Low noise cavities in interferometric gravitational wave detectors

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CES Boulder
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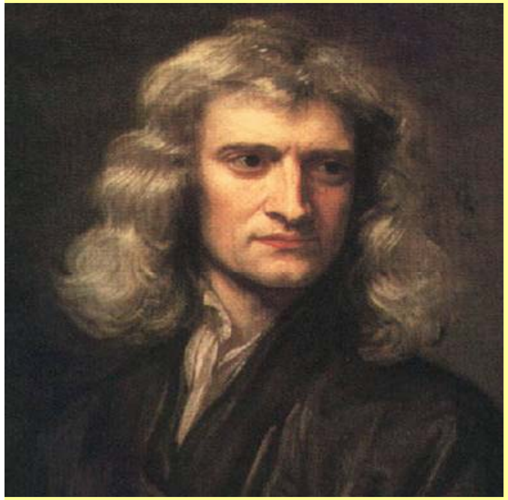
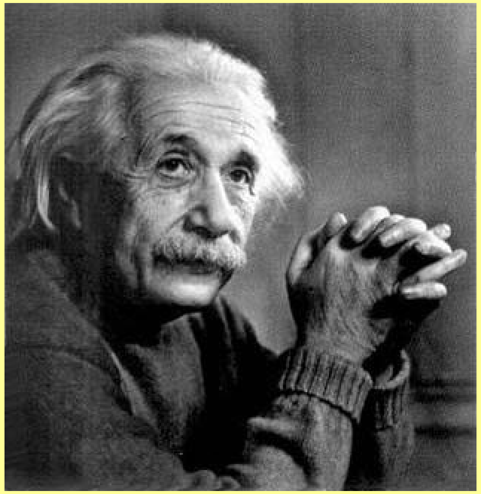
Gravitation





The Einstein field equations of GR have wave solutions

- Emitted by a rapidly changing configuration of mass
- Travel away from the source at the speed of light
- Change the effective distance between inertial points —

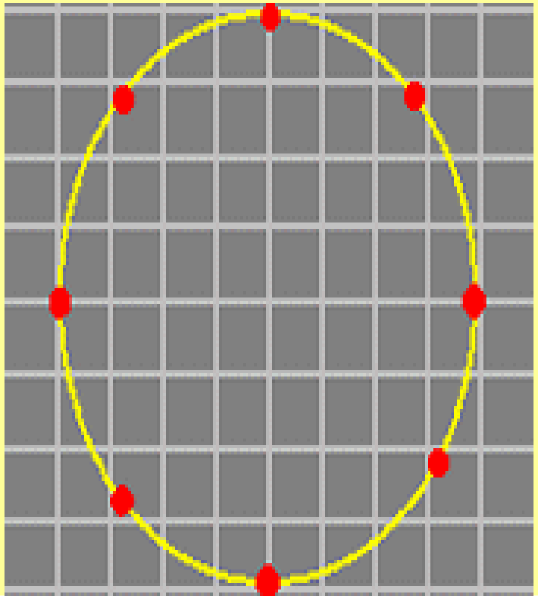
  i.e. the spacetime metric — transverse to the direction of travel

Newton's Theory

"instantaneous action at a distance"

Einstein's Theory

information cannot be carried faster than speed of light – there must be gravitational radiation

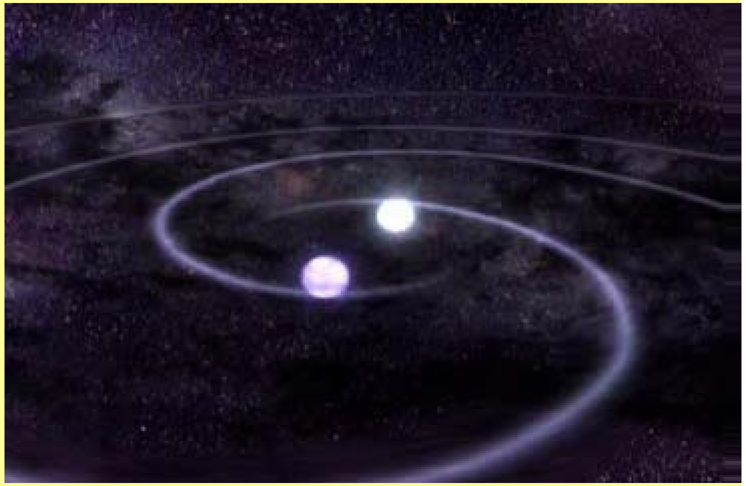


Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* the space

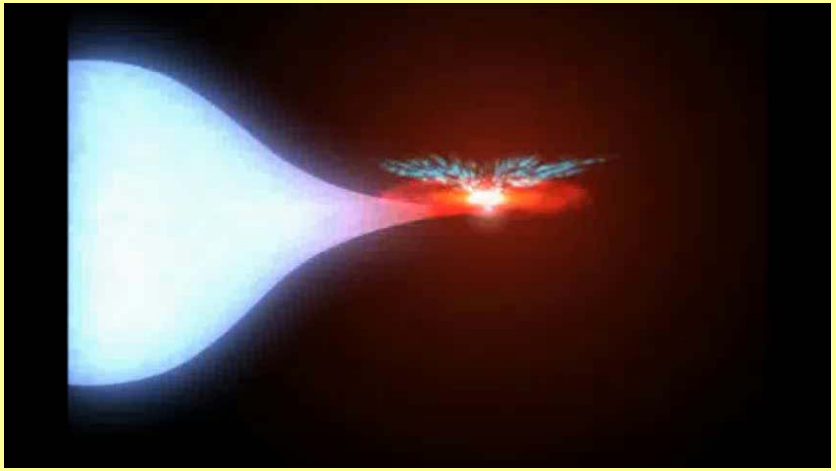
Gravitational wave sources in ground-based detectors

Supernovae and black hole formation

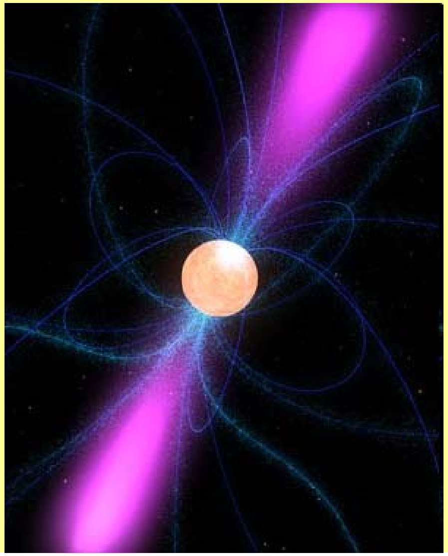
Binaries of black holes and neutron stars



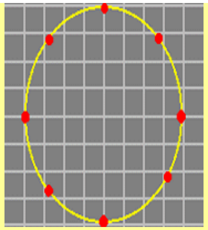
Pulsars; modes and instabilities of neutron stars



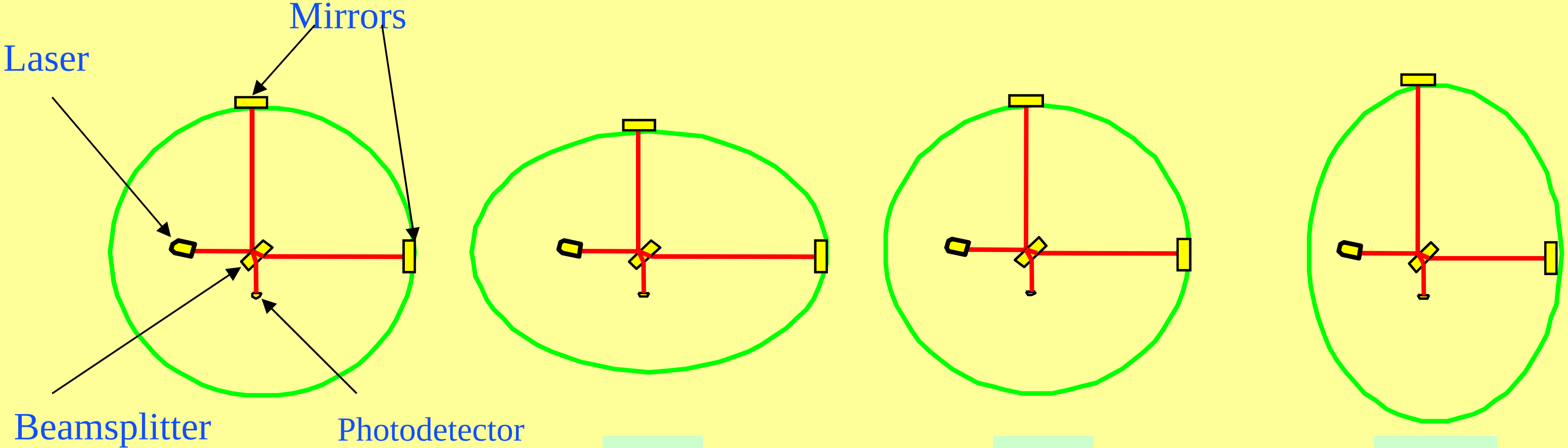
Spinning neutron stars in X-ray binaries



- GWs trace the bulk motion of their source
- Non-imaging
- Very weakly scattered / absorbed.
- Complementary to properties of photons



