Fused Silica Suspensions

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LIGO/Caltech

Elba GWADW Meeting
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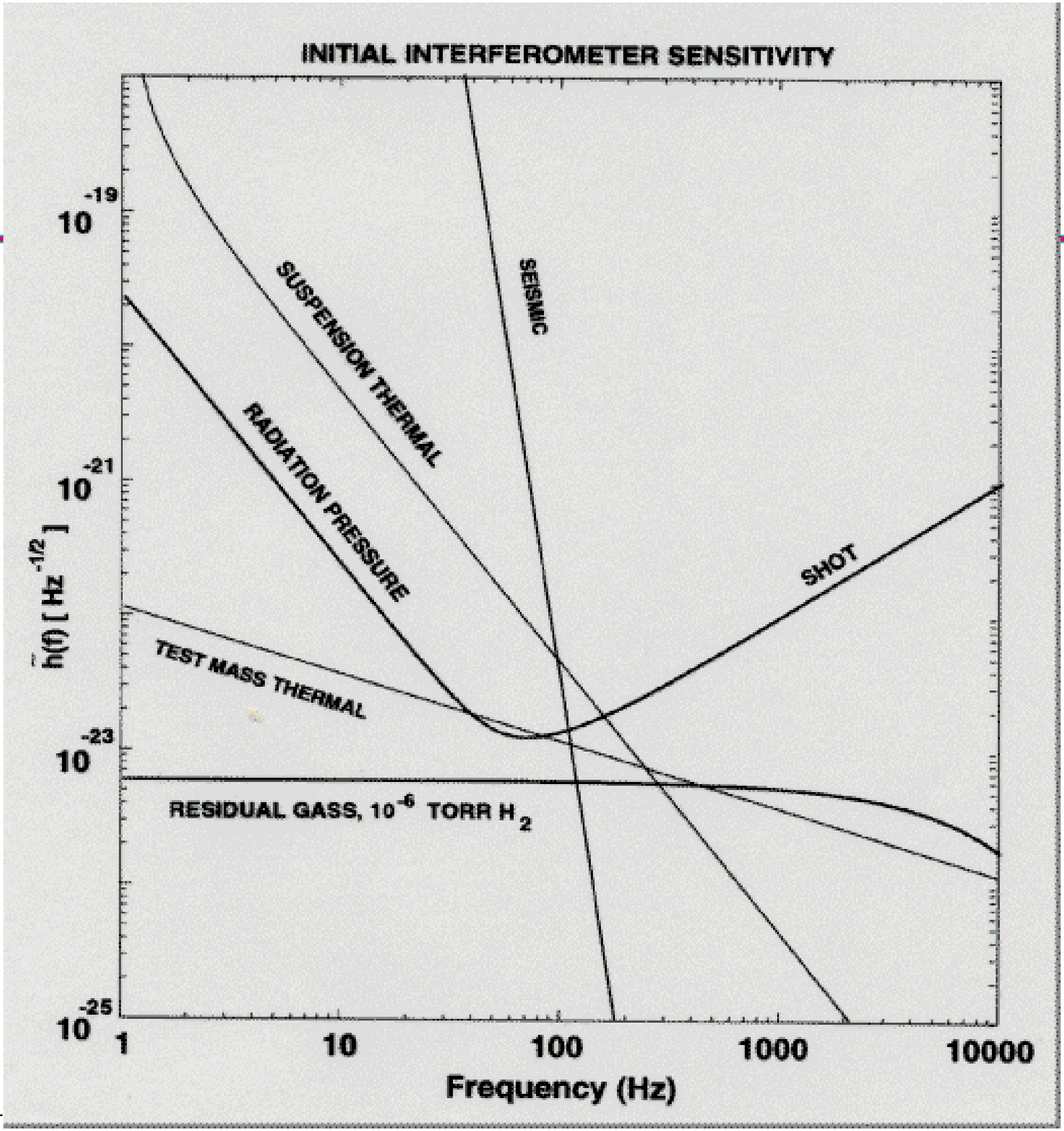
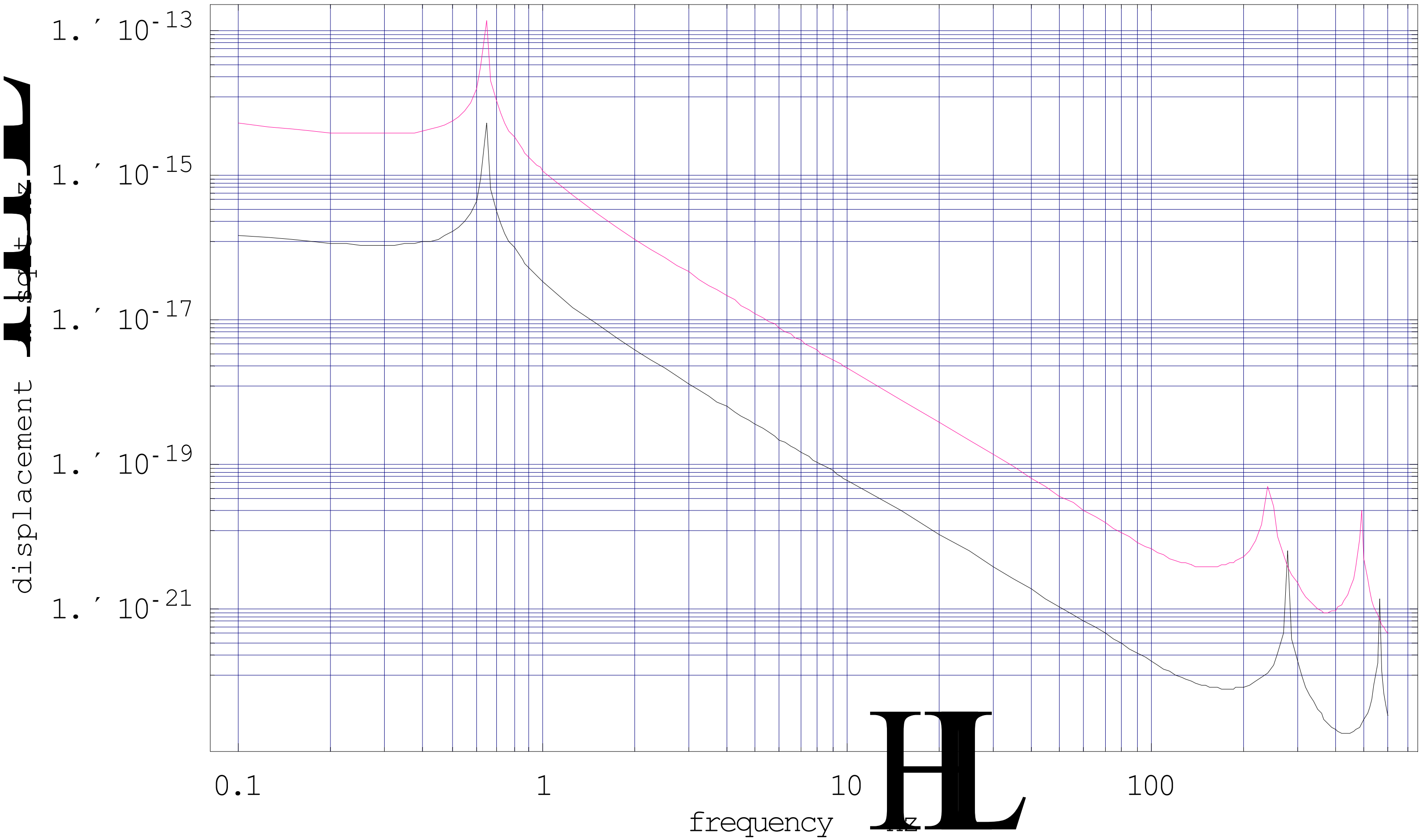
LIGO-G020260-00-D


