Hobart & William Smith Colleges
LIGO Group

# An RUI Research Proposal on Minimizing Thermal Noise in Advanced LIGO Test Mass Optics and Exploring Bilinear Noise in Initial LIGO Data

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# Overview

- Thermal Noise Research
  - Fused Silica
    - Stress Dependent Losses and Annealing
    - Surface Dependent Losses and the Bulk Loss Limit
  - Mirror Coatings
    - Summary of Tantala/Silica Results
    - Plan for New Coating Materials
- Higher Order Statistical Noise
  - BicoMon and BicoViewer
- Impact of LIGO Research on HWS



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# Silica Thermal Noise Research



## Downselect of Test Mass Material for Advanced LIGO

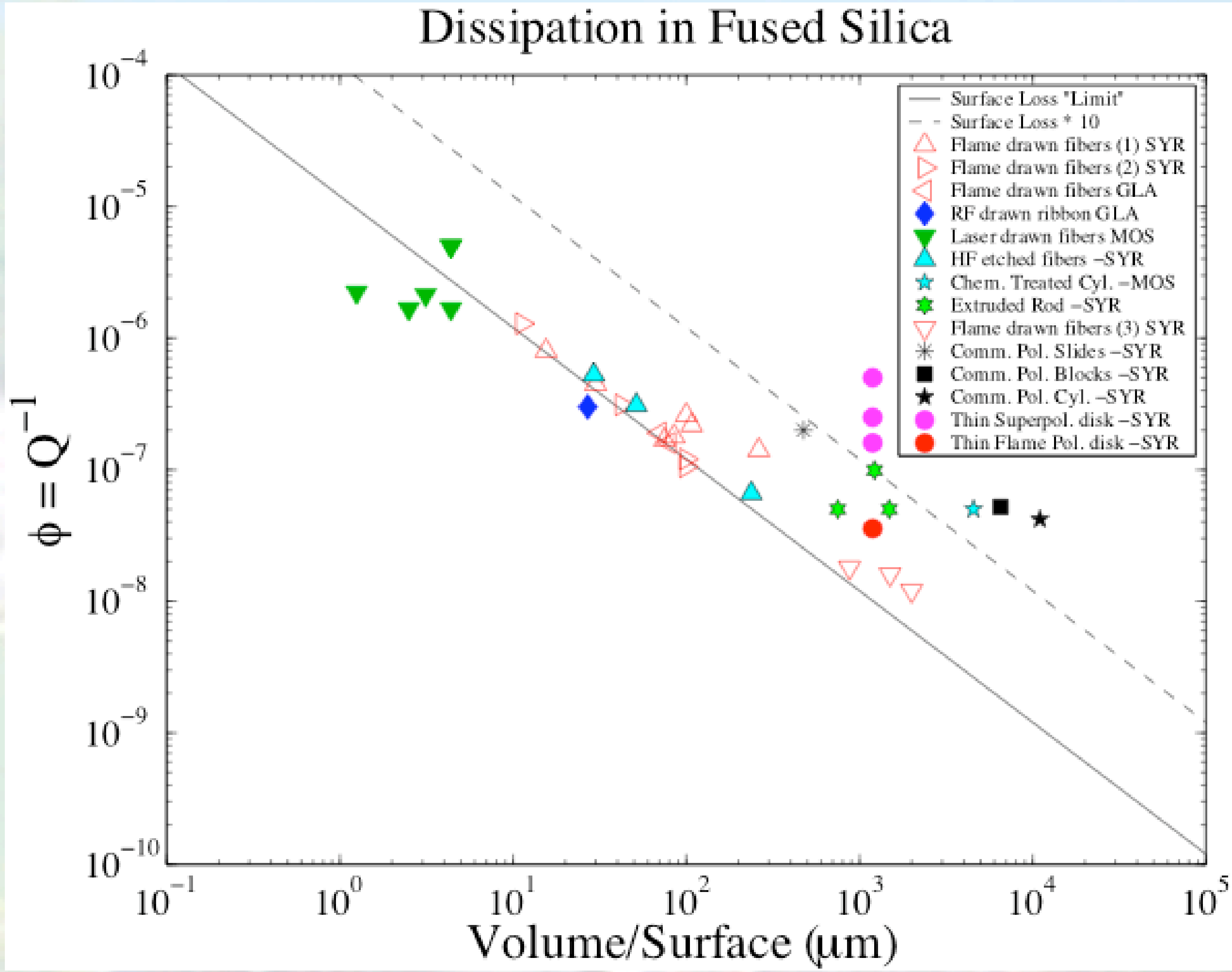
Fused Silica vs Sapphire

- Sapphire
  - $Q = 2 \times 10^8$ in large polished optics
  - Denser, Higher thermal conductivity, Higher Young's modulus
  - Higher Optical Absorption, Birefringence, Thermoelastic Noise

- Fused Silica
  - $Q = 2 \times 10^8$ in annealed rod samples & $Q = 1.2 \times 10^8$ in large optics
  - Low Optical Absorption, Low Thermoelastic Noise
  - Lower Density, thermal conductivity, Young's modulus

# Silica Thermal Noise Research

- Accumulated *Q* data shows an apparent surface loss limit.
- Flame polishing yields lowest surface loss for *V/S* < 1 mm.
- For *V/S* > 1 mm, flame-polished samples see additional loss



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# Silica Thermal Noise Research

