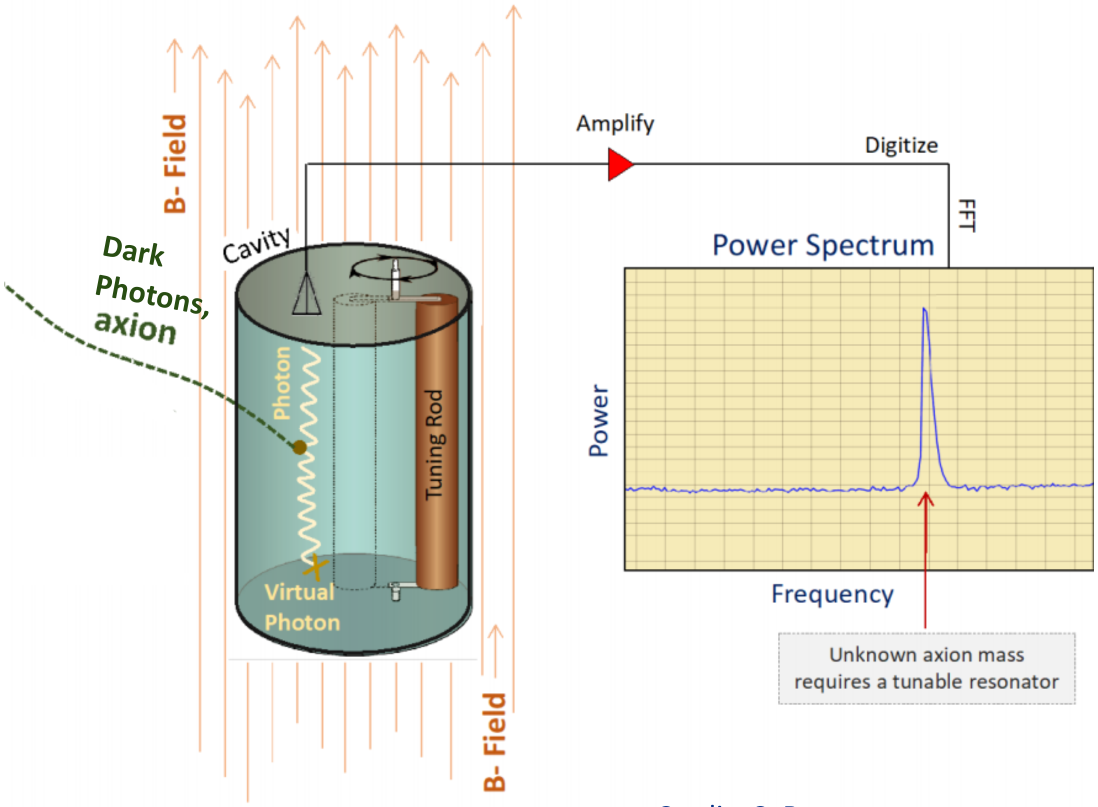
SERAPH: Wavelike Dark Matter Searches with SRF Cavities

Quantum Technologies for Fundametnal Physics 09/03/2023

Raphael Cervantes

Haloscope Search for Dark Matter



Credit: C. Boutan

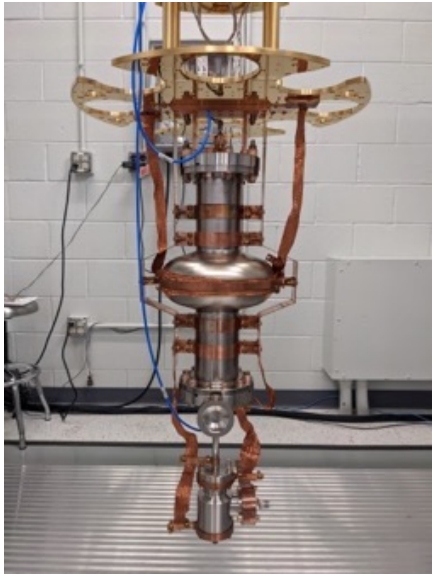
Microwave cavities can be used to detect dark photons and axions.

Dark photon searches don't need B-field.

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

SRF Cavity Search for Dark Matter Searches

SQMS



$$Q \sim 10^{10}$$

Compared to state-of-the-art

ADMX

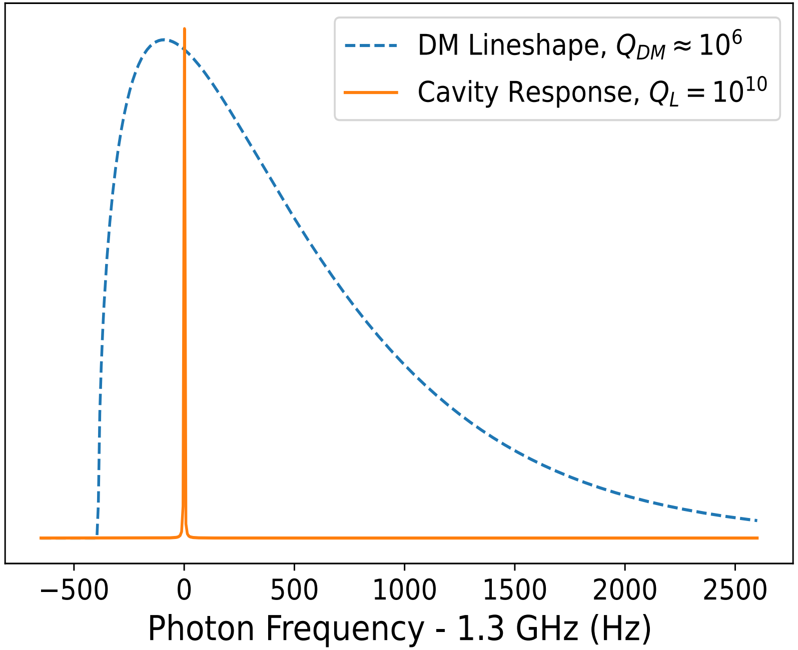
Credit: N. Du

$$Q \approx 8 \times 10^{4}$$

High Q improves SNR.

Possibly factor 10^5 increase in instantaneous scan rate.

