Elastic Loss in Amorphous Zirconia-Titania Coatings

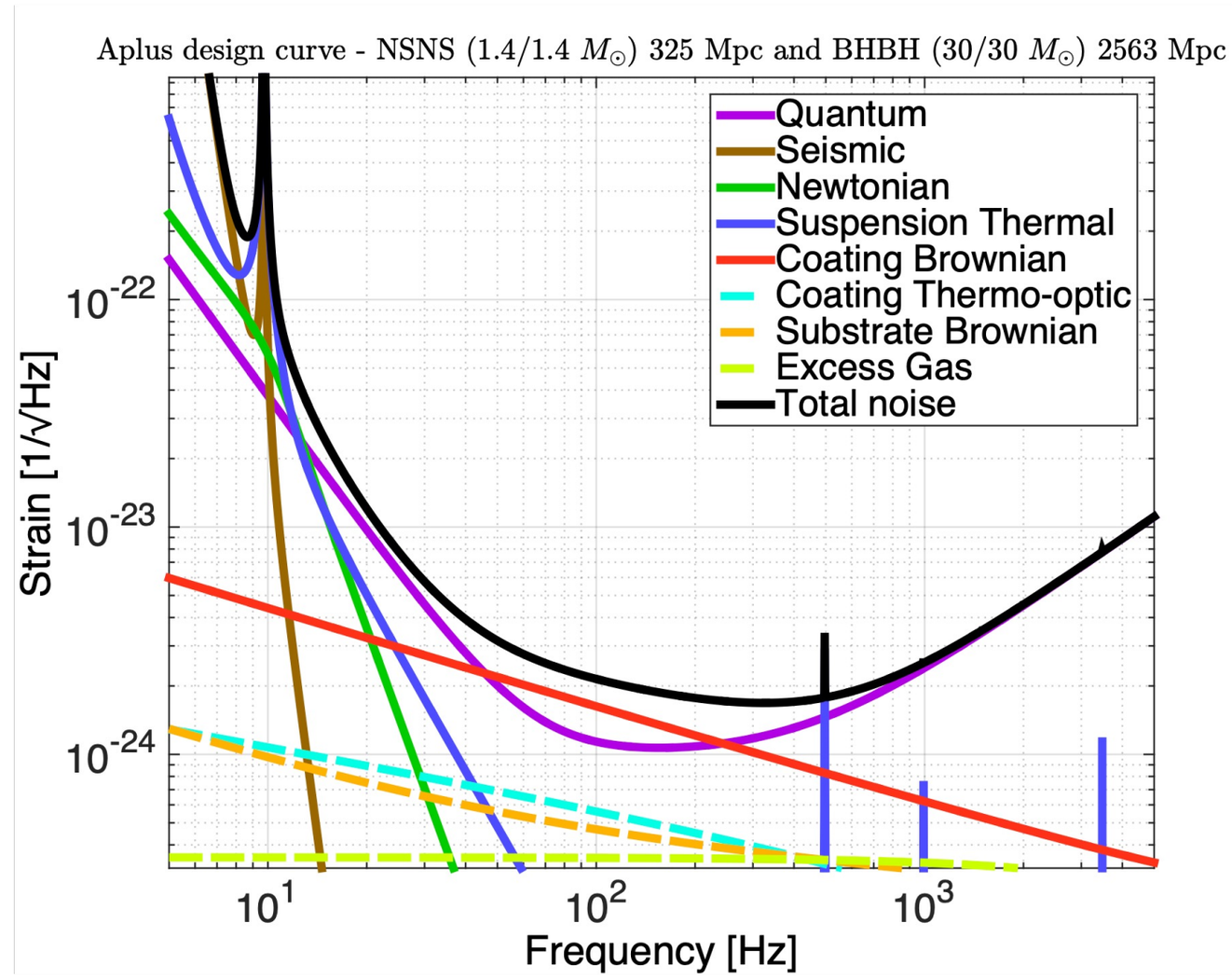
Elenna Capote, Satoshi Tanioka, Nicholas Didio, Steven Penn, Stefan Ballmer

Syracuse University
LIGO Scientific Collaboration

Background and Design

Low-loss Amorphous Coatings for Future Detector Upgrades

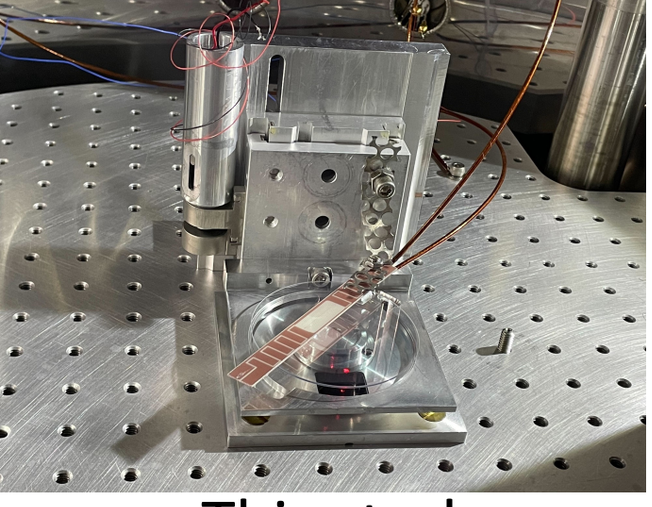
- Goal: find high index of refraction materials that withstand the high-temperature annealing that lowers elastic loss
- Tetrahedral metal dioxides that relax into low-loss, corner-sharing bonds are ideal
    - Similar to silica, the low index layer in current LIGO mirrors



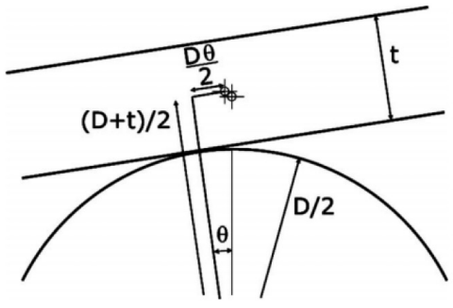
A+ Noise Budget design curve, L. Barsotti, L. McCuller, M.Evans, P. Fritschel

$$S_x(f) = \frac{4k_B T d}{f Y w^2 \pi^2} \phi_{\text{eff}}(f)$$

I MacMillan et al, Experimental Distribution of Mechanical Quality Factor and Implications for Gravitational Wave Detection LIGO Doc P1900306



Project Design

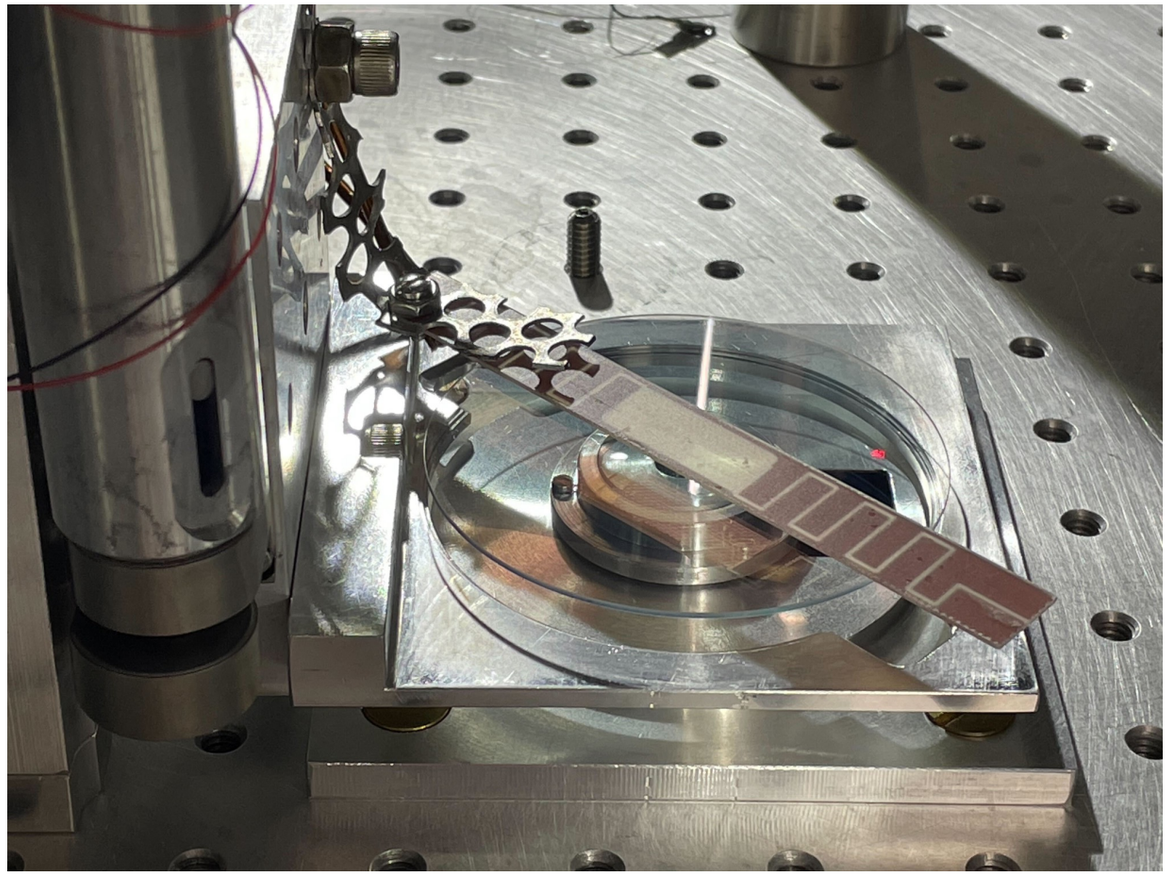


Cesarini, E., et al. "A "gentle" nodal suspension for measuren
of the acoustic attenuation in materials." Review of Scienti
Instruments 80.5 (2009): 053904.

