Deepest Sensitivity to Wavelike Dark Photon Dark Matter with SRF Cavities

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Wavelike, bosonic dark matter candidates like axion and dark photons can be detected using microwave cavities commonly referred to as haloscopes. Traditionally, haloscopes consist of tunable copper cavities operating in the TM010 mode, but the performance of these cavities has been limited by ohmic losses. In contrast, superconducting radio frequency (SRF) cavities can achieve quality factors of \( \sim 10^{10} \), perhaps five orders of magnitude better than copper cavities, which would lead to more sensitive dark matter detectors. In this paper, we first derive that the scan rate of a haloscope experiment is proportional to the loaded quality factor \( Q_L \), even if the cavity bandwidth is much narrower than the dark matter halo lineshape. We then present a proof-of-concept search for dark photon dark matter using a non-tunable ultra-high quality SRF cavity. We exclude dark photon dark matter with kinetic mixing strengths of \( \chi > 2 \times 10^{-16} \) for a dark photon mass of \( m_{A'} = 5.37 \text{ meV} \), achieving the deepest exclusion to wavelike dark photons by almost an order of magnitude.

I. INTRODUCTION

There is overwhelming evidence that 84.4% of the matter in the universe is made out of dark matter (DM) \([1-7]\). The \( \Lambda \)CDM model describes dark matter as feebly interacting, non-relativistic, and stable on cosmological timescales. Not much else is known about the nature of dark matter, particularly what particles beyond the standard model it is made of.

The dark photon (DP) is a compelling dark matter candidate. It is a spin-1 gauge boson associated with a new Abelian U(1) symmetry. It is one of the simplest possible extensions to the Standard Model (SM) \([8,9]\). The dark photon, having the same quantum numbers as the SM photon, generically interacts with the SM photon through kinetic mixing \([11,12]\) described by the Lagrangian

\[
\mathcal{L} = -\frac{1}{4} (F_{\mu
u}F^{\mu\nu} + F_{2\mu\nu}F_{2\mu\nu} - 2\chi F_{1 \mu\nu}F_{2\mu\nu} - 2m_{A'}^2 A'^2),
\]

where \( F_{\mu
u} \) is the electromagnetic field tensor, \( F_{2\mu\nu} \) is the dark photon field tensor, \( \chi \) is the kinetic mixing strength, \( m_{A'} \) is the DP mass, and \( A' \) is the DP gauge field. If both \( m_{A'} \) and \( \chi \) are sufficiently small, then it is stable on cosmological timescales, with three photons or neutrinos being the only available decay channels \([13]\). The dark photon is then an attractive dark matter candidate. If its mass is less than an eV, the DPDM is in the wavelike regime, where it is best described as a coherent wave oscillating at the frequency of its rest mass rather than a collection of particles. The dark matter kinetic energy distribution sets the degree of coherence of wavelike dark matter to be of order \( v_{DM}^2 \sim 10^{-6} \) \([14,15]\).

Several mechanisms could produce a relic of cosmic dark photons. One simple example is the displacement of the DP field through quantum fluctuations during inflation \([16]\). These fluctuations in the DP field serve as the initial displacement for dark photon field oscillations which commence once the Universe’s expansion rate falls below the DP mass. Other mechanisms are possible and are described in \([10,17]\).

Dark photon dark matter (DPDM) can be detected through their mixing with the SM photon. If dark photons oscillate into SM photons inside a microwave cavity with a large quality factor, then a feeble EM signal accumulates inside the cavity, which can be read by ultra-low noise electronics. This type of detector is called a haloscope and is often deployed to search for axionic DM \([18]\). The SM photon frequency \( f \) is related to the dark photon energy \( E_{A'} \) by the relationship \( f = E_{A'} \) (using natural units).