Instantaneous scan rate is proportional to Q_L



For virialized axions

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

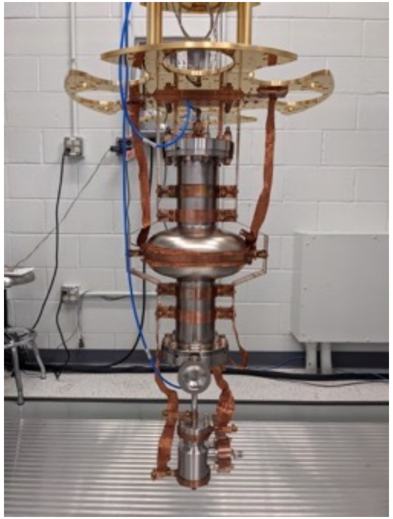
even if $Q_L \gg Q_{DM}$

- 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.

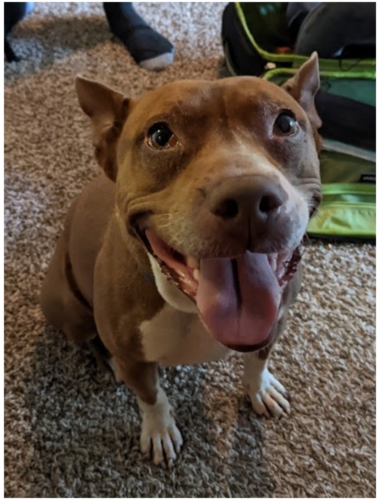
More details: arXiv:2208.03183

SERAPH: SupERconducting Axion and Paraphoton Haloscope

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



SRF

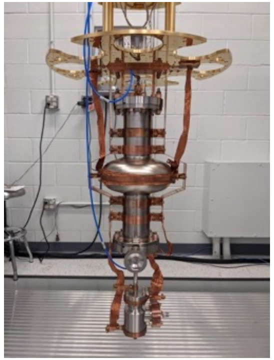


Seraphine

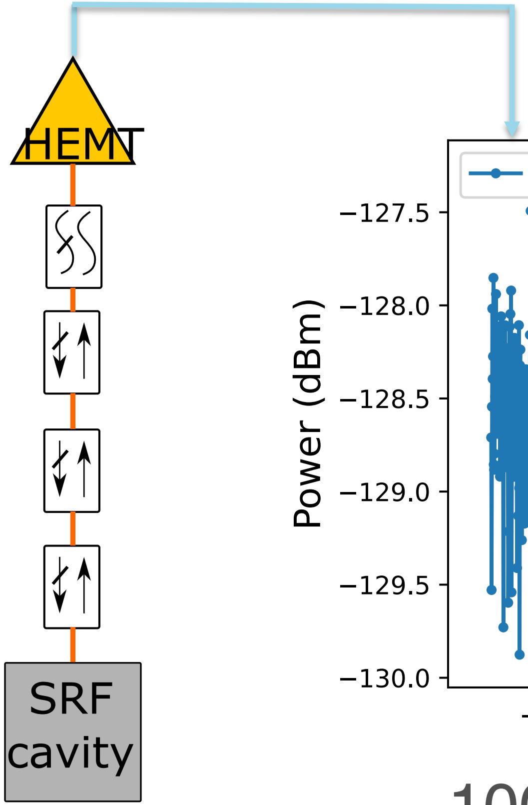
Sir Raph(ael)

SERAPHv1: Parasitic Search for Dark Photons

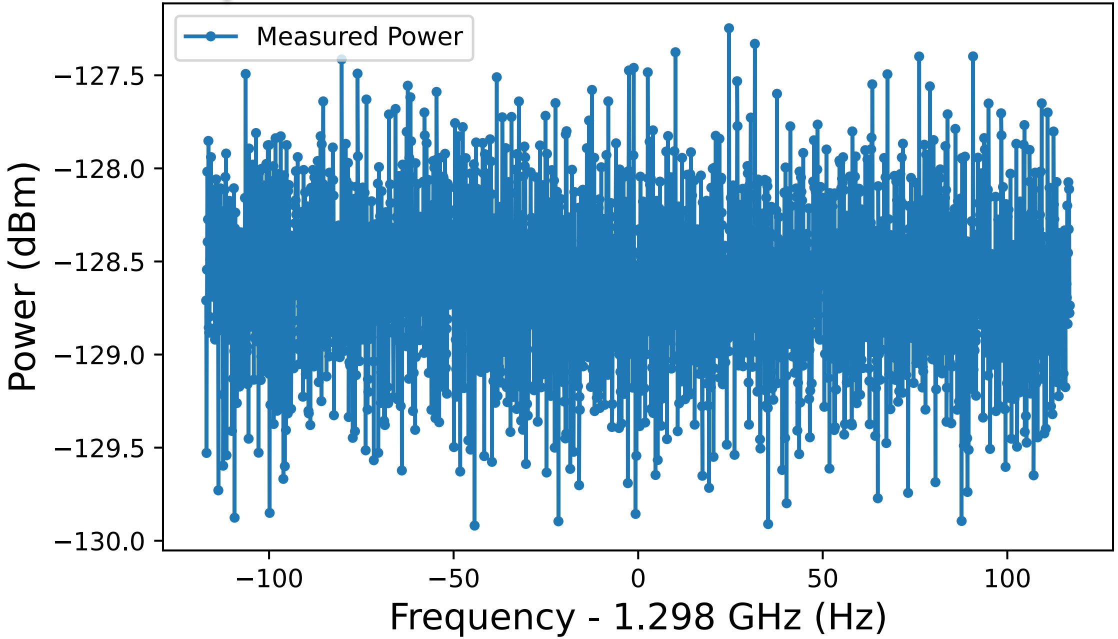
$T_a \approx 4.9$ K
G ≈ +37 dB



$T_c \approx 45$ mK
$Q_L > 8\times10^9$
$f_0 = 1.298$ GHz
$\beta \sim 0.7$

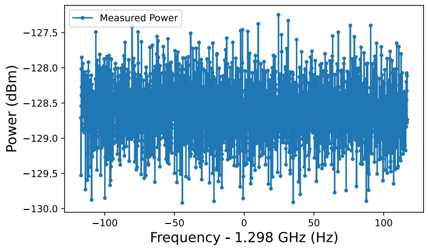


No DP signal. Just noise.

