LIGO
and the Search for Gravitational Waves

Norna A Robertson
for the LIGO Scientific Collaboration (LSC)

LIGO-Caltech & University of Glasgow

Miami 2008 Conference
Fort Lauderdale, FL
18th December 2008
G080628-00-R

Outline of Talk

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

What Are Gravitational Waves?

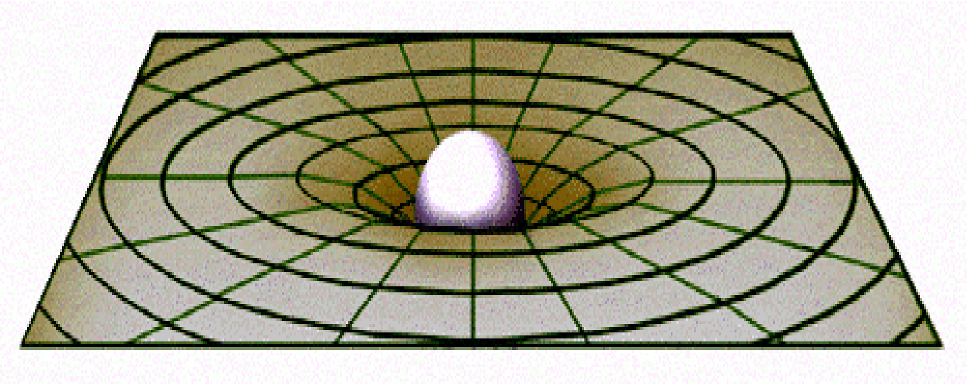
Einstein's theory

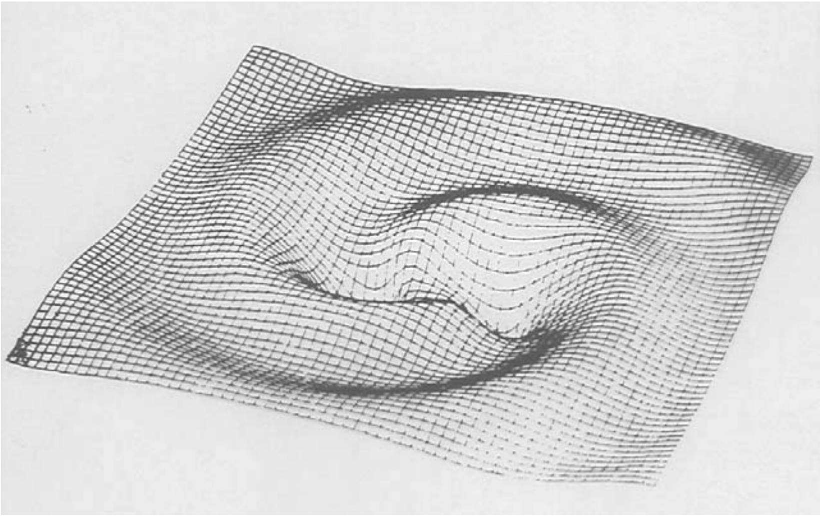
gravitation =

curvature of space-time

gravitational waves =

waves in curvature of space-time





Production of Gravitational Waves (GW)

Compare to EM waves:

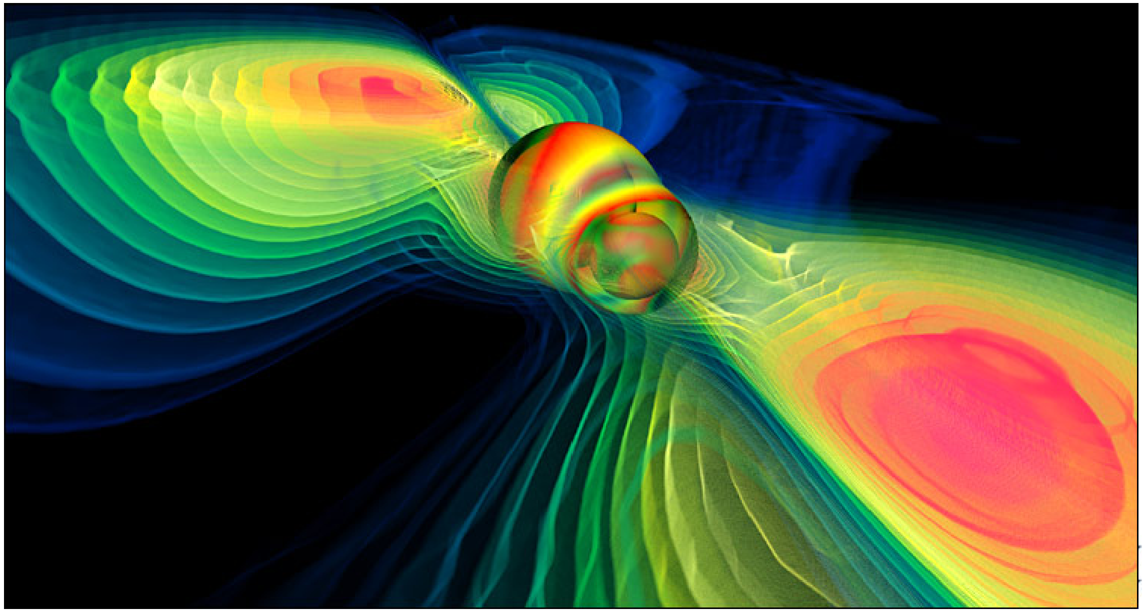
- GW produced by acceleration of mass
- GW travel at speed of light

However

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

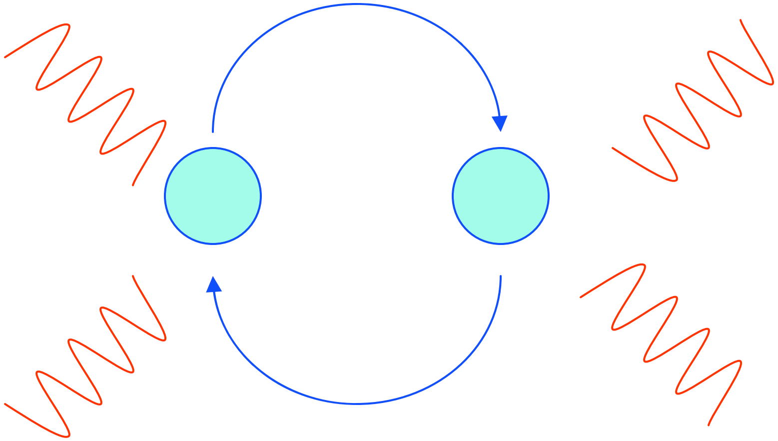
To produce significant flux requires asymmetric accelerations of large masses, i.e.

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



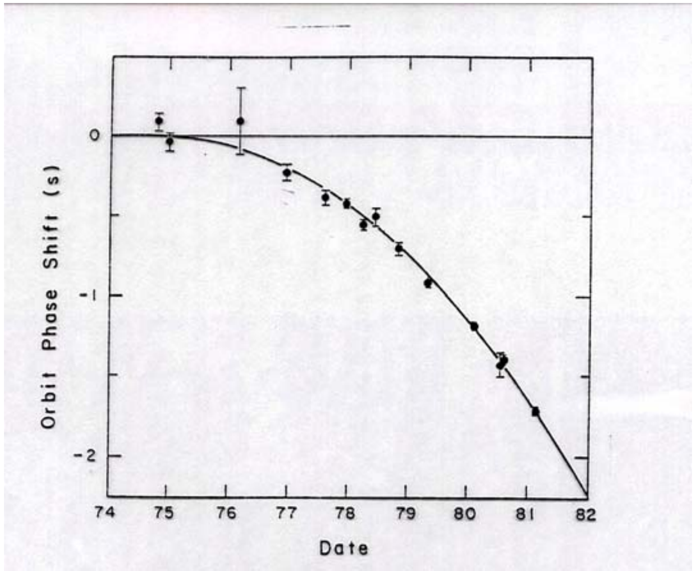
Orbit decaying, with emission of gravitational waves

(rate of decay ~10 mm per day, semimajor axis ~ 2 x 10^{12} mm, merger in ~300 million yrs)

A highly relativistic binary pulsar, PSR J0737-3039, was discovered in late 2003: merger in 85 Myrs

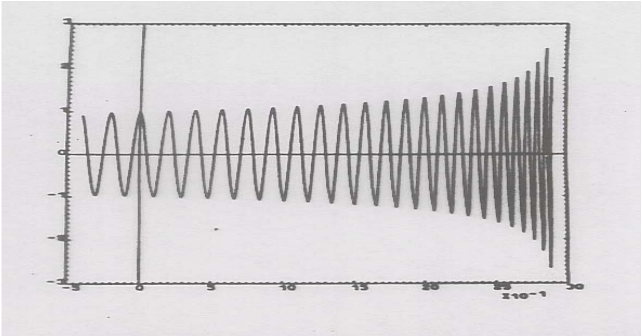
Statistics small – this observation increased merger rate estimate by almost an order of magnitude.

