

First Results from ABRACADABRA-10 cm: A Search for Sub- μeV Axion Dark Matter

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The axion is a promising dark matter candidate, which was originally proposed to solve the strong- CP problem in particle physics. To date, the available parameter space for axion and axionlike particle dark matter is relatively unexplored, particularly at masses $m_a \lesssim 1 \mu\text{eV}$. ABRACADABRA is a new experimental program to search for axion dark matter over a broad range of masses, $10^{-12} \lesssim m_a \lesssim 10^{-6} \text{ eV}$. ABRACADABRA-10 cm is a small-scale prototype for a future detector that could be sensitive to the QCD axion. In this Letter, we present the first results from a 1 month search for axions with ABRACADABRA-10 cm. We find no evidence for axionlike cosmic dark matter and set 95% C.L. upper limits on the axion-photon coupling between $g_{a\gamma\gamma} < 1.4 \times 10^{-10}$ and $g_{a\gamma\gamma} < 3.3 \times 10^{-9} \text{ GeV}^{-1}$ over the mass range 3.1×10^{-10} – $8.3 \times 10^{-9} \text{ eV}$. These results are competitive with the most stringent astrophysical constraints in this mass range.

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Introduction.—The particle nature of dark matter (DM) in the Universe remains one of the greatest mysteries of contemporary physics. Axions are an especially promising candidate as they can simultaneously explain both the particle nature of DM and resolve the strong- CP problem of quantum chromodynamics (QCD) [1–6]. Axionlike particles (ALP) are generically expected to have a coupling to electromagnetism of the form [7]

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}, \quad (1)$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling. The QCD axion is predicted to have a narrow range of couplings proportional to the axion mass, while a general ALP may have any $g_{a\gamma\gamma}$. In this work, “axion” refers to a general ALP. Axion DM (ADM) with mass $m_a \ll 1 \text{ eV}$ behaves today as a classical

field oscillating at a frequency $f = m_a/(2\pi)$ [3,4]. The Lagrangian (1) implies that a time-dependent background density of ADM modifies Maxwell’s equations. In particular, in the presence of a static magnetic field $\mathbf{B}_0$, ADM generates an oscillating magnetic field $\mathbf{B}_a$ as if sourced by an effective ac current density parallel to $\mathbf{B}_0$ [8],

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \mathbf{B}_0 \cos(m_a t). \quad (2)$$

Here ρ_{DM} is the local DM density, which we take to be $0.4 \text{ GeV}/\text{cm}^3$ [9,10]. The “A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B -field Ring Apparatus” (ABRACADABRA) experiment, as first proposed in Ref. [11], is designed to search for the axion-induced field $\mathbf{B}_a$ generated by a toroidal magnetic field (see also Ref. [12] for a proposal using a solenoidal field). ABRACADABRA searches for an ac magnetic flux through a superconducting pickup loop in the center of a toroidal magnet, which should host no ac flux in the absence of ADM. The time-averaged magnitude of the flux through the pickup loop due to $\mathbf{B}_a$ can be written as

$$|\Phi_a|^2 = g_{a\gamma\gamma}^2 \rho_{\text{DM}} V^2 \mathcal{G}^2 B_{\text{max}}^2 \equiv A, \quad (3)$$

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where V is the volume of the toroid, $\mathcal{G}$ is a geometric factor calculated for our toroid to be 0.027 [13], and $B_{\max}$ is the maximum B field in the toroid. The pickup loop is read out using a SQUID current sensor, where an axion signal would appear as a small-amplitude, narrow ($\Delta f/f \sim 10^{-6}$) peak in the power spectral density (PSD) of the SQUID output at a frequency given by the axion mass. The present design uses a simplified broadband readout, but the same approach can be significantly enhanced using resonant amplification and recent developments in powerful quantum sensors [14,15], which is the subject of future work.

