

Search for dark photons between 16.96–19.52 μeV with the HAYSTAC experiment

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(Received 20 October 2025; accepted 18 December 2025; published 20 January 2026)

We report dark photon results from HAYSTAC phase II using data from previously reported axion searches. Additionally, we present an analysis of an unpublished dataset covering a region between 19.46–19.52 μeV . This region overlaps with a recently reported dark photon signal at 19.5 μeV with a kinetic coupling strength of $|\chi_{\text{rand}}| \simeq 6.5 \times 10^{-15}$ resulting from a reanalysis of previously published data from the TASEH collaboration. Given HAYSTAC's sensitivity, if such a signal were present, it would have appeared as a large 17.1σ excess above the noise. However, no such signal was observed. We thus exclude couplings $|\chi_{\text{rand}}| \geq 4.90 \times 10^{-15}$ at the 90% confidence level over the newly reported region. In addition, using our previously reported axion data, we exclude couplings $|\chi_{\text{rand}}| \geq 2.90 \times 10^{-15}$ between 16.96–19.46 μeV at the 90% confidence level.

DOI: [10.1103/3txs-dz63](https://doi.org/10.1103/3txs-dz63)

The dark photon is a hypothetical massive vector boson, often considered a viable dark matter candidate alongside axions and axionlike particles [1]. Dark photons arise from the simplest form of a “dark sector” model, which introduces an additional U(1) symmetry to the standard model. Aside

from gravity, the only interaction between dark photons and standard model particles is kinetic mixing between dark photons and photons that would cause dark photons to oscillate to photons with mixing strength given by χ [2].

Dark photon analyses can be carried out by reinterpreting existing axion exclusions from haloscope experiments [3,4]. Haloscopes consist of a tunable resonant cavity placed in a strong magnetic field, enabling axion-photon conversion where axions convert to photons via the inverse Primakoff effect [5,6]. These cavities are also sensitive to kinetic mixing between dark photons and photons, which, unlike axion-photon conversion, can take place with or without the magnetic field.

The on resonance signal power, in natural units, for dark photons in a haloscope is given by

$$P = \left(V C_{mnl} Q_L \frac{\beta}{1 + \beta} \right) (\chi^2 m_\chi \rho_\chi \cos^2 \theta). \quad (1)$$

The first set of terms describes the properties of the haloscope, where V is the cavity volume, C_{mnl} is the form

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factor which quantifies the overlap between the cavity mode and the longitudinal axis, Q_L is the cavity's loaded quality factor, and β is the coupling strength of the readout antenna. The loaded quality factor is obtained from the unloaded value Q_0 through $Q_L = Q_0/(1 + \beta)$. The second set of terms describes the properties of the dark photon: χ is the strength of the kinetic mixing, m_χ is the dark photon mass, and $\rho_\chi = 0.45 \text{ GeV cm}^{-3}$ is the local dark matter density [7]. Finally, θ is the angle between the cavity's longitudinal axis and the dark photon's polarization.

The TASEH collaboration released axion search results between 19.4687–19.8436 μeV in 2022, excluding axion photon couplings $|g_{a\gamma\gamma}| \geq 8.1 \times 10^{-14} \text{ GeV}^{-1}$ [8]. Recently, collaborators of TASEH reanalyzed this data to search for dark photons and claimed a tentative dark photon signal at 19.479 727 μeV (4.710178 GHz) with a kinetic mixing strength of $|\chi_{\text{rand}}| \simeq 6.5 \times 10^{-15}$ assuming a randomly polarized dark photon field [9]. This tentative signal was present during the original TASEH axion analysis but was excluded because it persisted in the absence of a magnetic field. This is a valid method to veto false signals in an axion search, but it does not apply to a dark photon search, where the conversion process is independent of the magnetic field strength. While the HAYSTAC experiment's previously published data did not include this region, HAYSTAC has collected data in the range 19.46–19.52 μeV during a short run that was later aborted due to degraded cavity performance. Given the new results from TASEH, we have analyzed this data with careful treatment of the additional uncertainties in detector performance across this run. The results here include the analysis of this new region containing the TASEH candidate frequency, along with results for a dark photon search across all of HAYSTAC's phase II data.

