LIGO's Thermal Noise Interferometer: Progress and Status

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LSC Meeting Review

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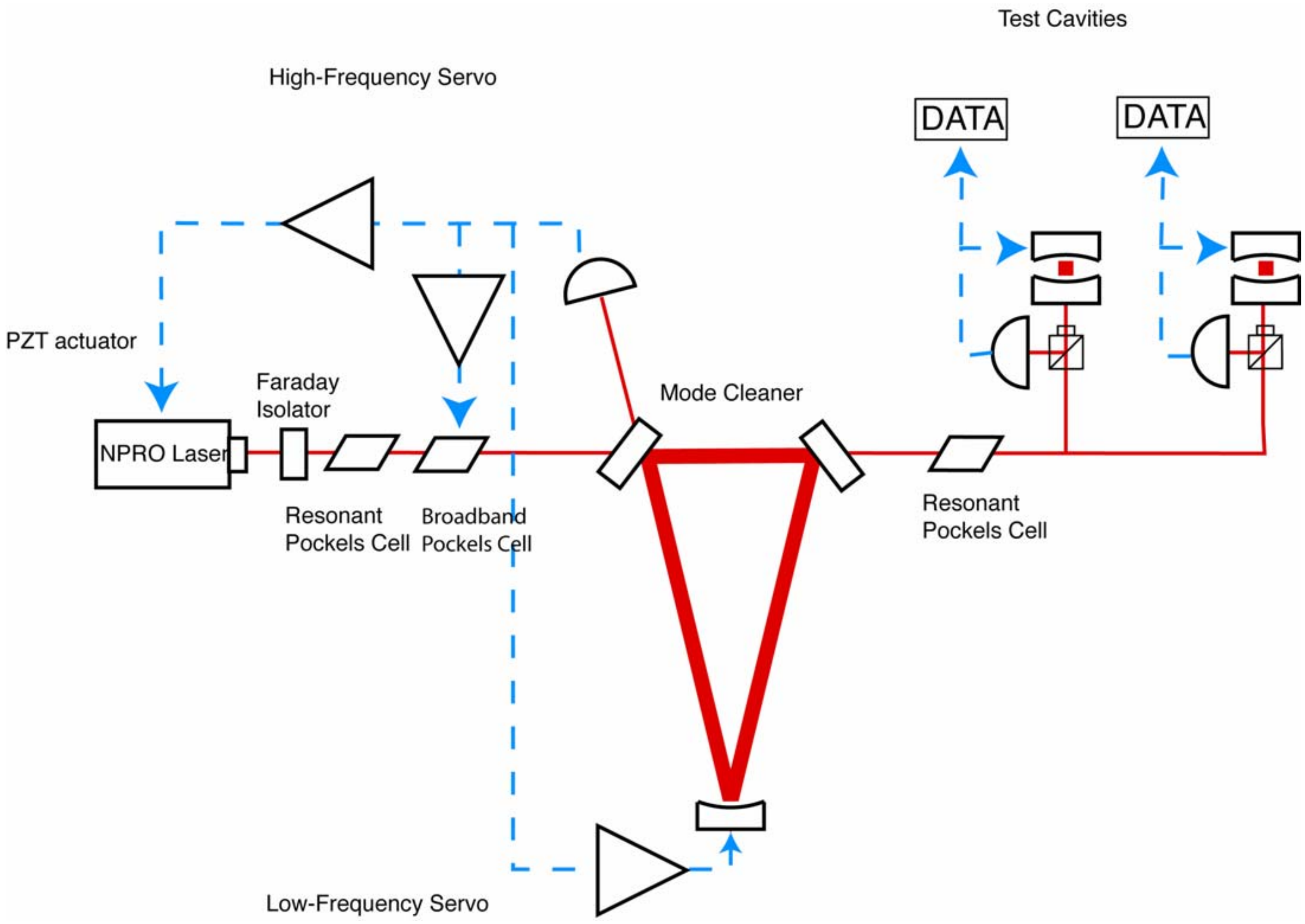
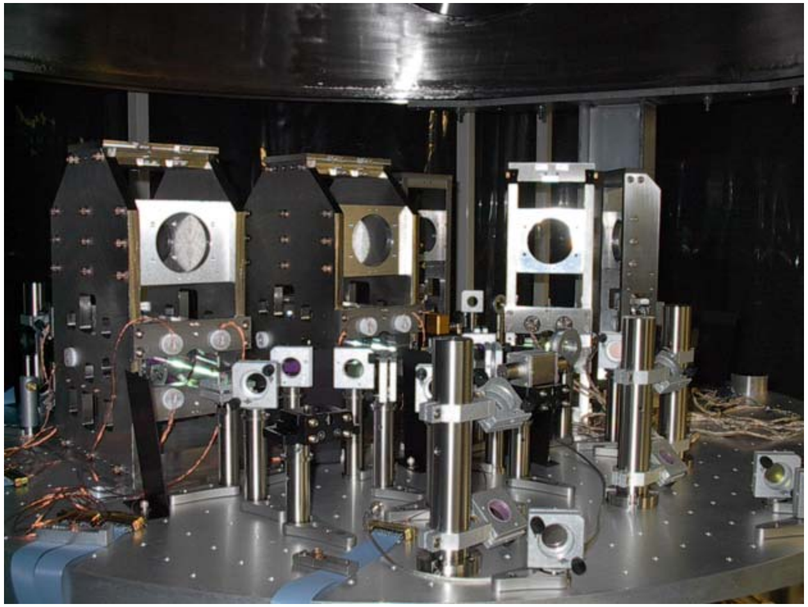
TNI Purpose and Goals

- Short Term
  - Characterize Sapphire for use in Advanced LIGO: Noise Performance, lead time, etc. Contribute to AdvLIGO COC downselect decision.
  - Evaluate thermal noise of coatings for AdvLIGO.
- Long Term
  - Isolate and study non-Gaussian noise in suspensions and mirrors.
  - Reach (and Exceed) the Standard Quantum Limit.
- Along the way
  - Identify and quantify any unexpected noise sources at sensitivity levels relevant to gravitational-wave detection.