- This study uses single-layer Zirconia-Titania mixtures in three ratios: 2:1, 1:1, 1:2
  - 6 samples in total deposited by CSU collaborators
- All deposited with IBS on blank 1mm thick, 76mm diameter silica disks with measured high Q (low loss)
- Coating loss measured as-deposited, and then after every annealing step between 300 C and 550 C (50 or 100 C increments)
- 1–inch witness samples annealed alongside 3-inch disks for XRD measurements to track crystallization
- Coating loss measured in a multimodal gentle nodal suspension, can detect several modes at a time (ignoring modes damped by suspension)

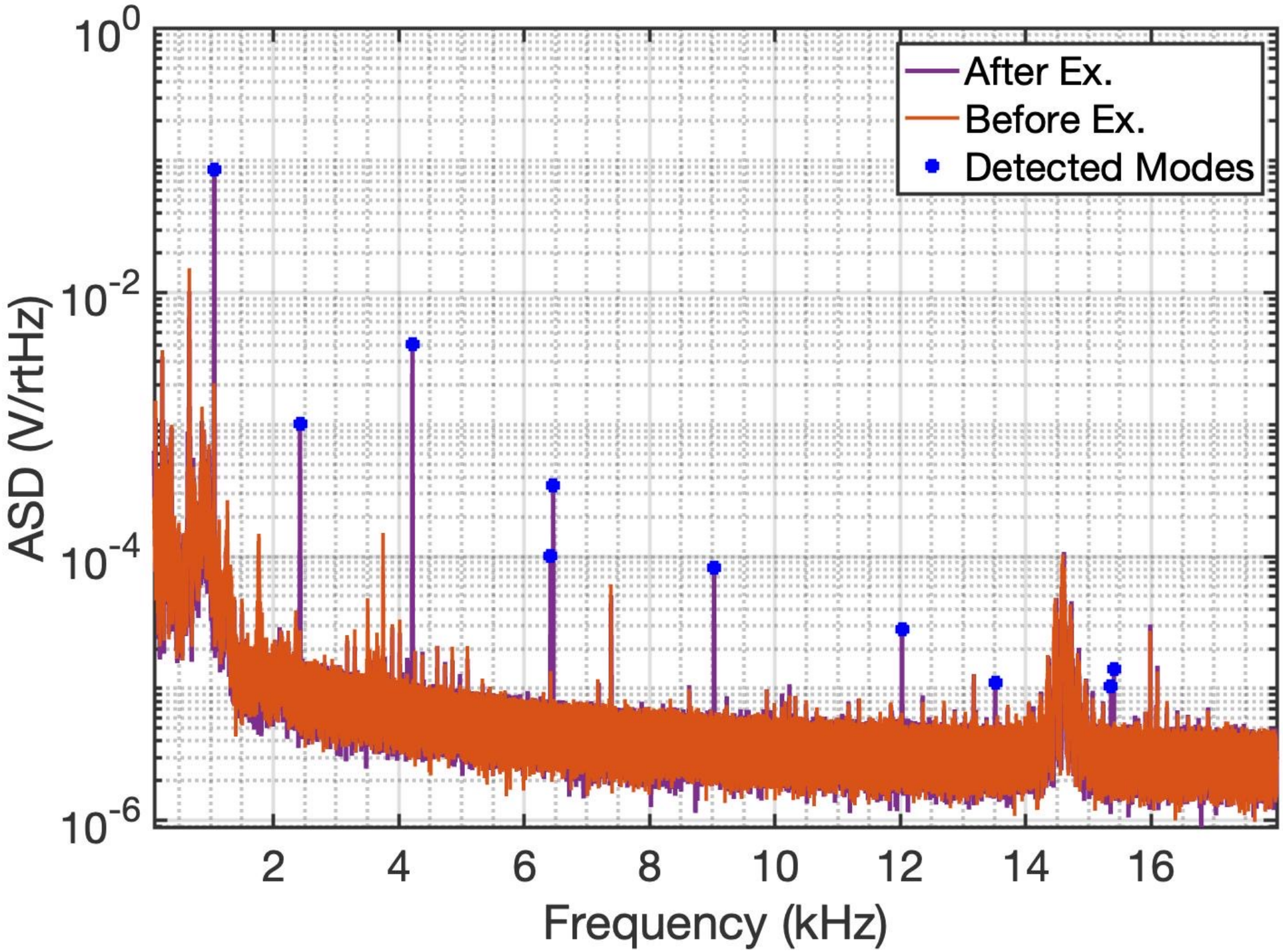
Multimodal GeNS Set up

- Samples suspended on sapphire lens (GeNS), etched copper exciter extends over diameter of sample to deliver high voltage excitation
    - Band-limited white noise excitation spectrum
- 2 mW HeNe laser used as optical lever, QPD board reads out signal to a multimodal DAQ
- Measurements performed at vacuum (below 1e-5 torr)



We can excite and detect ringdowns of 13 modes in one run!

Zirconia-Titania coated (1:2) 1 mm silica substrate, annealed to 450C



1600 V band-limited white noise excitation applied for 3 minutes

Analysis Methods

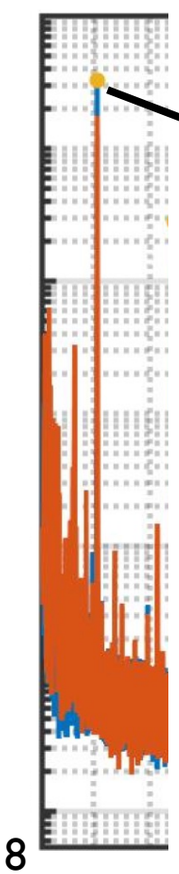
Two Methods of Analysis

- Data acquisition performed by MultiQ, multimodal LABView program that tracks spectra in real-time and outputs time series from X, Y, and SUM channels

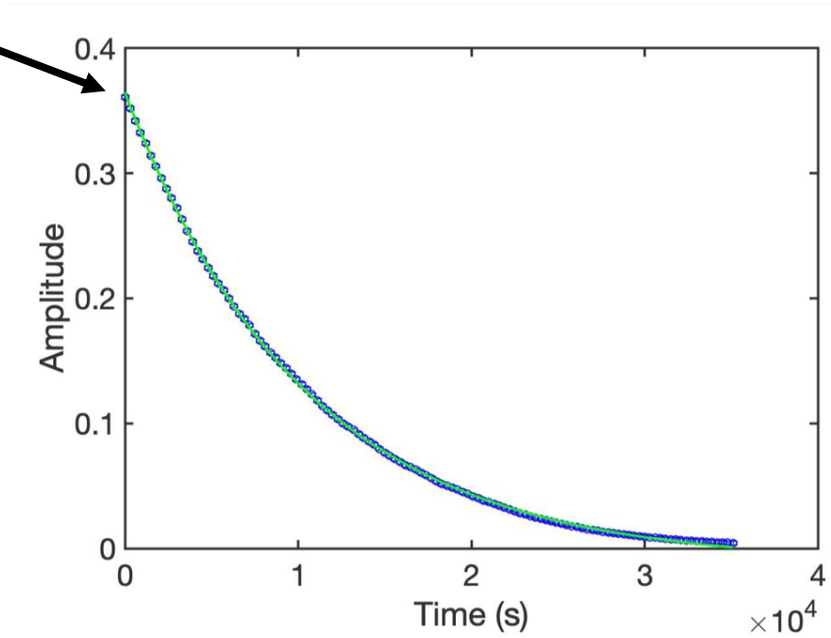
- Peak frequencies are identified as modes to perform two methods of analyses: frequency domain exponential decay and time series sinusoidal decay: calculate tau

$$Q = 1/\phi = \pi f \tau$$

$$\phi_{coated}(f_0) = \phi_{substrate}(f_0) + \frac{E_{coating}}{E_{substrate}}\phi_{coating}(f_0)$$

