SQMS axion searches based on $Q_0 \sim 10^{10}$ multimode superconducting cavities

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1. Introduction

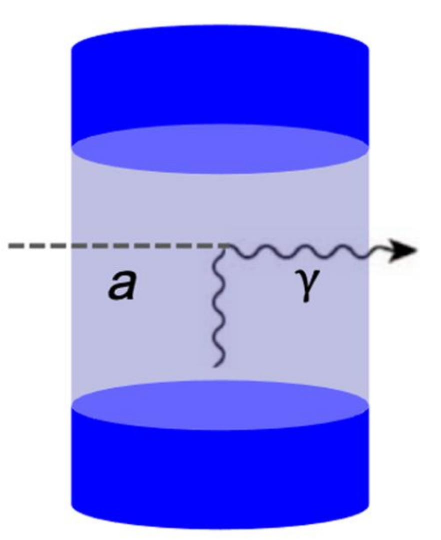
The Physics and Sensing thrust of the Superconducting Quantum Materials and Systems (SQMS) center is developing searches for dark photons, axions and ALPs with the goal of improving upon the current state-of-the-art sensitivity. We are actively working on multiple experiments, including axion haloscopes, DM dark photon searches and light-shining-through-the-wall experiments. All these efforts leverage on Fermilab expertise on ultra-high Q superconducting RF cavities combined with the center research on QIS and quantum technology. This poster focuses on three axion searches that utilize ultra-high Q SRF cavities and their resonant modes to enhance the production and/or detection of axions in the cavity volume. In addition, multi-mode and single mode non-linearity measurements are being carried out as part of an experimental feasibility study to gain insight on the behavior of the ultra-high Q resonators and the RF system in the regime relevant for axion searches.

2. SRF cavities for axion searches

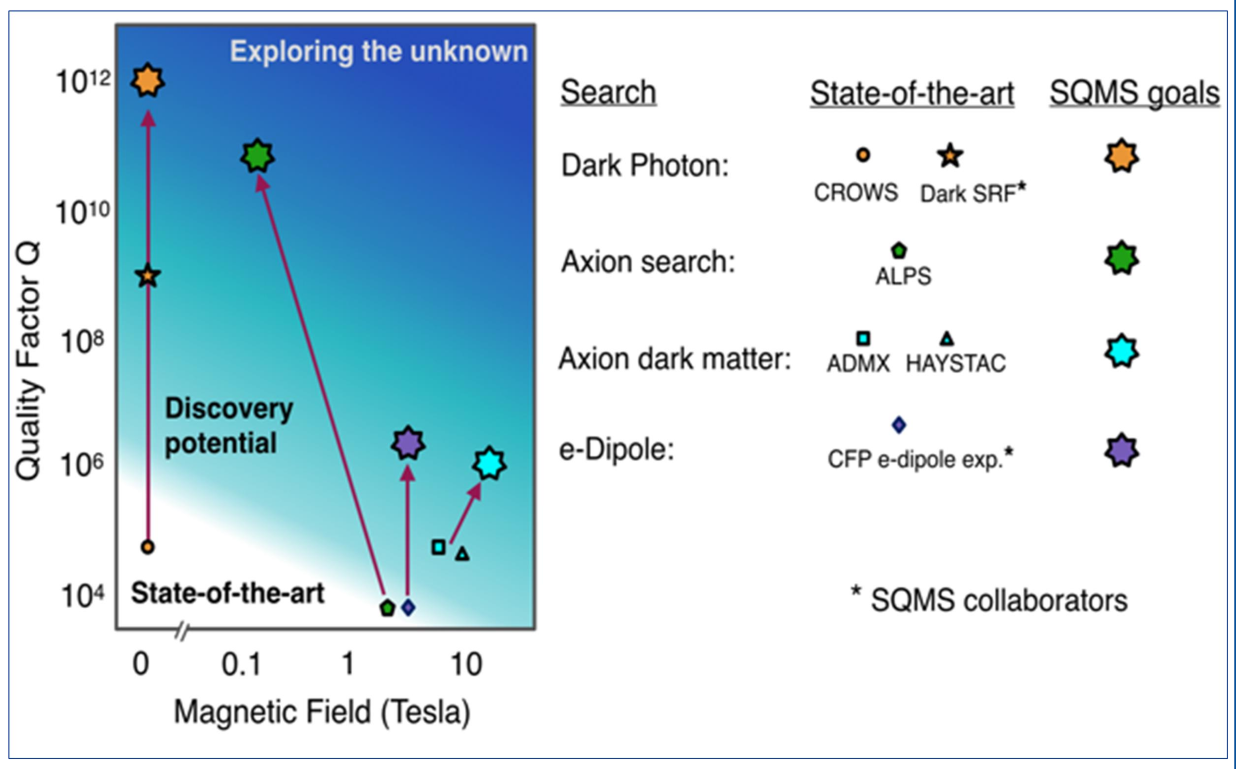
Sensitive to light axions and axion-like particles (ALPs)

