Suspension Thermal Noise in Initial LIGO

Gregory Harry
LIGO / MIT

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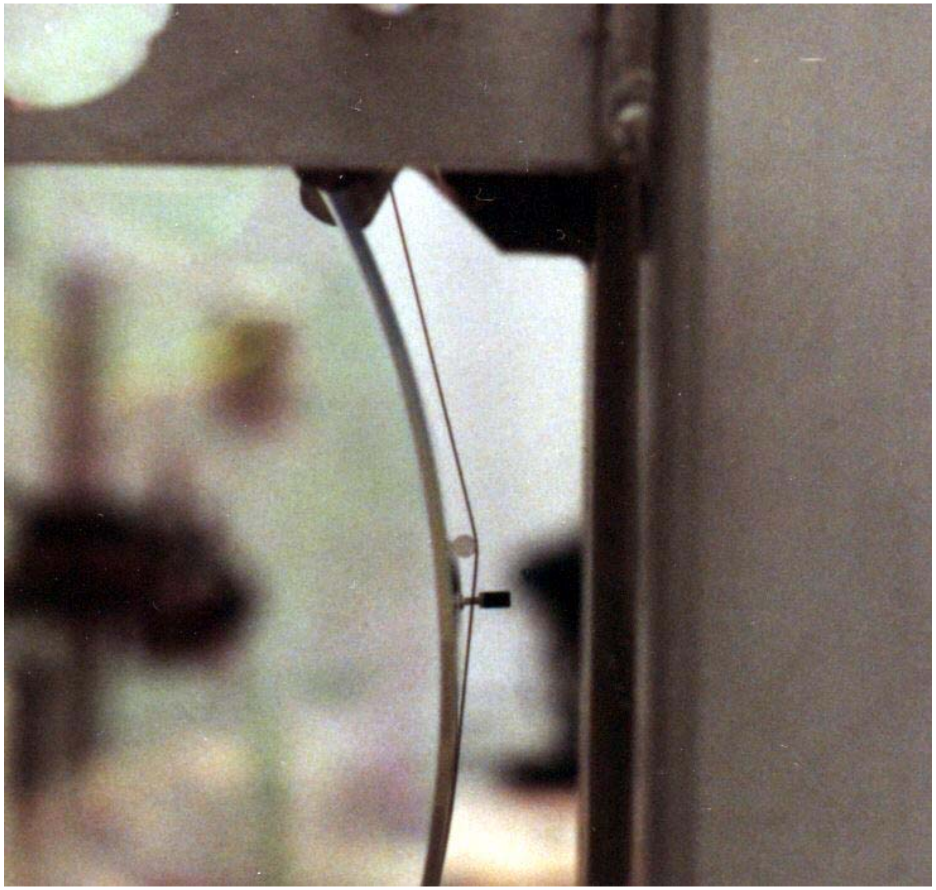
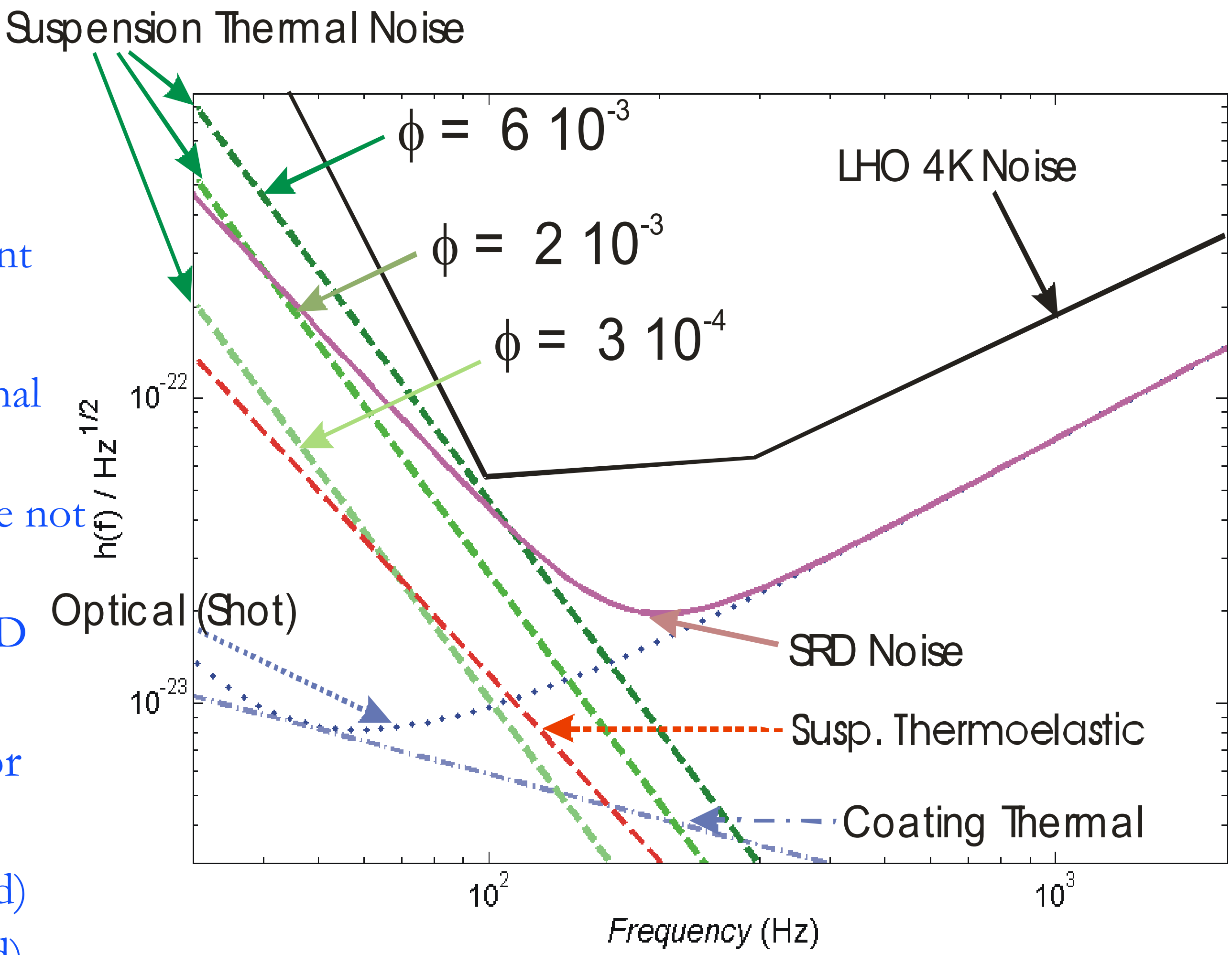
Outline

