Snowmass2021 - Letter of Interest

Probing the QCD Axion with DMRadio-m^3

Thematic Areas: (check all that apply □/■)

■ (CF2) Dark Matter: Wavelike
■ (IF1) Intensity Frontier: Quantum Sensors

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Abstract:

We present a phased program to search for axion dark matter in the $m_a \lesssim 1\,\mu\mathrm{eV}$ regime. In this regime, the classical microwave cavity haloscope approach requires impractically large cavities, however lumped element circuits – with separated inductive pickups and tunable capacitors – experience the same resonant enhancement and can achieve important science reach for axions and axion-like particles. DMRadio is a 10 year, two-stage program based on developing these lumped element detectors into a full-scale axion dark matter (ADM) search. The first stage, DMRadio-50L, is a cryogenic toroidal detector with $V = 50\,\mathrm{L}$ and $B = 0.1 - 1\,\mathrm{T}$ that will be able to probe ADM over the range $20\,\mathrm{peV} \lesssim m_a \lesssim 20\,\mathrm{neV}$ ($5\,\mathrm{kHz} - 5\,\mathrm{MHz}$) down to $g_{a\gamma\gamma} \sim 5\times10^{-15}\,\mathrm{GeV}$. It is currently in the late stages of design and expected to begin construction in late 2020. DMRadio-m^3 is a next-generation detector with $V \sim 1\,\mathrm{m}^3$ and $B \gtrsim 4\,\mathrm{T}$, that will be capable of probing ADM over the QCD axion band from $20\,\mathrm{neV} \lesssim m_a \lesssim 0.8\,\mu\mathrm{eV}$ ($5 - 200\,\mathrm{MHz}$) with DFSZ sensitivity over the range $0.1\,\mu\mathrm{eV} \lesssim m_a \lesssim 0.8\,\mu\mathrm{eV}$ ($30 - 200\,\mathrm{MHz}$) with 5 yr of run time. DMRadio-m^3 is in the early stages of design as part of the DOE's *Dark Matter New Initiative* program.

Over the past few years, the axion has re-emerged as one of the leading candidates to explain the dark matter (DM) abundance of the universe. The excitement around this particle, and experimental searches for it, can be highlighted by the upward trend in its share of talks at the APS April meetings over the past three years – recently becoming the most discussed DM candidate. Part of this excitement has been driven by improvements in detector technology (often leveraging the parallel development of low noise sensors developed for applications in Quantum Information Sciences), as well as new theoretical work which has led to a much richer understanding of the axion dark matter (ADM) landscape.

QCD Axion models – and models of axion-like particles (ALPs) more generally – depend on two parameters: the axion mass, m_a, and the axion to photon coupling, $g_{a\gamma\gamma}$. The QCD axion[1–3] has a coupling strength proportional to its mass ($g_{a\gamma\gamma} \propto m_a$) with an uncertainty on the proportionality constant of O(10). Further, if the QCD axion is responsible for DM it must lie in a range of masses from $1\,\mathrm{peV} \lesssim m_a \lesssim 1\,\mathrm{eV}$. This creates a compact band of favorable QCD axion models over this mass range. Generic ALPs can exist in this wide mass range but with arbitrary coupling $g_{a\gamma\gamma}$. Historically, ADM experiments have focused on the narrow range from $1 \lesssim m_a \lesssim 40\,\mu$eV. This was due to a model of axion cosmology called *post-inflationary* Peccei-Quinn (PQ) symmetry breaking. However, more recent theoretical work on scenarios with *pre-inflationary* PQ symmetry breaking have widened the range of preferred ADM models down to the lowest masses[4–15]. Of particular note, are QCD axions in the $1 \sim 10\,\mathrm{neV}$ range, which would correspond to new physics around the GUT-scale[4;5]. Moving forward, the community is coalescing around the goal of probing the entire QCD axion band from ∼peV all the way to ∼eV.