The dark photon signal power is \([9,19-21]\), in natural units,

\[
P_S = P_0 \frac{\beta}{\beta + 1} L(f, f_0, Q_L)
\]

\[
P_0 = \begin{cases} 
\eta \chi^2 m_{A'} \rho_{A'} V_{eff} Q_L, & \text{if } Q_L << Q_{DM} \\
\eta \chi^2 m_{A'} \rho_{A'} V_{eff} Q_{DM}, & \text{if } Q_L >> Q_{DM}
\end{cases}
\]

\[
V_{eff} = \left( \frac{\int dV E(\vec{x}) \cdot A'(\vec{x})}{\int dV \epsilon_r |E(\vec{x})|^2 |A'(\vec{x})|^2} \right)^2
\]

where \( \eta \) is a signal attenuation factor, \( \rho_{A'} \) is the local density of dark matter, \( V_{eff} \) is the effective volume of the cavity, \( Q_L \) is the cavity’s loaded quality factor, \( Q_{DM} \) is the dark matter “quality factor” related to the dark matter coherence time, and \( \beta \) is the cavity coupling coefficient. The Lorentzian term is \( L(f, f_0, Q_L) = 1/(1 + 4\Delta^2) \), where \( \Delta \equiv Q_L(f - f_0)/f_0 \) is a detuning factor that depends on the SM photon frequency \( f \), cavity resonant
frequency \( f_0 \) and \( Q_L \). \( V_{eff} \) is the overlap between the dark photon field \( A'(\vec{x}) \) and the dark photon-induced electric field \( E(\vec{x}) \). Equations 2, 3, and 4 assume that the cavity size is much smaller than the DP de Broglie wavelength.

The dark photon mass is unknown, so haloscopes must be tunable to search through the \( \chi \) vs. \( m_{A'} \) parameter space. The scan rate for haloscope experiments is a key figure of merit strongly dependent on the SNR. The SNR for a haloscope signal is \( \text{SNR} = \frac{P_s}{P_n} \sqrt{b \Delta t} \) \[22, 23\], where \( P_s \) is the noise power, \( b \) is the frequency bin width and \( \Delta t \) is the integration time. \( P_n \) is the combination of the cavity’s blackbody radiation and the receiver’s Johnson noise. The noise power can be expressed as \( P_n = G k_b T n \), where \( k_b \) is the Boltzmann constant, \( G \) is the system gain, and \( T n \) is the system noise temperature referenced to the cavity.

If \( Q_L \gg Q_{DM} \), the cavity width is smaller than the dark matter halo lineshape width \( \Delta f_{DM} \). The resulting dark matter signal will follow the Lorentzian cavity response with bandwidth \( \Delta f_c = f_0/Q_L \). Fortunately, a haloscope is sensitive to a distribution of possible dark photon rest masses corresponding to the cavity resonant frequency \( f_c \). In other words, a single cavity tuning step can probe the entire dark matter lineshape bandwidth, and the tuning steps need only to be comparable to \( \Delta f_{DM} \).

The frequency bin width \( b \) is typically chosen to be comparable to the dark matter signal bandwidth. Typical haloscope experiments use copper cavities with \( Q_L \ll Q_{DM} \), so \( b \sim \Delta f_{DM} = f_0/Q_{DM} \). However, if \( Q_L \gg Q_{DM} \), the signal bandwidth is the same as the cavity bandwidth and \( b \sim f_0/Q_L \). This means that the noise power is inversely proportional to the \( Q_L \), i.e., \( P_n \sim G k_b (f_0/Q_L) T n \). The higher \( Q_L \) is, the lower the noise power.

An estimate of the integration time can be obtained by rearranging the SNR equation \( \Delta t = \frac{1}{b} \frac{(\text{SNR} \times P_n / P_s)^2}{Q_L} \).

