Extended Haloscope Search and Exclusion of a Candidate Signal near 1.036 GHz

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We report a follow-up axion haloscope search near 1.036 GHz that completes and extends our previous work [Ahn *et al.* Phys. Rev. X **14**, 031023 (2024)], in which a portion of the HEMT-based data could not be analyzed due to unrecorded experimental information. While recovering this dataset, we identified an excess near 1.036 GHz that satisfied our candidate-selection criteria, motivating dedicated validation studies, including independent cross-checks and reexamination with the original apparatus. The excess did not persist under these investigations and was not confirmed as an axion dark-matter signal. We subsequently extended the search over a 20-MHz band surrounding the candidate using a quantum-noise-limited amplifier, achieving sensitivity close to the Dine-Fischler-Srednicki-Zhitnitsky benchmark. In the absence of a confirmed signal, we set improved 90% confidence-level upper limits on the axion-photon coupling over the frequency range 1.026–1.045 GHz. This Letter highlights the importance of robust candidate-validation strategies as haloscope searches approach discovery-level sensitivity.

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The axion, originally proposed as a solution to the strong charge-parity problem in quantum chromodynamics [1–9], is a well-motivated candidate for cold dark matter [10]. Resonant microwave haloscopes search for axion dark matter through axion-to-photon conversion in a strong magnetic field, with the conversion power enhanced by a high-Q cavity. The expected signal power is given by [11]

$$P_{\mathrm{sig}} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C Q \frac{\beta}{\beta + 1}, \tag{1}$$

where $g_{a\gamma\gamma}$ denotes the axion-photon coupling, ρ_a the local axion dark-matter density, m_a the axion mass, B_0 the applied magnetic field strength, V the cavity volume, C the mode-dependent form factor, Q the cavity quality factor, and β the antenna coupling. Benchmark axion models such as Kim-Shifman-Vainshtein-Zakharov (KSVZ) [12,13] and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [14,15] define the natural sensitivity goals for haloscope experiments. As advances in cryogenic amplification bring receiver noise toward the quantum limit, haloscope experiments are entering a regime of discovery-level sensitivity. In this regime, rigorous candidate identification and validation become essential to distinguish genuine axion signals from instrumental artifacts and environmental radio-frequency interference.

In a recent search reported in Ref. [16], we set stringent limits on the axion-photon coupling over a broad frequency range. Most of the range was scanned using Josephson parametric amplifiers (JPAs) [17,18], while certain intervals outside the JPA bandwidth were covered with high-electron-mobility transistor (HEMT) amplification. A subset of data in the 1.033–1.037 GHz range could not be analyzed due to missing antenna-coupling measurements and was therefore excluded from the original report.

In this Letter, we complete the missing frequency band to provide continuous exclusion coverage and establish a reference point for subsequent higher-sensitivity searches. The restored data revealed a feature near 1.036 GHz that met our candidate-selection criteria, prompting a comprehensive program of validation studies. We report the outcome of these investigations: independent cross-checks with a separate haloscope system and reexamination using the original apparatus. We subsequently extended the search using a JPA receiver and report updated 90% confidence-level limits on the axion-photon coupling over the frequency range 1.026–1.045 GHz.

The original scan [16] was performed with a haloscope, featuring a 12-T superconducting solenoid, a 37-L cylindrical copper cavity, and near-quantum-limited JPAs. The system was maintained below 40 mK by a dilution refrigerator, substantially suppressing thermal noise from both the cavity and the receiver chain. The experiment operated in the TM_{010} cavity mode, which maximizes axion-photon conversion power, with frequency tuning

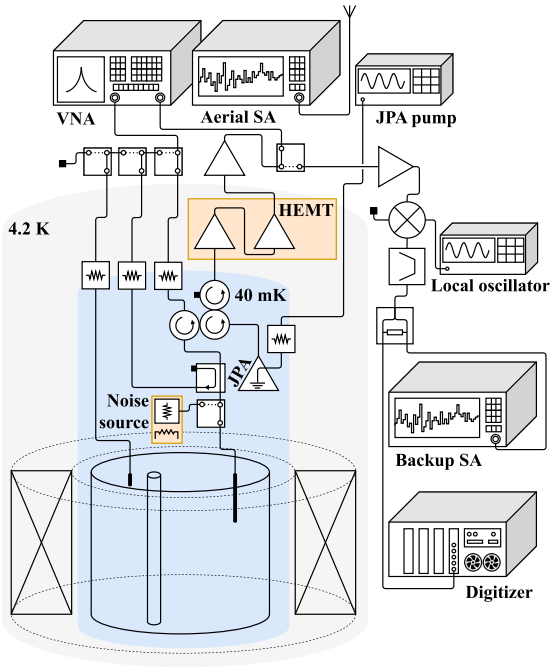


FIG. 1. Schematic of the axion haloscope setup, including the microwave cavity in a superconducting magnet and the associated cryogenic and room-temperature receiver chain.

