Thermal Noise in Initial LIGO

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Outline

Impact of thermal noise on sensitivity

Measurements of suspension thermal noise

- Measurements
- Results
- Future plans

Ideas for improving thermal noise

Measurements of mirror thermal noise

- Measurements
- Calculation and limits

Impact of Thermal Noise I

Science Requirement Document Noise

Limited by Suspension Thermal Noise

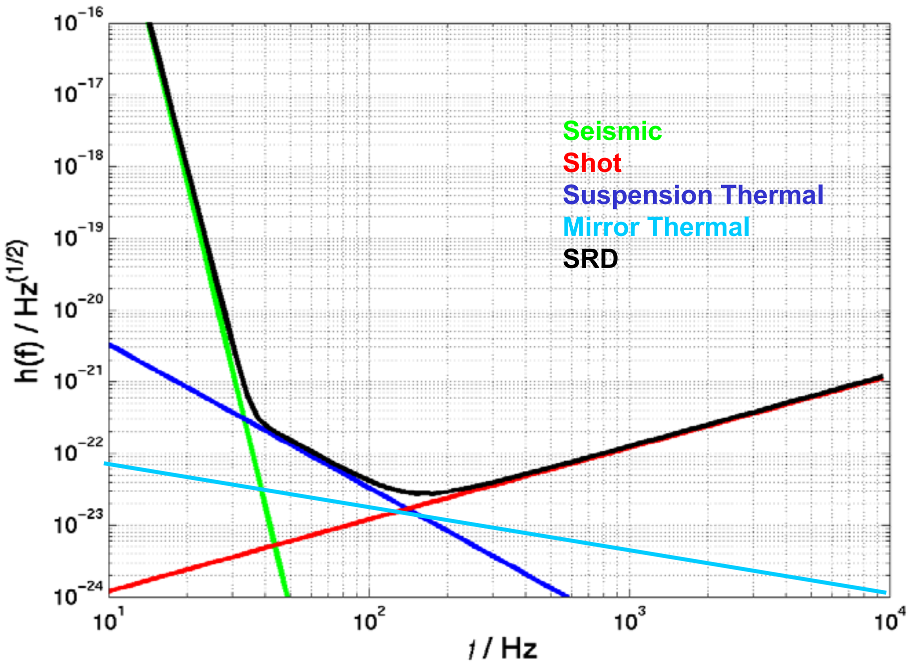
- 40 Hz to 100 Hz
- Steel wires connected by standoffs to mirror

Mirror Thermal

- Contributes around 150 Hz
- Based solely on modal Q's measured in laboratory

Astrophysical reach

- Binary neutron star inspiral range 16 Mpc
- 10 M_o black hole inspiral range 63 Mpc
- Stochastic background 2.3 X 10^{-6}
- Crab nebula pulsar upper limit (1 year integration time) ε = 1.6 X 10^{-5}
- Sco X-1 pulsar upper limit (1 year integration time) ε = 3.1 X 10^{-7}



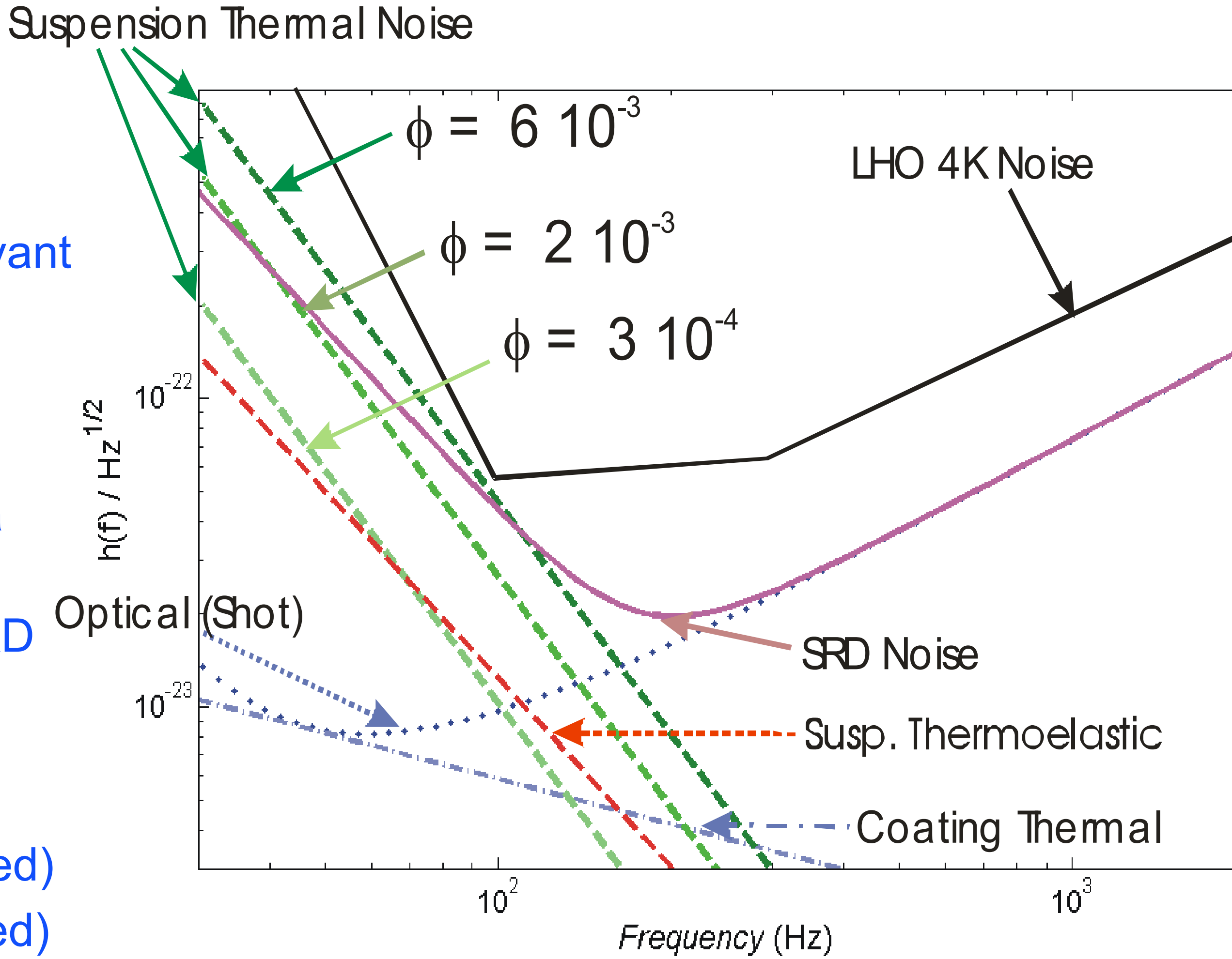
- Includes a number of overly-conservative and/or outdated assumptions
- Suspension thermal noise
  - Viscous damping (wrong frequency dependence)
  - High level of mechanical loss
- Mirror thermal noise
  - Modal Q model
  - Coating contribution not included