The tuning steps are \( \Delta f \sim f_0/Q_{DM} \). Putting all together, the scan rate for a dark photon haloscope consisting of an ultra-high Q microwave cavity, i.e., \( Q_L \gg Q_{DM} \), is

\[
\frac{df}{dt} = \Delta f \sim Q_L Q_{DM} \left( \frac{\eta \chi^2 m_{A'} \rho A' V_{eff} \beta}{2 \text{SNR} T n (\beta + 1)} \right)^2. \quad (5)
\]

The scan rate equation, Equation 5, happens to be the same whether \( Q_L \gg Q_{DM} \) or \( Q_L \ll Q_{DM} \) \[24\]. In both cases, the scan rate is directly proportional to \( Q_L \). It behooves the community to achieve the highest \( Q_L \) possible as it is perhaps the only parameter in Equation 5 that can increase by many orders of magnitude\[1\].

\[1 \] \( V_{eff} \) may also increase substantially using multi-wavelength haloscope designs \[22, 23\].

As a comparison, ADMX uses copper cavities with \( Q_L \approx 8 \times 10^4 \) \[22\], whereas niobium SRF cavities can achieve \( Q_L \approx 10^9 - 10^{11} \) depending on the temperature and cavity treatment \[33\]. This suggests that SRF cavities can increase the instantaneous scan rate of haloscope experiments by as much as a factor of \( 10^5 \).

II. DARK PHOTON DARK MATTER SEARCH WITH AN SRF CAVITY

The Superconducting Quantum Materials and Systems (SQMS) Center, hosted by Fermilab, performs a wide range of multidisciplinary experiments with SRF cavities. An experiment studying the material properties of an SRF cavity for temperatures below 1 K was underway when it was decided that a dark photon dark matter search should be performed with the same cavity. This proof-of-principle search using a \( Q_L \approx 8 \times 10^9 \), a HEMT amplifier, and the standard haloscope analysis is enough to demonstrate superior sensitivity to wavelike dark photons compared to previous searches.

A. Experimental Setup

The haloscope consists of a TESLA-shaped single-cell niobium cavity \[34\] with TM\(_{010}\) resonant frequency \( f_0 \approx 1.3 \text{ GHz} \). The cavity is made of fine-grain bulk niobium with a high residual resistivity ratio of \( \approx 300 \). The associated electric and magnetic field distribution is shown in Fig. 1. The cavity volume is 3875 mL, and the effective volume calculated from Equation 4 is \( V_{eff} = 669 \text{ mL} \), assuming a randomly polarized DP field. Electromagnetic coupling to the cavities is performed using axial pin couplers at both ends of the beam tubes.
FIG. 2. The microwave electronics for the dark photon dark matter search. Power from the cavity is amplified by a cryogenic HEMT amplifier and a room temperature amplifier before reaching the spectrum analyzer. A series of isolators prevent the cavity from being excited by the amplifier’s noise.

The cavity underwent heat treatments in a custom-designed oven to remove the niobium pentoxide (Nb$_2$O$_5$) and to mitigate the two-level system (TLS) dissipation $^{36, 57}$. The central cell 1.3 GHz cavity is heat treated at $\sim 450^\circ$C in vacuum for eight hours.

The cavity is cooled to $\approx 45$ mK using a BlueFors XLD 1000 dilution refrigerator. A double-layer magnetic shielding around the entire cryostat is used, and magnetometers placed directly on the outside cavity surfaces indicate that the DC ambient magnetic field level is shielded to below 2 mG.

A diagram of the microwave electronics is shown in Fig. 2. A series of attenuators on the cavity input line attenuates the room-temperature noise. The power from the cavity is first amplified by a cryogenic HEMT amplifier (LNF-LNC0.3,14A $^{28}$). At 1.3 GHz, the amplifier noise temperature is 4.9(5) K and the gain is about 36 dB. The uncertainty in the amplifier noise temperature comes from private correspondence with Low Noise Factory, and additional references include $^{39, 40}$.

