G060626-00-R

LIGO
and the Search for Gravitational Waves

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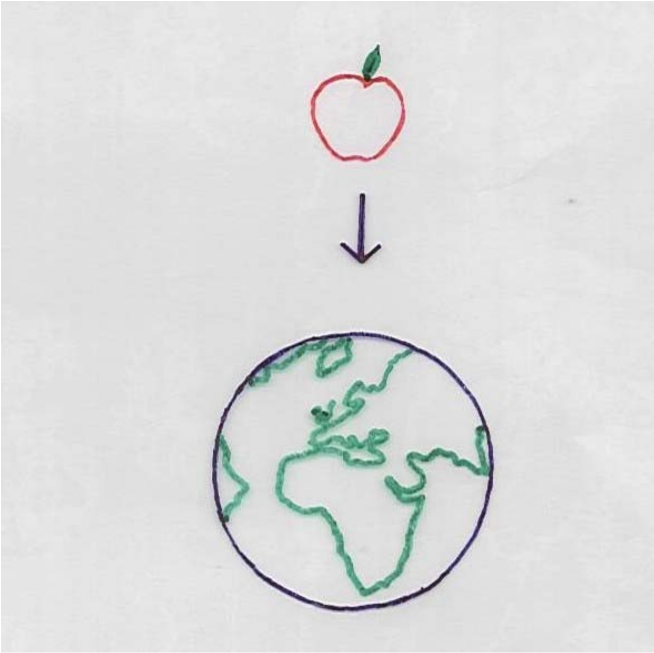
Electronics and Optics Seminar
& HEPL/KIPAC Seminar
11th December 2006

Outline of Talk

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

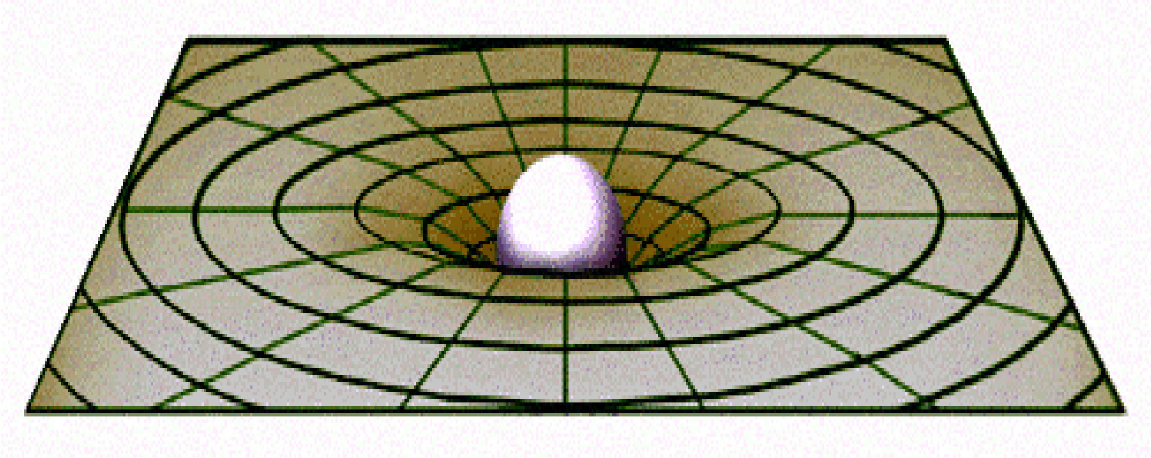
Newtonian Gravity | Einstein's Theory

"action at a distance"



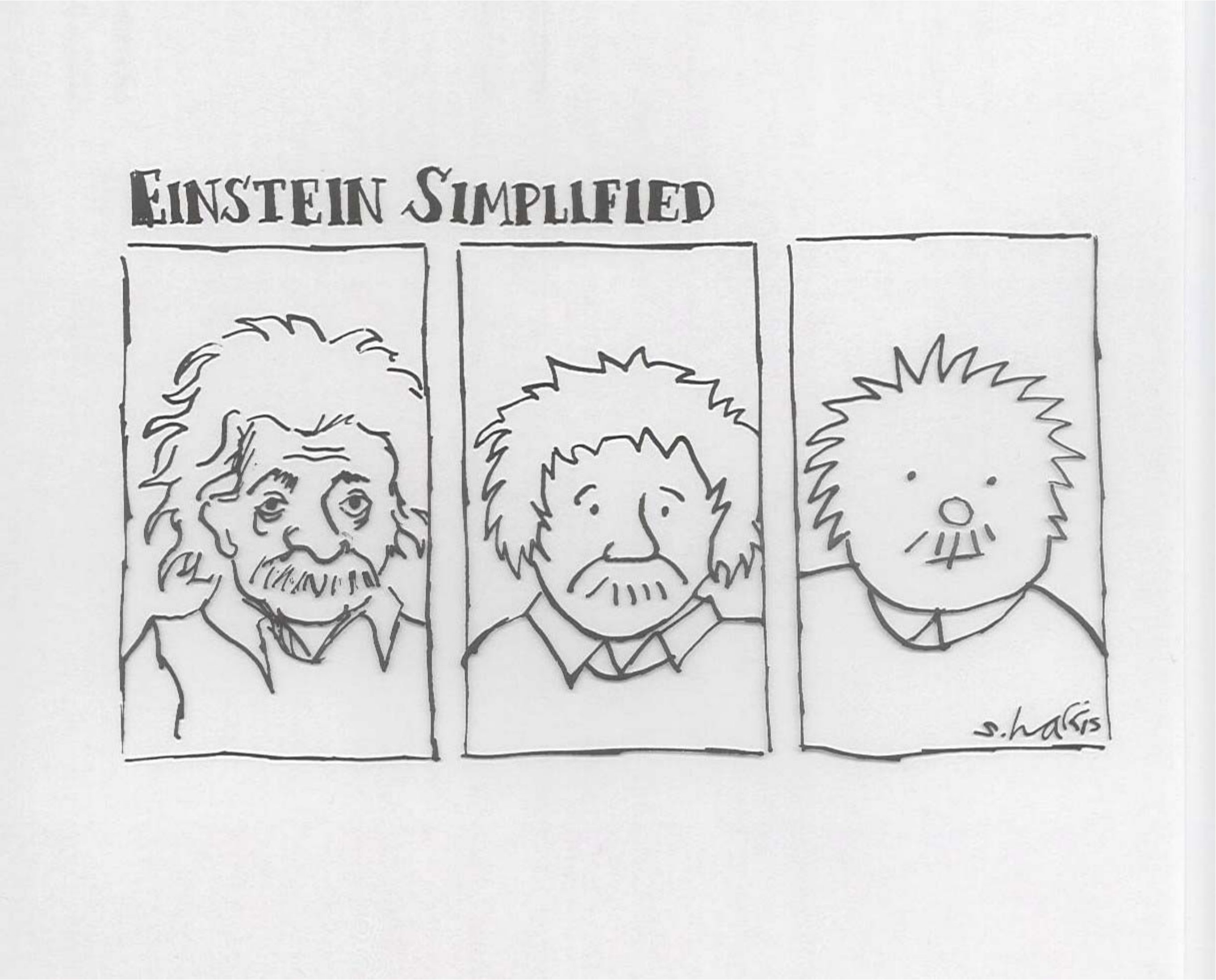
$$F = \frac{GMm}{r^2}$$

gravitation =
curvature of space-time



Einstein's field equations

Einstein Simplified

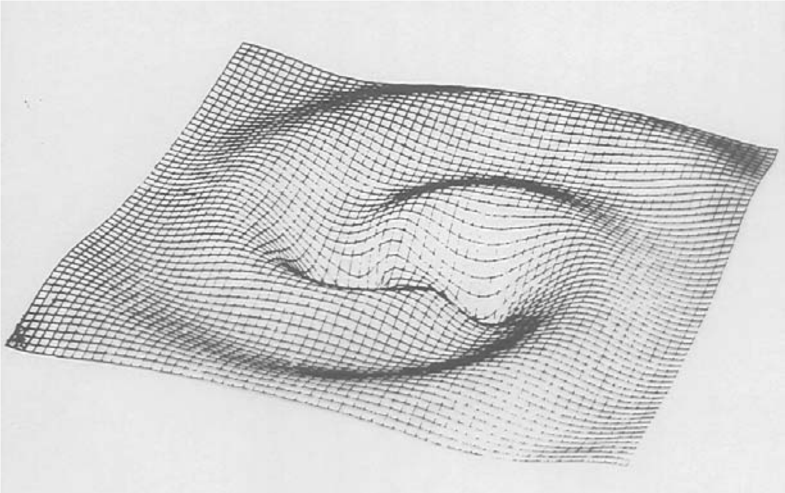


Gravitational Waves (GW)

- What are GW?
  - waves in curvature of space-time
  - a prediction of general relativity
  - produced by acceleration of mass
    (c.f. EM waves produced by accelerated charge)
  - travel at speed of light

BUT

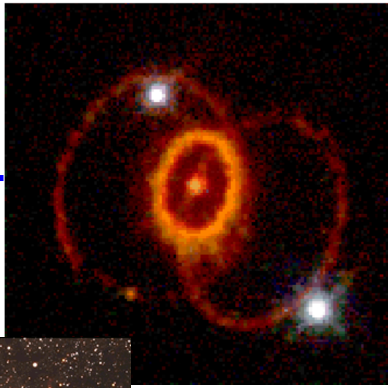
  - gravitational interactions are very weak
  - no dipole radiation (due to conservation of momentum and mass of only one “sign”)



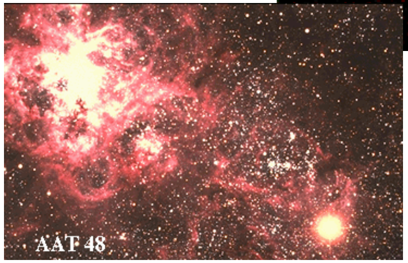
To produce significant flux requires asymmetric accelerations of large masses

→ Astrophysical Sources

Gravitational Wave Sources

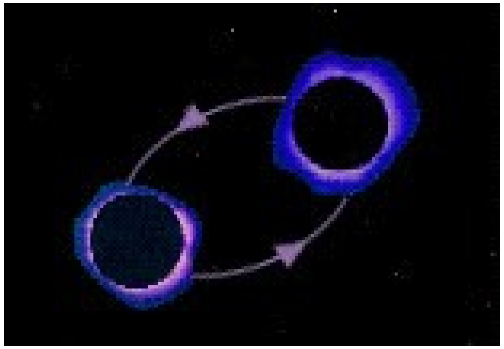


SN1987a



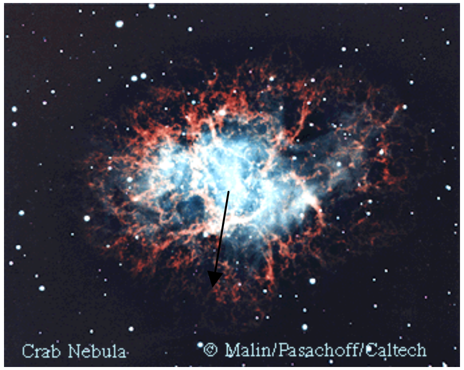
- *Bursts*
  - catastrophic stellar collapse to form black holes or neutron stars
  - final inspiral and coalescence of neutron star or black hole binary systems

  (possibly associated with gamma ray bursts)