Impact of Thermal Noise II

Suspension thermal noise
- Structural damping
- Lower loss
- Thermoelastic can be relevant

Mirror thermal noise
- Coating thermal noise dominated
- Silica substrate not really a factor
- About factor of 5 below SRD

Three scenarios for suspension thermal noise
- Pessimistic (worst measured)
- Nominal (average measured)
- Optimistic (material limit)



Sensitivity to Sources

	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

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

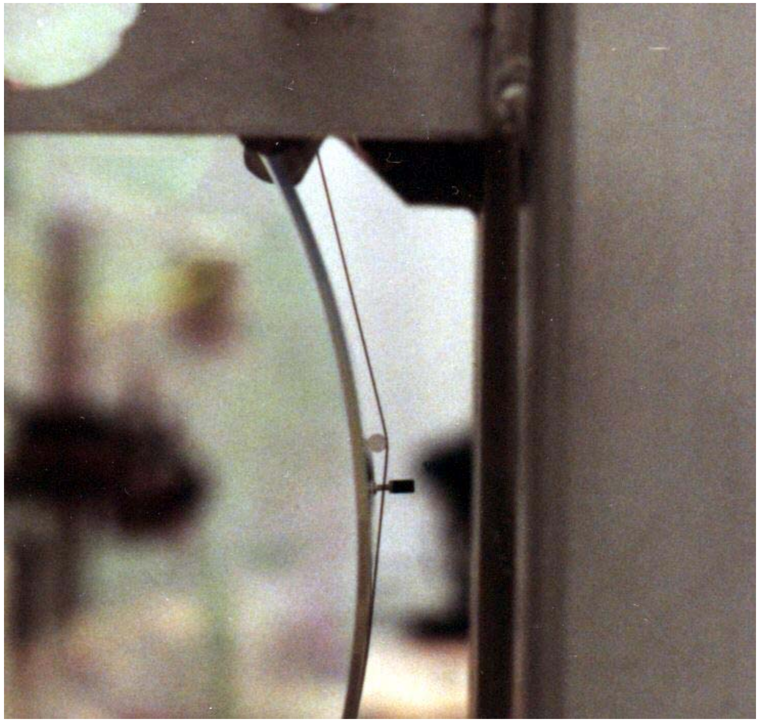
$$(k_e/k_g)_{violin} = 2/L \sqrt{(E\, I/T)}\, (1+1/(2\, L) \sqrt{(EI/T)}\, n^2\, \pi^2)$$

$$\approx 2/L \sqrt{(EI/T)} = 3.5\ 10^{-3}$$

- Correction for first three violin mode harmonics is negligible

Properties of Suspension Wires

- C70 Steel
- Mechanical parameters
  - Density 7800 kg/m^3
  - Young's modulus 165 X 10^9 Pa
  - Loss Angle 3 X 10^{-4}
    - measured in lab setting (Gillespie)
- Thermal parameters
  - Heat capacity 486 J/kg/K
  - Thermal conductivity 49 W/m/kg
  - Thermal expansion 5.1 X 10^{-7} 1/K



