SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Managed by Fermi Research Alliance, LLC for the U.S Department of Energy Office of Science

Preparation for DM searches with high Q SRF cavities

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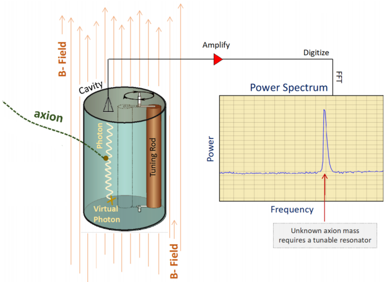
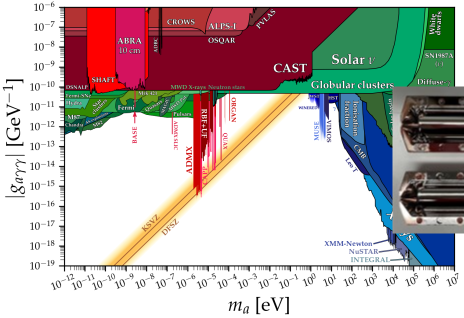
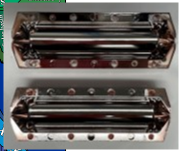
Dark matter detection

Haloscopes need to be TUNABLE cavities



Credit: C. Boutan





Credit: O'Hare [7]
Credit: QUAX

Scan rate: $\frac{df}{dt} \propto Q_L Q_a$

Experimental requirements

$$P_a = 1.85 \times 10^{-25}\,\mathrm{W} \left(\frac{\boldsymbol{B}}{2T}\right)^2 \left(\frac{\rho_a}{0.45\,\mathrm{GeVcm}^{-3}}\right) \left(\frac{f_c}{9.067\,GHz}\right) \left(\frac{\boldsymbol{Q_L}}{2.01 \times 10^5}\right)$$ [1]

- Multi Tesla Magnetic Field (only for Axion)
- High Q factor and tunable cavities
- Cryogenic temperature $\rightarrow$ Reduce thermal noise
- Low noise amplification

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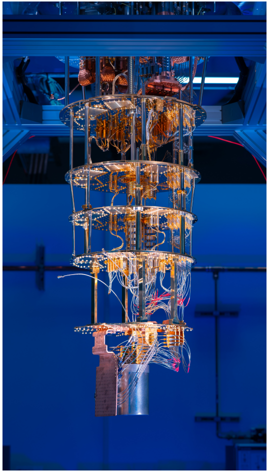
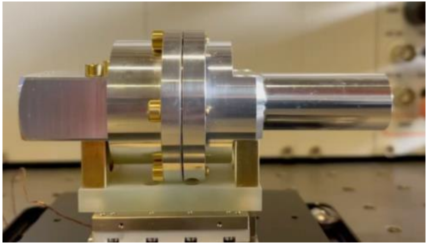
Tunable cavity measurements in dilution refrigerator

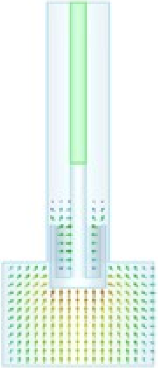


Credit:SQMS

Tunability

- in DR (mK): > 250 MHz
- in LHe (2 K): ~ 3 GHz





Credit: R. Cervantes[4]

Cavity Characterization - Decay measurement

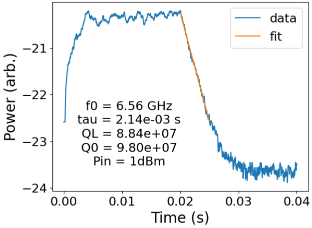
An undrived cavity decays as

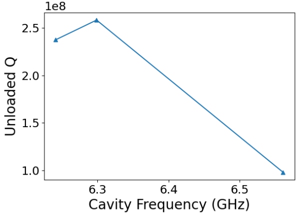
$$U = U_0 e^{-\frac{t}{\tau_L}}, \quad \tau_L = \frac{Q_L}{\omega_0}$$

Decay measurements allow to measure the loaded quality Q_L, which relates to the unloaded Q_0:

$$\frac{1}{Q_L} = \frac{1}{Q_0}(1 + \beta_i + \beta_t)$$

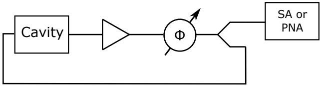
$$\beta_\alpha = \frac{Q_0}{Q_\alpha} = \frac{P_\alpha}{P_c}$$



