High Fidelity Probe and Mitigation of Mirror Thermal Fluctuations

Direct observation of Brownian noise in SiO_2/ Ta_2O_5 coatings and a plan for optimizing Thermo-Optic noise in AlGaAs coatings.

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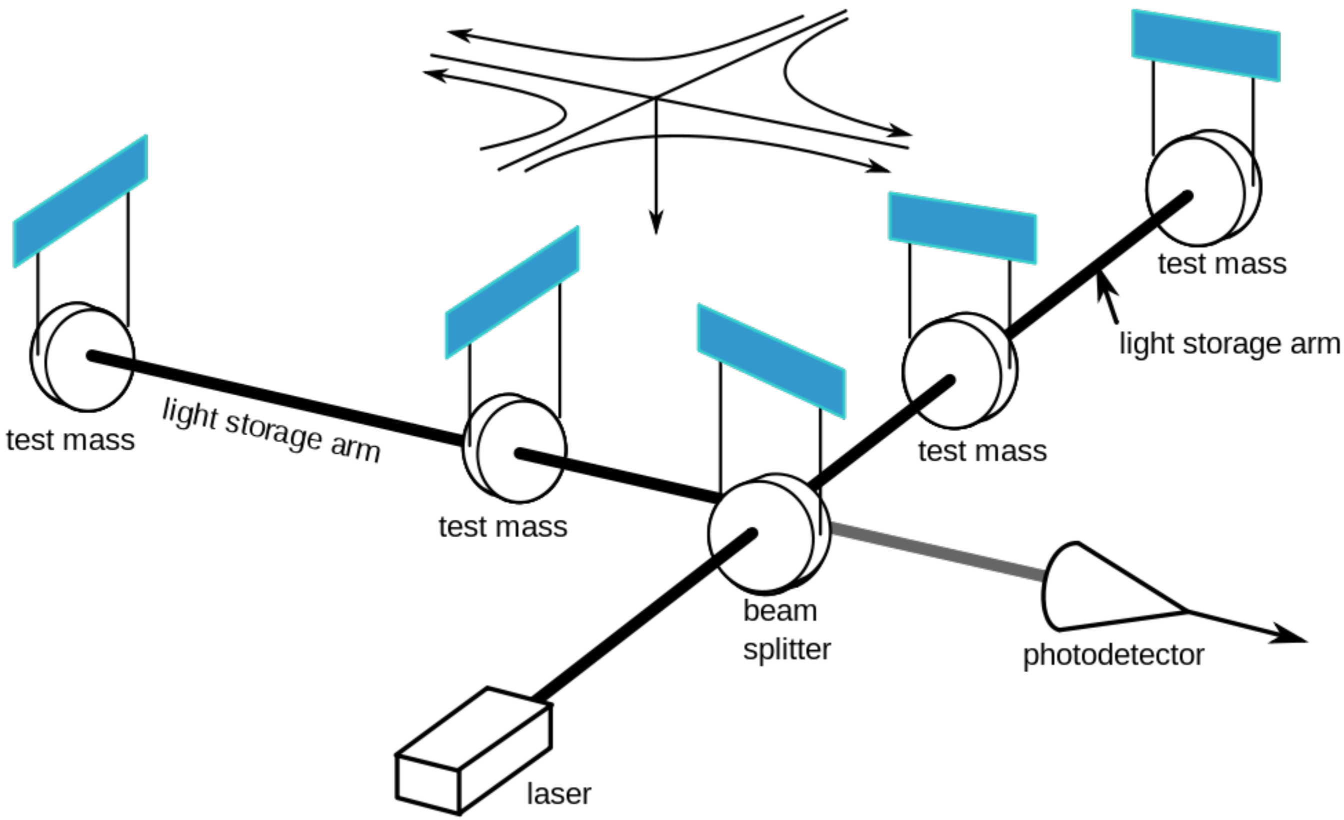
Introduction to Thermal Noise

- Motion of molecules, atoms due to thermal energy $k_B T$

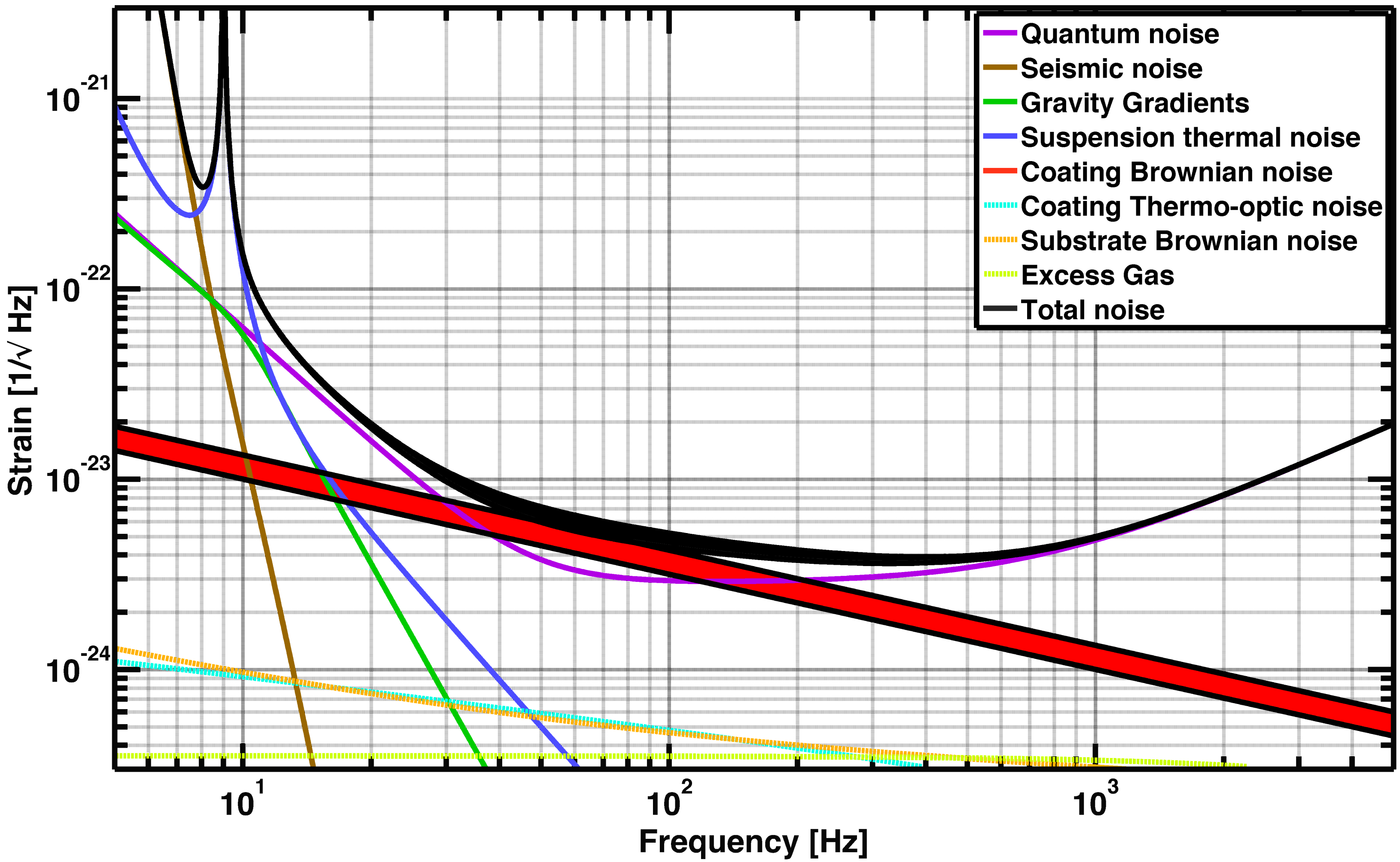
- Johnson-Nyquist Noise in resistors (due to electrons motion),
- Brownian Motion of a particle suspended in liquid (due to collisons from liquid molecules).

Schematic Diagram of LIGO

- Thermal noise in LIGO



aLIGO Noise Budget



Thermal Noise calculation

- Fluctuation-Dissipation Theorem: Loss and Noise are related.

$$S_x(f) = \frac{2k_B T}{\pi^2 f^2} \frac{W_{diss}}{F_0^2}$$

- **Mechanical Loss**: dislocations, impurities in materials, can be represented as an imaginary part in the Young's modulus, $E = E_0(1+i\phi)$.
  - Causes Brownian noise
- **Heat flow loss**: dissipation due to heat flow down temperature gradients.
  - Causes temperature fluctuations

Direct Approach For an Optical System

- Applying force with Gaussian profile
- Calculate dissipated power due to the applied force

- For Brownian noise:

$$W_{Brownian} = 2\pi f U_0 \phi$$

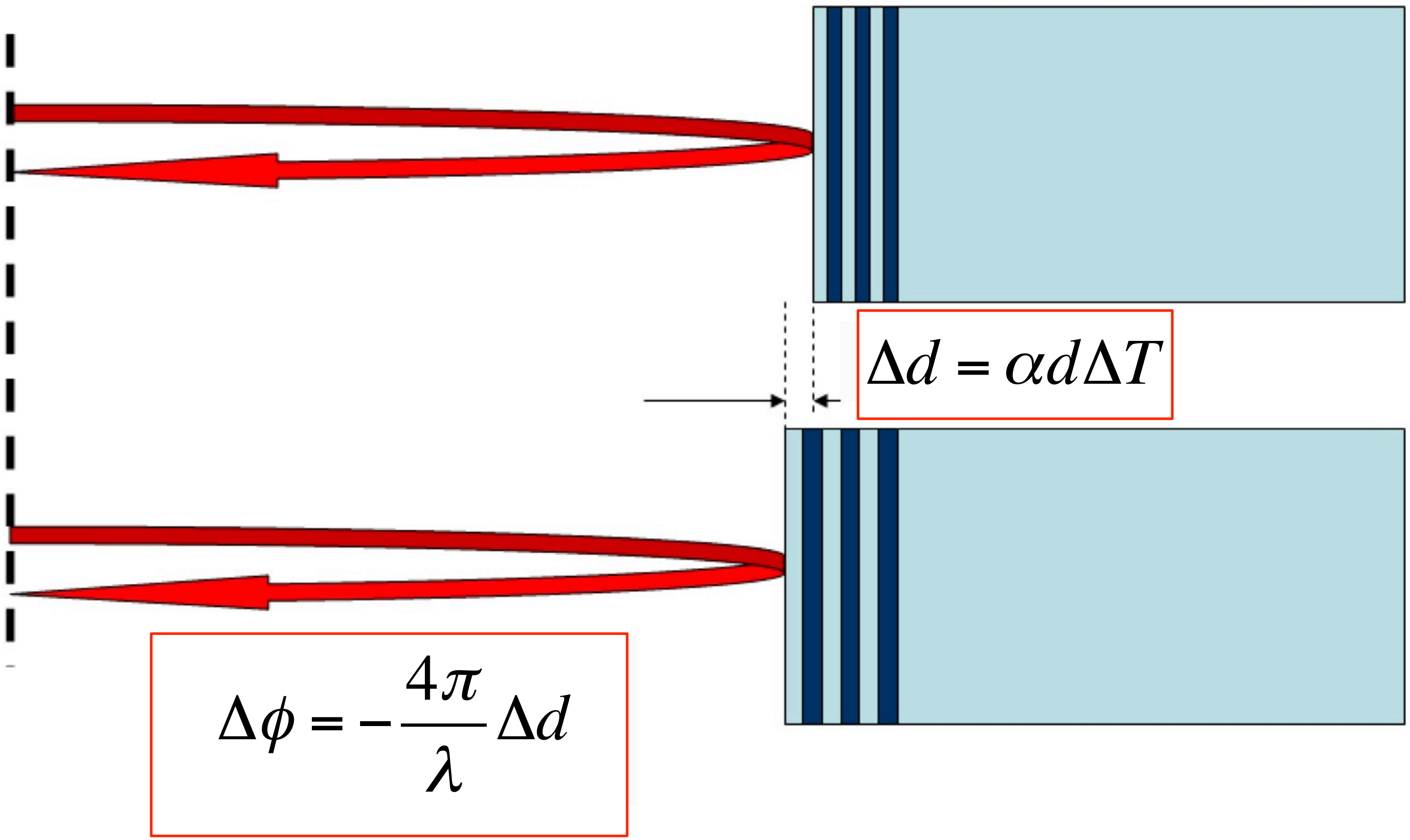
- For temperature fluctuations:

$$W_{thermo} = \left\langle \int d^3 r \frac{\kappa}{T} (\nabla \delta T)^2 \right\rangle$$

- For an optical system, temperature noise is converted to displacement noise by thermal expansion coefficient α and thermorefractive coefficient β.