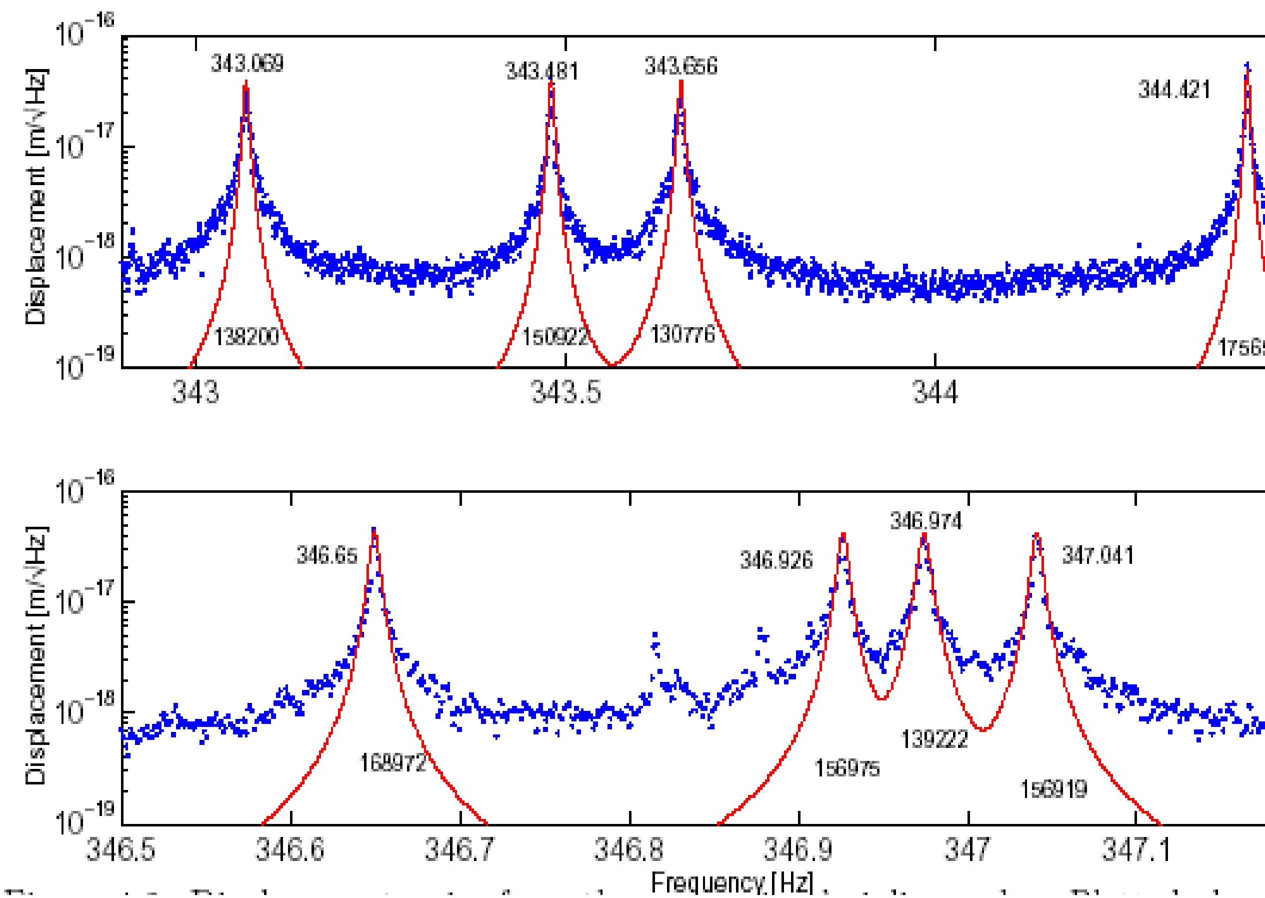
- Wire dimensions
  - Diameter 150 μm
  - Length 0.44 m

Q Measurements
Frequency Domain

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

Limitations

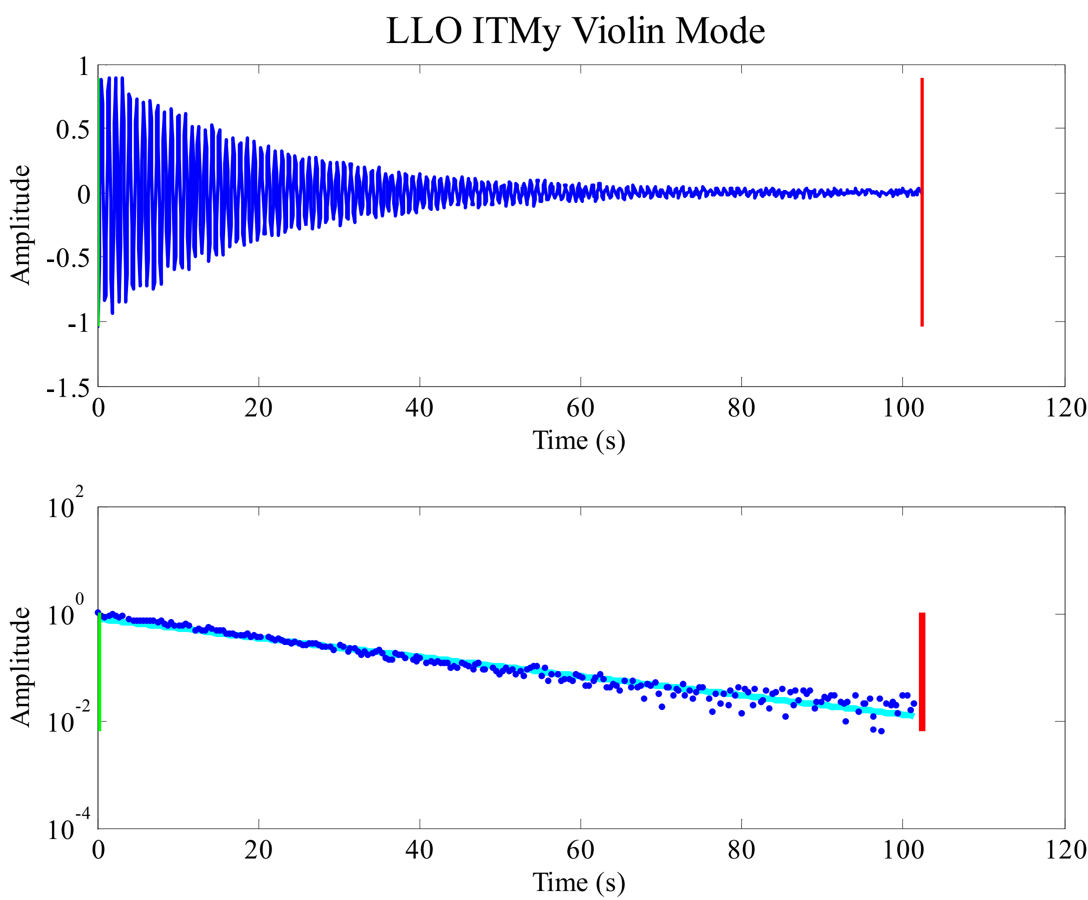
- Optical gain drift ?
  - Get similar results with S2 data as current data with improved wavefront sensors
- Temperature drift can cause central frequency to migrate
  - Minimal over a few hours