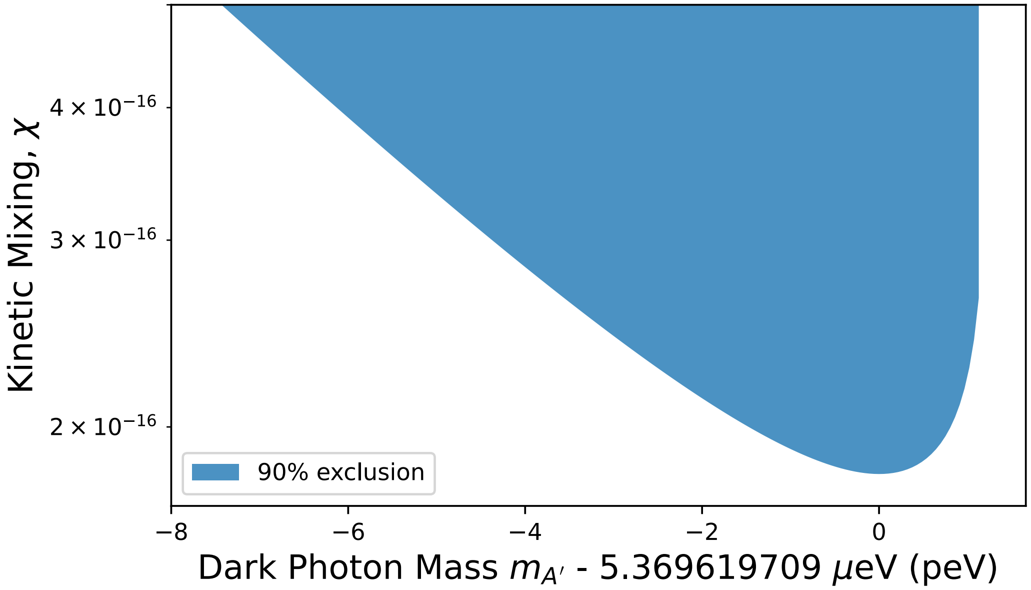


1000 seconds integration time

Excluded Dark Photon Parameter Space



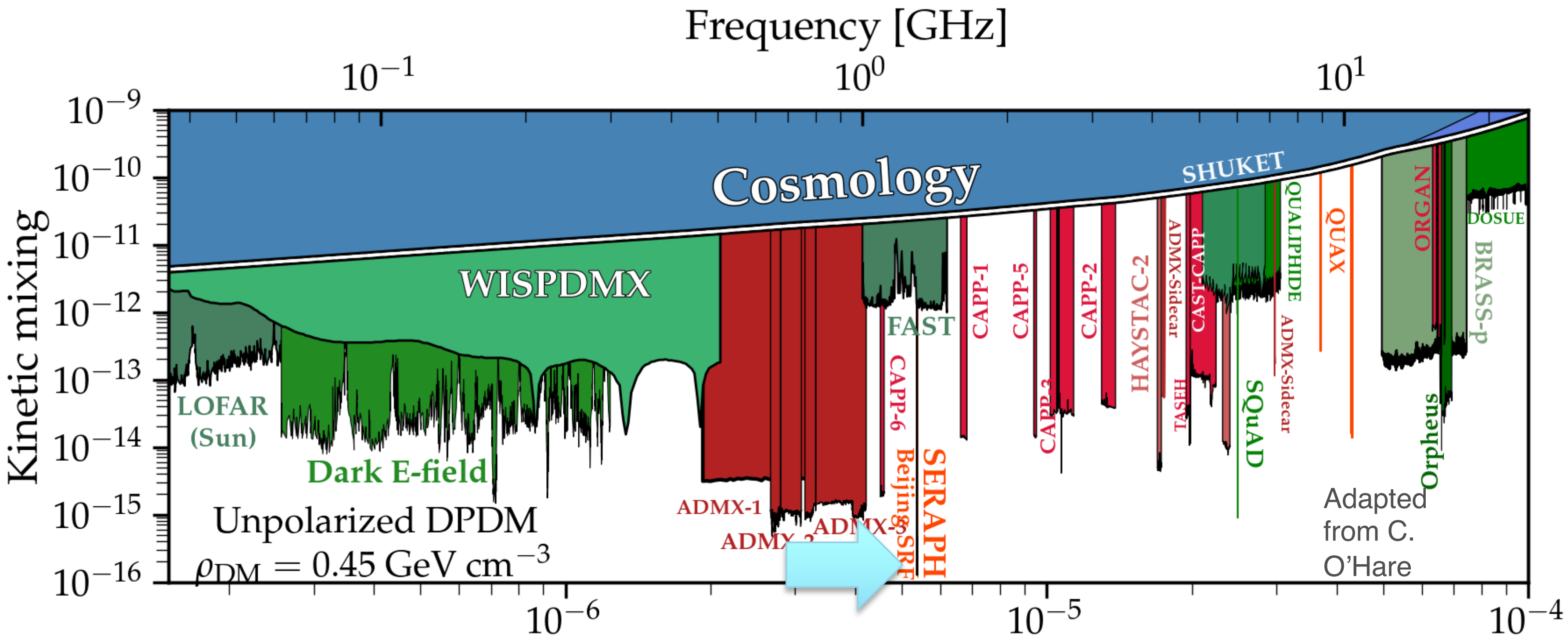
haloscope analysis



arXiv:2208.03183

In review purgatory. Measurements recently performed to address reviewer comments.