INITIAL INTERFEROMETER SENSITIVITY
SUSPENSION THERMAL
SEISMIC
RADIATION PRESSURE
SHOT
TEST MASS THERMAL
RESIDUAL GASS, 10^-6 TORR H2
10^-19
10^-21
10^-23
10^-25
h̃(f) [Hz^-1/2]
1
10
100
1000
10000
Frequency (Hz)

Justification for Silica

- Metal wire suspension thermal noise dominates in the low audio frequency range
- Best metal wires get about $Q=10^5$-10^6 for violin modes (Niobium flexures approach 10^7)
- Very high intrinsic Q of fused silica, plus other nice mechanical properties, allow far lower thermal noise
- Estimates are that suspension noise will drop below radiation pressure noise in AdLIGO

Thermal noise, metal vs. silica



Red: metal   Black: silica

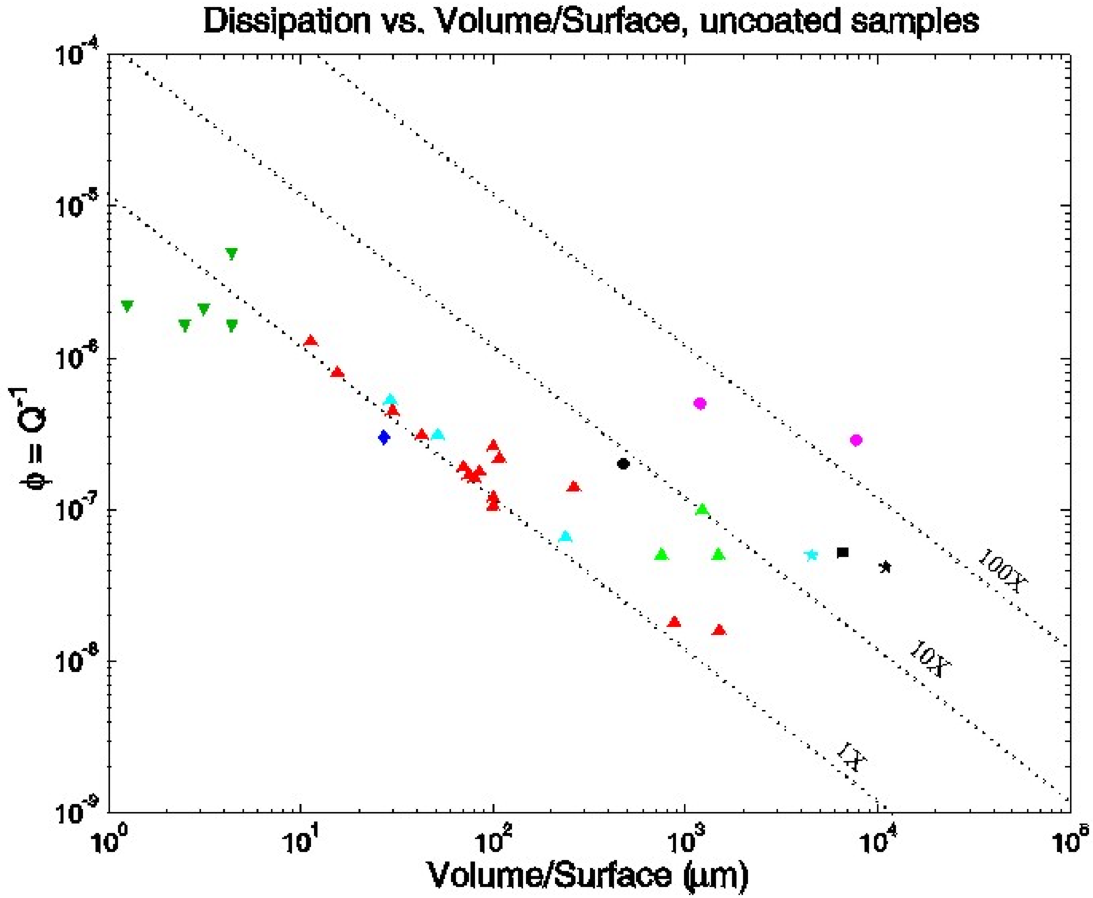
What’s so nice about silica

- Intrinsic Q is very high (8×10^7 and climbing)
- Surface losses limit this, but still to very high values
- Thermal expansion low, giving small thermoelastic damping
- Young’s modulus increases with temperature, allowing cancellation of nonlinear thermoelastic damping
- Silica is strong (same yield load as same diameter steel)
- But has lower elastic modulus, so less bending stiffness, higher dilution

