Optics Thermal Noise Work at American

**Gregg Harry, Sam Hickey,
Jonathan Newport, Hannah Fair**

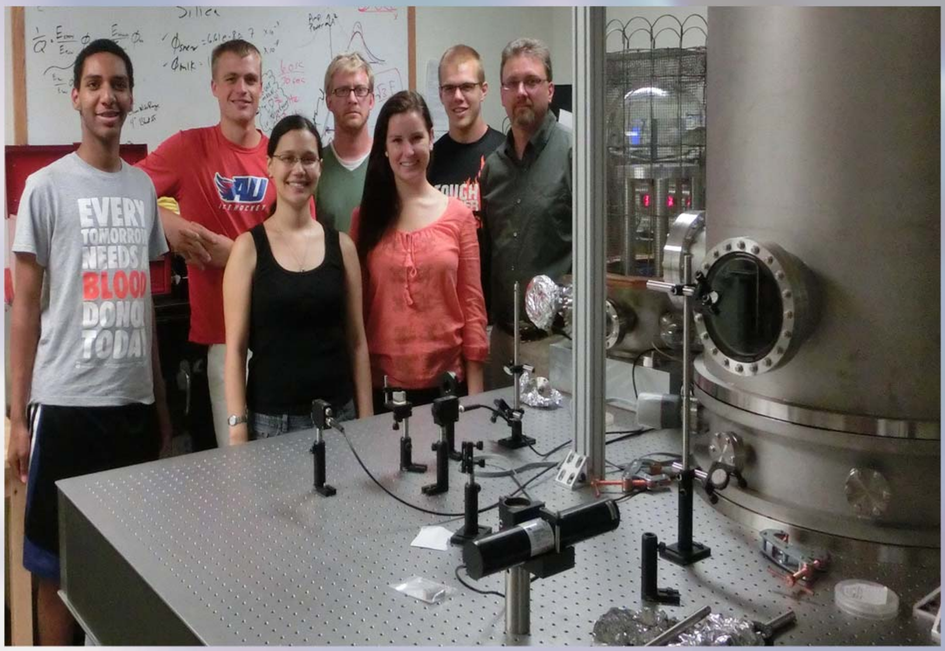
American University

OWG Session, August 2014 LVC Meeting

G1400961

Overview of AU Lab

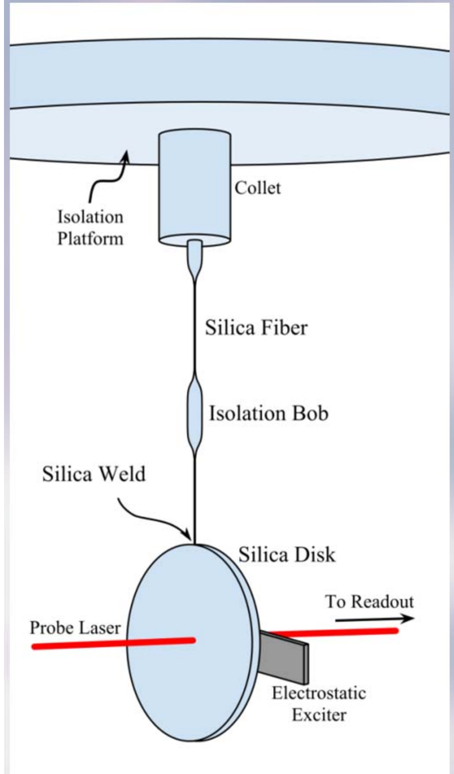
- The AU Thermal Noise lab has two bell jars dedicated to studying thermal noise in gravitational wave detector optics
  - Dedicated finite element modeling computer
- PI Gregory Harry, Lab Specialist Jonathan Newport
  - Typically two students, currently Hannah Fair and Sam Hickey



Technique

Q Measuring

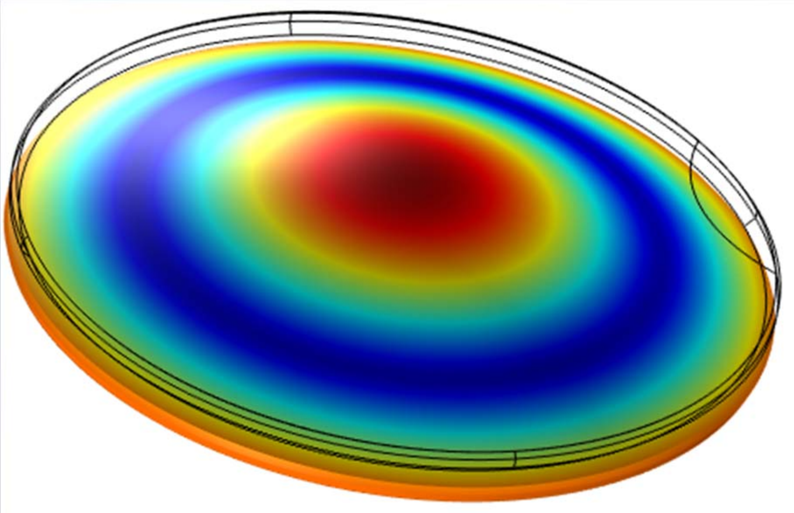
- Measure modal Q’s of sample optics



- Determine mechanical loss from Q’s
- In vacuum, silica fiber suspension, electrostatic excitation, birefringence laser readout

