LIGO and GEO Developments for Advanced LIGO

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on behalf of the LIGO Scientific Collaboration

APS Annual Meeting
6th April 2003

Introduction: LIGO

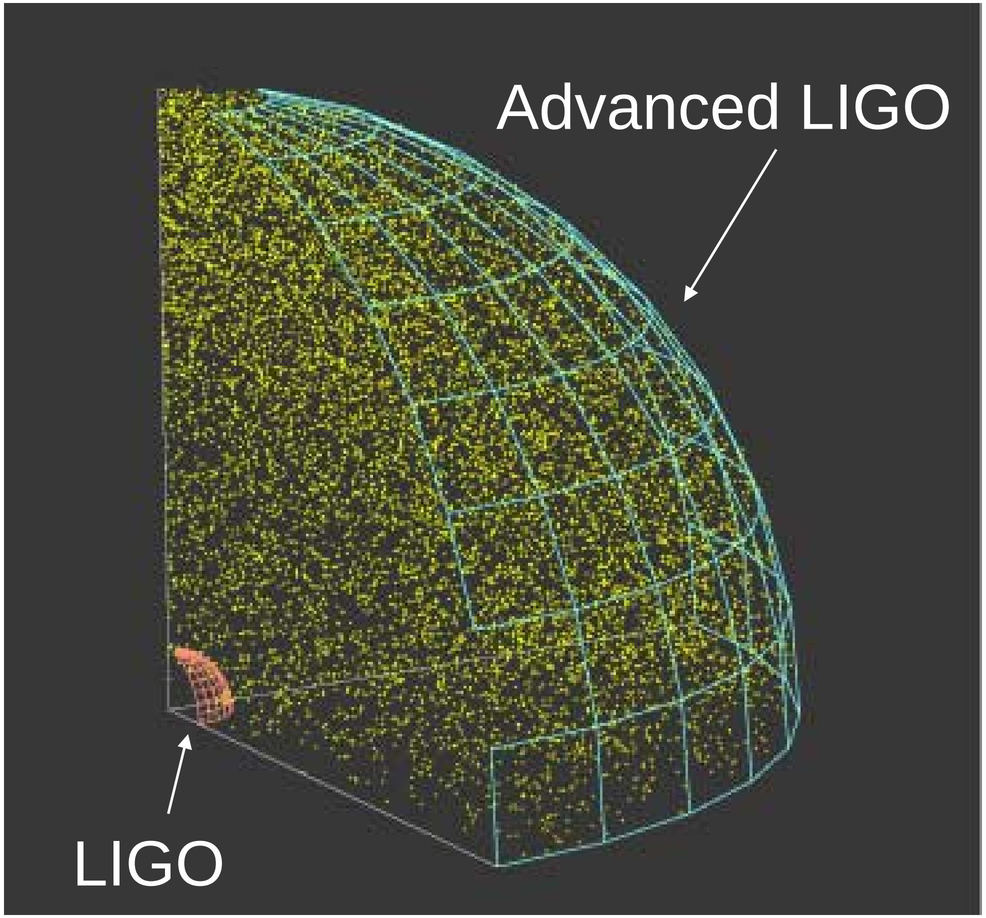
- LIGO interferometers in operation
- Steady sensitivity improvements throughout commissioning phase - very close to design goals
- First science runs carried out, more on the way, (plan for one year of integrated data at $h = 10^{-21}$ by end of 2006)
- Science results currently being prepared for publication, presented at this meeting

- Current sensitivity levels make gravitational wave detection plausible
- Improved detector sensitivities will let us fully exploit the wealth of potential gravitational wave sources

- Way forward: **Advanced LIGO**

Advanced LIGO aims

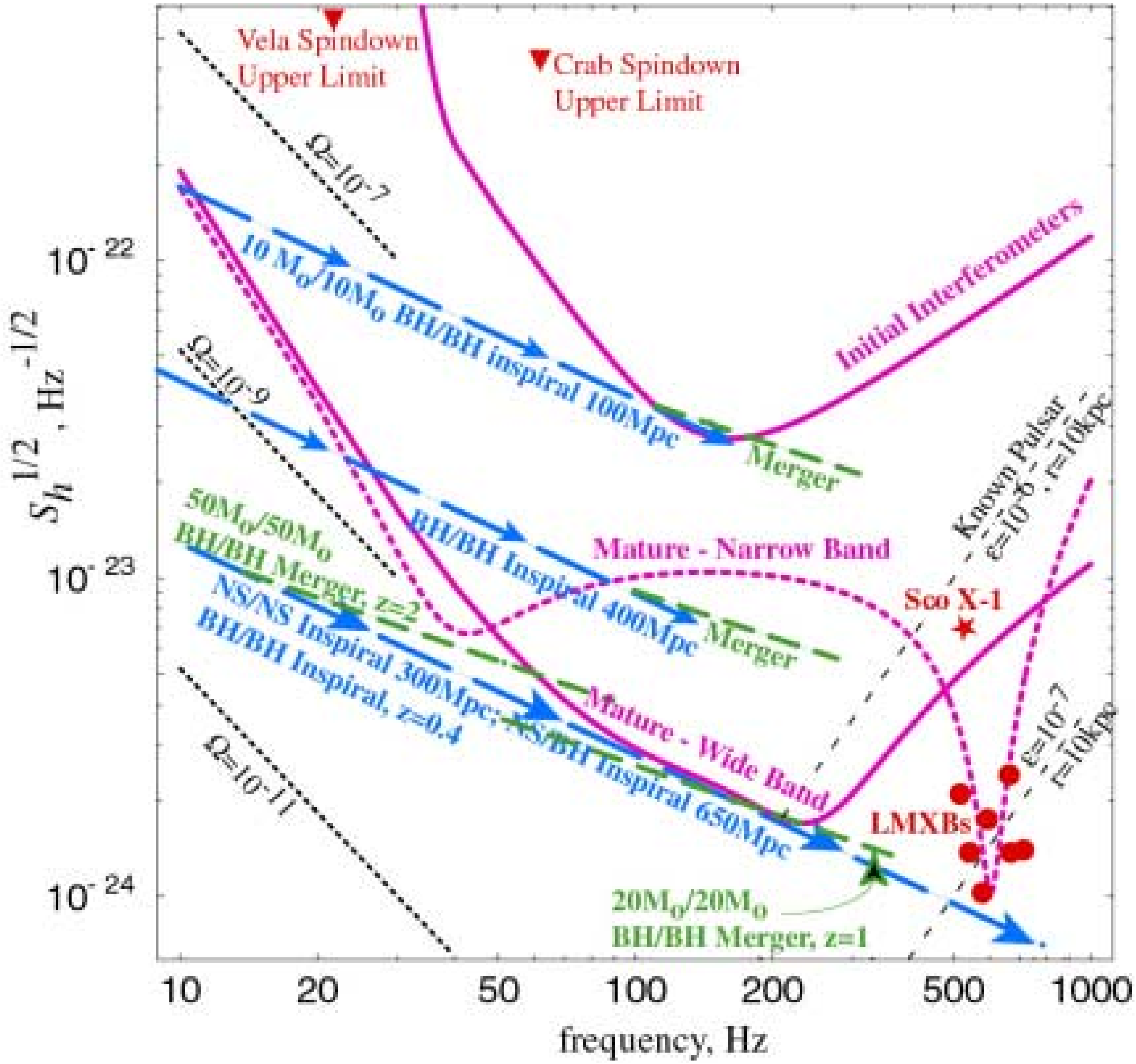
- Improve sensitivities by building on the experience and achievements of LIGO
- Do this by creating a detector whose design exploits evolution of detector technologies since the freezing of the initial LIGO design
- Aim:
  - » to see x10 further into Universe over a broad range of frequencies
  - » access sources in a volume x1000 greater
  - » build a quantum-noise limited interferometer system
- Move from gravitational wave detection to gravitational wave astronomy



Astrophysical Reach

(Kip Thorne)

- Neutron Star & Black Hole Binaries
  - » inspiral
  - » merger
- Spinning NS's
  - » LMXBs
  - » known pulsars
  - » previously unknown
- NS Birth
  - » tumbling
  - » convection
- Stochastic background
  - » big bang
  - » early universe