achieved via a piezoelectric-actuated copper rod inside the cavity. The cavity signal was extracted via a strongly coupled coaxial antenna with $\beta \sim 1.5$. The receiver chain comprised of JPAs operated with gains of ∼20 dB with a bandwidth of ∼100 kHz, followed by cryogenic HEMT amplifiers and subsequent room-temperature amplification. The cavity resonant frequency was set 100 kHz away from the JPA resonance in order to operate the JPA in the phase-insensitive mode. The amplified signals were down-converted to an intermediate frequency of 10.7 MHz using an image-rejection mixer and digitized with a resolution bandwidth of 10 Hz. A dedicated aerial antenna system was employed to monitor environmental radio-frequency interference. A schematic of the experimental setup is shown in Fig. 1.

In the original search, near-quantum-limited sensitivity was achieved using multiple JPAs operated in a parallel configuration, in which a single pump tone simultaneously drove individual amplifiers with different frequency bandwidths. The effective resonant frequency was selected by the pump frequency, enabling an extended search bandwidth while sharing a common circulator and receiver chain. Although JPAs provided near-quantum-limited amplification over most of the frequency range, frequency intervals outside their bandwidth were necessarily scanned with HEMTs. In one such dataset spanning 1.033–1.037 GHz, the antenna coupling was not recorded, and the data were therefore excluded from the previous analysis. We subsequently recovered the coupling by exploiting the smooth frequency dependence of the loaded quality factor Q_L,

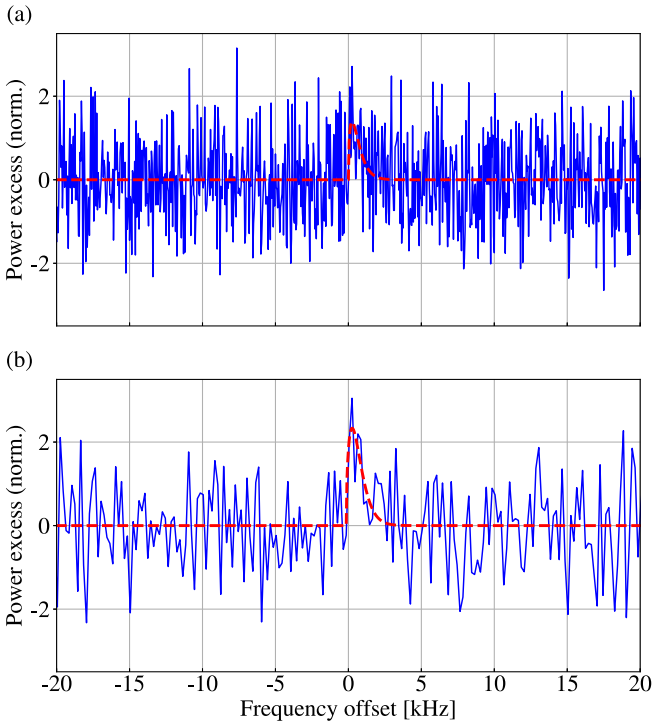


FIG. 2. Power spectra centered on the candidate frequency for different frequency-bin widths: (a) 50 and (b) 200 Hz. The expected signal line shape from the standard axion halo model is overlaid as red dashed lines.

which was measured across the full range. Motivated by this behavior, we assumed the antenna coupling to vary smoothly with frequency and inferred β in the missing region by interpolating coupling values measured in adjacent frequency regions. A quadratic interpolation was employed to reflect the overall frequency dependence. The resulting reconstruction showed negligible boundary discontinuities, and the inferred β was insensitive to the interpolation order, with a maximum deviation of $\sim$0.37%.

During the analysis of the recovered dataset, an excess was observed at 1.036 315 GHz ($m_a = 4.285\,857$ μeV) in data acquired on January 23, 2023. The excess exhibited a local statistical significance of 5.1σ, which is reduced to a global significance of 3.5σ after accounting for the look-elsewhere effect. The observed spectral profile was consistent with that expected from virialized axion dark matter [19]. The corresponding power spectra are shown in Fig. 2. The signal strength as a function of frequency tuning is consistent with the cavity resonance response, as shown in Fig. 3. The inferred signal strength corresponded to roughly 1.3 times the KSVZ axion-photon coupling, assuming a local axion density of 0.45 GeV/cm^3 [20,21]. Given its statistical significance and characteristic spectral profile, the excess was treated as an axion candidate and subjected to follow-up investigations.

