G060275-00-R

Suspension Design for Advanced LIGO

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University of Glasgow

CQG Scientific Meeting
King’s College, London
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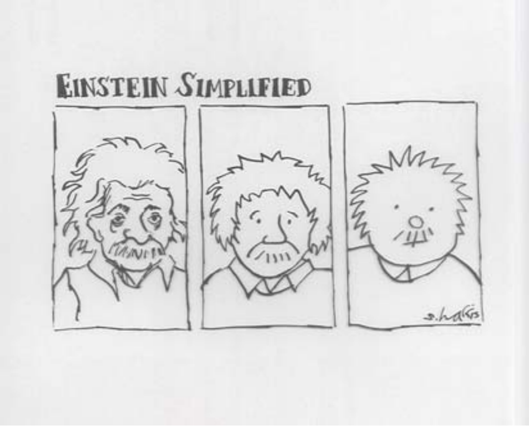
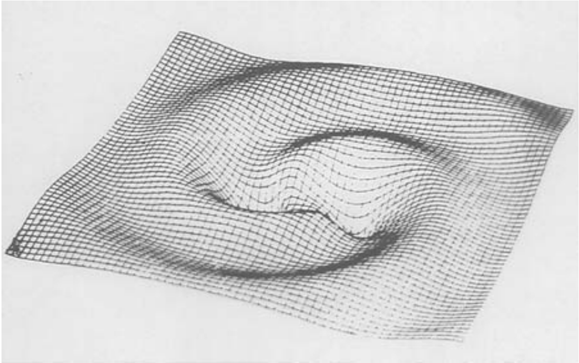
Outline of Talk

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

What Are Gravitational Waves?





- 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

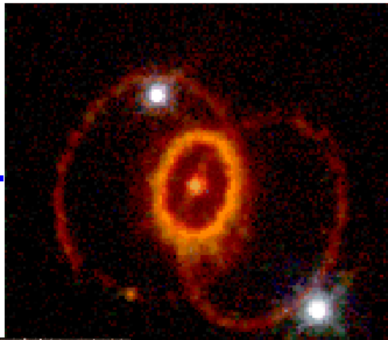
- gravitational interactions are very weak
- no dipole radiation (due to conservation of momentum and mass of only one “sign”)

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

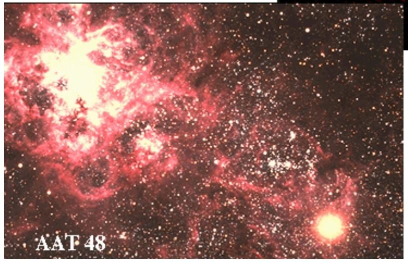
Astrophysical Sources

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

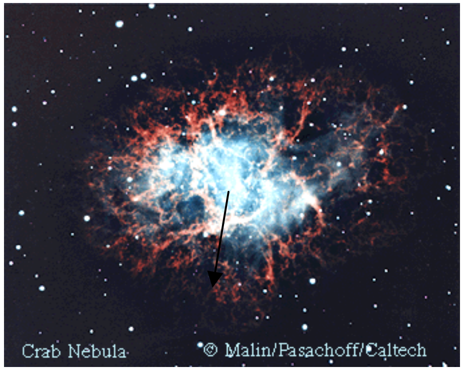


SN1987a



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

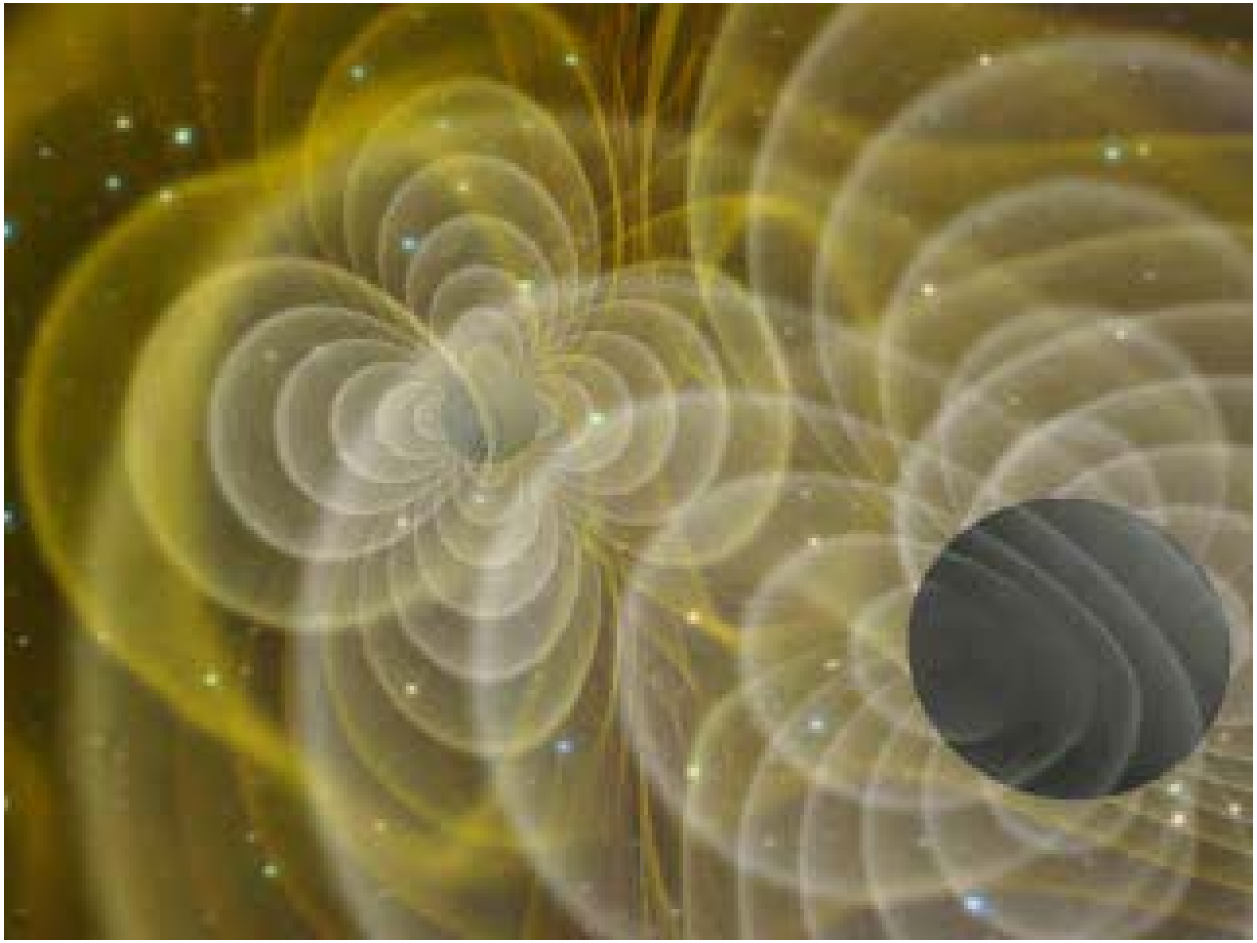
  (sign up for Einstein@home)
  - low mass X-ray binaries (e.g. Sco-X1)



