

Probing Kim-Shifman-Vainshtein-Zakharov Axion Dark Matter near 5.9 GHz Using an 8-Cell Cavity Haloscope

Saebyeok Ahn^{1,2,*}, Çağlar Kutlu^{2,3,*†}, Soohyung Lee^{2,4,*}, SungWoo Youn^{1,2,‡}, Sergey V. Uchaikin^{1,2},
Sungjae Bae^{1,2,3}, Junu Jeong^{2,5}, Arjan F. van Loon^{6,7}, Yasunobu Nakamura^{6,7},
Seongjeong Oh^{1,2}, Jihn E. Kim⁸ and Yannis K. Semertzidis^{2,3}

¹Dark Matter Axion Group, *Institute for Basic Science*, Daejeon 34126, Republic of Korea

²Center for Axion and Precision Physics Research, *Institute for Basic Science (IBS)*, Daejeon 34051, Republic of Korea

³Department of Physics, *Korea Advanced Institute of Science and Technology (KAIST)*, Daejeon 34141, Republic of Korea

⁴Center for Accelerator Research, *Korea University*, Sejong 30019, Republic of Korea

⁵Oskar Klein Centre, Department of Physics, *Stockholm University*, AlbaNova, SE-10691 Stockholm, Sweden

⁶RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351-0198, Japan

⁷Department of Applied Physics, Graduate School of Engineering, *The University of Tokyo*, Bunkyo-ku, Tokyo 113-8656, Japan

⁸Department of Physics, *Seoul National University*, Seoul 08826, Republic of Korea



(Received 8 July 2025; revised 11 October 2025; accepted 21 October 2025; published 17 November 2025)

We report on a search for axion dark matter in the frequency range near 5.9 GHz, conducted using the haloscope technique. The experiment employed an 8-cell microwave resonator designed to extend the accessible frequency range by a multifold factor relative to conventional single-cell configurations, while maintaining a large detection volume. To enhance sensitivity, a flux-driven Josephson parametric amplifier operating near the quantum noise limit was utilized, together with a sideband-summing method that coherently combines mirrored spectral components generated by the Josephson parametric amplifier. Data were acquired over the frequency range 5.83–5.94 GHz. With no statistically significant excess observed, we exclude axion-photon couplings $g_{a\gamma\gamma}$ down to $1.2 \times 10^{-14} \text{ GeV}^{-1}$ at a 90% confidence level. The achieved sensitivity approaches the Kim-Shifman-Vainshtein-Zakharov benchmark prediction, setting the most stringent limits to date in this range.

DOI: 10.1103/fztl-2dyr

A well-motivated solution to the strong CP problem in the standard model of particle physics [1–6] is the so-called Peccei-Quinn mechanism [7]. It introduces a new global $U(1)$ symmetry, which is spontaneously broken and dynamically relaxes the CP -violating term in the quantum chromodynamics Lagrangian. The spontaneous symmetry breaking gives rise to a pseudo-Nambu-Goldstone boson known as the axion [8,9]. The axion is also a leading candidate for cold dark matter, which constitutes approximately 85% of the matter content of the present Universe [10], yet remains unidentified.

The haloscope is one of the most promising experimental strategies to detect the axion in our galactic halo [11]. It

relies on the axion's electromagnetic interaction, enabling axion-to-photon conversion in the presence of a static magnetic field. Microwave cavities are often employed to resonantly enhance the photon signal. The axion-photon coupling is given by $g_{a\gamma\gamma} = (\alpha g_\gamma / \pi f_a)$, where α is the fine structure constant, f_a is the axion decay constant, and g_γ is a model-dependent dimensionless coefficient. In the most popular models, Kim-Shifman-Vainshtein-Zakharov (KSVZ) [12,13] and Dine-Fischler-Srednicki-Zhitnitskii [14,15], g_γ takes values of -0.97 and 0.36 , respectively.

