Gravitational Wave Detection Using Precision Interferometry

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- On Behalf of the LIGO Science Collaboration -

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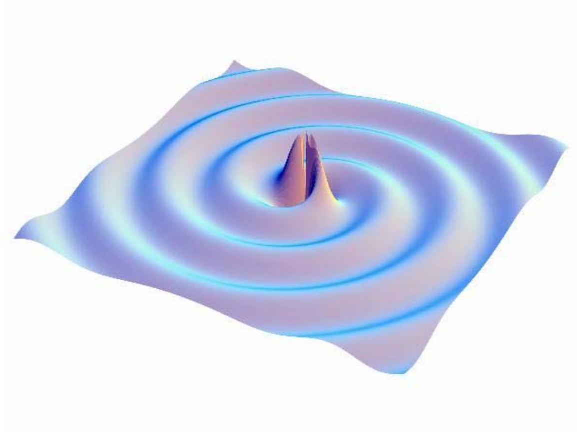
Gravitational Wave Detection

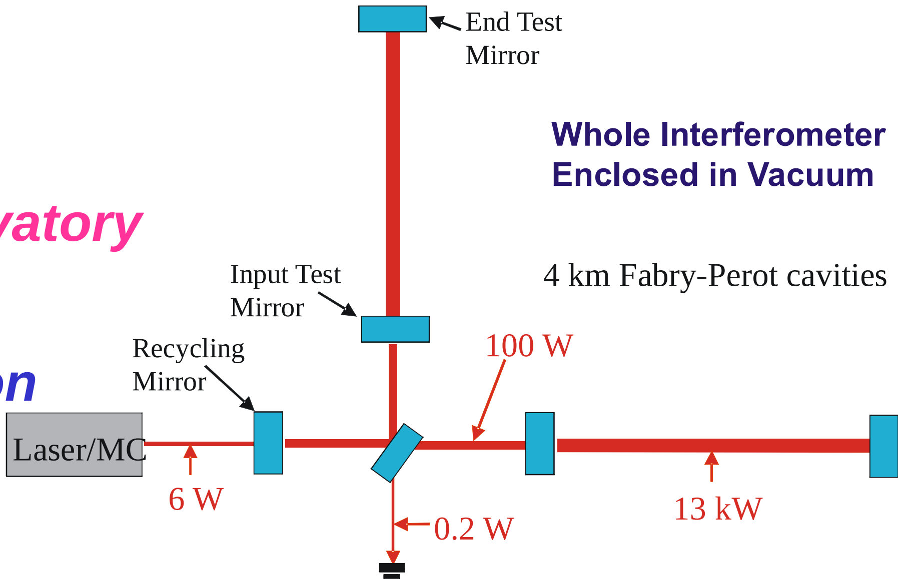


- *Gravitational waves predicted by Einstein*
- *Accelerating masses create ripples in space-time*
- *Need astronomical sized masses moving near speed of light to get detectable effect*

LIGO

Laser Interferometer Gravitational-wave Observatory

- *Two 4 km and one 2 km long interferometers*
- *Two sites in the US, Louisiana and Washington*
- *Similar experiments in Italy, Germany, Japan*
- *Whole optical path enclosed in vacuum*
- *Sensitive to strains around 10^{-21}*

