Snowmass2021 - Letter of Interest

DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter

Thematic Areas: (check all that apply □/■)
□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) IF1 Quantum Sensors

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Abstract: (maximum 200 words)

We describe DMRadio-GUT, a future search for electromagnetic coupling to QCD axion dark matter in the 400 peV-125 neV mass range, with sensitivity to GUT-scale models. DMRadio-GUT is a challenging, long-term experiment that will follow on earlier experiments, including the DMRadio-50L and DMRadio-m^3 searches, described in a separate LOI. DMRadio-GUT will scan for GUT-scale QCD axion dark matter by leveraging techniques developed for DMRadio-50L and DMRadio-m^3 and by bringing together emerging and future developments in superconducting magnet technology, high-Q lumped-element resonators, and quantum metrology. In this LOI, we describe the technological developments that may enable DMRadio-GUT to carry out a definitive search for GUT-scale QCD axion dark matter.

The QCD axion is a well-motivated cold dark matter candidate, possessing natural mechanisms for generating the observed dark matter abundance.[1;2] Originally motivated as a solution to the strong CP problem—to explain, for example, why the neutron electric dipole moment is much smaller than expected—the QCD axion arises as a Goldstone boson of the spontaneously broken Peccei-Quinn (PQ) symmetry.[3–5] The axion mass is determined by the PQ symmetry-breaking energy scale f_{PQ},[6]

$$m_{\mathrm{a}}c^2 \approx 6 \times 10^{-10}\ \mathrm{eV}\left(\frac{10^{16}\ \mathrm{GeV}}{f_{\mathrm{PQ}}}\right). \tag{1}$$

Recent theoretical work has shown that QCD axion dark matter can exist over the entirety of the 1 peV-1 eV mass range.[7;8] Concurrently, a large number of techniques have been proposed to search the wide-open parameter space for QCD axion dark matter.[9] A particularly promising approach is the lumped-element circuit technique[10–14] used by the DMRadio program[15;16], with potential sensitivity to QCD axion models at masses below 1 μeV. In particular, the DMRadio program may probe well-motivated QCD axion models at the GUT (Grand Unified Theory) scale $f_{\mathrm{PQ}} \sim 10^{16}$ GeV ($m_a \sim 1$ neV), the energy scale at which the electromagnetic, strong, and weak forces unify into a single force.[17–20]

DMRadio: An Optimized Search for Axion Dark Matter Below 1 μeV

DMRadio is an optimized lumped-element superconducting resonator search for axion-like-particle and QCD axion dark matter in the sub-μeV mass range.[21;22] (Hereafter, both axion-like particles and QCD axions are referred to collectively as "axions.") DMRadio exploits the axion's small coupling to two photons, characterized by the interaction strength $g_{\mathrm{a}\gamma\gamma}$. In the presence of a DC magnetic field, an axion of mass m_{a} acts as an effective electromagnetic current density oscillating at frequency $f_{\mathrm{a}} = m_{\mathrm{a}}c^2/h$. The current density produces a small oscillating magnetic field. The oscillating magnetic field is inductively coupled to a lumped-LC resonator. When the resonance frequency is near the axion rest-mass frequency, the current signal in the resonator is enhanced and is read out with a low-noise amplifier. By tuning the resonance frequency, one can conduct a sensitive probe of axion dark matter over many decades in mass. In this manner, the experiment works much like an AM radio, tuning into a radio station at particular frequency.

The sensitivity of the DMRadio experiment to axion-photon coupling scales as[21;22]

$$g_{\mathrm{a}\gamma\gamma}^{-1} \sim \frac{B_0 V^{5/6} Q^{1/4} t_{\mathrm{int}}^{1/4}}{T^{1/4}\eta^{1/4}} \tag{2}$$

where B_0 is the magnet field strength, V is the magnet volume, Q is the resonator quality factor, t_{int} is the integration time, T is the physical temperature, η characterizes the amplifier noise floor. $\eta = 1$ corresponds to the Standard Quantum Limit (SQL) of phase-insensitive amplification. The figure of merit represented by (2) informs the design choices, as well as the upgrade path for the experimental campaign.