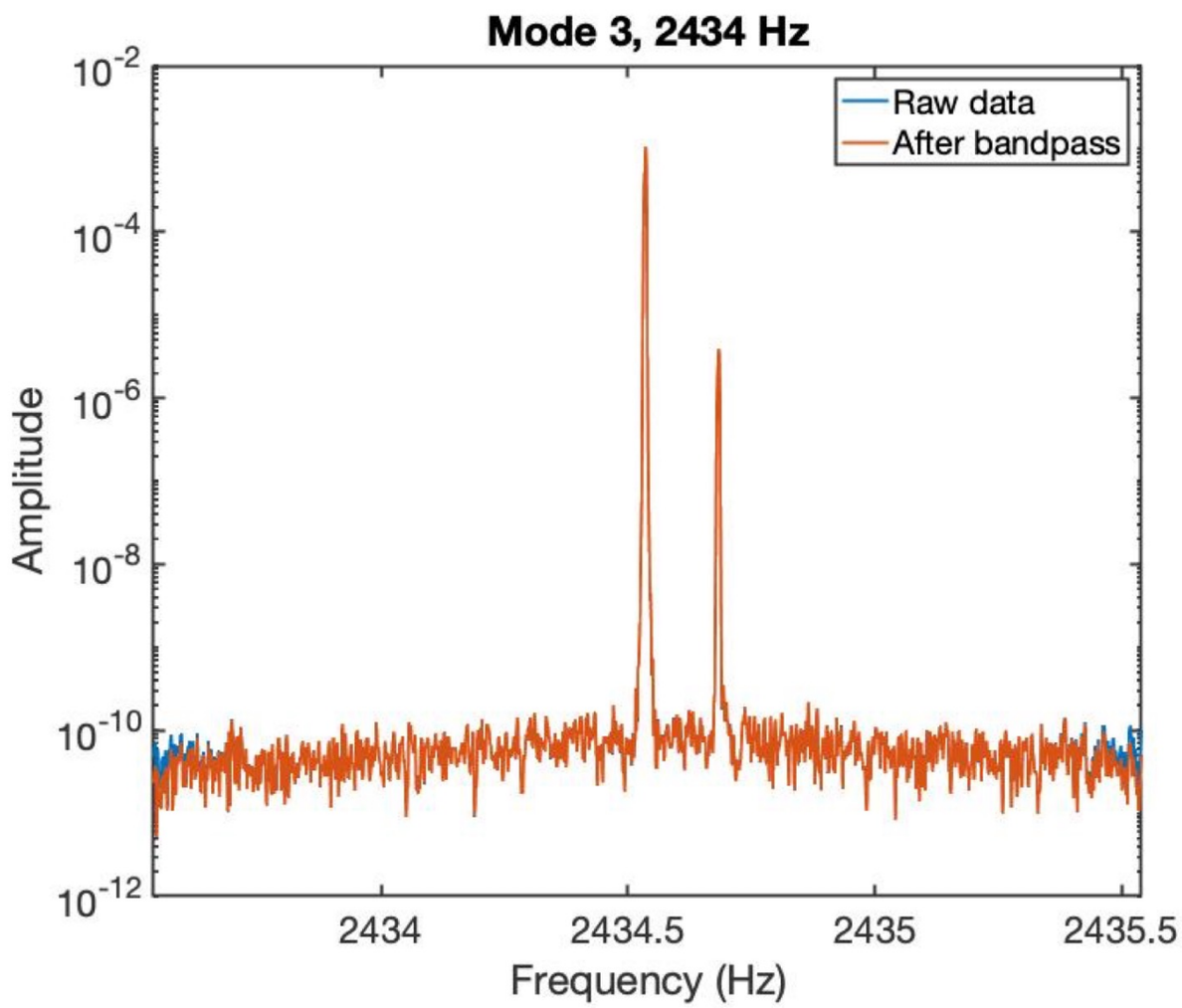


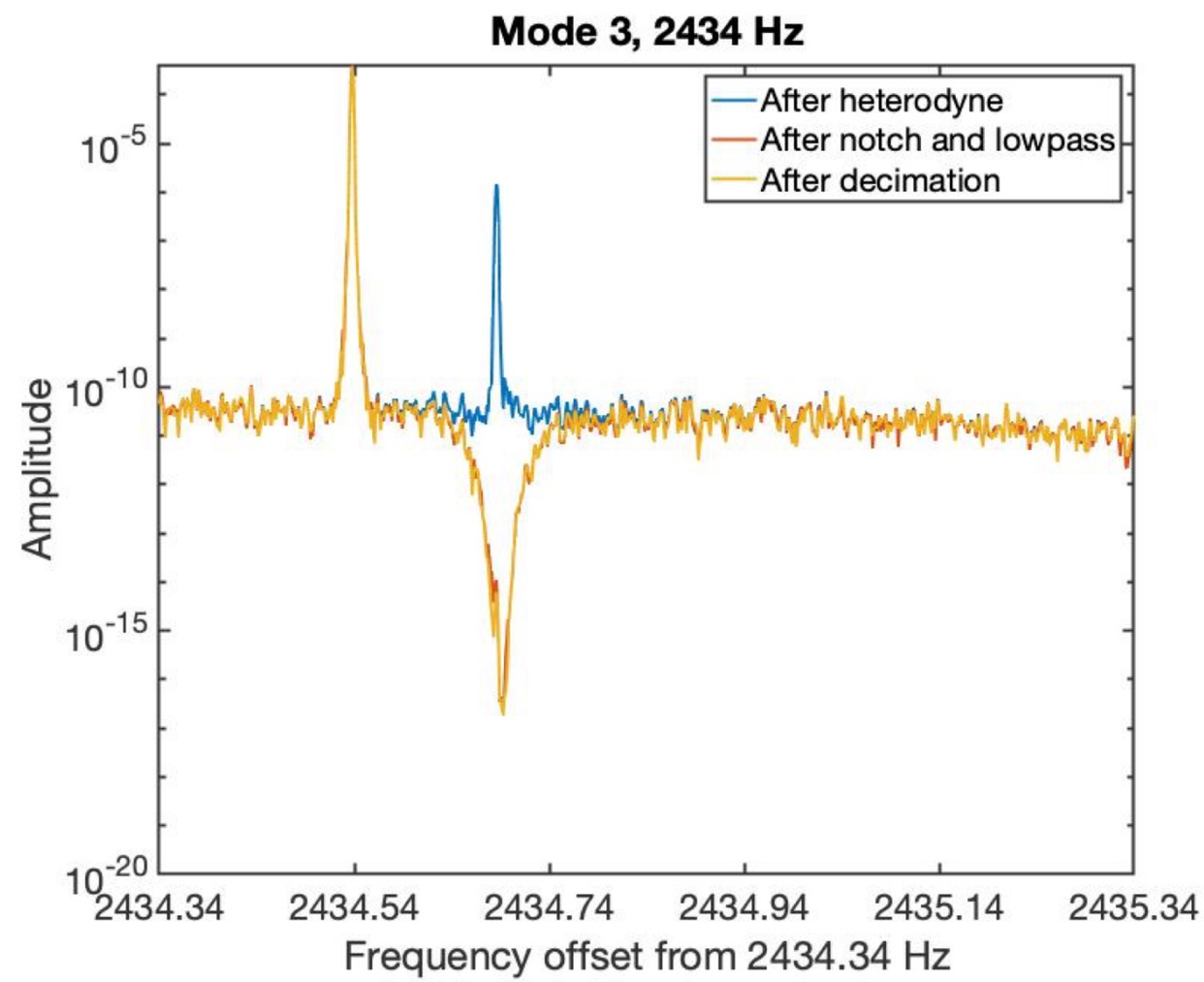
$$Ae^{-t/\tau}$$



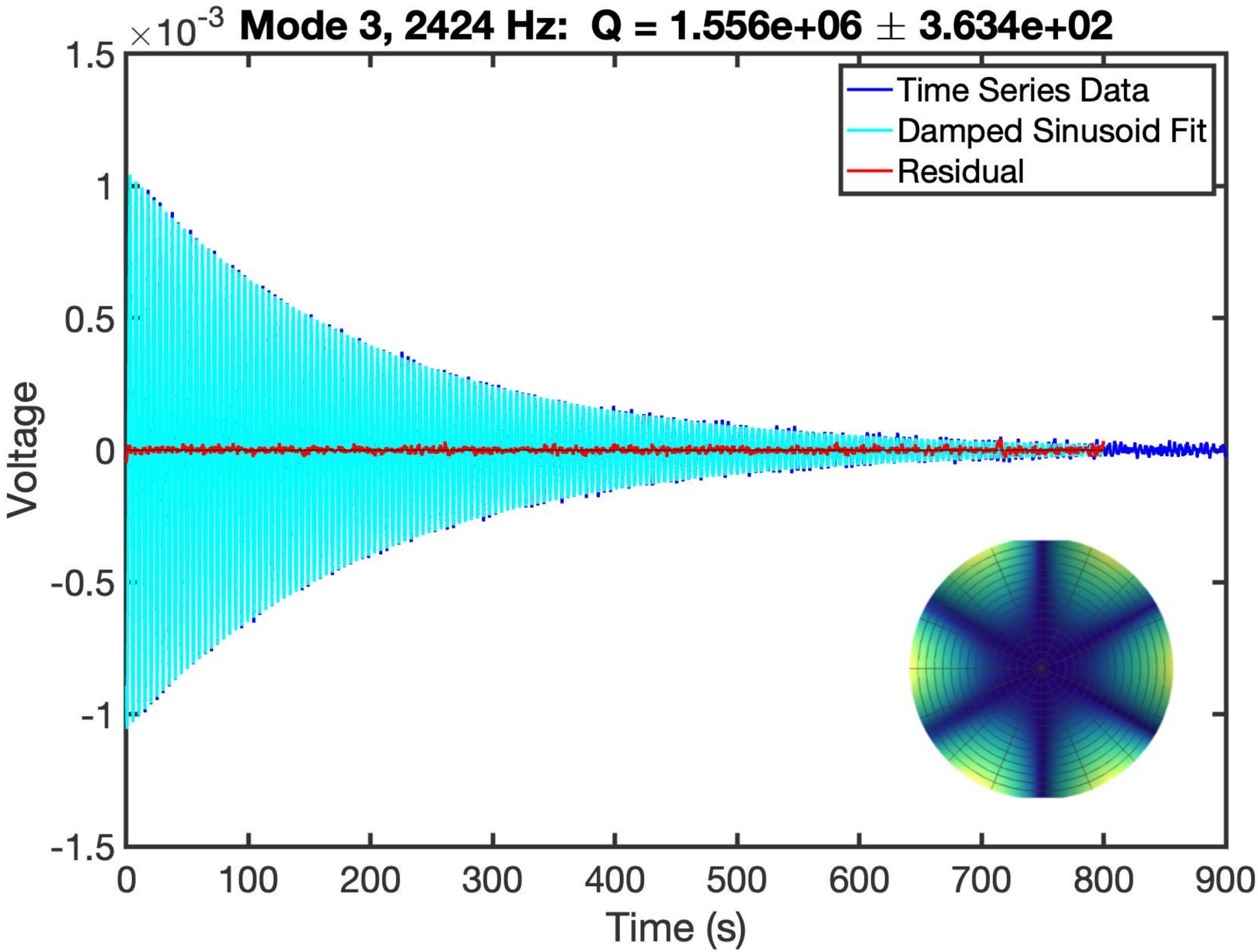
Implementing Time Series Analysis

- By applying digital filters (similar to a lock-in amplifier), a large time series file with several detected modes can be reduced to several smaller files centered around the frequencies of interest
  - By applying 2 Hz bandpass and heterodyne method
- Quasi-degenerate peaks easy to remove via notch filtering
- Phase information from signal can show frequency shift over length of run
  - Fitting phase shift and reapplying in heterodyne can account for drift

