LIGO
and the Search for Gravitational Waves

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G080272-00-R

Outline of Talk

- Introduction to gravitational waves: sources and detection
- LIGO – current status
- Introduction to Advanced LIGO
- Advanced LIGO suspension design
- Conclusion

What Are Gravitational Waves?

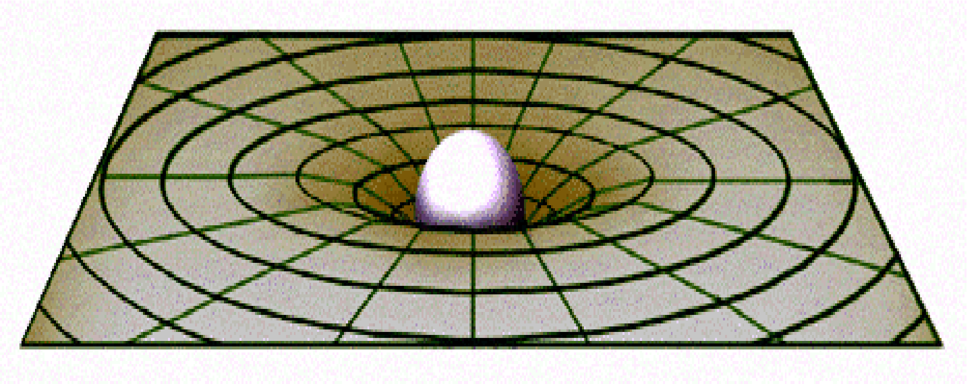
Einstein's theory

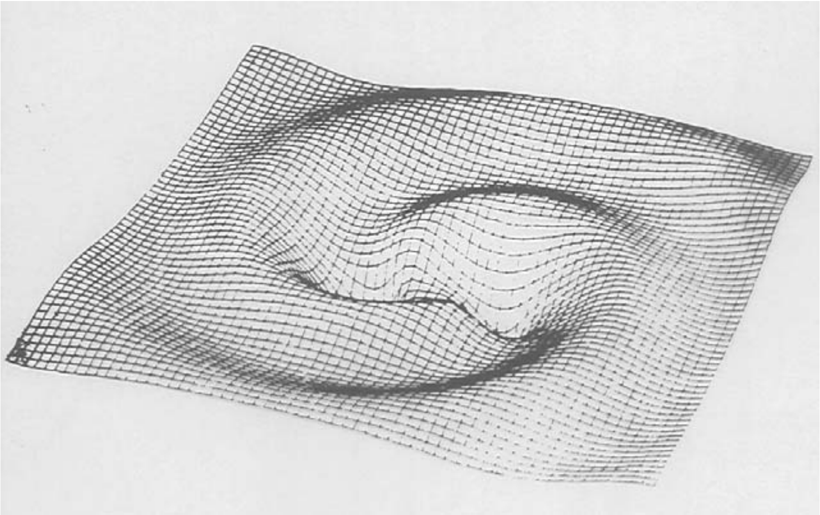
gravitation =

curvature of space-time

gravitational waves =

waves in curvature of space-time





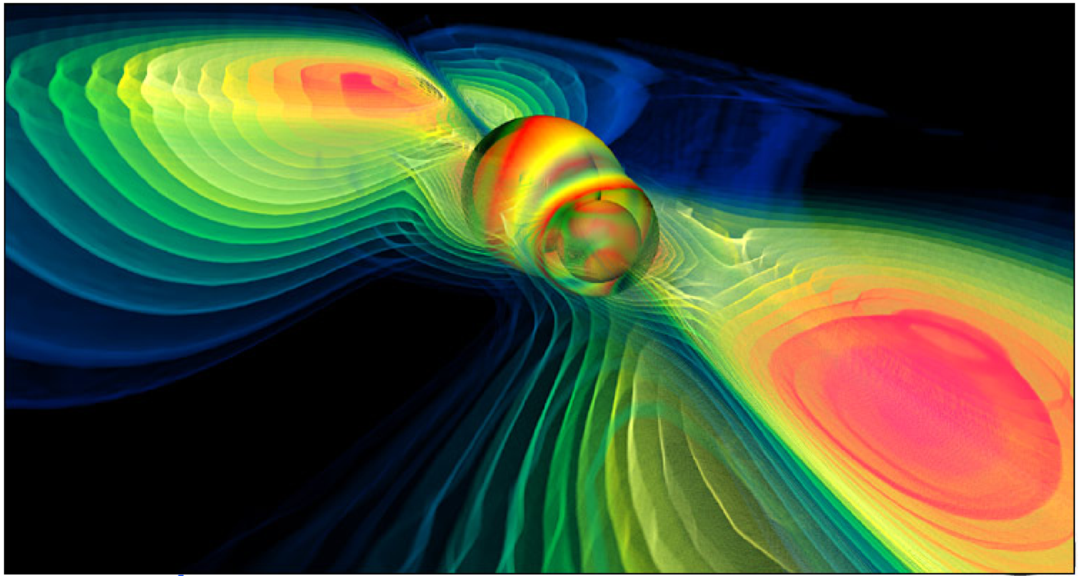
Production of Gravitational Waves (GW)

- Compare to EM waves:
  - » GW produced by acceleration of mass
  - » GW travel at speed of light

    BUT
  - » gravitational interactions are very weak
  - » no dipole radiation due to momentum conservation, one sign of mass

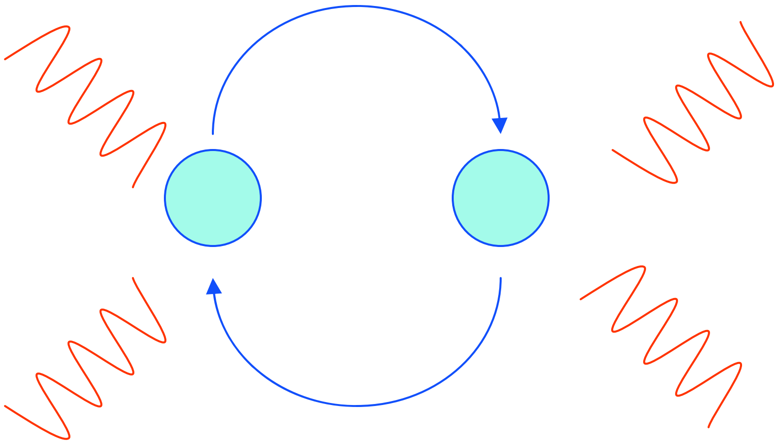
To produce significant flux requires asymmetric accelerations of large masses, i.e.

Astrophysical Sources



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

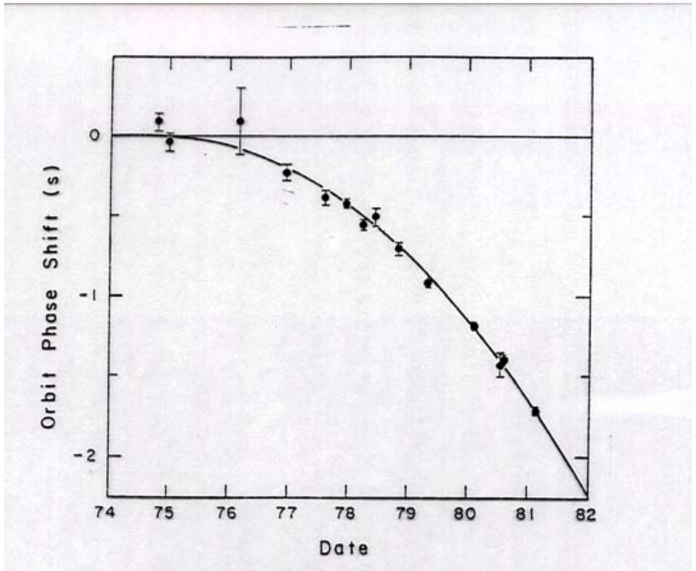
Evidence for Gravitational Waves: Radio Observations of Binary Pulsar PSR1913+16



Orbit decaying, with emission of gravitational waves
(rate of decay ~3 mm per orbit, merger in ~300 million yrs)

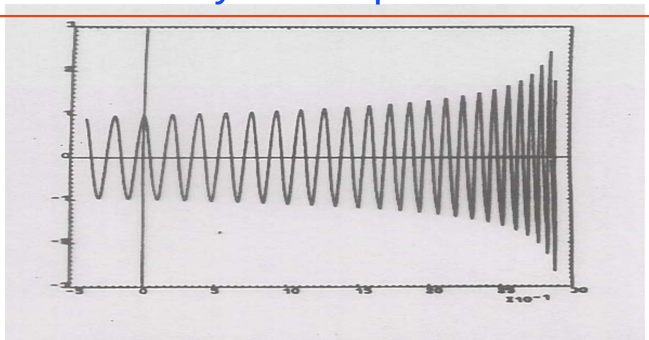
A highly relativistic binary pulsar was discovered in late 2003: merger in 85 Myrs (much shorter than other known systems)

Statistics small – this observation increased merger rate estimate by order of magnitude



(Taylor and Weisberg, Ap. J. 253, 1982)

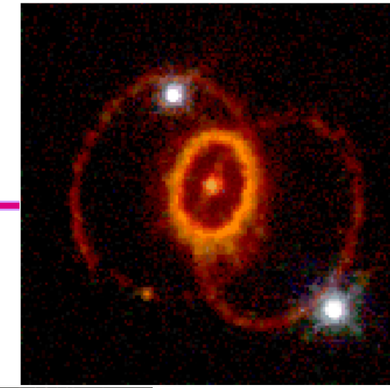
Hulse and Taylor won Nobel Prize in 1993 for discovery of this pulsar

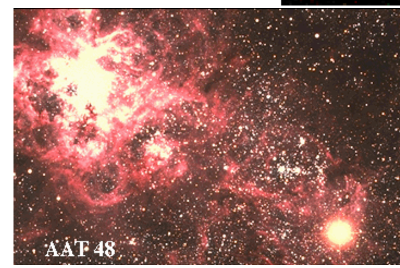


Expected GW signal from binary coalescence

Gravitational Wave Sources

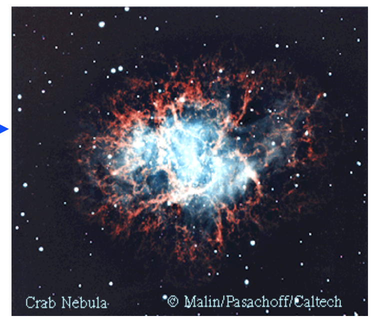
- ***Bursts***
  - » catastrophic stellar collapse to form black holes or neutron stars
  - » final inspiral and coalescence of neutron star or black hole binary systems – possibly associated with gamma ray bursts