Between the HEMT and SRF cavity, there is a series of three microwave isolators (QuinStar QCY-G0110151AS circulators with the third port terminated) and a low pass filter (Mini-Circuits VLFX-1350+). The isolators prevent the HEMT amplifiers from injecting noise into the cavity. According to the manufacturer datasheets, the combined insertion loss is at maximum 2.5 dB.

The signal is further amplified at room temperature using a Fairview FMAM1028 amplifier. The signal is then injected into the appropriate measurement device (spectrum analyzer, network analyzer, or phase noise analyzer).

B. Characterization of Cavity and Microphonics

The cavity’s resonant frequency is identified using a self-excitation loop shown in Fig. 3. The thermal noise from the output of the cavity is amplified, phase-shifted, and fed back into the input of the cavity. The phase shifting is performed with an ATM P2506. A power splitter feeds the cavity’s output power to the spectrum analyzer to monitor the response to the self-excitation loop.

The resulting power is shown in Fig. 4. The central peak corresponds to the resonant frequency. There are sidebands spaced 58 Hz apart from the central peak and a forest of smaller peaks. The power within the carrier peak and sidebands are confined within the cavity bandwidth. These sidebands are caused by the modulation of the resonant frequency due to microphonics, i.e., vibrations. These vibrations originate primarily from the dilution refrigerator’s pulse tubes. The sidebands are about 13.5 dB smaller than the carrier frequency. A separate measurement with the Rohde & Schwarz FSWP Phase Noise Analyzer shows that for the modulation frequency 58 Hz, the cavity peak frequency deviation from the resonant frequency is 40(10) Hz.

The microphonics were reduced substantially by turning off the pulse tubes. Fig. 4 shows that the sidebands are 31 dB smaller than the main carrier. Independent measurements with the phase noise analyzer show that for a modulation frequency 58 Hz, the cavity peak frequency deviation is $\approx 3.5$ Hz. Since less than 0.1% of the power is spread to the sidebands, microphonics is a negligible effect when the pulse tubes are off. The pulse tubes were turned off for the dark photon dark matter search, and the cavity temperature was stable for over 20 min before the pulse tubes were turned back on.

Turning off the pulse tubes to mitigate microphonics is not a viable strategy for an extended dark matter search scanning over a wide range of frequencies. It should be noted that these sidebands were not present in a previous operational run. This suggests that something in the mechanical structure loosened after the DR was thermally-cycled. Readjusting the mechanical structure and perhaps mechanically isolating the pulse tubes will likely mitigate the microphonics.

If microphonics cannot be mitigated, then the dark matter signal may be modeled as a frequency-modulated signal. This effect reduces the SNR of a dark matter signal because it spreads the dark matter signal over a larger bandwidth. But it is a quantifiable systematic that can be incorporated into the haloscope analysis.

The cavity’s loaded quality factor $Q_L$ is measured using a decay measurement $^{41}$. This decay measurement is implemented with a Keysight ENA Network Analyzer E5080B. At the resonant frequency, the network analyzer injects a 15 dBm signal with a bandwidth of 1 kHz into the input transmission line. Port 2 of the VNA measures...
The combination of these contributions leads to a signal attenuation factor of $\eta = 0.51$.

For modeling the system noise temperature, the cryogenic electronics in Fig. 2 can be approximated as a cavity connected to the first-stage amplifier by a transmission line. The system noise temperature is then

$$T_n = T_{cav} + T_{amp}$$

where $T_{cav}$ is the physical temperature of the cavity and $T_{amp}$ is the noise temperature of the cryogenic amplifier. Boson statistics need not be considered in the Raleigh-Jeans limit ($k_B T_{cav} >> \hbar\nu$). The three isolators and the low-pass filter are not included in the thermal model because they are at the same temperature as the cavity. The electronics beyond the cryogenic amplifier are also not included in the thermal model because their contribution is suppressed by the Friis cascade equation [45]. The amplifier noise temperature $T_{amp} = 4.9(5)$ K dominates the system noise temperature. The cavity temperature, measured to be $T_{cav} = 45(5)$ mK, is much less than the uncertainty in $T_{amp}$.