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

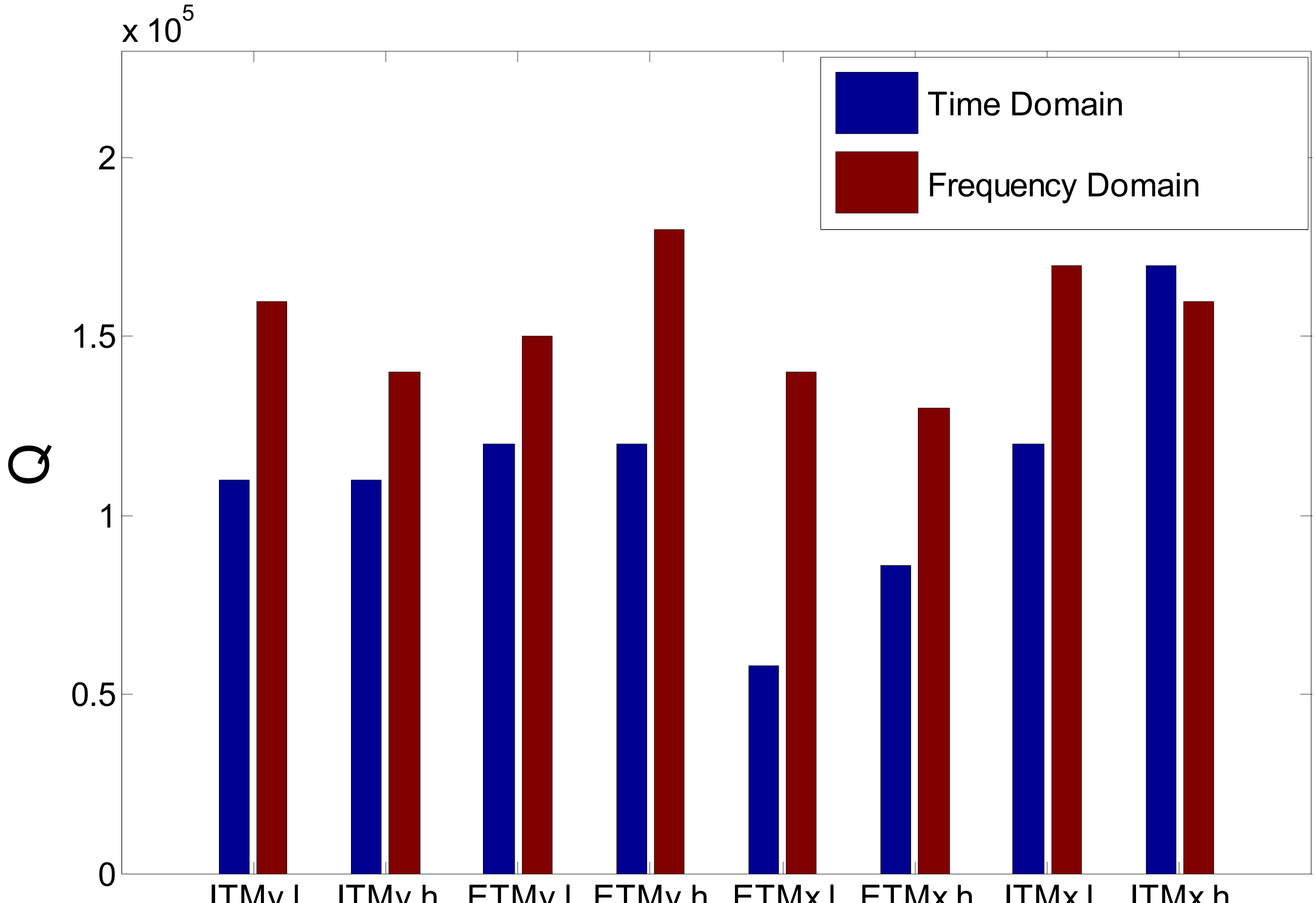
- Gillespie laboratory results

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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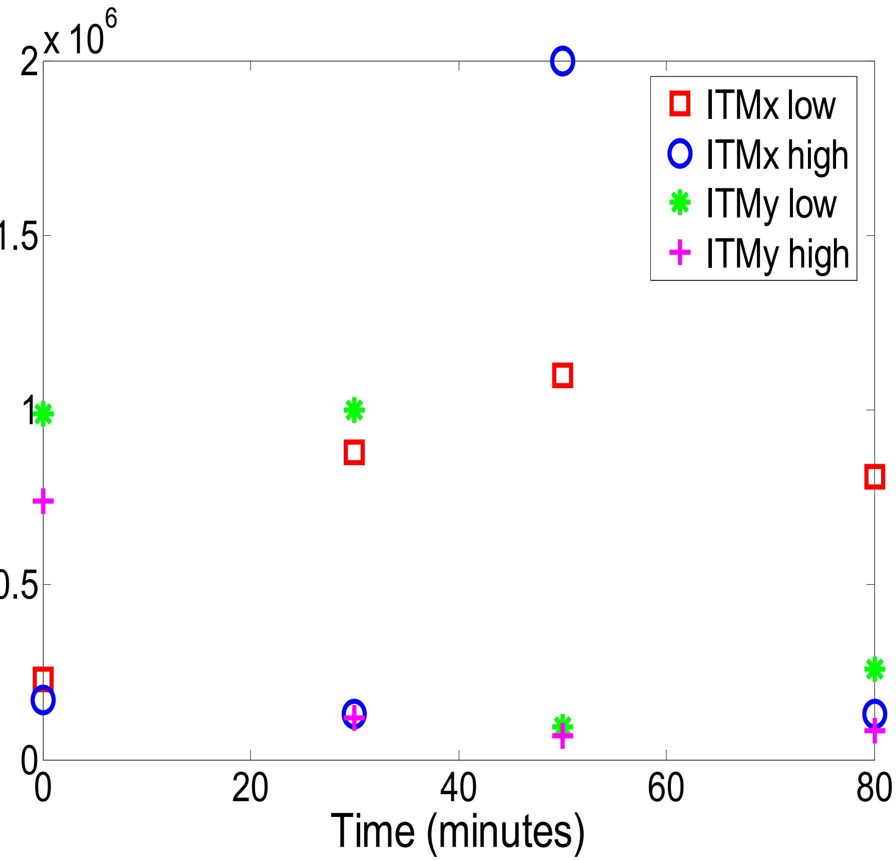