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

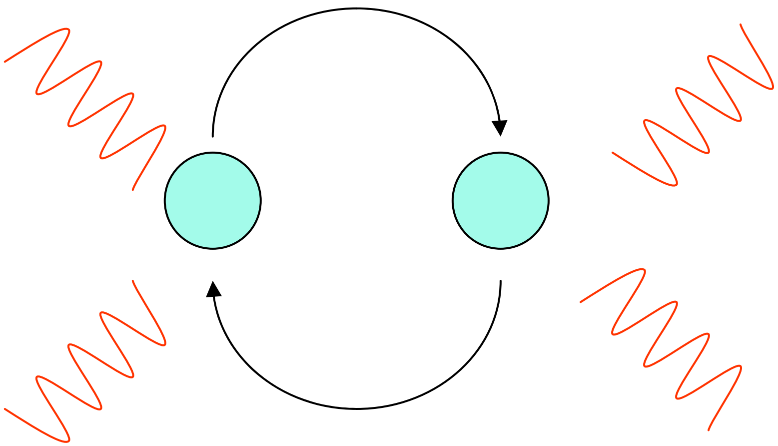
  (sign up for Einstein@home)
  - low mass X-ray binaries (e.g. Sco-X1)



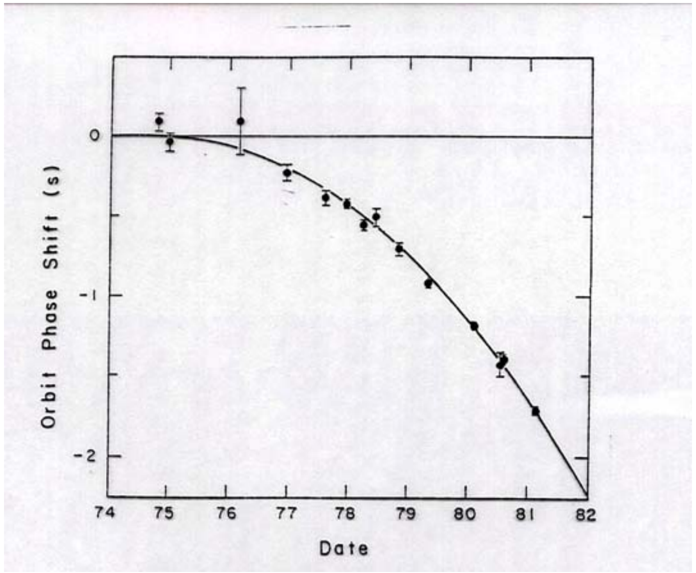
- *Stochastic Background*
  - random background noise associated with cosmological processes, e.g. inflation, cosmic strings….

A New Astronomy

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)

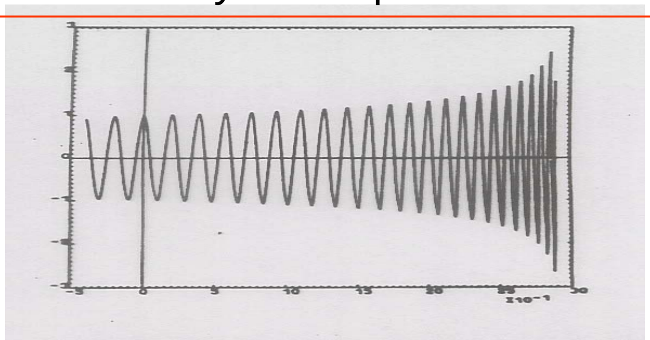


(Taylor and Weisberg, Ap. J. 253, 1982)

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

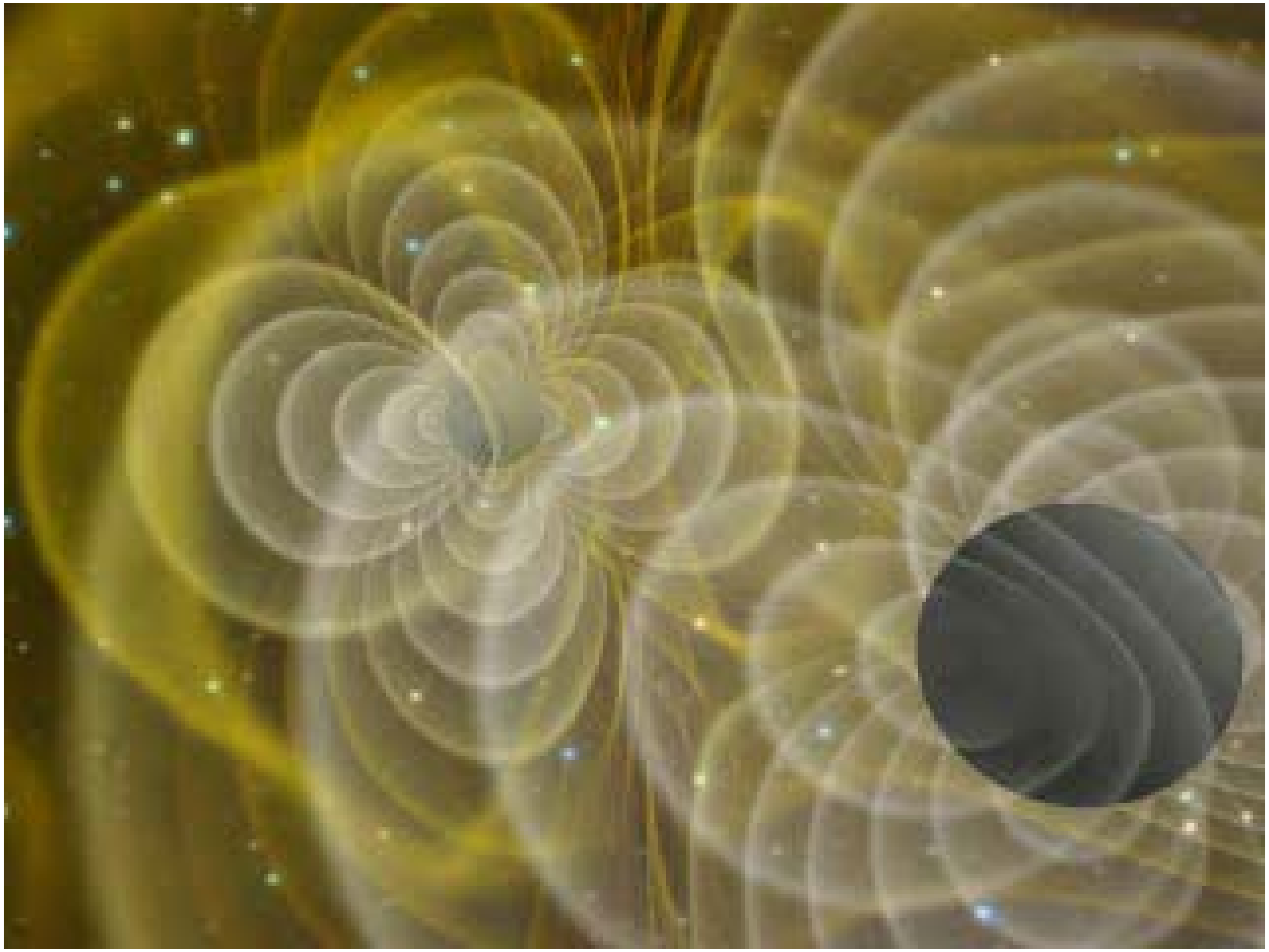
A highly relativistic binary pulsar was discovered in late2003: merger in 85Myrs (much shorter than other known systems)

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



Expected GW signal from binary coalescence

Simulation of Merging Black Holes

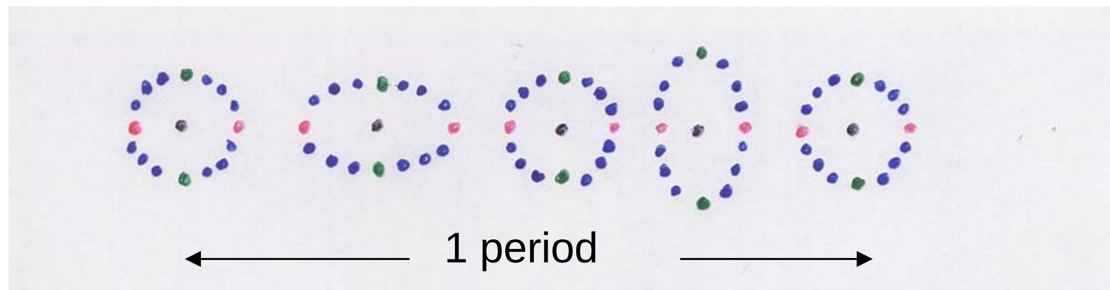


Credit: Henze, NASA

J Baker et al. PRL 96, 111102, 2006

Gravitational Wave Detection

- Detection of GW - How?
  - Measure the time-dependent tidal strain in space produced by the waves

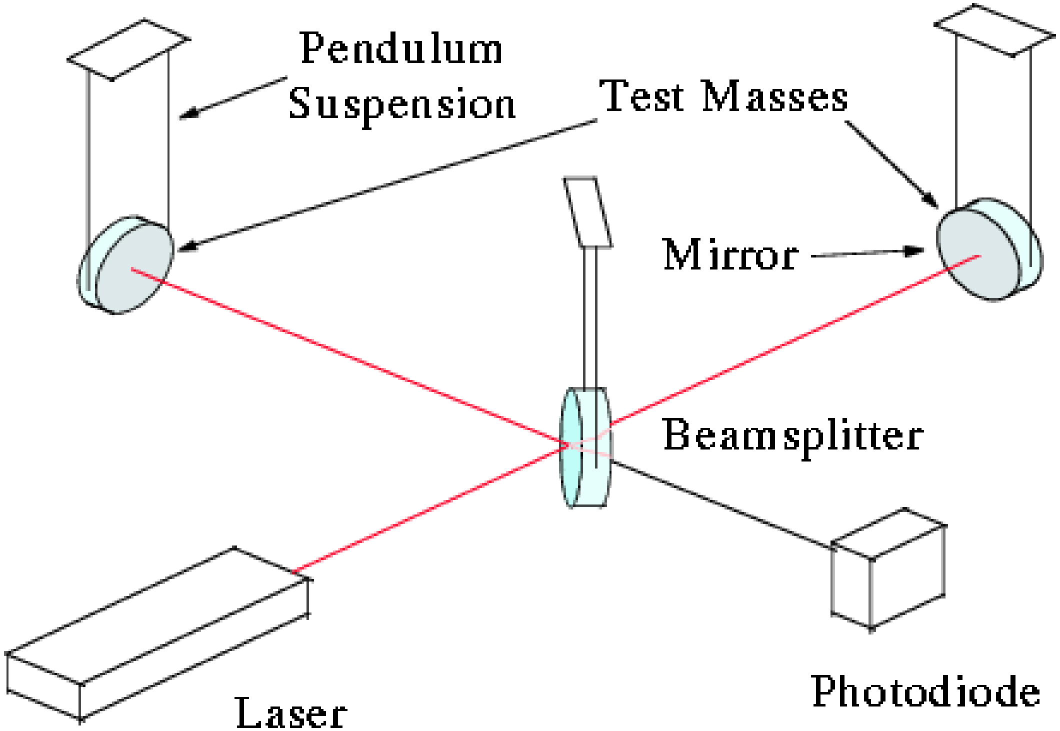


- Magnitude of effect?
  - consider simplest detector – two free masses a distance *L* apart whose separation is monitored

  - a gravitational wave of amplitude *h* will produce a strain given approximately by $\frac{\Delta L}{L} \approx h$
  - largest signals (very rare) : $h \sim 10^{-19}$
  - for reasonable event rate : $h \sim 10^{-22} - 10^{-23}$