Operation of Interferometric Gravitational Wave Detectors

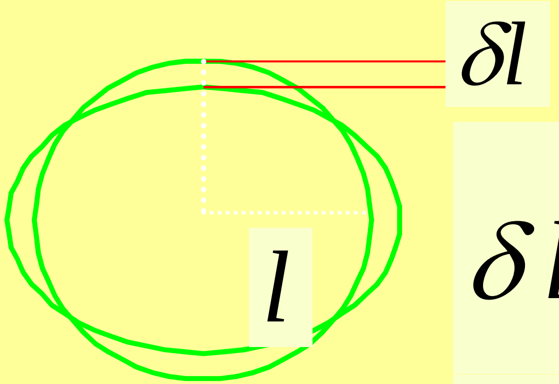


$t = 0$

$t = \frac{\tau}{4}$

$t = \frac{\tau}{2}$

$t = \frac{3\tau}{4}$



$$\delta l = \frac{h}{2} l$$

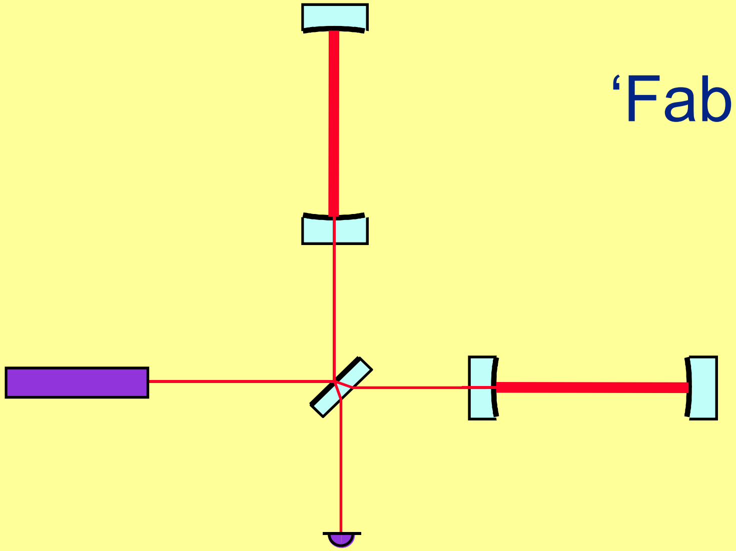
Gravitational wave amplitude

For Typical Astronomical sources

$$h = \frac{2\,\delta\, l}{l} \leq 10^{-22}$$

Laser Interferometer

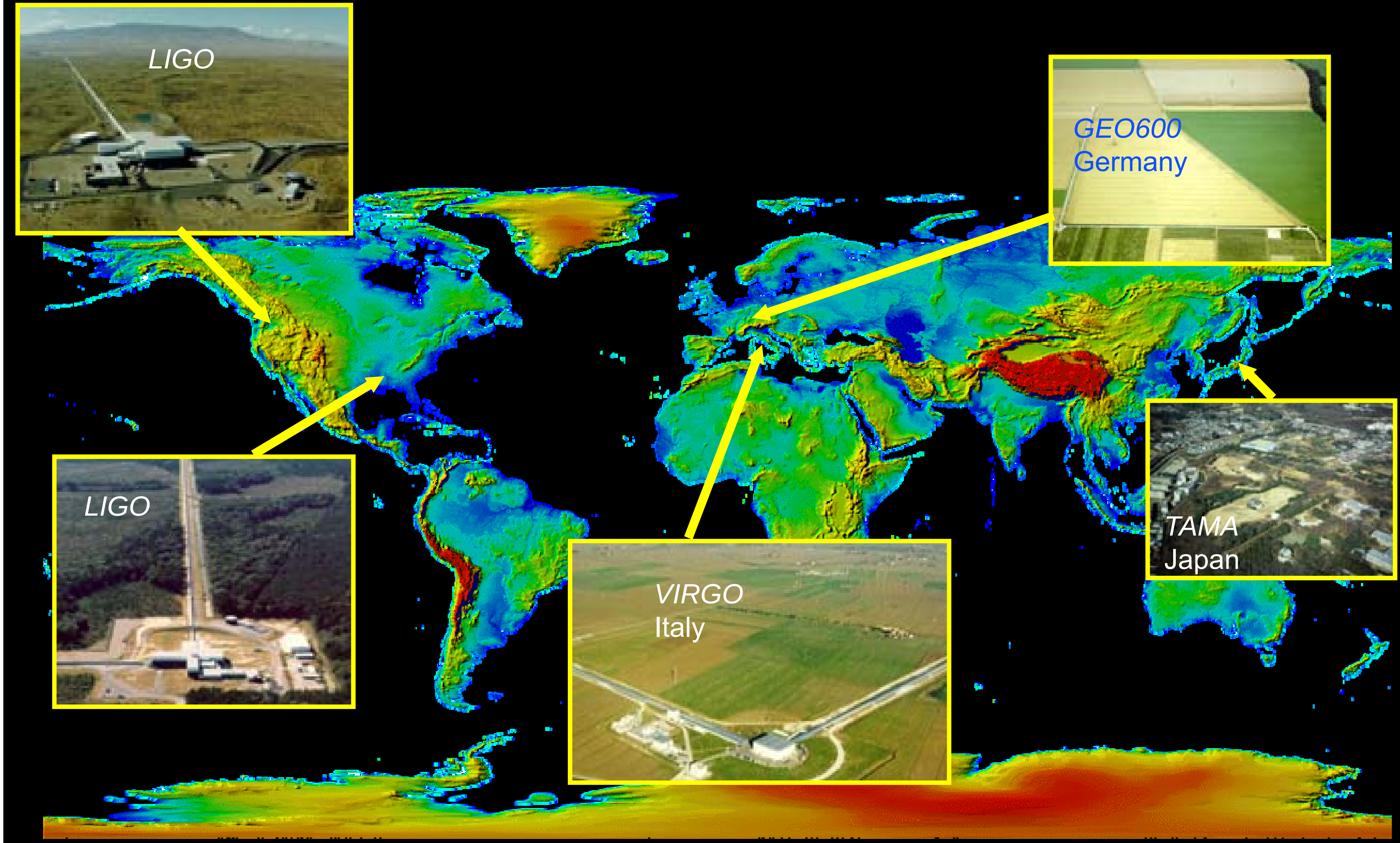
- For best performance want arm length ~ λ/4
  - i.e. for 1kHz signals, length = 75 km
- Such lengths not really possible on earth, but optical path can be folded – reduce arm lengths to ~few km



‘Fabry-Perot Michelson’

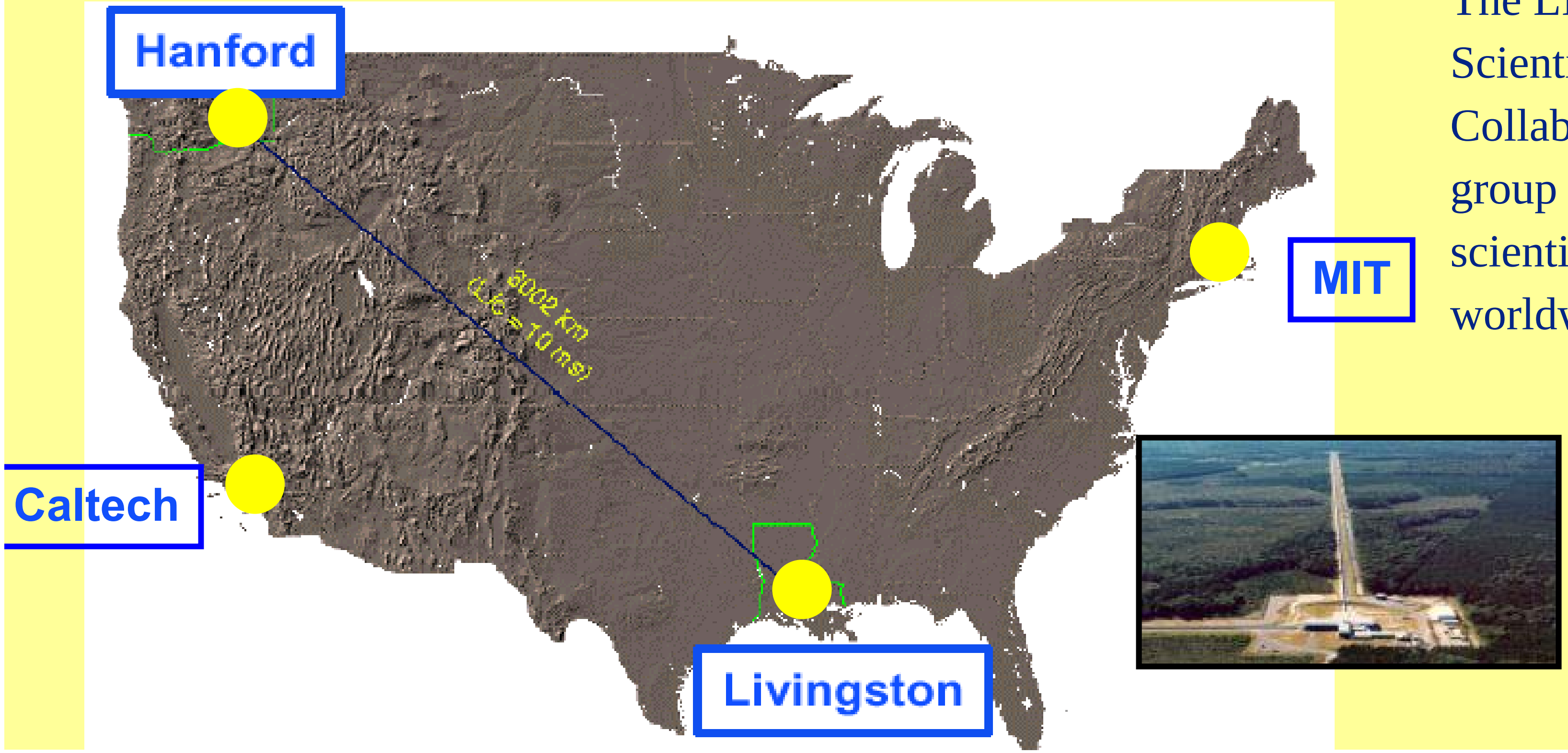
- Much longer arm lengths are possible in space