A cross-check was performed using an independent haloscope system, previously utilized for an early axion search [22]. The apparatus consists of an 8-T

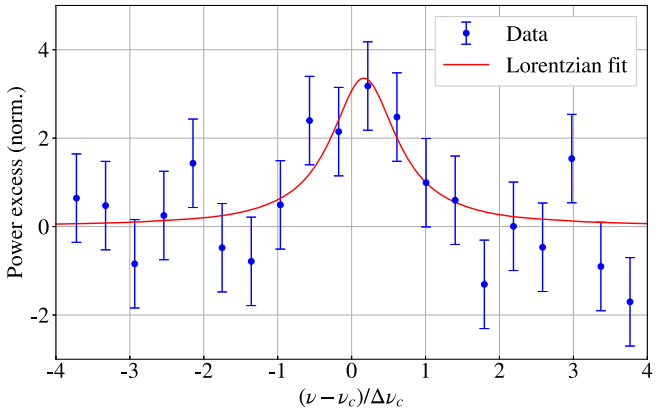


FIG. 3. Signal strength as a function of frequency detuning $\nu - \nu_c$, normalized to the cavity bandwidth ($\Delta\nu_c = 28.25$ kHz). The error bars indicate statistical uncertainties. The data are fitted with a Lorentzian profile whose linewidth is consistent with the measured cavity resonance.

superconducting magnet with a 165-mm bore and a cryogen-free dilution refrigerator operating below 40 mK. For this Letter, a dedicated cylindrical copper cavity with internal dimensions of Ø134 mm × 246 mm was fabricated. Its natural TM_{010} resonance at 1.713 GHz was tuned down to the candidate frequency by inserting a Ø30-mm alumina rod. This modification resulted in a reduced form factor of $C_{010} \approx 0.12$, as estimated from electromagnetic numerical eigenmode computations. Quantum-limited amplification was achieved using a single flux-driven JPA optimized for the target frequency. An initial dataset acquired in December 2023, taken with a cryogenic HEMT amplifier exhibiting elevated system noise ($T_{\mathrm{sys}} \sim 500$ mK), showed a transient excess at the candidate frequency with an observed SNR of $\sim$3.7, prompting further integration to assess its persistence; however, the excess did not reappear with increased exposure. Data collected in a subsequent run in January 2024, after replacement of a cryogenic HEMT amplifier that reduced the system noise to $\sim$200 mK, revealed no statistically significant excess, failing to confirm the candidate.

Following the independent cross-check, we reexamined the candidate using the original apparatus reconfigured with the same single JPA used in the cross-check experiment. This configuration enabled a direct test of whether the previously observed excess originated from systematic effects associated with the amplification chain or other setup-specific artifacts. A follow-up scan conducted between April and June 2024, comprising several segmented data-taking periods due to system instability that required repeated helium recondensing procedures, found no persistent signal with a spectral profile or temporal stability consistent with virialized axion dark matter. We therefore find no evidence supporting a dark-matter interpretation of the candidate and conclude that the initially observed excess does not indicate galactic axion dark

TABLE I. Classification of candidate signals, their characteristic features, and the verification procedures leading to their elimination.

Category	No. of candidates	Characteristic feature	Eliminated by
Instrumental or environmental	146	High significance or narrow linewidth	rf monitoring
Statistical fluctuation	15	Low significance	Rescan
DM-like candidate	1	Persistent and expected line shape	Full verification procedure

matter, although its precise origin remains unidentified. We note that alternative scenarios involving clustered or transient axion dark matter have been proposed in the literature [23,24]; however, the present data are not sufficient to support such interpretations. For clarity and future reference, the classification of identified candidate signals, their characteristic features, and the verification procedures leading to their elimination are summarized in Table I.

To further strengthen this conclusion, we performed a targeted rescan over the ∼20-MHz band surrounding the candidate frequency. Data were collected over a total of 12 days from June 20 to July 10, 2024, with an interruption due to facility maintenance. The analysis procedure followed Ref. [16], consisting of baseline estimation, spectral preprocessing, and statistical combination. Baselines extracted from cavity transmission and reflection spectra, JPA noise, and gain spectra are used to determine the cavity parameters, expected signal power, and system noise temperature. The performance of the baseline removal and normalization was verified by the resulting spectra following standard normal distributions. Correlations between mirrored frequency bins induced by the JPA were accounted for by optimally combining correlated pairs using their expected SNRs and measured correlation coefficients, yielding an average SNR improvement of 4.1%. The analysis efficiency was quantified by injecting software-synthesized axion signals with a reference SNR of 5 directly into the obtained power spectra and comparing the injected and recovered SNRs after the full analysis chain. Repeating this procedure across the scanned frequency range, we found an average efficiency of $92.7 \pm 0.9\%$.