- Impact of thermal noise on sensitivity and commissioning
- Measurements of suspension thermal noise
  - Frequency domain
  - Time domain
  - Discrepancies
- Questions and ideas
  - Feedback contamination
  - Modeling



Impact of Thermal Noise

- Suspension thermal noise
  - Structural damping
  - Lower loss
  - Thermoelastic can be relevant
- Mirror thermal noise
  - Coating (SiO_2/Ta_2O_5) thermal noise dominant
  - Silica substrate thermal noise not really a factor
  - About factor of 5 below SRD
- Three presented scenarios for suspension thermal noise
  - Pessimistic (worst measured)
  - Nominal (average measured)
  - Optimistic (material limit)



Sensitivity to Sources

Single Interferometer Sensitivity

	Neutron Star Inspirals	10 M_O Black Hole Inspirals	Stochastic Background	Crab Pulsar (ε limit)	Sco X-1 Pulsar (ε limit)
SRD	16 Mpc	63 Mpc	$2.3\ 10^{-6}$	$1.6\ 10^{-5}$	$3.1\ 10^{-7}$
$\phi = 6\ 10^{-3}$	16 Mpc	60 Mpc	$4.7\ 10^{-6}$	$2.3\ 10^{-5}$	$3.0\ 10^{-7}$
$\phi = 2\ 10^{-3}$	20 Mpc	84 Mpc	$1.9\ 10^{-6}$	$1.4\ 10^{-5}$	$3.0\ 10^{-7}$
$\phi = 3\ 10^{-4}$	26 Mpc	120 Mpc	$5.9\ 10^{-7}$	$7.5\ 10^{-6}$	$3.0\ 10^{-7}$
Thermoelastic Limit	29 Mpc	140 Mpc	$2.7\ 10^{-7}$	$5.7\ 10^{-6}$	$3.0\ 10^{-7}$