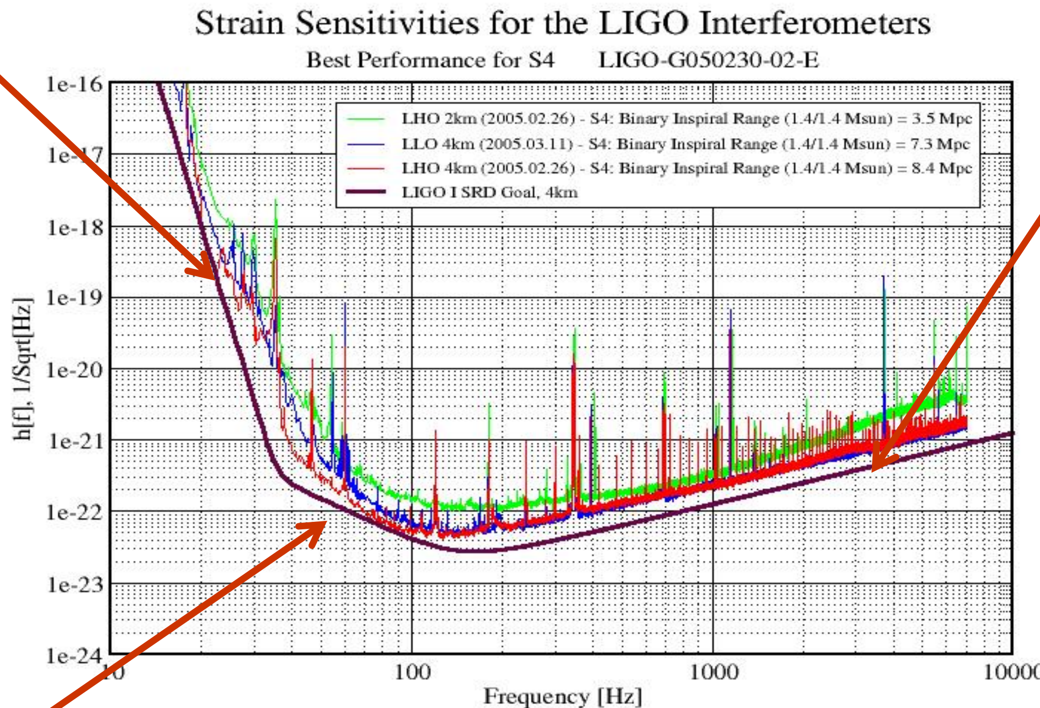


Interferometer Sensitivity

Measured sensitivity 3/2005

Seismic noise < 40 Hz

Optics sit on multi-stage vibration isolation



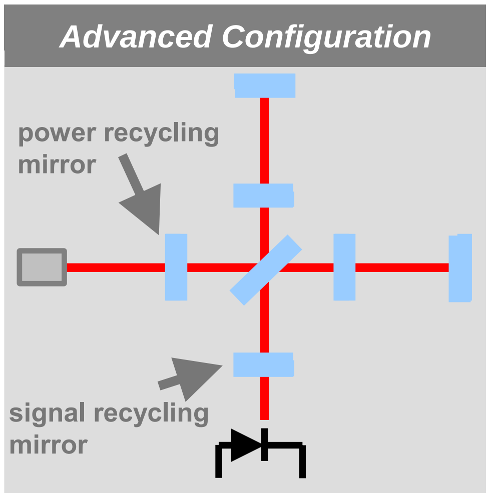
Laser shot noise > 200 Hz

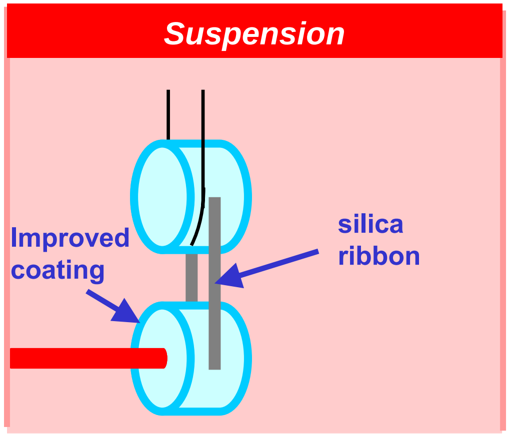
10 W frequency and amplitude stabilized laser