The axion-induced photon signal power, maximized when the axion frequency ν_a (corresponding to mass $m_a = 2\pi\nu_a$) matches the resonant frequency ν_c of the cavity, can be expressed as

$$P_{a\gamma\gamma} = 14.2 \text{ yW} \left(\frac{g_\gamma}{0.97} \right)^2 \left(\frac{\rho_a}{0.45 \text{ GeV}} \right) \left(\frac{\nu_a}{5.9 \text{ GHz}} \right) \times \left(\frac{B_{\text{rms}}}{6.97 \text{ T}} \right)^2 \left(\frac{V}{3.1 \text{ L}} \right) \left(\frac{C}{0.6} \right) \left(\frac{Q_L}{15000} \right) \left(\frac{\beta}{1 + \beta} \right), \quad (1)$$

where ρ_a is the local axion dark matter density, B_{rms} is the root-mean-square magnetic field inside the cavity

*These authors contributed equally to this work.

†Present address: Zurich Instruments, Technoparkstrasse 1, 8005 Zürich, Switzerland.

‡Contact author: swyoun@ibs.re.kr

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](#). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

volume V , C , and Q_L are the form factor and loaded quality factor of the cavity mode considered for the experiment, respectively, and β is the antenna coupling coefficient.

For cylindrical resonators, the lowest fundamental transverse magnetic (TM) mode, TM_{010} , is typically chosen due to its maximal form factor under a uniform solenoidal magnetic field, thereby optimizing sensitivity to axion-induced signals. However, the cavity dimensions are generally fit to the magnet bore to maximize the detection volume, which in practice limits conventional haloscope designs to relatively low-frequency and thus low-mass axion searches. To overcome this limitation, we implement a novel multicell cavity architecture that enables operation at higher resonant frequencies while maintaining a large detection volume [16,17]. In this Letter, we report on a haloscope search for KSVZ axion dark matter near 5.9 GHz (corresponding to a mass of 24.4 μeV), employing an 8-cell microwave cavity for high-frequency access and a flux-driven Josephson parametric amplifier (JPA) for quantum-limited signal readout.

The experimental setup featured (1) a superconducting magnet with a 165-mm bore, capable of generating a maximum field of 8 T at the center of the magnet, and (2) a dilution refrigerator that provides the required cryogenic environment—4 K for the magnet and below 40 mK for the detector components, including the resonant cavity and the JPA. The resonant cavity, symmetrically positioned within the magnet bore, served as the detection volume for axion conversion. Signal amplification was initiated by the JPA and followed by two high-electron-mobility transistor (HEMT) amplifiers. The amplified signal was then routed through a chain of room-temperature electronics, including an additional HEMT amplifier and a digitizer with a built-in down-converter, before being recorded. To enable real-time monitoring of the signal chain, an auxiliary spectrum analyzer was incorporated. A vector network analyzer (VNA) was also employed for system calibration and diagnostics through multiple signal paths. The overall experimental setup is shown in Fig. 1.

The resonant cavity used in this experiment consisted of eight identical cells separated by metal partitions within a cylindrical structure of 128 mm inner diameter, optimized to fully utilize the available volume inside the magnet bore. This 8-cell configuration supports the TM_{010} resonant mode at approximately 6.0 GHz, increasing the search frequency to more than 3 times that of a conventional single-cell cavity, without incurring significant volume loss. An additional key design feature is the strong intercell coupling via a central gap, which enables coherent signal extraction through a single antenna located at the cavity center. The cavity has an inner height of 270 mm, yielding a total detection volume of 3.1 L, over which the rms magnetic field is estimated to be 6.97 T. The cavity was fabricated from oxygen-free high thermal conductivity

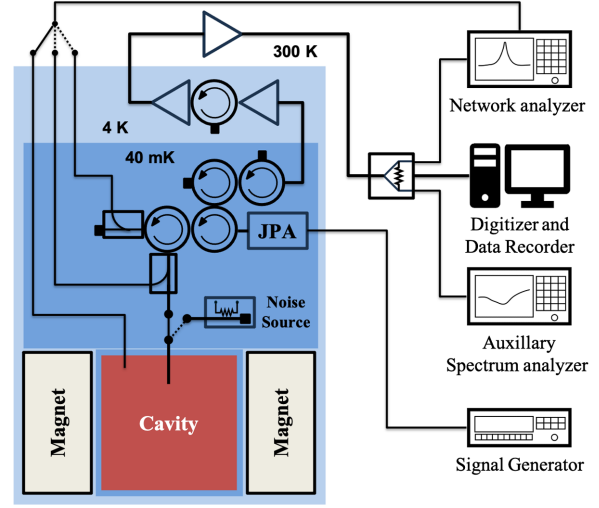


FIG. 1. Schematic diagram of the experimental setup.

copper, and its unloaded quality factor was measured to be approximately 45 000 at cryogenic temperatures.

