

A Dark Photon Dark Matter Search with a Widely-Tunable SRF Cavity

CPAD 2025 at Penn

October 8, 2025

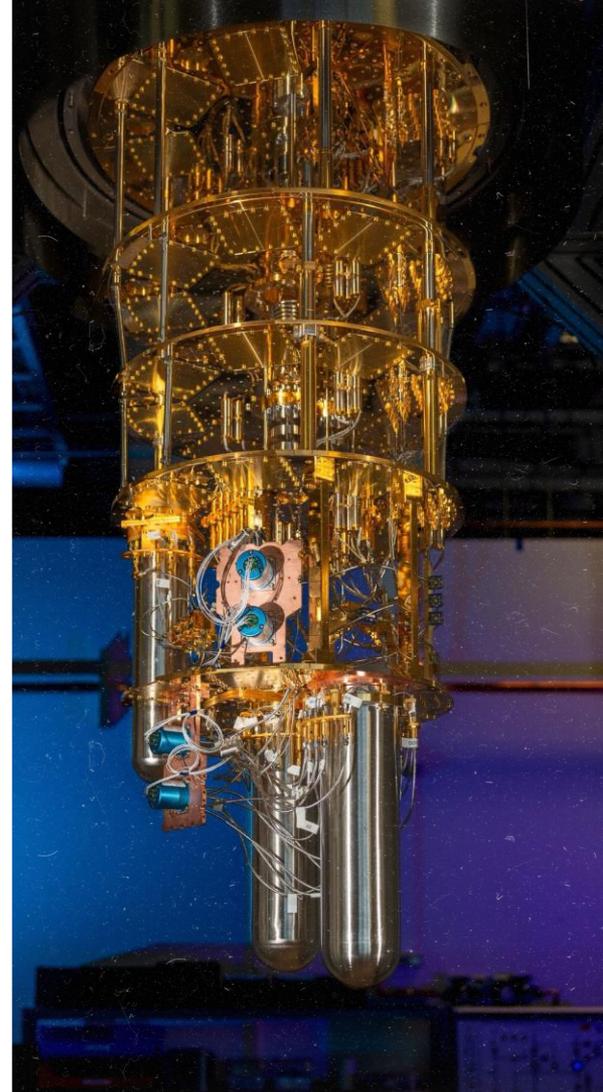
Raphael Cervantes,

Bianca Giaccone, Oleksandr Melnychuk, Sergey Kazakov, Ivan Nekrashevich,
Oleg V. Pronitchev Soka Suliman, Daniel Molenaar, Fabio Castañeda, Asher
Berlin, Sam Posen, Roni Harnik, Crispin Contreras-Martinez, Yuriy Pischalnikov,
Roman Pilipenko, Anna Grassellino



U.S. DEPARTMENT
of ENERGY

Office of
Science



Superconducting Quantum Materials and Systems Center



Credit: A. Grassellino

The Quantum Garage

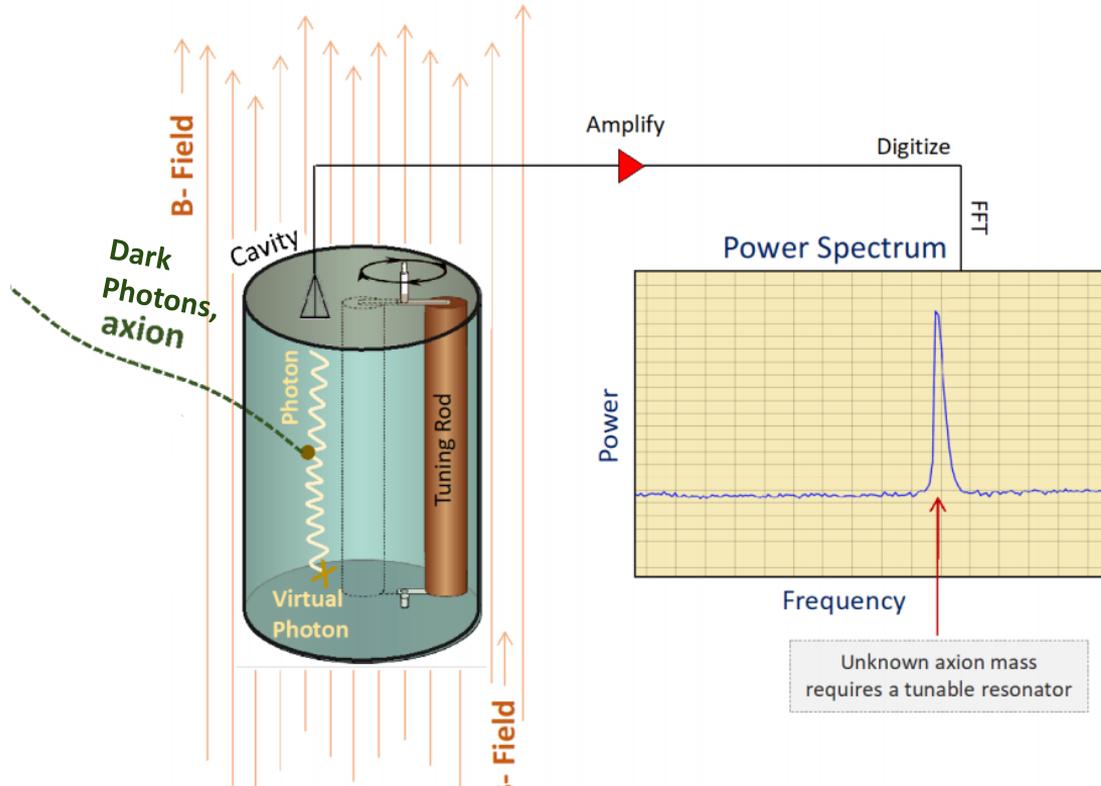
"If someone is to progress, we need is the ability to experiment, honesty in reporting results, and intelligence to interpret the results."
—Richard Feynman



Hosted at Fermilab. Interdisciplinary QIS center comprising of experts in materials, quantum devices, SRF cavities, HEP, and algorithms.

SRF Cavities $Q_L \sim 10^9$, transmon qubit $T_1 > 100 \mu\text{s}$.

Sikivie Haloscope Search for Axion and Dark Photon Dark Matter



$$P_S \propto B^2 V_{eff} Q_L$$

if $Q_L \ll Q_{DM}$

Credit: C. Boutan

Microwave cavities can be used to detect dark photons and axions.

Dark photon searches don't need B-field.

Looking for $< 10^{-24}W$ signal over wide range of frequencies.

Excruciatingly slow. Everyone wants to go faster.

Motivation for superconducting cavities. Instantaneous scan rate is proportional to Q_L

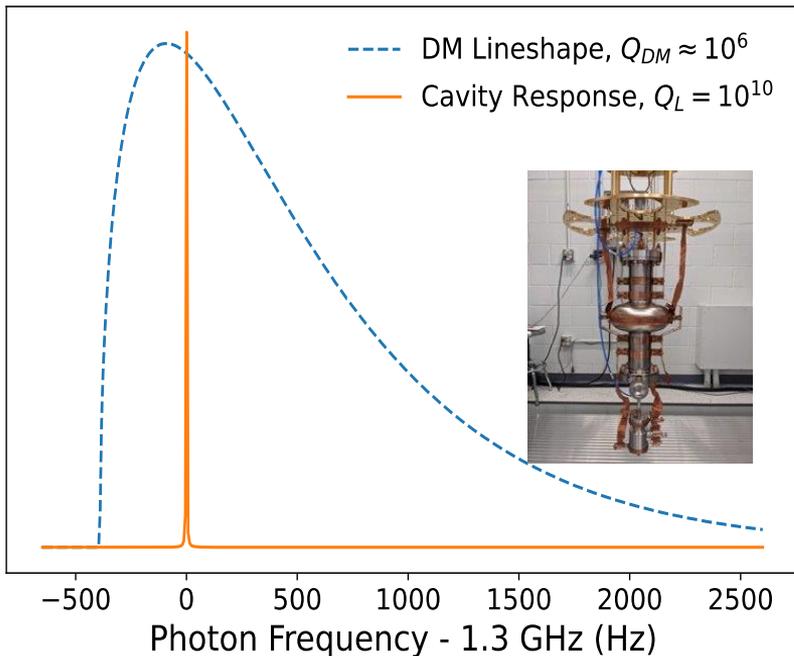
$$\frac{df}{dt} \sim Q_L Q_{DM} \left(\frac{\eta \chi^2 m_{A'} \rho_{A'} V_{eff} \beta}{SNR T_n (\beta + 1)} \right)^2$$

Even if $Q_L \gg Q_{DM}$

- Signal power $P_S \propto \min(Q_L, Q_{DM})$, but care more about SNR.
- Noise power reduces with Q_L .
- Tuning steps $\Delta f \propto \Delta f_{DM}$. Cavity sensitive to distribution of possible DM rest masses.

