Measurements of Thermal Noise in Optimized Coatings

Thermal Noise Interferometer

Akira Villar, Eric Black, Greg Ogin, Tara Chelermsongsak, Riccardo DeSalvo

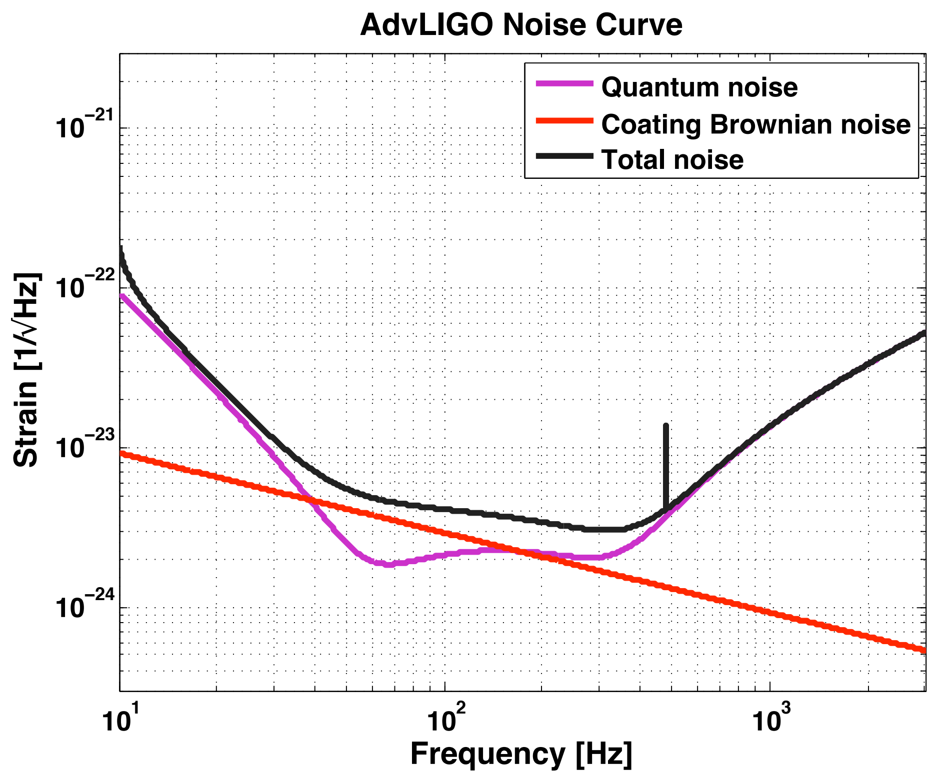
University of Sannio

Innocenzo Pinto, Vincenzo Pierro, Maria Principe

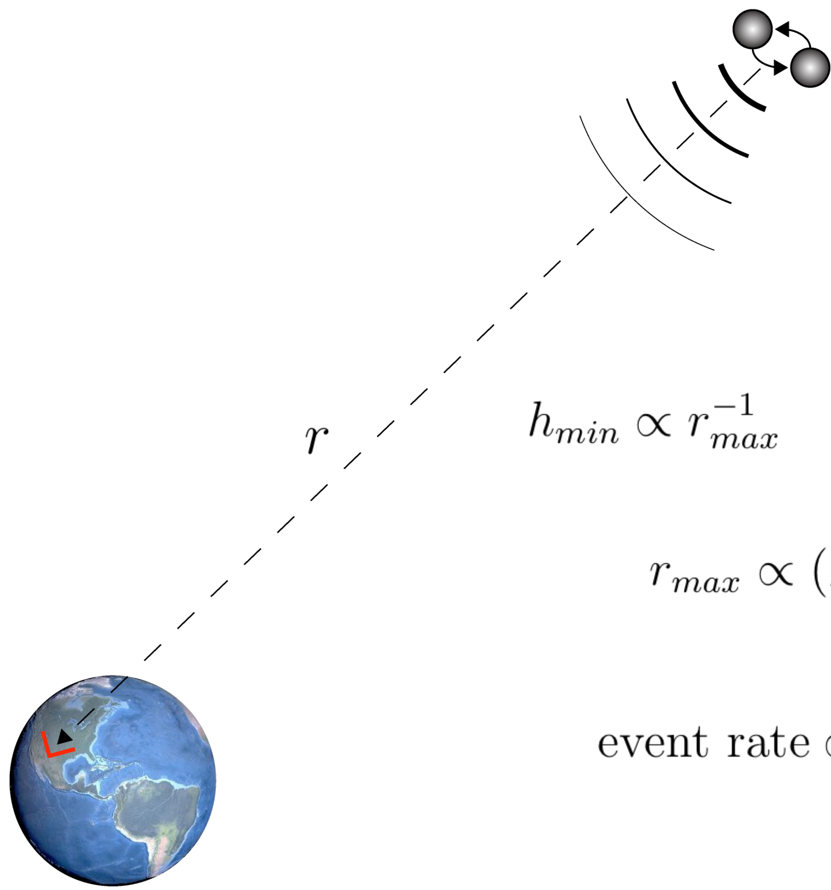
G0900647-v1

Advanced LIGO Noise Floor

- Coating thermal noise will limit sensitivity around 100 Hz
- Reductions in coating noise lead directly to improvements in sensitivity



Lower Noise Floor Means More Events



- Small improvement in thermal noise floor means big gain in event rate

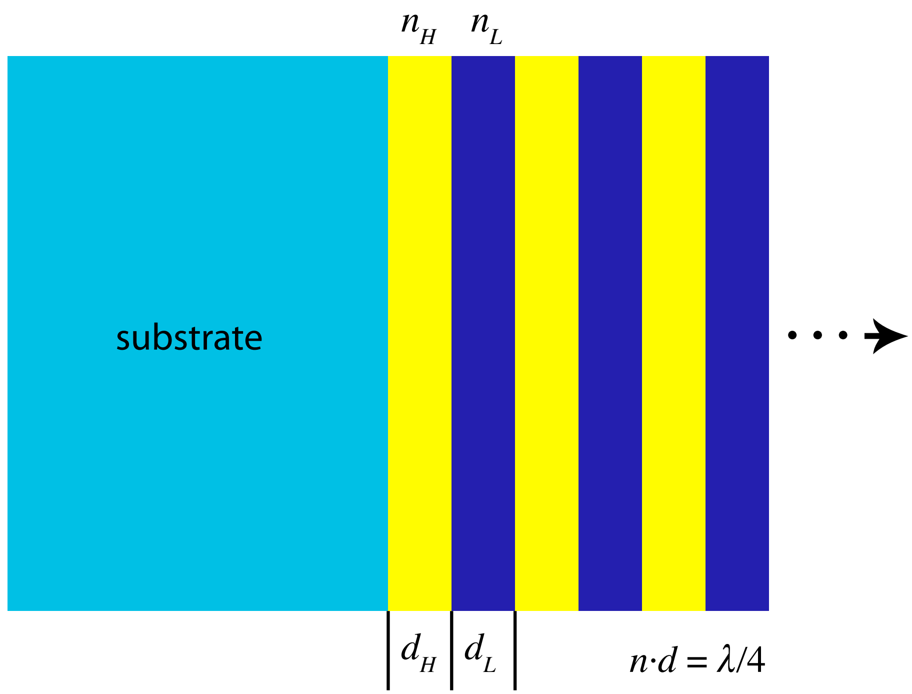
$$h_{min} \propto r_{max}^{-1} \qquad h_{min} \propto S_{therm}^{1/2}$$