In this Letter, we present first results from ABRACADABRA-10 cm, probing the axion-photon coupling $g_{a\gamma\gamma}$ for ADM in the frequency range $f \in [75 \text{ kHz}, 2 \text{ MHz}]$, corresponding to axion masses $m_a \in [3.1 \times 10^{-10}, 8.3 \times 10^{-9}] \text{ eV}$. This mass range is highly motivated for QCD axions, where the axion decay constant lies near the GUT scale and is easily compatible with pre-inflationary Peccei-Quinn (PQ) breaking in a variety of models, including grand unified theories [16] or string compactifications [17,18], and such low-mass axions may be favored anthropically [19]. Additionally, such light ALPs may explain the previously observed transparency anomaly of the Universe to TeV gamma rays [20–23], though in this case the ALP is not required to be DM. Recently, this mass range has gathered significant experimental interest: [11,12,24–28] to name a few, or see Ref. [29] for a comprehensive review. Furthermore, this mass range is highly complementary to that probed by the ADMX experiment [30–32], HAYSTAC [33], and other microwave cavity experiments [34–36], which probe $m_a \sim 10^{-6} \text{--} 10^{-5} \text{ eV}$. Our result represents the most sensitive laboratory search for ADM below $1 \mu\text{eV}$, is competitive with leading astrophysical constraints from CAST [37], and probes a region where low-mass ALPs, which can accommodate all the DM of the universe without overclosure [38–42], as well as particular models of QCD axions with enhanced photon couplings [43,44]. Aside from the ALP models currently being probed, this result is a crucial first step towards a larger-scale version of ABRACADABRA sensitive to the smaller values of $g_{a\gamma\gamma}$ relevant for the typical QCD axion models in the mass range where axions can probe GUT-scale physics.

Magnet and cryogenic setup.—ABRACADABRA-10 cm consists of a superconducting persistent toroidal magnet produced by Superconducting Systems Inc. [45] with a minimum inner radius of 3 cm, a maximum outer radius of 6 cm, and a maximum height of 12 cm (see Fig. 1). The toroidal magnet is counterwound to cancel azimuthal currents; see Ref. [13] for details. We operate the magnet in a persistent field mode with a current of 121 A, producing a maximum field of 1 T at the inner radius. We confirmed this field with a Hall sensor to a precision of $\sim 1\%$. Because of the toroidal geometry of the magnet, the

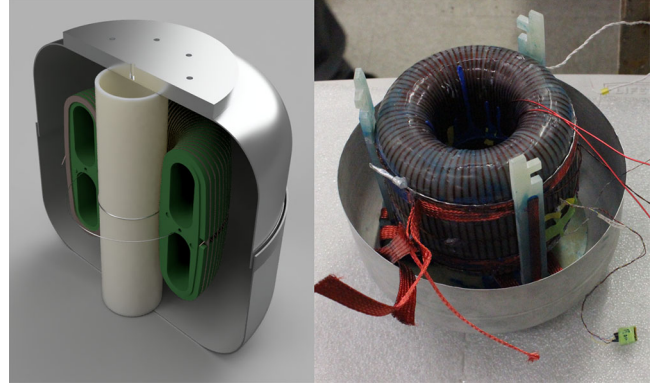


FIG. 1. Left: Rendering of the ABRACADABRA-10 cm setup. The primary magnetic field is driven by 1280 superconducting windings around a POM support frame (green). The axion-induced field is measured by a superconducting pickup loop mounted on a PTFE support (white). A second superconducting loop runs through the volume of the magnet to produce a calibration signal. All of this is mounted inside a superconducting shield. Right: Picture of the exposed toroid during assembly.

field in the center should be close to zero (in the absence of an axion signal).

To reduce ac magnetic field noise, we use both magnetic shielding and vibrational isolation. The toroid is mounted in a G10 support inside a tin-coated copper shell which acts as a magnetic shield below 3.7 K, when the tin coating becomes superconducting. The toroid and shield assembly is thermalized to the coldest stage of an Oxford Instruments Triton 400 dilution refrigerator and cooled to an operating temperature of $\sim 1.2 \text{ K}$. The weight of the shield and magnet is supported by a Kevlar string that runs $\sim 2 \text{ m}$ to a spring attached to the top of the cryostat. This reduces the mechanical coupling and vibration between the detector and cryostat.

We measure ac magnetic flux in the center of the toroid with a solid NbTi superconducting pickup loop of radius 2.0 cm and wire diameter 1 mm. The induced current on this pickup loop is carried away from the magnet through $\sim 50 \text{ cm}$ of $75 \mu\text{m}$ solid NbTi twisted pair readout wire up to a Magnicon two-stage SQUID current sensor. The $75 \mu\text{m}$ wire is shielded by superconducting lead produced according to Ref. [46]. The majority of the 1 mm wire is inside the superconducting shielding of the magnet, but about 15 cm is only shielded by a stainless steel mesh sleeve outside the shield.