Gravitational Wave Detection

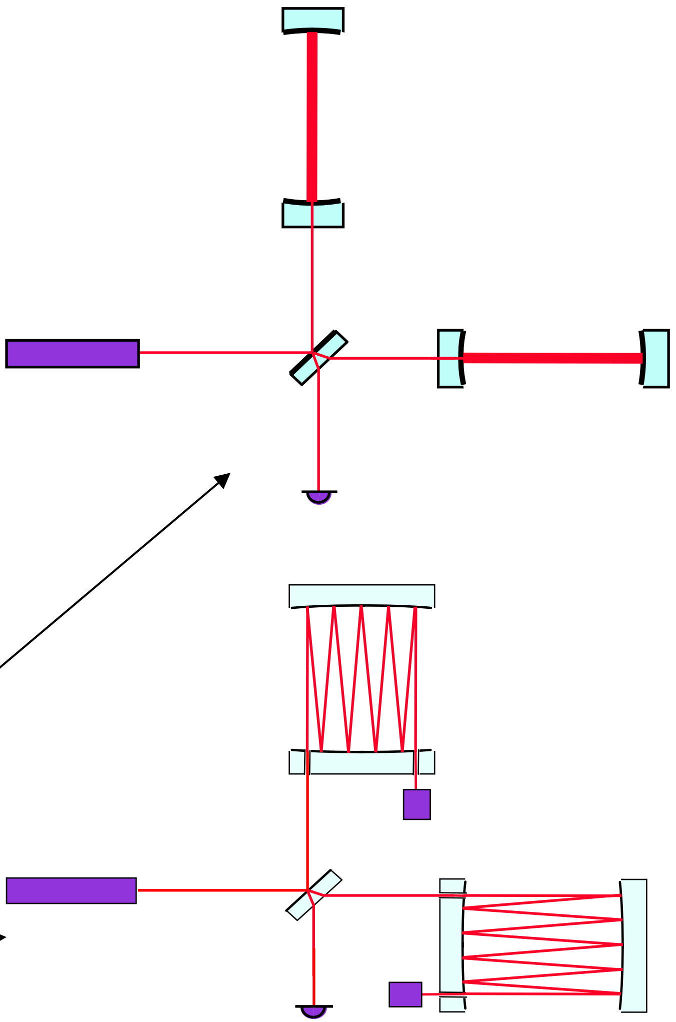
- long baseline laser interferometry between freely suspended test masses using a Michelson Interferometer



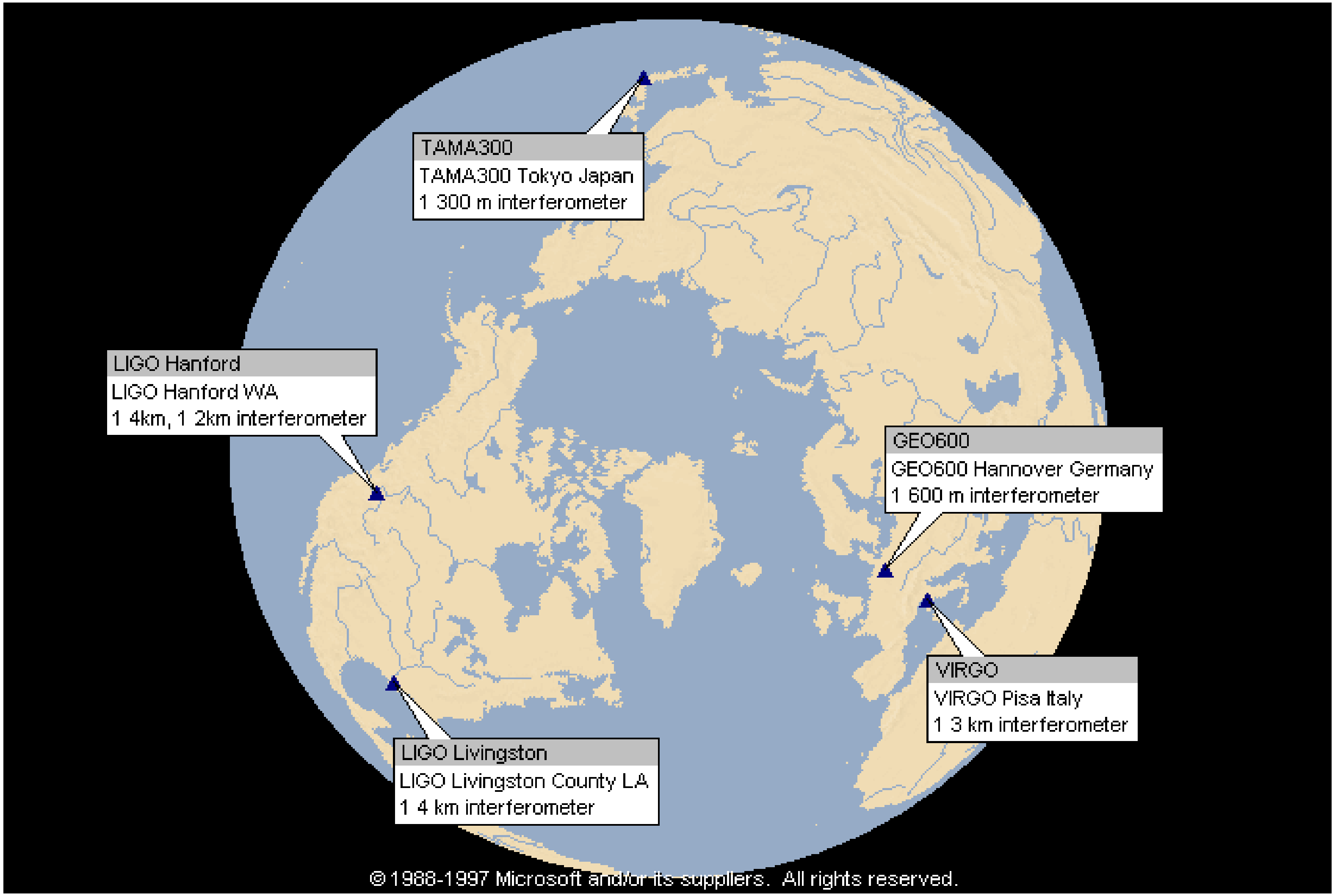
Simplified optical layout

Advantages of Interferometer

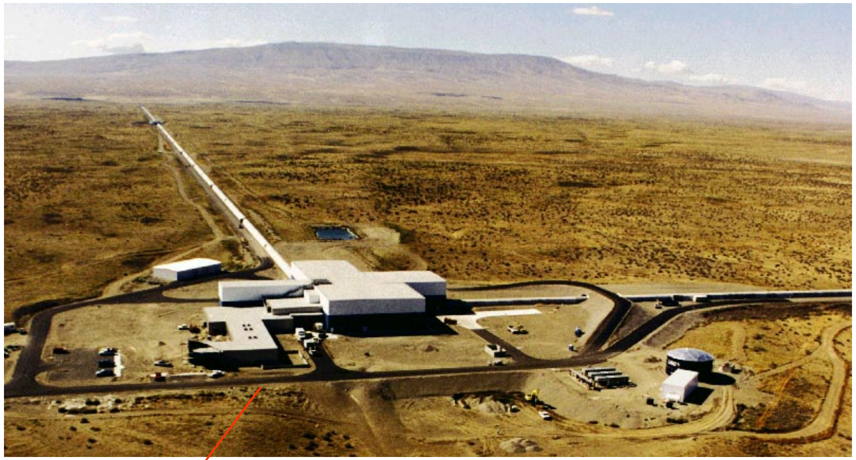
- Differential measurement – relaxes requirement on laser frequency stability
- Matches to quadrupole nature of gravitational wave
- Wideband operation
- Sensitivity to strain scales with armlength: use long baseline, L
- Further increase in sensitivity by folding light in the arms:
  - Fabry Perot cavities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



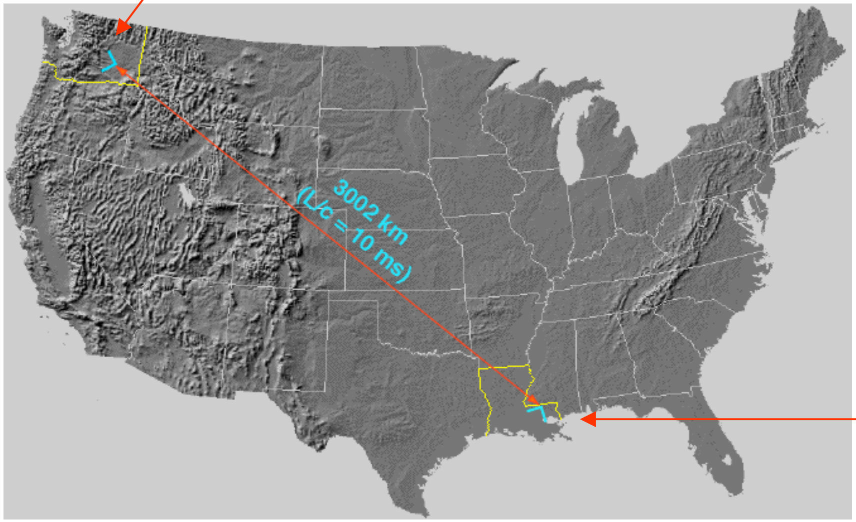
WORLDWIDE GW INTERFEROMETER NETWORK



LIGO Observatories



LIGO Hanford Observatory, WA

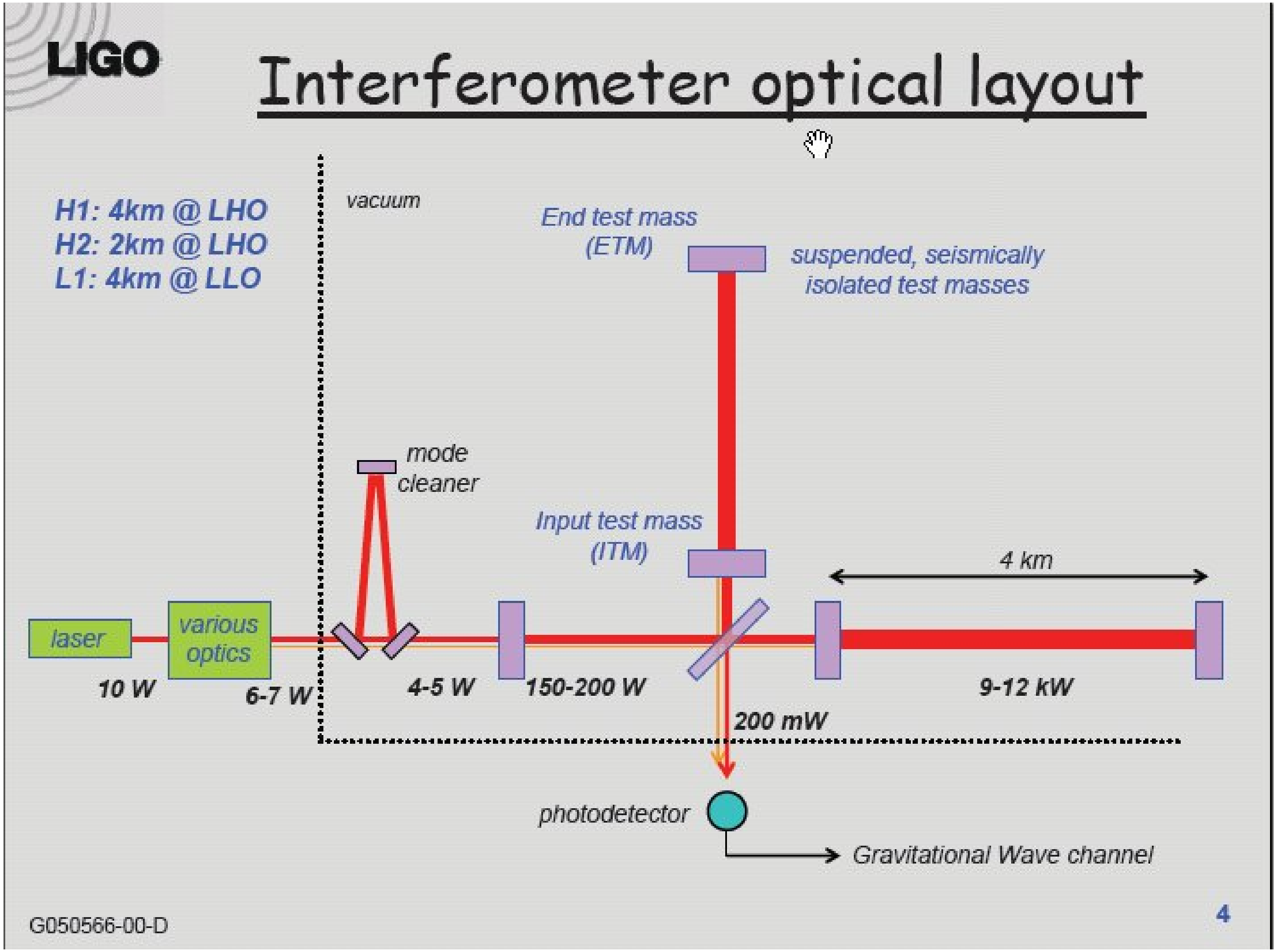


LIGO Livingston Observatory, LA

NSF funded. Designed and built by Caltech and MIT.

