Shear and Bulk Mechanical Loss in Titania-Doped Tantala

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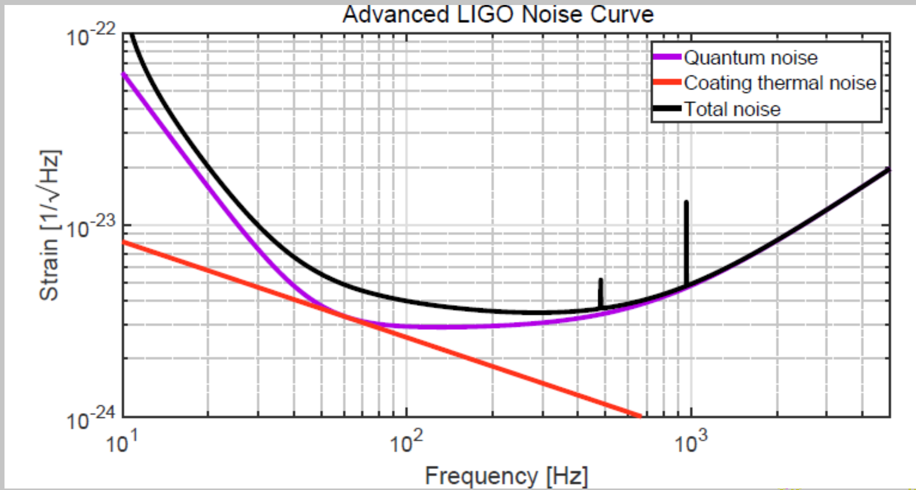
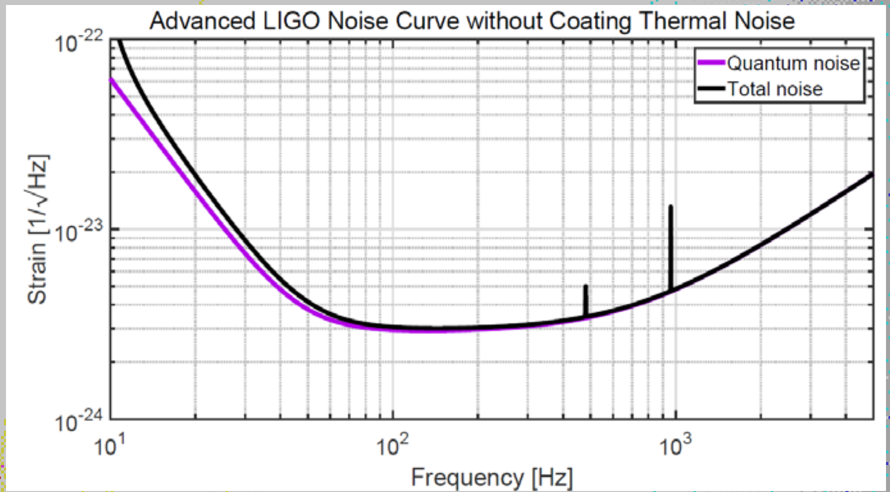
Limitation from Coating Noise





- Coating thermal noise decreases Advanced LIGO design sensitivity between 40-300 Hz
- Reduces astronomical reach

Coating/Inspiral	Binary Neutron Stars	GW150914 Black Holes
aLIGO Coating	190 Mpc	1740 Mpc
No Coating Noise	230 Mpc	2110 Mpc

