FERMILAB-SLIDES-25-0256-SQMS

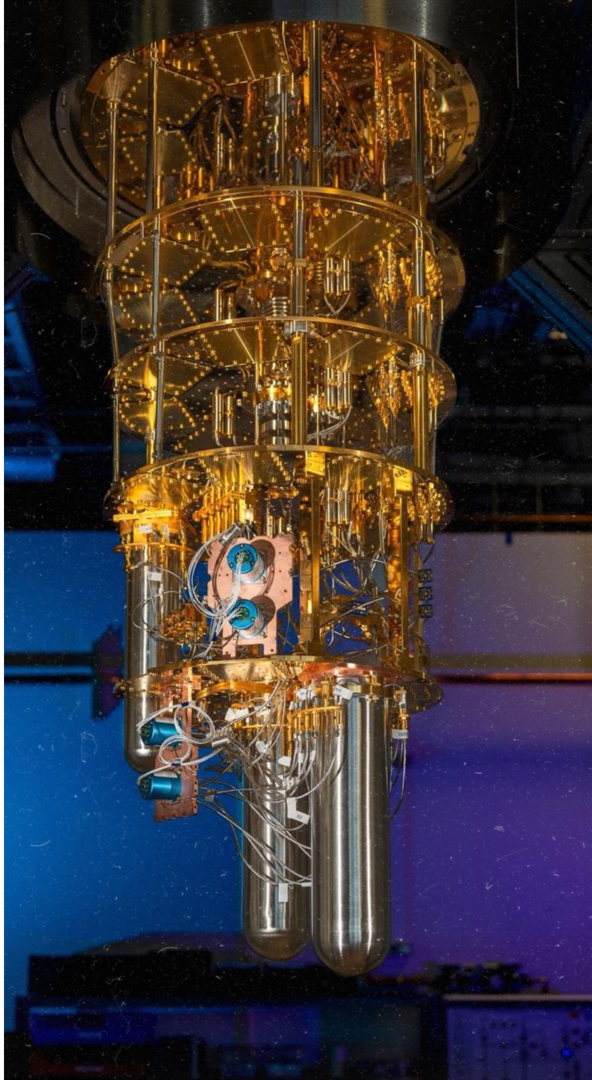
A Dark Photon Dark Matter Search with a Widely-Tunable SRF Cavity

20th Patras Workshop on Axions, WIMPs and WISPs

Sep 25, 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

SQMS Fermilab U.S. DEPARTMENT of ENERGY Office of Science

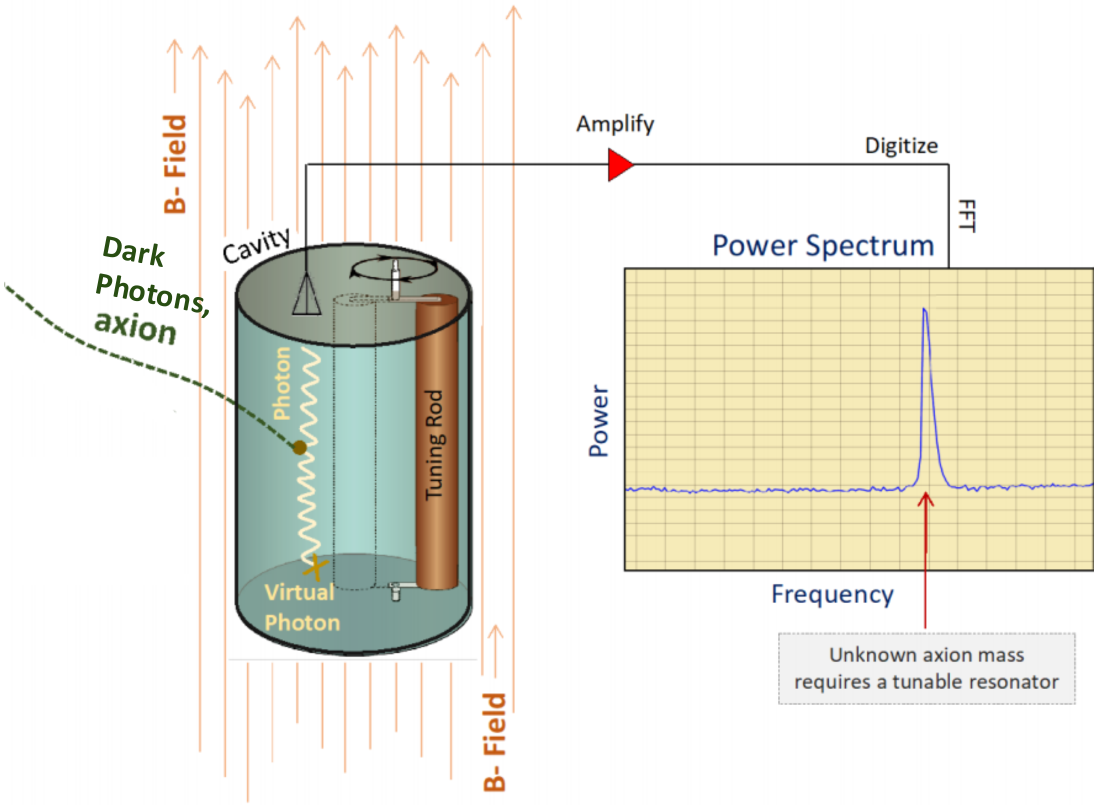


Superconducting Quantum Materials and Systems Center

Credit: A. Grassellino

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

Sikivie Haloscope Search for Axions and Dark Photons Dark Matter



Credit: C. Boutan

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

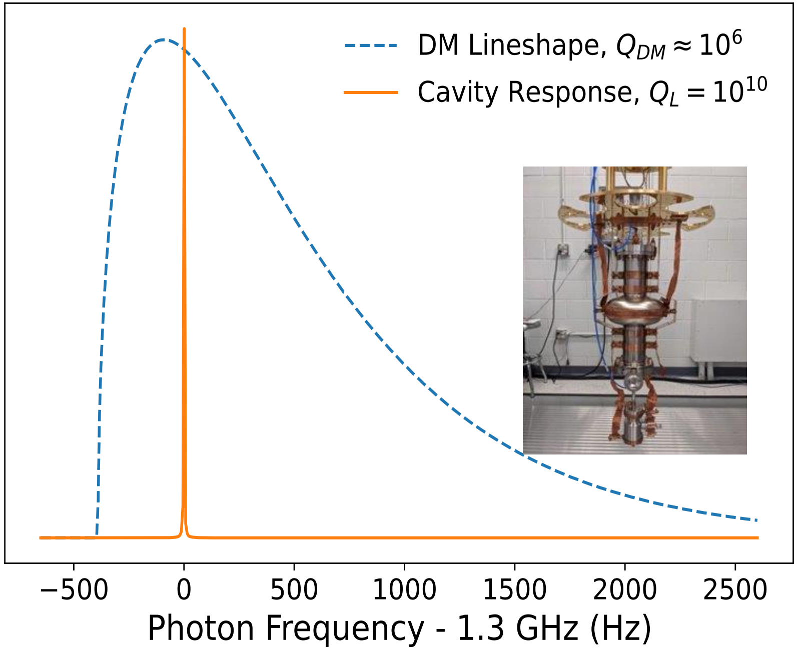
Dark photon searches don't need B-field.

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

$$\frac{\mathrm{d}f}{\mathrm{d}t} \sim Q_L Q_{DM} \left(\frac{\eta \chi^2 m_{A'} \rho_{A'} V_{eff} \beta}{\mathrm{SNR} T_n (\beta + 1)} \right)^2$$



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

Even if $Q_L \gg Q_{DM}$

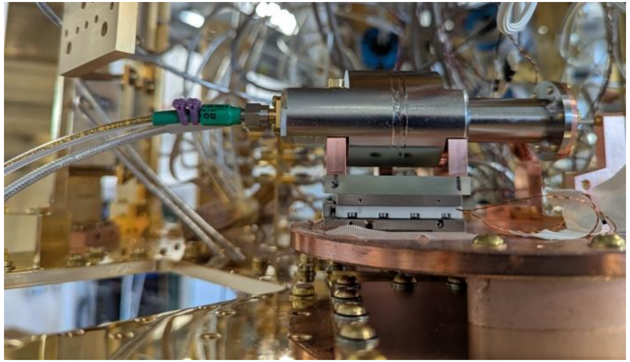
- Signal power $P_s \propto \min(Q_L, Q_{DM})$
- Noise power reduces with Q_L.
- Tuning steps $\Delta f \propto \Delta f_{DM}$. Cavity sensitive to distribution of possible DM rest masses.