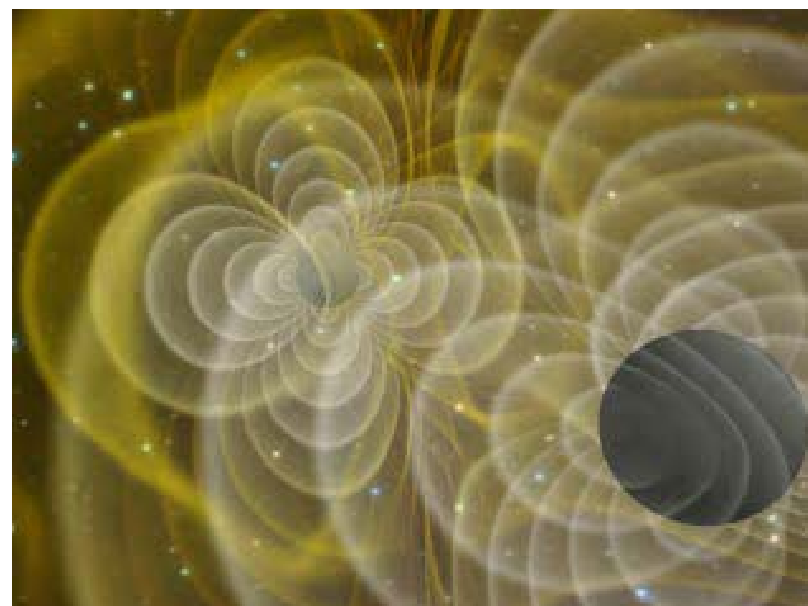
SN1987a

- ***Continuous***
  - » pulsars (e.g. Crab)
  (sign up for Einstein@home)
  - » low mass X-ray binaries Sco-X1)



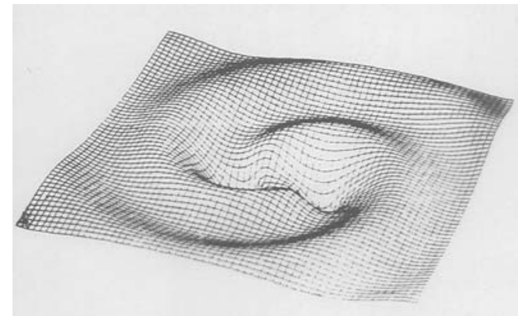
- ***Stochastic Background***
  - » random background “noise” associated with cosmological processes, e.g. inflation, cosmic strings…..

A New Astronomy

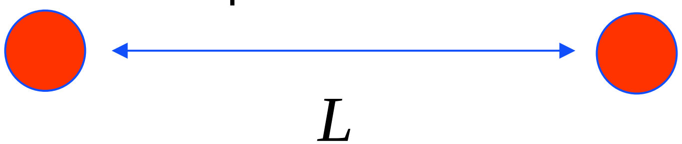


Credit: Henze, NASA

Gravitational Wave Detection

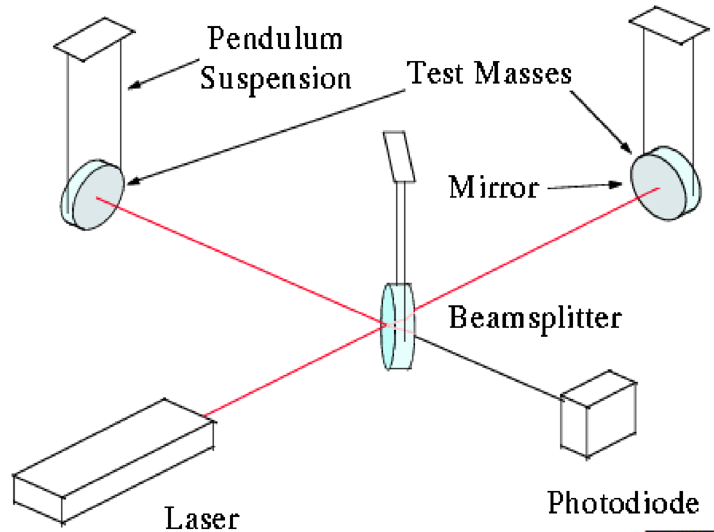


- Measure the time-dependent tidal strain, *h*, in space produced by the waves
- Simplest detector – two free masses a distance *L* apart whose separation is monitored



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

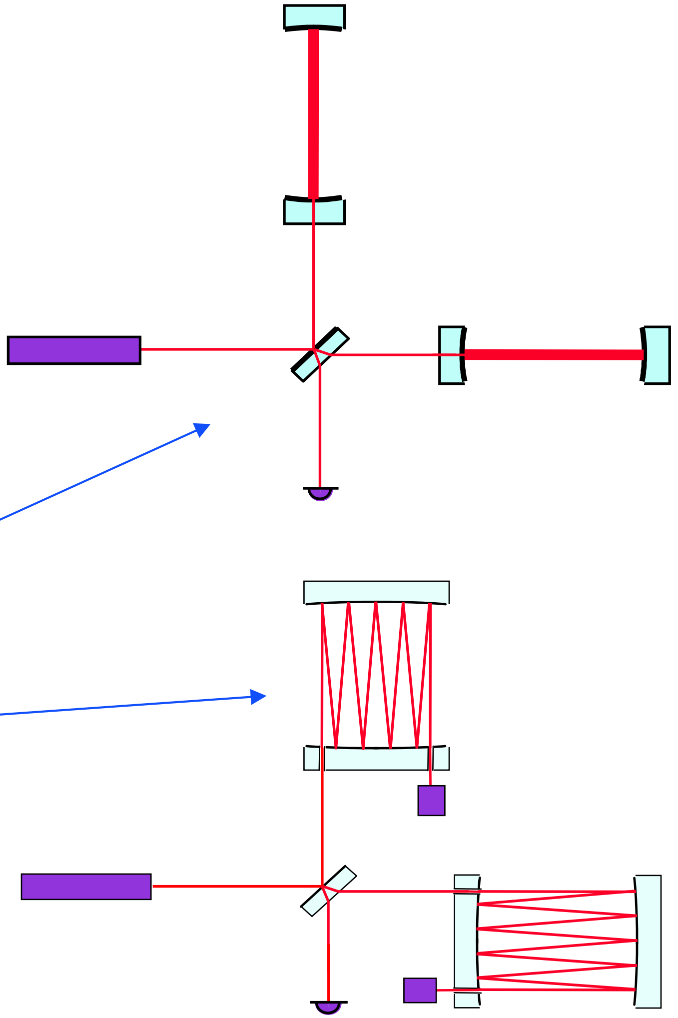
- Magnitude of h
  - » Largest signals (very rare) h ~ 10^{-19}
  - » For reasonable event rate *h* ~ 10^{-22} -10^{-23}



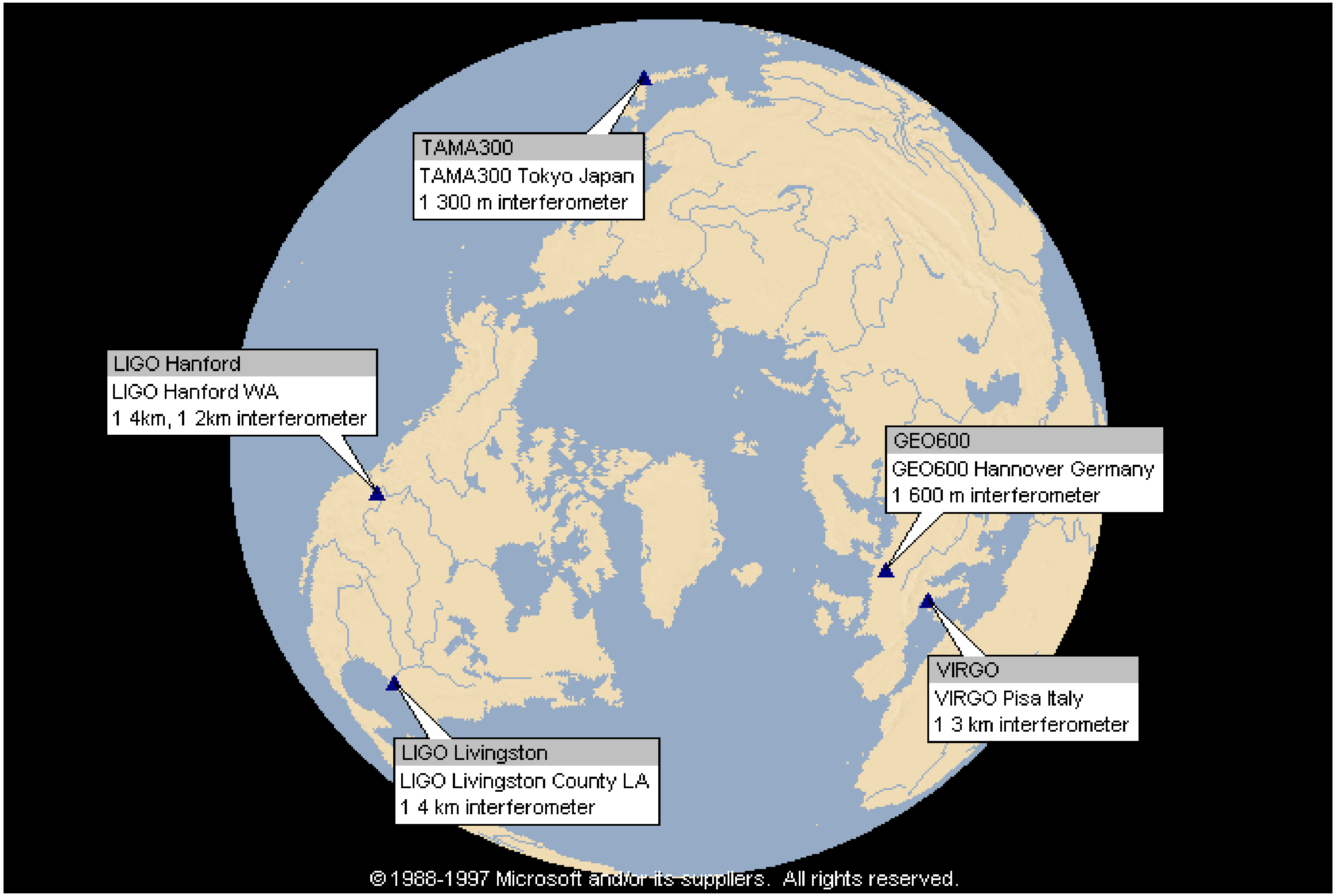
- Practical detector: Michelson Interferometer
  - » long baseline interferometry between freely suspended test masses