The two-stage Magnicon SQUID current sensor is optimized for operation at $< 1 \text{ K}$; we operate it at 870 mK. The input inductance of the SQUID is $L_{\text{in}} \approx 150 \text{ nH}$ and the inductance of the pickup loop is $L_p \approx 100 \text{ nH}$. The SQUID is operated with a flux-lock feedback loop (FLL) to linearize the output, which limits the signal bandwidth to $\approx 6 \text{ MHz}$. We read out the signal with an AlazarTech ATS9870 8-bit digitizer, covering a voltage range of $\pm 40 \text{ mV}$. The digitizer is clocked to a

Stanford Research Systems FS725 Rb frequency standard. In order to fit the signal into the range of our digitizer, we filter the signal through a 10 kHz high-pass filter and a 1.9 MHz anti-aliasing filter before sending it to the digitizer.

To calibrate the detector, we run a superconducting wire through the volume of the toroid at a radius of 4.5 cm into which we can inject an ac current to generate a field in the pickup loop, similar to what we expect from an axion signal. The coupling between the calibration and pickup loop can be calculated from geometry to be ≈ 50 nH. We perform a calibration scan to calculate the end-to-end gain of our readout system. Our calibration measurements indicate that our pickup-loop flux-to-current gain is lower than expected by a factor of ~ 6 . We determined this to be likely due to parasitic impedances in the circuit, and we will address this issue in future designs.

Data collection.—We collected data from July 16, 2018 to August 14, 2018, for a total integration time of $T_{\text{int}} = 2.45 \times 10^6$ s. The data stream was continuously sampled at a sampling frequency of 10 MS/s for the duration of the data-taking period. After completing the magnet-on data run, we collected two weeks of data with the magnet off, but otherwise in the same configuration.

During data taking, the data follow two paths. First, we take the discrete Fourier transform (DFT) of individual sequential 10 s buffers of 10^8 samples each to produce a series of PSDs. These are accumulated together to produce an average PSD, called $\bar{\mathcal{F}}_{10\text{M}}$, with a Nyquist frequency of 5 MHz and a frequency resolution of $\Delta f = (10\text{s})^{-1} = 100$ mHz. In the second path, the streamed data are decimated by a factor of 10, to a sampling frequency of 1 MS/s, collected into a 100 s buffer of 10^8 samples, then

transformed and compiled into a similar running average PSD, $\bar{\mathcal{F}}_{1\text{M}}$, with Nyquist frequency of 500 kHz and $\Delta f = (100\text{s})^{-1} = 10$ mHz. The 1 MS/s data stream is further decimated in real time to a 100 kS/s stream and written directly to disk. This can be transformed offline to produce $\mathcal{F}_{100\text{k}}$, with a Nyquist frequency of 50 kHz and $\Delta f = 1/T_{\text{int}} \approx 408$ nHz. We do not use $\mathcal{F}_{100\text{k}}$ for the present search. All DFT transforms are taken with the FFTW3 library [47].

The $\bar{\mathcal{F}}_{10\text{M}}$ spectra are written to disk and reset after every 80 averages; each stored spectrum thus covers a period of 800 s. This allows us to separate time-dependent noise signals from a constant axion signal. Similarly, the $\bar{\mathcal{F}}_{1\text{M}}$ spectra are written to disk and reset every 16 averages, and cover a period of 1600 s. Figure 2 shows the full $\bar{\mathcal{F}}_{10\text{M}}$ spectrum as well as close-ups of the $\bar{\mathcal{F}}_{1\text{M}}$ spectra, converted to pickup loop flux spectral density using the calibration measurements.

Each of the $\bar{\mathcal{F}}_{10\text{M}}$, $\bar{\mathcal{F}}_{1\text{M}}$, and $\mathcal{F}_{100\text{k}}$ spectra have a usable range limited by the Nyquist frequency on the high end, and the frequency resolution required to resolve a potential axion signal on the low end. With our sampling frequency and integration times, we could perform a search over the range from 440 mHz–5 MHz with enough resolution that a potential signal would span 5–50 frequency bins (assuming a typical ADM velocity of ~ 220 km/s), though in practice our search range is limited by the signal filters.

