Snowmass2021 - Letter of Interest

High-field magnets for next generation axion haloscopes

Thematic Areas:

☐ (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) *[Please specify frontier/topical group]*

Contact Information:

Submitter Name/Institution: David Tanner/University of Florida
Collaboration (optional): ADMX & NHMFL
Contact Email: `tanner@phys.ufl.edu`

Abstract:

This LOI describes our vision of a path forward for the next generation of axion haloscopes: the use of a strong magnet to extend the sensitivity to QCD axions up to axion masses of 50 μeV. The QCD axion affects two important issues in particle physics and astrophysics: the origin of CP symmetry in the strong interactions and the composition of the dark matter of the universe. Current laboratory, astrophysical, and cosmological observations place the mass m_a of the axion in the 1 μeV–10 meV range. Axions are especially significant as dark matter if their mass is of order 1–50 μeV. They would then make up the dark-matter halos of galaxies. These halo axions may be detected using the Sikivie process, by which they decay to photons through the $\vec{E} \cdot \vec{B}_0$ interaction in a tunable high-Q microwave cavity whose resonant frequency f satisfies $hf = m_a c^2$, permeated by a strong external magnetic field B_0. (Here, $\vec{E}$ is the photon field of the cavity's resonant mode.) The Axion Dark Matter eXperiment (ADMX) conducts the preeminent microwave-cavity based axion search, using a cavity with $\sim$200 ℓ volume and a 7.6 T magnet in conjunction with a near quantum-limited SQUID-based receiver. Both cavity and amplifier are operated at ultralow temperatures (below 0.2 K) to reduce background and technical noise. Generation-2 ADMX has demonstrated the sensitivity to detect even the most weakly-coupled QCD axions, the so-called DFSZ limit. Over the next 2–3 years, ADMX will search the 2–8 μeV range at the DFSZ limit. A stronger magnet is required to enable searches up to 50 μeV. Here we describe a process to build and deploy an axion haloscope employing a 32 T high-temperature superconducting magnet that will increase the power emitted from the cavity by more than an order of magnitude.

Axion haloscopes[1] search for axions[2;3] in the halo of our galaxy[4] by stimulating their decay to photons through an $\vec{E}\cdot\vec{B}_0$ interaction in a tunable high-Q microwave cavity immersed in a strong static magnetic field. This method has been used by the Axion Dark Matter eXperiment (ADMX)[5–9] to search for axions with masses between 2.7 and 3.3 μeV; over the next two years the experiment will continue to 8 μeV with sensitivity to even the most weakly-coupled QCD axions, the DFSZ limit.

The power emitted by the detector is proportional to the stored energy of the magnet: B_0^2V. As the search moves to higher axion masses, and therefore also to higher photon frequencies, the size of the cavities, typically half of the wavelength in two dimensions and 4–8 times the wavelength in the third, becomes smaller. To maintain adequate converted power, one may employ multiple cavities[10] or very elaborate resonant structures.[11] (The number of cavities increases more or less as the cube of the mass.) Clever microwave engineering can support the growth in cavity complexity to some extent, but there is a substantial cost of such intricate resonant structures and the supporting bits and pieces.

We believe that a superior approach is to increase the magnetic field substantially and decrease the volume. This large-volume, high-field magnet is a necessary although not sufficient condition for axion detection at higher frequencies. Exceptional microwave resonator engineering and ultra-sensitive quantum-limited detectors are also needed. But unless the product B_0^2V is large enough, the signal generated in the cavity will not be large enough to be pulled out of the noise.

A conservative, two phase process is proposed. For the Phase-1 detector, searching in the 8–16 μeV range, we will use a conventional if large magnet based on Nb_3Sn or NbTi technology. In Phase 2, searching in the 16–50 μeV range, we add a high-temperature superconducting (HTSC) insert.

There is a reason that we seek to search for axions with masses up to about 50 μeV. In the last few years there have been a very large number of estimates of the axion mass that included the timing of inflation and the PQ transition, string decay, domains with various PQ realignment angles, and related considerations.[12–21] The results are scattered over a range of 5–50 μeV.

