Search for 70 µeV Dark Photon Dark Matter with a Dielectrically-Loaded Multi-Wavelength Microwave Cavity

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Microwave cavities have been deployed to search for bosonic dark matter candidates with masses of a few µeV. However, the sensitivity of these cavity detectors is limited by their volume, and the traditionally-employed half-wavelength cavities suffer from a significant volume reduction at higher masses. ADMX-Orpheus mitigates this issue by operating a tunable, dielectrically-loaded cavity at a higher-order mode, which allows the detection volume to remain large. The ADMX-Orpheus inaugural run excludes dark photon dark matter with kinetic mixing angle \( \chi > 10^{-13} \) between 65.5 µeV (15.8 GHz) and 69.3 µeV (16.8 GHz), marking the highest-frequency tunable microwave cavity dark matter search to date.

Introduction.—There is overwhelming evidence that 84.4% of the matter in the universe is made out of dark matter (DM) [1,7]. The ΛCDM 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 makes up dark matter.

The dark photon (DP) is a compelling dark matter candidate. It is a vector boson associated with an added Abelian U(1) symmetry, the simplest possible extension to the Standard Model (SM) [8-10]. The dark photon, having the same quantum numbers as the SM photon, interacts with the SM photon through kinetic mixing [11] [12] described by the Lagrangian

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

where \( F_{\mu\nu}^\prime \) is the electromagnetic field tensor, \( F_{2\mu\nu}^\prime \) is the dark photon field tensor, \( \chi \) is the kinetic mixing, \( m_A^\prime \) is the DP mass, and \( A' \) is the DP gauge field. The photon frequency \( f \) is related to the dark photon energy \( E_A^\prime \) by the relationship \( f = E_A^\prime \) (using natural units). For non-relativistic dark photons, \( f \approx m_A^\prime \).

If \( \chi \) is sufficiently small, then it is stable on cosmological timescales. The lifetime is about the same as the age of the universe if \( m_A^\prime (\chi^2 \alpha)^{1/9} < 1 \text{ keV} \) [13], where \( \alpha \) is the fine structure constant. This condition is easily met if \( m_A^\prime \approx 10^{-4} \text{ eV} \) and \( \chi < 10^{-12} \).

Several mechanisms could produce cosmic dark photons, the simplest being through quantum fluctuations during inflation [17]. These fluctuations seed excitations in the dark photon field, resulting in the cold dark matter observed today in the form of coherent oscillations of this field. The predicted mass from this mechanism is \( m_A^\prime \approx 10 \mu \text{eV} (10^{14} \text{ GeV}/H_I)^3 \), where \( H_I \) is the Hubble constant during inflation. Measurements of the cosmic microwave background tensor to scalar ratio constrain \( H_I < 10^{14} \text{ GeV} \) [15], which makes the search for \( m_A^\prime > 10^{-5} \text{ eV} \) well-motivated. Other mechanisms are possible and are described in [10] [16].

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 [17]. The dark photon signal power is \( P_S \), in natural units,

\[
P_S = \eta \chi^2 m_A^\prime \rho_A V_{\text{eff}} Q_L \frac{\beta}{\beta + 1} L(f, f_0, Q_L)
\]

\[
V_{\text{eff}} = \int dV e_{\vec{x}} |A(\vec{x})|^2 \left| A'(\vec{x}) \right|^2
\]

where \( \eta \) is a signal attenuation factor, \( \rho_A \) is the local density of dark matter, \( V_{\text{eff}} \) is the effective volume of the cavity, \( Q_L \) is the loaded quality factor, 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 \( Q_L \).
is the overlap between the dark photon field $\mathbf{A}'(\vec{x})$ and the dark photon-induced electric field $\mathbf{E}(\vec{x})$. Equation 2 assumes the cavity size is much smaller than the DP de Broglie wavelength and the cavity bandwidth is much larger than the dark matter velocity dispersion, $Q_L \ll Q_{DM}$ [18, 19].

