Snowmass2021 - Letter of Interest

Axion Dark Matter eXperiment (ADMX) 2-4 GHz

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) *[Please specify frontier/topical group]*

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Abstract:

The Axion Dark Matter eXperiment (ADMX) collaboration is currently operating a search for axion dark matter at the University of Washington. In 2018-2019, ADMX was able to exclude axions with standard halo density and DFSZ-strength couplings to the electromagnetic field over the frequency range 648-802 MHz, corresponding to the mass range 2.7-3.3 μeV. We expect to probe frequencies up to 2 GHz by the end of 2023. We are designing a next-stage experiment to cover the range from 2-4 GHz in the period 2024-2027. This requires a combination of higher magnetic field, a larger number of resonator cells, reduced noise and an improved resonator quality factor to meet sensitivity goals in a three-year run.

The QCD axion is arguably the best motivated of dark matter candidates, because its existence would solve not only the dark matter problem but also the strong CP problem. Axions and axion-like particles naturally arise in many frameworks for beyond standard model physics and the vacuum relaxation process in the early universe can quite naturally produce the observed abundance of dark matter.

An elegant technique to detect resonant conversion of dark matter axions into photons in a cavity immersed in a magnetic field (the so-called ”axion haloscope”) was proposed in 1983 by Sikivie[1]. Early haloscope experiments[2–8] established the basic feasibility of the axion haloscope, but covered only a very narrow mass range and did not have the sensitivity needed to test the full range of axion-photon couplings allowed by the most cited models. Only in 2018, with the implementation of Josephson-junction based amplifiers and dilution refrigeration technology, did ADMX achieve sensitivity to the very weakly coupled DFSZ axions[9–11]. At the time of writing, the ADMX-G2 project has scanned the 648-802 MHz range with DFSZ-level sensitivity. Now that this sensitivity has been achieved, the challenge for future axion haloscopes is to scan a wider mass range.

The rate at which frequencies can be scanned at constant sensitivity in a haloscope experiment is related to frequency f, cavity volume V, form factor C, magnetic field B, cavity resonant quality Q, and system noise temperature T as:

$$\text{Scan Rate (MHz/s)} \propto \frac{fQV^2C^2B^4}{T^2}. \quad (1)$$

For example, the scan speed in the 2018 ADMX run near 700 MHz was roughly 1 MHz per day. This result was obtained with a single copper cavity in a 7.6 Tesla magnetic field, read out with a Microstrip Squid Amplifier at a noise temperature of approximately 350 mK.

Since the frequency of a resonant microwave cavity is inversely proportional to its diameter, the achievable scan rate drops rapidly with frequency for single cavity experiments. ADMX and other groups are exploring ways to offset this decrease in sensitivity at high frequency by:

- Combining large numbers of individual cavities to maintain the total volume[12,13].
- Increasing the magnetic field strength through the use of high - field superconducting magnet materials such as Nb_3Sn and rare earth superconductors (REBCO)[14,15].
- Increasing the quality factor of the resonators by using superconductors or loss-loss dielectrics to contain the fields rather than resistive metals[16–18]
- Reducing the noise level of the amplifier by exploiting the properties of squeezed states or developing single photon counting techniques to evade the Standard Quantum Limit.[19–21]

We expect the current generation of the ADMX experiment to complete operations in 2024, having scanned frequencies up to 2 GHz (8.3 μeV). The next phase experiment will cover the 2-4 GHz range. The collaboration has begun design work for ADMX 2-4 GHz, with support from the DOE’s Dark Matter New Initiatives program. We expect to be ready to begin building the experiment in 2022 and operations are anticipated in 2024-2027. The long term plan for ADMX includes phases beyond 2027 to include frequencies up to at least 10 GHz.

In Table 1 we compare the key performance parameters of the currently operating experiment with what is needed to achieve sensitivity in the next frequency band. Two scenarios are considered, a ”baseline performance” which requires no improvement in the key parameters and a ”target performance” which requires improvements in the design of the magnet, cavity and/or electronics as discussed briefly above. The target performance thresholds have all been demonstrated individually in published work, but have not been demonstrated simultaneously in a complete system for detection of dark matter. The primary challenge for the design of the experiment is the integration of several new technologies into a system that will be practical to build and reliable to operate over an extended period.

	2018 Achieved Run	Baseline Requirement	Target Performance
Frequency Range	680-800 MHz	2-4 GHz	2-4 GHz
Volume	139 Liters	80 Liters	80 Liters
Q	60,000	30,000	90,000
B Field	7.6 T	7.6 T	12.0 T
Form Factor	0.4	0.4	0.4
Noise Temperature	350 mK	350 mK	325 mK
Live Time Fraction	40%	70%	70%
Amplifier Squeezing	1	1	1.4
Operations Days	150	1000	1000
Dark Matter Sensitivity for DFSZ Coupling	0.45 GeV/cm^3	0.65 GeV/cm^3	0.12 GeV/cm^3
for KSVZ Coupling	0.09 GeV/cm^3	0.15 GeV/cm^3	0.02 GeV/cm^3

Table 1: Parameters for the most recent operation of ADMX and an example parameter set with enhanced quality factors, squeezing, and a new magnet that would allow completion of the 2-4 GHz scan within a 1000-day run.

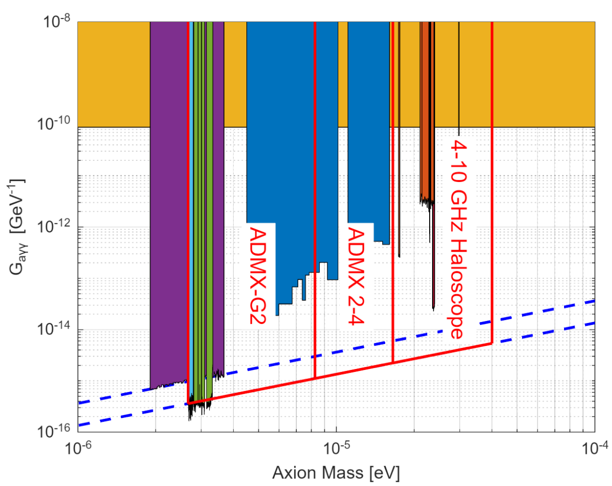

Figure 1: Sensitivity Projections for ADMX-G2 and ADMX 2-4 GHz. The sensitivity to an effective axion-photon coupling $G_{a\gamma\gamma}$ is shown as a function of axion mass. The shaded areas include the results from CAST[22], HAYSTAC[23], RBF[2,3], UF[4] and previous ADMX runs[7–11]. The dashed lines indicate sensitivity needed to probe the benchmark KSVZ and DFSZ models.

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