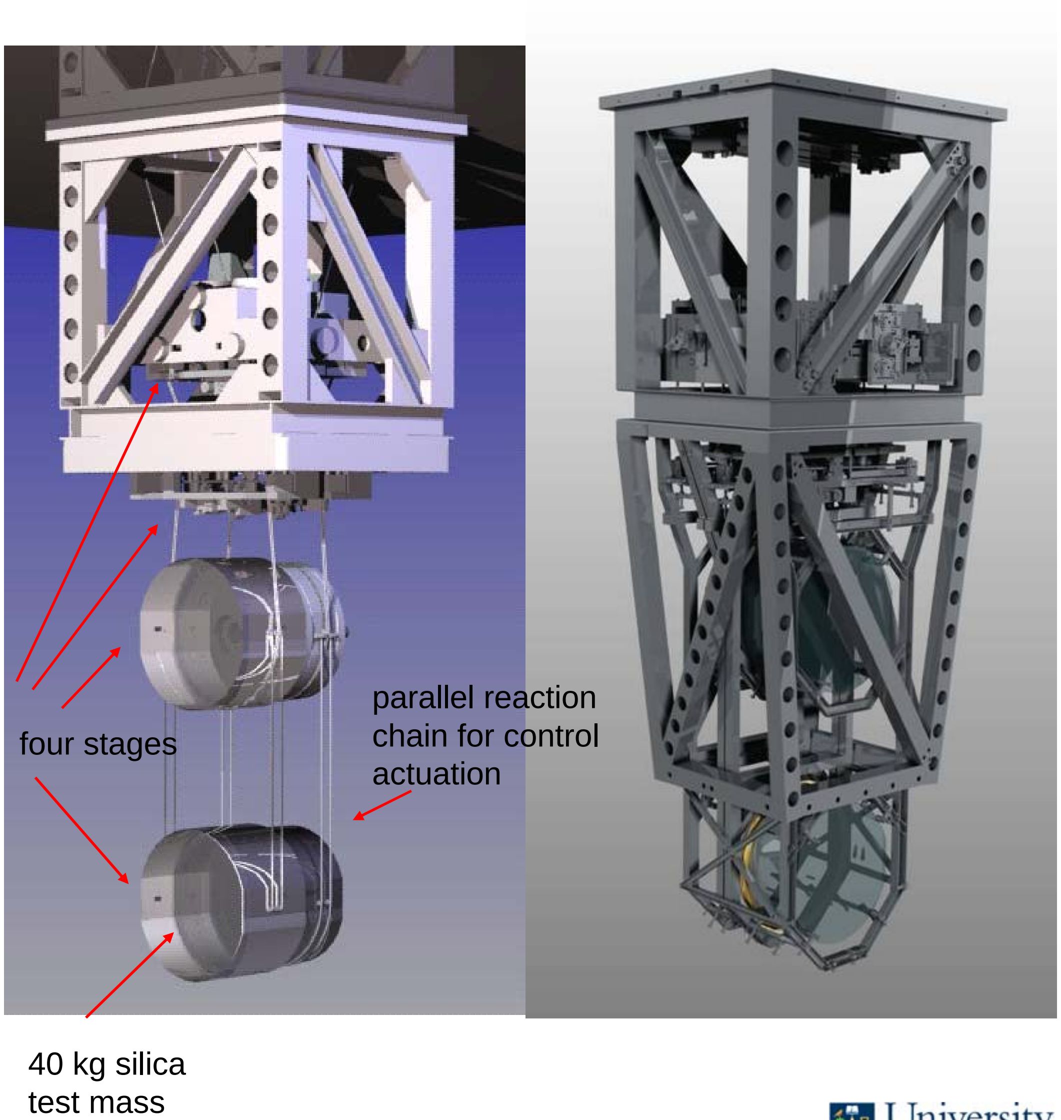
Initial LIGO uses a single stage wire suspension



Quadruple pendulum transfer function: predicted longitudinal isolation ~ 3 x 10^{-7} at 10 Hz