TNI Layout

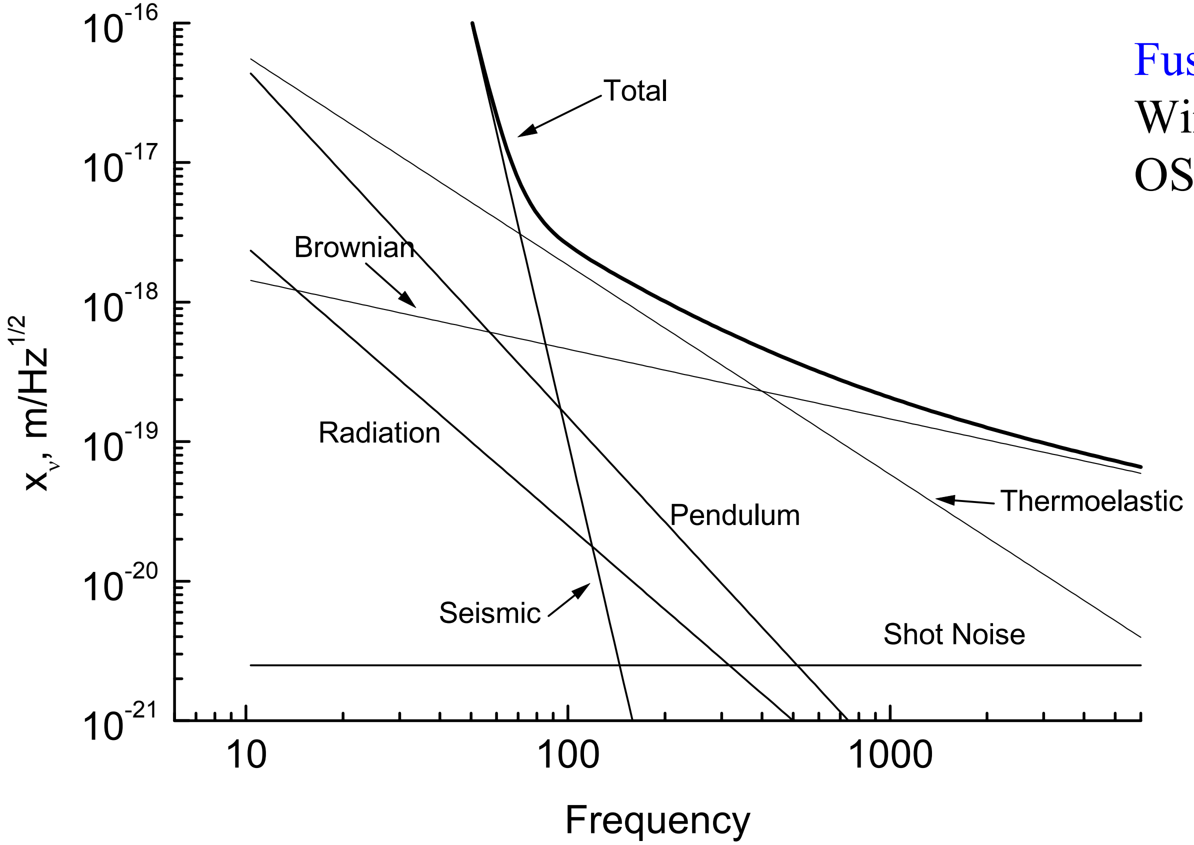

Test Cavities
High-Frequency Servo
DATA
DATA
PZT actuator
Faraday
Isolator
Mode Cleaner
NPRO Laser
Resonant
Pockels Cell
Broadband
Pockels Cell
Resonant
Pockels Cell
Low-Frequency Servo

TNI Hardware



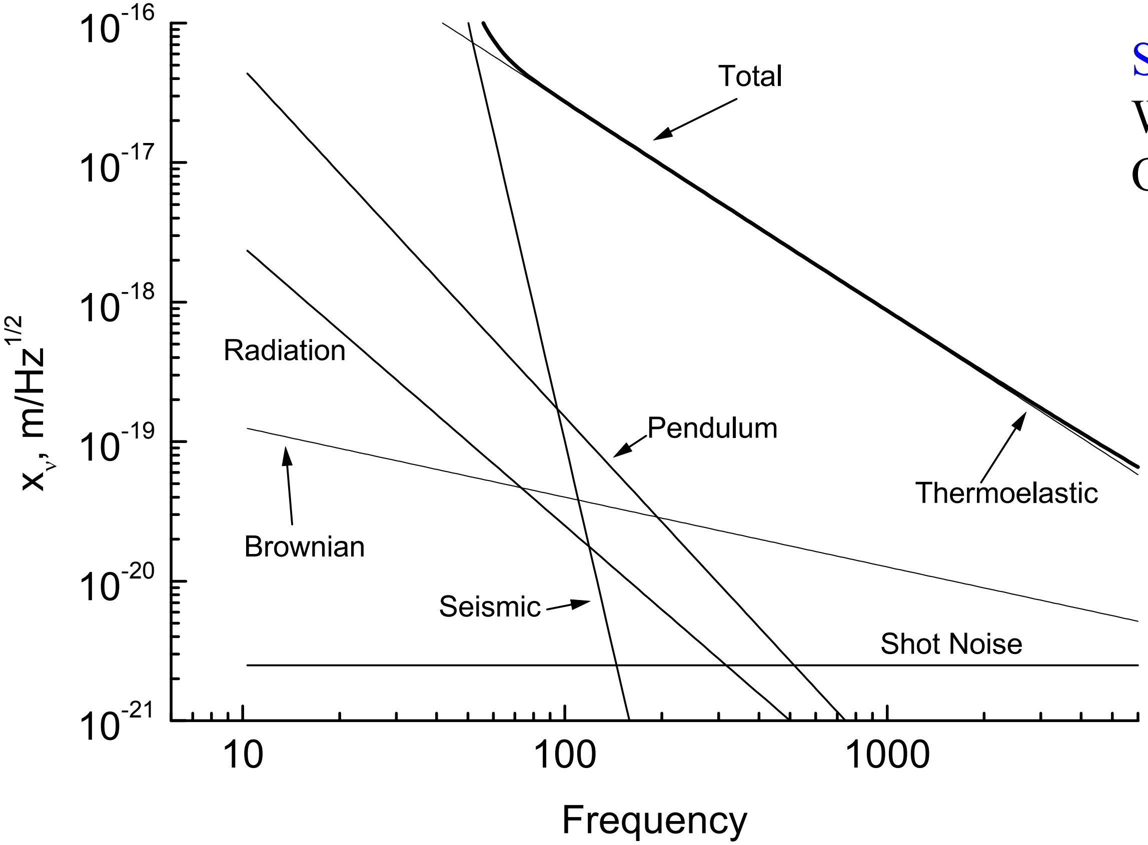
- Mode cleaner, arm cavities all contained in one chamber, mounted on a single stack.
- Wire suspensions similar to LIGO-I Small Optics Suspensions.
- OSEM actuation, all analog.
- Laser: 750mW NPRO (Lightwave).
- All hardware constructed (purchased) and installed.