The dark photon mass is unknown, so haloscopes must be tunable to search through the $\chi$ vs. $m_A^\prime$ parameter space. The scan rate for halo experiments is a key figure of merit that is strongly dependent on the signal-to-noise ratio (SNR). The SNR for a halo's signal is $SNR = (P_S/P_n)\sqrt{b\Delta f}$ [20 21], where $P_n$ 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 written as $P_n = Gk_bT_n$, where $k_b$ is the Boltzmann constant, $G$ is the system gain, $T_{cav}$ is the cavity temperature, and $T_n$ is the system noise temperature referenced to the cavity. If $Q_L < Q_{DM}$, a halo is sensitive to dark matter within its cavity bandwidth $\Delta f = f_0/Q_L$. The instantaneous scan rate is then

$$\frac{df}{dt} = \frac{\Delta f}{\Delta t} = \frac{f_0Q_L}{b} \left( \frac{\eta\chi^2m_A^\prime\rho_AV_{eff}\beta}{SNR T_n (\beta + 1)} \right)^2. \tag{4}$$

Traditional haloscopes, such as those implemented by the Axion Dark Matter eXperiment (ADMX), have consisted of a right-cylindrical cavity operating at the TM$_{010}$ mode as this mode often maximizes $V_{eff}$. ADMX currently uses this halo design to look for axions around a few $\mu$eV with great success [22–24]. Unfortunately, this design becomes increasingly difficult to implement at higher frequencies. Increasing mass corresponds to higher-frequency photons. Operating at the TM$_{010}$ mode would require smaller-diameter cavities. The volume scales by $V_{eff} \propto f^{-3}$ for a fixed aspect ratio, and consequently $P_S \propto f^{-3}$. This problem can be addressed by combining many cavities, as ADMX plans to do for future runs [25]. However, if the ADMX cavity’s $V_{eff} = 54L$ at an operating frequency $f_0 = 740$ MHz [23], then it would be about 5.4 mL at an operating frequency $f_0 = 16$ GHz. Combining enough cavities to be sensitive enough to the QCD axion is challenging. This unfavorable frequency scaling motivates the design of more sophisticated resonators.

The volume can remain large if the cavity operates at a higher-order mode (as is done by the ORGAN experiment [26] to implement a 26.5 GHz non-tunable haloscope). But higher-order modes would not couple well to dark photons since the spatial oscillations in $\mathbf{E}(\vec{x})$ would overlap poorly with the DP field, i.e., $\int \mathbf{E}(\vec{x}) \cdot \mathbf{A}'dV \approx 0$. However, dielectrics suppress electric fields and can be placed strategically to shape the electric field and increase $V_{eff}$. With a periodic dielectric structure, the cavity can be made arbitrarily large and operate at a higher-order mode while maintaining coupling to the dark photon. This makes dielectric cavities well-suited for higher frequency dark photon searches. Because of their potential, other collaborations are developing experiments with dielectric haloscopes. Examples include MADMAX [27 28], LAMPOST [29 30], MuDhi [31], and DBAS [32 33].

This Letter reports results from the highest-frequency tunable microwave cavity dark matter search to date. The results exclude DPDM between 65.5 $\mu$eV and 69.3 $\mu$eV with kinetic mixing $\chi > 10^{-13}$ at a 90% confidence limit. A more detailed description of the experimental design, implementation, operation, and data analysis can be found in the companion paper [34].

The ADMX-Orpheus Cavity—Orpheus implements this dielectric halo concept to search for dark photons around 70 $\mu$eV. Orpheus [35] is a dielectrically-loaded Fabry-Perot open cavity. The cavity operates at the TEM$_{00-18}$ mode (19 antinodes across the cavity axis), and dielectrics are placed on every fourth antinode to increase the mode’s coupling to the dark photon (Fig. 1a).

The dielectrics, purchased from Superior Technical Ceramics, consist of 99.5% alumina sheets. Their dimensions are 15.2 cm $\times$ 15.2 cm $\times$ 3 mm. The dielectric constant is $\epsilon_r = 9.8$ and the loss tangent is tan $\delta < 0.0001$ [36]. A 3 mm thickness is chosen because it is approximately half a wavelength at 16.5 GHz.

![Image](image-url)
room-temperature stepper motor (Applied Motion Products STM23S-2EE [40]). The scissor jacks constrain the inner two dielectric plates so that they are evenly spaced between the top and bottom dielectric plate (Fig. 1b). Thus the cavity has three degrees of freedom.