If axions are the dominant constituent of our galactic halo,[22] their local mass density is of order 0.8×10^{-24} g/cm^3. Galactic halo axions have speeds v of order $10^{-3}c$ and hence their energies, $\epsilon_a = m_ac^2 + m_av^2/2$, have a spread of order 10^{-6} above the axion mass.[23] Consider a cylindrical electromagnetic cavity of arbitrary cross-sectional shape, permeated by a large static longitudinal magnetic field of magnitude B_0. When the frequency $\omega = 2\pi f$ of an appropriate cavity mode equals $m_a[1+O(10^{-6})]$, galactic halo axions can convert to quanta of excitations (photons) of that cavity mode. Only the $TM_{n\ell 0}$ modes couple in the limit where the cavity is much smaller than the de Broglie wavelength $\lambda_a = 2\pi(\beta m_a)^{-1} \approx 2\pi 10^3 m_a^{-1}$ of the galactic halo axions (10 meters for $m_a = 12$ μeV).

The power on resonance from axion $\rightarrow$ photon conversion into the $TM_{n\ell 0}$ mode is[1]

$$P_{n\ell} = g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} C_{n\ell 0}\, Q_L$$

where $g_{a\gamma\gamma}$ is the coupling of the axion to two photons, V is the the cavity volume, B_0 is the magnetic field strength, ρ_a is the local dark-matter density, $C_{n\ell 0}$ is a mode-dependent form factor, proportional to the integral of $\vec{E}_{n\ell 0}\cdot\vec{B}_0$ over the cavity volume, and Q_L is the loaded quality factor of the cavity. The output of the detector is spectrum-analyzed to search for an axion peak within the cavity bandwidth. Because the axion mass is only known within a factor of 10–20 at best, the cavity must be tunable and allow the exploration of a large a range of frequencies.

The magnet requirements are chosen to enable a cavity search covering an octave in two to three years, allowing for several changes of cavity and amplifiers during this time as well as for rescans of potential candidate signals. This LOI gives details of a system that will do the job; our last paragraph summarizes more ambitious possibilities. The Phase-1 magnet will produce a 15 T field in a 25 cm clear bore and with an overall length of 60 cm. This magnet uses both Nb_3Sn and NbTi coils. Some distance above the main magnet, there is another coil to provide a zero-field region. The superconducting electronics are located in this zero-field region. In Phase 2, an inner coil is added to the main magnet to raise the central field to 32 T over a 15 cm diameter.

The magnet, current leads, the cryostat containing the magnet, liquid helium reservoirs, sensors, and the dilution refrigerator would be built as a single unit. A diagram of the magnet, with the high-T_c insert in place, is shown in Fig. 1. The Phase-1 magnet, composed of NbTi (blue) and Nb_3Sn (red) coils and the Phase-2 high-temperature superconductor (yellow) are shown. The zero-field coil is shown in yellow also, although it almost certainly will use NbTi. The inside diameter of this "bucking coil" will be as big as the main magnet to allow the cavity/superconducting amplifier package to be installed from above.

The dilution refrigerator maintains the cavity and superconducting electronics at milliKelvin temperatures. A very high cooling capacity is required: at least 1000 μW at 100 mK, 200 μW at 50 mK, and 15 μW at 20 mK.

The Phase 2 insert adds 17 T within a 15-cm-diameter bore to the 15 T Phase 1 magnet. It must be made from high temperature superconducting (HTSC) tape, probably $YBa_2Cu_3O_{7-\delta}$, REBCO for short. Unlike the Phase-1 magnet, there is a substantial engineering and R&D investment required before the 32 T field can be completed.

While the proposed HTSC magnet is beyond today's state-of-the-art, HTSC magnet technology is advancing rapidly. In 2017 the National High Magnetic Field Laboratory (MagLab) operated a 32 T, 34 mm bore user magnet, with a REBCO coil inside a Nb3Sn/NbTi outer magnet.[24] The same year a small MagLab REBCO test coil made 14 T inside a 31 T resistive magnet for a total field of 45 T. Bruker is now delivering 28.2 T NMR magnets based on REBCO. The MagLab is now developing a 40 T superconducting magnet also using REBCO.

The REBCO conductor (a multi-layer tape) is now a commercial product with nine suppliers worldwide. Production has risen steadily in recent years as engineers develop applications from high field magnets to power transmission cables to generators, etc. Quality of the tape continues to improve. However, the magnets proposed here store several MJ of energy which can damage the magnet if not properly managed if a section of conductor were to go normal (quench). Quench management involves sensors to detect the onset of a quench and heaters to drive the rest of the coil normal, spreading out the energy dissipation from a small hot spot to (in principal) the entire magnet. The engineering study will insure that local hotspots as well as large internal stresses will be avoided during quench.

The location of the dilution refrigerator is between the the main magnet and the bucking coil. It is built to mate with the cavity/SQUID package as a "top loader," allowing the cavities and superconducting electronics to be removed and installed without removing the dilution refrigerator.