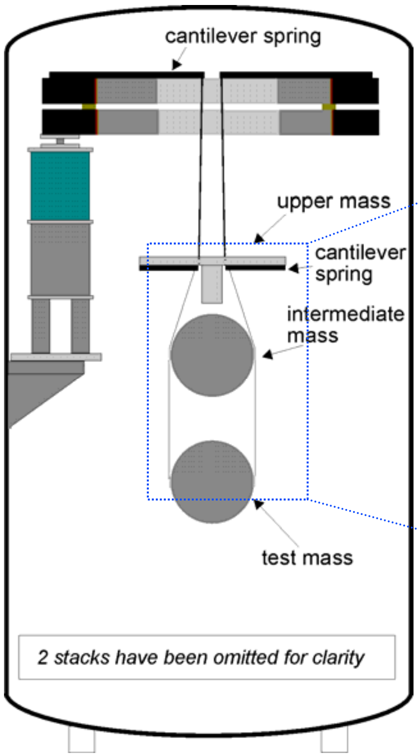
Suspension Design for Advanced LIGO

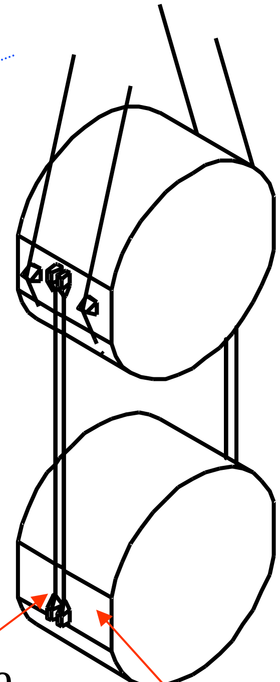
- Target noise level (both for thermal and seismic noise): 10^{-19} m/ √ Hz at 10 Hz
- Thermal noise reduction: use monolithic fused silica suspension as final stage
- Seismic isolation: use quadruple pendulum + 3 stages of maraging steel blades for vertical isolation
  - *isolation @ 10Hz: quad ~ 3e-7, c.f. single stage ~ 5e-3*
- Control noise minimisation: apply damping at top mass (for 6 degrees of freedom) + use quiet reaction pendulum for global control actuation
  - coil/magnet actuation at top 3 stages
  - electrostatic drive at test mass

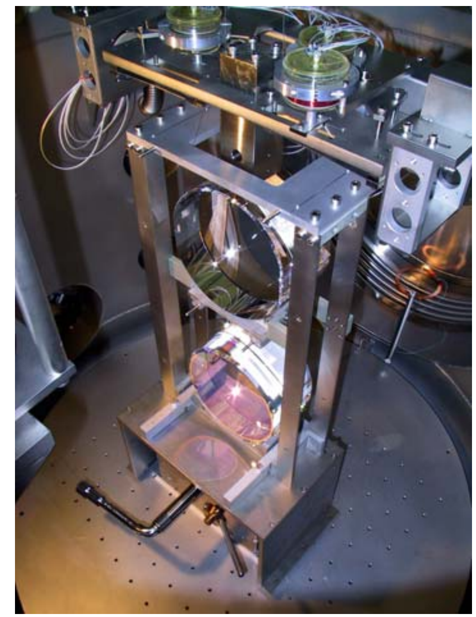


Monolithic Silica Suspensions developed for GEO 600

Monolithic fused silica suspensions are used in the German/UK GEO600 detector: makes use of silicate bonding technique developed for Gravity Probe B

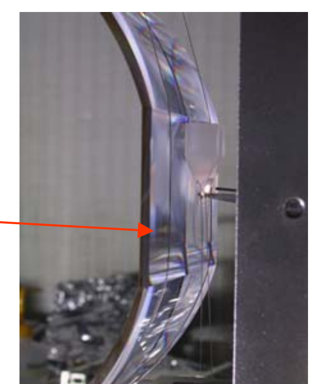




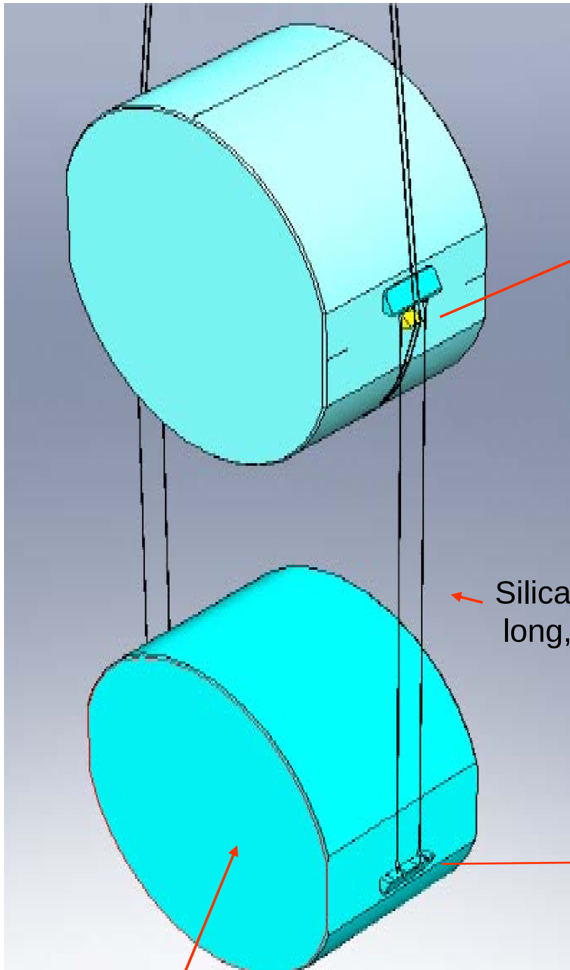


Ears silicate bonded to masses

Silica fibres welded to ears

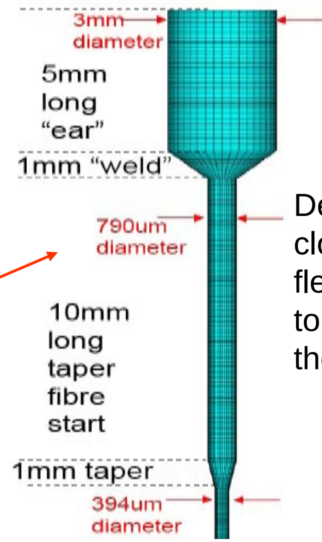


Development of Monolithic Suspensions for Advanced LIGO



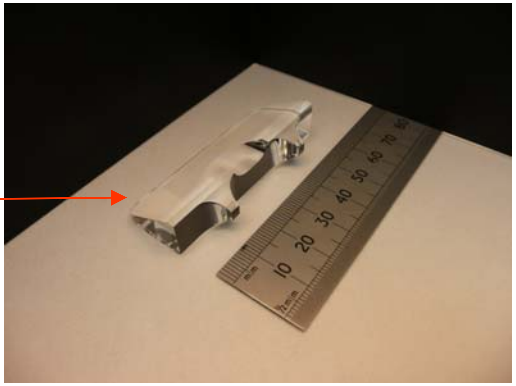
Silica fibres 600 mm long, 0.4 mm diam.