Size Dependence of Fiber Loss

- Loss inversely proportional to volume/surface ratio

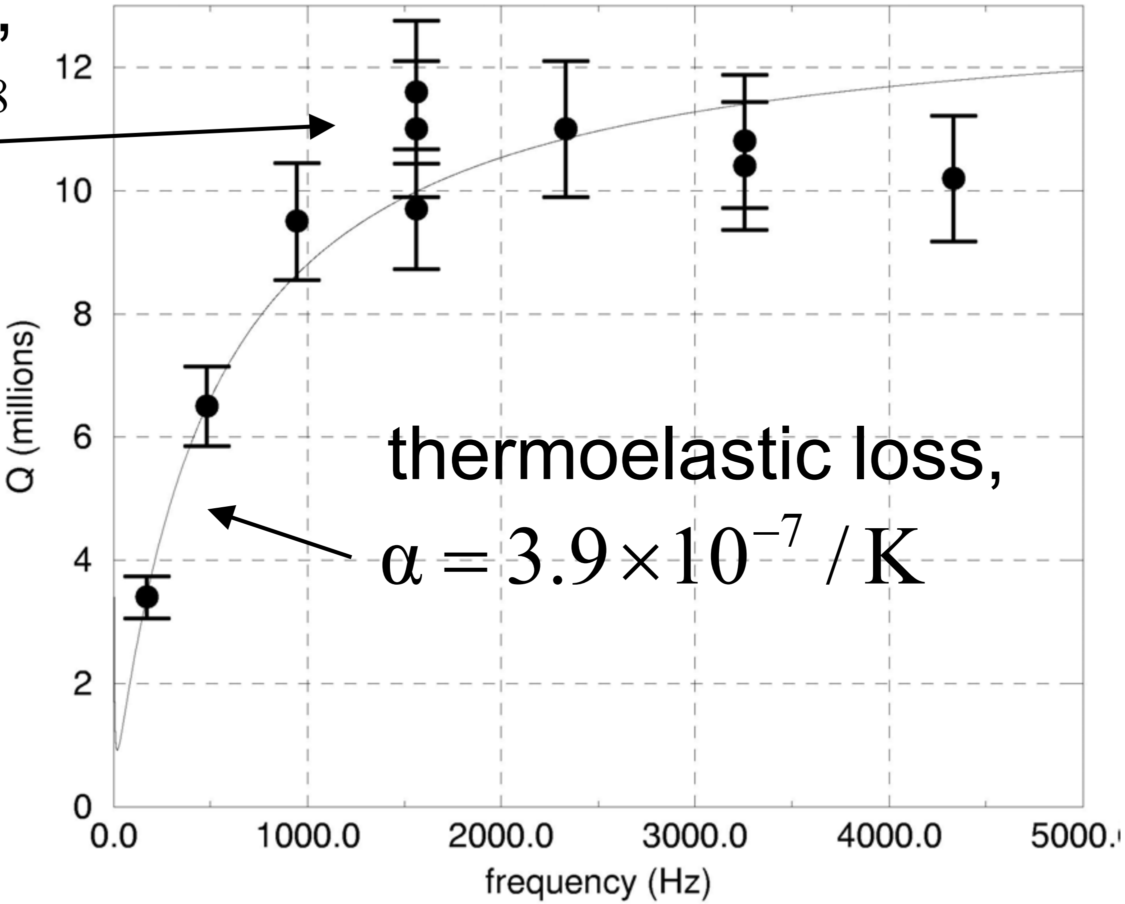
Data from Syracuse group



Q of Typical Silica Fiber

intrinsic loss,

$\varphi = 7.6\times10^{-8}$



thermoelastic loss,

$\alpha = 3.9\times10^{-7}\,/\,\mathrm{K}$

Nonlinear Thermoelastic Damping

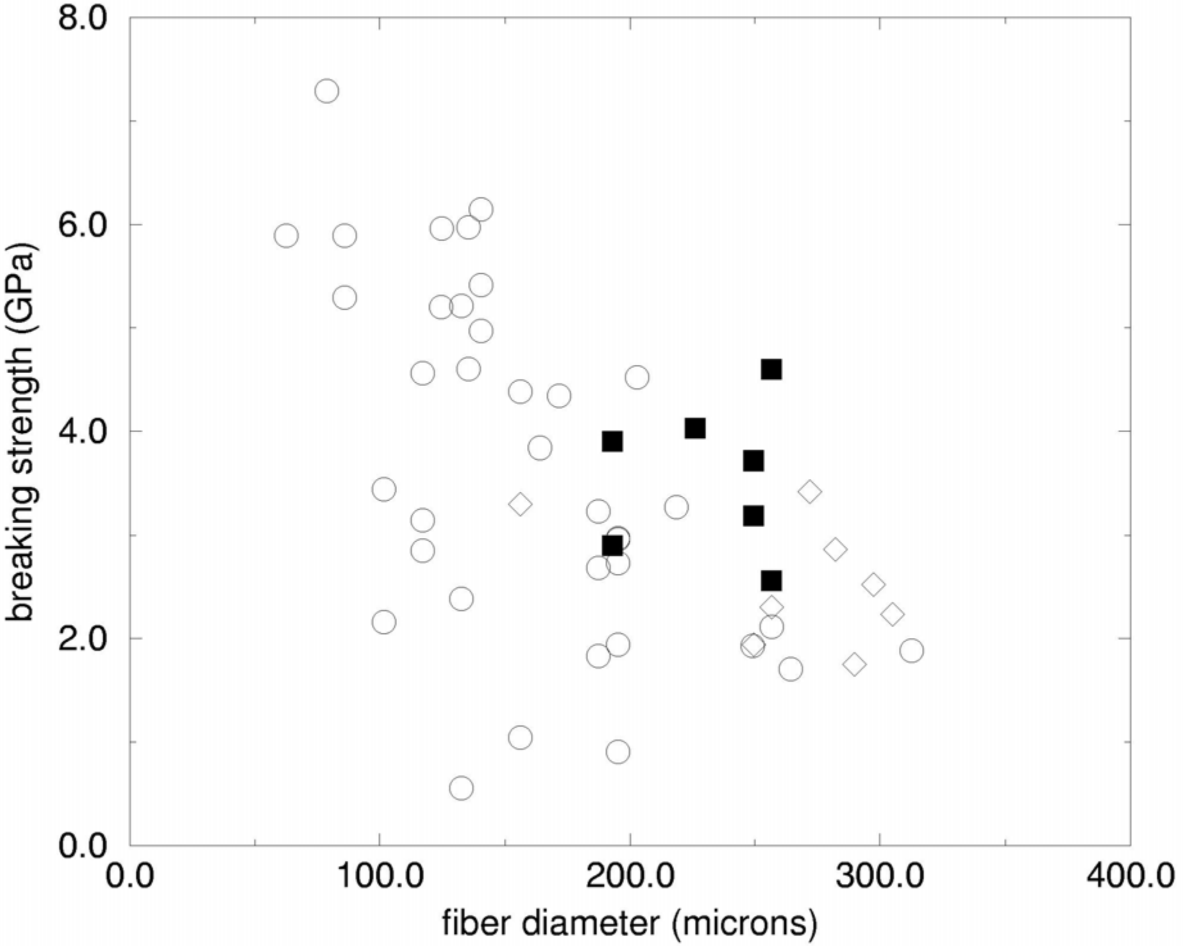
Loss function ϕ:

$$\phi_{\mathrm{NTE}} = \frac{TE}{\rho C_V}\left(\alpha - \frac{dE}{dT}\frac{u}{E}\right)^2 \frac{\omega\tau}{1+(\omega\tau)^2}$$

$$\tau_{ribbon} = \frac{t^2}{\pi^2}\frac{\rho C_V}{k} \qquad \tau_{fiber} = \frac{.0737\rho C_V r^2}{4k}$$