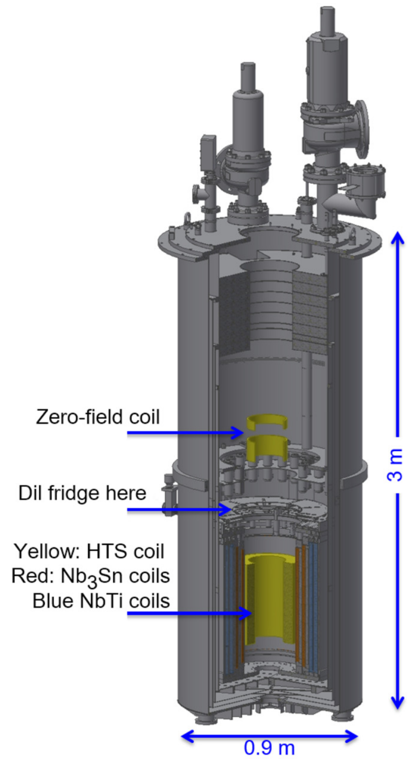

Fig. 1. Magnet and magnet cryostat.

The magnet specifications above give us an adequate magnetic volume, but many years are required to cover the 8–50 μeV range. We also therefore will consider a magnetic volume that is bigger in every phase. On the one hand, we will investigate the possibility of utilizing existing magnets, in both US and Europe, as the outsert. On the other, we could start with a new-build MRI-size NbTi outsert magnet of 90 cm diameter and 9.4 T field, with B_0^2V about 5$\times$ that of the ADMX magnet. To establish capability, we would build HTSC coils of 25 T/16 cm, 32 T/16 cm, 32 T/28 cm, and finally 32 T/40 cm. Inserts 1 and 3 might be used briefly; inserts 2 and 4 could conduct serious searches. The final magnet has B_0^2V about 12$\times$ that of the ADMX magnet; it would enable a greater than 50 times increase in scan speed.

References

[1] "Experimental tests of the 'invisible' axion," P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).

[2] "A new light boson?," S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978)

[3] "Problem of strong P and T invariance in the presence of instantons," F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[4] "Can galactic halos be made of axions?" J. Ipser and P. Sikivie, Phys. Rev. Lett. **50**, 925 (1983).

[5] "Cryogenic cavity detector for large-scale cold dark-matter axion search," H. Peng, S. Asztalos, E.J. Daw, N.A. Golubev, C.A. Hagmann, D. Kinion, J. LaVeigne, D.M. Moltz, F.A. Nezrick, J. Powell, L.J. Rosenberg, P. Sikivie, W. Stoeffl, N.S. Sullivan, D.B. Tanner, M.S. Turner, and K. van Bibber, Nucl. Instrum. Methods A **444**, 569–583 (2000).

[6] "A large-scale microwave cavity search for dark-matter axions," S. Asztalos, E. Daw, H. Peng, L.J. Rosenberg, C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, P. Sikivie, N.S. Sullivan, D.B. Tanner, F. Nezrick, M.S. Turner, D.M. Moltz, J. Powell, M.-O. André, J. Clarke, and M. Mück, Phys. Rev. D **64**, 092003-1–28 (2001).

[7] "SQUID-based microwave cavity search for dark-matter axions," S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L.J Rosenberg, G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, D.B. Tanner, R. Bradley, and J. Clarke, Phys. Rev. Lett. **104**, 041301/1–4 (2010).

[8] "Search for invisible axion dark matter with the axion dark matter experiment," N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L.J Rosenberg, G. Rybka, G. Carosi, N. Woollett, D. Bowring, A.S. Chou, A. Sonnenschein, W. Wester, C. Boutan, N.S. Oblath, R. Bradley, E.J. Daw, A.V. Dixit, J. Clarke, S.R. O'Kelley, N. Crisosto, J.R. Gleason, S. Jois, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner, and G.C. Hilton, Phys. Rev. Lett. **120**, 151301/1–5 (2018).