Spectra from different cavity tunings were combined using SNR weighting. In the resulting spectrum, 146 clusters (multibin excesses) exceeding 5σ were identified; all were found to be inconsistent with axion dark-matter signals based on their narrow bandwidths, correlations with aerial antenna data, lack of the expected cavity response, or nonpersistence upon rescanning and were, therefore, removed together with neighboring bins. The power of frequency bins spanning a 5-kHz window was weighted and combined according to the expected axion signal shape from the standard halo model [19], providing a maximum-likelihood estimate of the axion signal power for each assumed axion frequency. A total of 16 clusters exceeding the rescan threshold of 3.718σ underwent follow-up measurements, yielding one persistent candidate, which was subsequently excluded as a galactic axion signal based on its persistence with the magnetic field turned off. While incompatible with axion dark matter, such behavior is consistent with magnetic-field-independent scenarios, such as dark photon dark matter, and may warrant further investigation.

The dominant source of uncertainty in the analysis arises from the estimation of the system noise. The noise temperature was measured at each frequency-tuning step, and its slow variation across the scanned frequency range was removed using a Savitzky-Golay filter [25]. The residual fluctuations about the mean were taken as the associated uncertainty, yielding a fractional uncertainty of 6.4%. Figure 4 compares the system noise measured over the rescanned frequency range with that obtained in the original scan over the full frequency range. Other analysis uncertainties, including those associated with the cavity parameters, contribute at the sub-1% level.

With no signal consistent with axion dark matter observed, we set 90% confidence-level upper limits on the axion-photon coupling over a frequency (mass) range 1.026–1.045 GHz (4.244–4.322 μeV), as shown in Fig. 5. Because of the performance of the JPA, the upper portion of

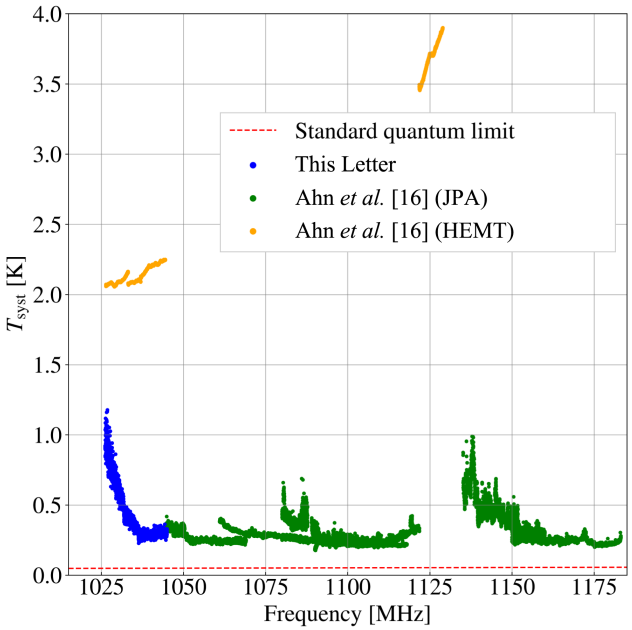


FIG. 4. Measured system noise temperature T_{sys} for this scan (blue), compared with the original scans employing JPA-based (green) and HEMT-based (yellow) receiver chains [16]. The red dashed line indicates the standard quantum limit.