Caveats:

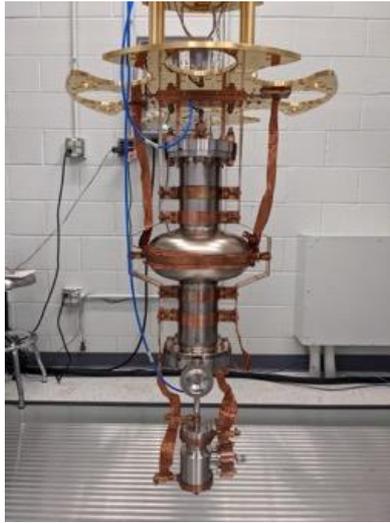
- operational time and complexity
- minimum time needed to resolve narrow signals.
- Miss non-virialized DM



Phys. Rev. D **110**, 043022

SERAPH: SupERconducting Axion and Paraphoton Haloscope

Family of SQMS SRF haloscope experiment. Name works on different levels.



SRF



Seraphine

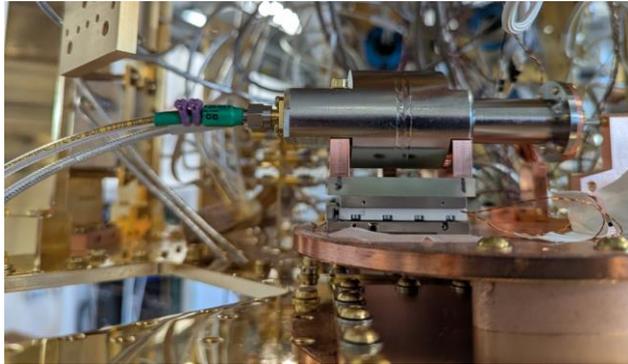
Edited by T. Hucks.



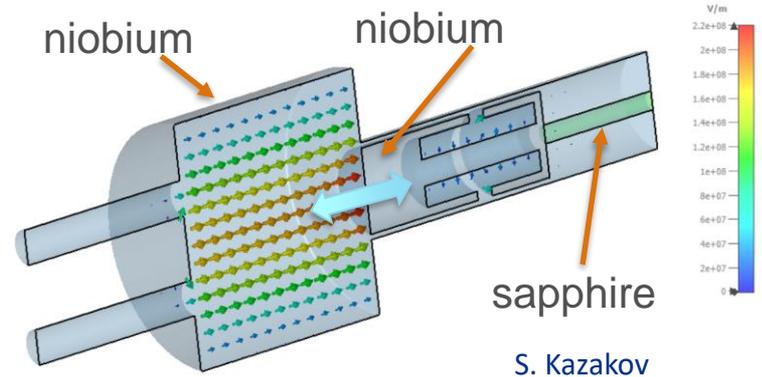
Sir Raph(ael)

SERAPH: Widely tunable 4-7 GHz superconducting cavity

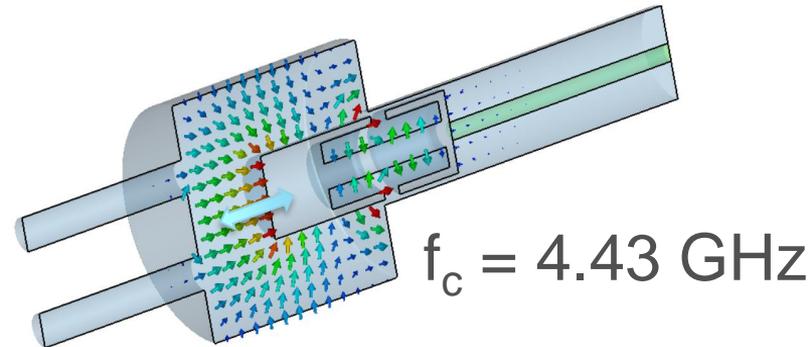
Niobium cavity. Niobium tuner is also RF choke held in place with sapphire rod. Originally designed to characterize dielectric losses in the context of transmon qubits, the design was readapted for dark matter searches.



Plunger cavity installed in fridge.

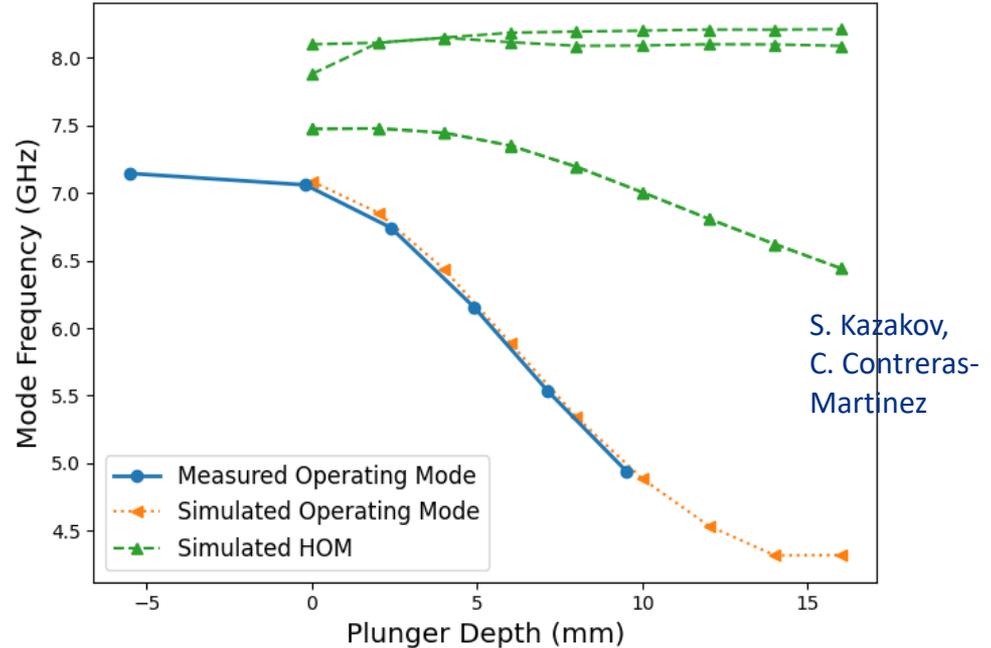
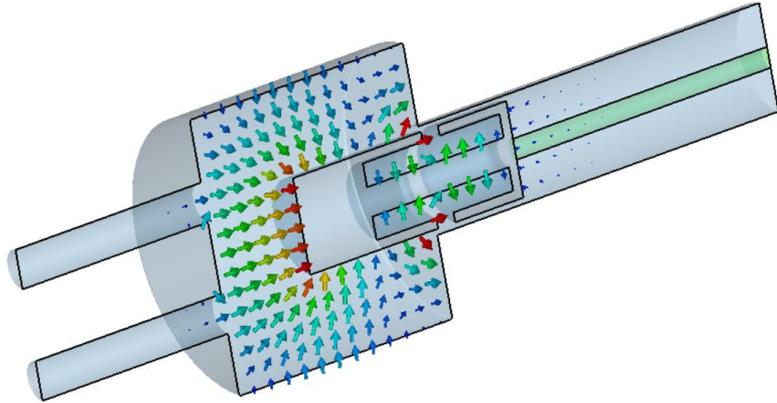