The detector sensitivity is estimated from the operating parameters shown in Table I. The equation for sensitivity in $\chi$ is

$$\chi = \sqrt{\frac{\beta + 1}{\beta} \cdot \frac{\text{SNR} \times b} {m_{A'} \rho_A \nu_{eff} Q_L} \left( \frac{1}{b\Delta t} \right)^{1/4}}.$$

Equation 7 is derived from rearranging the SNR equation. For this estimate, the bandwidth $b$ is chosen to be comparable to cavity bandwidth. The SNR is also chosen to be two as this approximates a 90\% exclusion limit. From the parameters in Table I, the sensitivity is estimated to be $\chi = 2.4 \times 10^{-16}$.

For the dark photon search, power from the cavity is measured using the Rohde & Schwarz FSW-26 Signal and Spectrum Analyzer. The cavity $Q_L \sim 8 \times 10^9$, so the frequency resolution needs to be $b \sim 100$ mHz. This sub-Hertz resolution is achieved using the spectrum analyzer’s I/Q-analyzer mode. For these measurements, a 312 Hz sample rate is used, and the sweep time of 10 s is used. The spectrum’s center frequency is set to the cavity’s...
FIG. 5. Raw spectrum as measured by the spectrum analyzer. Assuming the spectrum is just noise, the raw spectrum is the noise power of the system.

resonant frequency. The frequency bin size is 100 mHz. The resulting power spectrum is shown in Fig. 5.

Once the power spectrum is measured, the standard haloscope analysis is applied to either find a spectrally narrow power excess consistent with a dark photon signal or to exclude parameter space. The procedure for deriving the exclusion limits follows the procedure developed by ADMX and HAYSTAC [43, 44, 46], and is adapted for dark photon searches [9, 10, 19].

There are a few important deviations from the standard haloscope analysis for this search. First, only one spectrum was measured, so there is no need to combine many spectra at different RF frequencies. Second, past haloscope experiments with $Q_L << Q_{DM}$ typically convolved the spectra with the dark matter halo lineshape to account for the signal being spread across multiple bins. For this search, $Q_L >> Q_{DM}$, so the signal will be Lorentzian from the cavity response. So the spectrum is convolved with the cavity lineshape $L(f, f_0, Q_L) = 1/(1 + 4Q_L^2)$. Third, a single measurement is sensitive to a range of dark photon masses. Thus the excluded power on resonance is convolved with the dark matter halo lineshape. This convolution was also performed in other dark photon searches with $Q_L > Q_{DM}$ [17].

No spectrally narrow power excess with an SNR > 4 is found in the measured power spectrum. The excluded parameter space using a 90% confidence limit is shown in Fig. 6. The derived limit assumes dark photon dark matter is randomly polarized and that the dark photon energy distribution follows the standard halo model. The excluded kinetic mixing strength is $\chi_{90\%} = 2 \times 10^{-16}$ for a dark photon mass of $m_{A'} = 5.370 \mu$eV. This is consistent with the expected sensitivity estimated from Equation 17. This is also the deepest exclusion to wavelike dark photon dark matter by almost an order of magnitude.

FIG. 6. Top: A 90% exclusion on the kinetic mixing strength parameter space. Bottom: SQMS limits in the context of other microwave cavity haloscopes. Figure adapted from [48].

III. OUTLOOK AND THE POTENTIAL OF SRF CAVITIES FOR AXION DARK MATTER SEARCHES

The exclusion in Fig. 6 is an impressive demonstration of how SRF cavities can benefit dark matter searches. But an honest dark matter search with a finite probability of making a discovery requires that the haloscope tune through a wider range of frequencies. SQMS is currently developing experiments using tunable SRF cavities that will search through a wider range of parameter space.

