

Dark Photon Limits from Patchy Dark Screening of the Cosmic Microwave Background

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Dark photons that kinetically mix with the Standard Model photon give rise to new spectral anisotropies (patchy dark screening) in the cosmic microwave background (CMB) due to conversion of photons to dark photons within large-scale structure. We utilize predictions for this patchy dark screening signal to provide the tightest constraints to date on the dark photon kinetic mixing parameter [$\epsilon \lesssim 4.5 \times 10^{-8}$ (95% confidence level)] over the mass range 10^{-13} eV $\lesssim m_{A'} \lesssim 10^{-11}$ eV, almost an order of magnitude stronger than previous limits, by applying state-of-the-art component separation techniques to the cross-correlation of *Planck* CMB and unWISE galaxy survey data.

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Introduction—The cosmic microwave background (CMB) is an exquisitely well-calibrated source of photons. It has a near-perfect blackbody frequency spectrum and small “primary” anisotropies (anisotropies imprinted on its release), consistent with Gaussian statistics. These properties can be used to isolate “secondary” CMB anisotropies, induced by the interaction of CMB photons with large-scale structure (LSS) over cosmic history. For example, scattering from free electrons in LSS induces non-Gaussian and nonblackbody temperature and polarization anisotropies (Sunyaev-Zel’dovich, or SZ, effects [1,2]) that can be distinguished from the primary CMB. If the photon has interactions with particles beyond the Standard Model (BSM), the associated secondary CMB anisotropies provide a powerful discovery tool to search for new physics [3,4].

One of the simplest extensions of the Standard Model is a light, massive vector boson [5,6], the dark photon (DP) A' , which can couple to the photon γ through kinetic mixing. The DP is motivated as a low-energy consequence of string theory [7–9], a dark matter candidate [9–11], and a mediator of interactions with a larger dark sector (see [12] and references within). The mass range of interest for the DP spans many orders of magnitude, generating a diverse

experimental program [13–21]. For a DP with mass below $\sim 10^{-7}$ eV, the signatures of interest are mainly cosmological and astrophysical [22–27].

As a consequence of kinetic mixing, CMB photons can convert to DPs as they propagate [22]. The strongest, *resonant* conversion occurs in regions where the photon plasma mass (proportional to the square root of the number density of electrons) is equal to the mass of the DP [23]—this is analogous to the Mikheyev-Smirnov-Wolfenstein effect for neutrino oscillations in matter [28,29]. Resonant conversion can occur due to the evolution of the cosmic mean density as the Universe expands [23] or due to the variation in density associated with the formation and evolution of LSS [24,25]. Measurements of the CMB monopole spectrum [30] constrain the strength of the kinetic mixing [23–25]. Reference [3] demonstrated that these previous constraints could be greatly improved at $\sim$ peV DP masses by measuring the “patchy screening” of the CMB monopole, the frequency- and spatially dependent reduction of intensity due to resonant conversion inside of nonlinear structures. The characteristic spatial and spectral shape of the signal, as well as its correlation with tracers of LSS, can be used to separate the signal from the primary CMB and astrophysical foregrounds. [This framework can be extended to other BSM particles such as axions (e.g., [4,31]).]

In this Letter, we perform the first search for DPs via patchy dark screening of the CMB in cross-correlation with LSS, using data from the *Planck* mission [32] cross-correlated with the unWISE galaxy catalog [33–37]

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assembled from data taken by the Wide-Field Infrared Survey Explorer (WISE) mission [38,39]. We place the strongest constraints to date on the strength of DP kinetic mixing in the mass range $10^{-13} \text{ eV} \lesssim m_{A'} \lesssim 10^{-11} \text{ eV}$, improving existing constraints by almost an order of magnitude. Forecasts [3] suggest that even more dramatic improvements will be possible with data from future CMB [40,41] and galaxy surveys [42–44].

