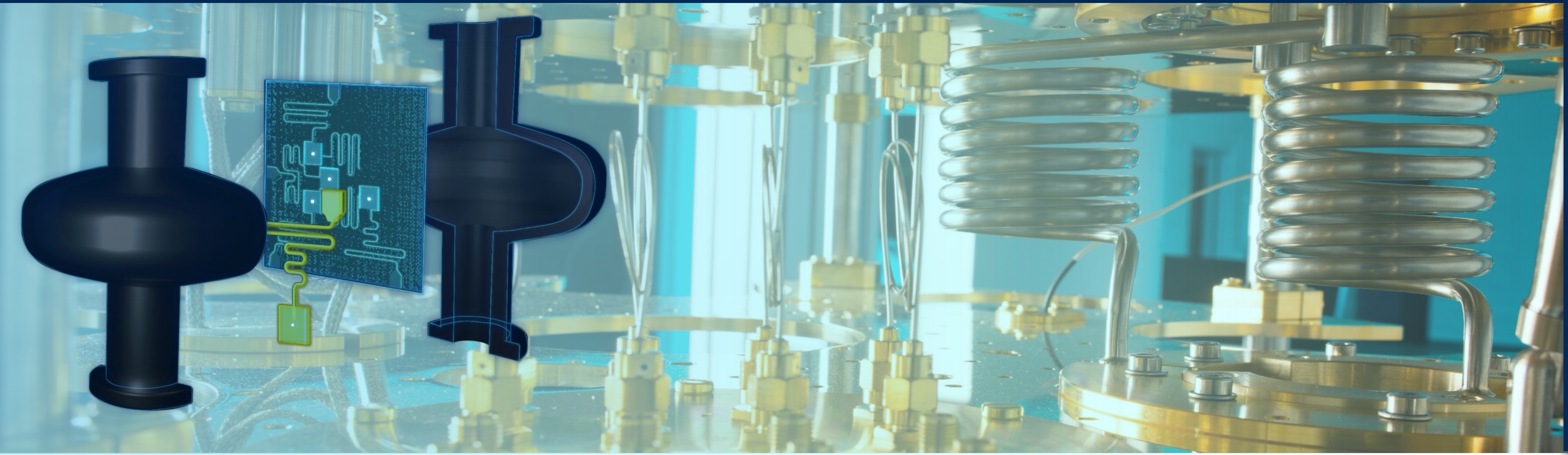
FERMILAB-SLIDES-24-0084-SQMS

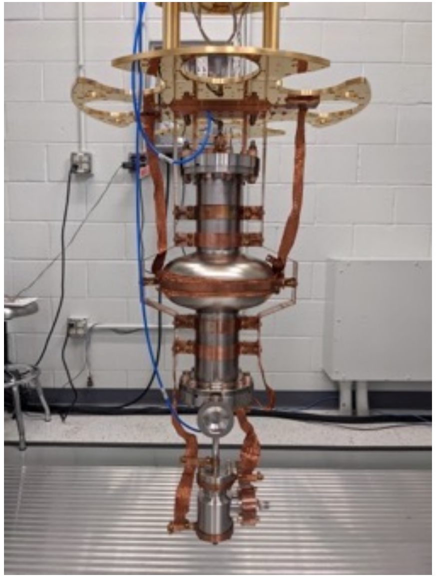


This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

Superconducting Cavities for 4-10 GHz

Raphael Cervantes
SQMS, Fermilab

SRF Cavities for Dark Matter Searches



Compared to copper-based searches →

Credit: N. Du

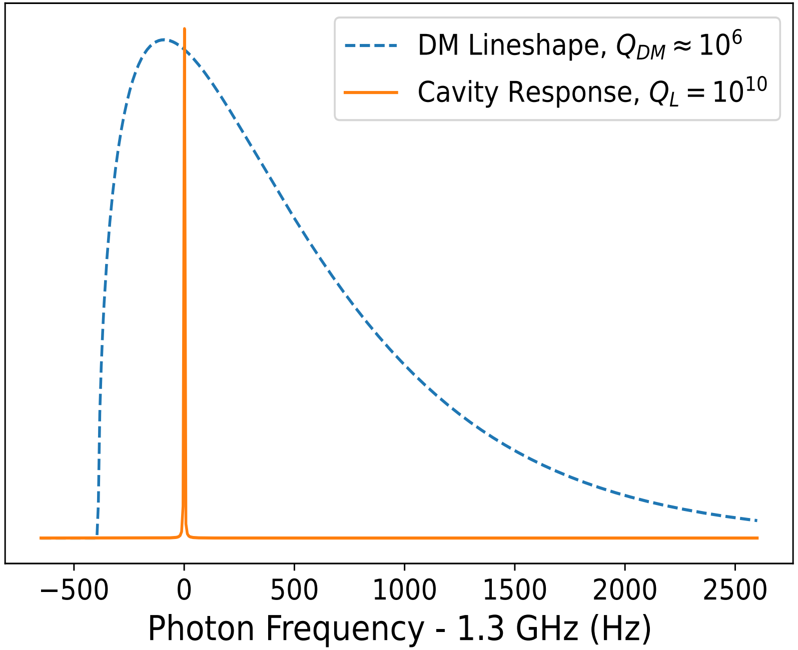
SQMS → $Q \approx 10^{10}$

ADMX and CAPP → $Q \approx 10^{5}$

High Q allows for larger signal and lower noise floor.

Possibly factor 10^5 increase in instantaneous scan rate.

Instantaneous scan rate is proportional to Q_L



arXiv:2208.03183

For virialized axions

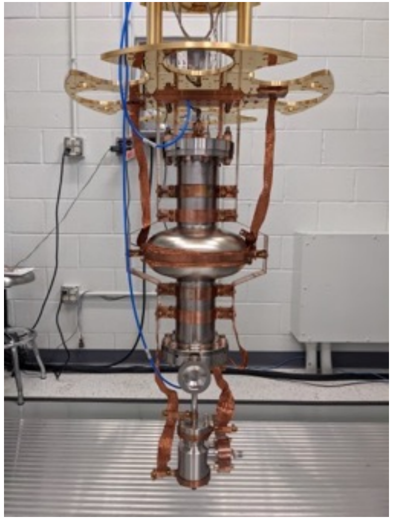
$$\frac{\mathrm{d}f}{\mathrm{d}t} \sim Q_L Q_{DM} \left(\frac{\eta \chi^2 m_{A'} \rho_{A'} V_{eff} \beta}{\mathrm{SNR} T_n (\beta + 1)} \right)^2$$

even if $Q_L \gg Q_{DM}$

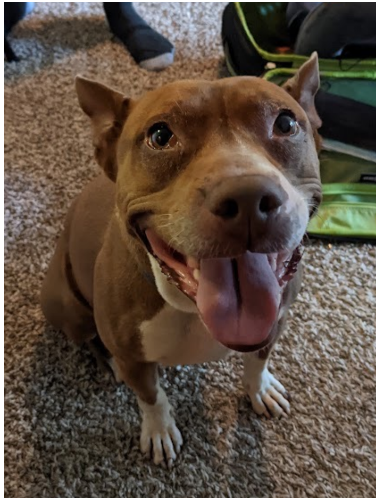
- Signal power $P_s \propto \min(Q_L, Q_{DM})$
- Noise power reduces with Q_L.
- Tuning steps $\Delta f \propto \Delta f_{DM}$. Cavity sensitive to distribution of possible DM rest masses.
- Sacrificing sensitivivity to cold streams.

SERAPH: SupERconducting Axion and Paraphoton Haloscope

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



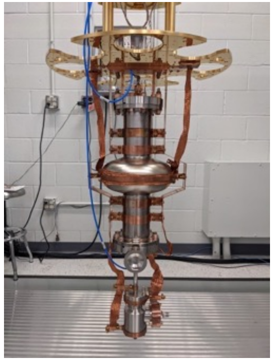
SRF



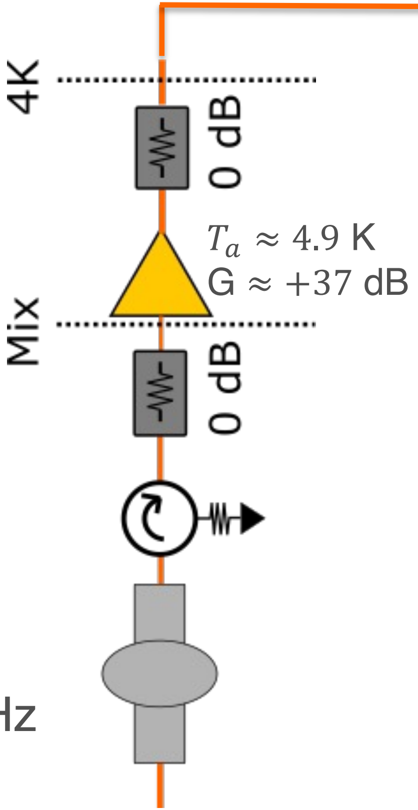
Seraphine

Sir Raph(ael)

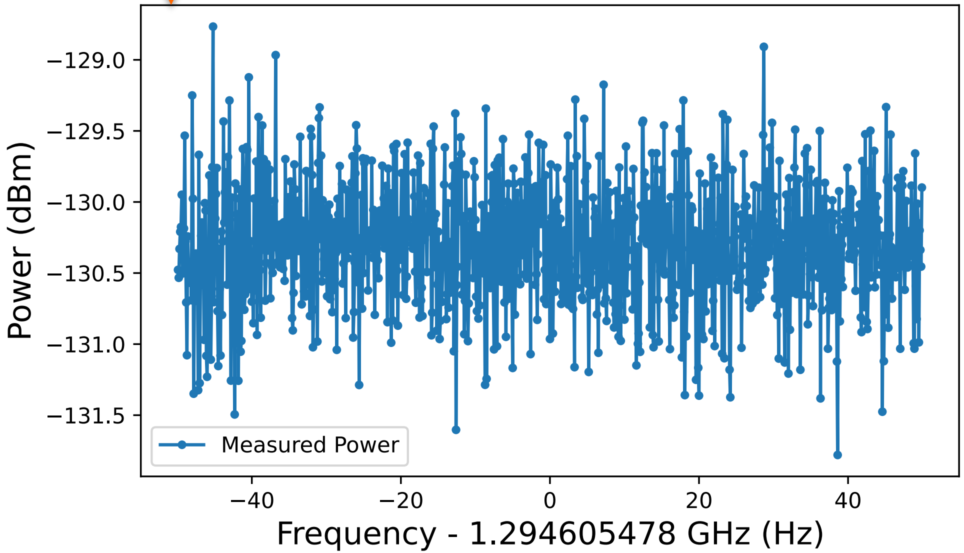
SERAPHv1: Parasitic Search for Dark Photons