In addition to dark photons, there is a growing interest in dark matter axions. Axions are particularly well motivated because they solve the strong CP problem [49]. Axion haloscope searches require multi-Tesla magnetic fields to be sensitive enough to the QCD axion. The scan rate for axion haloscope searches is still directly proportional to $Q_L$. Unfortunately, the performance of superconductors degrades under a multi-Tesla magnetic field. Achieving high quality factors is thus a very active area of research [55, 50, 52], and it seems likely that axion haloscopes with $Q_L > 10^6$ are achievable in the near future.

This experiment also demonstrates that axion haloscopes with $Q_L \sim 10^{10}$ are worth striving for. Applying a hypothetical 8T magnetic field to the dark photon data in Fig. 4 would have led to an exclusion on the axion-photon coupling constant at $g_{a\gamma\gamma} \sim 4 \times 10^{-16}$, well below DFSZ coupling ($g_{a\gamma\gamma} = 8 \times 10^{-16}$).
Despite decades of searching for the axion, only a small fraction of the QCD axion parameter space has been explored. Perhaps a combination of ultra-high Q cavities, sub-SQL metrology [47, 53], multi-wavelength detector designs [24–31], and innovations in multi-Tesla continuous magnets will enable experiments to probe most of the post-inflation QCD axion parameter space within the next few decades.

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[20] D. Kim, J. Jeong, S. Youn, Y. Kim, and Y. K. Smetzidis, Revisiting the detection rate for axion haloscopes, Journal of Cosmology and Astroparticle Physics 2020 (03), 066.

[21] P. Sikivie, Detection rates for “invisible”-axion searches, Phys. Rev. D 32, 2988 (1985).

[22] R. H. Dicke, The measurement of thermal radiation at microwave frequencies, Review of Scientific Instruments, 17, 268 (1946). https://doi.org/10.1063/1.1770483.

[23] H. Peng et al., Cryogenic cavity detector for a large scale cold dark-matter axion search, Nucl. Instrum. Meth. A 444, 569 (2000).

[24] R. Cervantes, G. Carosi, C. Hanretty, S. Kimes, B. H. LaRoque, G. Leum, P. Mohapatra, N. S. Oblath, R. Otten, Y. Park, G. Rybka, J. Sinnis, and J. Yang, Search for 70 µeV dark photon dark matter with a dielectrically-loaded multi-wavelength microwave cavity (2022), arXiv:2204.03818.

[25] P. Brun, A. Caldwell, L. Chevalier, G. Dvali, P. Freire, E. Garutti, S. Heyminck, J. Jochum, S. Knirck, M. Kramer, C. Krieger, T. Lasserre, C. Lee, X. Li, A. Lindner, B. Majorovits, S. Martens, M. Matysek, A. Millar, G. Raffelt, J. Redondo, O. Reimann, A. Ringwald, K. Saikawa, J. Schaffran, A. Schmidt, J. Schütte-Engel, F. Steffen, C. Straudhagen, G. Wieching, and M. A. D. M. A. X. Collaboration, A new experimental approach to probe qcd axion dark matter in the mass range above 40 µeV, The European Physical Journal C 79, 186 (2019).

[26] A. Caldwell, G. Dvali, B. Majorovits, A. Millar, G. Raffelt, J. Redondo, O. Reimann, F. Simon, and F. Steffen (MADMAX Working Group), Dielectric haloscopes: A new way to detect axion dark matter, Phys. Rev. Lett. 118, 091801 (2017).

[27] M. Baryakhtar, J. Huang, and R. Lasenby, Axion and hidden photon dark matter detection with multilayer optical haloscopes, Phys. Rev. D 98, 035006 (2018).

[28] J. Chiles, I. Charnev, R. Lasenby, M. Baryakhtar, J. Huang, A. Roshko, G. Burton, M. Colangelo, K. V. Tilburg, A. Arvanitaki, S. W. Nam, and K. K. Berggren, First constraints on dark photon dark matter with superconducting nanowire detectors in an optical haloscope (2021), arXiv:2110.01582 [hep-ex].