$$r_{max} \propto (S_{therm}^{1/2})^{-1}$$

$$\text{event rate} \propto V \propto r_{max}^{3}$$

$$\text{event rate} \propto (S_{therm}^{1/2})^{-3}$$

Standard Multilayer Dielectric Coatings



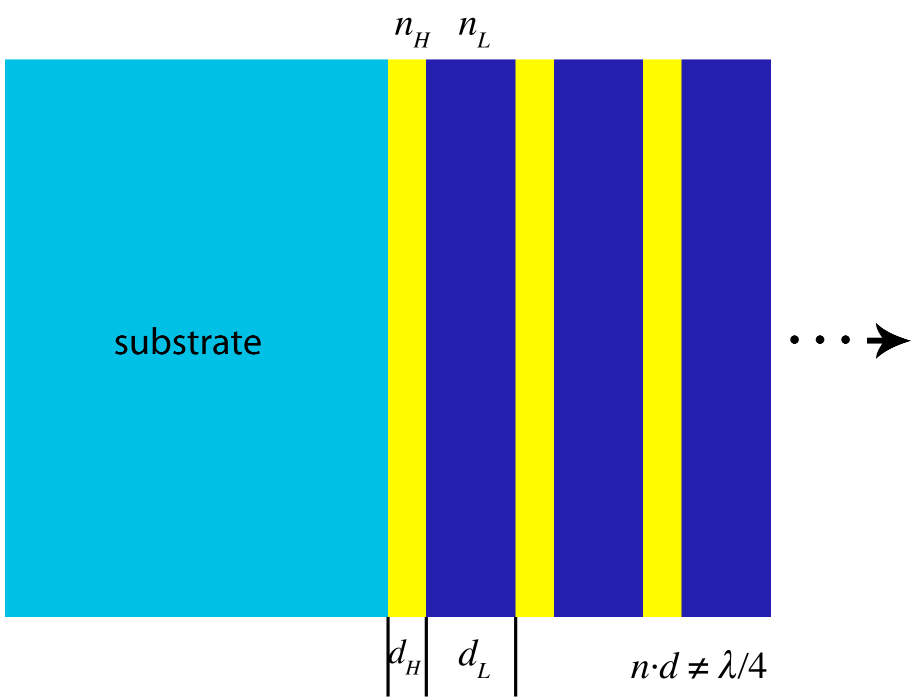
- Alternating layers of high and low index materials
- Quarter wavelength optical thickness for best reflectivity
- Silica low-index, tantala high-index for good performance at 1064nm
- Thermal noise arises from internal friction in the coatings

$$S_x(f) = \frac{2k_B T}{\pi^{3/2} f} \frac{(1-\sigma^2)}{wY} \phi_{eff}$$

$$\phi_{eff} \propto (L_L + \gamma \cdot L_H)$$

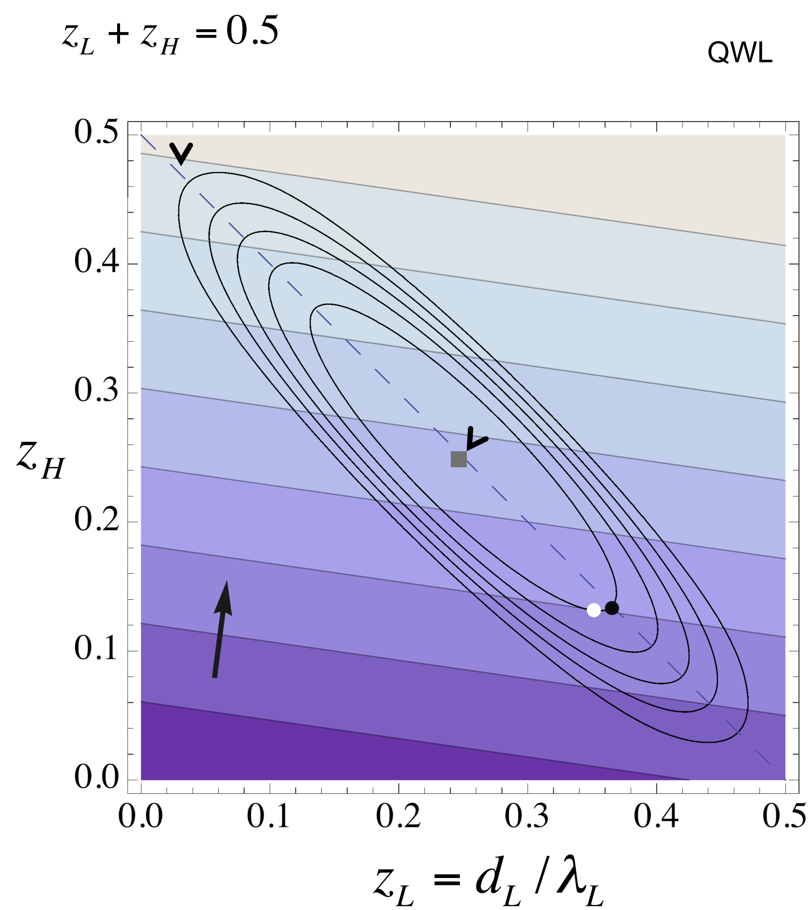
$$\gamma \propto \frac{Y_H \phi_H}{Y_L \phi_L}$$

Optimized Coatings



- Optimum coating is still a stack of identical “doublets”
- Simplify things by making the doublets $\lambda/2$ thick

- Tantala is more lossy than silica
- Reduce the amount of tantala in the coating



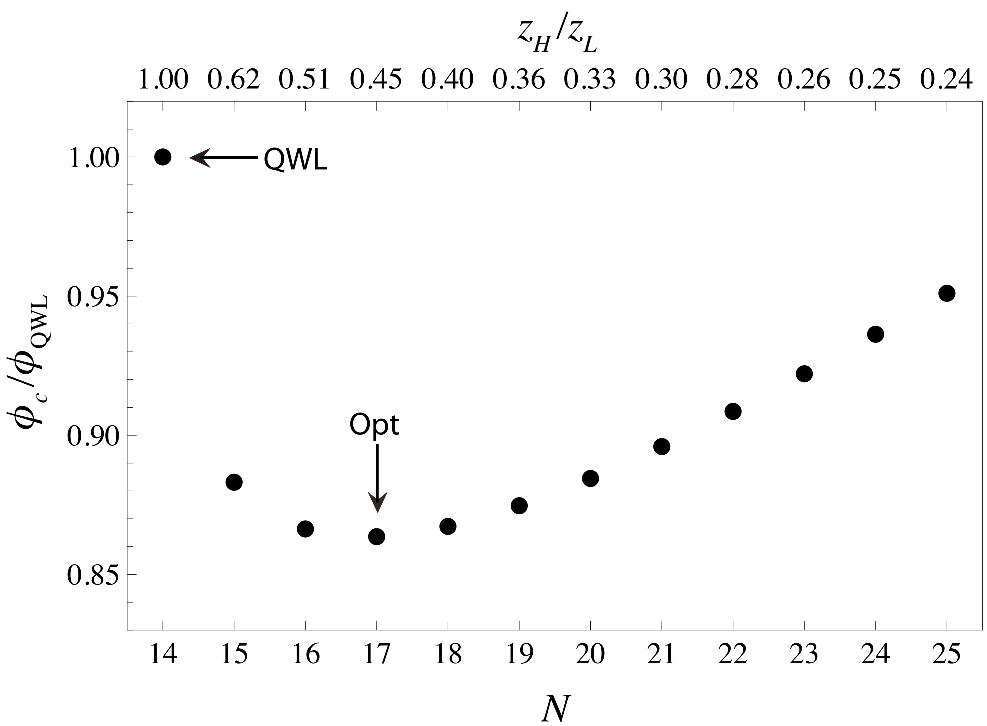
Optimization Strategy

$$\tau(N_d, z_H) = \tau_{QWL}$$

$$\phi_{eff} = b_L L_L + b_H L_H$$

$$b_{L,H} = \frac{\lambda_0}{\pi w}\frac{\phi_{L,H}}{n_{L,H}}\left(\frac{Y_{L,H}}{Y_s} + \frac{Y_s}{Y_{L,H}}\right)$$