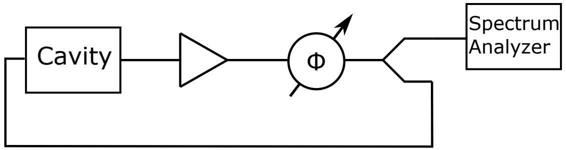
Deepest Exclusion to Wavelike DPDM



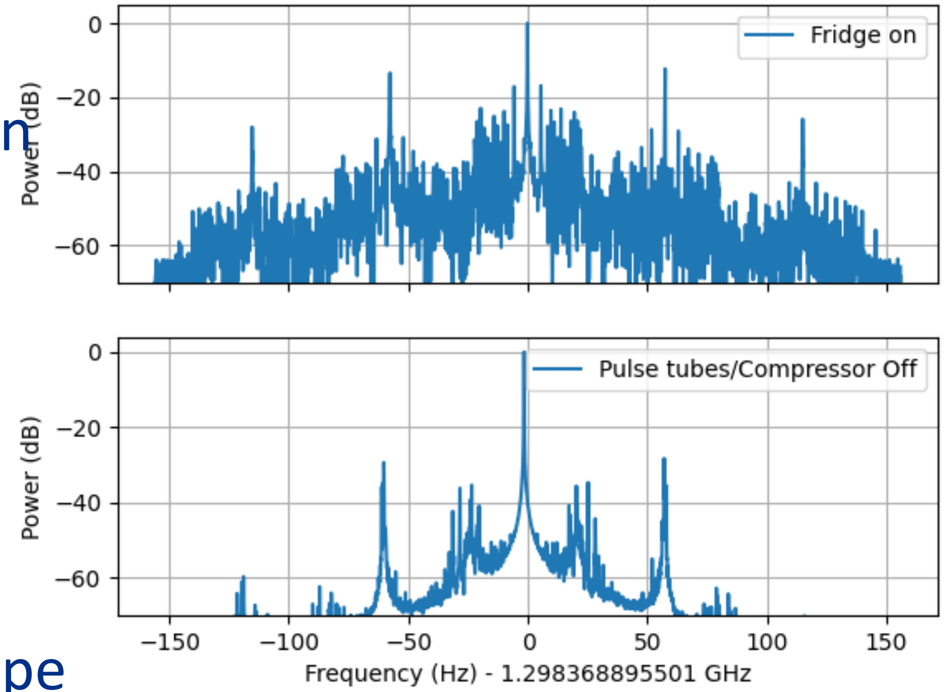
arXiv:2208.03183

Low-hanging fruit.

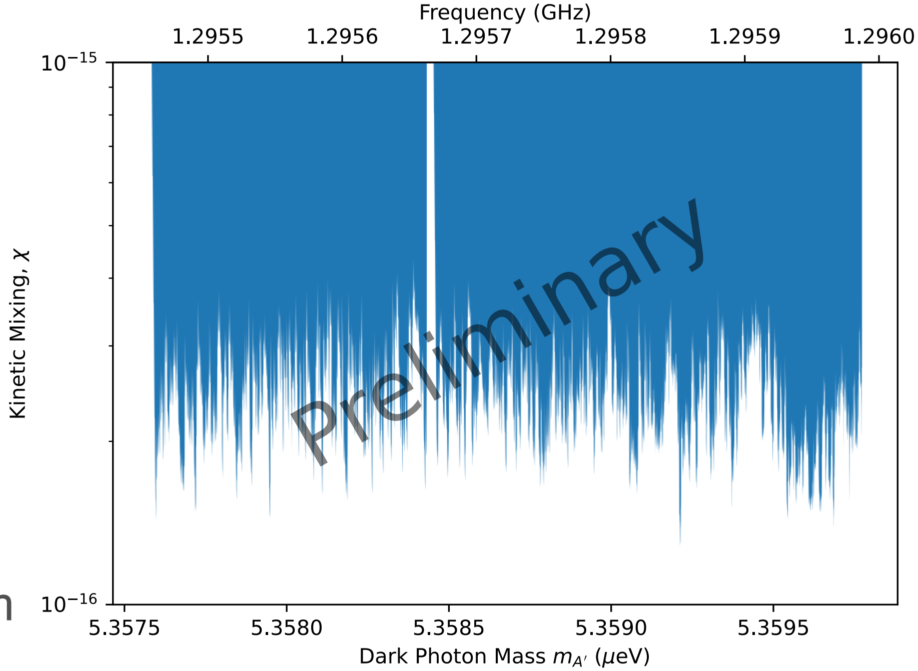
Debugging Microphonics



- Measured with self-excitation loop.
- Creates modulation of dark matter signal. Power gets spread into sidebands.
- Mitigated by turning off DR pulse tubes. But not a viable solution for a tuning haloscope
- Quantifiable systematic.



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.

Similar experiment posted by Chinese collaboration

SRF Cavity Searches for Dark Photon Dark Matter: First Scan Results

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(Dated: May 26, 2023)

We present the first use of a tunable superconducting radio frequency cavity to perform a scan search for dark photon dark matter with novel data analysis strategies. We mechanically tuned the resonant frequency of a cavity embedded in the liquid helium with a temperature of 2 K, scanning the dark photon mass over a frequency range of 1.37 MHz centered at 1.3 GHz. By exploiting the superconducting radio frequency cavity's considerably high quality factors of approximately 10^{10}, our results demonstrate the most stringent constraints to date on a substantial portion of the exclusion parameter space, particularly concerning the kinetic mixing coefficient between dark photons and electromagnetic photons ϵ, yielding a value of $\epsilon < 2.2 \times 10^{-16}$.

