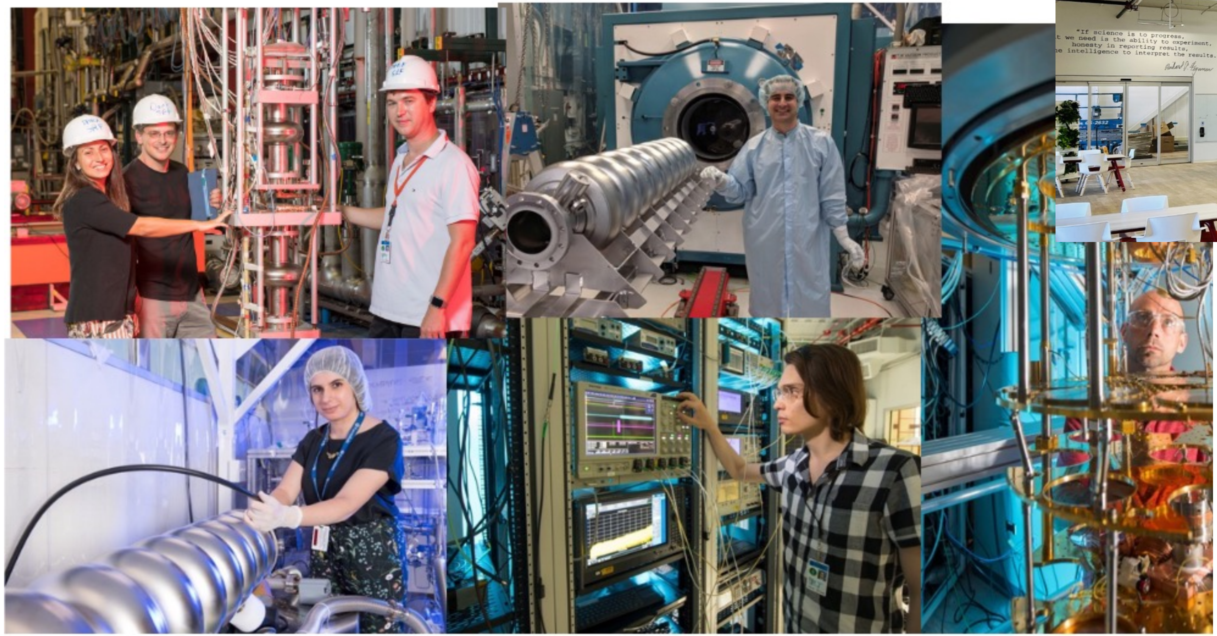
SERAPH: Wavelike Dark Matter Searches with SRF Cavities

07/06/2023

Raphael Cervantes

SQMS and Fermilab



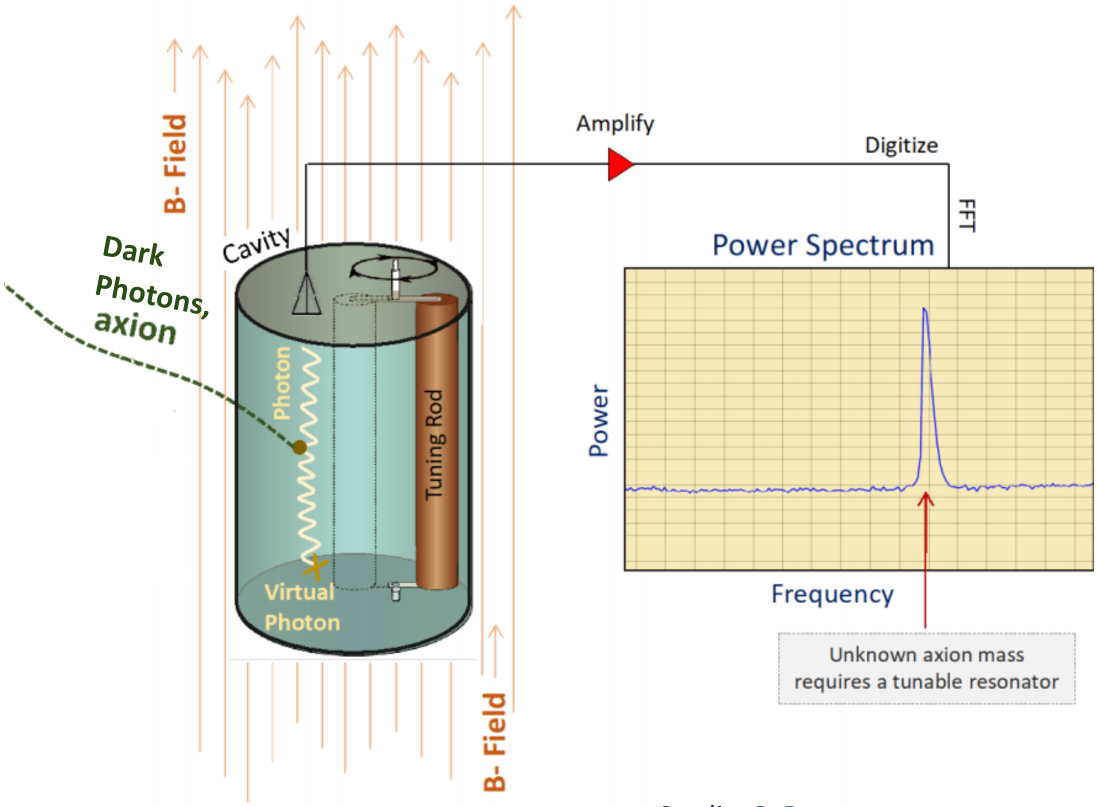
Credit: A. Grasselino

Partners include:

- Northwestern University
- Rutgers
- NIST
- INFN
- University of Illinois Urbana-Champaign
- rigetti

How far can we push SRF technology for BSM physics searches?