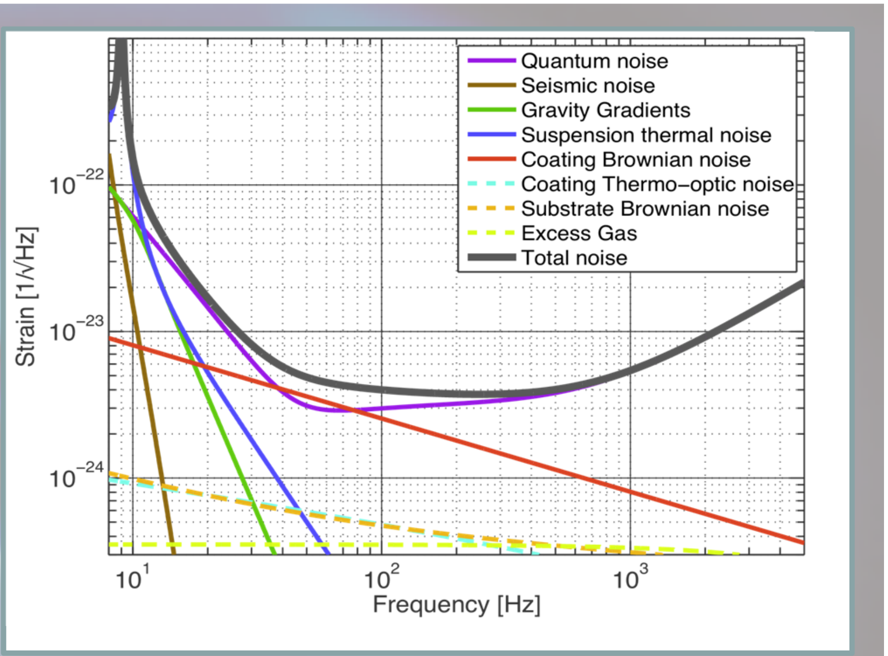
Finite Element Model

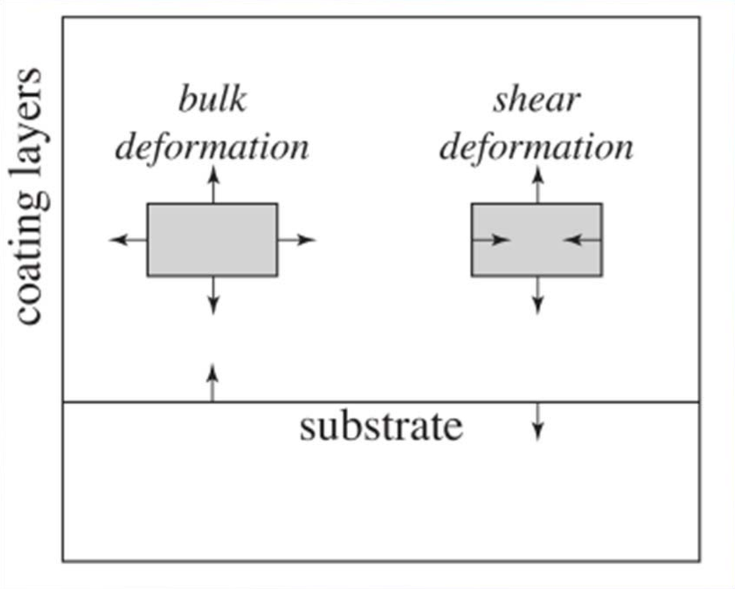
- Energy distribution in sample by FEA
- Determine modally (frequency), spatially, tensor elements



Coating Thermal Noise

- Coating thermal noise caused by mechanical loss
- Sensitivity limiting in aLIGO
  - Titania doping, et al.
- Continuing in 3rd generation
  - Many approaches





- Hong et al, Phys. Rev. D **87**, 082001
- Coating thermal noise depends on shear & bulk mechanical loss
  - Hong et al estimate 37% uncertainty in thermal noise from ignorance of these values in aLIGO