Review: Thermo-Optic Noise

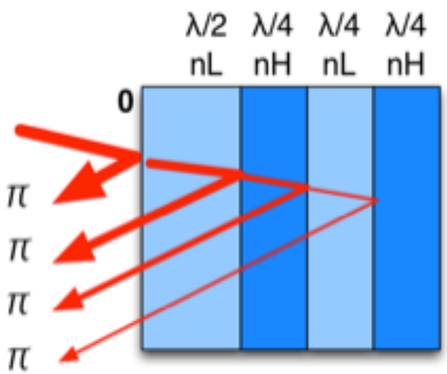
- **Thermo-Elastic (TE):** Mirror's surface expands into probe beam. By convention, negative dφ/dT

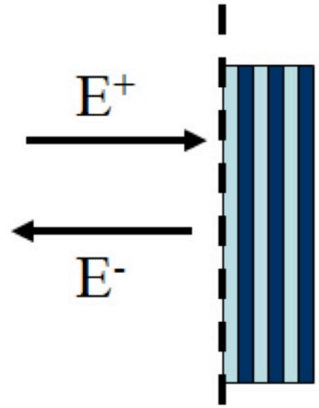


[Ogin 2013]

Review: Thermo-Optic Noise(2)

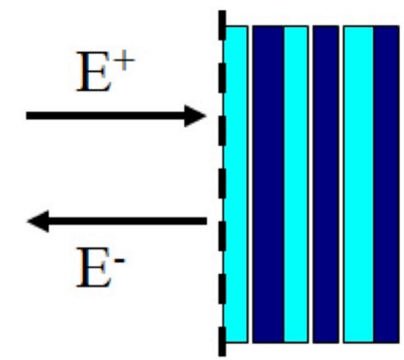
- **<u>Thermo-Refractive (TR):</u>** Coating layers deviate from λ/4 condition – due to both physical expansion and change in index of refraction. To first order, this manifests as a change in the phase of the reflected beam.





Quarter-wave stack:

$$E^{-} = E^{+} r e^{i\varphi} \cong -E^{+}$$



After expansion, index change:

$$E^{-} = E^{+} r' e^{i\varphi'} \cong E^{+} r e^{i(\varphi + \Delta\varphi_{TR})}$$

$$= -E^{+} e^{i\Delta\varphi_{TR}}$$

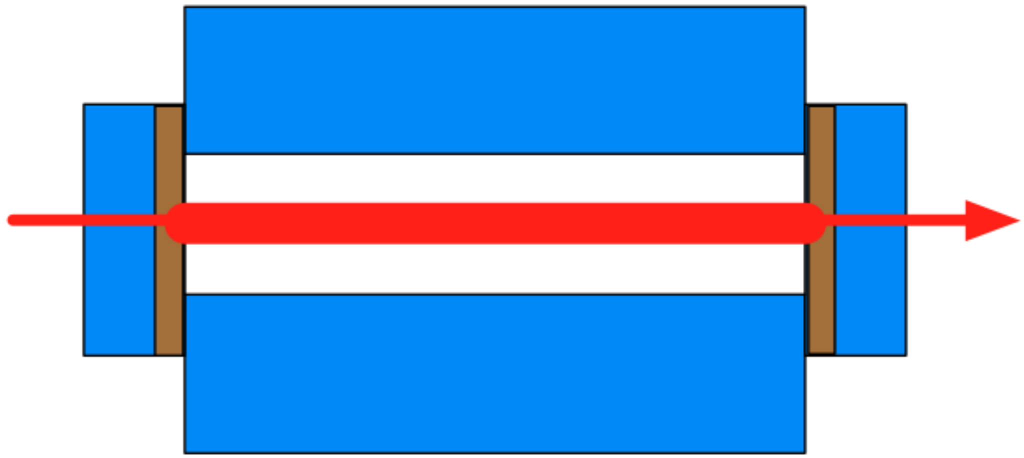
[Ogin 2013]

Direct Measurement

- Previous experiments (Numata,TNI)
  - Measured coating Brownian noise in 500 – 10 kHz band.
  - Large substrates.

- Develop a setup that can measure coating thermal noise around 10 Hz – 1 kHz.
  - Use commercial 1-inch diameter substrate
  - Use fixed-spacer Fabry-Perot cavity

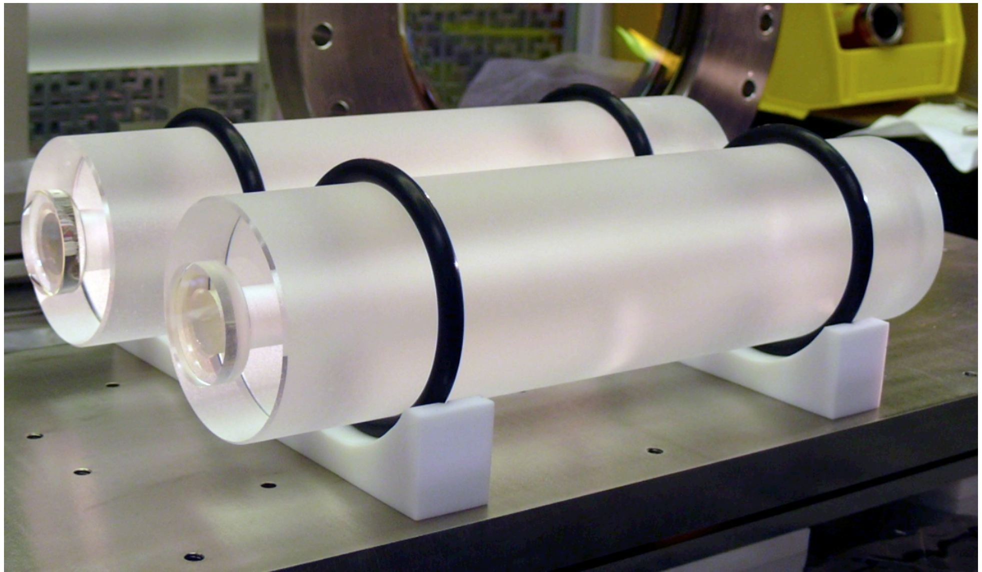
Thermal Noise in Fixed-Spacer Cavity



	Brownian	Thermo-elastic	Thermo-refractive
Coating	yes	**Thermo-Optic Noise**	
Substrate	yes	yes	negligible
Spacer	yes	yes	no

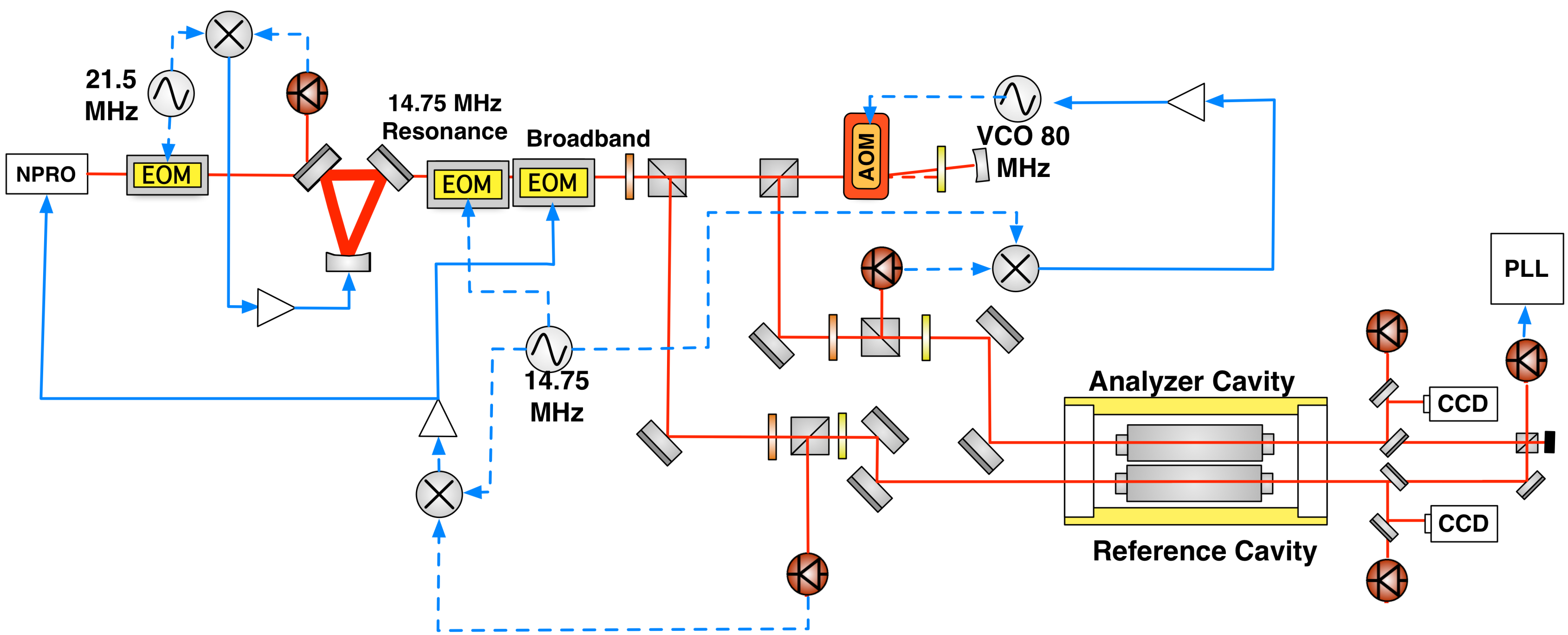
iLIGO Reference Cavity

- SiO_2 spacer
- SiO_2 substrates
- SiO2/Ta2O5 Coatings, 27 Layers + λ/2 cap (28 layers total).
- Coated by REO in 1998, Ion beam sputtering method.
- Coating Brownian noise limits the cavity sensitivity