We observed large $1/f$ -type behavior below ~ 20 kHz, with broad noise peaks extending up to ~ 100 kHz. This noise is strongly correlated with vibration on the top plate of the cryostat up to the highest frequency measured by our accelerometer, ~ 10 kHz [13]. We believe that the tail of this noise continues up to higher frequencies

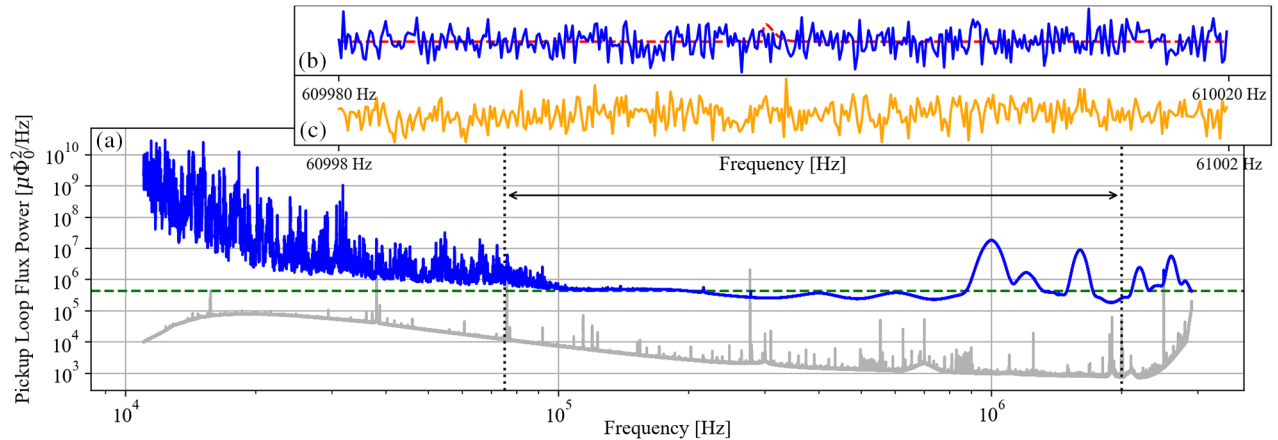


FIG. 2. Flux spectrum averaged over the data used in this analysis. (a) The spectrum over the frequency range $11 \text{ kHz} < f < 3 \text{ MHz}$, corrected for the predigitizer filters (blue). For comparison, we also show the digitizer noise floor, corrected for predigitizer filters (gray) and the characteristic SQUID flux floor (green dashed). The axion search range is between the dotted black lines. (b) A zoomed view of the 10 MS/s spectrum (blue) with $\Delta f = 100$ mHz and an example axion signal at the 95% upper limit (red dashed). (c) A zoomed view of the 1 MS/s spectrum with $\Delta f = 10$ mHz. Note that the digitizer data was collected at a different time from the SQUID data, and shows a few transient peaks that are not present in the SQUID data.

before becoming subdominant to the flux noise of the SQUID above 100 kHz. This noise degrades our sensitivity at lower frequencies and we restrict our search range to $75 \text{ kHz} < f < 2 \text{ MHz}$.

For ~ 1 week after starting the data collection, we observed very narrow and variable noise peaks in the PSD above $\sim 1.2 \text{ MHz}$. We are investigating the source of these peaks. After about a week, these peaks died away slowly and did not return until we re-entered the lab to refill an LN_2 dewar, then died away again after a few days. The affected time periods were removed and account for a $\sim 30\%$ decrease in our exposure. We hope that in the future, a more detailed analysis will allow us to recover a significant fraction of this lost exposure.

Data analysis approach.—Our data analysis procedure closely follows the method introduced in Ref. [48]. Our expected signal is a narrow peak in the pickup loop PSD, with a width $\Delta f/f \sim 10^{-6}$ arising from the DM velocity dispersion. When averaged over N_{avg} independent PSDs, the signal in each frequency bin k (f_k) will follow an Erlang distribution with shape parameter N_{avg} and mean

$$s_k = \begin{cases} A \frac{\pi f(v)}{m_a v} \Big|_{v=\sqrt{4\pi f_k/m_a-2}} & f_k > m_a/2\pi, \\ 0 & f_k \leq m_a/2\pi, \end{cases} \quad (4)$$

where A is defined in Eq. (3). We assume $f(v)$ is given by the Standard Halo Model, with velocity dispersion $v_0 = 220 \text{ km/s/c}$, and $v_{\text{obs}} = 232 \text{ km/s/c}$ the DM velocity in the Earth frame [49], with c the speed of light. With the DM density and velocity distribution specified, the only free parameter in the predicted signal rate is $g_{\text{a}\gamma\gamma}$.