HAYSTAC has run thus far in two unique phases. Phase I (January 2016–July 2017) scanned axion masses from 23.15 μeV –24.0 μeV using a single Josephson parametric amplifier (JPA) with near quantum-limited noise [10,11]. In phase II, the experiment was upgraded with a squeezed state receiver, leveraging squeezed vacuum states to achieve scan rate enhancements up to a factor of two relative to unsqueezed operation [12]. The upgraded experiment ran in subphases: phase II(a) (September 2019–April 2020) which scanned 16.96–17.28 μeV [13], phase II(b) (July 2021–November 2021) which scanned 18.44–18.71 μeV [14], and phase II(c) and II(d) (September 2022–August 2024) which scanned 17.28–18.44 μeV and 18.71–19.46 μeV [15]. Finally, a previously unpublished dataset, referred to as phase II(e), was collected in July 2022 and scanned 19.46–19.52 μeV .

The HAYSTAC experiment consists of a tunable copper-plated stainless steel cavity that is 25.4 cm long with an inner diameter of 10.2 cm. The tuning rod occupies 25% of the cavity's total volume, leaving an unfilled volume of 1.545 L. The cavity is suspended from the mixing chamber, which is cooled to 60 mK, and placed inside an 8 T superconducting solenoidal magnet. HAYSTAC operates

by observing the excess noise of the cavities TM_{010} mode, which maximizes the overlap of the axion field with the magnetic field, giving an average C_{010} of 0.44 over the frequency range of phase II (a)–(d) and 0.37 over phase II(e). An antenna coupled to the cavity detects the internal field, with coupling strength β tuned by adjusting its insertion depth, which was maintained between 6–11 over phase II in order to optimize the scan rate with the squeezed state receiver [12]. The unloaded quality factor is measured to be on average $\sim 40\,000$ over phase II (a)–(d) and $\sim 39\,000$ over phase II(e). The extracted signal is then amplified by the squeezed state receiver and digitized. Further experimental details are given in [16].

Data taking follows the standard procedure described in [15], which uses an automated script that rotates the tuning rod to move the cavity's frequency by $\sim 80 \text{ kHz}$ and then reoptimizes the squeezed state receiver at the new frequency. For each tuning step, the digitizer records data over integration time τ and computes the average power spectral density (PSD) by dividing the data into 10 ms segments so as to achieve a frequency resolution of 100 Hz. For phase II(a) and II(b) and phase II(e), the integration time for each spectrum is 60 min, and for phase II(c) and II(d), it is reduced to 20 min to increase the scan rate. Each PSD is then filtered to remove structures wider than expected from the axion line shape with a predicted width of $\sim 5 \text{ kHz}$ at the reported mass range [17]. The spectra are then scaled by their signal-to-noise ratio, aligned in frequency, and summed to form a combined spectrum. The power from neighboring bins is then cross correlated with the axion line shape, and the resulting spectrum is corrected to account for correlations introduced by the filtering. This gives a final grand spectrum, which is approximately Gaussian distributed with $\mu = 0$ and $\sigma = 1$ in the absence of a signal.

This work builds on our previous dark photon results from phase I and phase II(a) [4], adding results from phase II(b), phase II(c), and II(d), and a previously unpublished dataset, phase II(e). Phase II(e) was collected between July 14th and July 25th, 2022, spanning the frequency range of 19.46–19.52 μeV (4.707–4.721 GHz) and consisting of 145 total spectra. During phase II(e) data taking, we observed a sharp drop in the quality factor when the cavity's TM_{010} frequency was at $\sim 4.71 \text{ GHz}$, resulting in $Q_0 \sim 20\,000$, roughly a factor of two lower than expected from previous measurements and simulations. Due to the degraded performance, the run was aborted. Once at room temperature, the cavity was inspected and it was observed that the tuning rod had slipped and come in contact with the bottom end cap of the cavity. This was subsequently fixed, and upon cooling down the cavity Q_0 was observed to return to its nominal value of $\sim 40\,000$. Aside from the degraded Q, the system functioned normally, but due to the deviation from the nominal operating conditions and the uncertainty in how the rod position changing might impact the form factor, we chose not to include this dataset in our

previous publication. Because the tentative dark photon signal reported in [9] is well within the reach of HAYSAC's sensitivity, we have carefully reanalyzed the data with a study of potential uncertainty that could arise from the degraded cavity performance.