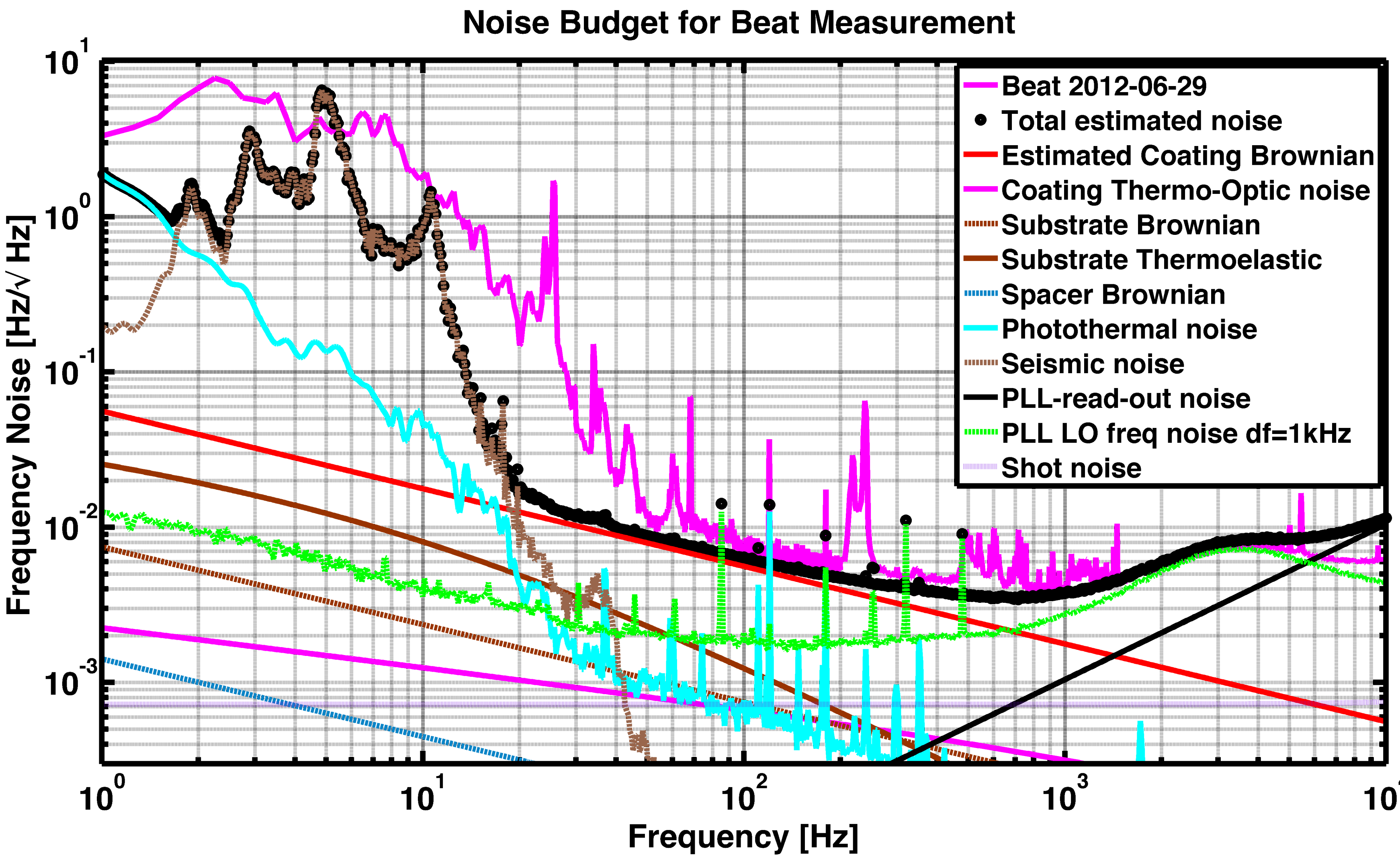


Setup with 8 Inch Cavities

- Main beam is locked to the first cavity
- Second beam is frequency shifted by a doubled passed AOM, and locked to the second cavity
- Transmitted beams are recombined and readout by Phase Locked Loop (PLL).



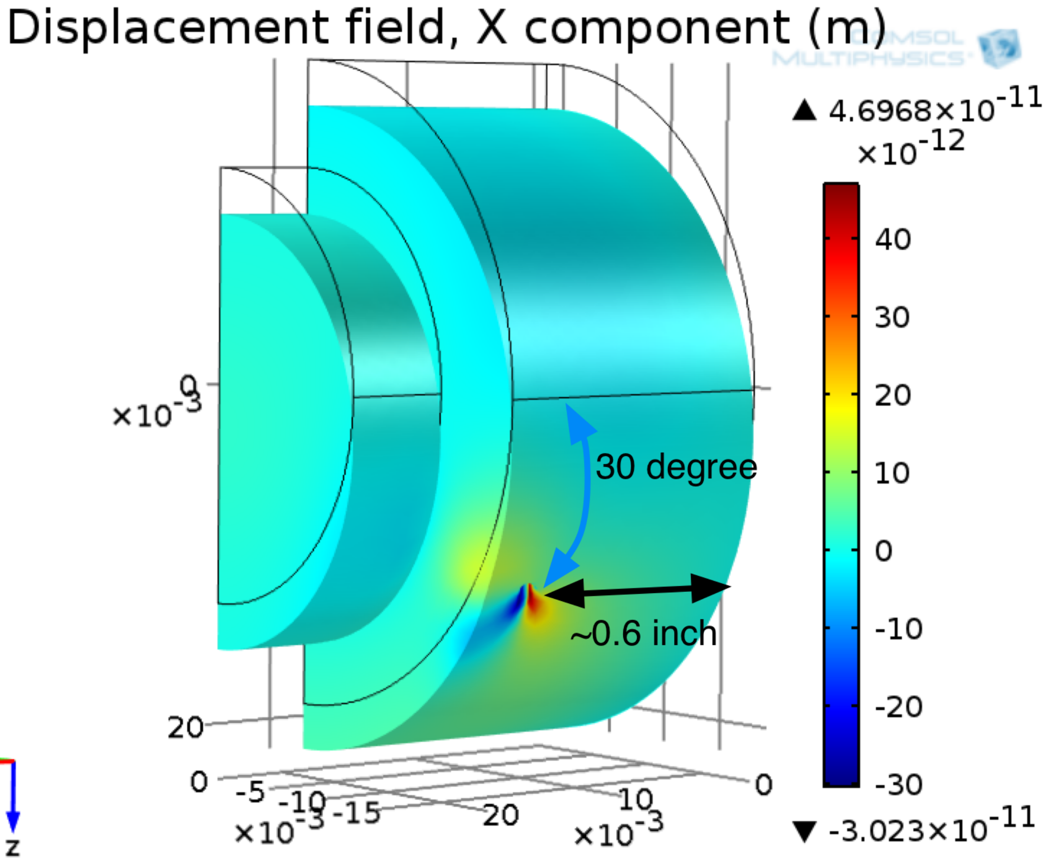
Result: 8 Inch Cavities

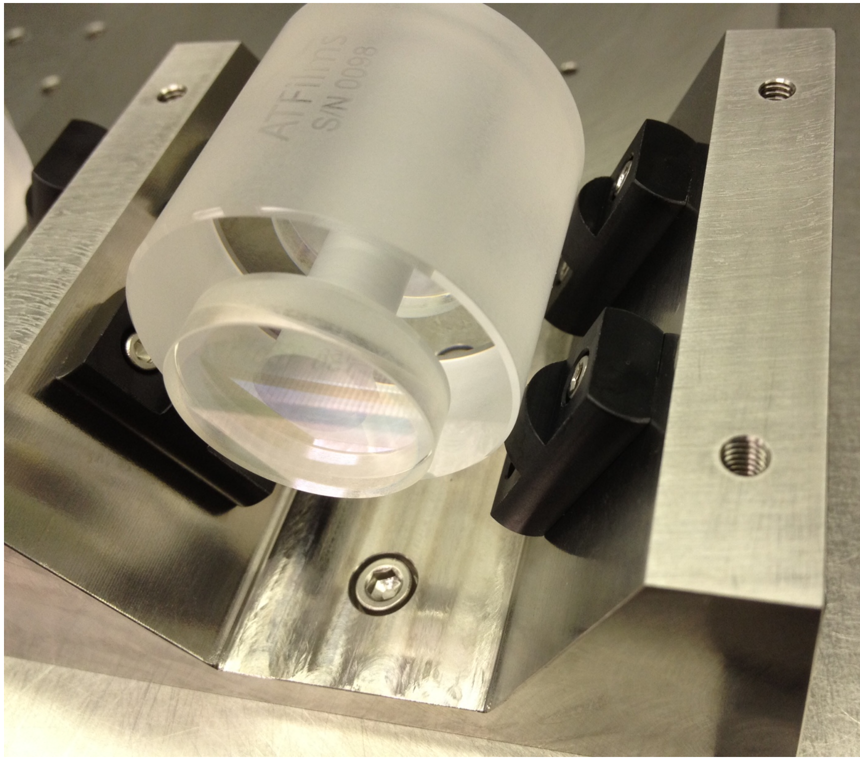


Improvements in Experimental Setup

- Shorter cavity raises frequency noise $$\frac{\delta\nu}{\nu} = \frac{\delta L}{L}$$
- Shorter cavity gives smaller spot size for similar mirrors (same radii of curvature, same coating run).
- The lower bound of the cavity length is determined by the ability to tune the cavity via thermal expansion, higher order mode consideration, and cavity stability.
- Use two lasers instead of one. The beat frequency is not limited by the operational range of the AOM.
- Similar cavities provide common mode rejection