Advantages of Interferometer

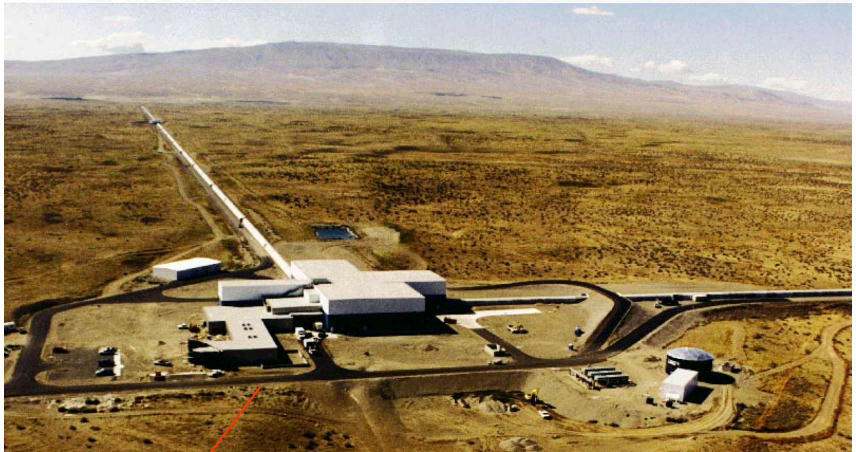
- Differential measurement – relaxes requirement on laser frequency stability
- Matches to quadrupole nature of gravitational wave
- Wideband operation
- Sensitivity to strain scales with armlength: use long baseline, L
- Further increase in sensitivity by folding light in the arms:
  - » Fabry Perot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



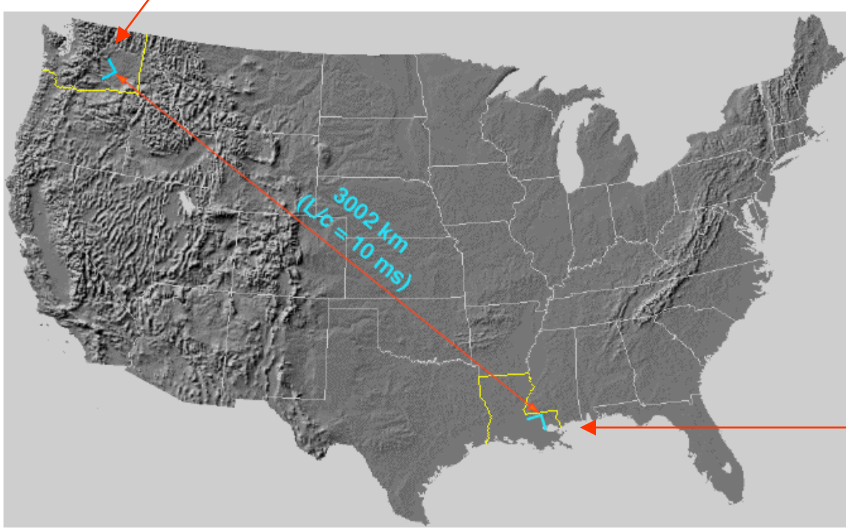
WORLDWIDE GW INTERFEROMETER NETWORK



LIGO Observatories



LIGO Hanford Observatory, WA

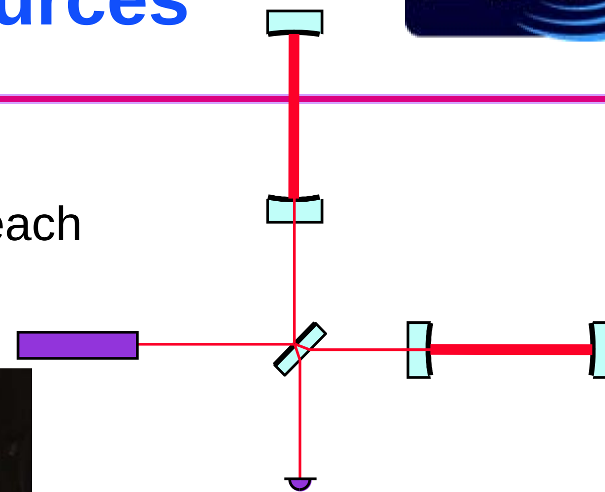


LIGO Livingston Observatory, LA

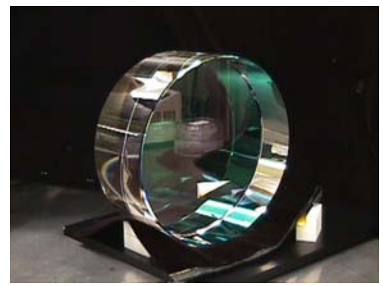
NSF funded. Designed and built by Caltech and MIT.

LIGO = **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory

Mitigation of Noise Sources



- Photon shot noise
  - » 10 W Nd-YAG laser, Fabry Perot cavities in each arm, power recycling mirror



- Thermal Noise
  - » Use low loss materials
  - » Work away from resonances
  - » Thin suspension wires

Operate under high vacuum

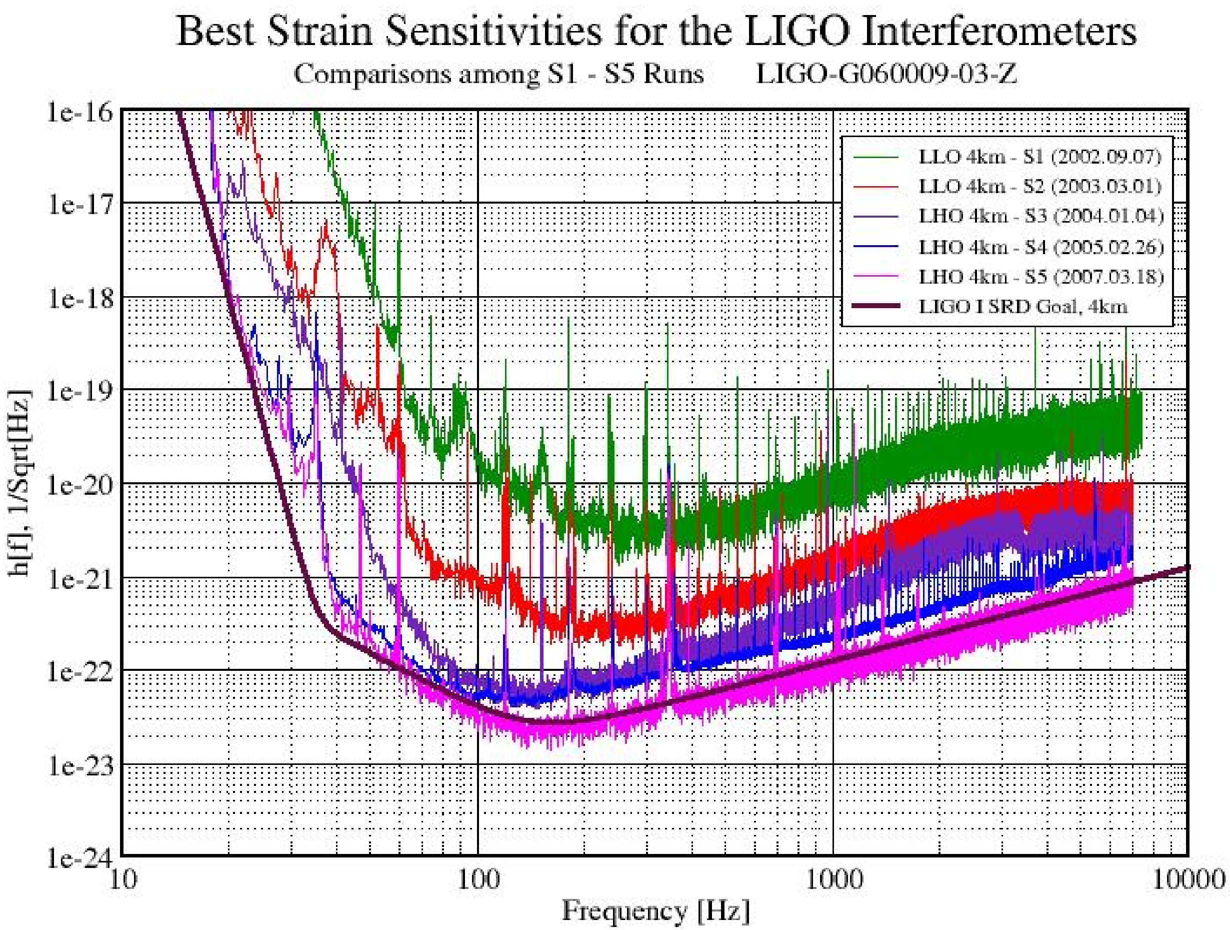
- Seismic Noise
  - » Passive isolation stack
  - » Pendulum suspension

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravit

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washingto

Evolution of LIGO Sensitivity



The S5 run – one year of triple coincidence data at design sensitivity - officially ended Oct 1st 2007.

NSF review (Nov 07): "The review panel congratulates LIGO for the wonderful progress made in the past year."

Best sensitivity: ~16 MPc for neutron star/neutron star inspiral range

LIGO Status – Data Analysis

- ~30 papers published from S1-S5 science runs (and more to come!) presenting searches and upper limits on a variety of sources, plus numerous technical papers.