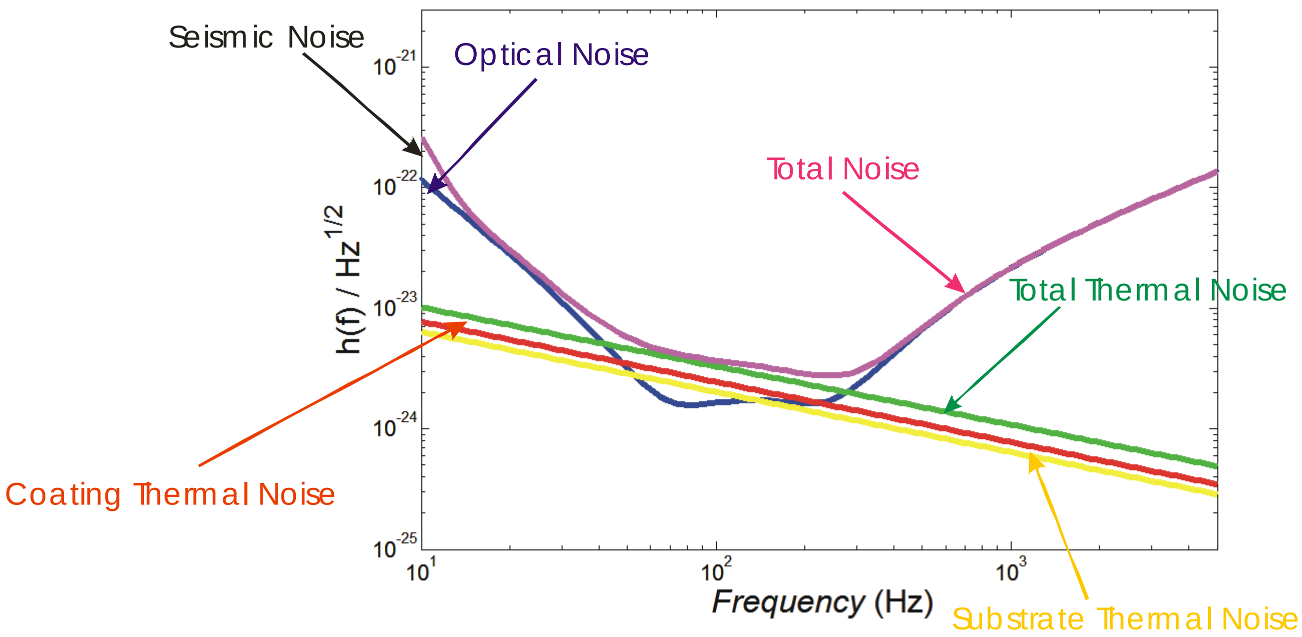
Thermal noise 40 Hz < f < 200 Hz

Metal wire pendulum suspensions allow optic to move freely with gravity wave

Advanced LIGO



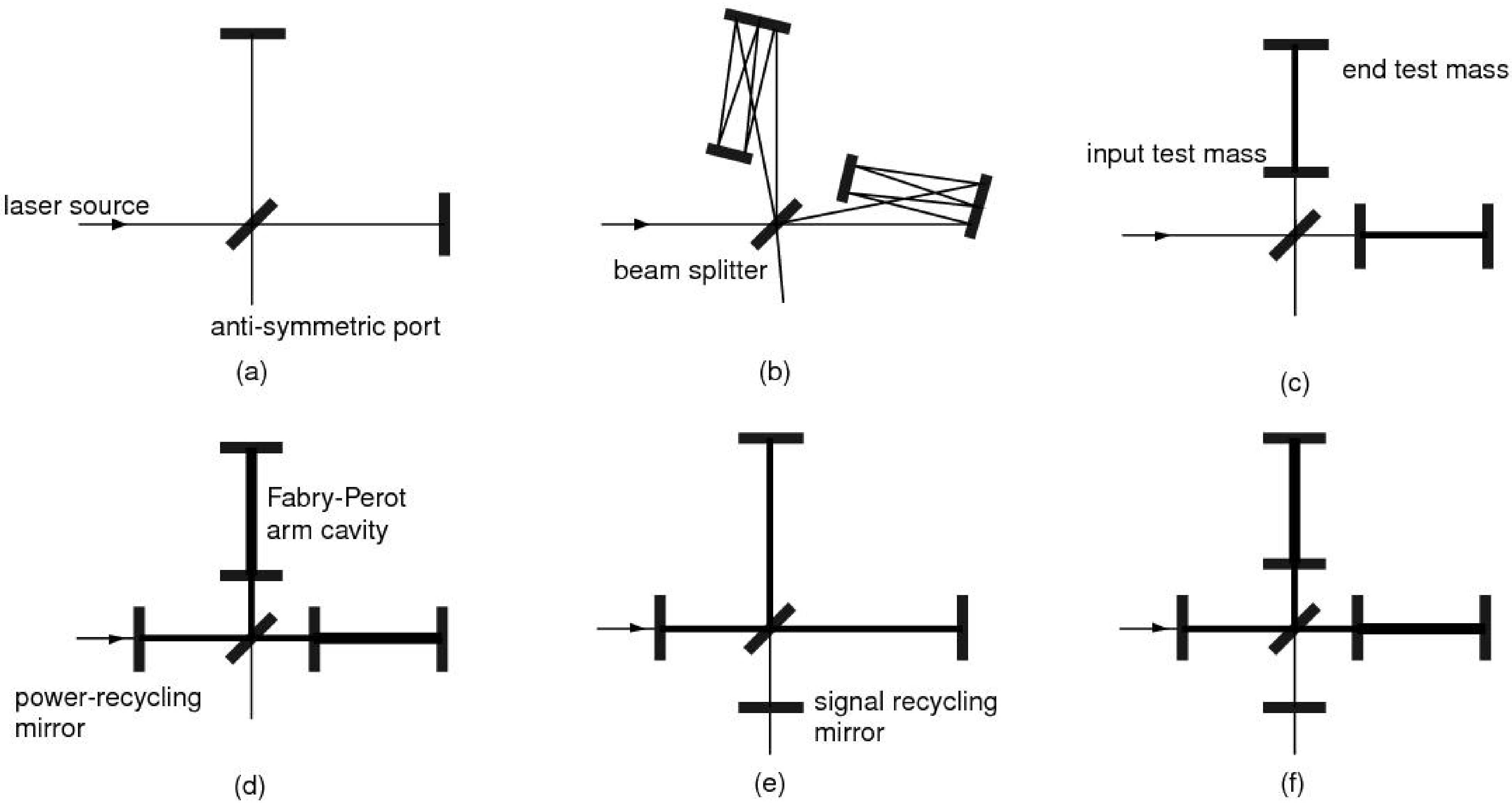




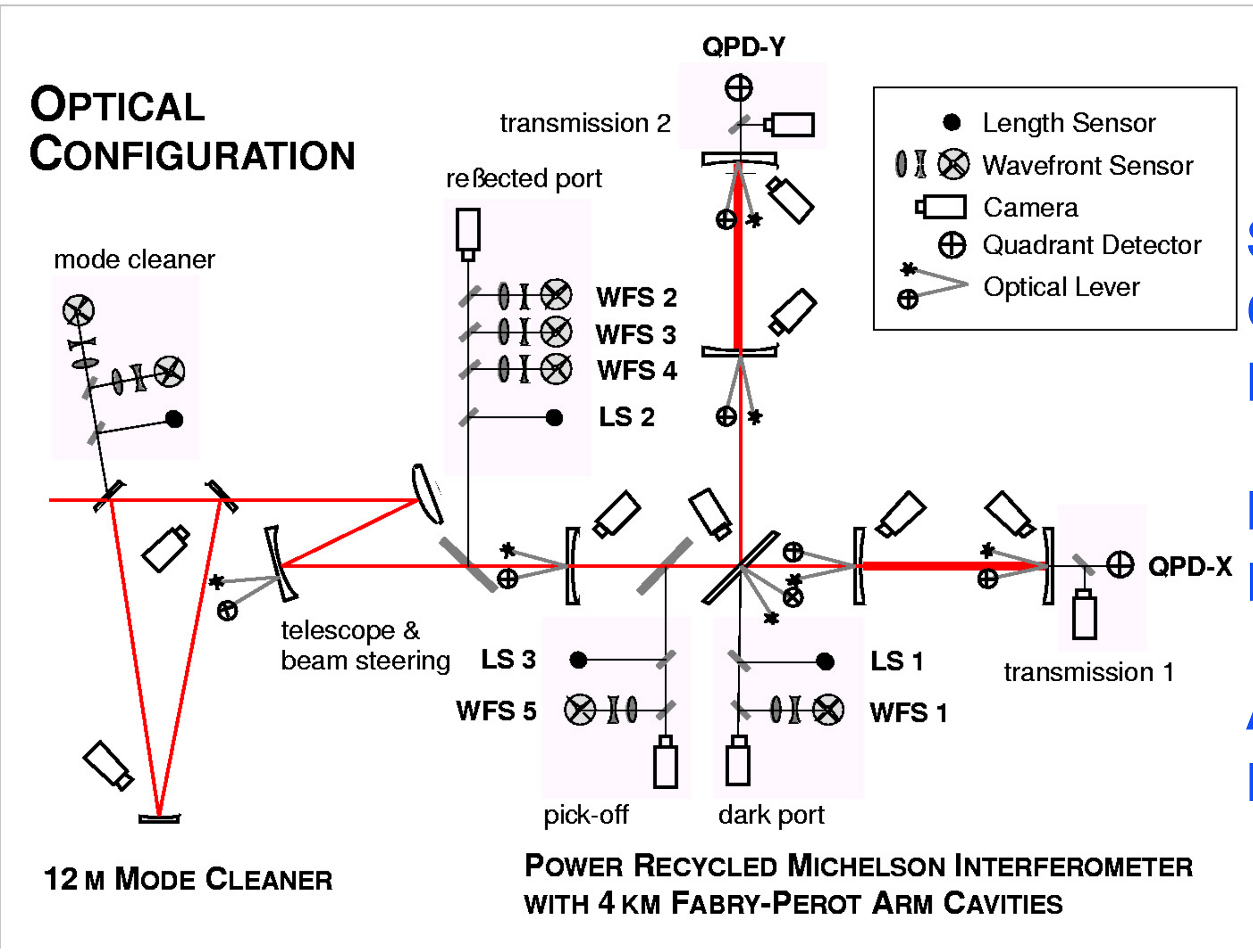
Proposed Sensitivity

- ***Factor of 15 in strain improvement***
- ***Seismic isolation down to 10 Hz***
- ***180 W of laser power***
- ***Larger optics with improved coating***
- ***Additional mirror for signal recycling***

LIGO Interferometry



Optical Configuration



Some Requirements

- Sensitivity ~10^{-19} m/√Hz (150 Hz)
- Controller range ~100 μm (tides)
- Differential arm length ≤10^{-13} m rms
- Intensity noise ≤10^{-7}/√Hz (150 Hz)
- Frequency noise ≤3×10^{-7} Hz/√Hz (150 Hz)