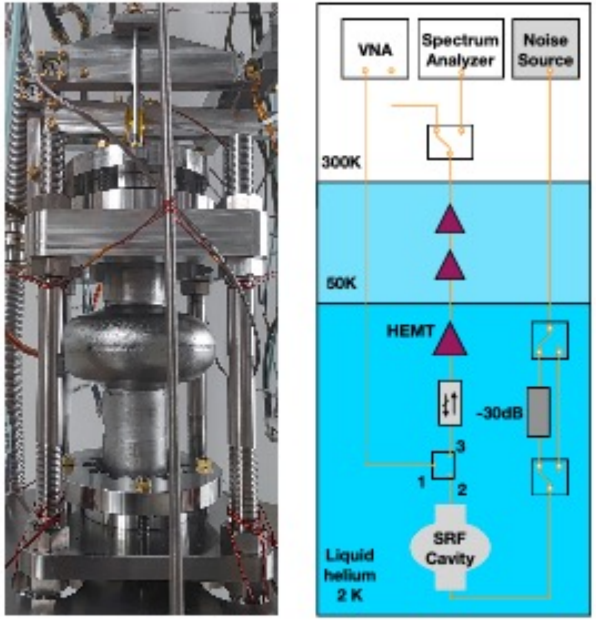
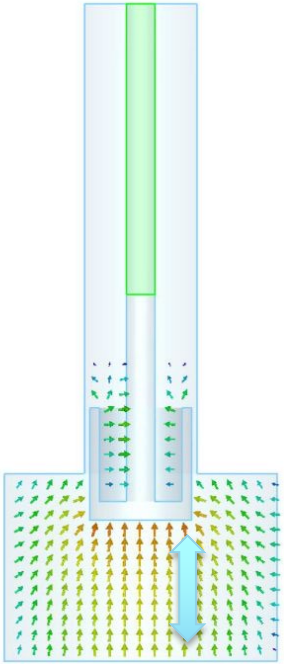
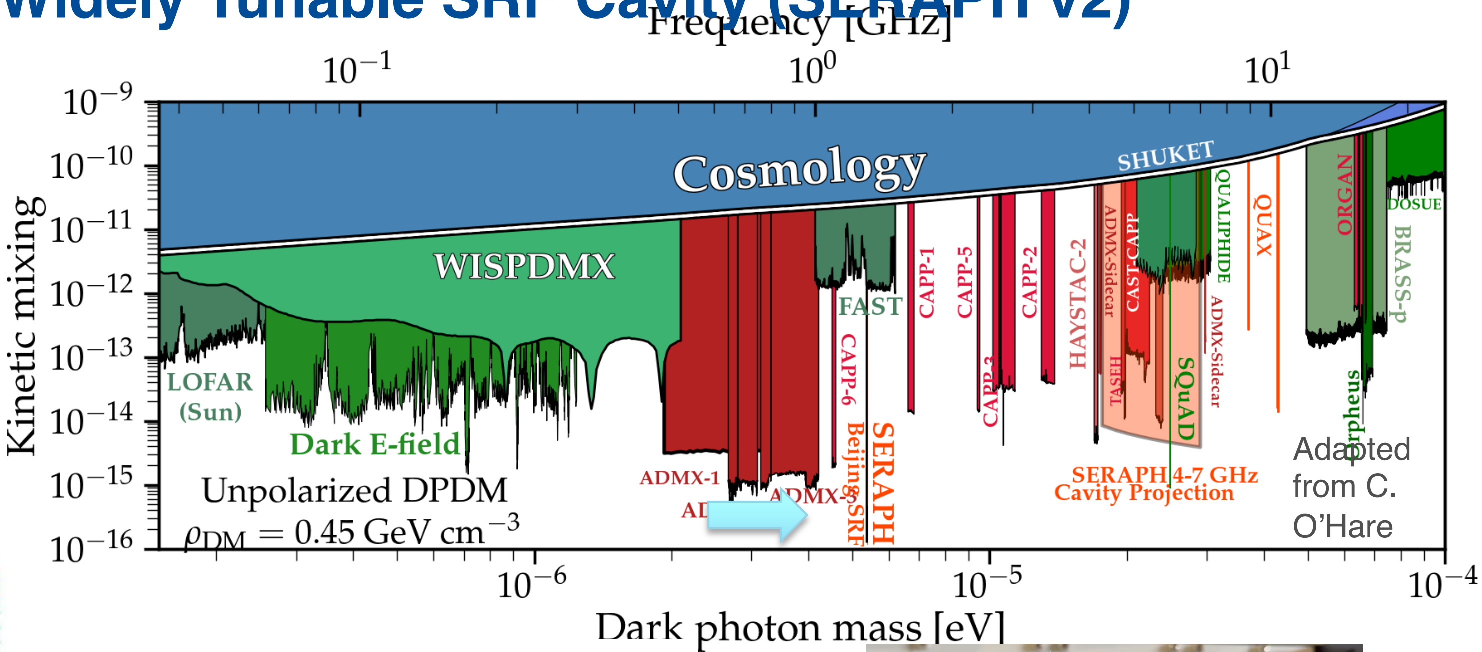


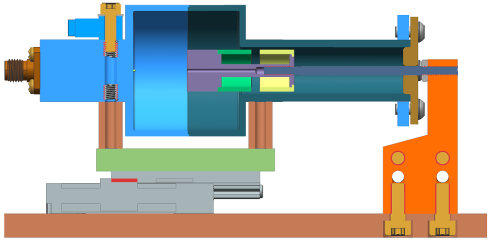
FIG. 1: Left: the single-cell SRF cavity equipped with frequency tuner. Right: Schematic of the microwave electronics for DPDM searches. The VNA measures the net amplification factor G_{net} of the amplifier circuit consisting of an isolator, a HEMT amplifier and two room-temperature amplifiers. The noise source and the spectrum analyzer calibrate the resonant frequencies f_0^i. The time-domain signals from the SRF, with sequential amplification, are finally recorded by the spectrum analyzer.

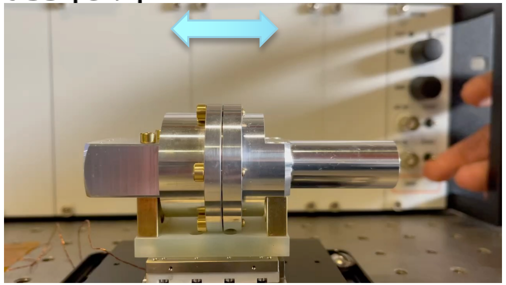
Developing Widely Tunable SRF Cavity (SERAPH v2)