Resonant detectors can exploit the coherence of the axion field:

- if $m_a \sim \mu eV$, the axion oscillates at ~GHz → searches implemented using NC cavities in static external **B** field
- For lower axion masses: prohibitive large cavities → different approach is necessary: heterodyne detection



Axion-photon interaction [1]



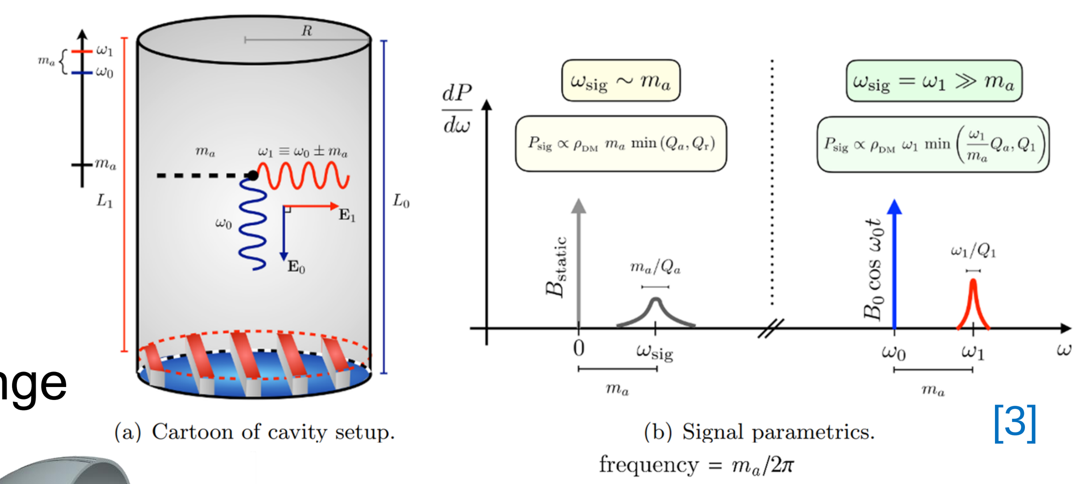
[1] Semertzidis & Youn, Sci Adv, DOI:10.1126/sciadv.abm9928