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

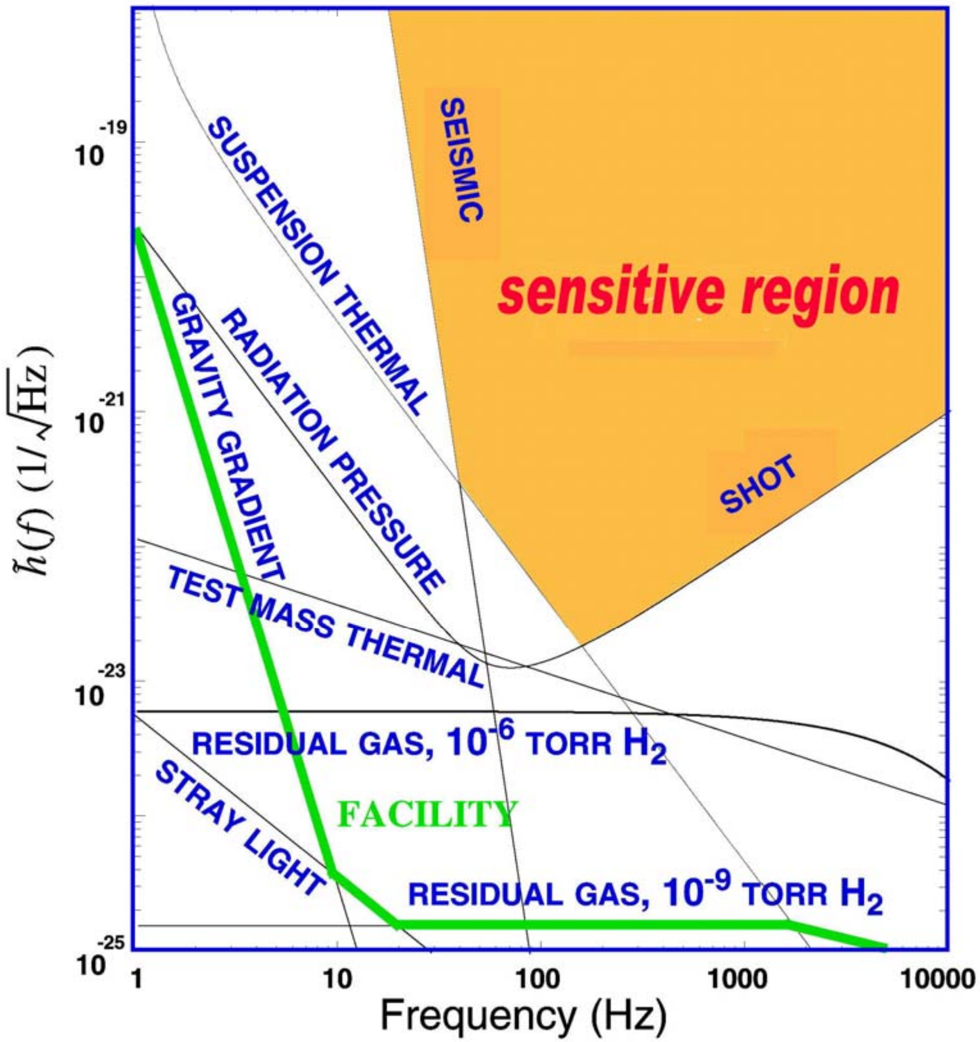
LIGO Interferometry



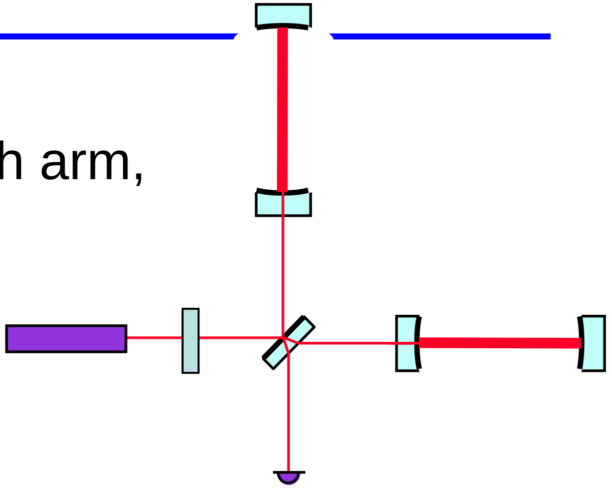
Sensitivity Limits and Noise Sources

- *Photon Shot Noise*
  -high frequencies
- *Thermal Noise* (in suspensions and test masses)
  - mid frequencies
- *Seismic noise*
  - low frequencies
- Many “technical” noise sources

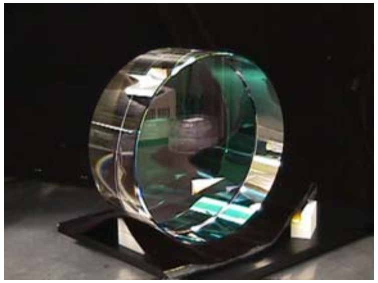
e.g. electronics noise from control systems, laser intensity noise, frequency noise, beam jitter, upconversion of low frequency noise



Mitigation of Noise Sources



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

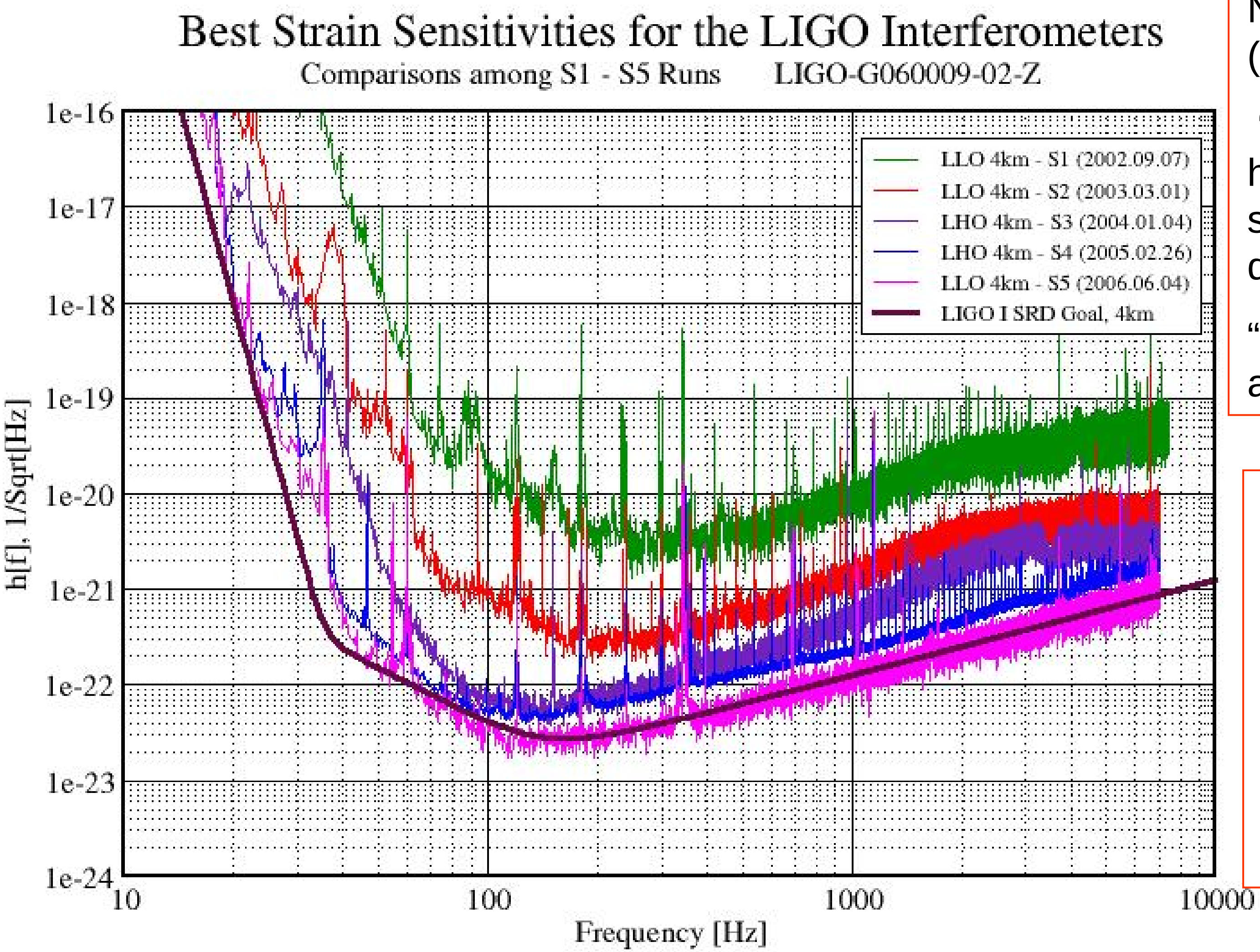


- Thermal Noise
  - Use low loss materials
  - Work away from resonances
  - Thin suspension wires

- Seismic Noise
  - Passive isolation stack
  - Pendulum suspension

Operate under high vacuum

Evolution of LIGO Sensitivity



NSF review report (Nov 05):

"All three interferometers have achieved, and slightly surpassed the design requirement……"

"… remarkable milestone achievement…"

Science Runs

- S1 Aug-Sept 02
- S2 Feb-April 03
- S3 Oct 03-Jan 04
- S4 Feb-March 05
- S5 From Nov 05

Binary neutron star inspiral range S1: ~20 kpc -> S5: ~15 Mpc

Results so far

- 15 papers published from S1 – S3 presenting searches and upper limits:
  - inspiralling binary neutron stars
  - Inspiralling binary black holes and primordial black hole coalescences
  - stochastic background
  - gravitational waves bursts, general and specific (associated with gamma ray bursts)
  - periodic gravitational waves from known and unknown sources
- Numerous technical papers on instrumentation and data analysis techniques

Info on observational results at http://www.ligo.org/results/

LIGO Science 5 (S5) Run and Beyond

- Target: 1 year's worth of coincidence data at design sensitivity
- Started Nov 2005: currently > 50% towards target, should complete early Autumn 2007
- Online and offline analysis ongoing
- LIGO could possibly detect a signal during its current observing run.
- Advanced LIGO is aimed at achieving a sensitivity at which at least several signals per month (perhaps per week) should be detected.
- Start of Adv. LIGO funding possibly FY08