Adapted from C. O'Hare

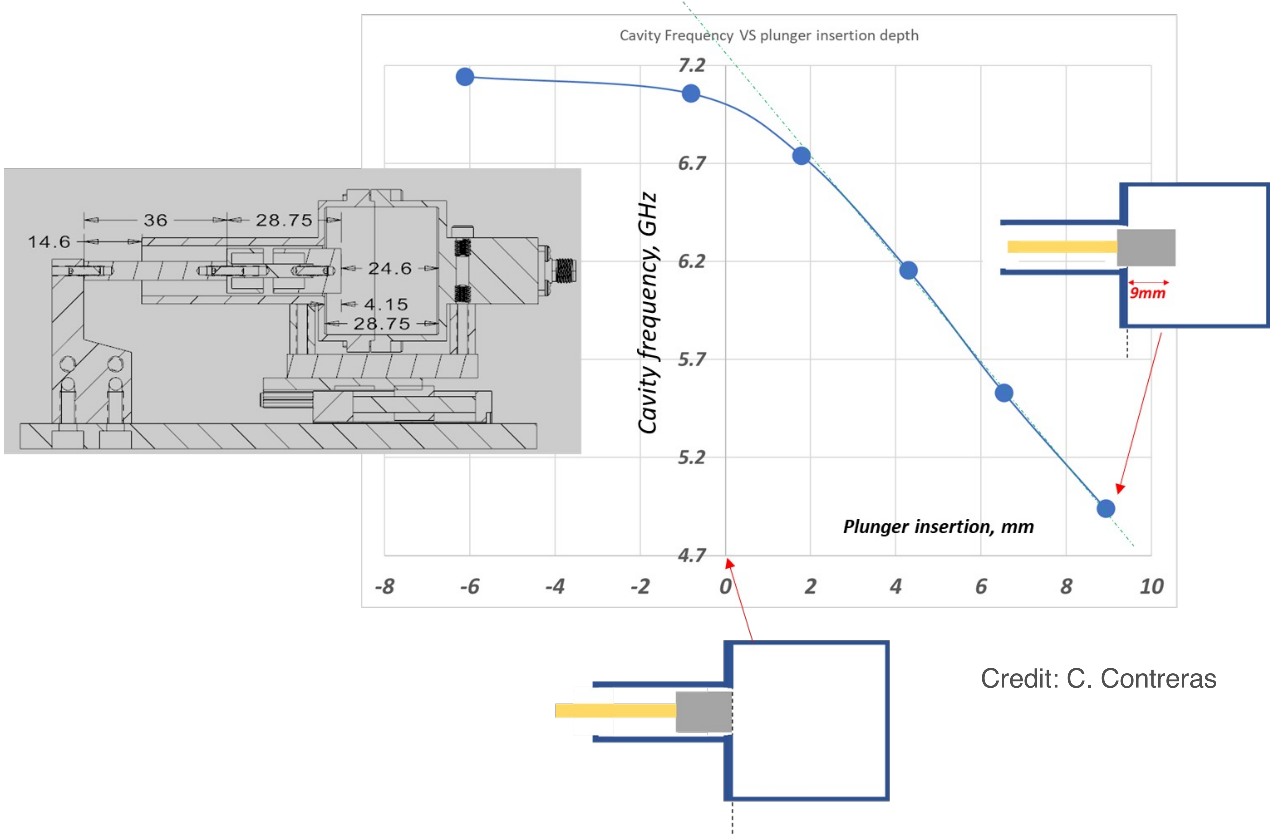




"plunger" cavity

4-7 GHz

Aluminum prototype works at 2 K LHe bath



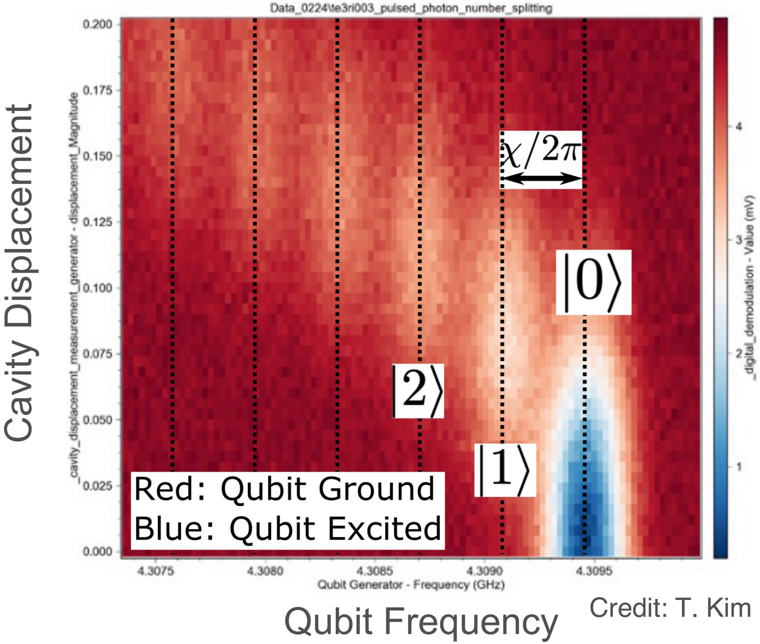
Credit: C. Contreras

Consistent with simulation.

Niobium cavity has alignment issues that we are currently fixing.

Subverting SQL Noise with Qubit-based Photon Counting (SERAPH v3)

Superconducting qubit in SRF cavity.



Credit: T. Kim

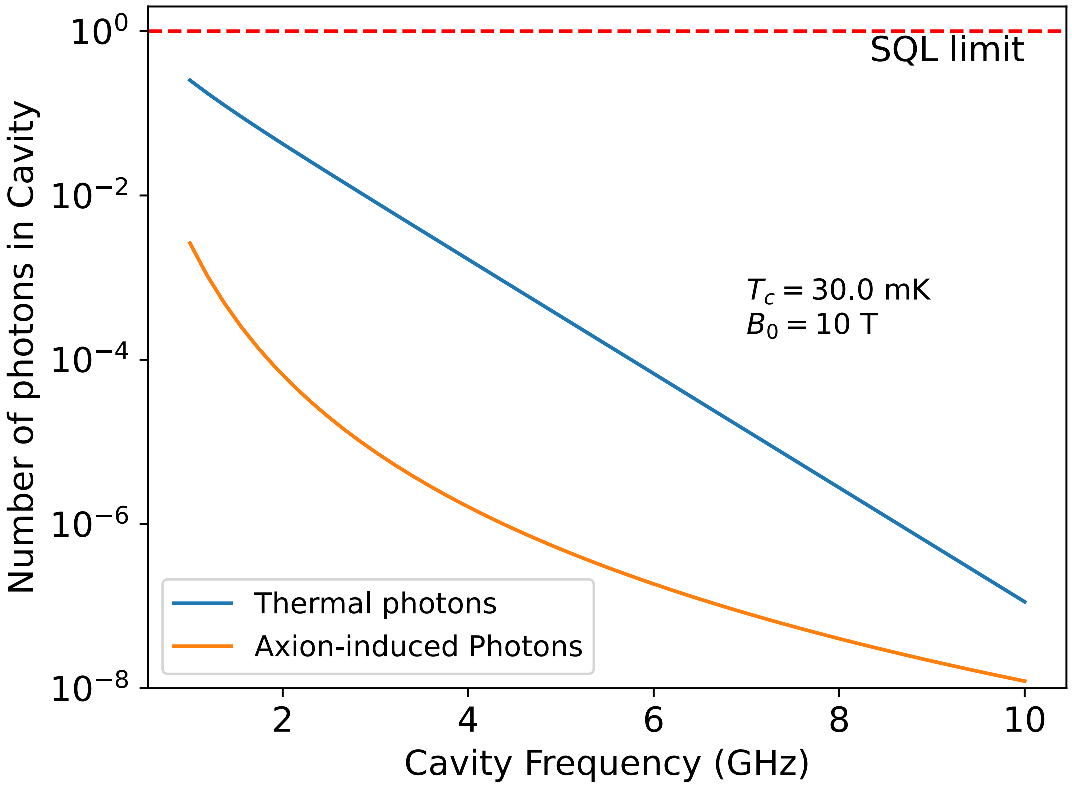
Quantum protocols counts photons non-destructively.

