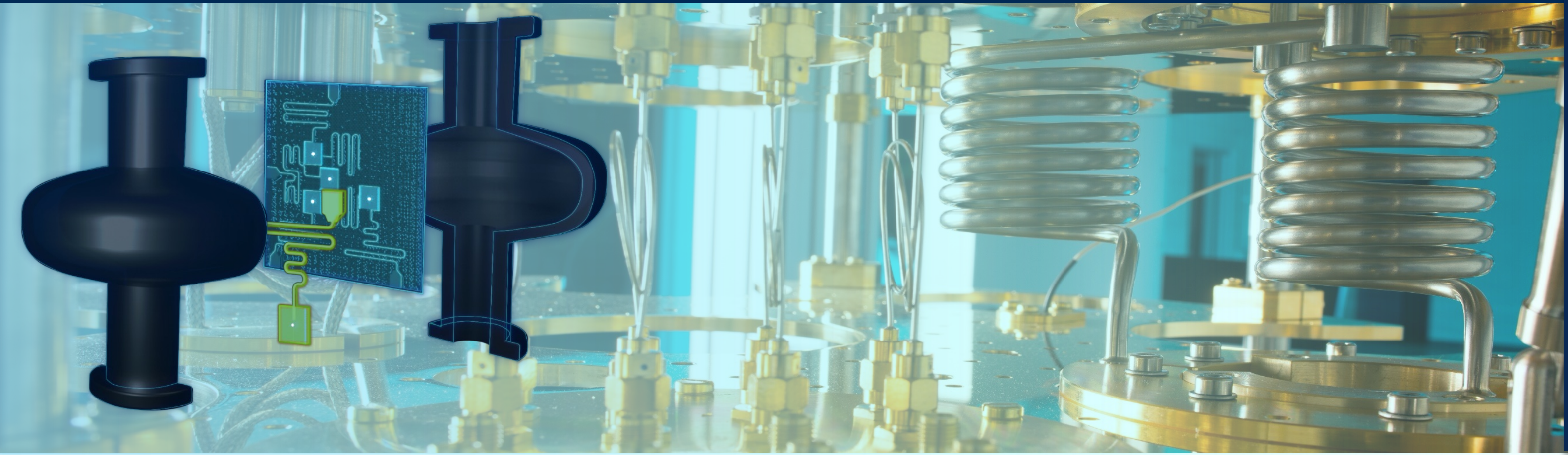
FERMILAB-SLIDES-24-0054-SQMS

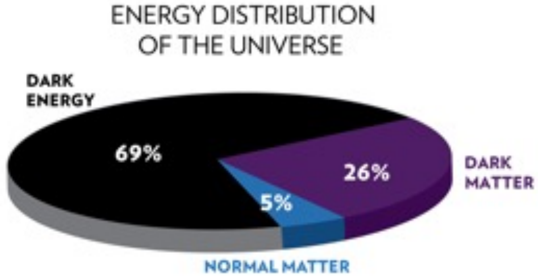


This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

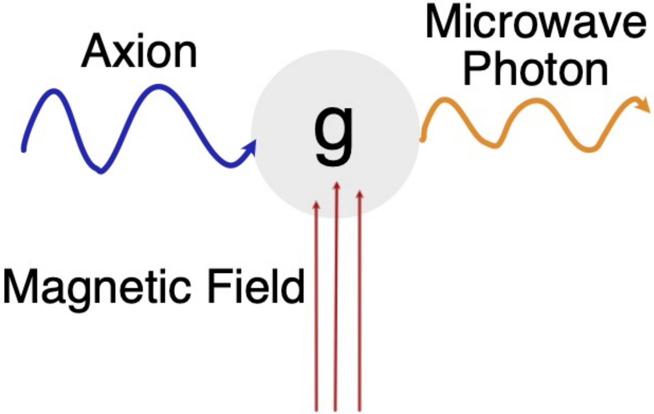
SERAPH: Wavelike Dark Matter Searches with SRF Cavities and Superconducting Qubits at SQMS

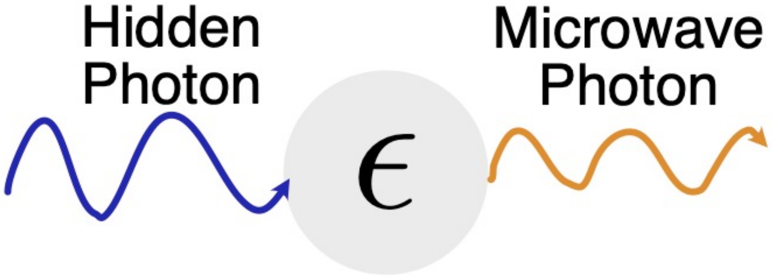
Raphael Cervantes
SQMS, Fermilab

What is Dark Matter?



Can it be Axions? Dark Photons?



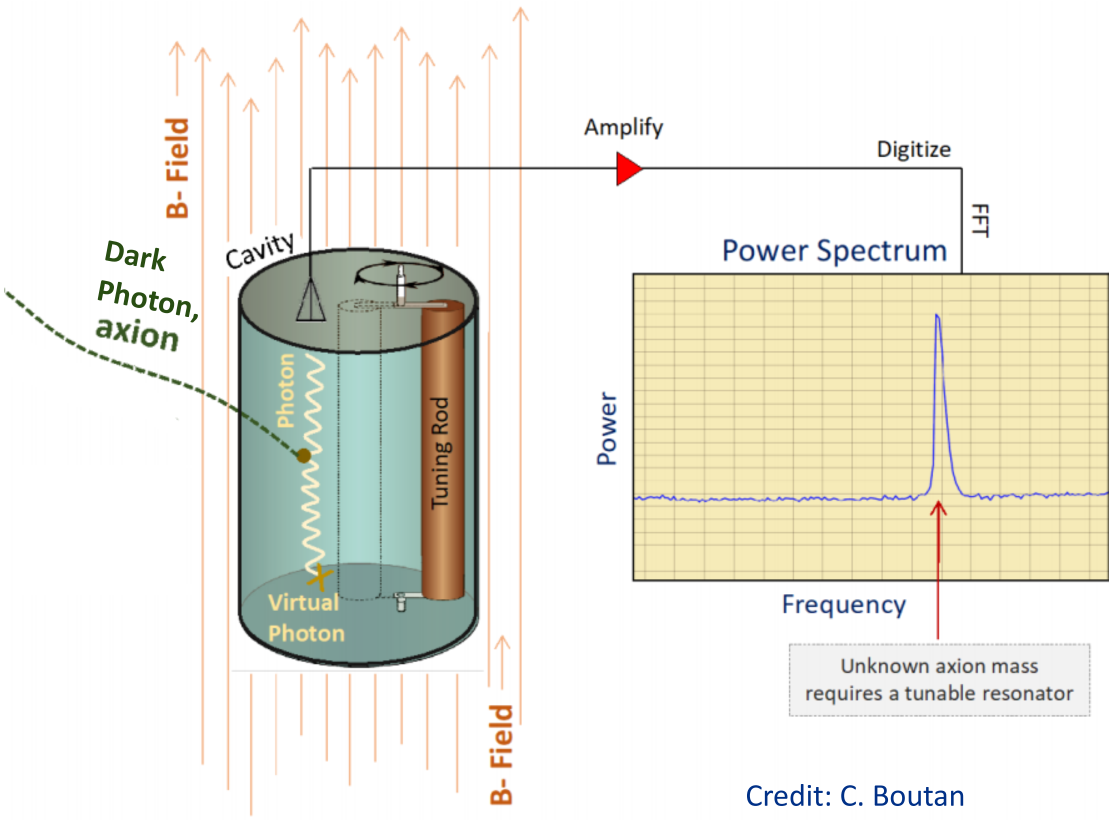


Credit: A. Dixit

Feeble interaction with photons.

We can look for that.

Haloscope Search for Dark Matter



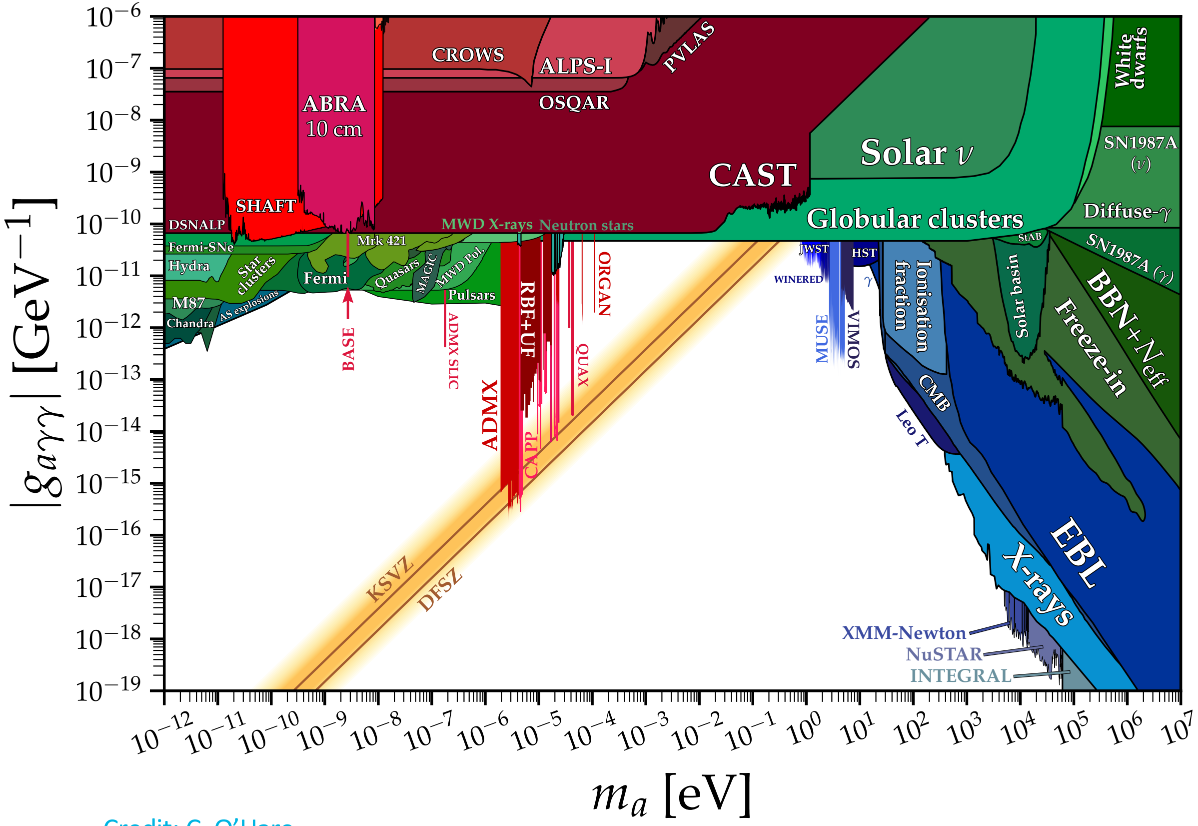
Credit: C. Boutan

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.