$$\gamma = b_H / b_L = [5,10]$$

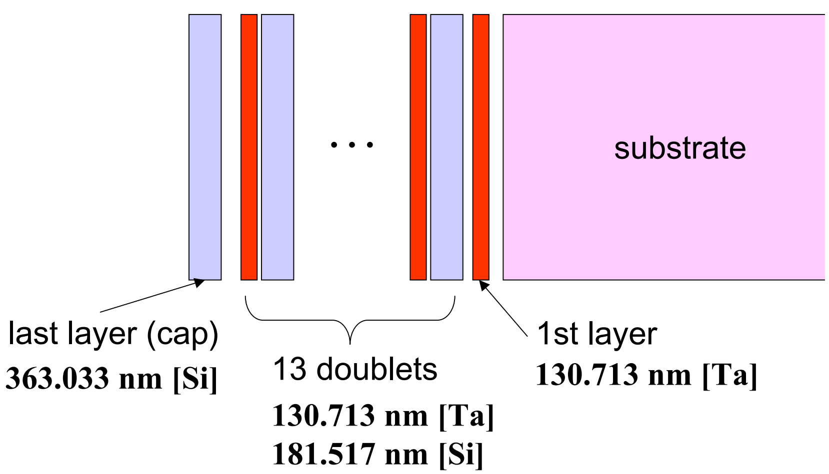


- Start from QWL design of N_{QWL} doublets and transmission τ_{QWL}
- Add one doublet and adjust layer thickness (keeping $z_H + z_L = 0.5$) until τ_{QWL} is recovered
- Calculate new ϕ_{eff}
- Repeat until minimum noise design is found