Two phases of the DMRadio search will be carried out over the next several years. DMRadio-50L, using a 50 liter, $0.1 \sim 1$ T toroidal magnet, is under construction and will probe axion-like-particle dark matter in the 5 kHz-5 MHz frequency range (corresponding approximately to axion masses 20 peV-20 neV). DMRadio-m^3, using a cubic meter, 4.0 T magnet, is presently undergoing project study, funded by the DOE Dark Matter New Initiatives program. DMRadio-m^3 will probe axions in the 5 Mz-200 MHz ($\sim$ 20 neV-800 neV) range, with sensitivity to the benchmark DFSZ QCD axion model above 30 MHz. DMRadio-50L and DMRadio-m^3 will utilize superconducting lumped-LC resonators with quality factor of 10^6, which have previously been demonstrated in the literature.[23;24] The experiments will be cooled to dilution-refrigerator temperatures and will utilize conventional, near-quantum-limited SQUID amplifiers. The status and plans of DMRadio-50L and DMRadio-m^3 are described in more detail in a separate LOI.

DMRadio-GUT: A Quantum-Accelerated, Resonant Search for GUT-Scale QCD Axion Dark Matter
In this letter, we express interest in developing DMRadio-GUT, a challenging, long-term experiment with sensitivity to well-motivated QCD axion models near the GUT scale $f_{\rm PQ} \sim 10^{16}$ GeV ($m_{\rm a} \sim 1$ neV). DMRadio-GUT will search the 100 kHz-30 MHz frequency range (approximately 400 peV-125 neV) for QCD axions over 7 years of run time (4.5 years of live integration time), possessing sensitivity to DFSZ QCD axions in a wide frequency range below DMRadio-m^3. See Fig. 1. DMRadio-GUT will build upon the techniques used in the DMRadio-50L and DMRadio-m^3 searches. It will adopt a staged approach in implementing new technologies, taking advantage of emerging and future developments in superconducting magnet technology, high-Q lumped-LC resonators, and quantum metrology to improve DMRadio sensitivity (see Section 2). We overview these developments below, describing how they may enable DMRadio-GUT.

DMRadio-GUT will build upon the experience gained during the DMRadio-50L and DMRadio-m^3 campaigns in constructing and operating large superconducting magnets. DMRadio-GUT will utilize a 12 Tesla, 10 m^3 magnet. This is a factor of three enhancement in field and a factor of ten enhancement in volume relative to DMRadio-m^3, resulting in a magnet with approximately 570 MJ stored energy. A magnet of similar energy is planned for the International Axion Observatory[25], while a magnet of four times larger energy is used in the Compact Muon Solenoid at the LHC. Magnet R&D for DMRadio is described in a separate LOI.

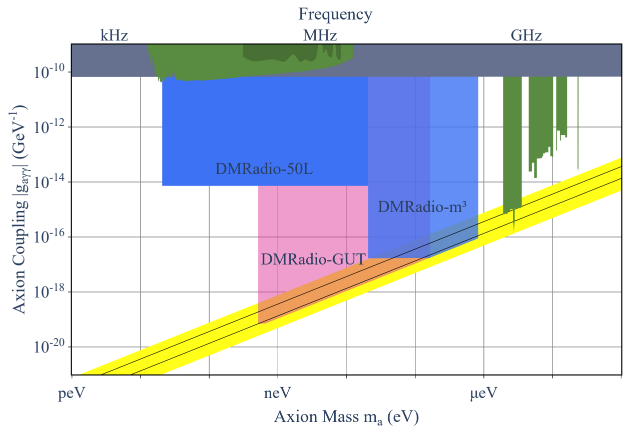

Figure 1: Projected 3σ sensitivity curves for DMRadio-50L, DMRadio-m^3, and DMRadio-GUT. The yellow band represents QCD axion models, with the top and bottom black lines representing the KSVZ and DFSZ models, respectively. Limits from other experiments (e.g. ADMX) are described at dmradio.org.