Ti-Ta Sample

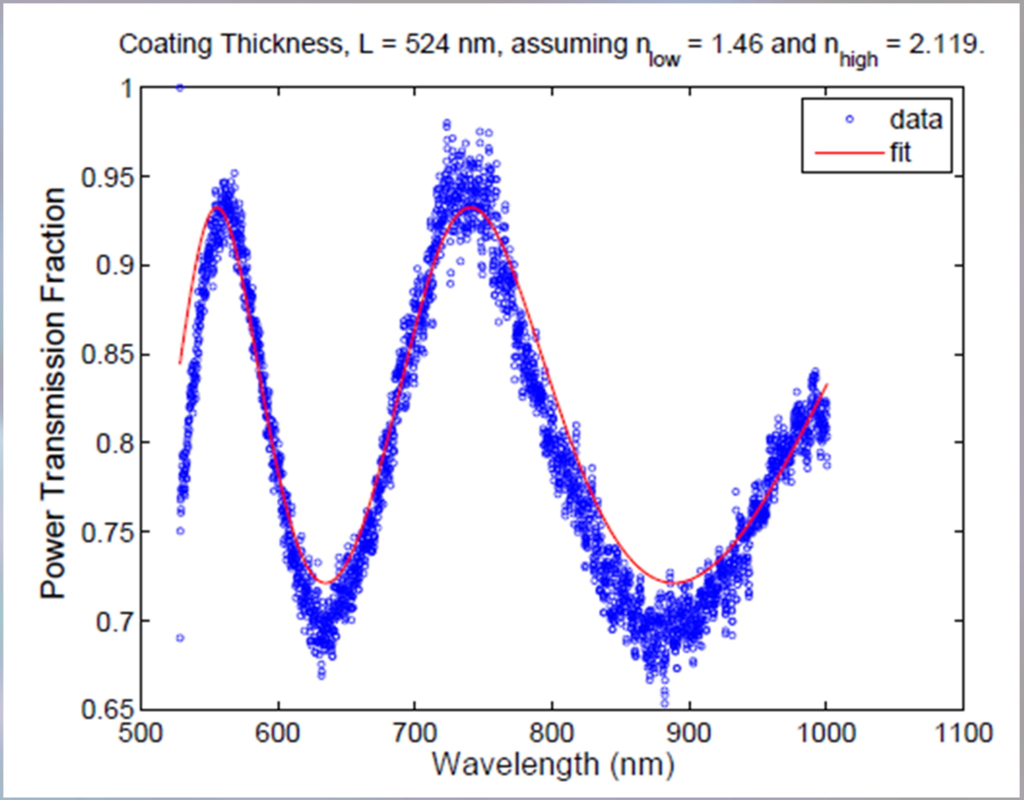
- Nominal thickness 0.5 μm
  - Being measured at ERAU
- Using standard values for
  - Young’s Modulus 140 GPa
  - Poisson ratio 0.23
  - Density 2200 kg/m^3

- Jonathan Newport has been doing FEA work

Mode	Frequency	Q	δQ	E_{shear}/E_{tot}	E_{bulk}/E_{Tot}
BF	2773 Hz	1.14×10^6	2.5×10^3	9.93×10^{-3}	6.58×10^{-4}
DH	4178 Hz	8.70×10^5	2.6×10^4	6.85×10^{-3}	4.79×10^{-3}
Hex	6307 Hz	9.32×10^5	3.2×10^4	9.37×10^{-3}	9.65×10^{-4}
DDH	9707 Hz	9.16×10^5	3.8×10^3	7.68×10^{-3}	3.62×10^{-3}
Oct	10943 Hz	8.87×10^5	1.6×10^4	9.05×10^{-3}	1.18×10^{-3}