The Global Network
of (initial) Interferometric Gravitational Wave Detectors



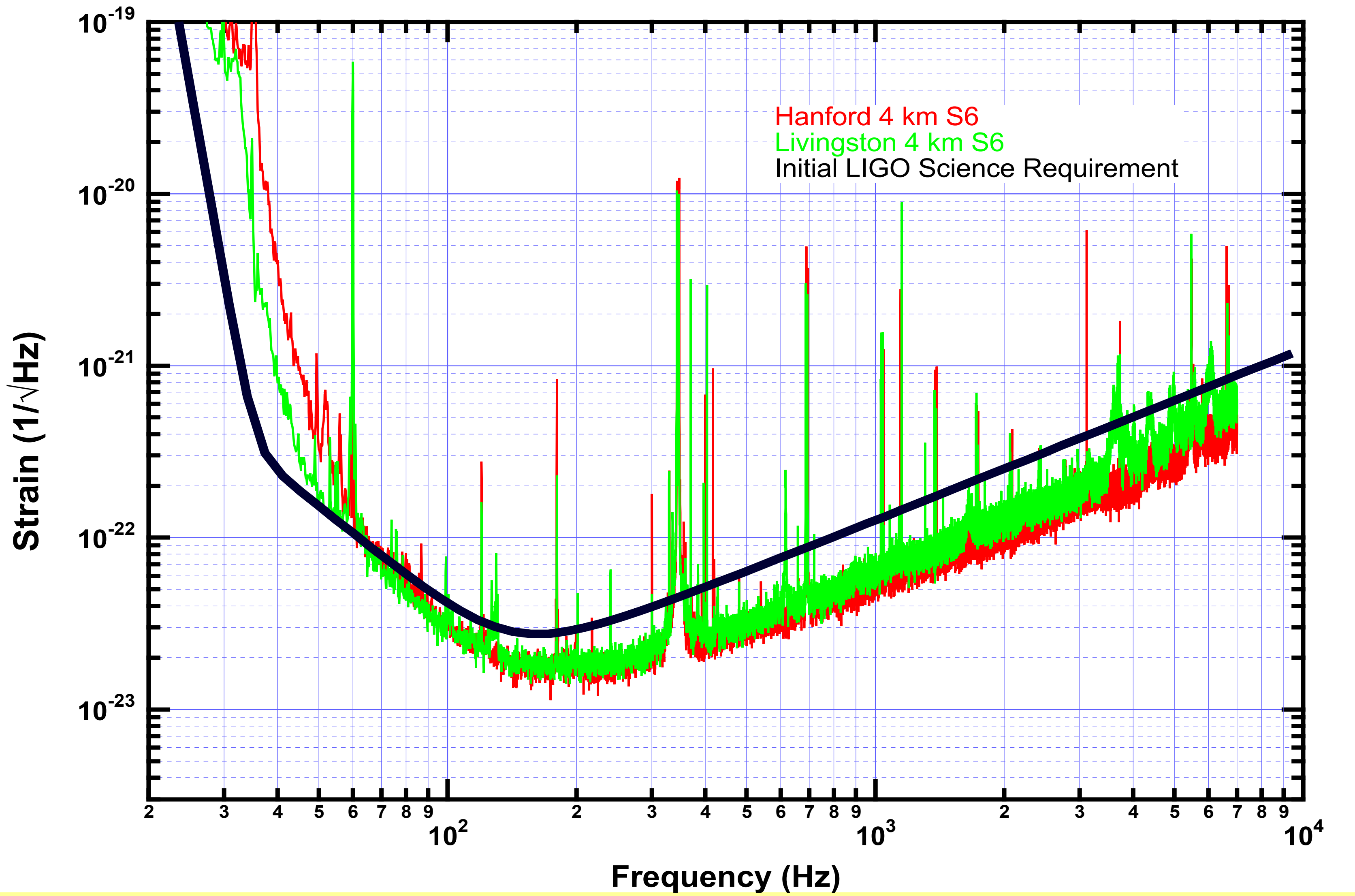
LIGO Laboratory: two Observatories and Caltech, MIT campuses

- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



The LIGO Scientific Collaboration: a group of 900+ scientists worldwide

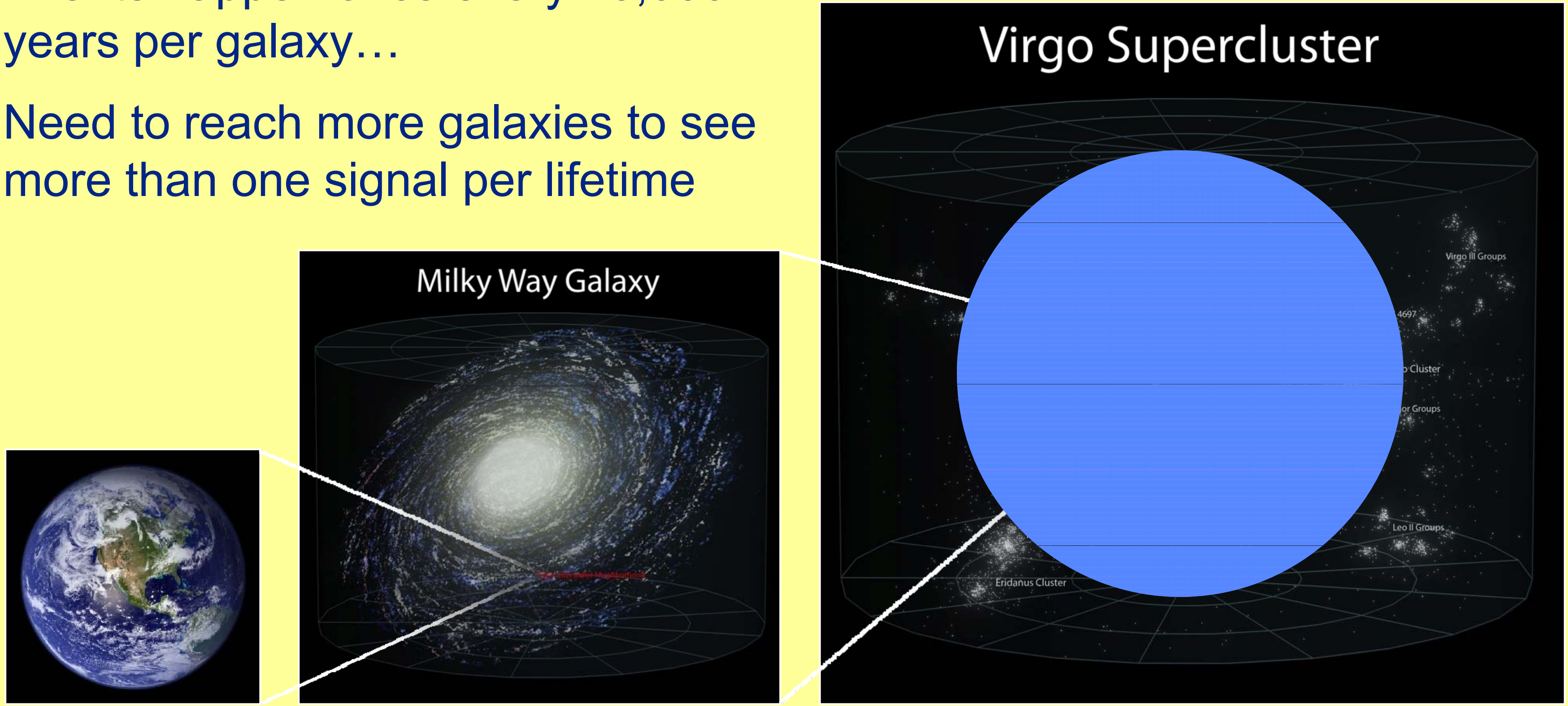
LIGO Detectors 2009-10 (S6)



No Detections Yet…
Why not?

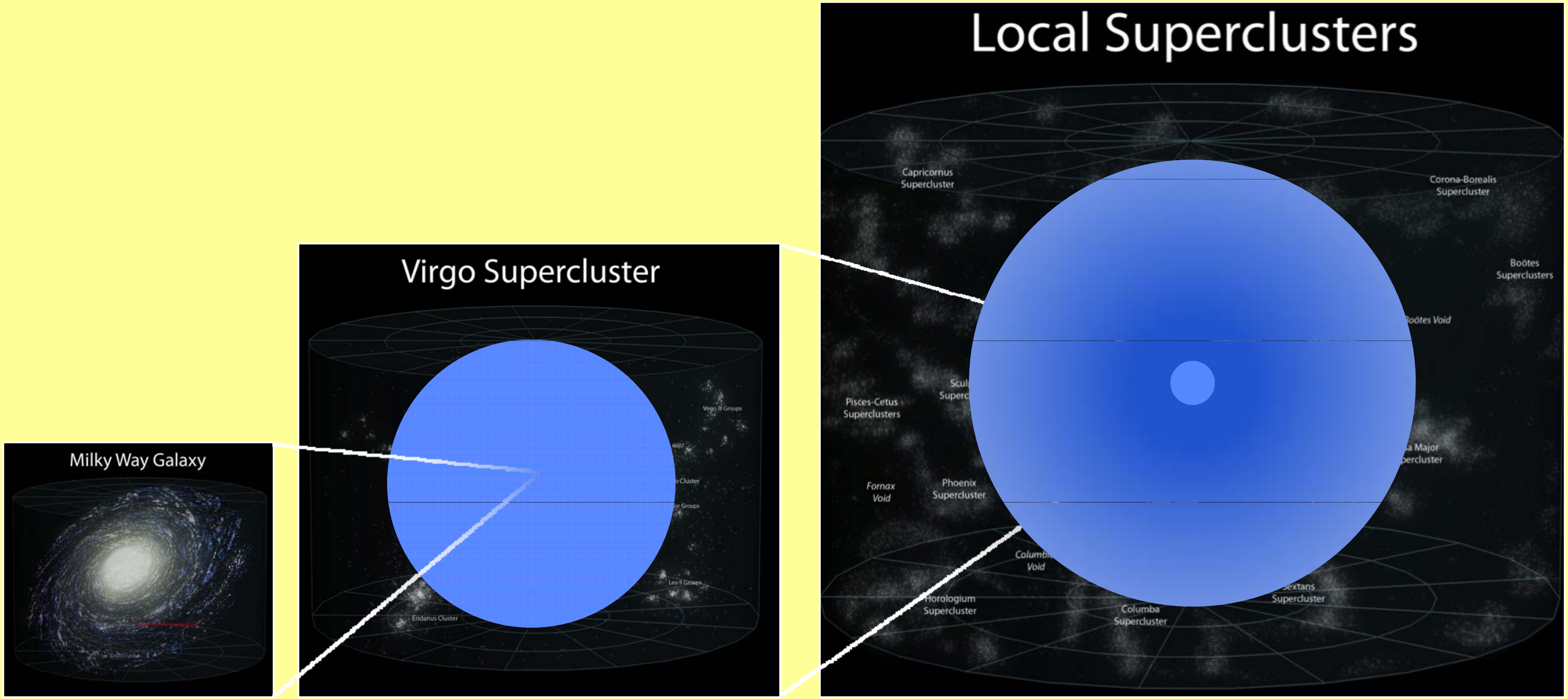
- First generation detectors reached about 100 galaxies
- Events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see more than one signal per lifetime

(considering mergers of pairs of neutron stars)