We expect our background noise sources to be normally distributed in the time domain, such that when combined with an axion spectrum, the resulting PSD data are still Erlang distributed. Accordingly, our combined signal-plus-background model prediction in each frequency bin is an Erlang distribution $P(\tilde{\mathcal{F}}_k; N_{\text{avg}}, \mu_k)$ with shape parameter N_{avg} and mean $\mu_k = s_k + b$ (see Ref. [48] for details). Although the background PSD varies slowly with frequency, the axion signal for a given mass is narrow enough that we restrict to a small frequency range and parametrize the background as a constant b across the window. We verified that the results of our analysis were not sensitive to the size of the window chosen.

We performed our analysis on the $\tilde{\mathcal{F}}_{10\text{M}}$ and $\tilde{\mathcal{F}}_{1\text{M}}$ spectra over frequency ranges 500 kHz to 2 MHz and 75 to 500 kHz, respectively. We chose the frequency at which we transition from one set of spectra to the other so that the axion signal window is sufficiently resolved everywhere, though we have seen that the exact choice has little effect on the final result. We rebin the $\tilde{\mathcal{F}}_{10\text{M}}$ ($\tilde{\mathcal{F}}_{1\text{M}}$) spectra in time into 53 (24) spectra that cover 32 000 s (64 000 s) each. This was done to speed up

processing time, though it is not necessary for our analysis approach.

We test for an axion signal at mass m_a and coupling strength A by constructing a joint likelihood of Erlang distributions over the 53 (24) $\tilde{\mathcal{F}}_{10\text{M}}$ ($\tilde{\mathcal{F}}_{1\text{M}}$) given the observed PSD data [13,48]. For each axion mass, we assign a unique background nuisance parameter to each of the rebinned $\tilde{\mathcal{F}}_{10\text{M}}$ ($\tilde{\mathcal{F}}_{1\text{M}}$) spectra and profile over the joint likelihood to construct the profile likelihood for A at that mass. This accounts for the possibility that the background level might change on timescales of hours to days.

To detect an axion signal, we place a 5σ threshold on a discovery test statistic (TS). To evaluate this we first calculate the profile likelihood ratio $\lambda(m_a, A)$, at fixed m_a , as the ratio of the background-profiled likelihood function as a function of A to the likelihood function evaluated at the best-fit value $\hat{A}$. From here, we define $\text{TS}(m_a) = -2 \log \lambda(m_a, 0)$ for $\hat{A} > 0$ and zero otherwise. This quantifies the level at which we can reject the null hypothesis of $A = 0$. The 5σ condition for discovery at a given m_a is $\text{TS}(m_a) > \text{TS}_{\text{thresh}}$, where [48]

$$\text{TS}_{\text{thresh}} = \left[\Phi^{-1} \left(1 - \frac{2.87 \times 10^{-7}}{N_{m_a}} \right) \right]^2, \quad (5)$$

accounts for the local significance as well as the look-elsewhere effect (LEE) for the N_{m_a} independent masses in the analysis (here Φ is the cumulative distribution function for the normal distribution with zero mean and unit variance). For this analysis, $N_{m_a} \approx 8.1 \times 10^6$ between 75 kHz and 2 MHz, and $\text{TS}_{\text{thresh}} = 56.1$.

Where we have no detection, we set a 95% C.L. limit, $A_{95\%}$, again with the profile likelihood ratio. To do so, we use the statistic $t(m_a, A) = -2 \log \lambda(m_a, A)$, with $A > \hat{A}$, by $t(m_a, A_{95\%}) = 2.71$. We implement one-sided power-constrained limits [50], which in practice means that we do not allow ourselves to set a limit stronger than the 1σ lower level of the expected sensitivity band. We compute the expected sensitivity bands using the null-hypothesis model and following the procedure outlined in Ref. [48].

We had to exclude a few specific mass points from our discovery analysis due to narrow background lines that were also observed when the magnet was off. To veto these mass points as potential discoveries, we analyze data collected while the magnet was off (where no axion signal is expected) using the same analysis framework. If in this analysis we find a mass point with LEE-corrected significance greater than 5σ , we exclude that mass point from our axion discovery analysis. In total, this procedure ensures a signal efficiency of $\gtrsim 99.8\%$. Our axion search yielded 83(0) excesses with significance $\geq 5\sigma$ in the frequency range 500 kHz to 2 MHz (75 to 500 kHz); however all of these points are vetoed by the magnet-off data. We do not exclude these points from our upper-limit analysis, though the