Haloscope Search for Dark Matter



Credit: C. Boutan

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

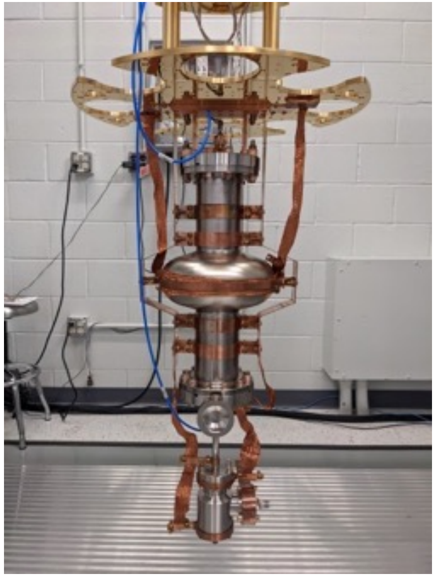
Dark photon searches don't need B-field.

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

Fermilab SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

SRF Cavity Search for Dark Matter Searches

SQMS



$Q \sim 10^{10}$

Compared to state-of-the-art

ADMX

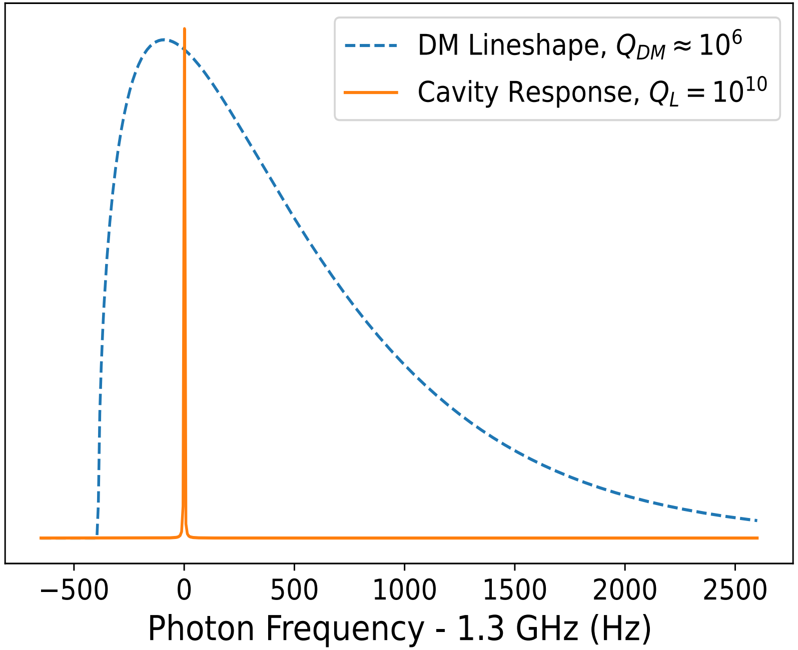
Credit: N. Du

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

High Q improves SNR.

Possibly factor 10^5 increase in instantaneous scan rate.

Instantaneous scan rate is proportional to Q_L



For virialized axions

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

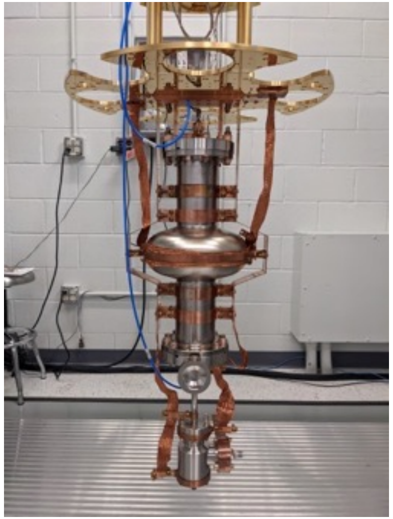
even if $Q_L \gg Q_{DM}$

- 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.

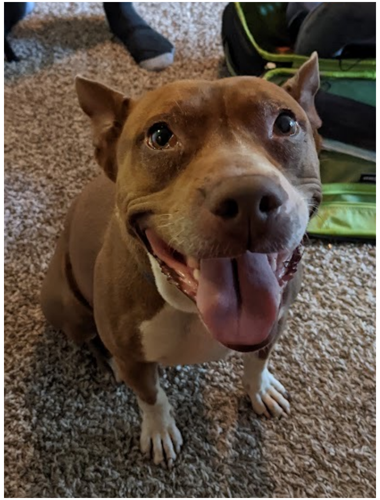
More details: arXiv:2208.03183

SERAPH: SupERconducting Axion and Paraphoton Haloscope

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



SRF

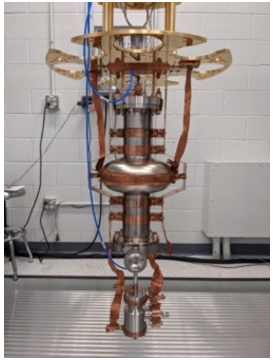


Seraphine

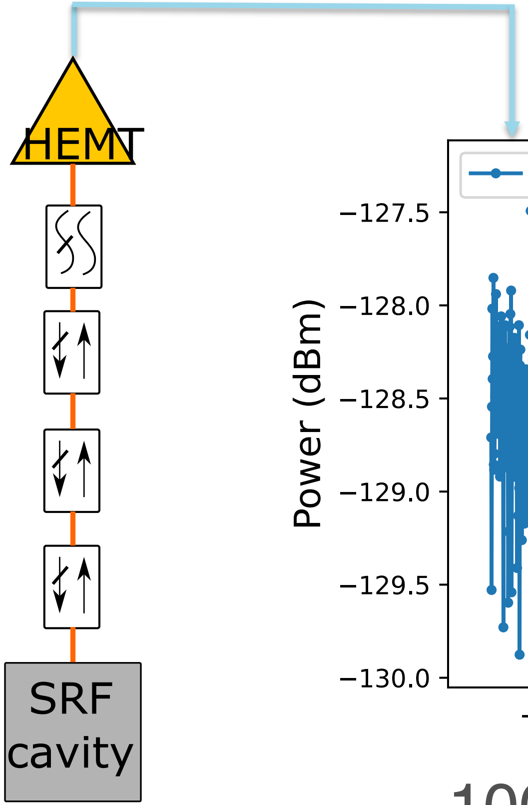
Sir Raph(ael)