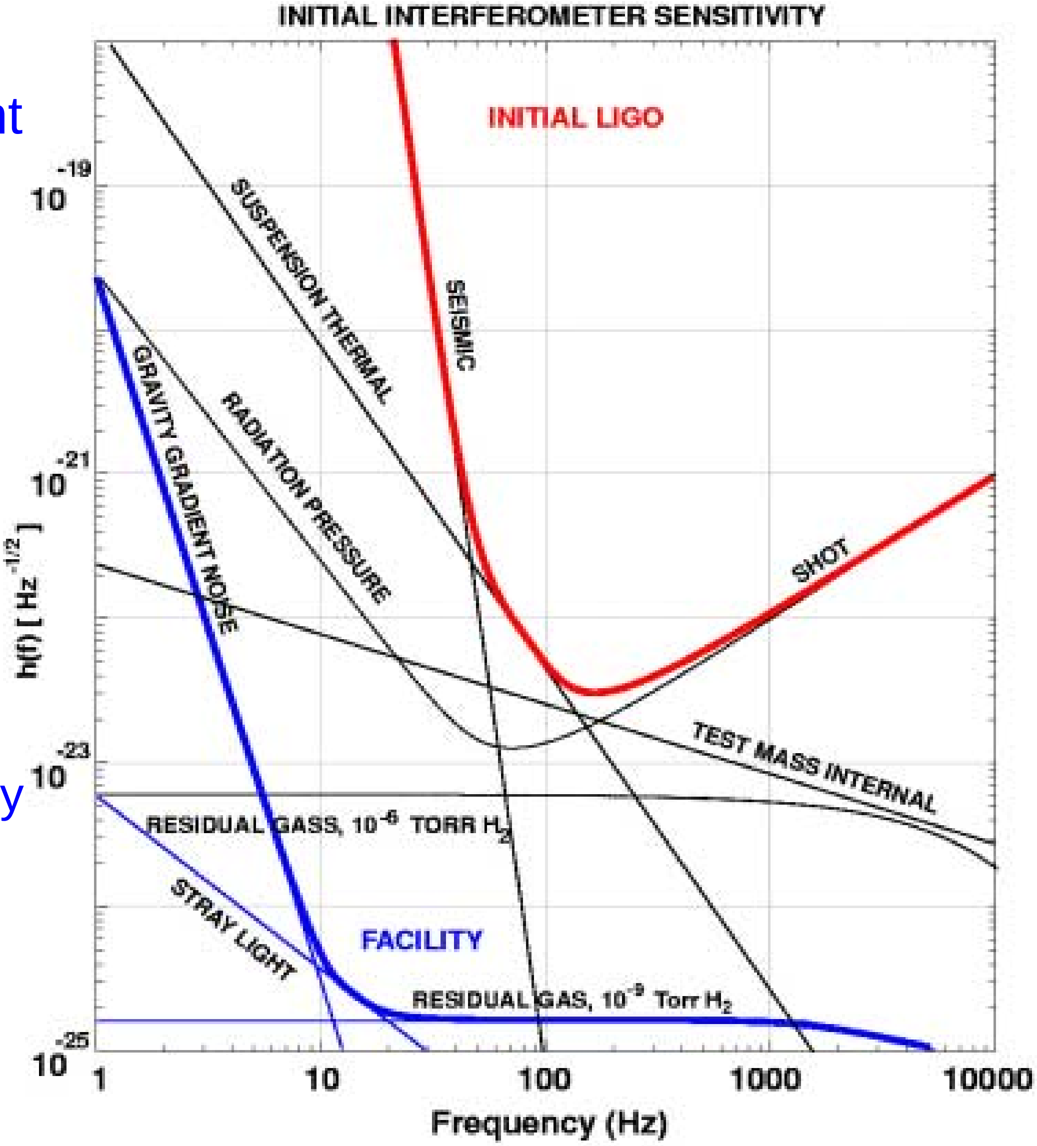


What limits the sensitivity of LIGO

- Design sensitivity limited by different types of noise in different frequency ranges:
  - » below ~50Hz
    - – seismic noise
  - » 50 - 200Hz
    - – thermal (Brownian) noise
  - » > 200Hz
    - – shot noise

- Whilst LIGO observatories are instruments of phenomenal sensitivity they do not yet reach facility limits

- Wish to improve sensitivities in each of areas above



Advanced LIGO: how to get where we want to go

- Use experience with development of LIGO instruments in concert with technology developments in gravity wave community

- Develop precision measurement capability to required levels though a comprehensive and targeted program of R & D:
  - » within the US LIGO laboratory
  - » throughout groups in the wider LIGO Scientific Collaboration
  - » with significant contributions from international partners, including:

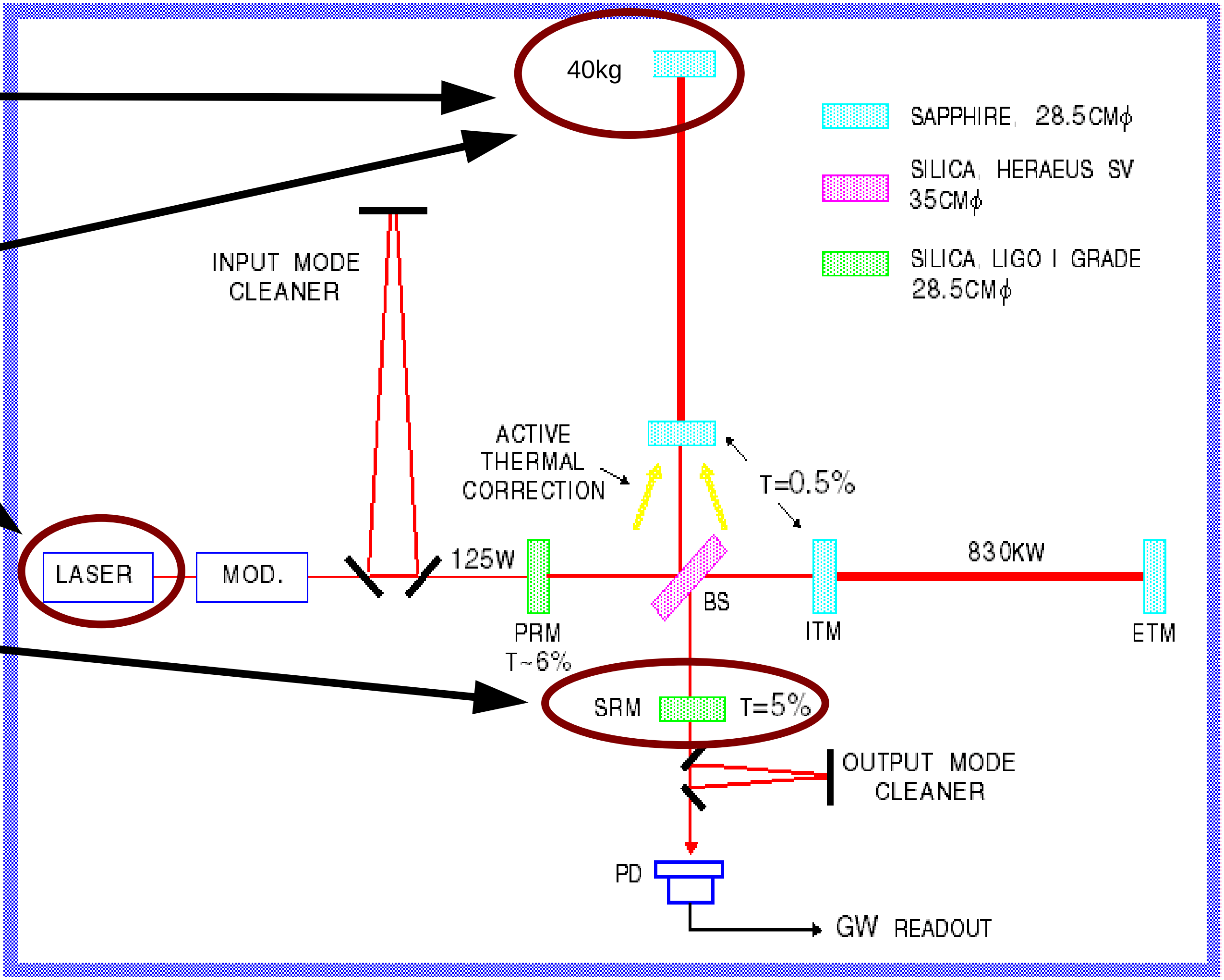
GEO (UK/Germany) - suspension developments, laser developments, interferometric techniques