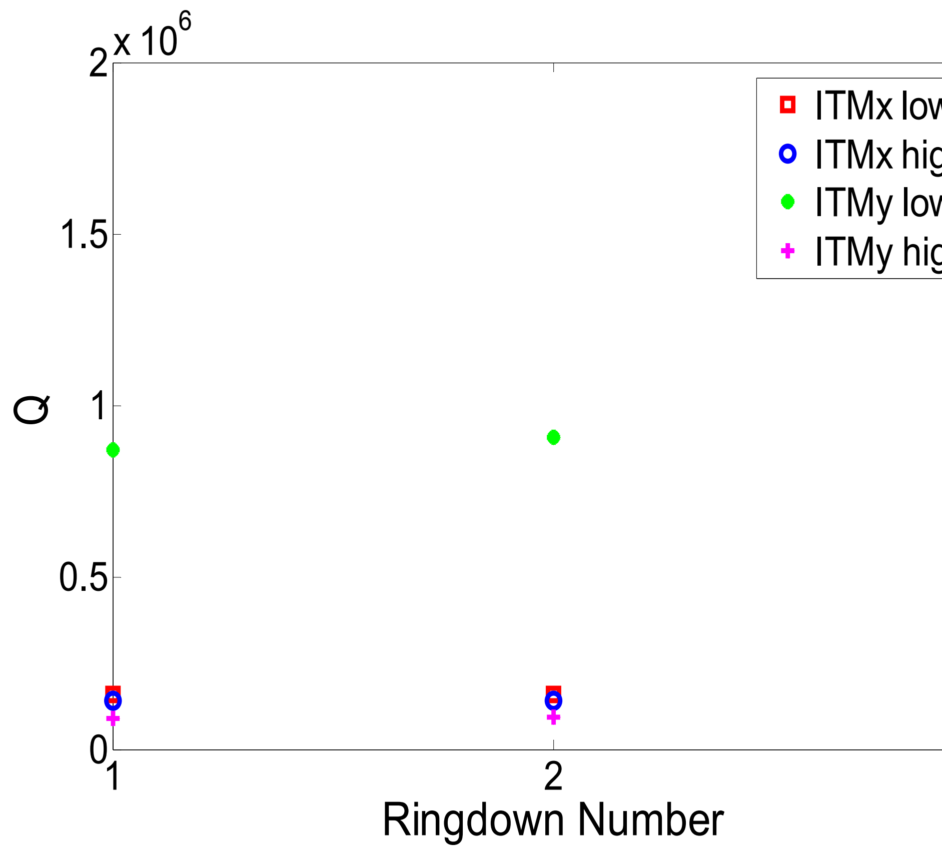


Comparison of Time Domain Q’s in Same Lock

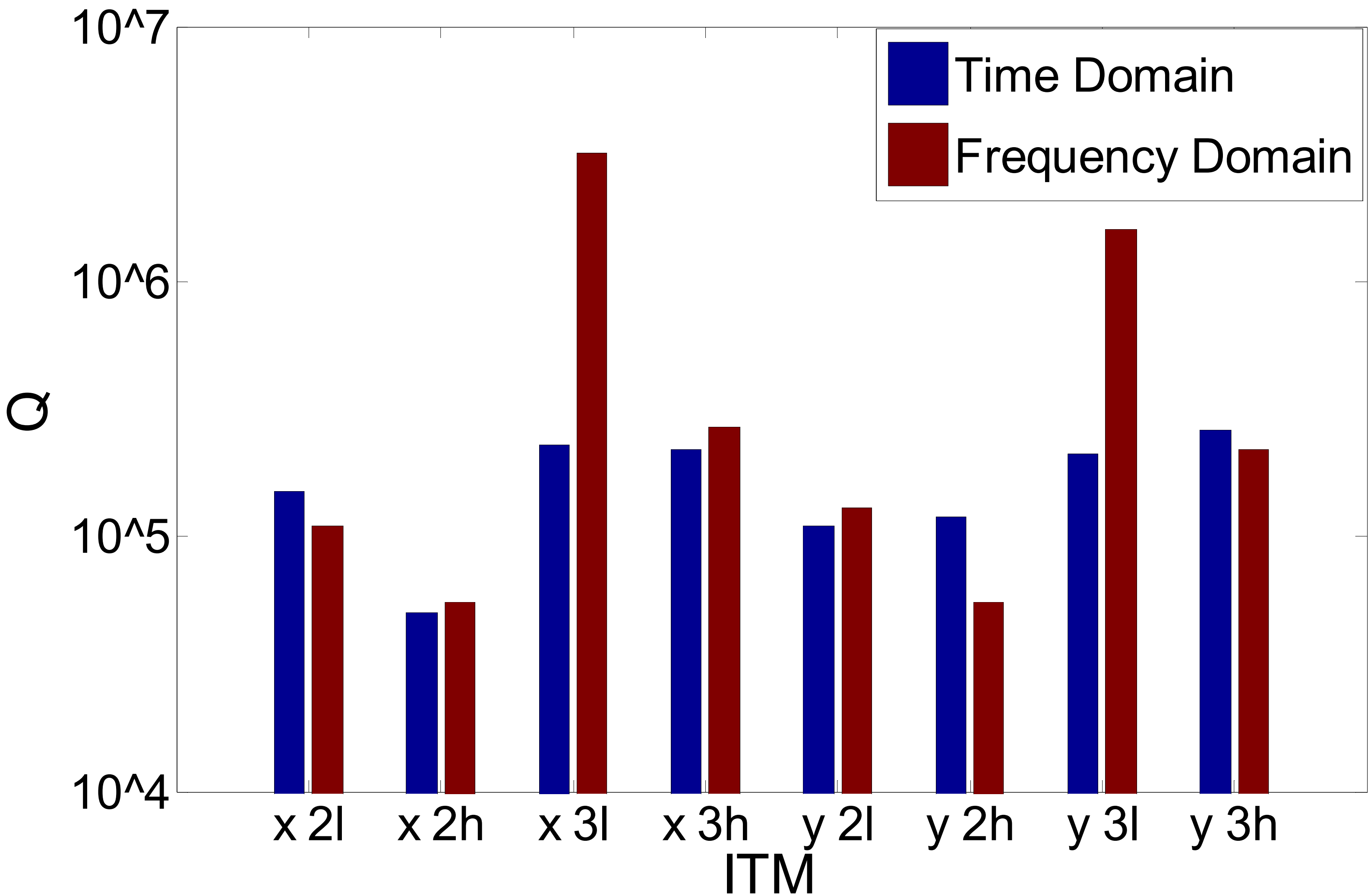


Violin Mode Results
Hanford 2K/Livingston

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?