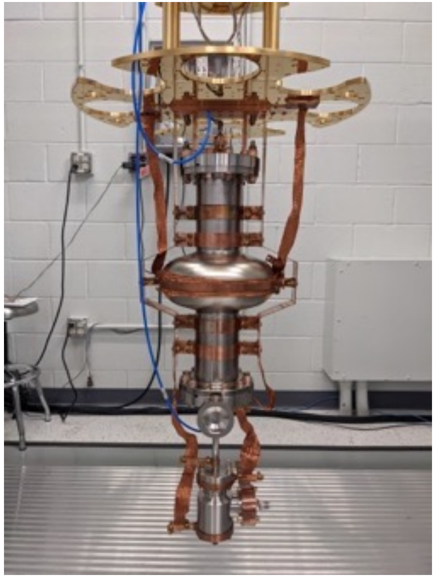
No axions were found (yet).



Credit: C. O'Hare

- No discovery, but still progress because of the excluded parameter space.
- But a lot more parameter space left to explore.

SRF Cavities for Dark Matter Searches



Compared to copper-based searches →

Credit: N. Du

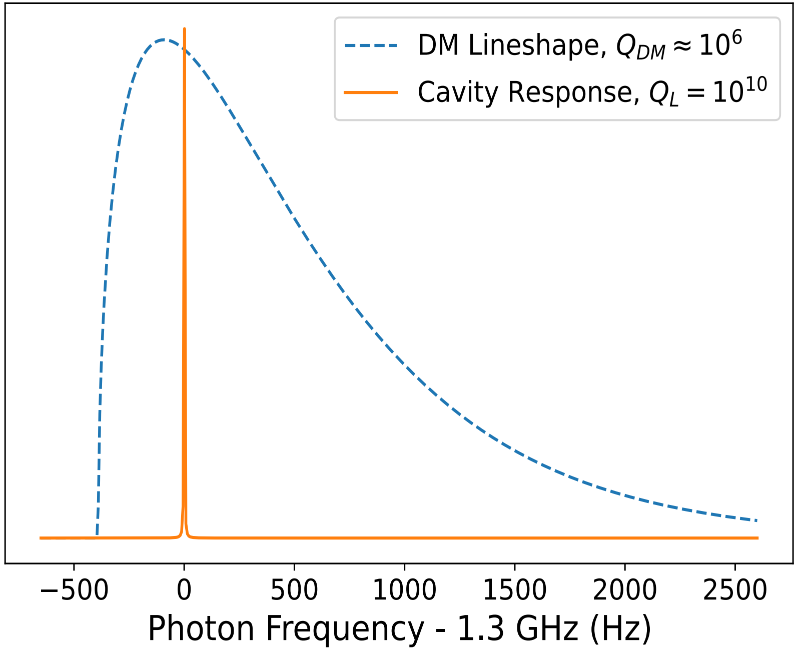
SQMS $\rightarrow Q \approx 10^{10}$

ADMX and CAPP $\rightarrow Q \approx 10^{5}$

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



For virialized axions

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

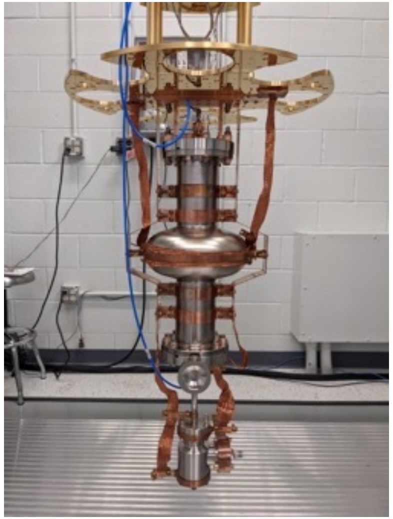
even if $Q_L \gg Q_{DM}$

- 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.

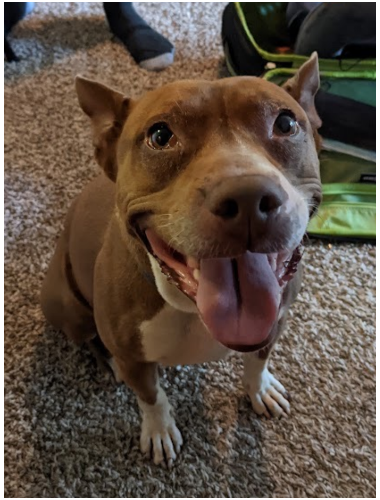
More details: [arXiv:2208.03183]

SERAPH: SupERconducting Axion and Paraphoton Haloscope

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



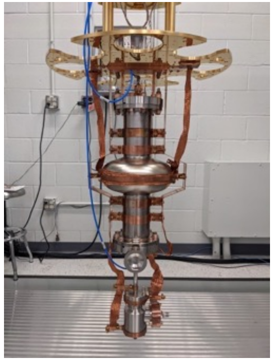
SRF



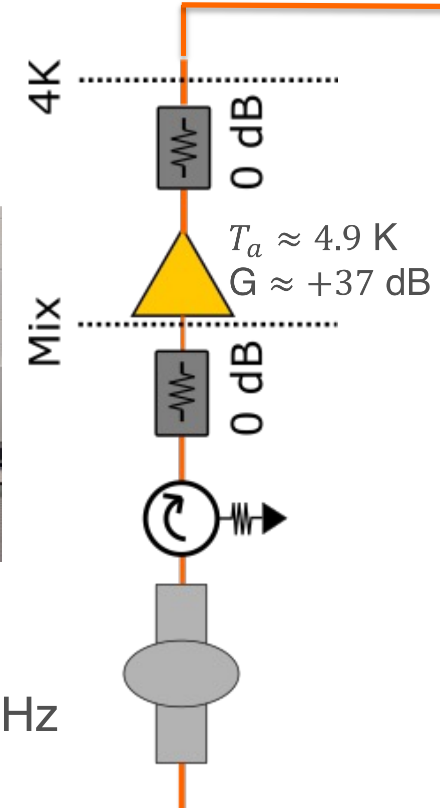
Seraphine

Sir Raph(ael)

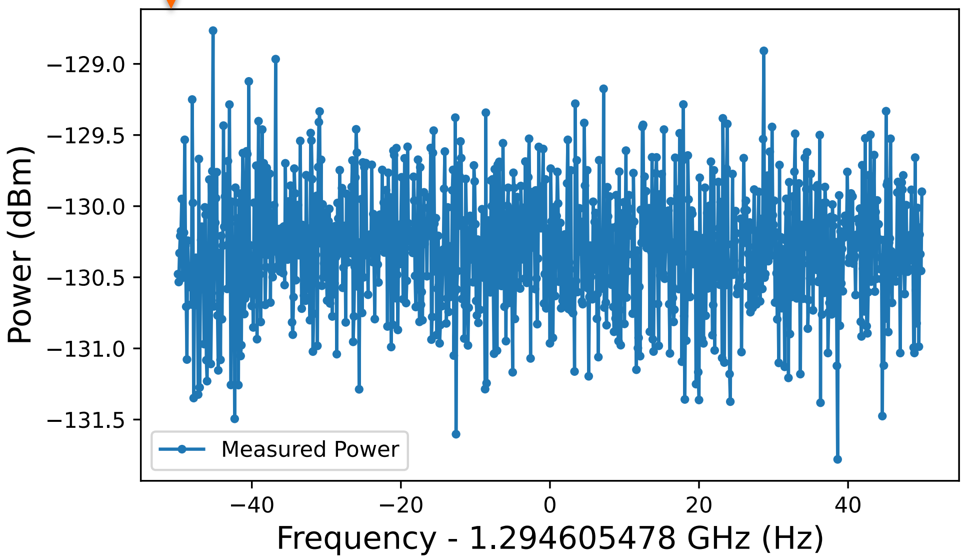
SERAPHv1: Parasitic Search for Dark Photons



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

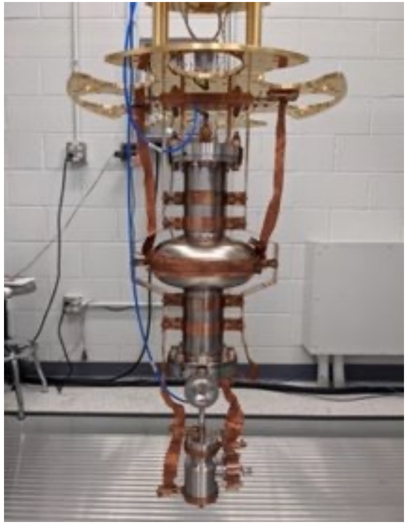


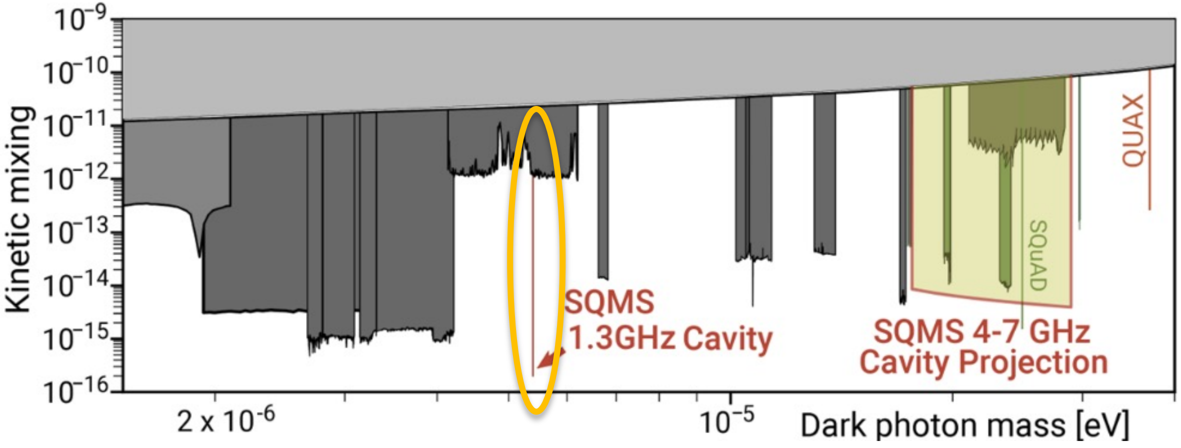
No DP signal. Just noise.



1000 seconds integration time

Deepest sensitivity: Ultrahigh Q for Dark photon DM





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

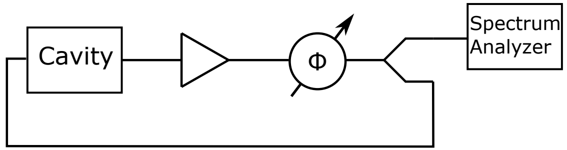
DPDM search in DR with 1.3 GHz cavity with $Q_0 \approx 10^{10}$.

Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

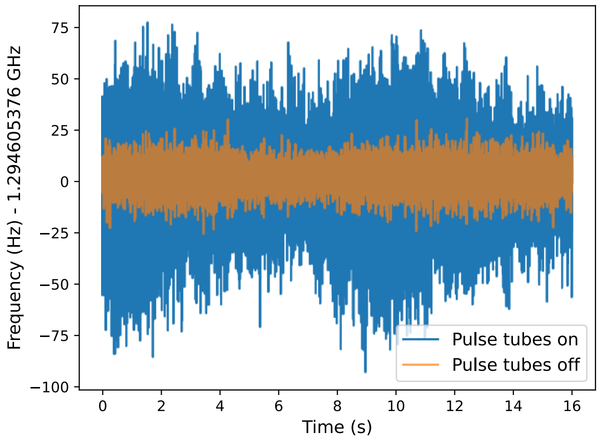
- Tunable DPDM search from 4-7 GHz ("low hanging fruit")
- Implement photon counting to subvert SQL noise limit.