Mirror: 40 kg silica mass

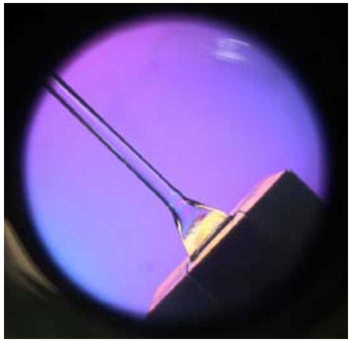


Detail of fibre shape close to weld: thick flexure region used to minimise thermoelastic noise

Fibre pulling machine at MIT



Example of ear to be bonded to silica mass



Visual inspection of test weld using crossed polarisers at Glasgow

Welding test at Glasgow

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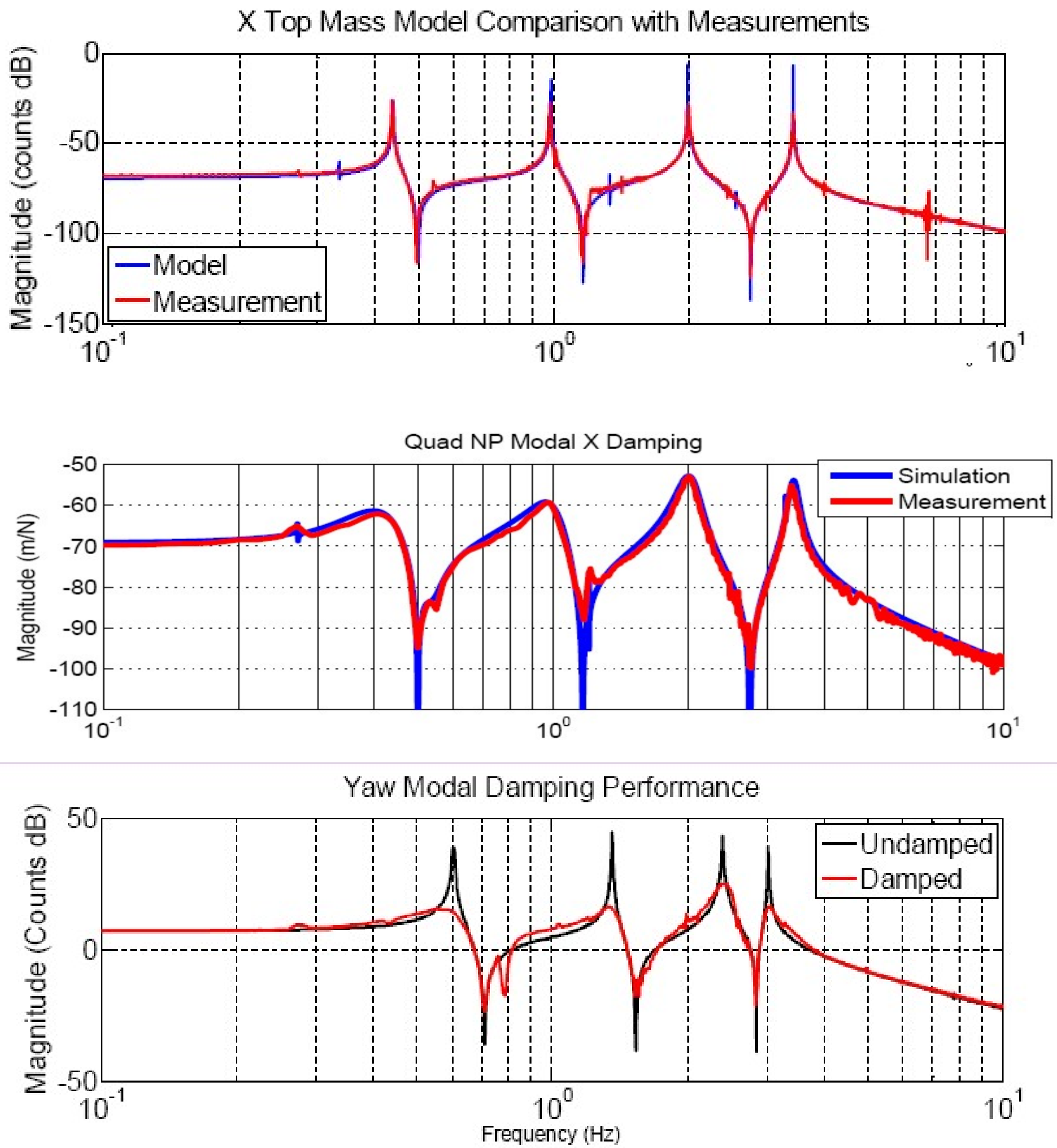
Quadruple Pendulum Transfer Functions