ACIGA (Australia) - high power optic tests

Plus colleagues in Japan, Russia, India, Spain

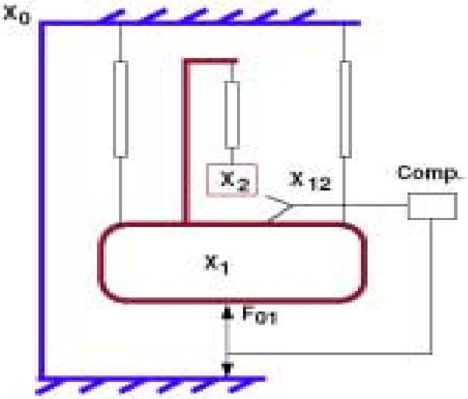
Advanced LIGO: how to get where we want to go

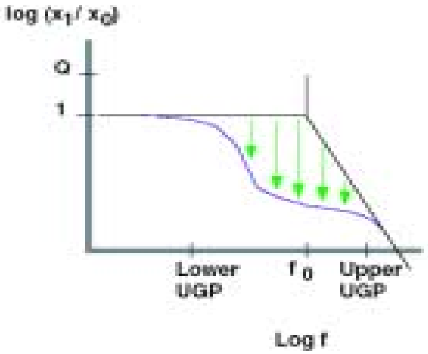
- Make significant improvements in interferometer subsystems including:
  - » seismic isolation and control of optics
  - » thermal noise and high power optics
  - » high power lasers
  - » tunability of response - signal recycling

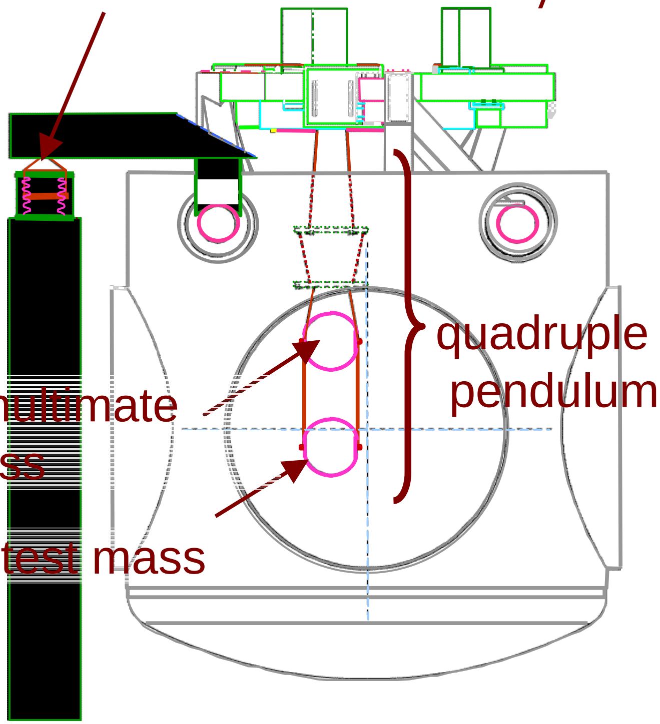


Sensitivity improvements: seismic isolation and control

- At low frequencies (few Hz) ground motion ~few µm rms
- Advanced LIGO targets
  - » displacement of test mass $<10^{-19}$m /√Hz @10Hz
  - » push seismic noise ‘wall’ down to 10Hz
- Need ~10 orders of magnitude reduction in ground motion
- Strategy for this uses multi-stage approach to vibration isolation
- Each stage uses an array of sensors and actuators to measure and suppress excess vibrations







6 DOF ‘quiet hydraulics’

2 stage active isolation

quadruple pendulum

penultimate mass

test mass

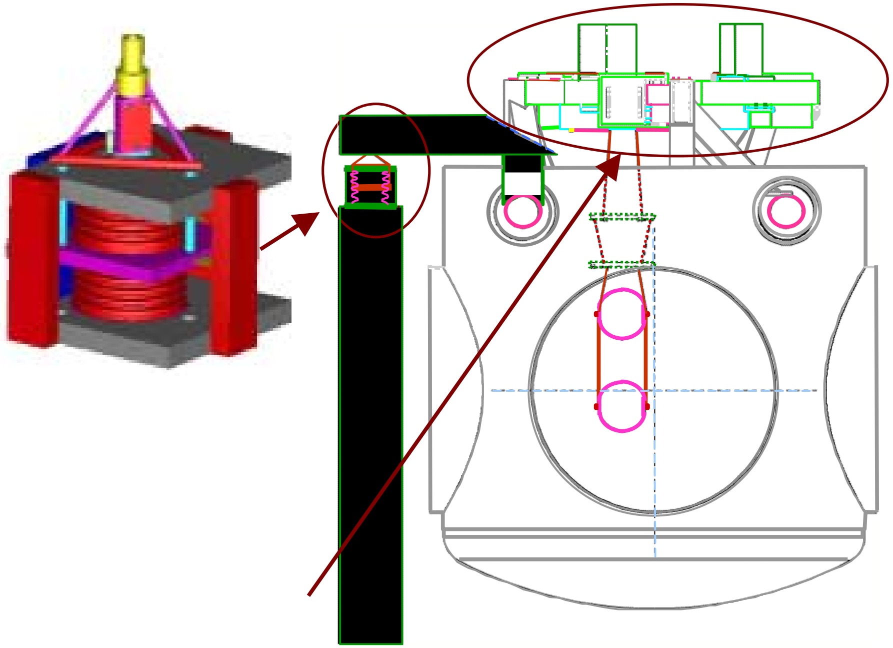
ground

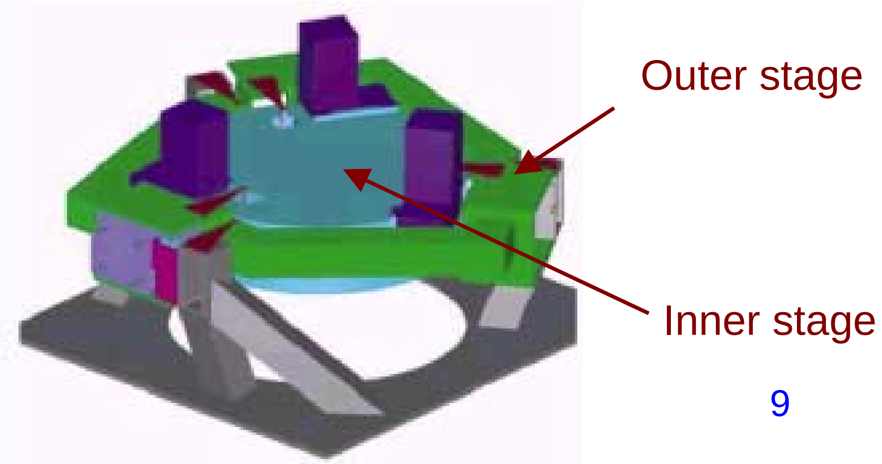
LIGO BSC vacuum chamber with top removed