SERAPHv1 Microphonics

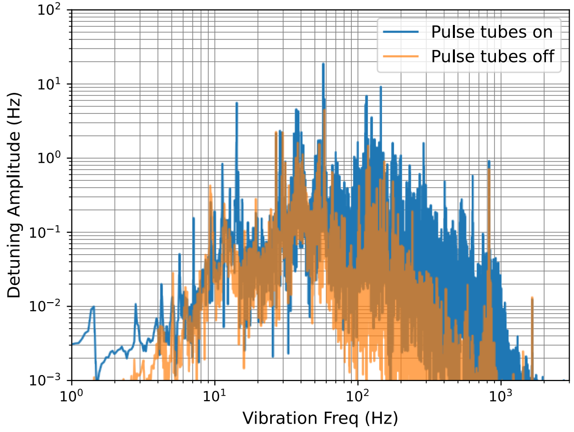


- Measured with self-excitation loop and phase noise analyzer+spectrum analyzer.
- 25 Hz RMS
- Mitigated by turning off pulse tubes (7 Hz RMS), but not viable for a dark matter search.

PNA measurement



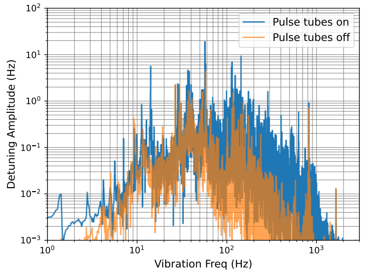
FFT of PNA measurement

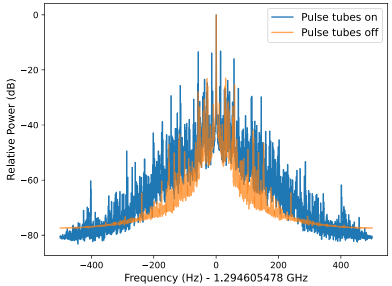


SERAPHv1 Microphonics and Frequency Modulation

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



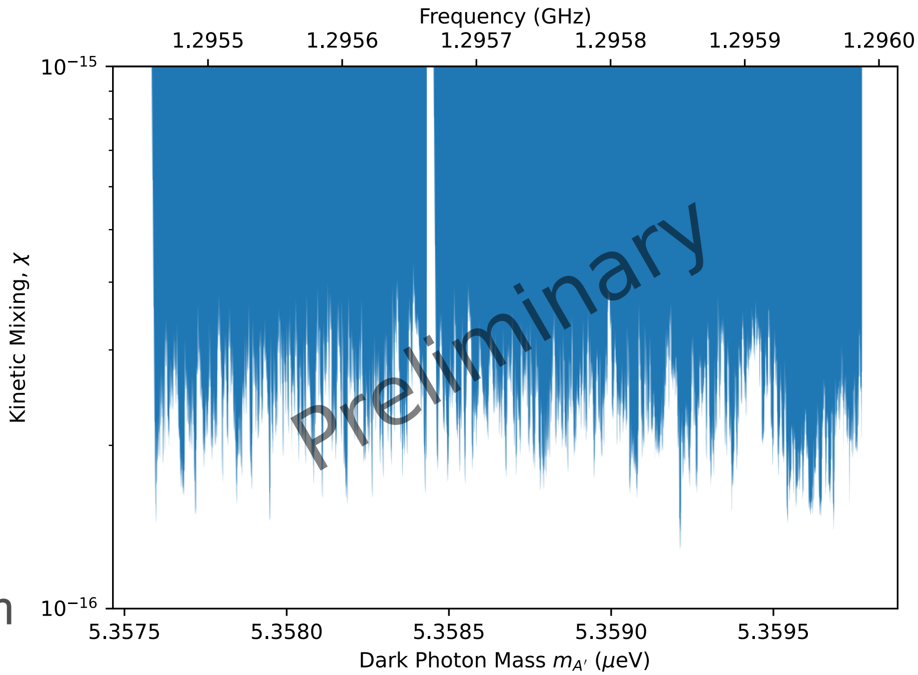


Carrier band attenuated by 0.54 dBc.

DM signal attenuated $\eta \approx 0.88$

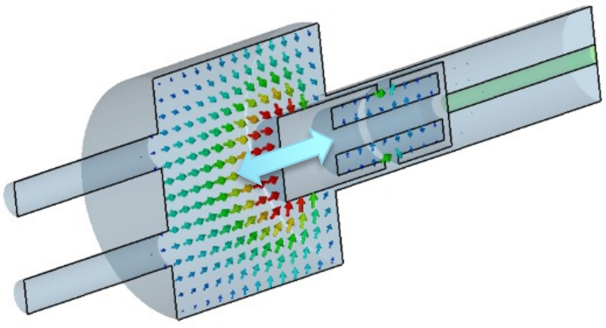
Might recover if analysis looks for sidebands.

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

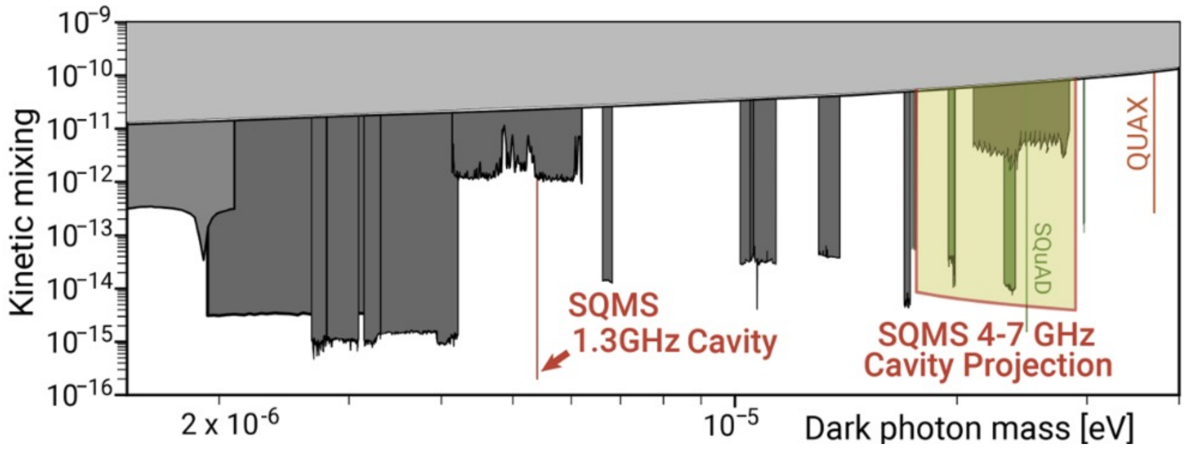


Similar 1.3 GHz cavity in liquid helium bath. Tunes by mechanical compression for 500 kHz tuning range. T_{cav} = 1.4 K, Q_L = 2.4e8. Very overcoupled.

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:

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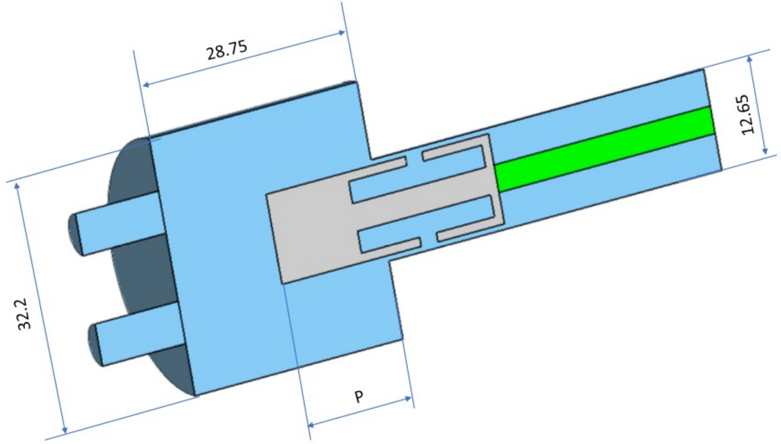
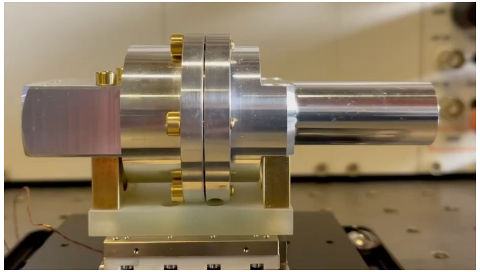
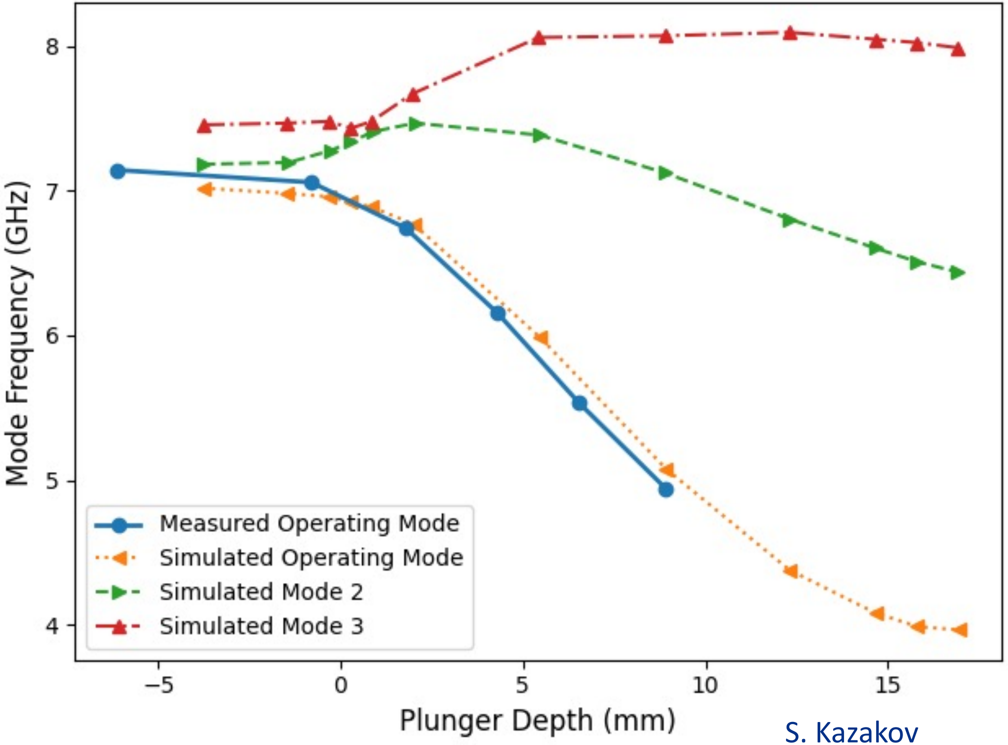
- Implement photon counting to subvert SQL noise limit.