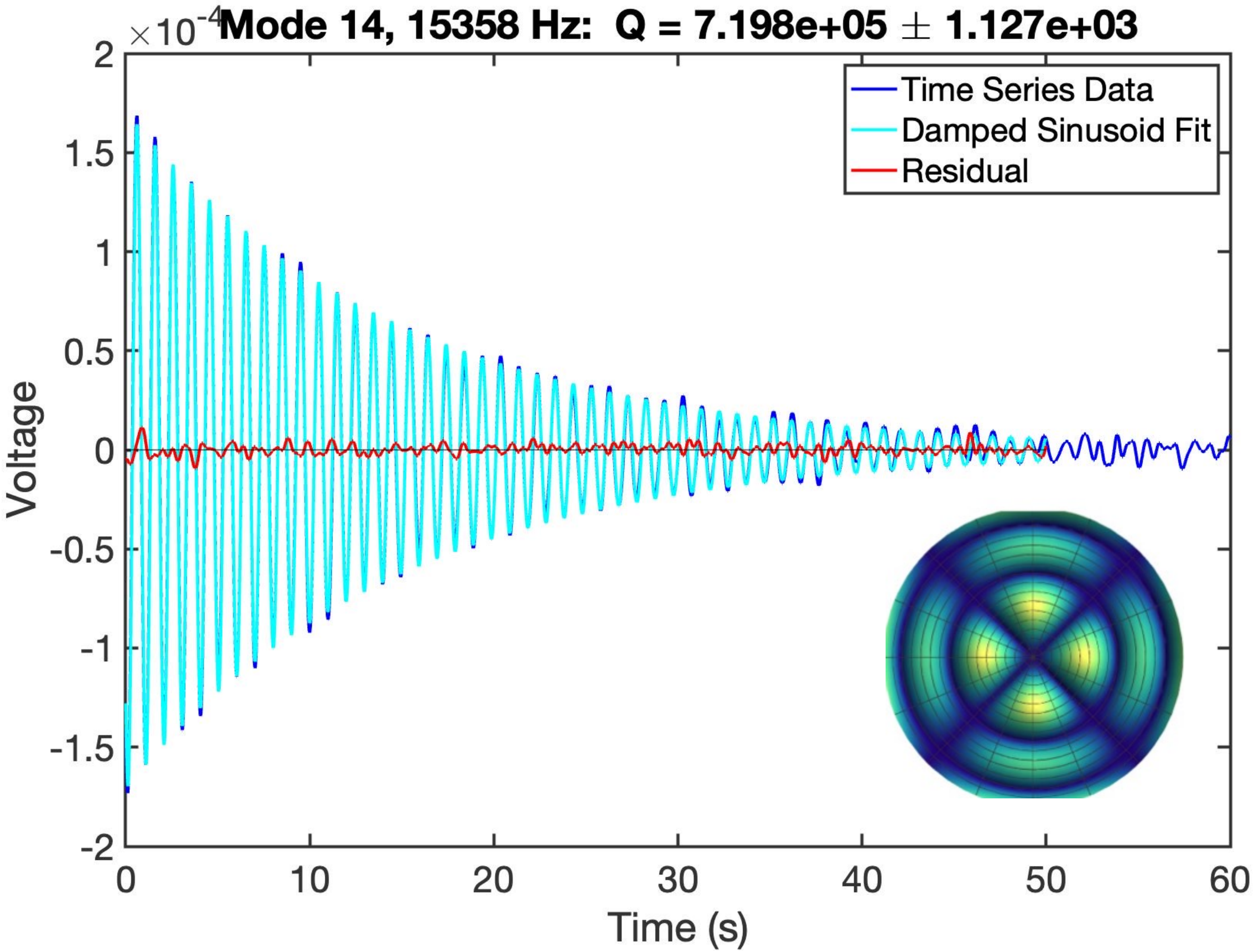




Secondary Peak removal



Mode geometry image created by Andri Gretarsson



Mode geometry image created by Andri Gretarsson

Calculating Coating Loss

$$\phi_{coating} = \frac{\phi_{total} - (1 - D)\phi_{substrate}}{D}$$

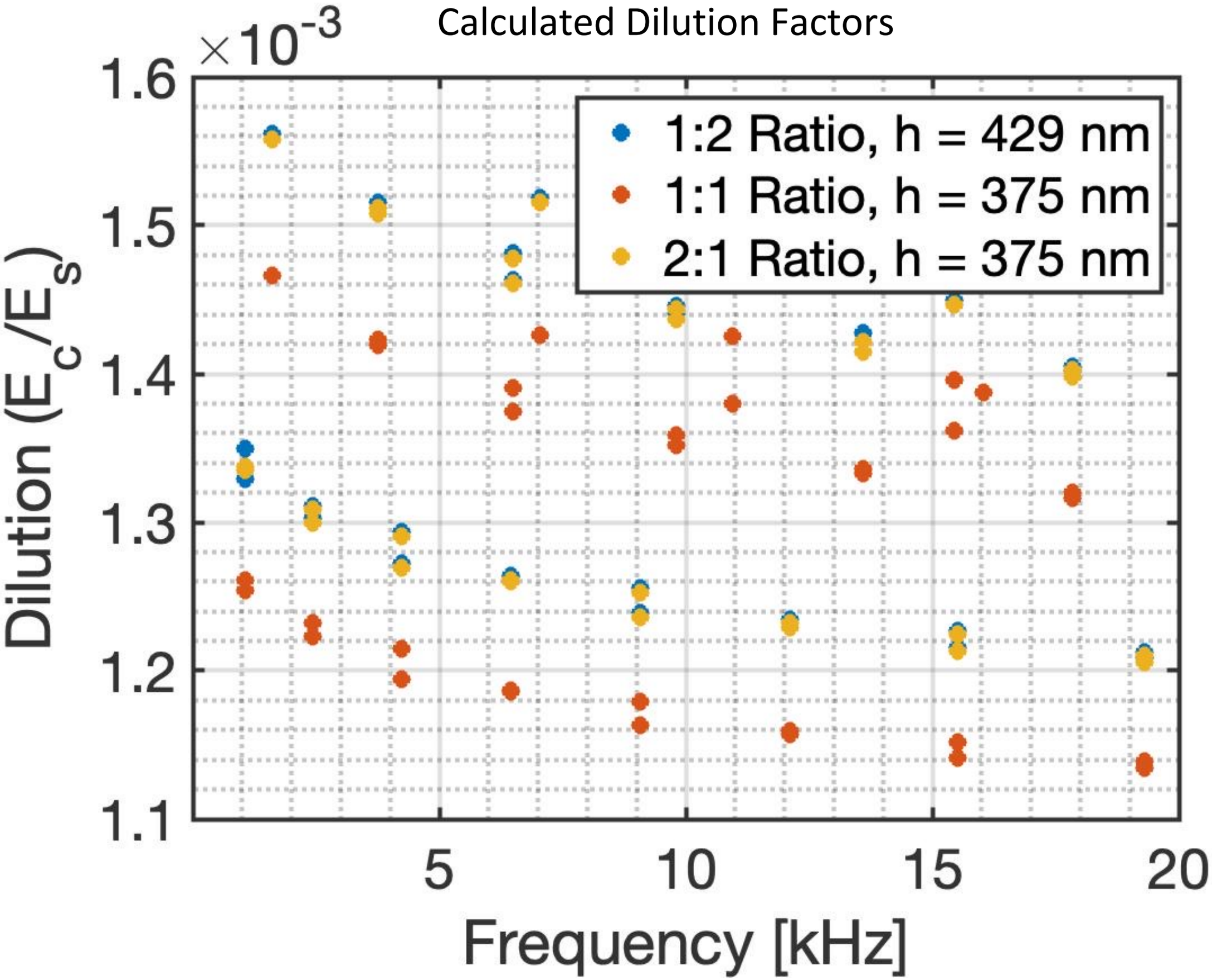
$$D = \frac{E_{coating}}{E_{substrate}}$$

- Dilution factors are generated from a finite element analysis performed in COMSOL
- Use estimates of Young's modulus for Zir-Ti mixtures from literature: Y_Zir = 215 GPa, Y_Ti = 147 GPa

220 — 210 GPa Annealed at 400 & 600 C. *****
F. Samiee, K. Raeissi & M. A. Golozar (2013) "Nanoindentation testing of pulse electrodeposited thin zirconia coatings",
Surface Engineering, 29:10, 726-730, DOI: 10.1179/1743294413Y.0000000204

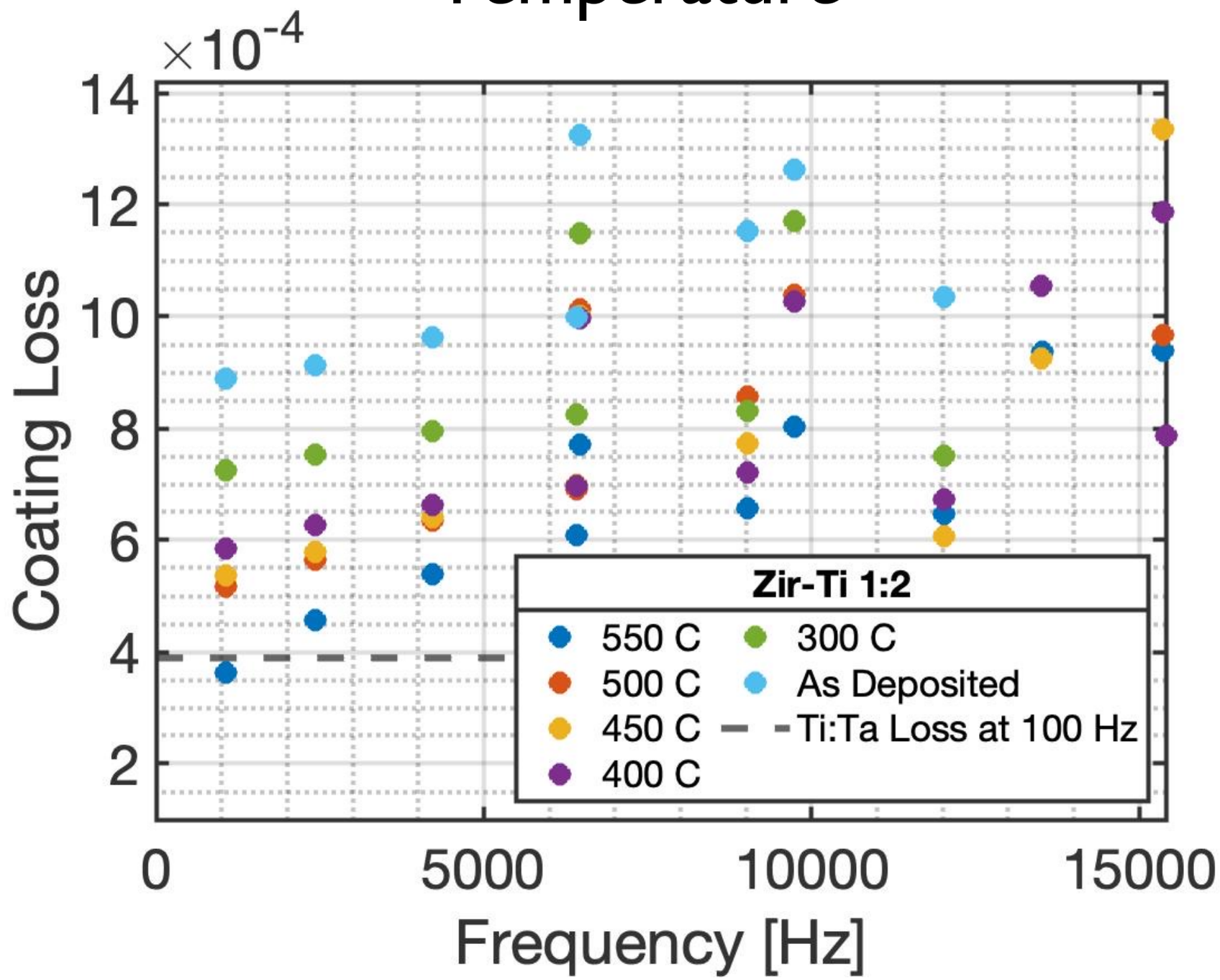
147 GPa (Ion Plating). ****
O. Anderson · C. R. Ottermann · R. Kuschnereit · P. Hess · K. Bange
Density and Young's modulus of thin TiO2 films
Fresenius J Anal Chem (1997) 358:315–318 – © Springer-Verlag 1997