$T_c \approx 35$ mK
$Q_L \approx 5\times10^9$
$f_0 = 1.295$ GHz
$\beta \sim 1.3$

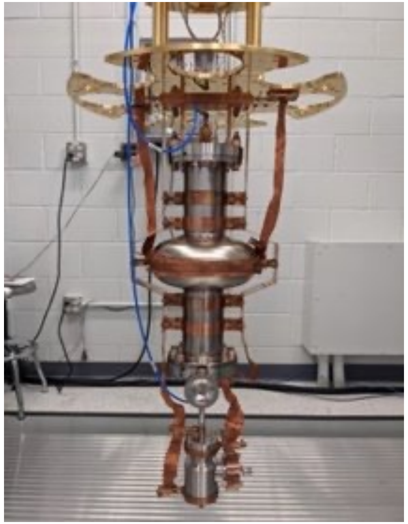


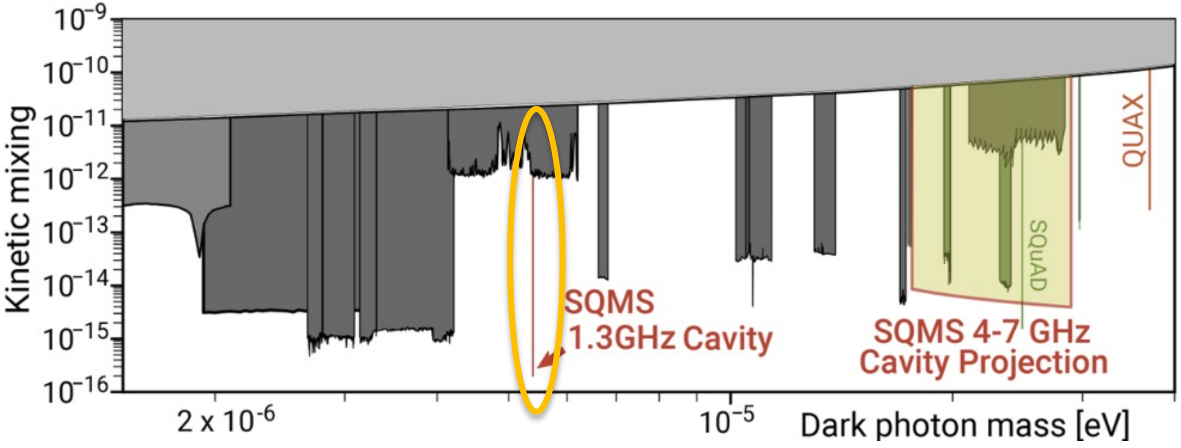
No DP signal. Just noise.



1000 seconds integration time

Deepest sensitivity: Ultrahigh Q for Dark photon DM





Cervantes et al., arXiv:2208.03183v3 (2022)

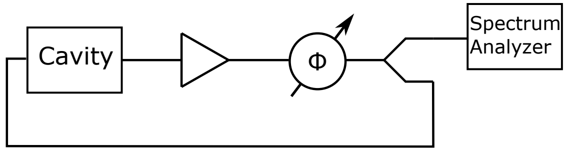
DPDM search in DR with 1.3 GHz cavity with $Q_0 \approx 10^{10}$.

Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

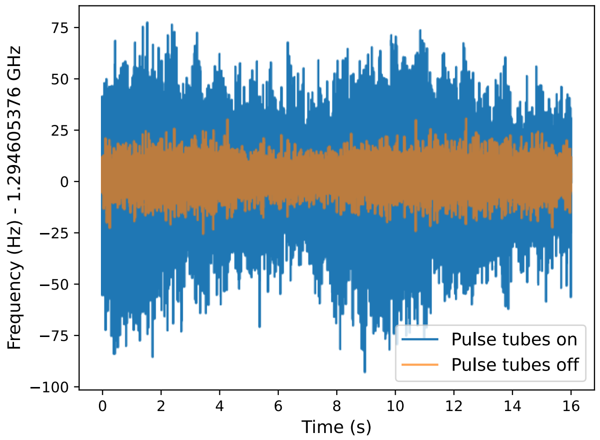
- Tunable DPDM search from 4-7 GHz (“low hanging fruit”)
- Implement photon counting to subvert SQL noise limit.

SERAPHv1 Microphonics

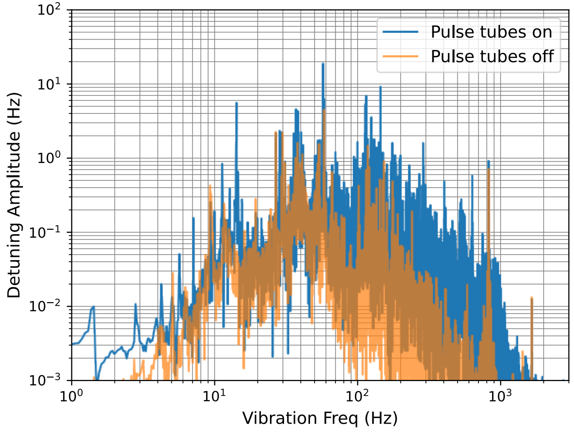


- Measured with self-excitation loop and phase noise analyzer+spectrum analyzer.
- 25 Hz RMS
- Mitigated by turning off pulse tubes (7 Hz RMS), but not viable for a dark matter search.
- Dark Wave Lab should be designed to minimize vibration.

PNA measurement



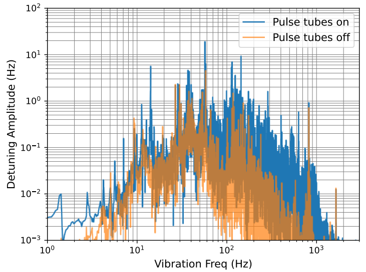
FFT of PNA measurement

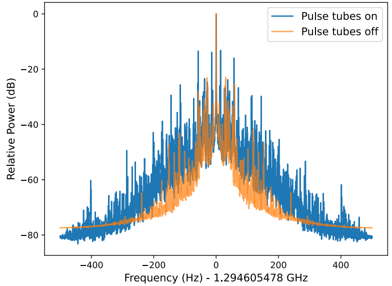


SERAPHv1 Microphonics and Frequency Modulation

Creates modulation of dark matter signal. Power gets spread into sidebands.

Modulation Frequency f_m (Hz)	Detuning Amplitude f_Δ (Hz)	Modulation Index $\frac{f_m}{f_\Delta}$	Carrier amplitude (dBc)	Sideband amplitude (dBc)
14.3	5.5	0.4	-0.32	-14.5
57.2	18.2	0.3	-0.22	-16.1



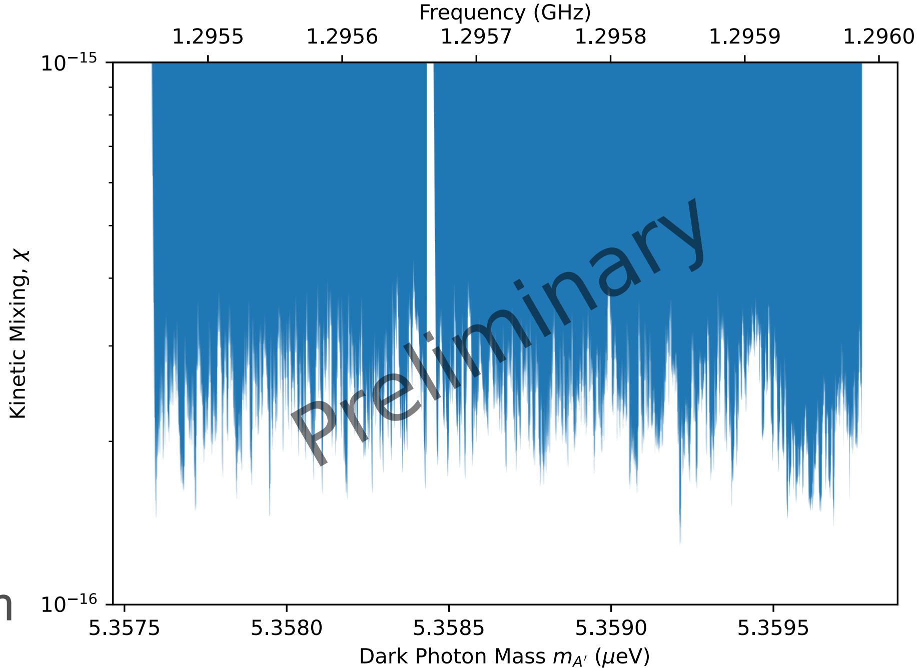


Carrier band attenuated by 0.54 dBc.

DM signal attenuated in the central band $\eta \approx \mathbf{0.88}$

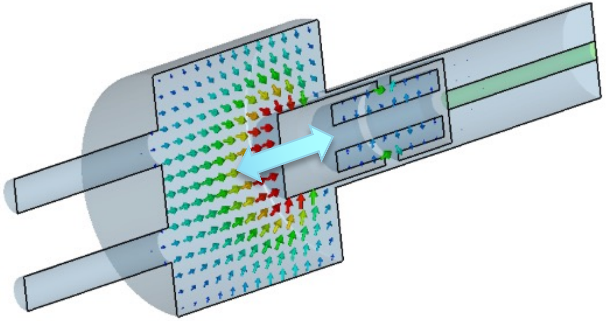
Might recover if analysis looks for sidebands.

Tunable search with 1.3 GHz Cavity (SERAPH v1.1)

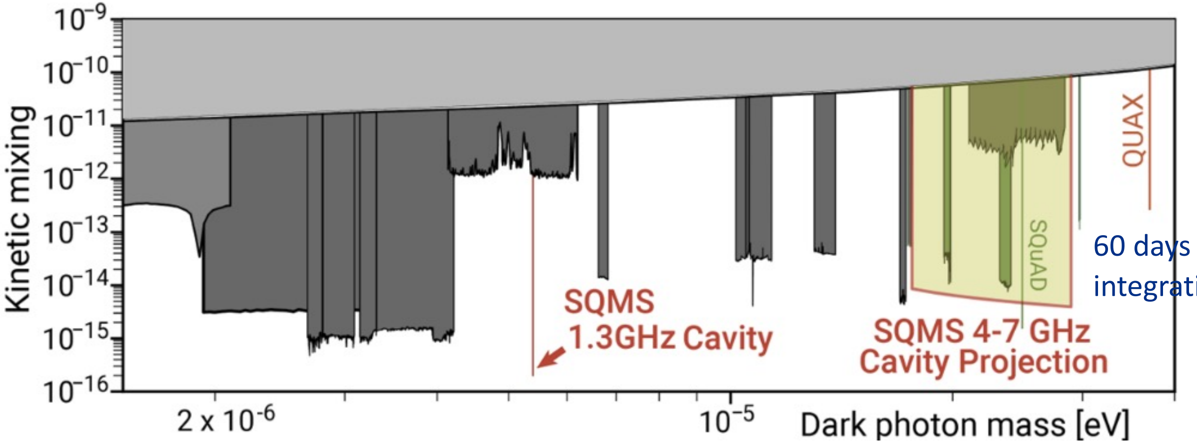


Similar 1.3 GHz cavity in liquid helium bath. Tunes by mechanical compression for 500 kHz tuning range. T_{cav} = 1.4 K, Q_L = 2.4e8. Very overcoupled.