To quantify the effect of the rod's position changing during phase II(e), primarily on the form factor, we performed simulations in COMSOL [18] and showed that the form factor $C_{010} = 0.41$ at the reported signal frequency 4.710178 GHz is highly insensitive to the vertical position of the rod in the cavity, varying by less than 1% between the center position and the extreme upper or lower position. Furthermore, we have confirmed that the broadening of a nearby mode crossing at ~ 4.73 GHz, where there is a large dip in C_{010} , was too far away from the frequency of the reported signal to affect the C_{010} there. The reduction of the quality factor when the tuning rod slipped is a well known phenomenon due to the resulting high resistance and weak contact between the tuning rod and the bottom end cap. Out of prudence, for the results from phase II(e) we assume a baseline form factor which is 2x lower than predicted in simulation, chosen to match the observed reduction in quality factor.

Phase II(e) data are analyzed using procedures described in [10,14,15] and potential candidates are identified as power excesses exceeding 3.468σ , corresponding to a 10% two-scan false negative rate for a target significance of 5.1σ in the frequentist framework used in [10,11]. Three candidates are identified at 4.719720, 4.719816, and 4.719925 GHz. The excess at 4.719925 GHz is part of the synthetic axion signal injection used for phase II(c) and II(d) as described in [15], where we injected an RF signal through the cavity's weak port whose spectral shape matches the expected axion line shape [19]. This injected signal was correctly identified, and a data cut of 10 kHz was applied to remove data around the signal. Because the run was aborted, rescans were not performed on any of the candidates, and the data cut of the injected signal was not filled in as we did in phase II(c) and II(d). The other two candidates were smaller excesses ($P_{\text{GS}} < 4.5\sigma$) and did not correspond to any external sources. While also not rescanned, the Bayesian framework [20] accounts for these power excesses by degrading the exclusion both at the observation frequency and of the overall aggregated exclusion. This resulted in an exclusion on the axion-photon coupling of $|g_\gamma| > 3.43 \times |g_\gamma^{\text{KSVZ}}|$ at the 90% confidence level between 19.46–19.52 μeV in phase II(e).

Because phase II(c) and II(d) were previously analyzed to search for axions, careful treatment of certain candidates is required to ensure no axion specific vetos, such as the magnetic field veto, have been used. This applies specifically to 12 excesses later identified as radio frequency interference (RFI), summarized in Table II of [15], 5 of which persisted after ramping down the magnetic field. However, all excesses were found to correlate with signals detected by an ambient RF receiver, a simple room-temperature antenna

located in the same room as the main detector, ruling them out as dark photon candidates. Persistent RFIs were removed from the data by applying a 10 kHz cut around each affected frequency.

Given no signal was observed during phase II, the limits on axion photon coupling $g_{a\gamma\gamma}$ can be recast to limits on dark photon kinetic mixing χ , using the prescription described in [3]

$$\chi = g_{a\gamma\gamma} \frac{B_0}{m_\chi \sqrt{\langle \cos^2 \theta \rangle}}, \quad (2)$$

where $B_0 = 1.56 \times 10^{-15} \text{ GeV}^2$ is the magnetic field in the experiment in natural units. Since the polarization is unknown, two scenarios are considered in order to convert axion limits into dark photon limits [3]. In the first scenario, the polarization of the dark photon field is random and changes every coherence time τ_{coh} , which is $\sim 200 \mu\text{s}$ at the masses we are probing. In this case, as long as the $\tau \gg \tau_{\text{coh}}$, we expect $\cos^2 \theta = 1/3$. Using this, we can convert the axion exclusion from phase II (a)–(d) to a dark photon limit with an aggregated exclusion of $|\chi_{\text{rand}}| \geq 2.90 \times 10^{-15}$ at the 90% confidence level between 18.71–19.46 μeV . The same is done for phase II(e), which we treat separately due to a conservative assumption about the form factor degradation described above, giving an aggregated exclusion of $|\chi_{\text{rand}}| \geq 4.90 \times 10^{-15}$ at the 90% confidence level between 19.46–19.52 μeV .