Caveats:

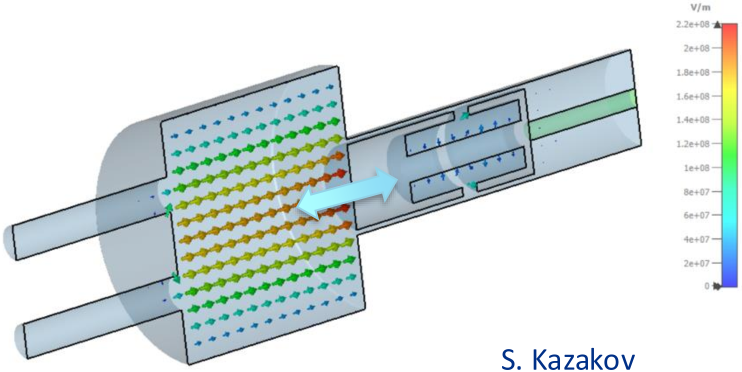
- operational time and complexity
- minimum time needed to resolve narrow signals.
- Miss non-virialized DM

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.

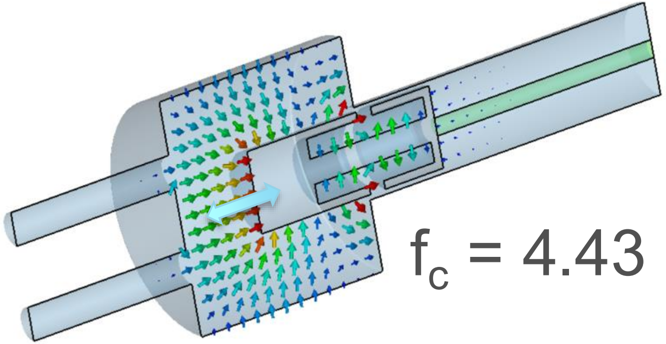


Plunger cavity installed in fridge.