Why changes in ringdowns between lock stretches?

- Changes in suspension during lock?
- 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 makes them worthless?

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Modeling
Some Hope for Answers

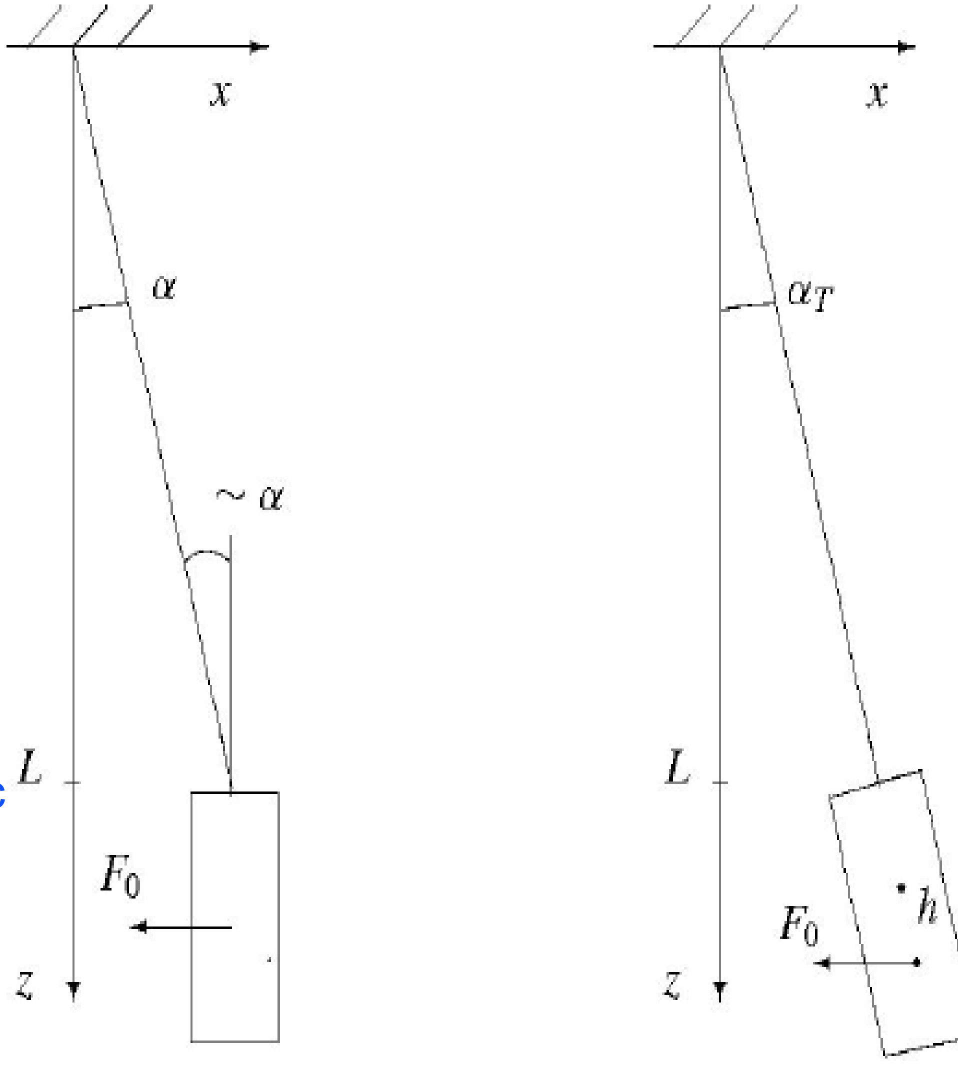
- Is feedback mechanism feasible?
  - Violin modes coming soon to e2e
- What about loss from optical spring?
  - Thomas Corbitt at MIT has done preliminary modeling
  - Need to have cavity offset from resonance slightly
    - Output Mode Cleaner data shows arm cavities are off resonance by about 1 pm
    - 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 needed 100 pm
    - Does not look likely

Violin Modes : Future Directions

- Modeling and theory
  - Need some ideas
- More time domain data
  - Same and different lock stretches
- Put notch filters in ASC loop
- Measure Q vs. cavity power to assess feedback
  - 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

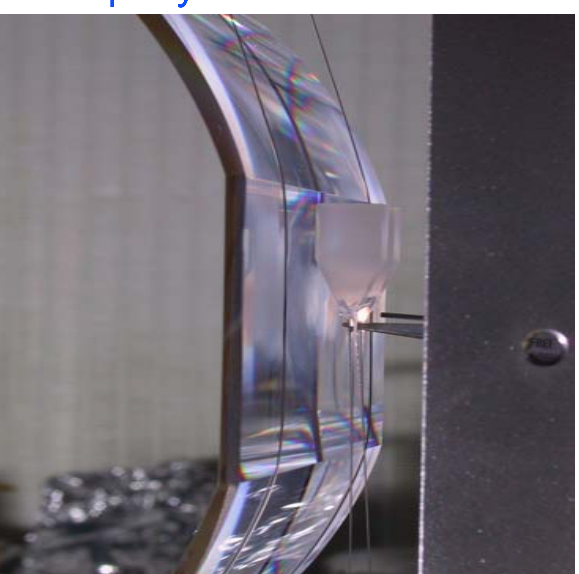
Possible Improvements
Levin's "Sweet Spot"