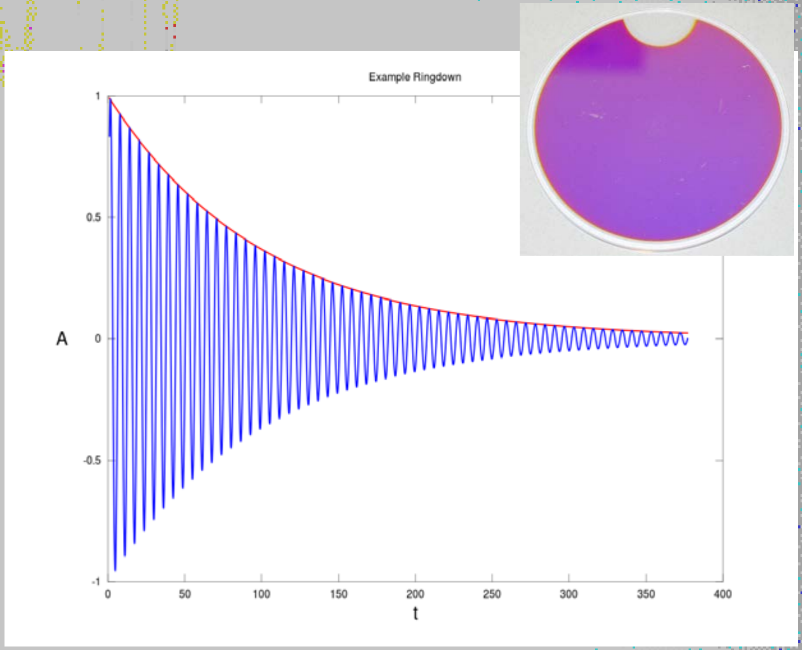
Coating Thermal Noise

$$S_{\mathrm{x,coating}}(f) = \frac{2k_B T}{\pi^2 f} \frac{d\, Y_{\mathrm{coat}}}{w^2 Y_{\mathrm{sub}}^2} \phi$$

- Mechanical loss ϕ crucial to predicting thermal noise
- Not tabulated as not used in many other applications

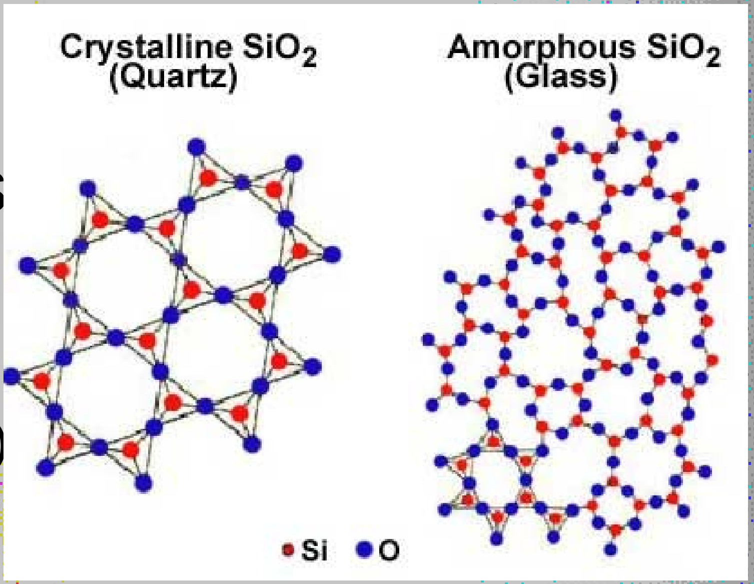
  Also depends on many parameters

- Measured from quality factor Q of normal modes of coated disks
- Mechanical loss of coating contributes to overall energy loss
- Energy loss in silica substrate typically negligible
- Generally no interaction between coating and substrate



Multiple Loss Angles

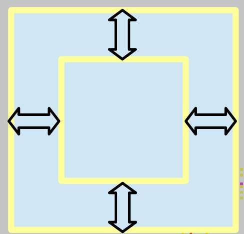
- Current literature reports mechanical loss as single value
- Elasticity theory shows materials have multiple loss angles
  - Imaginary component of elastic constants
  - Amorphous materials have 2 constants (Y, σ)
  - Crystals (AlGaAs, AlGaP, sapphire, silicon) can have more than 2 elastic constants



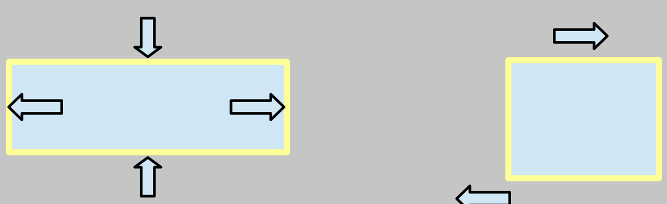
- Hong et al Phys. Rev. D **87** (2013) 082001 showed how to calculate thermal noise from loss associated with shear and bulk strains