SERAPHv2: Simulated and measured modes



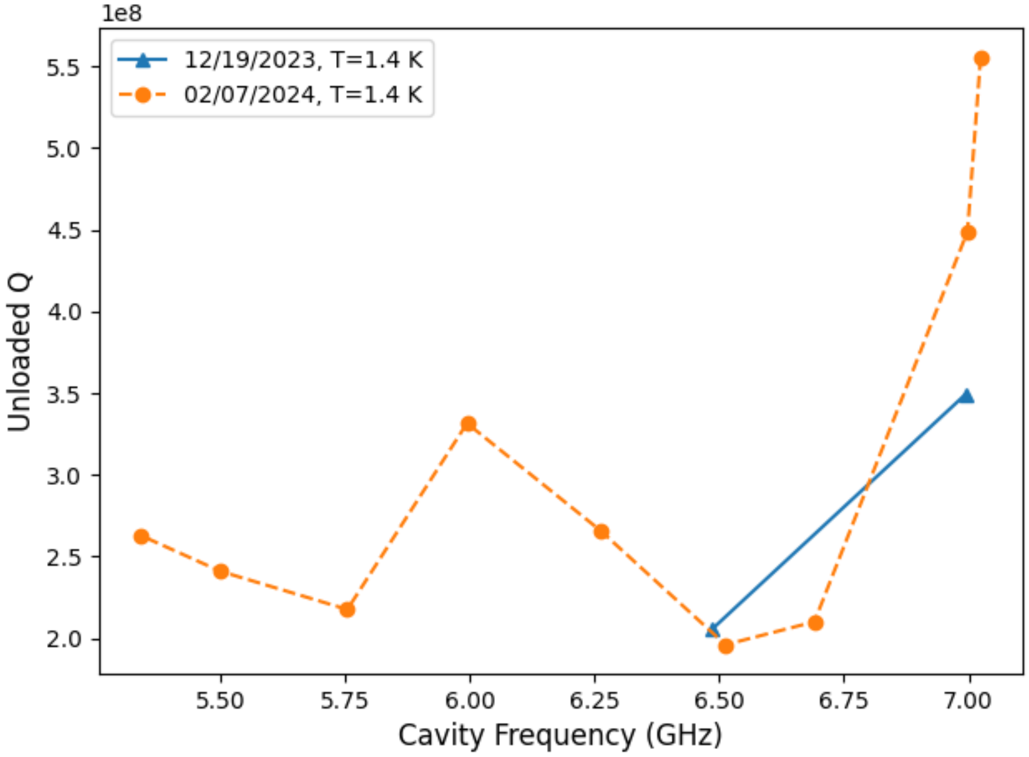




S. Kazakov

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

Measured Unloaded Q with decay measurement

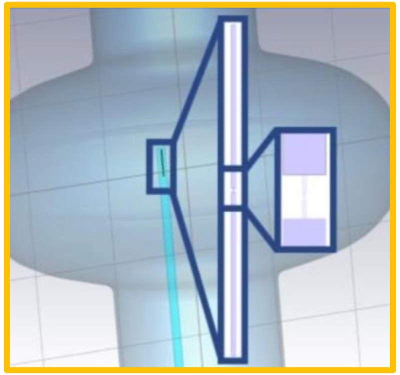


Cavity Q can improve but is acceptable.

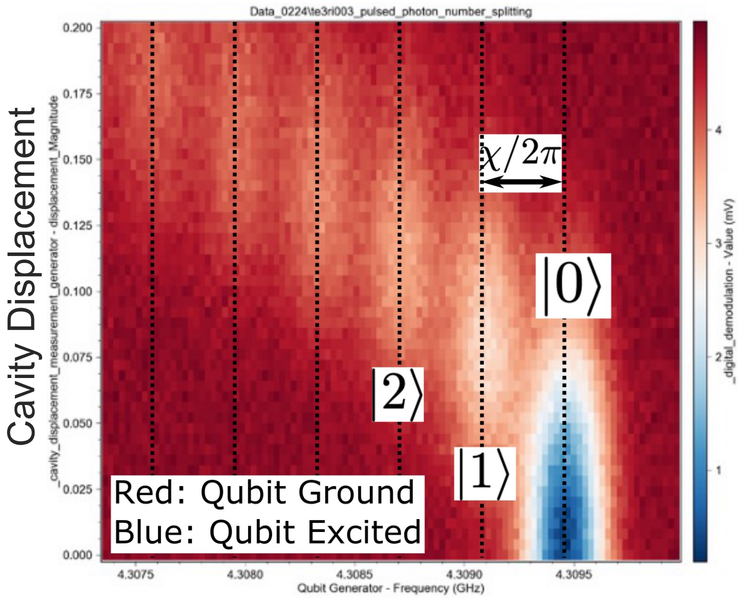
Next steps:

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.



Credit: T. Kim

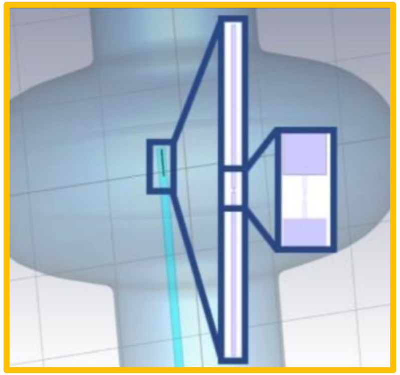
Quantum protocols counts photons non-destructively.

SQL noise: hf/k
240 mK @ 5 GHz

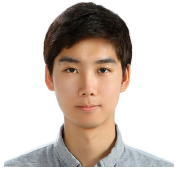
dominates compared to 30 mK thermal photons.

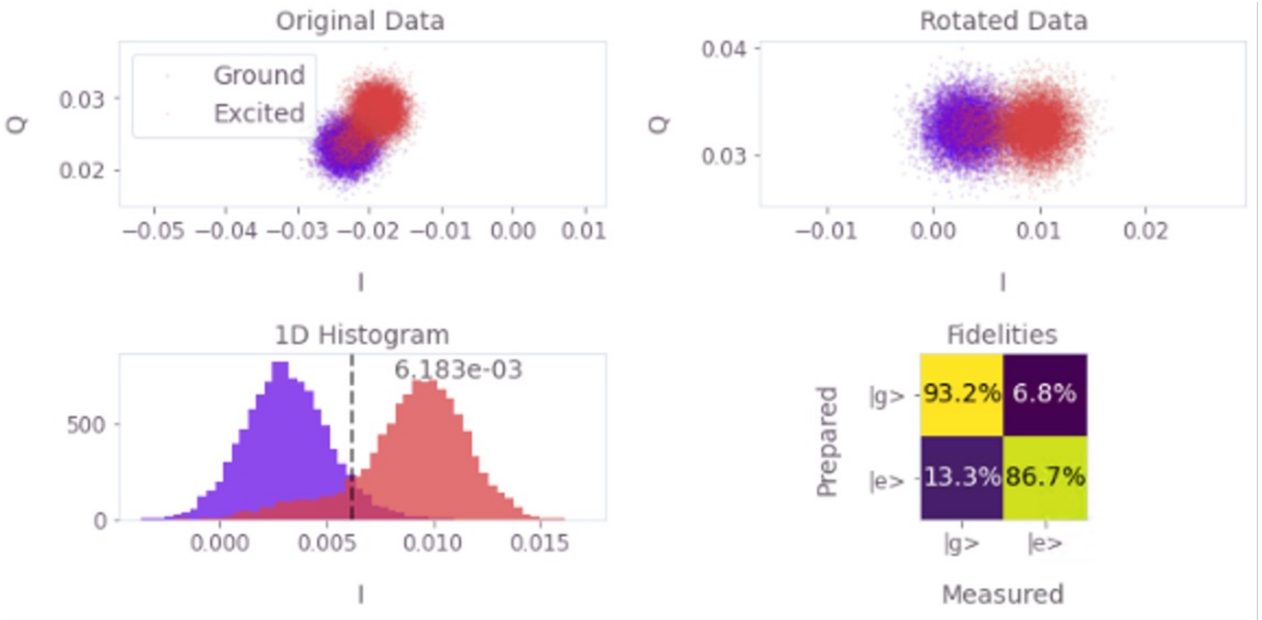
Regularly perform photon counting with dispersive measurements.

Current photon counting scheme



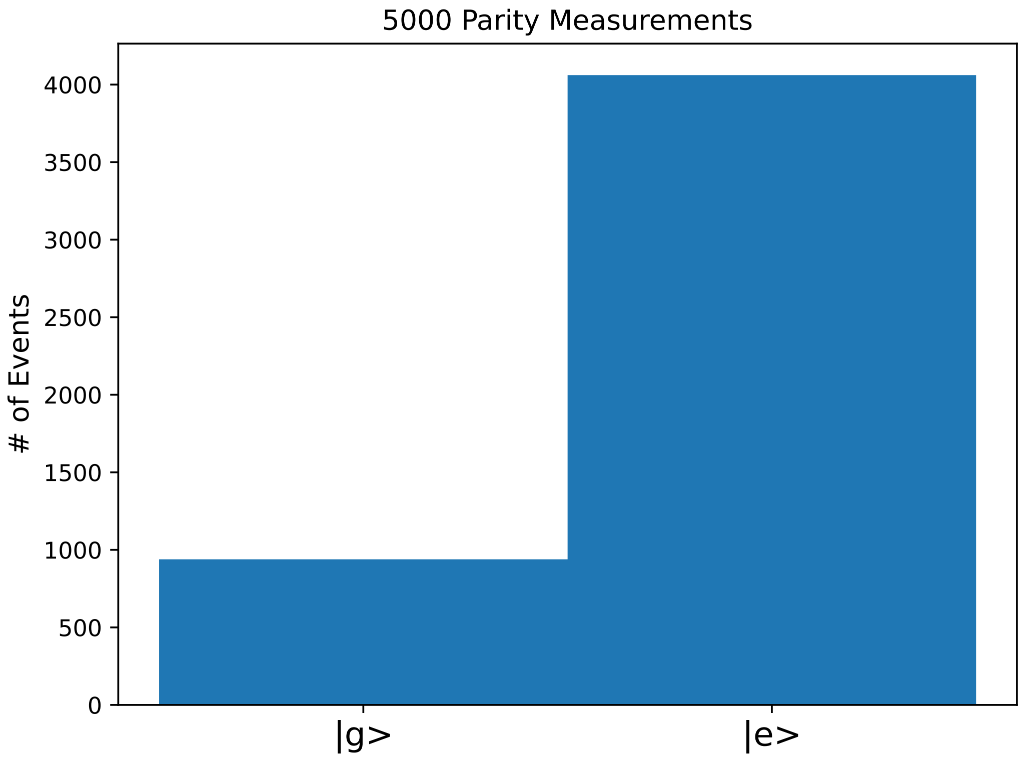
Measurements performed by Taeyoon Kim





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.