LIGO vs Advanced LIGO

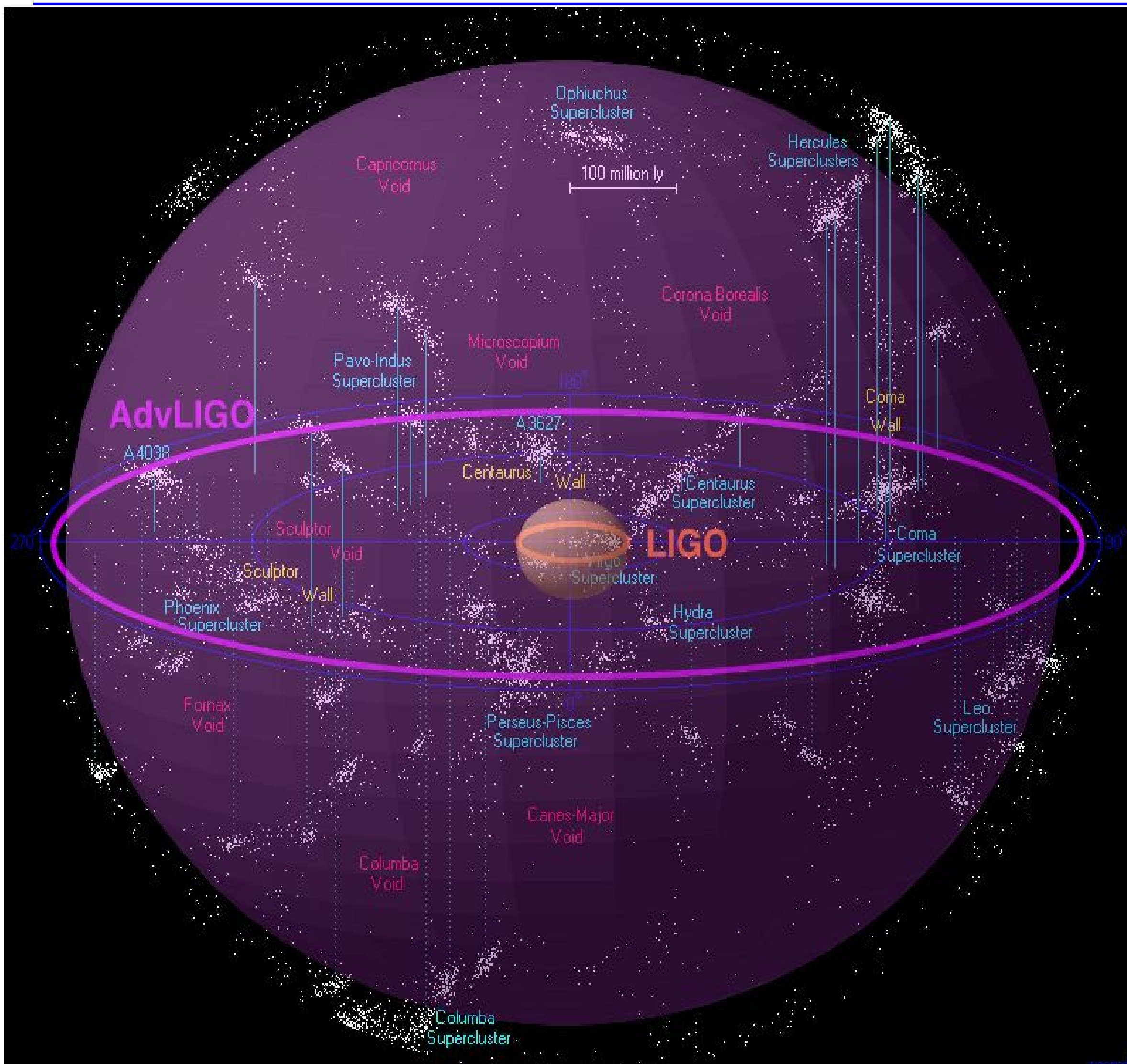


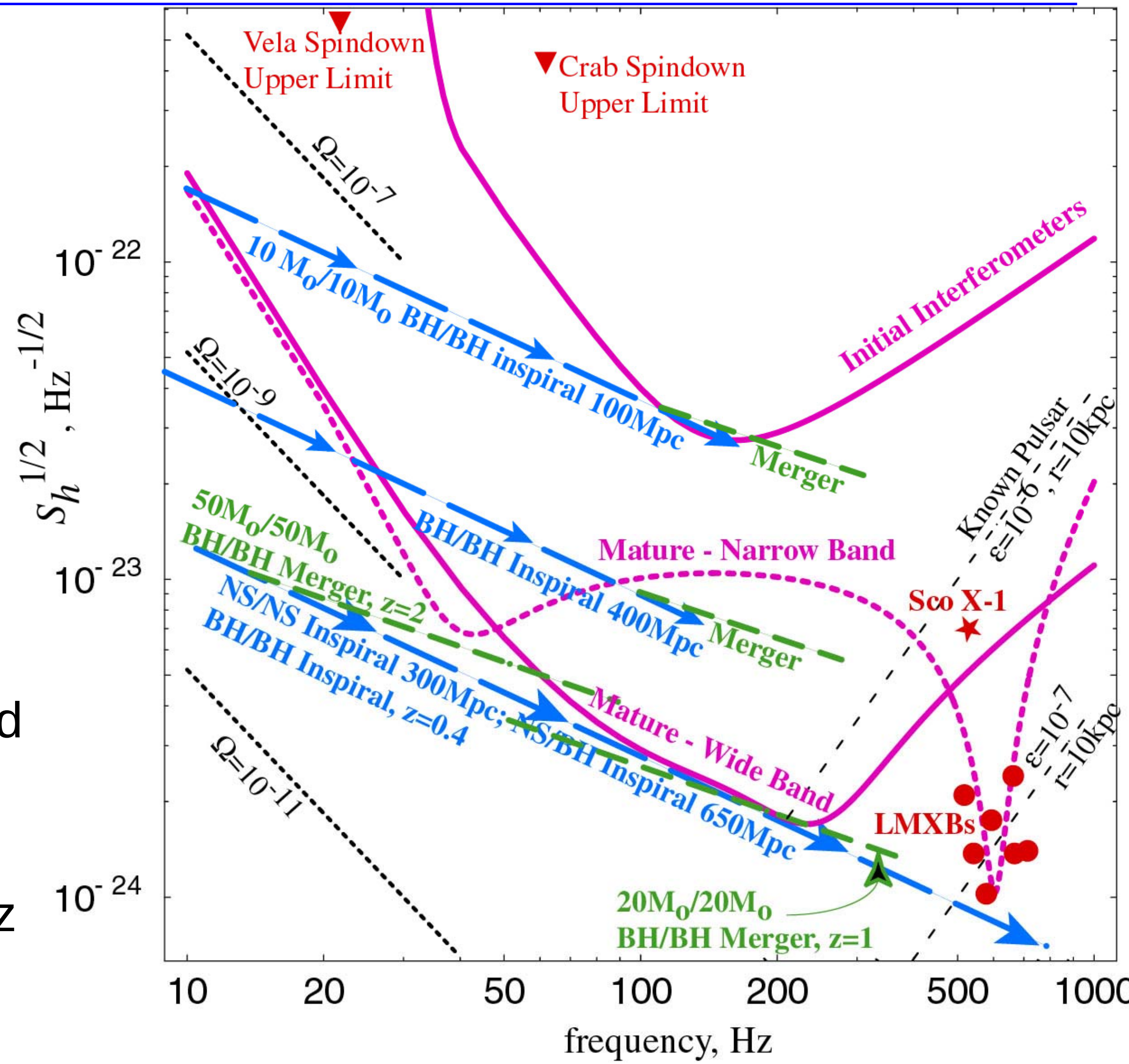
Figure from B Berger

Factor of 10 in sensitivity gives factor of 1000 in volume

- NS-NS inspiral reach:15 Mpc → 160 Mpc
- z = 0.4 range for $20M_o$ BH/BH collisions
- upper limit for Ω_{GW} $<10^{-8}$ after 1 year of integration

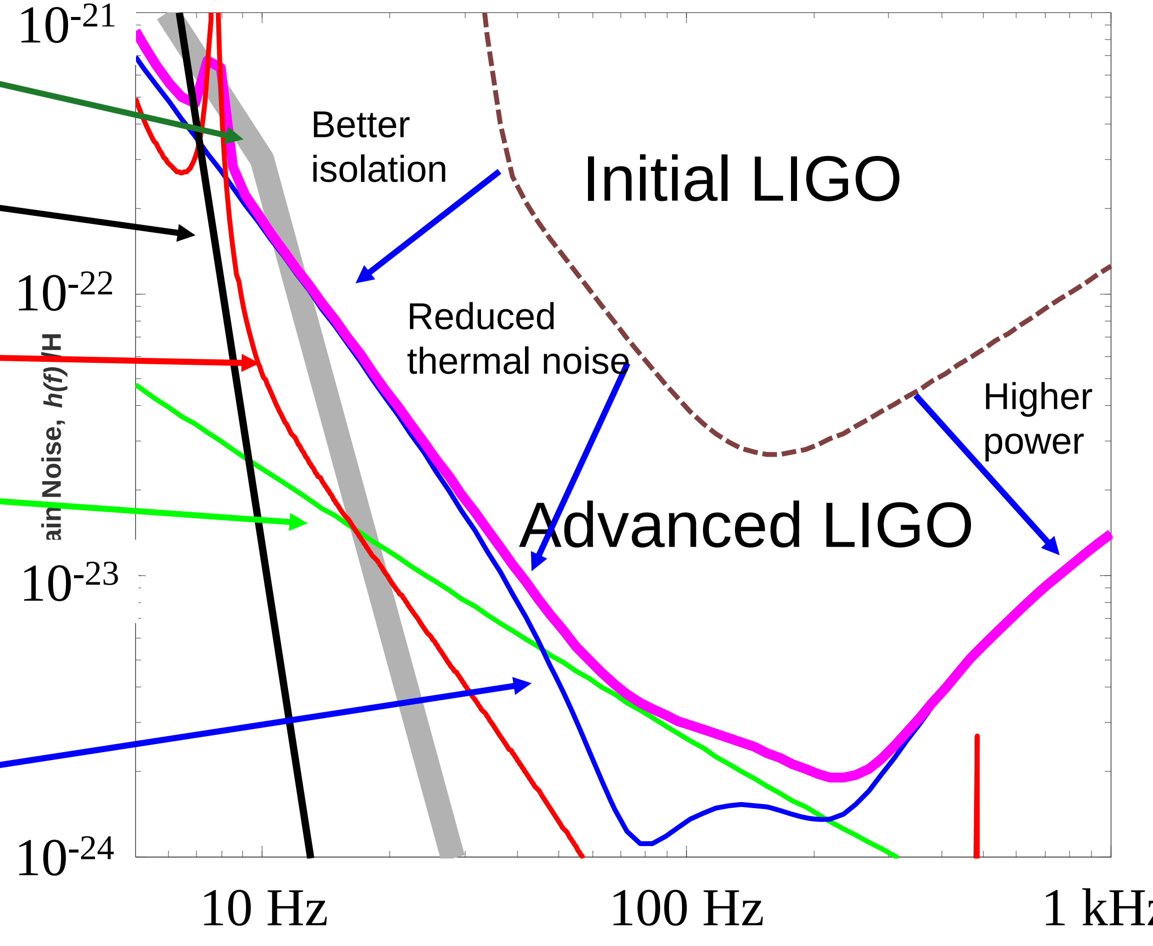
Projected Advanced LIGO Sensitivity

- 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



Advanced LIGO performance

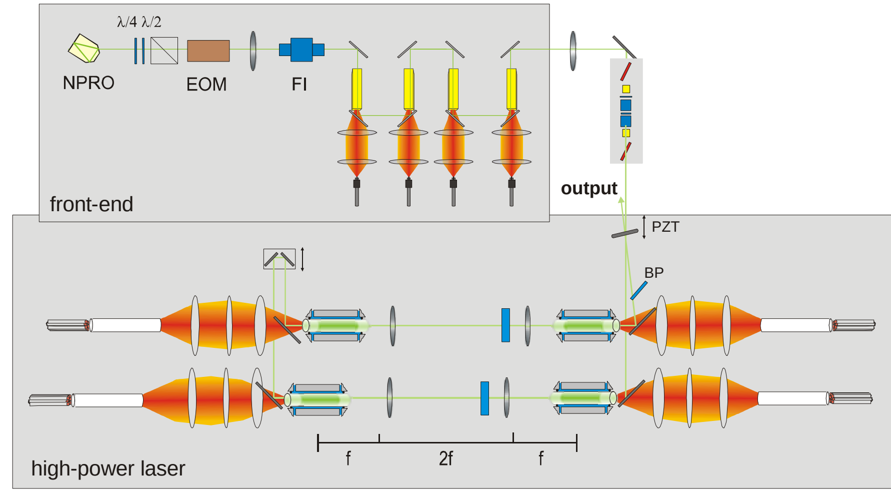
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass + coating thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning

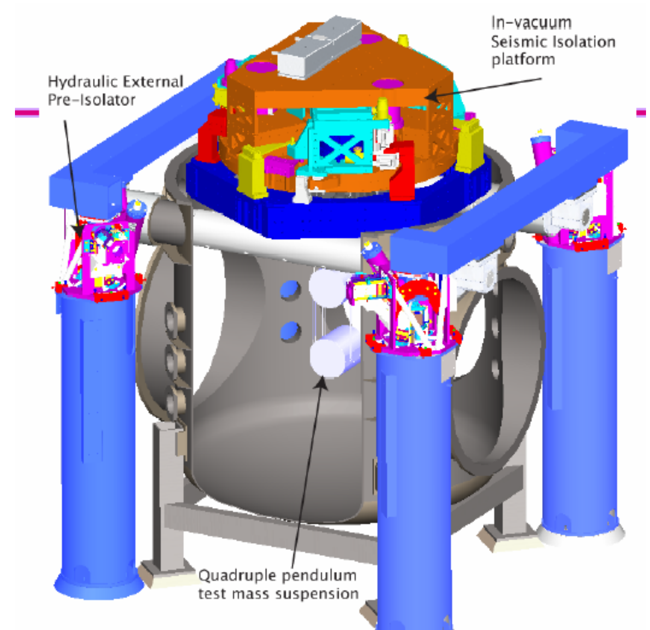


(y scale: h/rt Hz)

Advanced LIGO Subsystems

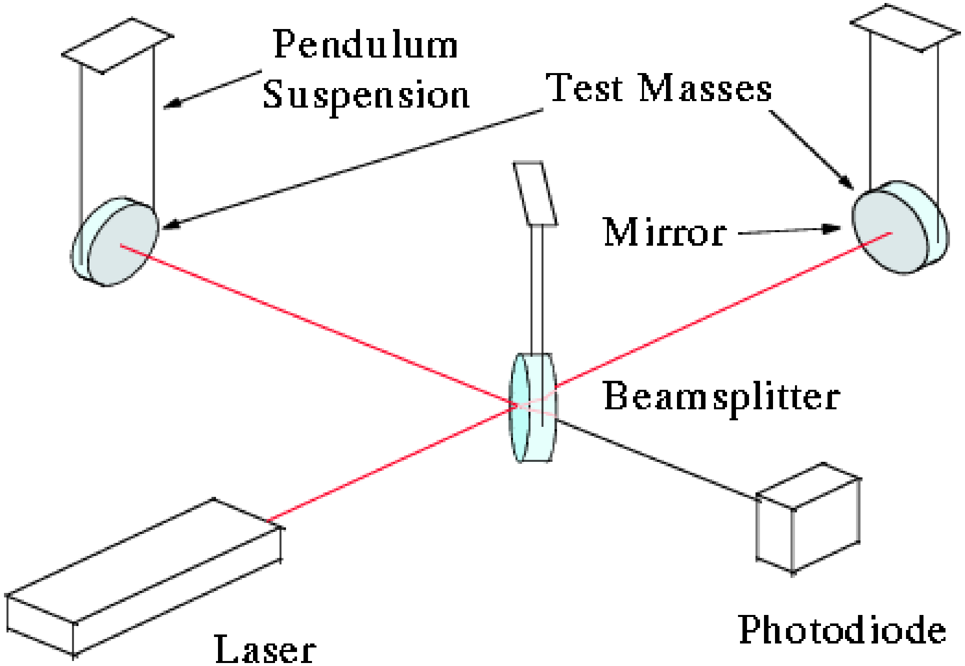
- Laser: 180 W prestabilised Nd:YAG (from Laser Zentrum Hannover)
- Suspensions: quadruple pendulum with silica monolithic final stage (from UK)
- Core Optics: 40 kg 34 cm x 20 cm Hereaus 311 fused silica plus low loss (optical and mechanical) coatings
- Seismic Isolation: 6 DOF active isolation for all suspended optics
- Interferometry: high and low power operation, use of signal recycling mirror, DC readout system





Suspension Design for GW Detectors

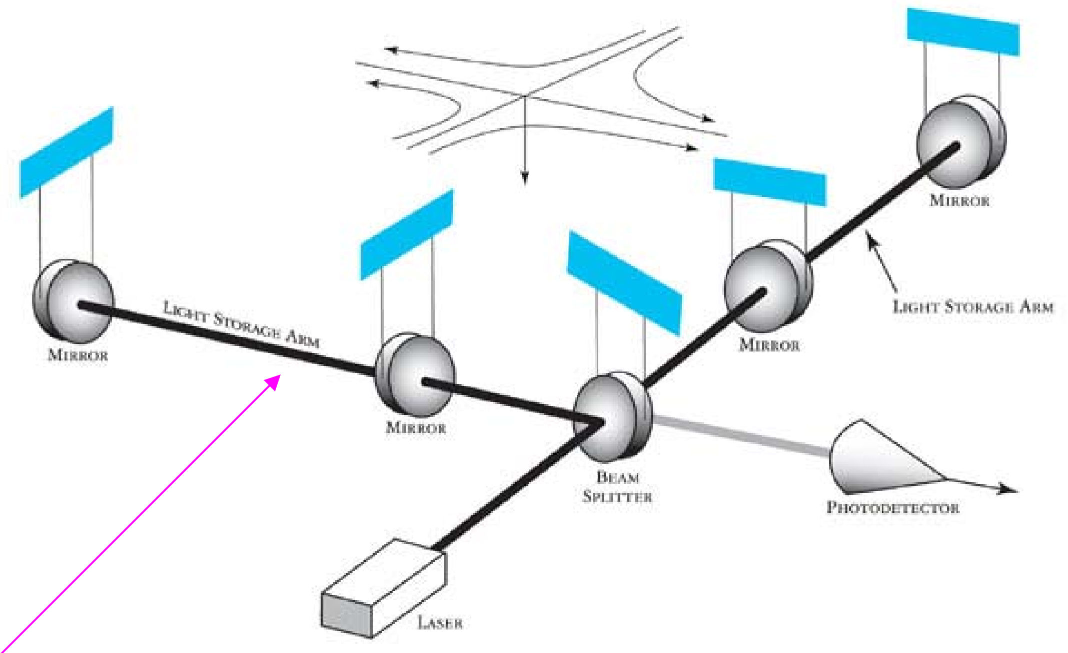
- long baseline laser interferometry between *freely suspended* test masses



Suspension Design for GW Detectors continued

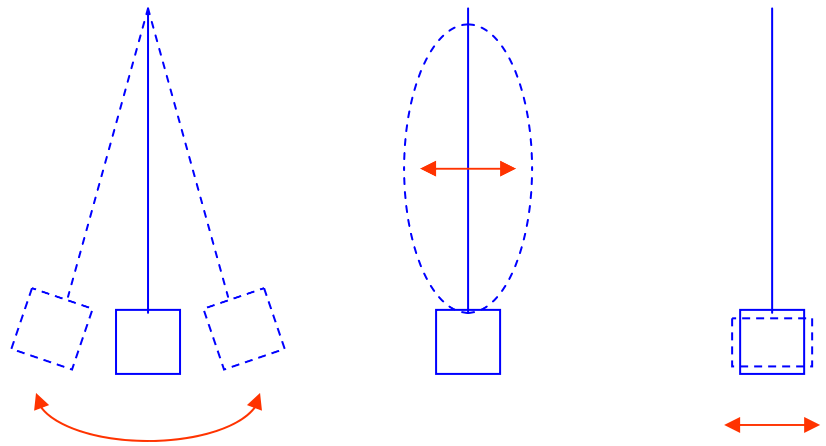
- Fundamental requirements
  - support the mirrors to minimise the effects of
    - **thermal noise** in the suspensions
    - **seismic noise** acting at the support point
- Technical requirements
  - allow a means to damp the low frequency suspension resonances (local control)
  - allow a means to maintain arm lengths as required in the interferometer (global control)

    (*without* adding additional noise)

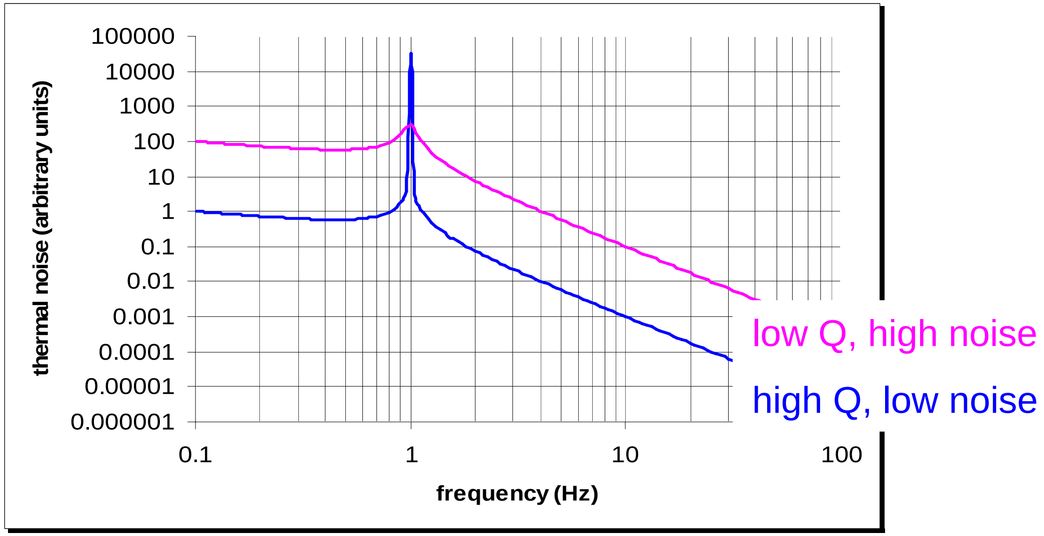


Thermal Noise

- Thermally excited vibrations of pendulum and violin modes of suspensions and of mirror substrates and coatings
- Apply fluctuation-dissipation theorem to find thermal motion

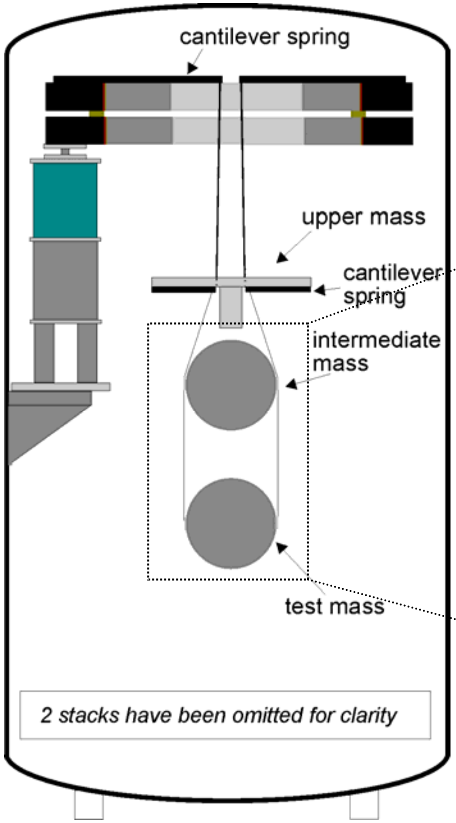


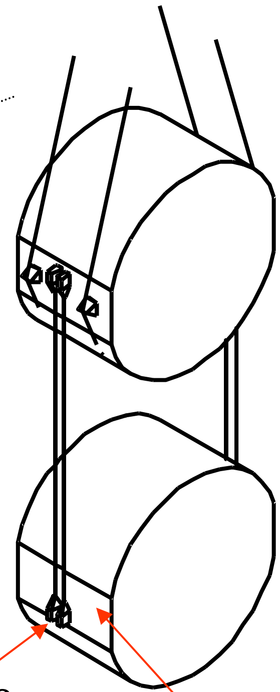
- To minimise:
  - use low loss (high quality factor, Q) materials for mirror and suspension – gives low thermal noise level off resonance -*silica* is a good choice
    - *loss angle ~ 2e-7, c.f. steel ~2e-4*
    - *breaking stress can be larger than steel*
  - use thin, long ribbons to reduce effect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