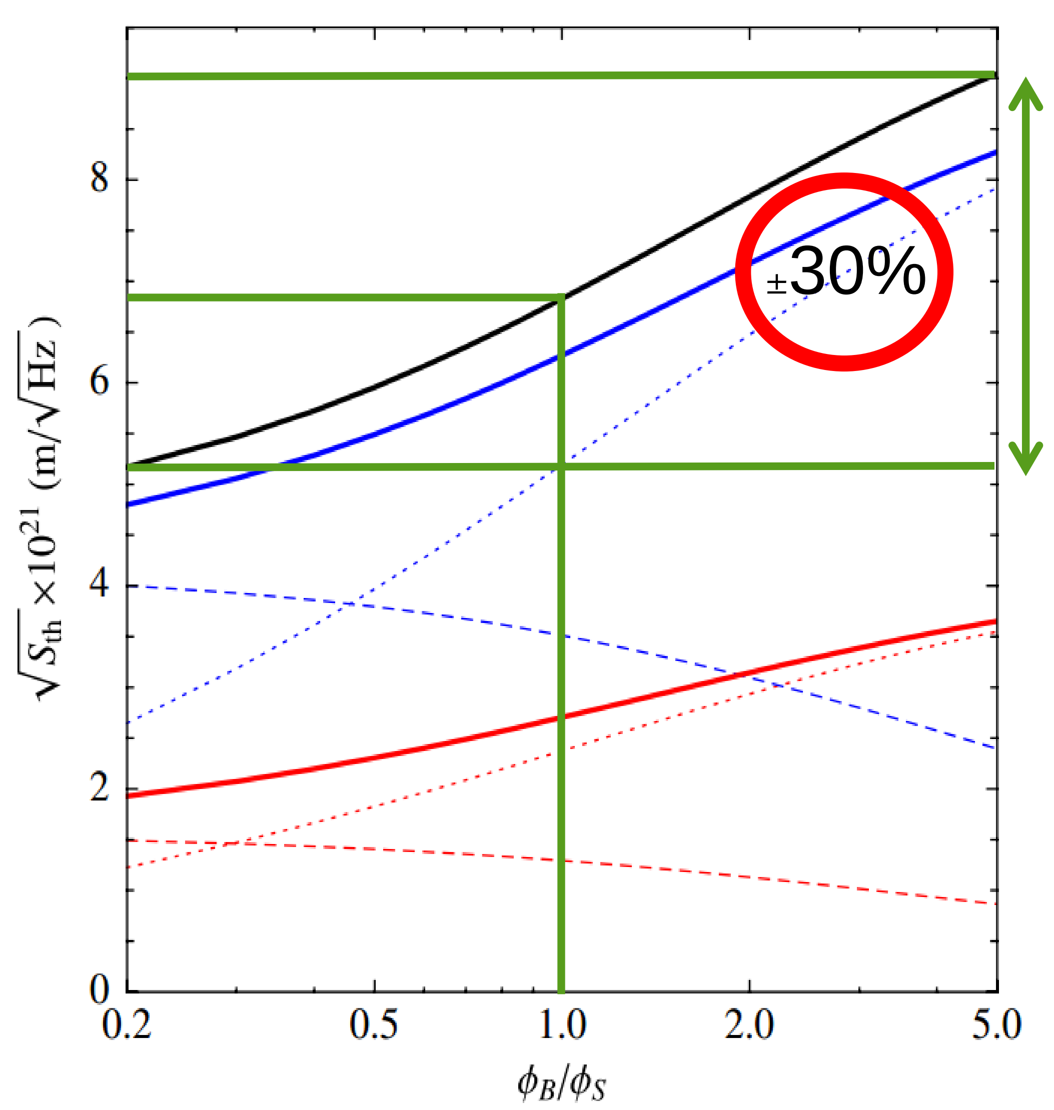
Hong Model

Bulk



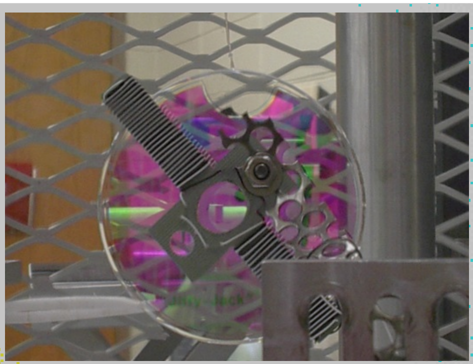
Shear

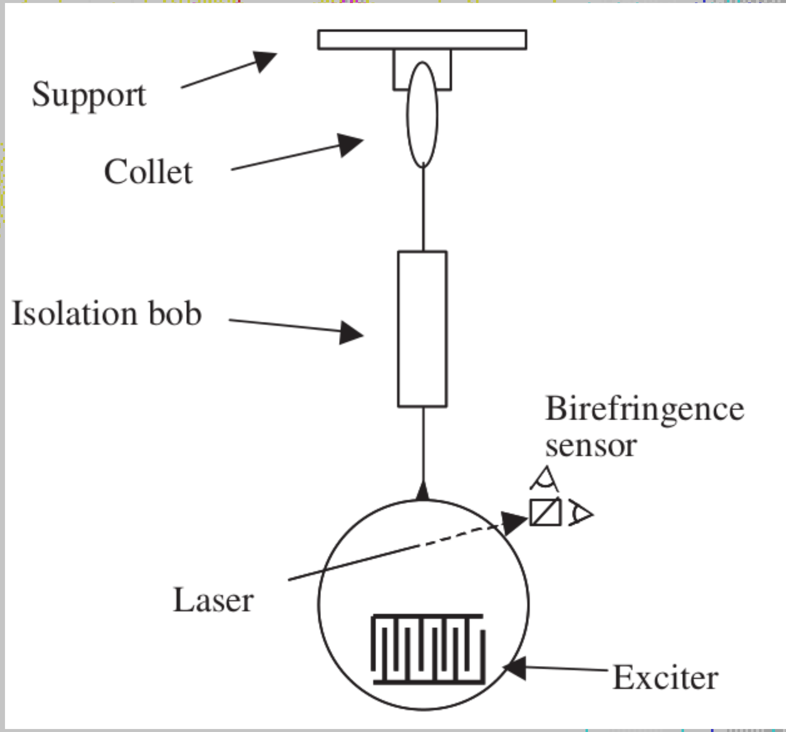




Q Measurements

- 2.5 mm thick silica disk
- Unannealed 25% ti-ta coating from CSIRO
- 500 nanometer thick
- Q measuring
  - Silica suspension
  - Electrostatic exciter
  - Birefringence readout
