Heterodyne Detection of Axion Dark Matter via Superconducting Cavities

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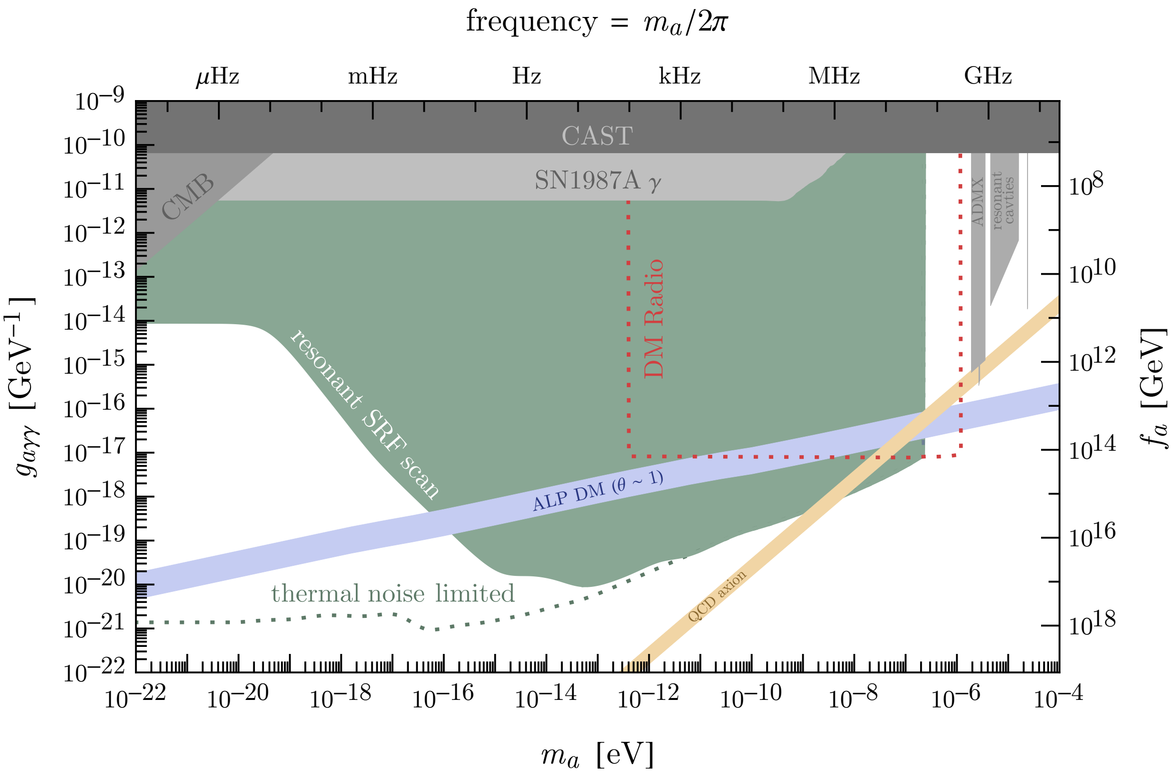
Introduction: In the past decade, interest in small-scale experiments has dramatically increased. Such searches rely on precision measurements rather than high energies, and their sensitivities rely on innovations in a broad range of fields, ranging from atomic to accelerator physics. Many of these searches target ultralight bosonic dark matter (DM), and a particularly well-motivated example is a light pseudoscalar protected by a shift symmetry, which we refer to as an axion.

In the presence of a static background electromagnetic field, an axion DM field generically sources a very small effective current oscillating with frequency equal to the axion mass m_a, which may be resonantly enhanced. To date, most axion search experiments have used systems with resonant frequency equal to m_a, such as microwave cavities or lumped-element circuits.

Recently, we have proposed a "heterodyne" approach to axion DM detection [1, 2] (see also [3]), where a microwave cavity is prepared by driving a "pump" mode with nonzero frequency $\omega_0 \sim$ GHz. The axion field causes frequency conversion, resonantly driving power into a "signal" mode with nearly degenerate frequency $\omega_1 \simeq \omega_0 \pm m_a$. This approach has the advantages of lower readout noise at low axion masses, since the signal is always at GHz frequencies, and a parametrically larger signal power compared to static-field haloscopes [4]. The axion signal is extremely narrow compared to its frequency ω_1, and one of the major noise sources is power "leaking" from the driver to the readout. These two considerations motivate the use of superconducting radiofrequency (SRF) cavities, which have achieved intrinsic quality factors as high as $Q_0 \sim 2 \times 10^{11}$ [5].

Expected Sensitivity: As a benchmark, we consider using two low-lying modes of a cubic-meter SRF cavity with $Q_0 = 10^{12}$ at typical superconducting temperatures $T = 1.8\,\mathrm{K}$, whose pump mode has a maximum magnetic field $B_0 = 0.2\,\mathrm{T}$. We base some of our noise estimates on measurements taken from a prototype cavity built by the MAGO collaboration [6], which sought to detect gravitational waves using a similar technique. As shown, the reach of a several-year resonant scan encompasses axions that can be produced at the appropriate DM abundance through the misalignment mechanism, across a wide range of masses. At high axion masses, the sensitivity is similar to static-field haloscopes of comparable size, since the advantage of higher Q_0 is balanced by the disadvantages of higher T and lower B_0. However, the advantage of our heterodyne approach grows for lower axion masses. In this range the main noise source is leakage, which we parametrize by a dimensionless cross-coupling ϵ, where $\epsilon = 10^{-7}$ was reported by MAGO.

Experimental Prospects: Realizing this potential physics reach will require optimization of several aspects of the experimental design. This would include a detailed study of potential cavity and mode geometries, as well as the development of technology for manufacturing and tuning the



cavity. A particular challenge is to design a cavity whose mode frequencies can be tuned over the required range, while maintaining a high Q_0 and B_0.

Simultaneously, it would be useful to develop systems to monitor and minimize the leakage noise and cavity frequency drift. The performance of these systems will depends on many technical factors, such as the frequency stability of the driving oscillator, the degree of mechanical vibration of the cavity walls, and the precision to which the geometry of the loading and readout architecture can be controlled. Some of these aspects would synergize with the ongoing efforts of the DarkSRF collaboration [7], which seeks to use SRF cavities to detect dark photons. In particular, DarkSRF has recently confirmed the feasibility of stabilizing cavity mode frequencies to one part in $Q_0 \sim 10^{10}$, corresponding to sub-nanometer control of the cavity walls.

As an intermediate step, one could fix the pump and signal mode frequencies to be degenerate, $\omega_1 \simeq \omega_0$, and overcouple the signal mode to widen its frequency response [2]. This would result in a broadband search, avoiding the need to develop and perform a resonant scan. We estimate that unexplored parameter space spanning several orders of magnitude in axion mass could be probed in this way in as little as a week of data taking, assuming conservative Q_0 and ϵ values which have already been exceeded in existing setups.

Conclusion: The steady improvement of SRF cavities in the context of accelerator physics has led to new opportunities in precision measurement. Our heterodyne approach can probe the QCD axion in a range complementary to lumped element circuits, and similar ideas could be applied to other bosonic fields, such as dark photons, dilaton-like scalars, or non-DM axions [8, 9]. It is also sensitive to axion DM across a wide mass range, corresponding to symmetry breaking scales of up to $f_a \sim 10^{16}$ GeV, thus allowing accelerator technology to probe, through an unexpected route, some of the highest fundamental energy scales in nature.

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