Suspension Thermal Noise

$$S_x(f) = 4\ k_B\ T\ g/(m\ L\ (2\ \pi\ f)^5)\ \Phi$$

Dissipation Dilution

- Restoring force in pendulum is due to both elastic bending and gravity
- Effective loss angle for thermal noise ‘diluted’ by the ratio

$$\Phi = k_e/k_g\ \phi$$

$$(k_e/k_g)_{violin} = 2/L\ \surd(E\ I/T)\ (1+1/(2\ L)\ \surd(E\ I/T)\ n^2\ \pi^2)$$

$$\approx 2/L\ \surd(E\ I/T) = 3.5\ 10^{-3}$$

- Correction for first three violin mode harmonics is negligible

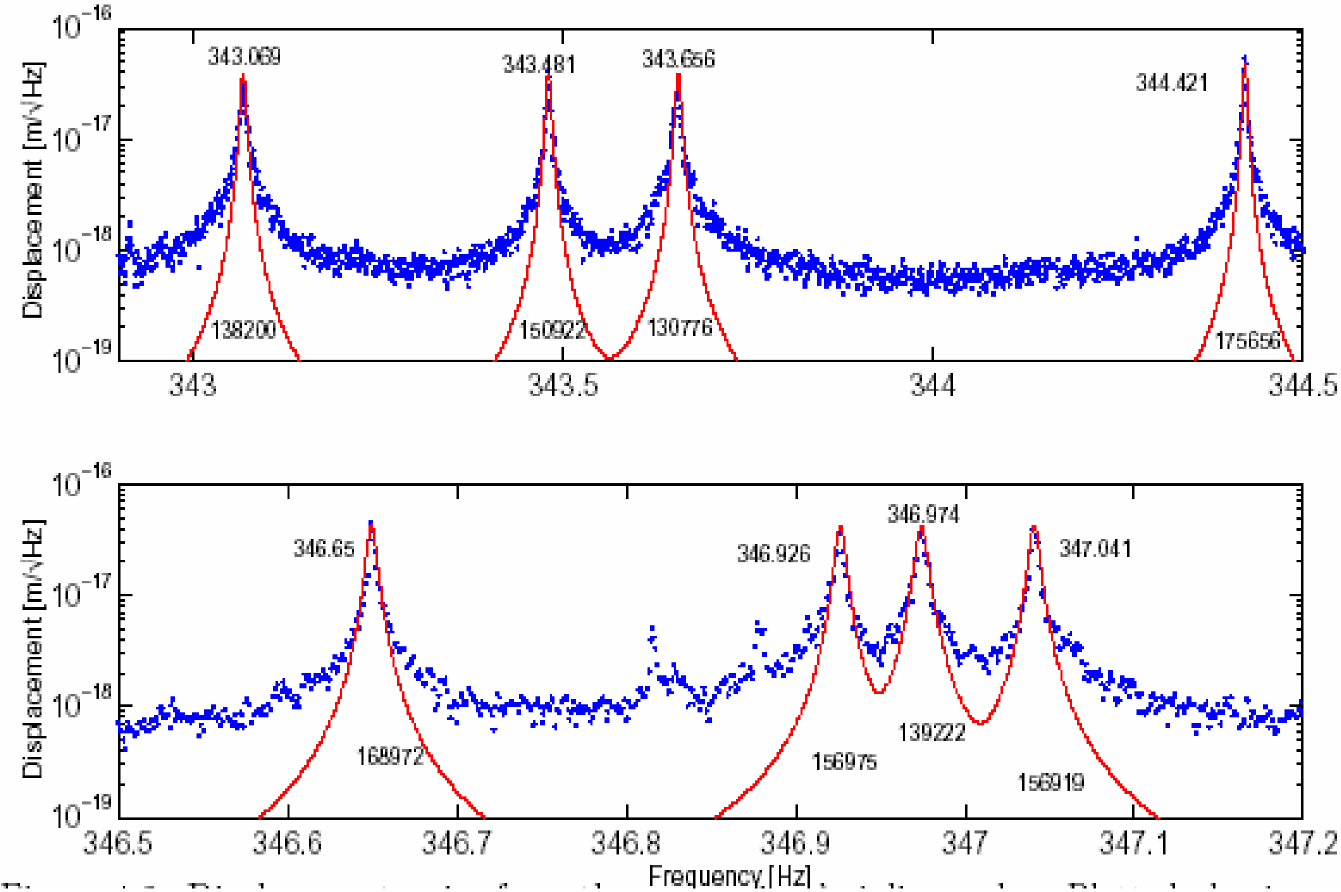
Q Measurements

Frequency Domain

- Collect data for ~ 2 h
- Associate peaks with mirrors
- Fit Lorentzians to peaks