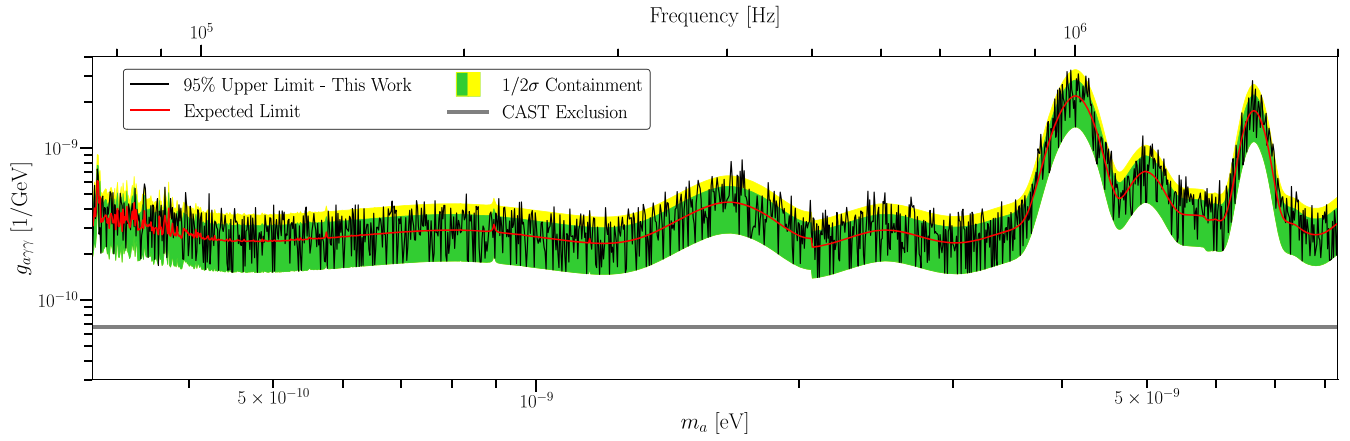


FIG. 3. The limit on the axion-photon coupling $g_{a\gamma\gamma}$ constructed from ABRACADABRA-10 cm data described in this work. We compare the observed limit, which has been down-sampled in the number of mass points by a factor of 10^4 for clarity of presentation, to the expectation for the power-constrained limit under the null hypothesis. This down-sampling excludes the 87 isolated mass points vetoed in the discovery analysis; further details will be presented in Ref. [13]. Additionally, we show the astrophysical constraint on $g_{a\gamma\gamma}$ in this mass range from the CAST helioscope experiment [37]; the region above the gray line is excluded.

observed limits at these isolated points are weaker (they do not appear in Fig. 3 because of down-sampling for clarity).

We verified our analysis framework by injecting a simulated software axion signal into our real data and confirmed that the data-quality cuts and analysis framework described above are able to correctly detect or exclude the presence of an axion signal. In the future we hope to build this into a hardware-based option, using the calibration loop to inject “blinded” signals similar to the approach used by ADMX [32]. Further details of the analysis and statistical tests we have performed, as well as an extended discussion of the noise in the excluded exposure, will be further described in a future publication [13].

Results and discussion.—We observe no evidence of an axion signal in the mass range 3.1×10^{-10} – 8.3×10^{-9} eV and place upper limits on the axion-photon coupling $g_{a\gamma\gamma}$ of at least 3.3×10^{-9} GeV $^{-1}$ over the full mass range and down to 1.4×10^{-10} GeV $^{-1}$ at the strongest point. Our full exclusion limits are shown in Fig. 3 and can be found in Ref. [51]. This result represents the first search for ADM with $m_a < 1$ μ eV, and with one month of data is already competitive with the strongest present astrophysical limits from the much larger CAST helioscope [37] in the range of overlap.

We note that for a significant range in frequency, we achieved the SQUID noise limit. However, constraints on the detector configuration introduced parasitic impedances into the readout circuit, which lead to a loss in the ultimate axion coupling sensitivity [13]. This will be addressed in future efforts and could yield up to a factor of ~ 6 improvement in sensitivity with a similar exposure.

As ABRACADABRA-10 cm is a prototype detector, there are many potential directions for future improvement. Our focus in this work has been on demonstrating the feasibility and power of this new approach. Future upgrade

paths for the ABRACADABRA program will include improvements to shielding and mechanical vibration isolation, reduction of parasitic inductances, improvements to the readout configuration, expanded frequency range, and construction of a larger toroid.