Dark photon model—A kinetically mixed DP is described by the following Lagrangian (we use units where $\hbar = k_B = c = 1$) [5,6]:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{m_{A'}^2}{2}A'_\mu A'^\mu - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}, \quad (1)$$

where $m_{A'}$ is the mass of the DP, ε is the kinetic mixing parameter, and $F_{\mu\nu}$ ($F'_{\mu\nu}$) is the photon (DP) field-strength tensor. The photon obtains a medium-dependent plasma mass $m_\gamma(\vec{x}(t)) = \sqrt{4\pi\alpha n_e(\vec{x}(t))/m_e} = 3.7 \times 10^{-11} \text{ eV} \sqrt{n_e/\text{cm}^{-3}}$, where n_e is the free electron number density, and resonant conversion of CMB photons to DPs occurs at t_{res} , when $m_\gamma(\vec{x}(t_{\text{res}})) = m_{A'}$ along any photon trajectory $\vec{x}(t)$. The conversion probability can be computed via the Landau-Zener formula [3,23], resulting in a position- and frequency-dependent (scaling as $1/\nu$) dark screening optical depth $\tau^{\text{dsc}}(\nu, \hat{n})$,

$$\tau^{\text{dsc}}(\nu, \hat{n}) = \sum_{t_{\text{res}}} \frac{\pi \varepsilon m_{A'}^2}{2\pi\nu(t_{\text{res}})} \times \varepsilon \left| \frac{d}{dt} \ln m_\gamma^2(\hat{n}, t) \right|_{t=t_{\text{res}}}^{-1}, \quad (2)$$

where the sum is over all resonances in the line of sight direction $\hat{n}$. The dark screening optical depth couples to the CMB monopole intensity $B(\nu, T_{\text{CMB}})$, where $B(\nu, T_{\text{CMB}})$ is the Planck blackbody specific intensity at the CMB monopole temperature T_{CMB} , resulting in a frequency-dependent specific intensity anisotropy $\Delta I(\nu, \hat{n}) = -\tau^{\text{dsc}}(\nu, \hat{n})B(\nu, T_{\text{CMB}})$, which can be extracted from multifrequency CMB maps. In CMB thermodynamic temperature units, this takes the form $\tilde{T}^{\text{dsc}}(\nu, \hat{n}) = T_{\text{CMB}}\tau^{\text{dsc}}(\nu, \hat{n})[(1 - e^{-x})/x]$ where $x \equiv h\nu/k_B T_{\text{CMB}} = 2\pi\nu/T_{\text{CMB}}$ is the dimensionless photon frequency [45], with $T_{\text{CMB}} \simeq 2.726 \text{ K}$ [30,46].

In Ref. [3], angular correlation functions of the dark screening map $\langle \tilde{T}^{\text{dsc}}(\nu, \hat{n}) \tilde{T}^{\text{dsc}}(\nu, \hat{n}') \rangle$ and of its cross-correlation with a template $\hat{\tau}$ for the dark screening signal constructed from a tracer of LSS, $\langle \tilde{T}^{\text{dsc}}(\nu, \hat{n}) \hat{\tau}(\hat{n}') \rangle$, were computed within the halo model (see, e.g., [47]). In Supplemental Material [48] we adapt this result to compute the cross-correlation $\langle \tilde{T}^{\text{dsc}}(\nu, \hat{n}) \delta_g(\hat{n}') \rangle$, where the galaxy overdensity δ_g is modeled using the halo occupation distribution (HOD) described in Ref. [49] for the unWISE galaxies. As in Ref. [3], we model the electron distribution in halos using the active Galactic nuclei (AGN) feedback model of Ref. [50]. We work with the harmonic

transforms of the statistics, i.e., $C_\ell^{g\tilde{T}^{\text{dsc}}}$, where ℓ is the multipole moment.

Data and measurement: Dark screening map—The *Planck* satellite [32] mapped the full sky in nine microwave frequency bands. In our standard measurement, we use the sky maps of the NPIPE (*Planck* public release 4) data processing [91] at $\{30, 44, 70, 100, 143, 217, 353, 545\} \text{ GHz}$. We preprocess the maps as described in Ref. [51]; in particular, we mask and inpaint regions with bright point sources, as defined by the *Planck* point source masks, and a region near the Galactic Center.