- Also measured Young's modulus

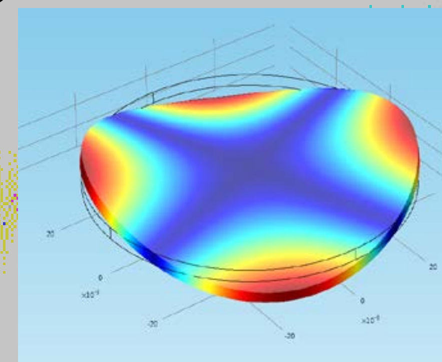


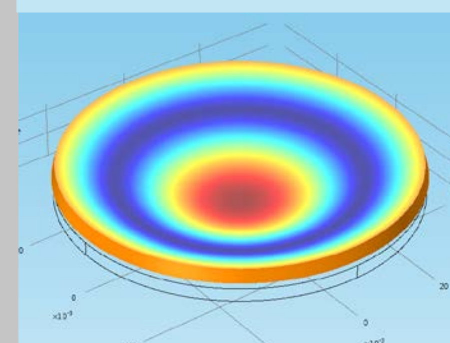


Modes and Energies

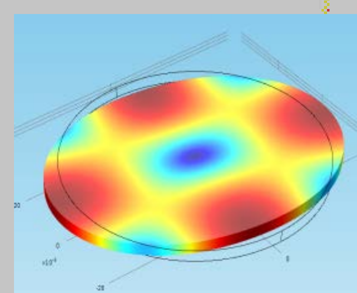
$$\frac{1}{Q} = \phi_{\mathrm{sub}} + \frac{U_{\mathrm{bulk}}}{U_{\mathrm{tot}}}\phi_{\mathrm{bulk}} + \frac{U_{\mathrm{shear}}}{U_{\mathrm{tot}}}\phi_{\mathrm{shear}}$$