Frequency tuning was achieved using 3-mm-thick alumina (Al_2O_3) rods, one placed in each cell. These rods were configured to rotate azimuthally and synchronously about the cavity center, driven by a single piezoelectric actuator mounted at the top, as illustrated in Fig. 2. Finite element method simulations [18] showed that the form factor increases from 0.5 to 0.7 with frequency. In practice, fabrication tolerances and mechanical misalignments can induce asymmetries in the electromagnetic field distribution within the cavity, leading to deviations from the ideal form factor. To quantify this effect, we measured the electric field strength in each cell and estimated a form factor degradation of up to 5%, depending on the position of the tuning rods. This degradation was mitigated to below 1% by optimizing the tuning rod diameters, as described in

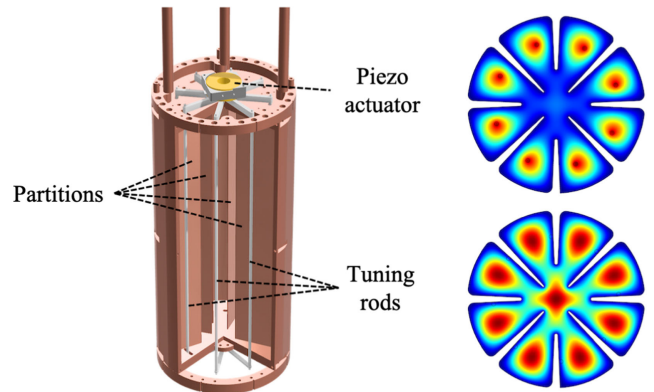


FIG. 2. Left: cutaway view of the 8-cell cavity design. Right: simulated TM_{010} electric field distributions with the tuning rod positioned near the center (top) and near the edge (bottom) of each cell, corresponding to low and high frequencies, respectively.

Ref. [19]. The field distribution, measured at room temperature, was assumed to remain nearly unchanged at cryogenic temperatures, as supported by simulations incorporating the thermal contraction of copper ($\sim 0.3\%$) and alumina ($\sim 0.1\%$), which showed deviations of less than 1%.

For quantum-noise-limited amplification, we employed a flux-driven JPA, whose fundamental design and operational principles are detailed in Refs. [20,21]. The device consists of a $\lambda/4$ coplanar waveguide resonator terminated by a superconducting quantum interference device (SQUID), which serves as a nonlinear inductor. To operate the JPA as a linear amplifier in the three-wave mixing regime, an external magnetic flux is applied to modulate the SQUID in conjunction with a microwave pump tone at frequency f_p and power P_p . Upon application of an input signal at frequency f_s (the signal mode), the JPA generates an intermodulation tone at $f_i = f_p - f_s$, referred to as the idler mode. This nonlinear mixing process enables phase-preserving amplification of the input signal. The resonance frequency of the JPA can be tuned by varying the magnetic flux applied to the SQUID, delivered via a superconducting coil located beneath the device. To protect the JPA from residual magnetic fields of up to 100 mT originating from the main magnet, we employed a three-layer magnetic shield composed of aluminum, μ metal, and niobium. The JPA was thermally anchored to the base-temperature stage and integrated into the signal path via a circulator, as shown in Fig. 1.

For optimal operation targeting a gain of 20 dB, chosen to maximize signal amplification near the quantum noise limit while maintaining linearity and low distortion, we constructed a look-up table of optimal pump parameters following the measurement protocol described in Ref. [22]. At each cavity tuning step, we coarsely tuned the JPA according to the look-up table entry to the cavity frequency. This was followed by a fine-tuning procedure, adjusting P_p in increments of 0.01 dB until the gain settled within an acceptance threshold of 0.5 dB, all completed within 3 s. The JPA gain was measured *in situ* using the VNA by comparing the transmission spectra obtained with the JPA turned on and off.