Advanced Sensitivity:
10x More Range makes a qualitative difference

- Advanced detectors will reach about 100,000 galaxies
- Events happen once every 10,000 years per galaxy…
- Order of 10’s per year



M. Evans

Initial Range

Advanced Range

Advanced GW detector era – the coming years (2015-2020)

Timescales Advanced LIGO

- Design began 1999 as a LIGO Scientific Collaboration concept paper
- (Capital contributions via hardware by UK (2003), Germany, Australia)
- **Advanced LIGO Project officially began on April 1, 2008**
- **Official inauguration May 19th 2015**

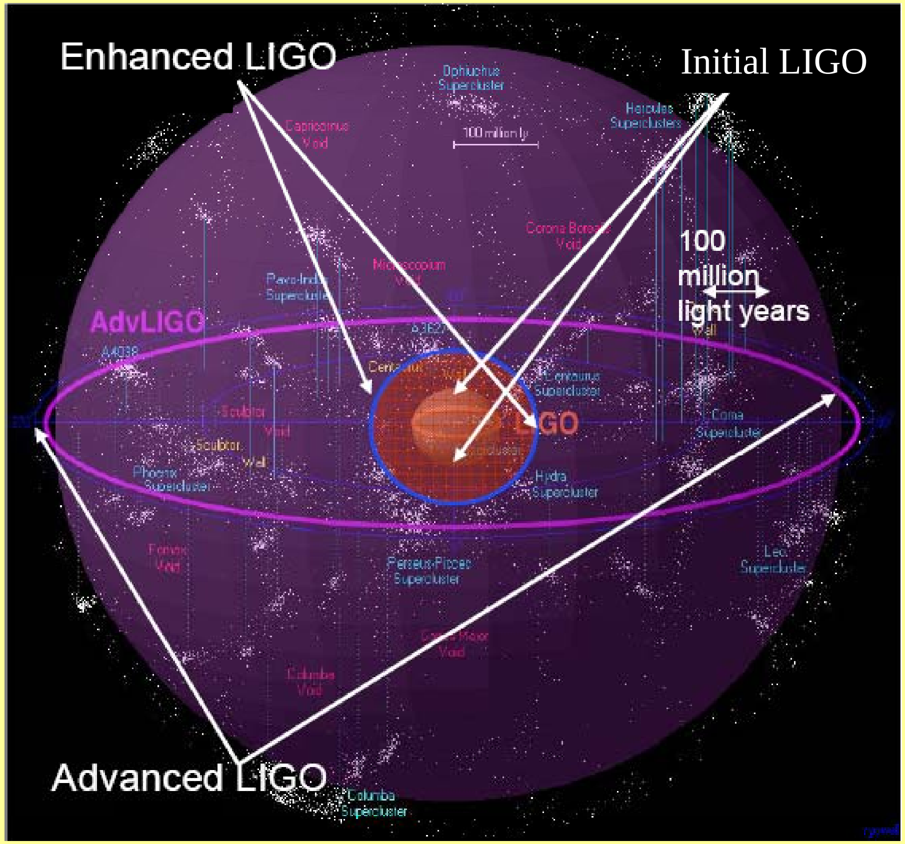
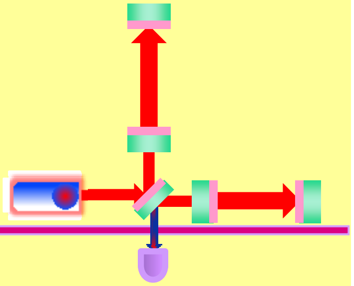
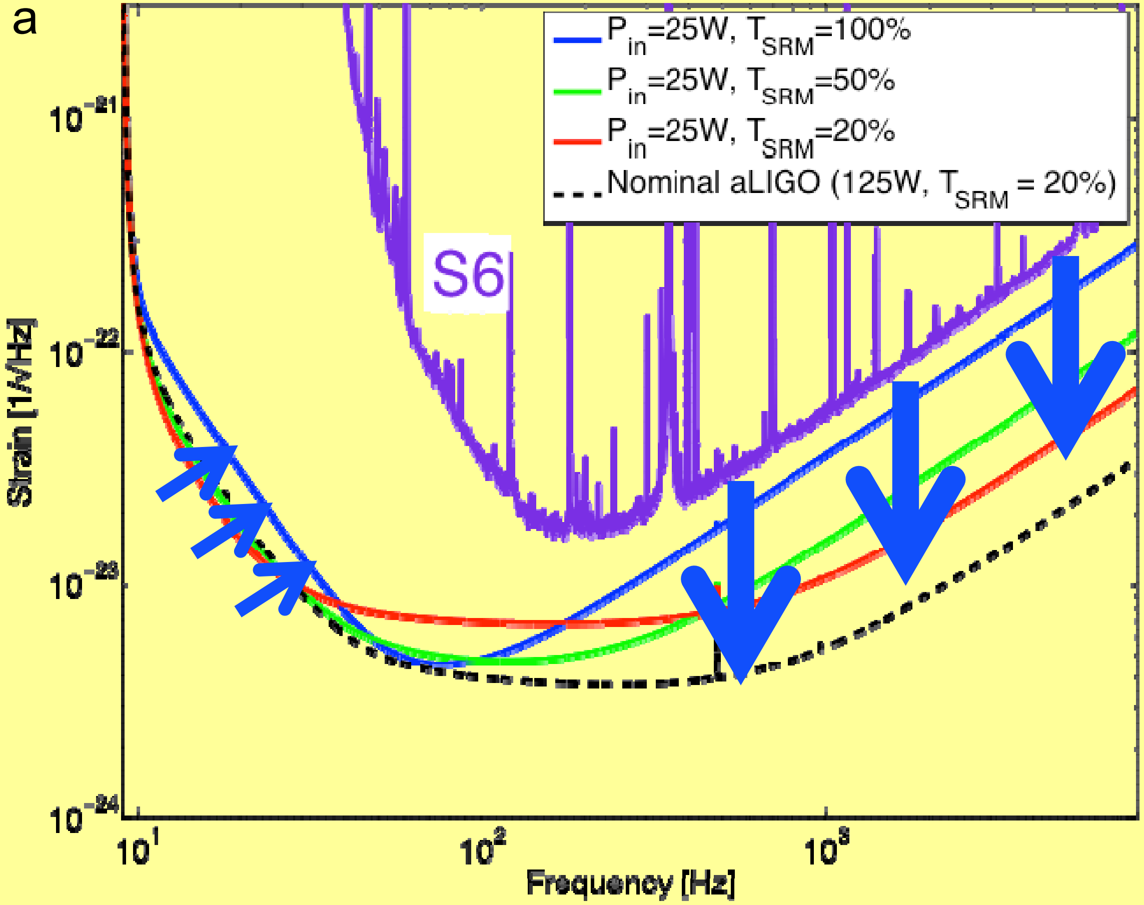


Image courtesy of Beverly Berger
Cluster map by Richard Powell

How to get there: Addressing limits to performance

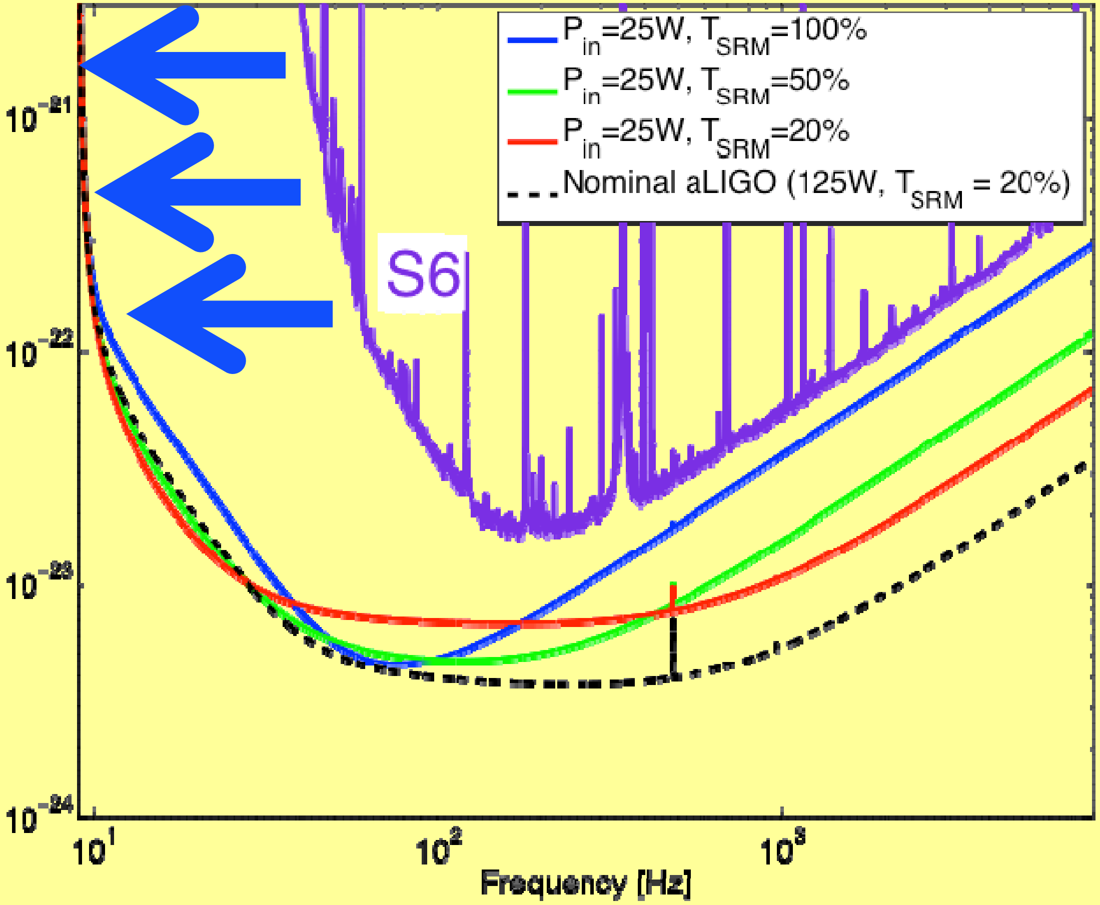


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Fringe Resolution at high frequencies improves as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses
- ‘Standard Quantum Limit’
- Advanced LIGO reaches this limit with its **200W laser, 40 kg test masses**