Sensitivity improvements: seismic isolation and control

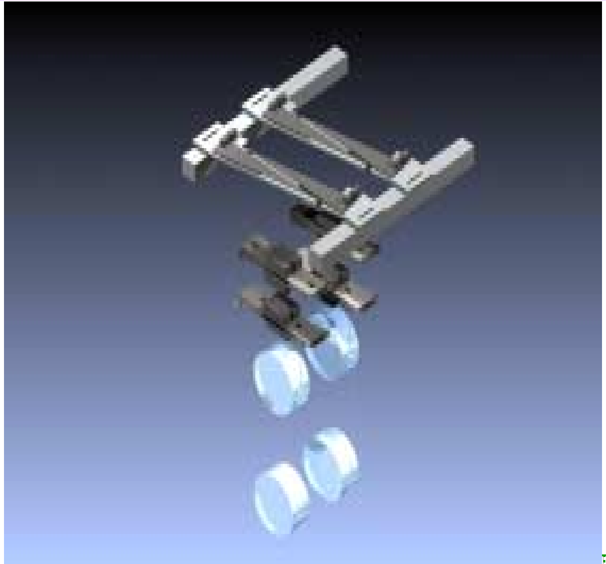
- External hydraulic actuators
  - » Large dynamic range (+/-1mm) - low frequency bandwidth, below GW detection band
  - » Reduce rms motion to allow sensing system at higher frequencies to remain linear

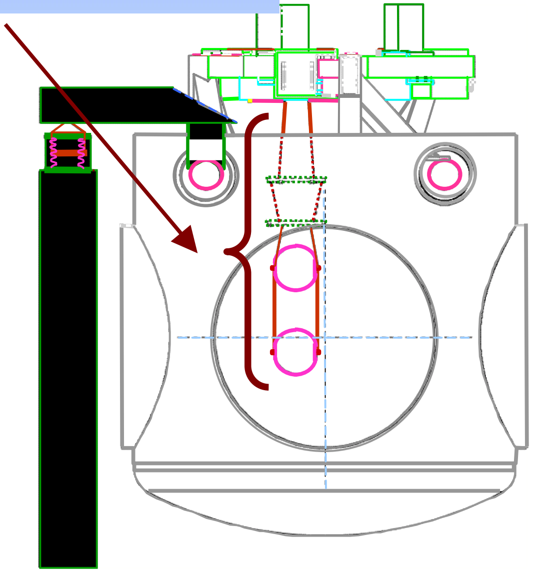
- Two stages of active servo-controlled platforms
  - » Active suppression of noise from 0.1Hz to 30Hz
  - » Provide a quiet platform (2×10^{-13} m/$\sqrt{\text{Hz}}$ @ 10Hz) from which to hang delicate optics





Sensitivity improvements: seismic isolation and control





- Augment the seismic isolation provided by the active stages - use a multiple pendulum chain ending with the final interferometer mirror
- The free motions of the mirror suspensions must be damped – using local sensors & actuators
  - » place the sensors and actuators high up the chain of pendulums so that control noise is filtered by the lower pendulum stages
- The spacings between the mirrors and their orientation must be controlled – using “global” signals derived from the interferometer
  - » global control signals are applied at all stages of the multiple pendulum
  - » the forces are applied from a reaction pendulum to avoid re-introduction of noise

Sensitivity improvements: thermal noise

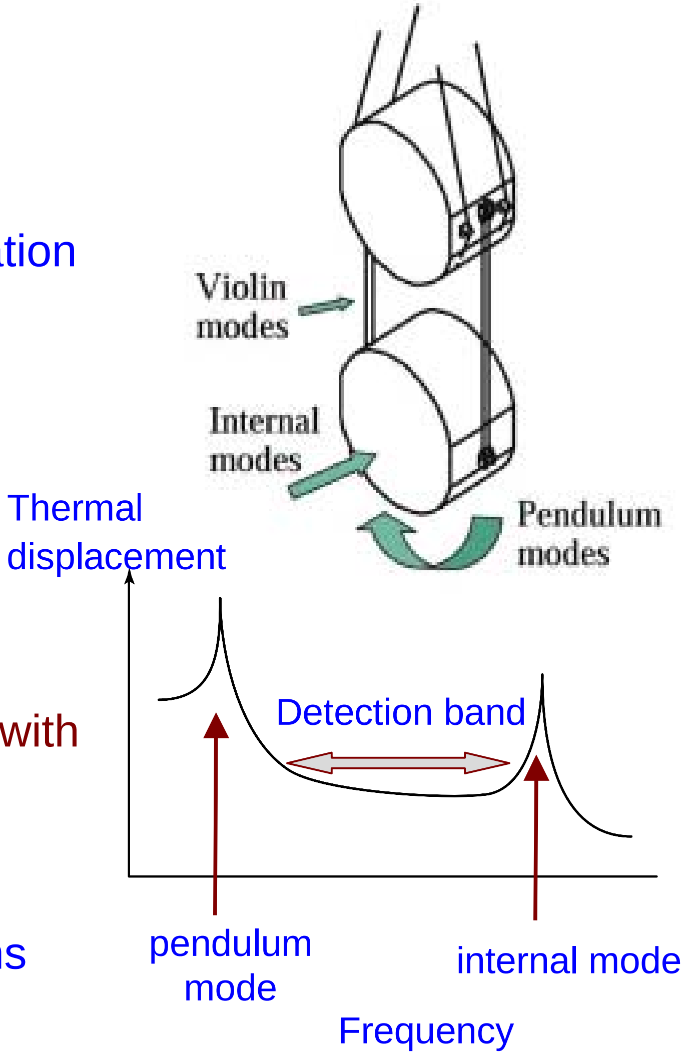
- Once seismic noise is reduced to suitable levels - Brownian (thermal) motion of test masses and suspensions becomes a fundamental noise source
- Thermal noise is directly linked to mechanical dissipation according to the fluctuation-dissipation theorem

$$\left|X^{2}(f)\right| = \frac{4k_{B}T}{\pi f}U\phi(f)$$

Where U is the energy stored in the system

  - » Want $\phi(f)$, the mechanical loss factor associated with test masses and suspensions to be very low

- Mechanical dissipation depends both on intrinsic behaviour of materials chosen for mirrors/suspensions and how they are constructed