The system noise is commonly characterized by the equivalent noise temperature T_{sys} , which can be decomposed as $T_{\text{sys}} = T_{\text{cav}} + T_{\text{rcv}}$, where T_{cav} and T_{rcv} represent the thermal noise from the cavity and the added noise from the receiver chain, respectively. The noise temperature estimation was based on a comparative analysis of the power spectral density measured with the JPA turned on and off. Following the Johnson-Nyquist formula [23,24], the power spectral densities are given by $P_{\text{on}} = k_B G_{\text{on}} T_{\text{sys}} \Delta\nu = k_B G_{\text{on}} (T_{\text{cav}} + T_{\text{on}}) \Delta\nu$ and $P_{\text{off}} = k_B G_{\text{off}} (T_{\text{cav}} + T_{\text{off}}) \Delta\nu$, where G denotes the system gain and $\Delta\nu$ is the measurement bandwidth. T_{cav} was obtained directly from the physical temperature of the cavity during the experiment, while T_{off} was measured separately over a

wide range at the initial stage of the experiment using the Y-factor method with the designated noise source, as illustrated in Fig. 1. Using $G^{\text{JPA}} = G_{\text{on}}/G_{\text{off}}$, we obtain the system noise temperature as

$$T_{\text{sys}} = \frac{1}{G^{\text{JPA}}} \frac{P_{\text{on}}}{P_{\text{off}}} (T_{\text{cav}} + T_{\text{off}}). \quad (2)$$

This approach requires the stability of both G^{JPA} and T_{off} throughout the experiment. To ensure this, we continuously monitored these parameters over 24 h, well exceeding the data acquisition (DAQ) time at a given search frequency, and found the statistical uncertainties in G^{JPA} and T_{off} to be below 1% and approximately 2%, respectively. Aggregating data from all tuning steps, the system noise temperature was found to range between 380 and 500 mK, with step-to-step variations within 10 mK.

DAQ was carried out from December 28, 2021, to July 19, 2022, with a total downtime of approximately two months due to system warm-ups for maintenance. The frequency range from 5.83 to 5.94 GHz was scanned with an average tuning step of 17.4 kHz. Each step began with an initial calibration, involving adjustment of the antenna coupling—determined by fitting to the Smith circle using the VNA, typically yielding a value of 2—and characterization of cavity parameters such as ν_c and Q_L . The JPA was then tuned to the cavity frequency following the aforementioned procedure. Subsequently, the system noise temperature was estimated using Eq. (2). Upon completion of these calibrations, DAQ was conducted. The signal from the cavity was first amplified by the JPA and a pair of HEMTs within the cryogenic system. The signal was further amplified at room temperature and down-converted to an intermediate frequency of 10.7 MHz. The intermediate frequency time-series signal was digitized and processed via a discrete Fourier transform to produce power spectra with a resolution bandwidth of 62.5 Hz over a 1-MHz span. For each frequency step, a total of 85 200 and 88 000 spectra were collected for the lower and upper halves of the scan range, respectively, which were split due to mixing with a transverse magnetic (TM) mode, and then averaged into five grouped spectra. The total DAQ efficiency, accounting for time spent on calibrations and characterization, was estimated to be 92%.

Data analysis proceeded in four stages: preprocessing, sideband summing, spectrum combination, and hypothesis testing. In the preprocessing stage, each averaged raw power spectrum was cleaned by excluding a 25 kHz bandwidth centered at $f_p/2$, 4 times the expected axion bandwidth ($Q_a \sim 10^6$), covering 99.9% of the potential signal power, to eliminate the interference from the pump tone and simplify the analysis. The baseline of the remaining spectrum was estimated using a Savitzky–Golay (SG) filter [25] with a polynomial degree of 4 and a window size of 1921 (corresponding to 120 kHz),

sufficiently larger than the axion signal bandwidth but smaller than the cavity half-bandwidth. Each spectrum was then normalized by this baseline and shifted by unity to yield the relative power excess in each frequency bin, denoted by δ . The distribution of δ was consistent with the standard normal distribution, validating the baseline removal procedure and confirming statistical independence among frequency bins.