- Angular Control ≤10^{-8} rad
- Input beam jitter ≤4×10^{-9} rad/√Hz (150 Hz)

Coating Thermal Noise and Thermal Compensation

Thermal Noise

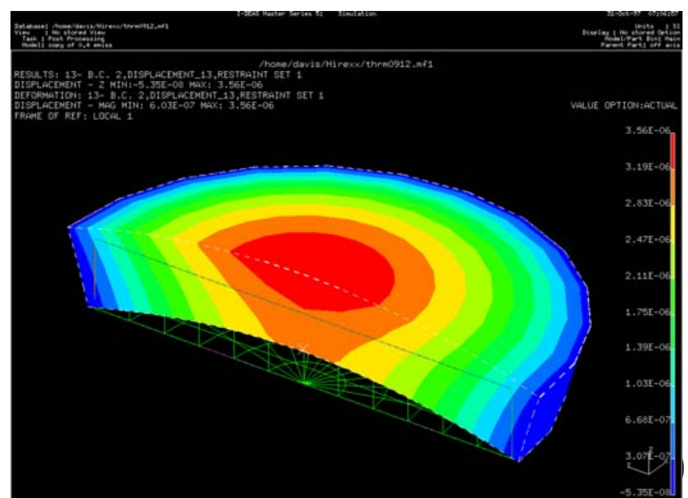
- Sets sensitivity limit to LIGO
- Floor on sensitivity in all applications
    - Laser frequency stabilization
    - Atomic force microscopy
    - Small systems (bio and nano)
- Fluctuation Dissipation Theorem

$$S_F(f) = 4\, k_B\, T \;\; Re[Z]$$

- Dissipation in coating limit in advanced LIGO

Thermal Compensation

- Optics absorb energy from laser
- Heating causes thermal distortions
- Optics designed for expected absorption
    - Coating 0.5 ppm
    - Silica substrate 4 ppm/cm
- Deviations from this require additional heating
- Thermal compensation using CO_2 laser now in place