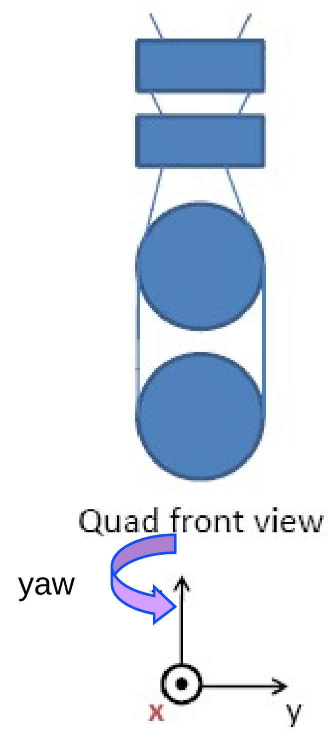


Example of transfer functions (TF) taken at top mass (drive to response)

Top: measured and modelled TF in X direction with no damping applied

Middle: simulated and measured modal damping of TF in X direction

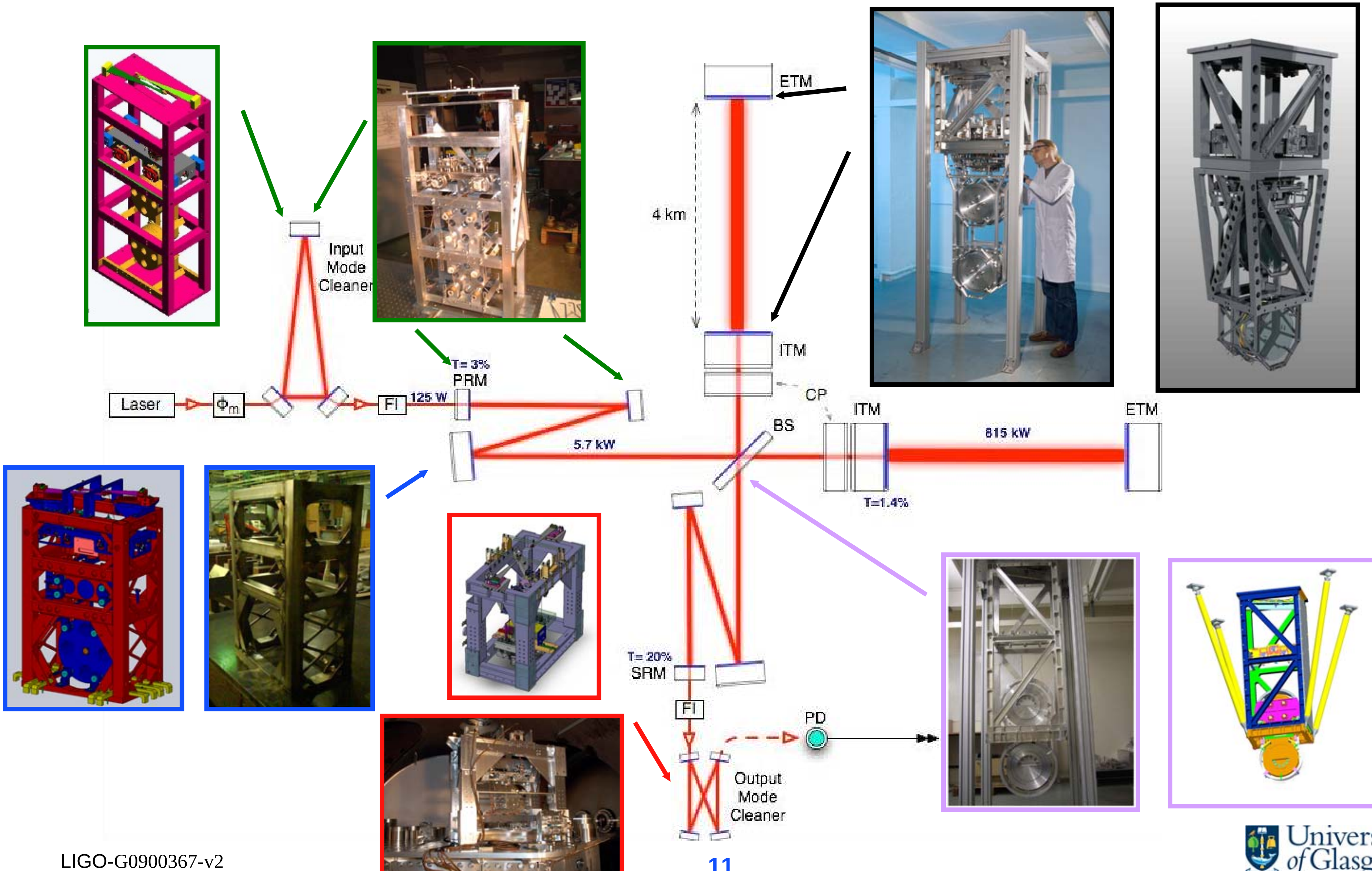
Bottom: measurements of yaw TF undamped and damped



Data from Brett Shapiro

Design Concept: other suspensions

Similar concept to test mass suspensions but with reduced number of stages, use of wire suspensions, and no reaction chain