TNI Phase I Expected Spectrum



Fused-Silica Test Masses
Wire Suspensions
OSEM Actuation

TNI Phase II Expected Spectrum

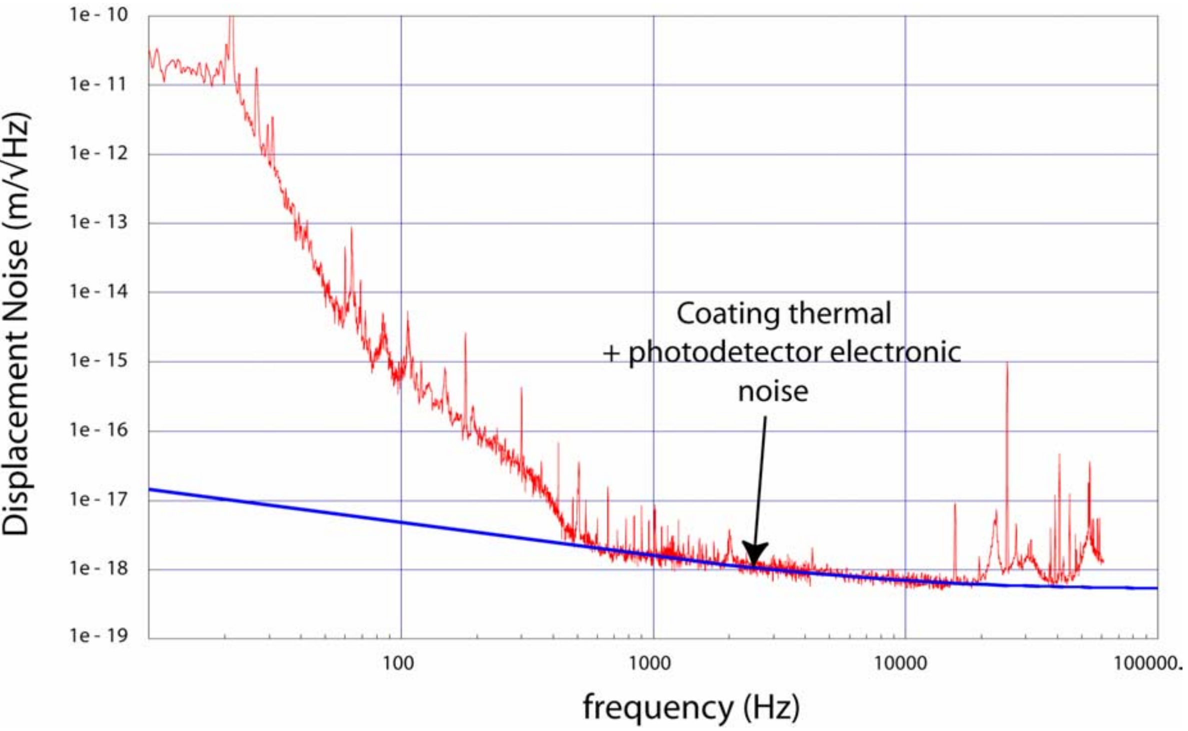


Sapphire Test Masses
Wire Suspensions
OSEM Actuation

Schedule: Major Milestones

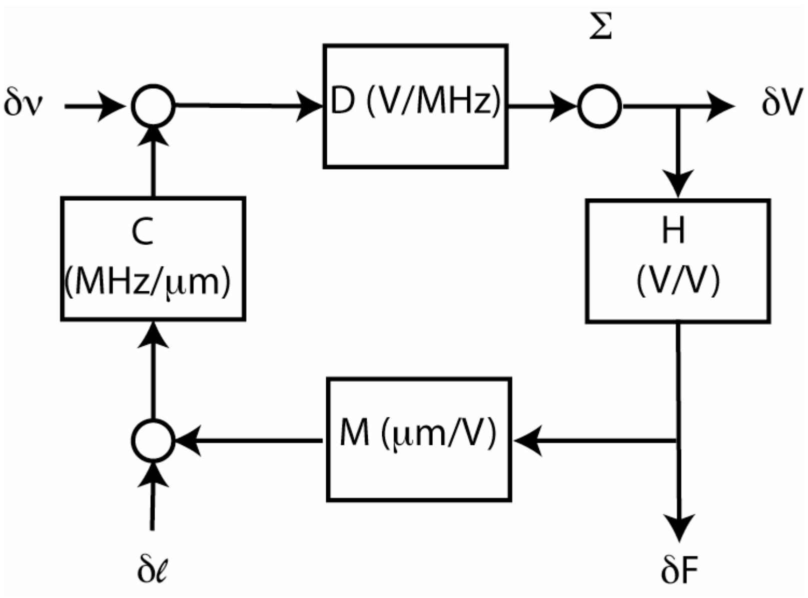
- Summer 2001: First data.
- December 2001: SAC noise level approaches “scientifically interesting” region, ~1e-18 m/√Hz from 1-6 kHz, but instrument only locks late at night. NAC noise still high.
- 2002: Instrument Improvements
  - Improved lock acquisition, stability (robustness). Developing daytime locking capability resulted in loss of sensitivity.
  - Identified, quantified individual noise source contributions.
  - Equalized arm-cavity noise levels. “Quality control” in photodetectors, beamsplitter; polarization optimization.
- 2003: Sensitivity Gains, Preliminary Science Results
  - Recovered initial good SAC sensitivity, comparable NAC sensitivity, and retained ability to lock in a challenging seismic environment (MINOS detector assembly next door).
  - Measurement of coating thermal noise on fused silica substrates.
- March 2004: Provide sapphire data for AdvLIGO COC downselect decision.

Latest Sensitivity Curve: 10/23/03



- Major improvements since August LSC meeting:
  - Increased modulation depth to suppress photodetector electronic noise.
  - Careful calculation of thermal noise to account for multiple mirrors, difference measurement.
- Best sensitivity is now approximately **5e-19 m/√Hz.**
- **Noise floor appears to be dominated by coating thermal noise from approx. 500 Hz to 20 kHz.**

Calibration



$$\delta V = \frac{DC}{1 + DHMC}\delta \ell$$

- To convert the measured voltage into an equivalent length noise, we must know the transfer functions of each servo block.
  - D = Pound-Drever Frequency Discriminant
  - H = Electronic transfer function
  - M = Mirror response (displacement) to signal applied to OSEM controller's FAST-INPUT (voltage)
  - C = Cavity length to frequency conversion factor
- Specify H and C, verify H by direct measurement.
- How to determine D and M?