A distinctive feature of our analysis is the incorporation of idler modes generated by the JPA as supplementary spectral information to enhance sensitivity. For each preprocessed spectrum, the analysis band was centered at $f_p/2$, approximately aligned with the cavity resonance frequency. A potential axion signal and its JPA-generated idler counterpart appear at frequency bins symmetrically distributed around $f_p/2$, as illustrated in Fig. 3. We implemented a sideband-summing technique that optimally combines these power excesses with the JPA-induced correlation accounted for. The sideband-summed excess is defined as

$$\delta_{ss,k} = \frac{w_k \delta_k + w_{-k} \delta_{-k}}{\sqrt{w_k^2 + w_{-k}^2 + 2\rho w_k w_{-k}}}, \quad (3)$$

where δ_k and δ_{-k} are the power excesses in the signal and its idler bins, respectively, with optimized weighting factors w_k and w_{-k} that account for differences in the expected signal-to-noise ratio (SNR) between the two. ρ quantifies the measured correlation between them. The covariance of the correlated power excesses was estimated from all individual spectra and used to determine the correlation coefficient. A detailed discussion of the sideband-summing technique can be found in Appendix C of [27]. Applying this combination across all frequency steps yielded a

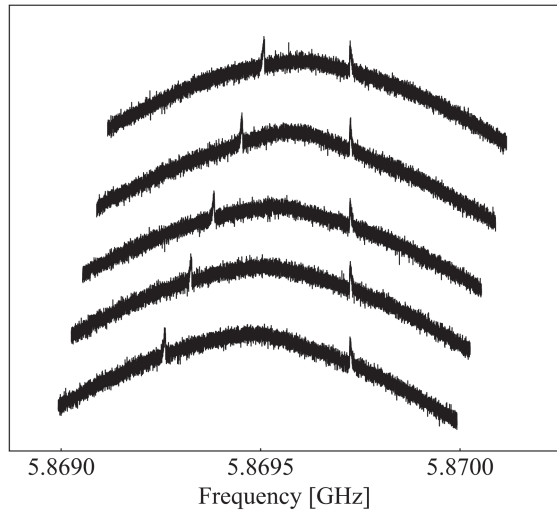


FIG. 3. Power spectra with a synthetic axion signal injected at 5.869 72 GHz over multiple tuning steps. The idle signals appear symmetrically with respect to the JPA center at $f_p/2$.

consistent SNR improvement of about 4% compared to conventional analysis methods.

To proceed with data combination, we first aligned the sideband-summed excess in the radio-frequency domain, then combined the data in each frequency bin using weighting factors proportional to the expected SNR of hypothetical KSVZ axion signals. From the combined spectrum, we constructed the grand spectrum by performing a weighted sum over 25 kHz windows at each frequency bin. The weights were determined by the expected signal line shape in the laboratory frame, assuming the standard halo axion model [26], with an rms halo velocity of 270 km/s and a solar-system velocity of 230 km/s relative to the Galactic frame. We observed several strong negative excesses deviating from the expected Gaussian distribution, particularly in the 5.87–5.88 GHz range, similar observations reported in [27,28]. Although the origin of these features remains unknown, a follow-up supplementary scan with twice the statistics showed no such excesses. Accordingly, we excluded the anomalous bins from the original preprocessed spectra and substituted them with data from the supplementary scan.

The resulting grand spectrum exhibited a standard deviation slightly below unity, a typical consequence of bin-to-bin correlations induced by the SG filter. The observed width of 0.85 agreed with the analytical prediction described in [29]. For convenience of statistical interpretation, the grand spectrum was normalized to a standard normal distribution using its observed mean and standard deviation. To estimate signal degradation caused by the SG filter, software-synthesized axion signals of various masses were injected into the data. The signal-injected data were then analyzed using the same procedure described above. A comparison between the injected and recovered SNRs yielded an average SNR efficiency of $\epsilon_{\text{SNR}} = 84.7\%$, with minor variations of $\pm 3.9\%$ across the frequency range. Various sources of uncertainty considered for the analysis are summarized in Table I.

For hypothesis testing, we adopted a null hypothesis that assumes the presence of a KSVZ axion signal with $\text{SNR} = 5$. Defining a detection threshold at 3.47 for 90% confidence level (CL), we identified 85 candidate

TABLE I. Uncertainties quoted in the analysis, expressed as percentages relative to the central values of the corresponding parameters.