- Surface Loss
  - Water adsorption (Braginsky, many others)
  - Alkali absorption (Marx and Sivertsen)

- Additional Loss
  - Additional loss for $V/S > 1$ mm to be stress-induced loss arising from larger thermal gradients during manufacturing. Annealing shown to decrease of stress-related loss (Numata, Lunin, Harry, Penn)

- Bulk loss
  - Bulk loss at 400 Hz estimated as $2.5 \times 10^{-9}$ ($Q = 4 \times 10^{8}$) (Wiedersich)
    - Extrapolation down from the GHz regime.
    - Loss arises from Asymmetric double-well potential, $Q^{-1} = A f^{\alpha}$, $\alpha \approx 0.77$



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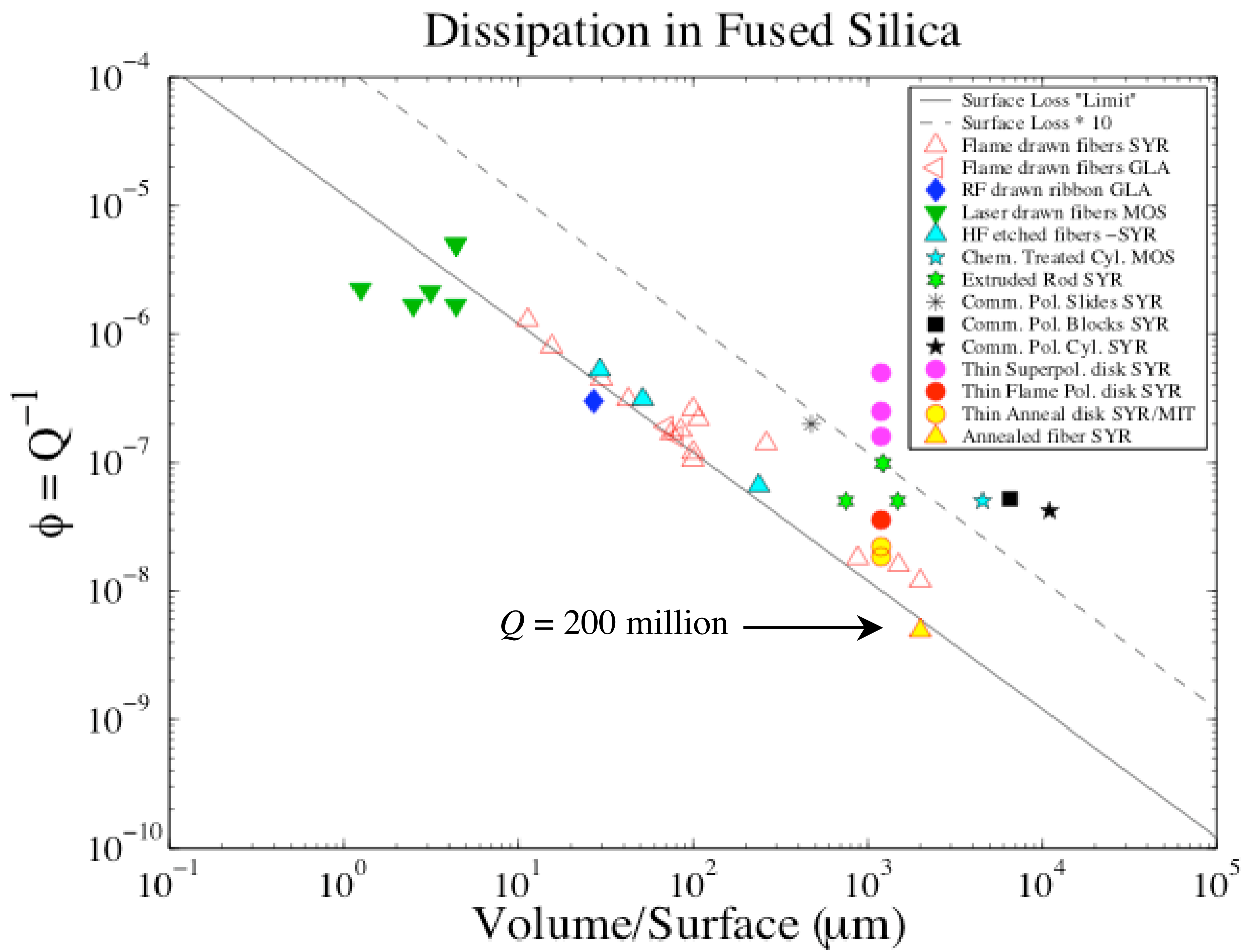
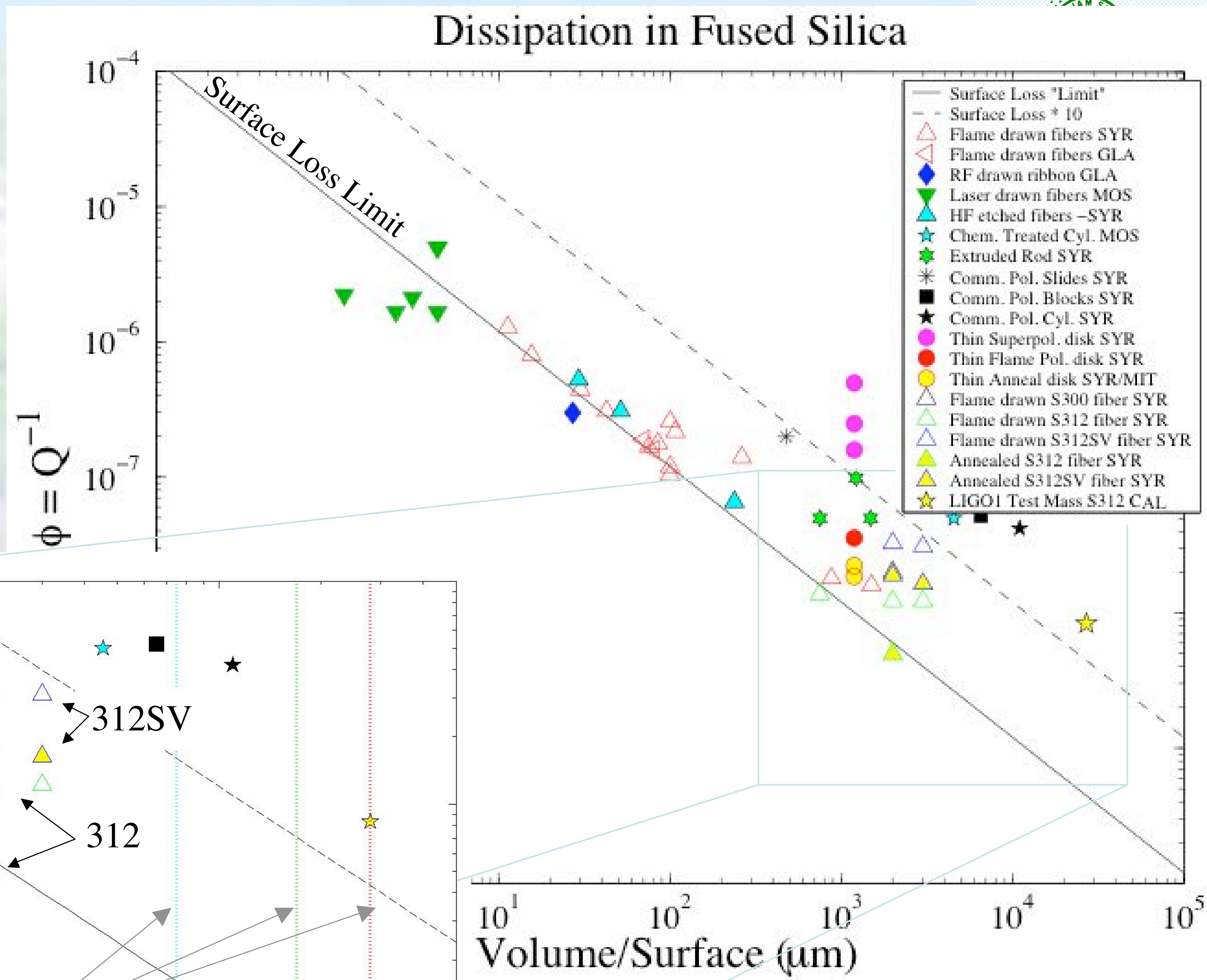
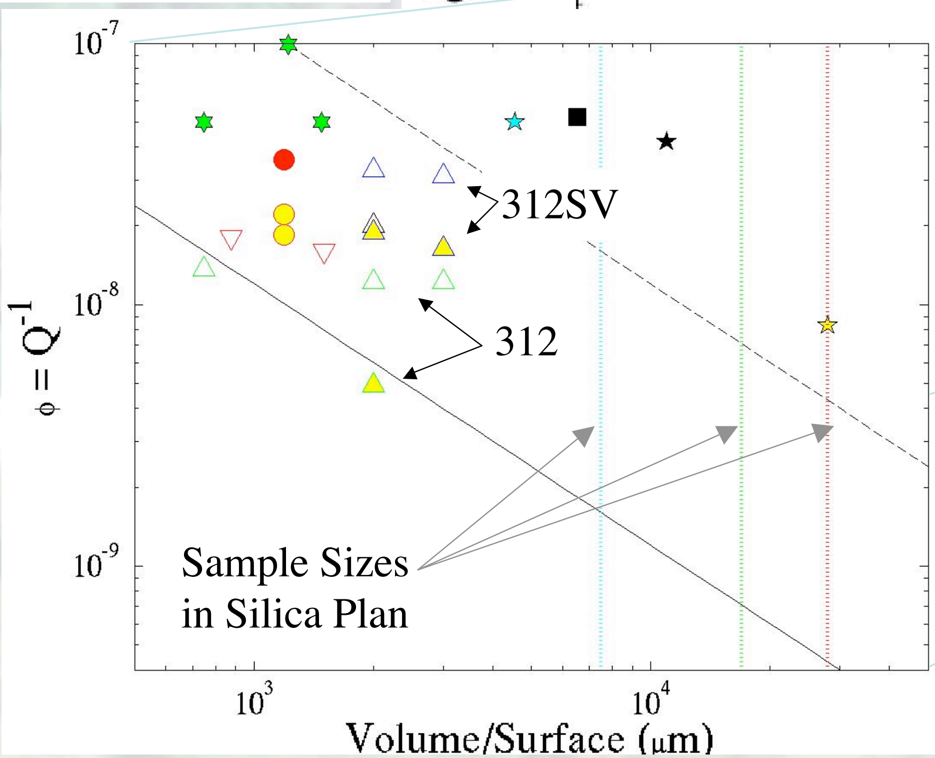