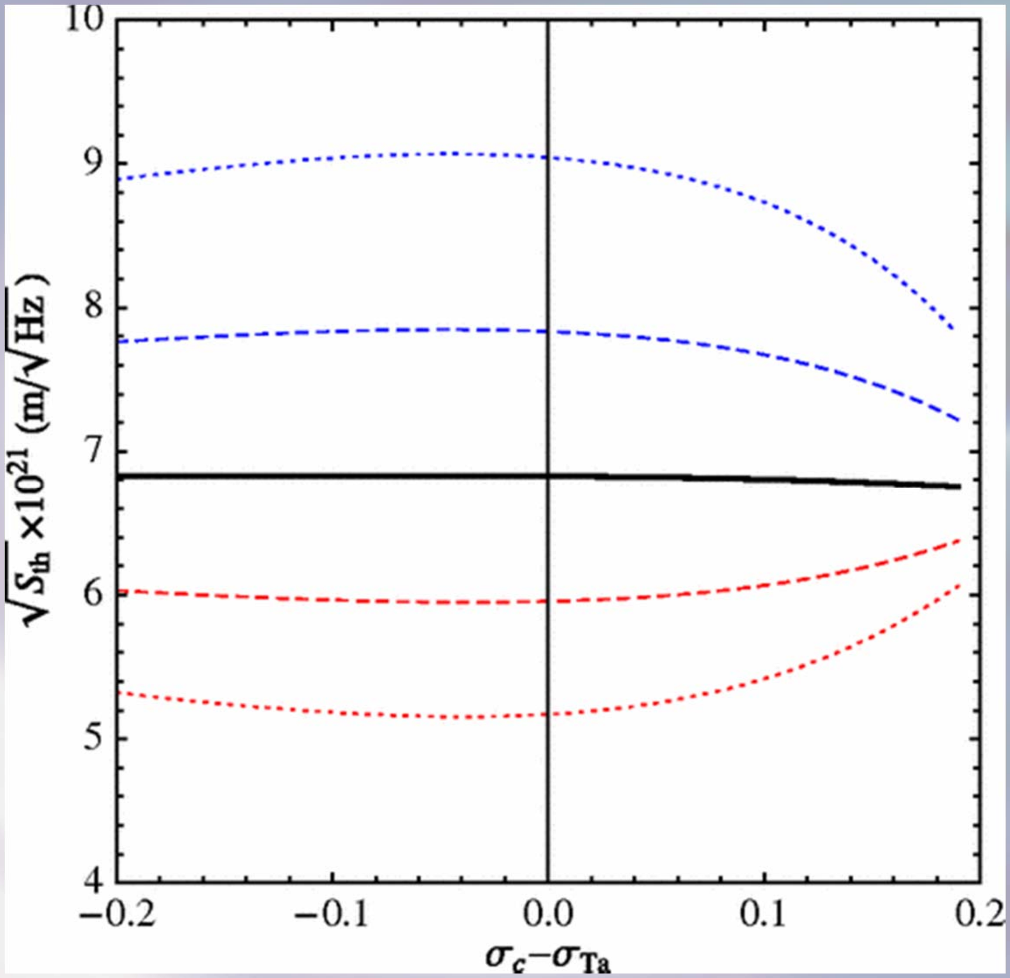
Coating Thickness

- Transmission vs angle at ERAU by Andri Gretarsson



- $n = 2.119$ for 25% ti in ta from CGQ **24**, 405 2007.
- Single layer fit gives $d = 0.524\ \mu\text{m}$

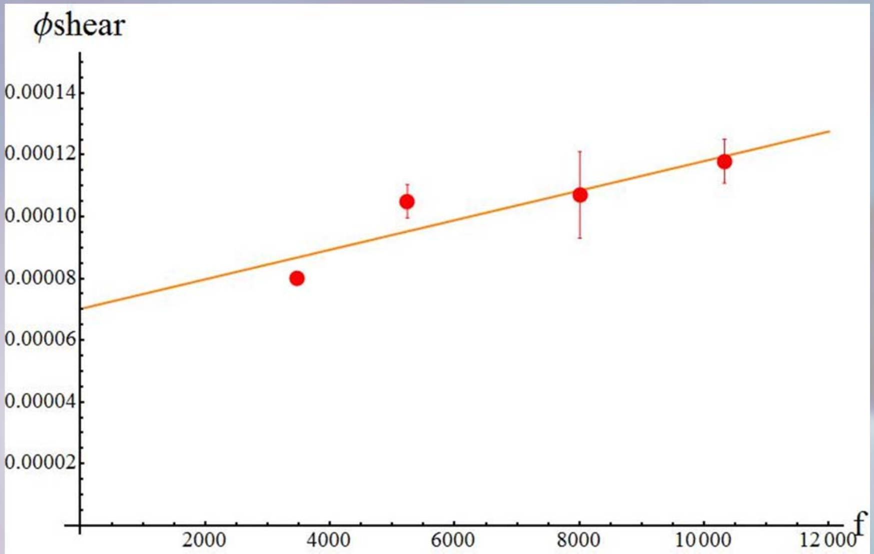
Poisson Ratio

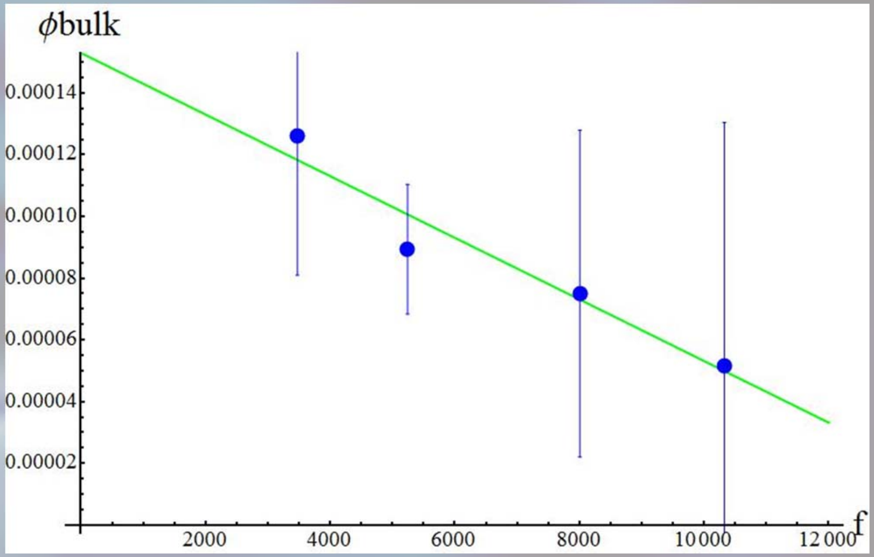


- Uncertainty in ti-ta Poisson ratio significant contributor to uncertainty in energy ratios
- Hong et al estimate it accounts for ~10% uncertainty in thermal noise

Results

Bulk and shear ϕ as functions of frequency





$$\varphi_{shear} = 7.0 \times 10^{-5} + 4.8\ \times 10^{-9}\, f$$
$$\varphi_{bulk} = 1.5 \times 10^{-4} - 1.0\ \times 10^{-8}\, f$$

Random uncertainties from energy ratios, systematic uncertainty from Poisson ratio