Parameter	Uncertainty [%]	Source
ϵ_{SNR}	3.9	Frequency-dependent variation
β	3.2	Fitting uncertainty
T_{sys}	1.5	Statistical error in G^{JPA} and T_{off}
Q_L	< 1.0	Statistical fluctuation
C	< 1.0	Thermal contraction effects

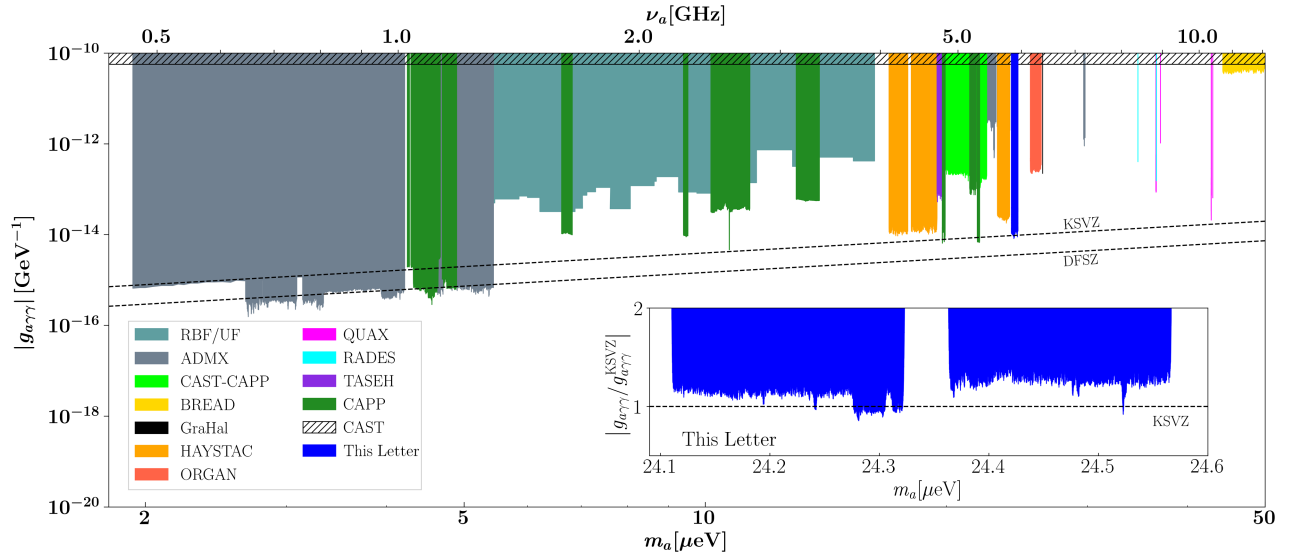


FIG. 4. Exclusion limit on the axion-photon coupling, $g_{a\gamma\gamma}$, as a function of axion mass, m_a , set by this Letter at the 90% CL, assuming $\rho_a = 0.45 \text{ GeV/cm}^2$. It includes limits from previously reported haloscopes [27,28,30–63] sourced from AxionLimits GitHub repository [64]. The black dashed line represents the KSVZ and the Dine-Fischler-Srednicki-Zhitnitskii benchmark models. The inset shows the limit set by this Letter, and the gap around $24.35 \mu\text{eV}$ is attributed to mixing with a transverse electric mode, as confirmed by simulations.

bins exceeding the threshold, typically appearing in small clusters. To evaluate the nature of these excesses, we performed follow-up scans at the corresponding frequencies with higher integration time. None of the candidates exhibited excess power consistent with a persistent signal, indicating they were statistical fluctuations or originated from other sources, such as momentary rf interference. In the absence of a confirmed signal, we set a 90% CL upper limit on the axion-photon coupling, reaching $g_{a\gamma\gamma} < 1.2 \times 10^{-14} \text{ GeV}^{-1}$ over the axion frequency (mass) range $5.82 < f_a < 5.93 \text{ GHz}$ ($24.11 < m_a < 24.57 \mu\text{eV}$). This corresponds to the most stringent limit to date in this mass range, achieving sensitivity near the KSVZ benchmark prediction. The resulting exclusion limit is presented in Fig. 4.