Addressing limits to performance

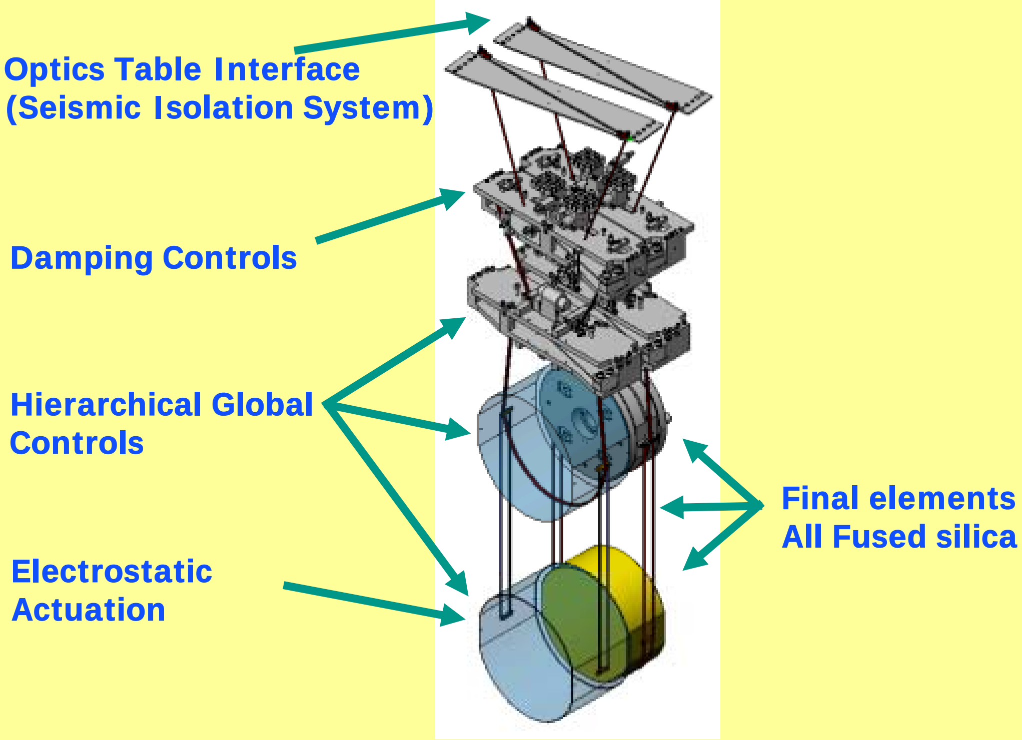
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Motion from waves on coasts…and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band



Test Mass Quadruple Pendulum suspension

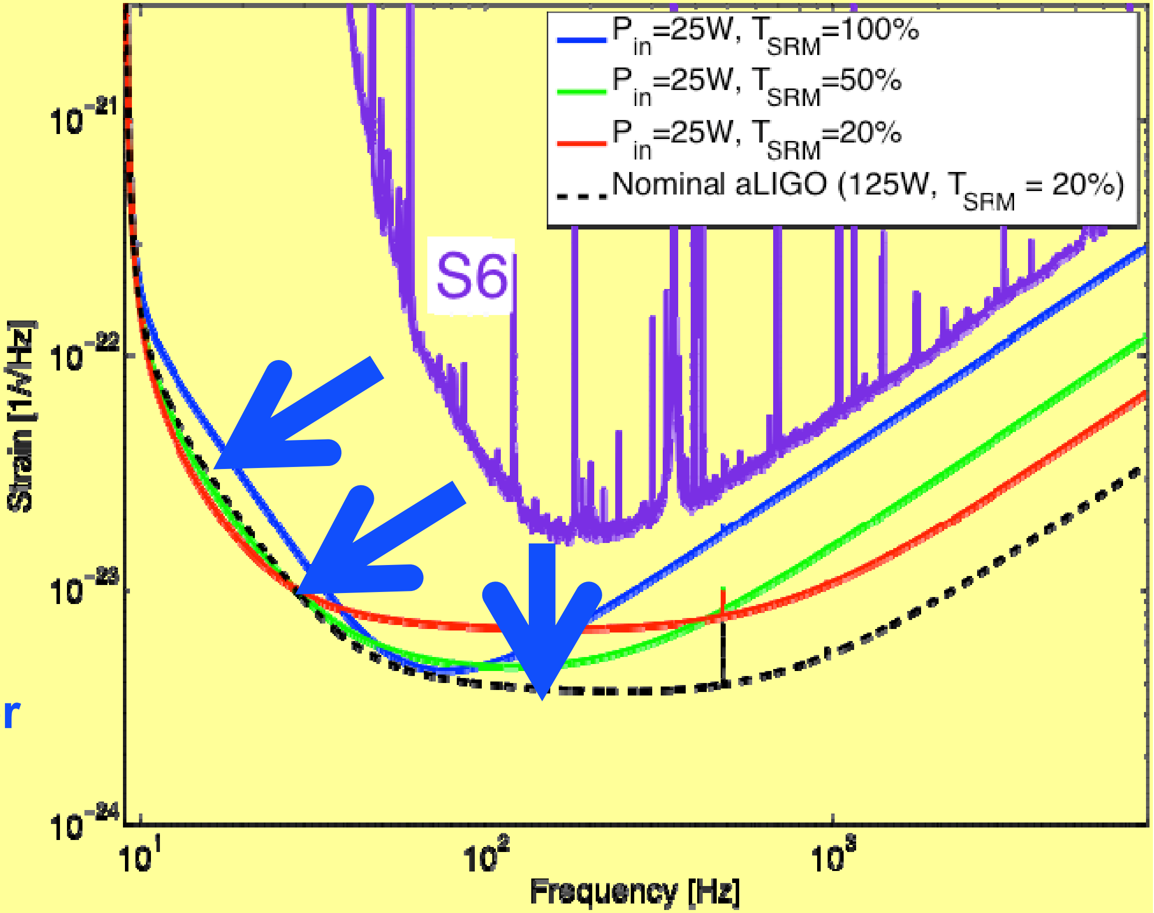
designed jointly by the UK and LIGO lab,

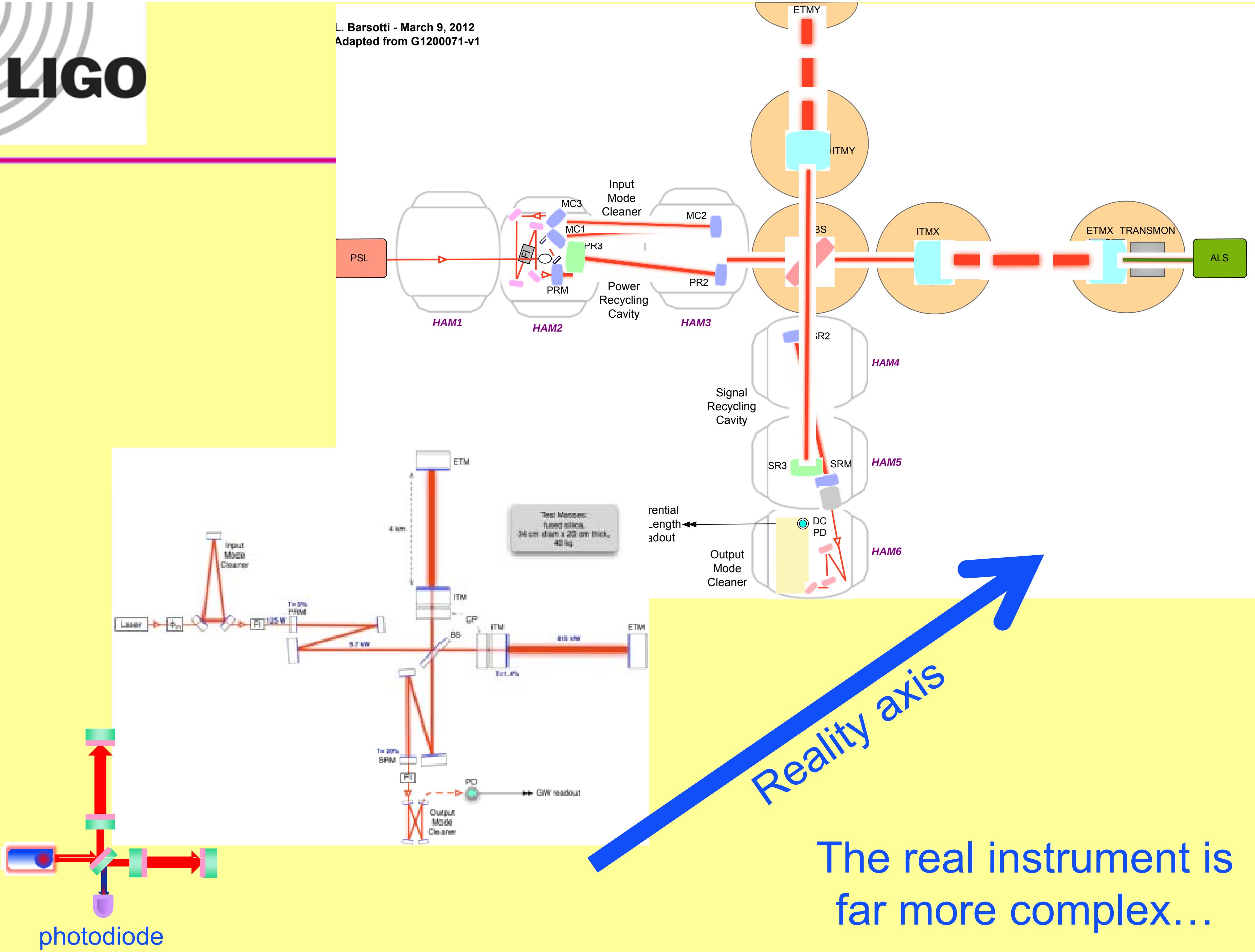
- Quadruple pendulum suspensions for the main optics; second ‘reaction’ mass to give quiet point from which to push
- Create quasi-monolithic pendulums using fused silica fibers to suspend 40 kg test mass
  - Very low thermal noise



Addressing limits to performance

- **Thermal noise** – kT of energy per mechanical mode
- Wish to keep the motion of components due to thermal energy below the level which masks GW
- Low mechanical loss materials
- Realized in aLIGO with an all **fused-silica test mass suspension**
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**