Dissipation in Fused Silica
$\phi = Q^{-1}$
Volume/Surface (μm)
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$
$10^{5}$
Surface Loss "Limit"
Surface Loss * 10
Flame drawn fibers SYR
Flame drawn fibers GLA
RF drawn ribbon GLA
Laser drawn fibers MOS
HF etched fibers –SYR
Chem. Treated Cyl. MOS
Extruded Rod SYR
Comm. Pol. Slides SYR
Comm. Pol. Blocks SYR
Comm. Pol. Cyl. SYR
Thin Superpol. disk SYR
Thin Flame Pol. disk SYR
Thin Anneal disk SYR/MIT
Annealed fiber SYR
$Q$ = 200 million

# Silica Research

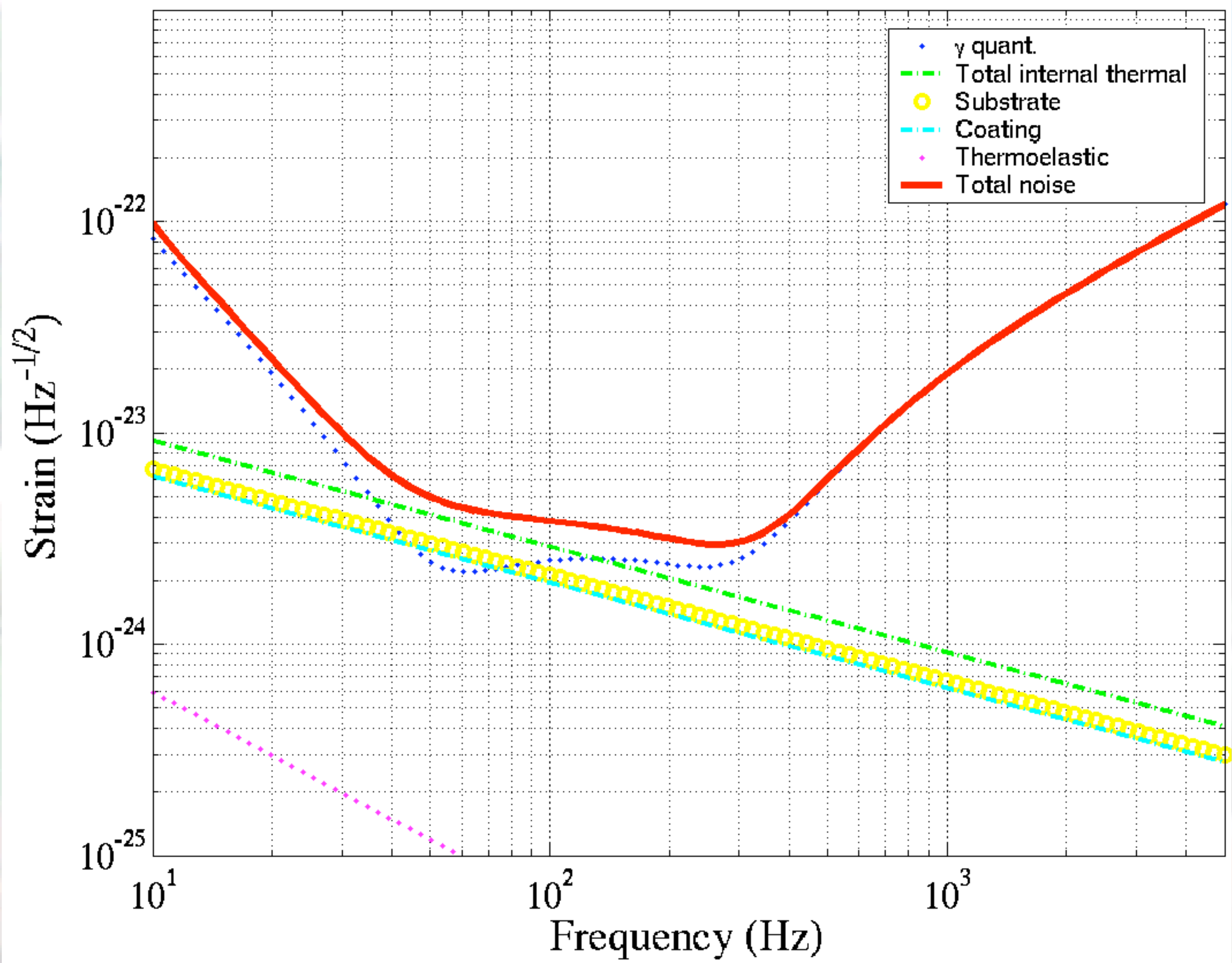
- Very low loss measured in annealed, flame-polished fibers ($\phi = 5e\text{-}9$) and in uncoated LIGO I test masses ($\phi = 8e\text{-}9$).
- Planned research to use annealing and increases in V/S to minimize loss.