Conclusion.—The axion is a promising DM candidate, but its couplings remain largely unconstrained at low masses. In this Letter we have demonstrated the capabilities of the broadband axion search ABRACADABRA-10 cm, which can cover many decades of axion mass with relatively short data-taking time and which has nonetheless set competitive limits on the coupling $g_{a\gamma\gamma}$. We have already identified stray fields from the toroid, vibration, and cross talk with the DAQ to be significant sources of background [13]. Understanding these sources will be critical for scaling the experiment up to the ~ 1 – 5 m scale to search for the QCD axion.

The ABRACADABRA program is highly complementary to microwave cavity experiments like ADMX and HAYSTAC, as well as proposed experiments like MADMAX [52], which can probe the coupling $g_{a\gamma\gamma}$ for axion masses in the range 10^{-6} – 10^{-5} and 10^{-5} – 10^{-3} eV, respectively. By demonstrating the efficacy of ABRACADABRA-10 cm, we have set the stage for a full-scale experiment which can probe the QCD axion [13]. The combination of ABRACADABRA, microwave cavities, and MADMAX type detectors, along with experiments probing the axion-nucleon coupling [25] and indirect constraints from black hole superradiance [53,54] will be able to probe the range of couplings expected for typical QCD axion models in the coming decades.

The supporting data for this Letter are openly available from the Zenodo repository [51].

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- [1] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977).
- [2] L. F. Abbott and P. Sikivie, *Phys. Lett.* **120B**, 133 (1983).
- [3] J. Preskill, M. B. Wise, and F. Wilczek, *Phys. Lett.* **120B**, 127 (1983).
- [4] M. Dine and W. Fischler, *Phys. Lett.* **120B**, 137 (1983).
- [5] S. Weinberg, *Phys. Rev. Lett.* **40**, 223 (1978).
- [6] F. Wilczek, *Phys. Rev. Lett.* **40**, 279 (1978).
- [7] P. Sikivie, *Phys. Rev. Lett.* **51**, 1415 (1983); **52**, 695(E) (1984).
- [8] J. Ouellet and Z. Bogorad, *Phys. Rev. D* **99**, 055010 (2019).
- [9] R. Catena and P. Ullio, *J. Cosmol. Astropart. Phys.* **08** (2010) 004.
- [10] F. Iocco, M. Pato, G. Bertone, and P. Jetzer, *J. Cosmol. Astropart. Phys.* **11** (2011) 029.
- [11] Y. Kahn, B. R. Safdi, and J. Thaler, *Phys. Rev. Lett.* **117**, 141801 (2016).
- [12] P. Sikivie, N. Sullivan, and D. B. Tanner, *Phys. Rev. Lett.* **112**, 131301 (2014).
- [13] J. L. Ouellet *et al.*, [arXiv:1901.10652](https://arxiv.org/abs/1901.10652).
- [14] S. Chaudhuri, K. Irwin, P. W. Graham, and J. Mardon, [arXiv:1803.01627](https://arxiv.org/abs/1803.01627).
- [15] Z. Ahmed *et al.*, in First Workshop on Quantum Sensing for High Energy Physics Lemont, IL, USA, 2017 (2018), <https://www.osti.gov/biblio/1436708>.
- [16] L. Di Luzio, A. Ringwald, and C. Tamarit, *Phys. Rev. D* **98**, 095011 (2018).
- [17] P. Svrcek and E. Witten, *J. High Energy Phys.* **06** (2006) 051.
- [18] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, *Phys. Rev. D* **81**, 123530 (2010).
- [19] M. Tegmark, A. Aguirre, M. J. Rees, and F. Wilczek, *Phys. Rev. D* **73**, 023505 (2006).
- [20] D. Horns and M. Meyer, *J. Cosmol. Astropart. Phys.* **02** (2012) 033.
- [21] M. Meyer, D. Horns, and M. Raue, *Phys. Rev. D* **87**, 035027 (2013).
- [22] M. Roncadelli, A. De Angelis, and O. Mansutti, *AIP Conf. Proc.* **1018**, 147 (2008).
- [23] C. Burrage, A.-C. Davis, and D. J. Shaw, *Phys. Rev. Lett.* **102**, 201101 (2009).
- [24] M. Silva-Feaver *et al.*, *IEEE Trans. Appl. Supercond.* **27**, 1 (2017).
- [25] D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran, and A. O. Sushkov, *Phys. Rev. X* **4**, 021030 (2014).
- [26] C. Gatti *et al.*, in 14th Patras Workshop on Axions, WIMPs and WISPs (AXION-WIMP 2018) (PATRAS 2018) Hamburg, Germany, 2018 (Deutsches Elektronen-Synchrotron, Hamburg, 2018).
- [27] W. DeRocco and A. Hook, *Phys. Rev. D* **98**, 035021 (2018).
- [28] H. Liu, B. D. Elwood, M. Evans, and J. Thaler, [arXiv:1809.01656](https://arxiv.org/abs/1809.01656).
- [29] I. G. Irastorza and J. Redondo, *Prog. Part. Nucl. Phys.* **102**, 89 (2018).
- [30] 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, M. Mück, and R. F. Bradley, *Phys. Rev. D* **64**, 092003 (2001).
- [31] 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 (2010).
- [32] N. Du *et al.* (ADMX Collaboration), *Phys. Rev. Lett.* **120**, 151301 (2018).
- [33] L. Zhong *et al.*, *Phys. Rev. D* **97**, 092001 (2018).
- [34] C. Hagmann, P. Sikivie, N. S. Sullivan, and D. B. Tanner, *Phys. Rev. D* **42**, 1297 (1990).
- [35] S. DePanfilis, A. C. Melissinos, B. E. Moskowitz, J. T. Rogers, Y. K. Semertzidis, W. U. Wuensch, H. J. Halama, A. G. Prodell, W. B. Fowler, and F. A. Nezrick, *Phys. Rev. Lett.* **59**, 839 (1987).
- [36] C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, E. Daw, H. Peng, L. J. Rosenberg, J. LaVeigne, P. Sikivie, N. S. Sullivan, D. B. Tanner, F. Nezrick, M. S. Turner, D. M. Moltz, J. Powell, and N. A. Golubev, *Phys. Rev. Lett.* **80**, 2043 (1998).
- [37] V. Anastassopoulos *et al.* (CAST Collaboration), *Nat. Phys.* **13**, 584 (2017).
- [38] H. Davoudiasl, D. Hooper, and S. D. McDermott, *Phys. Rev. Lett.* **116**, 031303 (2016).
- [39] P. W. Graham and A. Scherlis, *Phys. Rev. D* **98**, 035017 (2018).
- [40] P. Agrawal, G. Marques-Tavares, and W. Xue, *J. High Energy Phys.* **03** (2018) 049.