Power is extracted from the cavity via aperture coupling connected to a WR-62 waveguide 20 dB crossguide coupler [41]. The aperture is 5.4 mm in diameter and 3.8 mm thick. This was empirically determined to have an acceptable β without too much detriment to the mechanical stability or unloaded Q (Q₀). β ~ 1 under cryogenic conditions. β = 2 would optimize the scan rate, but this is not attainable without making the aperture unreasonably large.

There are two sets of measurements and simulations relevant for this Letter: a room-temperature tabletop measurement that measures the cavity spectrum and the cryogenically-cooled DPDM haloscope search. These measurements differ in two major aspects. First, the dielectric dissipation is substantially reduced in the cryogenic search, the dielectric plate positions deviated from the evenly-spaced configuration. This deviation where the dielectric plates were evenly-spaced in the cryogenic measurement, which increases κ eff (Equation 2) overestimates the effect of the mode crossing, possibly because the mode crossing requires more resolution to simulate accurately. Regardless, the mode crossing was mitigated in the cryogenic dark photon search because the dielectric plates deviated from the evenly-spaced configuration.

Orpheus’s sensitivity to the dark photon is determined from the cavity’s f₀, Vₑff, Q₀, β (Equation 2). The crux of the Orpheus experiment is to increase Vₑff using the dielectric structure. Since E cannot be measured directly, E is simulated using Finite Element Analysis simulation software (specifically, ANSYS® HFSS 2021 R1). The field is simulated for the cryogenic search and used to calculate Vₑff (Equation 3). Because of the orientation of the WR-62 waveguide, the receiver is only sensitive to Eₓ (one of the transverse coordinates), so Vₑff = (∫ dV Eₓ(x))² / (∫ dV e₀ Eₓ(x)²) (cos²θ)₁, where θ is the angle between the electric field along y and the dark photon field. θ is unknown, but (cos²θ)₁ = 1/3 if the dark photon is randomly polarized [8, 10, 16].

The simulated field is shown in Fig. 1a and cryogenic simulation of Vₑff and Q₀ is shown in Fig. 3 Vₑff(cos²θ)₁ ~ 55 mL for much of the tuning range, which is about a factor of 10 times larger than the ADMX cavity rescaled to operate the same frequency. After the dark photon search concluded, it was discovered that deviations from the evenly-spaced configuration serendipitously increased Vₑff and mitigated a problematic mode crossing (more detail in [12]). The relative uncertainty in Vₑff is 7.14%. This uncertainty is determined by simulating how Vₑff is affected by possible misalignments of the mirrors and dielectric plates, uncertainty in dielectric constant and loss tangent, and the effects of the mechanical structure [12]. Simulating these perturbations also caused the simulated Q₀ to vary by 50%. Fig. 3 shows that within the uncertainty of the cryogenic simulation, Q₀ matches the measured Q₀ determined from the measured Q₀ and β, Q₀ = Q₀(1 + β). This matching Q₀ corroborates the simulated Vₑff.

The measured Q₀ drops off below 16 GHz and above 16.2 GHz, suggesting Orpheus has a natural bandwidth. This is because the fixed dielectric thickness and mirror radius of curvature are optimal for a small range of frequencies. These parameters can be adjusted to allow Orpheus to scan for dark matter at different frequencies.

**Dark Photon Search Experimental Setup**—The cavity is cooled down to liquid helium temperatures. The power

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**FIG. 2.** Orpheus mode map with the simulated TEM₀₀⁻₁₈ mode overlaid. Both measurement and simulation correspond to a room-temperature tabletop setup in which the dielectrics maintained even spacing throughout the cavity. This configuration suffers from a mode crossing at about 16.4 GHz. This mode crossing was mitigated in the dark photon search by deviating from the evenly-spaced configuration.

The cavity spectrum is measured with the room-temperature setup and is visualized with a mode map,
of the cavity is first amplified by a cryogenic heterostructure field effect transistor (HFET) amplifier (LNF-LNC6 20C [43]) and then is processed by the superheterodyne receiver in Fig. 4.

The search strategy is to tune the cavity to scan for dark photons with different $m_{\psi}$. For each cavity length, a series of ancillary measurements are taken to extract a noise power calibration and expected dark photon signal power. These measurements include the cavity length, dielectric positions, cavity temperature, transmission coefficient, and reflection coefficient. The cavity temperature is used to determine the noise power, and the transmission and reflection coefficients are used to extract $f_0$, $Q_L$, and $\beta$. The power spectrum is then measured out of the cavity for either 30 s or 100 s, depending on the desired SNR. The dark matter signal would be observed in the power spectra as a spectrally-narrow power excess over the noise floor.