  A couple of highlights:

  » "Implications for the Origin of GRB 070201 from LIGO Observations"

  (to appear in ApJ)

  GRB sky position coincides with Andromeda Galaxy (M31). No GW candidate seen – we conclude it was not a binary neutron star merger in M31 (at 99% confidence level)

  » "Upper limits on gravitational wave emission from 78 radio pulsars"

  (in Phys Rev D)

  strain upper limit for the Crab pulsar is only 2.2 times greater than the fiducial spin-down limit (S4 result – S5 still to come)

  equatorial ellipticity of PSRJ2124-3358 is less than 10^{-6}

- MOU with Virgo in place – started data sharing in May 2007

M31*

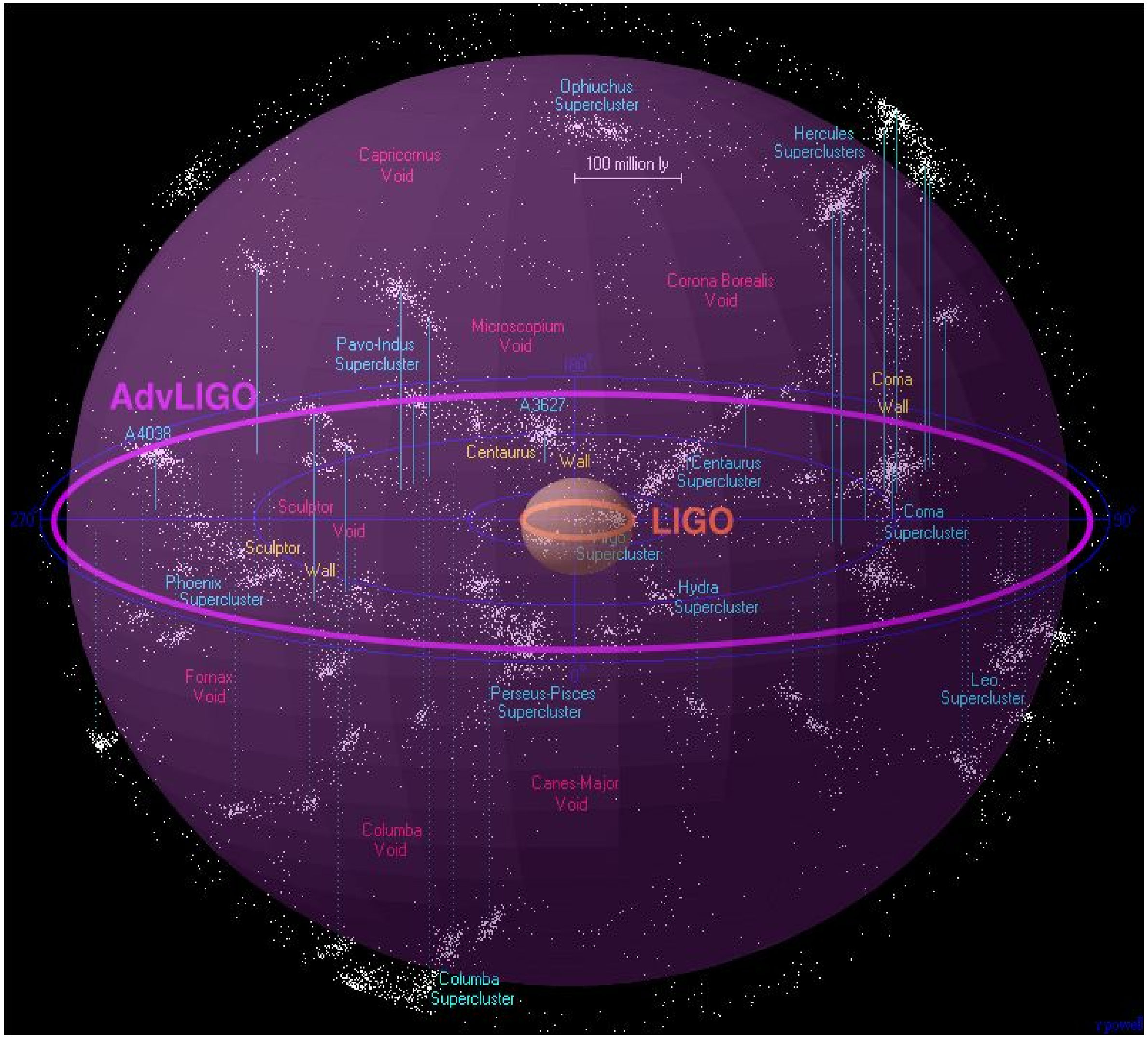
Crab pulsar (combined Hubble/Chandra image)

*Credit: John Lanoue

LIGO Status – Funding and Technical Advances

- **Good news! – the National Science Board announced approval for the construction of Advanced LIGO:**
  - » **formal start of funding April 2008, budget $205M**
- **Advanced LIGO is aimed at achieving a sensitivity at which at least several signals per month (perhaps per week) should be detected**
  - » **Factor of 10 better sensitivity at ~100 Hz**
  - » **Wider bandwidth (extending down to ~10 Hz)**
- **Current schedule for Advanced LIGO**
  - » **start of installation - Dec 2010**
  - » **acceptance date (all 3 interferometers) - Autumn 2013**
    - – **followed shortly by a science run (low power, low frequency) assuming all goes well**

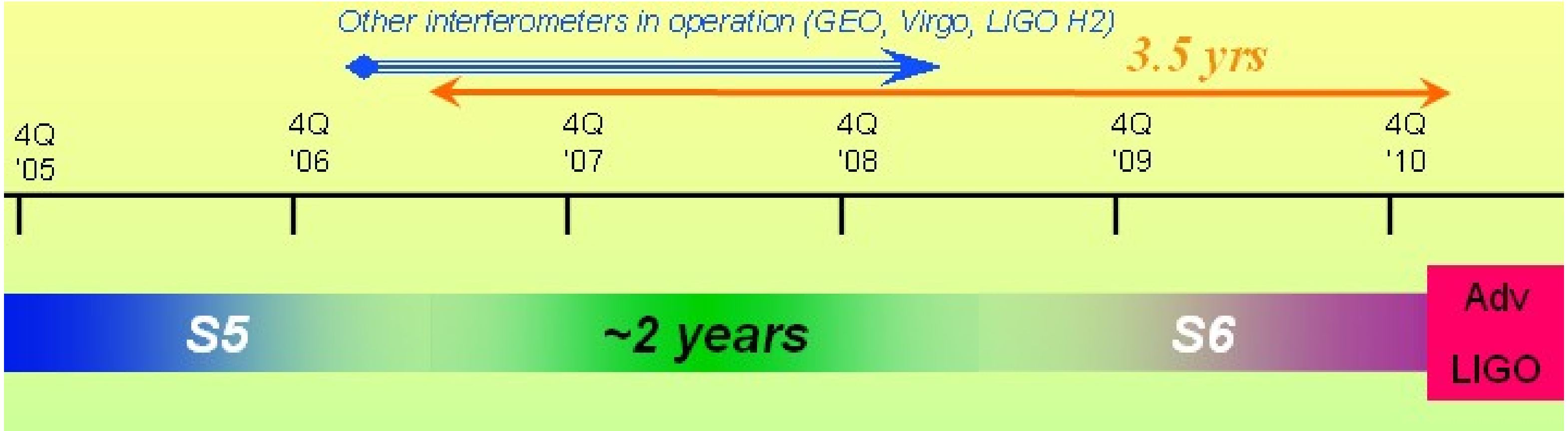
LIGO vs Advanced LIGO



Factor of 10 in sensitivity gives factor of 1000 in volume

Interim Upgrade - Enhanced LIGO

- **Gap between end of S5 science run (Oct 07) and start of installation of Advanced LIGO**

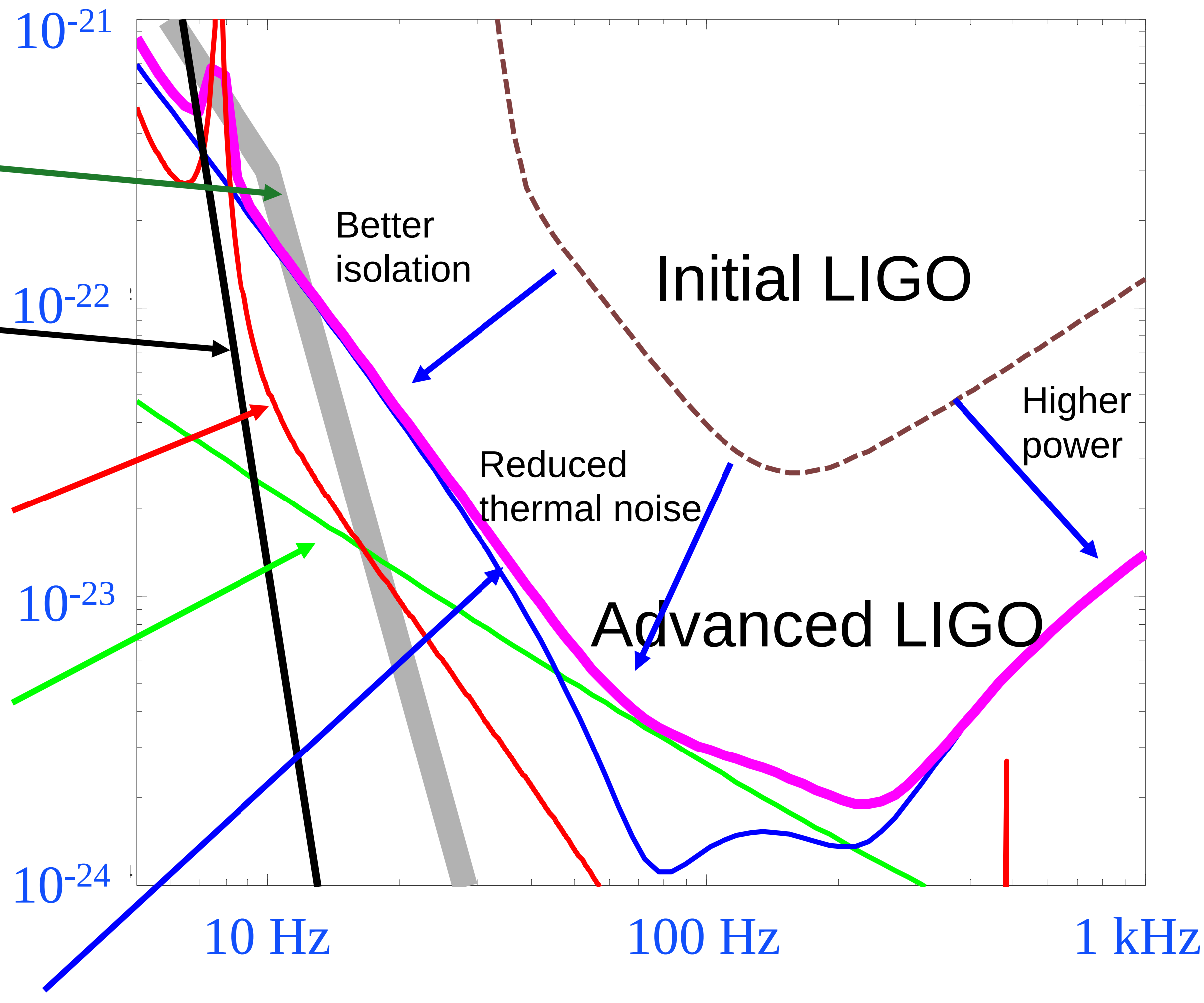


- **Enhanced LIGO: factor of ~ 2 improvement in sensitivity -> factor of ~ 8 in event rate**
- **Incorporate some Advanced LIGO technology early: higher power laser (30 W) + suitable input optics, new readout scheme, more thermal compensation**
- **Increase probability of detection and gain experience of critical technologies- reducing commissioning time for Advanced LIGO**