- Measure Q of multiple modes
- Solve for shear and bulk loss of modes with nearby frequencies
- Use finite element analysis to get shear and bulk energy ratios



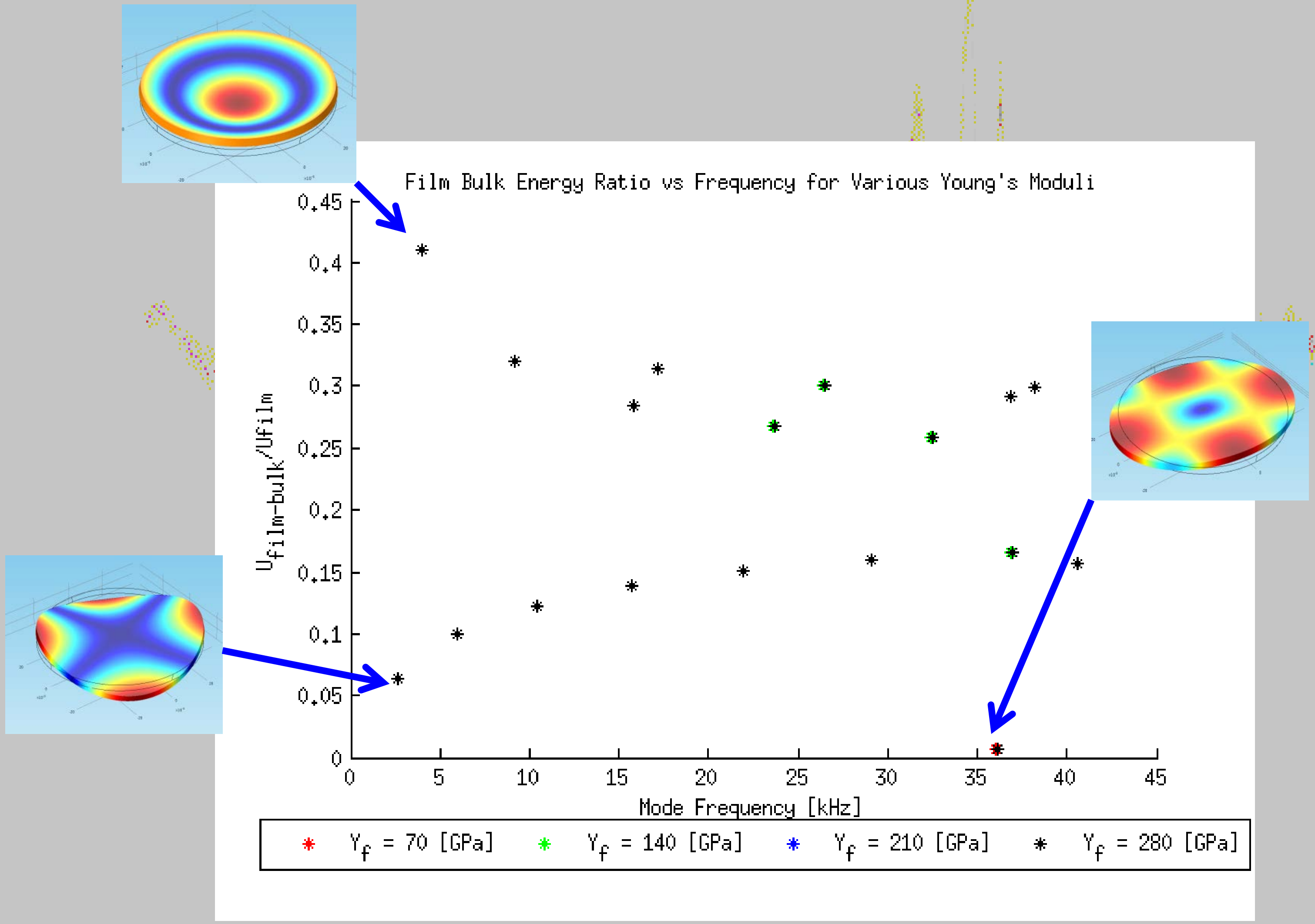


$$U_{\mathrm{bulk}} = \int_{\mathrm{coat}} \frac{K}{2} \Theta^2 \mathrm{d}V$$



$$U_{\mathrm{shear}} = \int_{\mathrm{coat}} \mu \, \Sigma_{ij} \Sigma^{ij} \, \mathrm{d}V \qquad U_{\mathrm{tot}} = U_{\mathrm{shear}} + U_{\mathrm{bulk}} + U_{\mathrm{sub}}$$