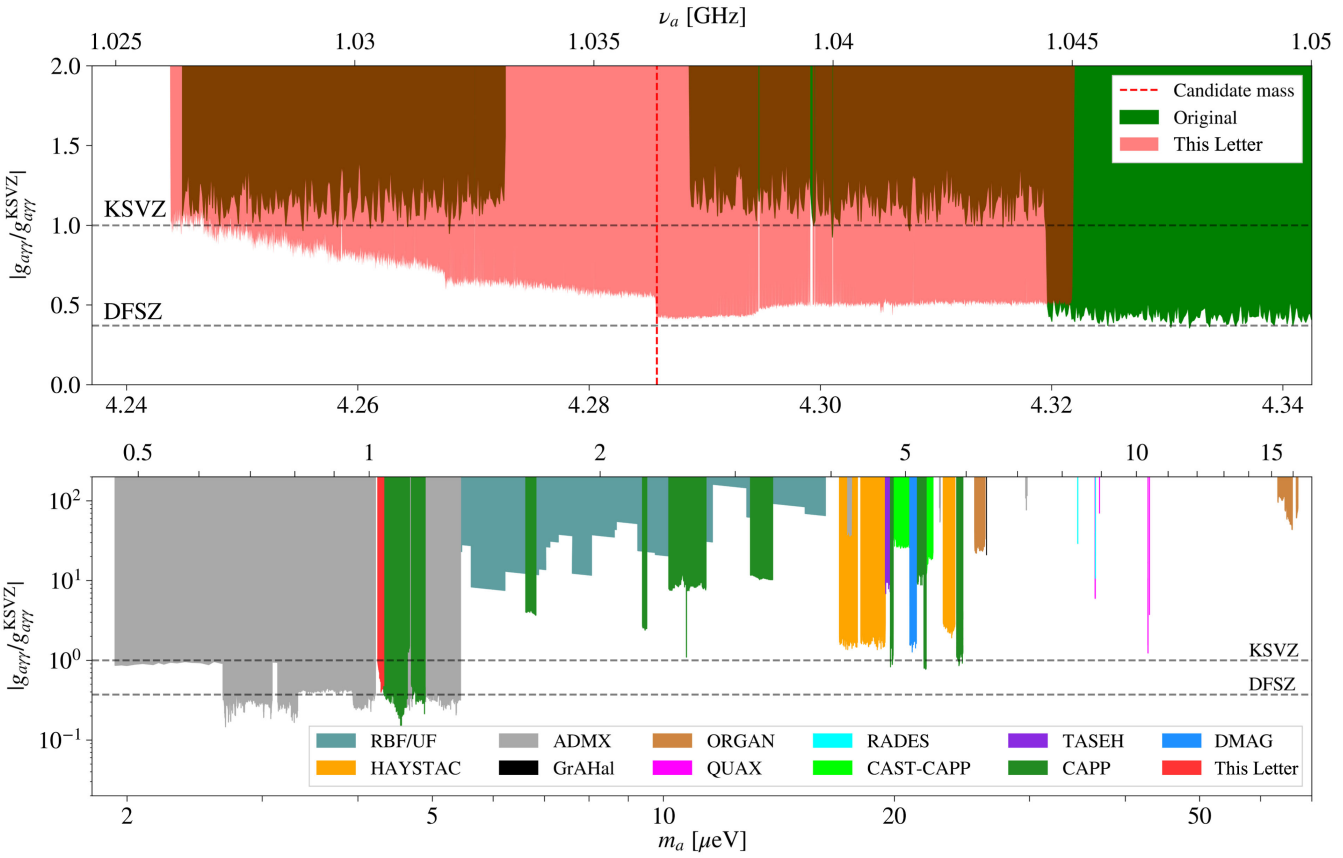


FIG. 5. Experimental limits on the axion-photon coupling $g_{a\gamma\gamma}$ as a function of axion mass m_a (frequency ν_a). The upper panel shows the 90% confidence-level limits set by this Letter, assuming a local axion density of $\rho_a = 0.45\ \mathrm{GeV/cm^3}$; the black dashed lines indicate the KSVZ and DFSZ benchmark models. The vertical red dashed line denotes the candidate frequency. The lower panel compares the results of this Letter with previously reported haloscope limits [16,22,26–61], with the exclusion data taken from the AxionLimits GitHub repository [62].

this range achieved sensitivity approaching the DFSZ benchmark, while the lower portion reached sensitivity at the KSVZ level. These results supersede previous constraints and represent among the most stringent haloscope limits reported to date in this range.

In summary, we completed an axion haloscope search by recovering the previously unrecorded frequency region near 1.036 GHz from Ref. [16]. A candidate excess was identified and subjected to a rigorous program of validation, ultimately failing to confirm as an axion dark-matter signal. Independent measurements by the ADMX experiment also probed this frequency region with adequate sensitivity and found no indication of an excess signal [63]. We subsequently extended the search around the candidate frequency using a quantum-noise-limited JPA receiver, enabling improved 90% confidence-level upper limits on the axion-photon coupling. This Letter demonstrates the robustness and importance of systematic candidate-validation strategies as axion haloscope searches approach discovery-level sensitivity.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

[1] G. 't Hooft, Symmetry breaking through Bell-Jackiw anomalies, Phys. Rev. Lett. **37**, 8 (1976).
[2] G. 't Hooft, Computation of the quantum effects due to a four-dimensional pseudoparticle, Phys. Rev. D **14**, 3432 (1976).
[3] G. t. Hooft, Erratum: Computation of the quantum effects due to a four-dimensional pseudoparticle, Phys. Rev. D **18**, 2199 (1978).
[4] J. H. Smith, E. M. Purcell, and N. F. Ramsey, Experimental limit to the electric dipole moment of the neutron, Phys. Rev. **108**, 120 (1957).