DMRadio-GUT will also aim to improve upon the resonator technology developed for DMRadio-50L and DMRadio-m^3. Through careful study of resonator geometry, materials, and loss, we aim to increase the quality factor by a factor of 20 to 2×10^7. Some Q improvement may result from the increase in magnet volume, which enables an increase in volume-to-surface-area ratio of the resonator, reducing participation from surface oxides.

Additionally, DMRadio-GUT will take advantage of the rapid advances being made in quantum metrology. Previous work[22] motivates the use of SQL-evading techniques to increase the sensitivity of searches for the axion-photon coupling. Recently, the Radio Frequency Quantum Upconverter has been proposed for quantum metrology in kHz-MHz lumped-LC resonators, such as those used in DMRadio.[26;27] The development of quantum metrology for DMRadio is described in a separate LOI. DMRadio-GUT will implement backaction evasion to increase receiver sensitivity. Similar to squeezing, backaction evasion suppresses the noise in one quadrature of the electromagnetic signal (relative to the SQL), at the expense of increased noise in the other quadrature. DMRadio-GUT will aim to achieve 20 dB of backaction-noise reduction ($\eta \approx 0.1$).

By combining these technological developments, DMRadio-GUT can carry out a definitive search for well-motivated GUT-scale QCD axion models.

Appendix
DMRadio-GUT will build on the DMRadio-50L and DMRadio-m^3 searches, described in the CF2 LOI "Probing the QCD Axion with DMRadio-m^3." It will also benefit from magnet development, as described in the AF5 LOI "Magnet R&D for Low Mass Axion Searches," as well as quantum metrology, as described in the IF1 LOI "Radio Frequency Quantum Upconverters: Precision Metrology for Fundamental Physics."

References

[1] Pierre Sikivie. Axion cosmology. In *Axions*, pages 19–50. Springer, 2008.

[2] Peter W Graham, David E Kaplan, and Surjeet Rajendran. Cosmological relaxation of the electroweak scale. *Physical review letters*, 115(22):221801, 2015.

[3] Roberto D Peccei and Helen R Quinn. CP conservation in the presence of pseudoparticles. *Physical Review Letters*, 38(25):1440, 1977.

[4] F. Wilczek. Problem of Strong p and t Invariance in the Presence of Instantons. *Physical Review Letters*, 40(5):279, 1978.

[5] S. Weinberg. A new light boson? *Physical Review Letters*, 40(4):223, 1978.

[6] Peter W Graham, Igor G Irastorza, Steven K Lamoreaux, Axel Lindner, and Karl A van Bibber. Experimental searches for the axion and axion-like particles. *Annual Review of Nuclear and Particle Science*, 65:485–514, 2015.

[7] Peter W Graham and Adam Scherlis. The Stochastic Axion Scenario. *arXiv preprint arXiv:1805.07362*, 2018.

[8] Fuminobu Takahashi, Wen Yin, and Alan H Guth. QCD axion window and low-scale inflation. *Physical Review D*, 98(1):015042, 2018.

[9] Pierre Sikivie. Invisible Axion Search Methods. *arXiv preprint arXiv:2003.02206*, 2020.

[10] P Sikivie, N Sullivan, and Dylan B Tanner. Proposal for Axion Dark Matter Detection Using an LC Circuit. *Physical review letters*, 112(13):131301, 2014.

[11] Saptarshi Chaudhuri, Peter W Graham, Kent Irwin, Jeremy Mardon, Surjeet Rajendran, and Yue Zhao. Radio for hidden-photon dark matter detection. *Physical Review D*, 92(7):075012, 2015.