Conversion Factor (C)

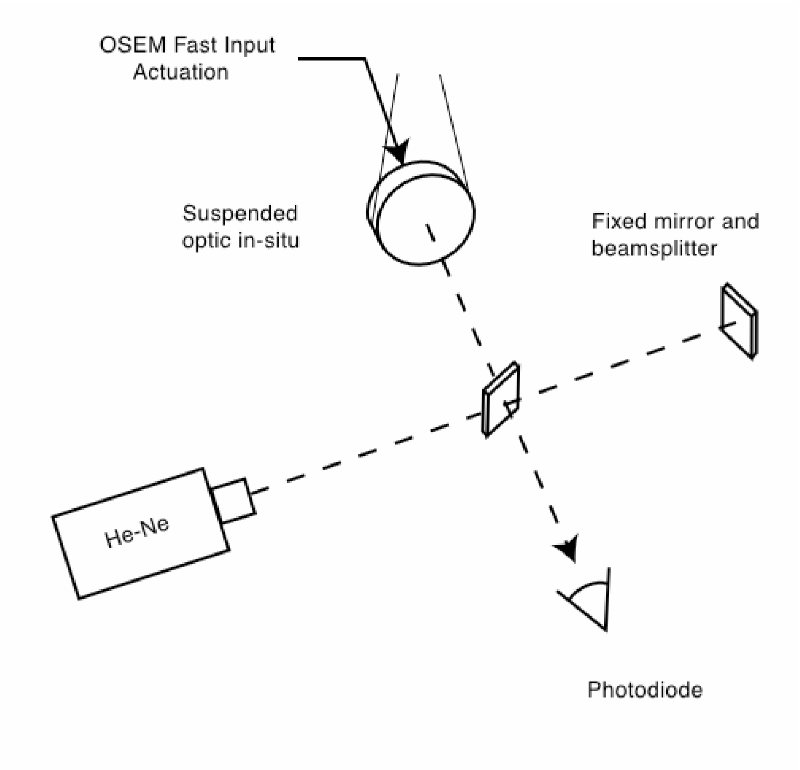
$$C = \frac{\nu}{L} = 3 \times 10^{4} \frac{MHz}{\mu m}$$

$$\nu = \frac{c}{\lambda} = 3 \times 10^{14} Hz$$

$$L = 1cm$$

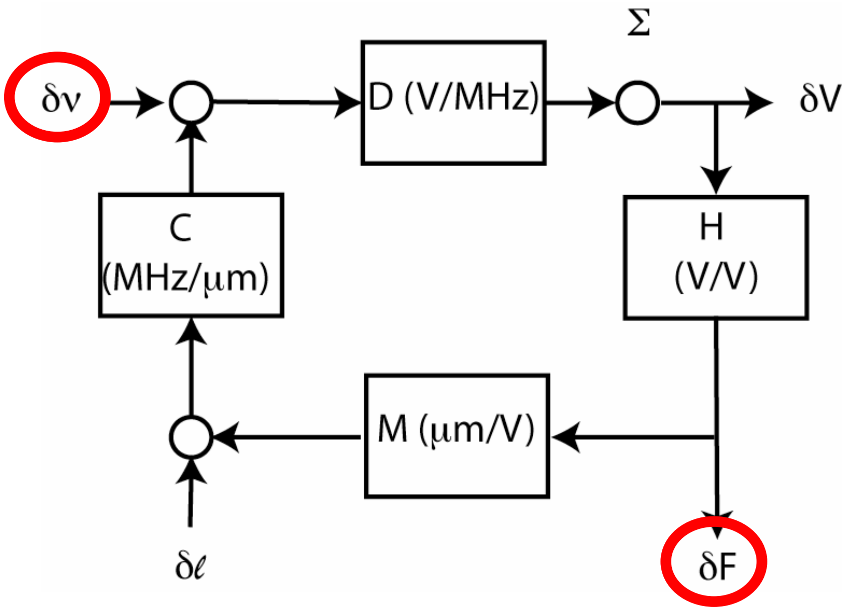
- This is just math.
- Converts length change to frequency change.
- No poles or zeroes, just a number we can calculate.

Mirror Response (M): Michelson Measurement



- Auxilliary Michelson interferometer.
- Sweep through multiple fringes and count.
- Rough estimate only!

Mirror Response (M): Frequency-Response Measurement



- Introduce known frequency fluctuation via Laser's PZT.
- Measure feedback voltage.
- Well below UGF, transfer function is

$$\delta F = \frac{DH}{1 + DHMC}\delta\nu \approx \frac{\delta\nu}{MC}$$

- Accuracy limited by how well we know the frequency fluctuation δν, which in turn depends on how well we know the laser's PZT response.
- PZT response measured using reference cavity and known sidebands, ultimately depends on frequency source used to produce sidebands (DS345).
- Measured PZT response is consistent with manufacturer's spec.

Mirror Response (M)

- Michelson method: Initial rough estimate

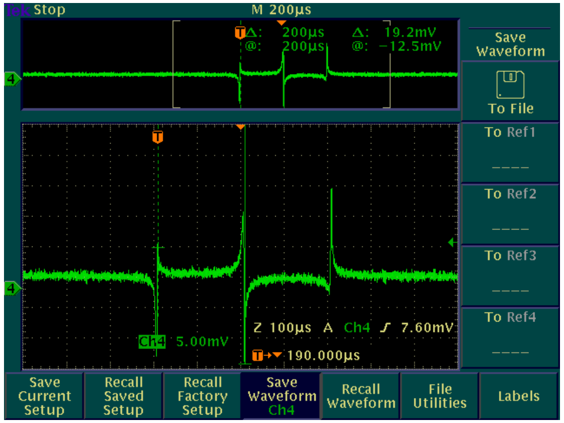
$$M(0) \approx 1 \frac{\mu m}{V}$$

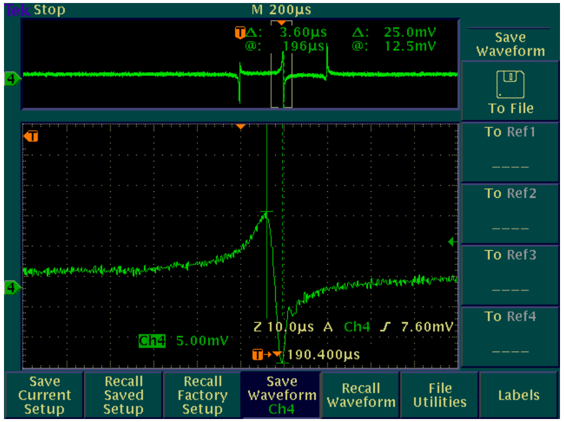
- Frequency-response method: Accuracy traceable to commercial frequency reference

$$M(0) = 0.633 \frac{\mu m}{V}$$

- Two methods agree. Use frequency-response value for final analysis.
- NAC and SAC M's are matched to within 7%.