[5] W. B. Dress, P. D. Miller, J. M. Pendlebury, P. Perrin, and N. F. Ramsey, Search for an electric dipole moment of the neutron, Phys. Rev. D **15**, 9 (1977).
[6] I. Altarev, Y. Borisov, A. Brandin, A. Egorov, V. Ezhov, S. Ivanov, V. Lobashov, V. Nazarenko, G. Porsev, V. Ryabov, A. Serebrov, and R. Taldaev, A search for the electric dipole moment of the neutron using ultracold neutrons, Nucl. Phys. **A341**, 269 (1980).
[7] R. D. Peccei and H. R. Quinn, CP conservation in the presence of pseudoparticles, Phys. Rev. Lett. **38**, 1440 (1977).
[8] S. Weinberg, A new light boson?, Phys. Rev. Lett. **40**, 223 (1978).
[9] F. Wilczek, Problem of strong P and T invariance in the presence of instantons, Phys. Rev. Lett. **40**, 279 (1978).
[10] P. A. R. Ade *et al.* (Planck Collaboration), Planck2015 results: XIII. Cosmological parameters, Astron. Asttophys. **594**, A13 (2016).
[11] D. Kim, J. Jeong, S. Youn, Y. Kim, and Y. K. Semertzidis, Revisiting the detection rate for axion haloscopes, J. Cosmol. Astropart. Phys. 03 (2020) 066.
[12] J. E. Kim, Weak-interaction singlet and strong CP invariance, Phys. Rev. Lett. **43**, 103 (1979).
[13] M. Shifman, A. Vainshtein, and V. Zakharov, Can confinement ensure natural CP invariance of strong interactions?, Nucl. Phys. **B166**, 493 (1980).
[14] A. R. Zhitnitskii, On possible suppression of the axion Hadron interactions, Yad. Fiz. **31**, 497 (1980).
[15] M. Dine, W. Fischler, and M. Srednicki, A simple solution to the strong CP problem with a harmless axion, Phys. Lett. **104B**, 199 (1981).
[16] S. Ahn *et al.*, Extensive search for axion dark matter over 1 GHz with CAPP's main axion experiment, Phys. Rev. X **14**, 031023 (2024).
[17] S. V. Uchaikin, J. Kim, Ç. Kutlu, B. I. Ivanov, J. Kim, A. F. van Loo, Y. Nakamura, S. Ahn, S. Oh, M. Ko, and Y. K. Semertzidis, Josephson parametric amplifier based quantum noise limited amplifier development for axion search experiments in CAPP, Front. Phys. **12**, 1437680 (2024).
[18] Ç. Kutlu, A. F. van Loo, S. V. Uchaikin, A. N. Matlashov, D. Lee, S. Oh, J. Kim, W. Chung, Y. Nakamura, and Y. K. Semertzidis, Characterization of a flux-driven Josephson parametric amplifier with near quantum-limited added noise for axion search experiments, Supercond. Sci. Technol. **34**, 085013 (2021).
[19] M. S. Turner, Periodic signatures for the detection of cosmic axions, Phys. Rev. D **42**, 3572 (1990).
[20] X. Ou, A.-C. Eilers, L. Necib, and A. Frebel, The dark matter profile of the Milky Way inferred from its circular velocity curve, Mon. Not. R. Astron. Soc. **528**, 693 (2024).
[21] S. H. Lim, E. Putney, M. R. Buckley, and D. Shih, Mapping dark matter in the Milky Way using normalizing flows and Gaia DR3, J. Cosmol. Astropart. Phys. 01 (2025) 021.
[22] S. Lee, S. Ahn, J. Choi, B. R. Ko, and Y. K. Semertzidis, Axion dark matter search around 6.7 μeV, Phys. Rev. Lett. **124**, 101802 (2020).