(Kalogera et al ApJ Lett **601**, **614,** 2004)



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

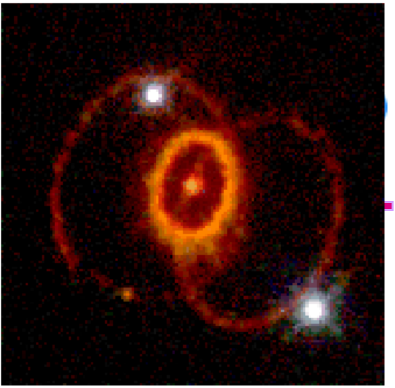
Hulse and Taylor won Nobel Prize in 1993 for discovery and study of PSR1913+16

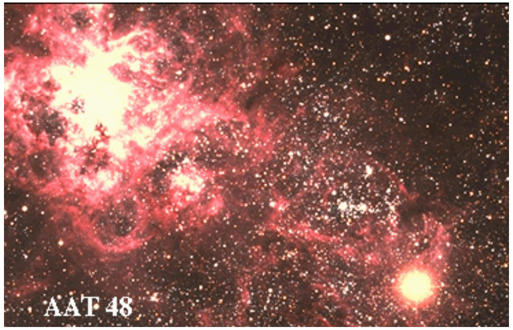


Expected GW signal from binary coalescence

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

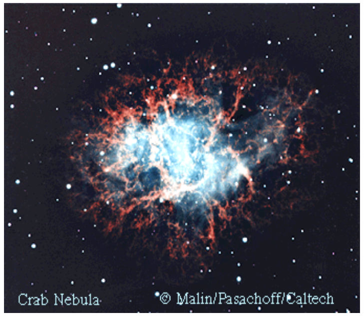




SN1987a

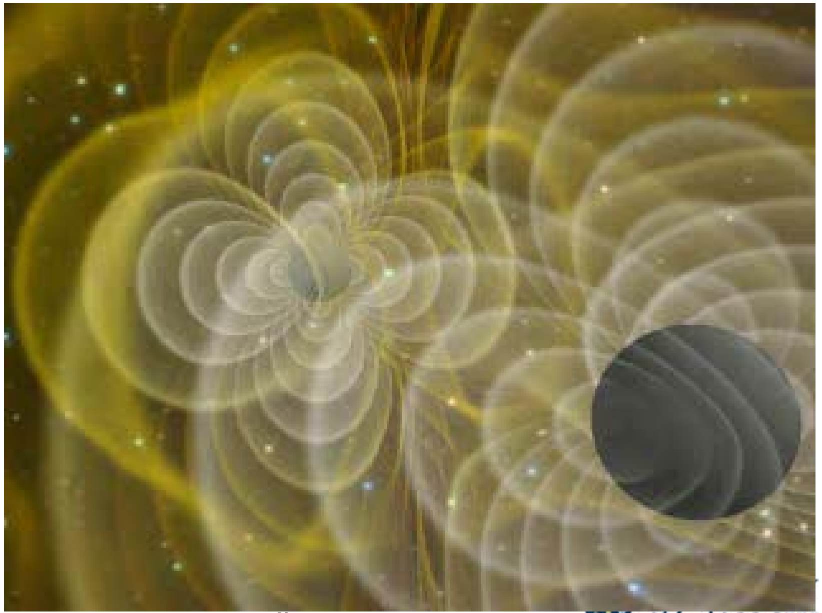
- ***Continuous***
  - » pulsars (e.g. Crab)

  (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…..

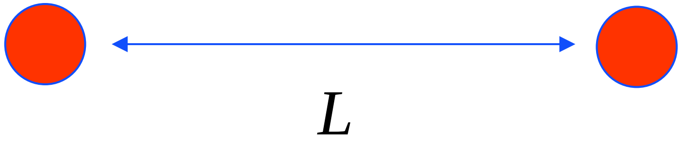
A New Astronomy



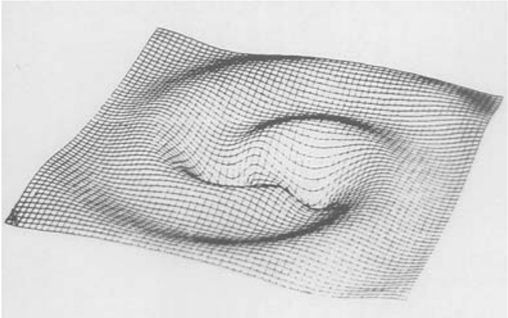
Credit: Henze, NASA

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

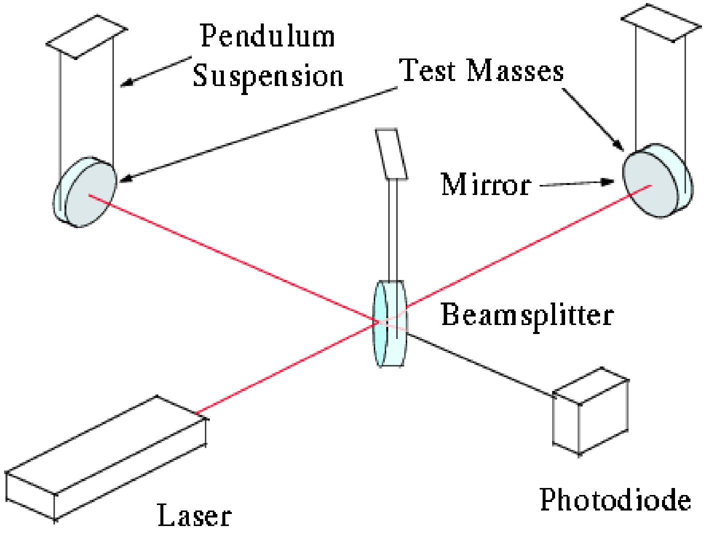


$$\boxed{\frac{\Delta L}{L} \approx h}$$



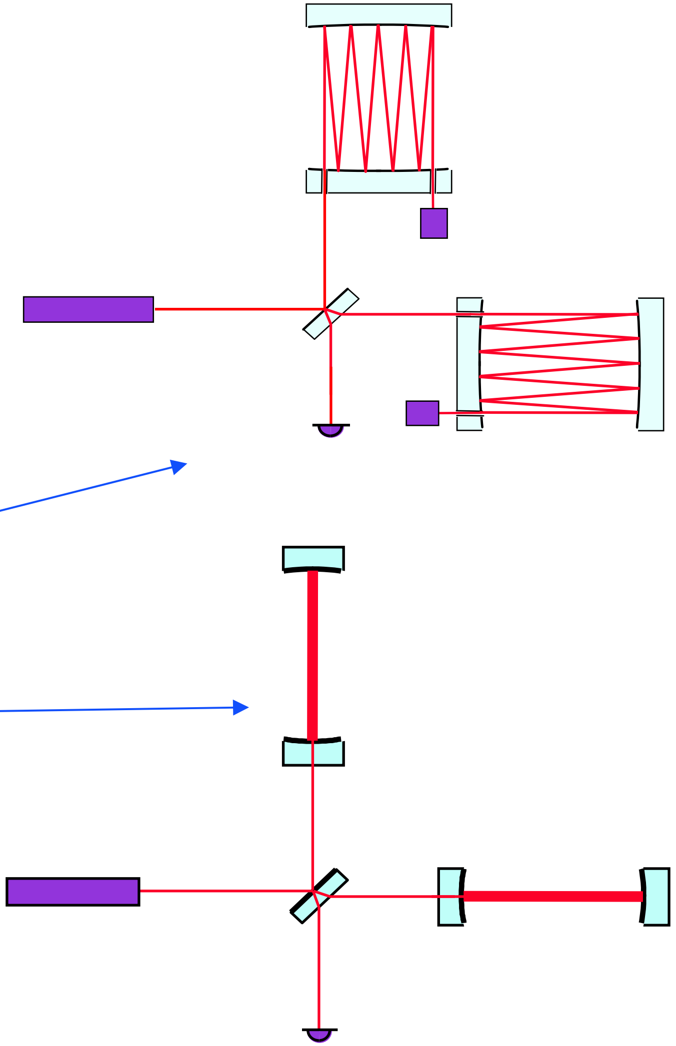
- Magnitude of h at Earth
  - » Largest signals (very rare) $h \sim 10^{-19}$
  - » For reasonable event rate $h \sim 10^{-22}$ -10^{-23}