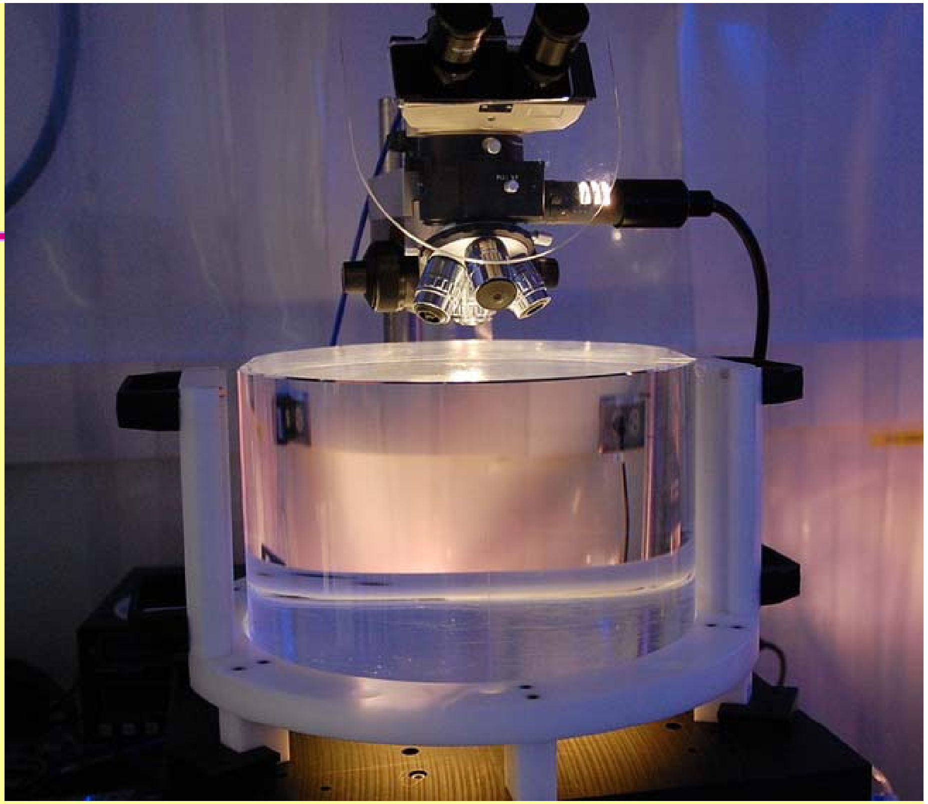


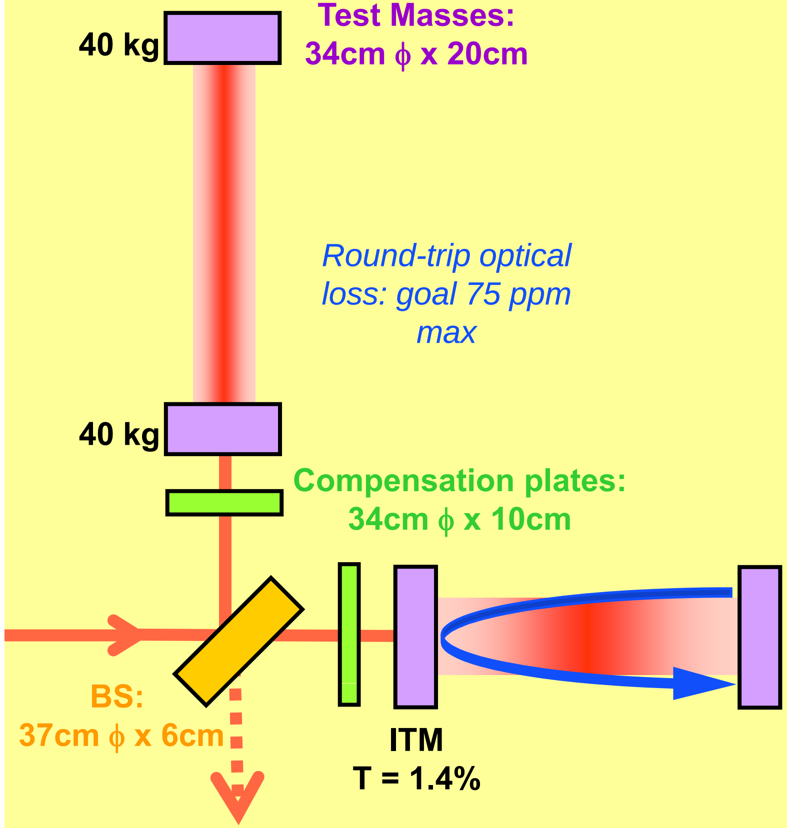
The real instrument is far more complex…

Test Masses – the Cavity Mirrors

Both the physical test mass – a free point in space-time – and a crucial optical element

Mechanical requirements: bulk and coating thermal noise, high resonant frequency

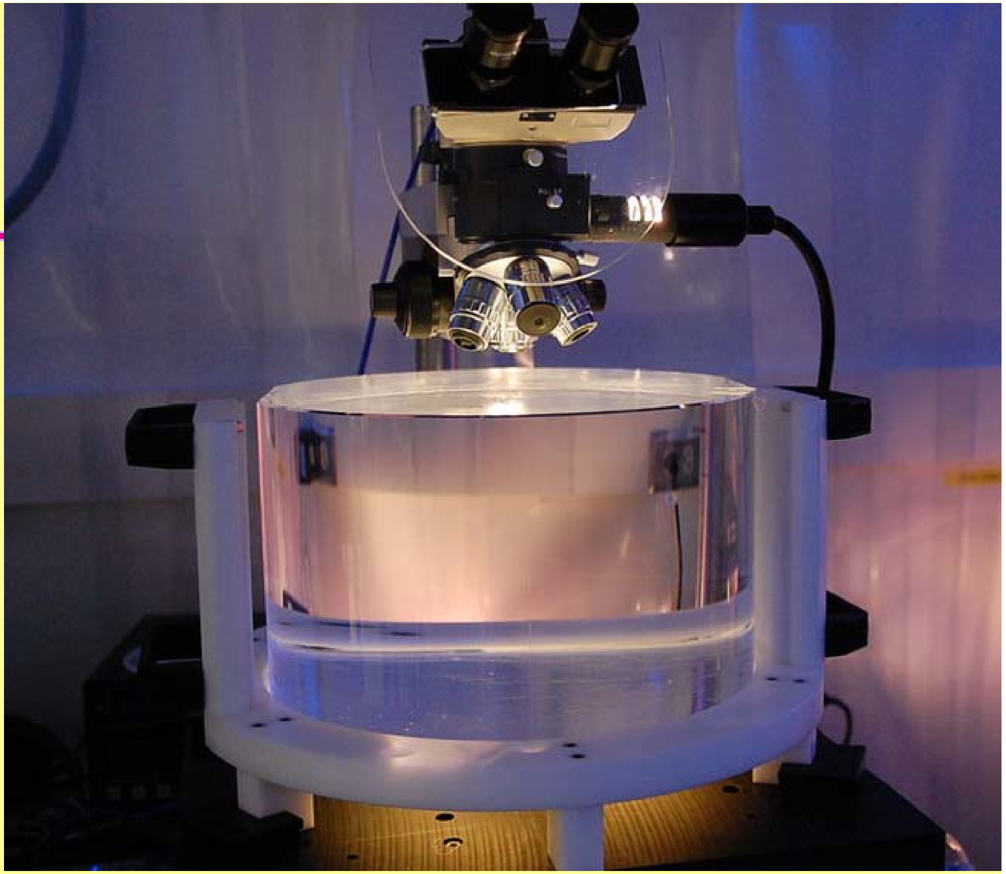


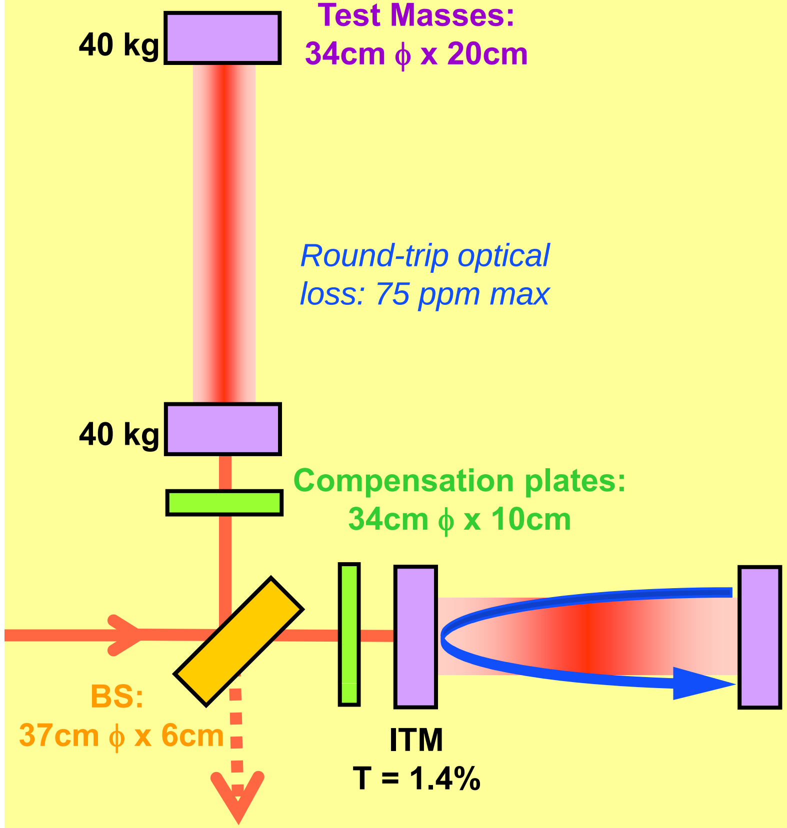


- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption
- Requires the state of the art in substrates and polishing
- Pushes the art for coating
- Sub-nm flatness over 300mm
- Radii of curvature: 2245m and 1934m (-5/+15)m
- Beam radii of 6.2 cm /5.3 cm

Test Masses – the Cavity Mirrors

- Cavity Input Test Masses are Suprasil 3001 (sub - 0.5 ppm/cm absorption at 1064nm)
- ETMs Suprasil 311/312