Final Design

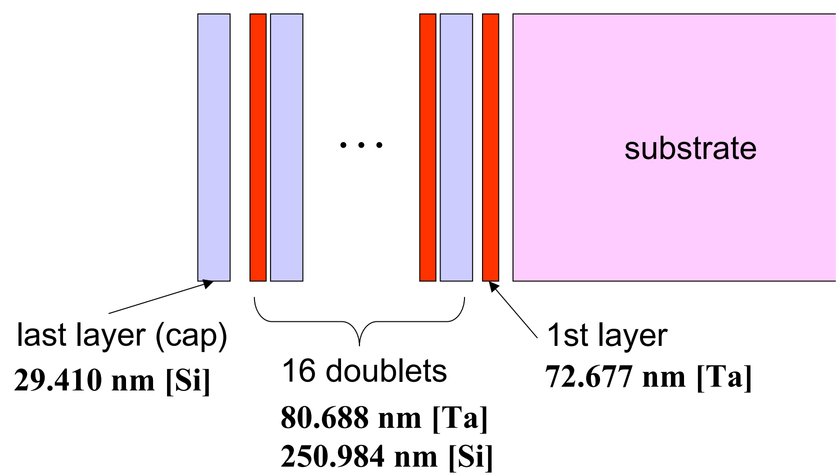
Reference QWL

Silica
Tantala



Optimized Prototype

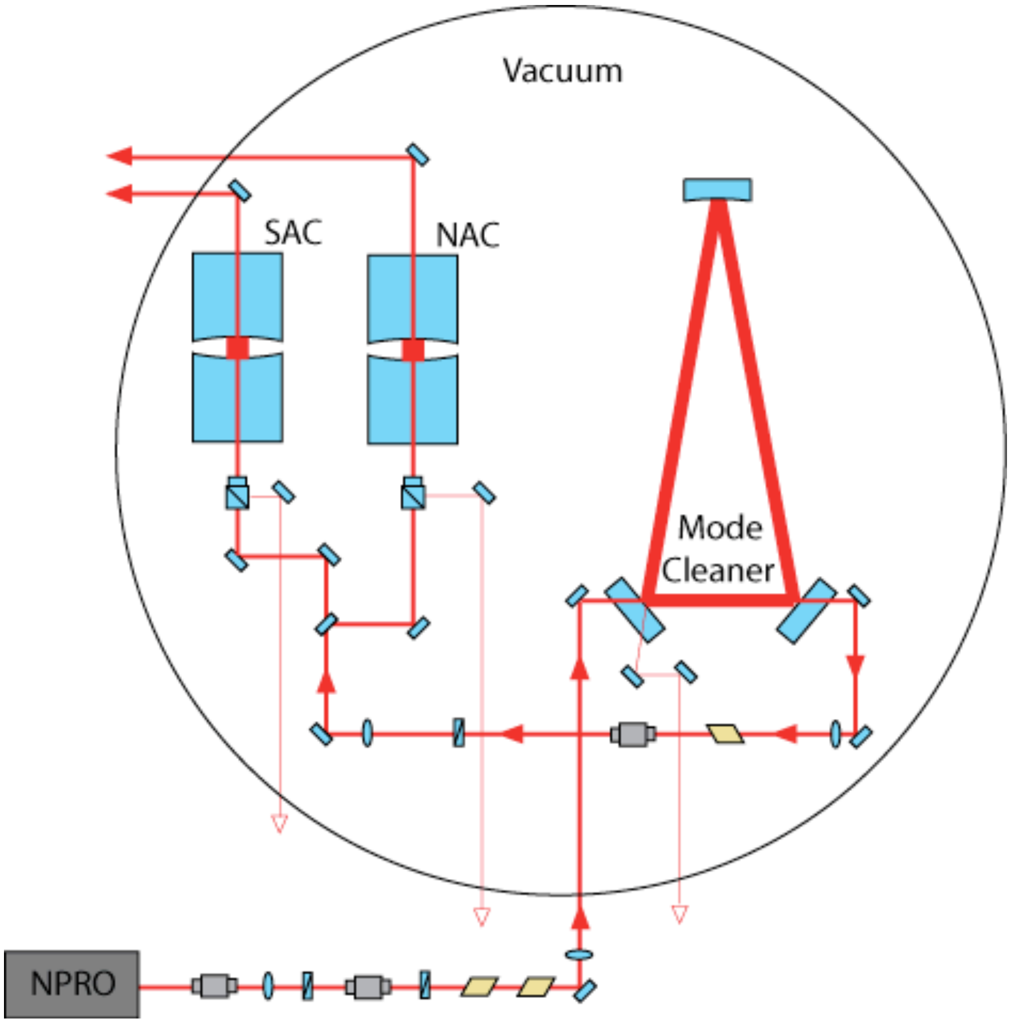
Silica
Tantala



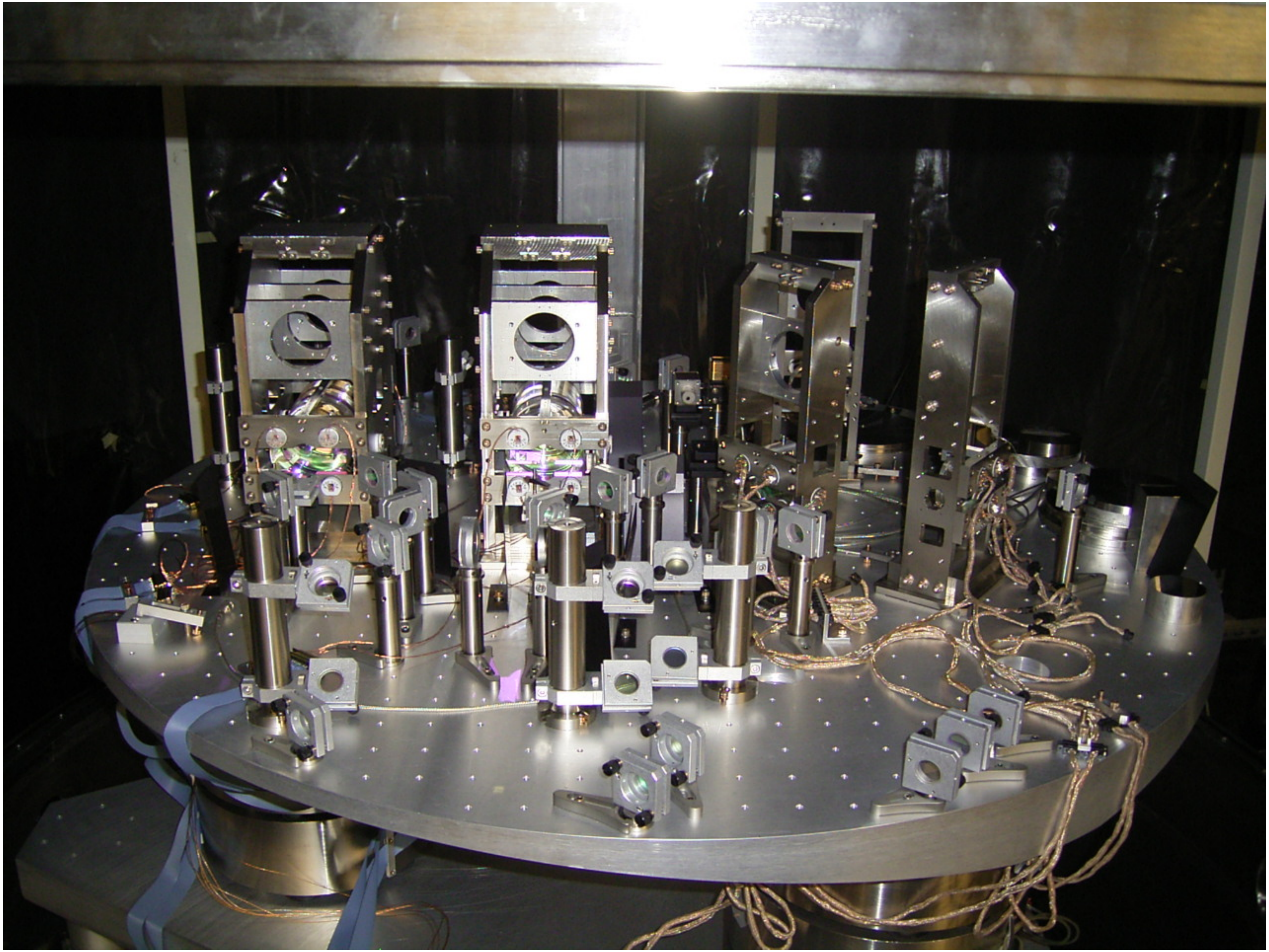
$$\tau = 278\, ppm$$

$$r = \frac{\phi_{Opt}}{\phi_{QWL}} = 0.843 \quad (\gamma = 7)$$

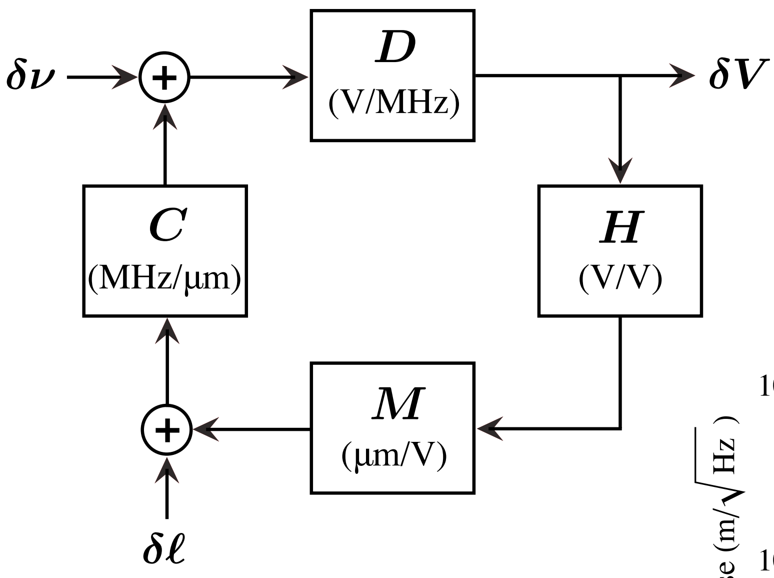
Thermal Noise Interferometer



- Test bed interferometer designed to measure thermal noise in optics
- Short test cavities reduce laser frequency noise
- Small spot size increases thermal noise
- Two test cavities permit CMR
- Sensitivity is better than 10^{-18} m/rHz



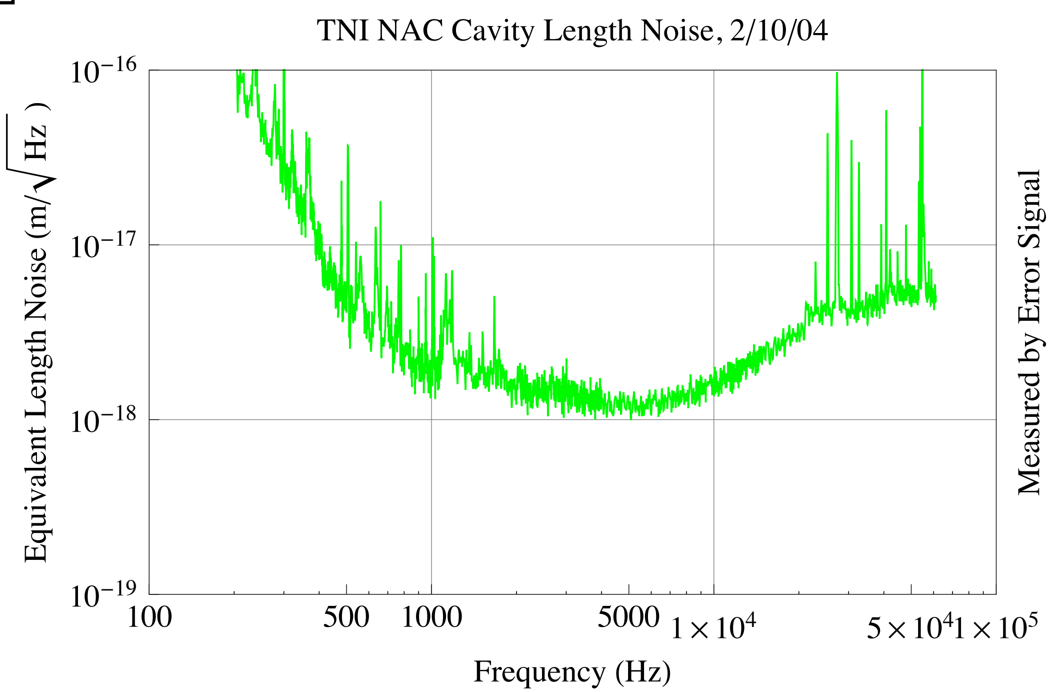
Test Cavity Servo



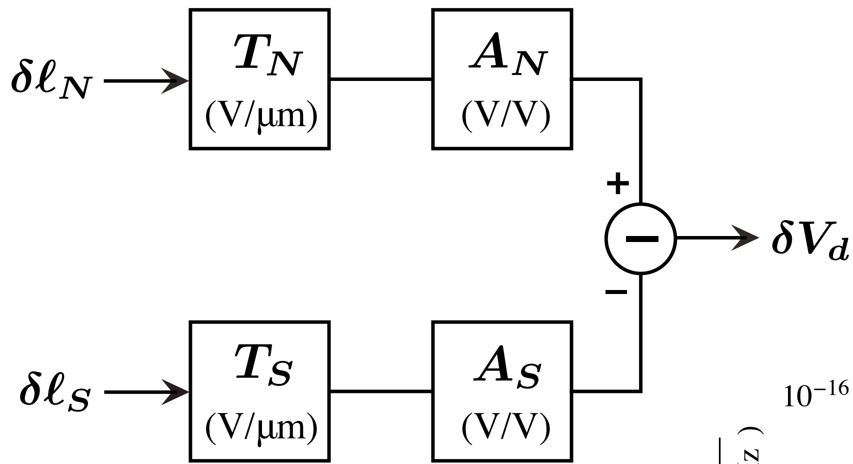
$$\delta V = \frac{DC}{1 - DCMH}\delta\ell$$