Deepest sensitivity: Ultrahigh Q for Dark photon DM



“plunger” cavity
4-7 GHz



Cervantes et al., arXiv:2208.03183v3 (2022)

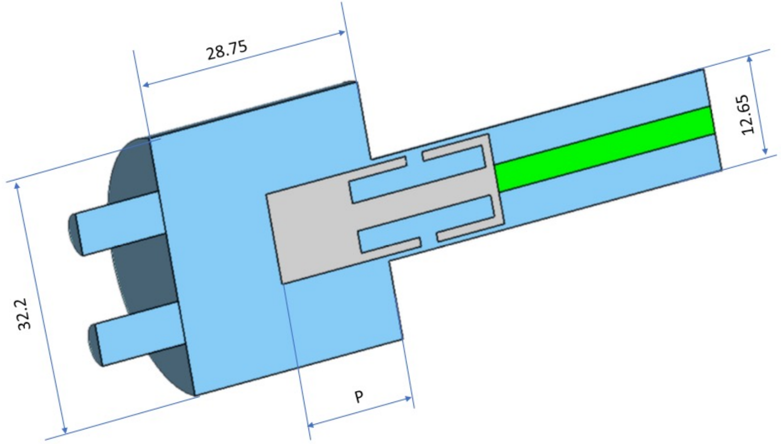
DPDM search in DR with 1.3 GHz cavity with $Q_L \approx 10^{10}$.

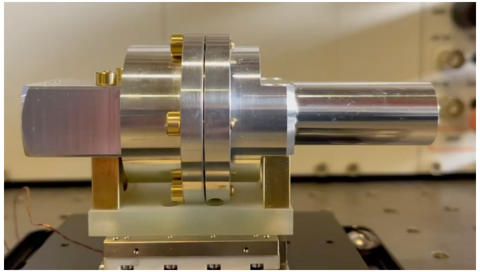
Deepest exclusion to wavelike DPDM by an order of magnitude.

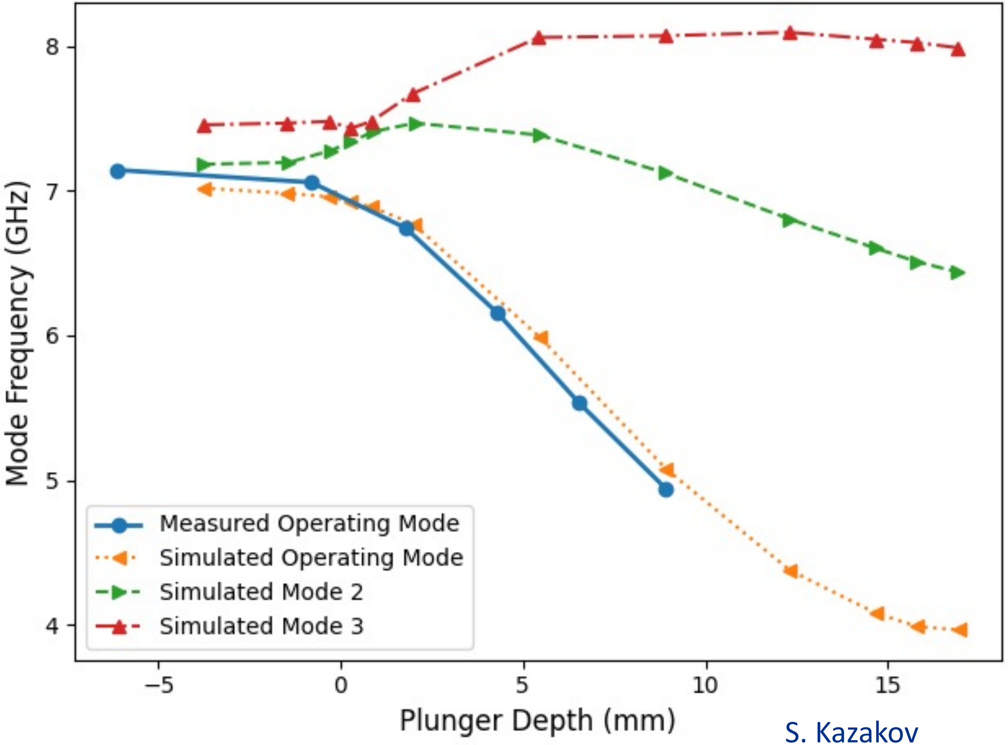
Next steps:

- Tunable DPDM search from 4-7 GHz (“low hanging fruit”)
- Implement photon counting to subvert SQL noise limit.

SERAPHv2: Widely-tunable SRF Haloscope



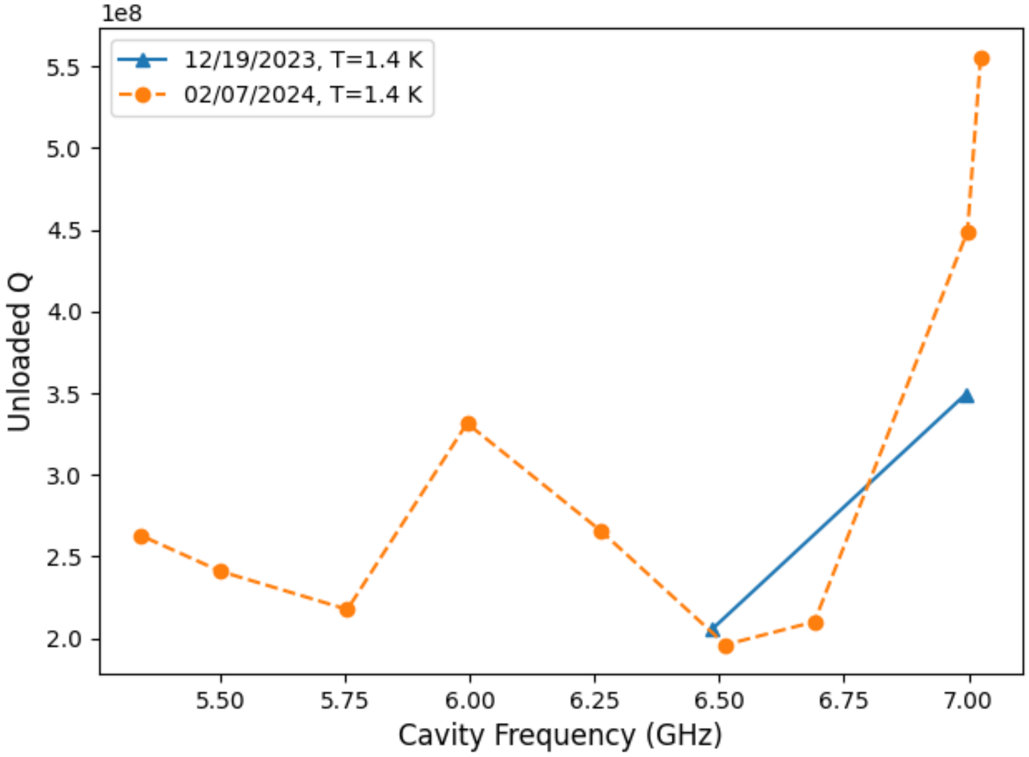




S. Kazakov

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

Measured Unloaded Q with decay measurement

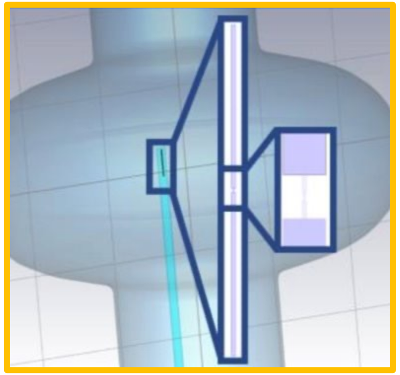


Cavity Q can improve but is acceptable.

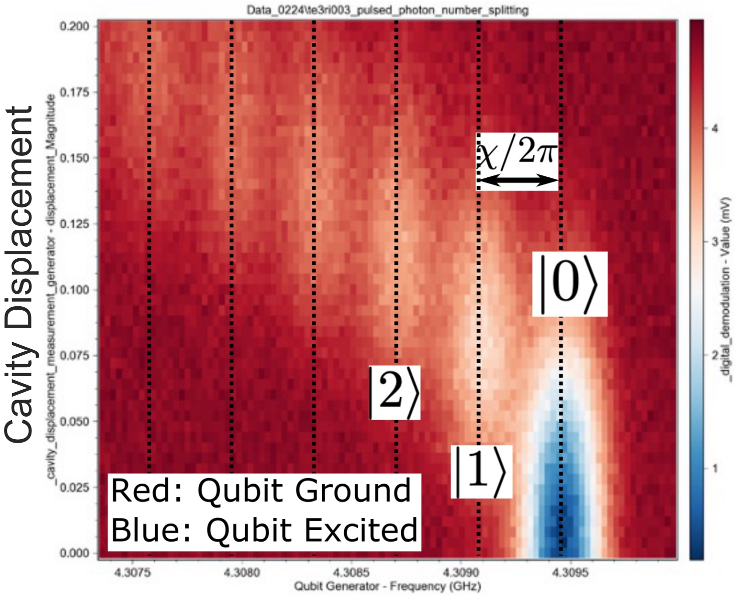
Next steps:

1. Mechanical modifications to reduce microphonics.
2. Characterize in fridge.
3. Dark photon search

Subverting SQL noise with qubit-based photon counting



Superconducting qubit in SRF cavity.



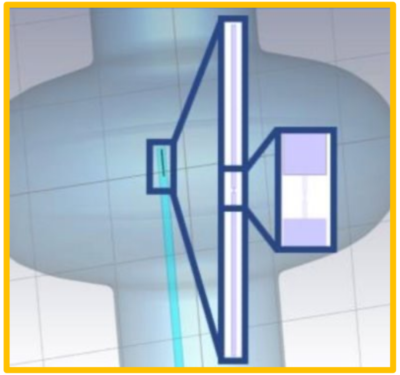
Quantum protocols counts photons non-destructively.

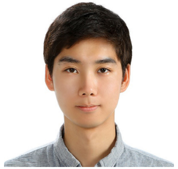
SQL noise: hf/k
240 mK @ 5 GHz

dominates compared to 30 mK thermal photons.