SERAPHv1: Parasitic Search for Dark Photons

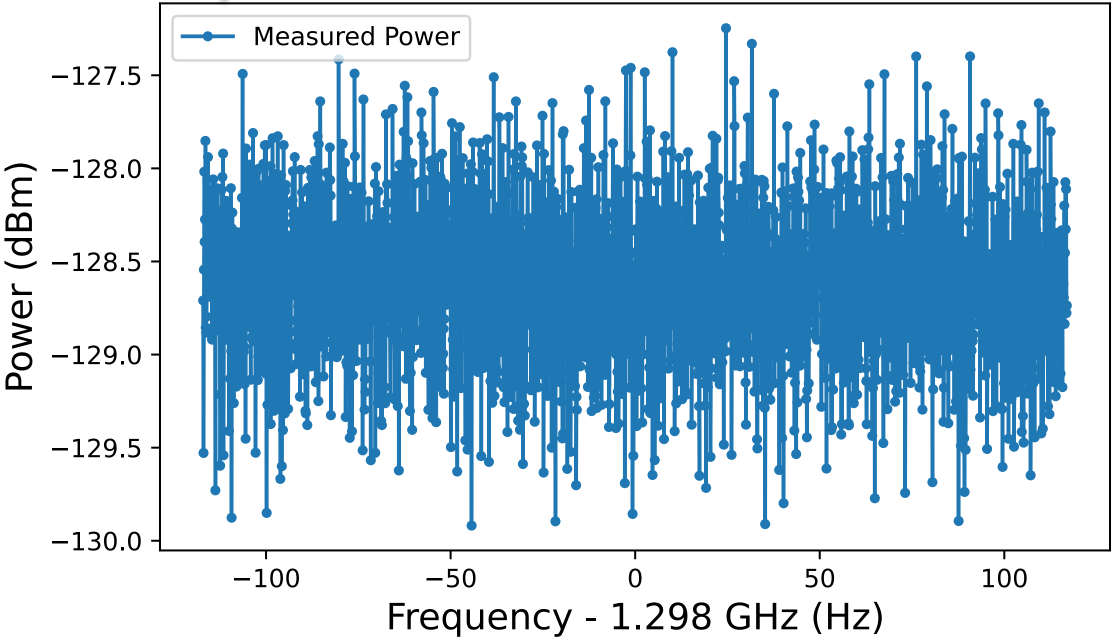
$T_a \approx 4.9$ K
G $\approx$ +37 dB



$T_c \approx 45$ mK
$Q_L > 8{\times}10^9$
$f_0 = 1.298$ GHz
$\beta \sim 0.7$

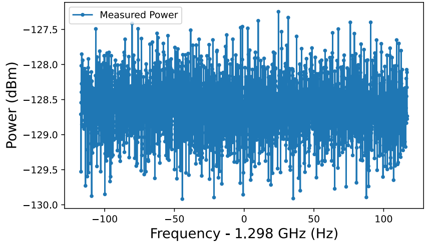


No DP signal. Just noise.