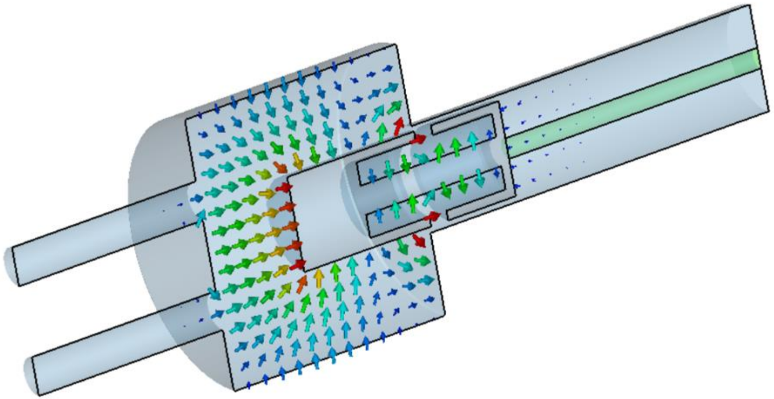
S. Kazakov

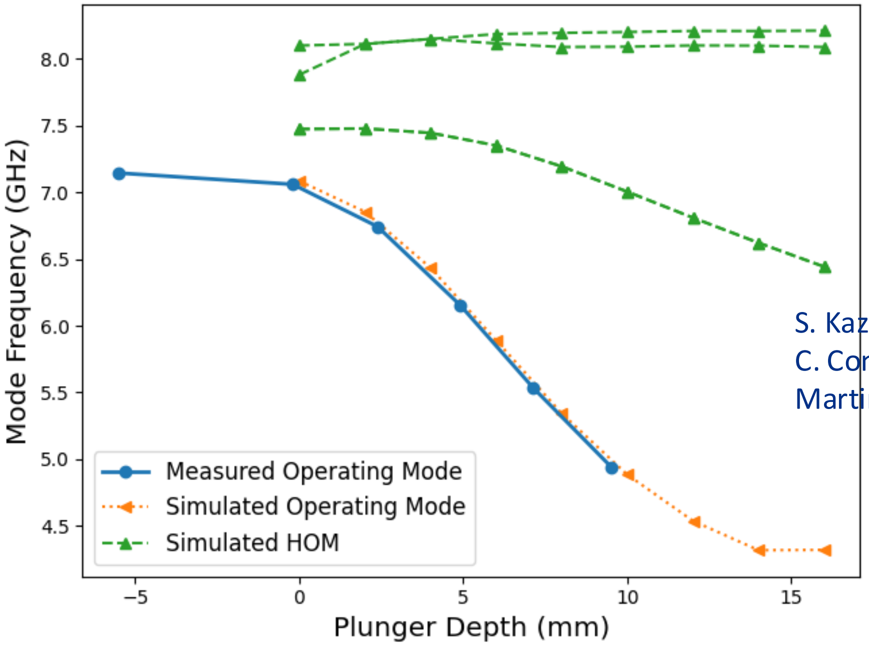
f_c = 7.08 GHz



f_c = 4.43 GHz

Simulated modes vs Measured Modes in Liquid Helium





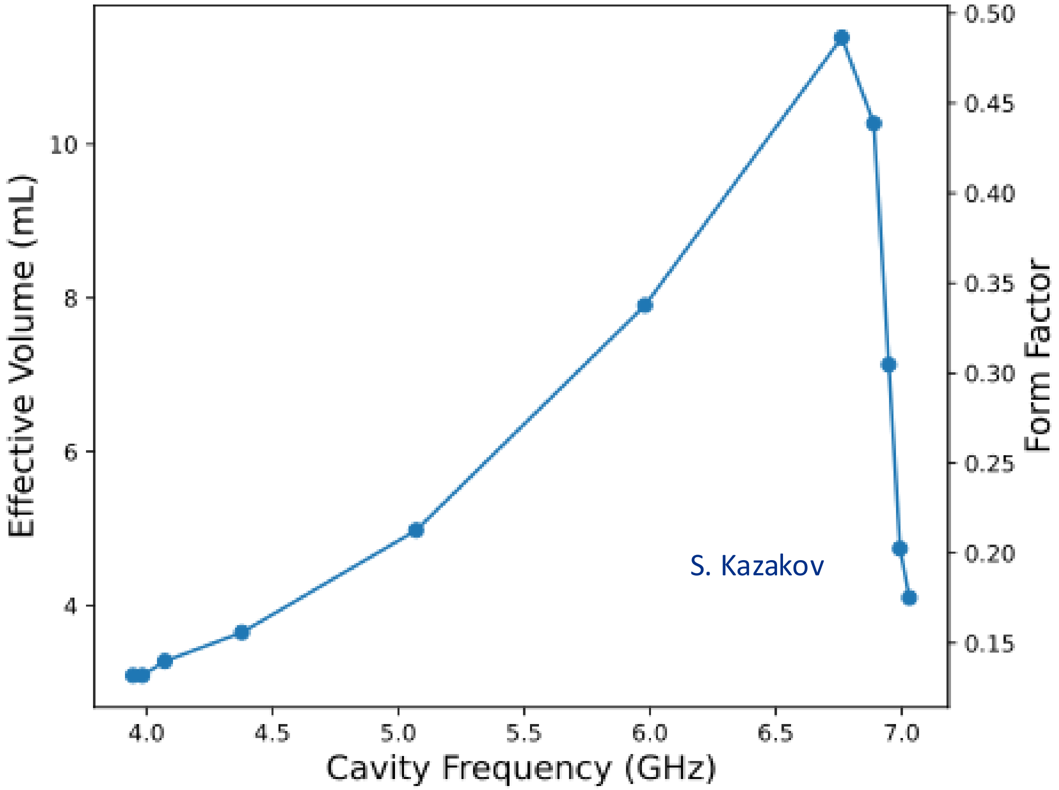
S. Kazakov,
C. Contreras-Martinez

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

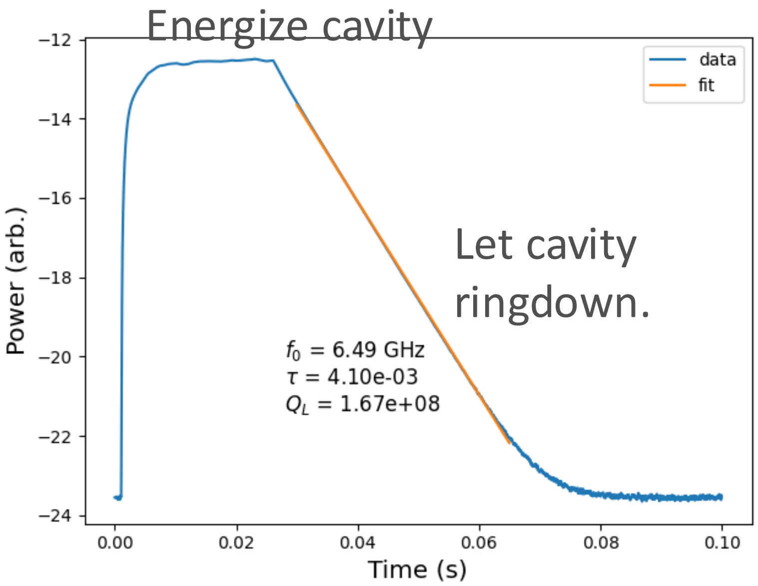
Simulated effective volume

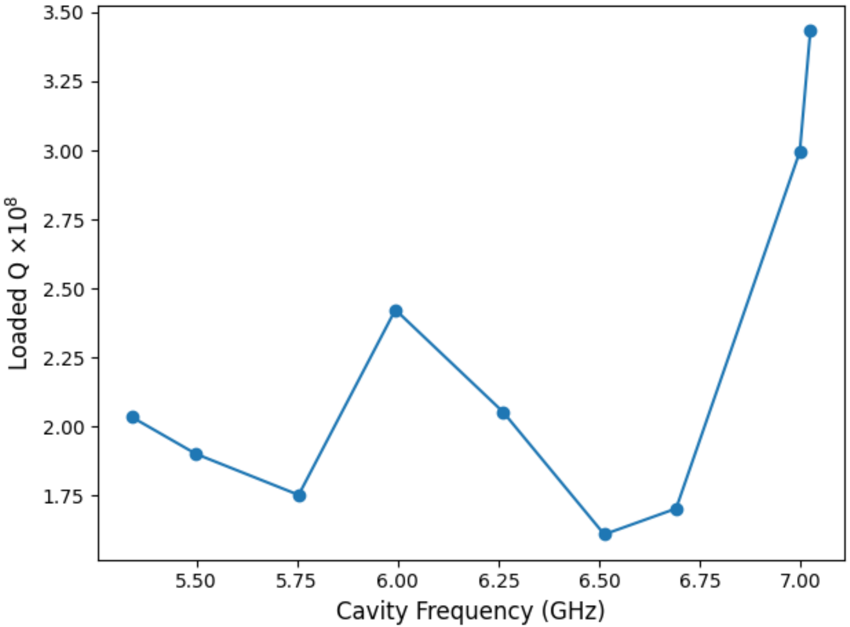
$$V_{\text{eff}} = \frac{1}{3}\frac{|\int dV\, E_z|^2}{\int dV |\mathbf{E}|^2}$$

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: QL ≈ Q0.

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

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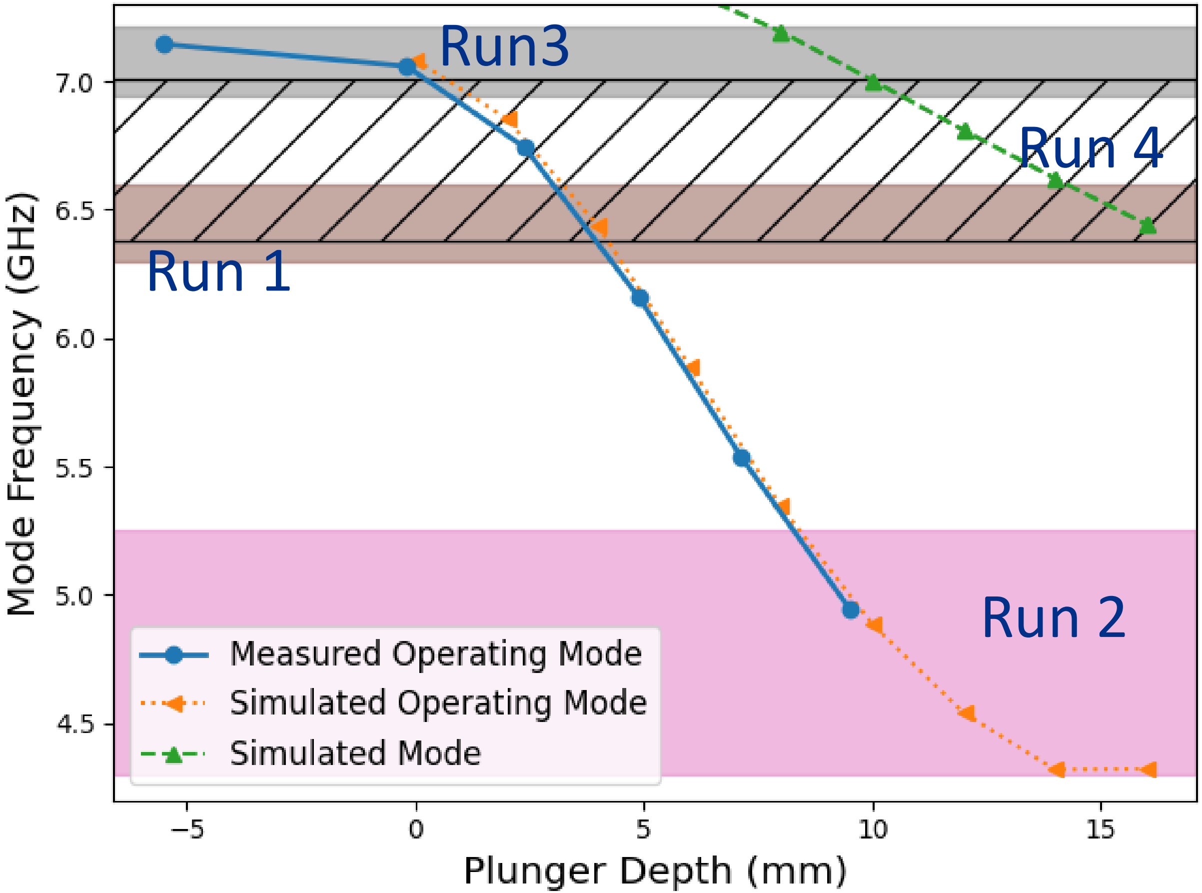
Plunger Cavity in the Fridge. Tuning is proving difficult.



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

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. Better, but still not enough.

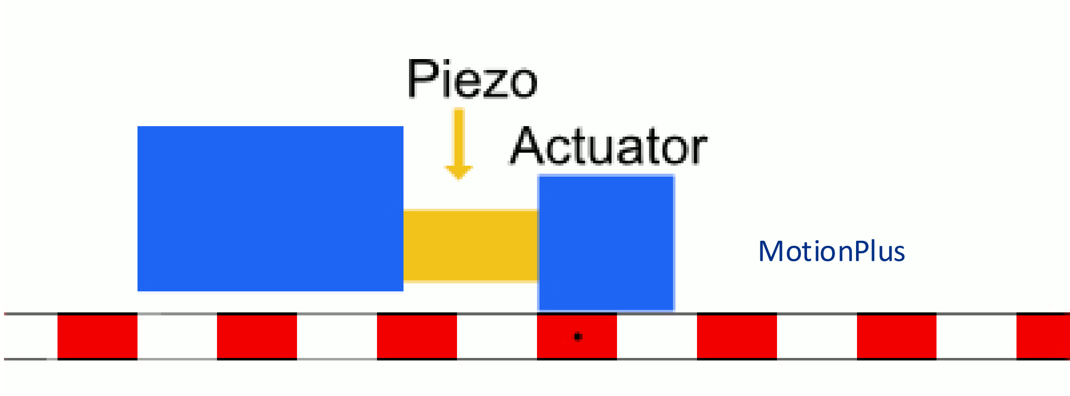
Piezo tuning requirements and strategy.

Requirements:

- 20 mm travel range.
- 10 nm (~kHz) resolution.
- Low dissipation.
- 500 grams Max Load.
- Low temperature. High Vacuum.
- Moving the cavity instead of the plunger to mitigate "hot rod."

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

Stick and slip mechanism.