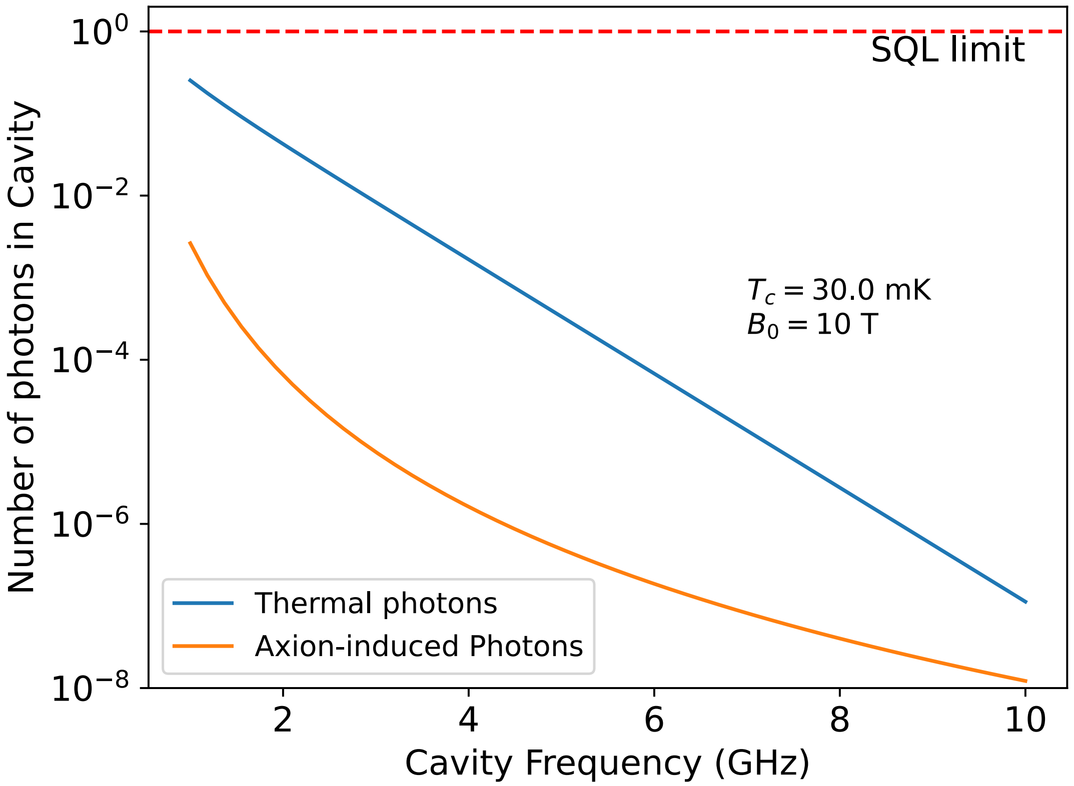
With perfect readout:

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.

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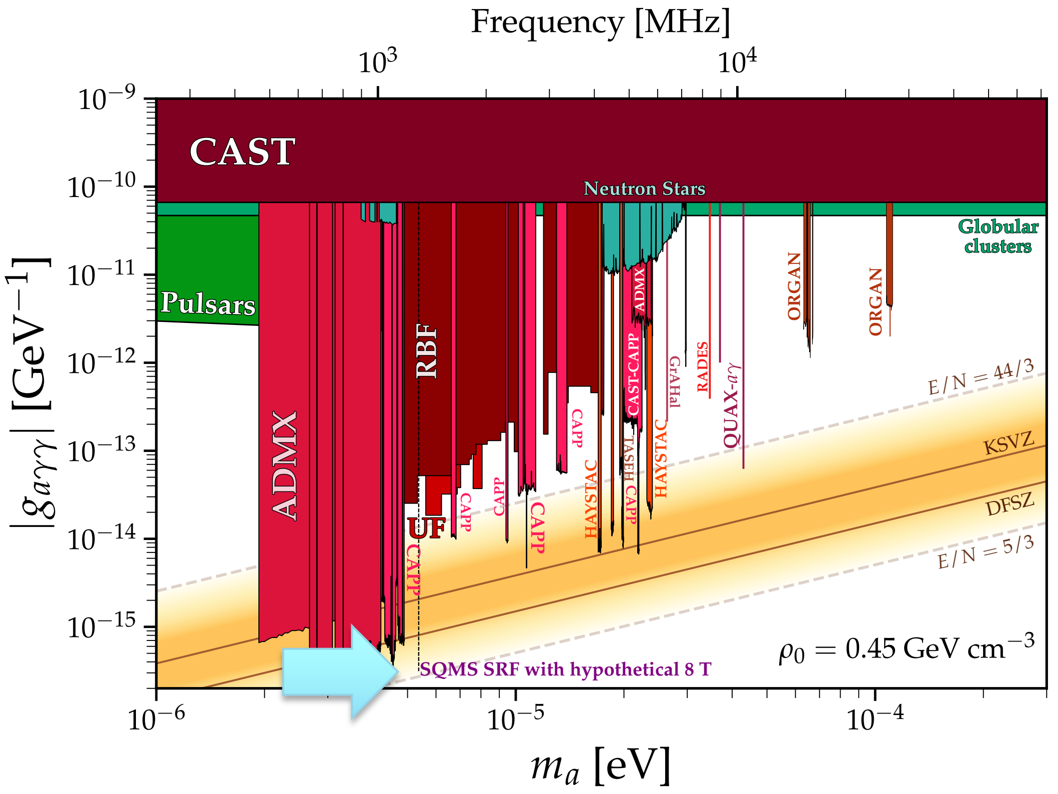
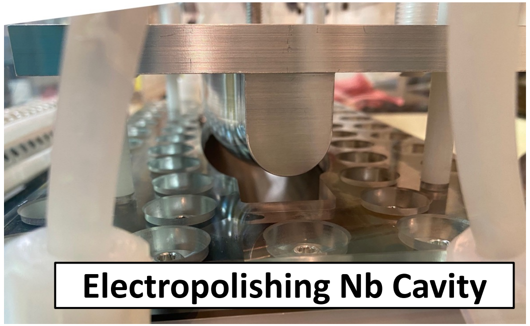
If Q~10^{10} cavities work in an 8T field

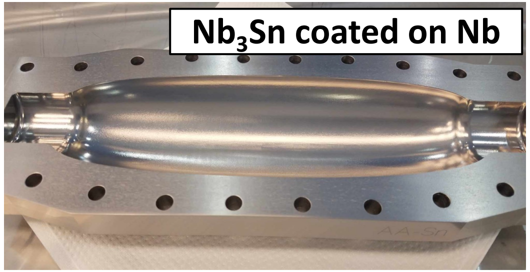


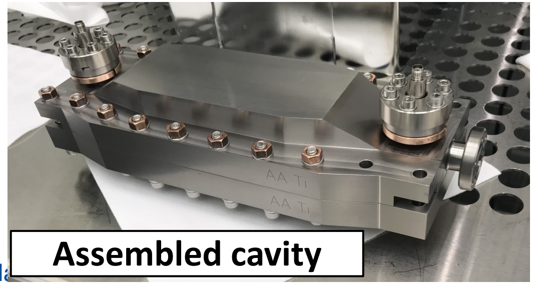
Sensitivity to **QCD axion** with single cavity and HEMT.

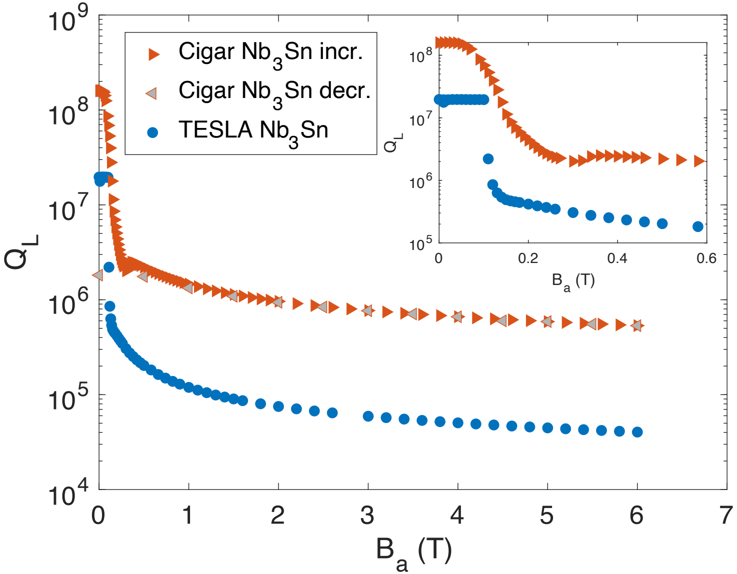
Just make $Q \sim 10^{10}$ cavities work in magnetic fields!

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









Q_0 of 5×10^5 at 6 T, 4.2 K, 3.9 GHz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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

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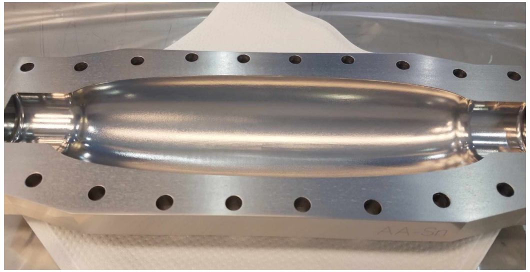
FNAL Nb_3Sn Cavities for ADMX and INFN

Initial R&D at Fermilab



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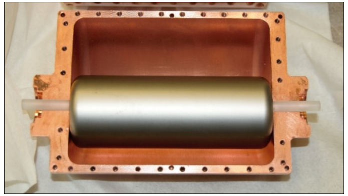
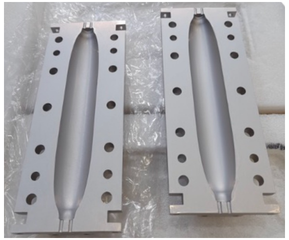
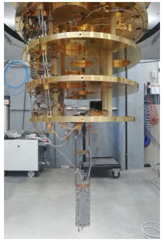
Prototypes sent to Partners



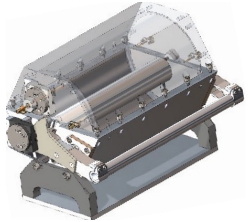
Nb_3Sn tuning rod for ADMX Sidecar sent to U. Washington (w/ LLNL)