Discriminant (D): Sweep Method



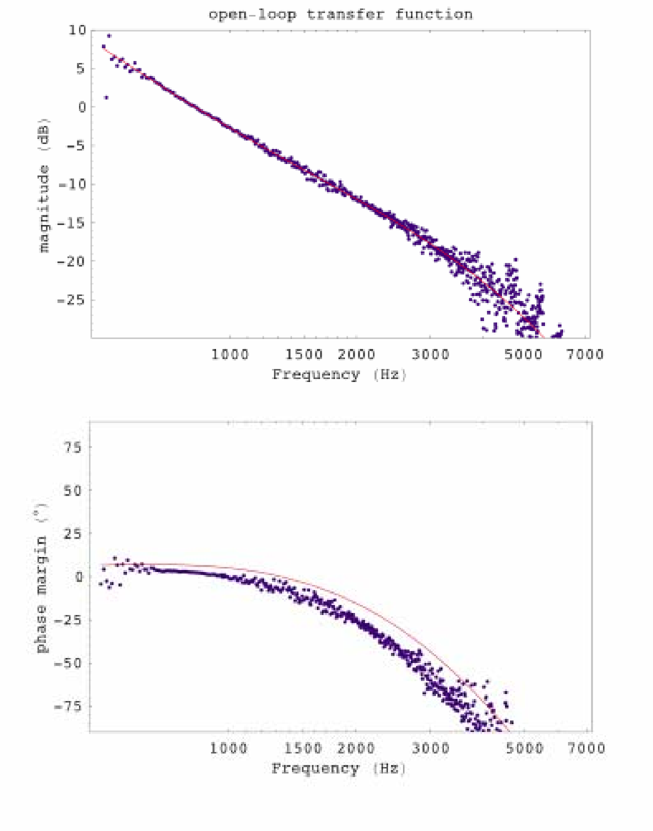


- Direct measurement of Pound-Drever-Hall error signal.
- Let mirror sweep through a fringe.
- Identify TEM-00 mode by visibility (not shown in this shot).

- **This is only an estimate of D.**

$$D = 2\frac{\Delta V}{\Delta t_c} \times \frac{\Delta t_{c-sb}}{14.75\,MHz}$$

Discriminant (D): UGF Method



- Measure open-loop transfer function with system locked
- Fit theory to data
- New calibration for every lock
- Blue is data, red is model.
- One parameter varied for fit: D
- This method appears to get frequency scaling right.
- Values obtained are consistent with those obtained by sweep method. Typical:

$$D = 9.0\frac{V}{MHz}$$

Expect: $T = DHMC$

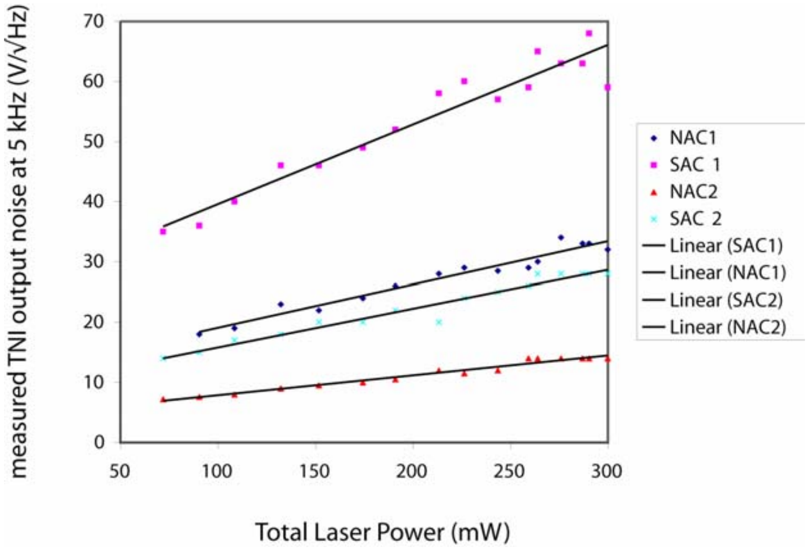
What Causes the Noise Floor?

- Having established that the instrument is well calibrated, we now want to know the origin of the noise floor. Where in the system does this noise originate? Clues:

1. Incoherence: Differential measurement selects for uncorrelated noise.
2. Scaling with power, modulation depth:
   - True length fluctuations in the arm cavities should be independent of both.
   - Measured voltage should scale linearly with power, product of Bessel functions with modulation depth.
   - Expect

$$\delta V = RP_0 \times J_0(\beta)J_1(\beta) \times \left(-16\frac{F}{\lambda}\right) \times \delta\ell$$

Power Scaling: δV vs. P_0



- Measured voltage noise is proportional to laser power for both high and low modulation depths.
- Expect this to be true if output voltage is dominated by either
  - Cavity length noise, or
  - Laser frequency noise
- This measurement rules out the photdetectors or any subsequent measurement electronics as the dominant noise source.