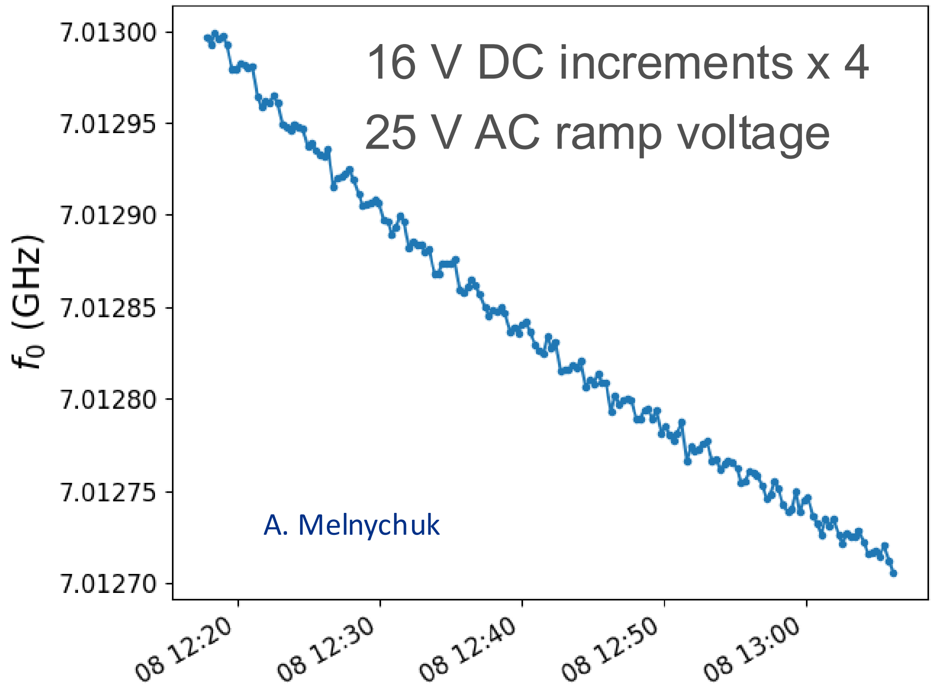
Strategy:

DC tuning steps to achieve 10 nm tuning resolution, up to ~100 V.
Very low power dissipation (~mK heating of cavity).

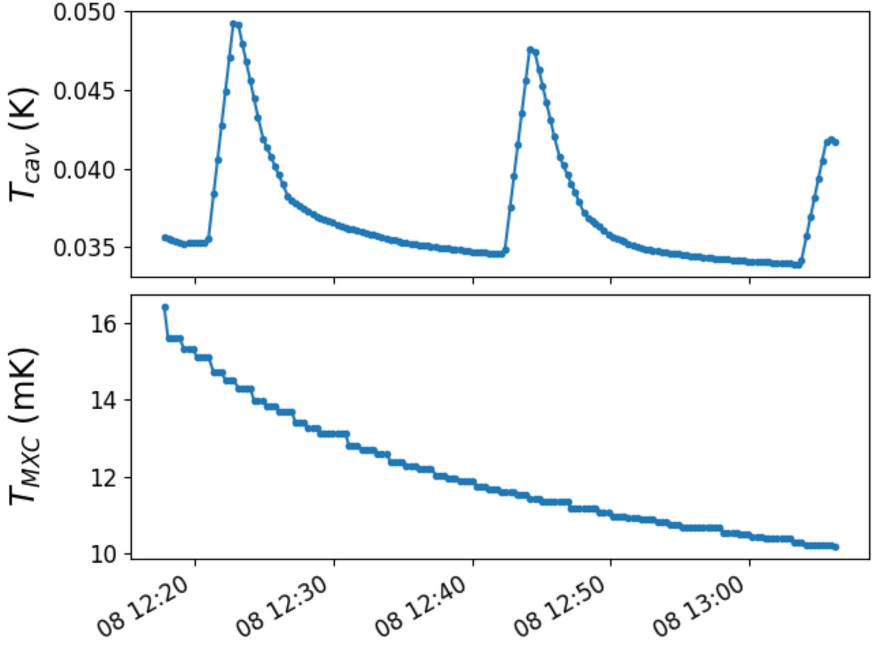
Then activate AC ramp to move large distance. Lots of dissipation.

Piezo tuning. Sometimes smooth with modest impact on cavity temperature

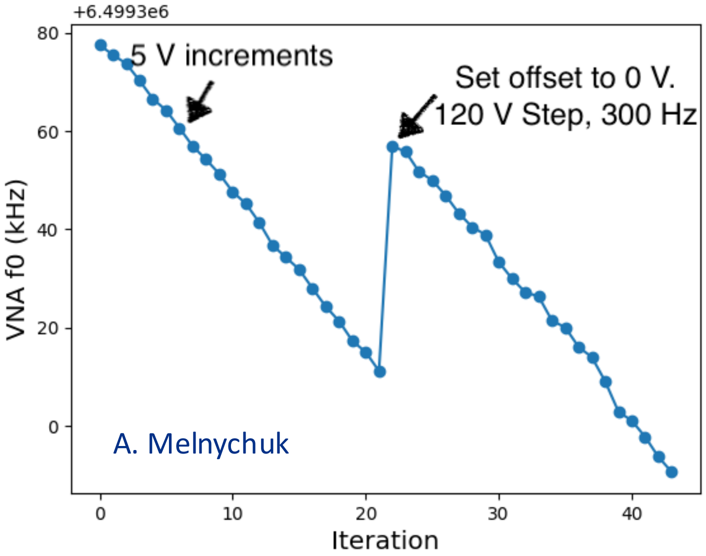
Cavity tuning

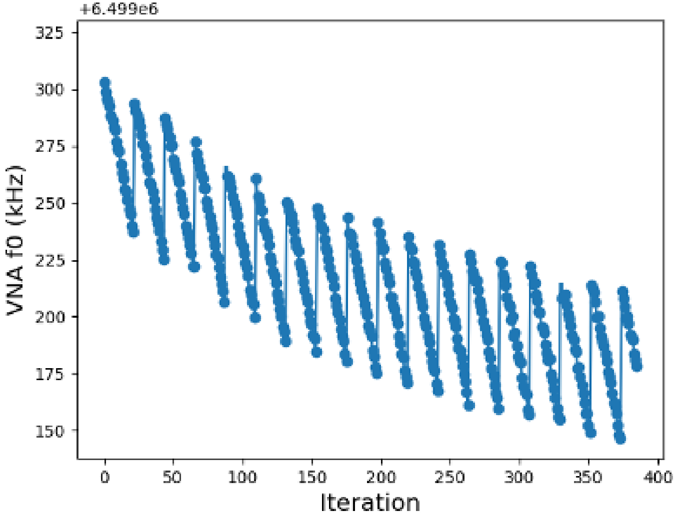


Cavity and Fridge temperatures “manageable”



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

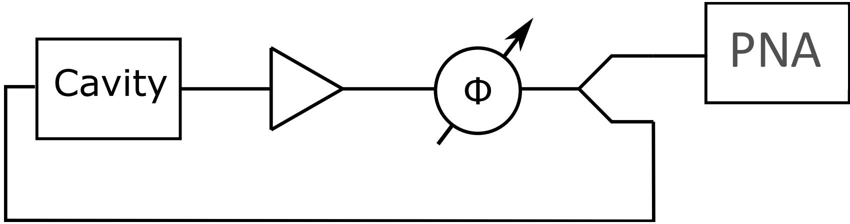




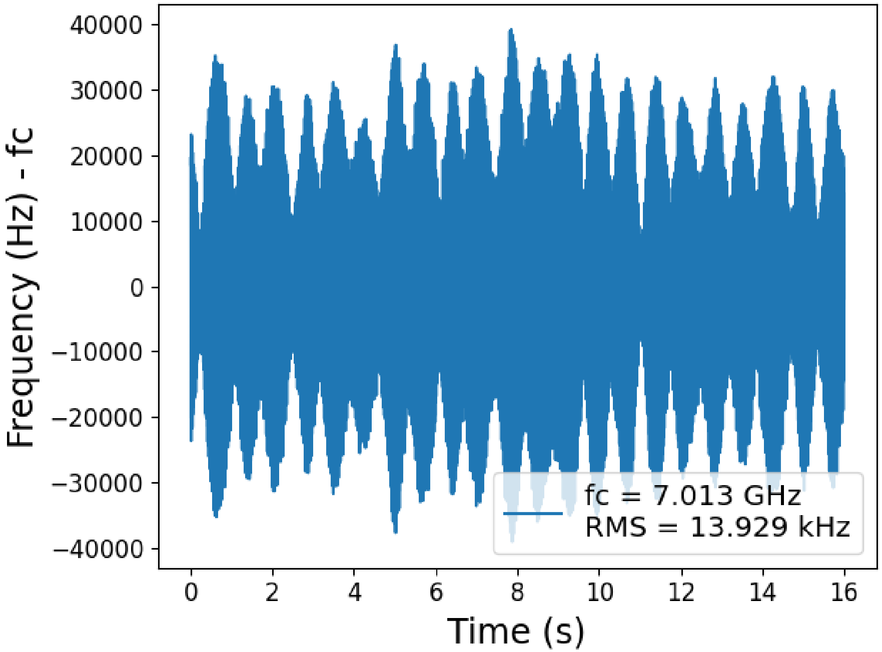
Slip part of the stick-slip not slipping enough.