Timeline adapted from LIGO: G060433

Projected Advanced LIGO performance

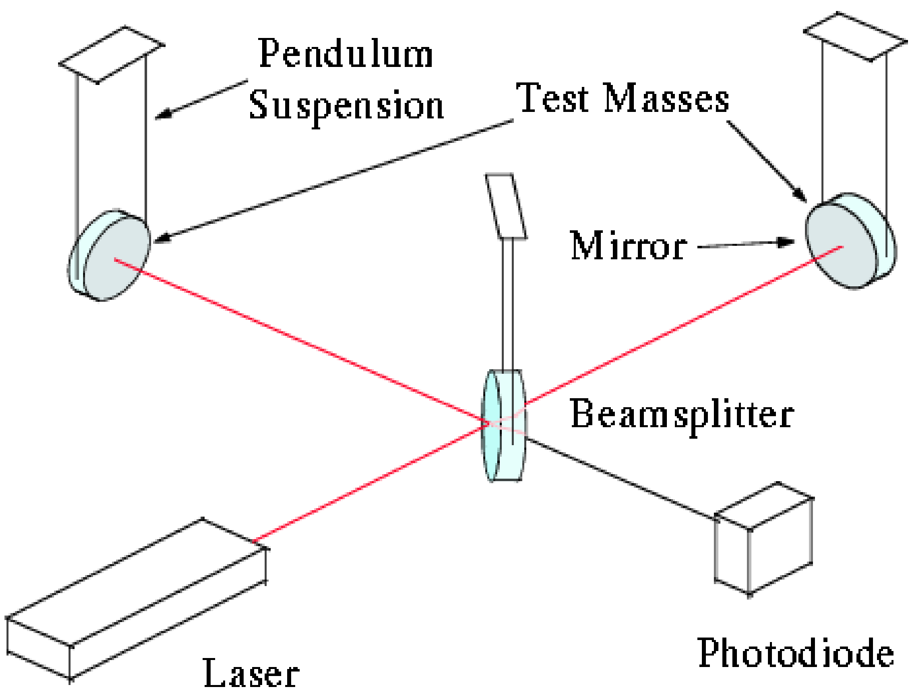
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass mirror coatings thermal noise
- Unified quantum noise: dominates at most frequencies for full power, broadband tuning



(y scale: h/rt Hz)

Suspension Design for GW Detectors

- **long baseline laser interferometry between *freely suspended* test masses**



Suspension Design for GW Detectors continued

- 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

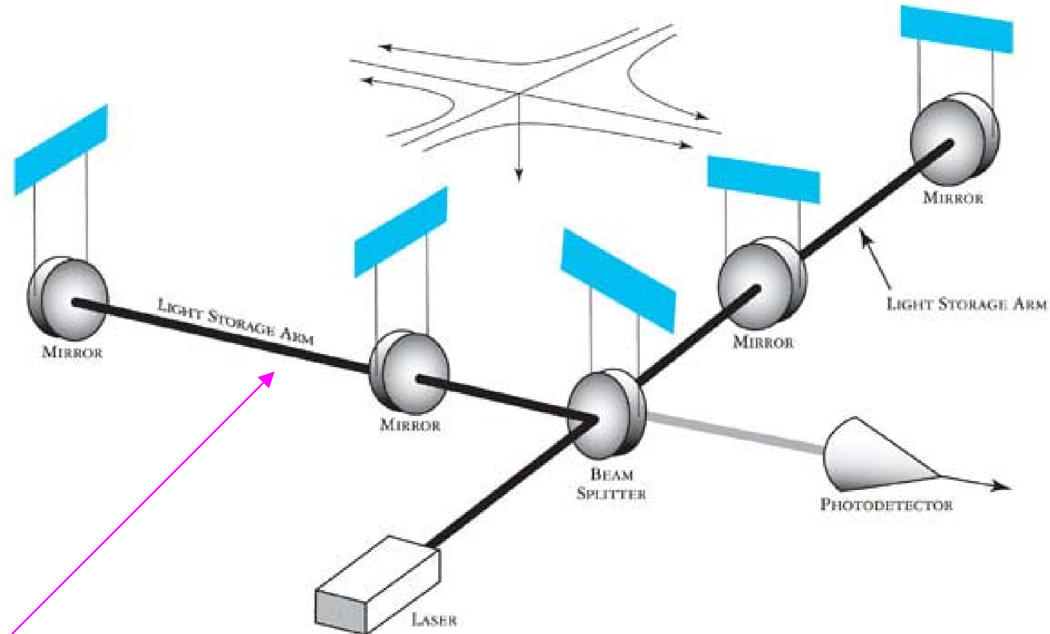


Diagram from LIGO web site

Advanced LIGO Suspensions Team

Wide membership from USA and UK*:

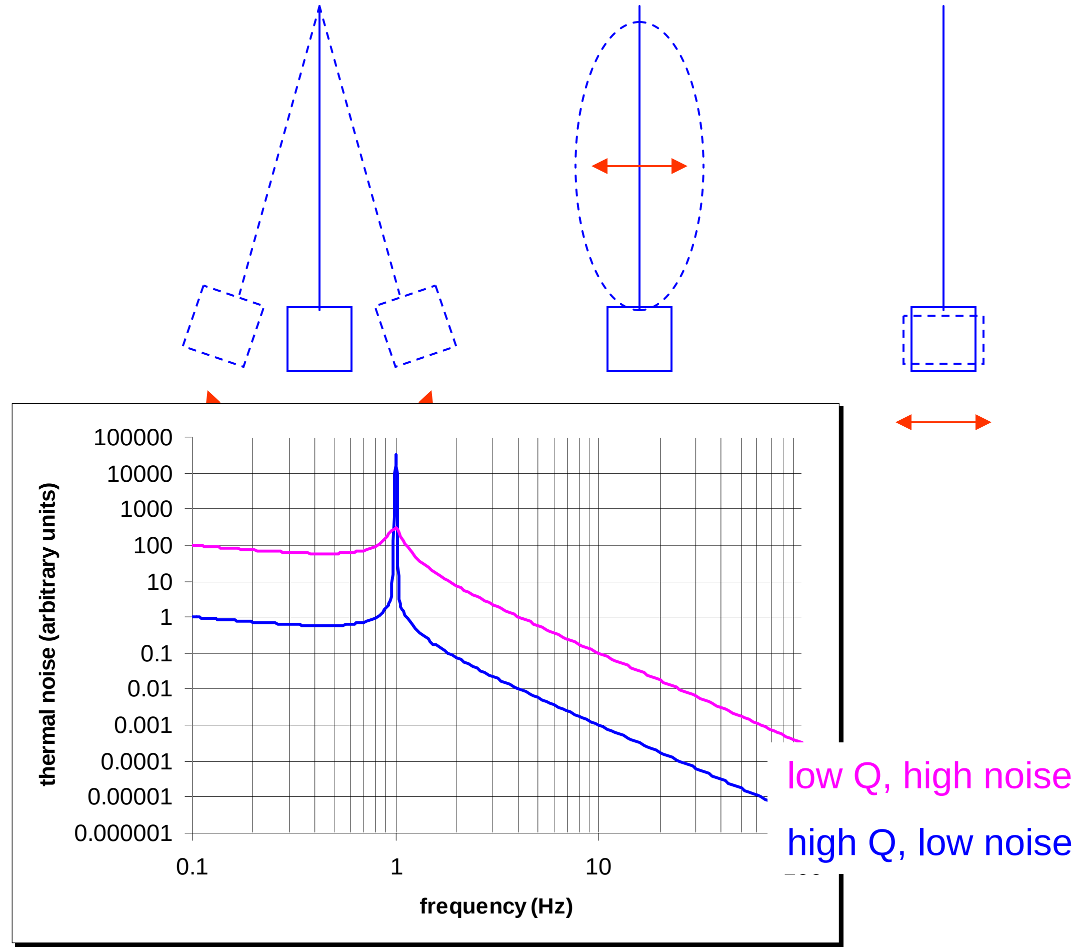
- **LIGO Caltech**: R. Abbott, H. Armandula, D. Coyne, C. Echols, J. Heefner, B. Kirsner, K. Mailand, N. Robertson (also Glasgow) – team leader, G. Scarborough, S. Waldman
- **LIGO Hanford Observatory**: B. Bland, D. Cook, G. Moreno
- **LIGO Livingston Observatory**: D. Bridges, T. Fricke, M. Meyer, J. Romie, D. Sellers, G. Traylor
- **LIGO MIT**: P. Fritschel, A. Heptonstall, R. Mittleman, B. Shapiro, N. Smith
- **University of Glasgow**: M. Barton, C. Craig, L. Cunningham, A. Cumming, G. Hammond, K. Haughian, R. Kumar, J. Hough, R. Jones, I. Martin, S. Rowan, K. Strain, K. Tokmakov C. Torrie, M. Van Veggel
- **Rutherford Appleton Laboratory**: A. Brummitt, J. Greenhalgh, T. Hayler, J. O'Dell, I. Wilmut
- **University of Birmingham**: S. Aston, R. Cutler, D. Lodhia, A. Vecchio
- **Strathclyde University**: N. Lockerbie

