Snowmass2021 - Letter of Interest

US Participation in MADMAX (MAgnetized Disc and Mirror Axion eXperiment)

Thematic Areas:

- ■ (CF2) Dark Matter: Wavelike
- ■ (Other) IF1 Quantum Sensors
- ■ (Other) IF2 Photon Detectors
- ■ (Other) RF3 Fundamental Physics in Small Experiments
- ■ (Other) AF5 Accelerators for Physics Beyond Colliders and Rare Processes
- ■ (Other) AF7 Accelerator Technology R&D (Magnets)

Authors and Contact Information:

On behalf of the ADMX collaboration:
Gray Rybka [`grybka@uw.edu`], Gianpaolo P. Carosi [`carosi2@llnl.gov`]
On behalf of the MADMAX collaboration:
Béla Majorovits [`bela@mpp.mpg.de`], Stefan Knirck [`knirck@mpp.mpg.de`]

Abstract: The QCD axion is an excellent light dark matter candidate, while also naturally explaining CP-conservation in strong interactions. Axions generated after inflation are expected to have masses in the range $\sim 10 - 100\,\mu\mathrm{eV}$. The lower part of this range will be explored in future resonant cavity experiments such as ADMX, which aims to ultimately reach $40\,\mu\mathrm{eV}$. Discovery of the axion in the higher part of the range will require different techniques. The MADMAX collaboration is pursuing an approach based on axion-photon conversion at the boundary of dielectric surfaces. Galactic axions can be converted to electromagnetic radiation at boundaries between different dielectric constants under a strong magnetic field. Combining many such surfaces, this conversion can be enhanced significantly using constructive interference and resonances. The proposed MADMAX setup, containing around 80 dielectric discs with $1\,\mathrm{m}^2$ area and a mirror in a $\sim 10\,\mathrm{T}$ magnetic field, could probe the QCD axion over the mass range of $40 - 240\,\mu\mathrm{eV}$. In many respects, the MADMAX approach can be considered a natural high frequency extension of the ADMX technique. Research groups involved in ADMX and MADMAX have identified synergies in the solutions to common R&D challenges, such as magnet development, cryogenic engineering, alignment technology and RF detection. Direct participation of US-based ADMX researchers in MADMAX and MADMAX researchers in ADMX would accelerate both projects by building on common expertise to build a comprehensive program for the detection of higher mass axions.

The Physics Case. The QCD axion and axion-like-particles (ALPs) are excellent cold dark matter (DM) candidates[1–3]. While axions have originally been proposed to solve the strong CP-problem[4–6], ALPs inter alia arise in string compactifications[7,8]. The DM abundance of QCD axions is determined by whether the Peccei-Quinn (PQ) symmetry is broken before or after cosmic inflation and the axion mass m_a. If the PQ symmetry is broken before inflation, axion masses below $m_a \lesssim 10^{-2}\,\mathrm{eV}$ could lead to the observed DM abundance[9]. In the post-inflationary scenario this is the case for axion masses around $10-100\,\mu\mathrm{eV}$[10–15].

Several experiments[9,16,17] are searching for galactic axions by using their conversion to photons under a strong magnetic field, which can be resonantly enhanced by a cavity[18,19]. Most notably, the ADMX collaboration[20] has excluded models for QCD axion DM for most masses between $\sim 2.7\,\mu\mathrm{eV}$ and $\sim 3.3\,\mu\mathrm{eV}$. A number of experiments try to generalize the cavity approach to higher masses[21–25]. These typically need to reduce the cavity volume to still match the lower photon wavelength and have lower quality factors, both reducing their sensitivity. Alternatively, one can give up some of the resonant quality factor in order to maximize the volume, which is the base of the dielectric haloscope concept[26–28] detailed in the following.

Detection Principle & Proposed Design. Placing a dielectric disc in a dipole-magnetic field, axions can convert to electromagnetic radiation on the disc surface. By placing multiple dielectric discs in front of a metal mirror (dielectric haloscope), the emissions from the different surfaces can constructively interfere and excite resonances between the dielectrics. Both effects give rise to the so called power boost factor β^2, defined as the ratio of power emitted by only a perfect mirror in vacuum and the dielectric haloscope. It is a function of frequency $\beta^2(\nu)$ and can be tuned to a specific frequency band by adjusting the disc distances.

The recently proposed MADMAX (MAgnetized Disc and Mirror Axion eXperiment)[27,29] is a dielectric haloscope designed to probe the QCD axion in the mass range motivated by the post-inflationary symmetry breaking scenario. Using 80 lanthanum aluminate ($\mathrm{LaAlO_3}$) discs, it is expected to reach a boost factor of $\beta^2 \sim 10^5$ over a bandwidth of $20\,\mathrm{MHz}$, giving an emitted power of

$$P_\gamma \approx 4 \times 10^{-22}\,\mathrm{W} \left(\frac{\beta^2}{10^5}\right)\left(\frac{B_\mathrm{e}^2\,A}{100\,\mathrm{T}^2\,\mathrm{m}^2}\right)\left(\frac{|C_{a\gamma}|}{1}\right)^2\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm}^{-3}}\right), \tag{1}$$

where B_e is the external magnetic field parallel to the disc surfaces, A is the disc area, $|C_{a\gamma}|$ is a model-dependent coupling constant proportional to the axion-photon coupling $g_{a\gamma}$ defined in[28], and ρ_a is the local axion DM density. For the KSVZ[30,31] and DFSZ[32,33] axion models $|C_{a\gamma}|$ is ~ 1.9 and ~ 0.7, respectively.