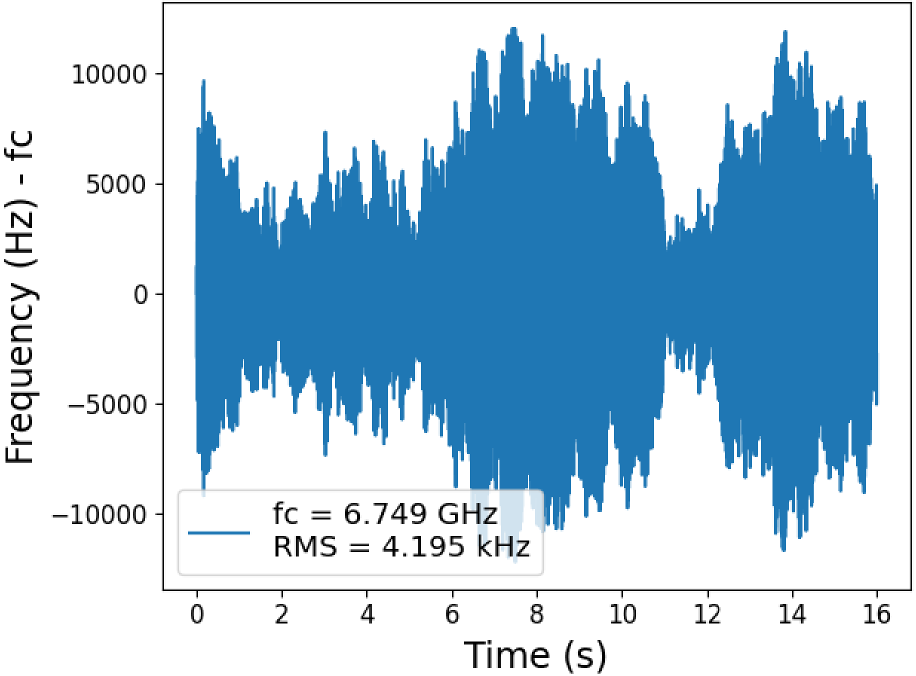
1. Need to better optimize thermal straps
2. Piezo has probably deteriorated after multiple cooldowns and abuses

Plunger cavity microphonics

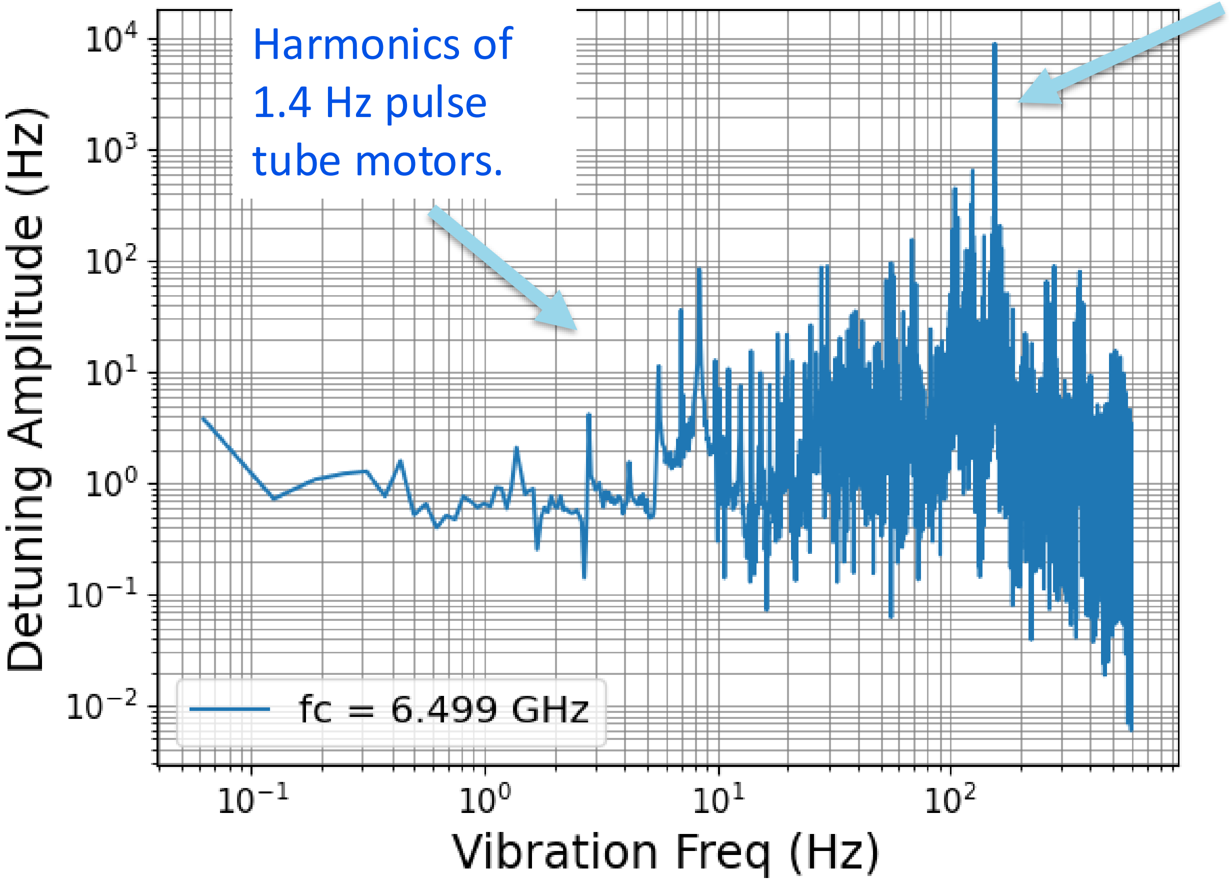


Measure with self-excited loop and phase noise analyzer.





Take FFT of microphonics to understand source



Mechanical eigenmodes of plunger.

Improvements:

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

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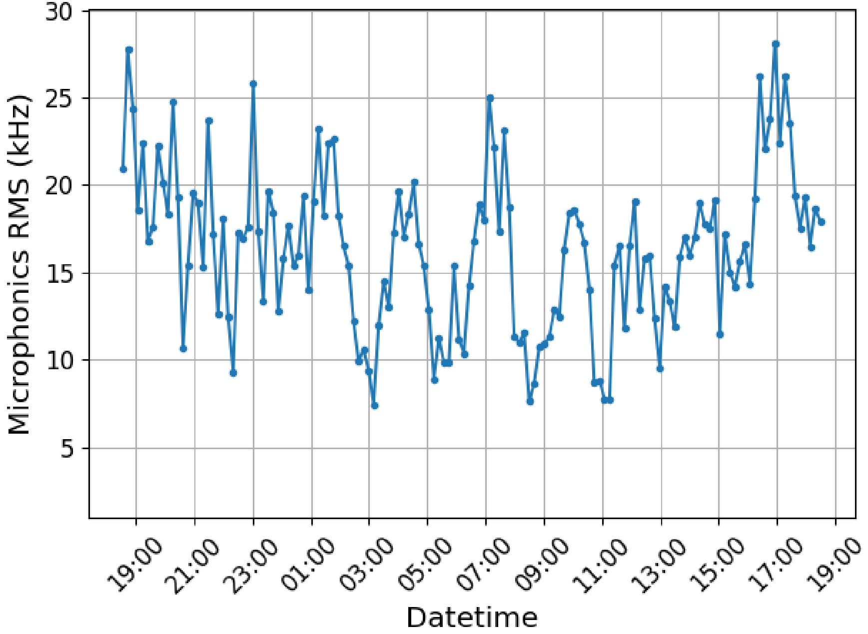
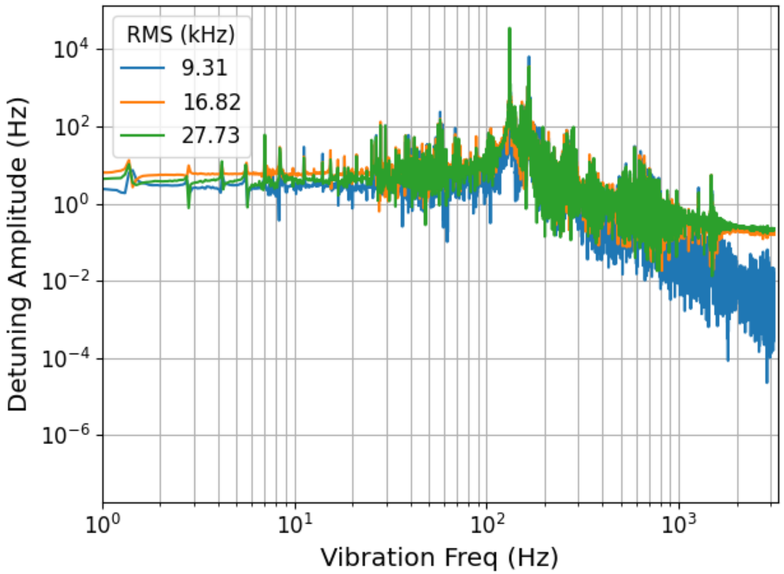
24 hour microphonics measurement at f_c~7 GHz