Note: true only for u large compared to oscillation strain

Typical silica fiber strengths



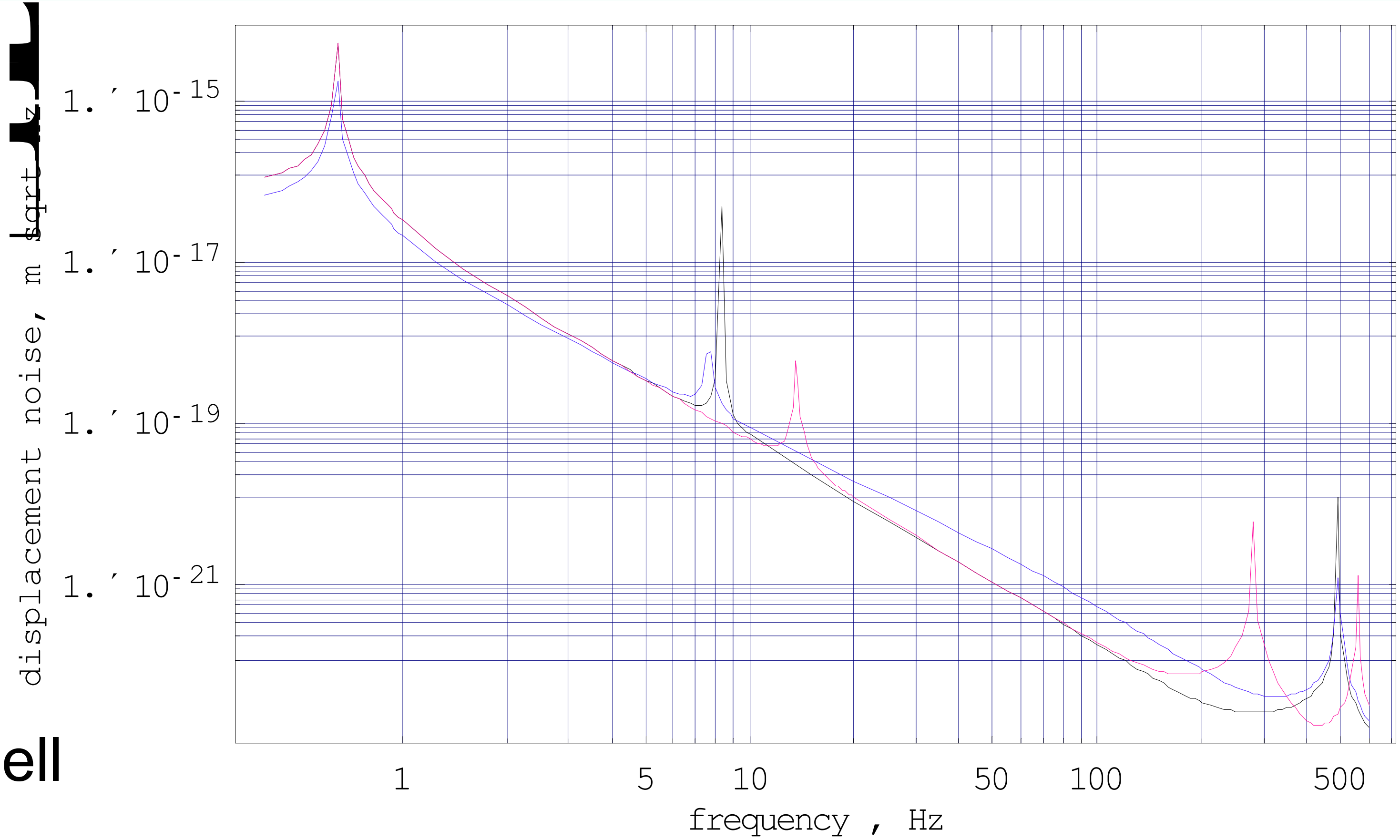
Some Notable Results

- Intrinsic Q=8x10^7 for thick annealed rod (Syracuse)
- Pendulum Q=2.5x10^8 for bifilar torsional pendulum (Moscow/Glasgow)
- Violin Q=5.2x10^8 (Caltech)
- Vertical Bounce Q=1.2x10^7 (Caltech)

Alternative Suspension Geometries

- Fiber- easy to make, low thermal noise, diameter fixed by NTE
- Ribbon- somewhat harder to make, but aspect ratio can be chosen to push increased NTE damping to higher frequency, allowing cross section choice to set vertical bounce frequency
- Dumbbell fiber- somewhat harder to make, optimizes end diameters for NTE and middle diameter for lower vertical bounce frequency

Thermal noise of fibers and ribbons



Red: fiber

Blue: ribbon

Black: dumbbell fiber

- Note: assumes AdLIGO suspension parameters

Difficulties, Peculiarities, and Work To Be Done

- Quartz suspensions are very brittle, need tender loving care.
- Silica fibers are welded, not clamped, into suspension. Effects of welding attachments and tapered ends must be considered.
- Demonstration of expected high Q's still elusive.
- Stress dependence of loss not yet known.
- Excess noise in fused silica not yet known.
- Violin modes have such high Q that they interfere with interferometer control and must be damped.

Influence of Welded Pins on Suspension Q

- The program that models dumbbell fibers can easily model the welded pins on the ends of suspension fibers (good approximation if pins are relatively long and thin)
- Used this analysis to confirm Mitrofanov and Tokmakov's estimate of Q limit due to lossy pins

$$Q_v^{-1} = \frac{4MgQ_p^{-1}}{Lm_p\omega_p^{2}}$$

- Our result: this is substantially correct, although for thicker fibers the torque also plays a significant role. Basic result:

A reasonably good, reasonably short pin will not unduly influence Q or thermal noise.

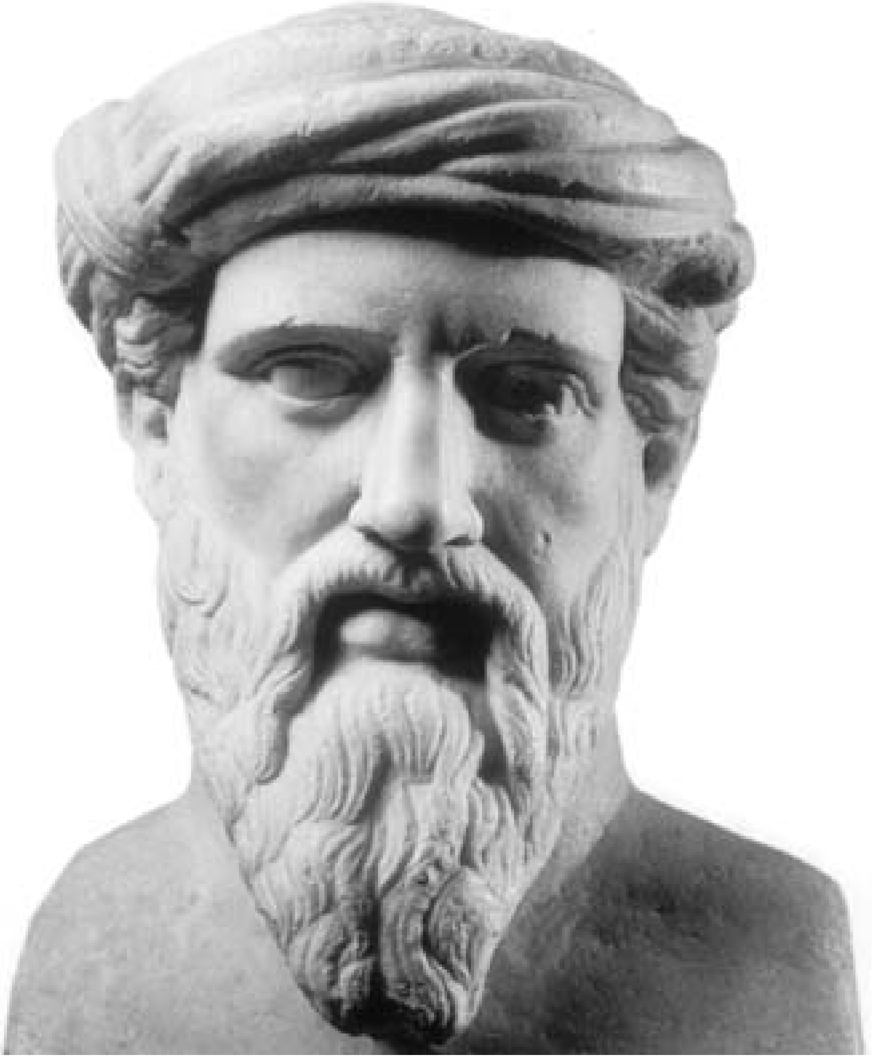
Influence of Taper Ends on Suspension Loss

- Suspension fibers drawn from rod stock often retain thick rod ends for ease in welding. The tapered transition from fiber to end increases the effective thickness of the fiber and reduces the dissipation dilution.
- Assuming diameter-independent loss (not strictly true), finite-element models show factor of two reduction of violin mode Q for typical suspension experimental parameters due to tapers.