Limitations

- Optical gain drift ?
  - Get similar results with S2 data as current data with improved wavefront sensors
- Temperature drift can cause central frequency to migrate
  - Minimal over a few hours

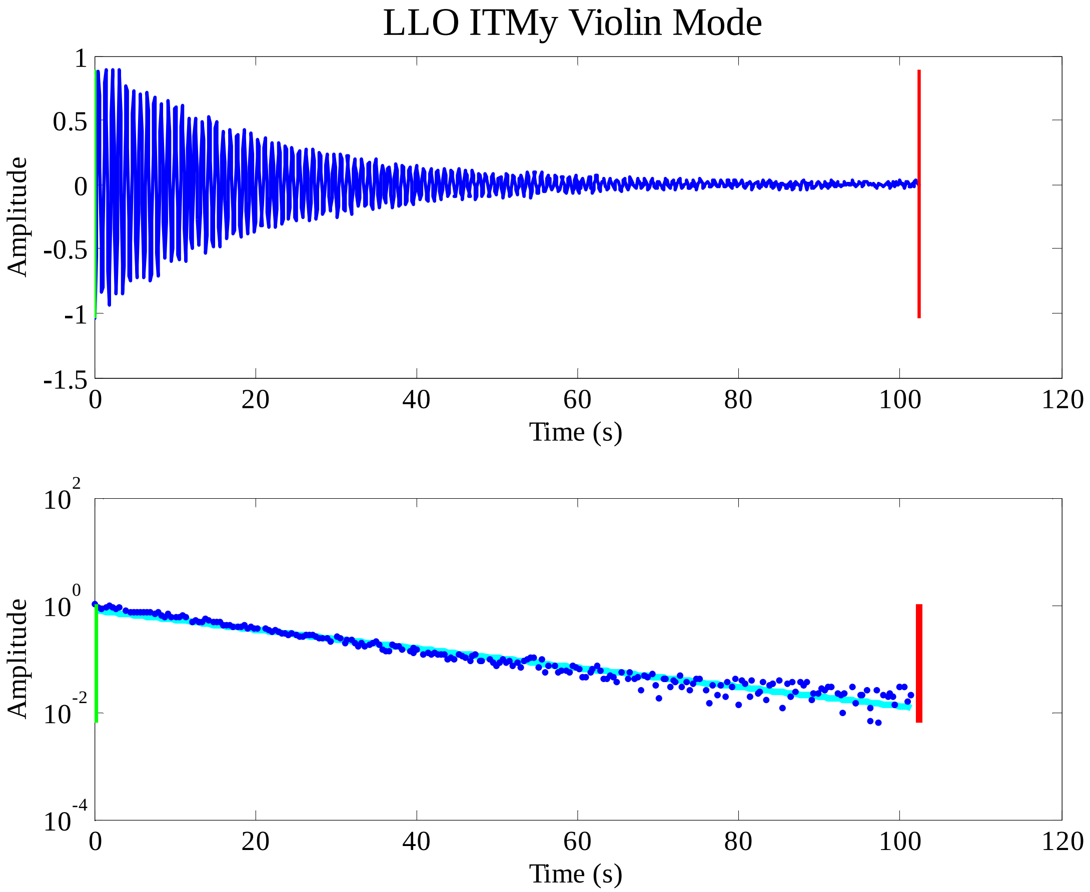


Graphic from R. Adhikari's Thesis

Q Measurements

Time Domain

- Excited modes with on-resonance drive to coil
- Let freely ring down
- Put notch filters in LSC loop
- Fit data to decaying exponential times sine wave



Limitations

- Must ring up to much higher amplitude than thermal excitation
    - No consistent difference between Michelson and Full IFO locks
- Feedback can effect measured Q