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

A New Astronomy

Simulation of Merging Black Holes

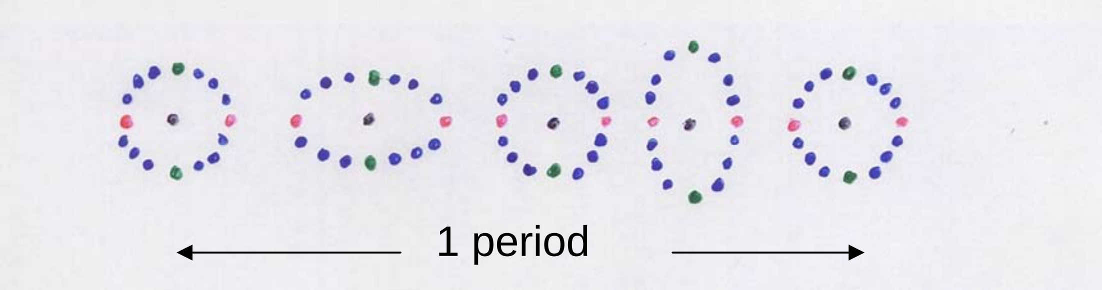


Credit: Henze, NASA

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

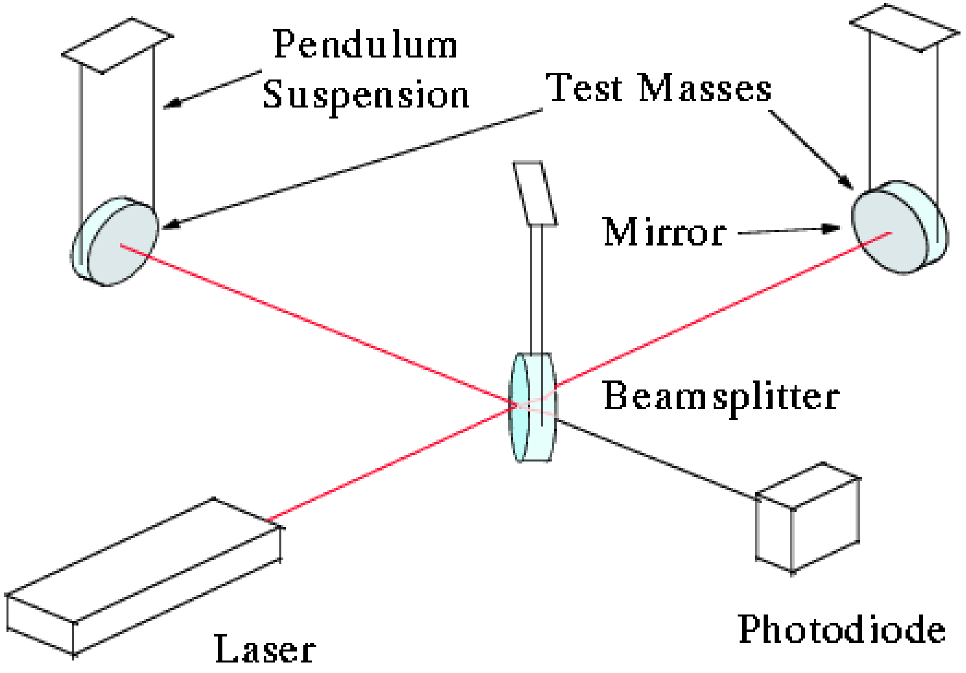
  - a gravitational wave of amplitude *h* will produce a strain given approximately by

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

  - largest signals (very rare) : $h \sim 10^{-19}$
  - for reasonable event rate : $h \sim 10^{-22}$-10^{-23}