Calculated Dilution Factors



Results

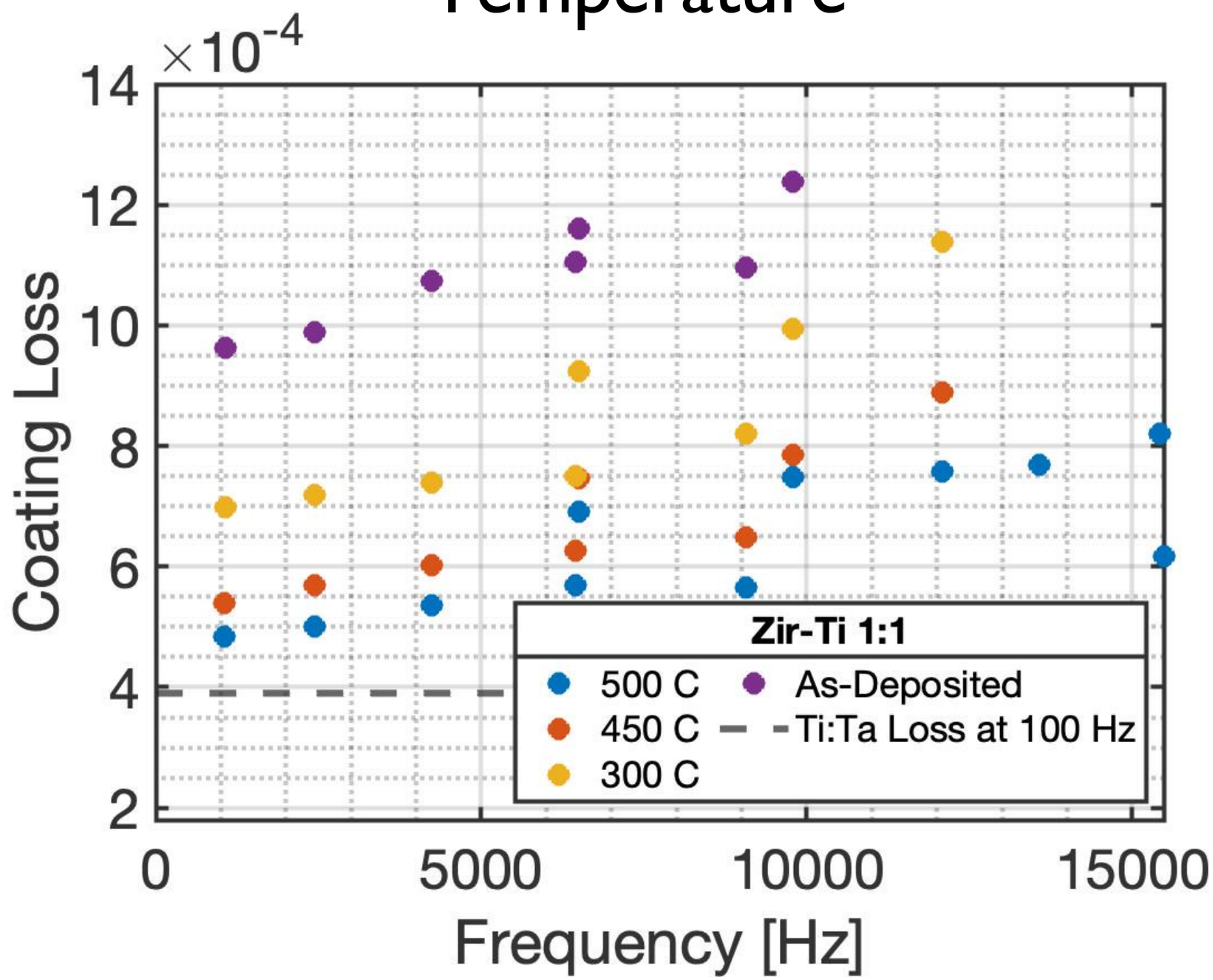
Coating Loss Decreases with Annealing Temperature



Single Layer Zirconia(33%)-Titania(67%)

n = 2.497, Y = 169 GPa

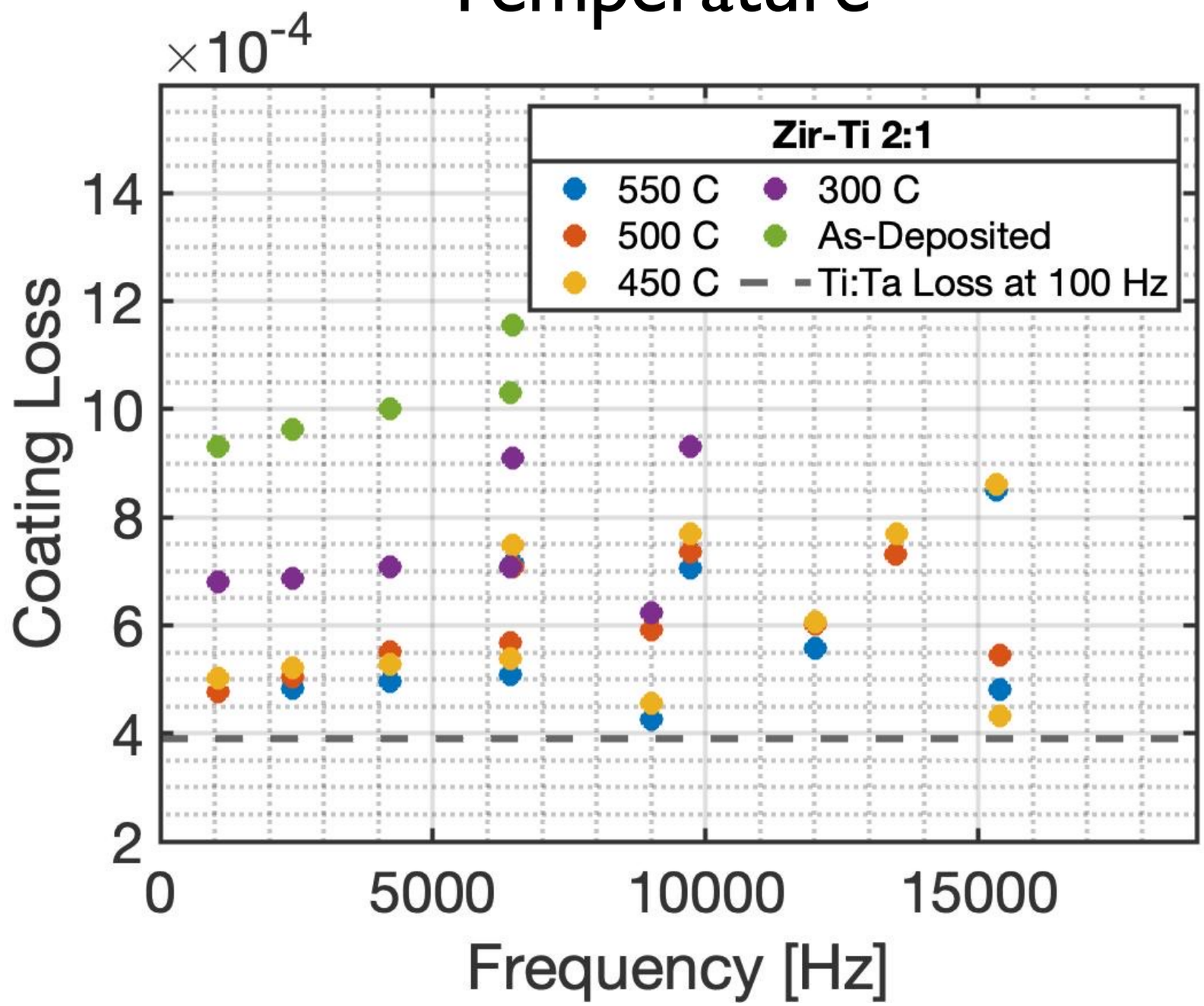
Coating Loss Decreases with Annealing Temperature



Single Layer Zirconia(50%)-Titania(50%)