$$f_c = 7.08 \text{ GHz}$$



$$f_c = 4.43 \text{ GHz}$$

Simulated modes vs Measured Modes in Liquid Helium



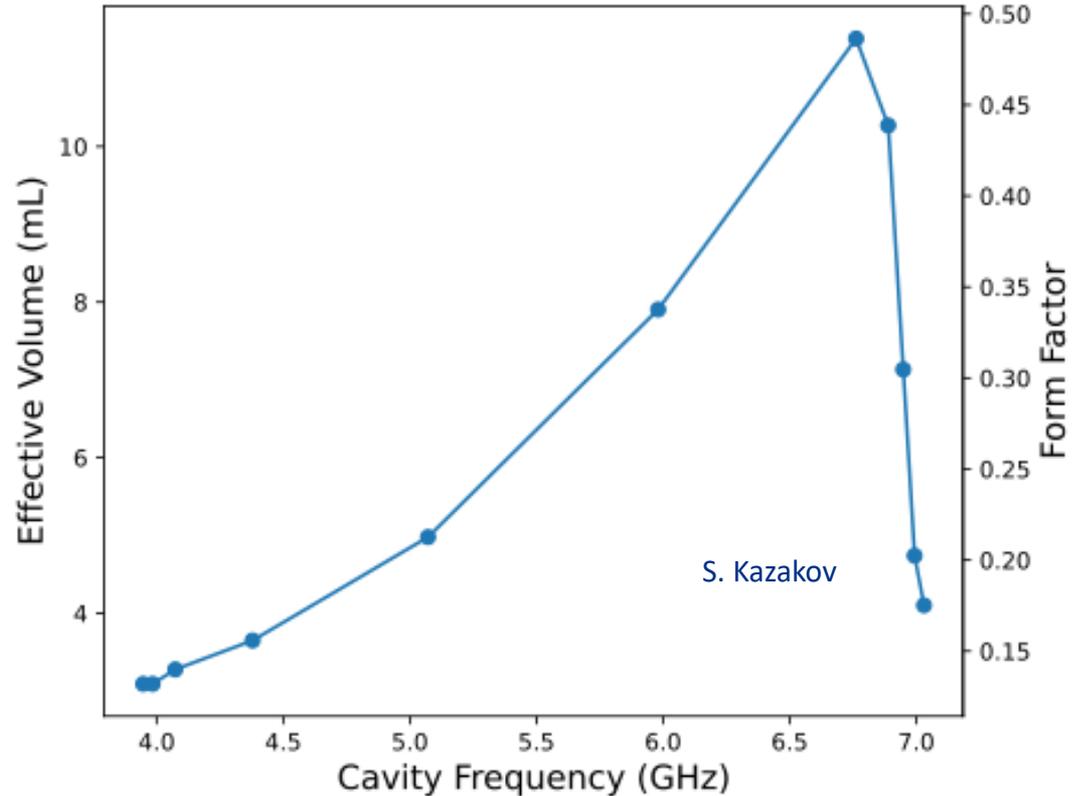
S. Kazakov,
C. Contreras-
Martinez

Straightforward tuning. No mode crossings. Good agreement between measurement and simulation.

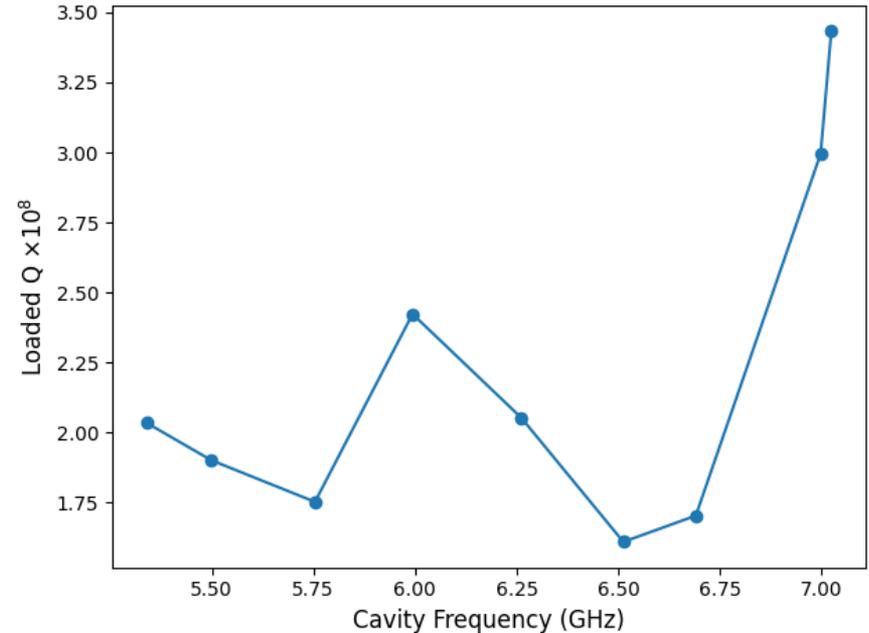
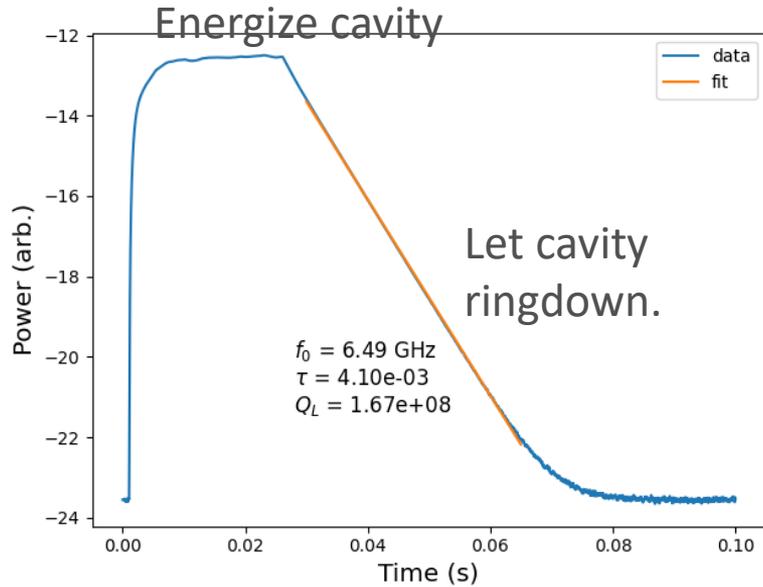
Simulated effective volume

$$V_{\text{eff}} = \frac{1}{3} \frac{|\int dV E_z|^2}{\int dV |\mathbf{E}|^2}$$

Too small for QCD
Axion sensitivity.
Need to optimize
volume at cost of
mode crossings.



Measured Unloaded Q with decay measurement in LHe (1.4 K)

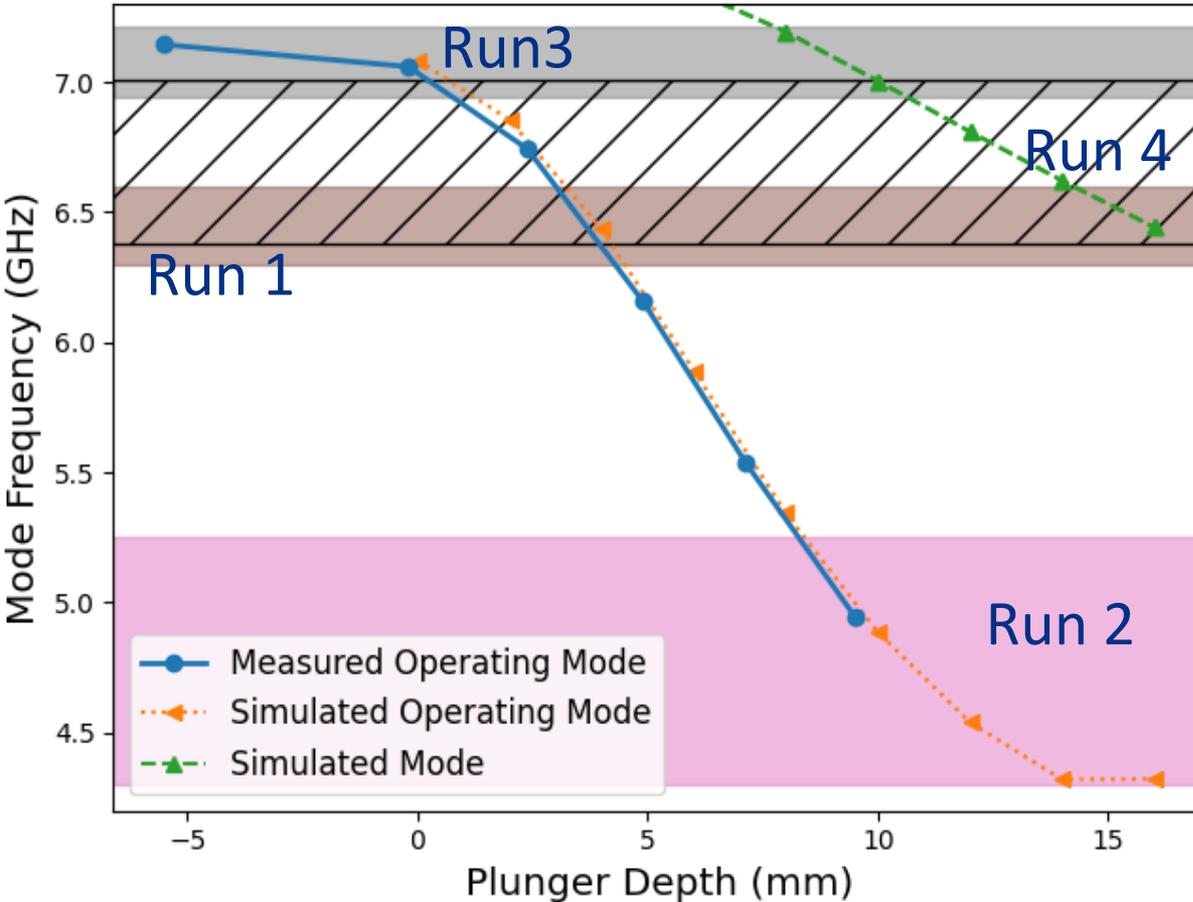


Limited range because sapphire rod broke during assembly.