SQMS 3D transmon qubit performance:

$$T_1 \approx 25\ \mu s$$
$$T_2 \approx 15\ \mu s$$

Regularly perform photon counting with dispersive measurements.

SQL noise dominates at higher frequencies



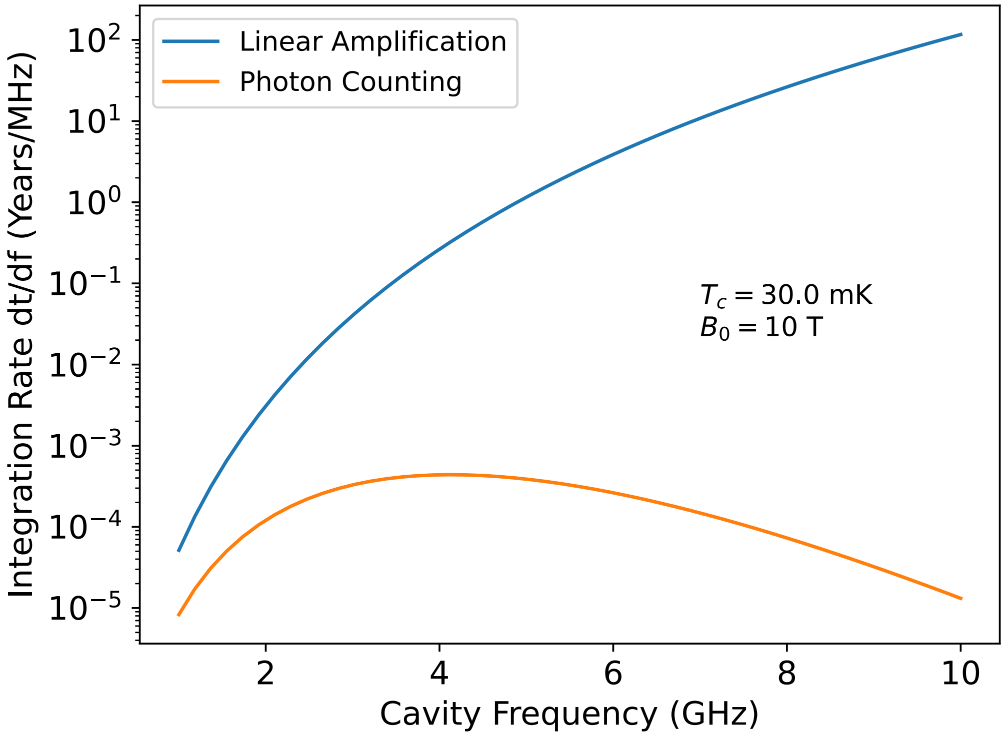
$$V_c = 136\,L \times \left(\frac{f}{1GHz}\right)^{-3}$$

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

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

Need to mitigate SQL.

Would take long time to scan DFSZ with single cavity



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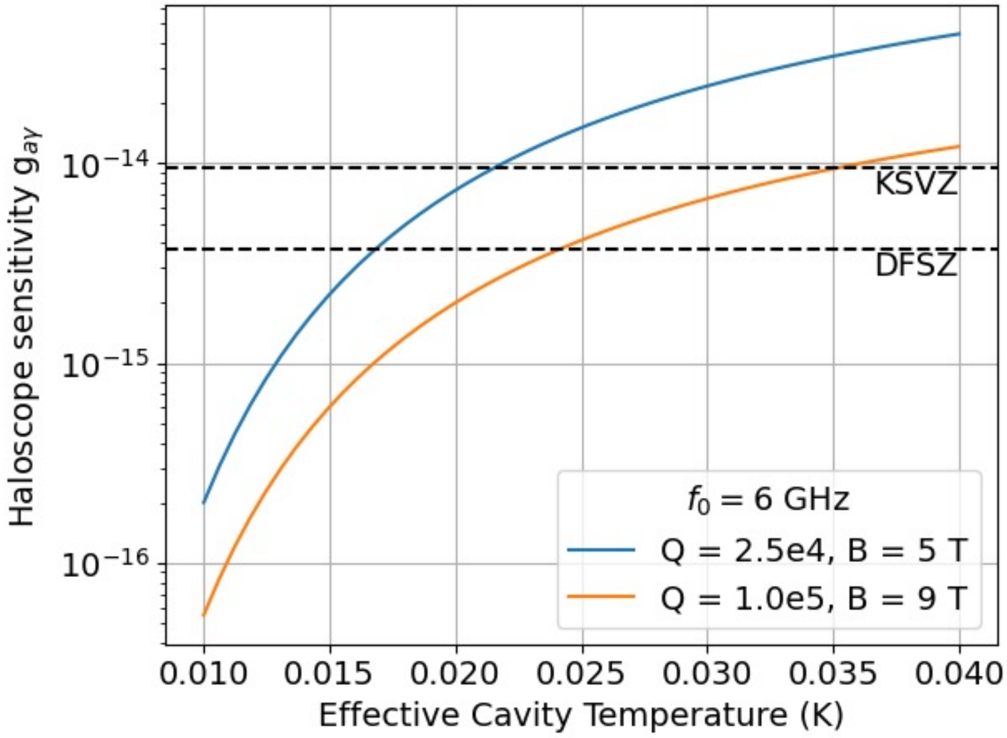
Note: photon counting estimate doesn't yet take into account counter errors. Numerical estimates sensitive to engineering parameters.