Thermal Noise

Noise prediction from Hong paper

- With $\varphi_B(f)$

$100\text{ Hz} \quad {}^{\varphi_B}/_{\varphi_S} = 2.2$

$1000\text{ Hz} \quad {}^{\varphi_B}/_{\varphi_S} = 1.9$

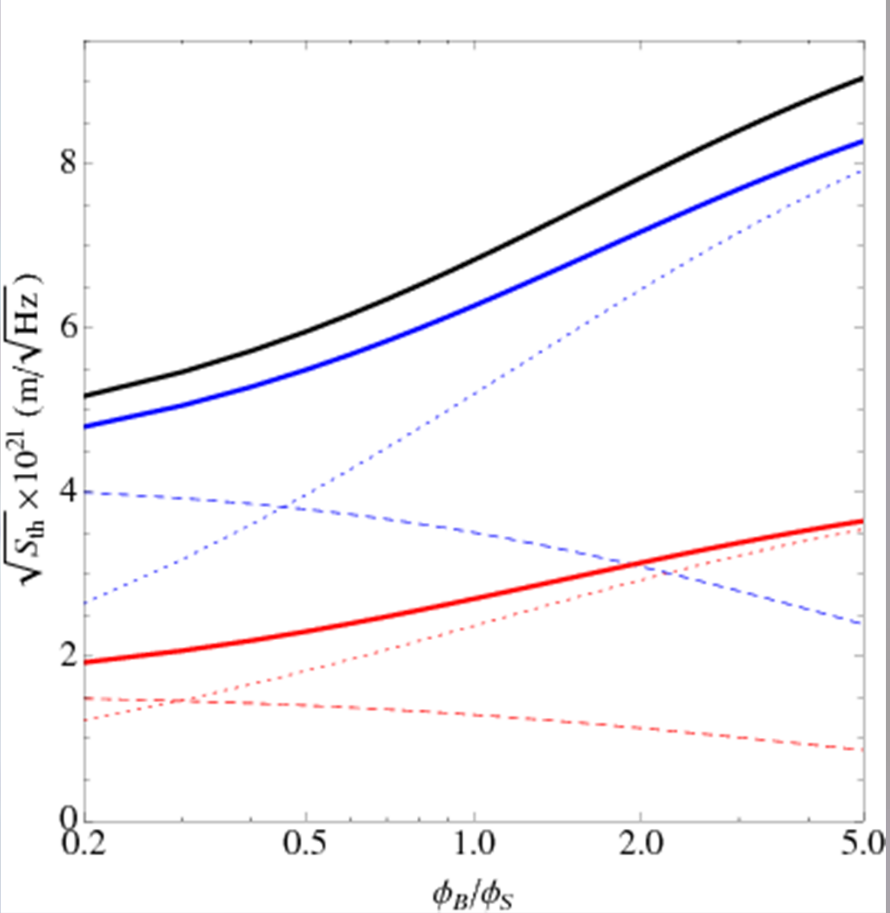
⟶20% worse aLIGO thermal noise

- With φ_B constant

$100\text{ Hz} \quad {}^{\varphi_B}/_{\varphi_S} = 1.3$

$1000\text{ Hz} \quad {}^{\varphi_B}/_{\varphi_S} = 1.3$

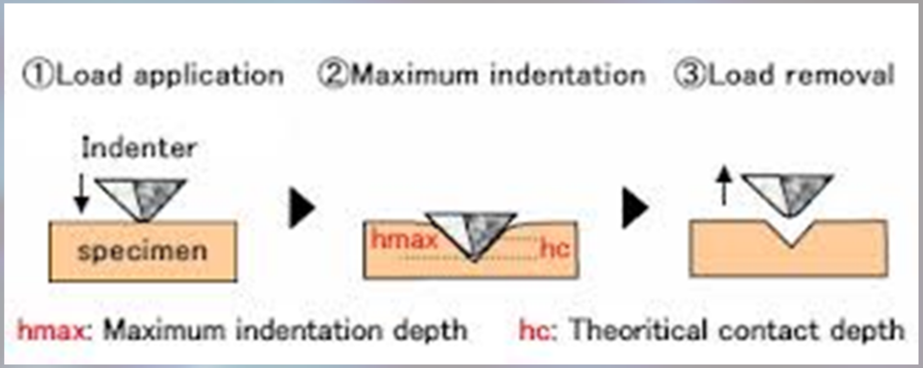
→2% worse aLIGO thermal noise

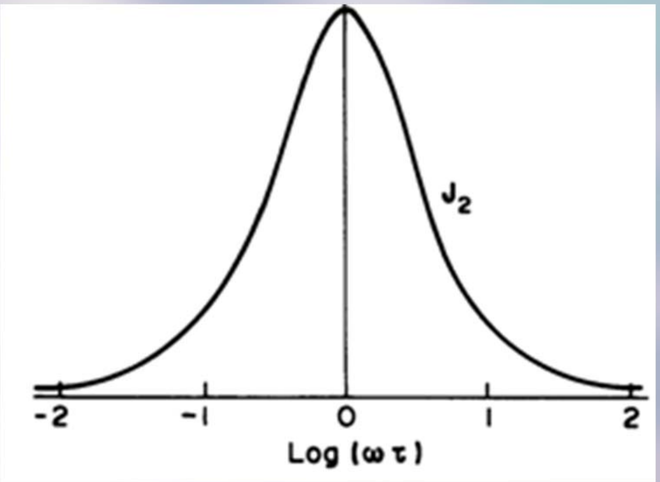


- Matt A found ${}^{\varphi_B}/_{\varphi_S} \approx 2$ in G1300063

Outstanding Issues

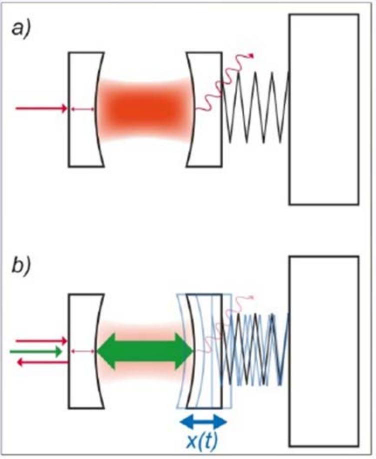
- Young's modulus and Poisson ratio
  - Nanoindenter
  - Acoustic reflection
  - Biggest source of uncertainty in aLIGO thermal noise