Weakly coupled: $Q_L \approx Q_0$.

Basic cavity processing. Surface resistance could be reduced with more optimization.

Plunger Cavity in the Fridge. Tuning is proving difficult.



Run 1 (6.3-6.6): Coax and heatsink braid push against piezo tuning. RF coupling too low.

Run 2 (4.3-5.25): Misalignment from multiple cooldowns. Plunger hits cutoff region wall.

Run 3(6.94-7.2): Added thermal strapping. Added too much mechanical tension for piezo.

Run 4(6.38-7.01(+)): Removed some thermal strapping. More range, but still not enough.

Piezo tuning requirements and strategy.

Requirements:

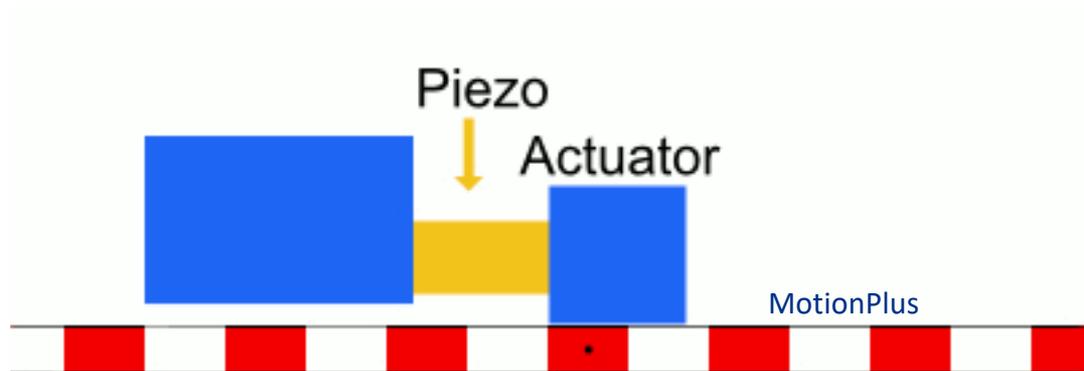
- 20 mm travel range.
- 10 nm (~kHz) resolution.
- Low thermal dissipation.
- 500 grams max Load.
- Low temperature. High Vacuum.

Strategy:

- Moving the cavity instead of the plunger to mitigate “hot rod.” Piezo installed on Mixing Chamber Stage.
- DC tuning steps to achieve 10 nm tuning resolution, up to ~100 V for ~100 kHz tuning. Very low power dissipation (~mK heating of cavity).
- Then activate AC ramp to move large distance. Lots of dissipation.

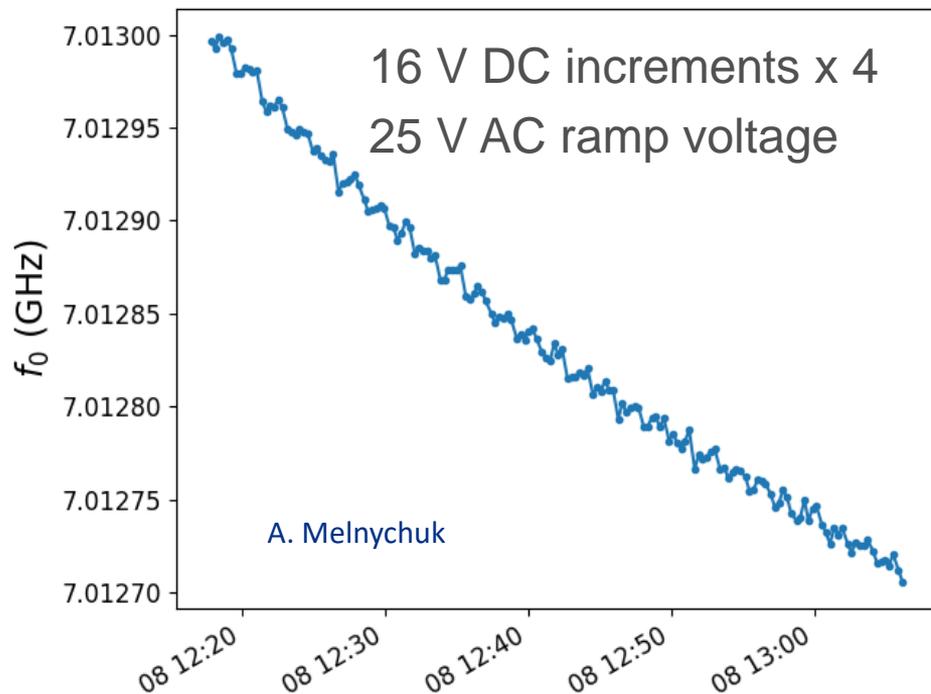
Chose Attocube ANPx341/LT/HV - linear x-nanopositioner.

Stick and slip mechanism.

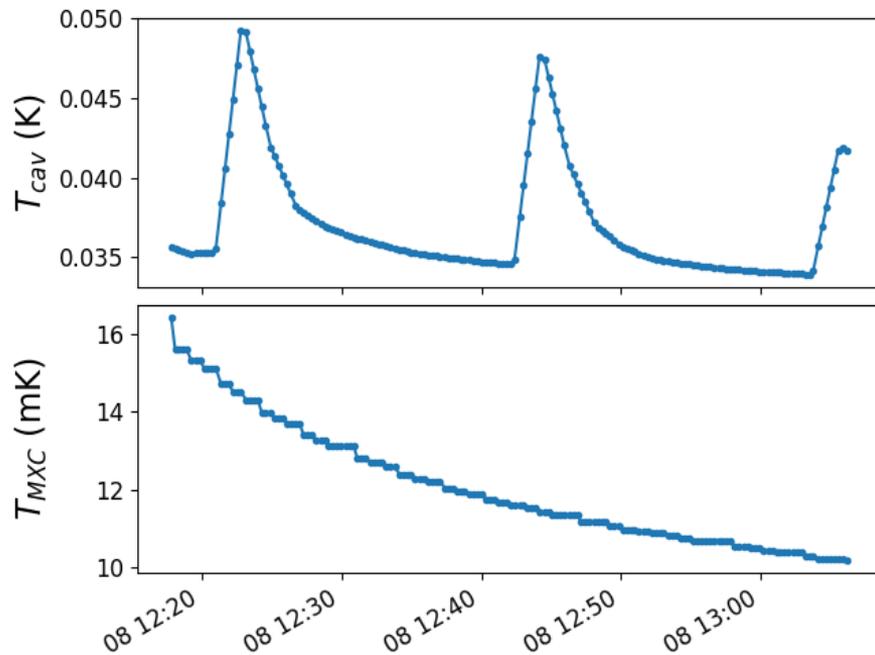


Piezo tuning. Sometimes smooth with modest impact on cavity temperature

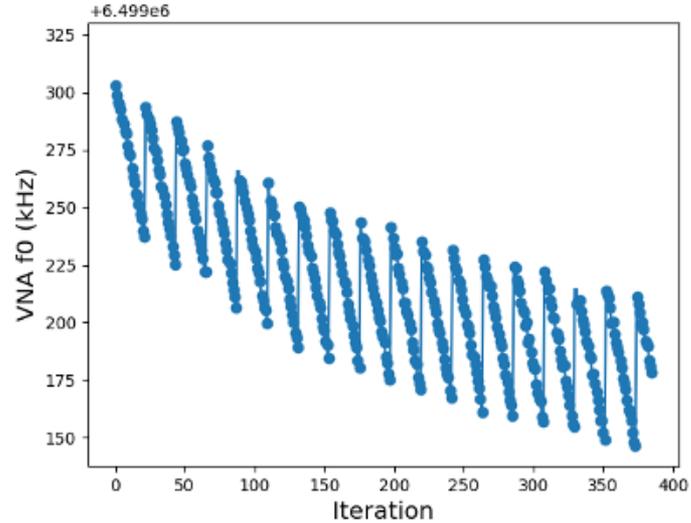
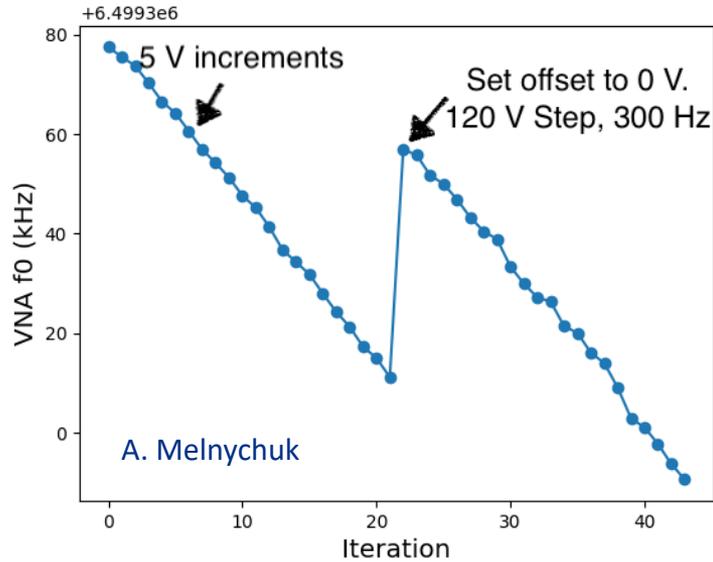
Cavity tuning



Cavity and Fridge temperatures “manageable”



Piezo tuning. Can see mechanics push back against the piezo.