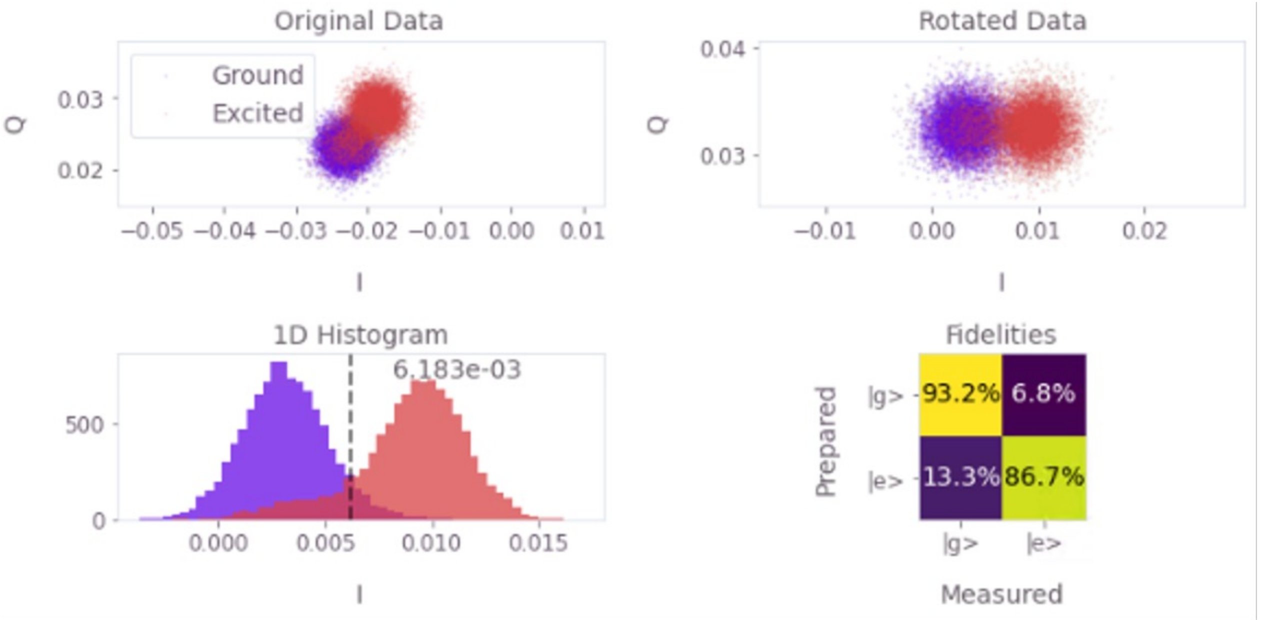
Regularly perform photon counting with dispersive measurements.

Current photon counting scheme



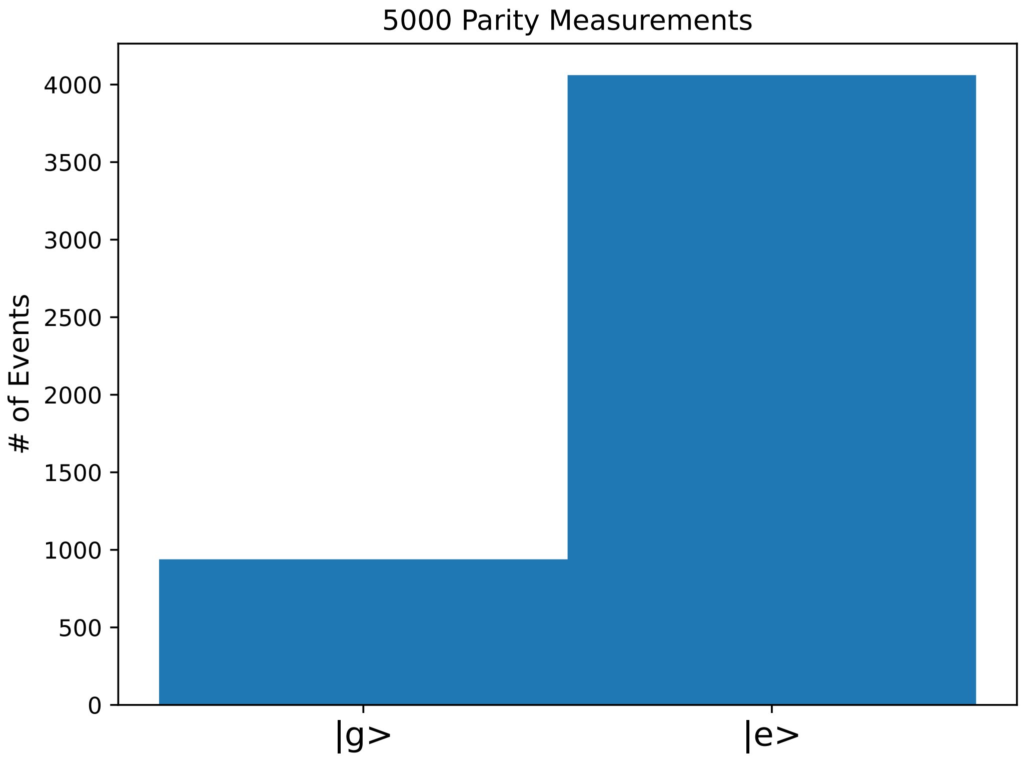


Measurements performed by Taeyoon Kim



Qubit T1 ~ 150 μs. Readout rate is 1/ms

Photon counting results



Parity measurement where qubit is prepared in ground state and we apply two $+\pi/2$ pulses.

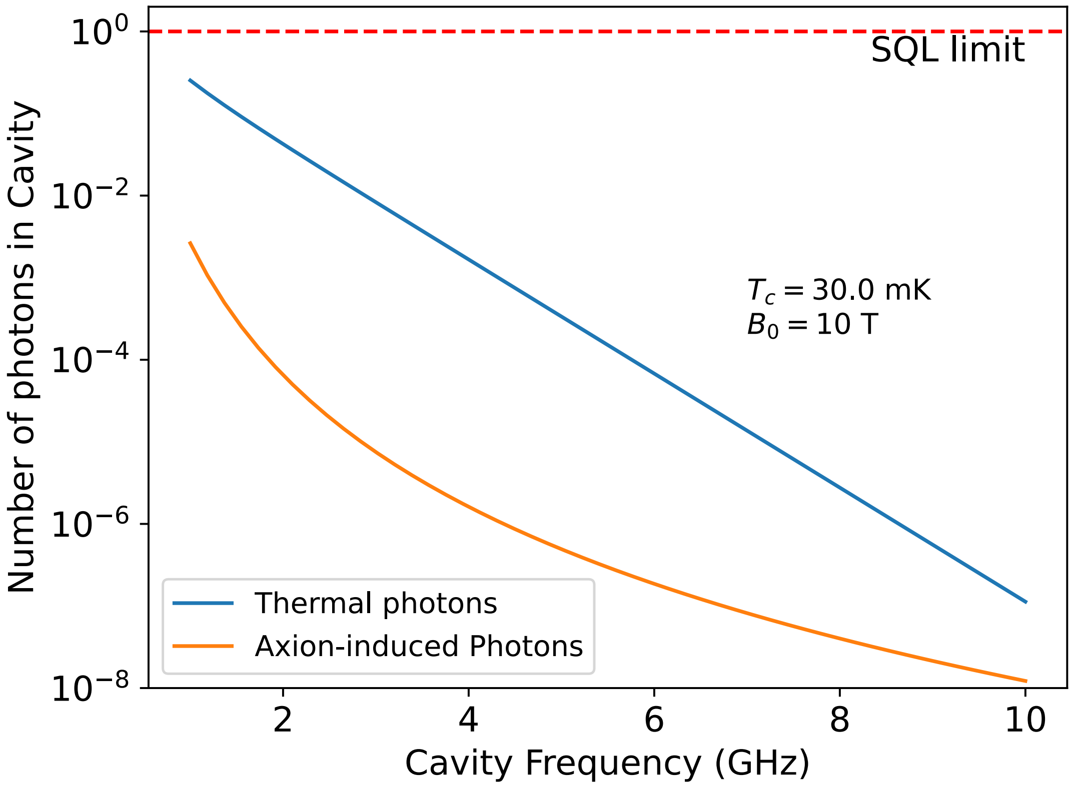
With perfect readout:

lg> corresponds to 1 photon.

le> corresponds to 0 photon.

Can use fidelity matrix and characteristics of the system to derive dark photon limit.

Why we need photon counting



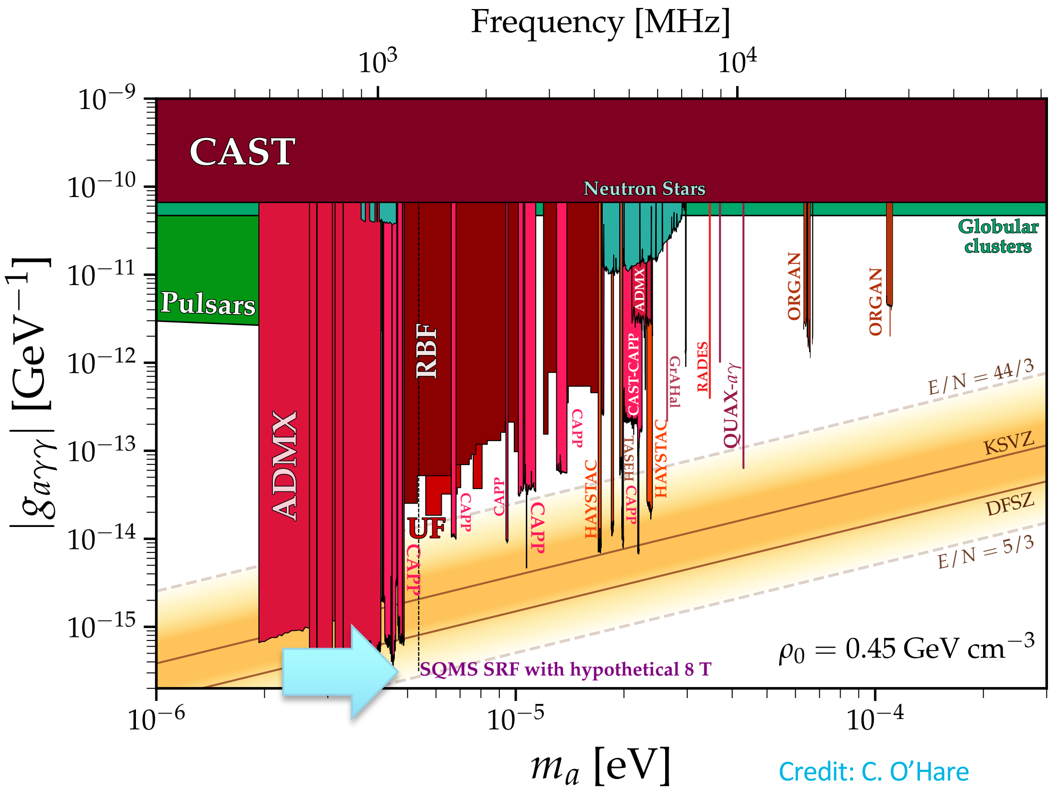
$$V_c = 136\,L \times \left(\frac{f}{1GHz}\right)^{-3}$$

$$Q_L = 80\,000 \times \left(\frac{f}{1GHz}\right)^{-\frac{2}{3}}$$

$$n_c = \frac{1}{\exp\left(\frac{hf}{k_b T}\right) - 1}$$

- SQL noise dominates at higher frequencies.
- Mitigating SQL could increase scan rate by many orders of magnitude.
- Magnetically-compatible qubits would make this viable for axion searches.