[29] B. T. McAllister, G. Flower, L. E. Tobar, and M. E. Tobar, Tunable supermode dielectric resonators for axion dark-matter haloscopes, Phys. Rev. Applied 9, 014028 (2018).

[30] A. P. Quiskamp, B. T. McAllister, G. Rybka, and M. E. Tobar, Dielectric-boosted sensitivity to cylindrical azimuthally varying transverse-magnetic resonant modes in an axion haloscope, Phys. Rev. Applied 14, 044051 (2020).

[31] M. Lawson, A. J. Millar, M. Pancaldi, E. Vitagliano, and P. Wilczek, Tunable axion plasma haloscopes, Phys. Rev. Lett. 123, 141802 (2019).

[32] C. Bartram, T. Braine, E. Burns, R. Cervantes, N. Crisosto, N. Du, G. Leum, L. J. Rosenberg, G. Rybka, J. Yang, J. Clarke, I. Siddiqi, A. Agrawal, A. V. Dixit, M. H. Awida, A. S. Chou, M. Hollister, S. Knirck, A. Sommescchein, W. Wester, J. R. Gleason, A. T. Hipp, S. Jois, P. Sikivie, N. S. Sullivan, D. B. Tanner, E. Lentz, R. Khatiwada, G. Carosi, N. Robertson, N. Woollett, L. D. Duffy, C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, M. S. Taubman, E. J. Daw, M. G. Perry, J. H. Buckley, C. Gaikwad, J. Hoffman, K. W. Murch, M. Goryachev, B. T. McAllister, A. Quiskamp, C. Thomson, and M. E. Tobar (ADMX Collaboration), Search for invisible axion dark matter in the 3.3 - 4.2 µeV mass range, Phys. Rev. Lett. 127, 261803 (2021).

[33] A. Romanenko, R. Pilipenko, S. Zorzetii, D. Frolov, M. Avida, S. Belomestnykh, S. Posen, and A. Gras- sellino, Three-dimensional superconducting resonators at t = 20 mK with photon lifetimes up to τ = 2 s, Phys. Rev. Applied 13, 034032 (2020).

[34] B. Aune et al., The superconducting TESLA cavities, Phys. Rev. ST Accel. Beams 3, 092001 (2000). arXiv:physics/0003011.

[35] S. Posen, M. Chechin, O. S. Melnychuk, T. Ring, and I. Gonin, Measurement of high quality factor superconducting cavities in tesla-scale magnetic fields for dark matter searches (2022).

[36] A. Romanenko and D. I. Schuster, Understanding quality factor degradation in superconducting niobium cavities at low microwave field amplitudes, Phys. Rev. Lett. 119, 264801 (2017).

[37] S. Posen, A. Romanenko, A. Grassellino, O. Melnychuk, and D. Sergatskov, Ultralow surface resistance via vacuum heat treatment of superconducting radio-frequency cavities, Phys. Rev. Applied 13, 014024 (2020).

[38] LNF-LNC0.3 = 2 s, Phys. Rev. ST Accel. Beams 3, 092001 (2000). arXiv:physics/0003011.

[39] J. Randa, E. Gerecht, D. Gu, and R. Billinger, Precision measurement method for cryogenic amplifier noise temperatures below 5 K, IEEE Transactions on Microwave Theory and Techniques 54, 1180 (2006).

[40] J. L. Cano, N. Wadefalk, and J. D. Gallego-Puyol, Ultrawideband chip attenuator for precise noise measurements at cryogenic temperatures, IEEE Transactions on Microwave Theory and Techniques 58, 2504 (2010).

[41] H. Padamsee, J. Knobloch, and T. Hays, RF Superconductivity for Accelerators, 2nd Edition (Wiley-VCH, 2008).