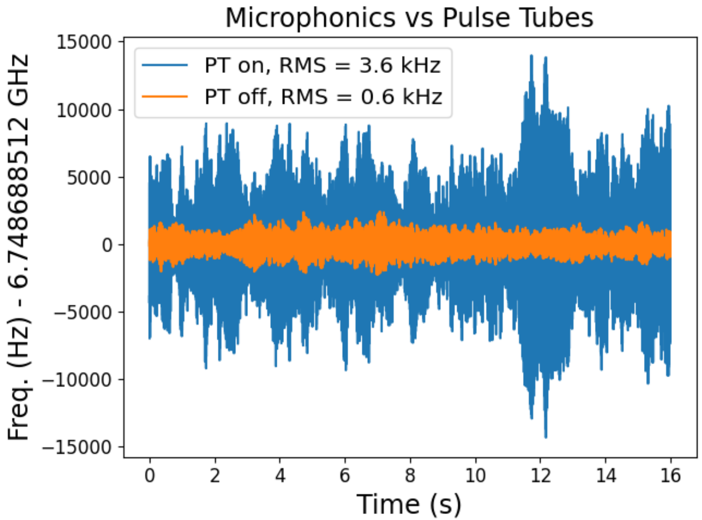
RMS varies from 4 kHz to 27 kHz throughout the day.

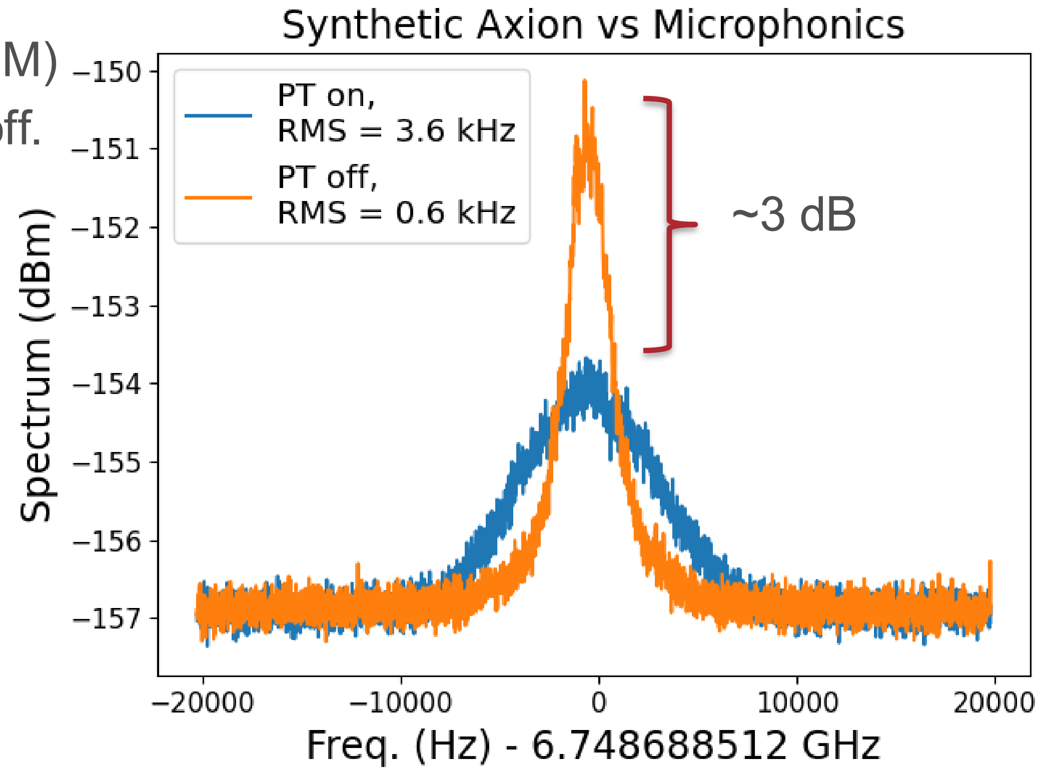
Spectral properties don't seem to change, just amplitude.

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

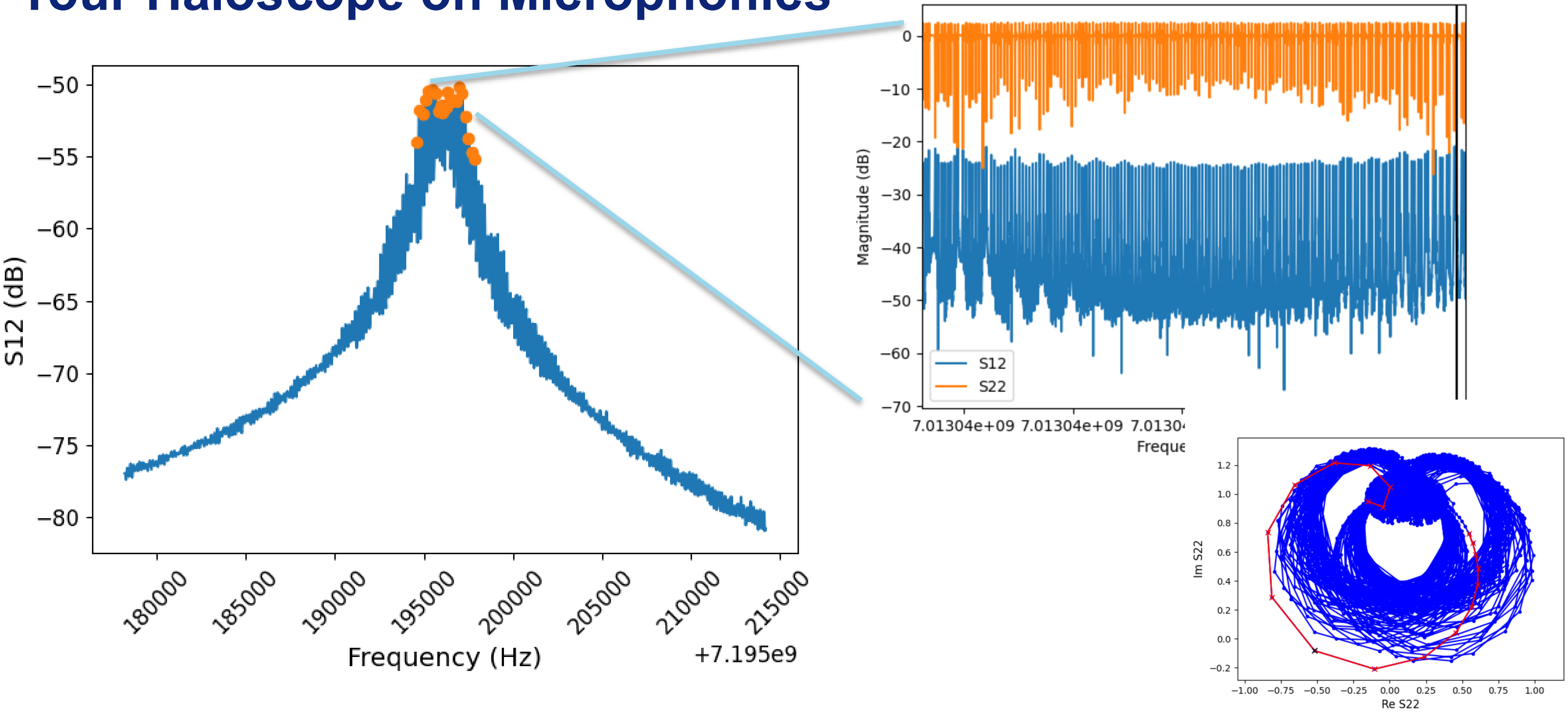
Measuring effect of microphonics on dark matter signal

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





Your Haloscope on Microphonics



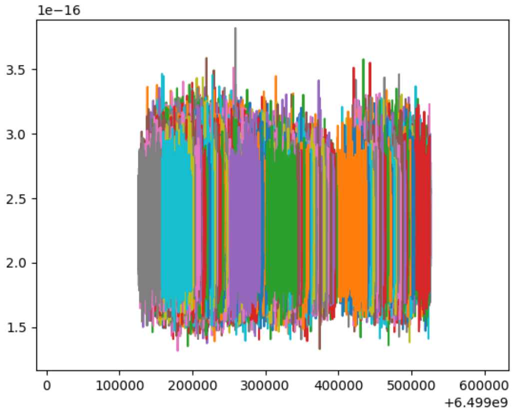
VNA sweeps harder to interpret. More tricks to characterize cavity and systematics.