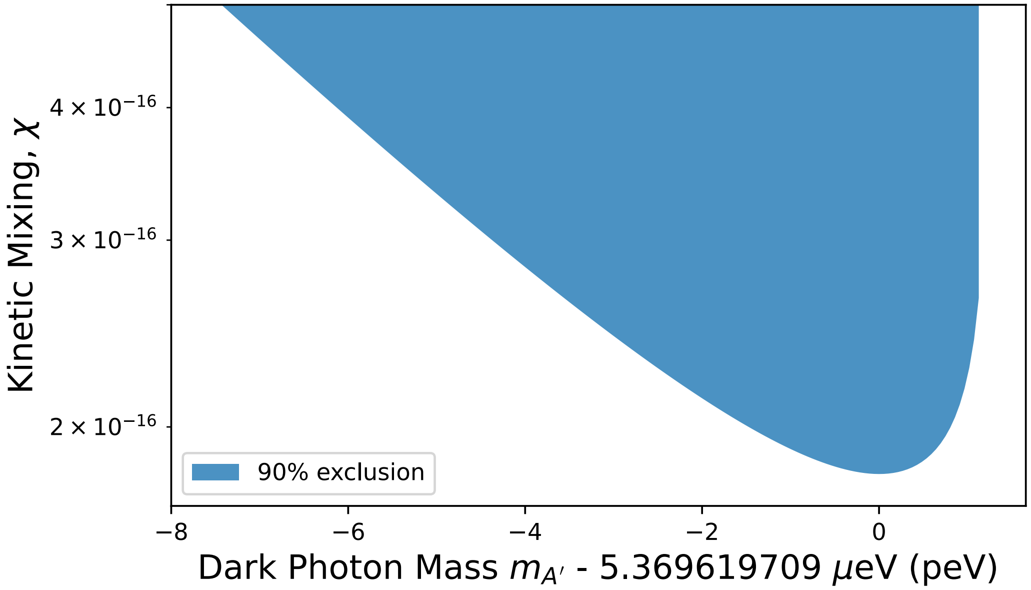


1000 seconds integration time

Excluded Dark Photon Parameter Space



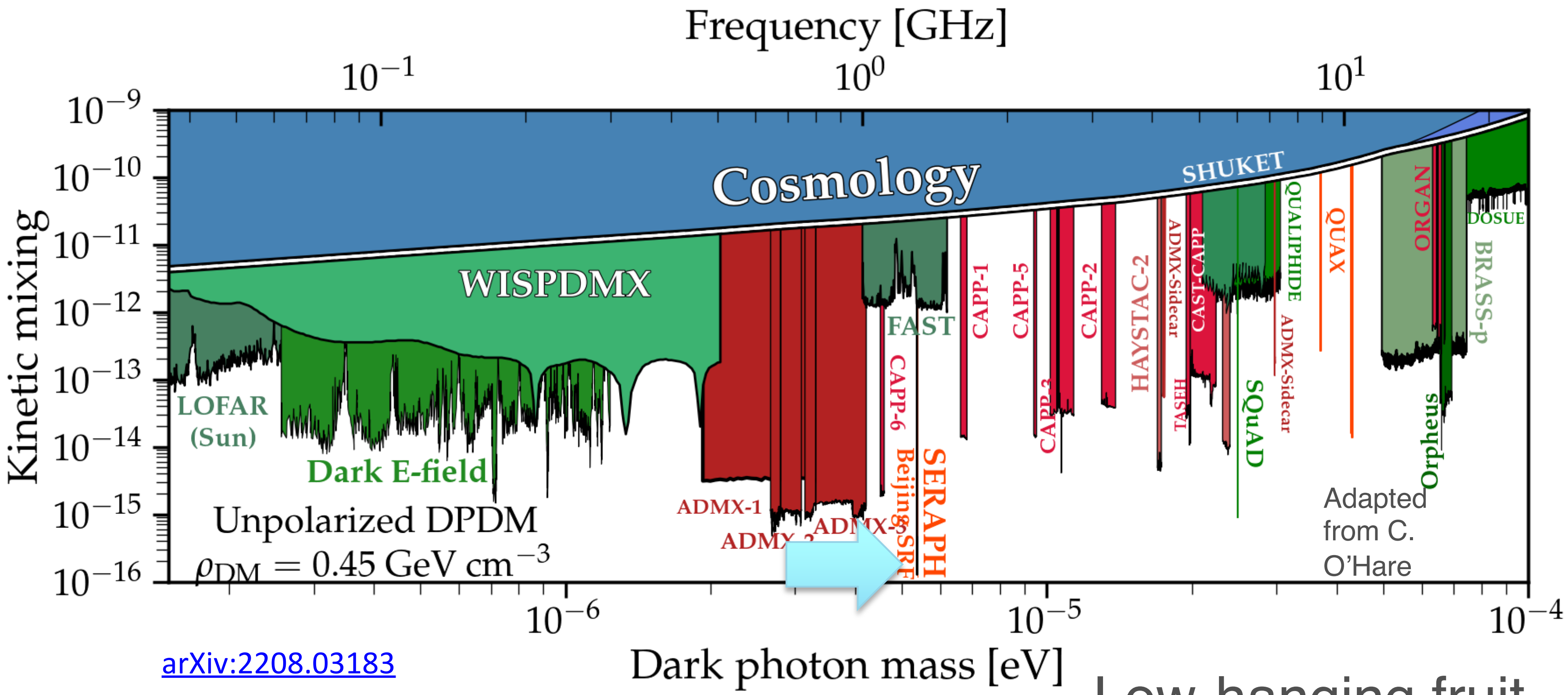
haloscope analysis



arXiv:2208.03183

In review purgatory until fridge is fixed. Measurements underway to address reviewer comments.

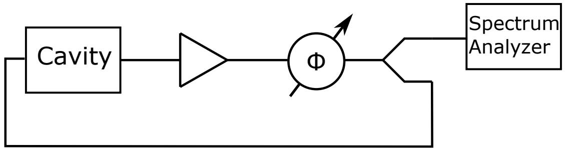
Deepest Exclusion to Wavelike DPDM



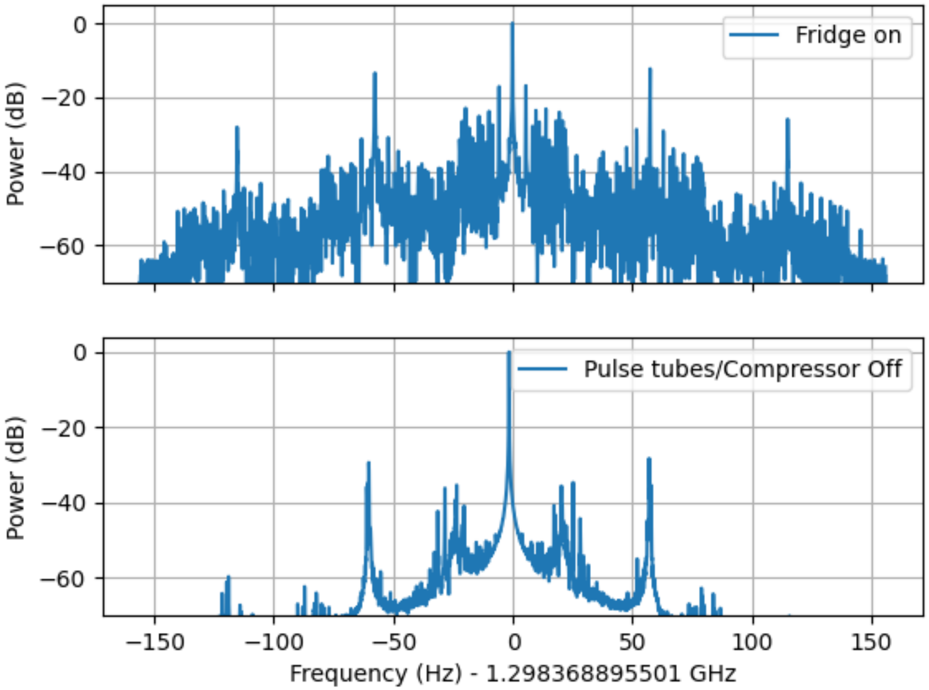
arXiv:2208.03183

Low-hanging fruit.