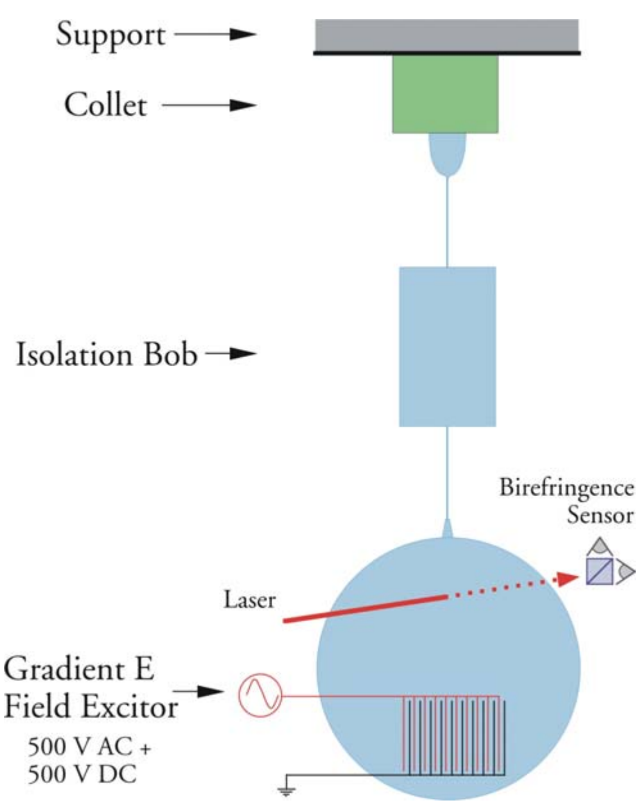
Coating Research

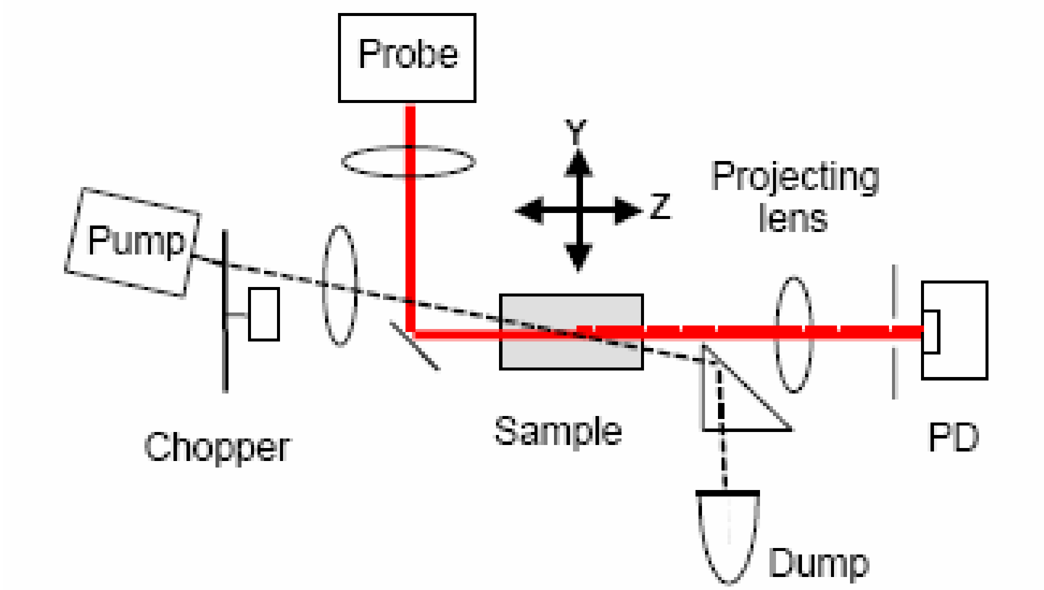
Mechanical Loss

Predicts thermal noise

Measure modal Q's

Model elastic energy distribution





Optical Absorption

Photothermal Common-Path Interferometry

- **Can measure sub-ppm absorption**
- **Spatial resolution sub-millimeter**

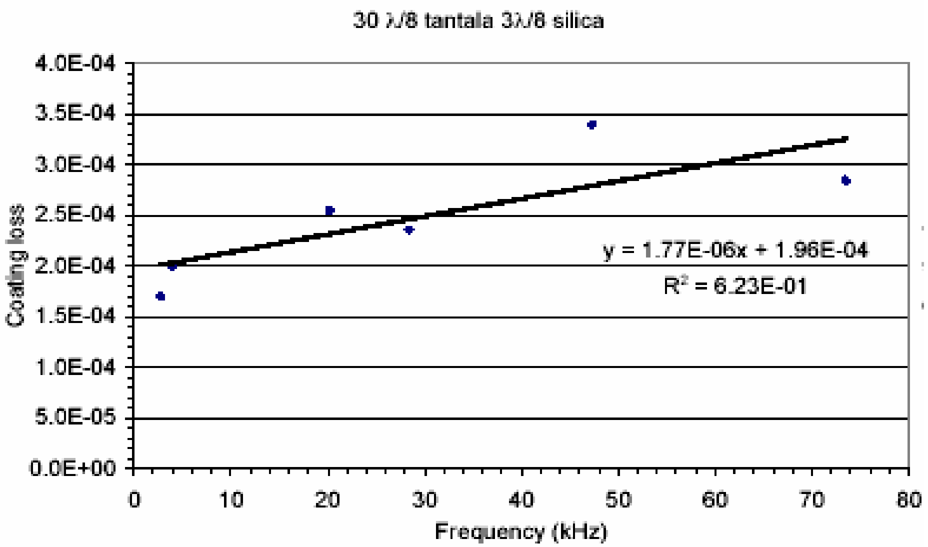
Silica/Tantala Coatings

Initial LIGO Coating

Layers	Materials	Loss Angle
30	$\lambda/4$ SiO_2 - $\lambda/4$ Ta_2O_5	$2.7\ 10^{-4}$
60	$\lambda/8$ SiO_2 - $\lambda/8$ Ta_2O_5	$2.7\ 10^{-4}$
2	$\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5	$2.7\ 10^{-4}$
30	$\lambda/8$ SiO_2 – $3\lambda/8$ Ta_2O_5	$3.8\ 10^{-4}$
30	$3\lambda/8$ SiO_2 – $\lambda/8$ Ta_2O_5	$1.7\ 10^{-4}$

- *Loss is caused by internal friction in materials, not by interface effects*
- *Differing layer thickness allow individual material loss angles to be determined*