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

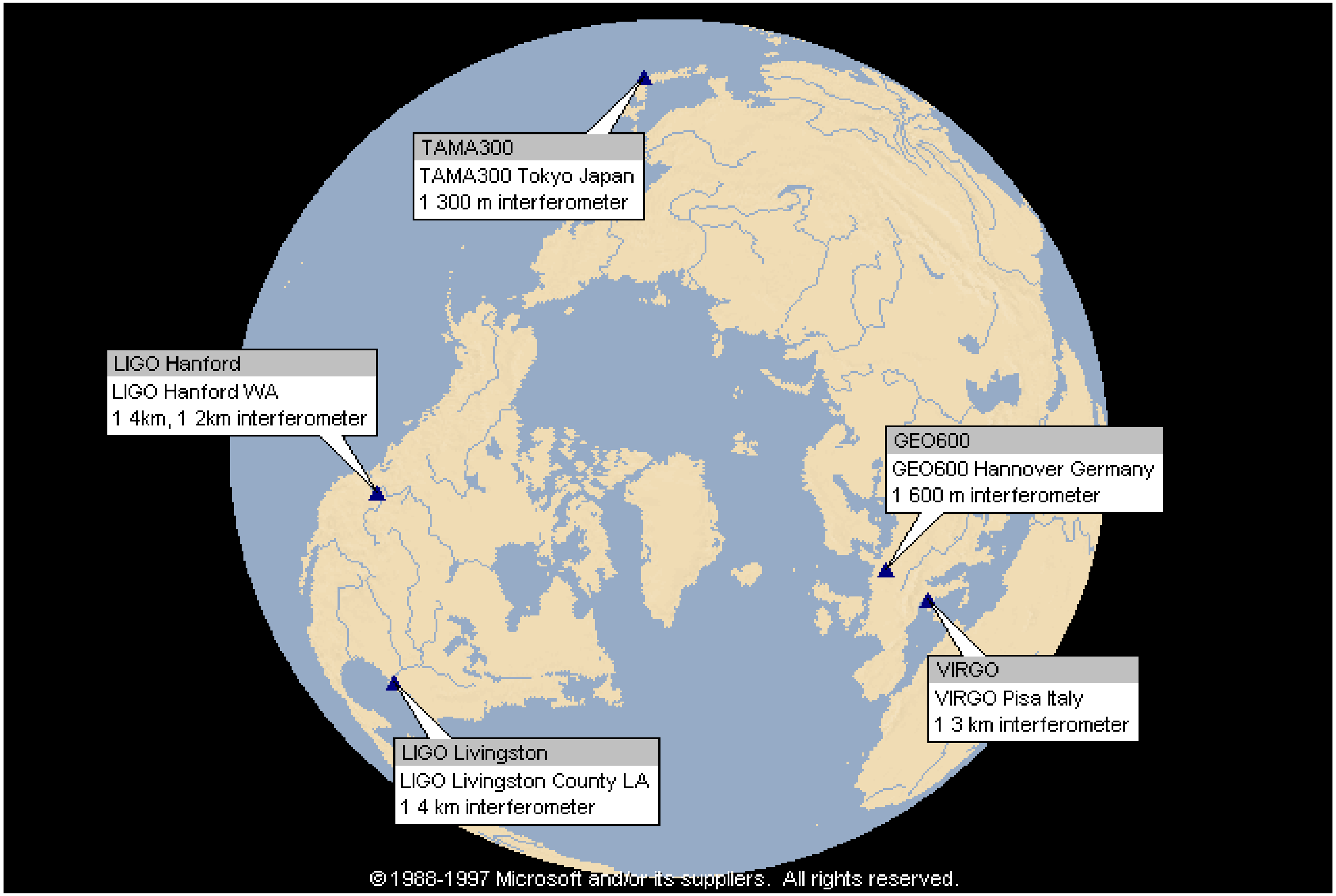


Advantages of Interferometer

- 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:
  - » delay lines
  - » Fabry Perot cavities



WORLDWIDE GW INTERFEROMETER NETWORK



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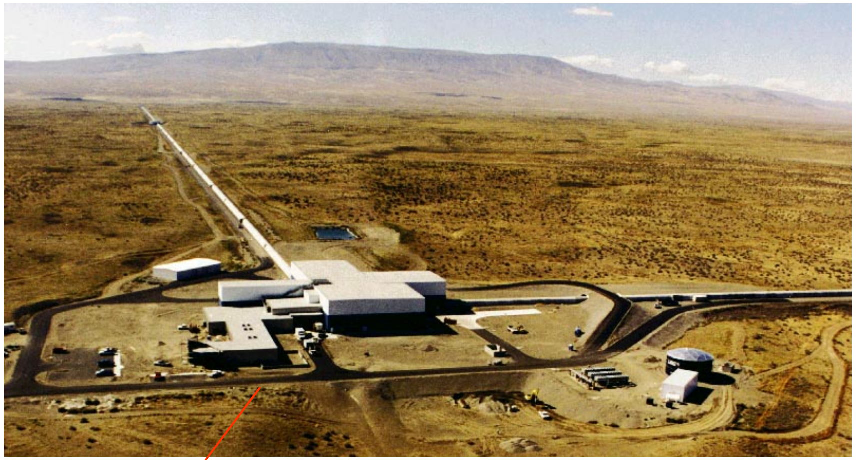
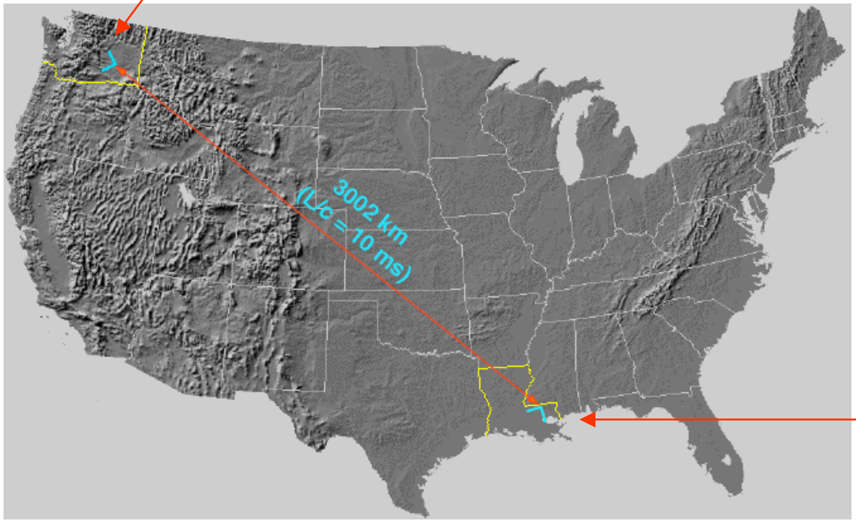
LIGO Observatories



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

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

Sensitivity Limits and Noise Sources

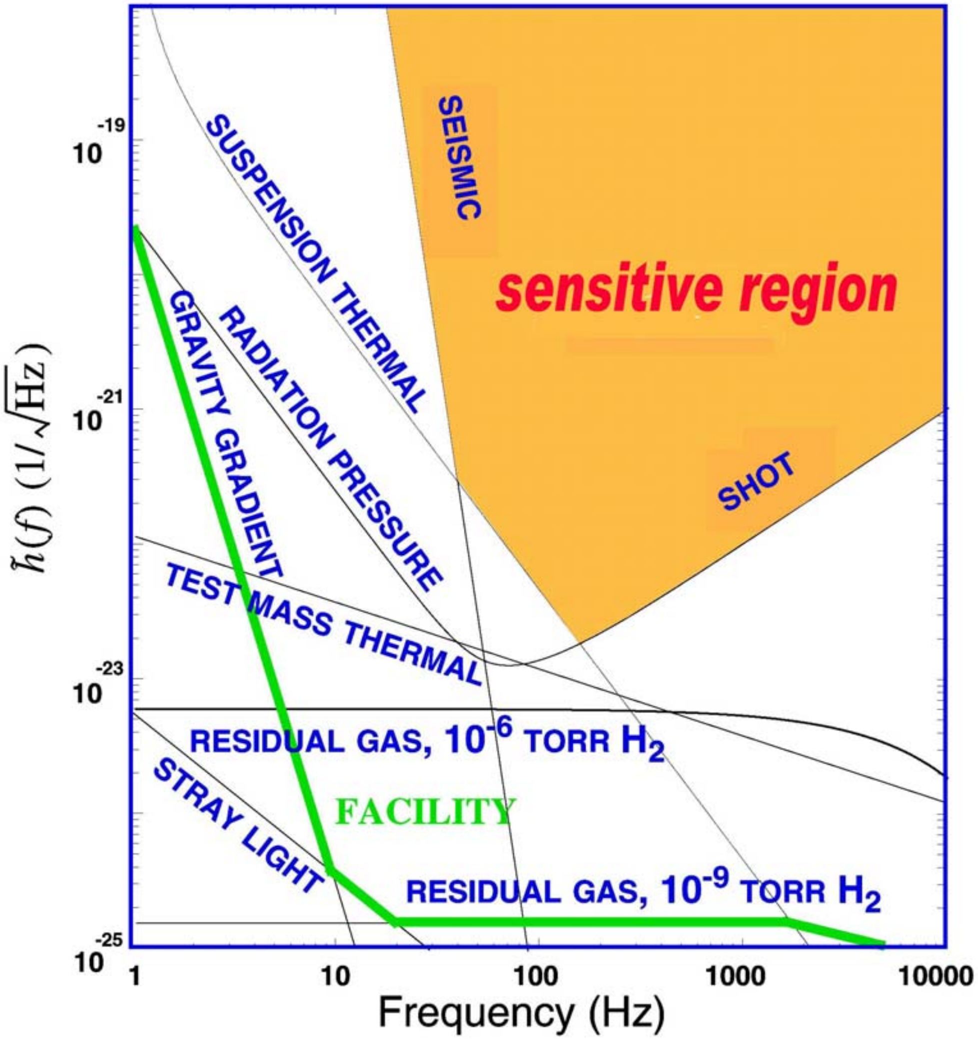
- *Photon Shot Noise*

  -high frequencies
- *Thermal Noise* (in suspensions and test masses)

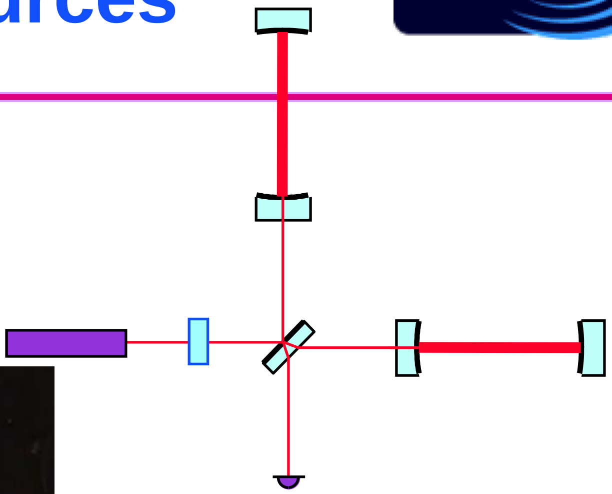
  - mid frequencies
- *Seismic noise*

  - low frequencies

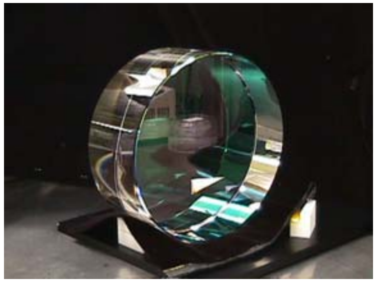
- Many technical noise sources
  - electronics noise from control systems
  - laser intensity noise
  - laser frequency noise
  - laser beam jitter
  - upconversion of low frequency noise
  - …….