- [41] L. Visinelli and P. Gondolo, *Phys. Rev. D* **81**, 063508 (2010).
- [42] R. T. Co, F. D'Eramo, and L. J. Hall, *Phys. Rev. D* **94**, 075001 (2016).
- [43] P. Agrawal, J. Fan, M. Reece, and L.-T. Wang, *J. High Energy Phys.* **02** (2018) 006.
- [44] M. Farina, D. Pappadopulo, F. Rompineve, and A. Tesi, *J. High Energy Phys.* **01** (2017) 095.
- [45] Superconducting systems inc. <http://www.superconducting systems.com>.
- [46] S. Henry, M. Pipe, A. Cottle, C. Clarke, U. Divakar, and A. Lynch, *Nucl. Instrum. Methods Phys. Res., Sect. A* **763**, 155 (2014).
- [47] M. Frigo and S. G. Johnson, *Proc. IEEE* **93**, 216 (2005), special issue on "Program Generation, Optimization, and Platform Adaptation".
- [48] J. W. Foster, N. L. Rodd, and B. R. Safdi, *Phys. Rev. D* **97**, 123006 (2018).
- [49] P. J. McMillan and J. J. Binney, *Mon. Not. R. Astron. Soc.* **402**, 934 (2010).
- [50] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, [arXiv:1105.3166](https://arxiv.org/abs/1105.3166).
- [51] J. L. Ouellet *et al.*, Data for "First Results from ABRA-CADABRA-10 cm: A Search for Sub- μ eV Axion Dark Matter", 2018 Data, Zenodo, <https://doi.org/10.5281/zenodo.2596057> (2019).
- [52] A. Caldwell, G. Dvali, B. Majorovits, A. Millar, G. Raffelt, J. Redondo, O. Reimann, F. Simon, and F. Steffen (MADMAX Working Group), *Phys. Rev. Lett.* **118**, 091801 (2017).
- [53] A. Arvanitaki, M. Baryakhtar, and X. Huang, *Phys. Rev. D* **91**, 084011 (2015).
- [54] A. Arvanitaki, M. Baryakhtar, S. Dimopoulos, S. Dubovsky, and R. Lasenby, *Phys. Rev. D* **95**, 043001 (2017).