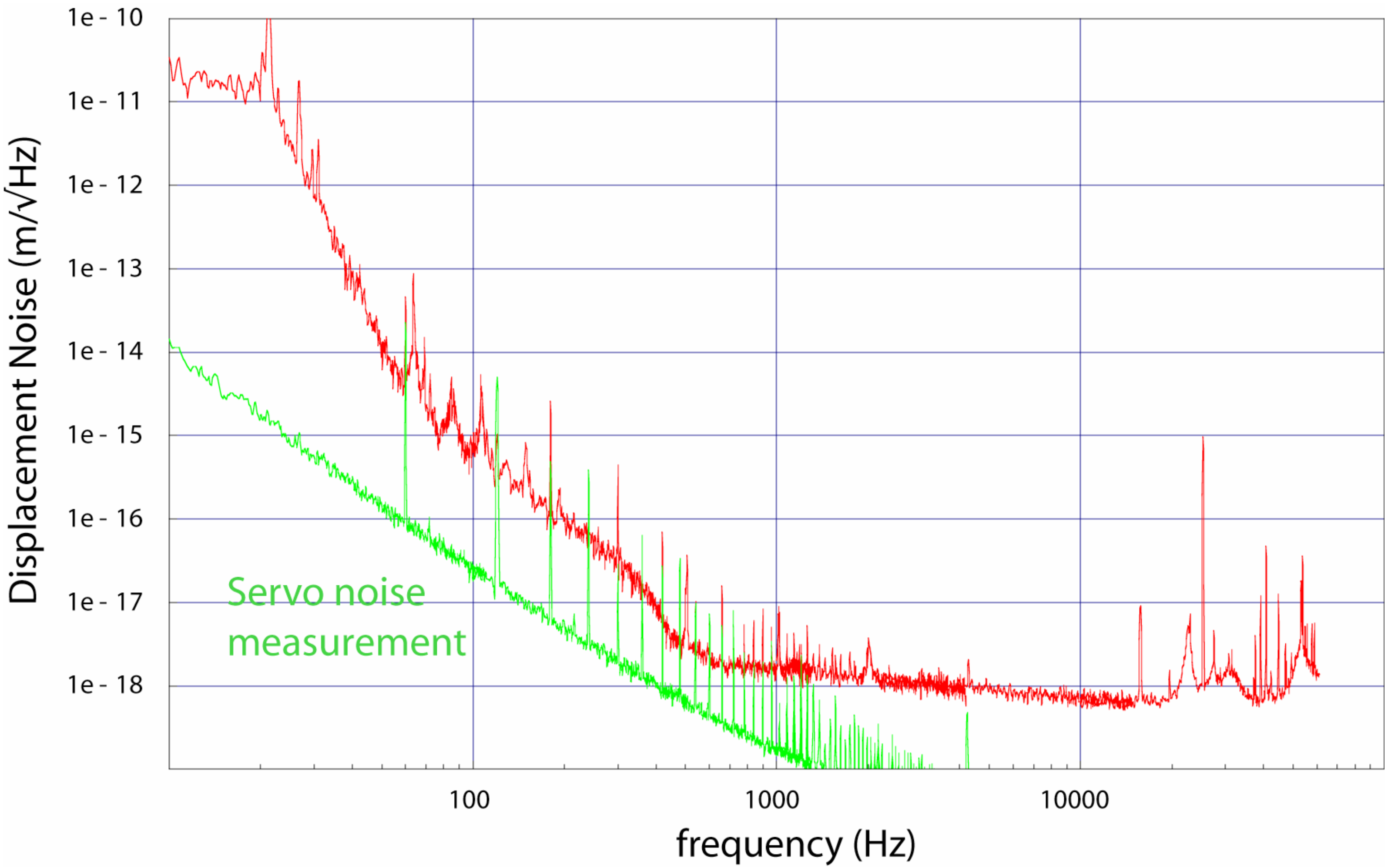
Modulation Depth: δV vs. β

- Discriminant D scales as expected (qualitatively) with modulation depth.
- Equivalenth length noise in each cavity is independent of modulation depth.
- Differential noise rises slightly at very low modulation depths due to photodetector electronic noise.
- Differential noise is only independent of modulation for high-β, where it is quite stable.
- The noise really is in the cavities, but *did it originate there?*

Servo Noise?

- Power and modulation-depth scaling indicates that the dominant noise source in the TNI does not come after the cavities in the measurement path.
- Differential measurement rules out laser frequency noise.
- Noise must be *inside* the cavities, but how do we know it *originates* there?
- Measure electronic noise going into M, convert to equivalent length noise.

Dominant Noise Source is Not Servo Noise



What We Have Not Ruled Out

1. OSEM noise: Noise in the local dampers.
   - Mirror transfer function scales as f^{-2}; noise floor has $f^{-1/2}$ dependence.
   - For OSEM noise to be responsible for our noise floor, it would have to have an $f^{+3/2}$ frequency dependence, which seems unlikely.
2. Thermal noise
   - Pendulum
   - Substrate
   - Coating

Pendulum Thermal Noise

- Pendulum thermal noise theory (above resonant frequency ω_0)

$$S_{pend}(f) = \frac{16 k_B T}{(2\pi f)^5} \frac{\omega_0^2}{Q_{pend}}$$

- One unknown parameter: Q_{pend}
- Estimate from similar systems
  - A. Gillespie and F. Raab, Phys. Lett. A, **190**, 213-220 (1994).
  - Music wire with steel clamps, our geometry and loading factor:

$$Q_{pend} \approx 3 \times 10^5$$

Substrate Thermal Noise and Observed Q's

- Mirror Q's may be determined by localized losses, e.g.
  - Barrel polish (visibly poor)
  - Magnets glued on backs and sides
  - Contact with suspension wires
- Expect bulk thermal noise to be lower than estimates based on Q measurements
  - Yamamoto, *et al.*, Phys. Lett. A 305, pp. 18-25 (2002)
  - Measured mirror Q's in the TNI range from 1e3 to 3e6.