[23] P. Tinyakov, I. Tkachev, and K. Zioutas, Tidal streams from axion miniclusters and direct axion searches, J. Cosmol. Astropart. Phys. 01 (2016) 035.
[24] L. Visinelli and J. Redondo, Axion miniclusters in modified cosmological histories, Phys. Rev. D **101**, 023008 (2020).
[25] A. Savitzky and M. J. E. Golay, Smoothing and differentiation of data by simplified least squares procedures, Anal. Chem. **36**, 1627 (1964).
[26] 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, SQUID-based microwave cavity search for dark-matter axions, Phys. Rev. Lett. **104**, 041301 (2010).
[27] N. Du *et al.* (ADMX Collaboration), Search for invisible axion dark matter with the axion dark matter experiment, Phys. Rev. Lett. **120**, 151301 (2018).
[28] T. Braine *et al.* (ADMX Collaboration), Extended search for the invisible axion with the axion dark matter experiment, Phys. Rev. Lett. **124**, 101303 (2020).
[29] C. Bartram *et al.* (ADMX Collaboration), Search for invisible axion dark matter in the 3.3–4.2 μeV mass range, Phys. Rev. Lett. **127**, 261803 (2021).
[30] C. Goodman *et al.*, ADMX axion dark matter bounds around 3.3 μeV with Dine-Fischler-Srednicki-Zhitnitsky discovery ability, Phys. Rev. Lett. **134**, 111002 (2025).
[31] G. Carosi *et al.* (ADMX Collaboration), Search for axion dark matter from 1.1 to 1.3 GHz with ADMX, Phys. Rev. Lett. **135**, 191001 (2025).
[32] C. Boutan *et al.* (ADMX Collaboration), Piezoelectrically tuned multimode cavity search for axion dark matter, Phys. Rev. Lett. **121**, 261302 (2018).
[33] C. Bartram *et al.*, Dark matter axion search using a Josephson traveling wave parametric amplifier, Rev. Sci. Instrum. **94**, 044703 (2023).
[34] J. Jeong, S. Youn, S. Bae, J. Kim, T. Seong, J. E. Kim, and Y. K. Semertzidis, Search for invisible axion dark matter with a multiple-cell haloscope, Phys. Rev. Lett. **125**, 221302 (2020).
[35] O. Kwon *et al.*, First results from an axion haloscope at CAPP around 10.7 μeV, Phys. Rev. Lett. **126**, 191802 (2021).
[36] Y. Lee, B. Yang, H. Yoon, M. Ahn, H. Park, B. Min, D. Kim, and J. Yoo, Searching for invisible axion dark matter with an 18 T magnet haloscope, Phys. Rev. Lett. **128**, 241805 (2022).
[37] J. Kim, O. Kwon, i. m. c. b. u. Kutlu, W. Chung, A. Matlashov, S. Uchaikin, A. F. van Loo, Y. Nakamura, S. Oh, H. Byun, D. Ahn, and Y. K. Semertzidis, Near-quantum-noise axion dark matter search at CAPP around 9.5 μeV, Phys. Rev. Lett. **130**, 091602 (2023).
[38] A. K. Yi *et al.*, Axion dark matter search around 4.55 μeV with Dine-Fischler-Srednicki-Zhitnitskii sensitivity, Phys. Rev. Lett. **130**, 071002 (2023).
[39] B. Yang, H. Yoon, M. Ahn, Y. Lee, and J. Yoo, Extended axion dark matter search using the CAPP18T haloscope, Phys. Rev. Lett. **131**, 081801 (2023).
[40] Y. Kim, J. Jeong, S. Youn, S. Bae, K. Lee, A. F. van Loo, Y. Nakamura, S. Oh, T. Seong, S. Uchaikin, J. E. Kim, and Y. K. Semertzidis, Experimental search for invisible dark matter axions around 22 μeV, Phys. Rev. Lett. **133**, 051802 (2024).