Debugging Microphonics

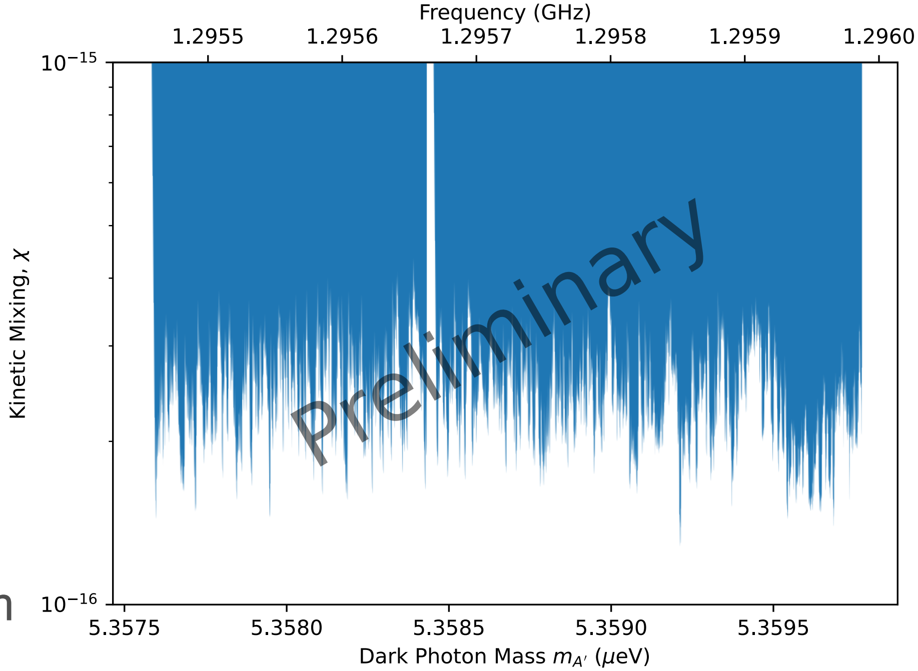


- Measured with self-excitation loop.
- Creates modulation of dark matter signal. Power gets spread into sidebands.
- Mitigated by turning off DR pulse tubes.
- Quantifiable systematic



Not expected to be a problem in future runs.

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

Zhenxing Tang,[1,2,*] Bo Wang,[3,*] Yifan Chen,[4] Yanjie Zeng,[5,6] Chunlong Li,[5] Yuting Yang,[5,6] Liwen Feng,[1,7] Peng Sha,[8,9,10] Zhenghui Mi,[8,9,10] Weimin Pan,[8,9,10] Tianzong Zhang,[1] Yirong Jin,[11] Jiankui Hao,[1,7] Lin Lin,[1,7] Fang Wang,[1,7] Huamu Xie,[1,7] Senlin Huang,[1,7] and Jing Shu[1,2,12,†]

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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 $\epsilon < 2.2 \times 10^{-16}$.

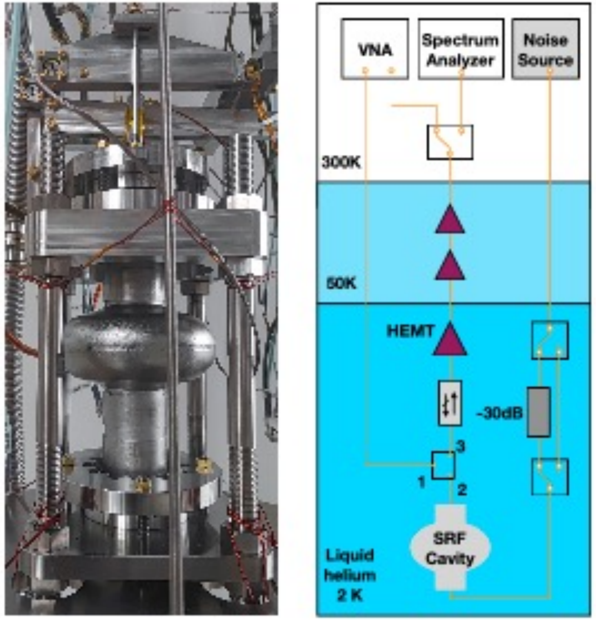
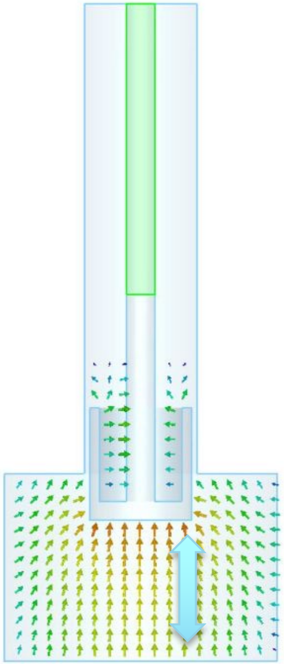
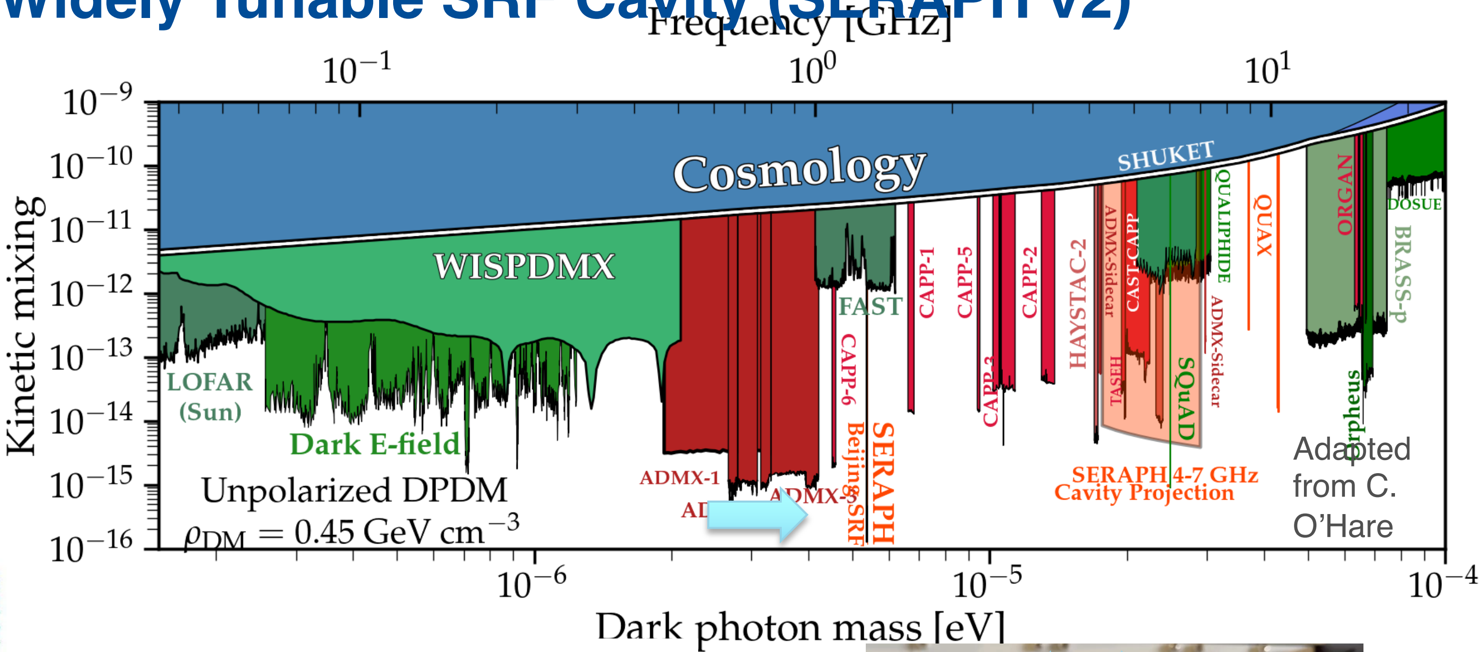