Optimum Support for Cavity

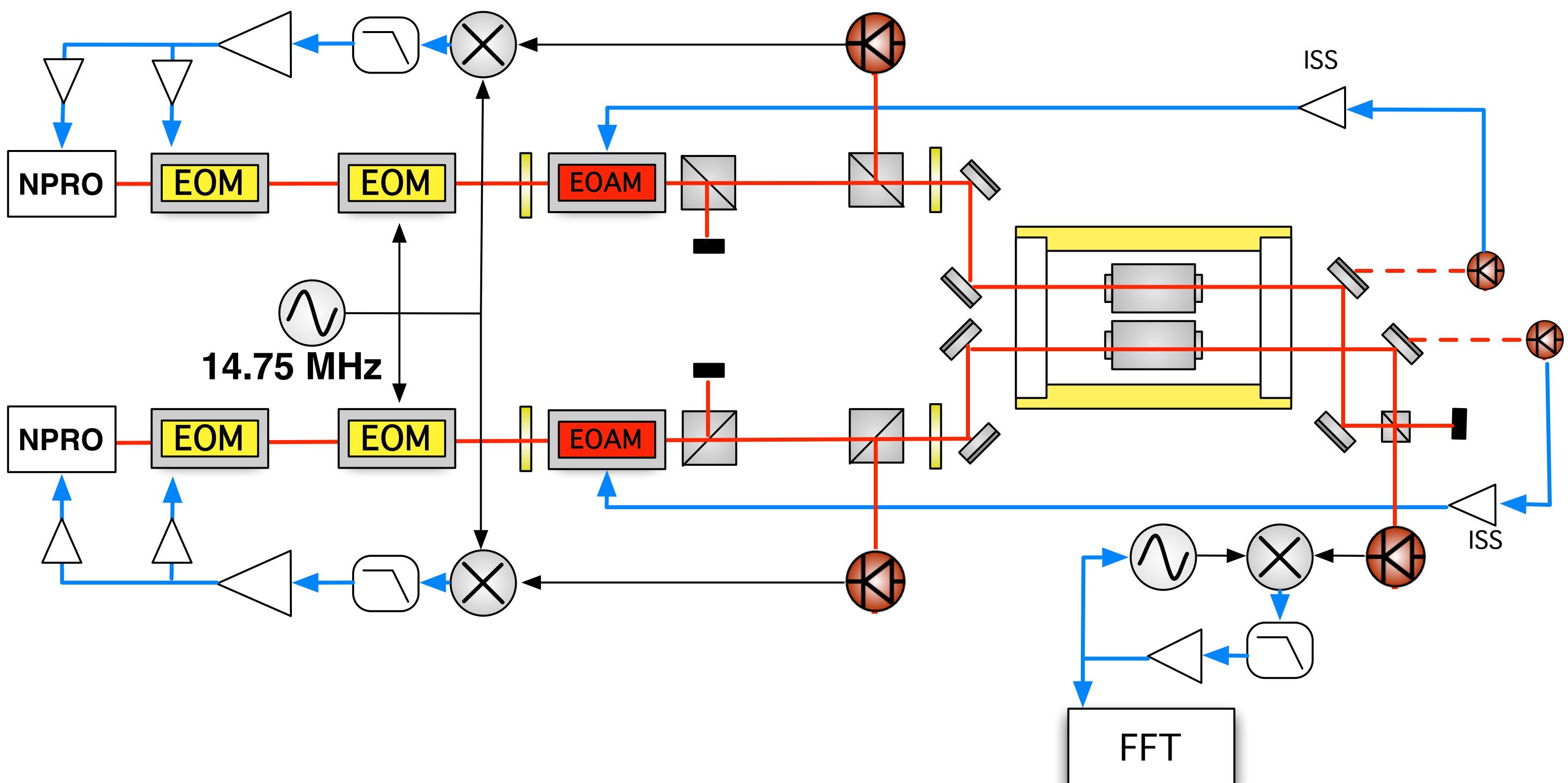




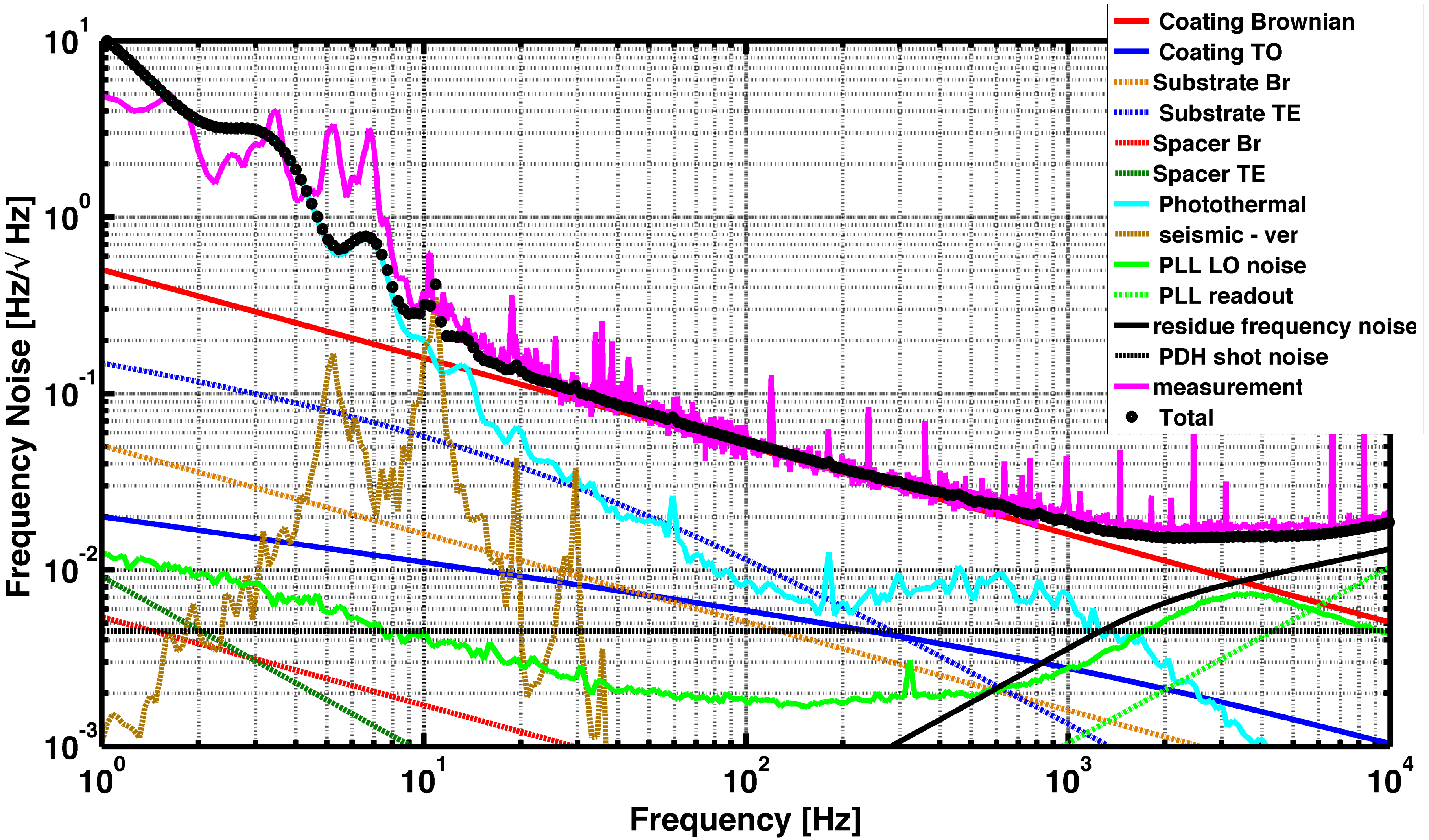
-1.45” cav Strain ~ 10^{-10} [s^2/m], with common mode ~ $6x10^{-12}$[s^2/m]
-Ludlow 2007/Alnis 2008: football shaped cavity ~ $5x10^{-11}$[s^2/m]
-Webster 2008: ~ 3 x 10^{-12} [s^2/m]

2 Laser Setup

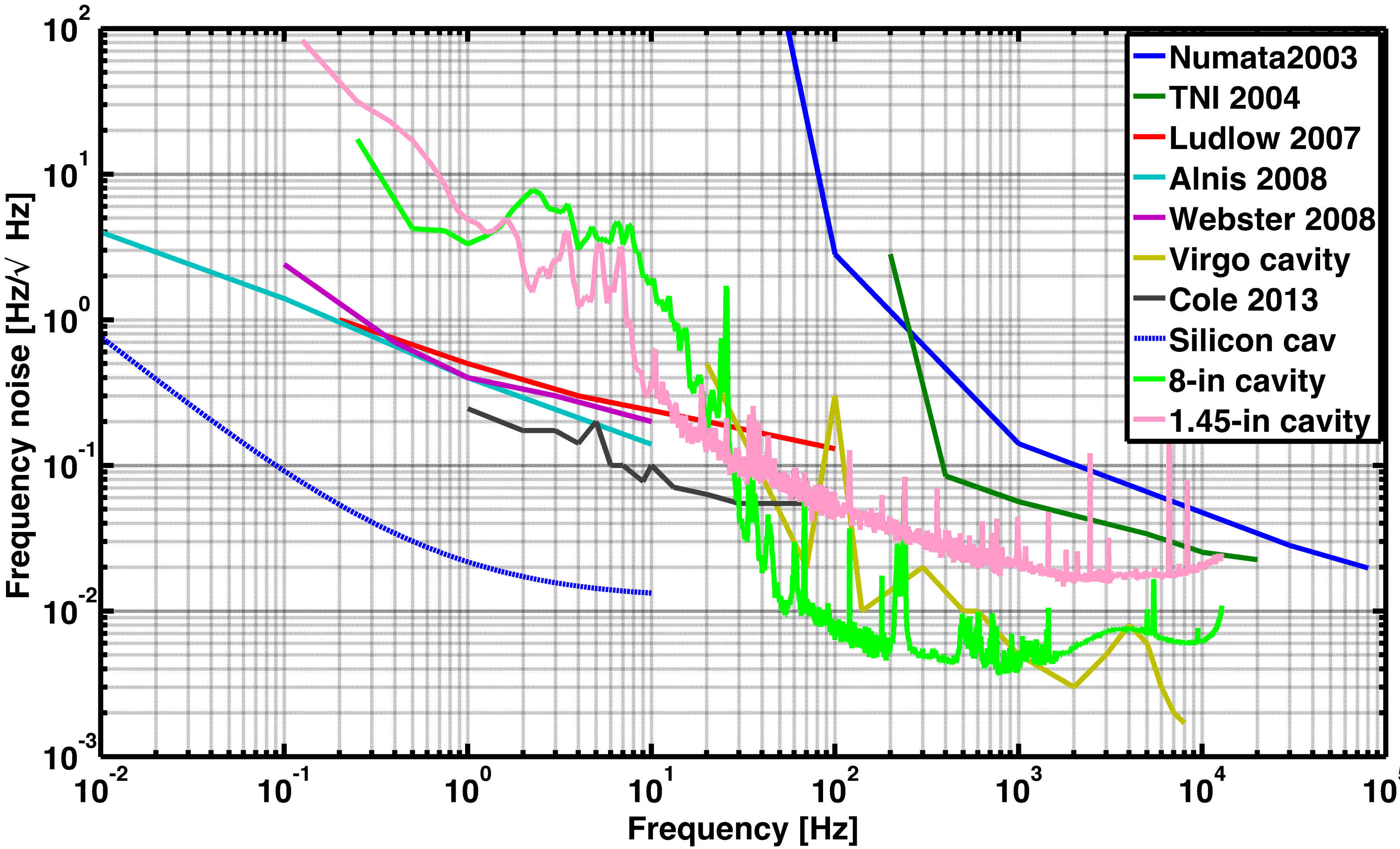
- Increase Coating Brownian Noise: Use Shorter Cavity (see details in LIGO-T1200057-v11)
- Spotsize ~200um, similar mirrors from the same coating run



Result: 1.45 Inch Cavities



Comparison with Other Exps



Loss Angle Extraction

- Nakagawa et al. 2002 (assuming coatings and substrate have the same elastic properties)

$$S_x^{(\mathrm{cBr})}(f) = \frac{4k_\mathrm{B}T}{\pi^2 f}\frac{\left(1-\sigma_\mathrm{s}-2\sigma_\mathrm{s}^2\right)d}{w^2 E_\mathrm{s}}\phi_\mathrm{c}.$$

- Numata et al. 2003: $\Phi_c = 4\mathrm{x}10^{-4}$
- From our measurement: $\Phi_c = 4.2\mathrm{x}10^{-4}$

- Three pieces of evidence suggest that the measured result is coating Brownian noise

1. The slope of the spectrum goes with 1/f.
2. Φ_c is comparable with previous measurement.
3. Thermal noise scales correctly with spot size.

Comparison with Another Calculation

- Hong et al. 2013, calculate coating Brownian noise in bulk and shear deformations.
- If $\phi_{SHEAR} = \phi_{BULK}$, the estimated thermal noise is

$$S_x(f) = c_1\phi_L + c_2\phi_H$$

- With nominal parameters ($\phi_L = 1\times10^{-4}$, $\phi_H = 4\times10^{-4}$)

$S_{cal}/S_{mea} = 0.6$

Comparison with Ring Down Result

- Harry et al. 2002 reported the coating loss due to multilayer of SiO2/Ta2O5 (same coating vendor, around the same time).

$$\phi_{\parallel} = \frac{Y_L d_L \phi_L + Y_H d_H \phi_H}{Y_L d_L + Y_H d_H}$$

Y = young's modulus
d = layer thickness

With our measurement, we can obtain **Φ_L** and **Φ_H**.

$$\phi_L = (1.1 \pm 0.3) \times 10^{-4},$$

$$\phi_H = (8.2 \pm 0.3) \times 10^{-4}.$$

	Penn 2003	Crooks 2004	Crooks 2006	LMA 2014
Φ_L $\times 10^{-4}$	0.5±0.3	0.4±0.3	1±0.2	0.62±0.4
Φ_H $\times 10^{-4}$	4.4±0.2	4.2±0.4	3.8±0.2	4.5±0.3

- Higher loss might be due to contaminants during the deposition process.

AlGaAs for High Reflective Coating

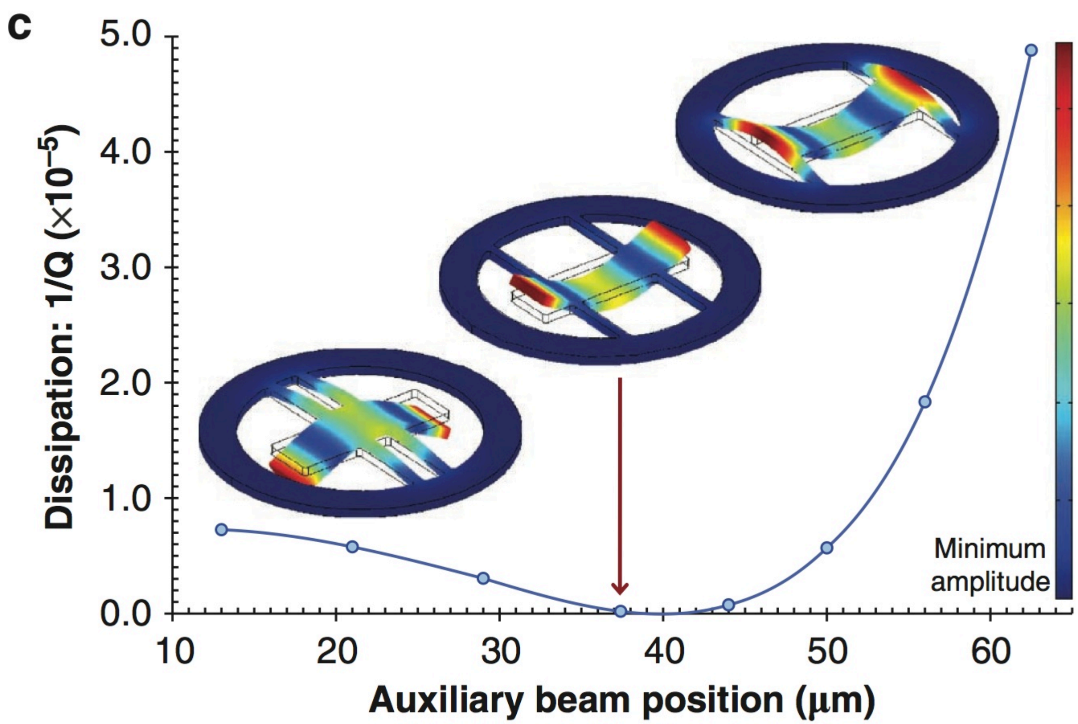
AlGaAs

- Hetero structure of GaAs and $Al_xGa_{1-x}As$.
- It has been used as a high reflective device in a laser since 1980s.
- Optical properties have been well studied.