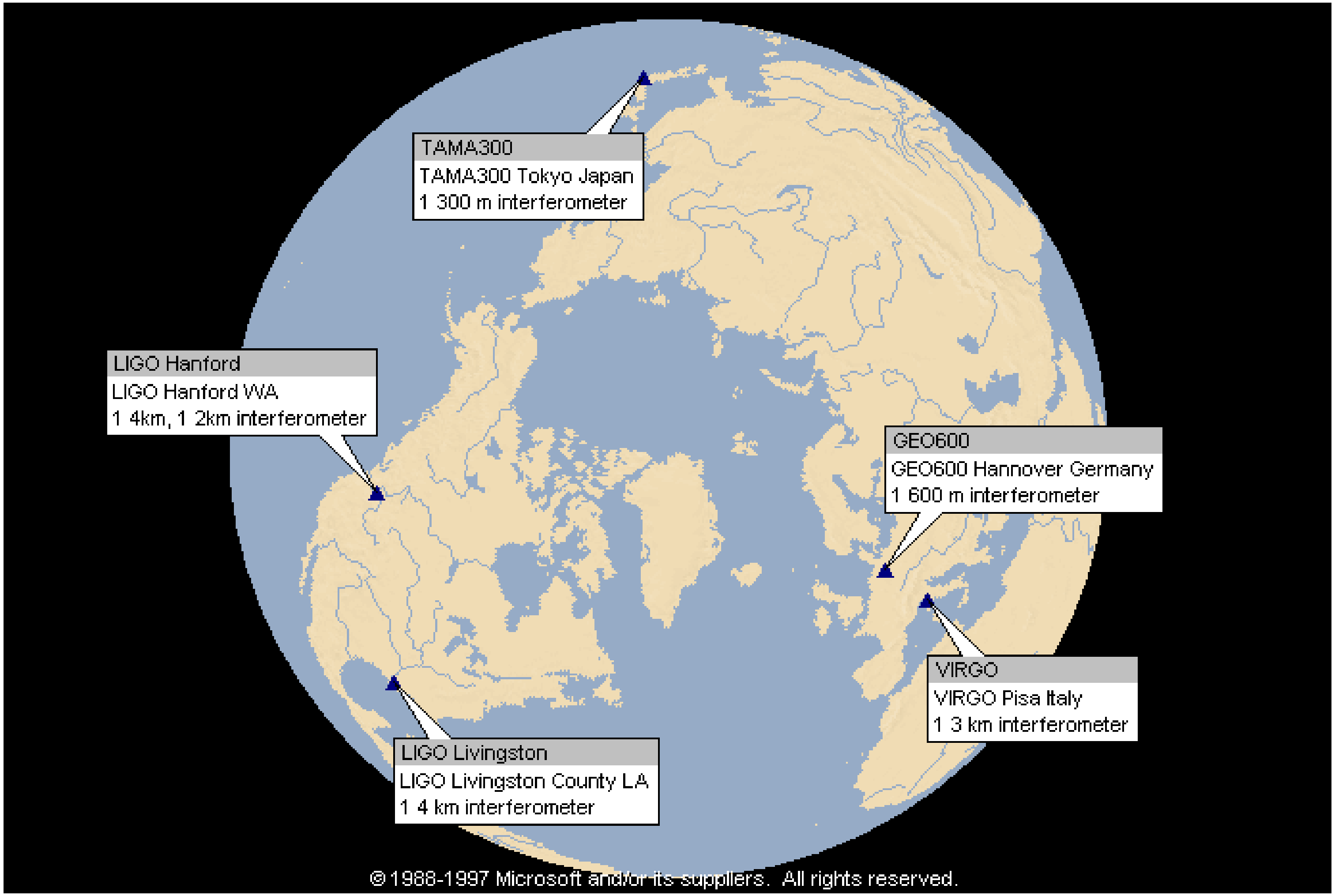
Gravitational Wave Detection

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

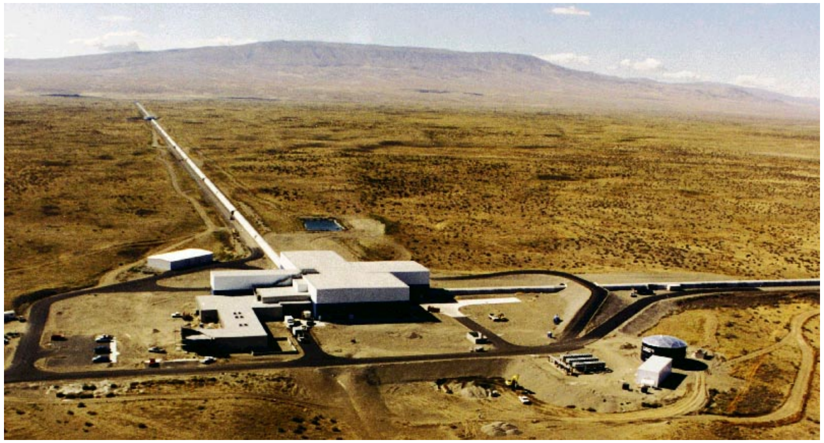


Simplified optical layout

WORLDWIDE GW INTERFEROMETER NETWORK

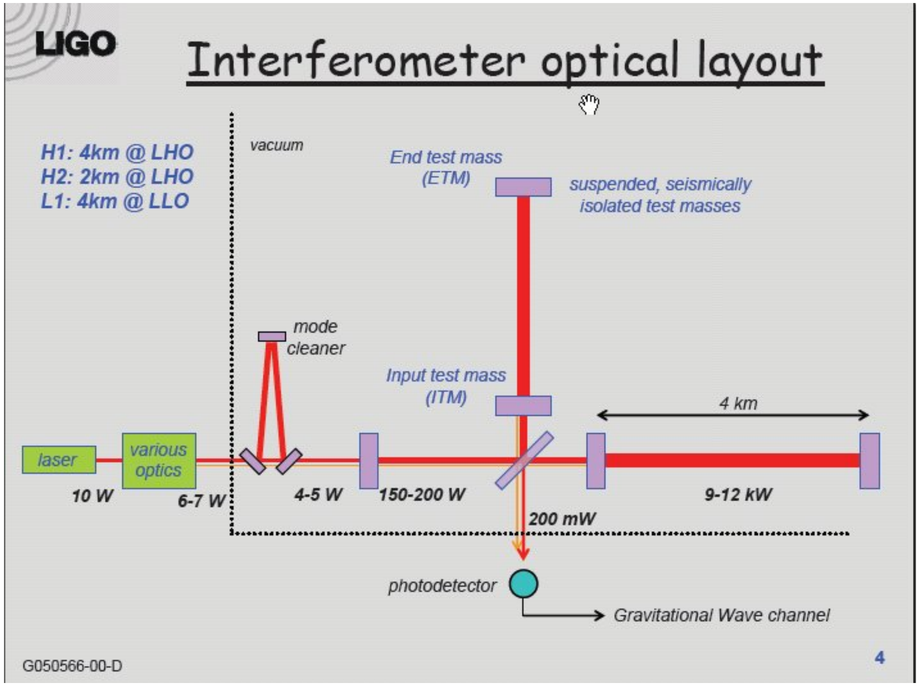


LIGO Observatories



LIGO Hanford Observatory, WA

LIGO Livingston Observatory, LA

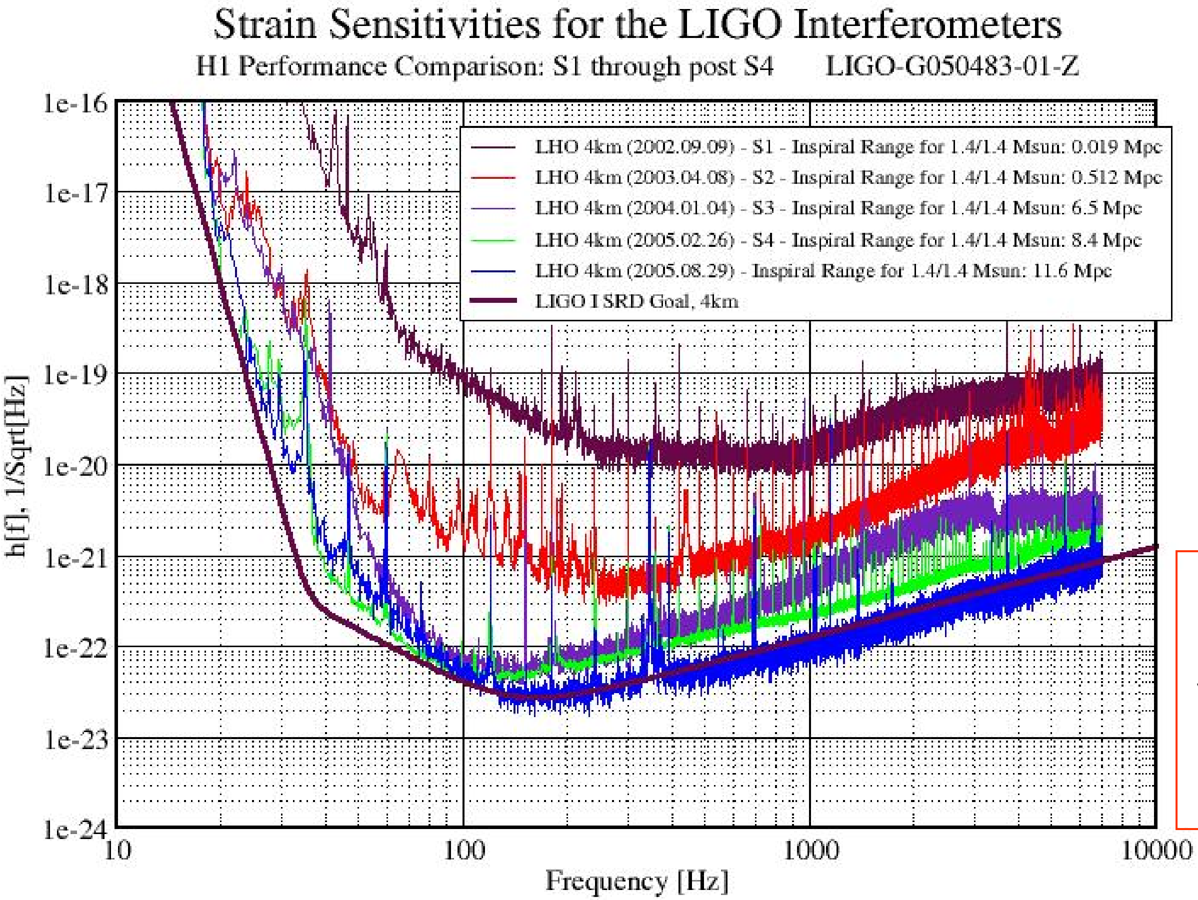


Interferometer optical layout

H1: 4km @ LHO
H2: 2km @ LHO
L1: 4km @ LLO

LIGO = **L**aser **I**nterferometer
Gravitational Wave **O**bservatory

Evolution of LIGO Sensitivity



NSF review report (Nov 05):

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

"… remarkable milestone achievement…"

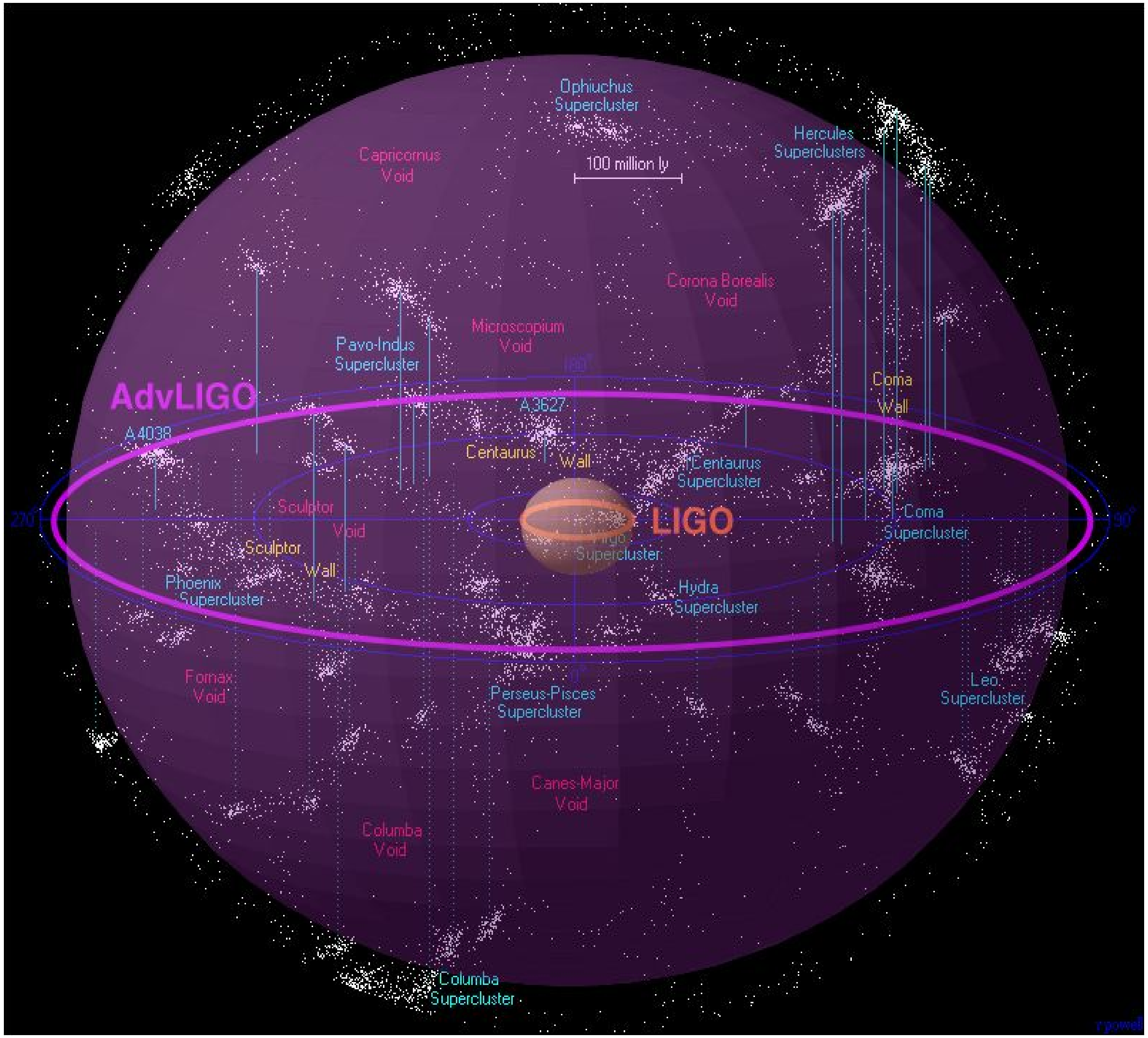
14 papers published from S1 – S3 presenting upper limits on a variety of possible sources
+
numerous technical papers

Best sensitivity now up to 14.5 MPc for inspiral range

LIGO Science 5 (S5) Run and Beyond

- Target: 1 year’s worth of coincidence data at design sensitivity
- Started Nov 2005
- 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.