$$\phi_{Ta2O5} = 4.4 \pm 0.2\ 10^{-4}$$
$$\phi_{SiO2} = 0.5 \pm 0.3\ 10^{-4}$$



Evidence of frequency dependence to loss

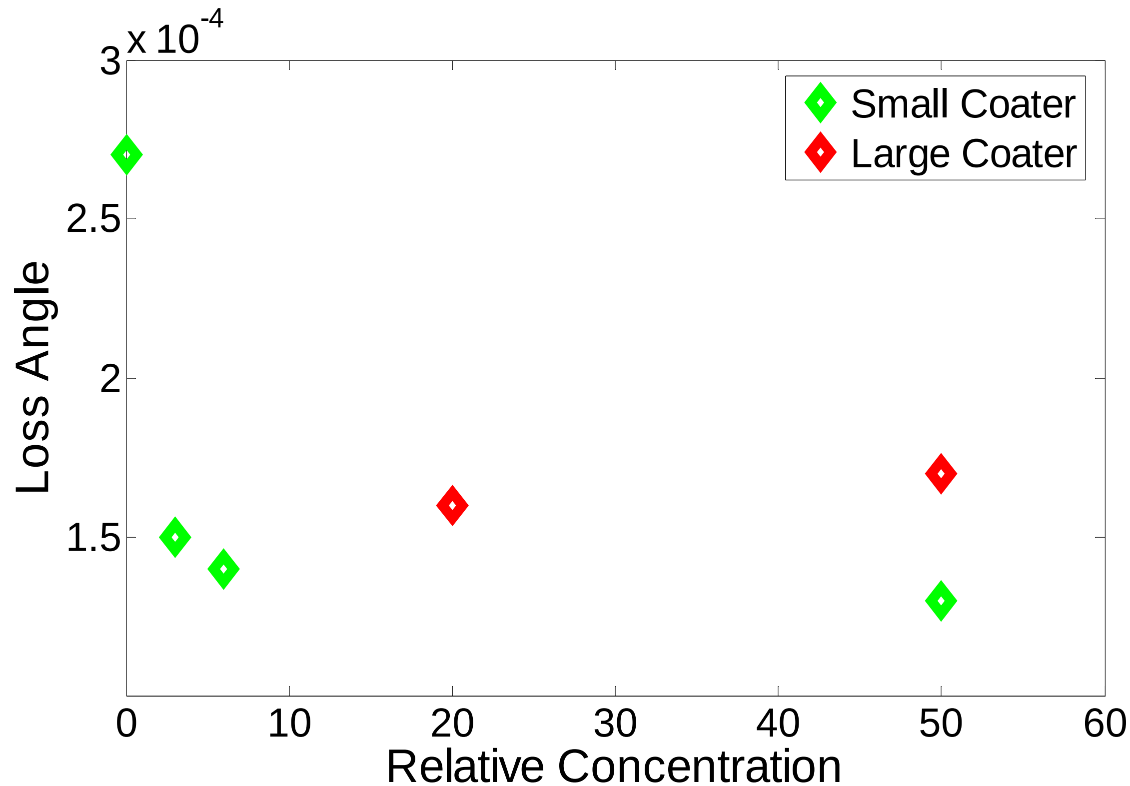
- *Only in silica layers*
- *Improving at lower frequencies*
- *Consistent with data on bulk silica*

Titania Dopant in Tantala

$\lambda/4$ SiO_2 – $\lambda/4$ Ta_2O_5
Coatings with TiO_2 dopant

Optical absorption between 1 and 2 ppm
Advanced LIGO requirement
<0.5 ppm

Also need scatter < 2 ppm
HR transmission < 5 ppm
Thickness uniformity < 10^{-3}



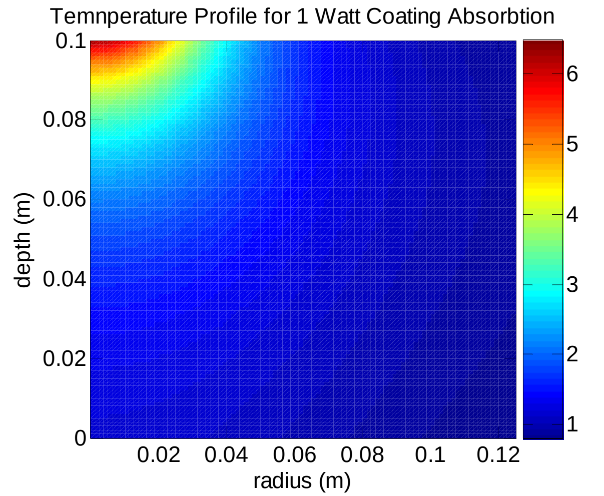
Any amount of titania reduces mechanical loss

- What physical mechanism causes this?
- Is there a better dopant? Or alloy?
- Can optical absorption be reduced?

Work done in collaboration with LMA/Virgo in Lyon, France as part of advanced LIGO coating research

Absorption in LIGO Optics

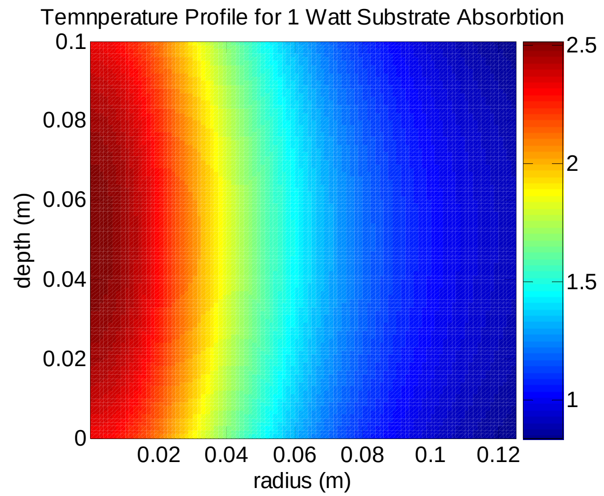
Laser light reflecting off coatings and traversing silica substrates will be absorbed.