Sensitivity & Timeline. Further assuming a $50\,\%$ detection efficiency, a total system noise temperature of $8\,\mathrm{K}$ including a HEMT amplifier at $4\,\mathrm{K}$, a signal-to-noise ratio of 5 and disc readjustment time of one hour, MADMAX will be sensitive to DFSZ axions in the mass range 40 to $240\,\mu\mathrm{eV}$ after ~ 10 years. This complements the reach of ADMX-G2[20] and ADMX2-4[34] as indicated in fig. 1.

To verify the experiment concept, the MADMAX collaboration is building a prototype with 20 discs of $30\,\mathrm{cm}$ diameter to be operated in the MORPURGO magnet at CERN, offering a $1.6\,\mathrm{T}$ dipole field. This setup is planned to take data in the upcoming LHC shutdown periods until 2024 and could be sensitive to ALP DM from 90 to $100\,\mu\mathrm{eV}$ with $g_{a\gamma} > 1 \times 10^{-12}\,\mathrm{GeV}^{-1}$. For the final MADMAX stage, the collaboration is working with CEA Saclay and Bilfinger NOELL to build the required high-field dipole magnet. In a first step, an intermediate dipole-magnet with $B_e^2 A \sim 24\,\mathrm{T}^2\,\mathrm{m}^2$ will be operated with the first produced coils. This should allow a start of data taking in 2025, with a scan rate similar to the final MADMAX setup, but at KSVZ sensitivity. The start of the physics run with DFSZ sensitivity after the completion of the full magnet with $B_e^2 A \sim 100\,\mathrm{T}^2\,\mathrm{m}^2$ is expected in 2030.

Opportunities for US Participation. Various opportunities to exploit synergies between MADMAX and ADMX have been identified: (involved institutions in brackets)

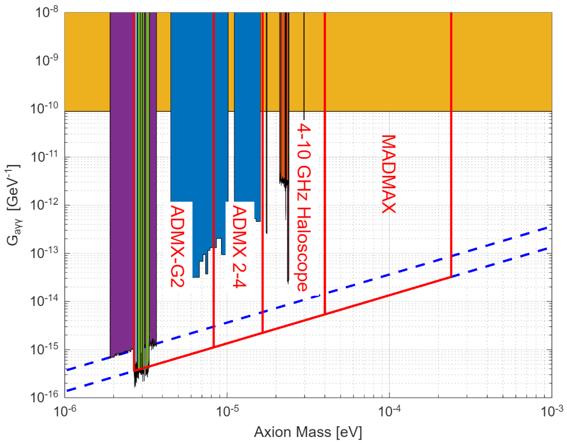

Figure 1: Expected sensitivities in the m_a-$g_{a\gamma\gamma}$ plane for ADMX-G2, ADMX2-4 and MADMAX (red contours), compared to existing limits (solid regions) and the KSVZ (DFSZ) QCD axion benchmark models denoted by upper (lower) blue dashed lines. Also shown is the potential reach of a generic future 4-10 GHz ADMX-like experiment.

- **Magnet:** The high magnetic field is central for MADMAX and gives the opportunity to take part in fabrication, commissioning and running a "world's first" large-bore, high-field dipole magnet. (FNAL, DESY, MPP)
- **Cryogenic Engineering:** Expertise at FNAL with large sub-kelvin cryostats could be exploited to decrease system temperature, leading to significant improvement in sensitivity. (FNAL, DESY, MPP)
- **Alignment technology:** The need to automatically tune the experimental setup to the desired axion mass range, i.e., resonance frequency, leads to the requirement to move components with cryogenic motors. Precision, repeatability and reliability are fundamental for the successful operation of both ADMX and MADMAX. (UFl, LLNL, FNAL, UHH, MPP, UTü)
- **Electronics / Detection Methods:** The system noise temperature could be significantly reduced using parametric amplifiers or single photon detectors and thus reach or even beat the quantum limit. Some of the US grouops are already using such technologies that could be applicable to MADMAX, thus guarantee significant improvement of sensitivity. (UW, FNAL, LLNL, MPP, NEEL)
- **RF behavior, calibration:** Experience in understanding RF behavior of ADMX will apply to reliably calibrating the power boost factor and receiver in the MADMAX setup. Hence US groups could significantly reduce the systematic uncertainties, in turn increasing the sensitivity of MADMAX. (UW, PNNL, MPP, DESY, MPIfR)
- **Dielectric material handling and characterization:** A good understanding of RF properties of dielectrics such as losses is important for many axion experiments, in order to keep systematic uncertainties under control. Both collaborations have experience with various metrology methods that need to be scaled up to frequencies relevant for MADMAX. (FNAL,UFL, LLNL, RWTH, UHH, UWA)

Conclusion. MADMAX is a promising experiment to search for axion DM around $100\,\mu$eV and broadly complementary to ADMX. Since both experiments face similar R&D challenges, a participation of US groups would extend the sensitivity and discovery potential for both efforts and complete the portfolio of US-funded axion experiments by closing the mass gap for the well-motivated post-inflationary-PQ-breaking scenario.

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Text in the first two sections is based on the introduction found in[35].