- Epitaxial Lift Off technique makes it possible to attach AlGaAs film on a fused silica substrate.

AlGaAs Coatings

- Low loss ~ $2.5x10^{-5}$, at room temp as measured on free standing mechanical resonators.
- Loss at 20K is ~ $2x10^{-5}$, good candidate for Si substrate at cryogenic temperature



Cole et al. 2011

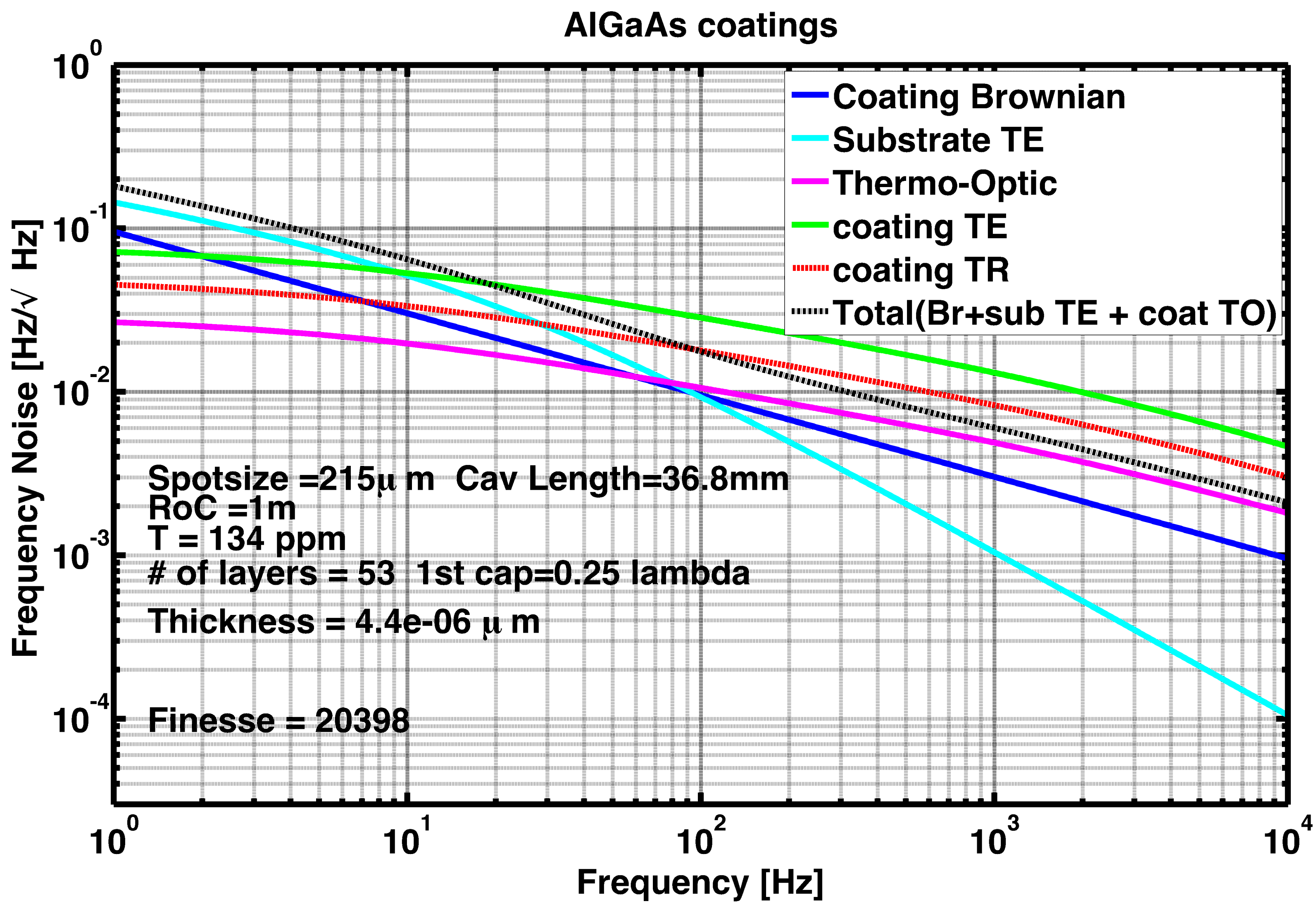
LIGO

Thermo-Optic noise in AlGaAs

- Higher Thermal expansion, Thermorefractive coefficient (dn/dT)
- Thermo-Optic noise is higher than Brownian noise

	α (x10^{-6}) [1/K]	β (x10^{-6}) [1/K]
SiO_2	0.5	8
Ta_2O_5	3.6	14
GaAs	5.7	366
$Al_{0.92}Ga_{0.08}As$	5.2	179

Noise Budget: QWL T~150ppm



How to Reduce TO Noise

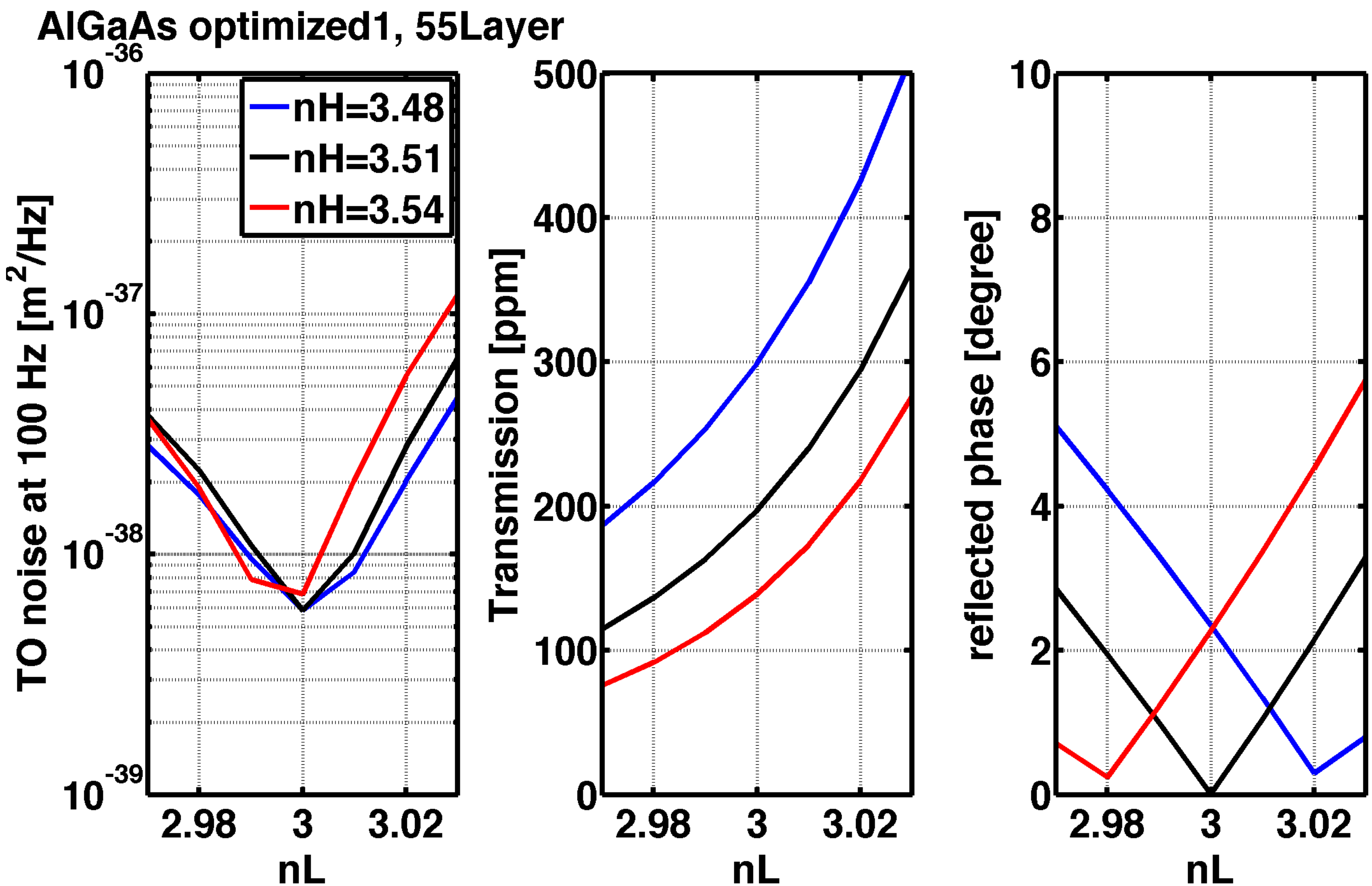
- Alter layer thickness, to change β_{eff}
- Achieve required transmission (100 ppm – 300 ppm)
- Get correct reflected phase (to prevent surface burning)

- Use fminsearch for minimizing a cost function.
- Cost function can be given by these three parameters:

$$y = (\text{TO noise})*w_1 + (\Delta\text{Transmission})*w_2 + (\Delta\text{Reflected phase})*w_3$$