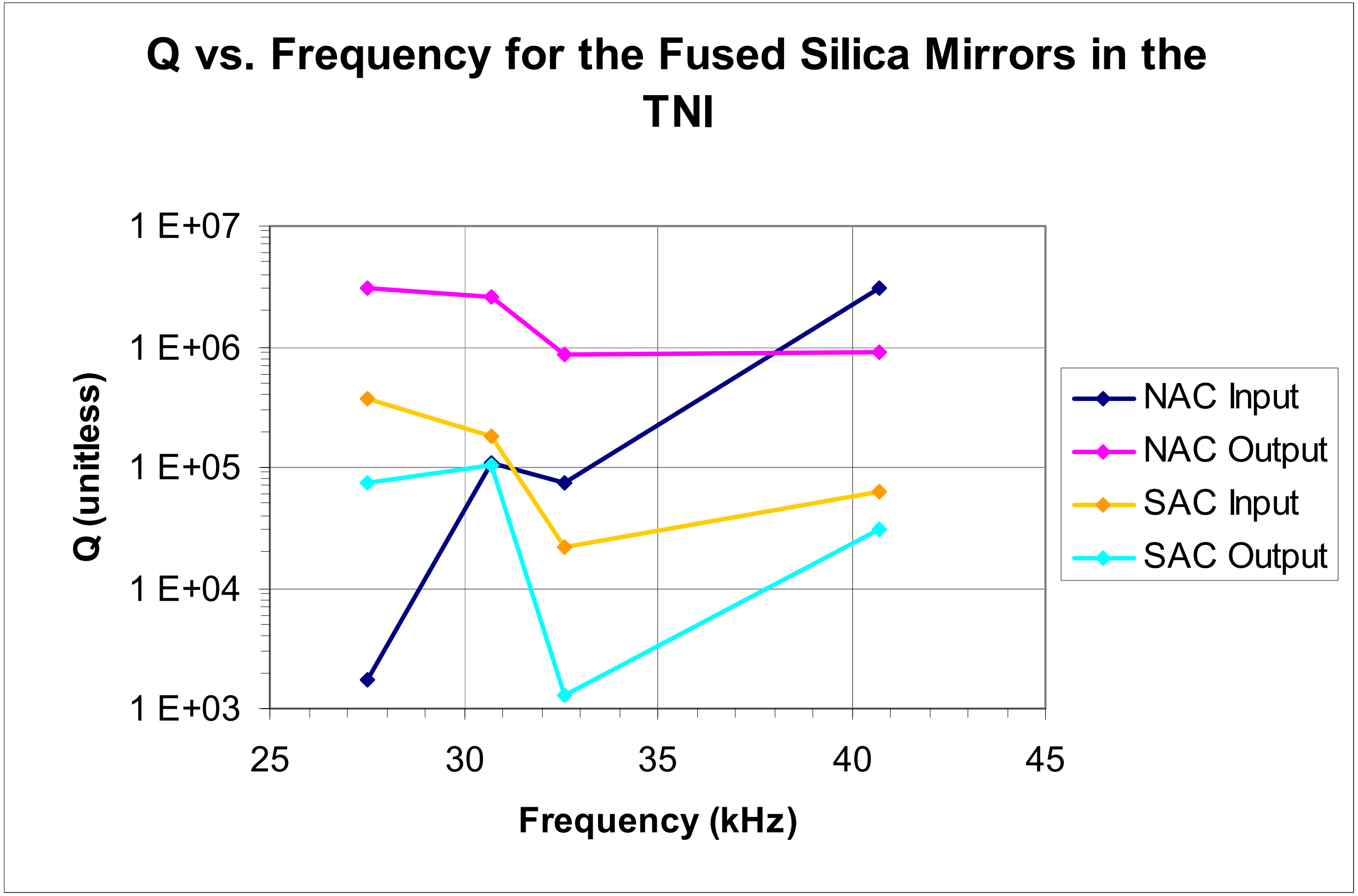
$$\phi_{substrate} = \frac{1}{Q}$$

$$\Rightarrow 3\times10^{-7} < \phi_{substrate} < 1\times10^{-3}$$

$$S_x(f) \approx \frac{2k_B T}{\pi^{3/2} f}\frac{1}{\omega Y}\phi_{substrate}$$

Q Measurements in Fused Silica Test Masses

- Q measurements were found to vary from 1700 to over 3 million.



Coating Thermal Noise

- Coating thermal noise, best estimate…
  - Crooks, *et al.,* Class. Quantum Grav. 19 (5) pp. 883-896 (2002)
  - Harry *et al.,* Class. Quantum Grav. 19 (5) pp. 897-917 (2002)

$$S_x(f) = \frac{8k_BT}{\pi^{3/2} f}\frac{1}{\omega Y}\left\{\phi_{substrate} + \frac{1}{\sqrt{\pi}}\frac{d}{\omega}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)\right\}$$

$$\sim \frac{k_BT}{\omega Y f}\left\{\phi_{substrate} + \frac{d}{\omega}\phi_{coating}\right\}$$

- Ringdown coating-Q measurements give $\phi_{\parallel}$, but only direct measurement can give $\phi_{\perp}$?
- Condition required to distinguish coating thermal noise from substrate thermal noise:

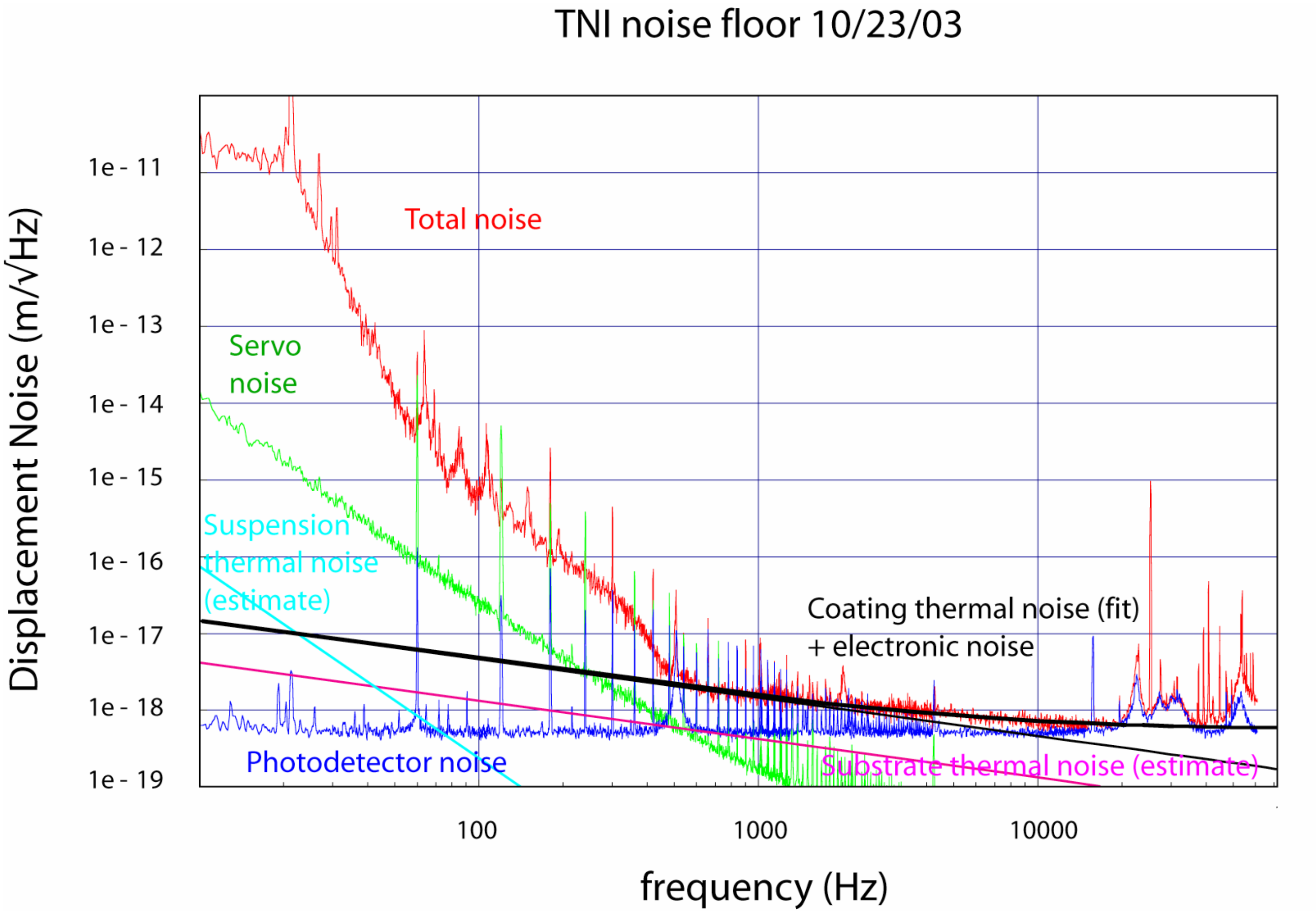
$$\phi_{coating} >> \frac{\omega}{d}\phi_{substrate}$$