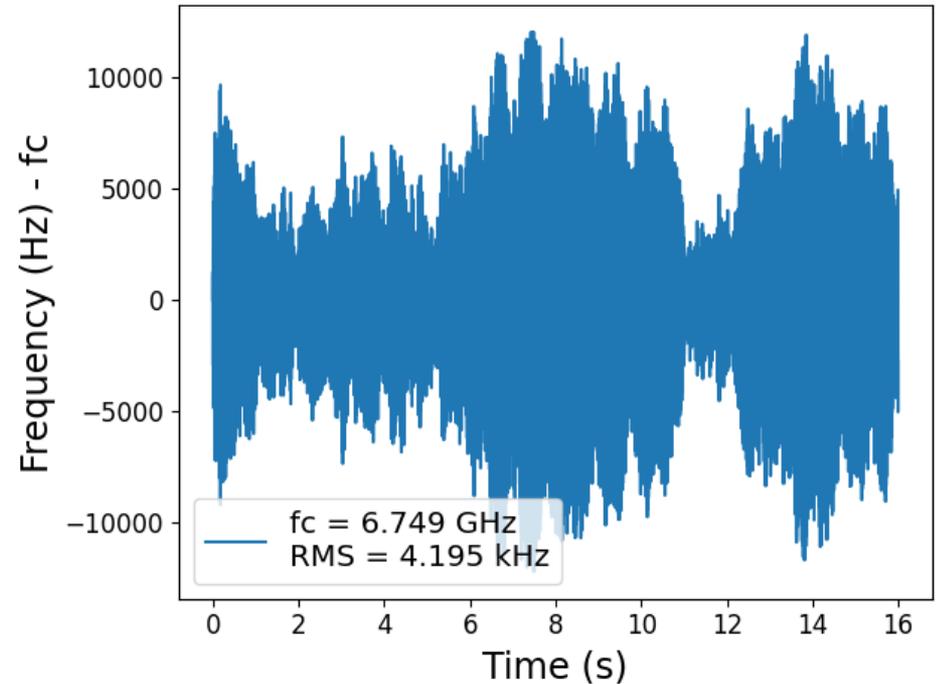
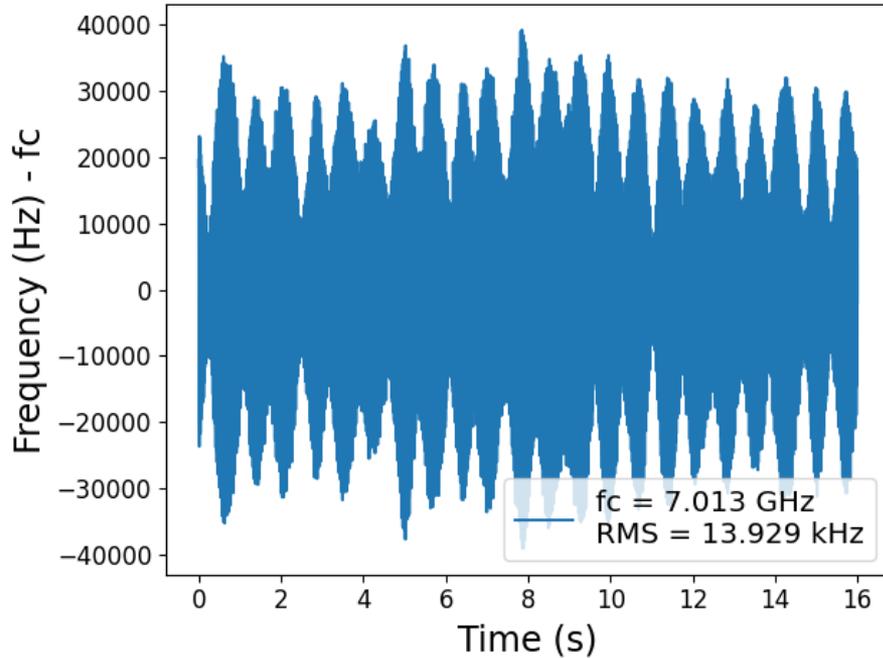
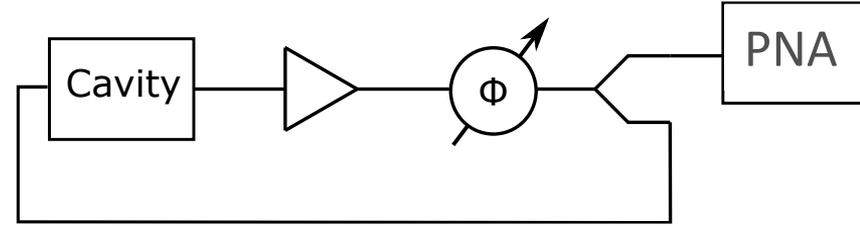


Slip part of the stick-slip not slipping enough.

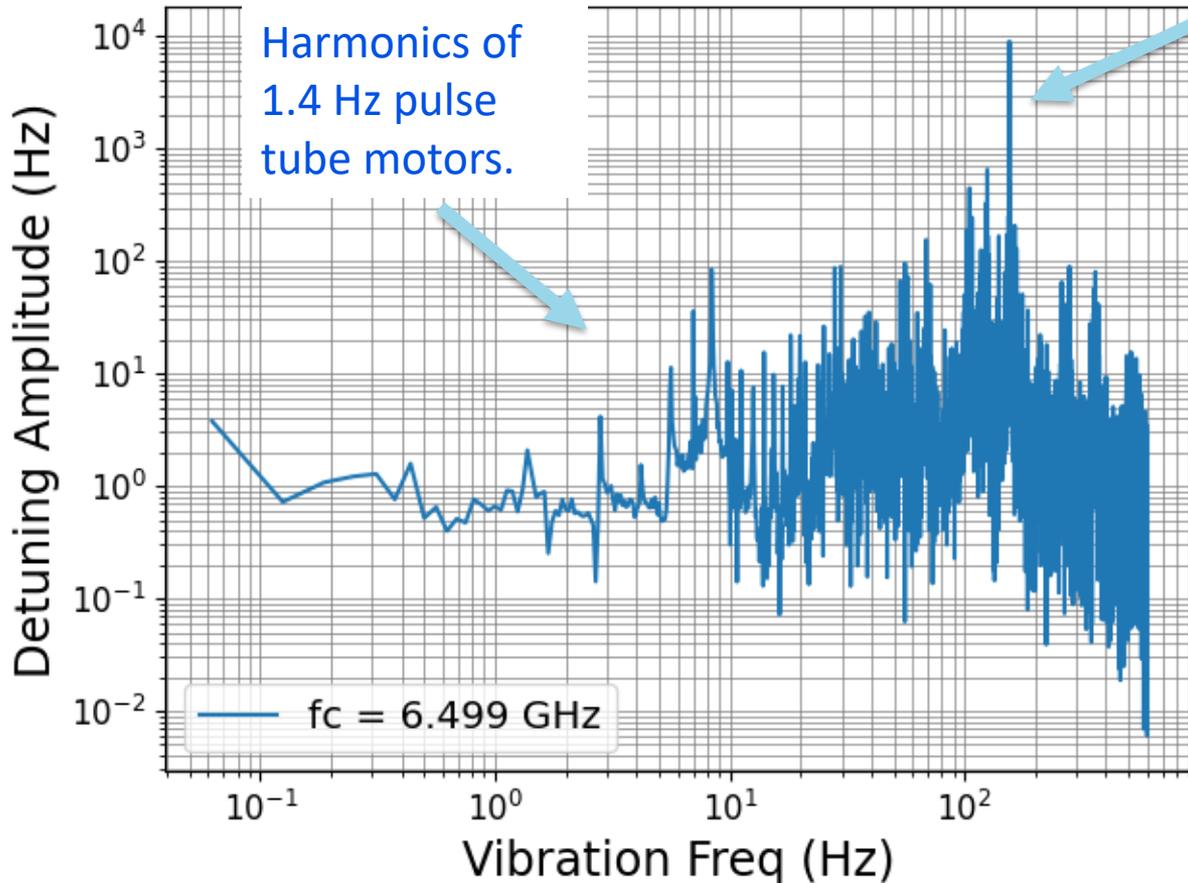
1. Need to better optimize thermal straps for smoother motion.
2. Piezo has probably deteriorated after multiple cooldowns and abuses.