We use PYLILC [51,52] to construct a constrained needlet internal linear combination (NILC) [53,54] map of the CMB spectral distortion induced by the DP conversion. NILC is a component separation technique that allows for minimum-variance estimation of the sky map of a component with a known frequency dependence (in this case, the DP distortion) via a linear combination of the frequency maps. In CMB thermodynamic temperature units, the frequency dependence of the DP distortion that we preserve is

$$\frac{\Delta T(\nu)}{T_{\text{CMB}}} \propto \frac{1}{x} \left(\frac{1 - e^{-x}}{x} \right). \quad (3)$$

We normalize the DP distortion in Eq. (3) at 353 GHz, and thus we denote our NILC dark screening map as $\tilde{T}_{353 \text{ GHz}}^{\text{dsc}}$. The angular power spectrum of the resulting map is plotted in Fig. 1 along with the predicted dark screening signal for several values of ε .

We choose constraints that allow us to directly remove, or “deproject,” contamination from residual foregrounds in

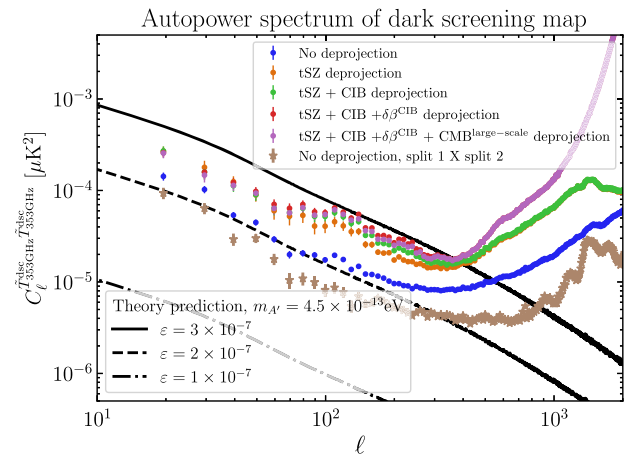


FIG. 1. The colored points show the measured autopower spectrum of the NILC dark screening map for various contaminant deprojection choices. We also show the power spectrum measured from two independent splits of the data, which do not contain correlated noise bias. We include theoretical predictions for the signal, with $m_{A'} = 5.2 \times 10^{-13} \text{ eV}$, for various values of ε , as indicated. The data and theory signals are shown at a reference frequency of 353 GHz.

the NILC, in particular, the thermal Sunyaev-Zel'dovich (tSZ) effect, the cosmic infrared background (CIB), and the blackbody CMB on large scales (which contains the integrated Sachs-Wolfe [55] signal). These signals are correlated with the unWISE galaxies [56,57,92–94] and, as demonstrated in Supplemental Material [48], bias our measurement of the cross-correlation if not removed. The tSZ effect has a well-understood spectral dependence [58] and can therefore be deprojected exactly (as can the blackbody CMB). The spectral dependence of the CIB is less well known, but we remove it by performing a Taylor expansion around an estimate of a model for its frequency dependence following Ref. [59]; such a method was demonstrated to remove CIB contamination in an internal linear combination (ILC) setting in Refs. [51,60].

We also construct two other versions of the undeprojected (standard ILC) map with independent noise realizations, from the independent half-ring splits of the NPIPE maps. Their cross-power spectrum does not contain an instrumental noise term, and so indicates the contribution from only foregrounds and signal.

As shown in Fig. 1, foreground deprojection comes at the expense of an increase in variance, since the NILC weights are constrained to explicitly remove the foregrounds rather than solely minimize the variance of the resulting map. This has the effect of weakening the sensitivity to dark screening, but increasing the robustness and interpretability of our results. We provide further details about the map making procedure, including stability tests of the foreground removal, in Supplemental Material [48].

Data and measurement: LSS tracer (unWISE galaxies)—We cross-correlate our dark screening map with galaxy catalogs extracted from unWISE [33–36]. We use both the “blue” and “green” unWISE samples described in Refs. [37,95]. These catalogs comprise objects from a broad range of redshifts, with the blue sample at median redshift $\bar{z} \sim 0.6$ and the green sample at $\bar{z} \sim 1.1$. We convert the green and blue galaxy number density maps $n_g(\hat{n})$ into overdensity maps by measuring the mean galaxy density $\bar{n}$ and calculating

$$\delta_g(\hat{n}) = \frac{n_g(\hat{n}) - \bar{n}}{\bar{n}}. \quad (4)$$

These catalogs have previously been used in various CMB cross-correlation analyses, including as a tracer of matter and galaxy overdensities for CMB lensing cross-correlations [95–97] and of electron overdensities for kinetic SZ cross-correlations [49,57,61,98] and patchy Thomson screening cross-correlations [61]. In this work, we similarly use these maps to trace the electron distribution.