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

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

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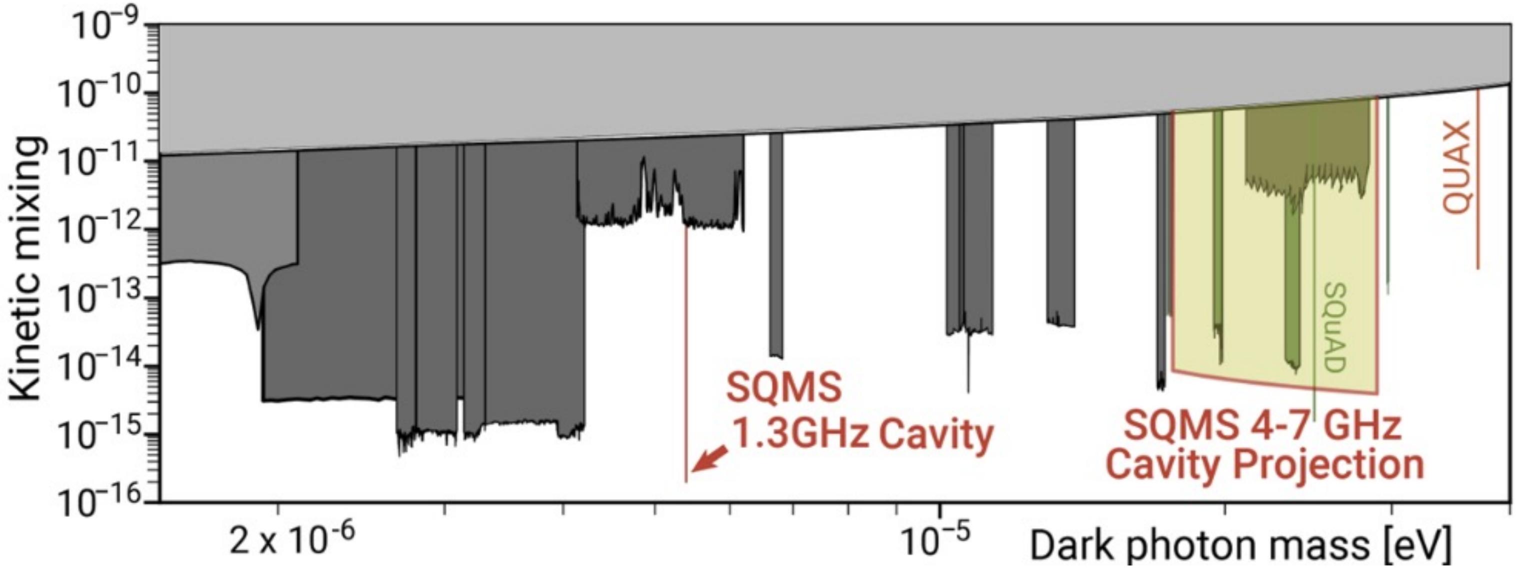
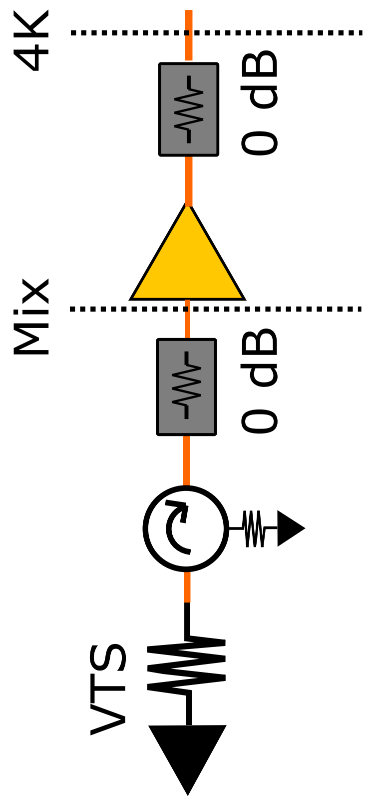
Summarize

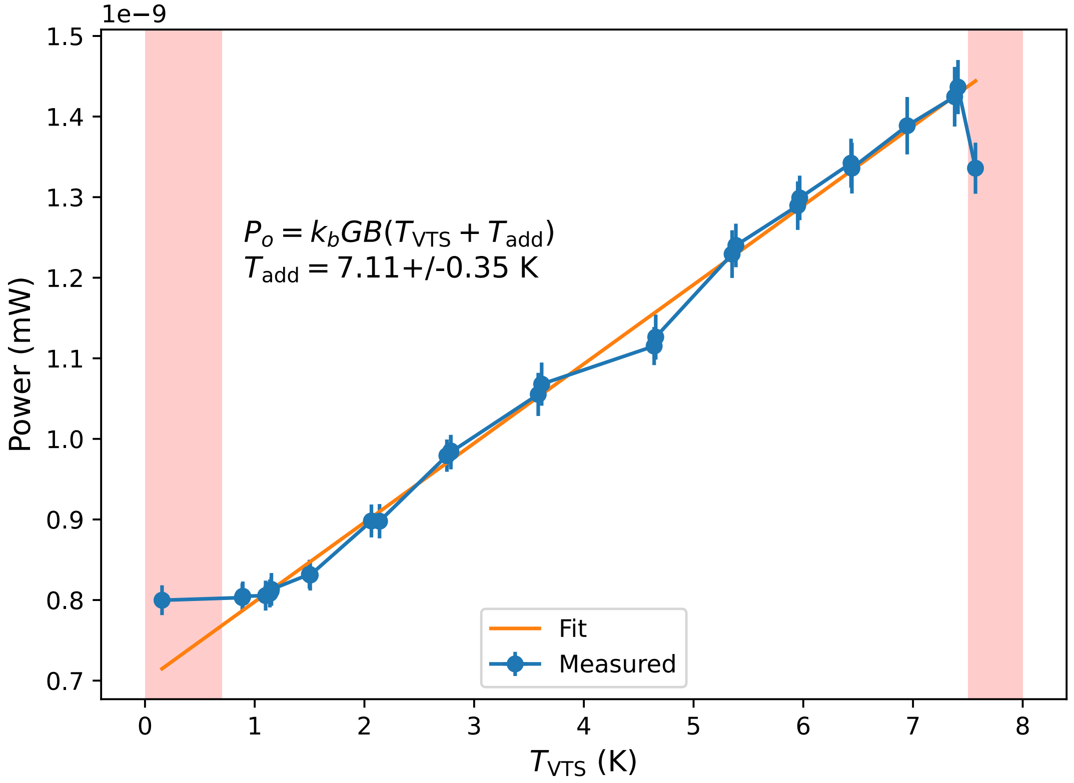
- Ultra-high Q cavities have achieved unprecedented sensitivity to wavelike DPDM and can boost by scan rate by orders of magnitude.
- Progress towards photon counting and high-Q cavities in magnetic fields for axion searches. Will be enabling technologies for future axion searches.



backup

SERAPHv1 Noise calibration with Variable Temperature Stage

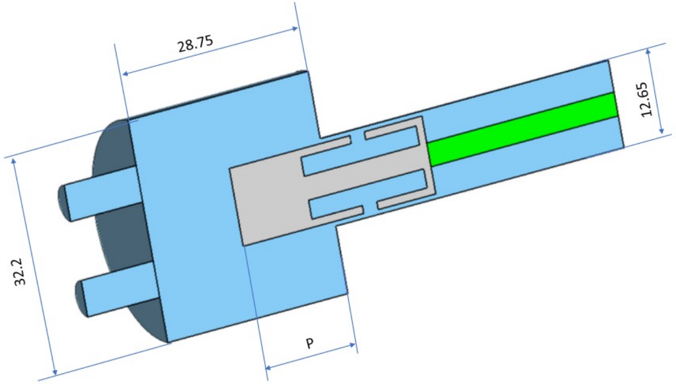


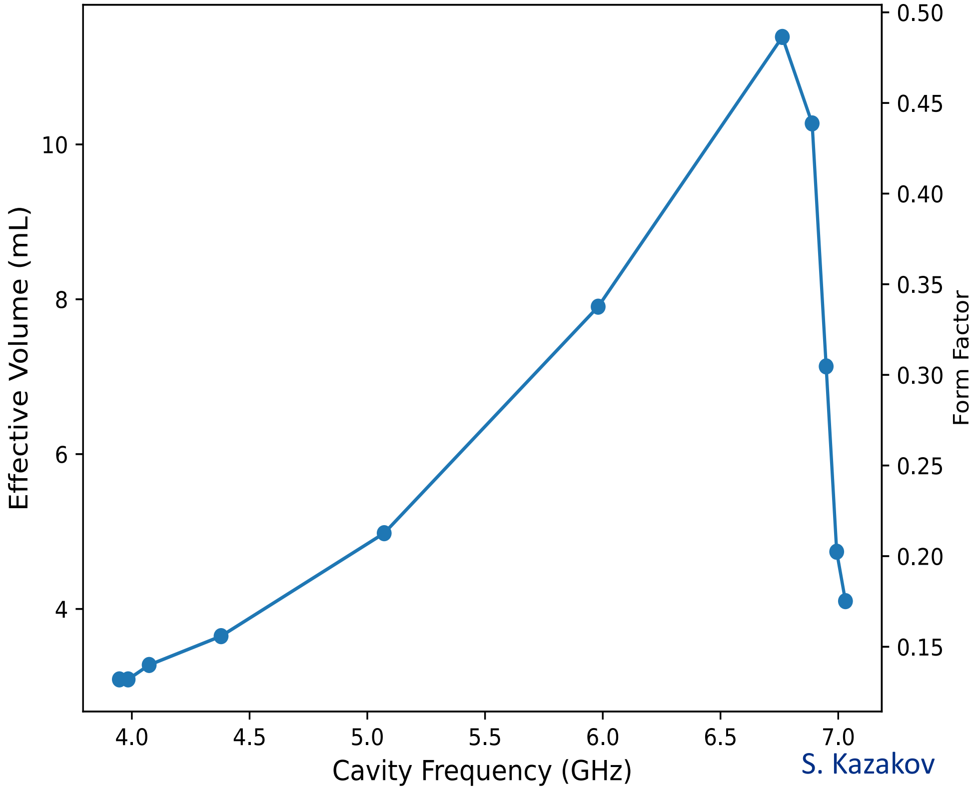


T_{add} consistent with 4.6 K amplifier noise and 2 dB insertion loss.

Plunger Cavity Simulated effective volume

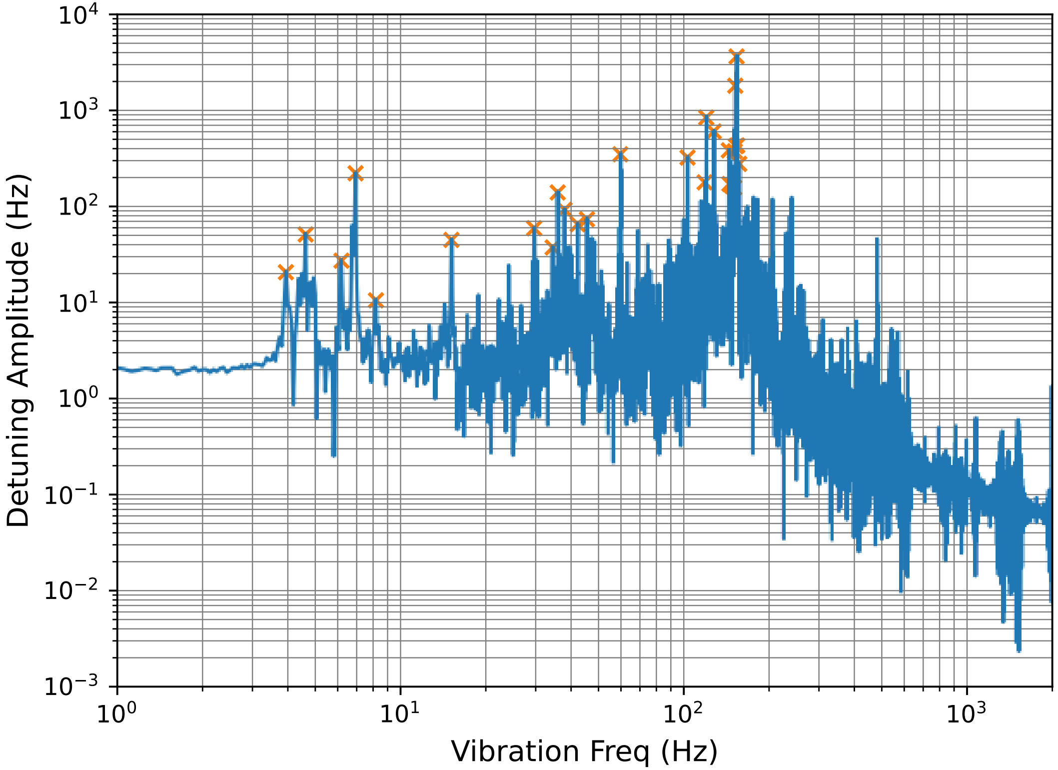
$$V_{\text{eff}} = \frac{\left|\int dV\, E_z\right|^2}{\int dV\, |\mathbf{E}|^2}$$