Plunger cavity microphonics

Measure with self-excited loop and phase noise analyzer.



Take FFT of microphonics to understand source

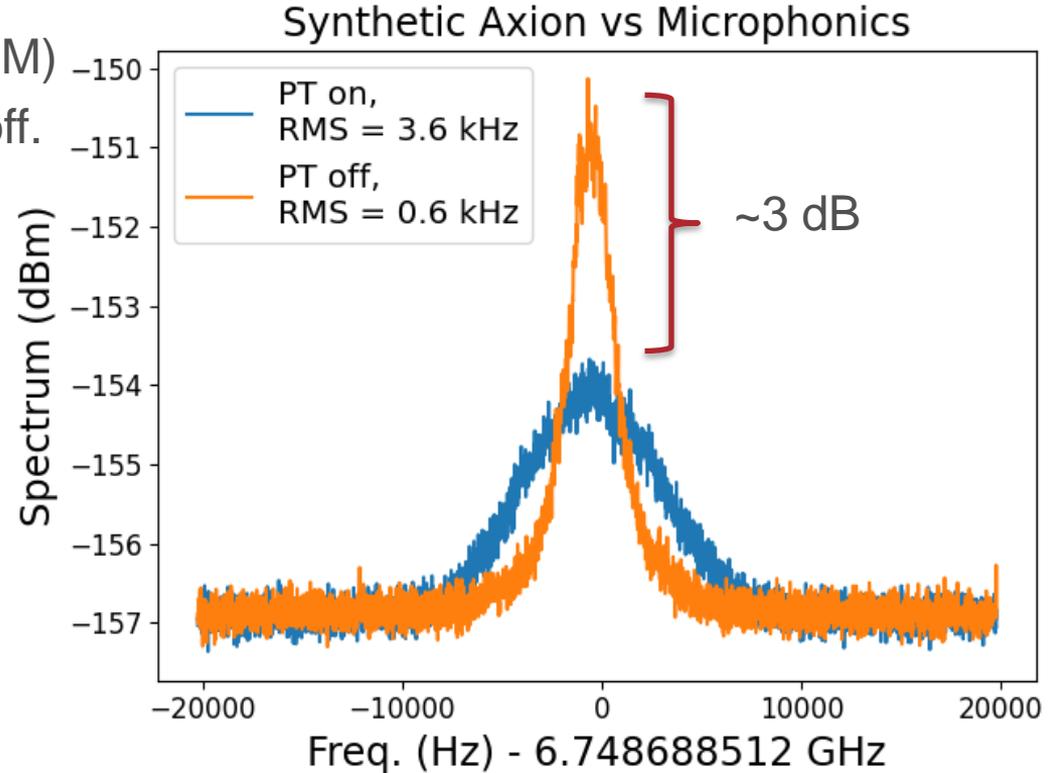
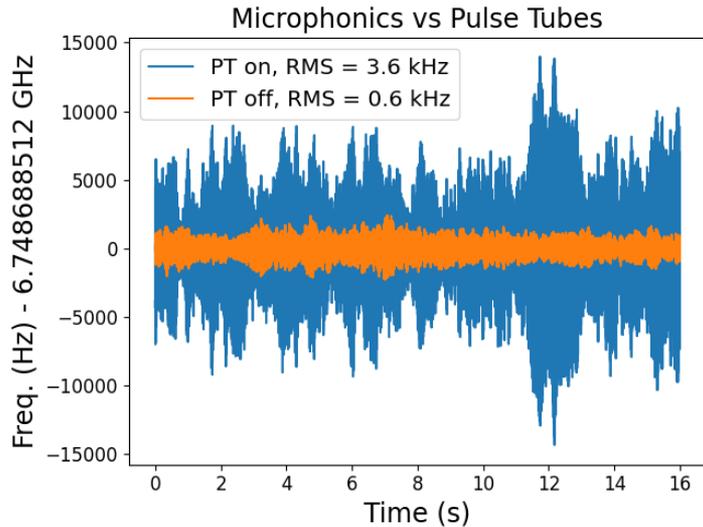


Improvements:

- Make plunger rod stiffer.
- Mount cavity on vibration isolation.
- Control phases between pulse tubes.
- Separate pulse tubes from cryostat.
- Stiffen cryostat frame.

Measuring effect of microphonics on dark matter signal

1. Inject $Q \sim 10^6$ synthetic signal into cavity
2. Measure cavity spectra (look for DM)
3. Compare with pulse tube motors off.



Dark Photon Dark Matter Search

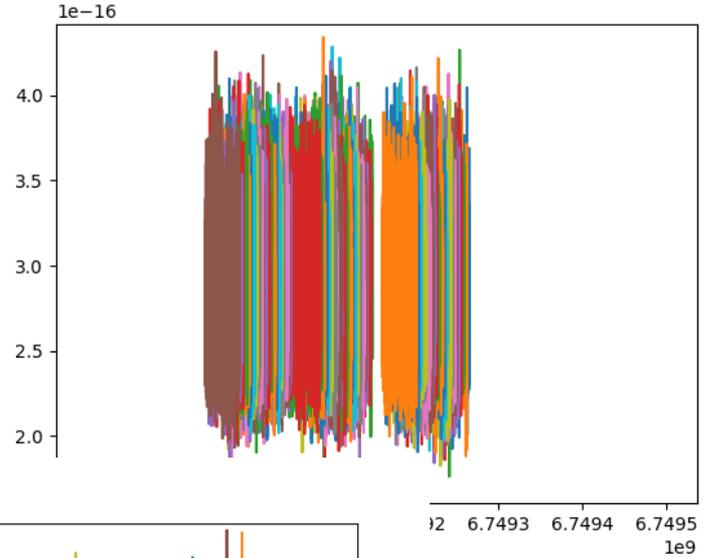
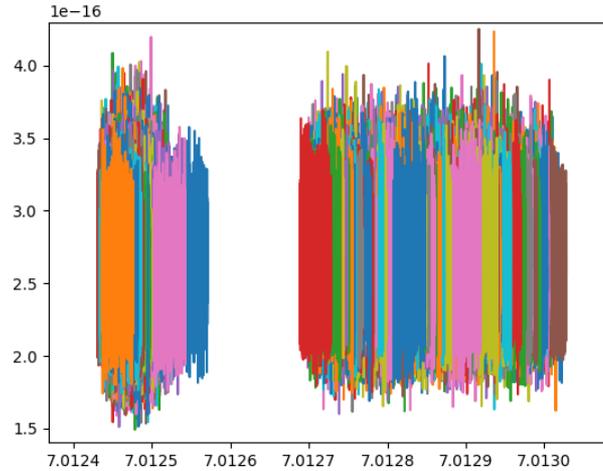
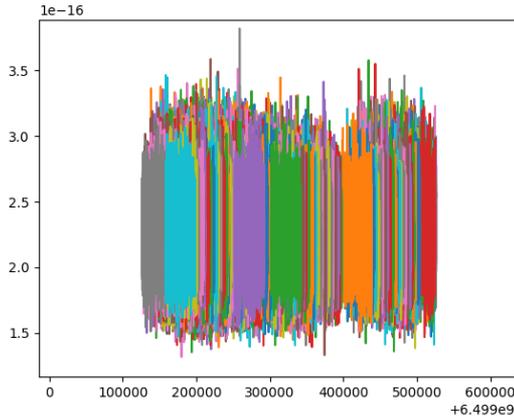
Strongly overcoupled: $Q_L \sim 10^7$