If Q~10^{10} cavities work in an 8T field

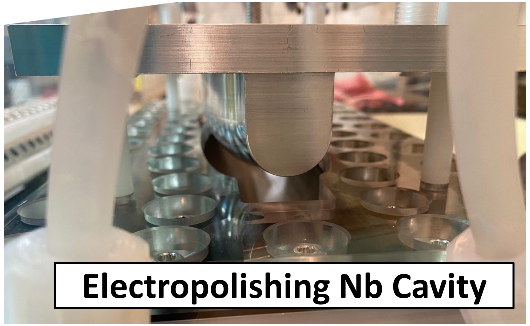


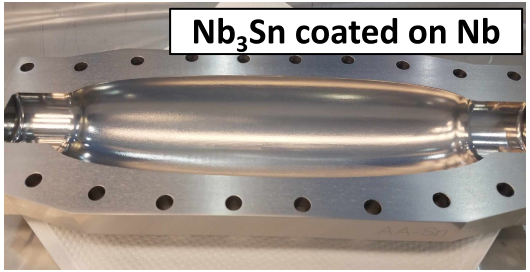
Credit: C. O'Hare

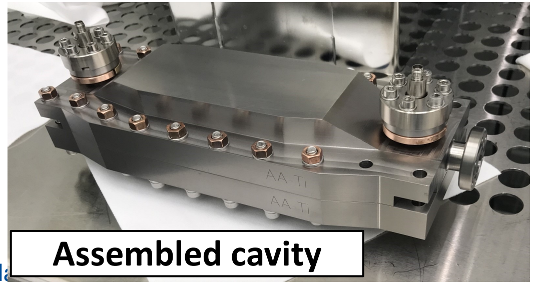
Sensitivity to **QCD axion** with single cavity and HEMT.

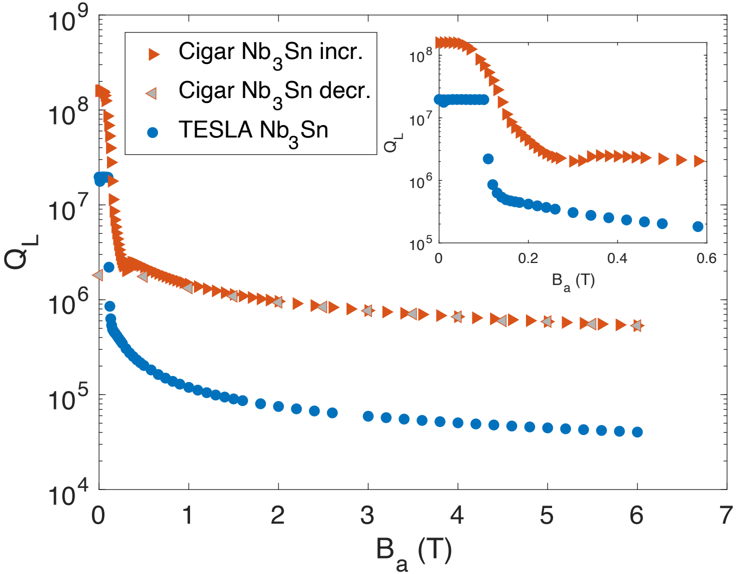
Just make $Q \sim 10^{10}$ cavities work in magnetic fields!

Nb_3Sn Cavities in Multi-Tesla Field R&D at Fermilab









Q_0 of $5x10^5$ at 6 T, 4.2 K, 3.9 GHz


PHYSICAL REVIEW APPLIED

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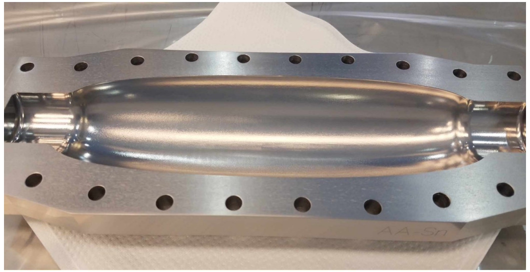
High-Quality-Factor Superconducting Cavities in Tesla-Scale Magnetic Fields for Dark-Matter Searches

S. Posen, M. Checchin, O.S. Melnychuk, T. Ring, I. Gonin, and T. Khabiboulline
Phys. Rev. Applied **20**, 034004 – Published 5 September 2023

FNAL Nb_3Sn Cavities for ADMX and INFN

Initial R&D at Fermilab

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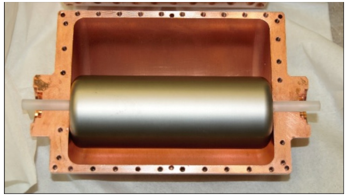
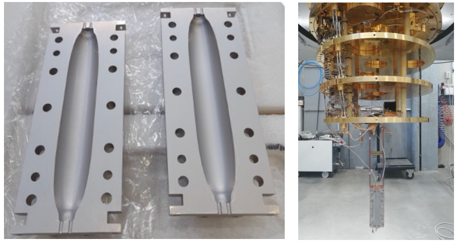
Prototypes sent to Partners

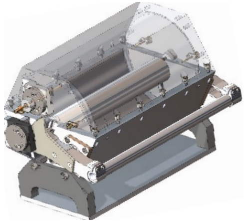


Nb_3Sn tuning rod for ADMX Sidecar sent to U. Washington (w/ LLNL)



9 GHz Nb_3Sn cavity sent to INFN Frascati for testing in 8 T fridge

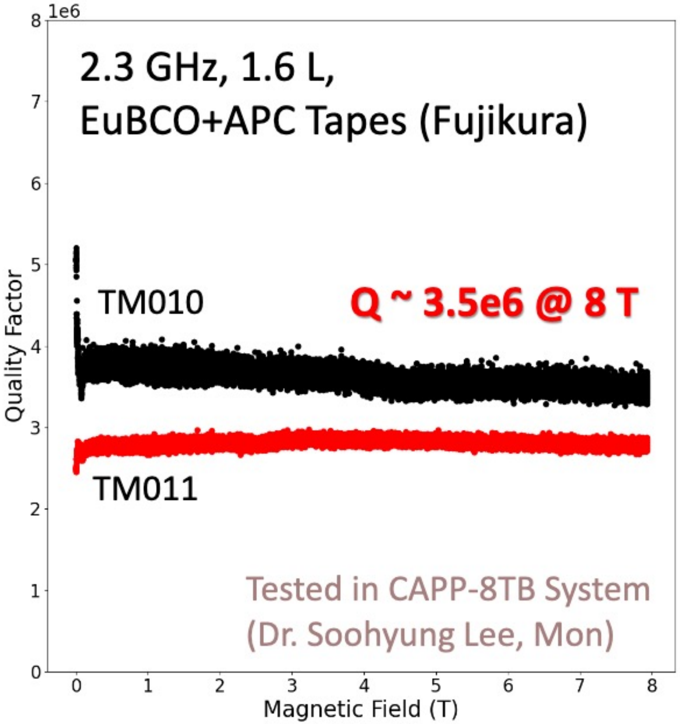
Potential Future Experiments



ADMX-EFR at Fermilab

Hybrid dielectric-Nb_3Sn cavity for INFN QUAX haloscope

CAPP colleagues with HTS cavities



Credit: D. Ahn

10x better than Nb3Sn so far.

But complicated to make and requires lots of craftsmanship.

Building an HTS cavity is like building a mechanical watch

Credit: Buzzufy

Would rather have

Credit: CD Peacock

Lots of craftsmanship.
Need an apprenticeship.

Simpler, 10x more accurate and 10x cheaper.

Let’s join forces to get a commercial company to make wider HTS tape

- It’s possible because I did it 10 years ago for my master's thesis (beam shielding EIC R&D).
- 48 mm from AMSC compared to 12 mm. But AMSC no longer makes this.
- The wider, the better.
- Maybe 10x improvement in Q because we have less gaps.

Sign my letter!

April 10, 2024

Raphael Cervantes
Research Associate

Superconducting Quantum Materials and Systems Division
P.O. Box 500, MS 312
Kirk Road and Pine Street
Batavia, Illinois 60510-5011 USA
Office: 630.840.4554
raphaelc@fnal.gov

Dear Fujikura,

My name is Raphael Cervantes, and I am a Research Associate at the Fermilab Superconducting Quantum Materials and Systems (SQMS) Division. I am writing on behalf of the dark matter community to request the **development of wider HTS tape than what is commercially available.**

Dark matter makes up 85% of the matter in the universe, but its nature remains a mystery. Dark matter detection requires cutting-edge technology and innovation to build sophisticated instruments capable of detecting the faintest signals. One promising way to detect dark matter is using cavity resonators as detectors cooled down to 30 mK using a dilution refrigerator. The cavities are immersed in a 10 T magnetic field because magnetic fields can convert dark matter into detectable light particles. **The rate at which we can search for dark matter is directly related to the surface conductivity of our cavity resonator. We could look for dark matter perhaps 1000 times faster if we were using superconducting cavities instead of copper cavities, but the cavities have to maintain their superconductivity in a 10 T magnetic field. The development of magnetically-resilient superconducting cavities could mean that dark matter could be detected in years rather than millennia.**

HTS tapes have been demonstrated to be the most viable option for achieving magnetically-resilient superconducting cavities with fantastic performance. This cavity was built by delaminating the HTS tapes to expose the superconducting surface and lining up the inside of a cavity with 12 mm-wide HTS tapes connected side-by-side (Ahn, 2022; Danho Ahn, 2022). However, the performance is limited by the gaps between the tape pieces and machining imperfections caused by connecting many tape pieces. The performance could improve by another factor of 10 if the superconducting layer were made from one continuous piece.

We’d like the tape as wide as possible, perhaps 40 cm wide. However, 4 cm wide tape would be incredibly beneficial in comparison to 12 mm wide tape.

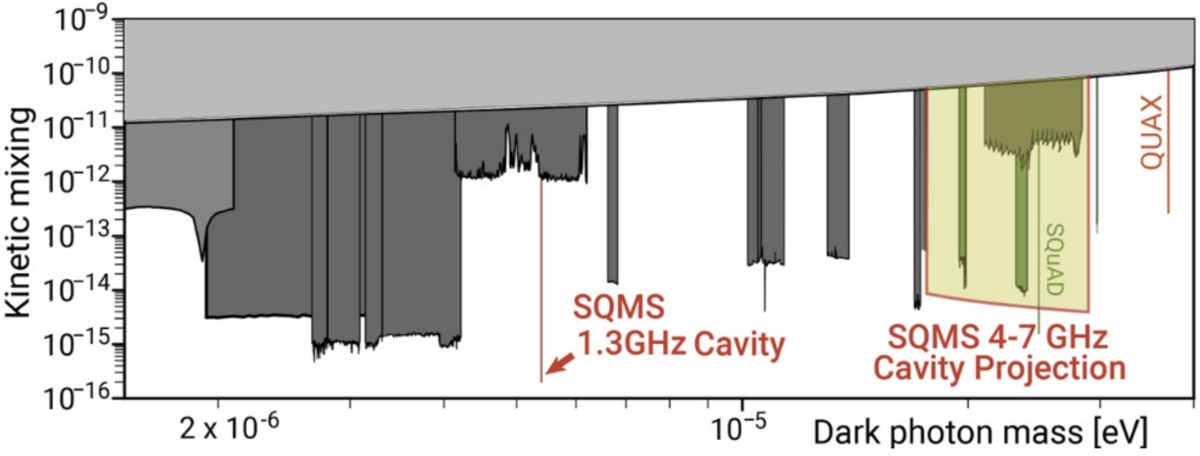
SQMS Center

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

Please wish the mascot well!