$$\delta V = T\,\delta\ell$$

$$\delta\ell = T^{-1}\,\delta V$$



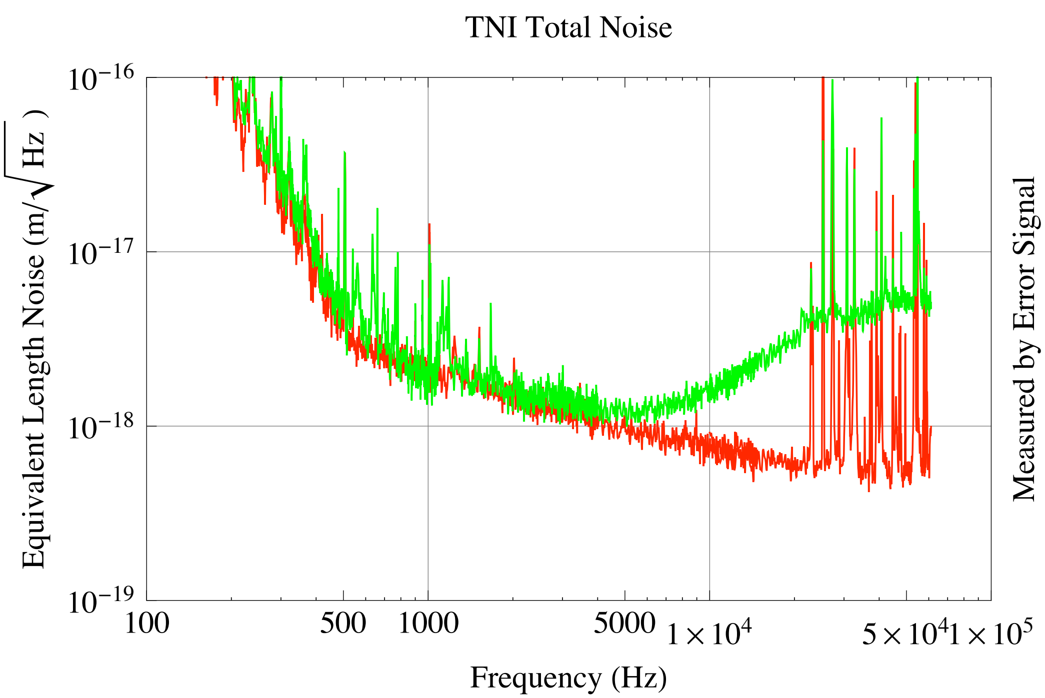
Common Mode Rejection



$$\delta\ell_d \equiv \delta\ell_N - \delta\ell_S$$

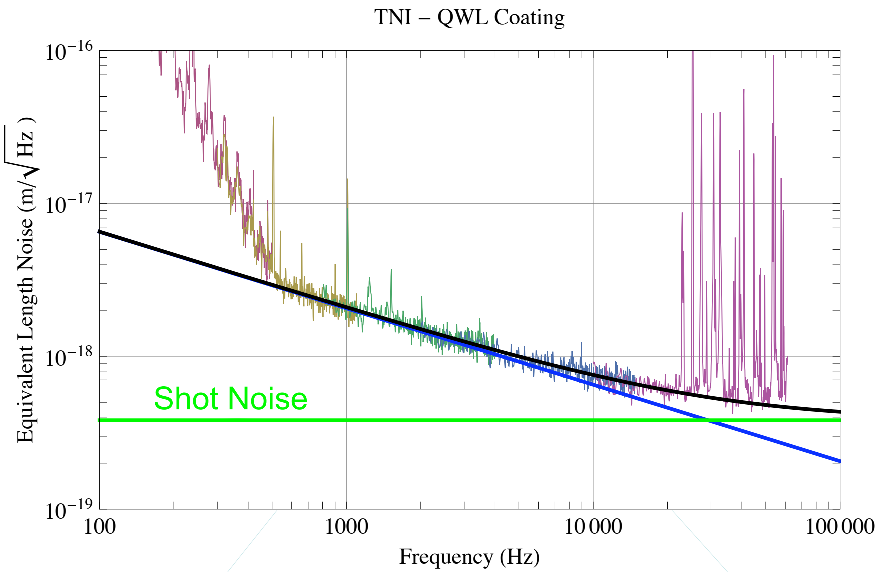
$$\delta\ell_d \approx \frac{1}{2}\left(A_N^{-1}T_N^{-1} + A_S^{-1}T_S^{-1}\right)\delta V_d$$

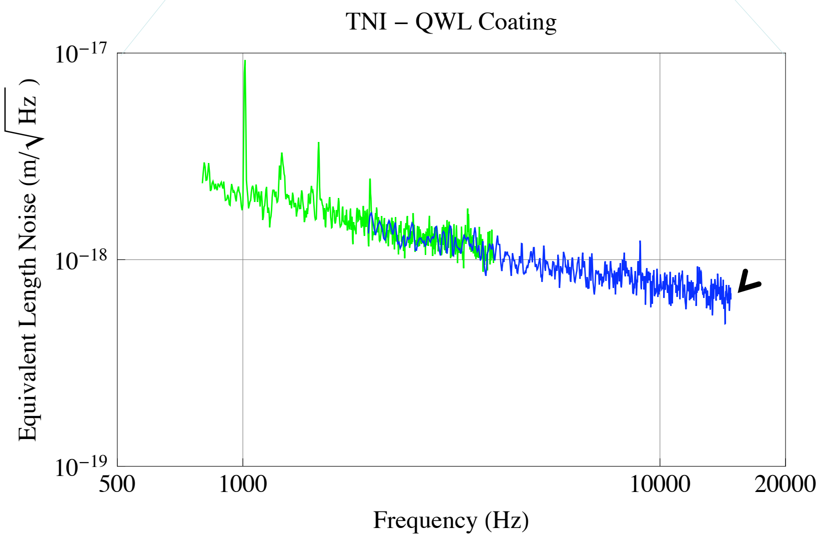
$$\delta\ell_d \approx \frac{1}{2}\left(A_N^{-1}D_N^{-1}C^{-1} + A_S^{-1}D_S^{-1}C^{-1}\right)\delta V_d$$



- Laser frequency noise is correlated in both cavities thermal noise is not
- CMR allows thermal noise to be visible up to higher frequencies
- Noise floor at high frequencies becomes shot noise dominated