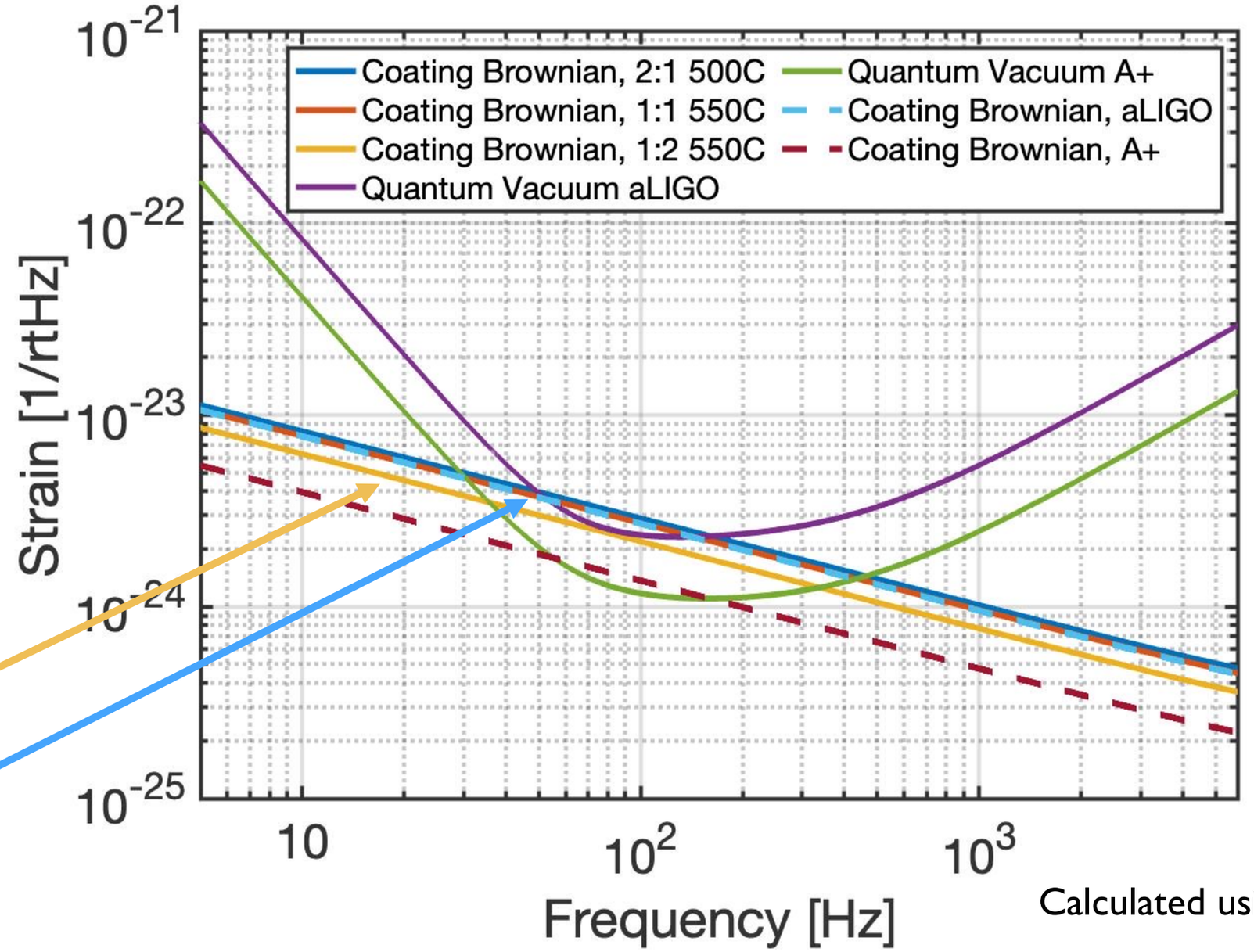
n = 2.37, Y = 181 GPa

Coating Loss Decreases with Annealing Temperature



Single Layer Zirconia(67%)-Titania(33%)

n = 2.315, Y = 192 GPa



Calculated using gwinc

	Zir-Ti	Ti-Tantala
Y (GPa)	169	120
ϕ	3.63e-4	3.89e-4
n	2.497	2.09

*assumes other optical properties similar to tantala

Improvement in CTN relative to aLIGO

Conclusions

- Zirconia-Titania mixtures show promise as a low-loss, high-index layer
  - More investigation required: mixture ratios, absorption, scatter
- Up next: adding Yttria for more stability => anneal to higher temperatures
- First amorphous coating studied by the Syracuse room temperature multimodal GeNS
  - Multimodal DAQ a success, time series analysis effective

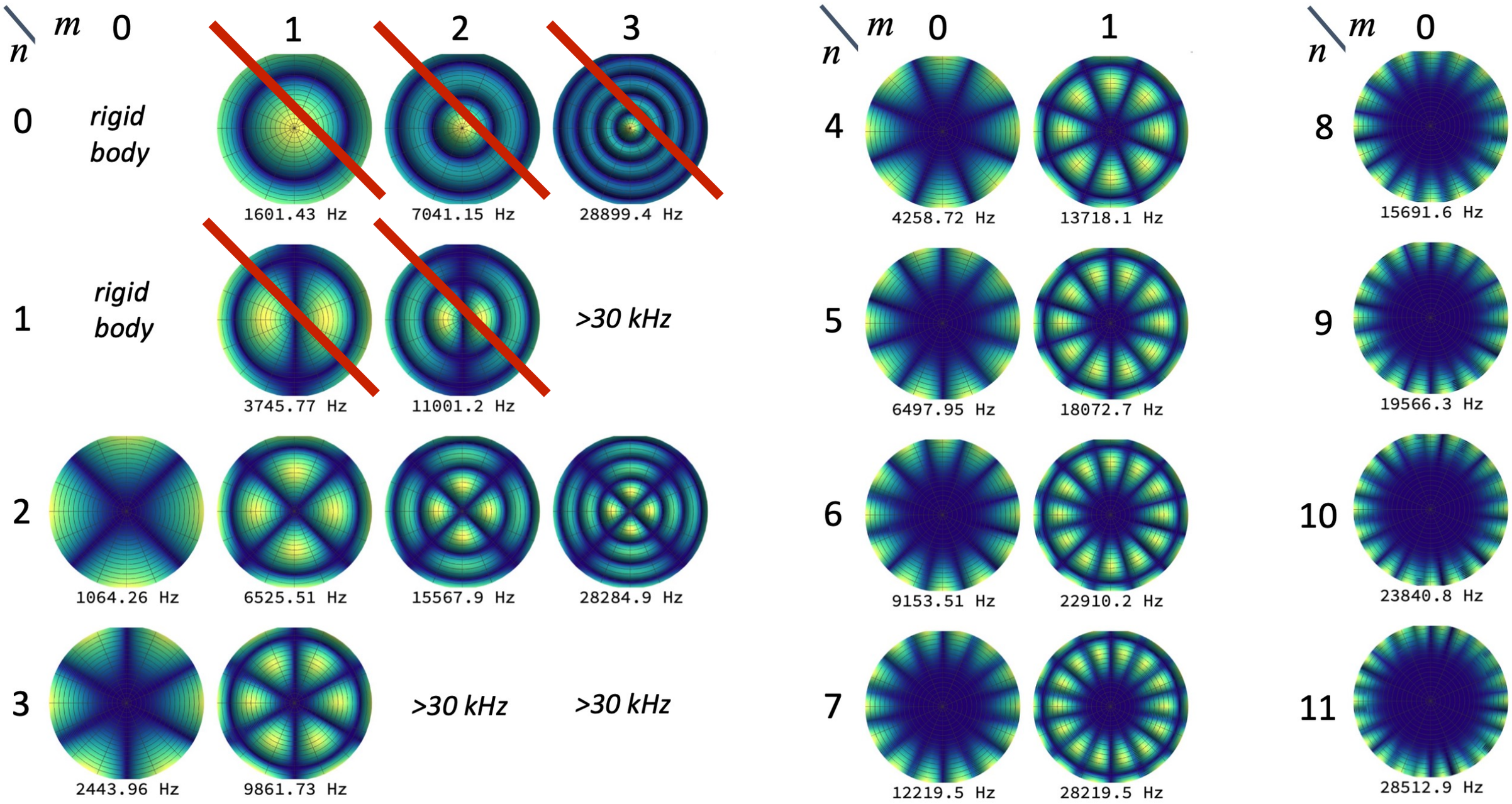
Thank you!