Silica Suspension Research at Caltech

P. Willems, V. Sannibale, V. Mitrofanov, J. Weel, M. Thattai, A. Heptonstall, J. Johnson, D. Berns

Suspensions Research 2,600 Years Ago

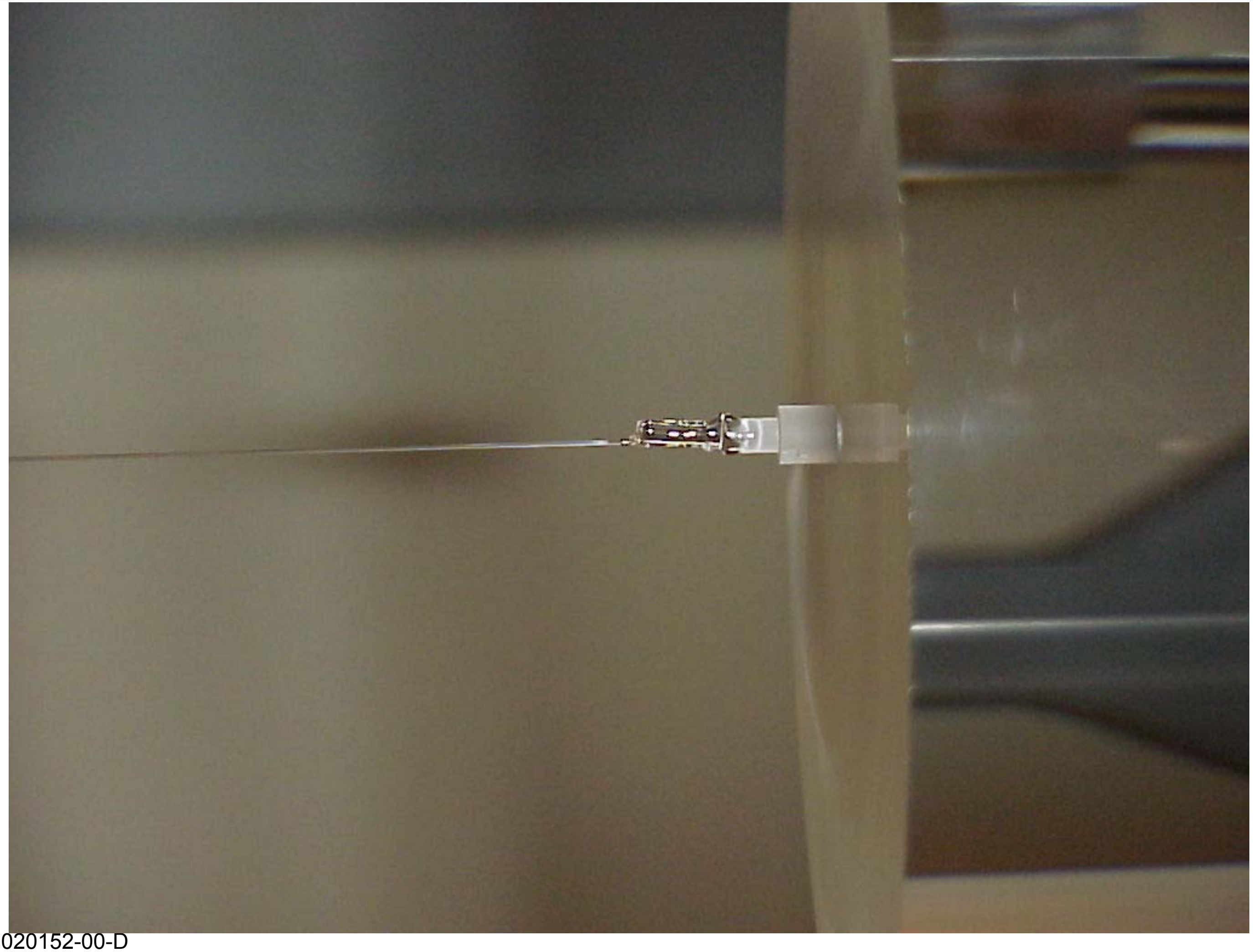


Suspensions Research Today

Automated fiber pulling lathe

Q-measurement rig

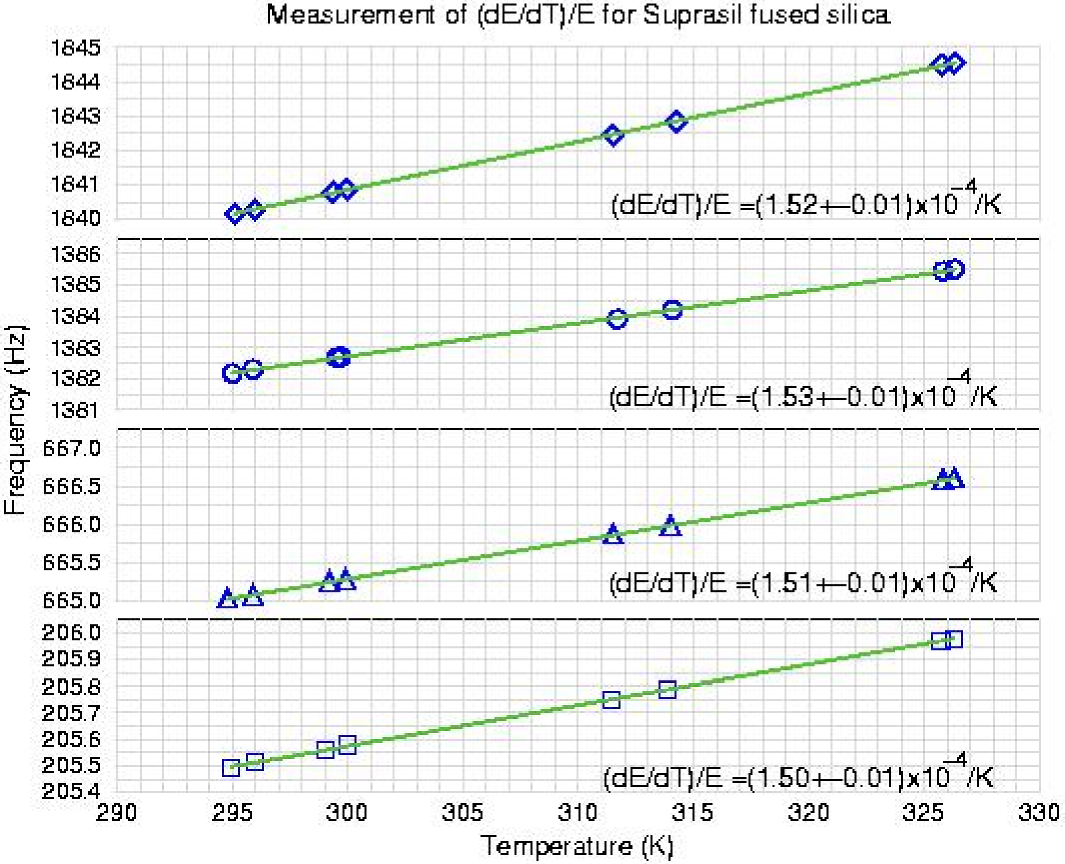
Welded Fiber End



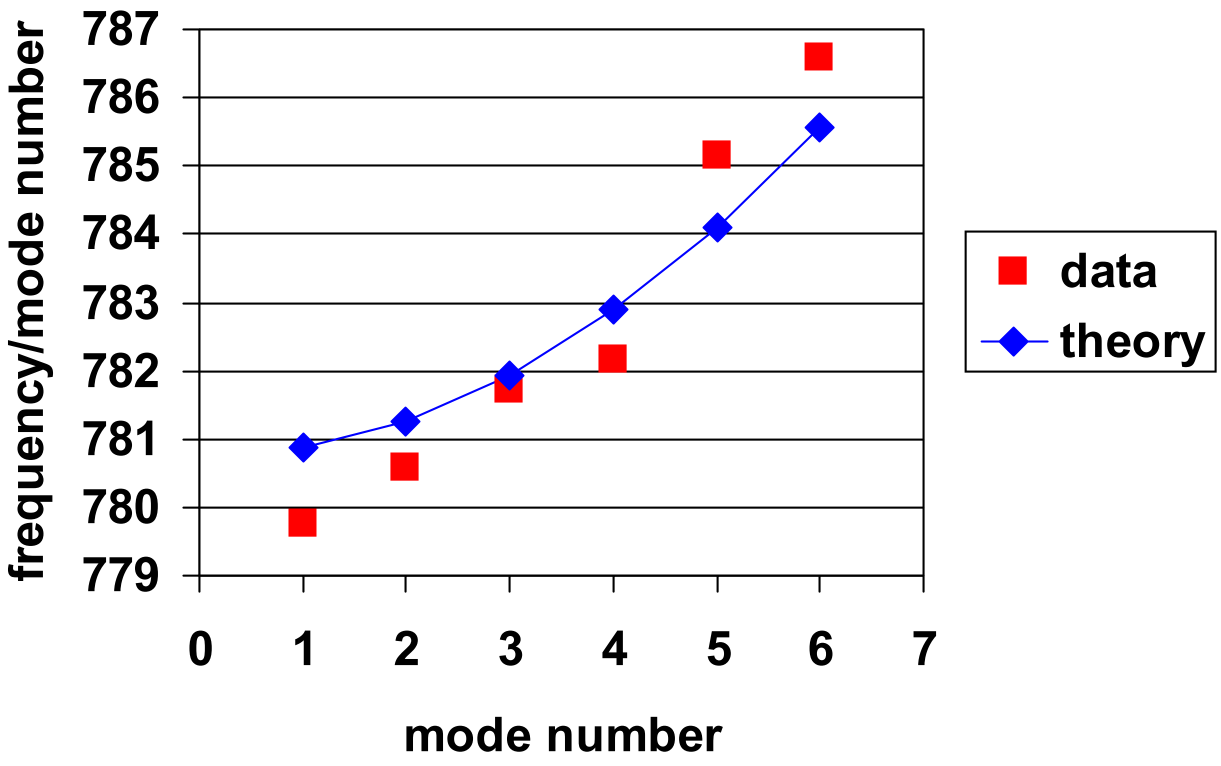
Measurement of (dE/dT)/E from Temperature Shift of Unloaded Fiber Mode Frequencies

$$\frac{dE/dT}{E} = 2\frac{df/dT}{f}$$

$$= 1.52 \times 10^{-4} / \mathrm{K}$$



Mode Frequencies: theory vs. experiment



Temperature Shift of the Violin Modes Yields the Dilution Factor

In general,

$$\frac{df_n/dT}{f_n} = -\frac{1}{2}(\alpha - u_0\beta) + \frac{1}{D_n}(\alpha + u_0\beta + \beta/2)$$

