Dark SRF - Theory

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Opportunities to Explore Dark Sectors

- Fermilab has a unique opportunity to launch a program of exploring dark sectors that couple to EM radiation using SRF technology.

  Well motivated theories:
  - Dark Photons
  - Axions and ALPs

  Well motivated searches:
  - Light mediators
  - Dark matter

- Leveraging existing Fermilab infrastructure and expertise.

- We are asking the PAC to endorse the physics goals and the effort to use SRF technology for fundamental discovery.
Dark Photons

- Imagine another photon, with a different mass.
- Common in top-down frameworks.
- Any heavy particle that is charged both photons will generate mixing.

\[ \gamma \rightarrow \text{oscillating} \rightarrow \gamma' \]

\[ \mathcal{L} = -\frac{1}{4} \left( F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu} - 2\epsilon F_{\mu\nu} F'^{\mu\nu} \right) + \ldots \supset \epsilon \left( \vec{E} \cdot \vec{E}' + \vec{B} \cdot \vec{B}' \right) \]

An oscillating EM field is a source of dark photons, and vice versa. (reminiscent of neutrino oscillations)
Axion-like particles

- Imagine an approximate symmetry broken at a high scale $f$. → a pseudo-Goldstone Boson $\approx$ an axion-like particle.
- Common in top-down constructions, the axion is invoked to solve the strong CP problem.
- Loops of heavy charged particles can generate interaction:

$$\mathcal{L} = \frac{\alpha}{f} aF_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

Axions and photons mix in a magnetic field.

An oscillating $\vec{E} \cdot \vec{B}$ is a source of dark photons.
Both axion-like particles and dark photons are well motivated as mediators of long range interactions that can be searched for.

Both axion-like particles and dark photons are dark matter candidates with nice production mechanisms.

In the Wave-like DM category. Oscillating at $\omega = m_{DM}$.
Searches with SRF Cavities

- Fermilab’s SRF Cavities are world’s highest quality photon resonators, with Q as high as $10^{11}$:
  - Large coherent fields when excited $\rightarrow$ source dark fields.
  - Resonant response $\rightarrow$ amplify coherent feeble signals.

Light Shining through wall:

Emitter $\rightarrow$ Receiver

A dark matter search:

Receiver

the DM filled Universe is the emitter

a search for a mediator.
Dark Photon Search

The first simple setup:

Emitter Cavity

Receiver Cavity
Dark Photon Search

The first simple setup:

- **Emitter Cavity**
  - Frequency of 1.3 GHz, excited to ~ 35 MV/m.
  - That's ~ $10^{25}$ Photons!

- **Receiver Cavity**
Dark Photon Search

The first simple setup:

Emitter Cavity

Frequency of 1.3 GHz, excited to \( \sim 35 \text{ MV/m} \).

That's \( \sim 10^{25} \) Photons!

a dark photon field is radiated at 1.3 GHz.

Receiver Cavity
Dark Photon Search

The first simple setup:

Emitter Cavity

Frequency of 1.3 GHz, excited to $\sim 35$ MV/m. That's $\sim 10^{25}$ Photons!

Receiver Cavity

Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise ($T=1.4$ K).

For correct cavity positioning

$$P_{\text{rec}} \sim G^2 \varepsilon^4 \left( \frac{m_{\gamma'}}{\omega} \right)^4 Q_{\text{rec}} Q_{\text{em}} P_{\text{em}}$$

[see Graham, Mardon, Rajendran, Zhao 2014]
Dark Photon Search

\[ \omega = 1.3 \text{ GHz} \]
\[ Q = 10^{10} \]
\[ t = 2 \text{ weeks} \]

Runs:
\[ T = 1.4 \text{ K} \]
\[ T = 10 \text{ mK} \]

CMB, Coulomb, Dark SRF @ Fermilab, CROWS (cavities)

Log_{10}(m\gamma/eV)

Log_{10}(\epsilon)

Preliminary
A further search for dark photon DM can follow using a tunable receiver cavity.
Axion Searches (future directions)

**Emitter Cavity**

Excite *two* modes, with a non-zero (oscillating) $E_1 \cdot B_2$

*or*

search for cosmic DM.

**Receiver Cavity**

an axion field is radiated at $(f_1 \pm f_2)$.

Several possibilities to explore:

- One excited and one quiet mode.
- Inserting a region of static B field.
- …. R&D is required
On to Anna...
Deleted Scenes
**Light Shining through Wall versus a DM Search**

Independent of whether the A’ or axion are the DM.

- *No need to scan.*
- Need to tune cavities to one another.

Assumes the A’ or axion are the DM, but is often more sensitive.

- Need to scan.
- *No need to tune.*
Some References LSTW