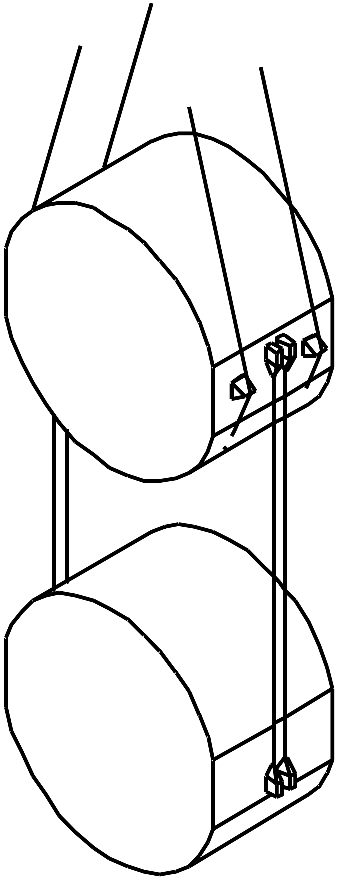


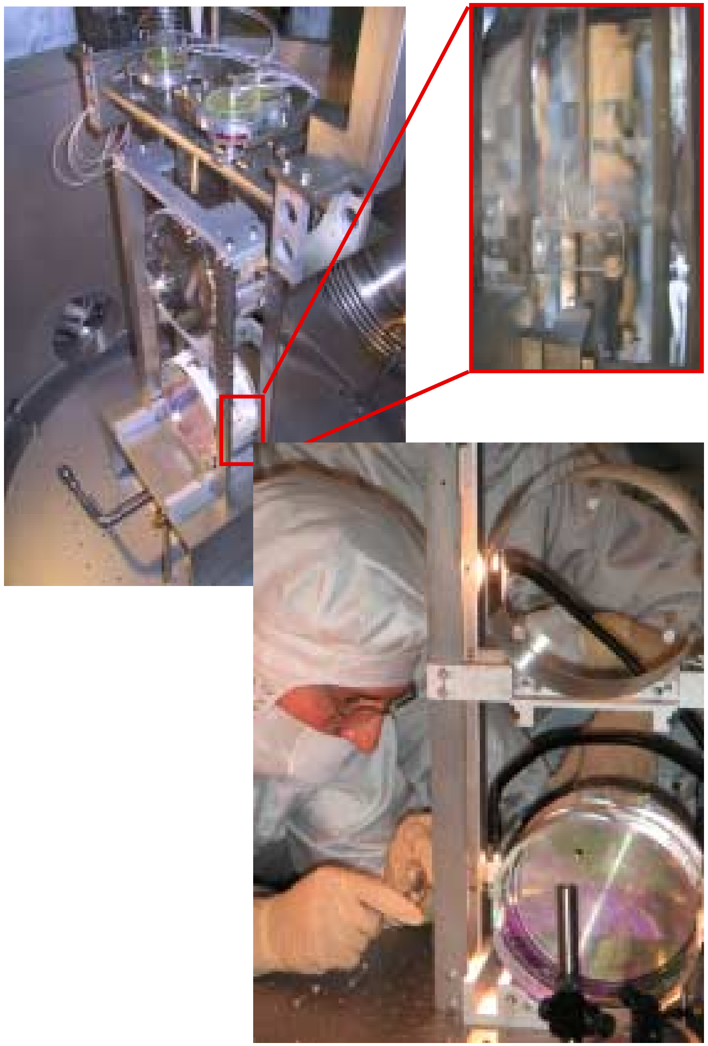
Sensitivity improvements: thermal noise

- 600m long German-UK GEO interferometer currently using triple-suspension systems with quasi-monolithic final stages for all main optics (installed Dec 02)

- Fused silica test masses bonded to silica suspension fibers

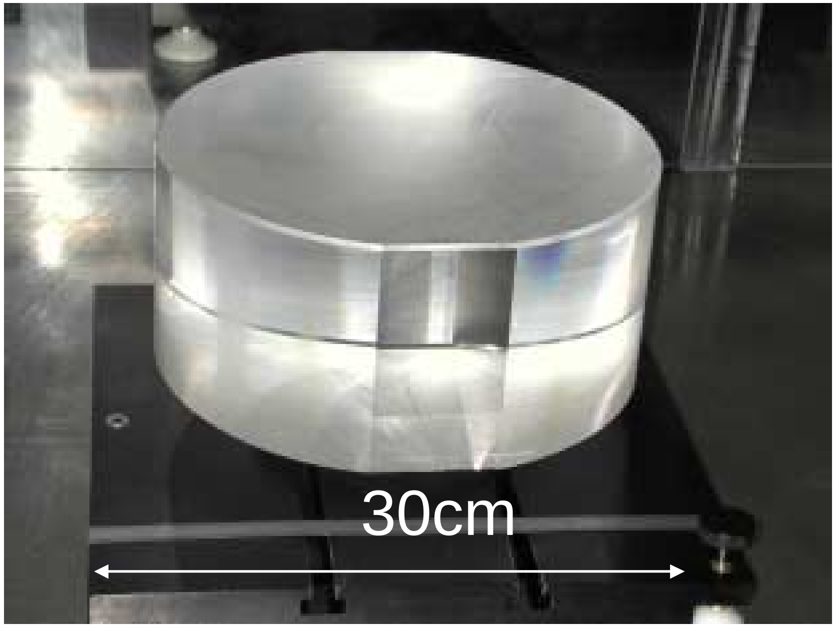
- Ultra-low mechanical loss suspensions at the heart of the interferometer





Sensitivity improvements: thermal noise

- Advanced LIGO will benefit from developments in monolithic suspension designs
- Baseline for test masses:
  - Single crystals of sapphire, 40 kg, 32 cm diameter
  - To be suspended on 4 fused silica fibers
  - Should allow improved thermal noise performance over LIGO design of silica optics on metal wires
- GEO forms a testbed for Advanced LIGO for combination of multiple pendulum suspension design and monolithic suspension technology



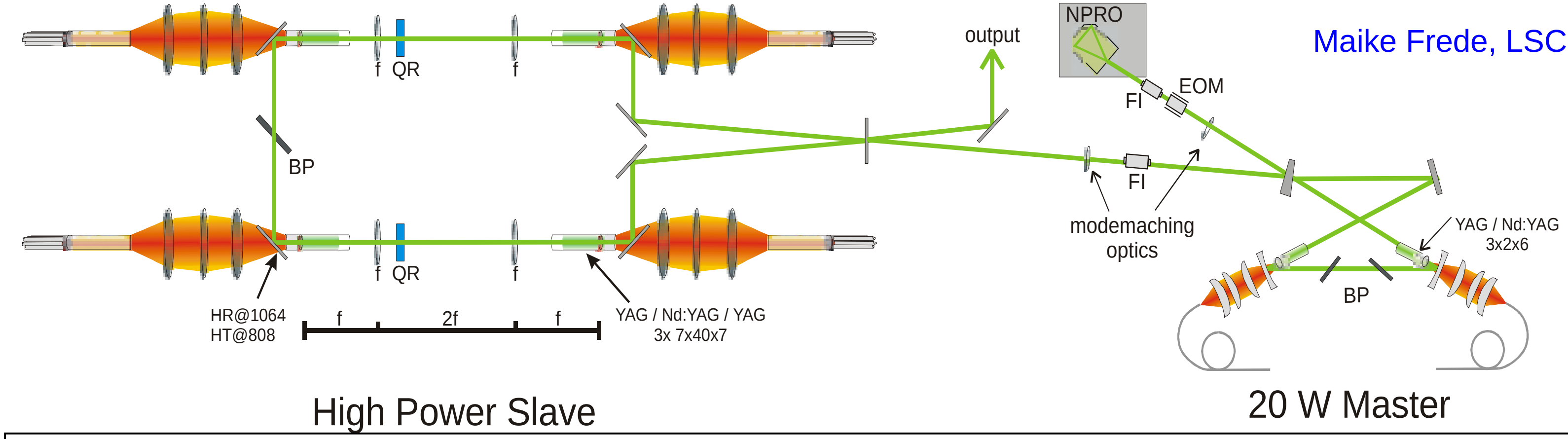
Single crystal sapphire test optic

- Proposal to PPARC in UK approved (24th March) for ~$12 million to supply quad suspension for Advanced LIGO
- GEO (UK) will become an international partner for Advanced LIGO

Sensitivity improvements: laser developments

- At high frequencies shot noise - counting statistics of photons - sets limit to sensitivity
  - » Improves with $\sqrt{P_{\text{laser}}}$
- LIGO laser = 10W ⇒ Advanced LIGO = 180W
- LSC collaboration to develop laser source led by GEO (Germany) group - LIGO lab sets requirements, interfaces
- Design: injection locked YAG with 20 W Master Oscillator

  ⇒ 85W demonstrated, design in place for > 200 W laser



Maike Frede, LSC talk, March 03

- Proposal to BMBF to be submitted by GEO (Germany) this year for capital contribution to Adv. LIGO (same level as UK contribution) - used to provide the pre-stabilized lasers
- Would allow GEO (Germany) to become an international partner for Advanced LIGO