In conclusion, we report a search for axion dark matter using a novel 8-cell microwave cavity designed to increase frequency coverage while preserving detection volume, combined with a state-of-the-art flux-driven JPA operating near the quantum noise limit. A sideband-summing technique was employed to coherently combine symmetric spectral features from the JPA's signal and idler modes, resulting in a 4% improvement in SNR. Over a 100-MHz frequency range near 5.9 GHz ($24.4 \mu\text{eV}$), we exclude axion-photon couplings $g_{a\gamma\gamma} \gtrsim 1.2 \times 10^{-14} \text{ GeV}^{-1}$ at 90% confidence level, approaching the sensitivity of the KSVZ benchmark model. Future efforts will extend the search to adjacent axion frequencies with sustained sensitivity, utilizing alternative cavity and amplifier configurations.

Acknowledgments—This work was supported by the Institute for Basic Science (No. IBS-R017-D1 and

No. IBS-R040-C1) and JSPS KAKENHI (Grant No. JP22H04937). J.J. was partially supported by the Knut and Alice Wallenberg Foundation. A.F.v.L. was supported by a JSPS Postdoctoral Fellowship. J.E.K. was partially supported by the Korea Academy of Science.

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 (1978).
- [3] G. 't Hooft, 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. S. Altarev, Y. V. Borisov, A. B. Brandin, A. I. Egorov, V. F. Ezhov, S. N. Ivanov, V. M. Lobashov, V. A. Nazarenko, G. D. Porsev, V. L. Ryabov, A. P. Serebrov, and R. R. Taldaev, A search for the electric dipole moment of the neutron using ultracold neutrons, *Nucl. Phys. A* **341**, 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), Planck 2015 results XIII. Cosmological parameters, *Astron. Astrophys.* **594**, A13 (2016).
- [11] P. Sikivie, Experimental tests of the “Invisible” axion, *Phys. Rev. Lett.* **51**, 1415 (1983).
- [12] J. E. Kim, Weak-interaction singlet and strong CP invariance, *Phys. Rev. Lett.* **43**, 103 (1979).
- [13] M. A. Shifman, A. I. Vainshtein, and V. I. 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] J. Jeong, S. Youn, S. Ahn, J. E. Kim, and Y. K. Semertzidis, Concept of multiple-cell cavity for axion dark matter search, *Phys. Lett. B* **777**, 412 (2018).
- [17] 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).
- [18] COMSOL (1998), <https://www.comsol.com/comsol-multiphysics>.
- [19] J. Jeong, S. Youn, and J. E. Kim, Multiple-cell cavity design for high mass axion searches: An extended study, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1053**, 168327 (2023).
- [20] T. Yamamoto, K. Inomata, M. Watanabe, K. Matsuba, T. Miyazaki, W. D. Oliver, Y. Nakamura, and J. S. Tsai, Flux-driven Josephson parametric amplifier, *Appl. Phys. Lett.* **93**, 042510 (2008).
- [21] 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).
- [22] Ç. Kutlu, S. Ahn, S. V. Uchaikin, S. Lee, A. F. van Loo, Y. Nakamura, S. Oh, and Y. K. Semertzidis, Systematic approach for tuning flux-driven Josephson parametric amplifiers for stochastic small signals, *J. Phys. Soc. Jpn. Conf. Proc.* **38**, 011202 (2023).
- [23] J. B. Johnson, Thermal agitation of electricity in conductors, *Phys. Rev.* **32**, 97 (1928).
- [24] H. Nyquist, Thermal agitation of electric charge in conductors, *Phys. Rev.* **32**, 110 (1928).
- [25] A. Savitzky and M. J. E. Golay, Smoothing and differentiation of data by simplified least squares procedures, *Anal. Chem.* **36**, 1627 (1964).
- [26] M. S. Turner, Periodic signatures for the detection of cosmic axions, *Phys. Rev. D* **42**, 3572 (1990).
- [27] 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).
- [28] X. Bai *et al.* (HAYSTAC Collaboration), Dark matter axion search with Haystac phase II, *Phys. Rev. Lett.* **134**, 151006 (2025).
- [29] A. K. Yi, S. Ahn, B. R. Ko, and Y. K. Semertzidis, Analytical estimation of the signal to noise ratio efficiency in axion dark matter searches using a savitzky-golay filter, *J. High Energy Phys.* **11** (2023) 115.
- [30] 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).
- [31] N. Du *et al.* (ADMX Collaboration), Search for invisible axion dark matter with the axion dark matter experiment, *Phys. Rev. Lett.* **120**, 151301 (2018).