In the alternative scenario where the dark photon has a single fixed polarization, the value of $\cos \theta$ not only depends on the polarization angle itself, but also on the experiment's location on Earth and its orientation relative to Earth's rotation. Furthermore, $\cos \theta$ varies in time as the relative orientation between Earth and the dark photon field changes. Thus, converting an axion limit into a dark photon limit requires computing an effective value of $\cos \theta$ that preserves the statistical inference made in the original axion exclusion. HAYSTAC is located at a latitude of 41.32° with the cavity's longitudinal axis pointing along the radius of the Earth. Prior to phase II, HAYSTAC performed its analysis using the frequentist framework described in [10], where the exclusion limit is defined as the coupling strength for which, given a signal 5.1σ above the noise, the probability that the observed power (P_{obs}) falls below the rescan threshold is 10% after two scans. In this case, the effective $\langle \cos^2 \theta \rangle$ for an instantaneous measurement is determined by solving for the normalized signal power P_{sig} via simulation using a conditional probability relation, $\text{Prob}(P_{\text{obs}} > 3.468\sigma | P_{\text{sig}} = 5.1\sigma / \langle \cos^2 \theta \rangle) = \sqrt{0.9}$, which yields $\langle \cos^2 \theta \rangle = 5.1\sigma / P_{\text{sig}} \approx 0.004$. Note that this is different from the assumption made in [3,21], which estimated the dark photon signal strength that would exceed the mean noise 90% of the time, giving $\langle \cos^2 \theta \rangle = 0.019$. As stated in [3], this is a practical assumption for converting a generic experiment, but it does not correspond to the actual analysis used by HAYSTAC.