Extracting the Loss Angle



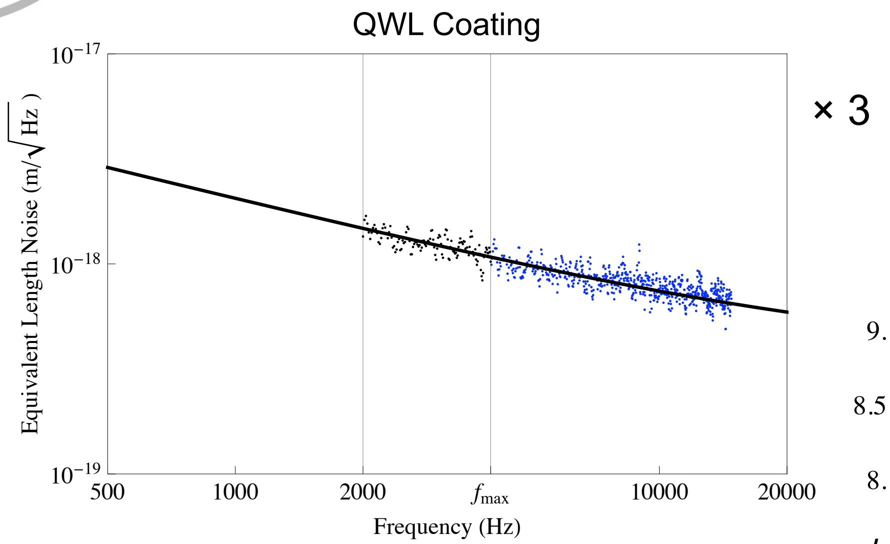


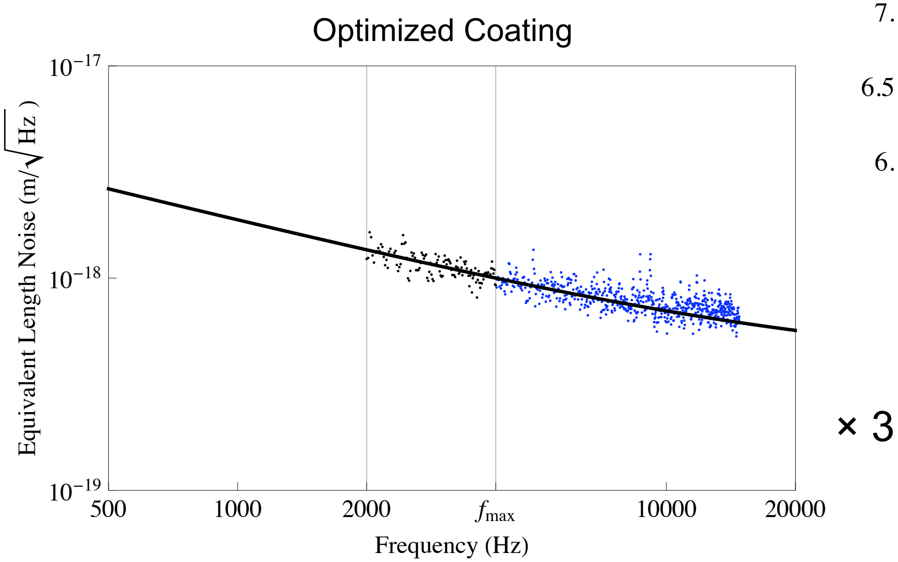
$$S_B(f) = \frac{2k_BT}{\pi^{3/2}f}\frac{(1-\sigma^2)}{wY}\phi_{eff}$$

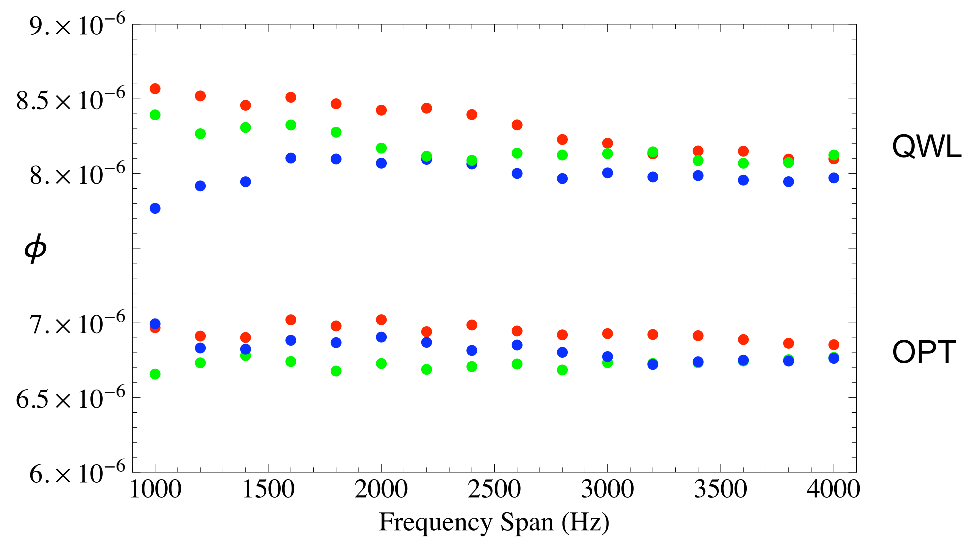
$$\ell(f) = \sqrt{4\,S_B(f) + S_s}$$

Fit to data with ϕ as the free parameter

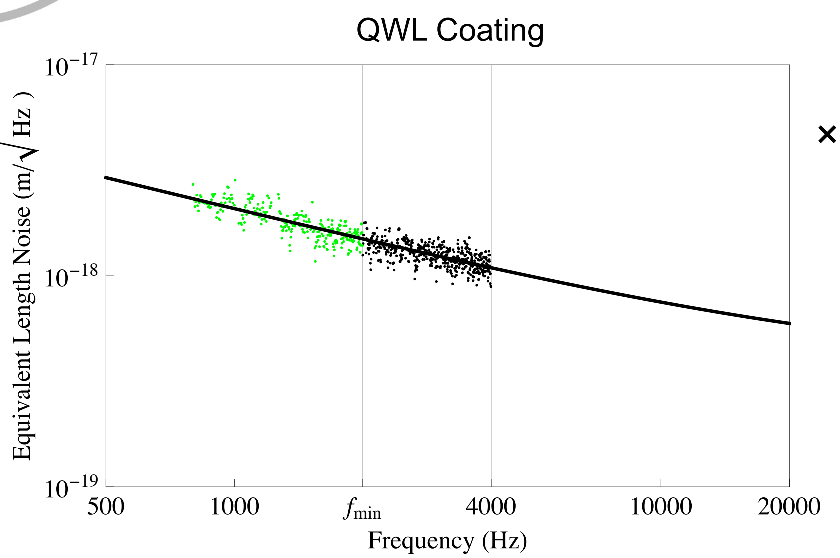
Consistency of Loss Angle



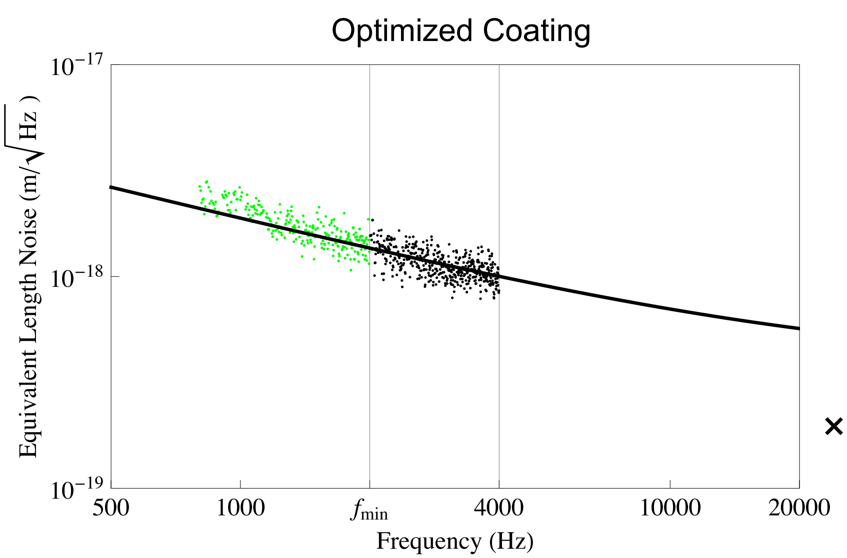




Consistency of Loss Angle



× 3



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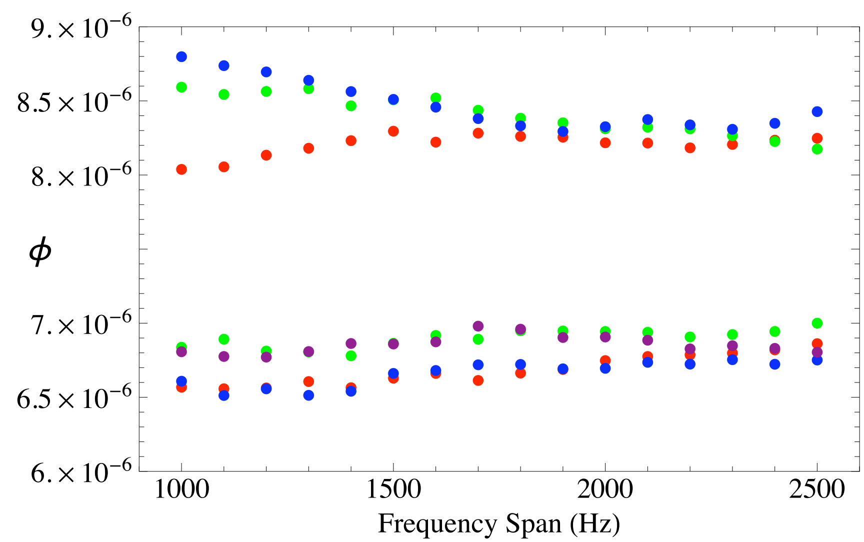