Coating absorption

Largest effect in input mirrors because of the transmission

Heating and lensing cause reduction in interference pattern and power buildup



Substrate absorption

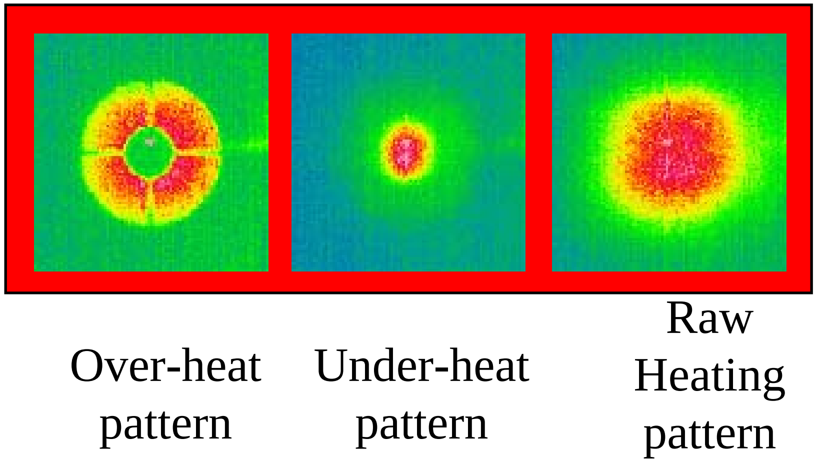
Thermal Compensation

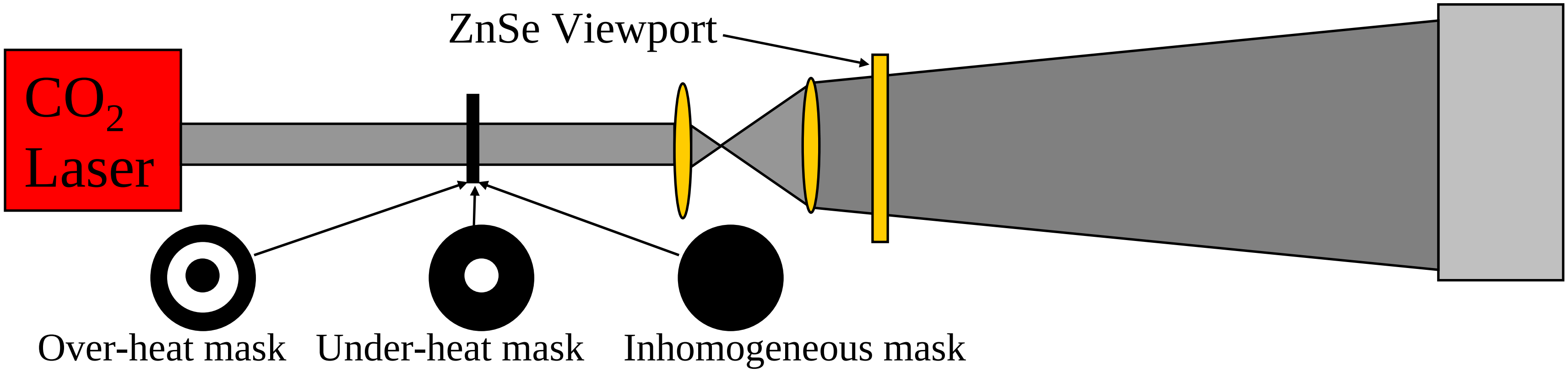
Heating and lensing controlled by adding additional heat with a CO_2 laser

Too much heating can be corrected by adding light to optic edge

Too little heating can be corrected by adding light to center

May have to correct for inhomogeneous heating in advanced LIGO





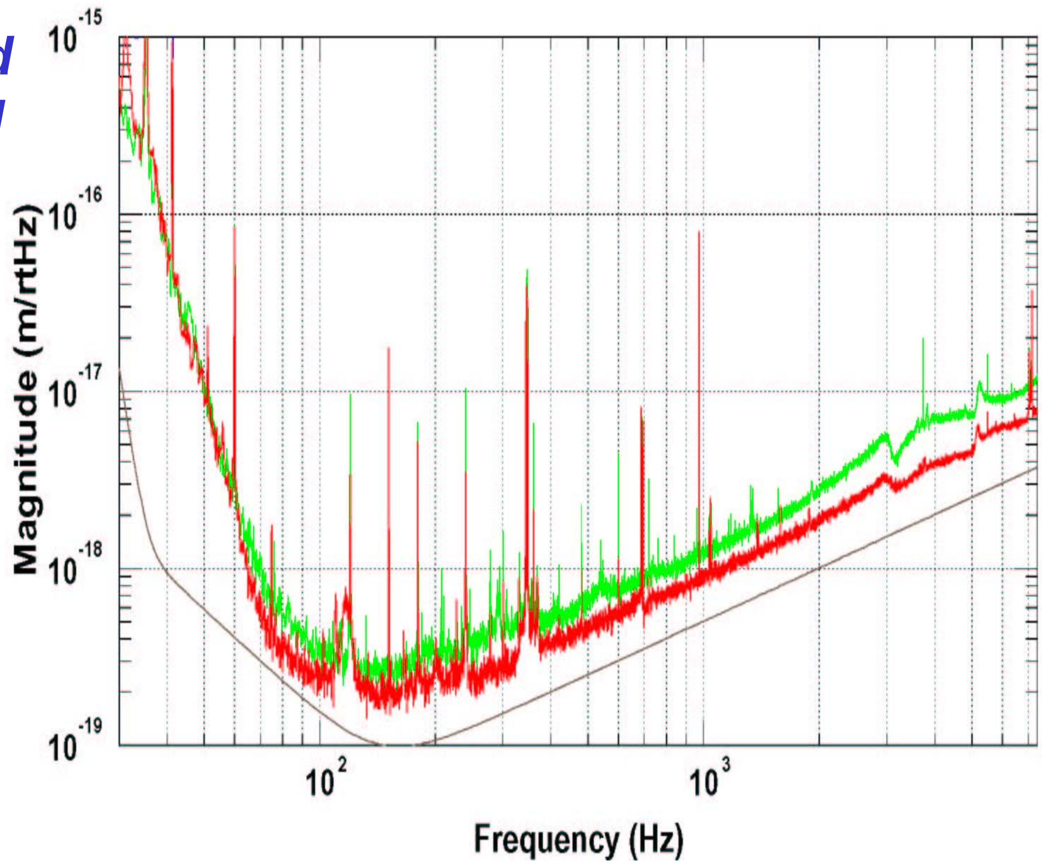
Sensitivity Improvement from Thermal Compensation

Lensing was bad enough at Hanford 4 kilometer interferometer could not operate above 4 W of input power