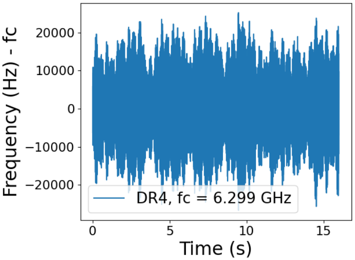


Noise sources

The external environment including the cryogenic system can excite mechanical modes that disturb the resonance



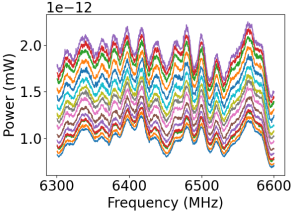
Self Excited Loop, SEL signal read by a Signal Analyzer, SA or a Phase Network Analyzer, PNA



RMS $\sim 8\,\mathrm{kHz}$
while $BW = \frac{1}{\tau_L} \sim 500 Hz$

The amplifier chain noise is parametrized as thermal noise

$$P = G k_b b \left(T_{sys} + T_{amp}\right)$$



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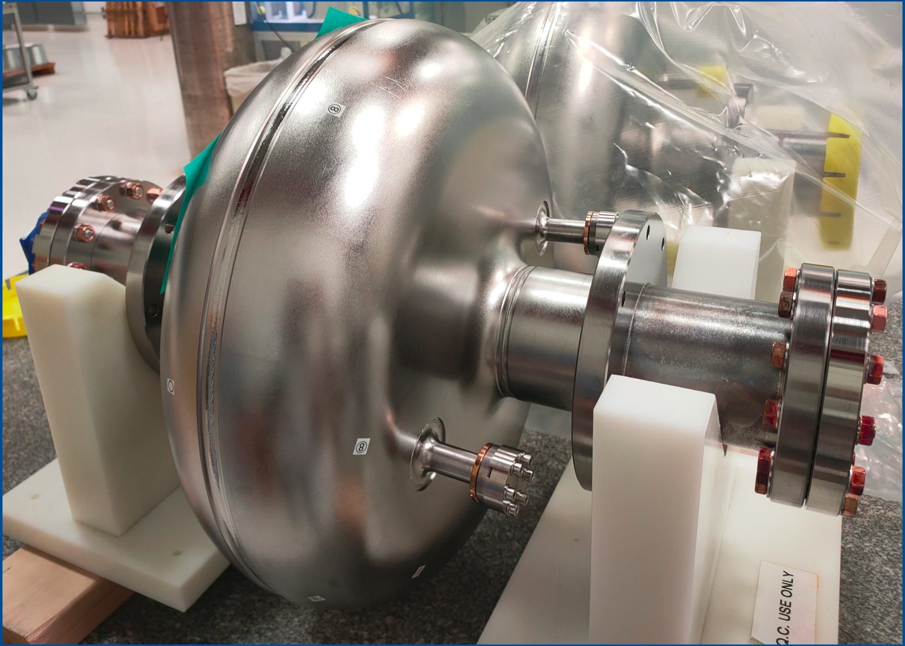
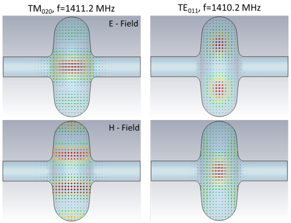

Q.C. USE ONLY

Heterodyne Detection

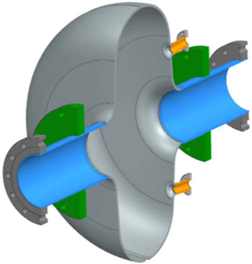
The axion field induces transitions between two well spatially separated but quasi-degenerate cavity modes:

- $TM_{020} \rightarrow$ pump mode: ω_0
- $TE_{011} \rightarrow$ signal mode: ω_{sig}



$$\omega_{sig} = \omega_0 \pm m_a$$

Tunable cavity to search a mass range:
$100\,\text{kHz} \leq m_a \leq 1\,\text{MHz}$