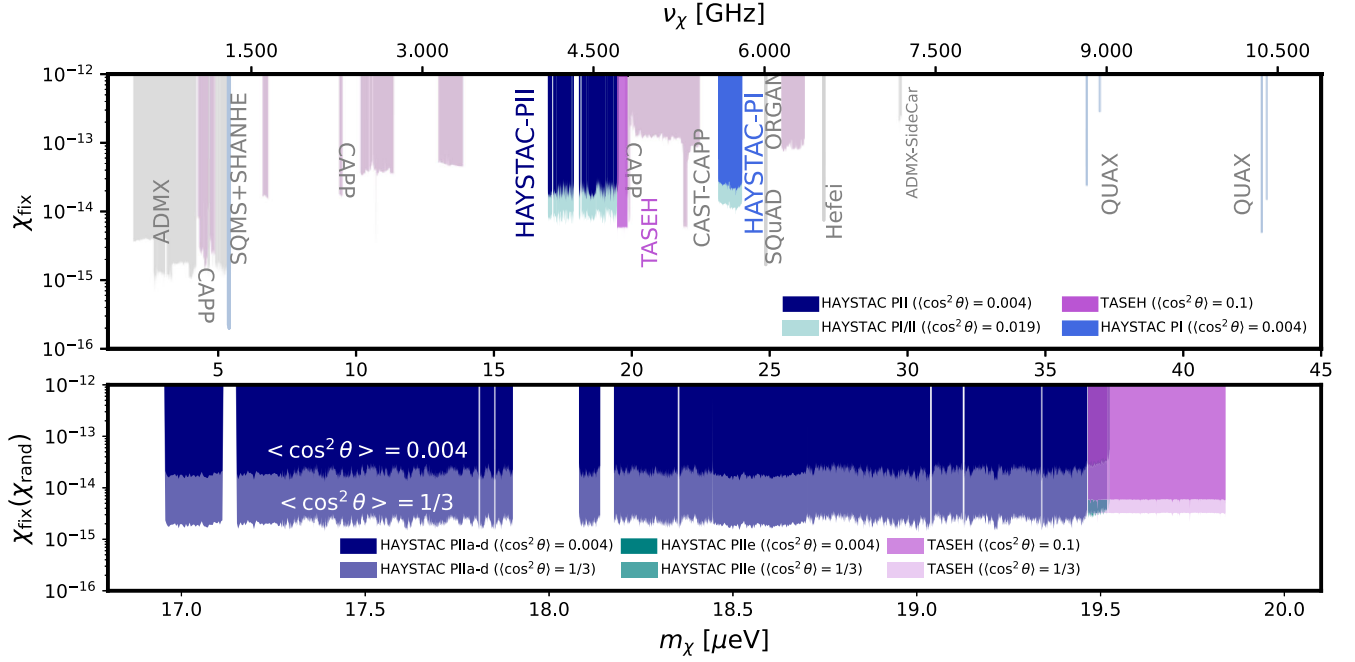


FIG. 1. Top: dark photon kinetic mixing for the fixed polarization scenario in the 1–45 μeV mass range, showing results from TASEH [8,9], ADMX [22], CAPP [23,24], CAST-CAPP [25], ORGAN [26], QUAX [27], SQUAD [28], SQMS [29], Hefei [30], SHANHE [31] (adapted from online repository [21]). Also shown are HAYSTAC phase I and phase II, including exclusions converted by the method discussed in the text which uses $\langle \cos^2 \theta \rangle = 0.004$ (blue), and what is currently shown in [21] (light green), which uses $\langle \cos^2 \theta \rangle = 0.019$ for a fair comparison with other results. Bottom: exclusion on the dark photon kinetic mixing, comparing both the random (light fill) and fixed (solid fill) polarization scenarios, highlighting HAYSTAC phases II (a)–(d) (blue), phase II(e) (green) and TASEH (purple). The narrow vertical gaps mark the regions that are removed from the exclusion due to RFI contamination described in the text.

It should be noted that starting with phase II, HAYSTAC adopted a Bayesian framework, in which the exclusion is instead defined as the coupling strength for which the probability of an axion existing falls below 10% given the observed power. In this case, because the exclusion is no longer a binary function of the observed power, the effective $\cos \theta$ value is not a constant across frequencies but varies in each frequency bin depending on the observed power. However, for the purpose of this work, we adopt the former value, $\langle \cos^2 \theta \rangle \sim 0.004$, as a straightforward yet conservative choice. Under this assumption, the exclusions from phase II (a)–(e) are converted to dark photon limits giving aggregated exclusion of $|\chi_{\text{fix}}| \geq 2.64 \times 10^{-14}$ for phase II (a)–(d) and $|\chi_{\text{fix}}| \geq 4.47 \times 10^{-14}$ for phase II (e) at the 90% confidence level. The resulting HAYSTAC dark photon limits, along with those from other experiments under both random and fixed polarization scenarios, are shown in Fig. 1.

In addition, given the overlap between phase II(e) and the tentative signal reported from TASEH’s reanalysis, we carefully analyzed our data to understand the expected response to such a signal. At the candidate frequency, HAYSTAC collected 27 spectra with varying sensitivity, corresponding to a total integration time of 27 hours. Assuming a randomly polarized dark photon field and adopting a conservative value

for the form factor, the resulting 5.1σ sensitivity corresponds to $|\chi_{\text{rand}}| = 3.54 \times 10^{-15}$ at the signal frequency. Under these conditions, the reported signal would be expected to appear as a $(6.48/3.54)^2 \times 5.1\sigma \simeq 17.1\sigma$ excess above the noise. As shown in Fig. 2 (right), no such excess is observed. It should be noted that to match the analysis used in the tentative claim, the analysis here assumes the random polarization scenario, which is not impacted by variations in $\cos \theta$. If instead the dark photon field polarization is fixed, the signal in HAYSTAC could have been suppressed. While we do not present a detailed analysis of this scenario, we will note that after accounting for downtime, the 27 contributing spectra correspond to a total elapsed observation time of ~ 40 hours with varying sensitivity in each scan. This is longer than one sidereal day, which reduces the effect from potential misalignment between the cavity axis and the dark photon field’s polarization angle as detailed in [3].