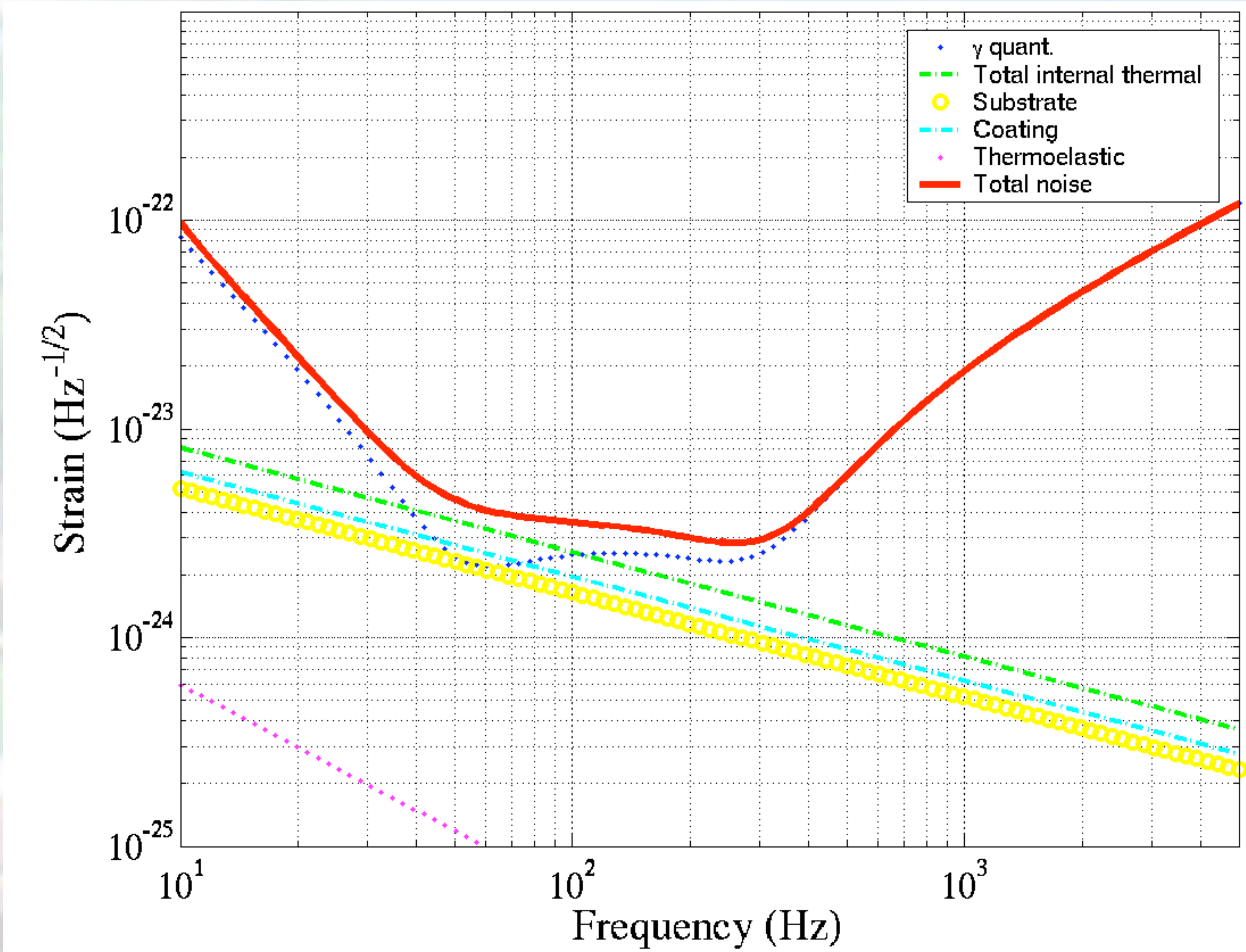




- Possible dependence of loss on silica type has been observed, being explored.
- Annealing oven has been purchased, will be installed in next few weeks.