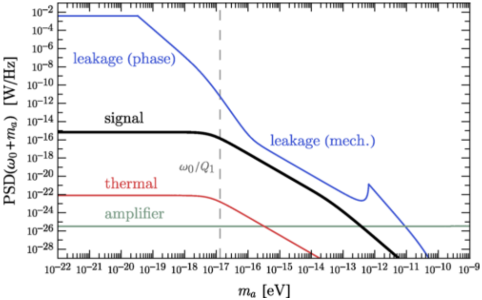


Credits: B. Giaccone et al.[6]

SNR

$$SNR \sim \frac{\rho_{DM} V}{m_a \omega_1} (g_{a\gamma\gamma} \eta_{10} B_0)^2 \left(\frac{Q_a Q_0 t_e}{T} \right)^{\frac{1}{2}}$$

within certain constraints and at relatively high axion masses ***temperature*** and ***amplifier noise*** dominate[2],
while at intermediate masses spurious signal comes from ***leakage noise***[3]



Credits: A. Berlin et al.[3]

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Next steps

- finalize the DA of the data collected with SERAPH cavity in DR
- collection of data from a Signal Analyzer to simulate the background thermal noise expected during a DM axion search with SHADE experiment
- understanding and analysis of main noise sources and their impact on the expected data
- development of code to extract a DM limit

$$SNR(g_{a\gamma\gamma}) < 1$$

$$SNR \propto g_{a\gamma\gamma}^2$$

Thank you!

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Bibliography I

[1] D. Alesini, C. Braggio, G. Carugno, N. Crescini, D. D'Agostino, D. Di Gioacchino, R. Di Vora, P. Falferi, S. Gallo, U. Gambardella, C. Gatti, G. Iannone, G. Lamanna, C. Ligi, A. Lombardi, R. Mezzena, A. Ortolan, R. Pengo, N. Pompeo, A. Rettaroli, G. Ruoso, E. Silva, C. C. Speake, L. Taffarello, and S. Tocci.
Galactic axions search with a superconducting resonant cavity.
Phys. Rev. D, 99:101101, May 2019.

[2] Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, Christopher Nantista, Jeffrey Neilson, Philip Schuster, Sami Tantawi, Natalia Toro, and Kevin Zhou.
Axion dark matter detection by superconducting resonant frequency conversion.
Journal of High Energy Physics, 2020(7):88, Jul 2020.

[3] Asher Berlin, Raffaele Tito D'Agnolo, Sebastian A. R. Ellis, and Kevin Zhou.
Heterodyne broadband detection of axion dark matter.
Phys. Rev. D, 104:L111701, Dec 2021.

[4] R. Cervantes.
Data, plots and code for constraints on axions, axion-like particles, and dark photons.
https://agenda.infn.it/event/34455/contributions/202525/attachments/108124/152842/RCervantesPatras2023.pdf.

Bibliography II

[5] R. Cervantes, J. Aumentado, C. Braggio, B. Giaccone, D. Frolov, A. Grassellino, R. Harnik, F. Lecocq, O. Melnychuk, R. Pilipenko, S. Posen, and A. Romanenko.
Deepest sensitivity to wavelike dark photon dark matter with superconducting radio frequency cavities.
Phys. Rev. D, 110:043022, Aug 2024.

[6] Bianca Giaccone, Asher Berlin, Ivan Gonin, Anna Grassellino, Roni Harnik, Yonatan Kahn, Timergali Khabiboulline, Andrei Lunin, Oleksandr Melnychuk, Alexander Netepenko, Roman Pilipenko, Yuriy Pischalnikov, Sam Posen, Oleg Pronitchev, Alex Romanenko, and Vyacheslav Yakovlev.
Design of axion and axion dark matter searches based on ultra high q srf cavities, 2022.

[7] Ciaran O'Hare.
Seraph: Wavelike dark matter searches with srf cavities.
`https://github.com/cajohare/AxionLimits/tree/master`.
[Github reposition].

[8] Hasan S Padamsee, J. Knobloch, T. Hays, and Perry B. Wilson.
Rf superconductivity for accelerators.
1998.