Mitigation of Noise Sources



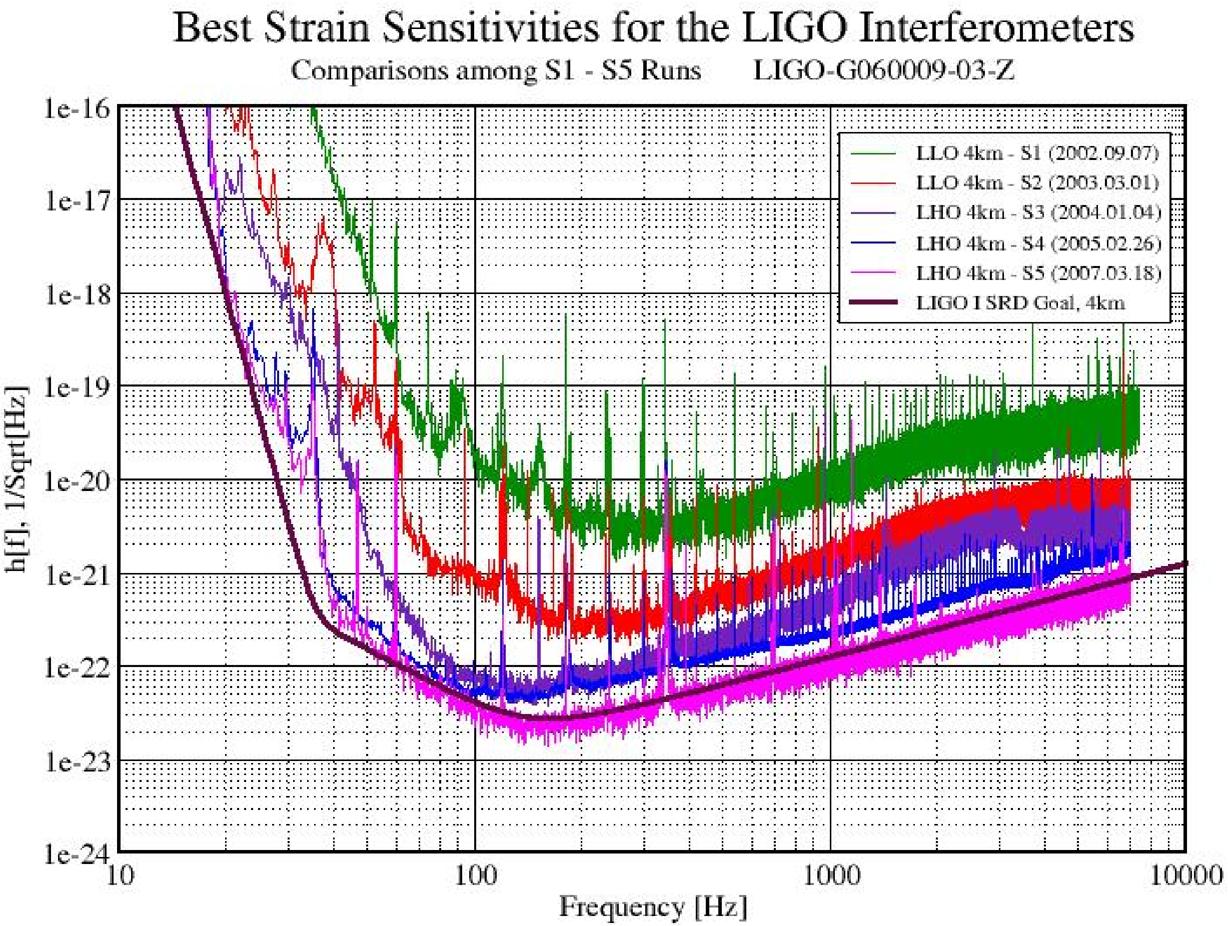
- Photon shot noise
  - 10 W Nd-YAG laser, Fabry Perot cavities in each arm, power recycling mirror
- Thermal Noise
  - Use low mechanical loss materials
  - Work away from resonances
  - Thin suspension wires



- Seismic Noise
  - Passive isolation stack
  - Pendulum suspension

Operate under high vacuum

Evolution of LIGO Sensitivity



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

Five S5 papers already published or submitted

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

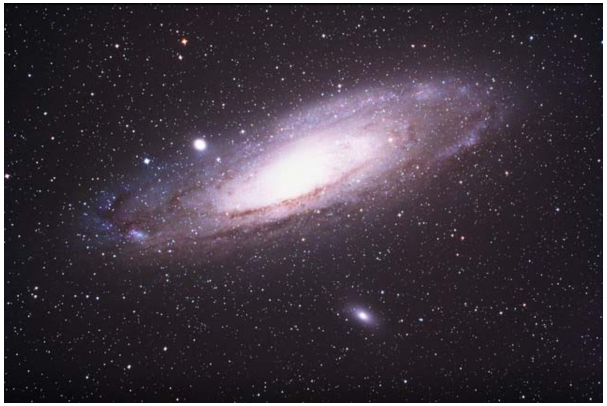
LIGO Status – Data Analysis

- Since 2004, a total of 35 observational papers published – see

https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html

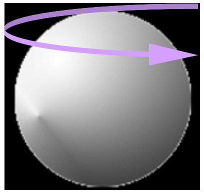
A couple of data analysis highlights:

- <u>“Implications for the Origin of GRB 070201 from LIGO Observations”</u> (Astrophys J, 681, (2008) 1419)
  - 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)



M31*

- <u>“Beating the spin-down limit on gravitational wave emission from the Crab pulsar”</u> (ApJ Lett 683 (2008) 45)
  - Neutron star - remnant from supernova in 1054
  - Spin frequency 29.8 Hz → GW frequency 59.6 Hz
  - Spin down due to
    - electromagnetic emission
    - *GW emission?*
  - GW strain upper limit: $h < 2.7 \times 10^{-25}$ → 5.3 x below spin down limit
  - Ellipticity upper limit $\varepsilon < 1.8 \times 10^{-4}$
  - GW energy upper limit < 4% of radiated energy is in GWs



Crab pulsar (combined Hubble/Chandra image)

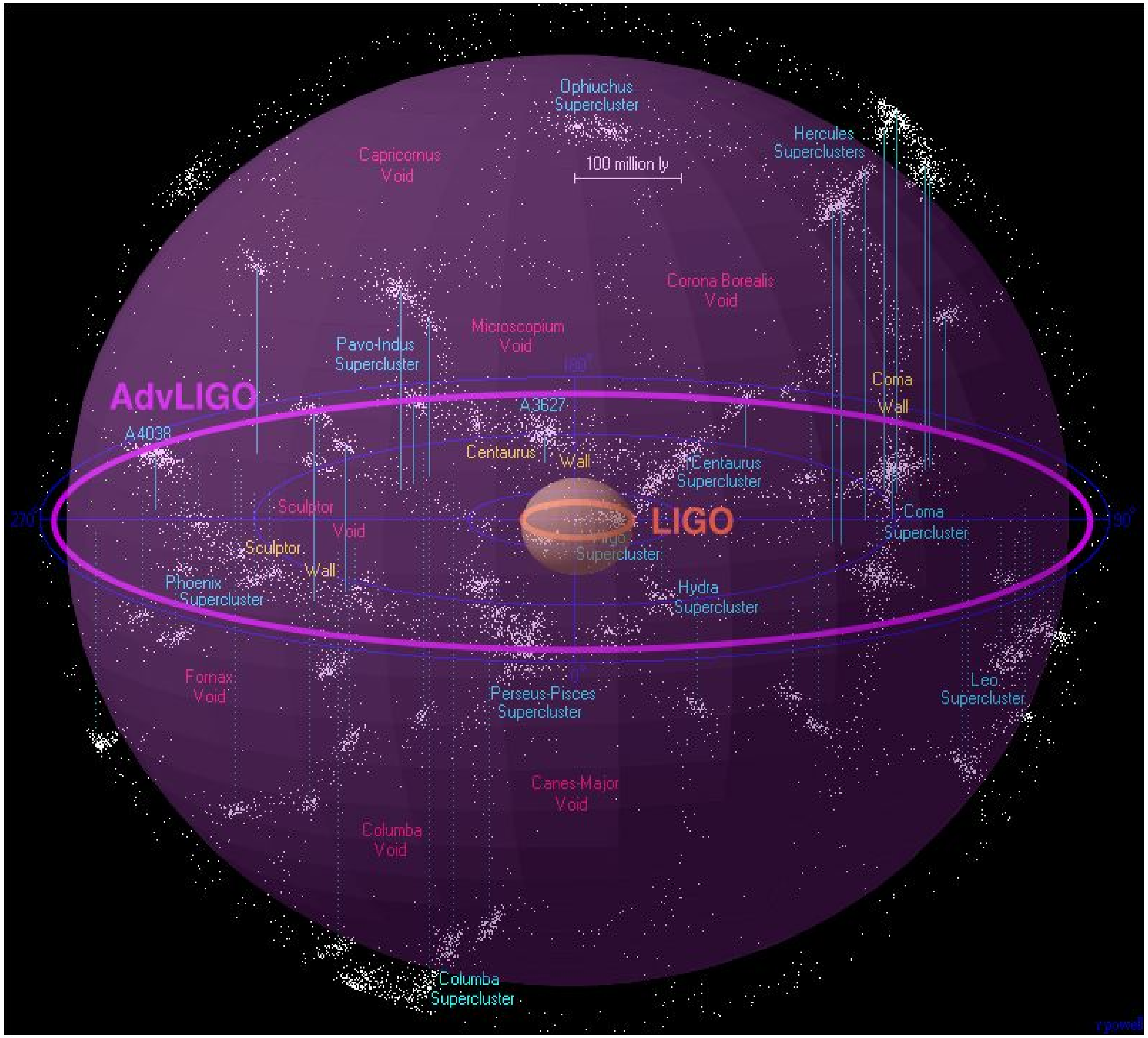
- MOU with Virgo in place – started data sharing in May 2007. Papers from 2nd year of S5 will include LSC+Virgo data.