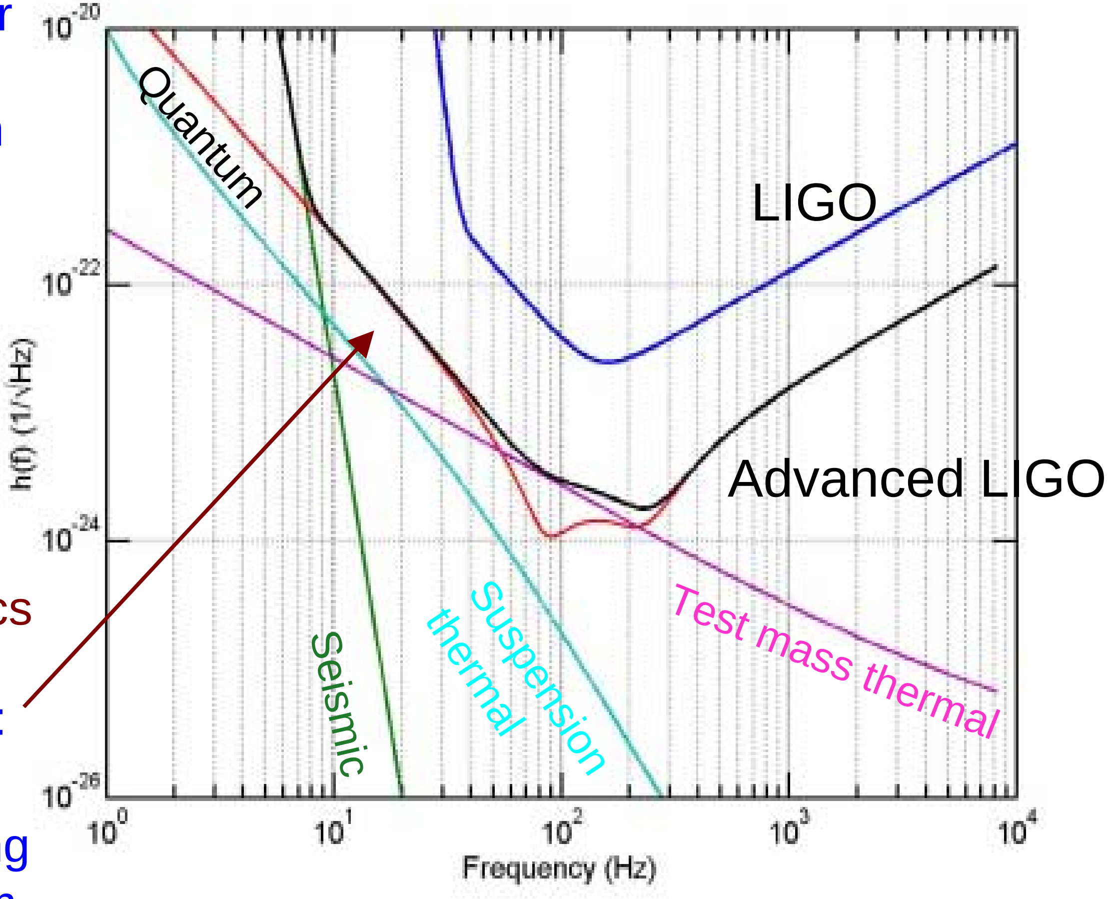
Sensitivity improvements: high power optics

- The high laser powers needed for good shot noise limited performance set requirements on mirror substrates and coatings

- 180W from laser at input to interferometer means that inside the cavities in interferometer arms:
  - » almost 1 MegaWatt of CW power incident on cavity optics

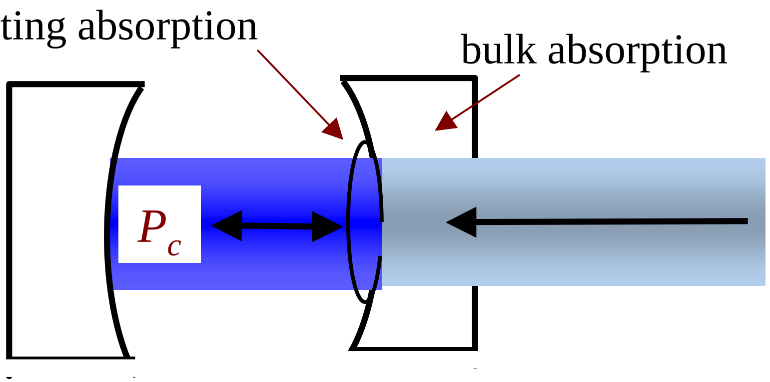
- Consequence at low frequencies: radiation pressure
  - » Form of quantum noise arising from momentum transfer from photons to mirrors

- Require sapphire mirror substrates to be ~ 40kg



Sensitivity improvements: high power optics

- Other consequence of high laser powers: thermal deformation of substrates
- Sets tolerable substrate and coating absorption
- R&D programme to develop:
    - » optical mirror coatings of sub-ppm absorption
    - » large sapphire substrates of low optical absorption: 20ppm/cm



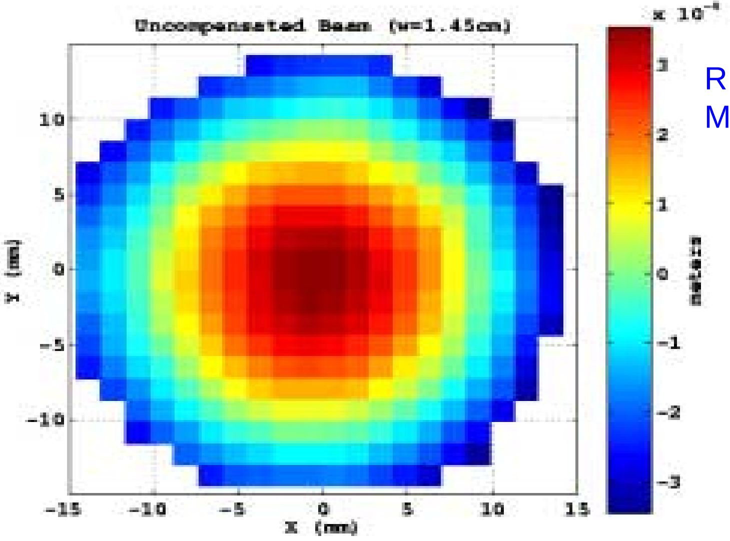
Material At 300K	Lensing Figure of merit (dn/dt)/K (nm/W)	Expansion Figure of merit (α/K) (nm/W)	Absorption (ppm/cm)	Power limit inside cavity (kW)
Transmissive				
Sapphire	250	125	20	**630**
Fused silica	7250	362	1	**196**

Following Winkler (1990):

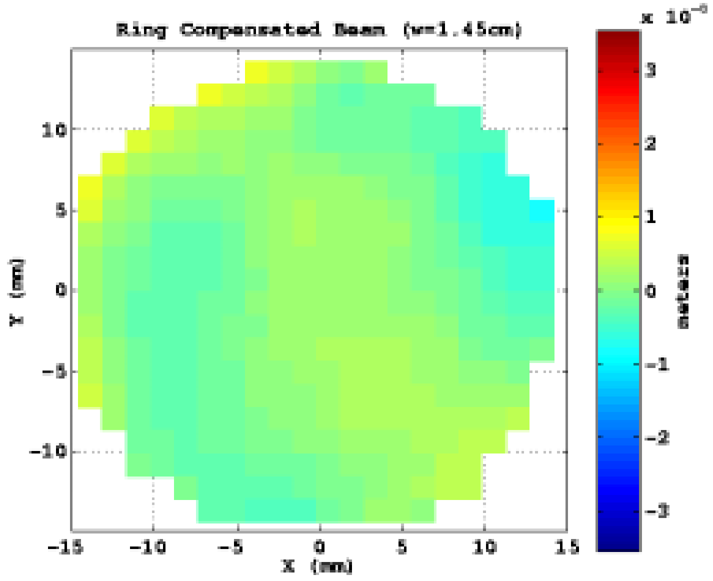
Shown is the power level inside an optical cavity of finesse 100, that produces thermal distortions equal to the sagitta of confocally spaced mirrors separated by 4 km. A coating absorption of 1ppm is assumed.