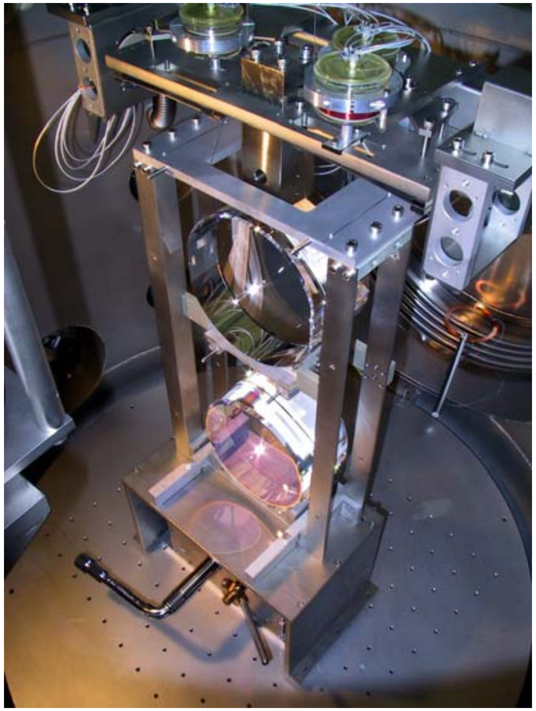


Monolithic fused silica suspensions have been pioneered in the GEO 600 detector: makes use of silicate bonding technique developed at Stanford for Gravity Probe B

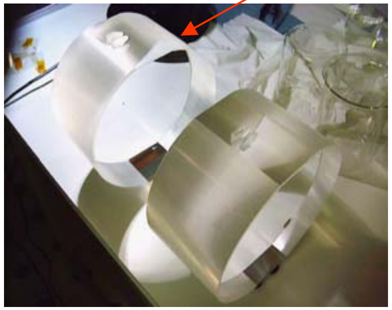
GEO Triple Pendulum Suspension



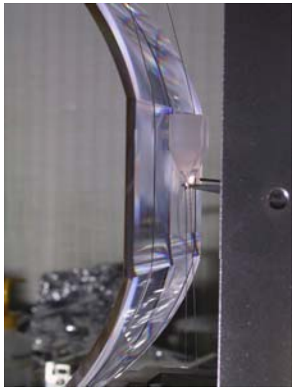




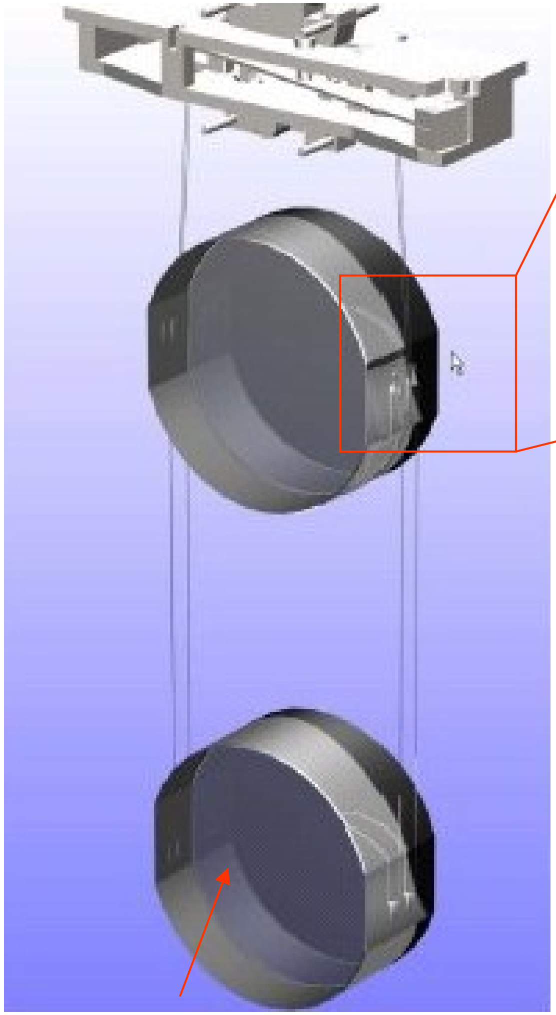
Ears silicate bonded to masses



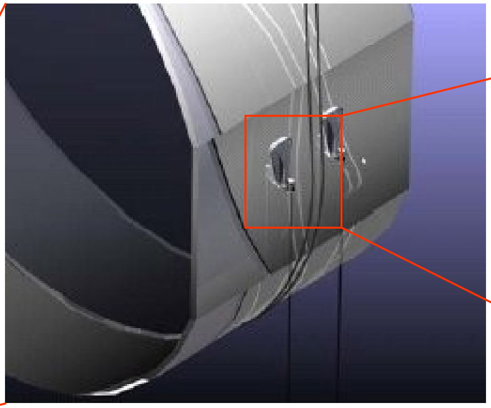
Silica fibres welded to ears



Development of Suspensions for Advanced LIGO



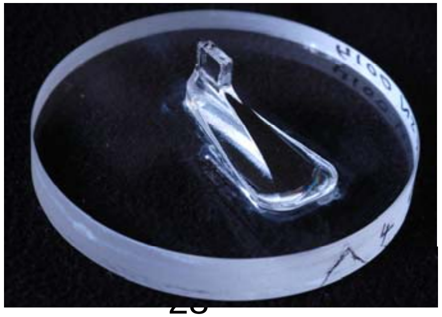
Mirror: 40 kg silica mass

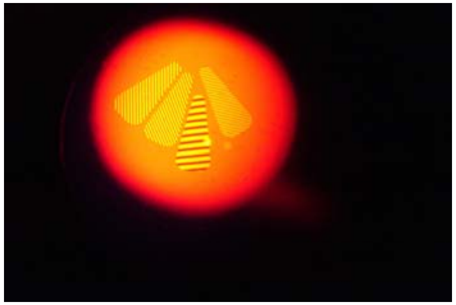


Above: detail of ear bonded to silica mass and ribbon (0.1 mm x 1 mm x 60 cm long) to be welded to ear

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

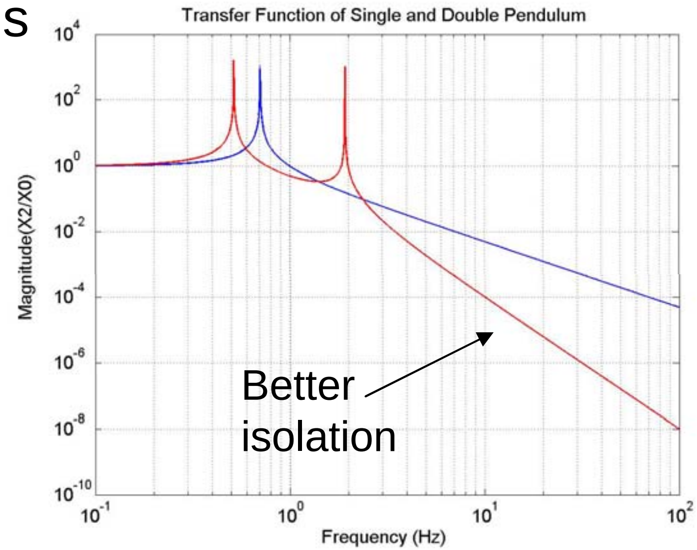




Seismic Noise

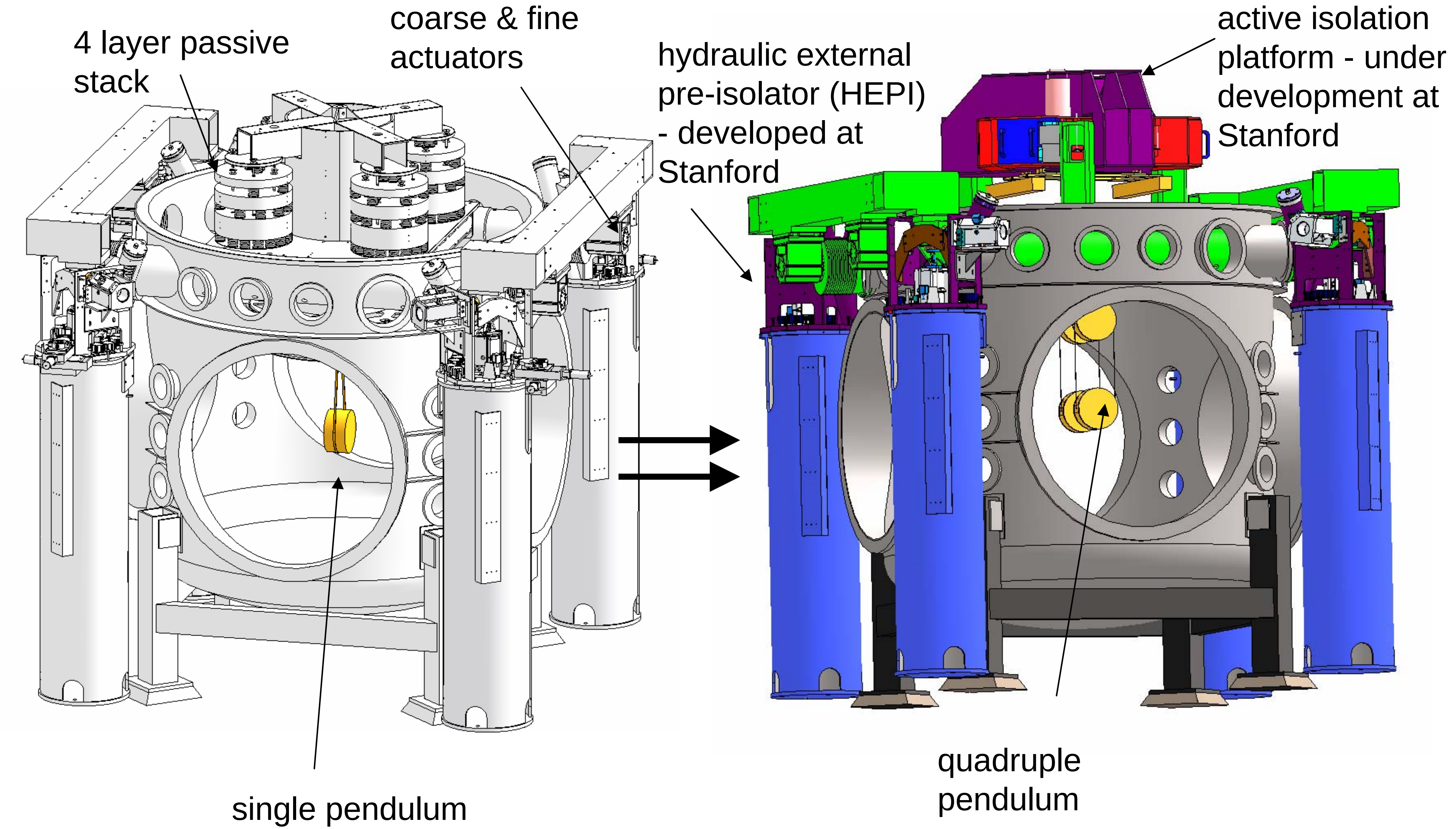
- Seismic noise limits sensitivity at low frequency - "seismic wall"
- Typical seismic noise at "quiet" site at 10 Hz is ~ few x 10^{-10} m/ √ Hz
- For Advanced LIGO more than 9 orders of magnitude of seismic isolation is required at 10 Hz – target is **10^{-19} m/ √ Hz**