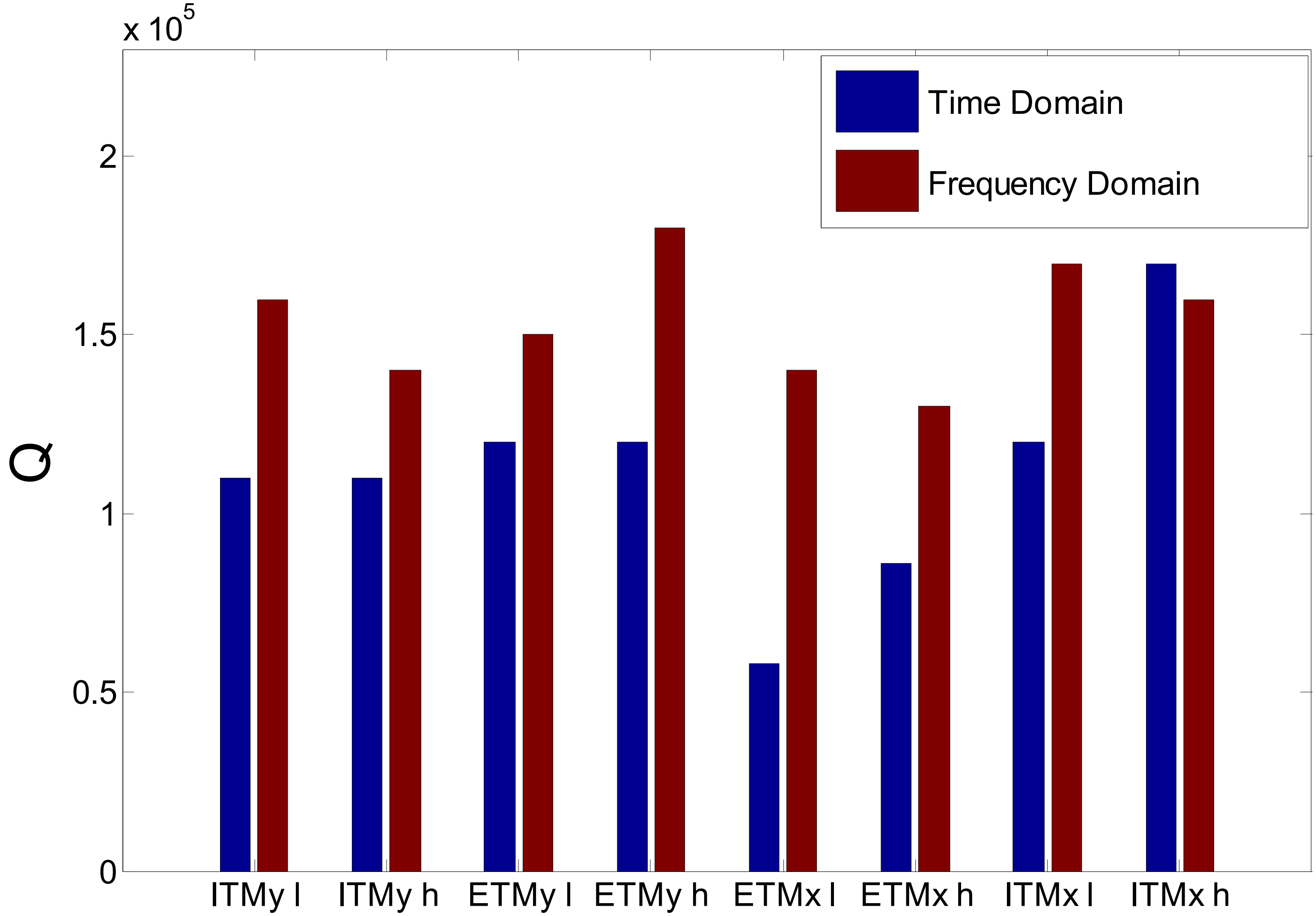
Violin Mode Results

Overview

- Ringdown Q’s and frequency domain fits do not agree
- Ringdown Q’s repeatable within a lock stretch but frequency domain fits are not
- Results different in different lock stretches
- High harmonics show a little more pattern
  - Still unexplained discrepancies
- Highest Q’s consistent with material loss in wires
  - Gillespie laboratory results
- Similar (lack of) patterns in all three IFOs
  - Data from all 3, but more data on H2 than others