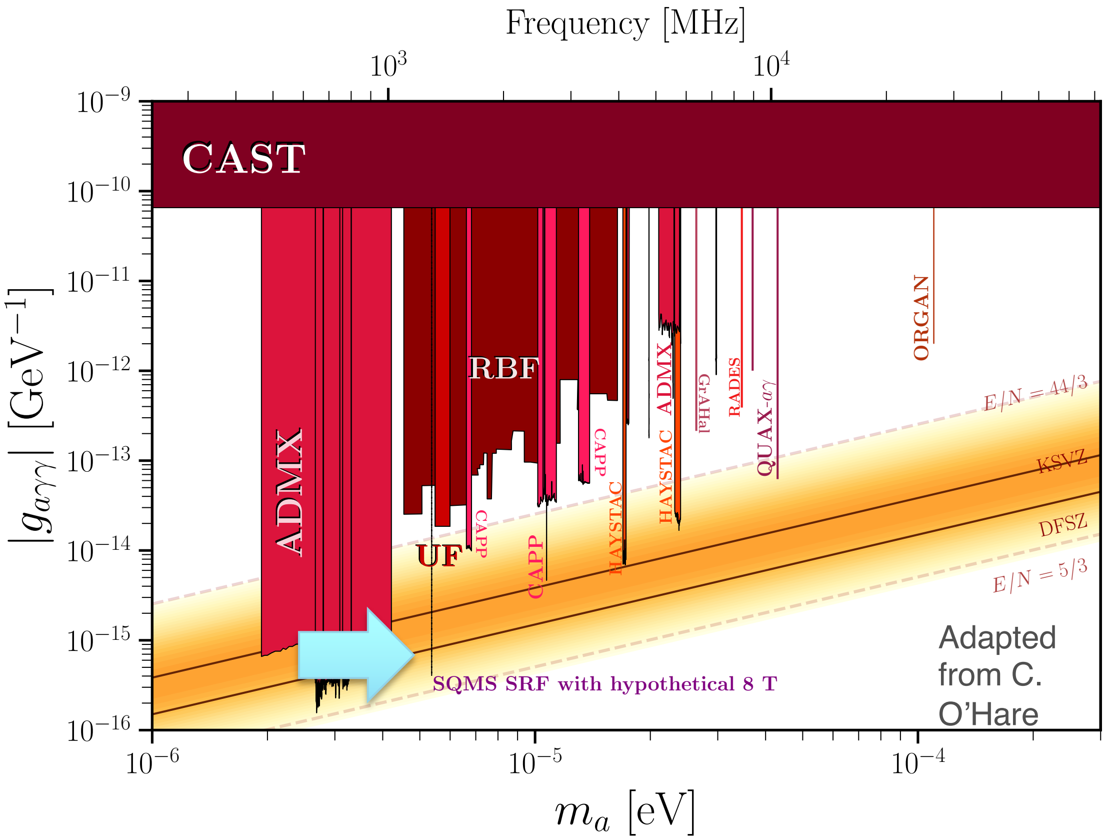
Photon Counter in Magnetic Field



Proposal to make magnetically-resilient photon counters out of NbN, or clever placement away in reduced-field region.

Interesting parameter space within an order of magnitude from reality.

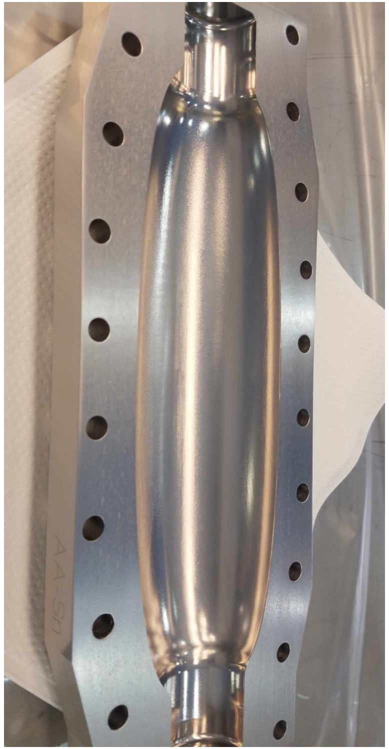
If this would work in an 8T field

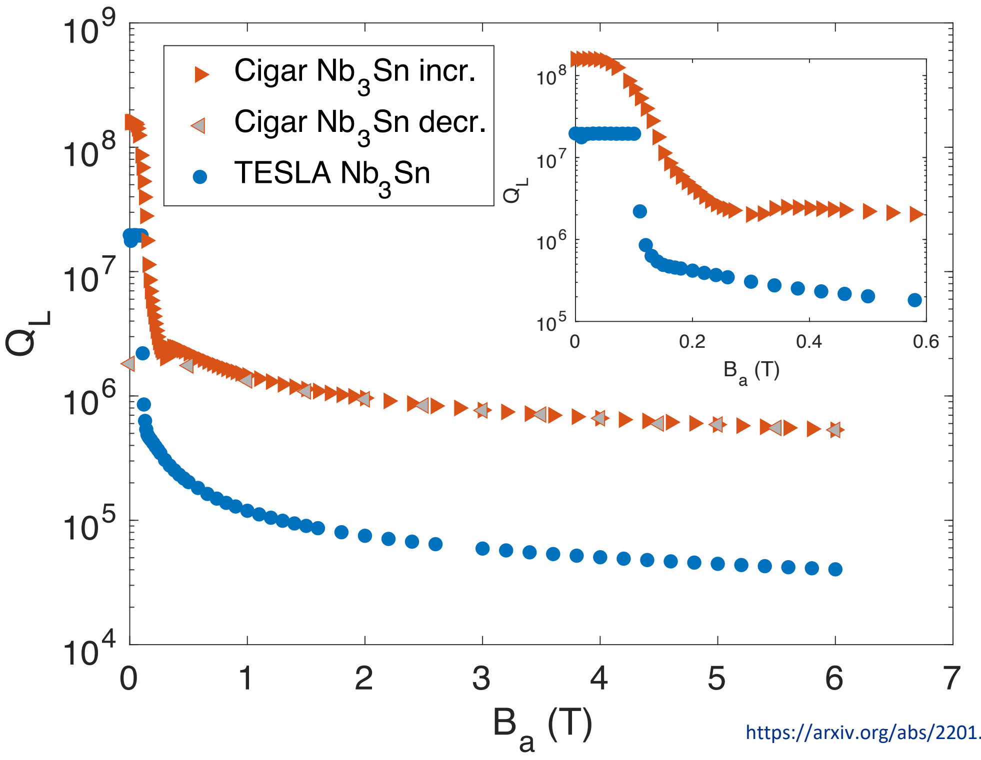


Sensitivity to **QCD axion** with single cavity and HEMT.

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

Nb_3Sn Cavities Maintain High Q in Magnetic Fields





https://arxiv.org/abs/2201.10733v4

Further improvements with better flux pinning and better alignment with magnetic field.

Waiting for new test stand.

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

Summarize

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