- Optical coatings are Ion-Beam-sputtered (LMA, Lyon)
- Multi-layers of SiO_2 alternating with Ta_2O_5 doped with TiO_2 (~10's%)
- ETM coating transmission spec. T<5+/1ppm
- Absorption <0.5ppm

Test Masses – Cavity Mirrors

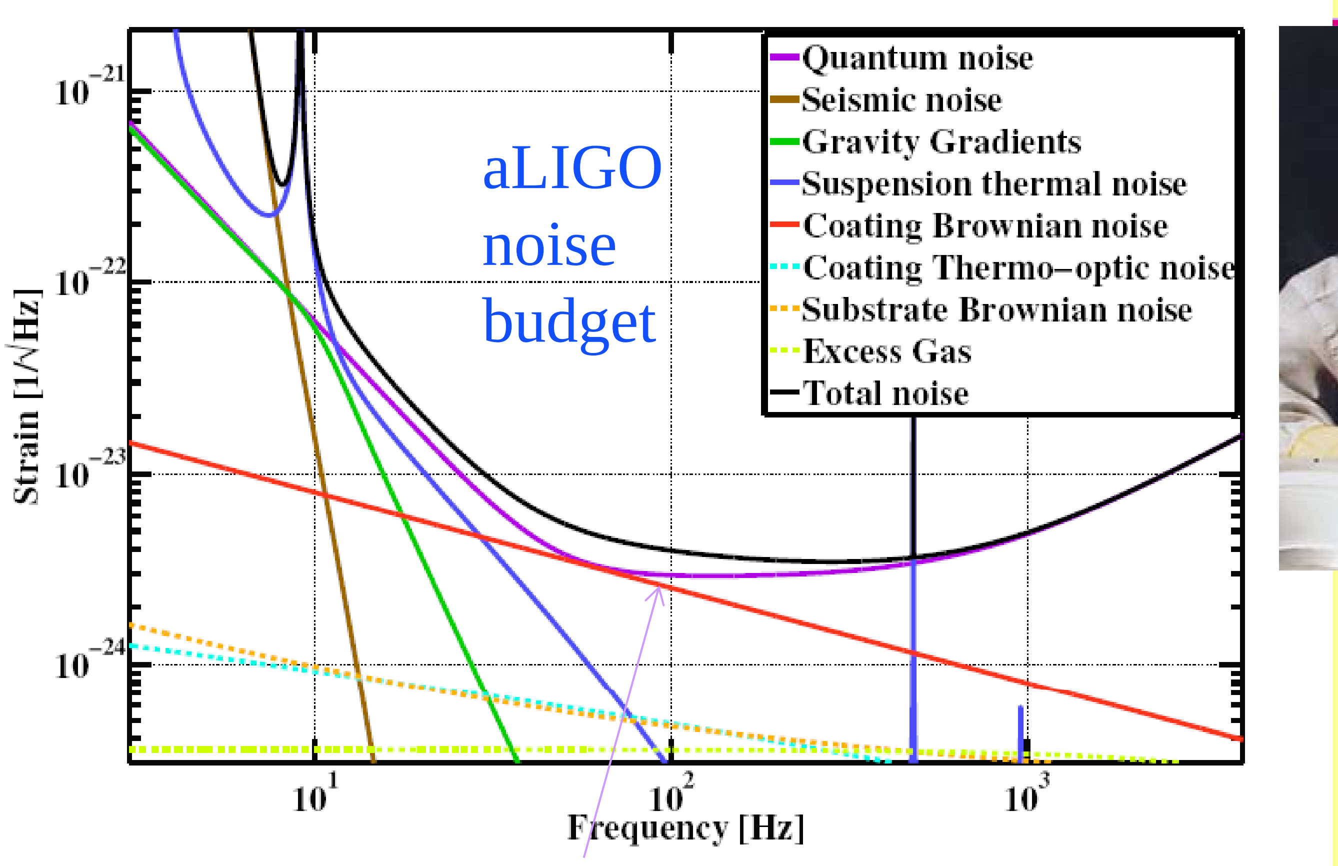
- Even at these ultra-low absorption levels, active thermal compensation is required to maintain the cavities on resonance
- Stored cavity power at design sensitivity ~800kW at 1064nm
- Thermal compensation via a combination a radiative ring heater (RH), and a CO_2 laser projector (CO2P)

  [plus a Hartmann wavefront sensor (HWS) to measure aberrations)

  (see 'Advanced LIGO' 2015 *Class. Quantum Grav.* **32** http://arxiv.org/ftp/arxiv/papers/1411/1411.4547.pdf)

Input test mass and compensation plate at Hanford Observatory

Advanced LIGO Noise Breakdown



- Research ongoing to reduce effects of thermal noise from **the optical coatings** for use in future detectors or detector upgrades

Coating Thermal Noise

Levin showed that the power spectral density is given by:

$$S_x(\omega) = \frac{8k_B T}{\omega^2}\frac{W_{\text{diss}}}{F_o^2}$$

power dissipated for a peak 'test force' F_o over the profile of the laser beam

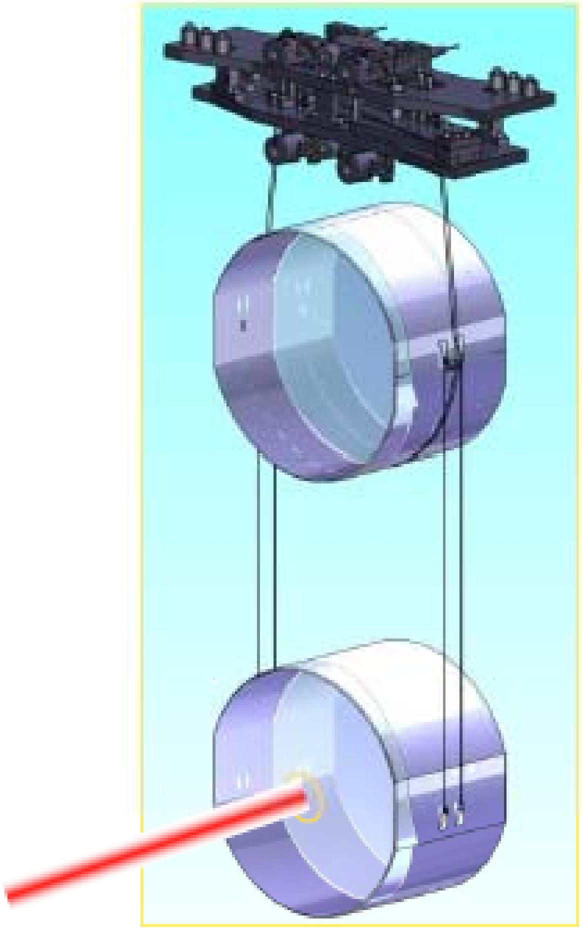
distribution of elastic energy

distribution of loss

$$W_{\text{diss}} = \omega \int_{\text{vol}} \varepsilon(x,y,z)\,\phi(x,y,z,f)\,dV$$

$$\phi(f_0) = \frac{\Delta f}{f_0} = \frac{E_{\text{lost per cycle}}}{2\pi E_{\text{stored}}}$$

Magnitude of coating mechanical loss highly important



Laser incident on front surface of test mass mirror

Current low thermal noise coatings

- Silica/tantala coating loss dominated (at room temperature) by the loss of the tantala layers
  - $\phi_{tantala} \sim 4\times10^{-4}$
  - $\phi_{silica} \sim 5\times10^{-5}$

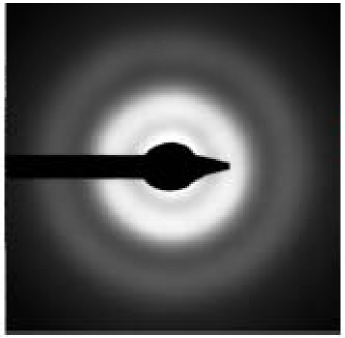
- Doping Ta_2O_5 with TiO_2 can reduce the loss by ~40%

G. Harry et al Classical and Quantum Gravity 2007

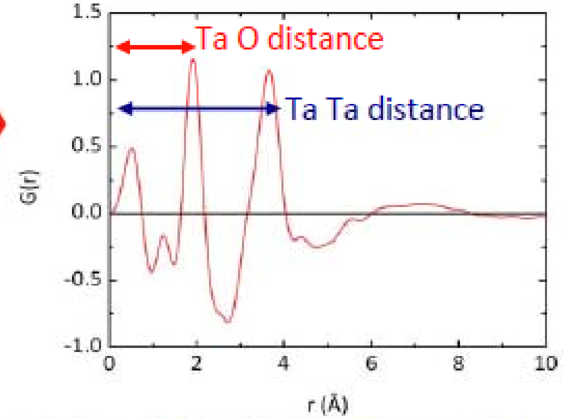
- $Ti:Ta_2O_5/SiO_2$ coatings for aLIGO of $\phi \sim 2\times10^{-4}$

WHY??