Cross-correlation measurement—We use PYMASTER [99,100] to estimate the mask-decoupled cross-power spectrum between the NILC foreground-deprojected dark

screening map and the unWISE maps. We apply the unWISE mask to the galaxies (retaining 51% of the sky) and the union of the apodized preprocessing mask and the *Planck* 70% Galactic Plane mask to the dark screening map (retaining 56.5% of the sky). The masks are described in Supplemental Material [48].

We measure power spectra in multipole bins of width $\Delta\ell = 150$, starting at $\ell = 5$. We do not use the largest-scale data point in our theoretical interpretation as it has a very large error bar (and is slightly unstable with respect to the choice of frequency coverage in the NILC). Our lowest multipole bin thus corresponds to $155 \leq \ell < 305$.

As described in greater detail in Supplemental Material [48], we find that our cross-correlation measurement is unstable to the removal of the lowest-frequency channels from the ILC, suggesting a residual extragalactic contribution from some other source in the NILC map. We expect that this is synchrotron emission from extragalactic radio sources, which we have not explicitly deprojected in the ILC.

To assess the size of a possible radio bias, we directly measure the cross-correlation between our dark screening map and a catalog of radio-selected objects from the Very Large Array Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey [62]. The FIRST sources are detected via bright emission at 1.4 GHz, a much lower frequency than those used in our NILC. We detect a correlation coefficient of $\approx 10\%$ – 20% between the FIRST sources and the unWISE samples. Additionally, the cross-correlation between our dark screening map and the FIRST catalog is positive and much higher than the cross-correlation between the dark screening map and the unWISE maps, indicating that there is some emission remaining in the NILC map that is more correlated with the radio sources than with unWISE. We build a template for the residual radio-unWISE signal $C_\ell^{g^j \text{radio}}$ as follows:

$$C_\ell^{g^j \text{radio}} = \frac{\hat{C}_\ell^{\text{FIRST } g^j}}{\hat{C}_\ell^{\text{FIRST FIRST}}} \hat{C}_\ell^{\text{FIRST } \tilde{T}_{353 \text{ GHz}}^{\text{disc}}} \quad (5)$$

where $\hat{C}_\ell^{X, \text{FIRST}}$ is the measured cross-power spectrum of map X with the FIRST map. This bias is small (equivalent in amplitude to a DP signal corresponding to $\varepsilon \sim 5 \times 10^{-8}$ in our most sensitive mass range, but with opposite sign). We describe this bias template in further detail in Supplemental Material [48]. The bias can be measured for NILC maps constructed with different sets of frequency maps, and we find that upon subtraction of this bias the cross-correlation measurements become stable with respect to the choice of frequency coverage. Thus, in the following analysis we use the NILC map constructed from all eight *Planck* channels between 30 and 545 GHz, which yields the tightest constraints on ε and shows no evidence of additional bias. We validate our full pipeline, including the