*Significant UK involvement : STFC (PPARC) awarded ~$12M grant for development and fabrication of the quadruple suspensions for Advanced LIGO

Thermal Noise

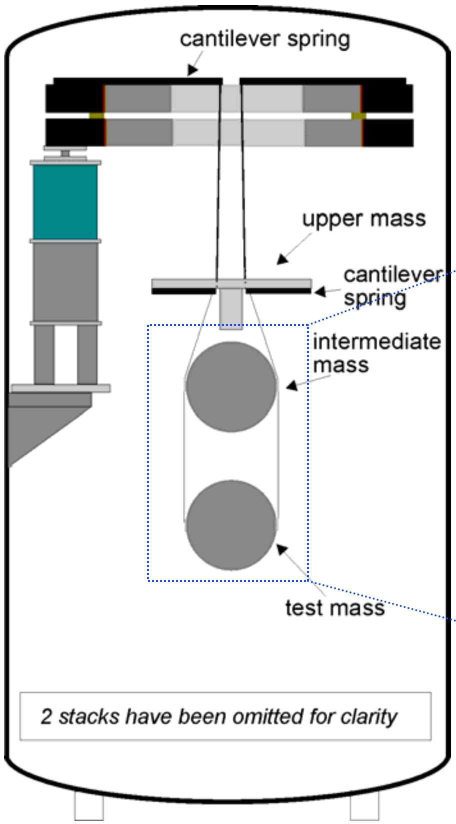
- Thermally excited vibrations of pendulum and violin modes of suspensions and of mirror substrates + coatings

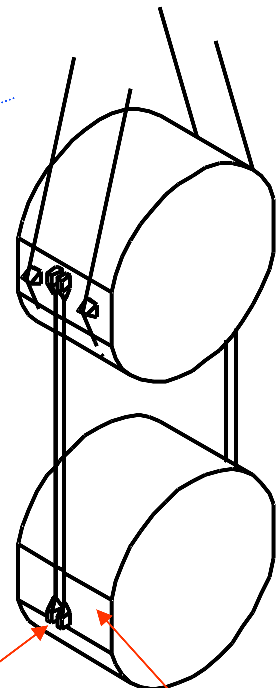
- To minimise:
  - » use low loss (high quality factor, Q) materials for mirror and suspension – gives low thermal noise level off resonance -*silica* is a good choice
    - – *loss angle ~ 2e-7, c.f. steel ~2e-4*
    - – *breaking stress can be larger than steel*
  - » use thin, long fibres to reduce effect of losses from bending

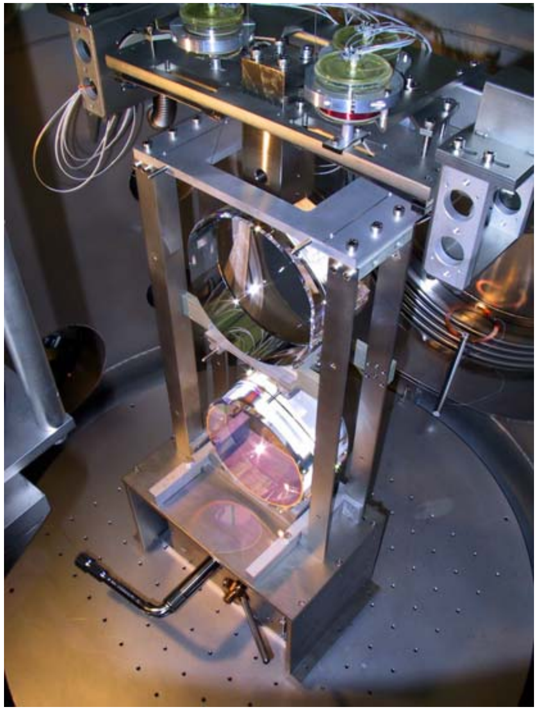


Monolithic fused silica suspensions have been pioneered in the GEO 600 detector: makes use of silicate bonding technique developed for Gravity Probe B

GEO Triple Pendulum Suspension

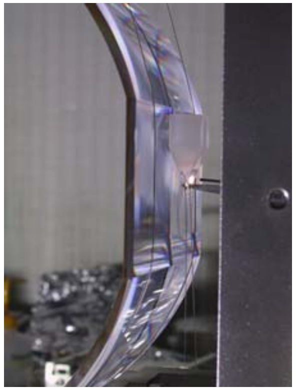




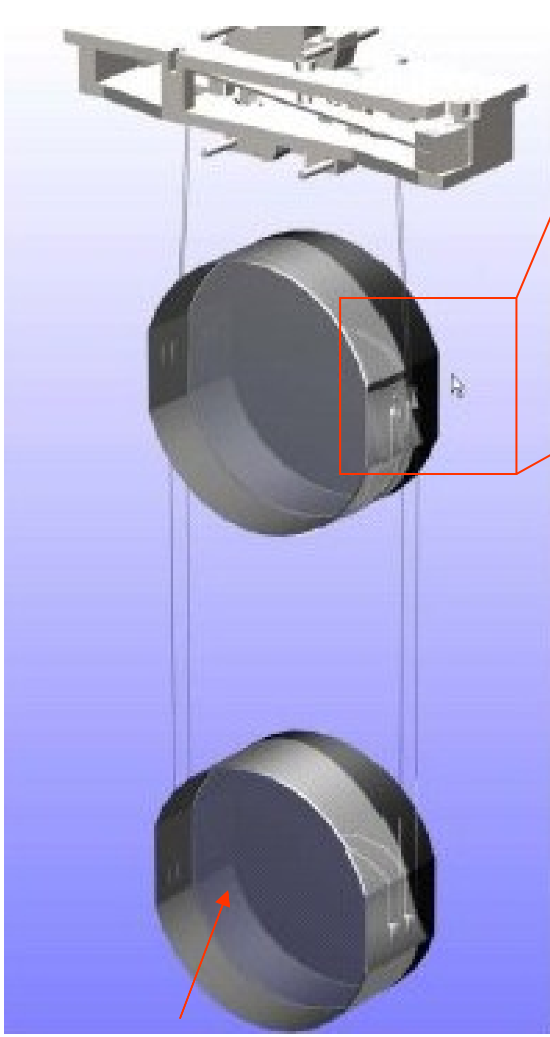


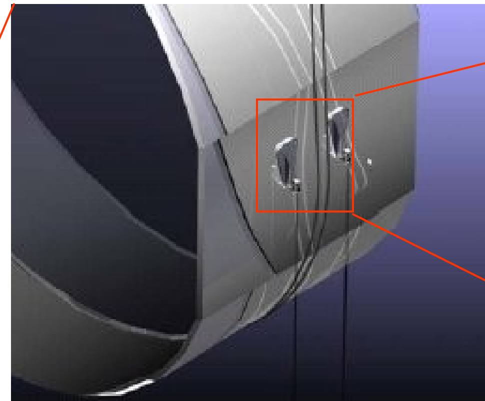
Ears silicate bonded to masses

Silica fibres welded to ears



Development of Suspensions for Advanced LIGO

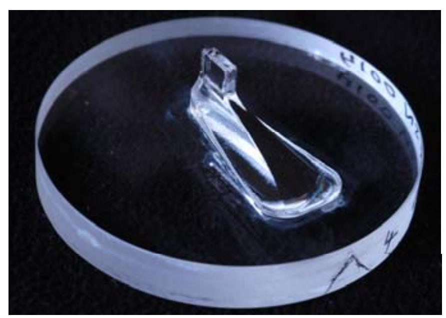


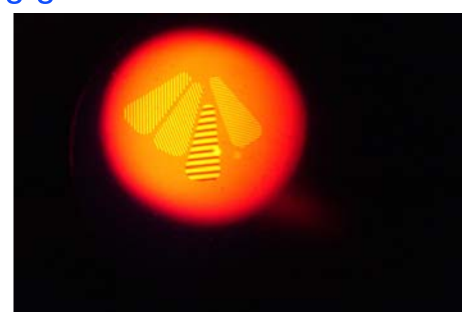


Above: detail of ear bonded to silica mass and ribbon* (0.1 mm x 1 mm x 60 cm long) to be welded to ear

Left: lower 3 stages of suspension with fused silica ribbons* between penultimate mass and mirror (both fused silica)

Below: ear bonded to silica disk for strength tests, and interferogram of ears indicating good flatness





Mirror: 40 kg silica mass

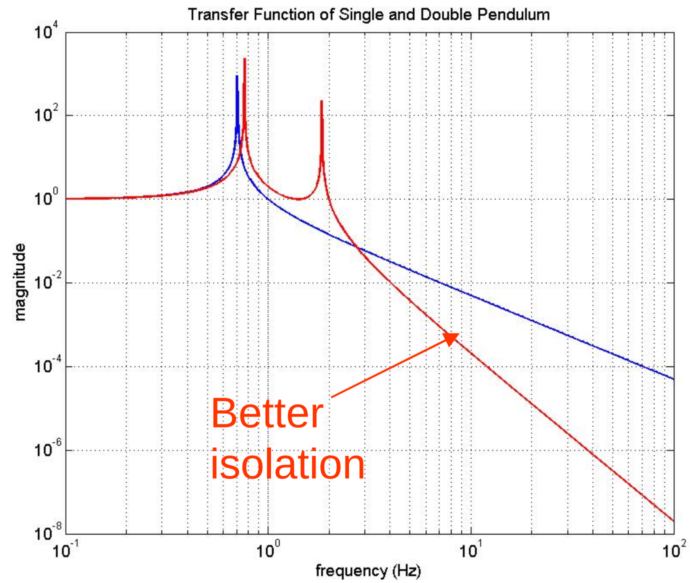
*Recent design change – optimised dumbell-shaped fibres rather than optimised ribbons (less surface loss)