*Credit: John Lanoue

LIGO Status – Funding and Technical Advances

- The National Science Board announced approval in March 2008 for the construction of Advanced LIGO:
  - formal start of funding April 2008, budget $205M
  - in addition capital contributions from UK and Germany
- Advanced LIGO is aimed at achieving a sensitivity at which several signals per month (perhaps per week) should be detected
  - Factor of 10 improved sensitivity at ~100 Hz
  - Wider bandwidth extending down to ~10 Hz
- Current schedule for Advanced LIGO:
  - start of installation – early 2011
  - acceptance date (all 3 interferometers) – early 2014
    - followed shortly by a science run (low power, low frequency) assuming all goes well

LIGO vs Advanced LIGO

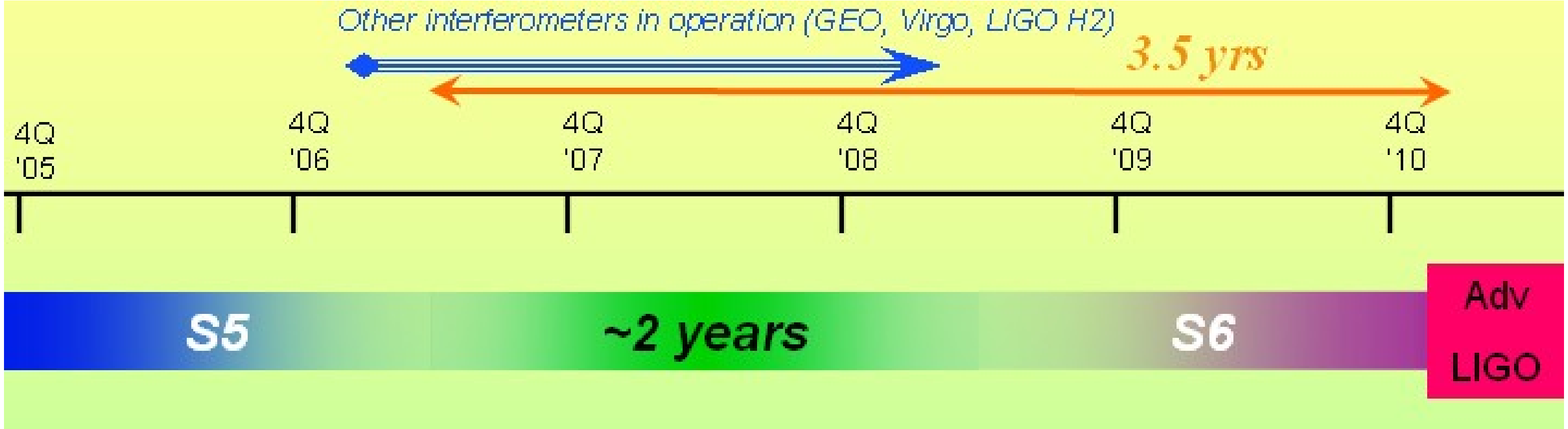


Factor of 10 in sensitivity gives factor of 1000 in volume and hence in event rate

slide from B Berger

Interim Upgrade - Enhanced LIGO

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

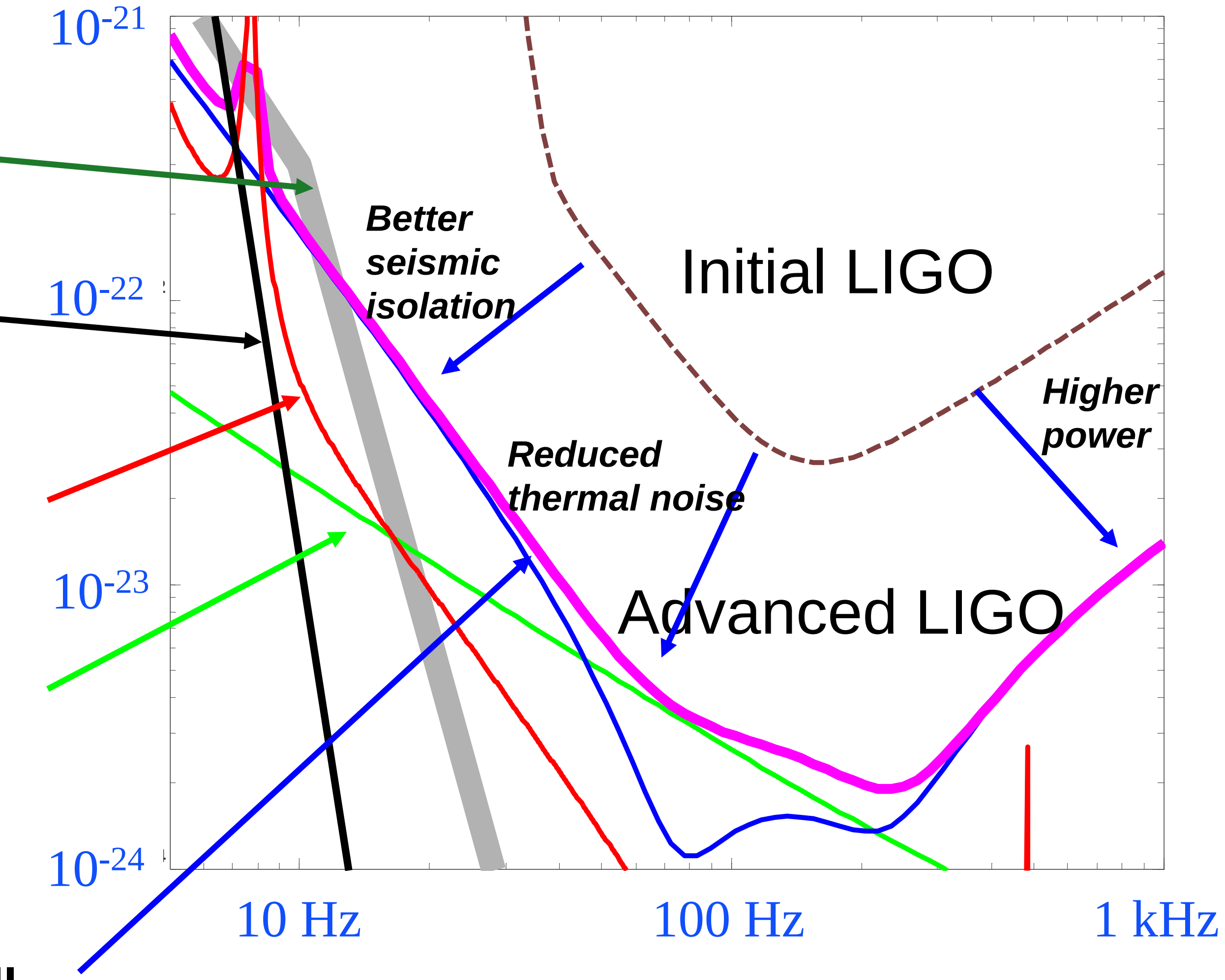


- Enhanced LIGO: factor of ~ 2 improvement in sensitivity -> factor of ~ 8 in event rate
- Incorporate some Advanced LIGO technology early: higher power laser (35 W) + suitable input optics, new readout scheme, more thermal compensation
- Increase probability of detection and gain experience of critical technologies- reducing commissioning time for Advanced LIGO
- S6 run – aiming for start date May 2009

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**

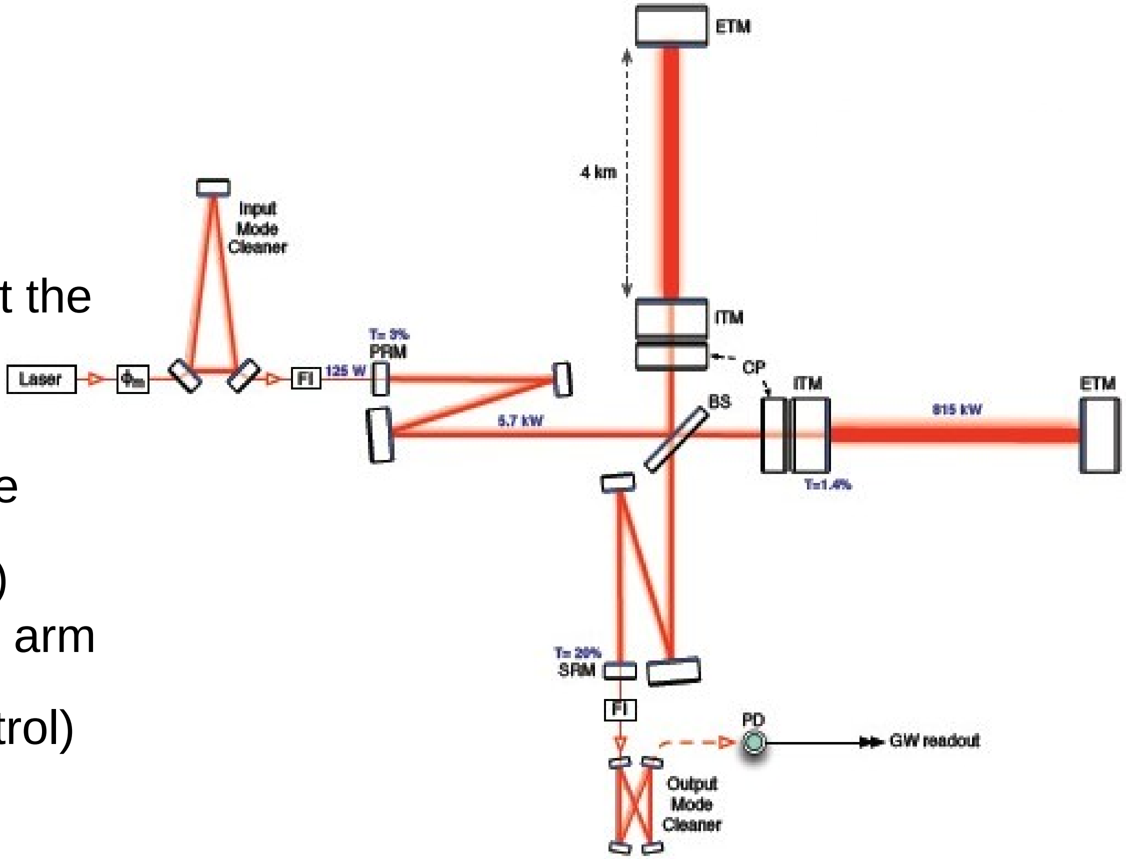


(y scale: h/rt Hz)