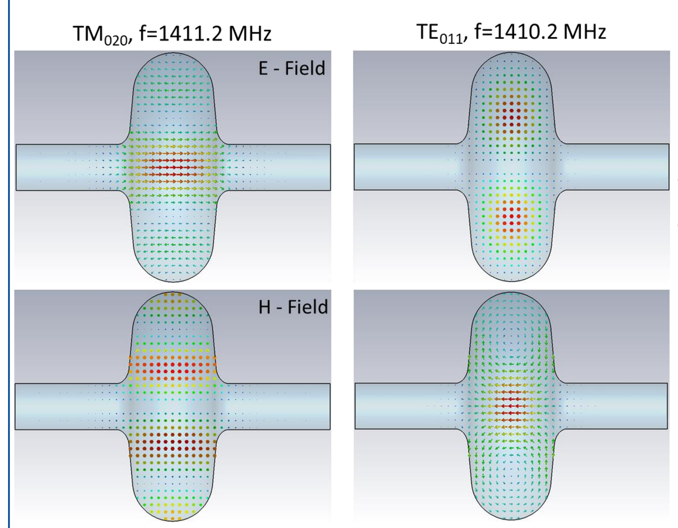
[2] Berlin, *et al.*, *arXiv:2203.12714* (2022)

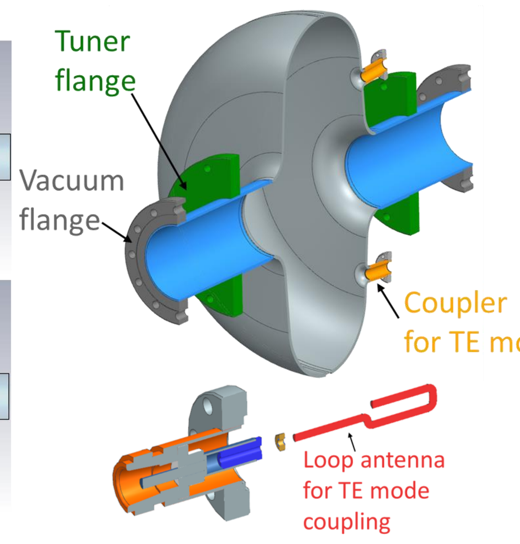
3. Search schemes for axions using ultra high Q SRF cavities

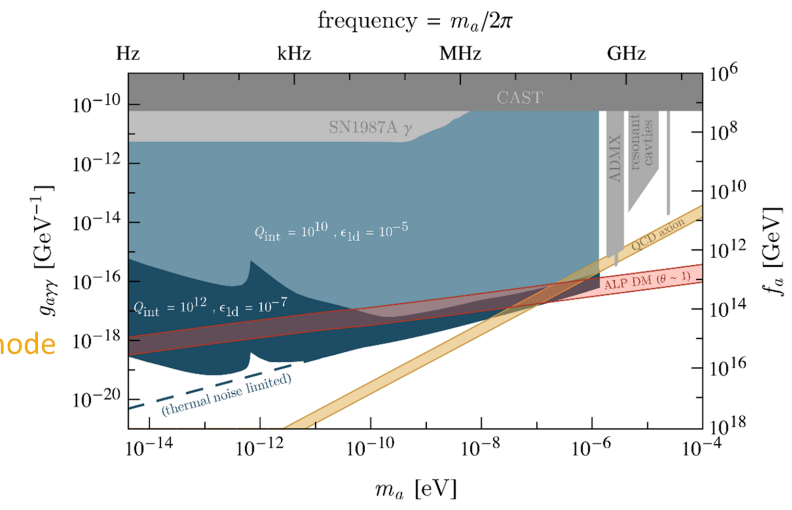
2-mode axion DM cavity:

- Design completed, currently procuring prototype cavity
- Pump mode: TM_{010}
- Signal mode: TE_{011}
- Δf≈1MHz, with 2MHz tunable range