Sensitivity improvements: high power optics

- To deal with thermal effects, technology has been developed to allow active control of lensing and figure of optics in situ
- Adaptive thermal compensation schemes can correct for axisymmetric thermal distortions
- Suspended heating element used to radiatively heat optic
- Figures show measured wavefront distortion of a probe laser beam without and with thermal compensation
- Technology successfully adopted by GEO to correct for mismatches in radius of curvature of mirrors in interferometer arms



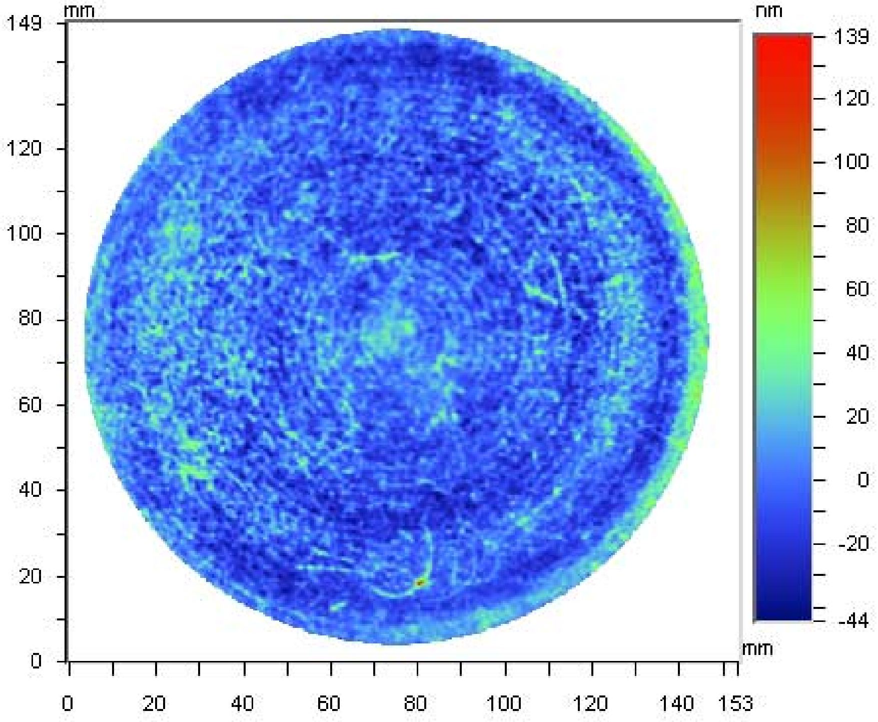
R. Lawrence
MIT



Sensitivity improvements: high power optics

- Sapphire: birefringent crystal
- Bulk material can have small variations in refractive index due to small variations in crystal axis
- Correct for index homogeneity by a compensating polish applied to side 2 of sapphire substrate to reduce the rms variation in bulk homogeneity to roughly 10-20 nm rms
- Plot shows a measurement of a 25 cm m-axis sapphire substrate, showing the central 150mm after compensation

- Metrology led by LIGO lab, high power tests of optics by LSC collaborators

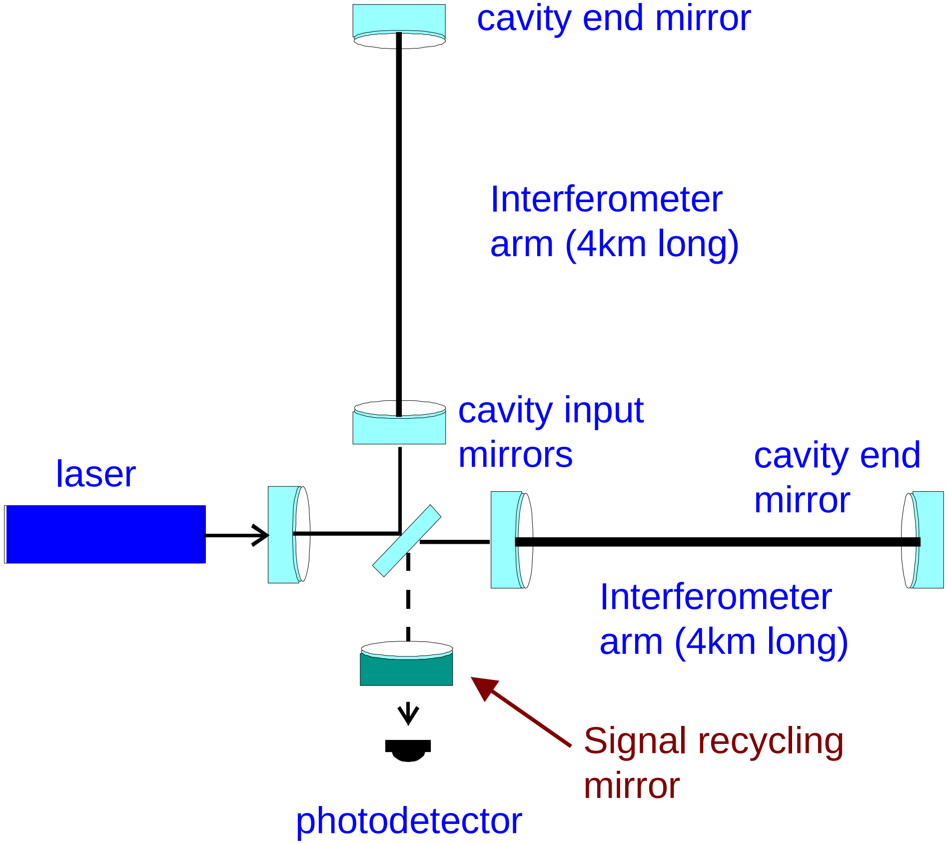


Date: 04/16/2002
Time: 14:37:03
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 183.6397 nm
RMS: 14.6141 nm

X Center: 282.00
Y Center: 243.00
Radius: 269.89 pix
Terms: Tilt
Filters: None
Masks: Detector Mask

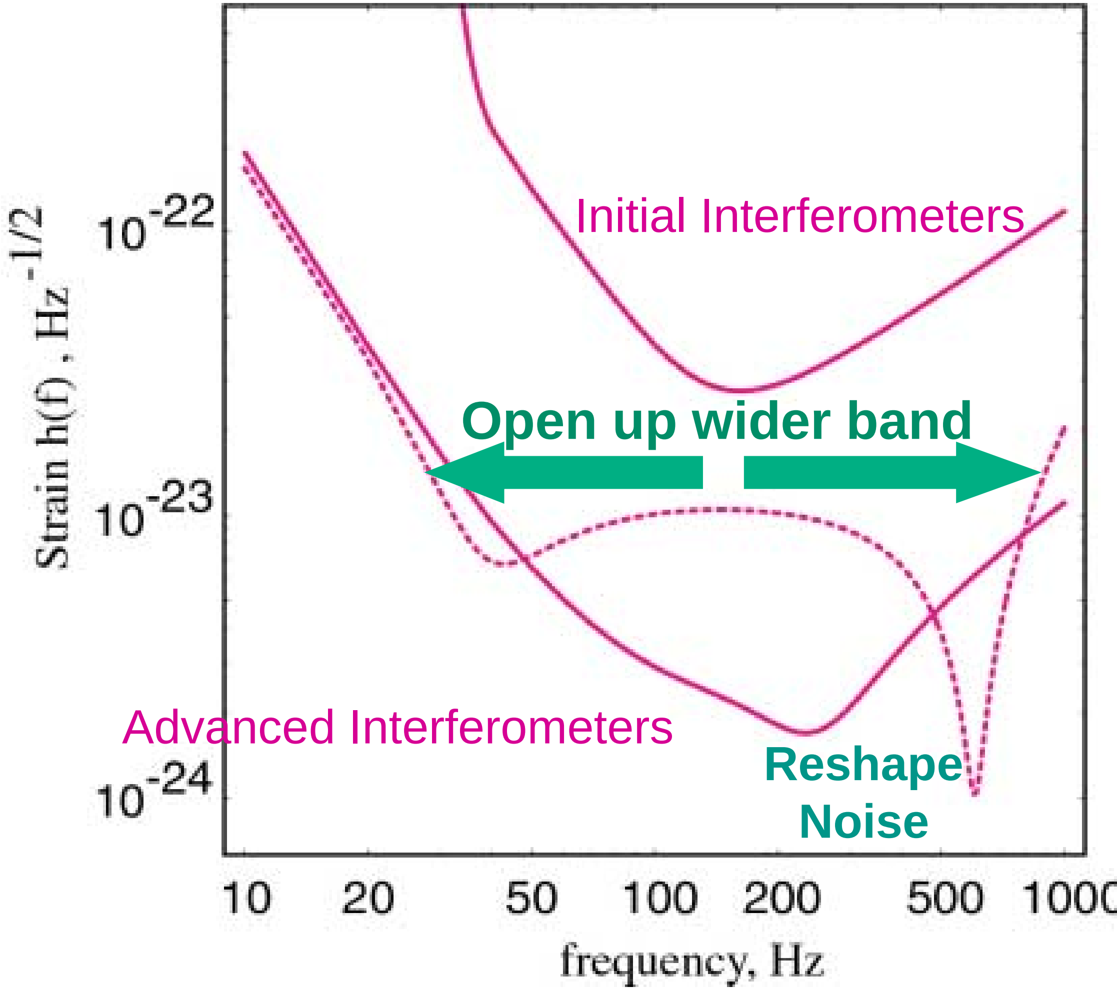
Sensitivity improvements: signal recycling