Extra Slides

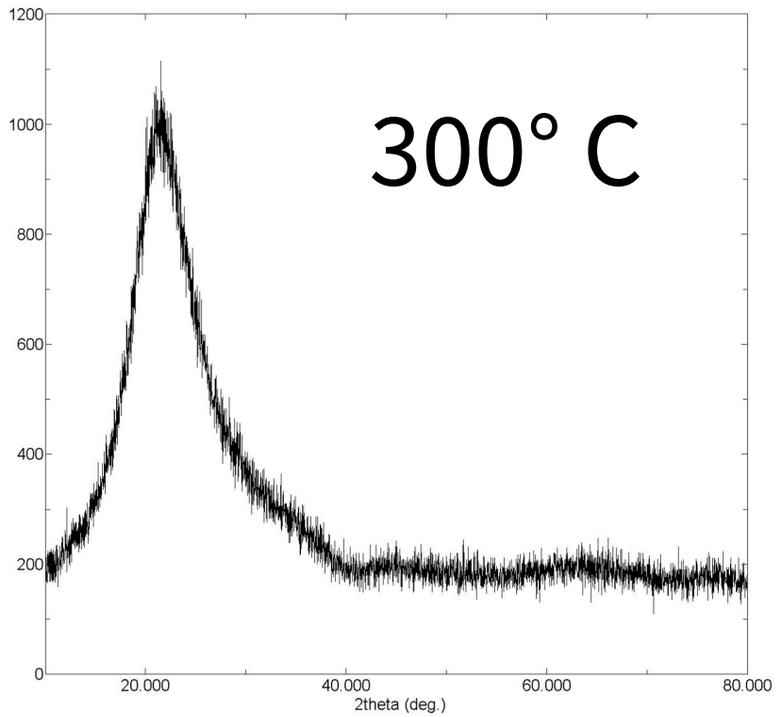
Modes below 30 kHz

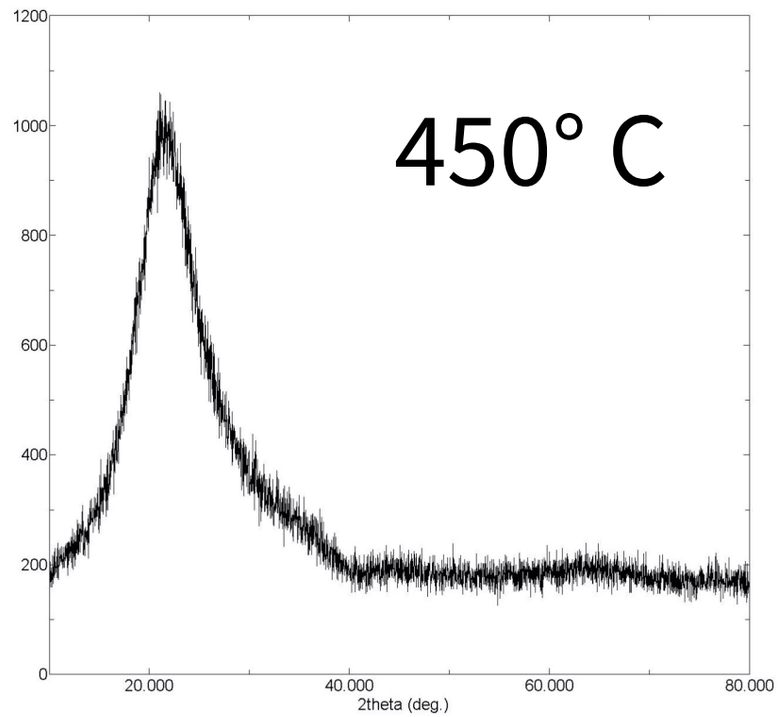
Silica disks: ø76 mm x 1.0 mm
Images show absolute value of displacement.