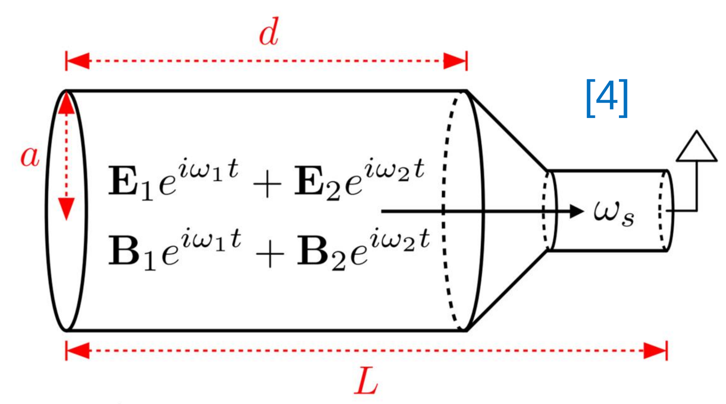


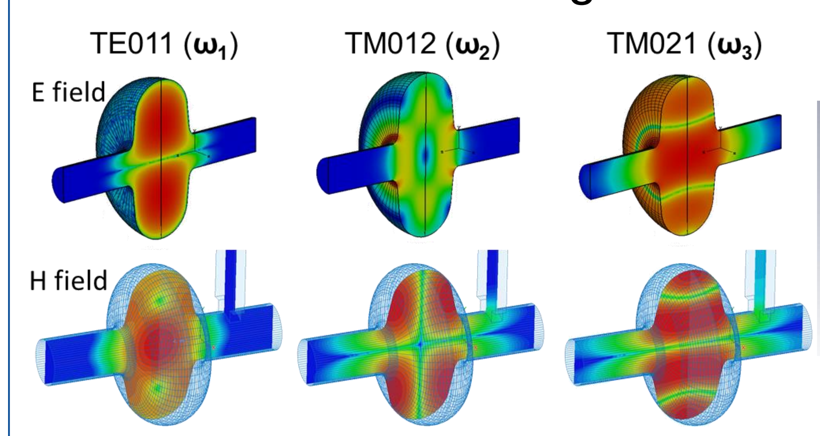


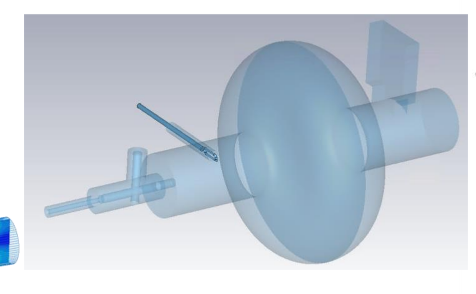
[3] Berlin, *et al.*, JHEP, DOI:10.1007/JHEP07(2020)088

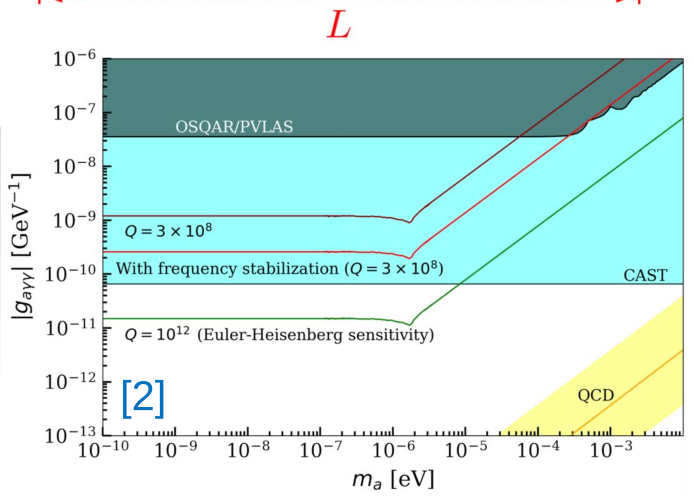
3-mode axion cavity:

- Design is being finalized
- Pump modes: TE_{011}, TM_{012}
- Signal mode: TM_{021}
- Exploring single or double stage notch to filter RT noise at signal mode