Diagrams from GEO-Glasgow group

Seismic Noise

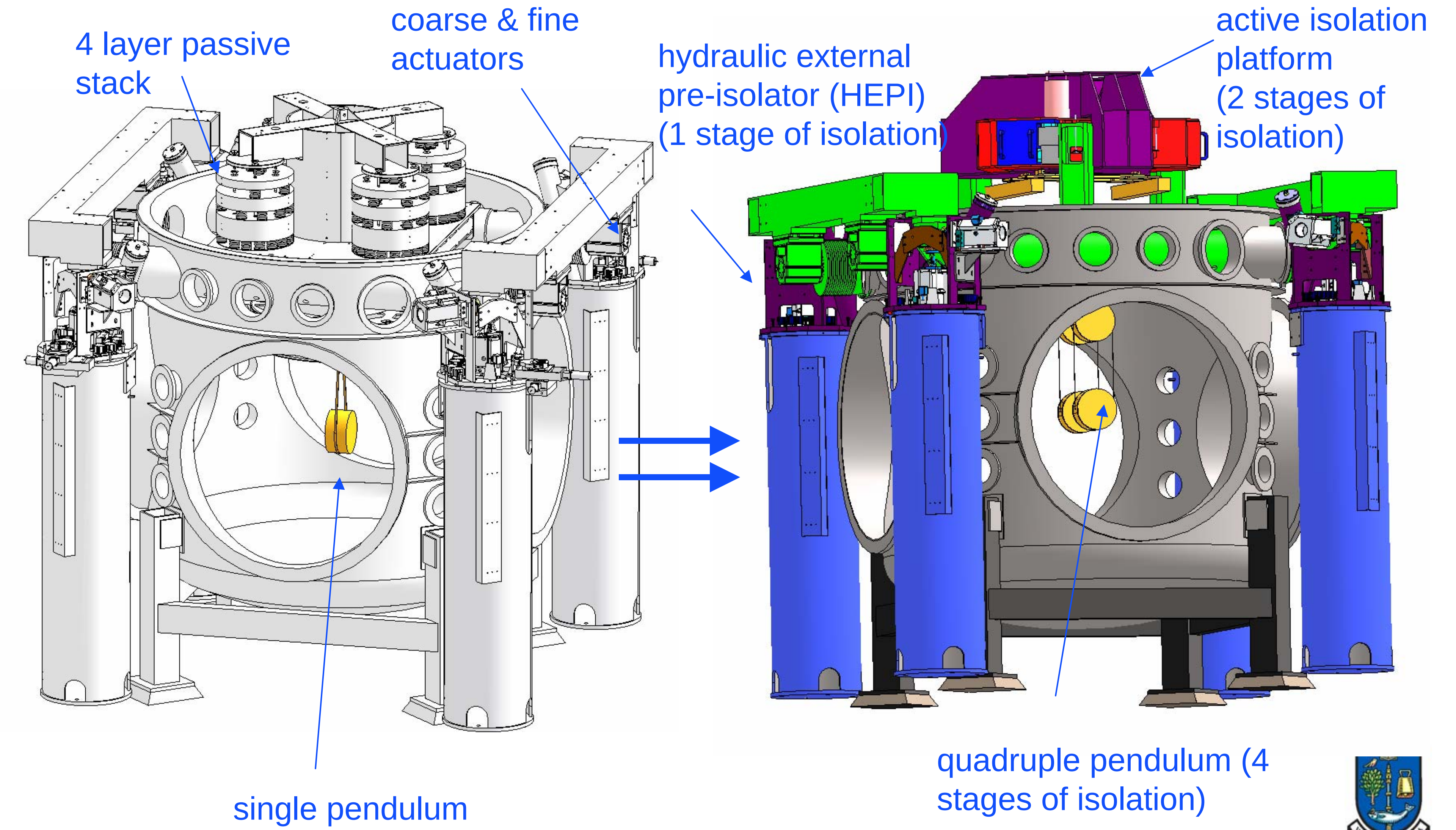
- Seismic noise limits sensitivity at low frequency - “seismic wall”
- Typical seismic noise at “quiet” site at 10 Hz is ~ few x 10^{-10} m/ √ Hz
- For Advanced LIGO more than 9 orders of magnitude of seismic isolation is required at 10 Hz – target is 10^{-19} m/ √ Hz

  Solution - use multiple stages of isolation
- Isolation required in vertical direction as well as horizontal due to cross-coupling effects
- Ultimately Newtonian noise will limit low frequency performance: – LISA (interferometer in space) for low frequency detection