[41] S. Bae, J. Jeong, Y. Kim, S. Youn, H. Park, T. Seong, S. Oh, and Y. K. Semertzidis, Search for dark matter axions with tunable TM_{020} mode, Phys. Rev. Lett. **133**, 211803 (2024).
[42] S. Ahn, i. m. c. b. u. Kutlu, S. Lee, S. Youn, S. V. Uchaikin, S. Bae, J. Jeong, A. F. van Loo, Y. Nakamura, S. Oh, J. E. Kim, and Y. K. Semertzidis, Probing Kim-Shifman-Vainshtein-Zakharov axion dark matter near 5.9 GHz using an 8-cell cavity haloscope, Phys. Rev. Lett. **135**, 211801 (2025).
[43] S. Bae, J. Jeong, Y. Kim, S. Youn, J. Kim, A. F. van Loo, Y. Nakamura, S. Oh, T. Seong, S. Uchaikin, J. E. Kim, and Y. K. Semertzidis, Axion dark matter search with sensitivity near the Kim-Shifman-Vainshtein-Zakharov benchmark using the TM_{020} mode, Phys. Rev. Lett. **135**, 091804 (2025).
[44] C. M. Adair *et al.*, Search for dark matter axions with CAST-CAPP, Nat. Commun. **13**, 6180 (2022).
[45] T. Grenet, R. Ballou, Q. Basto, K. Martineau, P. Perrier, P. Pugnat, J. Quevillon, N. Roch, and C. Smith, The grenoble axion haloscope platform (GrAHal): Development plan and first results, arXiv:2110.14406.
[46] K. M. Backes *et al.*, A quantum enhanced search for dark matter axions, Nature (London) **590**, 238 (2021).
[47] M. J. Jewell *et al.* (HAYSTAC Collaboration), New results from HAYSTAC's phase II operation with a squeezed state receiver, Phys. Rev. D **107**, 072007 (2023).
[48] X. Bai *et al.* (HAYSTAC Collaboration), Dark matter axion search with HAYSTAC phase II, Phys. Rev. Lett. **134**, 151006 (2025).
[49] A. P. Quiskamp, G. R. Flower, S. Samuels, B. T. McAllister, P. Altin, E. N. Ivanov, M. Goryachev, and M. E. Tobar, Near-quantum-limited axion dark matter search with the ORGAN experiment around 26 μeV, Phys. Rev. D **111**, 095007 (2025).
[50] D. Alesini *et al.*, Galactic axions search with a superconducting resonant cavity, Phys. Rev. D **99**, 101101 (2019).
[51] D. Alesini, C. Braggio, G. Carugno, N. Crescini, D. D'Agostino, D. Di Gioacchino, R. Di Vora, P. Falferi, U. Gambardella, C. Gatti, G. Iannone, C. Ligi, A. Lombardi, G. Maccarrone, A. Ortolan, R. Pengo, A. Rettaroli, G. Ruoso, L. Taffarello, and S. Tocci, Search for invisible axion dark matter of mass $m_a = 43$ μeV with the QUAX–$a\gamma$ experiment, Phys. Rev. D **103**, 102004 (2021).
[52] D. Alesini *et al.*, Search for galactic axions with a high-Q dielectric cavity, Phys. Rev. D **106**, 052007 (2022).
[53] R. Di Vora *et al.* (QUAX Collaboration), Search for galactic axions with a traveling wave parametric amplifier, Phys. Rev. D **108**, 062005 (2023).
[54] A. Rettaroli, D. Alesini, D. Babusci, C. Braggio, G. Carugno, D. D'Agostino, A. D'Elia, D. Di Gioacchino, R. Di Vora, P. Falferi, U. Gambardella, A. Gardikiotis, C. Gatti, C. Ligi, A. Lombardi, G. Maccarrone, A. Ortolan, G. Ruoso, S. Tocci, and G. Vidali (QUAX Collaboration), Search for axion dark matter with the QUAX–LNF tunable haloscope, Phys. Rev. D **110**, 022008 (2024).
[55] C. Braggio, L. Balembois, R. Di Vora, Z. Wang, J. Travesedo, L. Pallegoix, G. Carugno, A. Ortolan, G. Ruoso, U. Gambardella, D. D'Agostino, P. Bertet, and E. Flurin, Quantum-enhanced sensing of axion dark matter with a transmon-based single microwave photon counter, Phys. Rev. X **15**, 021031 (2025).
[56] G. Sardo Infirri *et al.* (QUAX Collaboration), Search for postinflationary QCD axions with a quantum-limited tunable microwave receiver, Phys. Rev. Lett. **135**, 211002 (2025).
[57] A. Álvarez Melcón *et al.*, First results of the CAST-RADES haloscope search for axions at 34.67 μeV, J. High Energy Phys. 10 (2021) 75.
[58] S. Ahyoune *et al.*, RADES axion search results with a High-Temperature Superconducting cavity in an 11.7 T magnet, J. High Energy Phys. 04 (2025) 113.
[59] W. U. Wuensch, S. De Panfilis-Wuensch, Y. K. Semertzidis, J. T. Rogers, A. C. Melissinos, H. J. Halama, B. E. Moskowitz, A. G. Prodell, W. B. Fowler, and F. A. Nezrick, Results of a laboratory search for cosmic axions and other weakly coupled light particles, Phys. Rev. D **40**, 3153 (1989).
[60] C. Hagmann, P. Sikivie, N. S. Sullivan, and D. B. Tanner, Results from a search for cosmic axions, Phys. Rev. D **42**, 1297 (1990).
[61] H. Chang, J.-Y. Chang, Y.-C. Chang, Y.-H. Chang, Y.-H. Chang, C.-H. Chen, C.-F. Chen, K.-Y. Chen, Y.-F. Chen, W.-Y. Chiang, W.-C. Chien, H. T. Doan, W.-C. Hung, W. Kuo, S.-B. Lai, H.-W. Liu, M.-W. OuYang, P.-I. Wu, and S.-S. Yu (TASEH Collaboration), First results from the Taiwan axion search experiment with a haloscope at 19.6 μeV, Phys. Rev. Lett. **129**, 111802 (2022).
[62] C. O'Hare, cajohare/AxionLimits: AxionLimits, https://cajohare.github.io/AxionLimits/ (2020).
[63] G. Rybka (private communication).