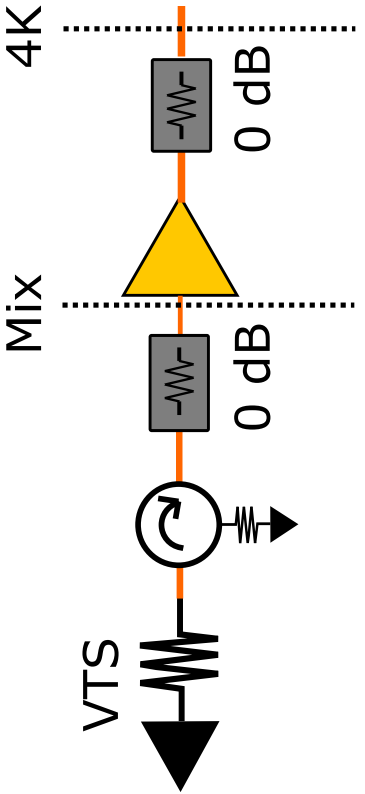
Summarize

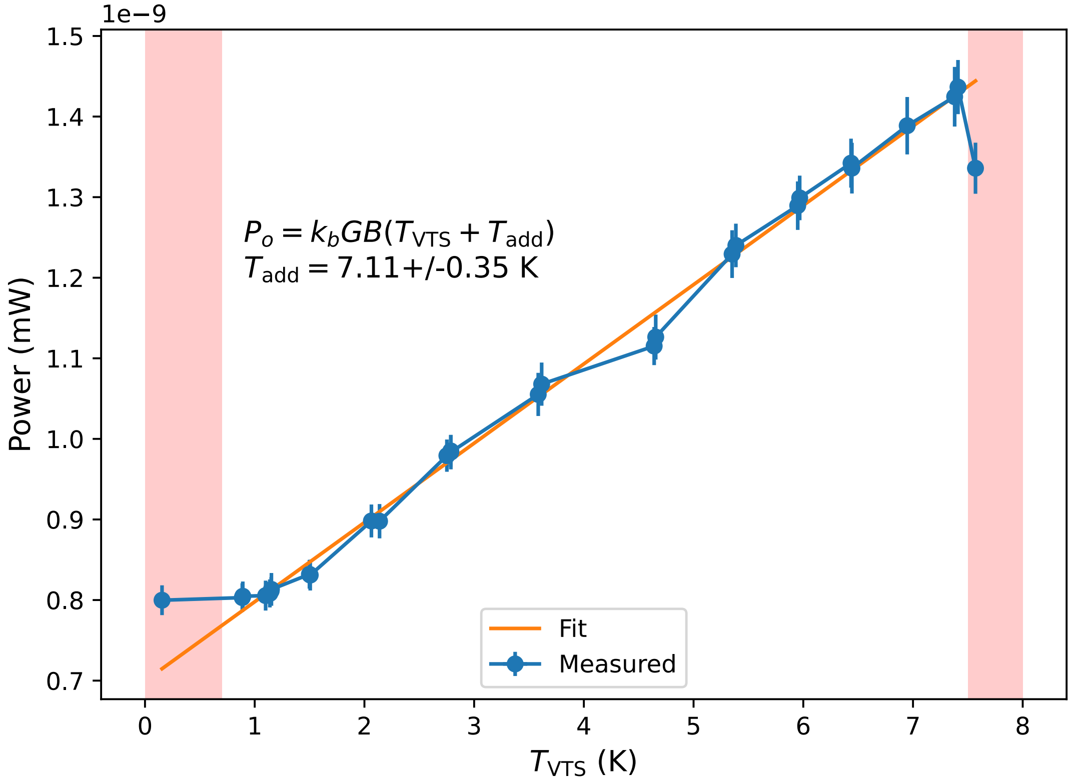
- Ultra-high Q cavities have achieved unprecedented sensitivity to wavelike DPDM and can boost by scan rate by orders of magnitude. Can also be made ultra-tunable.
- Progress towards photon counting and high-Q cavities in magnetic fields for axion searches. Will be enabling technologies for future axion searches. Coming to a Dark Wave Lab near you.



backup

SERAPHv1 Noise calibration with Variable Temperature Stage

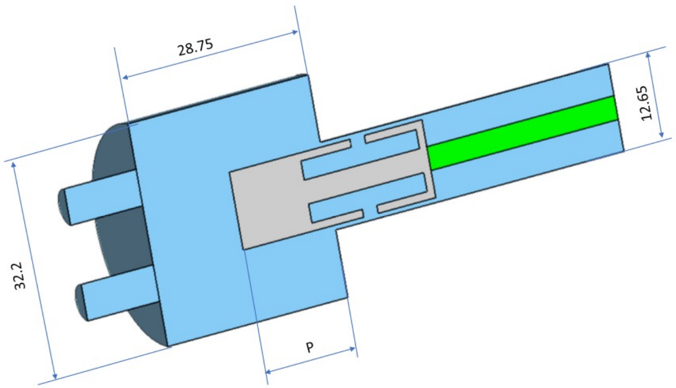


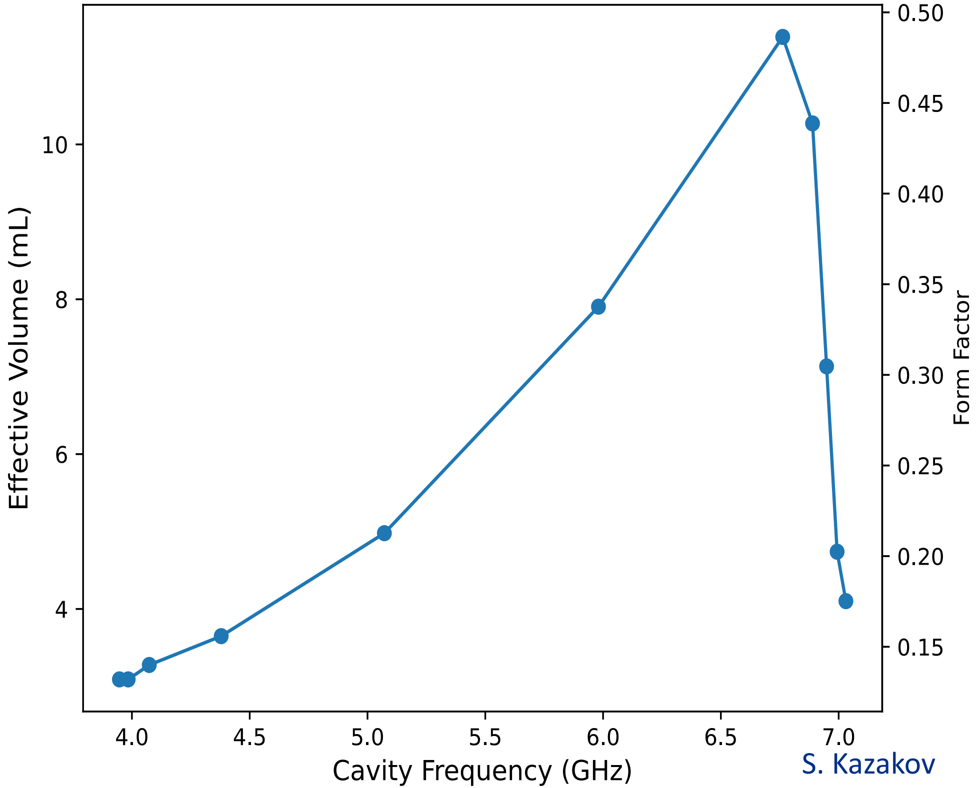


T_{add} consistent with 4.6 K amplifier noise and 2 dB insertion loss.

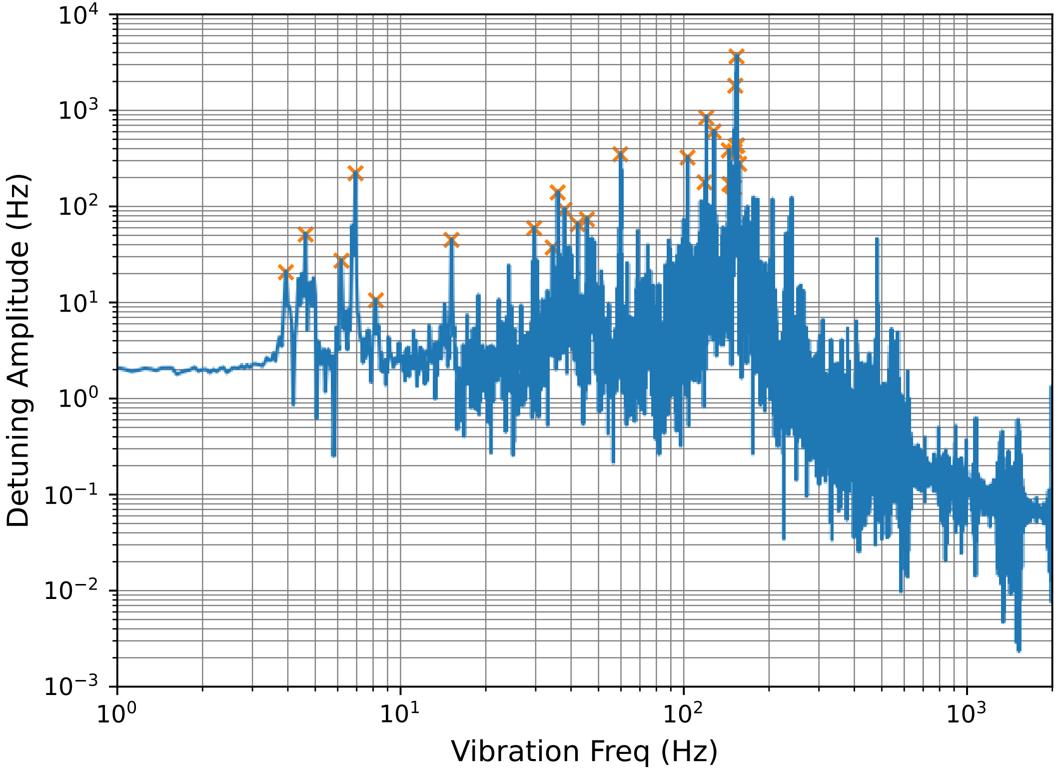
Plunger Cavity Simulated effective volume

$$V_{\mathrm{eff}} = \frac{\left|\int dV\, E_z\right|^2}{\int dV\, |\mathbf{E}|^2}$$