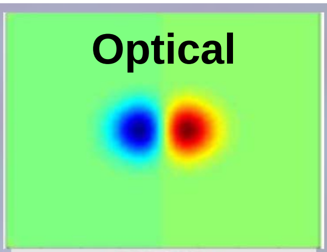


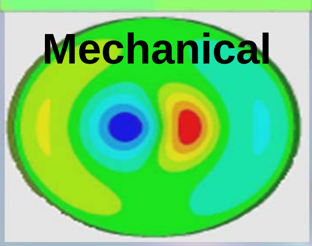


- More precise FEA model
  - Errors from energy ratios
- Linear loss model
  - Improve approximation
- Thermal noise predictions
  - Compare to prototypes

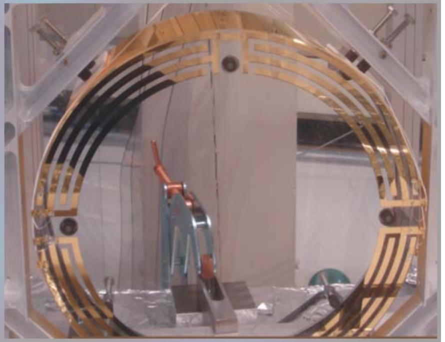
Parametric Instability





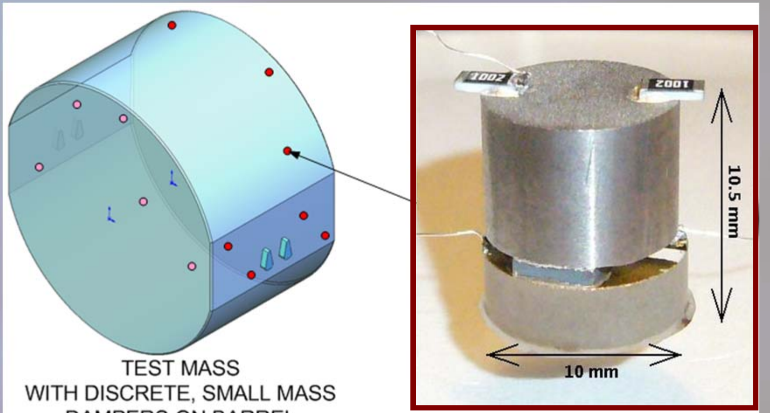


- Possibly problem in aLIGO from exchange of energy between optical cavities and mirror acoustic modes



Possible solutions

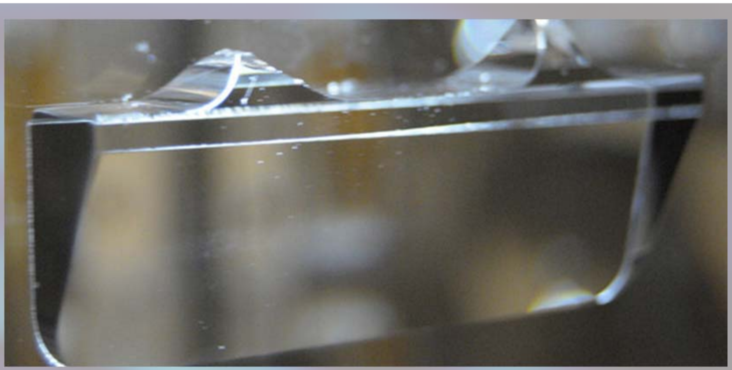
- Ring heaters to adjust mirror mode frequencies
- Electrostatic drive to actuate on and damp acoustic modes
- **Acoustic mass dampers to passively damp acoustic modes**
- Optical mode active damping