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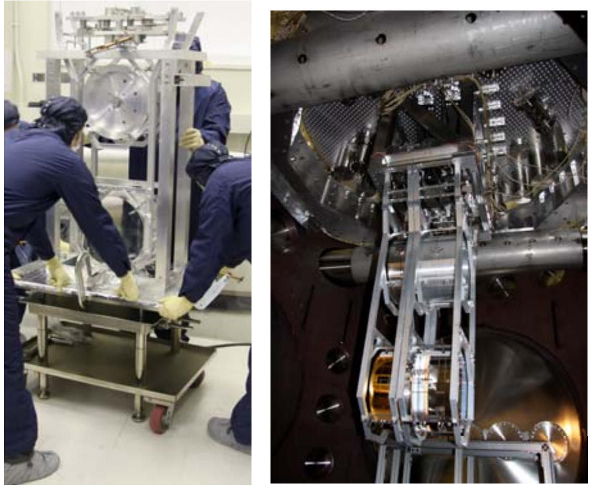
Conclusions

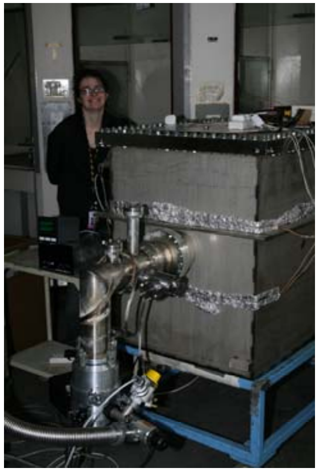
- Advanced LIGO suspensions work is progressing:
  - » Ongoing development work, in particular on the monolithic suspensions
  - » Program of tests on full-scale prototypes
  - » Production of some parts already underway and assembly imminent
    - – 2009 - 2011: 47 major suspensions will be constructed
  - » Experience to date gives us confidence that we can meet our requirements
  - » Large international team effort

Sensor/actuator units for control in production at Birmingham

Welding set-up at MIT



Installation of quad prototype with full optics at MIT



Testing rig for UHV compatibility at RAL

Welding test at Glasgow

Acknowledgements

Advanced LIGO Suspensions Team

- **LIGO Caltech**: M. Aronsson, D. Coyne, T Edzel, J. Heefner, A. Heptonstall, A. Ivanov, G. McIntyre, N. Robertson (also Glasgow) – team leader, C Torrie (also Glasgow)
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- **LIGO Livingston Observatory**: D. Bridges, M. Meyer, B. Moore, J. Romie, D. Sellers, G. Traylor
- **LIGO MIT**: P. Fritschel, R. Mittleman, B. Shapiro
- **University of Glasgow**: C. Craig, L. Cunningham, A. Cumming, G. Hammond, K. Haughian, J. Hough, R. Jones, R. Kumar, I. Martin, S. Rowan, K. Strain, M. Van Veggel, A. Wanner
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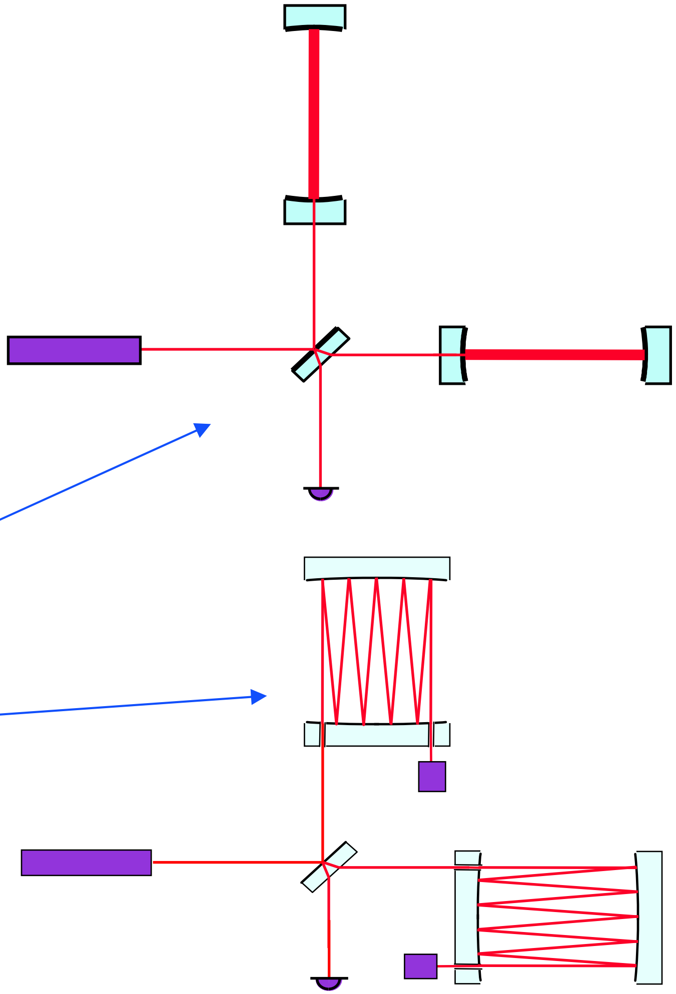
- **University of Birmingham**: S. Aston, R. Cutler, D. Lodhia, A. Vecchio
- **Strathclyde University**: N. Lockerbie, K. Tokmakov