LIGO vs Advanced LIGO

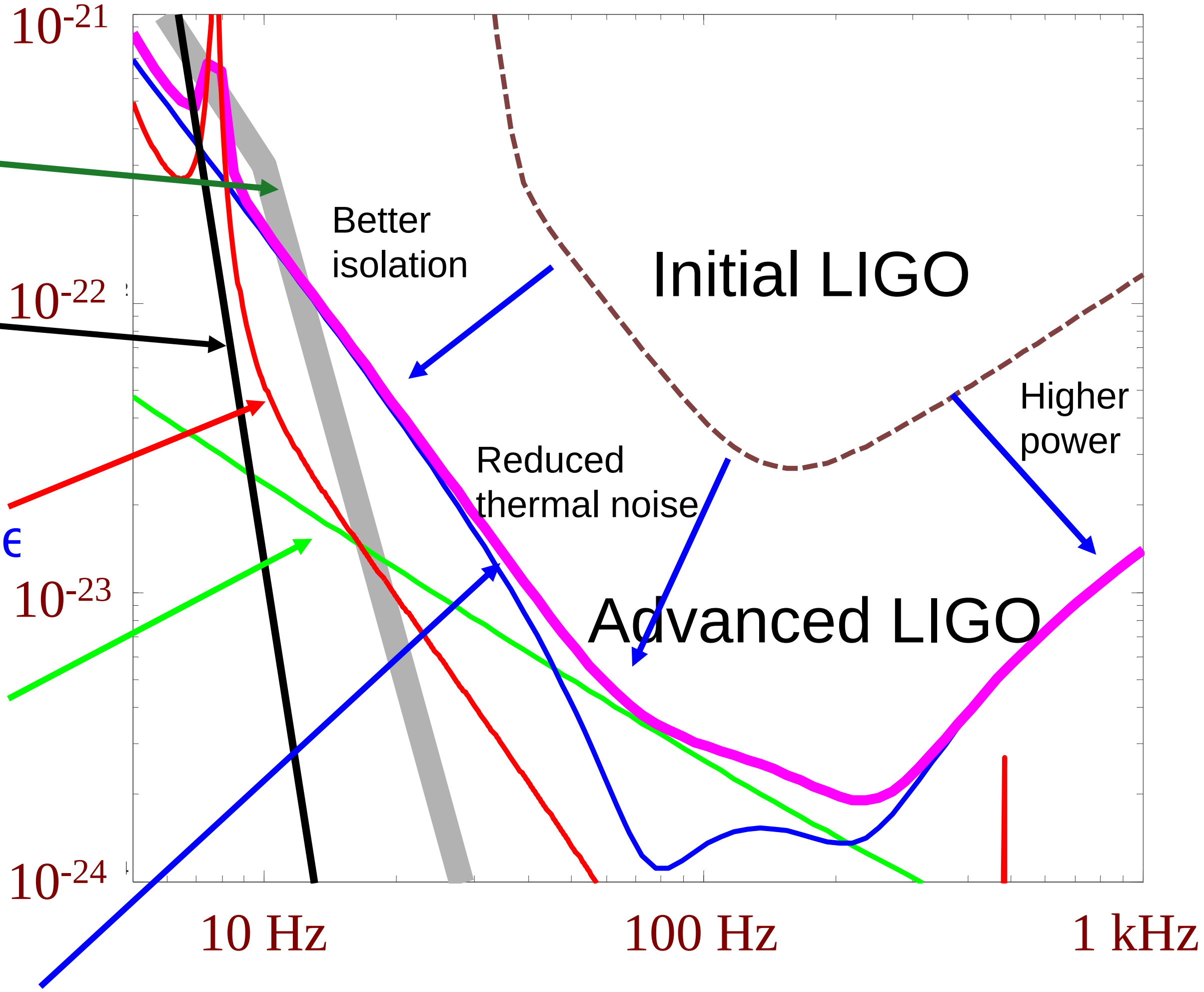


Factor of 10 in sensitivity gives factor of 1000 in volume

slide from B Berger

Projected Advanced LIGO performance

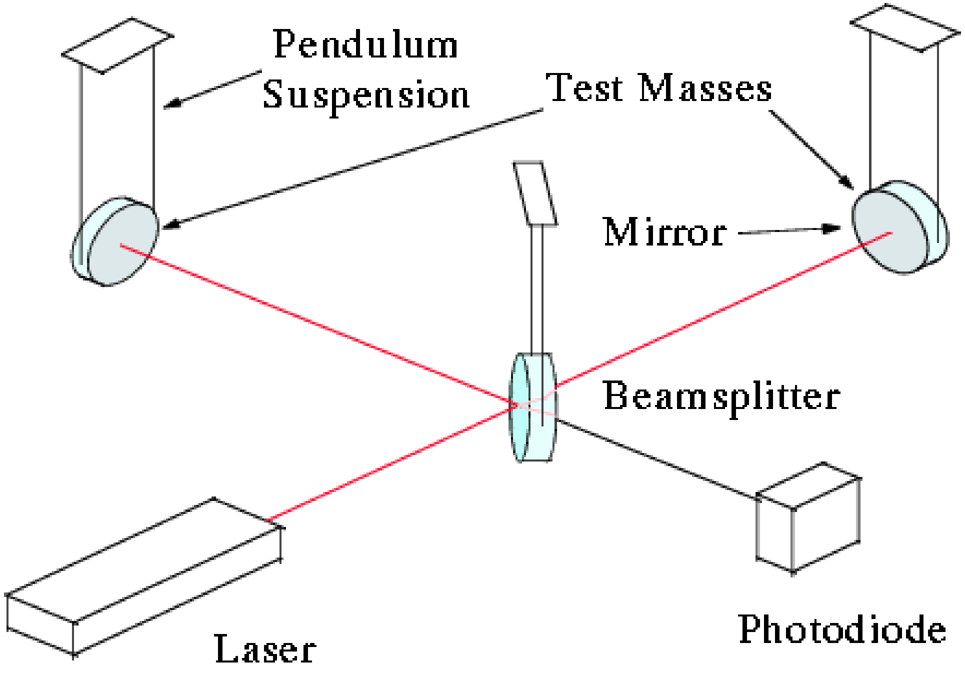
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



(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

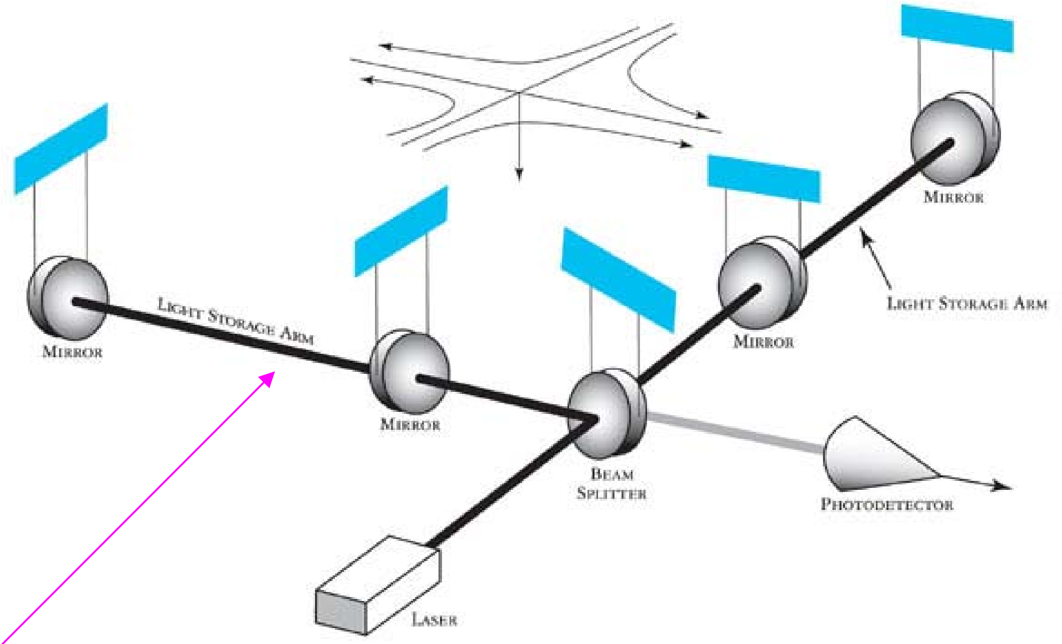


Diagram from LIGO web site

Advanced LIGO Suspensions Team

Wide membership from USA and UK*:

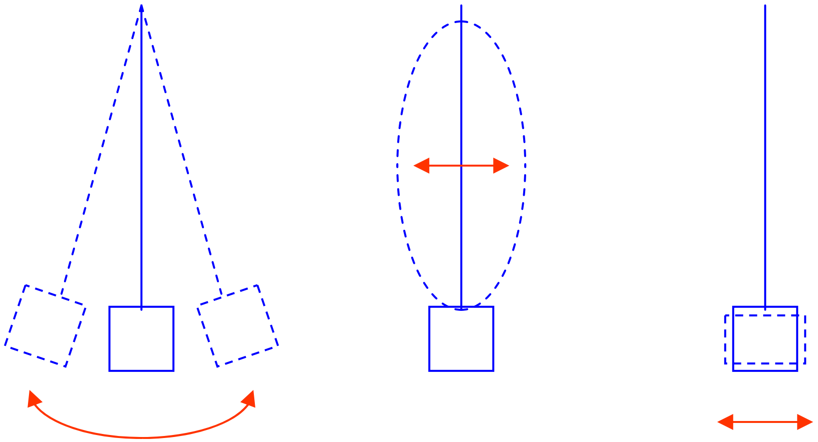
- **LIGO LAB**: CIT: H. Armandula, M. Barton, D. Coyne, J. Heefner, M. Mageswaran, K. Mailand, B Taylor, C. Torrie MIT: P. Fritschel, K. Mason, R. Mittleman, D Ottaway, L. Ruet, B Shapiro, D. Shoemaker LHO: B. Bland, D. Cook LLO: J. Romie, O. Spjeld, G.Traylor
- **STANFORD UNIVERSITY**: N. Robertson (also GEO/Glasgow) - Cognizant Scientist for Advanced LIGO suspensions development in USA and UK
- **GEO600**: GLASGOW: G. Cagnoli, C. Cantley, D. Crooks, A. Cumming, E. Elliffe, A Grant, A. Heptonstall, J. Hough, R. Jones, I. Martin, M. Perreur-Lloyd, M. Plissi, D. Robertson, S. Rowan, K. Strain, P. Sneddon, H. Ward, UNIVERSITAT HANNOVER: H. Lueck
- **RUTHERFORD APPLETON LABORATORY**: J. Greenhalgh, T. Hayler, J O'Dell, I. Wilmut
- **THE UNIVERSITY OF BIRMINGHAM**: S. Aston, D. Hoyland, C. Speake, A. Vecchio
- **STRATHCLYDE UNIVERSITY**: N. Lockerbie

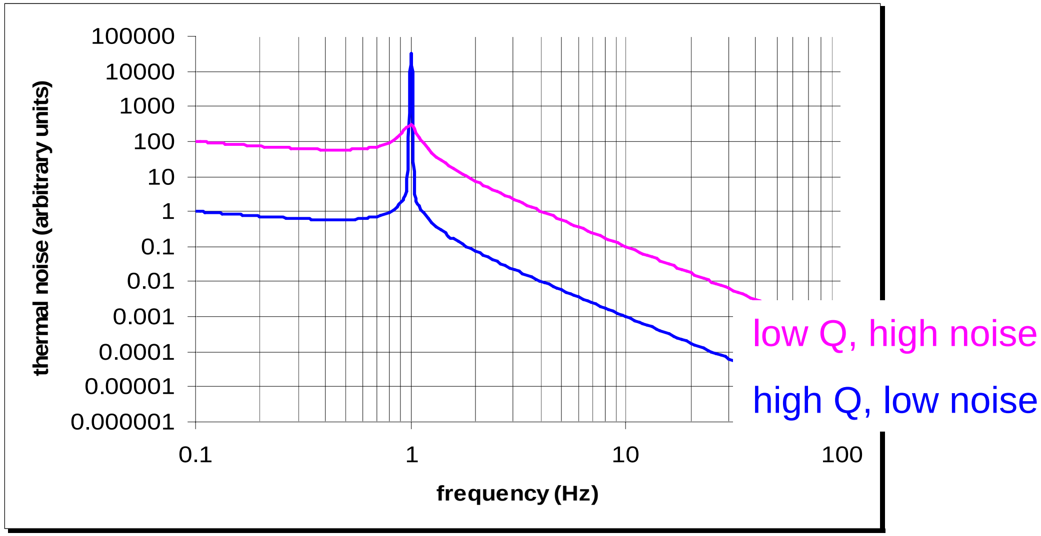
*Significant UK involvement : PPARC awarded ~$12M grant for development and fabrication of the quadruple suspensions for Advanced LIGO

Thermal Noise

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

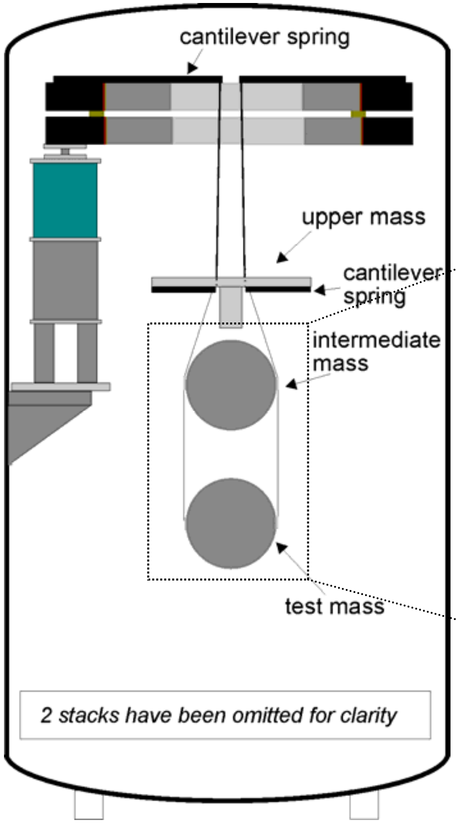
- To minimise:
  - use low loss (high quality factor, Q) materials for mirror and suspension – gives low thermal noise level off resonance -*silica* is a good choice
    - *loss angle ~ 2e-7, c.f. steel ~2e-4*
    - *breaking stress can be larger than steel*
  - use thin, long ribbons to reduce effect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

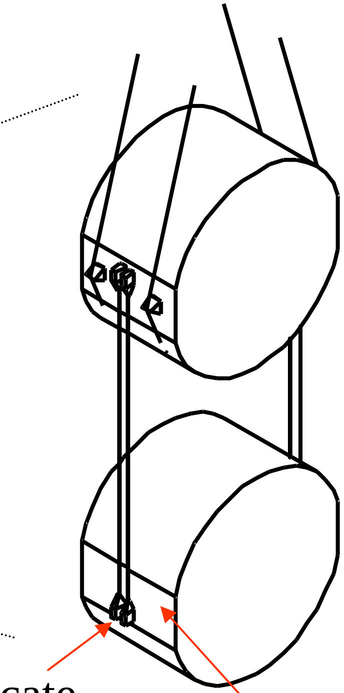


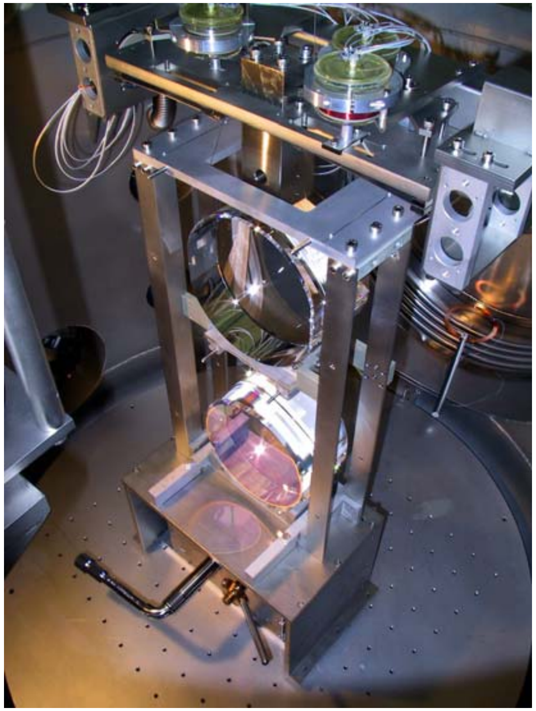


Monolithic fused silica suspensions have been pioneered in the GEO 600 detector: makes use of silicate bonding technique developed for Gravity Probe B