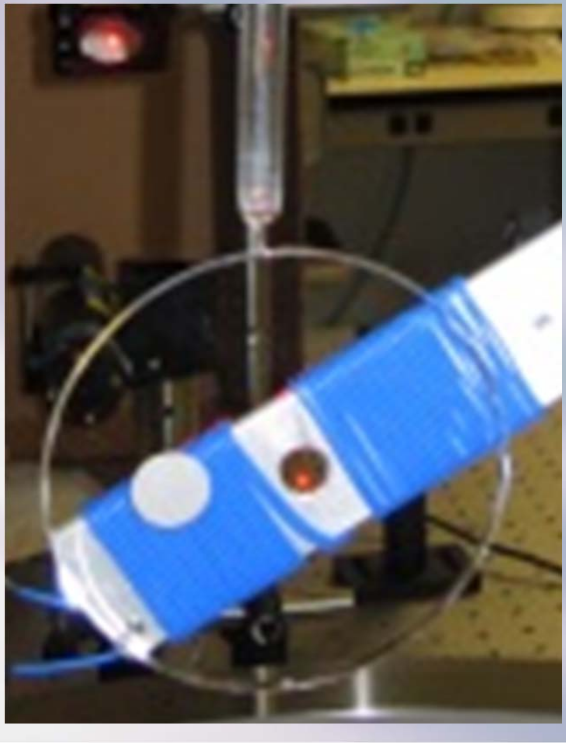


TEST MASS
WITH DISCRETE, SMALL MASS
DAMPERS ON BARREL

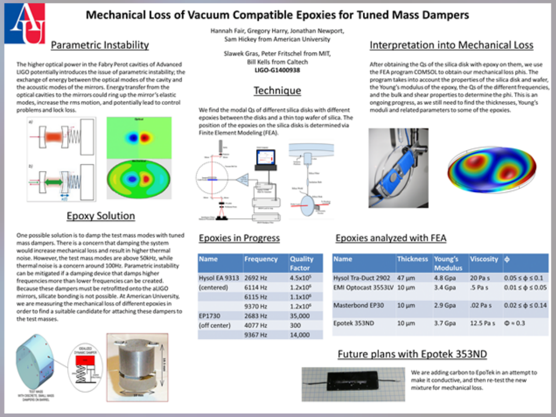
Epoxy Thermal Noise

- Retrofit rules out silicate bonding, best solution
- Use epoxy to connect dampers to mirrors





- Predict thermal noise for dampers
- Need mechanical loss of epoxies



Mechanical Loss of Vacuum Compatible Epoxies for Tuned Mass Dampers

Hannah Fair, Gregory Harry, Jonathan Newport,
Sam Hickey from American University

Slawek Gras, Peter Fritschel from MIT,
Bill Kells from Caltech
LIGO-G1400938

Parametric Instability

The higher optical power in the Fabry Perot cavities of Advanced LIGO potentially introduces the issue of parametric instability; the exchange of energy between the optical modes of the cavity and the acoustic modes of the mirrors. Energy transfer from the optical cavities to the mirrors could ring up the mirror's elastic modes, increase the rms motion, and potentially lead to control problems and lock loss.

Epoxy Solution

One possible solution is to damp the test mass modes with tuned mass dampers. There is a concern that damping the system would increase mechanical loss and result in higher thermal noise. However, the test mass modes are above 50kHz, while thermal noise is a concern around 100Hz. Parametric instability can be mitigated if a damping device that damps higher frequencies more than lower frequencies can be created. Because these dampers must be retrofitted onto the aLIGO mirrors, silicate bonding is not possible. At American University, we are measuring the mechanical loss of different epoxies in order to find a suitable candidate for attaching these dampers to the test masses.

Technique

We find the modal Qs of different silica disks with different epoxies between the disks and a thin top wafer of silica. The position of the epoxies on the silica disks is determined via Finite Element Modeling (FEA).

Interpretation into Mechanical Loss

After obtaining the Qs of the silica disk with epoxy on them, we use the FEA program COMSOL to obtain our mechanical loss phis. The program takes into account the properties of the silica disk and wafer, the Young's modulus of the epoxy, the Qs of the different frequencies, and the bulk and shear properties to determine the phi. This is an ongoing progress, as we still need to find the thicknesses, Young's moduli and related parameters to some of the epoxies.

Epoxies in Progress

Name	Frequency	Quality Factor
Hysol EA 9313	2692 Hz	4.5×10^5
(centered)	6114 Hz	1.2×10^6
	6115 Hz	1.1×10^6
	9370 Hz	1.2×10^6
EP1730	2683 Hz	35,000
(off center)	4077 Hz	300
	9367 Hz	14,000