- [32] T. Braine *et al.* (ADMX Collaboration), Extended search for the invisible axion with the axion dark matter experiment, *Phys. Rev. Lett.* **124**, 101303 (2020).
- [33] 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).
- [34] C. Goodman *et al.*, ASMX axion dark matter bounds around 3.3 μeV with Dine-Fischler-Srednicki-Zhitnitsky discovery ability, *Phys. Rev. Lett.* **134**, 111002 (2025).
- [35] G. Carosi *et al.* (ADMX Collaboration), Search for axion dark matter from 1.1 to 1.3 GHz with ADMX, [arXiv:2504.07279](https://arxiv.org/abs/2504.07279).
- [36] C. Boutan *et al.* (ADMX Collaboration), Piezoelectrically tuned multimode cavity search for axion dark matter, *Phys. Rev. Lett.* **121**, 261302 (2018).
- [37] C. Bartram *et al.*, Dark matter axion search using a Josephson traveling wave parametric amplifier, *Rev. Sci. Instrum.* **94**, 044703 (2023).
- [38] 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).
- [39] 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).
- [40] O. Kwon *et al.*, First results from an axion haloscope at CAPP around 10.7 μeV , *Phys. Rev. Lett.* **126**, 191802 (2021).
- [41] 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).
- [42] 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).
- [43] 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).
- [44] 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).
- [45] 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).
- [46] 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).
- [47] C. M. Adair *et al.*, Search for dark matter axions with CAST-CAPP, *Nat. Commun.* **13**, 6180 (2022).
- [48] G. Hoshino, S. Knirck, M. H. Awida, G. I. Canelo, S. Corrodi, M. Di Federico, B. Knepper, A. Lapuente, M. Littmann, D. W. Miller, D. V. Mitchell, D. Rodriguez, M. K. Ruschman, C. P. Salemi, M. A. Sawtell, L. Stefanazzi, A. Sonnenschein, G. W. Teafoe, and P. Winter (GigaBREAD Collaboration), First axionlike particle results from a broadband search for wavelike dark matter in the 44 to 52 μeV range with a coaxial dish antenna, *Phys. Rev. Lett.* **134**, 171002 (2025).
- [49] T. Grenet, R. Ballou, Q. Basto, K. Martineau, P. Perrier, P. Pognat, J. Quevillon, N. Roch, and C. Smith, The Grenoble Axion Haloscope platform (GrAHal): Development plan and first results, [arXiv:2110.14406](https://arxiv.org/abs/2110.14406).
- [50] B. M. Brubaker *et al.*, First results from a microwave cavity axion search at 24 μeV , *Phys. Rev. Lett.* **118**, 061302 (2017).
- [51] K. M. Backes *et al.*, A quantum enhanced search for dark matter axions, *Nature (London)* **590**, 238 (2021).
- [52] 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).
- [53] 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).
- [54] D. Alesini *et al.*, Galactic axions search with a superconducting resonant cavity, *Phys. Rev. D* **99**, 101101 (2019).
- [55] D. Alesini *et al.*, Search for invisible axion dark matter of mass $m_a = 43 \mu\text{eV}$ with the QUAX- $\alpha\gamma$ experiment, *Phys. Rev. D* **103**, 102004 (2021).
- [56] D. Alesini *et al.*, Search for galactic axions with a high- q dielectric cavity, *Phys. Rev. D* **106**, 052007 (2022).
- [57] R. Di Vora *et al.* (QUAX Collaboration), Search for galactic axions with a traveling wave parametric amplifier, *Phys. Rev. D* **108**, 062005 (2023).
- [58] A. Rettaroli *et al.* (QUAX Collaboration), Search for axion dark matter with the QUAX-Inf tunable haloscope, *Phys. Rev. D* **110**, 022008 (2024).
- [59] 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) 075.
- [60] 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.
- [61] 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).
- [62] C. Hagmann, P. Sikivie, N. S. Sullivan, and D. B. Tanner, Results from a search for cosmic axions, *Phys. Rev. D* **42**, 1297(R) (1990).
- [63] H. Chang *et al.* (TASEH Collaboration), First results from the taiwan axion search experiment with a haloscope at 19.6 μeV , *Phys. Rev. Lett.* **129**, 111802 (2022).
- [64] C. O'Hare, cajohare/axionlimits: Axionlimits, <https://cajohare.github.io/AxionLimits/> (2020).