Violin Mode Results
Livingston

Comparison of Time Domain and Frequency Domain



Violin Mode Results
Hanford 2K

Comparison of Frequency Domain Q's in Same Lock
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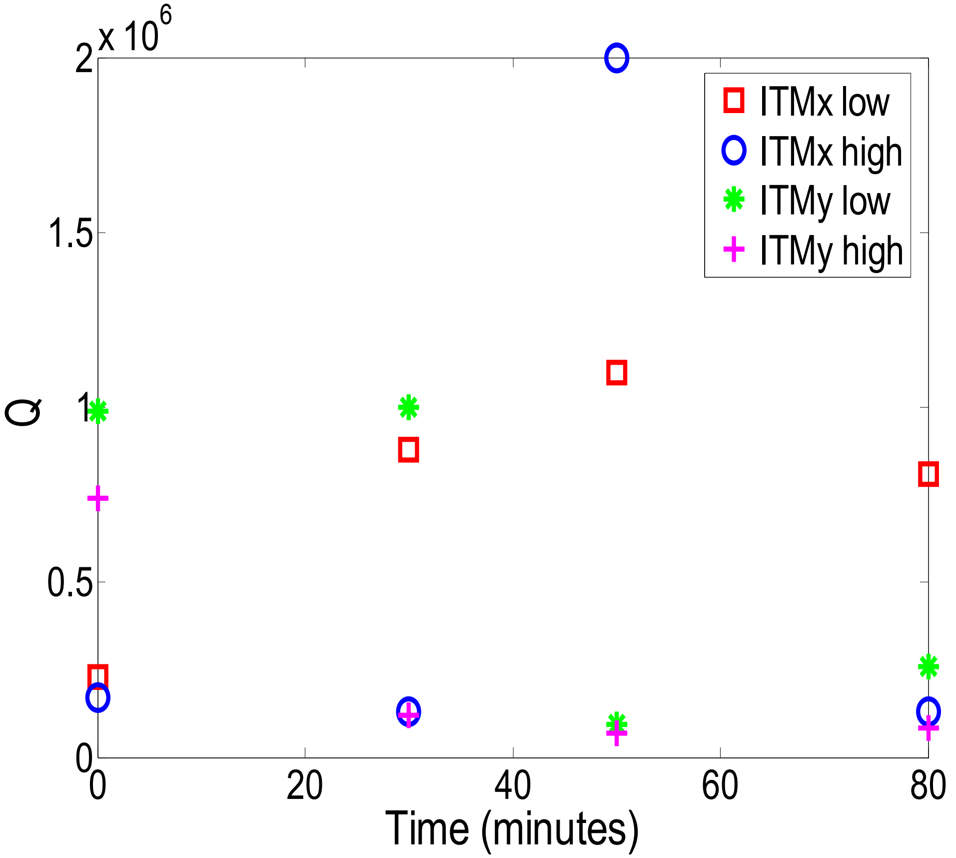
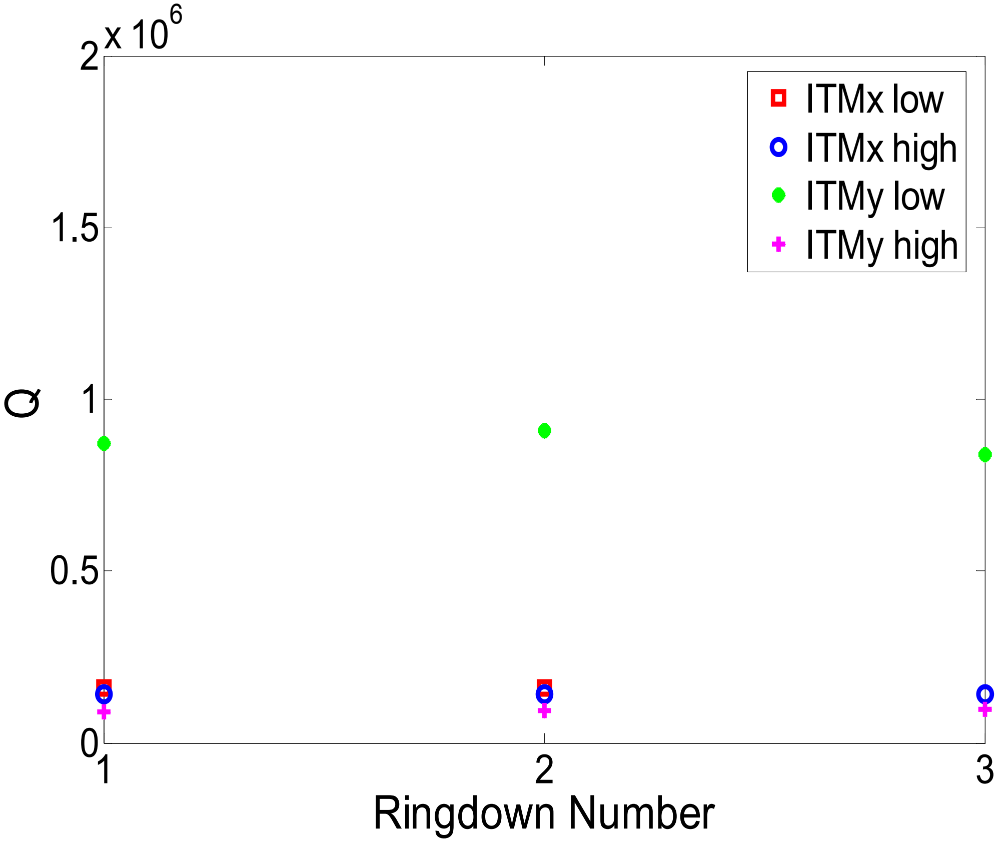