With thermal compensation, high power and less shot noise are achievable

Advanced LIGO will have nearly 1 MW of circulating power in cavities

Low absorption coatings and substrates, as well as high performance thermal compensation, are essential



Green: without thermal compensation
Red: with thermal compensation

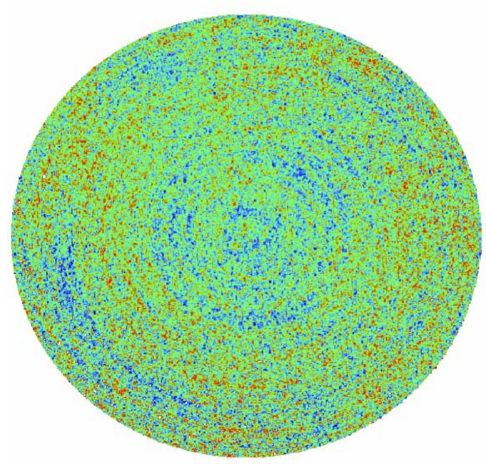
Conclusions

- *Gravitational wave detection is pushing the limits of interferometric sensing*
- *LIGO is close to achieving sensitivity goal*
- *Planned advanced LIGO will improve on initial interferometers*
- *Coating thermal noise will be limiting noise source in future interferometers*
- *Thermal lensing requires compensation system*

Optics Metrology

Initial LIGO

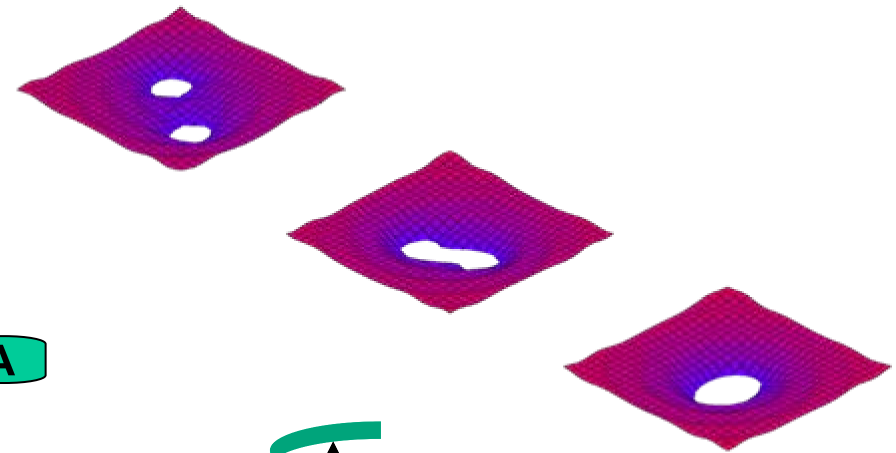
- ***Surface figure σ_{rms}< 0.8 nm over central 80 mm***
  - ***Repeatable to 0.2 nm***
- ***Radius of curvature***
  - ***Match between optics in same arm to 1.5 %***
  - ***Repeatability to 5 nm***
- ***Measured using Fizeau interferometry***



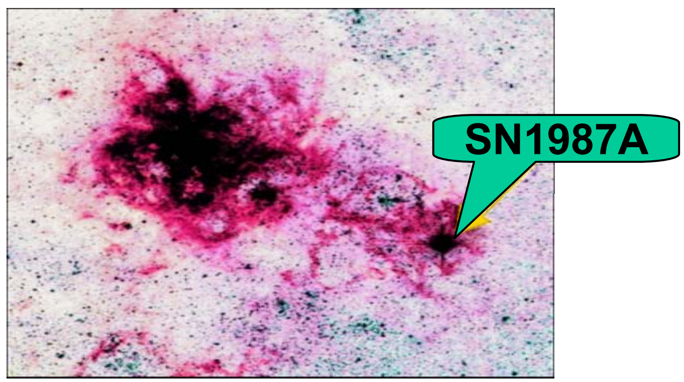
Difference in consecutive cavity measurements

Sources of Gravitational Waves

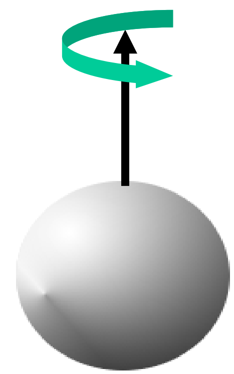
- Inspiralling binary neutron stars or black holes



- Supernova

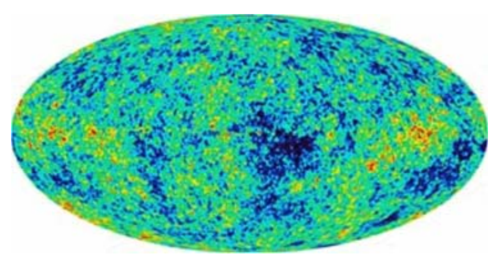


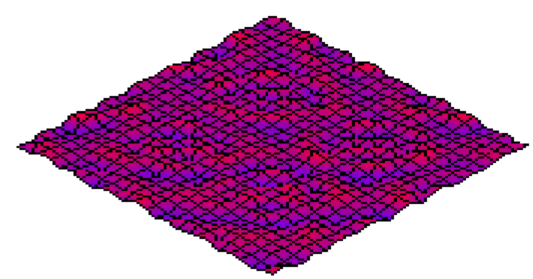
- Distorted pulsars



Bumpy Neutron Star

- Stochastic background





Direct Measurement of Coating Thermal Noise

- *LIGO/Caltech's Thermal Noise Interferometer*
- *1 cm long arm cavities, 0.15 mm laser spot size*
- *Consistent with ~ 4 10^{-4} coating loss angle*