Back-up Slides

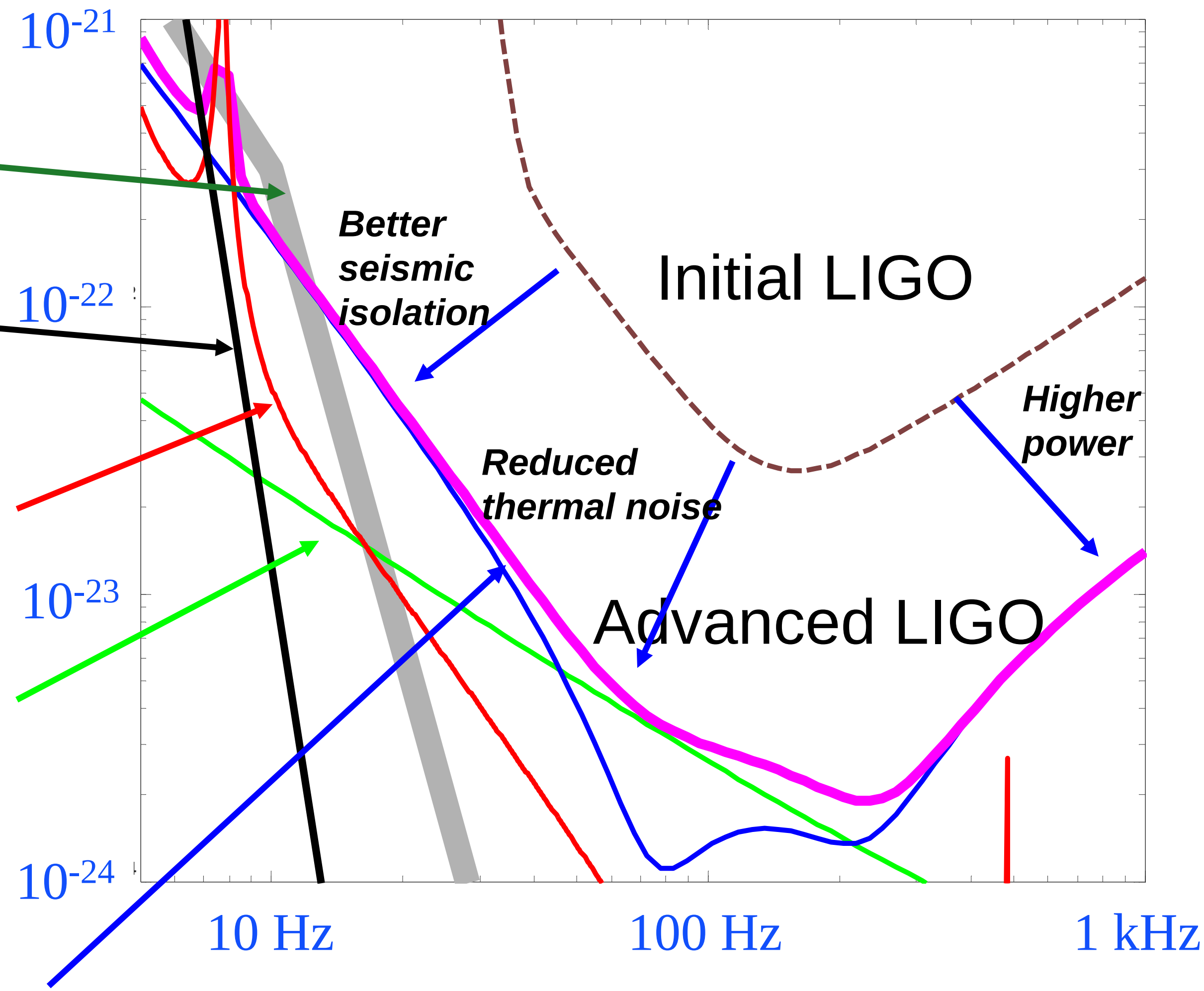
Advantages of Interferometer

- Differential measurement – relaxes requirement on laser frequency stability
- Matches to quadrupole nature of gravitational wave
- Wideband operation
- Sensitivity to strain scales with armlength: use long baseline, L
- Further increase in sensitivity by folding light in the arms:
  - » Fabry Perot cavities
  - » delay lines