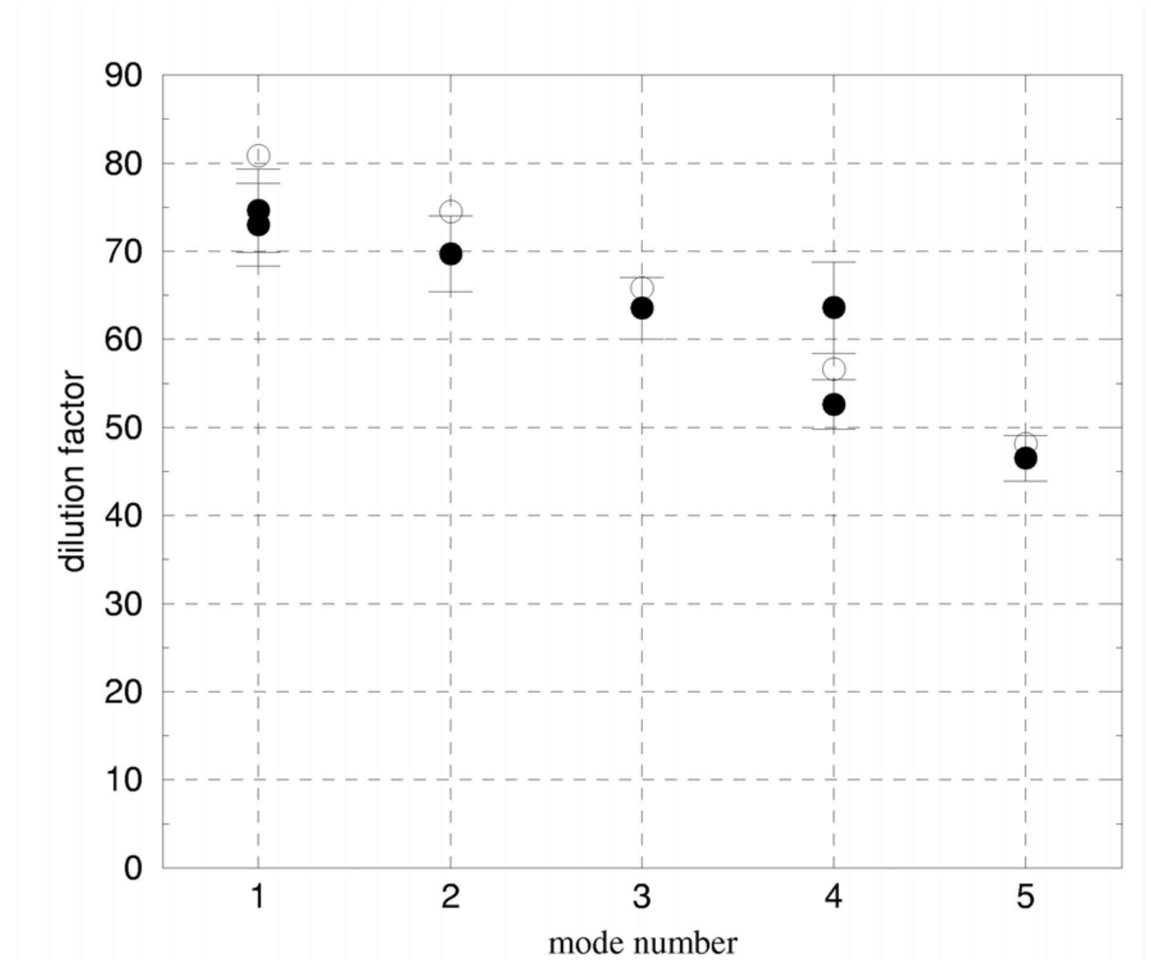
For this suspension,

$$\frac{df_n/dT}{f_n} \approx \frac{\beta}{2D_n}$$

Good Agreement with Theory

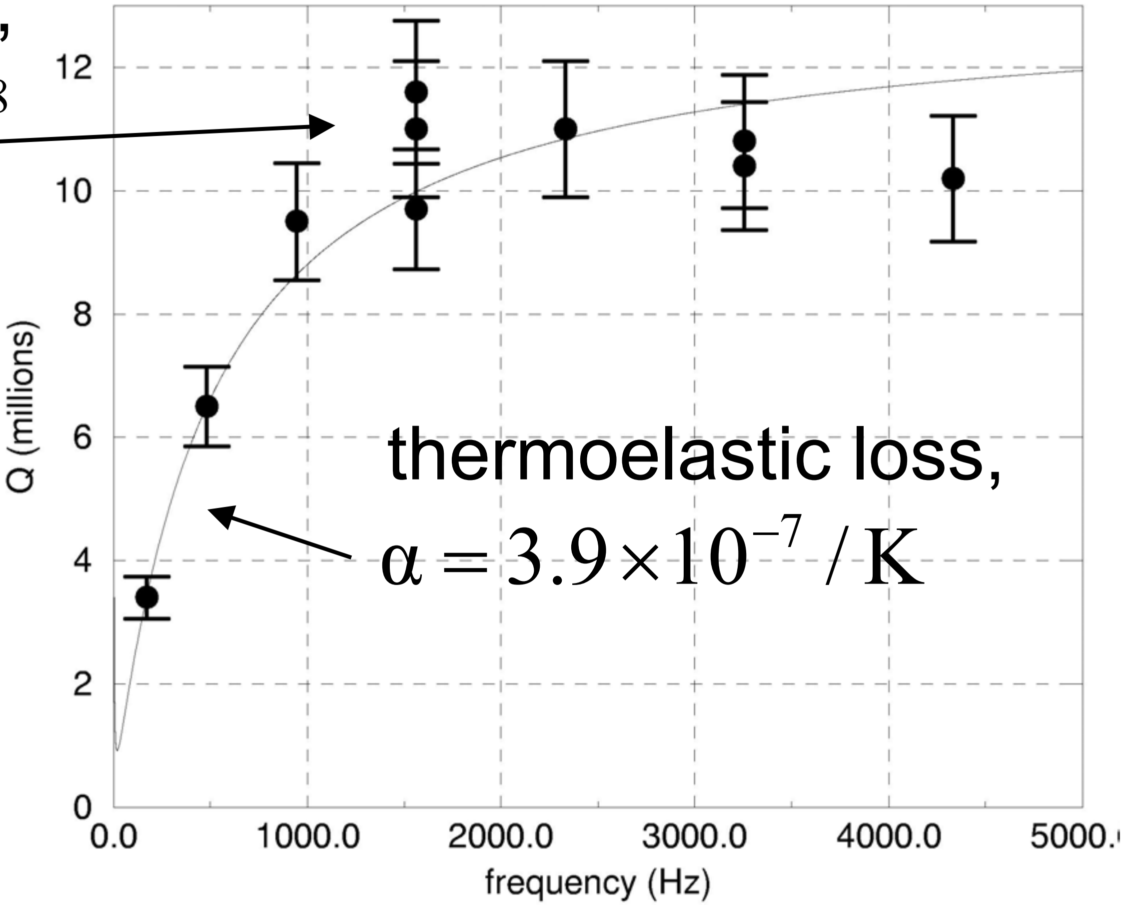
● data

o theory



Q of Typical Silica Fiber

intrinsic loss,
$\varphi = 7.6\times10^{-8}$