For the TNI, $\frac{\omega}{d} \approx \frac{160\mu m}{5\mu m} = 32$

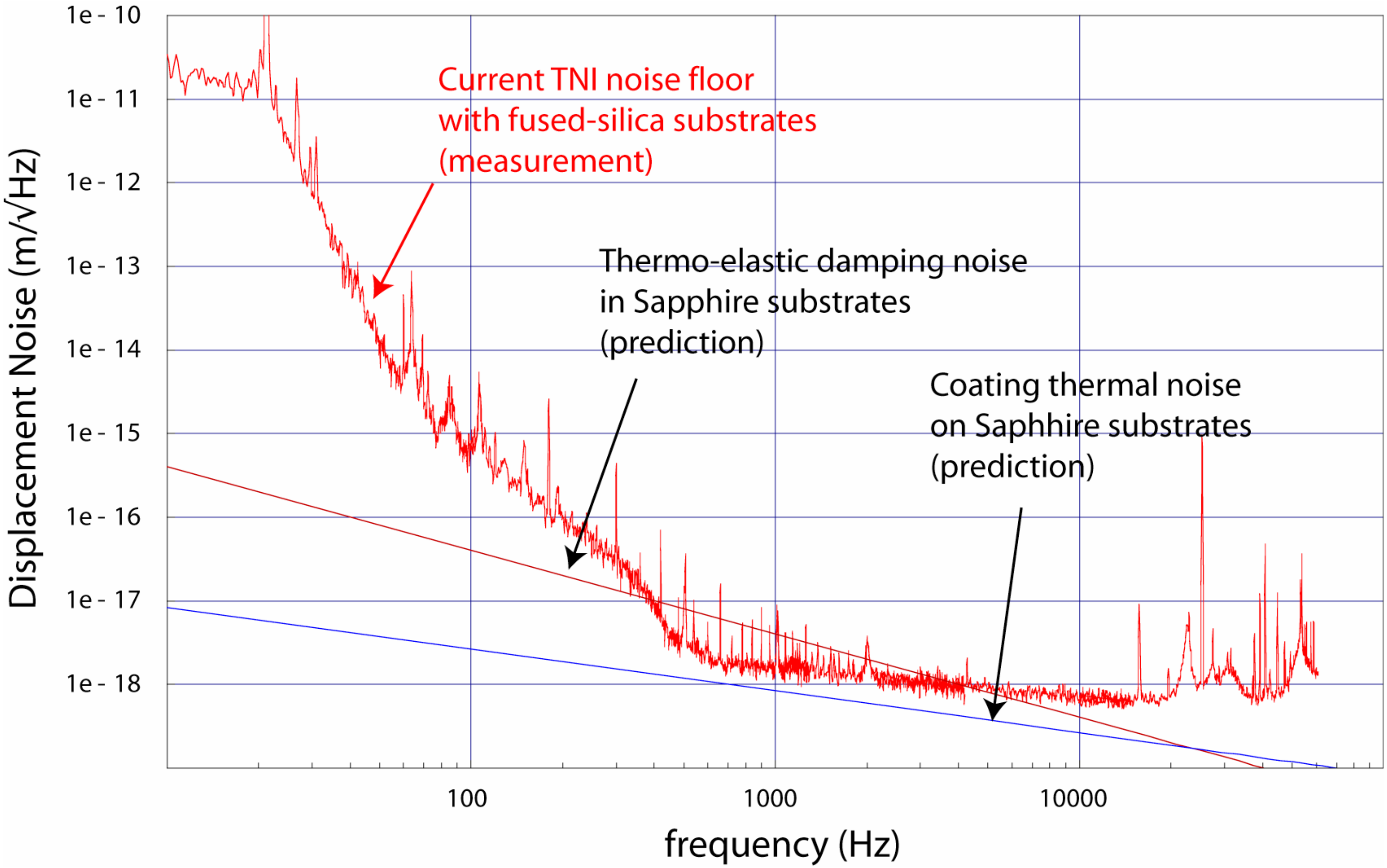
Expect: $\phi_{coating} \sim 1\times 10^{-4}$ $\phi_{substrate} \leq 3\times 10^{-7}$

Condition met by factor of ten in TNI.

TNI Noise Breakdown


TNI noise floor 10/23/03

Next Step: Sapphire Substrates



Current TNI noise floor with fused-silica substrates (measurement)

Thermo-elastic damping noise in Sapphire substrates (prediction)

Coating thermal noise on Saphhire substrates (prediction)

Conclusions

- TNI noise floor appears to be dominated by coating thermal noise from 500 Hz to 20 kHz.
- Losses in these SiO_2/Ta_2O_5 coatings appear to be isotropic:
  - Ringdown measurements give $\phi_{||}$
  - We obtain $\phi_{\perp}$ by experimental fit to our data

$$\phi_{||} = 1.0 \times 10^{-4} \qquad \phi_{\perp} = 1.3 \times 10^{-4}$$

- TNI is on track for April 2004 AdLIGO COC material downselect.
  - Deadline for thermal noise measurement with fused-silica mirrors was Oct. 29.
  - Our measurement was completed Oct. 23.
  - Current noise floor is below predicted Sapphire noise from 400 Hz to 4 kHz.
  - Expect coating thermal noise to go down due to increased Young’s modulus of substrate. Will it?