QWL

OPT

Final Results

Span (Hz)

	1500	2000	2500	2500
$\bar{\phi}_{QWL}$	8.4	8.3	8.2	8.3
$\bar{\phi}_{OPT}$	6.8	6.9	6.9	6.9
r	0.81	0.83	0.83	0.83

$\times 10^{-6}$

Measured loss angle ratio:

$$r = 0.83 \pm 0.05$$

Compare to expected value of:

$$r = 0.843$$

- 17% reduction in loss angle
- 32% increase in event rate

The Scatter Is Normal

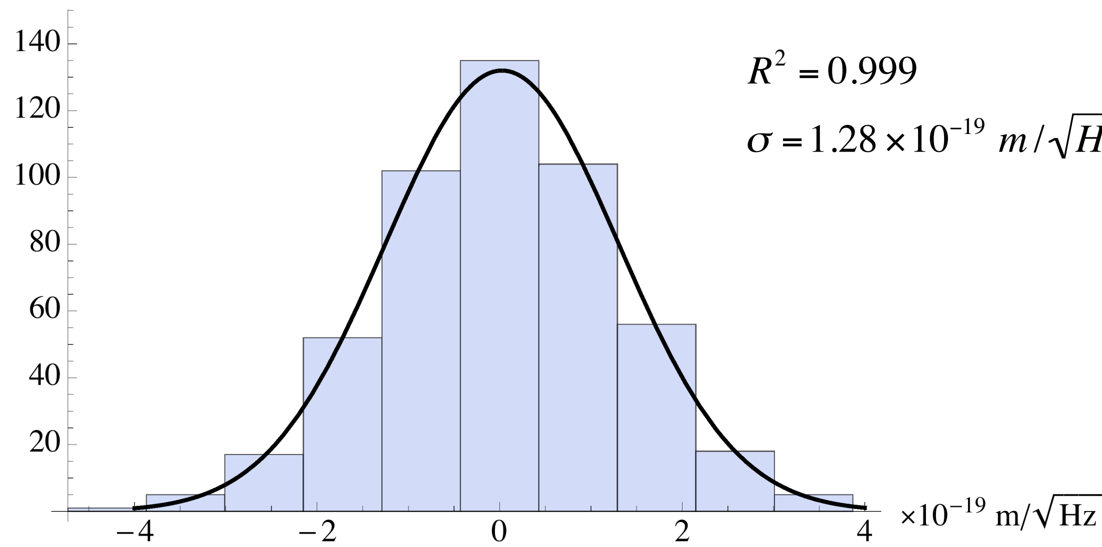
Data:

$$\{f_i, y_i\}$$

Fit Residuals:

$$\delta_i = y_i - \overline{\ell}(f_i)$$

Histogram >



$R^2 = 0.999$

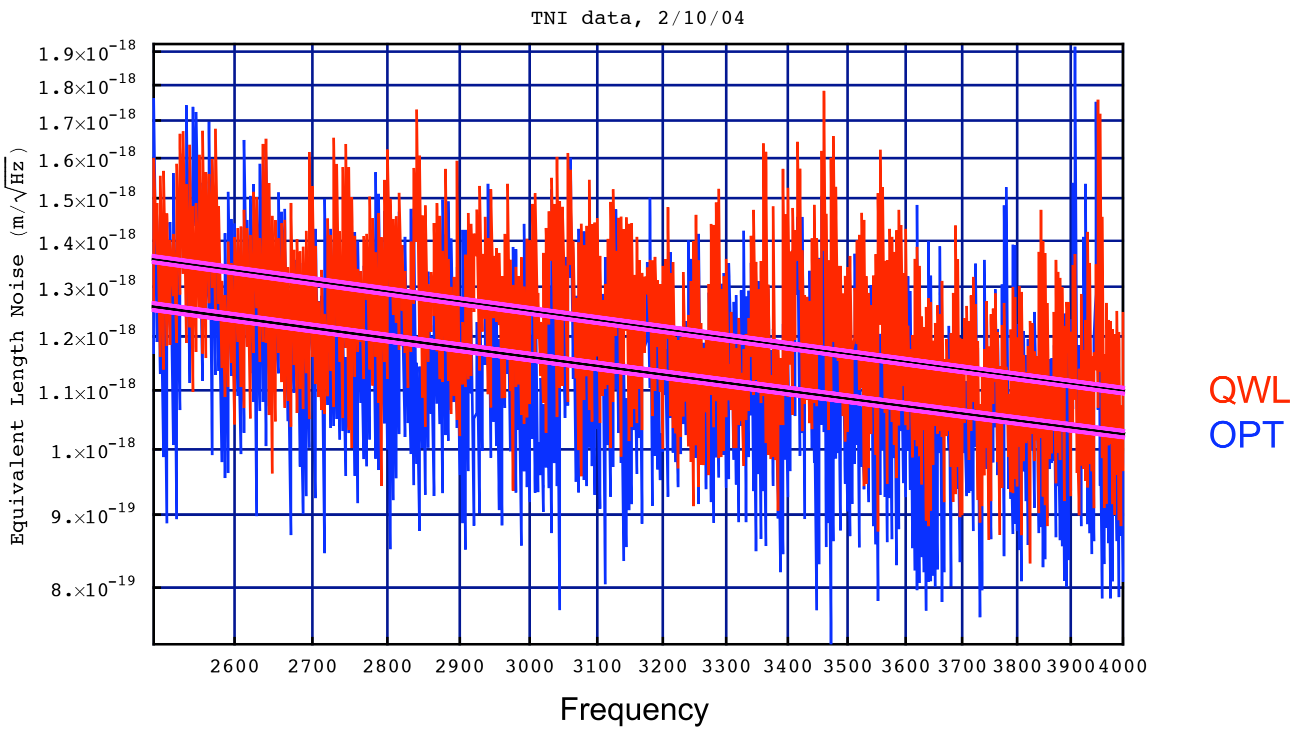
$\sigma = 1.28 \times 10^{-19}\ m/\sqrt{Hz}$