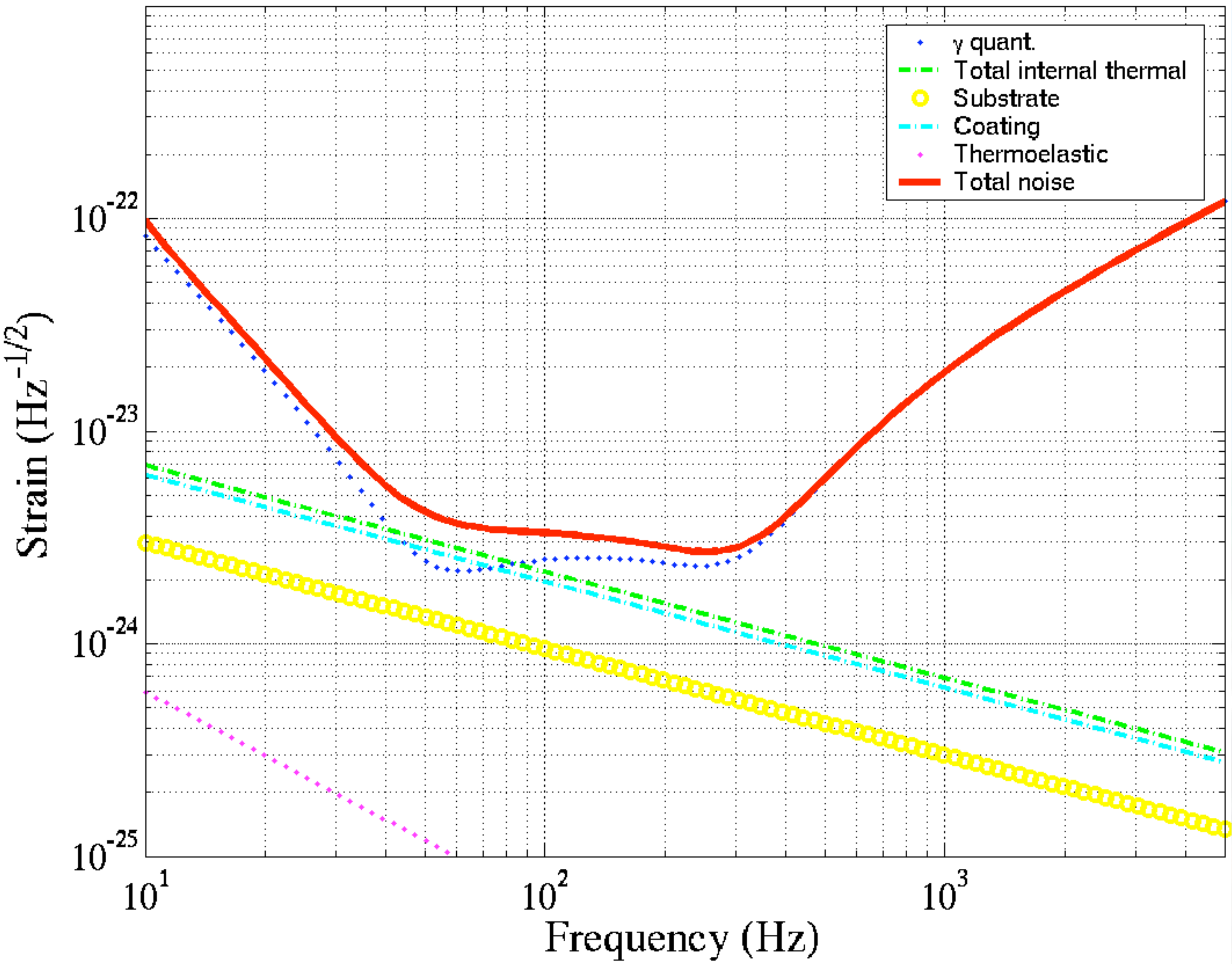
# Q = 120 million, NSB Range = 185 Mpc



# Q = 200 million,   NSB Range = 196 Mpc



# Q = 600 million,   NSB Range = 210 Mpc



# Silica Thermal Noise Research

- Silica thermal noise future work
  - Measurements on Silica Fibers (Syracuse, HWS)
    - Measure $Q$ vs $V/S$
    - Compare Suprasil 312 SV (LIGO glass) & Suprasil 312
    - Annealing in Argon to reduce loss to surface loss limit
  - Annealing of Silica Optics (HWS)
    - $Q$ vs Annealing temperature and rates
    - Test affect of annealing on polish and suspension
    - Anneal in Vacuum or Argon
    - Awarded NSF-MRI grant to purchase a vacuum annealing oven



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Specialists In Vacuum Technology

# Coating Thermal Noise Research

- Coating Loss Research: (MIT, Glasgow, HWS)
  - Initial LIGO mirror coatings are alternating layers of tantala, $Ta_2O_5$, and silica, $SiO_2$, applied with ion sputtering. Structure of coating suggests that mechanical loss should be high.
  - Levin shows that a high loss coating could dominate the thermal noise in the test mass.
  - Initial tests in 2000-1 confirmed high loss in tantala/silica coatings. (papers by Harry, *et al*., and Crooks, *et al*.)
  - We have determined that the coating loss is due to tantala, $\phi_{coating} = 2.75 \times 10^{-4}$ and $\phi_{tantala} = 4.6 \times 10^{-4}$ while $\phi_{tantala} \approx 0$. (Published in CQG).
  - New coating contract established with SMA & CSIRO. Testing new samples with Hafnia and doped tantala.



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# Monitoring Bilinear Coupling

- Correlation $C_{xy}(t) = \int_{-\infty}^{\infty} x(\tau)\, y(t+\tau)\, d\tau \quad \Leftrightarrow \quad X(f)\, Y^{*}(f) = S_{xy}(f)$

- Power Spectrum $C_{2x}(t) \quad \Leftrightarrow \quad X(f)\, X^{*}(f) = S_{2x}(f)$

- Coherence $\mathrm{C}_{xy}(f) = \dfrac{S_{xy}(f)}{\sqrt{S_{2x}(f)\, S_{2y}(f)}}$

# Monitoring Bilinear Coupling

- Cumulant

$$C_{xyz}(t,t') = \int_{-\infty}^{\infty} x(\tau)\, y(t+\tau)\, z(t'+\tau)\, d\tau \quad \Leftrightarrow \quad X(f_1)\, Y(f_2)\, Z^*(f_1+f_2) = S_{xyz}(f_1,f_2)$$

- Bispectrum

$$C_{3x}(t) \quad \Leftrightarrow \quad X(f_1)\, X(f_2)\, X^*(f_1+f_2) = S_{3x}(f_1,f_2)$$