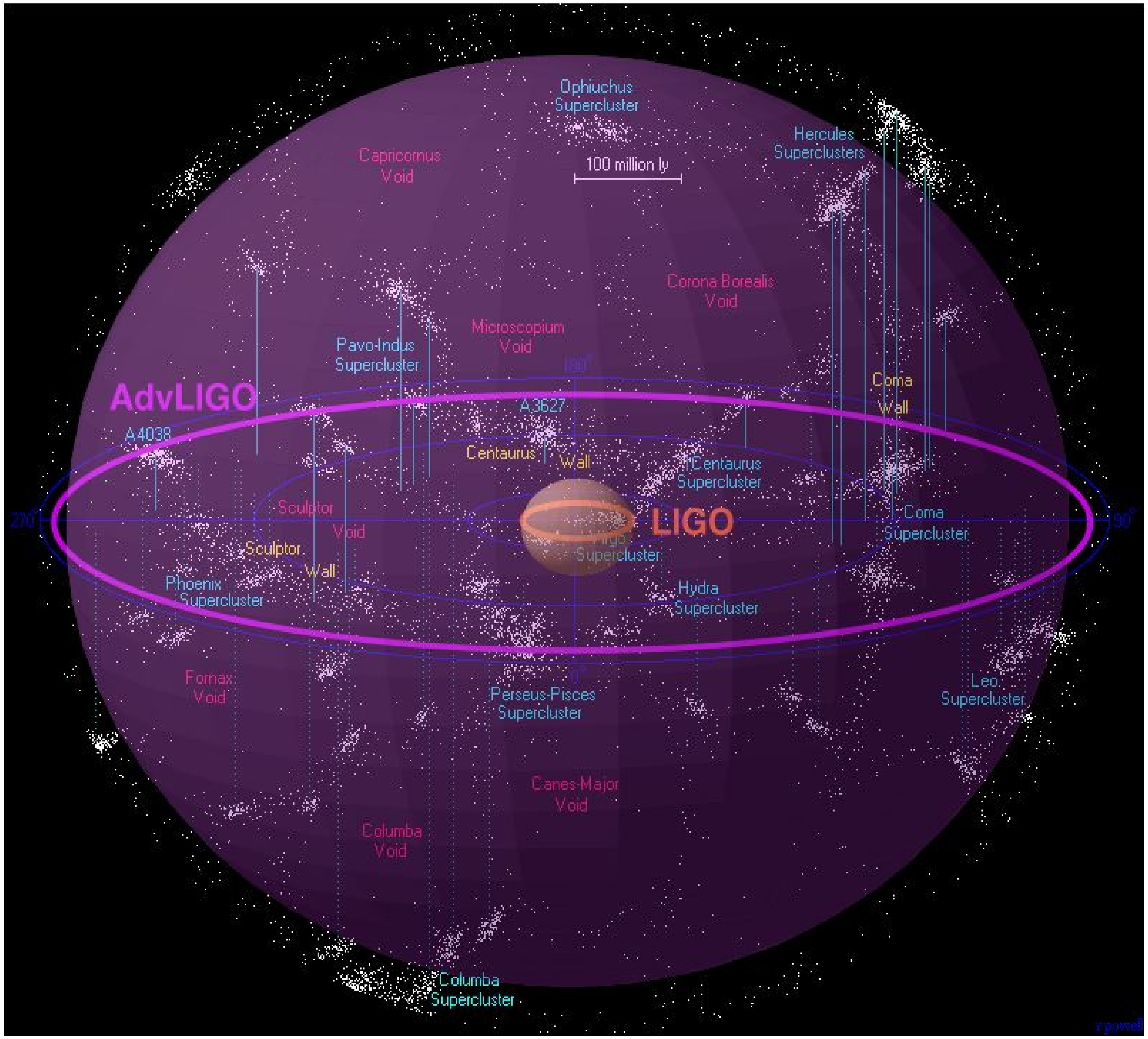
Projected Advanced LIGO performance

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

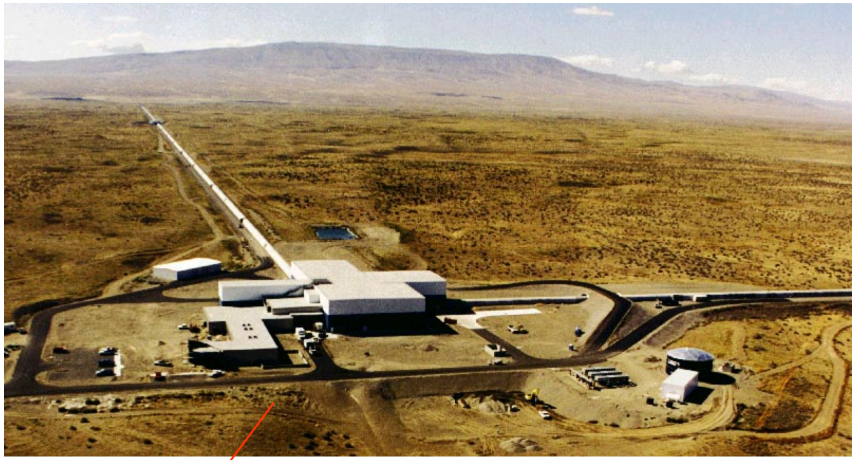


(y scale: h/rt Hz)

LIGO vs Advanced LIGO



Factor of 10 in sensitivity gives factor of 1000 in volume and hence in event rate