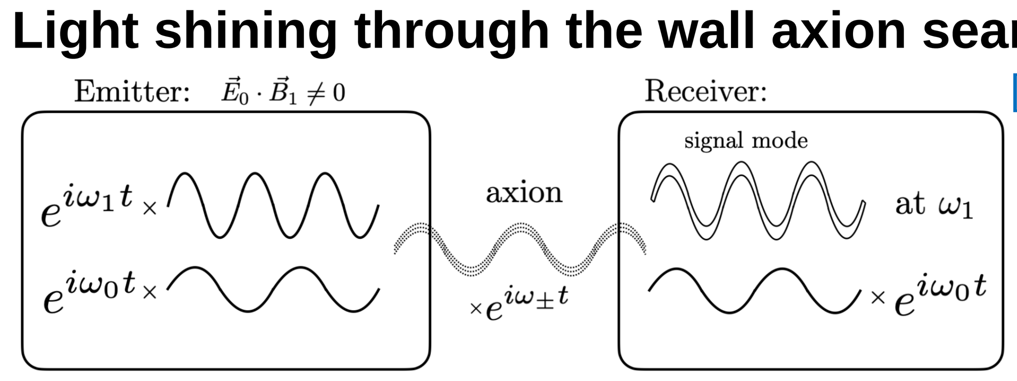


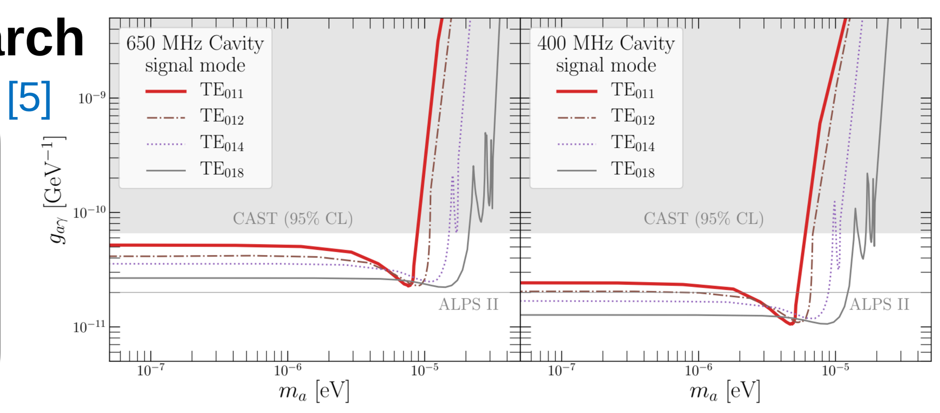




[4] Bogorad, *et al.*, PRL, DOI:10.1103/PhysRevLett.123.021801

Light shining through the wall axion search



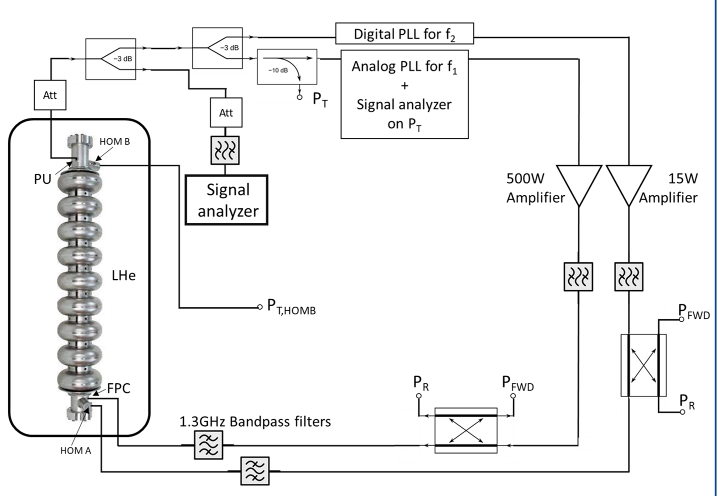


[5] Gao & Harnik, JHEP, DOI:10.1007/JHEP07(2021)053

4. Feasibility study at 2K

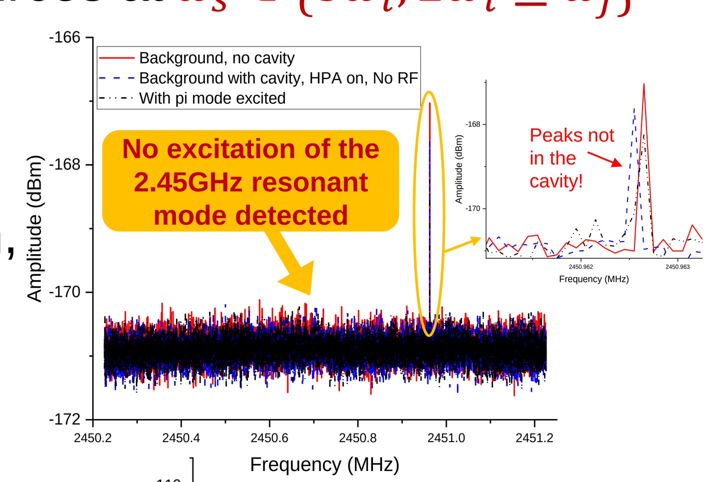
To understand how to successfully implement these search schemes:

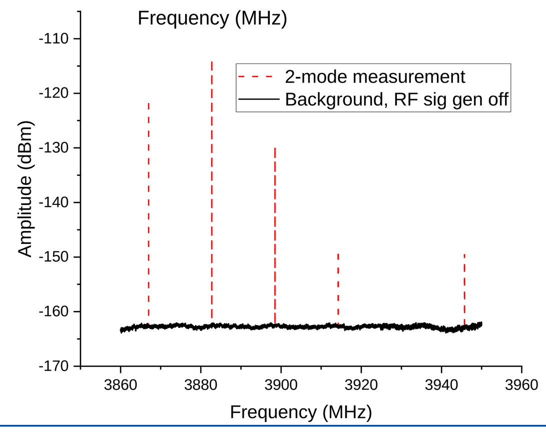
- Necessary to measure noise background in SRF cavity
- Study possible energy leak from excited mode(s) to other resonant modes or to linear combinations of pump modes



Nonlinear Meissner effect: for incident photons in 2 modes (ω_1, ω_2) nonlinear term in the current response can lead to current sources at $\omega_s \in \{3\omega_i, 2\omega_i \pm \omega_j\}$ with $i \neq j$ and $i, j = 1,2$ [6] Sauls, PTEP, DOI:10.1093/ptep/ptac034

- 1-mode measurements on 9-cell SRF cavity:
  - π mode excited in the cavity: E_{acc}=12.5MV/m, Q_0=2E10 → no excitation of other resonant modes ~1GHz away detected above background.
- 2-mode measurements:
  - ω_1 and ω_2 ∈ TM010 excited in the cavity
    - ➢ linear combinations at $2\omega_i - \omega_j$ → generated in signal analyzer (SA)
    - ➢ Linear combinations at $2\omega_i + \omega_j$ → generated in the SA or in the cavity or in the RF system?





5. Conclusions

- Three search schemes for axions and axion DM are under consideration:
  - 2-mode axion DM cavity: design completed
  - 3-mode axion cavity: finalizing the RF design
  - LSW axion search: design will start soon
- Feasibility study in preparation for axion searches development:
  - Study of nonlinearities in SC cavities: necessary step to successfully implement axion searches
  - 1-mode measurements on 1.3GHz 9-cell cavity:
    - ➢ Measurements of resonant modes ~1GHz away from pump mode showed no excitation above background level
  - 2-mode measurements on 1.3GHz 9-cell cavity:
    - ➢ Cavity geometry is not optimized for nonlinearity measurements: the sensitivity on $2\omega_i - \omega_j$ is limited by SA intermodulation of pump modes
    - ➢ Still determining the source of $2\omega_i + \omega_j$: thorough study of power dependency and decay measurements may help.

[7] Giaccone, *et al.*, *arXiv:2207.11346* (2022)

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.

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