LIGO

Optical Properties vs nH and nL: Optimization with Single Cost Function

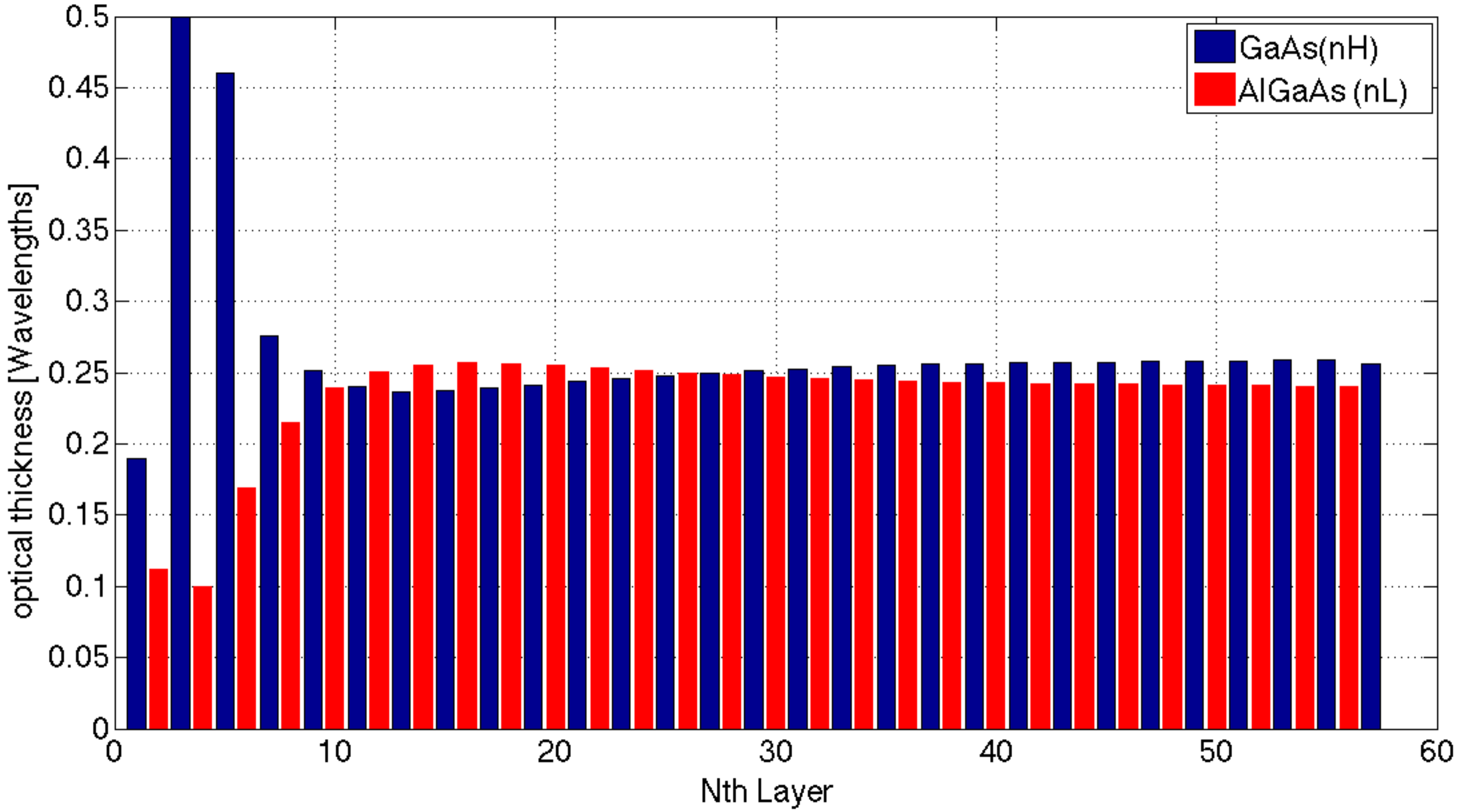


Modified Cost Function

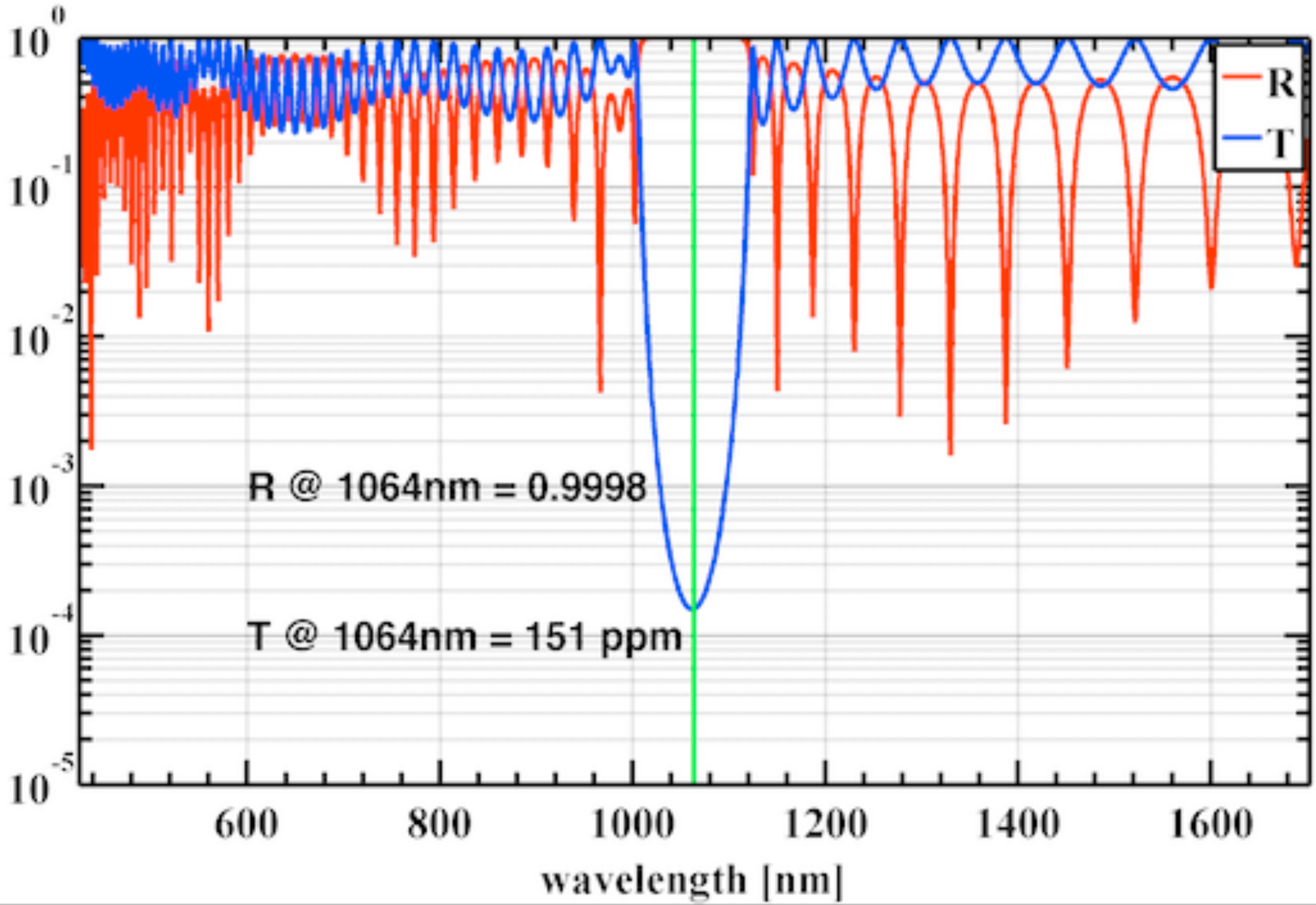
- Coatings' properties (Transmission, reflected phase, TO noise) may change from the desired values due to uncertainties in parameters. Mostly refractive indices.
- Modified Cost function: sum of cost functions from different values of refractive indices

$$y' = \sum_{n_H} \sum_{n_L} y(n_H, n_L)$$

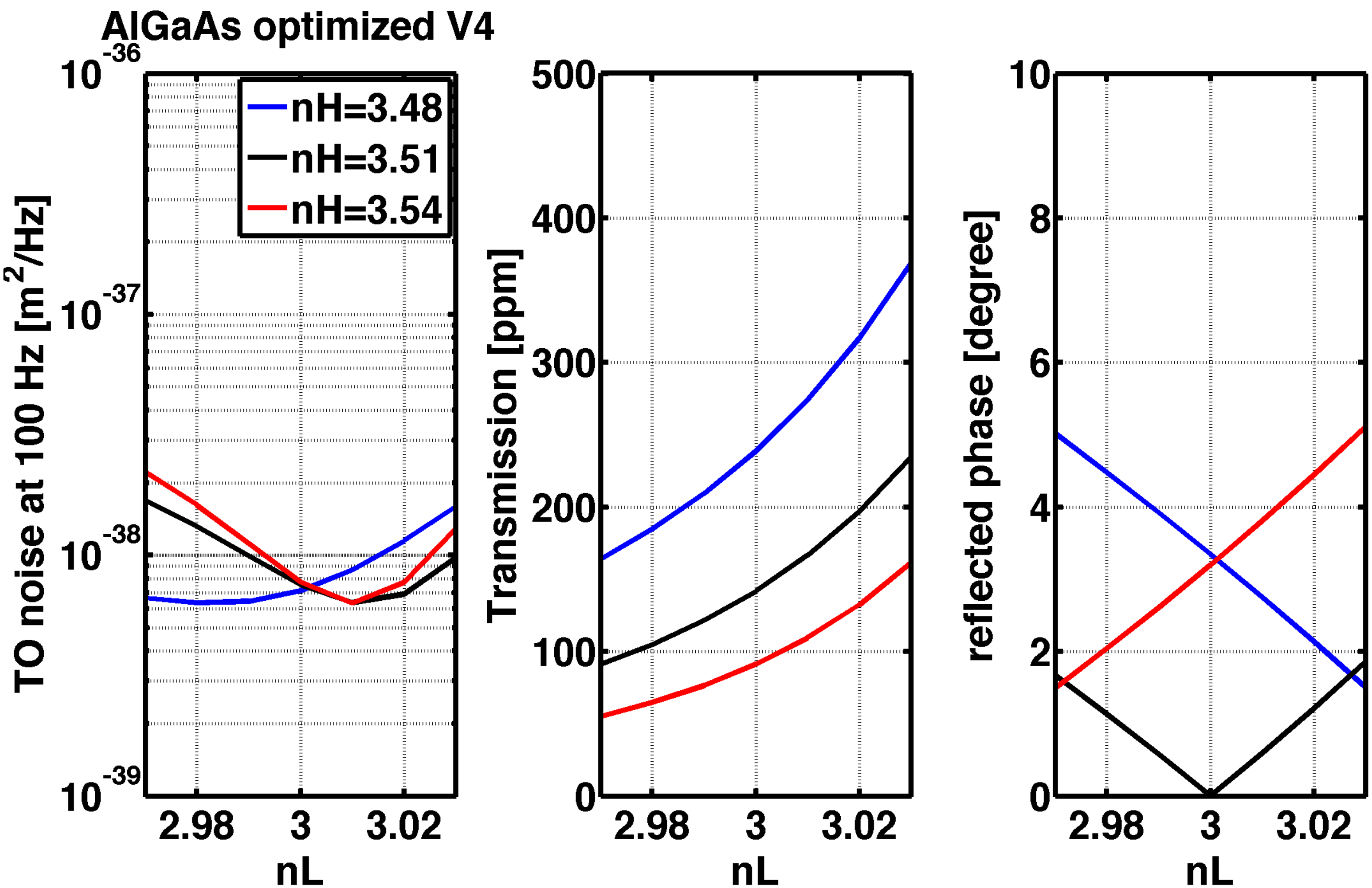
Optimized Structure



Transmission and Reflection at 1064 nm



Optical Properties vs nH and nL: Optimization with Robust Cost Function



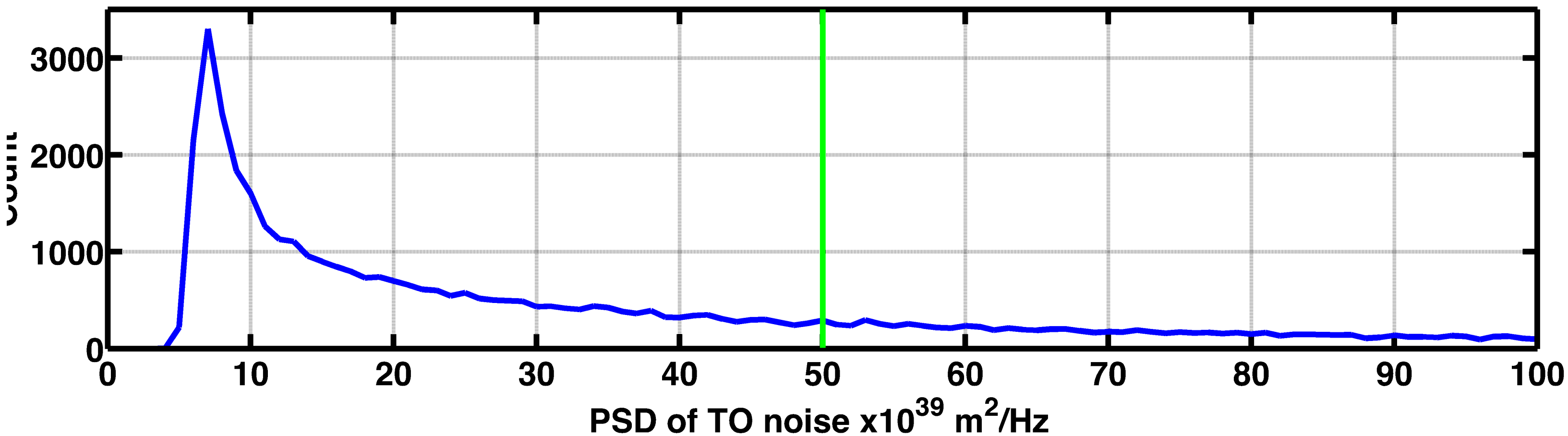
Will it Work?