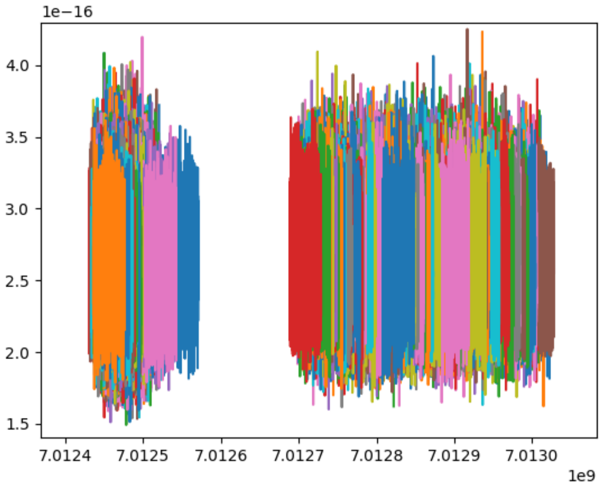
Dark Photon Dark Matter Search

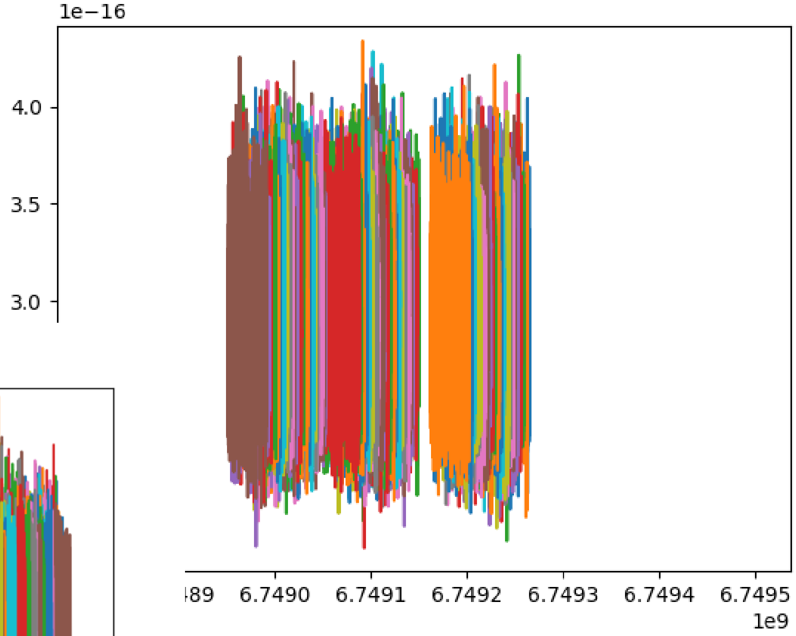
Strongly overcoupled: QL ~ 10^7

Tsys ~ 1 K

And here are some spectra







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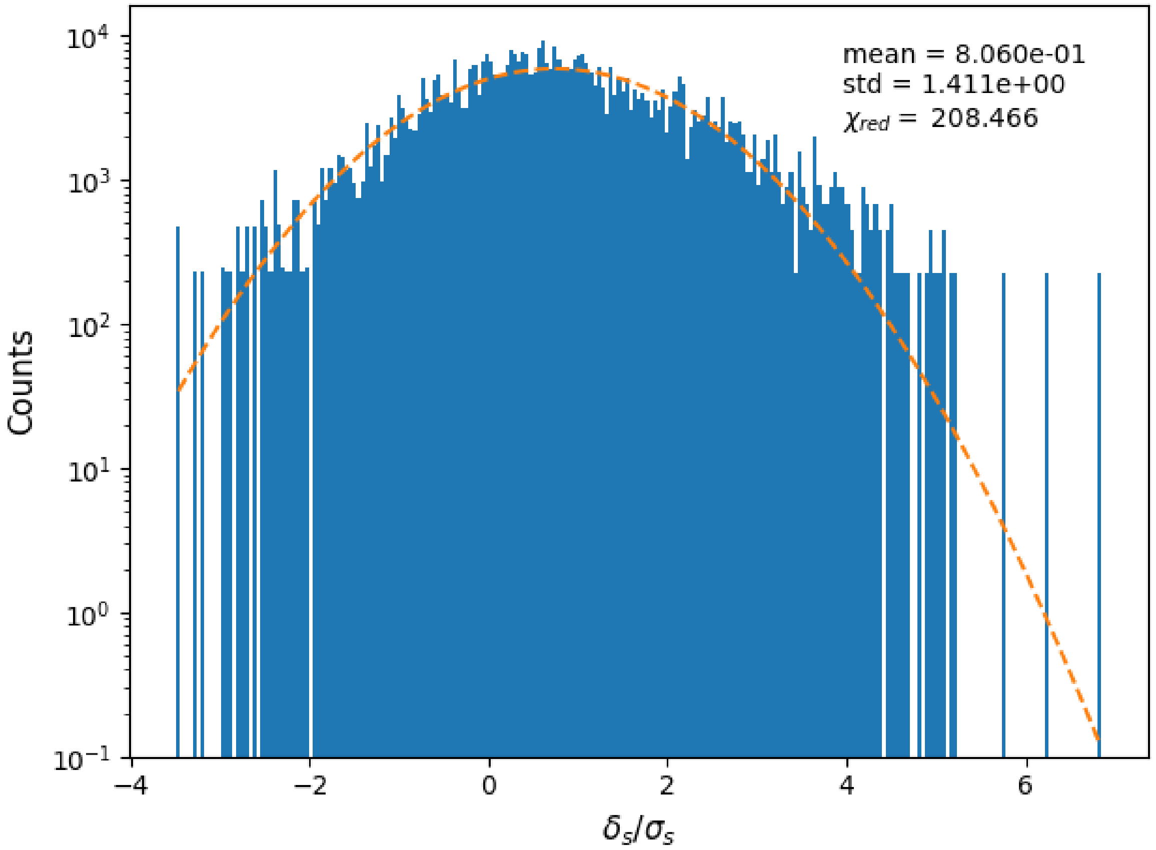
Spectra mostly white noise. Some candidates left to explore



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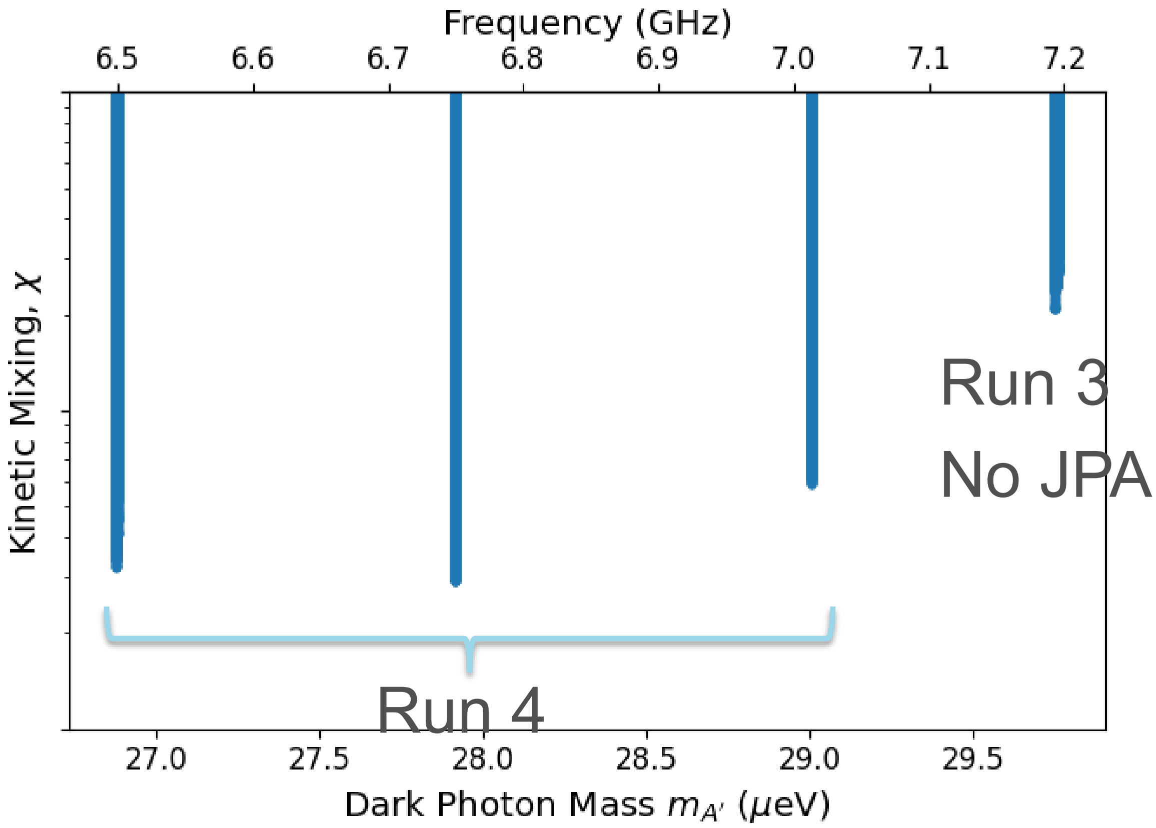
Dark Photon Dark Matter Limits in progress