Energy Ratios



Fit Procedure

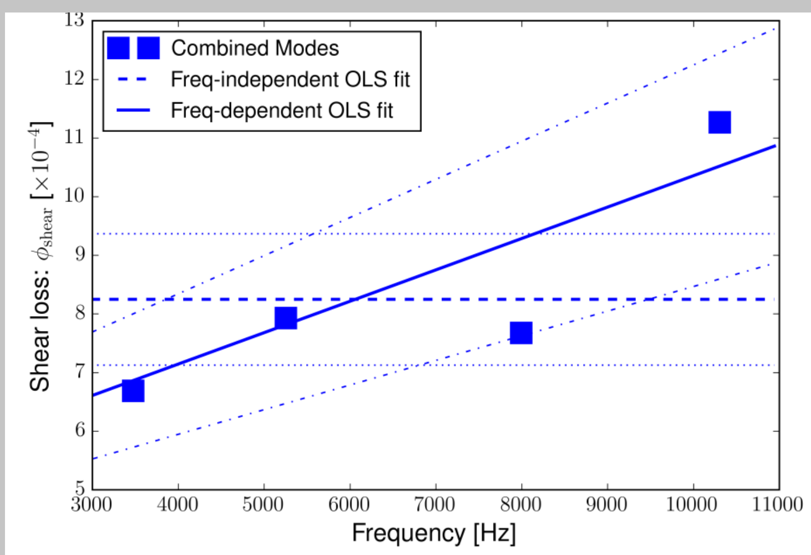
- Assume loss angles are the same at modes with nearby frequencies (weak $\phi_{\text{shear}}(f)$ and $\phi_{\text{bulk}}(f)$)
- Two modes, solve for ϕ_{shear} and ϕ_{bulk}
  Associate ϕ's with average frequency
- Repeat with first five modes, giving four separate results for ϕ_{shear} and ϕ_{bulk}
- Least squares fit to find frequency dependence

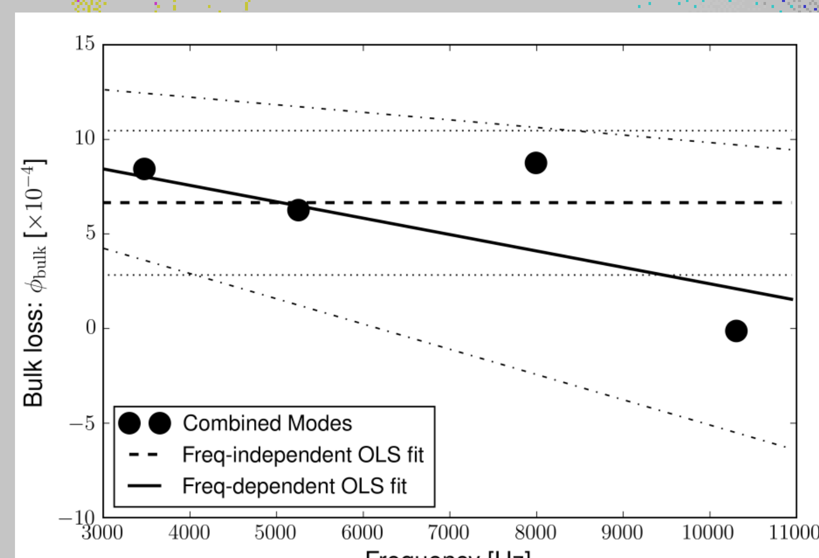
Modes	Ave Frequency	$\phi_{\text{shear}}(\times 10^4)$	$\phi_{\text{bulk}}(\times 10^4)$
1 and 2	3476 Hz	6.7 ± 0.2	8.4 ± 0.8
2 and 3	5251 Hz	7.9 ± 0.3	6.3 ± 1
3 and 4	7994 Hz	7.7 ± 0.4	8.8 ± 2
4 and 5	10306 Hz	11 ± 0.7	-0.1 ± 3