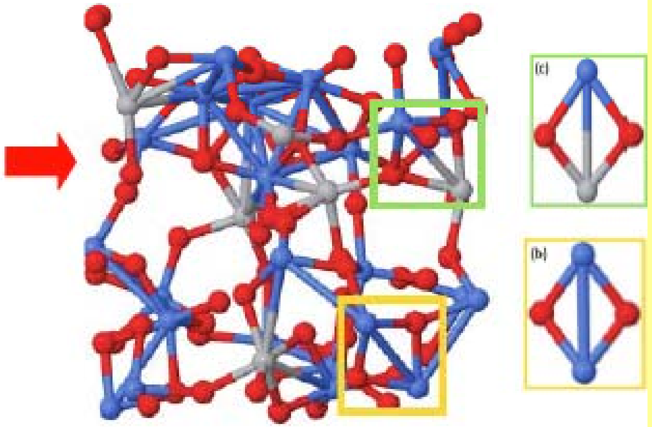
Correlations between coating material structure and mechanical dissipation

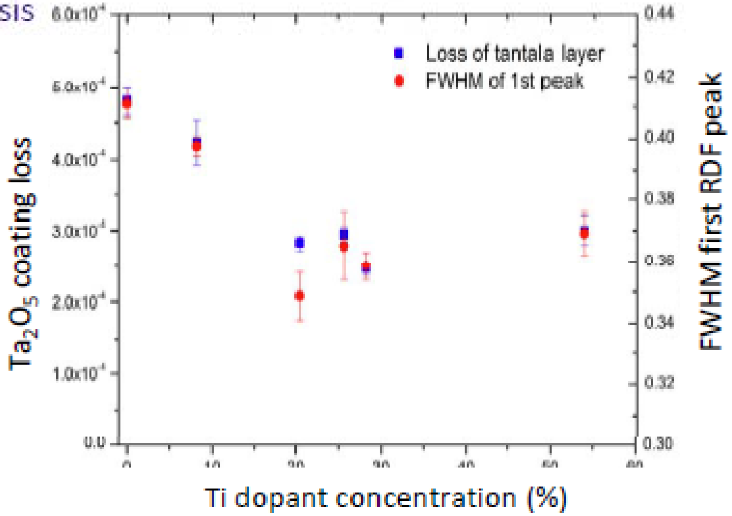


Electron diffraction measurement



Reduced Density Function analysis





Correlation between spread of metal-oxygen distance, loss and doping concentration

- Short range structure probed by electron diffraction
- First evidence of correlation between structural properties and loss in tantala

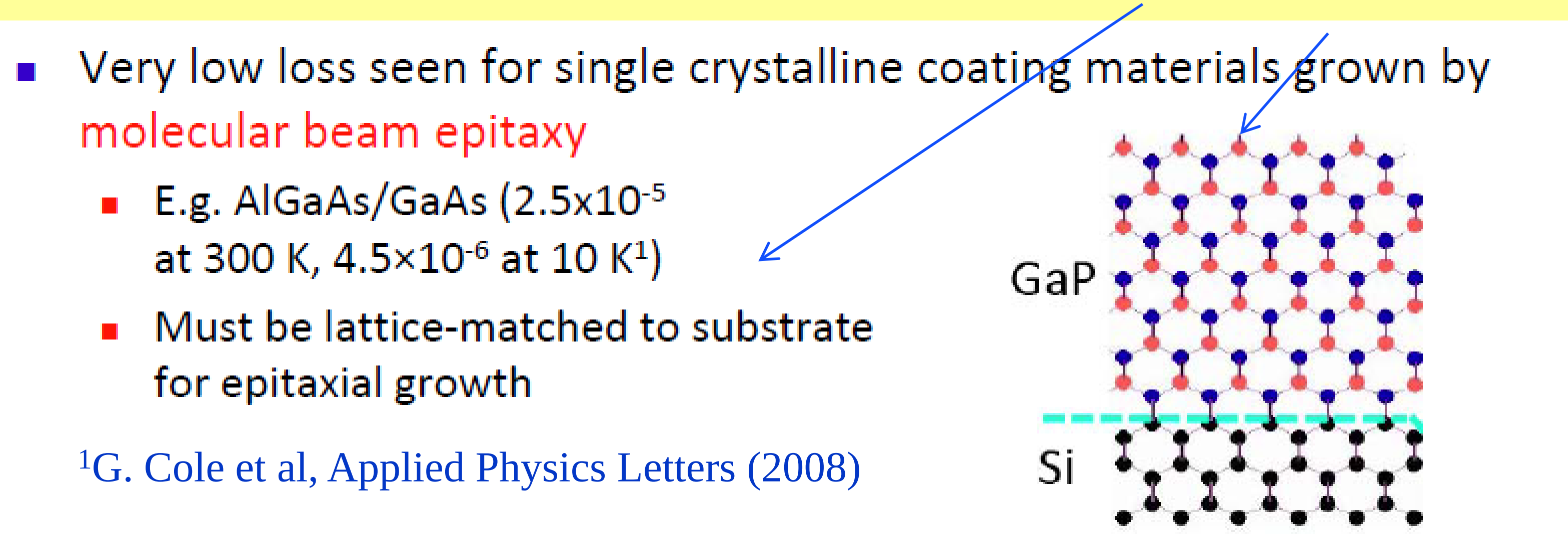
In parallel – modellng of microstructure for alternate dopants in progress to aim to design lower loss materials (use Zr dopant?)

R. Bassiri et al, Acta Materialia, 2013

Measurements in progress.... (S. Penn et al)

Coating thermal noise – crystalline coatings

Alternate approach: crystalline coatings of AlGaAs or AlGaP?



- Very low loss seen for single crystalline coating materials grown by molecular beam epitaxy
  - E.g. AlGaAs/GaAs ($2.5\text{x}10^{-5}$ at 300 K, 4.5×10^{-6} at 10 K[1])
  - Must be lattice-matched to substrate for epitaxial growth

[1] G. Cole et al, Applied Physics Letters (2008)

- AlGaAs/GaAs multi-layer coatings demonstrated on lab-scale optical cavities to give~ x3 reduction in (room T) thermal noise[2]

[2] G. Cole et al, Nature Photonics (2013)

- AlGaAs/GaAs grown on GaAs wafers, then transferred to optical substrates by bonding. Scalability to large sizes? - work in progress

Coating thermal noise – crystalline coatings

Alternate approach: crystalline coatings of AlGaAs or AlGaP?

- AlGaP/GaP lattice matched to **silicon**[1]

[1]A. Lin et al, Optical Interference Coatings 2013

- Of particular interest for future GW interferometers where silicon, cryo-cooled to ~120K, or 20K is a potential mirror substrate material

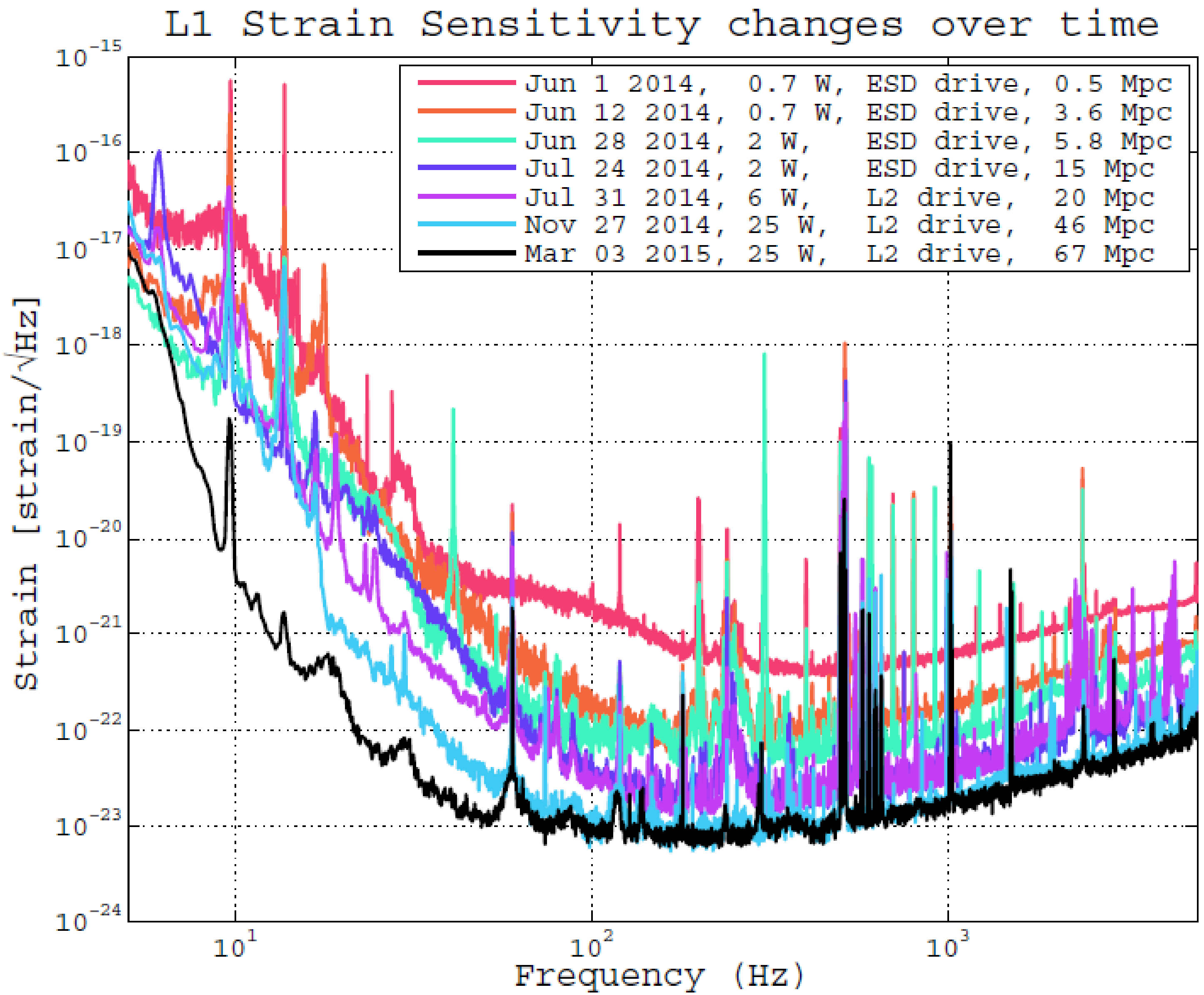
- Demonstrated to have low mechanical loss
- (~2 x 10^{-5} at 25K)

[1]A. Cumming et al, Classical and Quantum Gravity 2015

- Optical loss ~1% – work in progress....

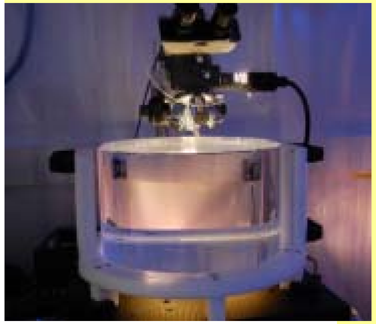
Summary – no clear answer yet for the optimum coating choice for future GW detectors but a number of interesting prospects...

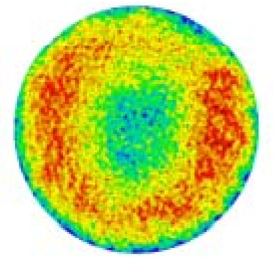
Sensitivity status Advanced LIGO:



On track for first science run soon!

In Summary





- The next generation of gravitational-wave detectors will have the sensitivity to make frequent detections
- The Advanced detectors are coming along well, - first data taking in 2015
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy

Goal: Direct Detection 100 years after Einstein's 1916 paper on GWs ?