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



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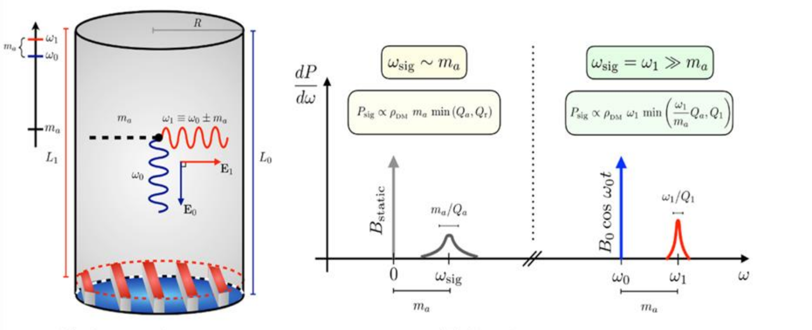
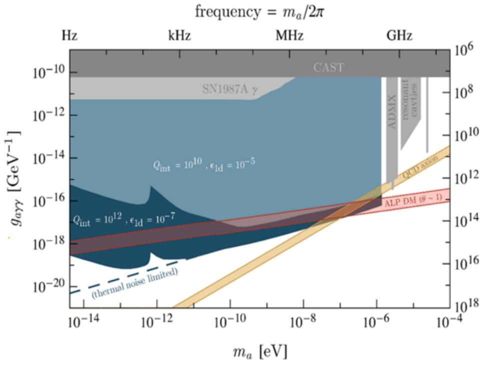
Shoutouts: Superconducting Heterodyne Axion Dark matter Experiment (SHADE)



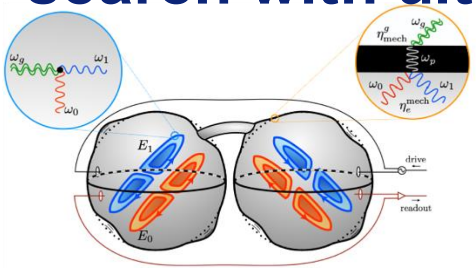
(a) Cartoon of cavity setup. (b) Signal parametrics.



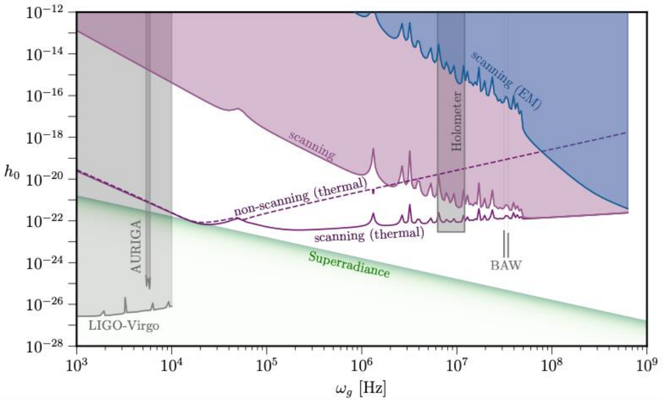
- Single SRF cavity, no applied B
- TE_{011} & TM_{020} modes for axion DM search ($m_a \approx \Delta f$)
- **Enables small mass searches without large cavities**
- Pump: TM_{020}, Signal: TE_{011}, **$\Delta f \approx$ 1 MHz** by design
- 2024**:** Two prototype cavities designed & fabricated
- Now: QC, bulk EP, heat treatment, room-temp RF tests
- 1st cold test conducted focused on characterization of cavity and ancillary systems
- Next: further cold tests to follow

A. Berlin, et al., Journal of High Energy Physics 2020.7 (2020)
B. Giaccone et al., arXiv:2207.11346 (2022)

Shoutouts: High-Frequency Gravitational Wave Search search with ultrahigh –Q SRF cavities



- MAGO (INFN & CERN, ~1998): Prototype experiments successful interaction but were later abandoned.
- SQMS theorists further developed detection formalism (direct vs indirect)
- Fermilab, DESY-UHH, and INFN are reviving MAGO
  - Extensive room-temperature studies (RF, mechanical, tuning) led to the first RF cold test recently at 2K at Fermilab, and 4K at DESY.
  - Developing an advanced RF readout system for the first physics run.
  - See latest updates presented at SRF2025 conference this week: Marconato, G., et al., TUP078 and Giaccone, B., & Wenskat, M. FRB05

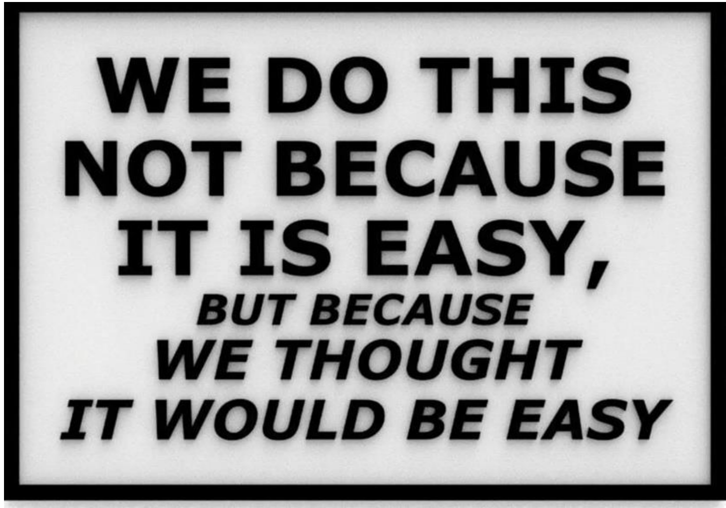


- Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003); - Berlin et al., Phys. Rev. D 105, 116011 (2022); - Berlin et al., arXiv:2303.01518v1 (2023); - Fischer et al, Class. Quantum Grav. 42 115015 (2025)

Summarize

- Demonstrated widely tunable SRF cavity, 4-7 GHz.
- Struggling against microphonics and tuning reliability. V_{eff} also needs to be increased.
- Preliminary dark photon search accomplished. Data analysis and systematic studies ongoing.

Seraphine the mascot.



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 Ill, Mackenzie Ring, Dominic Baumgart, Damon Bice, Abraham Diaz, David Burke, Davida Smith

Machinists: Eddie Piezchala

THANK YOU

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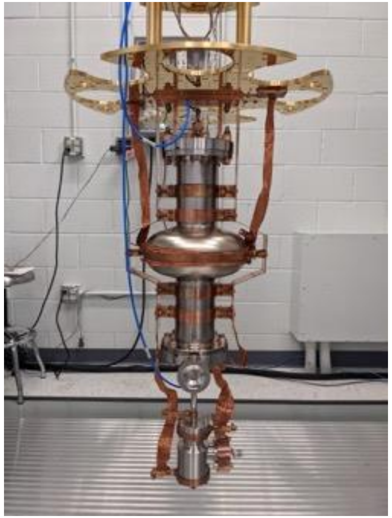
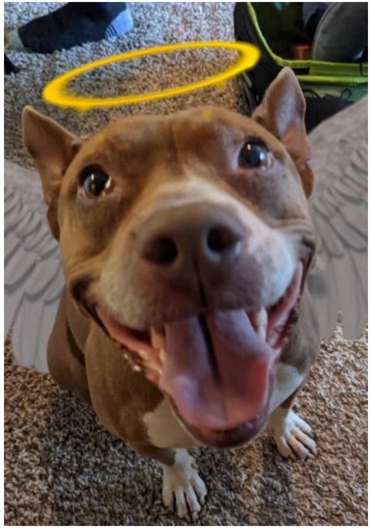
SERAPH: SupERconducting Axion and Paraphoton Haloscope

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



SRF



Seraphine

Edited by slimemoldgrappling

Sir Raph(ael)