FIG. 1: Left: the single-cell SRF cavity equipped with frequency tuner. Right: Schematic of the microwave electronics for DPDM searches. The VNA measures the net amplification factor G_{net} of the amplifier circuit consisting of an isolator, a HEMT amplifier and two room-temperature amplifiers. The 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.

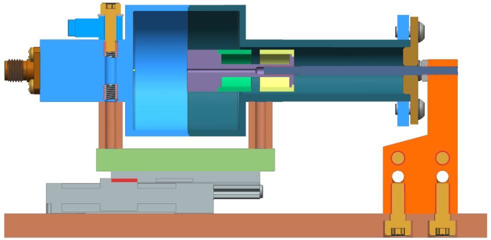
Developing Widely Tunable SRF Cavity (SERAPH v2)

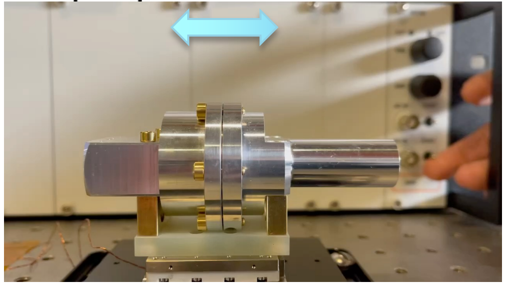