GEO Triple Pendulum Suspension

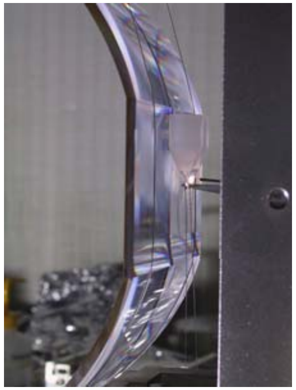




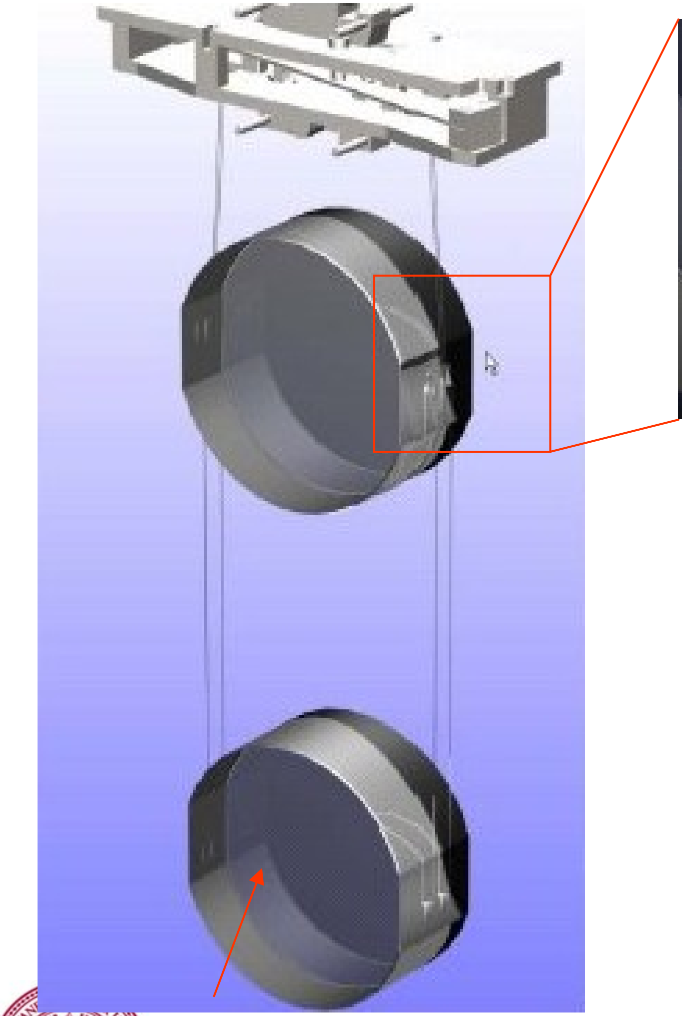


Ears silicate bonded to masses

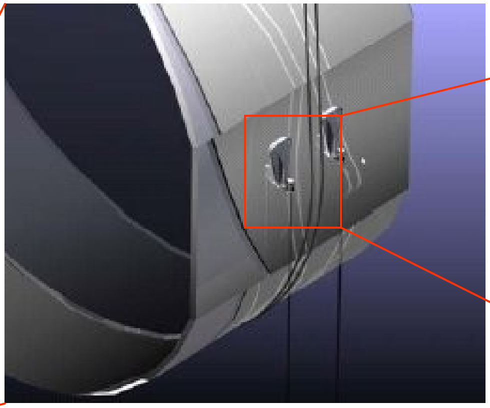
Silica fibres welded to ears



Development of Suspensions for Advanced LIGO



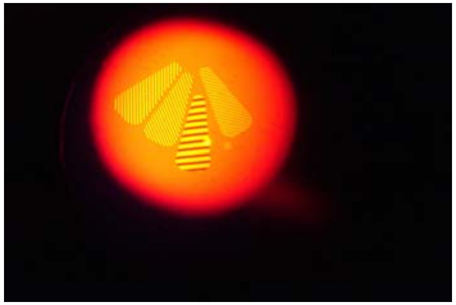
Mirror: 40 kg silica mass



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

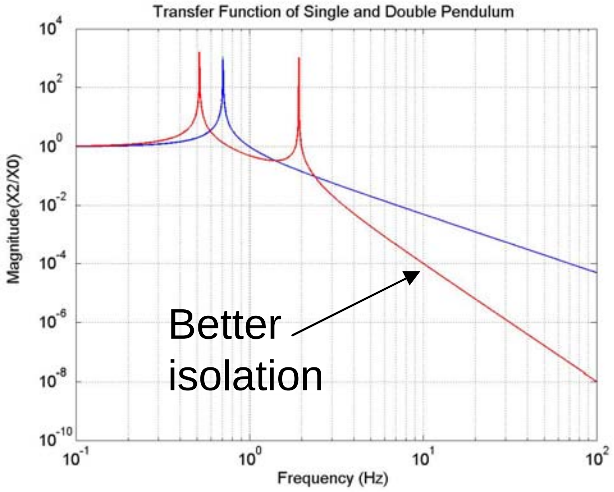


Diagrams from GEO-Glasgow group

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**

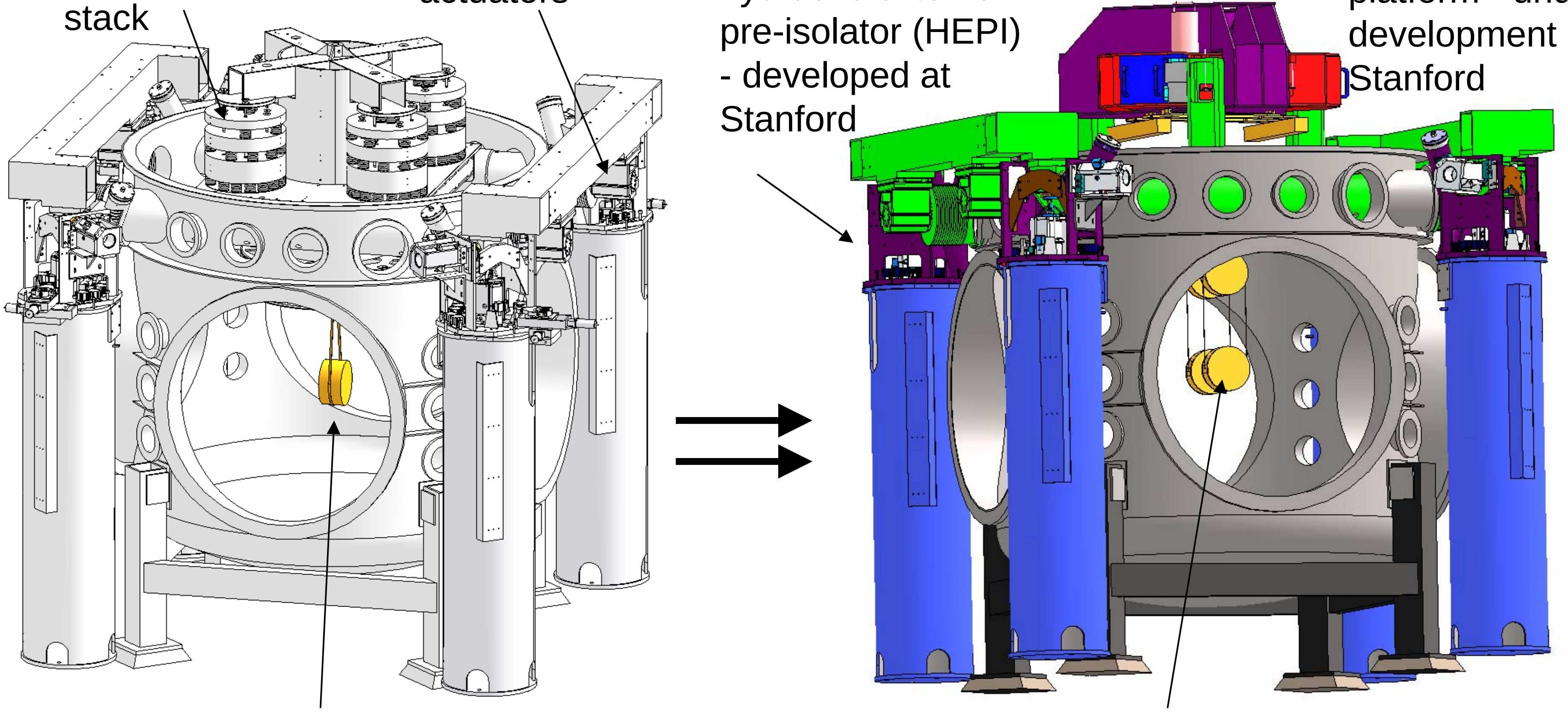
  Solution - use multiple stages of isolation
- Isolation required in vertical direction as well as horizontal due to cross-coupling effects
- Ultimately Newtonian noise will limit low frequency performance: – LISA (interferometer in space) for low frequency detection