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

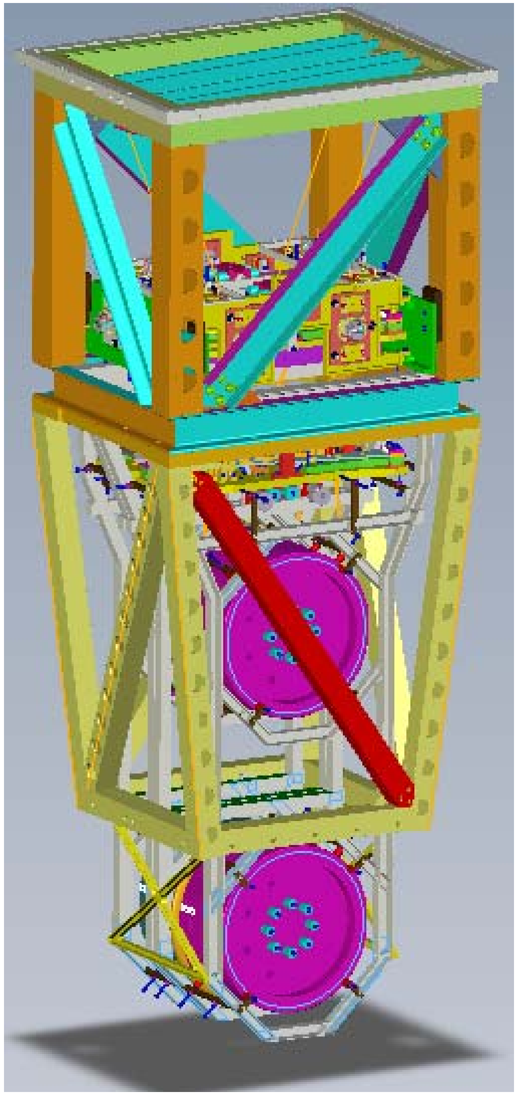


Advantage of double over single pendulum, same overall length

Seismic Isolation - From Initial to Advanced LIGO

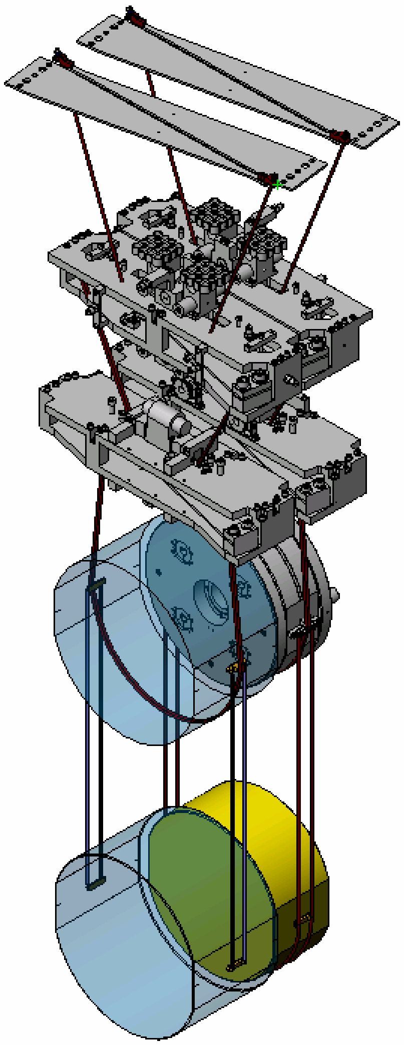


Advanced LIGO Quadruple Pendulum Suspension



Key design elements

- Monolithic final stage: 40 kg fused silica mirror on 4 fused silica ribbons for good thermal noise performance
- 4 stages for longitudinal seismic isolation plus 3 stages of blades for vertical isolation
- 6 degree of freedom damping (local control) at top mass for all low frequency modes (requires good mode coupling)
- Parallel reaction chain for quiet global control actuation: electrostatic at test mass, electromagnetic at upper stages (hierarchical)



Prototypes for Suspension System

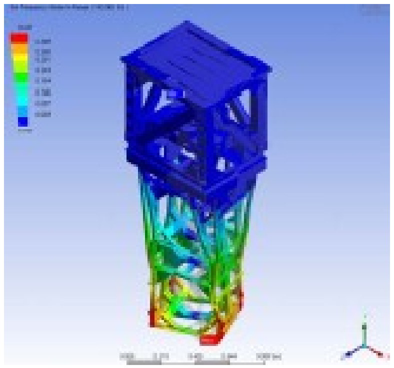
Metal prototype suspension
under test at Caltech

First article fused silica test mass:

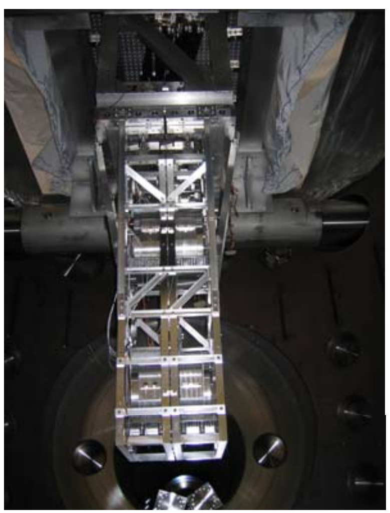
34 cm diam x 20 cm thick

Prototype gold-coated face-plate for electrostatic actuation

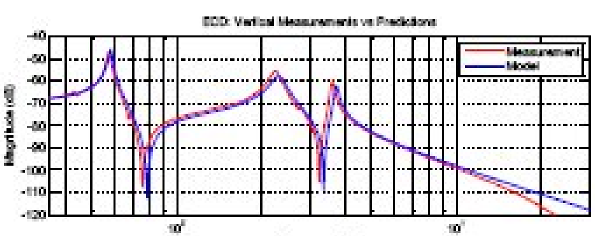
Suspensions: Ongoing and Future Work



- Continuing design and testing
  - Design/production of fibre/ribbon + ears
  - design of support structure



- Evolution of prototypes
  - all-metal controls prototypes under test at MIT
  - Noise prototype (with silica final stage) due for delivery to MIT March 2007 – test in conjunction with seismic isolation system



→leading to final design

Advanced LIGO Timeline

- Successful NSF baseline review (May/June 2006)
- Planned start of funding FY08 (Oct 2007)
- Planned start of installation 2010
- Planned operation from ~2014

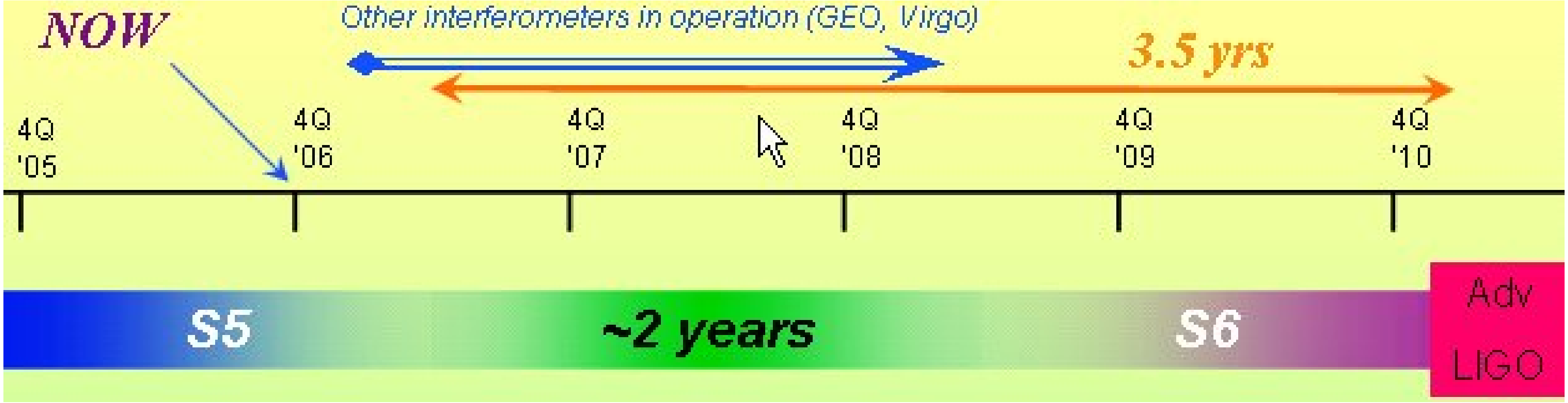
Large team effort

The LIGO Community

- **Scientific impetus, expertise, and development through the LIGO Scientific Collaboration (LSC)**
  - 500+ persons, 100+ graduate students, 40+ institutions
  - International effort
  - Especially strong coupling with German-UK GEO group, capital partnership for Advanced LIGO
- **Advanced LIGO design, R&D, and fabrication spread among participants**
  - LIGO Laboratory leads, coordinates, takes responsibility for Observatories
- **Continuing strong support from the NSF at all levels of effort – theory, R&D, operation of the Laboratory**
- **International network growing:**
  - GEO-600 (Germany-UK), ACIGA (Australia) LSC members
  - VIRGO (Italy-France), TAMA (Japan) – MOUs with LIGO

Interim Upgrade - Enhanced LIGO

- Gap between end of current science run and start of installation of Advanced LIGO

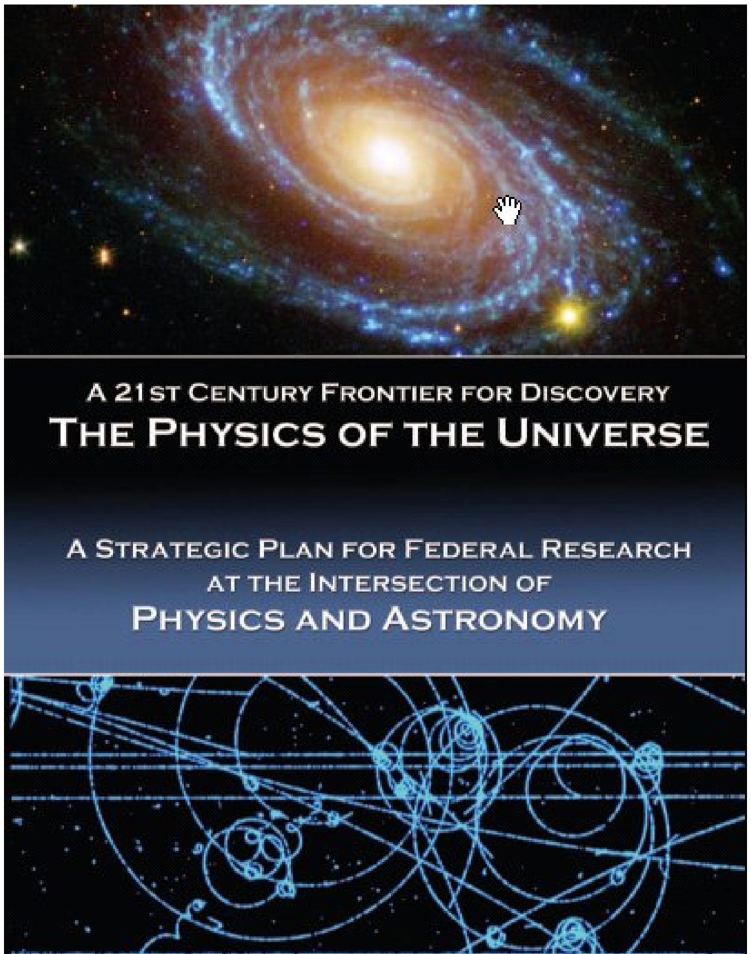


- Enhanced LIGO: factor of ~ 2 improvement in sensitivity -> factor of ~ 8 in event rate
- Incorporate some Advanced LIGO technology early: higher power laser (30 W) + suitable input optics, new readout scheme, more thermal compensation
- Increase probability of detection and gain experience of critical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

Timeline from LIGO: G060433

Conclusion

- Gravitational wave detection is 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.