S. Kazakov

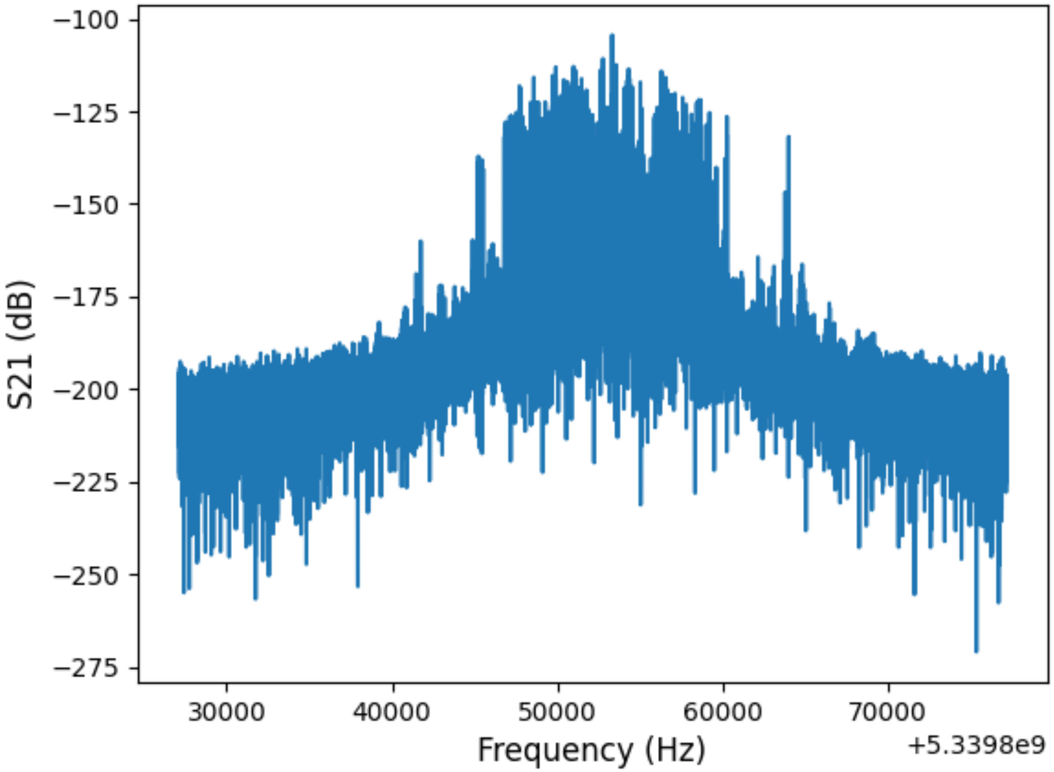
Plunger Cavity Microphonics FFT



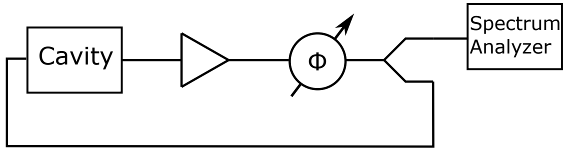
Vibration Frequency	Detuning amplitude / Vibration Frequency
6.9	31.9
153.6	23.7
151.9	11.9
4.6	11.0
120	7.0
59.7	5.9

Plunger Cavity has lots of microphonics in a helium bath

Resonance looks like this with a VNA.

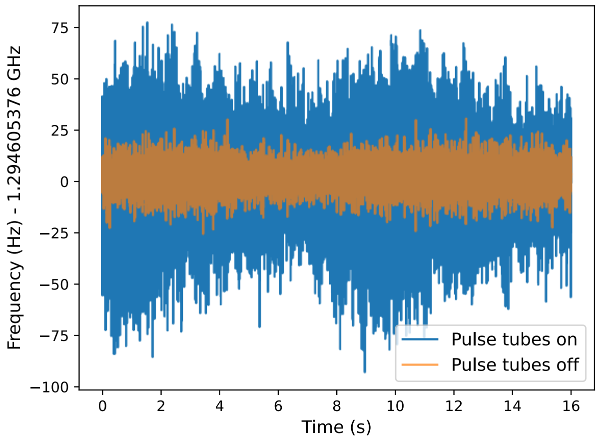


Microphonics

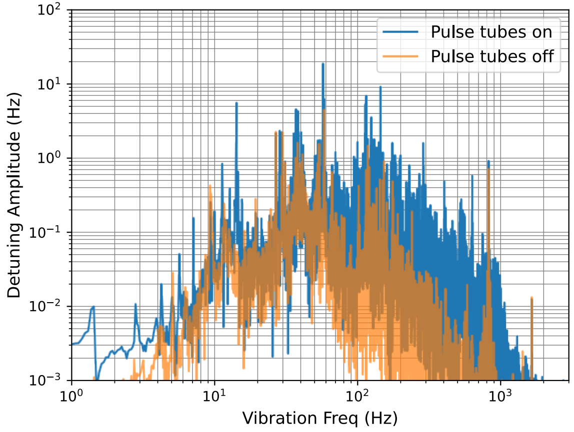


- Measured with self-excitation loop and phase noise analyzer+spectrum analyzer.
- 25 Hz RMS
- Mitigated by turning off pulse tubes (7 Hz RMS), but not viable for a dark matter search.

PNA measurement



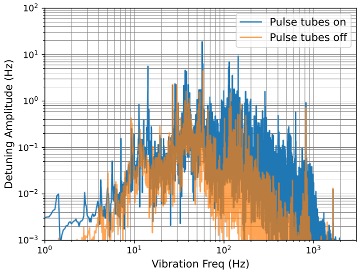
FFT of PNA measurement

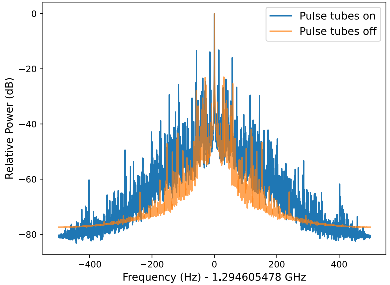


Microphonics and Frequency Modulation

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



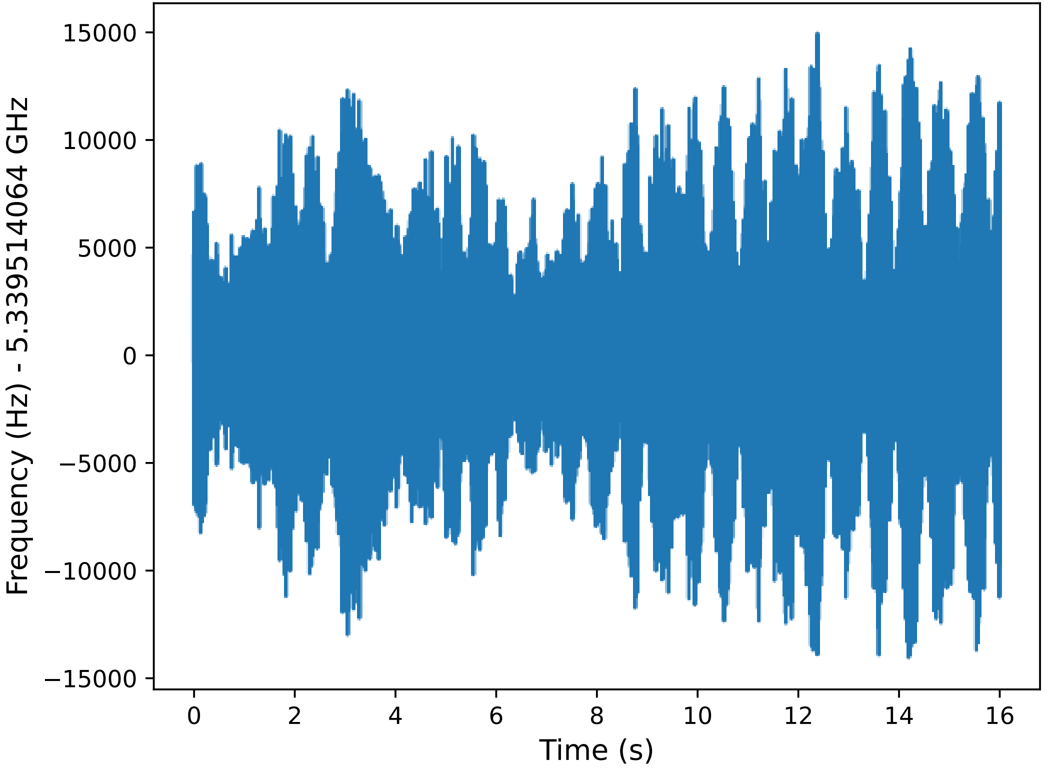


Carrier band attenuated by 0.54 dBc.

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.

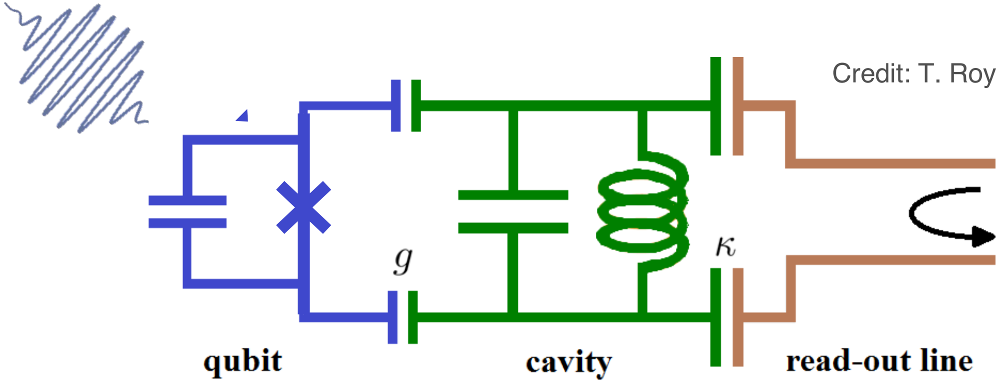
Count Photons with Superconducting Qubits

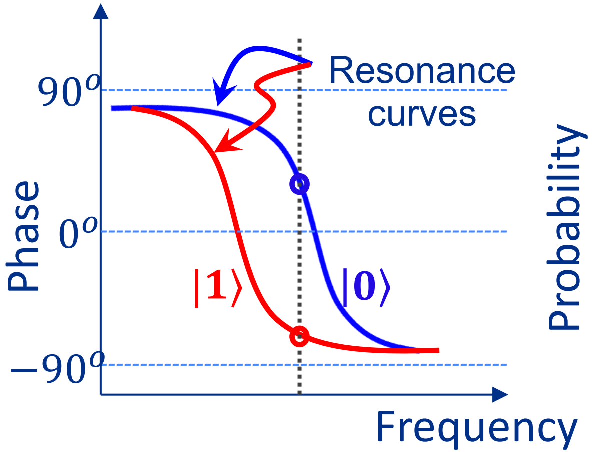
$$\mathcal{H}/\hbar = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

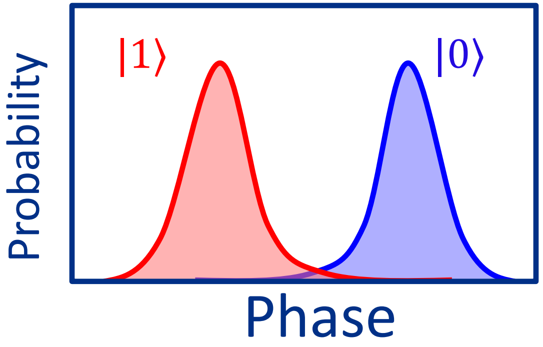
Qubit frequency depends on # of photons.