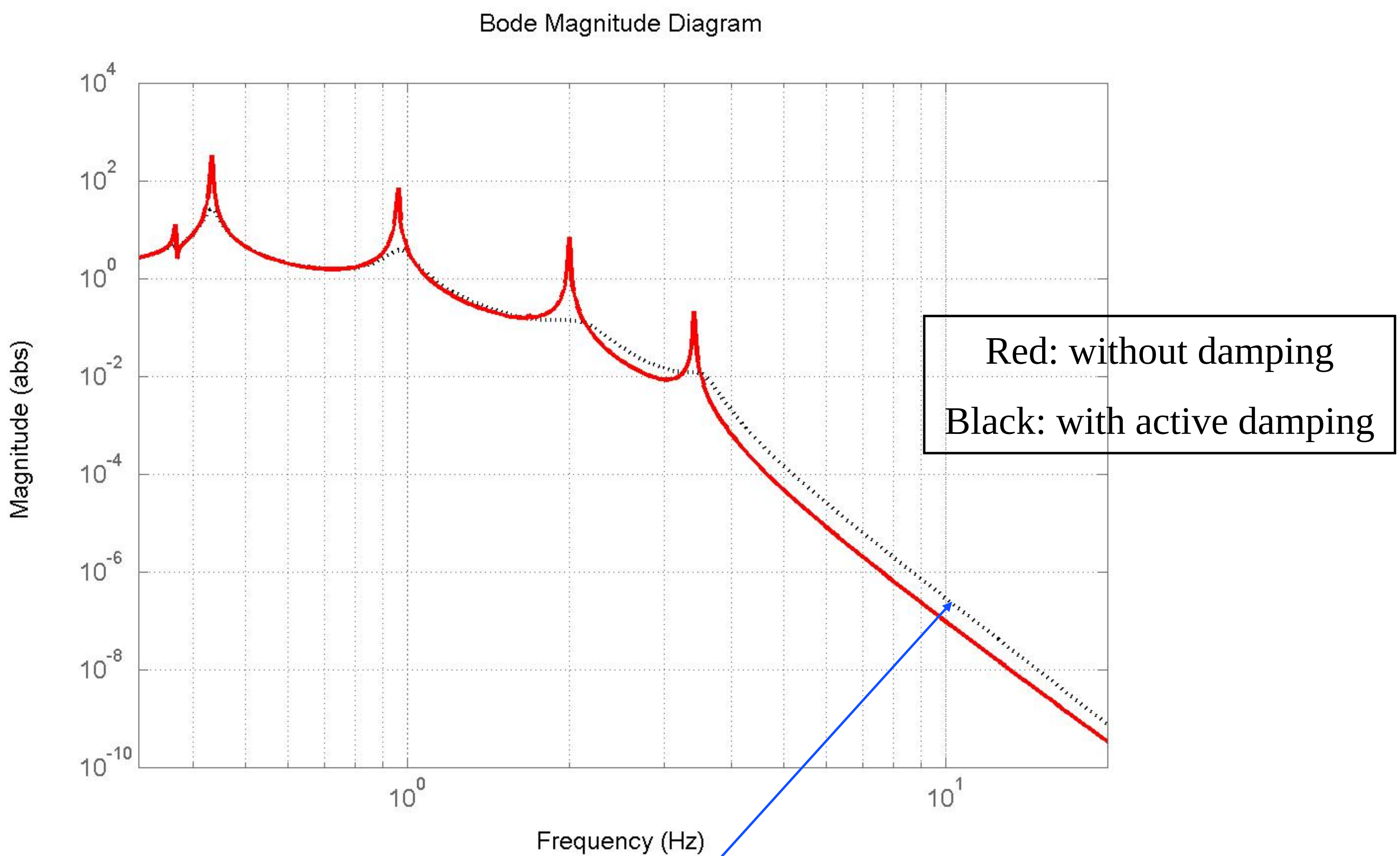


Advantage of double over single pendulum, same overall length

Seismic Isolation - From Initial to Advanced LIGO

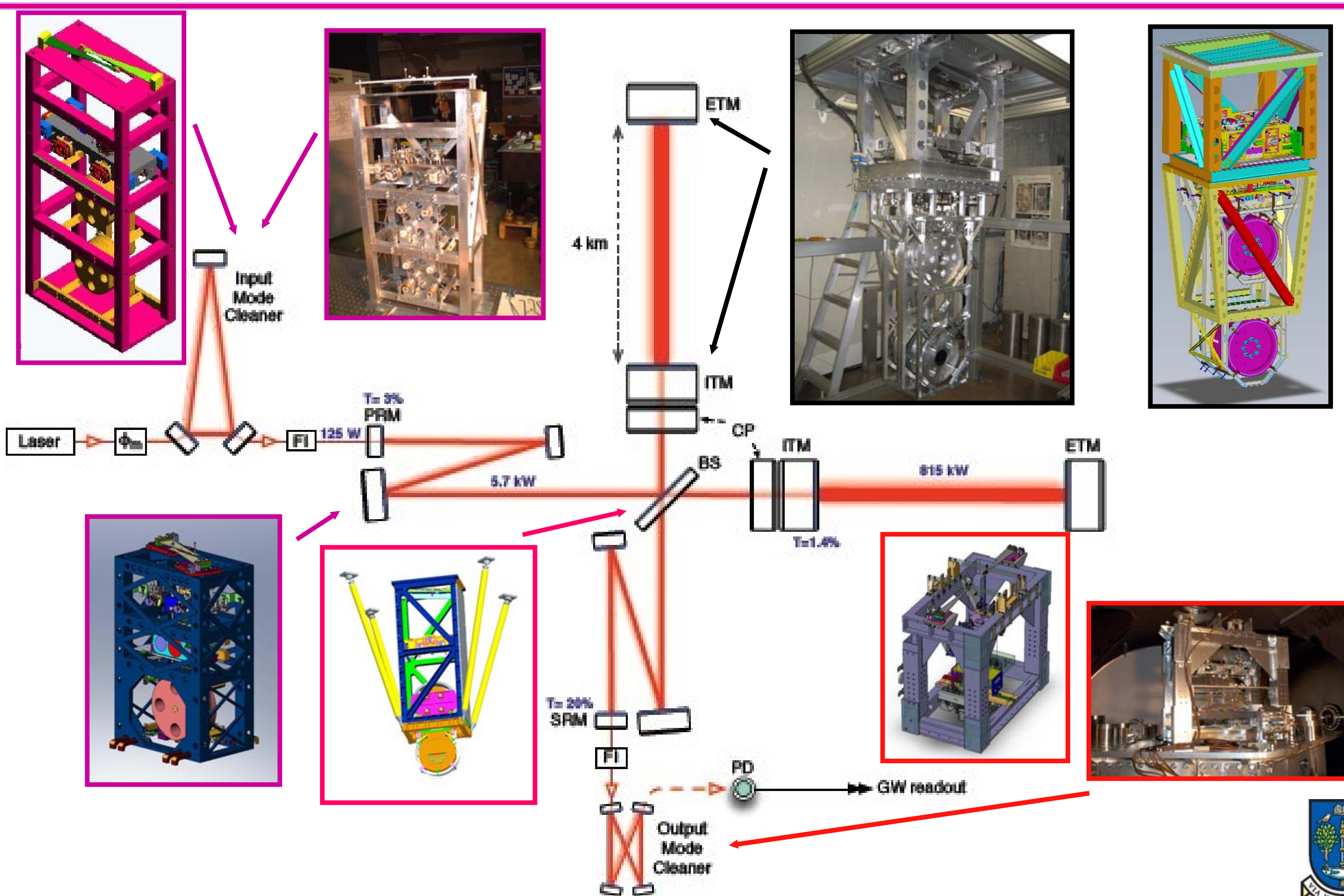


Isolation from Quadruple Pendulum



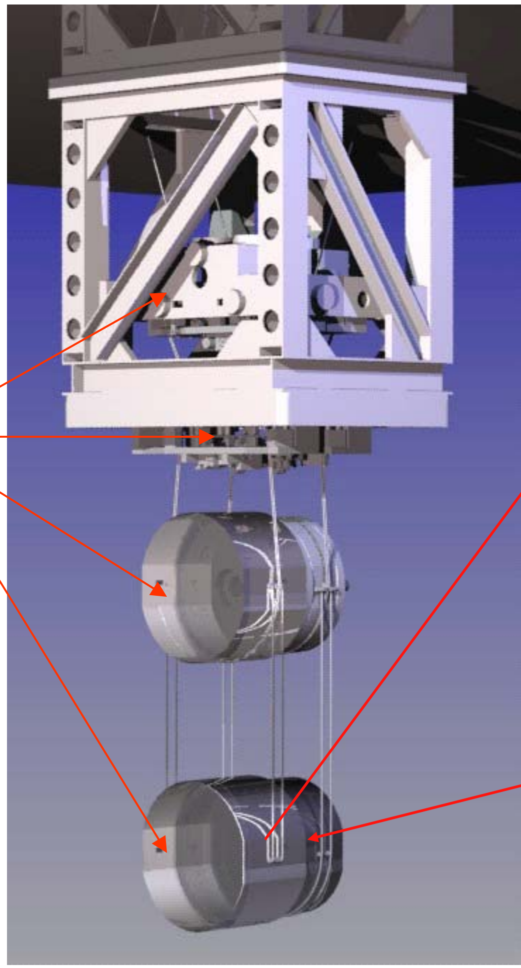
Predicted longitudinal isolation ~ 3 x 10^{-7} at 10 Hz
(from MATLAB model of suspension)

Optical Layout and Suspensions: Quadruples, Triples and Doubles



Advanced LIGO Quadruple Pendulum Suspension

Schematic



Four stages

Damping applied at top stage

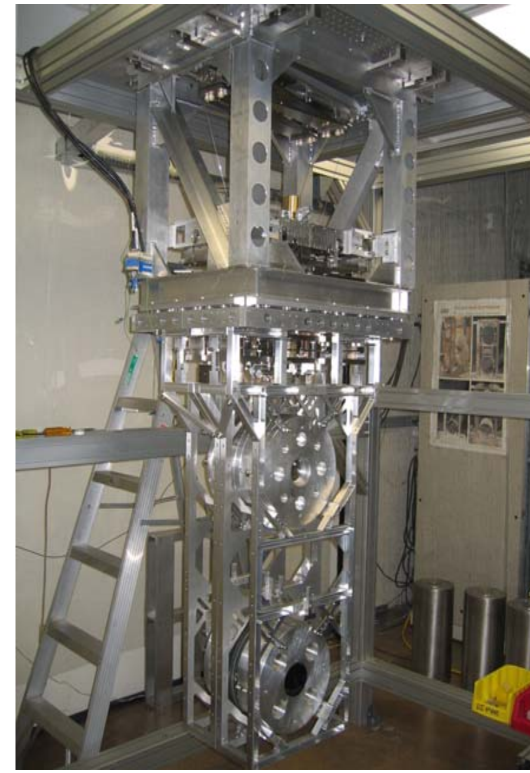
Main chain plus parallel reaction chain for control actuation

(Lower support structure removed for clarity)

First article test mass:
34 cm diam x 20cm thick

Prototype gold-coated face-plate for electrostatic actuation

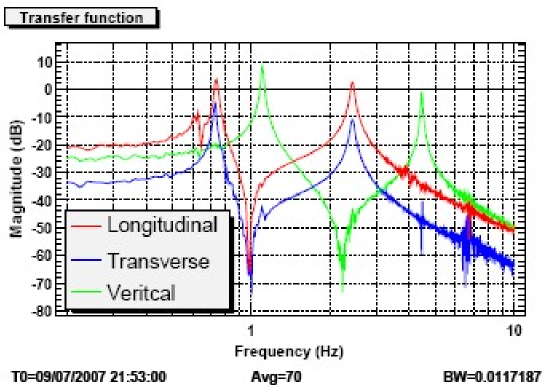
Metal prototype under test at Caltech

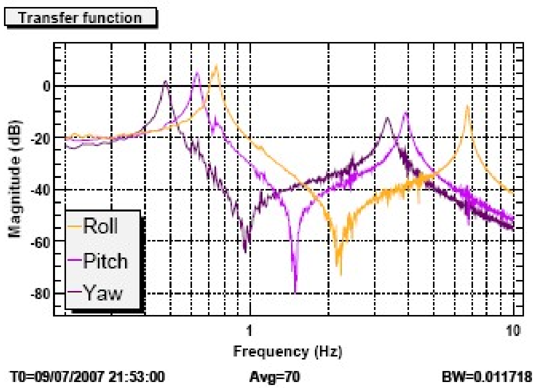


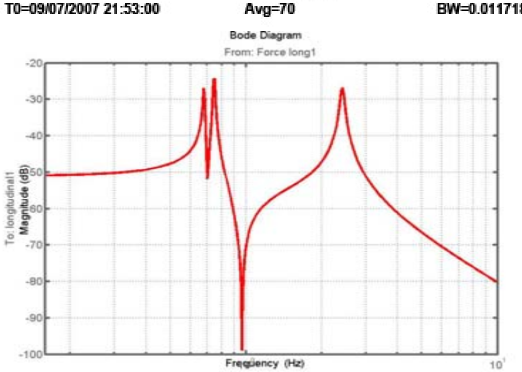
Diagram/picture from Adv. LIGO SUS team

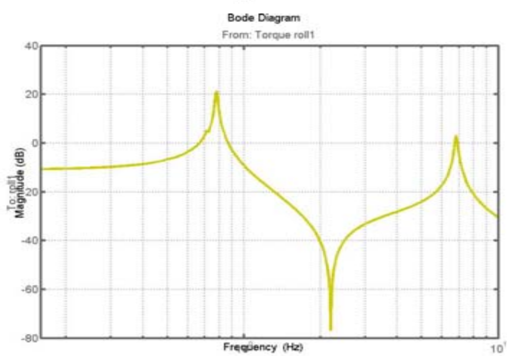
Current Status for Suspensions

- **Ongoing research and development**
- **Program of tests on full-scale prototypes**
  - » **Leading to final design and production (2008 - 2011: 47 major suspensions)**

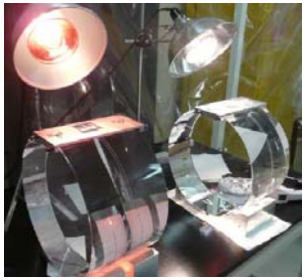






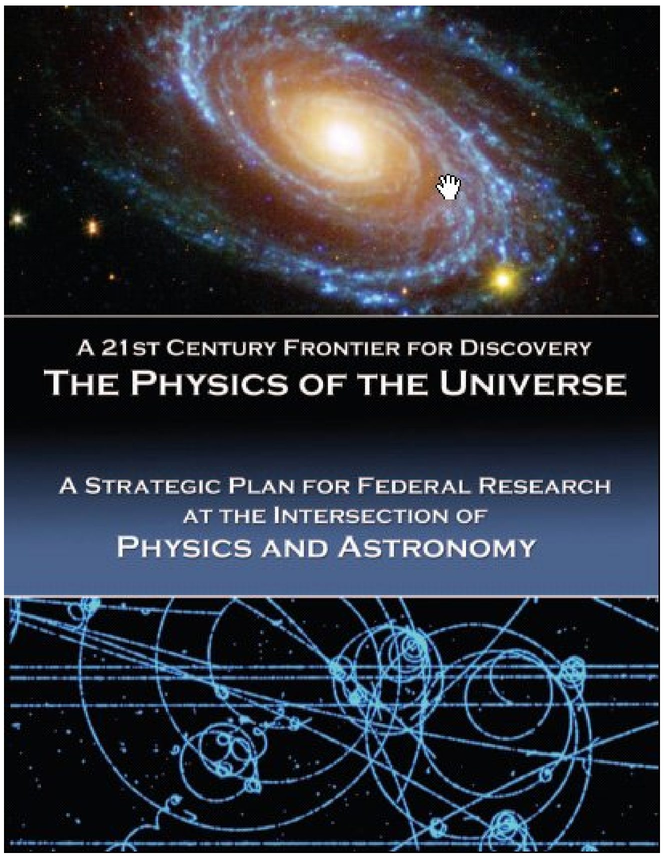


Example of measurements: upper set – experimental, lower set: from MATLAB model



Conclusion

- **Gravitational wave detection is recognised as a key research area: exciting times ahead!**



Report from Interagency Working Group, Feb 2004

Recommendations

* NSF, NASA, and DOE will strengthen numerical relativity research in order to more accurately simulate the sources of gravitational waves.

* The timely upgrade of LIGO and execution of the LISA mission are necessary to open this powerful new window on the universe and create the new field of gravitational wave astronomy.