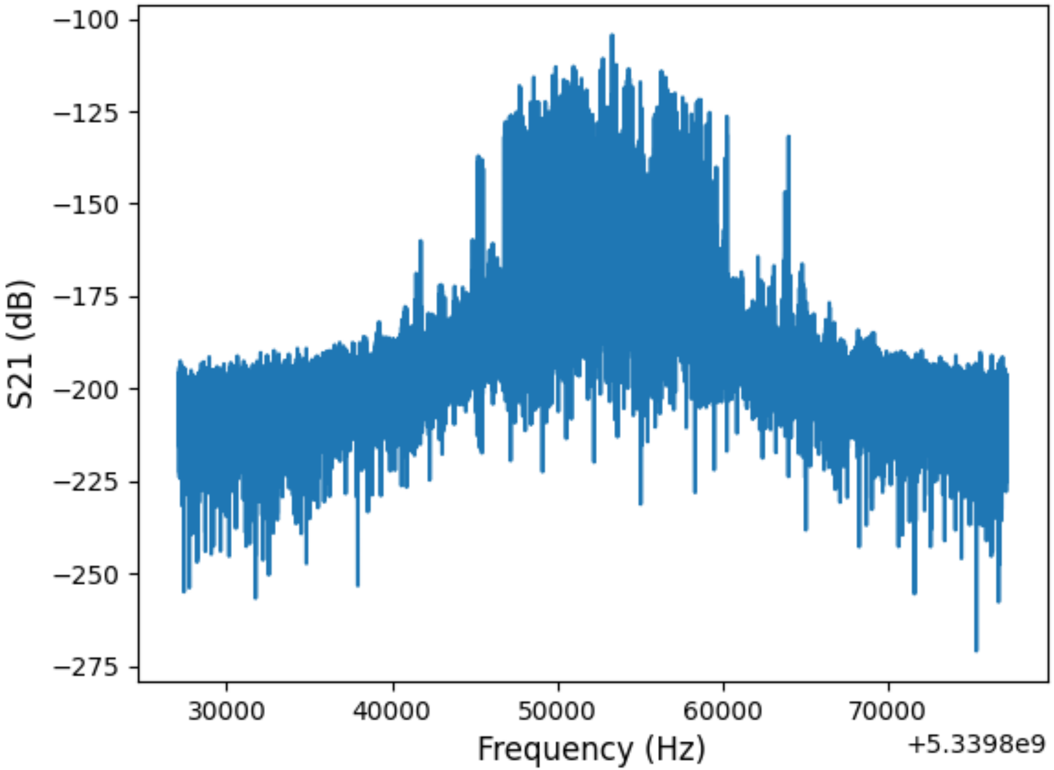
Plunger Cavity Microphonics FFT



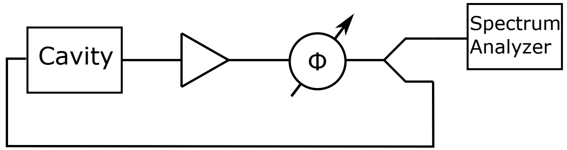
Vibration Frequency	Detuning amplitude / Vibration Frequency
6.9	31.9
153.6	23.7
151.9	11.9
4.6	11.0
120	7.0
59.7	5.9

Plunger Cavity has lots of microphonics in a helium bath

Resonance looks like this with a VNA.

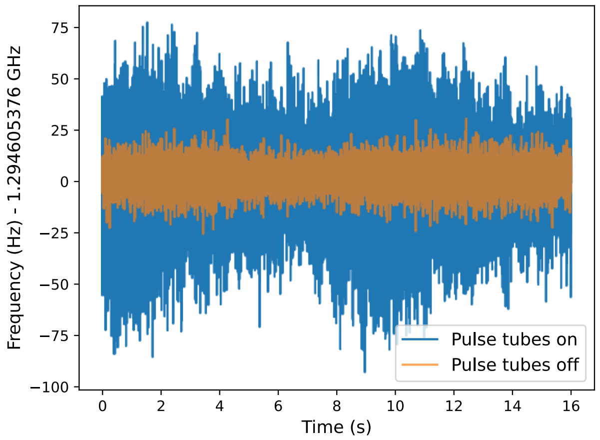


Microphonics

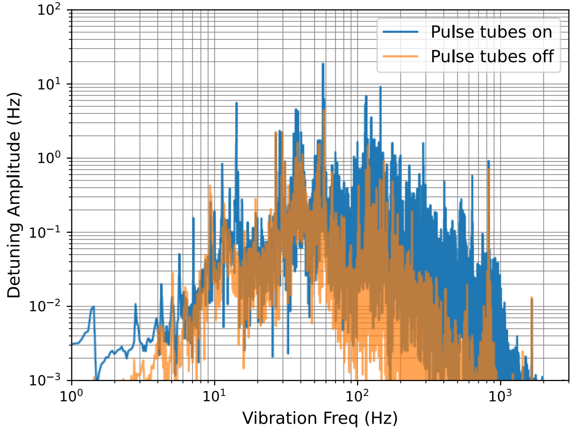


- Measured with self-excitation loop and phase noise analyzer+spectrum analyzer.
- 25 Hz RMS
- Mitigated by turning off pulse tubes (7 Hz RMS), but not viable for a dark matter search.

PNA measurement



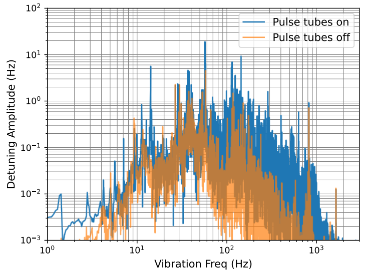
FFT of PNA measurement

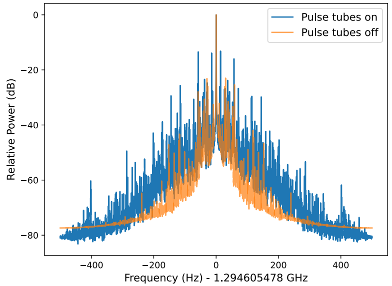


Microphonics and Frequency Modulation

Creates modulation of dark matter signal. Power gets spread into sidebands.

Modulation Frequency f_m (Hz)	Detuning Amplitude f_Δ (Hz)	Modulation Index $\frac{f_m}{f_\Delta}$	Carrier amplitude (dBc)	Sideband amplitude (dBc)
14.3	5.5	0.4	-0.32	-14.5
57.2	18.2	0.3	-0.22	-16.1



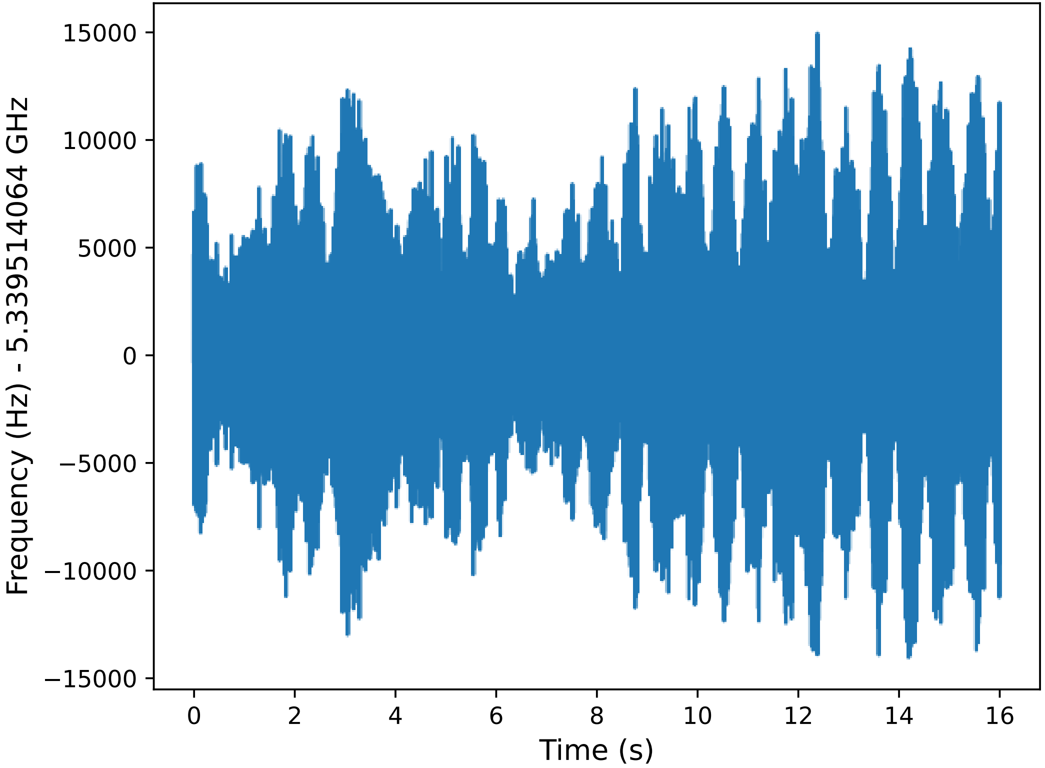


Carrier band attenuated by 0.54 dBc.

DM signal attenuated $\eta \approx 0.88$

Might recover if analysis looks for sidebands.

Plunger Cavity currently has too much microphonics



The RMS of the microphonics is 4.6 kHz!

Currently brainstorming how to mitigate.

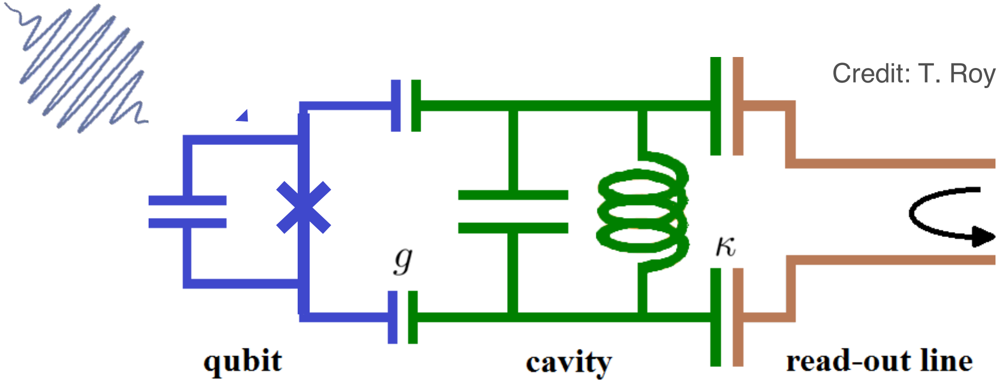
Count Photons with Superconducting Qubits

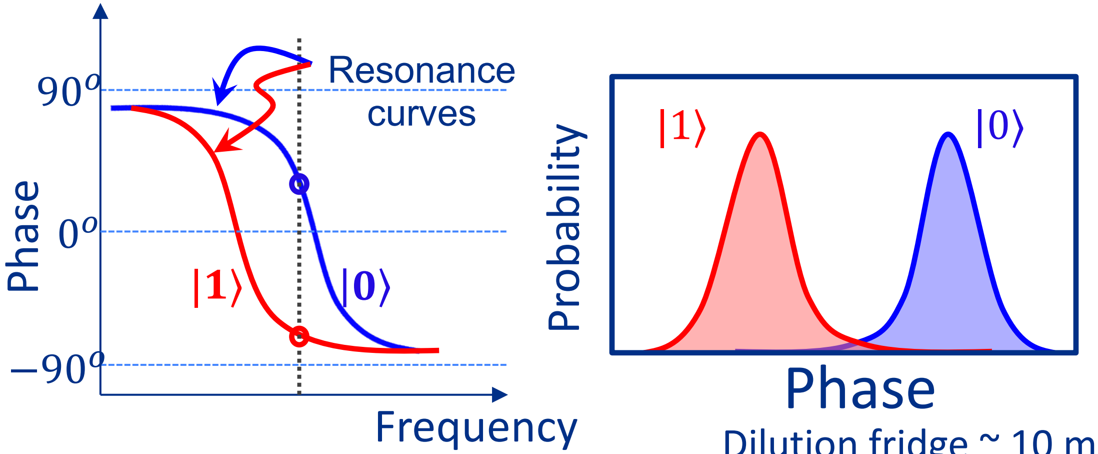
$$\mathcal{H}/\hbar = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

Qubit frequency depends on # of photons.