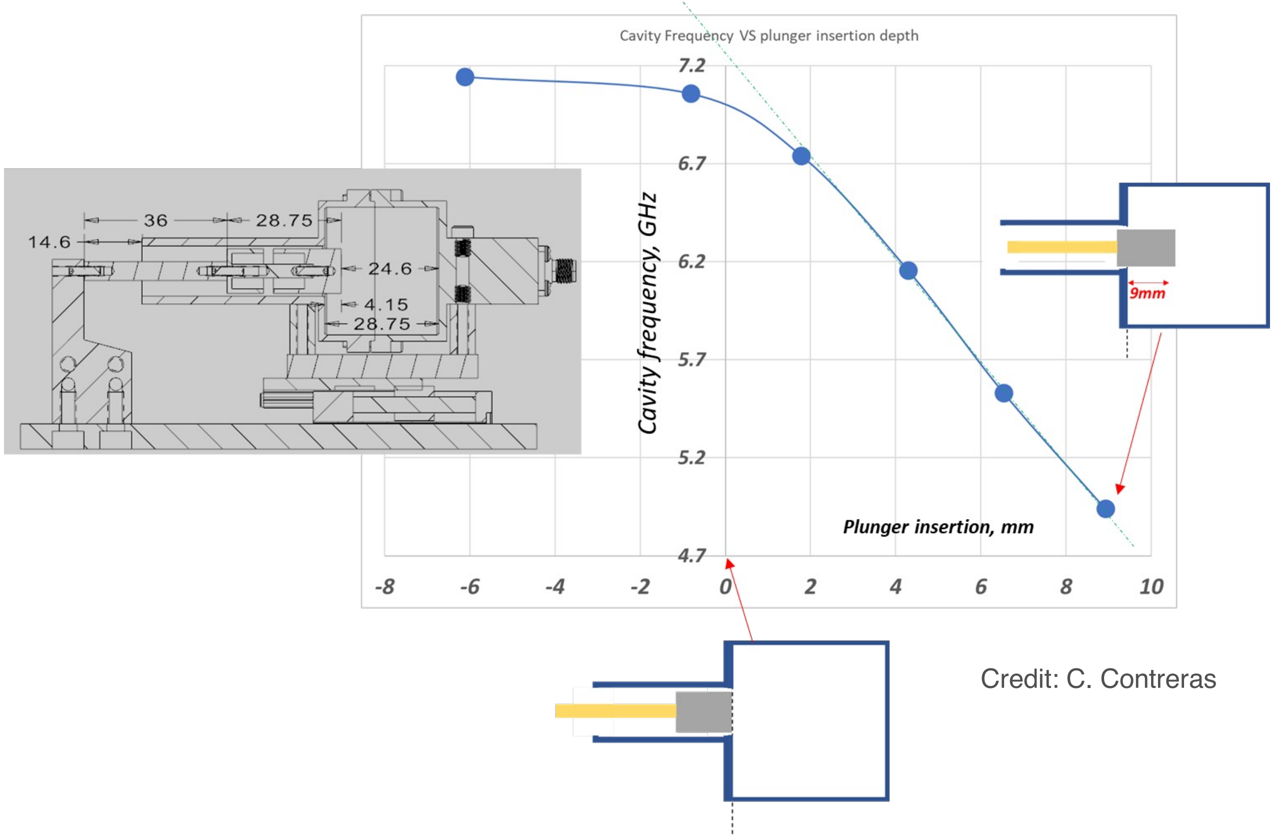
“plunger” cavity

4-7 GHz





Aluminum prototype works at 2 K LHe bath



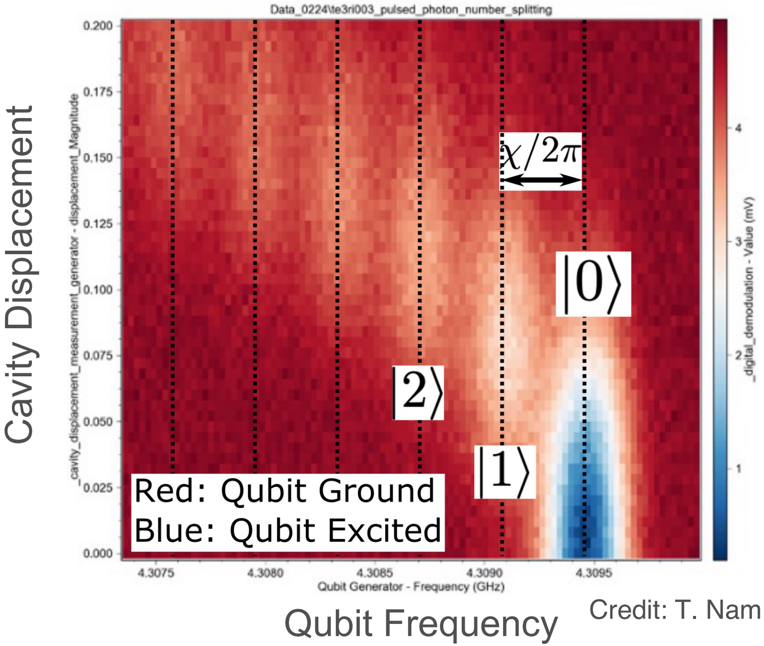
Credit: C. Contreras

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.



Quantum protocols counts photons non-destructively.

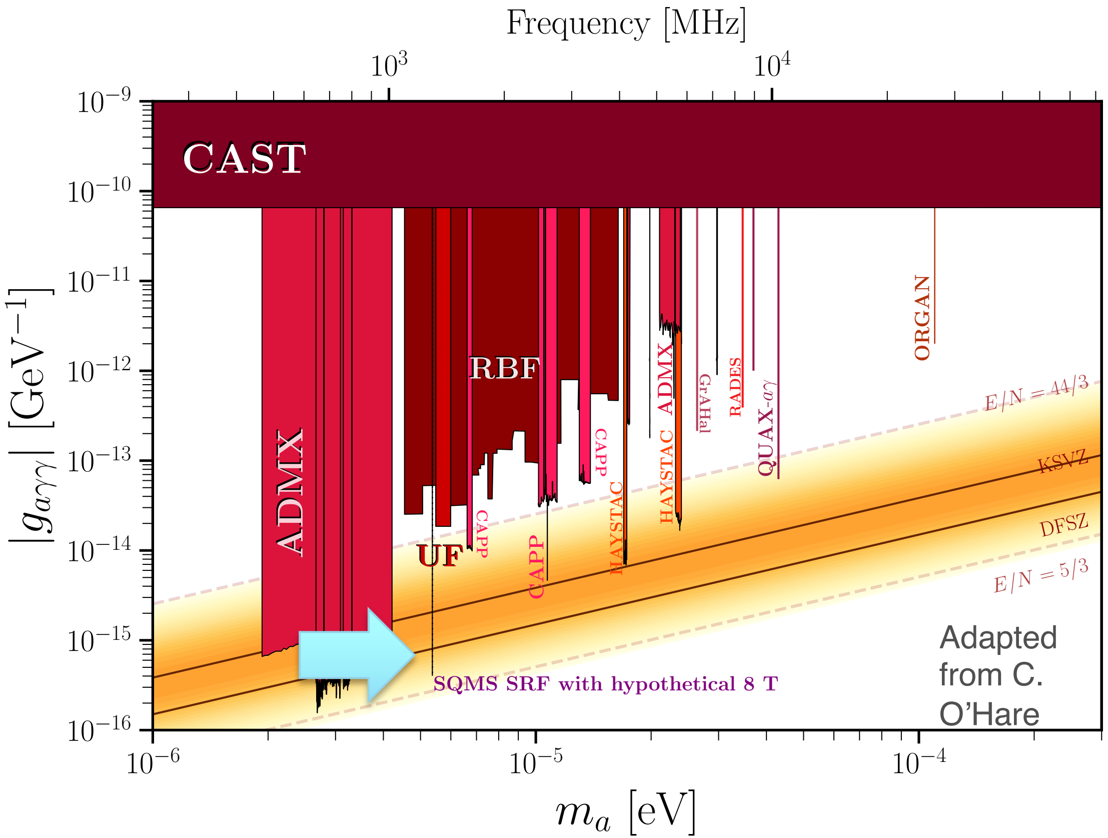
SQMS 3D transmon qubit performance:

$$T_1 \approx 25\ \mu s$$

$$T_2 \approx 15\ \mu s$$

Regularly perform photon counting with dispersive measurements.