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Fermilab

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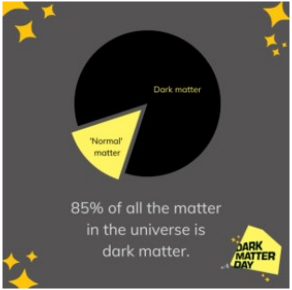
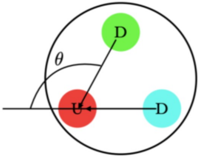
QCD Axion

Dark matter candidate



Solves the strong CP problem

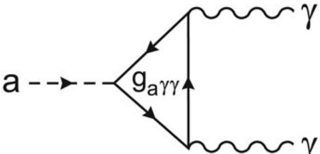
- QCD vacuum parametrized by θ field
- Peccei-Quinn Symmetry, global axial U(1)
- Nambu-Goldstone Boson arising from spontaneous symmetry breaking of PQ field



classical picture of the neutron

Axion detection

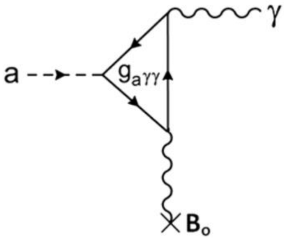
Inverse Primakoff Effect: multiTesla magnetic field



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

$$\tau_{a\gamma\gamma} \approx \left(\frac{1\times 10^5\,\mathrm{eV}}{m_a}\right)^5$$

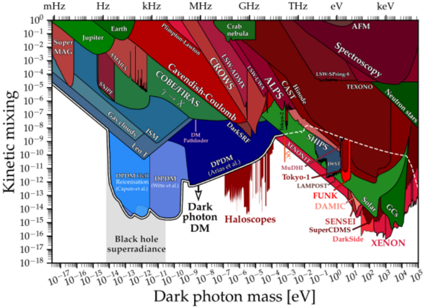
$$\mu ev \leq m_a \leq meV \rightarrow \tau_{a\gamma\gamma} \gg age\ of\ U$$



$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}_0$$

$$\tau_{a\gamma\gamma} \propto B_0^2$$

Dark Matter Dark Photon (DMDP)



Credit: O'Hare [7]

Massive vector boson that interacts through kinetic mixing χ, with the SM photon

- $P_S = \eta\chi^2 m_{DP}\rho_{DM} V_{eff} \frac{\beta}{\beta+1} L(f, f_0, Q_L) min(Q_L, Q_{DM})$
- $\frac{df}{dt} \sim Q_L Q_{DM} \left(\frac{\eta\chi^2 m_{DP}\rho_{DM} V_{eff}\beta}{SNR\ T_n\ (\beta+1)} \right)^2$ [5]

No need for magnetic field

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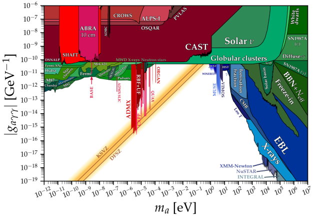
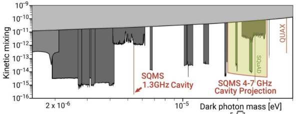
High Q SRF

high Q means higher then $Q_a \sim 10^6$
Copper cavities: $Q < 10^5$ limited by anomalous skin effect
SC cavities: ultra high $Q > 10^{10}$ (no external magnetic field)

Trying to detect $< 1 \times 10^{-24}$ W signal over a wide range of frequency
Fermilab and other labs have demonstrated the advantage of high Q SRF cavities for DM detection:

- higher power signal
- faster scan rates possibly by 10^5 (DMDP)
- higher SNR ratios, thus deeper exclusion limits





Credit: Cervantes et al. [5]
Credit: O'Hare[7]

Quality factor[8]

Characterizes the wall power losses of a cavity and in particular it's related to the power decay time

Joule heating

$$\frac{dP_c}{ds} = \frac{1}{2} R_s |\mathbf{H}|^2$$

Then if one defines the unloaded quality factor

$$Q_0 \equiv \frac{\omega_0 U}{P_c} = \frac{G}{R_s} \qquad (1)$$

where

$$U = \frac{\mu_0}{2} \int_V |\mathbf{H}|^2 dv = \frac{\epsilon_0}{2} \int_V |\mathbf{E}|^2 dv$$

$$G = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 dv}{\int_S |\mathbf{H}|^2 ds} \propto \omega_0 \ a$$