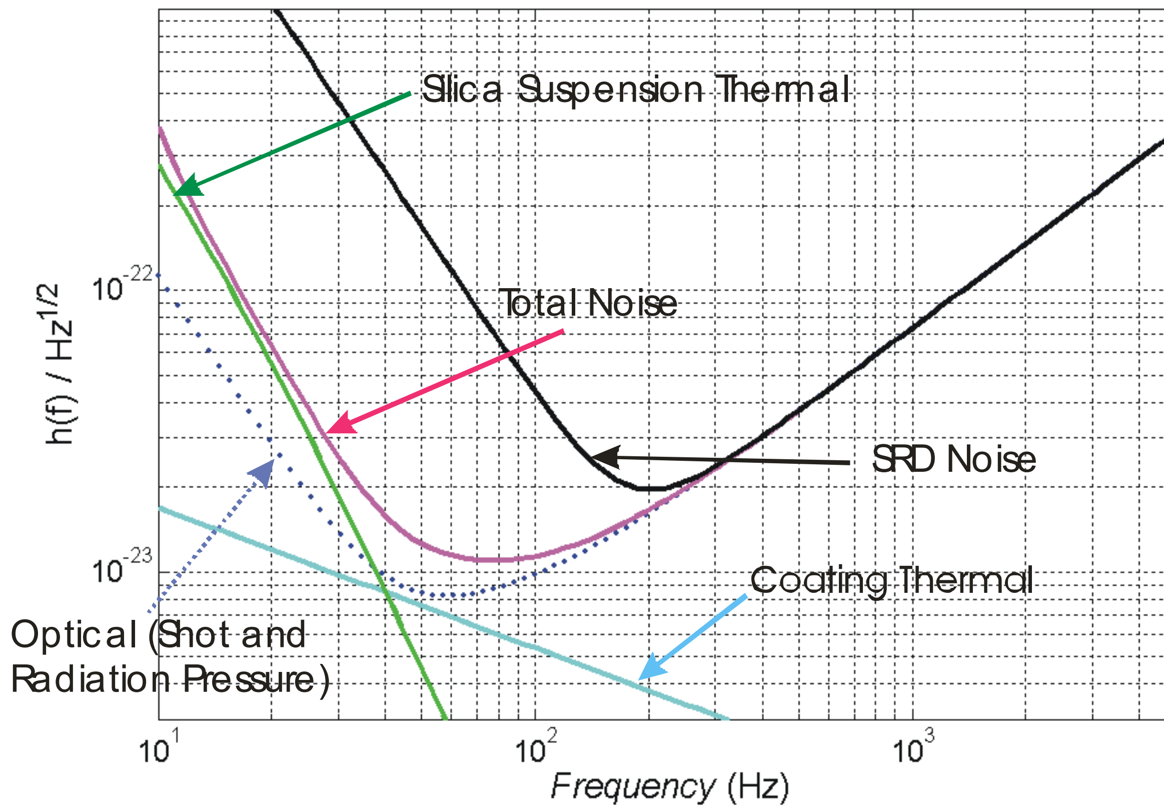
- Move laser down on mirror ~ 1 cm
- Decouples pitch and position thermal noise
- Removes loss from bending at wire-mirror connection
- Reduces both Brownian and thermoelastic noise
- Astrophysical reach limits
  - Binary neutron star inspiral range 29 Mpc
  - 10 M_o black hole inspiral range 137 Mpc
  - Stochastic backgroun 3 X 10^{-7}
  - Crab nebula pulsar upper limit (1 year integration time) ε = 6 X 10^{-6}
  - Sco X-1 pulsar upper limit (1 year integration time) ε = 3.0 X 10^{-7}



Possible Improvements
Silica Suspension

- Silica ϕ is ~ 3×10^{-8}
- Improvement at low f
- Can be done along with increase in laser power
- How do you connect
  - Polish flats on mirror – bond ears
  - Bond on curved ears
  - Epoxy on ears