Comparison of Time Domain Q's in Same Lock

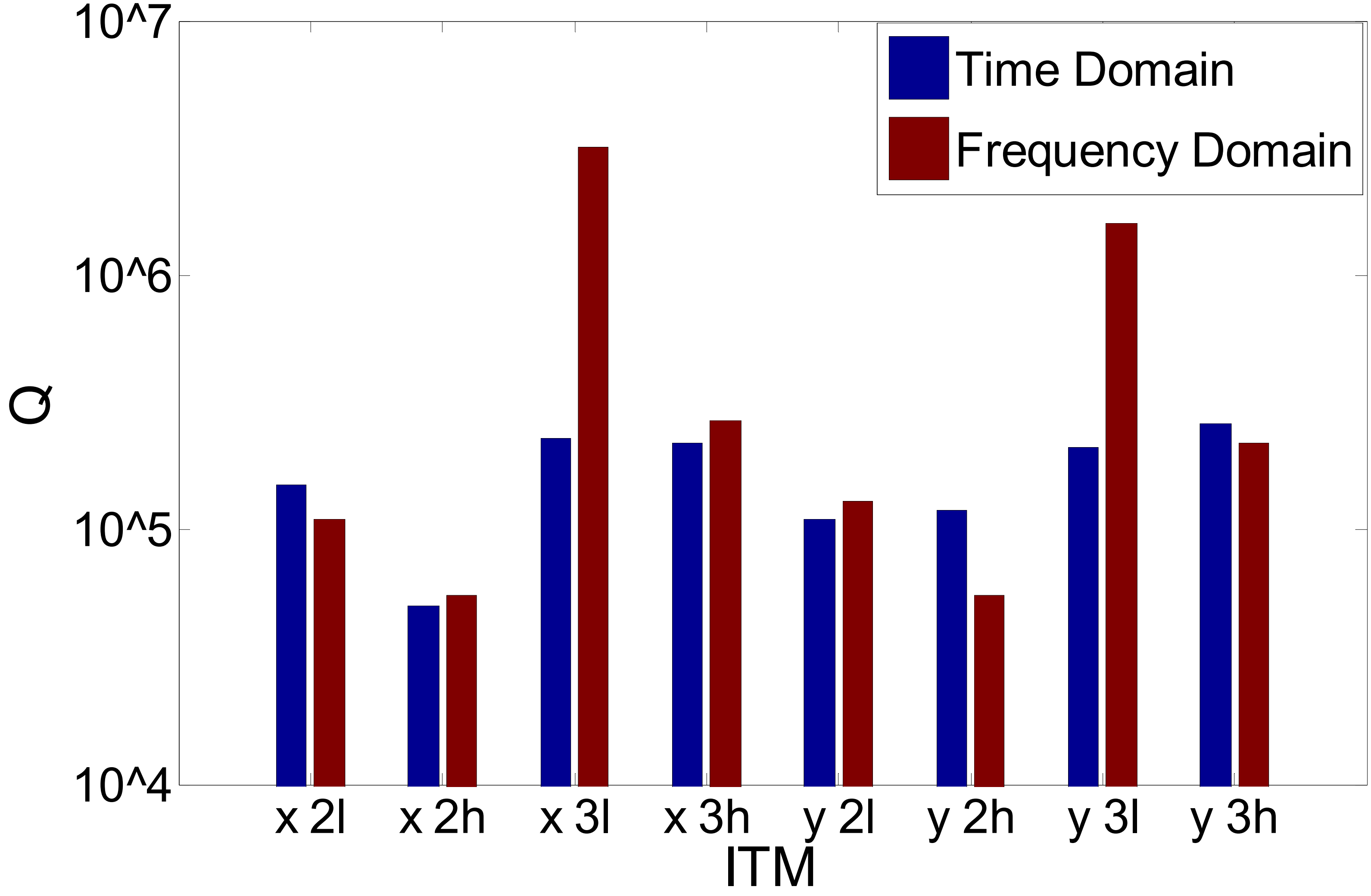


Violin Mode Results
Hanford 2K/Livingston

Comparison of Time Domain Q’s in Different Locks

LHO2K IMTx low	LLO ITMx high
8.6 10^4	1.7 10^5
1.6 10^5	1.4 10^5
1.6 10^5	
1.2 10^5	

Higher Harmonic Results
Hanford 2K



Violin Mode Results

Hanford

Highest Q's Measured

Frequency Domain	Q	ϕ
H2K ITMx Third Harmonic	$3.2\ 10^{6}$	$8.6\ 10^{-5}$
H2K ITMy Third Harmonic	$1.6\ 10^{6}$	$1.7\ 10^{-4}$
H4K ITMy Third Harmonic	$9.8\ 10^{5}$	$2.8\ 10^{-4}$
Time Domain		
H2K ITMy Third Harmonic	$2.3\ 10^{5}$	$1.2\ 10^{-3}$
Gillespie Lab Results		$3\ 10^{-4}$

Questions from Violin Q Measurements

- Why the disagreement between t and f domain?
  - Is f domain unreliable? Why?
  - Changes in instrument over hour time scales? Optical drift? Thermal drift?
  - Interaction between degenerate polarizations of modes?
- Why changes in ringdowns between lock stretches?
  - Changes in suspension during lock acquisition?
  - Feedback influence on Q’s? ASC? LSC and optical spring?
- Why are the highest Q’s in f domain third harmonic?
  - Higher frequency gets away from unity gain frequency of loop?
  - Why not seen in t domain?
- How reliable are these numbers?
  - Changing thermal noise from lock to lock?
  - Feedback contamination so Q’s do not predict thermal noise?
  - What about internal mode Q’s?

Modeling
Some Hope for Answers

- Is feedback mechanism feasible?
  - Violin modes coming soon to e2e