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.

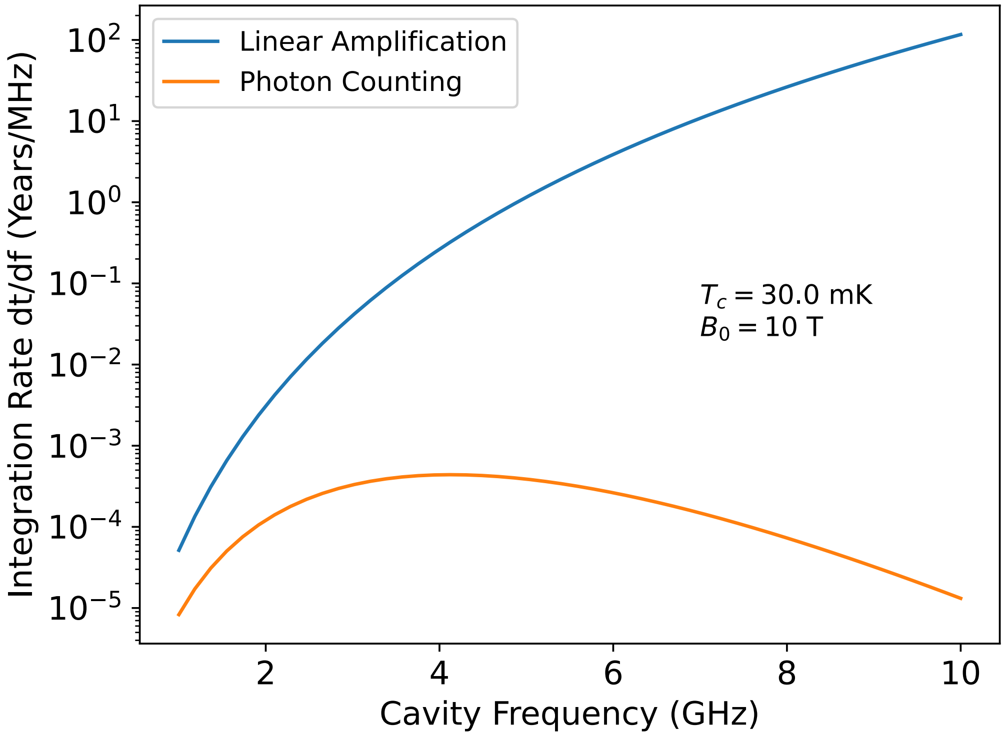






Dilution fridge ~ 10 mK

Would take long time to scan DFSZ with single cavity



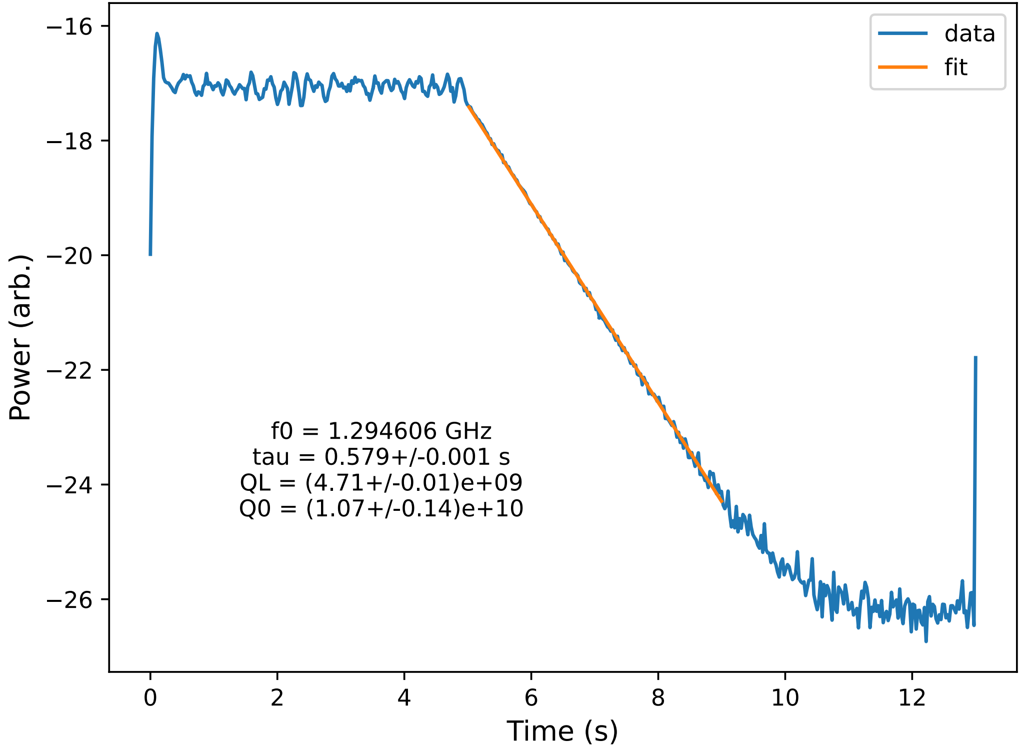
$$V_c = 136\,L \times \left(\frac{f}{1GHz}\right)^{-3}$$

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

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

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

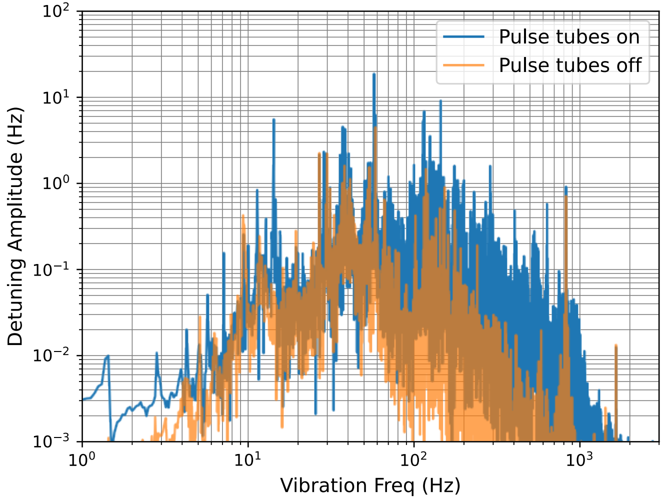
SERAPHv1 Measure Q with decay measurement



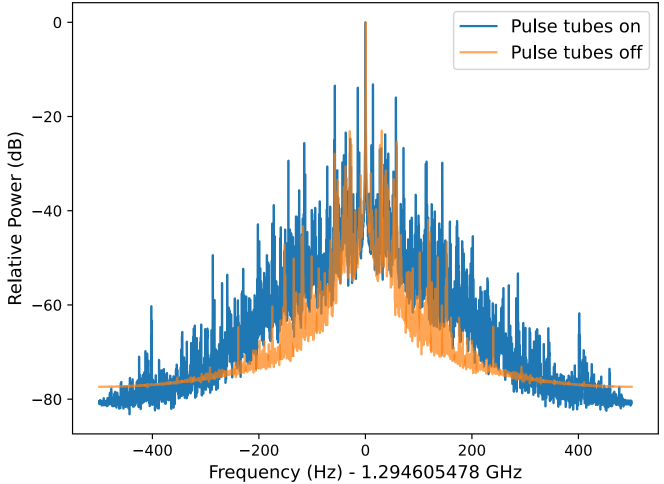
SERAPHv1 Microphonics and Frequency Modulation

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

FFT of PNA measurement



SA measurement



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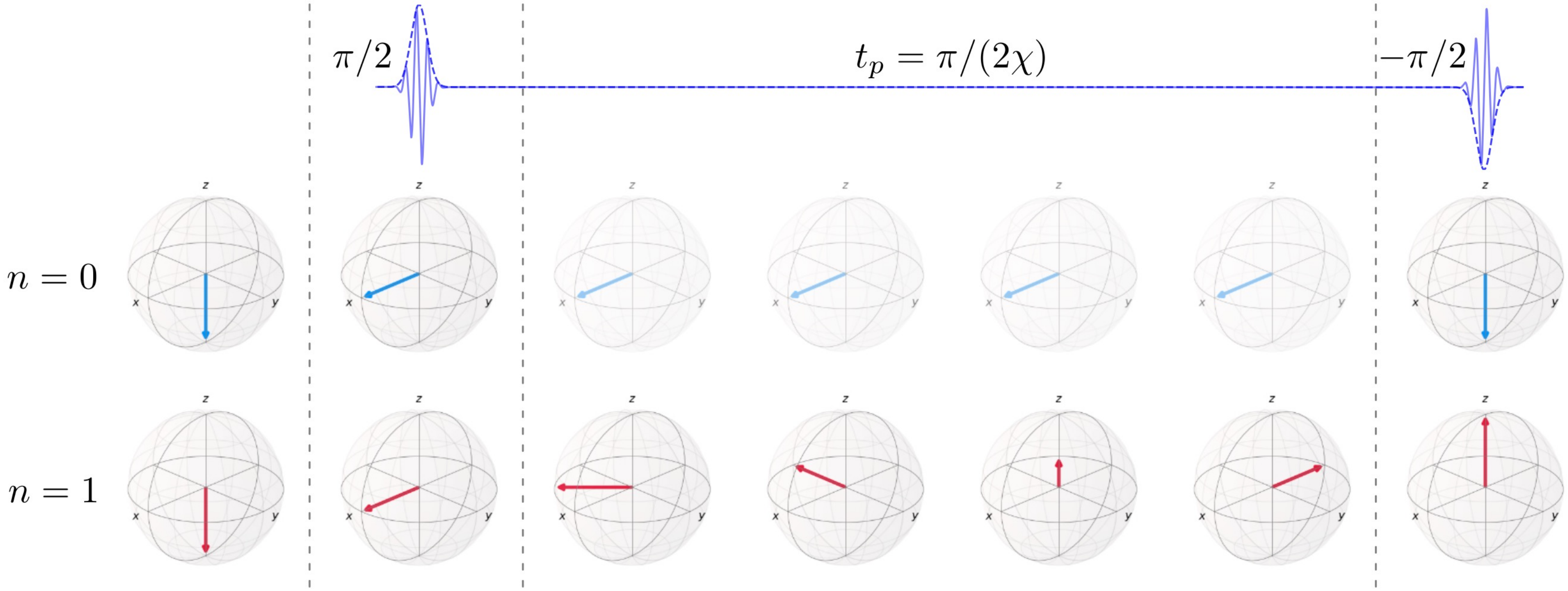
Parity measurement maps cavity state onto qubit



Credit: A. Dixit