**Analysis and Results**—For a critically-coupled Orpheus cavity operating in the Rayleigh-Jeans limit ($k_BT_{cav} >> hf$), the system noise temperature is modeled as $T_n = T_{cav} + T_{rec}$, where $T_{cav}$ is the physical temperature of the cavity, and $T_{rec}$ is the noise temperature of the receiver chain from the output of the cryogenic amplifier outward (see [42] for more details). $T_{cav}$ is measured using a pair of calibrated Cernox resistors and is typically 4.7(1) K. $T_{rec}$ is dominated by output noise temperature of the 1st stage amplifier $T_{amp}$, and is more accurately obtained by the Friis cascade equation [44] (future runs will incorporate an in-situ measurement of $T_{rec}$). From the manufacturer’s calibration [43], $T_{rec} = 5.0(5)$ K. This results in $T_n \sim 9.7$ K.

The cavity length and position of the dielectrics were calculated using the motor encoder values. However, there is a systematic offset between measured and simulated resonant frequency for a given cavity length. This frequency offset is removed by adding 0.7 mm to the measured cavity length derived from the motor encoder values. This systematic bias may be caused by mechanical contractions during cooldown or by tuning hysteresis. After accounting for the systematic bias, the measured $f_0$ matches the simulated $f_0$ often by less than one part per thousand.

The data collected between 9/3/2021 and 9/7/2021 are used to search for dark photons between 65.5 $\mu$eV (15.8 GHz) and 69.5 $\mu$eV (16.8 GHz). The system noise temperature $T_n$ is used to calibrate the power excess. All measured power excesses are consistent with Gaussian noise, so a 90% confidence level exclusion limit is placed on the kinetic mixing $\chi$ in this mass range. The procedure for deriving the exclusion limits follows the procedure developed by ADMX and HAYSTAC [45, 47], and is adapted for dark photon searches [9, 10, 42, 48]. The analysis for this measurement is described in more detail in the companion paper [42].

The derived 90% exclusion of dark photons is plotted in Fig. 5 assuming dark photons are randomly polarized $\langle \cos^2 \theta \rangle_T = 1/3$. If dark photons are polarized across elements, the scenario implies $\langle \cos^2 \theta \rangle \geq 0.076$ for a 90% confidence limit, and the results can be appropriately rescaled [9, 10].

**Conclusion and Discussion**—Orpheus has excluded DPDM higher in frequency than other haloscope experiments while also having a respectable tuning range. Orpheus also demonstrates the potential advantages of a cylindrical haloscope operating at similar frequencies...
Kinetic mixing, such as ORGAN [50]. Orpheus has three times microwave cavity haloscopes. Figure adapted from [49].

With more experimental iterations with different dielectric thicknesses and mirror radius of curvatures, Orpheus can potentially scan the axion and dark photon parameter space higher than $\sim 10\,\text{GHz}$.

Orpheus lays the groundwork for other future dielectric array experiments such as MADMAX. It demonstrates the feasibility and tolerance of the tuning mechanism. Orpheus can also become sensitive to the QCD axion by making it larger and colder. With the same integration time, Orpheus can achieve Kim-Shifman-Vainshtein-Zakharov (KSVZ) sensitivity if $V_{eff} \sim 120\,\text{mL}$ and $Q_L \sim 2 \times 10^4$, $T_n \sim 1\,\text{K}$, and $B_0 = 10\,\text{T}$. That would require the electromagnetic optimizations that increase $V_{eff}$ and reduce diffraction losses, cooling the cavity with a dilution refrigerator, quantum noise limited amplifiers, and technological advances in winding superconducting dipole magnets. Dine-Fischler-Srednicki-Zhitnitsk (DFSZ) sensitivity may be reached by increasing the cavity size to $V_{eff} \sim 600\,\text{mL}$. Detection mechanisms that subvert the Standard Quantum Limit, such as vacuum squeezing [51] and superconducting qubit photon counters [52] would be advantageous in this frequency range for increasing sensitivity.

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