Suspension Design for GW Detectors

- 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



Advanced LIGO Suspensions Team

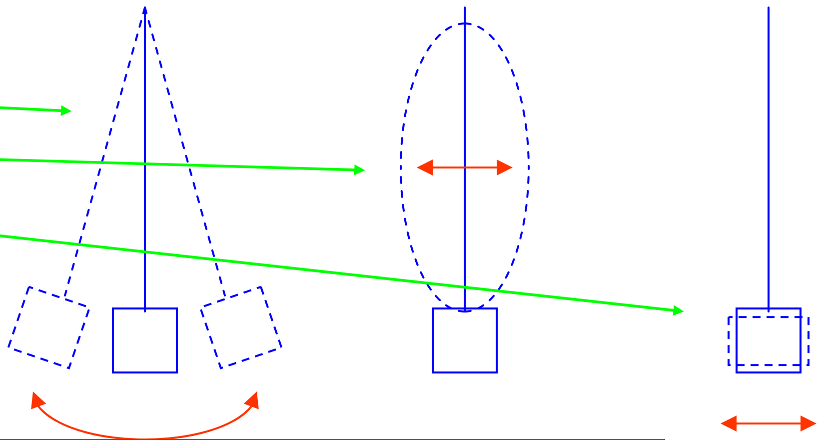
Wide membership from USA and UK*:

- LIGO Caltech
- LIGO Hanford Observatory
- LIGO Livingston Observatory
- LIGO MIT
- University of Glasgow
- Rutherford Appleton Laboratory
- University of Birmingham
- Strathclyde University

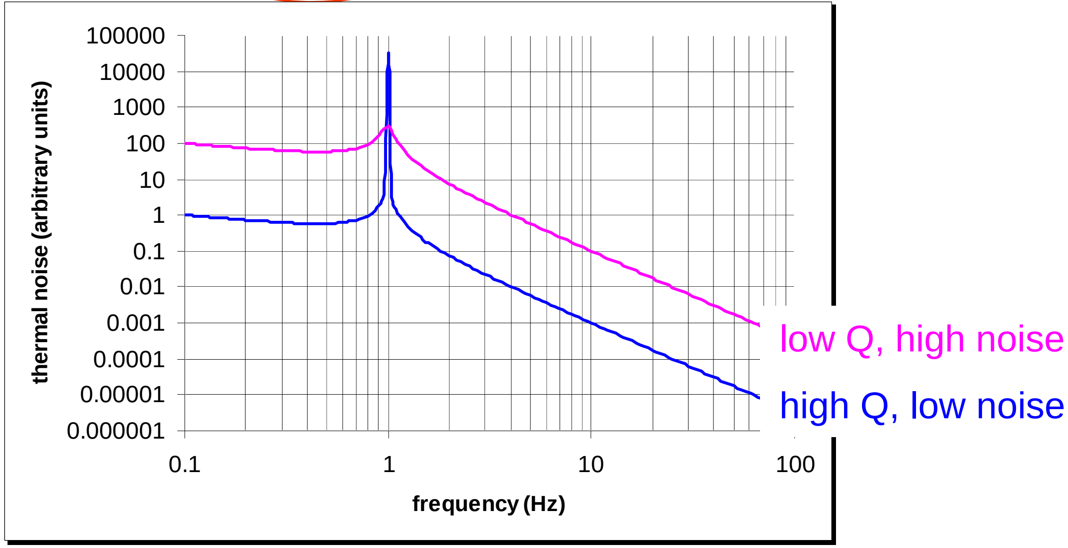
*Significant UK involvement : STFC (PPARC) awarded ~$12M grant for development and fabrication of the quadruple suspensions for Advanced LIGO

Thermal Noise

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

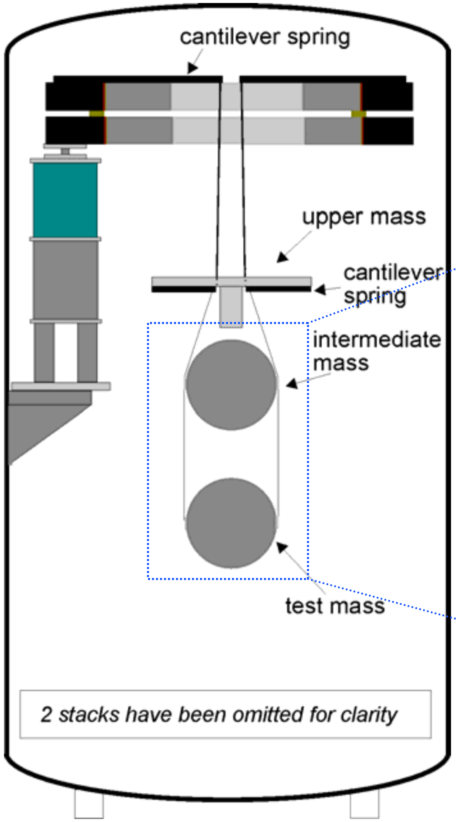


- To minimise:
  - use low loss (high quality factor, Q) materials for mirror and suspension – gives low thermal noise level off resonance -*silica* is a good choice
    - *loss angle ~ 2e-7, c.f. steel ~2e-4*
    - *breaking stress can be larger than steel*
  - use thin, long fibres to reduce effect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

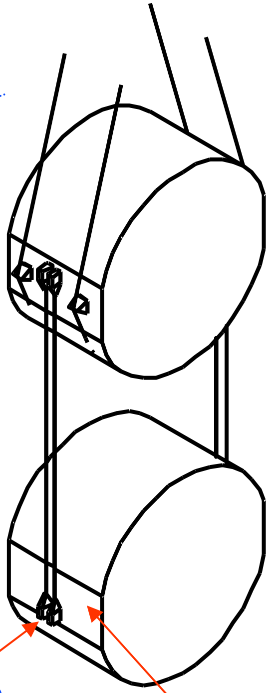


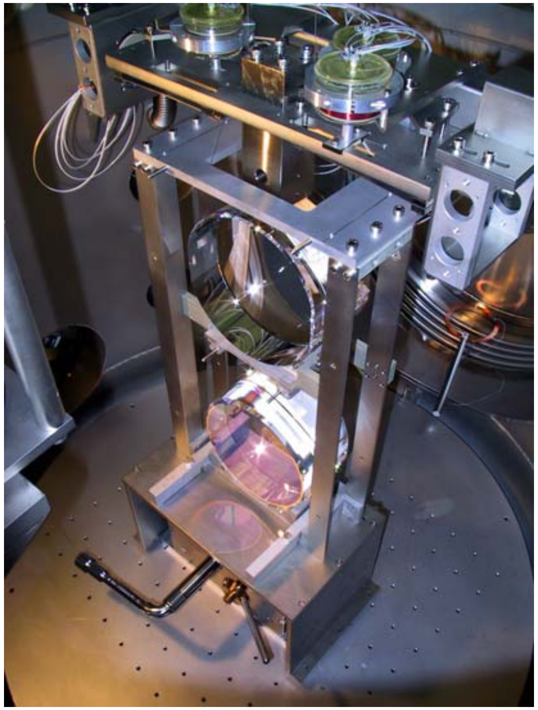
Monolithic fused silica suspensions have been pioneered in the GEO 600 detector: makes use of silicate bonding technique developed for Gravity Probe B