$T_{\text{sys}} \sim 1 \text{ K}$

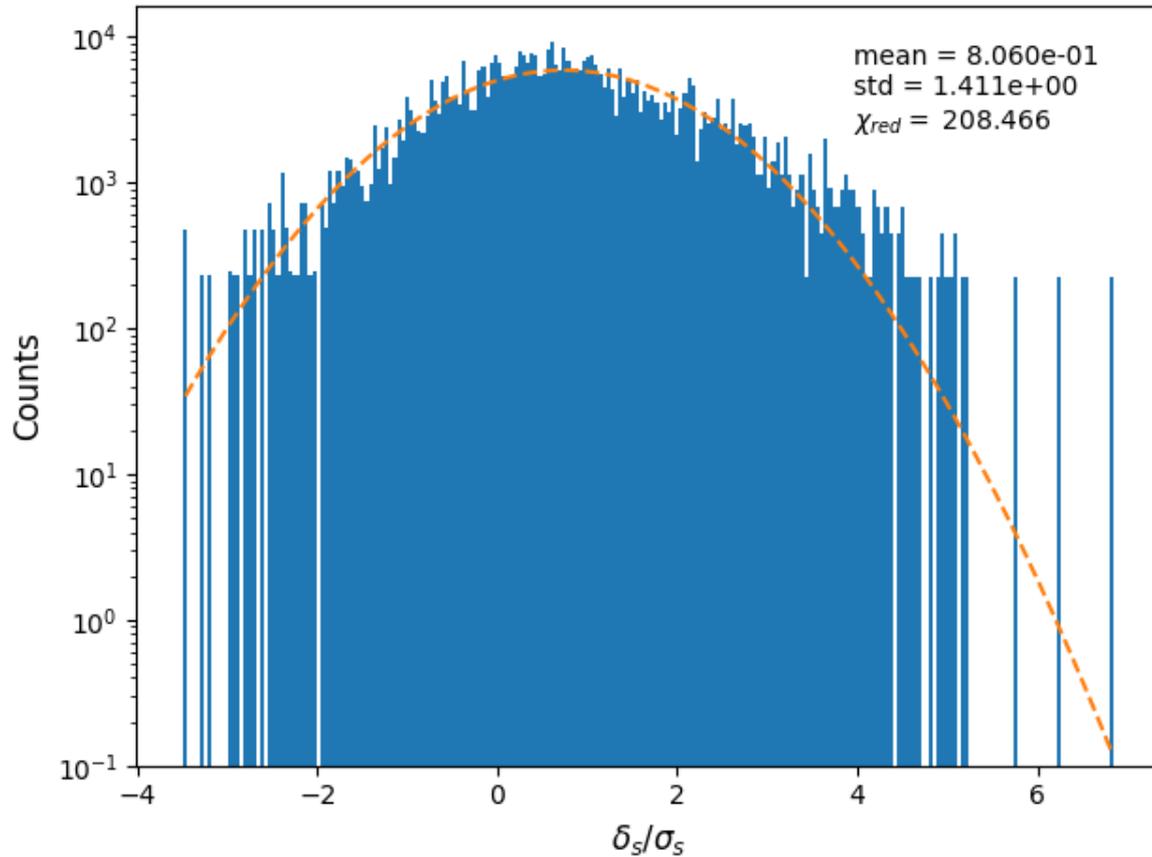
Taken over 1.5 days.

Prioritized demonstrating tunability.

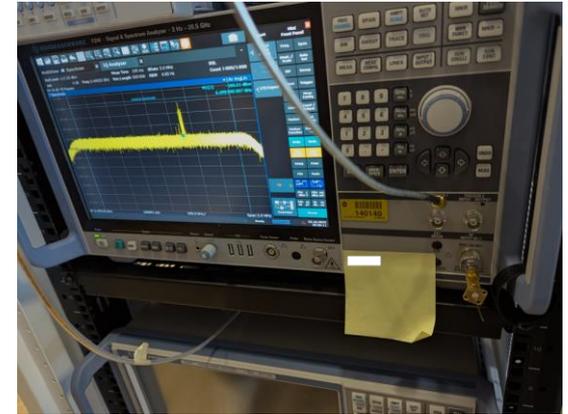
And here are some spectra



Spectra mostly white noise.



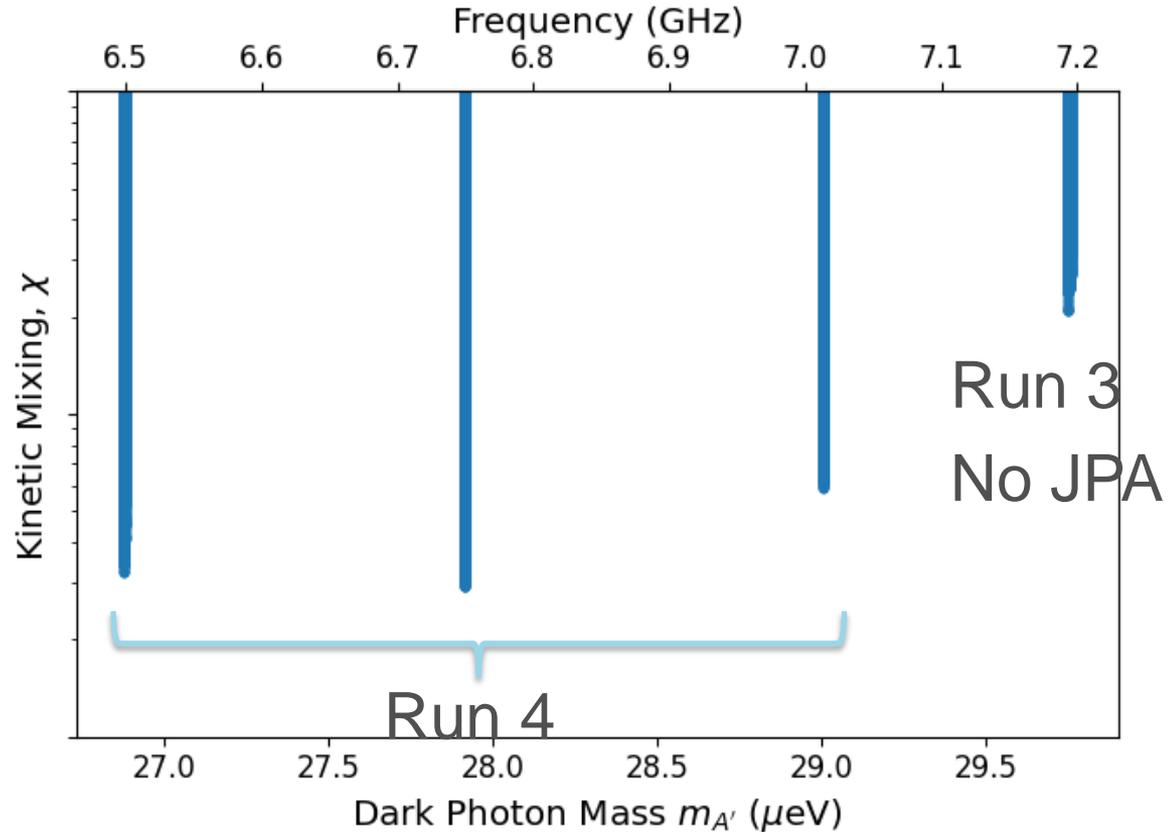
Candidates
are just RFI.



Antenna connected to SA

Dark Photon Dark Matter Limits in progress

Intentionally not showing other experiments and y-axis as analysis is ongoing.



Other Exciting SQMS Physics and Sensing

See S. Zorzetti

National Initiatives: QIS

Oct 8, 2025, 9:10 AM

- Type 2 superconductors for axion searches. Phys. Rev. Applied **20**, 034004 (2023)
- Implementing photon counting to subvert SQL limit
- Multimode SRF cavities for low mass axion searches (SHADE) and high-frequency gravitational waves (MAGO)
- Light-shining-through-wall experiments with Dark-SRF. Phys. Rev. Lett. **130**, 261801 (2023)
- Fundamental tests of quantum mechanics. Melnychuk, et al., Phys. Rev. D **112**, 012020 (2025)

The people

Scientists: Bianca Giaccone, Oleksandr Melnychuk, Ivan Nekrashevich, Asher Berlin, Sam Posen, Roni Harnik, Crispin Contreras-Martinez, Yuriy Pischalnikov, Anna Grassellino

Students: Soka Suliman, Daniel Molenaar, Fabio Castañeda

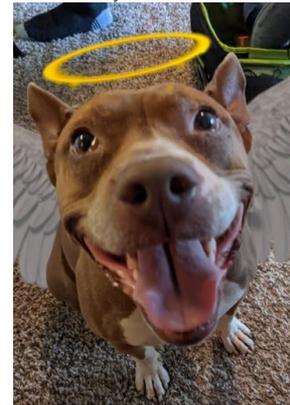
Engineers: Sergey Kazakov, Oleg V. Pronitchev, Akanksha Mishra, Roman Pilipenko, Tim Ring, Fumio Furata, Grzegorz Tatkowski, Matthew Dubiel, Michael Foley

Technicians: Tedd III, Mackenzie Ring, Dominic Baumgart, Damon Bice, Abraham Diaz, David Burke, Davida Smith

Machinists: Eddie Piezchala

Summarize

- Microwave cavities are key tools for looking for wavelike dark matter (axions, dark photons) from around ~ 100 MHz—20GHz.
- Superconducting cavities \rightarrow higher Q \rightarrow more parameter coverage.
- Demonstrated widely tunable SRF cavity, 4-7 GHz with $Q_0 \sim 10^8$
- Struggling against microphonics and tuning reliability. V_{eff} and thermal performance need improvement to improve sensitivity.
- Preliminary dark photon search accomplished. Data analysis and systematic studies ongoing.