[12] Yonatan Kahn, Benjamin R Safdi, and Jesse Thaler. Broadband and resonant approaches to axion dark matter detection. *Physical review letters*, 117(14):141801, 2016.

[13] Jonathan L Ouellet, Chiara P Salemi, Joshua W Foster, Reyco Henning, Zachary Bogorad, Janet M Conrad, Joseph A Formaggio, Yonatan Kahn, Joe Minervini, Alexey Radovinsky, et al. First results from ABRACADABRA-10 cm: A search for sub-μ eV axion dark matter. *Physical review letters*, 122 (12):121802, 2019.

[14] Jonathan L Ouellet, Chiara P Salemi, Joshua W Foster, Reyco Henning, Zachary Bogorad, Janet M Conrad, Joseph A Formaggio, Yonatan Kahn, Joe Minervini, Alexey Radovinsky, et al. Design and implementation of the ABRACADABRA-10 cm axion dark matter search. *Physical Review D*, 99(5): 052012, 2019.

[15] M. Silva-Feaver et al. Design Overview of DM Radio Pathfinder Experiment. *IEEE Transactions on Applied Superconductivity*, 27(4):1–4, 2017.

[16] Arran Phipps, SE Kuenstner, S Chaudhuri, CS Dawson, BA Young, CT FitzGerald, H Froland, K Wells, D Li, HM Cho, et al. Exclusion Limits on Hidden-Photon Dark Matter near 2 neV from a Fixed-Frequency Superconducting Lumped-Element Resonator. In *Microwave Cavities and Detectors for Axion Research*, pages 139–145. Springer, 2020.

[17] Peter Svrcek and Edward Witten. Axions in string theory. *Journal of High Energy Physics*, 2006(06): 051, 2006.

[18] A. Arvanitaki et al. String axiverse. *Physical Review D*, 81(12), JUN 28 2010. ISSN 1550-7998. doi: {10.1103/PhysRevD.81.123530}.

[19] Anne Ernst, Andreas Ringwald, and Carlos Tamarit. Axion predictions in SO (10)$\times$ U (1) PQ models. *Journal of High Energy Physics*, 2018(2):103, 2018.

[20] James Halverson, Cody Long, Brent Nelson, and Gustavo Salinas. Towards string theory expectations for photon couplings to axionlike particles. *Physical Review D*, 100(10):106010, 2019.

[21] Saptarshi Chaudhuri, Kent Irwin, Peter W Graham, and Jeremy Mardon. Fundamental limits of electromagnetic axion and hidden-photon dark matter searches: part I-the quantum limit. *arXiv preprint arXiv:1803.01627*, 2018.

[22] Saptarshi Chaudhuri, Kent D Irwin, Peter W Graham, and Jeremy Mardon. Optimal Electromagnetic Searches for Axion and Hidden-Photon Dark Matter. *arXiv preprint arXiv:1904.05806*, 2019.

[23] P Falferi, M Cerdonio, L Franceschini, R Macchietto, S Vitale, and JP Zendri. A high inductance kHz resonator with a quality factor larger than 10^6. *Review of scientific instruments*, $65(9) : 2916 - -2919, 1994$.

[24] H Nagahama, G Schneider, A Mooser, C Smorra, S Sellner, J Harrington, T Higuchi, M Borchert, T Tanaka, M Besirli, et al. Highly sensitive superconducting circuits at 700 kHz with tunable quality factors for image-current detection of single trapped antiprotons. *Review of Scientific Instruments*, 87 (11):113305, 2016.

[25] I Shilon, A Dudarev, H Silva, U Wagner, and HHJ ten Kate. The Superconducting Toroid for the New International AXion Observatory (IAXO). *IEEE transactions on applied superconductivity*, 24(3):1–4, 2013.

[26] Saptarshi Chaudhuri. *The Dark Matter Radio: A Quantum-enhanced Search for QCD Axion Dark Matter*. PhD thesis, Stanford University, 2019.

[27] Stephen Kuenstner and et al. in preparation.