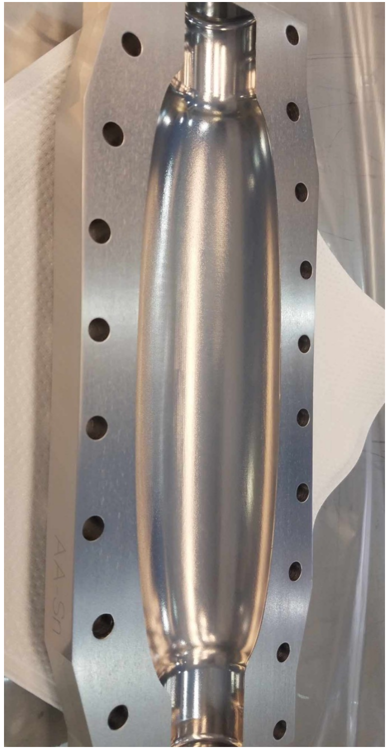
If this would work in an 8T field

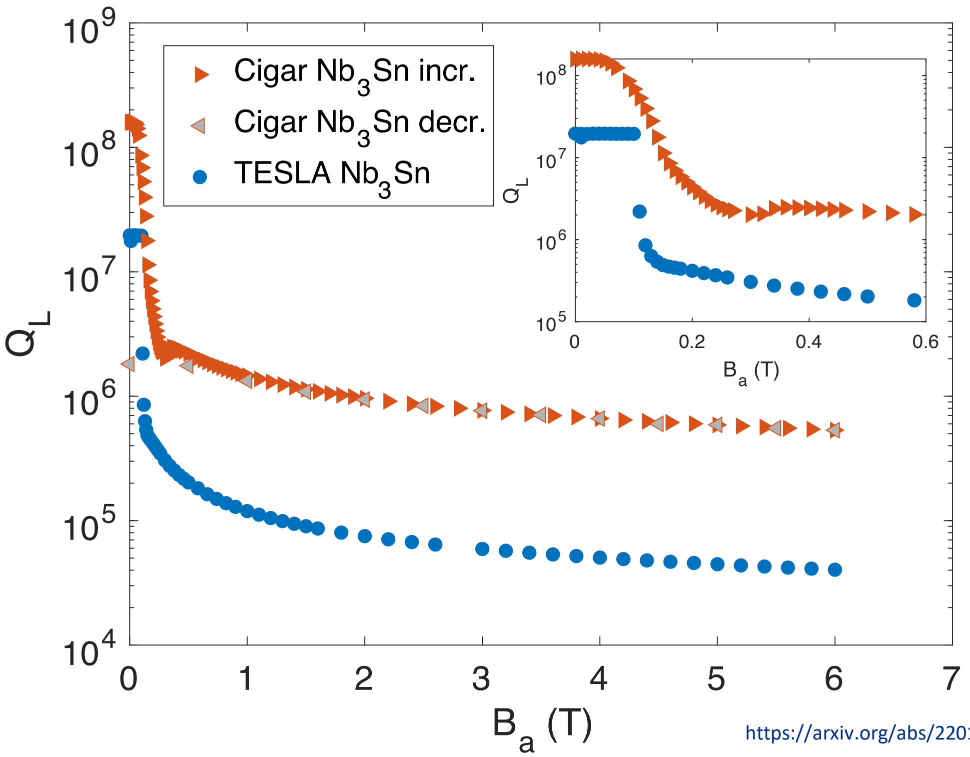


Sensitivity to **QCD axion** with single cavity and HEMT.

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

Nb_3Sn Cavities Maintain High Q in Magnetic Fields



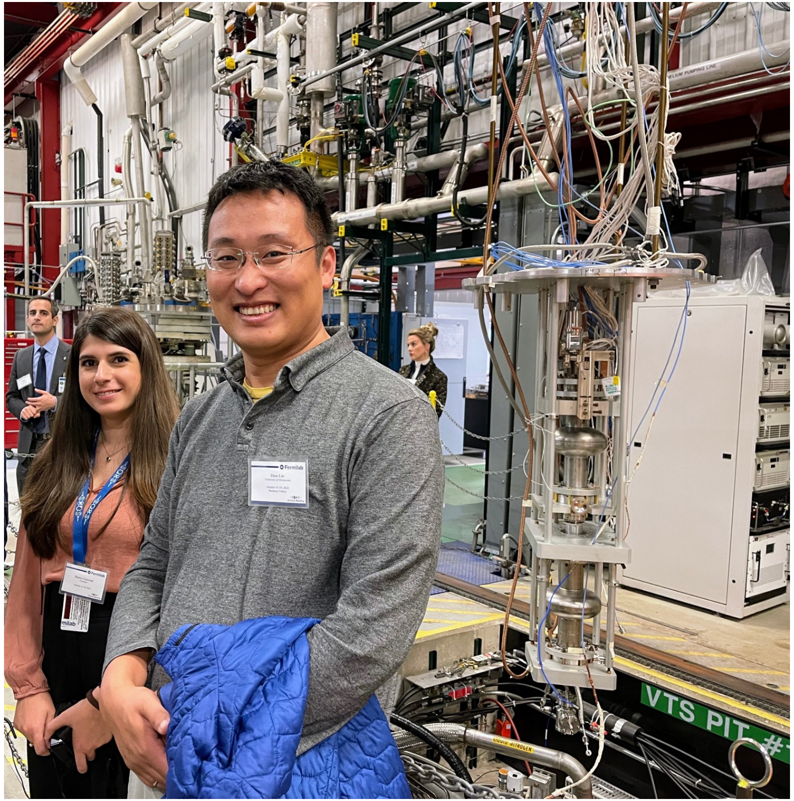


Further improvements with better flux pinning and better alignment with magnetic field.

Waiting for new test stand.

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

Bianca Giaccone will talk about DarkSRF



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Search for Dark Photons with Superconducting Radio Frequency Cavities

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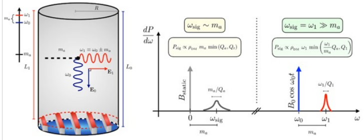
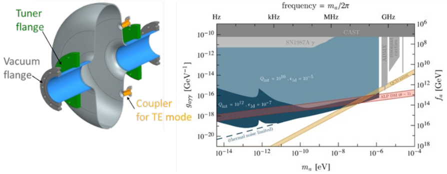
(Received 28 January 2023; accepted 23 May 2023; published 26 June 2023)

We conduct the first "light-shining-through-wall" (LSW) search for dark photons using two state-of-the-art high-quality-factor superconducting radio frequency (SRF) cavities —Dark SRF—and report the results

Also working on low mass axion search with 2-mode cavity.



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



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Maybe openings in the future. Get in touch.

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.