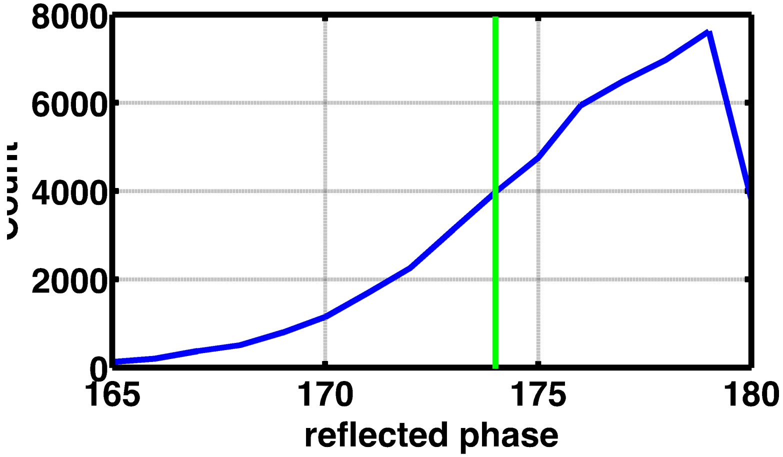
- Run MONTE CARLO test taking uncertainties in material parameters and errors from fabrication process

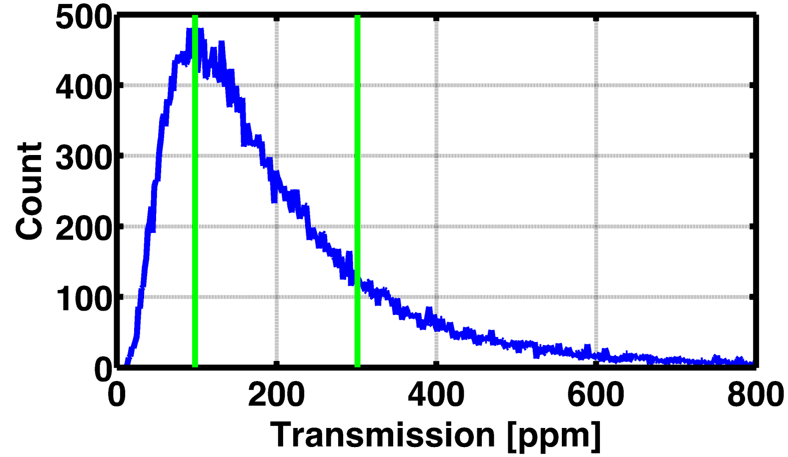
  -Thickness Control: GaAs, sigma ~ 0.5%
  AlGaAs, sigma ~ 1%

  - Al Content 92% +/- 0.6%

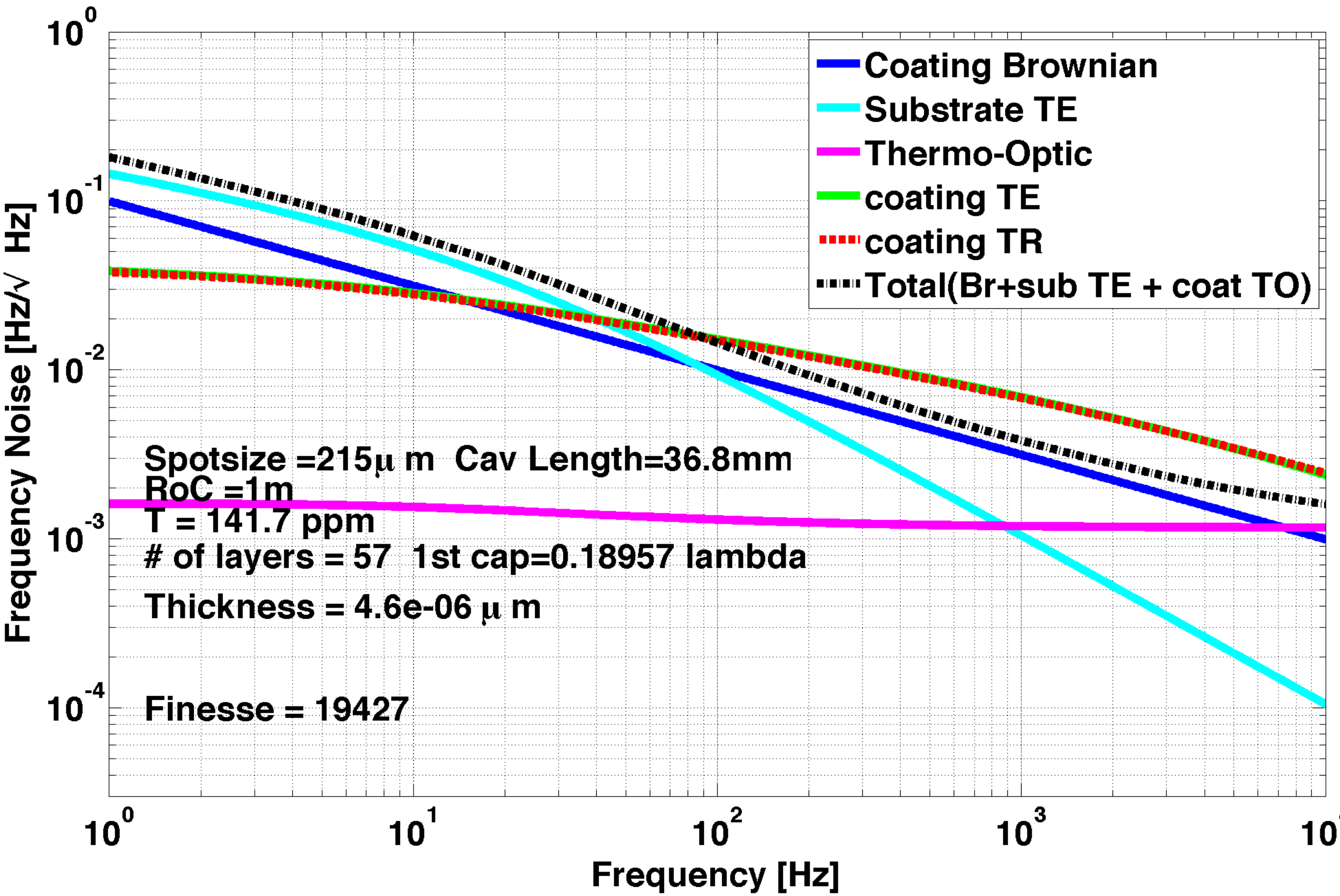
Histogram of Coating Properties







Noise Budget: Optimized T~150ppm



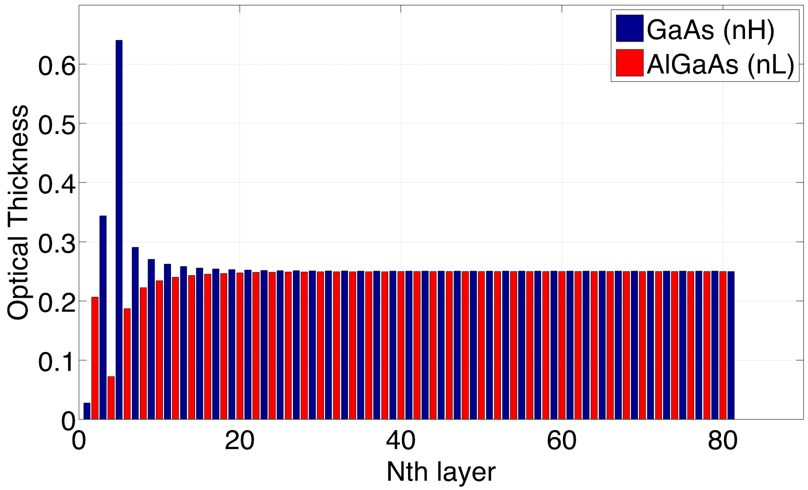
Implications for aLIGO

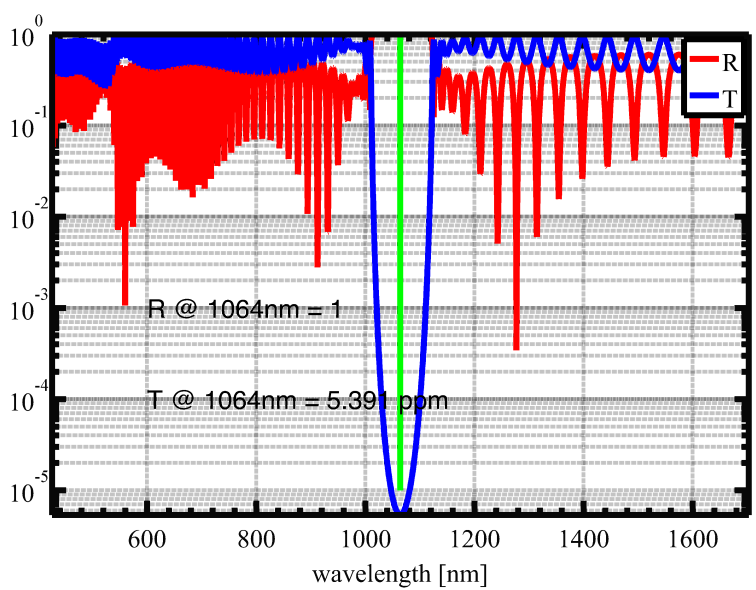
- If the optimized structure works for our test cavity, we can do the same optimization for ITM, ETM.
- For fused silica substrate.
- At room temperature.