Can avoid quantum noise if you just count the number of photons and don't try to measure their phase.

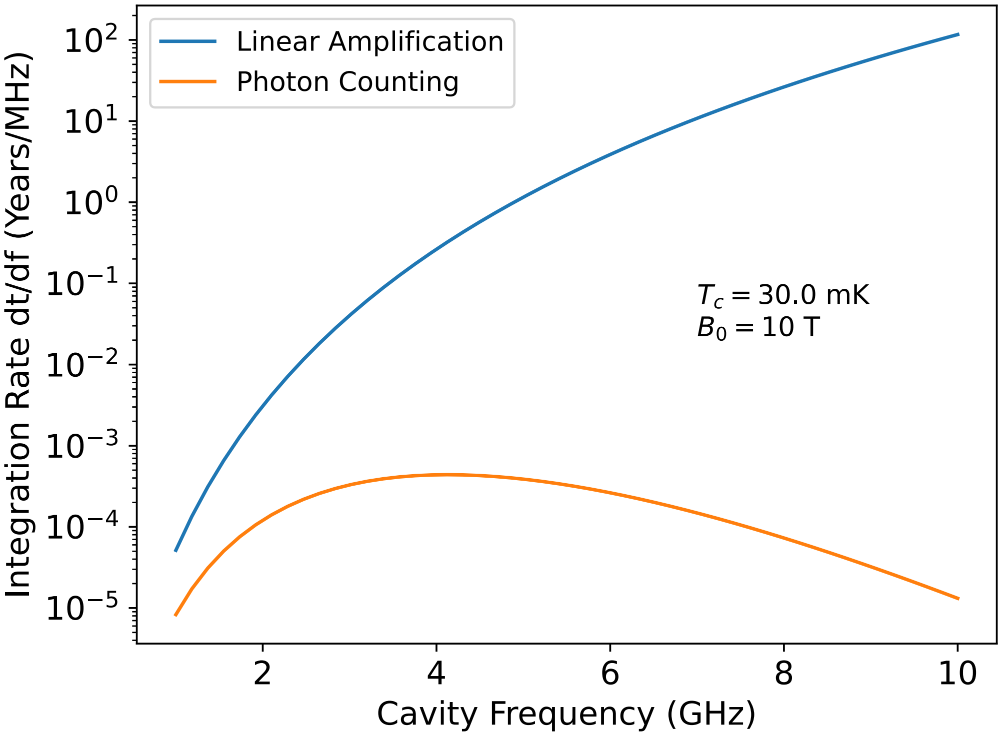
We can use superconducting qubits to count microwave photons inside the cavity.





Dilution fridge ~ 10 mK

Would take long time to scan DFSZ with single cavity



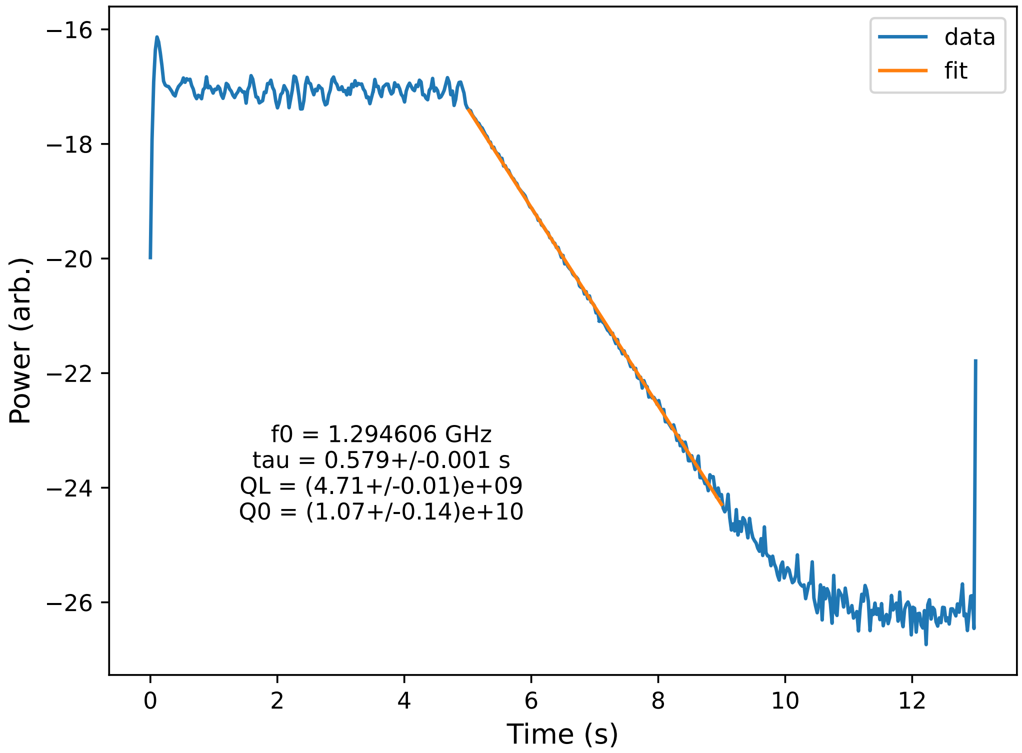
$$V_c = 136\, L \times \left(\frac{f}{1GHz}\right)^{-3}$$

$$Q_L = 80\,000 \times \left(\frac{f}{1GHz}\right)^{-\frac{2}{3}}$$

$$n_c = \frac{1}{\exp\left(\frac{hf}{k_b T}\right) - 1}$$

Note: photon counting estimate doesn't yet take into account counter errors. Numerical estimates sensitive to engineering parameters.

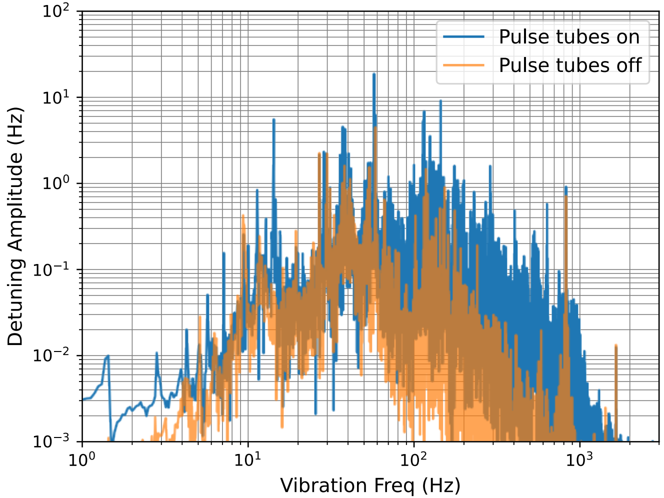
SERAPHv1 Measure Q with decay measurement



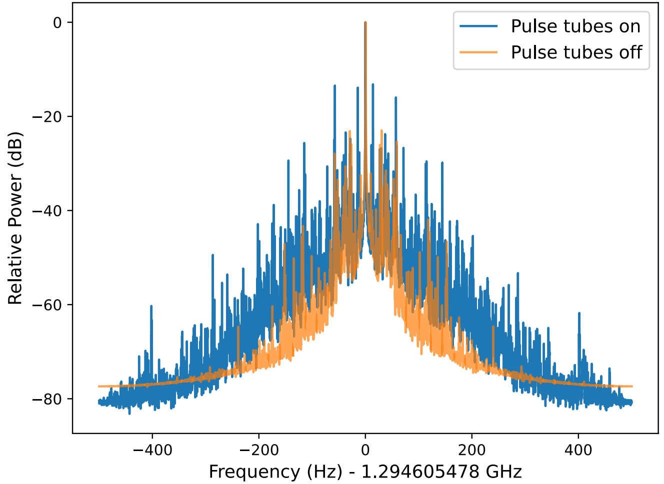
SERAPHv1 Microphonics and Frequency Modulation

Creates modulation of dark matter signal. Power gets spread into sidebands.

FFT of PNA measurement



SA measurement



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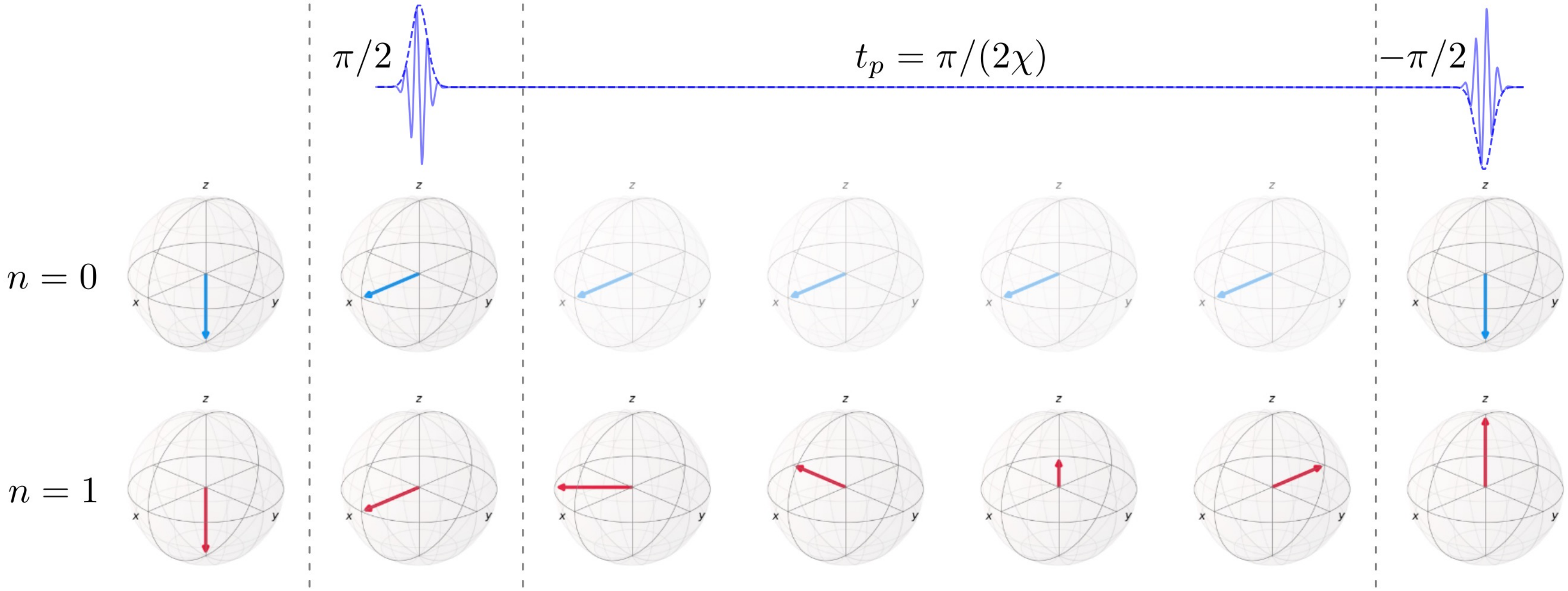
Parity measurement maps cavity state onto qubit



Credit: A. Dixit