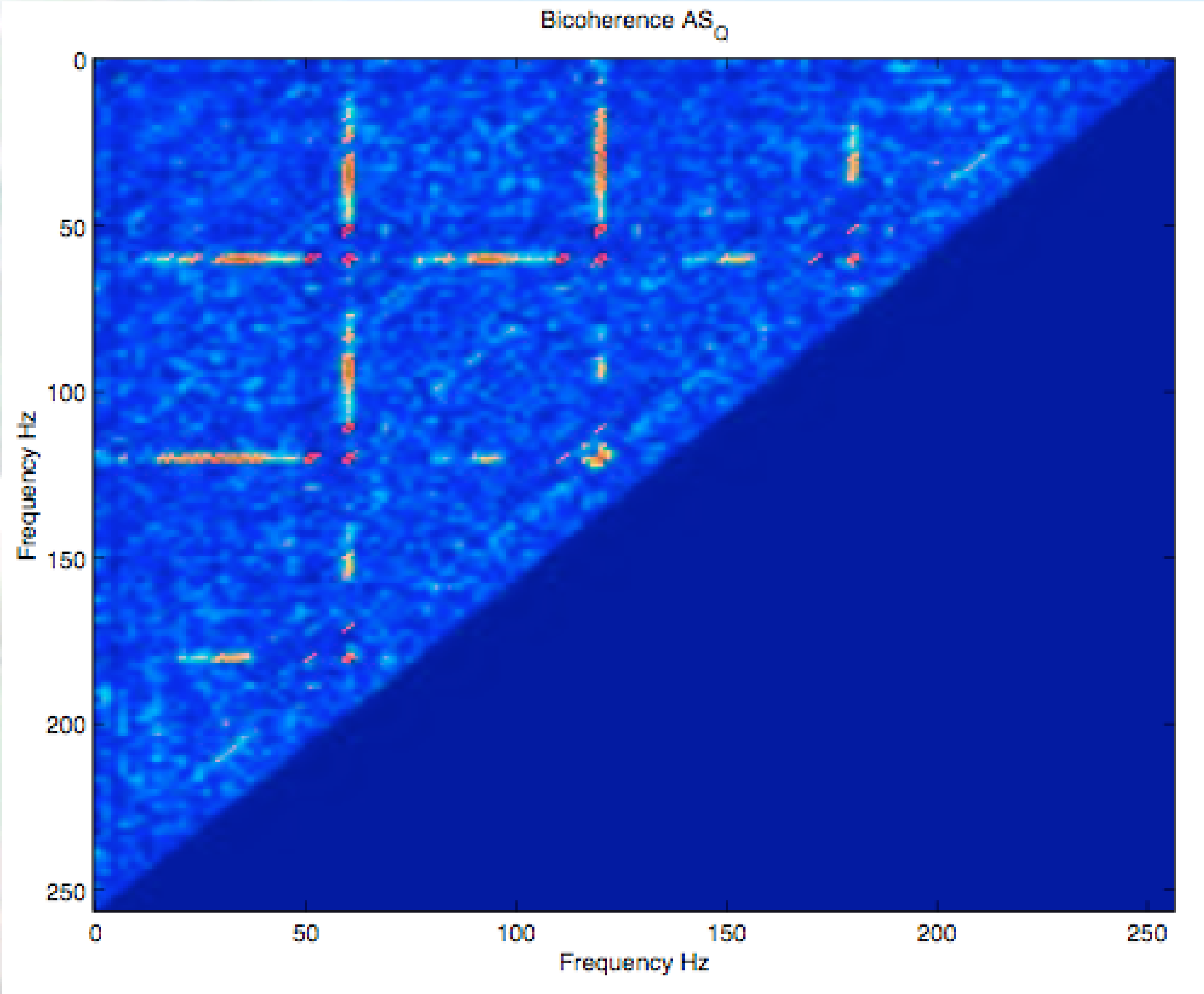
- Bicoherence

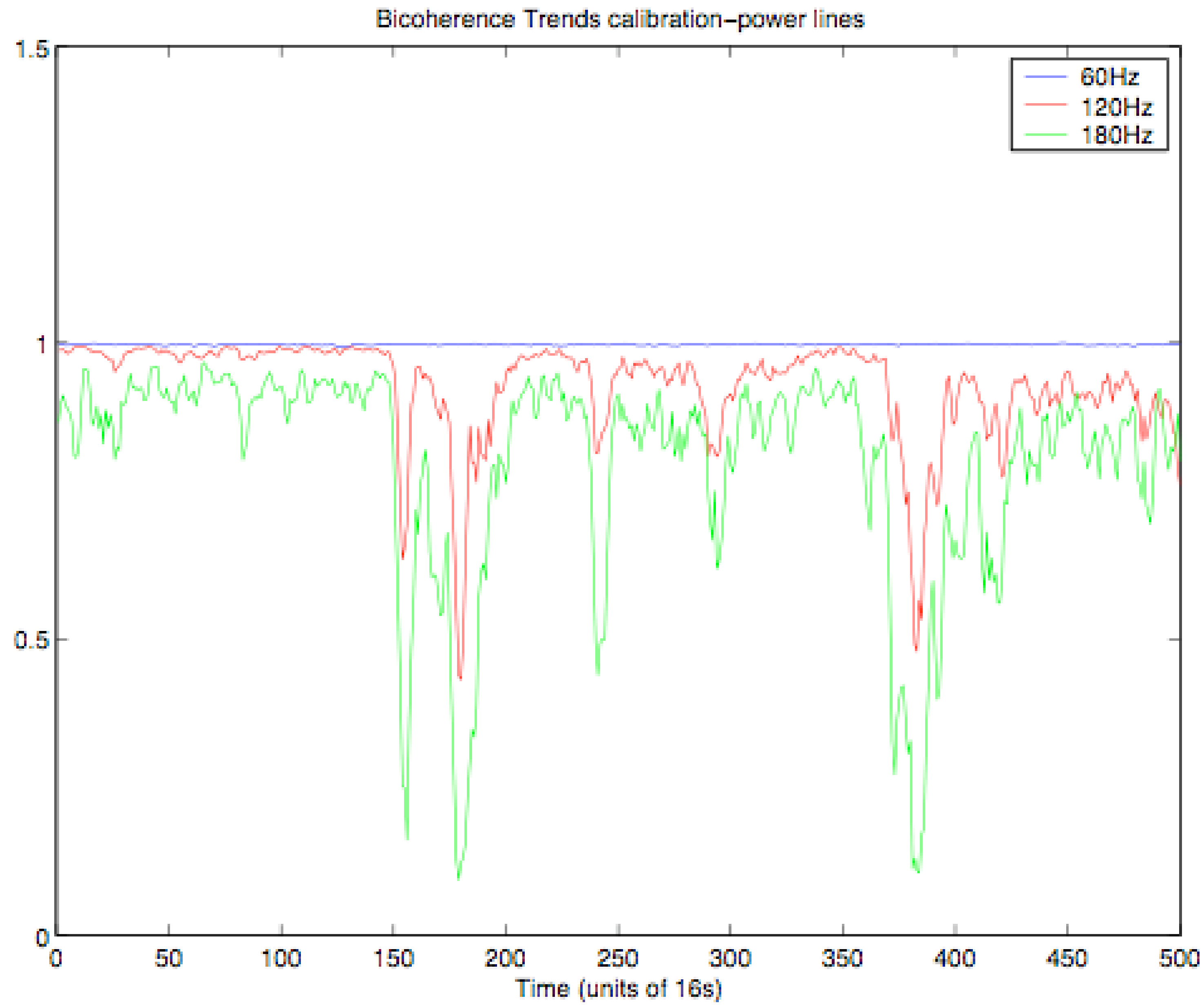
$$\mathrm{C}_{xyz}(f) = \frac{S_{xyz}(f_1,f_2)}{\sqrt{S_{2x}(f_1)\, S_{2y}(f_2)\, S_{2z}(f_1,f_2)}}$$