LIGO

ETM

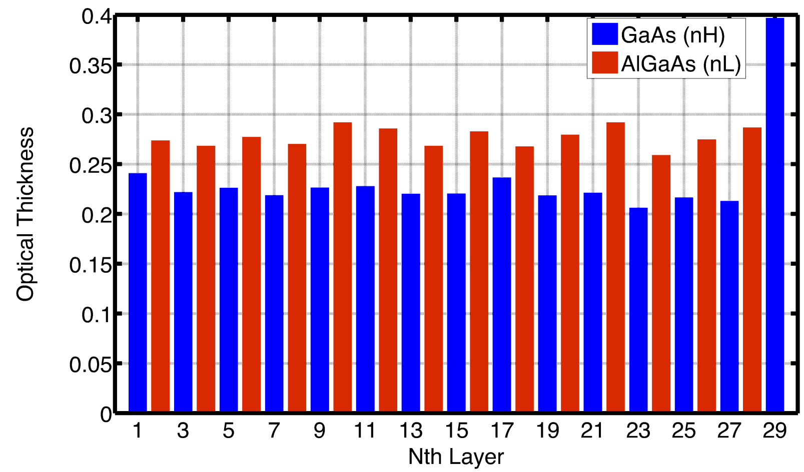
T = 5 PPM

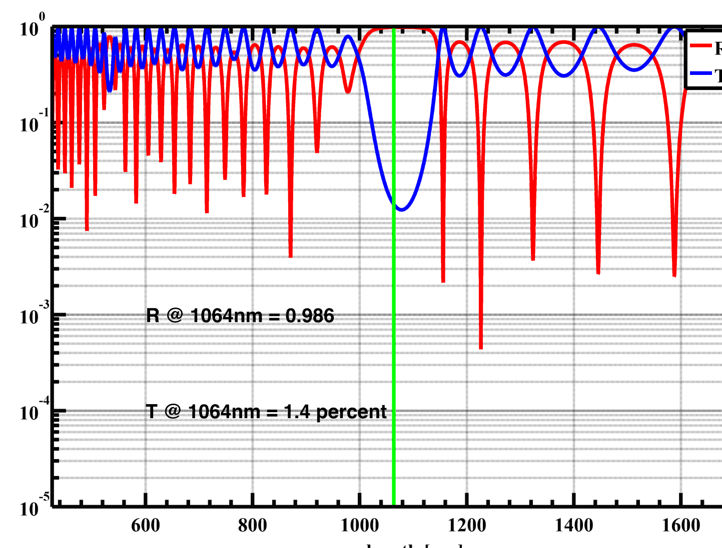




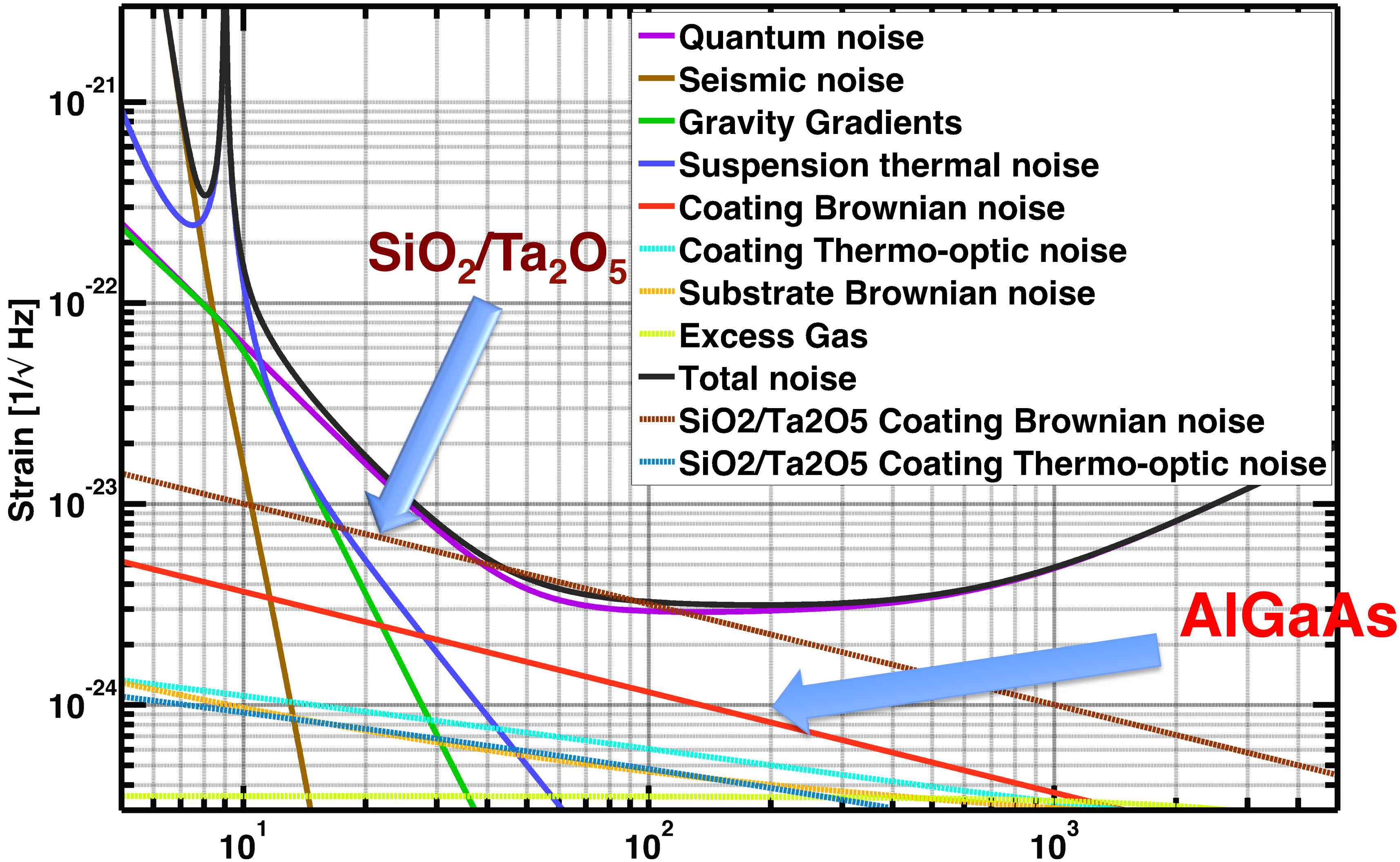
ITM

T = 1.4 %





aLIGO with Optimized AlGaAs Coatings



Conclusion

- We demonstrate a setup that can measure thermal noise in a reference cavity from 10 Hz to 1 kHz
- With data from a ring down measurement, loss angles of SiO_2 and Ta_2O_5 can be extracted.

- AlGaAs optimized coating is proposed.
- Fabrication is in progress.

- Optimization for AdvLIGO can improve its sensitivity.

Thank You

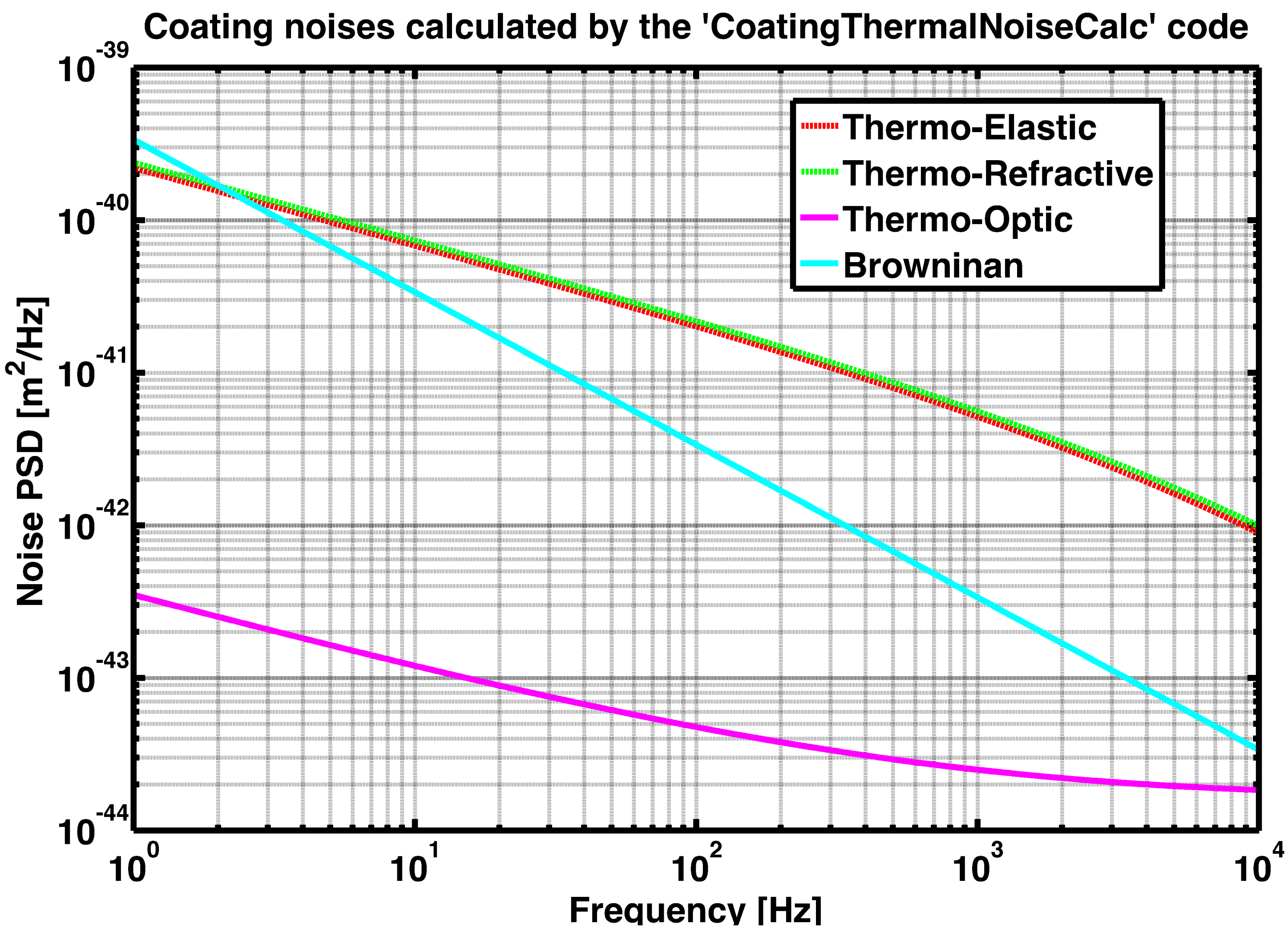
Acknowledgement

The experiment is made possible because of all of them

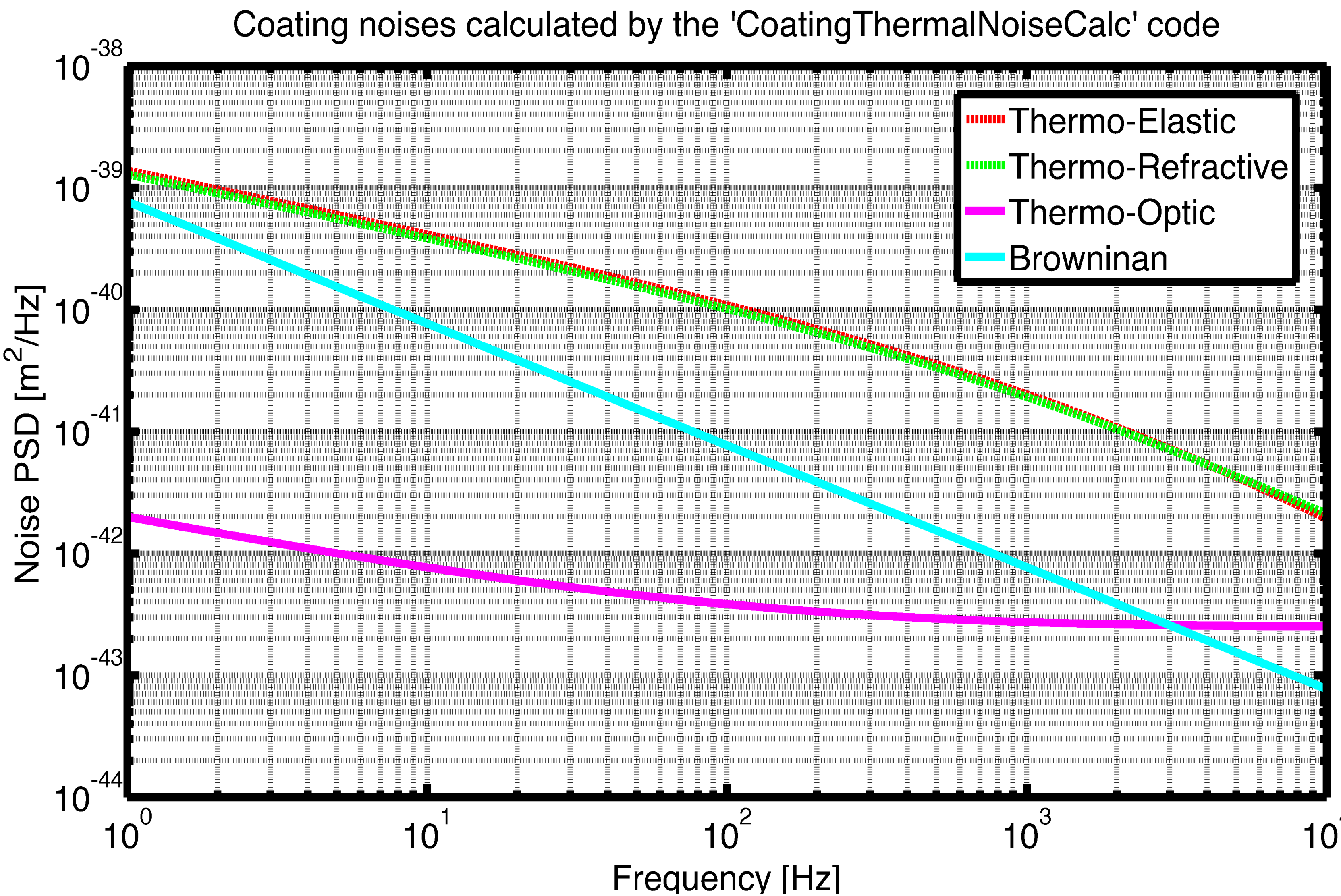
- Rana Adhikari, Eric Gustafson.
- Matt Abernathy, Koji Arai, Aidan Brooks, Peter King, Frank Seifert, Nic Smith.
- Rich Abbott, Daniel Sigg.
- Jenne Driggers, Evan Hall, Zach Korth, Denis Martynov, Eric Quintero, David Yeaton-Massey, and all LIGO colleagues.
- LIGO and NSF PHY-0757058.

Supplementary Information

ITM: Noise Budget



ETM: Noise Budget



Photothermal response