Fits to ϕ data

$$\phi_{\text{shear}} = (5.0 \pm 0.7) \times 10^{-4} + (5.4 \pm 1.2) \times 10^{-8} f$$
$$\phi_{\text{bulk}} = (11.0 \pm 2.8) \times 10^{-4} - (8.7 \pm 4.7) \times 10^{-8} f$$

$$\phi_{\text{shear}} = (8.3 \pm 1.1) \times 10^{-4}$$
$$\phi_{\text{bulk}} = (6.6 \pm 3.8) \times 10^{-4}$$





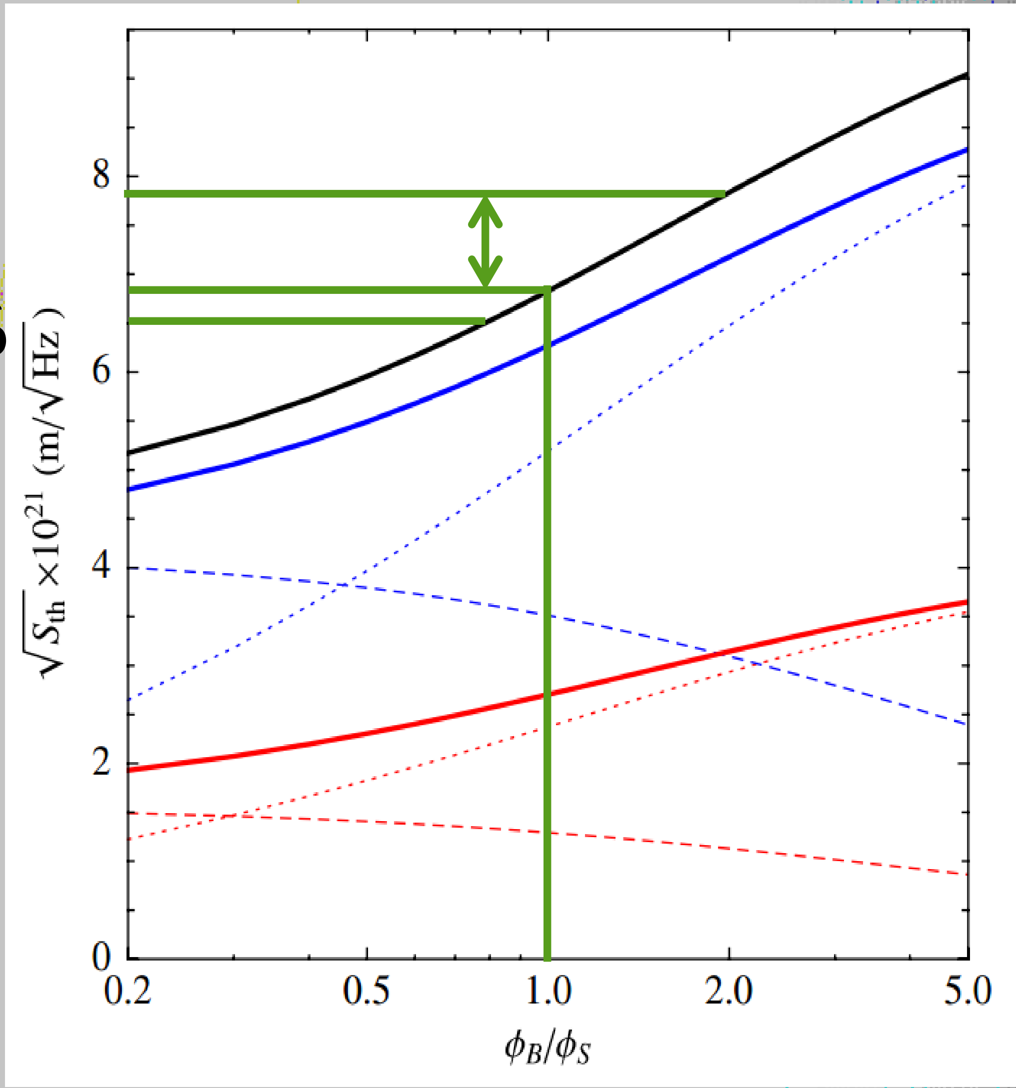
Impact on Thermal Noise

Frequency dependent

$$\frac{\phi_{\text{bulk}}(100\text{ Hz})}{\phi_{\text{shear}}(100\text{ Hz})} = 2.2 \pm 0.6$$