Axion Dark Matter Searches With Lumped Element Detectors

At masses $m_a \lesssim 1\,\mathrm{eV}$, axion-like DM behaves as a coherent field oscillating at a frequency equal to the mass of the axion. The coupling between the axion or ALP and the photon produces additional source terms in Maxwell's equations[16]. In the presence of a DC magnetic field, these terms act as effective source currents, which produce physical AC electric and magnetic fields that can be detected. The small axion-photon coupling, $g_{a\gamma\gamma}$, implies that the power transferred to the photon field is extremely small. The solution to this is to leverage the long coherence time of ADM by inserting a tunable resonator before the first amplification stage. The resonator improves the impedance match to the dark-matter signal, and can increase the signal-to-noise ratio (SNR) by many orders of magnitude[17;18]. In this way, an ADM experiment behaves analogously to an AM radio – with the magnetic field and resonator playing the role of the antenna and tuning circuit.

Classically, ADM searches have employed high-Q cryogenic microwave cavities[19;20] as resonators. However, this approach limits the accessible range of frequencies (and therefore axion masses) to those that can fit into the cavity. Lower axion masses are inaccessible with a practically-sized cavity. But as has been recently pointed out[21–24], lumped element circuits can also be built into high-Q resonators to decouple the resonance frequency from the physical size of the detector. This has opened up the entire range of ADM models with mass below $m_a \lesssim 1\,\mu$eV to experimental testing. In this regime, the sensitivity of a detector scales as

$$g_{a\gamma\gamma}^{-1} \propto \frac{B_0 V^{5/6} Q^{1/4}}{\eta^{1/4} T^{1/4}} \tag{1}$$

where V is the detector volume, B_0 the maximum magnetic field, η the amplifier noise floor, and T the thermal noise temperature[17;18].

The first demonstrations of this technology have been performed by the ABRACADABRA-10 cm prototype, DMRadio-Pathfinder, ADMX-SLIC, and SHAFT. ABRACADABRA-10 cm instrumented a $V \sim 1\,\mathrm{L}$ $B = 1\,\mathrm{T}$ toroidal magnet with a pickup loop (without a resonator) to search for ADM from $0.3\,\mathrm{neV} - 8.1\,\mathrm{neV}$ at $g_{a\gamma\gamma}$ down to $\sim 10^{-10}\,\mathrm{GeV}^{-1}$ in a broadband configuration[25;26]. DMRadio-Pathfinder has constructed a tunable high-Q resonator around a $V \sim 1\,\mathrm{L}$ toroidal pickup (without a magnetic field), achieving a $Q \gtrsim 10^5$ to probe dark photon models around 2 neV with kinetic mixing angles down to $\varepsilon \sim 10^{-9}$ in a narrowband configuration[27]. ADMX-SLIC inserted an inductive pickup loop in an 7 T field to probe the narrow ranges $(1.7498 - 1.7519) \times 10^{-7}$ eV, $(1.7734 - 1.7738) \times 10^{-7}$ eV, and $(1.8007 - 1.8015) \times 10^{-7}$ eV down to $g_{a\gamma\gamma} \sim 10^{-12}\,\mathrm{GeV}^{-1}$ [28]. SHAFT instrumented ferromagnetic toroidal magnets in a similar configuration to ABRACADABRA-10 cm and probed the region from 12 peV − 12 neV to $g_{a\gamma\gamma} \sim 0.4 \times 10^{-10}\,\mathrm{GeV}^{-1}$ [29].

DM Radio-50L (0 – 5 year program)

DMRadio-50L is a collaboration between SLAC, Stanford, UC Berkeley, LBNL, MIT, UNC Chapel Hill, and Princeton university. It builds on the success of the ABRACADABRA-10 cm and DMRadio-Pathfinder programs, scaling up in volume to a $V \sim 50\,\mathrm{L}$ magnet with a target $B = 0.1 - 1\,\mathrm{T}$ magnetic field. DMRadio-50L will operate inside a dilution refrigerator with the magnet operating at $\lesssim 4\,\mathrm{K}$ and the coldest stages of the readout – which set the thermal noise floor – operating at $\sim 100\,\mathrm{mK}$. In this configuration, DMRadio-50L will probe ALP DM between $20\,\mathrm{peV} \lesssim m_a \lesssim 20\,\mathrm{neV}$ ($5\,\mathrm{kHz} - 5\,\mathrm{MHz}$), down to $g_{a\gamma\gamma} \sim 5 \times 10^{-15}\,\mathrm{GeV}^{-1}$, but not reach the QCD axion band.