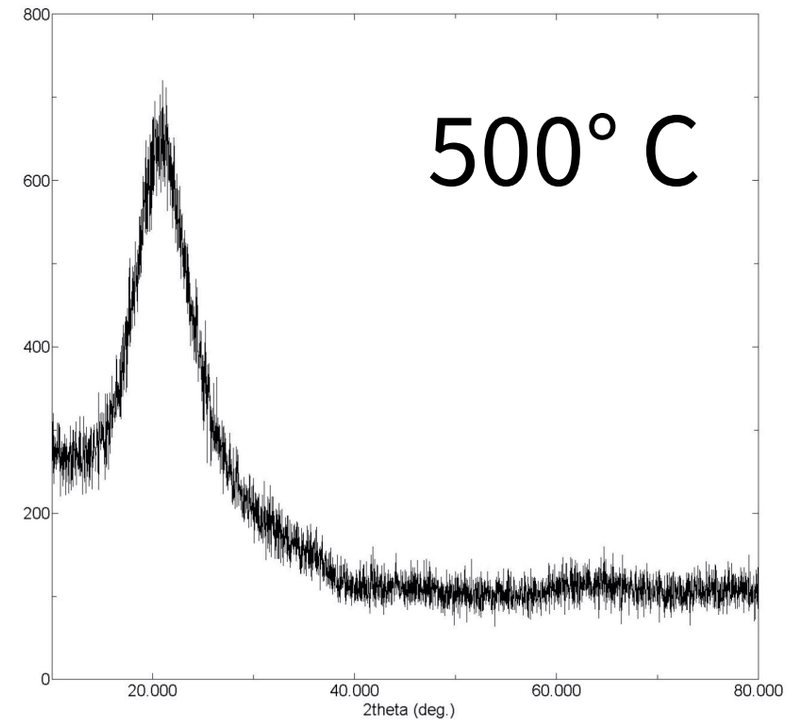
Damped by suspension

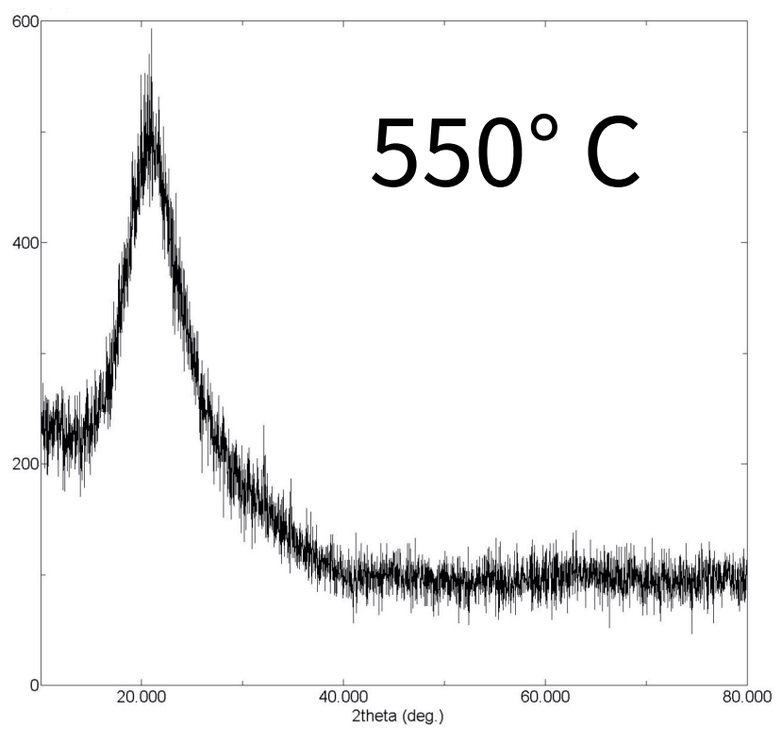


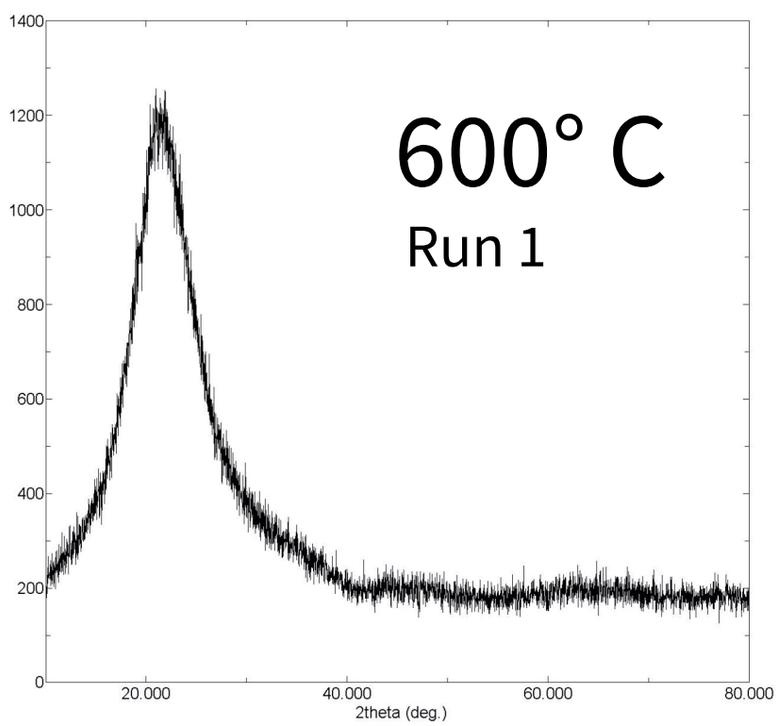
Zr(2):Ti(1) XRD Scans

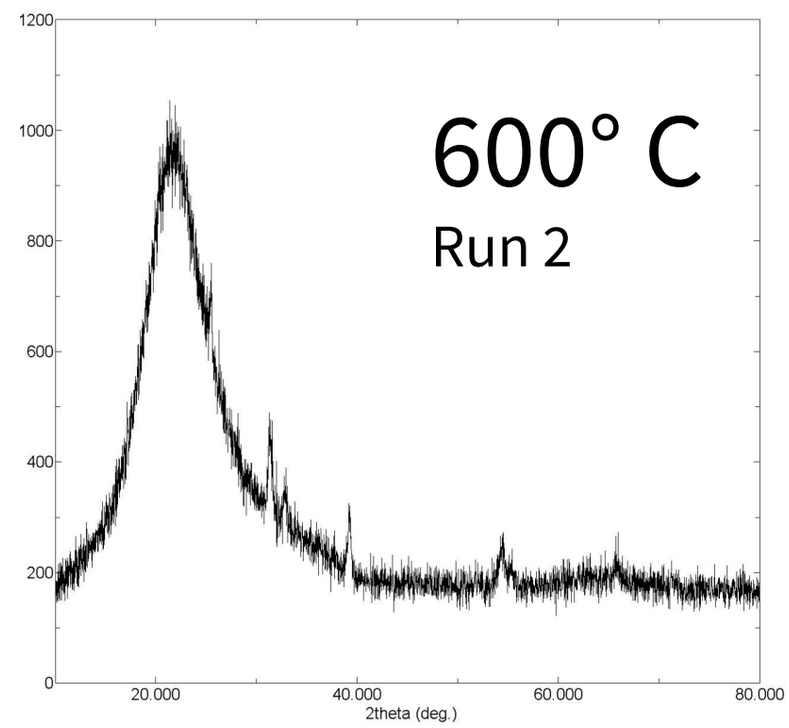




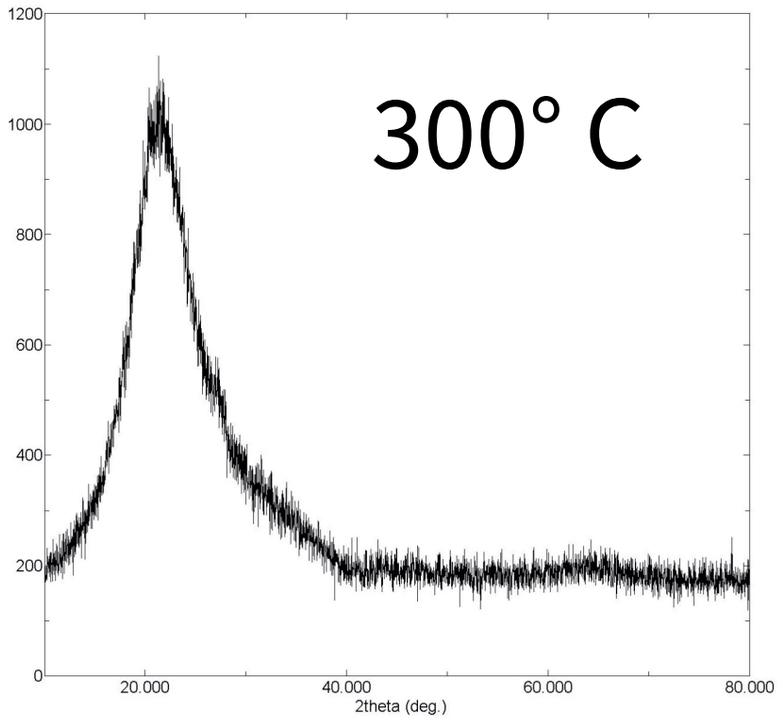


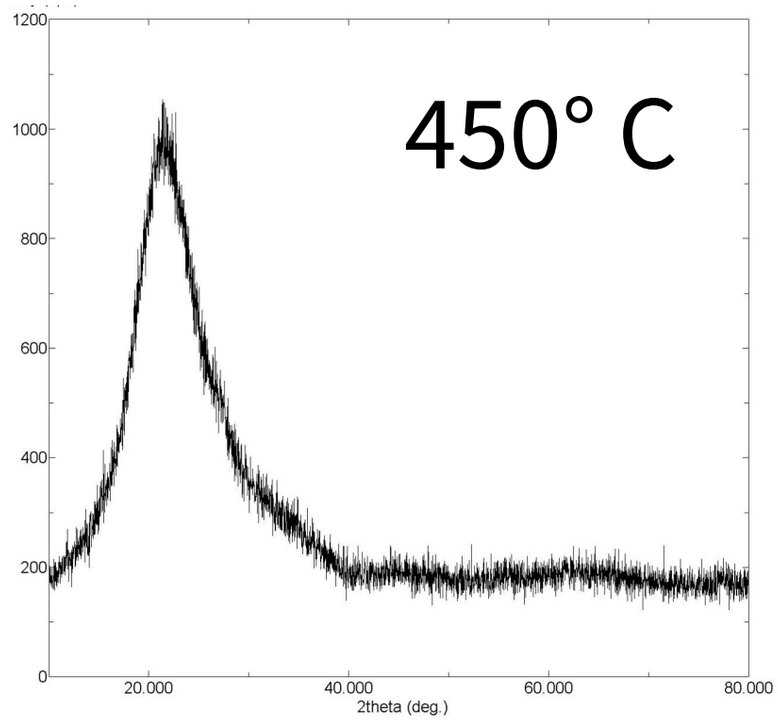


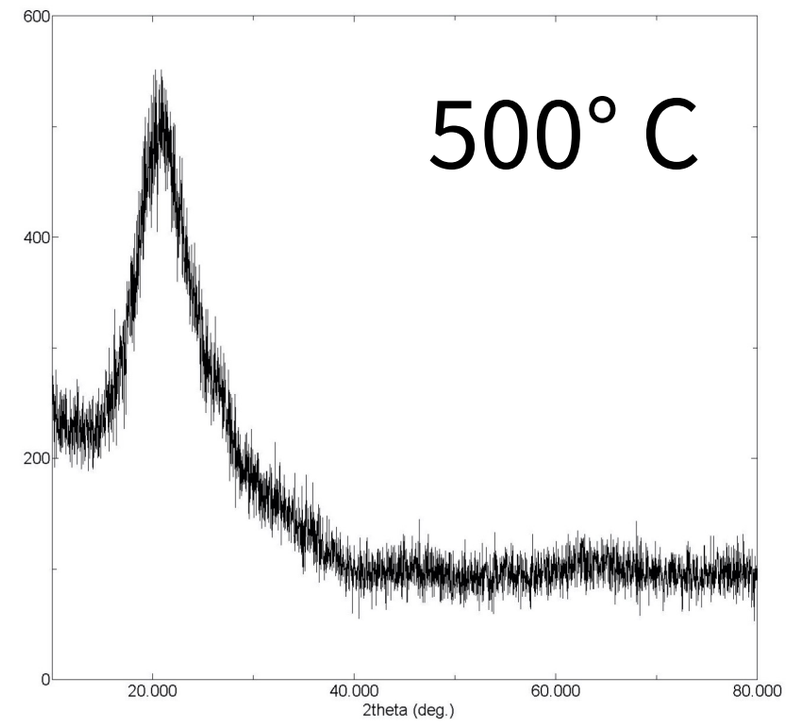


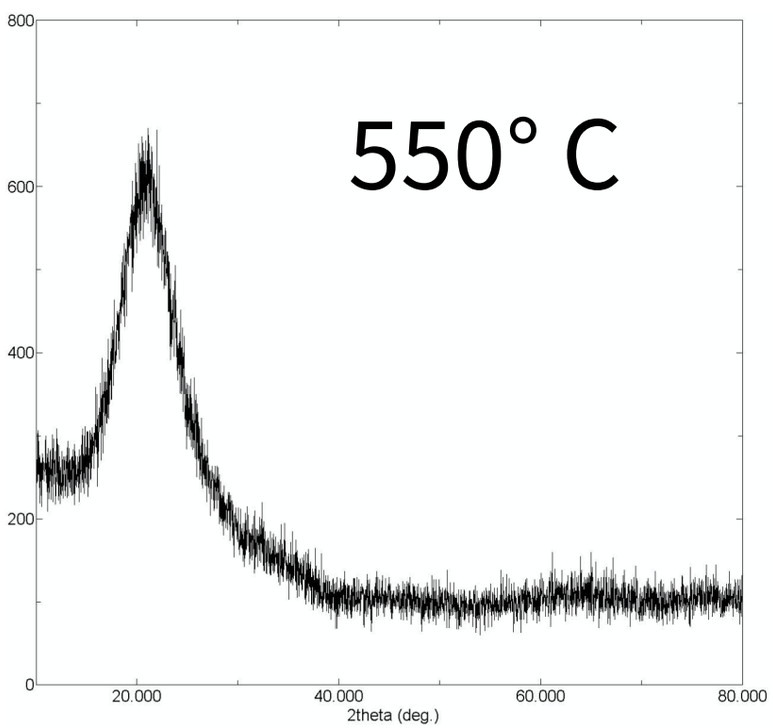


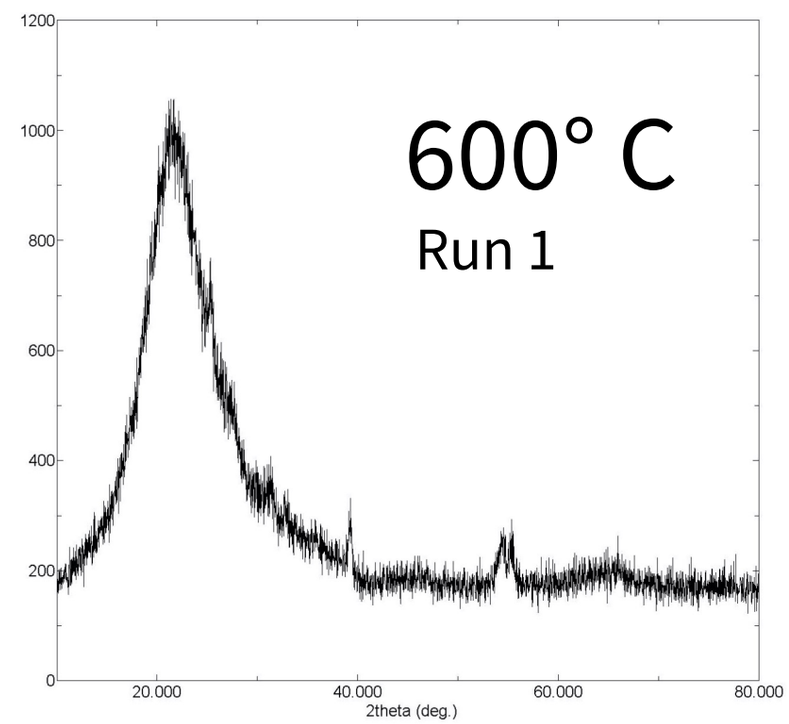
Zr(1):Ti(1) XRD Scans

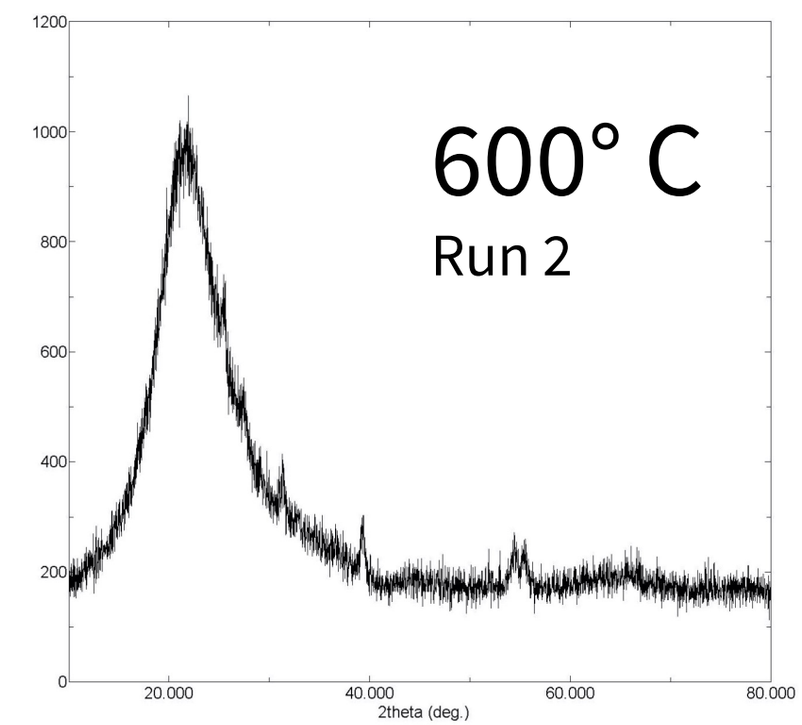












Zr(1):Ti(2) XRD Scans