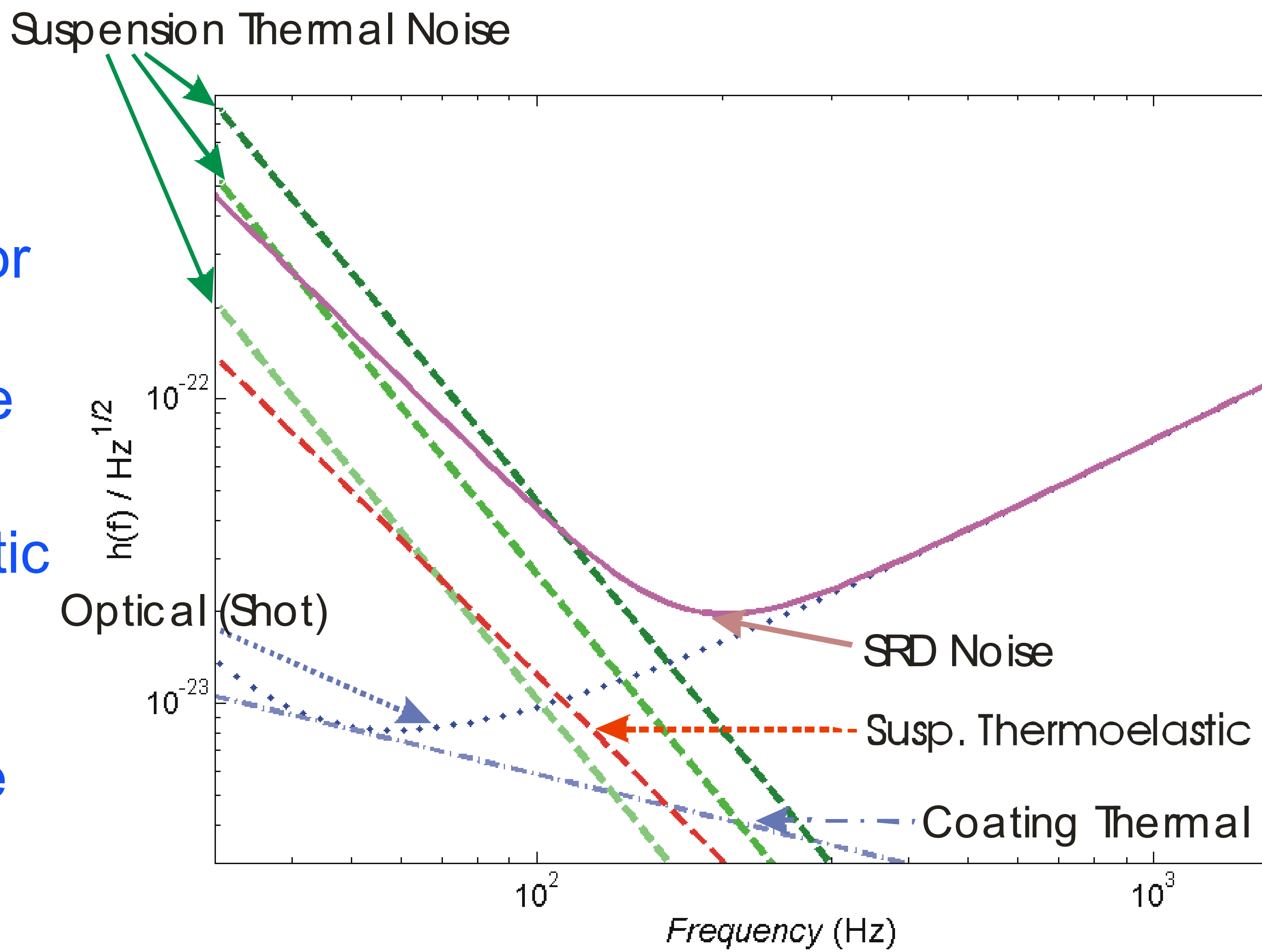


Astrophysical reach limits

- Binary neutron star inspiral range 63 Mpc
- 10 M_o black hole inspiral range 320 Mpc
- Stochastic background 3×10^{-8}
- Crab nebula pulsar upper limit 1.8×10^{-6}

Mirror Thermal Noise

- Contribution from coating and silica substrate
- Coating accounts for almost all expected mirror thermal noise
- Below total noise, even at thermoelastic limit of suspension
- Potentially bad coating or substrate could cause mirror thermal noise to be higher



Mirror Thermal Noise
Is it relevant?

Suspension ϕ	$2\ 10^{-3}$		$2\ 10^{-4}$	
Coating ϕ	$4\ 10^{-4}$	$2\ 10^{-4}$	$4\ 10^{-4}$	$2\ 10^{-4}$
BNS Range	20 Mpc	20 Mpc	26 Mpc	26 Mpc
BH/BH Range	80 Mpc	81 Mpc	115 Mpc	116 Mpc
Stochastic	$2.2\ 10^{-6}$	$2.2\ 10^{-6}$	$6.0\ 10^{-7}$	$6.0\ 10^{-7}$
Crab Pulsar	$1.5\ 10^{-5}$	$1.5\ 10^{-5}$	$7.7\ 10^{-6}$	$7.6\ 10^{-6}$
Coating ϕ limit	$8\ 10^{-4}$		$8\ 10^{-4}$	

Limit defined as when both BNS and BH/BH range fall more than 5 percent. REO

Effect of coating loss on modal Q's

What value of modal Q would rule out a coating ϕ that could effect sensitivity?

Mode	Coating Energy Ratio	Q Limit
7,8	5.1 10^{-5}	25 10^{6}
9	5.5 10^{-5}	23 10^{6}
10,11	2.0 10^{-5}	63 10^{6}
12,13	4.8 10^{-5}	26 10^{6}
14,15	2.0$10^{-5}$	63 10^{6}
16	1.8 10^{-5}	68 10^{6}
17,18	3.8 10^{-5}	33 10^{6}
19,20	2.1 10^{-5}	60 10^{6}

Measured Mirror Modal Q's

IFO	Mirror	Best Measurement		Coating ϕ Limit
		Mode	Q	
L1	ITMx	20	$13.5\ 10^{6}$	$3.5\ 10^{-3}$
	ITMy	7	$3.1\ 10^{6}$	$6.4\ 10^{-3}$
	ETMy	9	$0.7\ 10^{6}$	$25\ \ 10^{-3}$
H2	ITMy	16	$6.7\ 10^{6}$	$8.1\ 10^{-3}$
	ETMx	7	$2.8\ 10^{6}$	$7.0\ 10^{-3}$

Have some high Q data on modes above 20

L1	ITMy	Mode 32	$Q = 1.8\ 10^{6}$
H2	ITMy	Mode 32	$Q = 8.6\ 10^{6}$
H1	ITMx	Mode ~110	$Q = 27\ 10^{6}$

LIGO Needed for Mirror Thermal Noise

- FEA models of energy distribution to higher mode number
- More Q's
  - Nothing on L1 ETMx, H1 ITMy, ETMx, ETMy, H2 ITMx, ETMy
  - Very little on all H1 optics, H2 ETMx
  - Little data on superpolished ETMs (L1 and H2)
- Perhaps some laboratory measurements of coated spare optics
  - Need the extended FEA results before even considering
  - Keep eye on lab results on scatter and absorption
- Probably not a problem, these measurements are not high priority

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Conclusions

Suspension thermal noise has a large impact on astrophysical performance

Firm prediction of suspension thermal noise is still lacking

Need more information on violin mode losses

- 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

There are ways to reduce suspension thermal noise

- Some easier than others
- Some need more laboratory research

Mirror thermal noise not as crucial a question

- Probably won't limit sensitivity
- May want some more modal Q measurements to rule out