Frequency independent

$$\frac{\phi_{\text{bulk}}}{\phi_{\text{shear}}} = 0.8 \pm 0.5$$



Naïve impact on aLIGO

	Binary Neutron Star Range	GW150914 Range
Single ϕ Model	188 Mpc	1745 Mpc
Two ϕ Model	182 Mpc	1697 Mpc

- Predict ~15% increase in coating thermal noise
  Similar to Gras *et al.* Phys. Rev. D **95** (2017) 022001
- About 3% decrease in inspiral ranges
- About 10% impact on event rates
- *Measured coating was not Advanced LIGO coating: CSIRO, not annealed vs LMA annealed*

Possible LIGO A+ Improvement

- If these values for ϕ_{shear} and ϕ_{bulk} hold for LMA titania doped tantala
  - Could optimize coating design
  - Restore the 10% loss in rate

- Optimize to actual values
  - Possible fallback LIGO A+ strategy
  - No new technology
  - Layer thickness changes
  - Some impact on performance
  - Maybe up to ~10% in noise, ~30% rate (?)

Follow Up Work

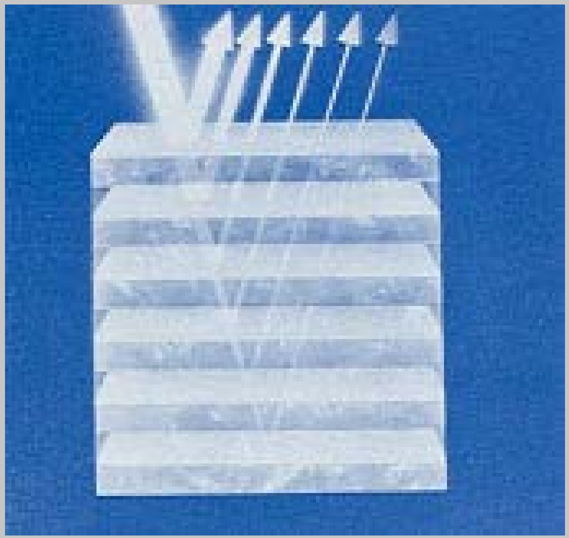
- Anneal this sample and remeasure
- Measure LMA annealed sample

  Thinner substrate

  Lower mode frequencies

  More energy in coating

- Improve Q and energy ratio uncertainties



  - Measure thin film silica
  - Measure other amorphous materials
  - Develop optimization code
  - Further theory work for crystals

    Lovelace et al working on this

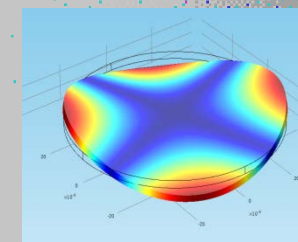
  - Direct thermal noise measurements

    AEI results with AlGaAs

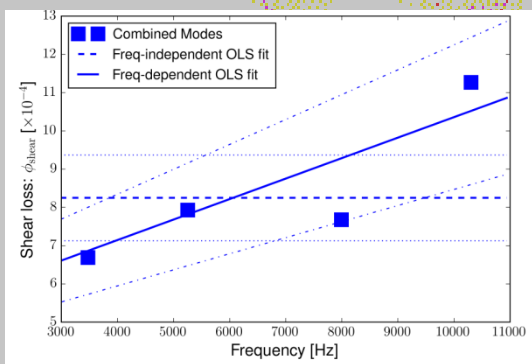
Summary

- Experimental technique works

  Thin disks have shear and bulk energy



- Suggestive of frequency dependence
- Need lower uncertainties/more measurements



- 2nd Gen detector noise may be higher than expected
- Possible improvement with LIGO A+

  Not full 2X improvement
- Explore more materials
- Important issue for crystals

  Sapphire, silicon, AlGaAs, AlGaP, etc.