[42] O. Melnychuk, A. Grassellino, and A. Romanenko, Error analysis for intrinsic quality factor measurement in superconducting radio frequency resonators, Review of Scientific Instruments 85, 124705 (2014). https://doi.org/10.1063/1.4903868.

[43] B. M. Brubaker, L. Zhong, S. K. Lamoreaux, K. W. Lehnert, and K. A. van Bibber, Haystac axion search analysis procedure, Phys. Rev. D 96, 123008 (2017).

[44] C. Bartram, T. Braine, R. Cervantes, N. Crisosto, N. Du, G. Leum, L. J. Rosenberg, G. Rybka, J. Yang, D. Bowring, A. S. Chou, R. Khatiwada, A. Sonnenschein, W. Wester, G. Carosi, N. Woollett, L. D. Duffy, M. Goryachev, B. McAllister, M. E. Tobar, C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, M. S. Taubman, J. Clarke, A. Dove, A. Eddins, S. R. O’Kelley, S. Nawaz, I. Siddiqi, N. Stevenson, A. Agrawal, A. V. Dixit, J. R. Gleason, S. Jois, P. Sikivie, J. A. Solomon, N. S. Sullivan, D. B. Tanner, E. Lentz, E. J. Daw, M. G. Perry, J. H. Buckley, P. M. Harrington, E. A. Henriksen, and K. W. Murch (ADMX Collaboration), Axion dark matter experiment: Run 1b analysis details, Phys. Rev. D 103, 072001 (2021).
[45] K. Blattenberger, Cascaded noise figure & noise temperature (2021).

[46] S. Asztalos, E. Daw, H. Peng, L. J. Rosenberg, C. Hagemann, 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, Large-scale microwave cavity search for dark-matter axions, Phys. Rev. D 64, 092003 (2001).

[47] A. V. Dixit, S. Chakram, K. He, A. Agrawal, R. K. Naik, D. I. Schuster, and A. Chou, Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126, 141302 (2021).

[48] C. O’Hare, cajoahre/axionlimits: Axionlimits (2020).

[49] R. D. Peccei and H. R. Quinn, Cp conservation in the presence of pseudoparticles, Phys. Rev. Lett. 38, 1440 (1977).

[50] D. Alesini, C. Braggio, G. Carugno, N. Crescini, D. D’Agostino, D. Di Gioacchino, R. Di Vora, F. Falferi, U. Gambardella, C. Gatti, G. Iannone, C. Ligi, A. Lombardi, G. Maccarrone, A. Ortolan, R. Pengo, C. Pira, A. Rettaroli, G. Ruoso, L. Taffarello, and S. Tocci, Realization of a high quality factor resonator with hollow dielectric cylinders for axion searches, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 985, 164641 (2021).

[51] R. Di Vora, D. Alesini, C. Braggio, G. Carugno, N. Crescini, D. D’Agostino, D. Di Gioacchino, 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, High-q microwave dielectric resonator for axion dark-matter haloscopes, Phys. Rev. Applied 17, 054013 (2022).

[52] D. Ahn, O. Kwon, W. Chung, W. Jang, D. Lee, J. Lee, S. W. Youn, H. Byun, D. Youm, and Y. K. Semertzidis, Biaxially textured yba$_2$cu$_3$o$_7-x$ microwave cavity in a high magnetic field for a dark-matter axion search, Phys. Rev. Applied 17, L061005 (2022).

[53] K. M. Backes, D. A. Palken, S. A. Kenany, B. M. Brubaker, S. B. Cahn, A. Droster, G. C. Hilton, S. Ghosh, H. Jackson, S. K. Lamoreaux, A. F. Leder, K. W. Lehnert, S. M. Lewis, M. Malnou, R. H. Maruyama, N. M. Rapidis, M. Simonovskaia, S. Singh, D. H. Speller, I. Urdinaran, L. R. Vale, E. C. van Assendelft, K. van Bibber, and H. Wang, A quantum enhanced search for dark matter axions, Nature 590, 238 (2021).