- Signal recycling enhances the sensitivity of the interferometer by shaping the response
- The interferometer is operated with the output port held at an interference minimum
  - » The only light at the output is (ideally) that containing information about differential length changes of the arms (the gravitational wave signal)
  - » The SR mirror reflects most of this light back into the interferometer
  - » The interferometer behaves like optical cavity – in which the gw signal amplitude builds up
  - » Resonant enhancement of the signal occurs at a Fourier frequency and over a bandwidth determined by the position and transmittance of the SR mirror



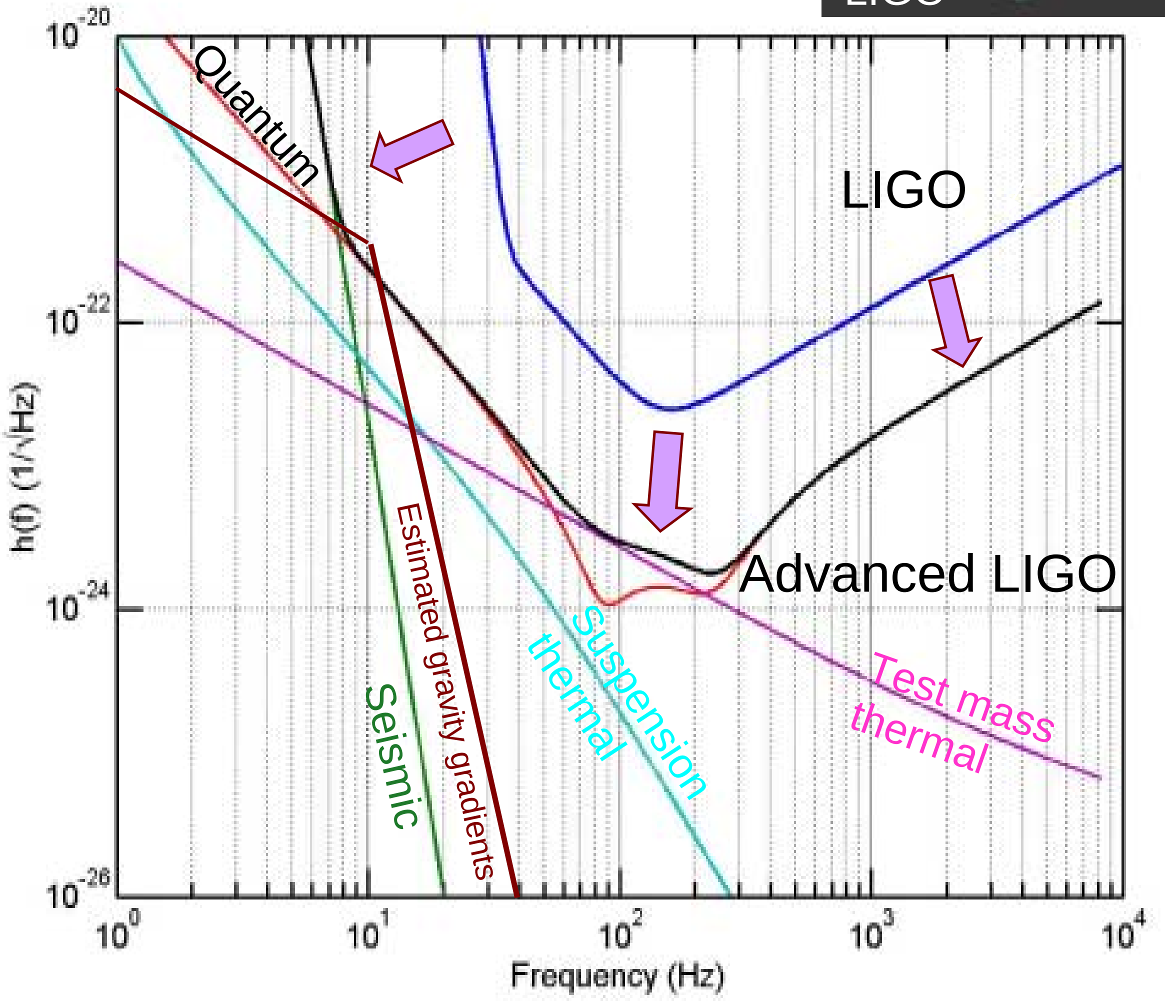
Sensitivity improvements: signal recycling

- **In narrowband mode, signal recycling allows targeting of the interferometer’s sensitivity in a narrow frequency range tuned to the anticipated frequency range of the signal**
- **Trade bandwith for sensitivity - ‘dig down’ into the shot noise to look for sources**
- **Technique invented in Glasgow, installed in GEO interferometer and being developed for Advanced LIGO through joint GEO/LIGO lab/LSC collaboration**



Advanced LIGO sensitivity goals

- Advanced LIGO
  - » Seismic noise reduced by x40 at 10Hz
  - » Thermal noise reduced by x15
  - » Optical noise reduced by x10
- Design reaches limits set by quantum noise, (and noise from Newtonian gravity gradients)
- Sensible ‘break point’ in what is achievable with current technologies on appropriate timescale



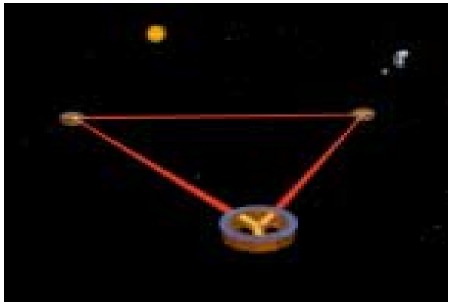
The Advanced LIGO Collaboration

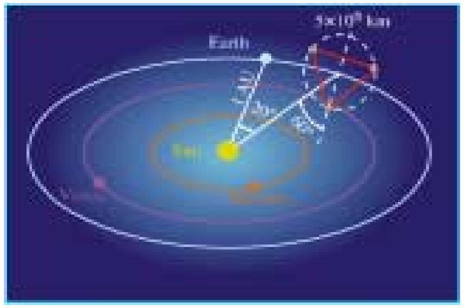
- Development throughout the LIGO Scientific Collaboration (LSC)
  - International support and significant material participation
  - Particularly strong collaboration with German-UK GEO group, capital partnership

- Advanced LIGO design, R&D, and fabrication spread among the LSC
  - LIGO Laboratory leads, coordinates, takes responsibility for Observatories
- Continuing strong support from the NSF at all levels – theory, R&D, operation of the Laboratory

- Forms part of the international network of current and planned detectors:
  - VIRGO (Italy-France), GEO-600 (Germany-UK), TAMA (Japan), ACIGA (Australia)

- Complementary to planned space-based experiment LISA - targeted at sources <<10Hz





Timeline

- Initial LIGO Observation 2002 – 2006
  - 1+ year observation within LIGO Observatory
  - Significant observation in coincidence with international detector network, GEO, LIGO, TAMA
- Targeted R&D program to develop technologies 1998 - 2005
  - Baseline design developed by LSC in 1998
  - R&D continues to refine Final Design, 2005
- Advanced LIGO proposal status
  - PPARC (UK) proposal for capital contribution submitted June 2002, approved March 2003
  - NSF construction proposal submitted Feb 2003 for fabrication, installation. Currently under review
  - ARC (Australia) proposal for capital contribution to be submitted in May 2003
  - BMBF (Germany) proposal for capital contribution to be submitted later in 2003
- Start installation in 2007
  - Baseline is a staged installation, Livingston and then Hanford Observatories
- **Start coincident observations in 2009**

Summary

- LIGO detectors are in operation
  - First science run completed, second run currently underway
  - First publications are in preparation
  - Discoveries plausible

- Evolution to Advanced LIGO
  - Develop advanced detectors that approach and exploit the facility limits on interferometer performance
  - R&D and prototyping well underway
  - Challenging astrophysics promised