And Negligible

Fit uncertainty is not σ

But rather $\dfrac{\sigma}{\sqrt{N}}$

Smoothed Spectra



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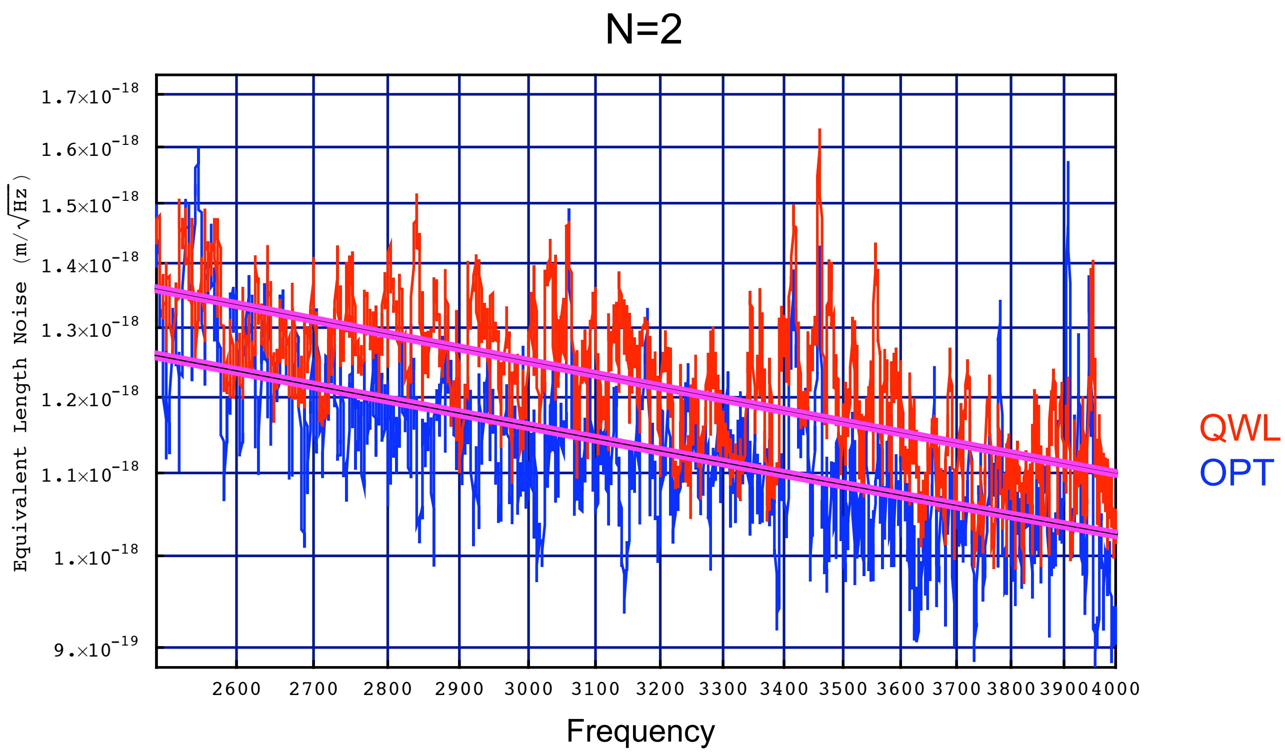

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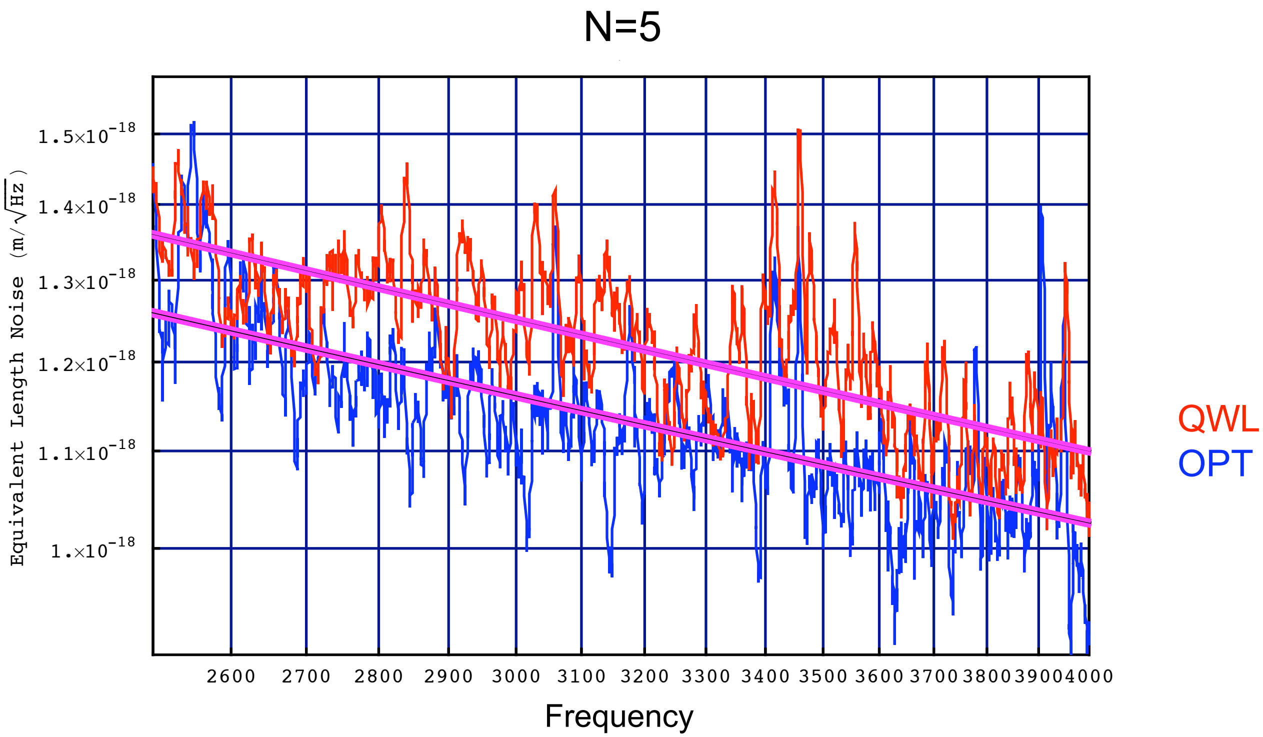

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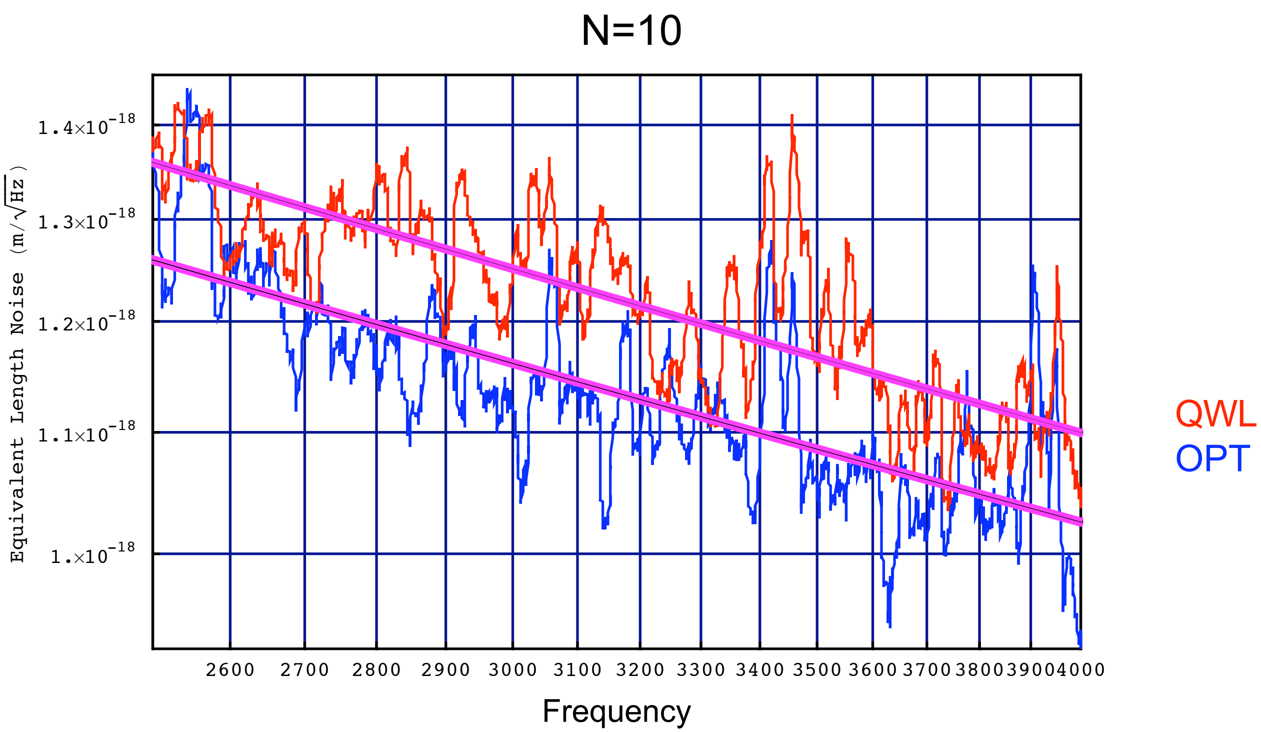

Smoothed Spectra