- What about loss from optical spring?
  - Thomas Corbitt at MIT has done preliminary modeling
  - Need to have cavity offset from resonance slightly
    - Output Mode Cleaner data shows arm cavities are off resonance by about 1 pm
    - Optical loss from cavity spring would look like mechanical loss
  - Thomas' model needs cavity power, expected Q, measured Q, frequency
    - For 2.5 kW, $Q_{exp} = 10^6$, $Q_{meas}=10^5$, f=350 Hz
    - Offset required: 100 pm - does not look likely
  - Needs more work

Violin Modes :
Future Directions

- Modeling and theory
  - Need some ideas
- More time domain data
  - Same and different lock stretches
- Measure Q vs. ASC loop gain and/or cavity power to assess feedback effect
  - If Q depends on power, extrapolate back to 0 to get true thermodynamic loss
- Measure more and higher harmonics
  - Get above from loops unity gain frequency
  - Less amplitude for same energy, so less motion of wire
- Collect data on all mirrors and wires
  - Maybe some data is more comprehensible

Conclusions

- Suspension thermal noise has a large impact on astrophysical performance
- Firm prediction of suspension thermal noise is still lacking
- Current results are numerous but confusing
    - No reason to believe suspension thermal noise will be above SRD, some hope that it will be significantly below
- Need more measurements
    - Higher harmonics
    - Q as a function of loop gain
- Mirror thermal noise not a limiting noise source