GEO Triple Pendulum Suspension



2 stacks have been omitted for clarity

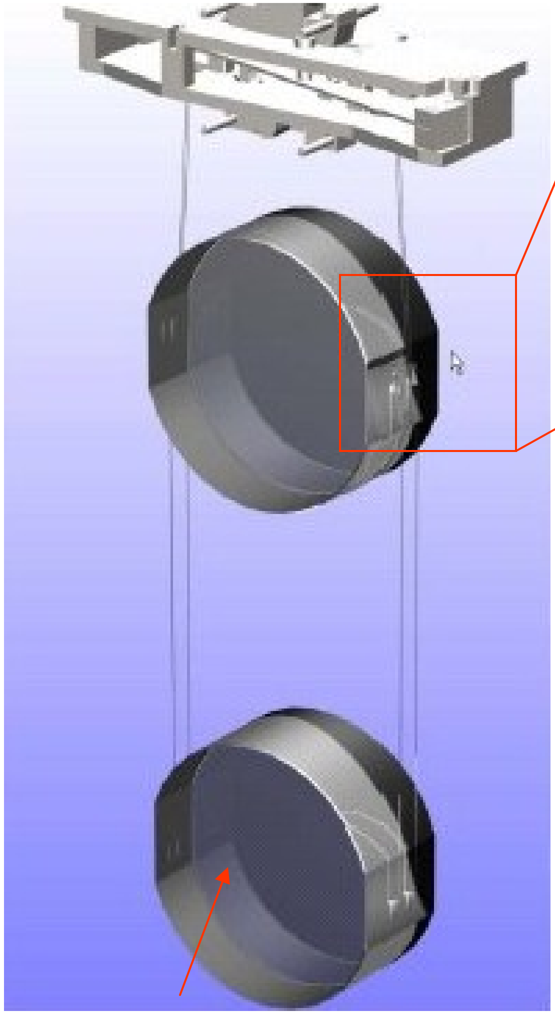




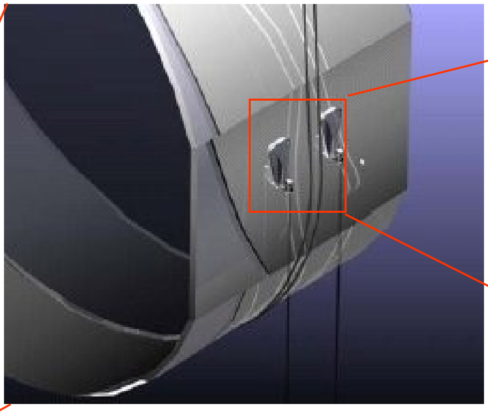
Ears silicate bonded to masses

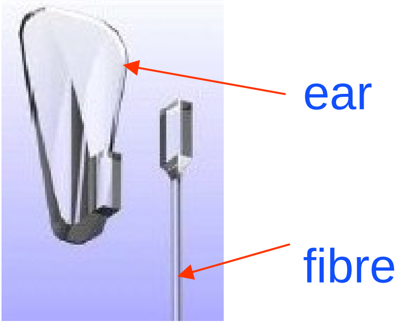
Silica fibres welded to ears

Development of Suspensions for Advanced LIGO



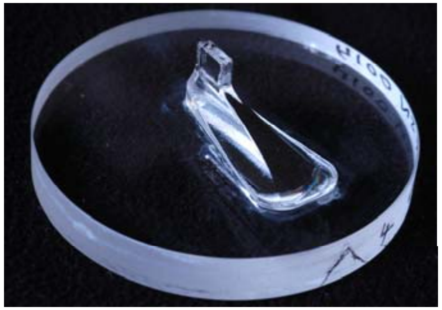
Mirror: 40 kg silica mass

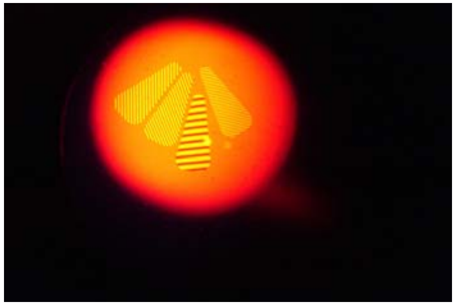




Above: detail of ear bonded to silica mass and fibre to be welded to ear

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





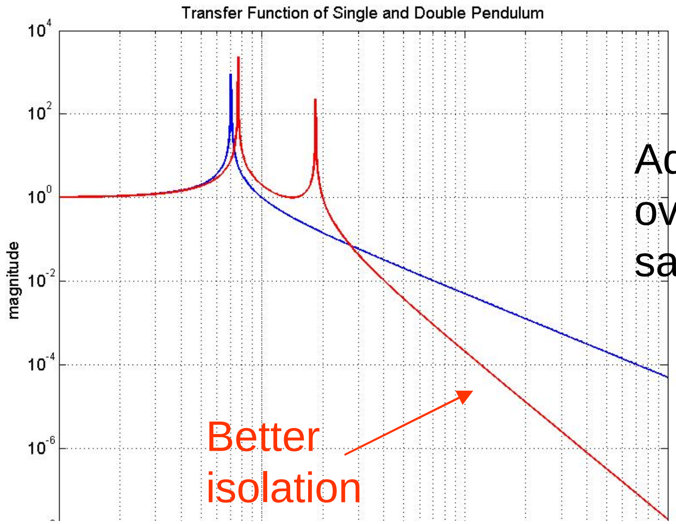
Diagrams from GEO-Glasgow group

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

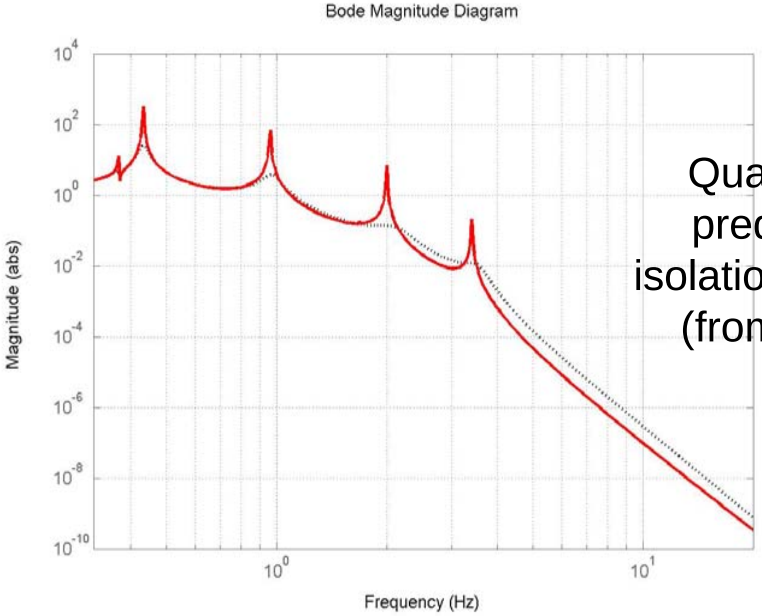
- Isolation required in vertical direction as well as horizontal due to cross-coupling
- Ultimately Newtonian noise will limit low frequency performance



Transfer Function of Single and Double Pendulum

Better isolation

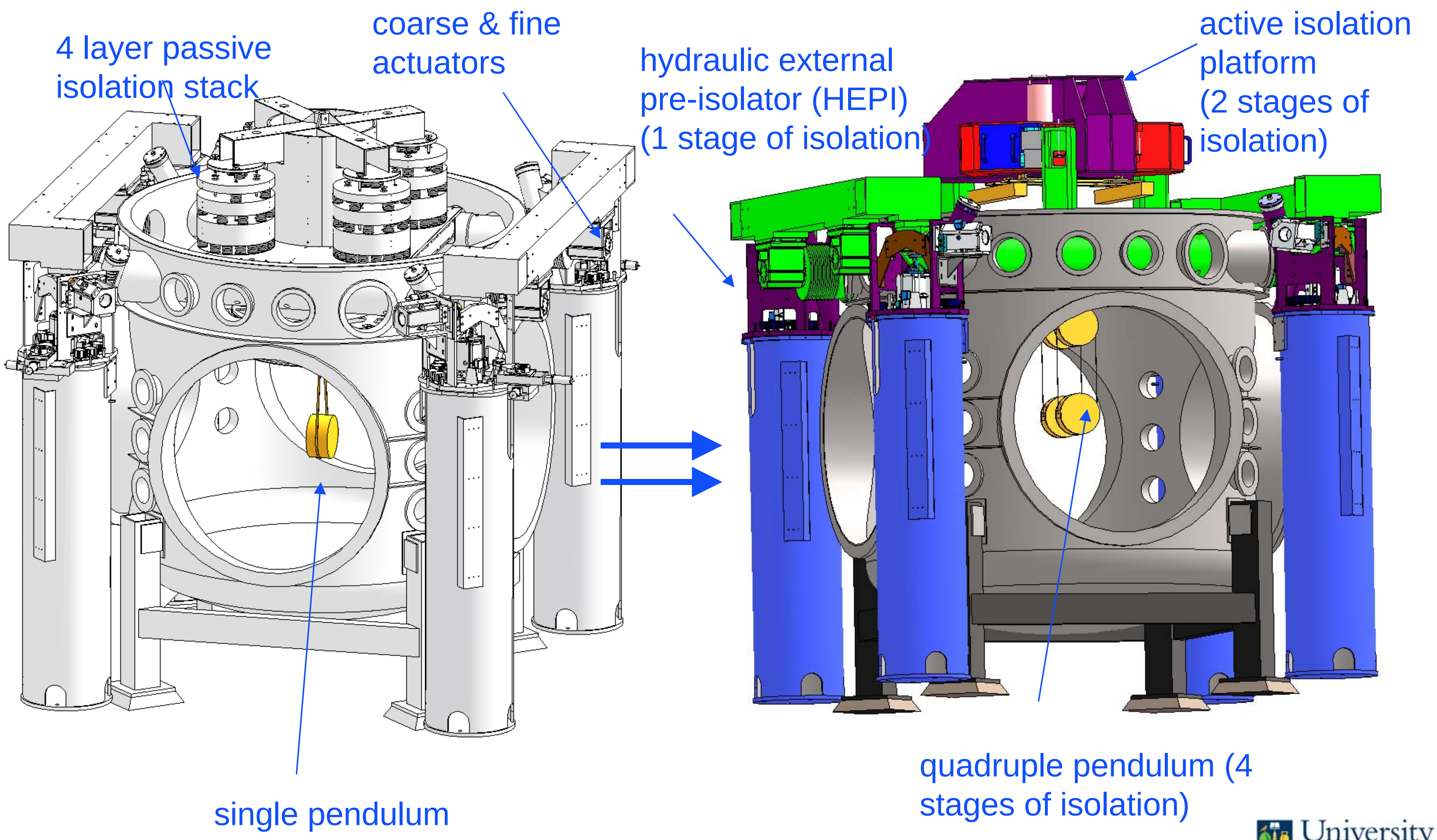
Advantage of double over single pendulum, same overall length



Bode Magnitude Diagram

Quadruple pendulum: predicted longitudinal isolation ~ 3 x 10^{-7} at 10 Hz (from MATLAB model)