Epoxies analyzed with FEA

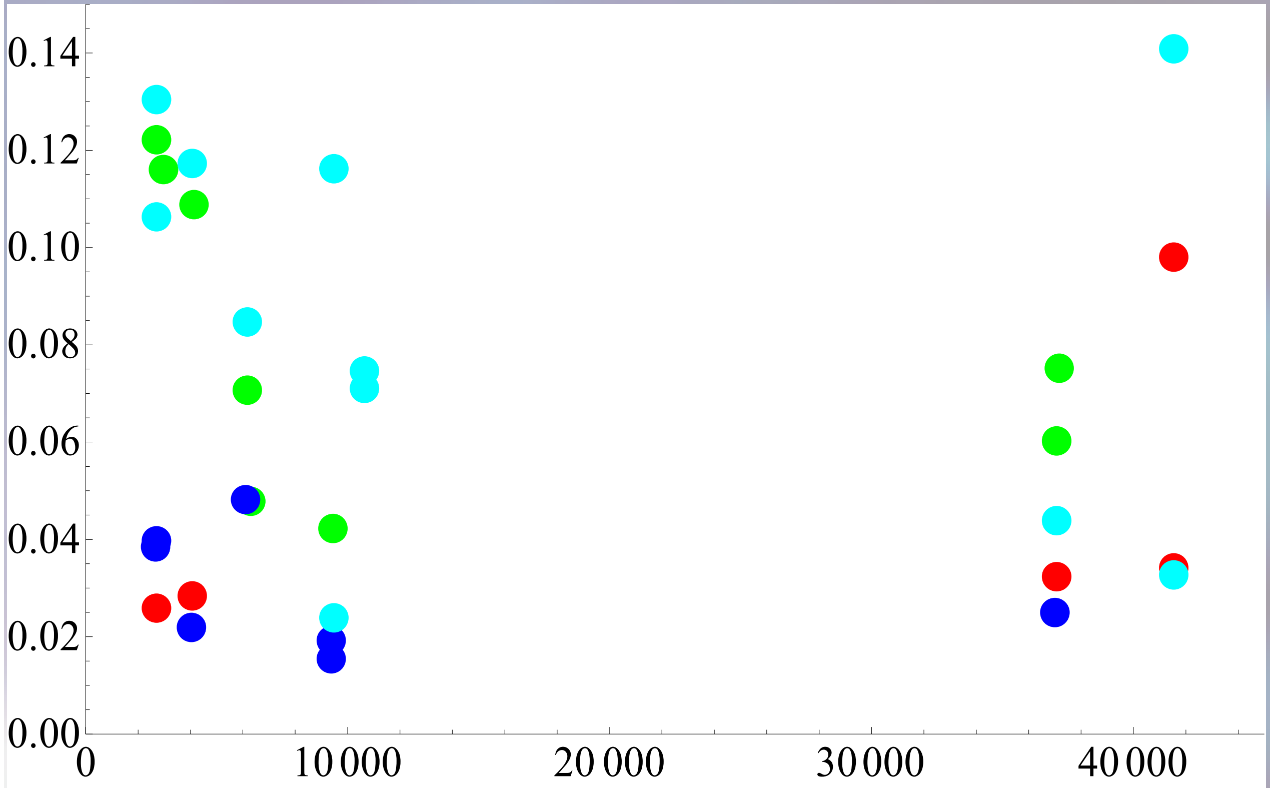
Name	Thickness	Young's Modulus	Viscosity	ϕ
Hysol Tra-Duct 2902	47 µm	4.8 Gpa	20 Pa s	$0.05 \le \phi \le 0.1$
EMI Optocast 3553LV	10 µm	3.4 Gpa	.5 Pa s	$0.01 \le \phi \le 0.05$
Masterbond EP30	10 µm	2.9 Gpa	.02 Pa s	$0.02 \le \phi \le 0.14$
Epotek 353ND	10 µm	3.7 Gpa	12.5 Pa s	$\Phi \approx 0.3$

Future plans with Epotek 353ND

We are adding carbon to EpoTek in an attempt to make it conductive, and then re-test the new mixture for mechanical loss.

  - All bad, some more than others
- Measure Q's, do FE analysis
- See H. Fair poster for details

Epoxy Results



Green – Tra-Duct 2902, conducting

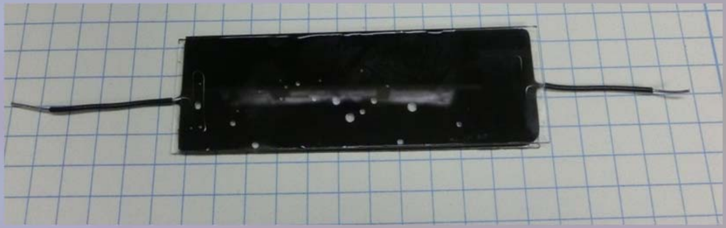
Red – Epotek 353ND, Nergis' lab

Blue – Optocast 3553LV, aLIGO OMC

Cyan – EP 30, aLIGO standoffs

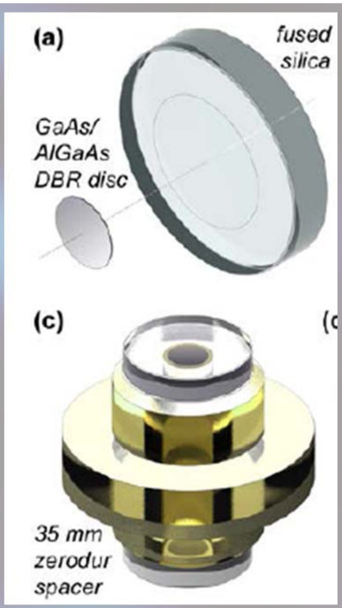
Also Hysol EA9313, EP1730, superglue

- Epotek 353ND now aLIGO vacuum approved
- Adding carbon to Epotek 353ND
  - Make conductive
  - First attempt $> 1\ \mathrm{M\Omega \cdot m}$



Aluminum Gallium Arsenide (AlGaAs)

- Mechanical loss/thermal noise results
  - Low TN in quantum experiments $\varphi \approx 2.5 - 4 \times 10^{-5}$
  - Two Q results on silica substrates $\varphi \approx 1 - 2 \times 10^{-4}$



- Crystalline Mirror Solutions recently able to make larger diameters, up to 10 cm
- Improvement in bond strength
- Flaw in AU/HWS sample due to scratch during transport/handling