[9] "An extended search for the invisible axion with the Axion Dark Matter eXperiment," T. Braine, R. Cervantes, N. Crisosto, N. Du, S. Kimes, L.J Rosenberg, G. Rybka, J. Yang, D. Bowring, A.S. Chou, R. Khatiwada, A. Sonnenschein, W. Wester, G. Carosi, N. Woollett, L.D. Duffy, R. Bradley, C. Boutan, M. Jones, B.H. LaRoque, N.S. Oblath, M.S. Taubman, J. Clarke, A. Dove, A. Eddins, S.R. O'Kelley, S. Nawaz, I. Siddiqi, A. Agrawal, A.V. Dixit, J. R. Gleason, S. Jois, P. Sikivie, N.S. Sullivan, D.B. Tanner, E. Lentz, E.J. Daw, J.H. Buckley, P.M. Harrington, E.A. Henriksen, and K.W. Murch, arXiv:1910.08638 [hep-ex].

[10] "Search for 5–9 μeV axions with the ADMX four cavity array," Jihee Yang, Joseph R. Gleason, Shriram Jois, Ian Stern, Pierre Sikivie, Neil S. Sullivan, and David B. Tanner, in *Microwave Cavities and Detectors for Axion Research II* edited by Gianpaolo Carosi and Gray Rybka (Springer-Verlag, Berlin, 2020) pp. 53–62.

[11] "Cavity design for high-frequency axion dark matter detectors," I. Stern, A.A. Chisholm, J. Hoskins, P. Sikvie, N.S. Sullivan, D.B. Tanner, G. Carosi, and K. van Bibber, Rev. Sci. Instrum. **86**, 123305/1–10 (2015).

[12] "Axion cosmology revisited," O. Wantz and E.P.S. Shellard, Phys. Rev. D **82**, 123508 (2010).

[13] "Production of dark matter axions from collapse of string-wall systems," T. Hiramatsu, M. Kawasaki, K. Saikawa, and T. Sekiguchi, Phys. Rev. D **85**, 105020 (2012).

[14] "Lattice QCD input for axion cosmology," E. Berkowitz, M.I. Buchoff, and E. Rinaldi, Phys. Rev. D **92**, 034507 (2015).

[15] "Axion phenomenology and θ-dependence from $N_f = 2 + 1$ lattice QCD," C. Bonati, M. D'Elia, M. Mariti, G. Martinelli, M. Mesiti, F. Negro, F. Sanfilippo, and G. Villadoro, J. High Energy Phys. **3**, 155 (2016).

[16] “The QCD axion, precisely,” Giovanni Grilli di Cortona, Edward Hardy, Javier Pardo Vega, and Giovanni Villadoro. JHEP **2016**, 34 (2015).

[17] “Calculation of the axion mass based on high-temperature lattice quantum chromodynamics,” S. Borsanyi, Z. Fodor, J. Guenther, K.-H. Kampert, S. D. Katz, T. Kawanai, T.G. Kovacs, S.W. Mages, A. Pasztor, F. Pittler, J. Redondo, A. Ringwald, and K.K. Szabo, Nature **539**, 69 (2016).

[18] “Unifying inflation with the axion, dark matter, baryogenesis, and the seesaw mechanism,” G. Ballesteros, J. Redondo, A. Ringwald, and C. Tamarit, Phys. Rev. Lett. **118**, 071802 (2017).

[19] “The topological susceptibility in finite temperature QCD and axion cosmology,” P. Petreczky, H.-P. Schadler, and S. Sharma, Phys. Lett. B 762, 498, 2016

[20] “Axions, instantons, and the lattice,” M. Dine, P. Draper, L. Stephenson-Haskins, and D. Xu, Phys. Rev. D **96**, 095001 (2017).

[21] “The dark-matter axion mass,” Vincent B. Klaer and Guy D. Moore, J. Cosmol. Astropart. Phys. **11**, 049 (2017).

[22] “Phase-space structure of cold dark matter halos,” P. Sikivie and J. Ipser, Phys. Lett. B **291**, 288 (1992).

[23] “Periodic signatures for the detection of cosmic axions,” M.S. Turner, Phys. Rev. D **42**, 3572 (1990).

[24] See the URL `https://nationalmaglab.org/magnet-development/magnet-science-technology/magnet-projects/32-tesla-scm`

Authors: Mark Bird (National High Magnetic Field Laboratory), Christian R. Boutan (Pacific Northwest National Laboratory), Gianpaolo Carosi (Lawrence Livermore National Laboratory), Edward Daw (Sheffield University), Erik Henriksen (Washington University, St Louis), Béla Majorovits (on behalf of the MADMAX magnet working group), Noah S. Oblath (Pacific Northwest National Laboratory), Leslie J Rosenberg (University of Washington), Gray Rybka (University of Washington), Andrew Sonnenschein (Fermi National Accelerator Laboratory), Neil S. Sullivan (University of Florida), and David B. Tanner (University of Florida)