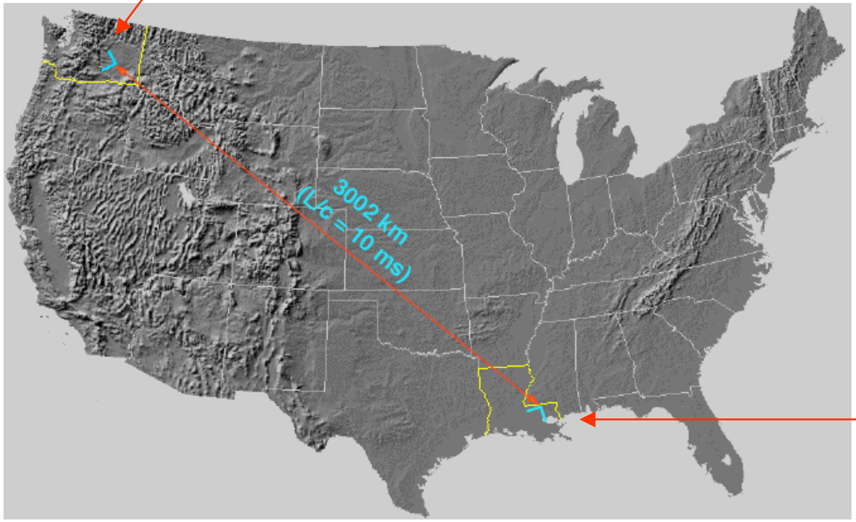


LIGO Hanford Observatory, WA

2 detectors: currently 4 km arm length and 2 km arm length

LIGO Livingston Observatory, LA

1 detector: 4 km arm length



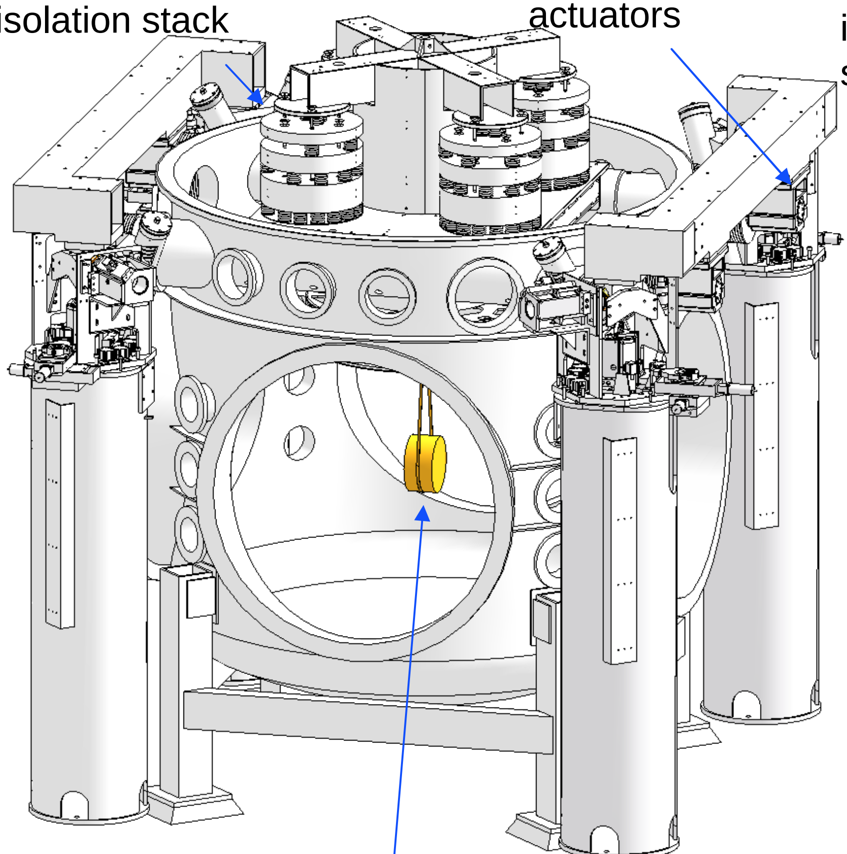
NSF funded. Designed and built by Caltech and MIT.

Suspensions and Seismic Isolation – From Initial to Advanced LIGO

LIGO

4 layer passive isolation stack

coarse & fine actuators

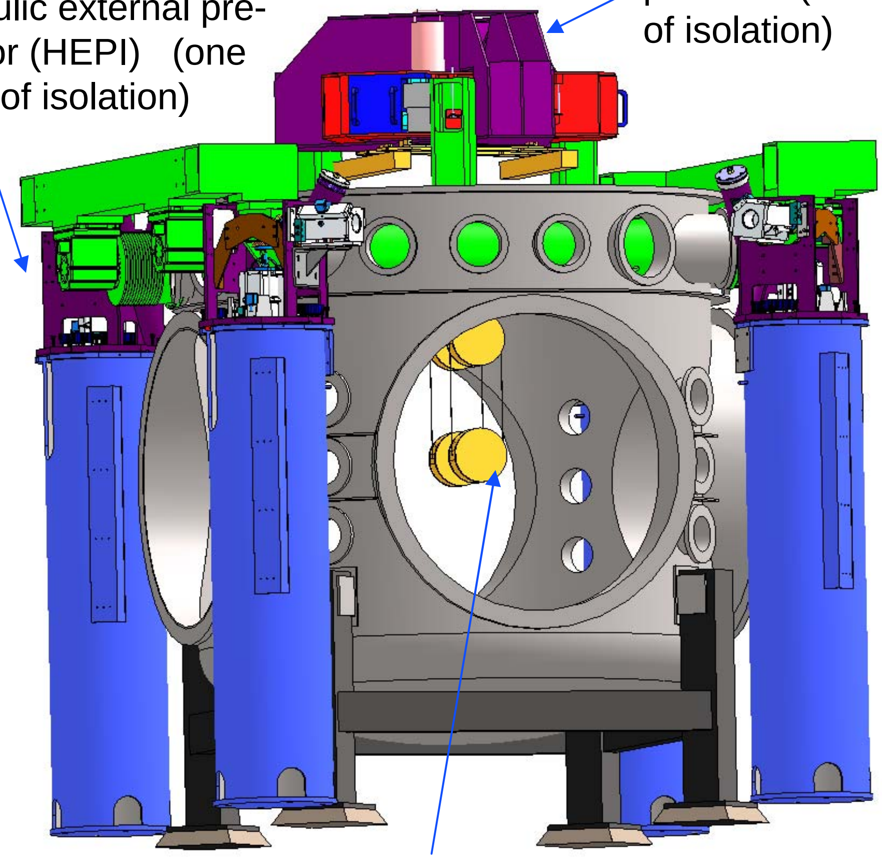


single pendulum on steel wire

Advanced LIGO

hydraulic external pre-isolator (HEPI) (one stage of isolation)

active isolation platform (2 stages of isolation)



quadruple pendulum (four stages of isolation) with monolithic silica final stage