In summary, we report dark photon results using HAYSTAC’s phase II axion search data, including a new search region from 19.46–19.52 μeV . This region overlaps with a recently claimed signal in a reanalysis of TASEH’s data near 19.5 μeV . Given HAYSTAC’s sensitivity, assuming a randomly polarized dark photon field, such a signal would have appeared well above the noise, but none was observed. We therefore exclude couplings at $|\chi_{\text{rand}}| \geq 4.90 \times 10^{-15}$

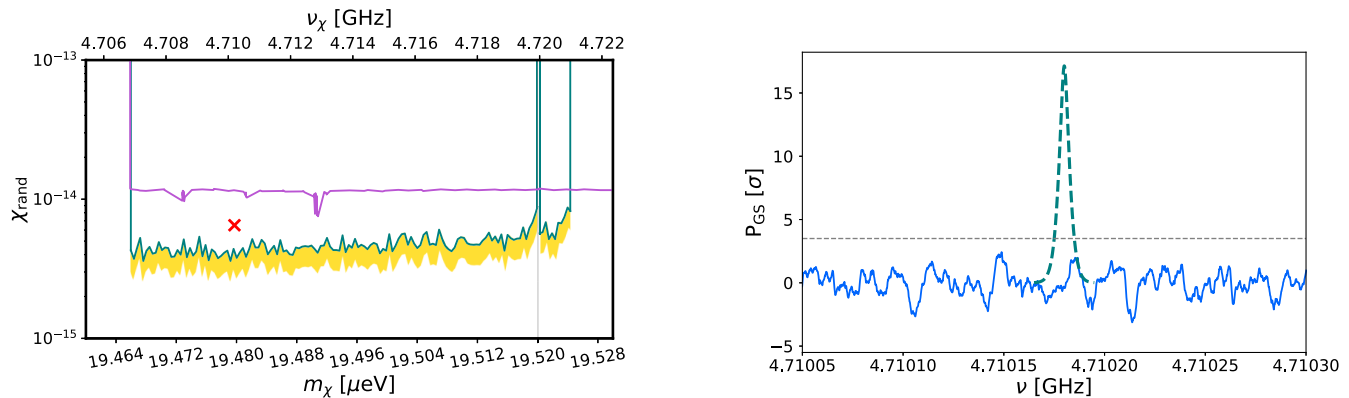


FIG. 2. Left: enlarged exclusion on the dark photon coupling with random polarization showing results from HAYSTAC phase II(e) in green and TASEH results in purple. The baseline exclusion, shown in green, assumes the conservatively degraded form factor, and the yellow shaded region highlights the degradation of the exclusion from the 50% systematic uncertainty on the form factor. The red cross denotes the reported tentative dark photon signal from the TASEH reanalysis at 19.479 727 μeV (4.710178 GHz) with a kinetic mixing strength of $|\chi_{\text{rand}}| \simeq 6.5 \times 10^{-15}$ [9]. The vertical gray line marks the injected signal discussed in the text. Right: normalized power observed in the grand spectrum P_{GS} (blue solid line) at each observed frequency ν , shown in a zoomed window around the reported dark photon signal. The horizontal gray dashed line corresponds to HAYSTAC’s 3.468 σ rescan threshold. The green dashed peak shows the expected signal strength of 17.1 σ , using the conservatively reduced form factor of 50%, had the tentative signal been present during HAYSTAC’s data taking.

with 90% confidence in this region. In addition, for the rest of phase II, we exclude couplings $|\chi_{\text{rand}}| \geq 2.90 \times 10^{-15}$ between 16.96–19.46 μeV at the 90% confidence level.

ACKNOWLEDGMENTS

HAYSTAC is supported by the National Science Foundation under Grants No. PHY-2514170, No. PHY-1306729, the Heising-Simons Foundation under Grants No. 2014-0904 and No. 2016-044, and the David and Lucile Packard Foundation Grant No. 2022-74683. We thank Kyle Thatcher and Calvin Schwadron for their work on the design and fabrication of the squeezed state receiver mechanical components, Felix Vietmeyer for his work on the room temperature electronics, and Steven Burrows for

his graphical design work. We thank Vincent Bernardo and the J. W. Gibbs Professional Shop as well as Craig Miller and Dave Johnson for their assistance with fabricating the system’s mechanical components. We also wish to thank the Cory Hall Machine shop at UC Berkeley and the efforts of Sergio Velazquez for the microwave cavity used in this run. We thank Dr. Matthias Buehler of low-T Solutions for cryogenics advice. Finally, we thank the Yale Wright laboratory for housing the experiment and providing computing and facilities support.

DATA AVAILABILITY

The data that support the findings of this article are openly available [21].

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