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

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What is Dark Matter?

Can it be Axions? Dark Photons?

Feeble interaction with photons. We can look for that.

Credit: A. Dixit
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).

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

Credit: C. O’Hare
SRF Cavities for Dark Matter Searches

High $Q$ allows for larger signal and lower noise floor. Possibly factor $10^5$ increase in instantaneous scan rate.

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

$ADMX$ and $CAPP \rightarrow Q \approx 10^5$
Instantaneous scan rate is proportional to $Q_L$

For virialized axions
\[
\frac{df}{dt} \sim Q_L Q_{DM} \left( \frac{\eta \chi^2 m_{A'} \rho_{A'} V_{eff} \beta}{\text{SNR} T_n (\beta + 1)} \right)^2
\]
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.

SERAPAH: SupERconducting Axion and Paraphotolon Haloscope

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

SRF  Seraphine  Sir Raph(ael)
SERAPHv1: Parasitic Search for Dark Photons

$T_c \approx 35 \text{ mK}$
$Q_L \approx 5 \times 10^9$
$f_0 = 1.295 \text{ GHz}$
$\beta \sim 1.3$

$T_a \approx 4.9 \text{ K}$
$G \approx +37 \text{ dB}$

No DP signal. Just noise.

1000 seconds integration time
Deepest sensitivity: Ultrahigh Q for Dark photon DM

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.
SERAPHi 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.
SERAPHv1 Microphonics and Frequency Modulation

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

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<thead>
<tr>
<th>Modulation Frequency $f_m$ (Hz)</th>
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Carrier band attenuated by 0.54 dBc. DM signal attenuated $\eta \approx 0.88$

Might recover if analysis looks for sidebands.
Similar 1.3 GHz cavity in liquid helium bath. Tunes by mechanical compression for 500 kHz tuning range. $T_{\text{cav}} = 1.4 \text{ K}$, $Q_L = 2.4 \times 10^8$. Very overcoupled.
Deepest sensitivity: Ultrahigh Q for Dark photon DM

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Next steps:

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Cervantes et al., arXiv:2208.03183v3 (2022)
SERAPHv2: Simulated and measured modes

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.

Credit: T. Kim
Current photon counting scheme

Qubit T1 $\sim$ 150 $\mu$s. 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:
$|g\rangle$ corresponds to 1 photon.
$|e\rangle$ corresponds to 0 photon.

Can use fidelity matrix and characteristics of the system to derive dark photon limit.
Why we need photon counting

\[ V_c = 136 L \times \left( \frac{f}{1 \text{GHz}} \right)^{-3} \]

\[ Q_L = 80000 \times \left( \frac{f}{1 \text{GHz}} \right)^{-2/3} \]

\[ n_c = \frac{1}{\exp\left(\frac{hf}{k_bT}\right) - 1} \]

SQL noise dominates at higher frequencies. Mitigating SQL could increase scan rate by many orders of magnitude.
If $Q \sim 10^{10}$ 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$_3$Sn Cavities in Multi-Tesla Field R&D at Fermilab

- Electropolishing Nb Cavity
- Nb$_3$Sn coated on Nb
- Assembled cavity

Up to ~6 T at 4.4 K

$Q_0$ of $5 \times 10^5$ at 6 T, 4.2 K, 3.9 GHz
**FNAL Nb$_3$Sn Cavities for ADMX and INFN**

**Initial R&D at Fermilab**
- Prototypes sent to Partners
  - Nb$_3$Sn tuning rod for ADMX Sidecar sent to U. Washington (w/ LLNL)

**Potential Future Experiments**
- ADMX-EFR at Fermilab
- Hybrid dielectric-Nb$_3$Sn cavity for INFN QUAX haloscope
- 9 GHz Nb$_3$Sn cavity sent to INFN Frascati for testing in 8 T fridge
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 photon counting and high-Q cavities in magnetic fields for axion searches. Will be enabling technologies for future axion searches.
SERAPHv1 Noise calibration with Variable Temperature Stage

$P_o = k_B G B (T_{\text{VTS}} + T_{\text{add}})$

$T_{\text{add}} = 7.11 \pm 0.35 \text{ K}$

$T_{\text{add}}$ consistent with 4.6 K amplifier noise and 2 dB insertion loss.
The simulated effective volume for the plunger cavity can be calculated as:

\[ V_{\text{eff}} = \frac{\left| \int dV E_z \right|^2}{\int dV |E|^2} \]
Plunger Cavity Microphonics FFT

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<tr>
<td>6.9</td>
<td>31.9</td>
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<tr>
<td>153.6</td>
<td>23.7</td>
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<td>120</td>
<td>7.0</td>
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<tr>
<td>59.7</td>
<td>5.9</td>
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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**

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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

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

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.
Would take long time to scan DFSZ with single cavity

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

$$Q_L = 80000 \times \left(\frac{f}{1 \text{GHz}}\right)^{-\frac{2}{3}}$$

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

Note: photon counting estimate doesn’t yet take into account counter errors. Numerical estimates sensitive to engineering parameters.
SERAPHv1 Measure Q with decay measurement

\[ f_0 = 1.294606 \text{ GHz} \]
\[ \tau = 0.579 +/- 0.001 \text{ s} \]
\[ Q_L = (4.71 +/- 0.01)e+09 \]
\[ Q_0 = (1.07 +/- 0.14)e+10 \]
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Parity measurement maps cavity state onto qubit

Credit: A. Dixit