Seismic Isolation - From Initial to Advanced LIGO



4 layer passive isolation stack

coarse & fine actuators

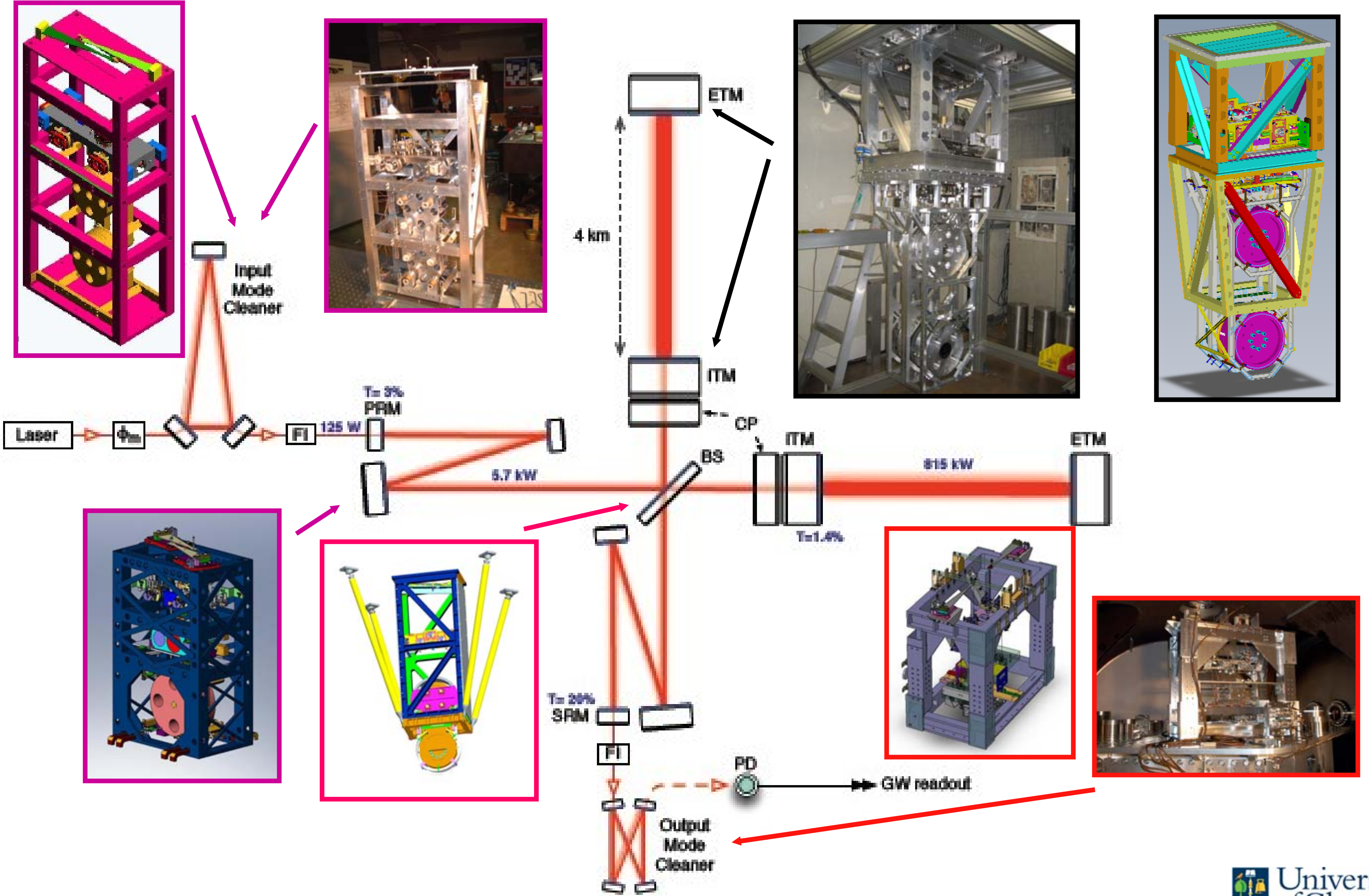
hydraulic external pre-isolator (HEPI) (1 stage of isolation)

active isolation platform (2 stages of isolation)

single pendulum

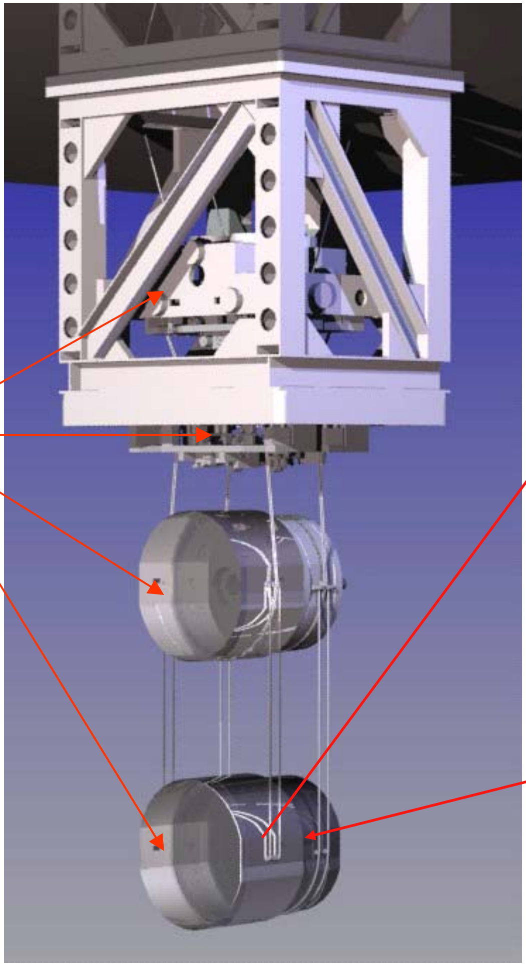
quadruple pendulum (4 stages of isolation)

Optical Layout and Suspensions: Quadruples, Triples and Doubles



Advanced LIGO Quadruple Pendulum Suspension

Schematic



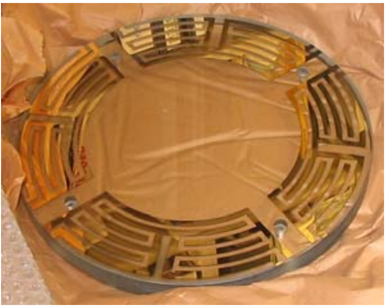
Four stages

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

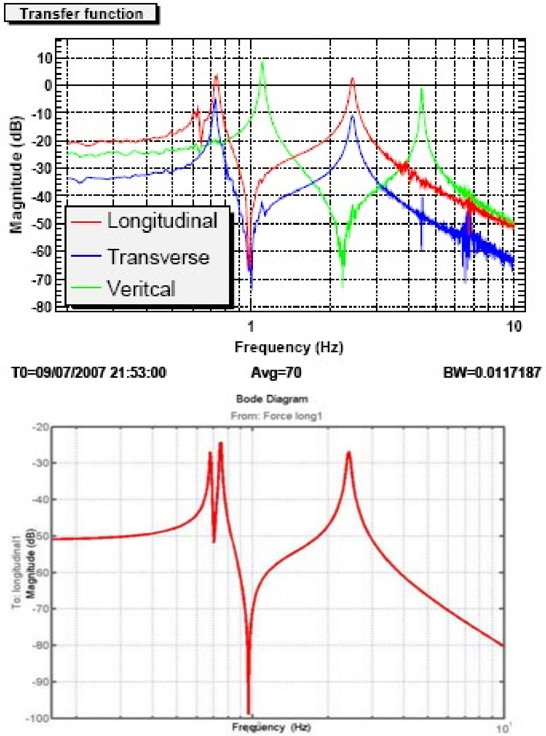


Prototype gold-coated face-plate for electrostatic actuation

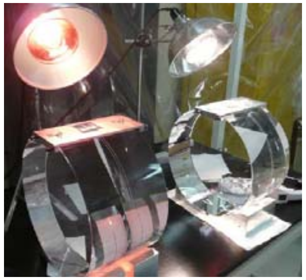
Metal prototype under test at RAL

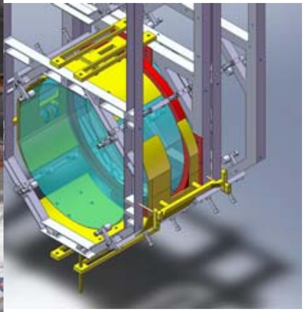
Current Status for Suspensions

- Ongoing research and development
- Program of tests on full-scale prototypes
- Production already underway for quads
  - 2008 - 2011: 47 major suspensions



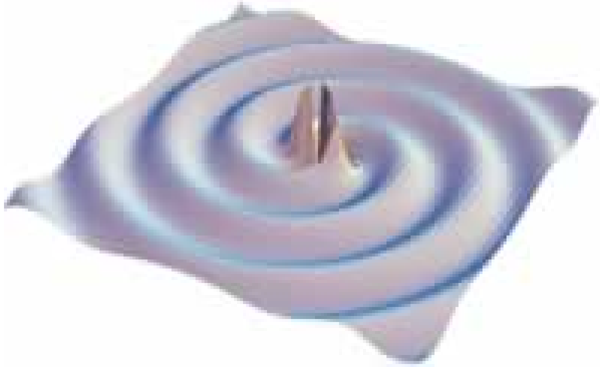
Example of transfer function measurements:
upper - experimental, lower - from MATLAB model





Conclusions

- Advanced LIGO work well underway: suspensions work described as an example – however many other areas including:
  - » active seismic isolation systems
  - » interferometer sensing and control
  - » high power lasers
  - » core optics and coatings
  - » input optics and auxiliary optics
  - » thermal compensation schemes
  - » electronics
  - » data acquisition
  - » facilities upgrades
  - » ……
- Advanced LIGO project running on schedule
- Enhanced LIGO science run next year



Exciting times ahead

Backup Slides

Projected Advanced LIGO Sensitivity

- **Major upgrade to all subsystems**
- **Improved performance at all frequencies**
  - » **Factor of ~10 in amplitude sensitivity (broadband)**
  - » **Tunable response for enhanced narrowband sensitivity**
  - » **Low frequency limit decreased from 40 Hz to 10 Hz**