Seraphine
the mascot.

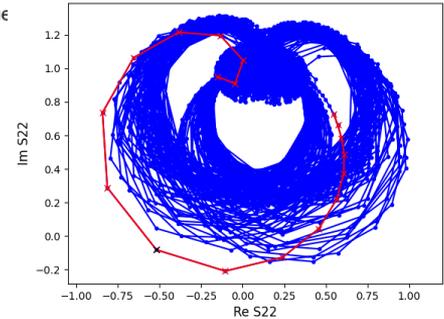
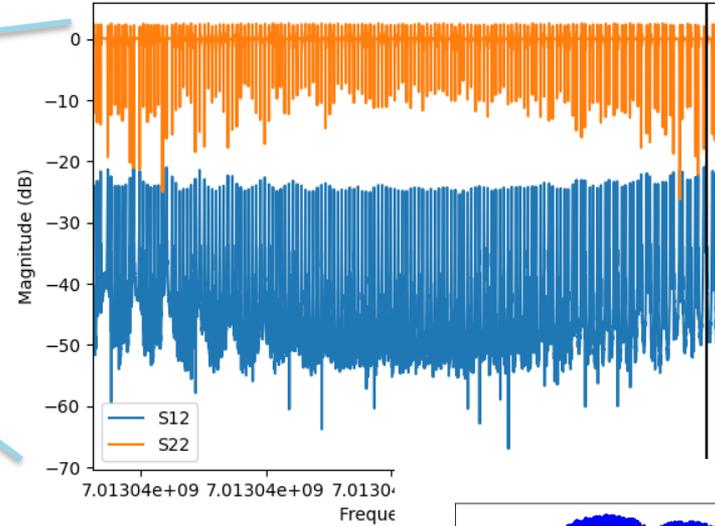
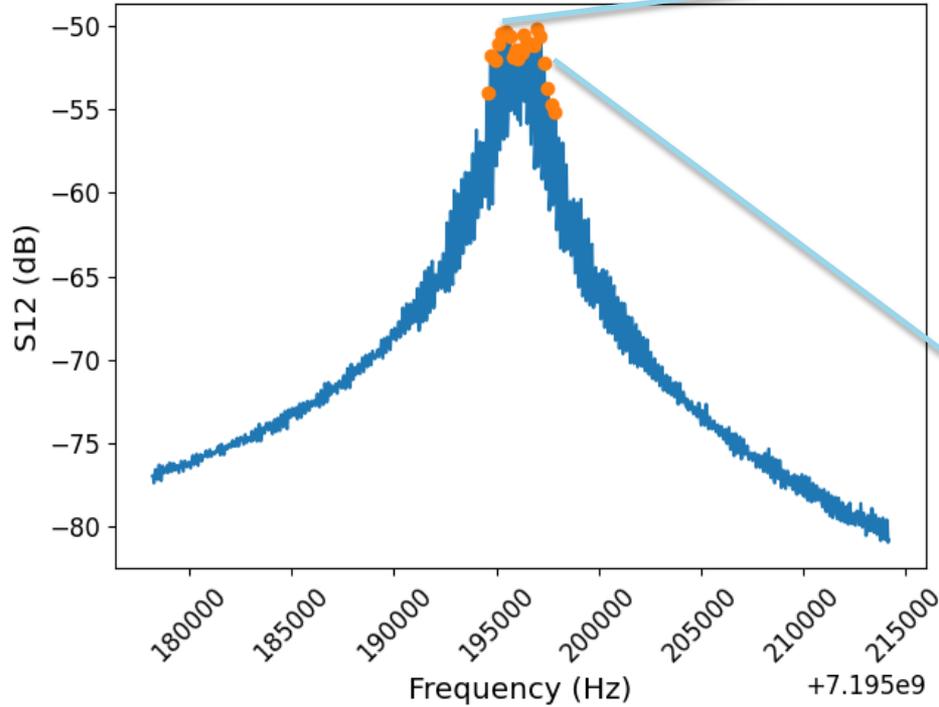
**WE DO THIS
NOT BECAUSE
IT IS EASY,
BUT BECAUSE
WE THOUGHT
IT WOULD BE EASY**

THANK YOU



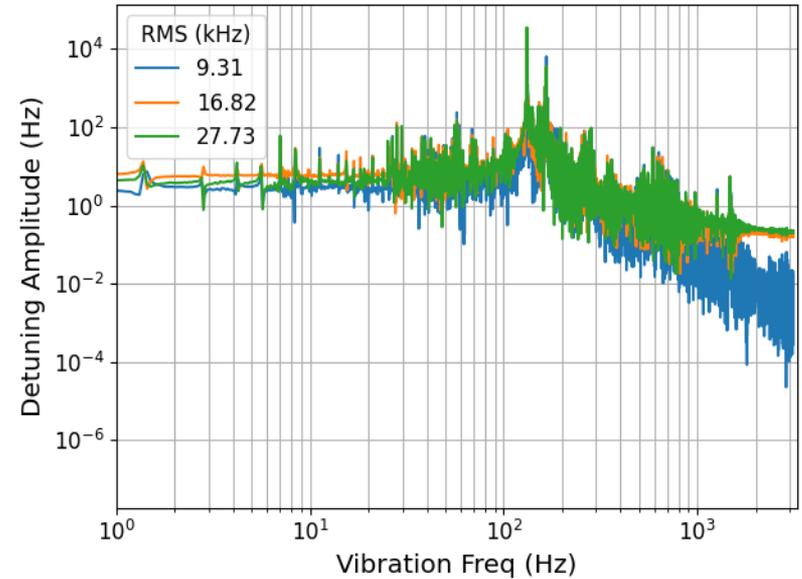
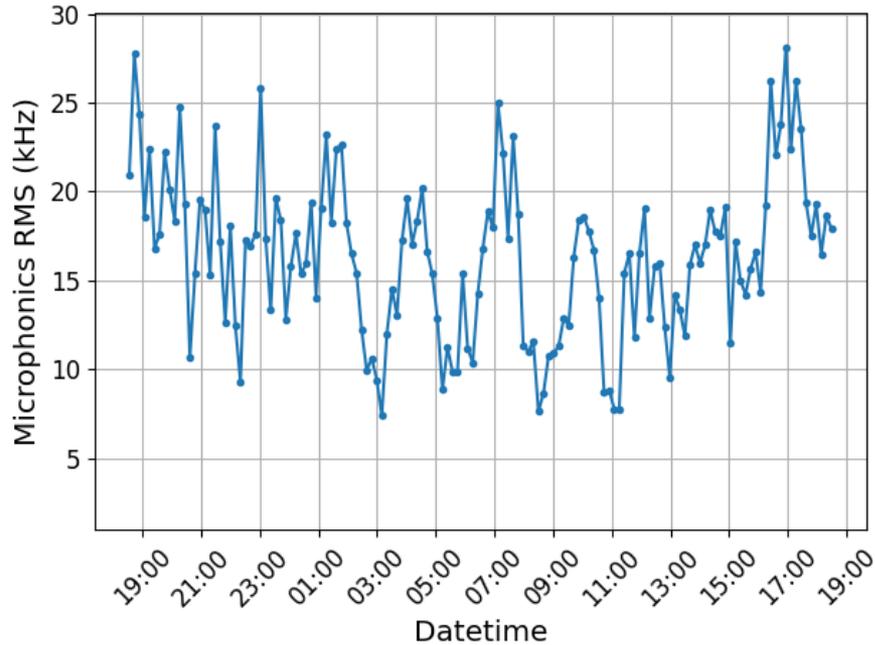
This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

Your Haloscope on Microphonics



VNA sweeps harder to interpret. More tricks to characterize cavity and systematics.

24 hour microphonics measurement at $f_c \sim 7$ GHz



RMS varies from 4 kHz to 27 kHz throughout the day.

Spectral properties don't seem to change, just amplitude.

Maybe because of 5 fridges running simultaneously + random phases between pulse tubes.