  - Gaussian Noise removed

$$z(t) = x(t) + y(t), \quad C_{nz}(t) = C_{nx}(t) + C_{ny}(t) \xrightarrow{n>2} C_{ny}(t)$$

$$C_{nx}(t) = 0, \text{ for } n > 2$$


Bicoherence $AS_Q$
Frequency Hz
Frequency Hz
0
50
100
150
200
250


Bicoherence Trends calibration–power lines
60Hz
120Hz
180Hz
1.5
1
0.5
0
0
50
100
150
200
250
300
350
400
450
500
Time (units of 16s)

# Monitoring Bilinear Coupling

- Two Bicoherence Data Monitors
  - BicoMon (Background)
    - Monitors known couplings
    - Integrates region in Bicoherence plane
    - Trends that result and feeds output to DMTviewer
  - BicoViewer (Foreground)
    - Interactive tool with GUI front end
    - Displays bicoherence, bispectrum and associated power spectra
    - Used to search for couplings
    - It will supply new configurations to BicoMon for longterm monitoring



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# Monitoring Bilinear Coupling

- BicoViewer Features
  - Operates on 1–3 channels
  - Automatically decimates to the lowest channel rate.
  - User selected $f_{max}$ and $\Delta f$ Limited to factor $2^n$
  - User specifies the duration and overlap
  - Windowing: Optimized Rao-Gabr windowing
  - Outputs GIF files of the plots
  - Help facility



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# Monitoring Bilinear Coupling

- Future Monitor Work
  - Frequency heterodyning to allow high resolution examination between widely separated frequencies
  - Add in gaussianity and linearity options
  - Use the HOS engine to build a bicepstrum monitor

LIGO

HWS LIGO

# Impact on HWS:

- Hobart (est. 1820) and William Smith (est. 1908) are jointly operated, unisex colleges in the Finger Lakes region of Upstate New York.
- The total enrollment ≈ 2,000 students, with a strong liberal arts focus.
- HWS in midst of long term campaign to become a strong science school.
- Chemistry has developed very successful research program with solid support from the NSF and Merck.
- GeoScience/Environmental Science has received $1M in state and federal funds to build the Finger Lakes Institute of Environmental Science.



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# Revamping HWS Physics

The New Chemistry Building

- Small department: 5 faculty, 15 majors.
  - Don Spector (Harvard, particle theorist),
  - Ted Allen (Caltech, particle/string theorist),
  - Larry Campbell, emeritus (CMU, nuclear/optics),
  - Michael Faux (Penn, string theorist), and
  - Steven Penn (MIT, nuclear/LIGO).
- My start-up fund of $100k, largest in HWS history.
- New faculty member within two years (likely to be LIGO experimentalist). New Post-Doc, if granted by NSF, would be excellent candidate to join faculty.
- Currently I have 1 undergraduate research student.
- Geneva High School very interested in staring a LIGO associated research project.
- Prominent publicity of my research by HWS



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# Summary

- Silica has achieved *Q*'s of $10^8$ in fibers and optics. Annealing and surface loss studies have been successful increasing high *Q*'s by factor 10 in last few years.  Silica is viable material for Advanced LIGO.
- Coating noise research is a high priority for Advanced LIGO.  The coatings research group has been quite successful in isolating the noise source in current LIGO coatings.  We need to find a mirror coating with a factor 10 lower loss to reach Advanced LIGO range goal.
- Upconversion and other bilinear processes are known noise sources in LIGO I.  The Bilinear investigation is working to produce tools to allow better exploration of this noise source.
- HWS & its students are excited about LIGO research.  This research is an ideal way to grow our department and spark interest in gravity physics.



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