thermoelastic loss,
$\alpha = 3.9\times10^{-7}\,/\,\mathrm{K}$

Q's of the Violin Modes

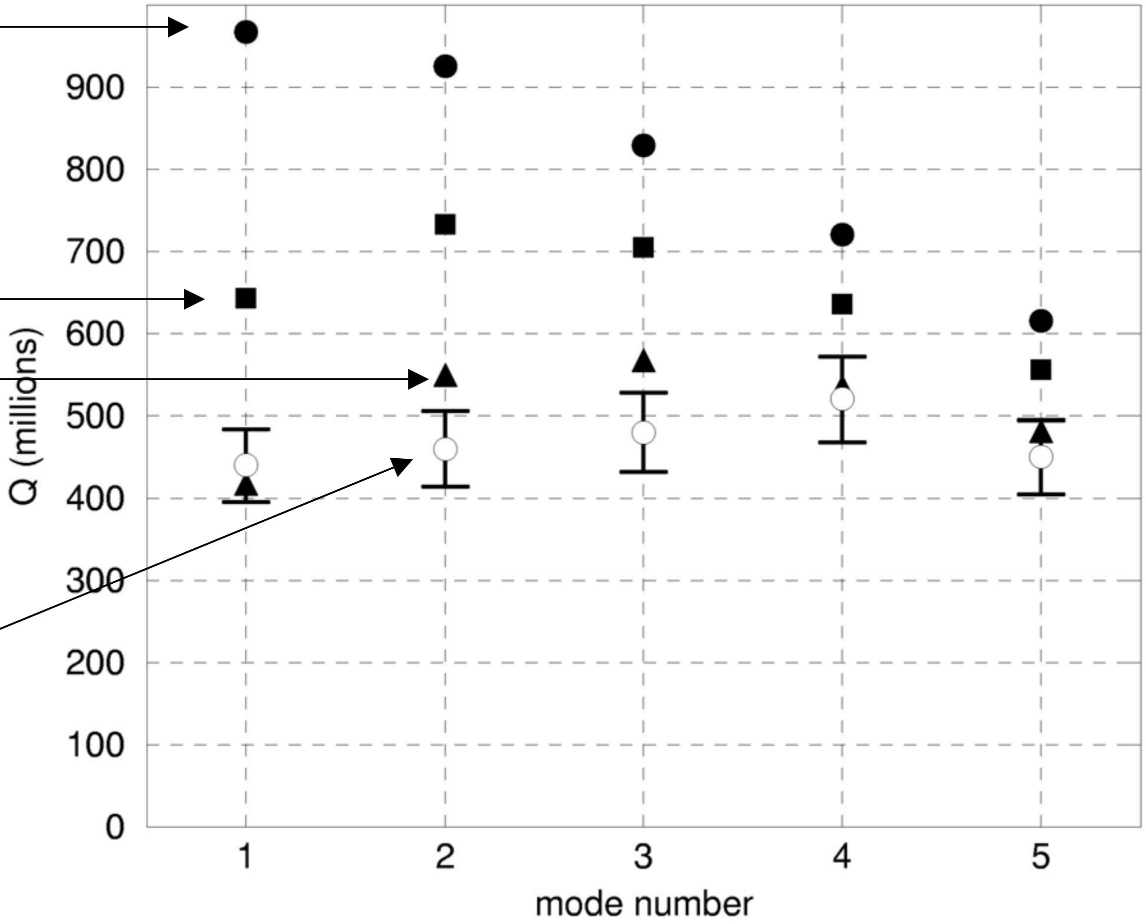
theory, with NTE

theory, w/o NTE

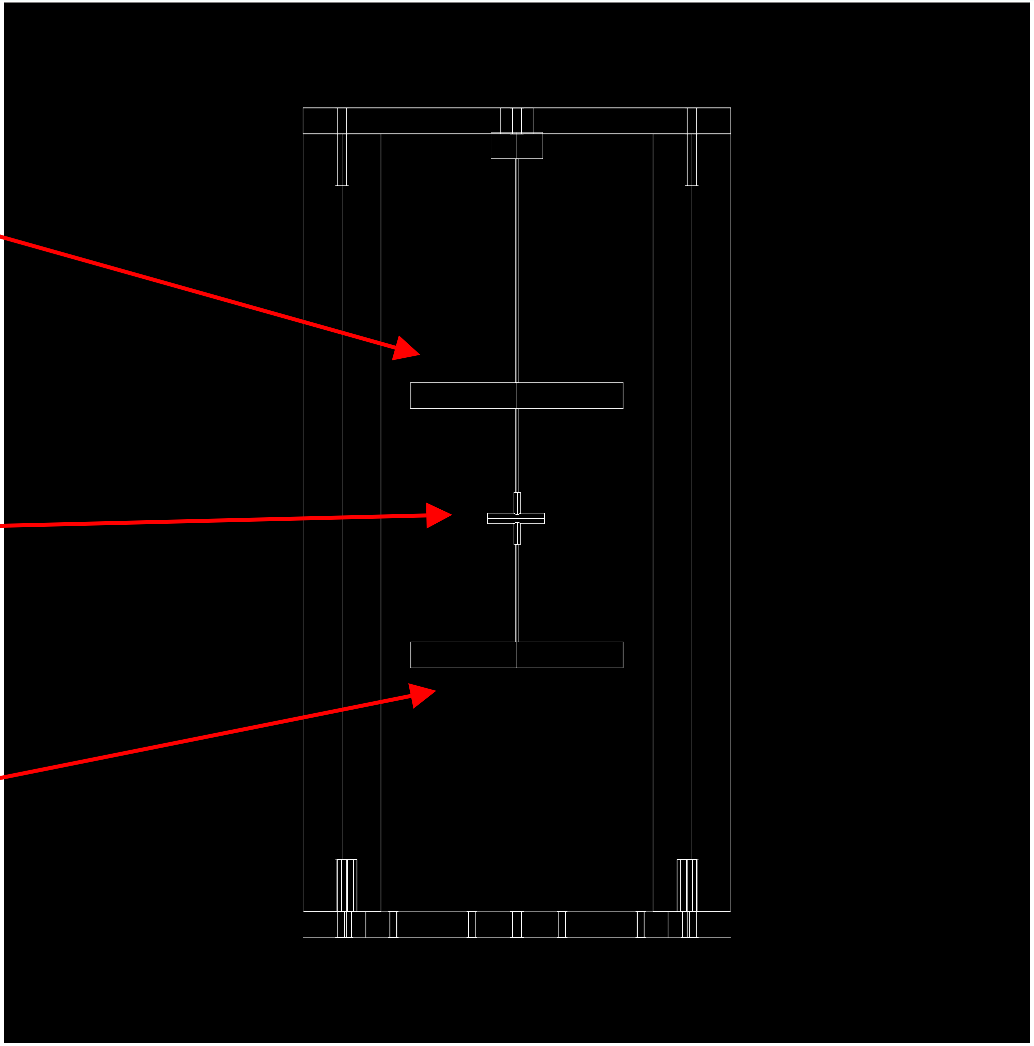
theory, w/o NTE

and $\alpha = 5.9 \times 10^{-7}$/K