Better isolation

Advantage of double over single pendulum, same overall length

Seismic Isolation - From Initial to Advanced LIGO



4 layer passive stack

coarse & fine actuators

single pendulum

hydraulic external pre-isolator (HEPI) - developed at Stanford

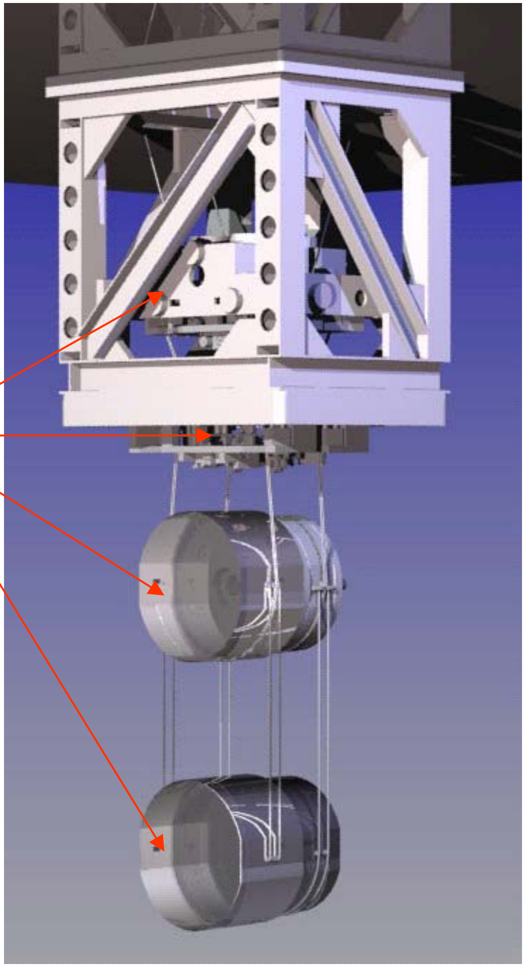
active isolation platform - under development at Stanford

quadruple pendulum

Diagram from Corwin Hardham

Advanced LIGO Quadruple Pendulum Suspension

Schematic



Four stages

Damping applied at top stage

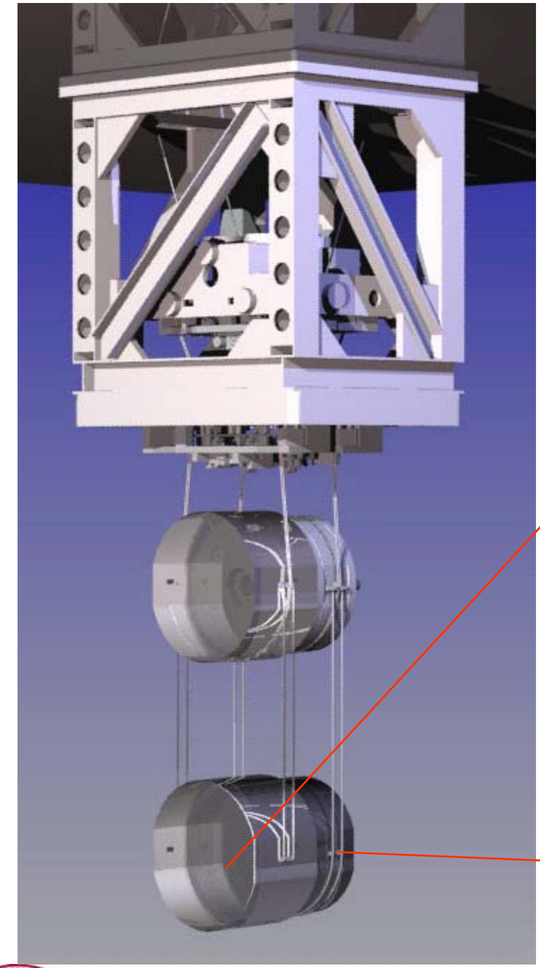
Main chain plus parallel reaction chain for control actuation

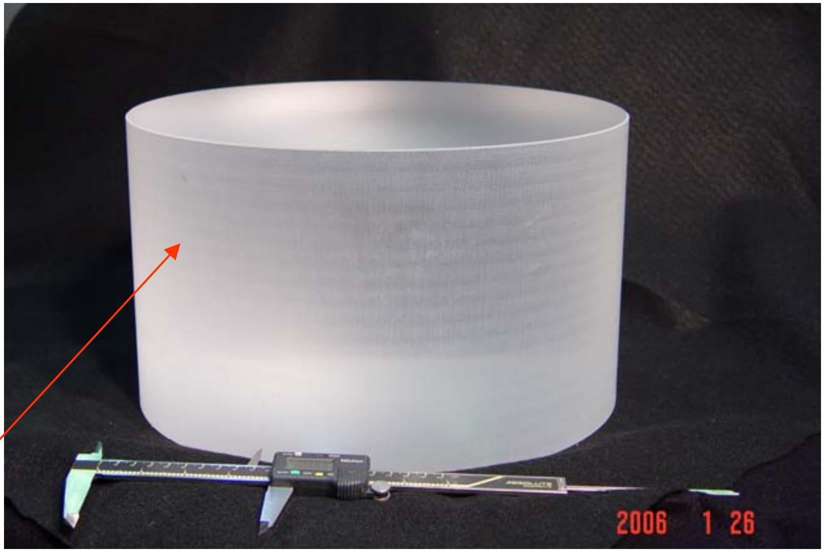
(Lower support structure removed for clarity)

Metal prototype under test at Caltech

Diagram/picture from Adv. LIGO SUS team

Test Mass and Electrostatic Actuator



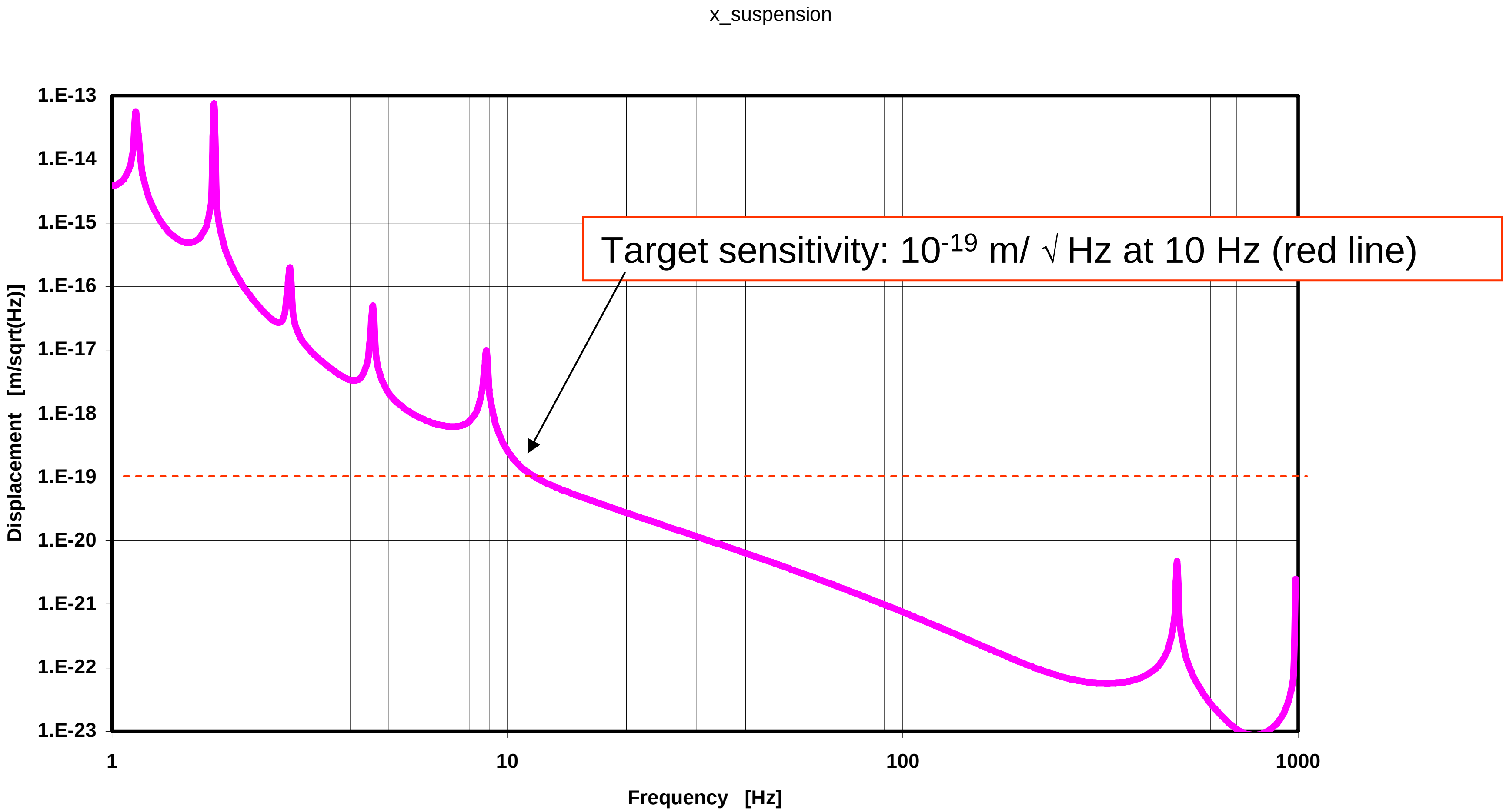


First article test mass:

34 cm diam x 20cm thick

Prototype gold-coated face-plate for electrostatic actuation

Suspension Thermal Noise Estimate

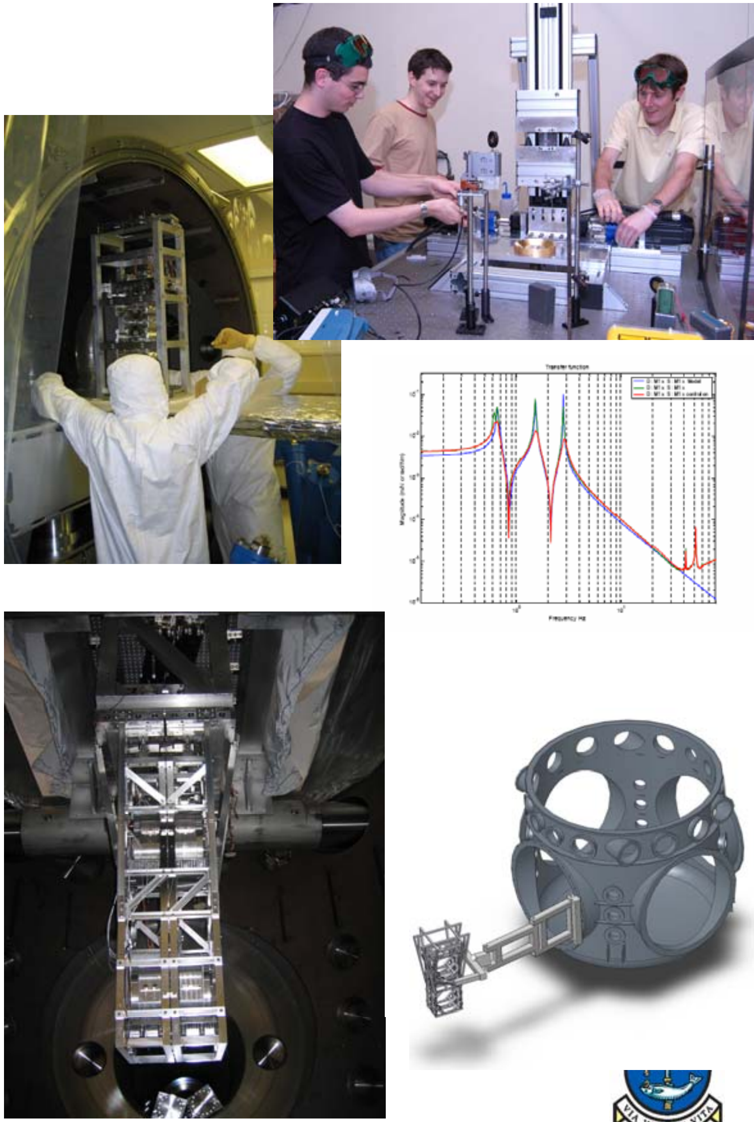


Target sensitivity: 10^{-19} m/ √ Hz at 10 Hz (red line)

Current Status and Future Prospects

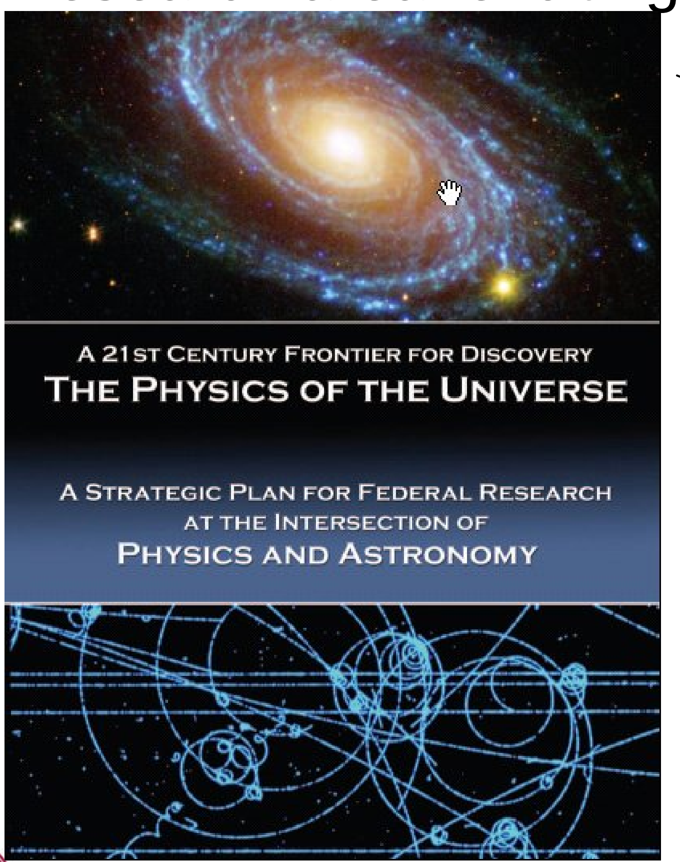
- Suspensions
  - Ongoing research and development
  - Program of tests on full-scale prototype with monolithic final stage
    - → Leading to final design and production

- Advanced LIGO
  - Upcoming NSF review for Adv LIGO (May/June 2006)
  - Planned start of funding FY08 (Oct 2007)
  - Planned start of installation 2010
  - Planned operation from ~2014



Conclusion

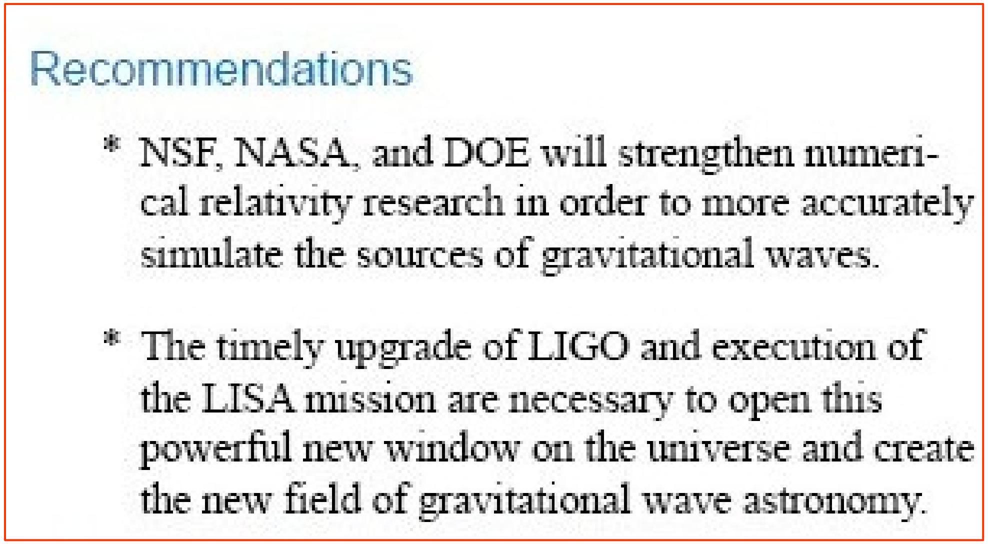
- Gravitational wave detection is recognised as a key research area: exciting times ahead!



A 21ST CENTURY FRONTIER FOR DISCOVERY
THE PHYSICS OF THE UNIVERSE

A STRATEGIC PLAN FOR FEDERAL RESEARCH
AT THE INTERSECTION OF
PHYSICS AND ASTRONOMY

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.