A major technical goal of DMRadio-50L is to achieve resonant enhancement of $Q \sim 10^6$ with the presence of the toroidal magnet. This requires careful balancing between coupling to the axion field and coupling to lossy materials in the detector. DMRadio-50L is in the advanced design stages and we expect to begin detector construction in late 2020 - early 2021. It will perform physics scanning for 2 − 3 years, before becoming a test bench for development of future quantum sensors to accelerate ADM.

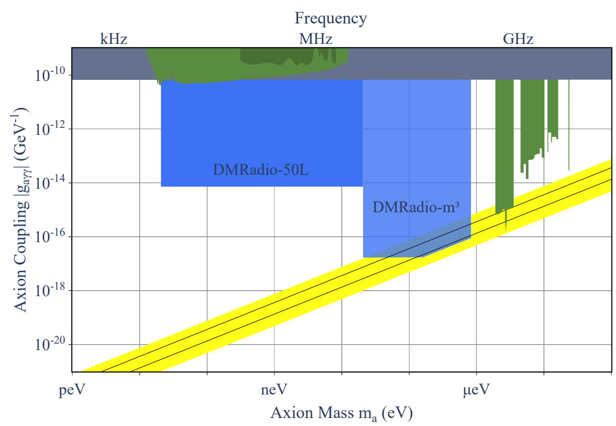

Figure 1: Projected 3σ sensitivity curves for DMRadio-50L with $B_0 = 1\,\mathrm{T}$ after 2 yr of scan time, and DMRadio-m^3 after 3 yr of scan time. The bounds above 1 μeV are from microwave cavity experiments [19;20;30], the grey band at the top from CAST [31], the green exclusion below 10 neV is from SHAFT [29] (lighter) and ABRACADABRA-10 cm [25;26] (darker).

DM Radio-m^3 (5 – 10 year program)

DMRadio-m^3 is a proposed next-generation ADM search with the goal of probing QCD axion models between $20\,\mathrm{neV} - 0.8\,\mu\mathrm{eV}$ ($5 - 200\,\mathrm{MHz}$). The design goal is to have 3σ sensitivity at least to the top of the QCD axion band (KSVZ) over the full range, and to the bottom of the QCD axion band (DFSZ) from $0.1 - 0.8\,\mu\mathrm{eV}$ ($30 - 200\,\mathrm{MHz}$). This is achieved with a detector that has an active volume of $V \approx 1\,\mathrm{m}^3$ and magnetic field of $B \gtrsim 4\,T$, with ~ 5 yr of running time.

The design of DMRadio-m^3 is based on a coaxial copper pickup inside a solenoidal magnet, coupled to a superconducting lumped-element LC resonator. The form of DMRadio-m^3 is different from DMRadio-50L, but is optimized for the higher search frequencies and leverages the higher quality factors achievable with its larger size. DMRadio-m^3 will build on the knowledge and experience gained with the DMRadio-50L resonator and readout. DMRadio-m^3 is being designed under the DOE Dark Matter New Initiatives program, and will produce a Conceptual Design Report by 2022. Design optimization is currently underway.

Appendix

DMRadio-50L and DMRadio-m^3 will also form the foundation of an ambitious long term goal of probing the QCD axion at the GUT scale, described in CF2 LOI: "DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter". They will also benefit from the development of specialized advanced magnet technology, described in AF5 LOI: "Magnet R&D for Low Mass Axion Searches", and advances in quantum metrology described in IF1 LOI "Radio Frequency Quantum Upconverters: Precision Metrology for Fundamental Physics."

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