data



Vertical Bounce Apparatus

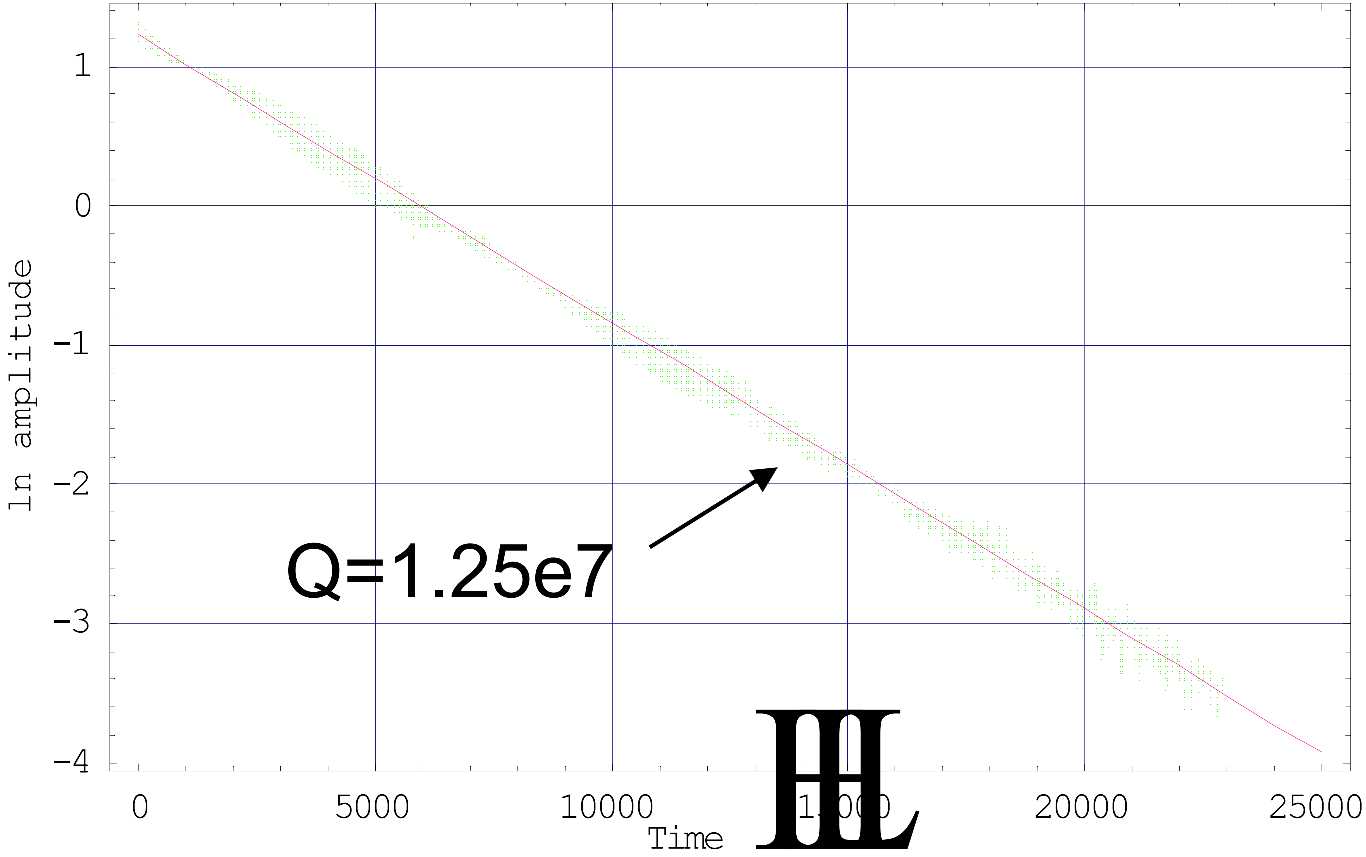


isolation mass

test mass

tensioner

Vertical Bounce Ringdown
(first result)



Q=1.25e7

Note: this fiber under the same stress planned for AdLIGO

Q of Typical Silica Fiber