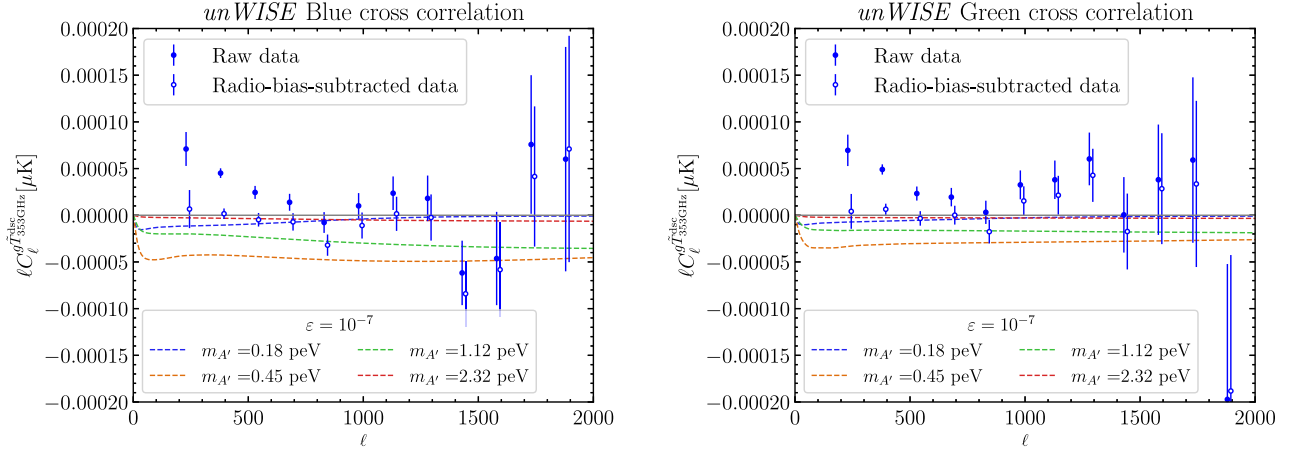


FIG. 2. The measured cross-correlation of our dark screening map with the unWISE blue (left) and green (right) galaxy samples. In both cases we show theoretical predictions for the signal for a range of DP masses to which these measurements are sensitive (roughly 10^{-13} eV $\lesssim m_{A'} \lesssim 10^{-11}$ eV) and with $\varepsilon = 10^{-7}$. We show both the raw cross-power spectrum data and the data with the radio-bias subtracted, which are offset slightly horizontally for clearer visualization.

radio-bias subtraction, with a signal injection test in Supplemental Material [48].

The measured cross-power spectra, before and after radio-bias subtraction, are shown in Fig. 2. We compute the mask-deconvolved covariance matrix for the cross-power spectrum assuming that the two maps are uncorrelated Gaussian random fields with underlying power spectra given by their measured power spectra [100,101]. Note that, by comparison with Fig. 1, it is clear that the cross-correlation is a more sensitive probe of ε than the autopower, confirming the forecasts of Ref. [3].

The χ^2 with respect to null for each of the samples, including the 12 data points, with the radio-bias subtracted, in the ℓ range we analyze, are 17.71 for blue, 9.85 for green, and 26.80 for the combination (including their covariance). The associated probability-to-exceed values are 0.12, 0.63, and 0.31, respectively, indicating consistency with no detection.

Constraints on dark photon parameters—As $C_{\ell}^{g^i \tilde{T}^{\text{dsc}}}$ is proportional to ε^2 , we construct a Gaussian likelihood for ε^2 ,

$$-2\ln\mathcal{L}(\mathbf{d}; \varepsilon^2, m_{A'}) = (\mathbf{d} - \varepsilon^2 \mathbf{C}_{\ell}^{g^i \tilde{T}^{\text{dsc}}}(m_{A'}))^T (\mathbf{C}_{\ell\ell'}^{ij})^{-1} (\mathbf{d} - \varepsilon^2 \mathbf{C}_{\ell}^{g^i \tilde{T}^{\text{dsc}}}(m_{A'})), \quad (6)$$

where $\mathbf{d}$ is the measured power spectrum data vector (with the radio-bias subtracted) and $\mathbf{C}_{\ell}^{g^i \tilde{T}^{\text{dsc}}}(m_{A'})$ is the theoretical model for this data vector (see Supplemental Material [48]) for DP mass $m_{A'}$, with the index i, j denoting either the blue or green unWISE sample. The covariance matrix $\mathbf{C}_{\ell\ell'}^{ij} \equiv \text{Cov}(C_{\ell}^{g^i \tilde{T}^{\text{dsc}}}, C_{\ell'}^{g^j \tilde{T}^{\text{dsc}}})$ is computed using PYMASTER to decouple the mask from the standard full-sky expression for uncorrelated Gaussian fields,

$$\text{Cov}(C_{\ell}^{g^i \tilde{T}^{\text{dsc}}}, C_{\ell'}^{g^j \tilde{T}^{\text{dsc}}}) = \frac{C_{\ell}^{\tilde{T}^{\text{dsc}} \tilde{T}^{\text{dsc}}} C_{\ell'}^{g^i g^j} \delta_{\ell\ell'}}{2\ell + 1}, \quad (7)$$

where $C_{\ell}^{\tilde{T}^{\text{dsc}} \tilde{T}^{\text{dsc}}}$ and $C_{\ell}^{g^i g^j}$ include all sources of signal and noise in the $\tilde{T}^{\text{dsc}}$ and g^i fields, respectively. In practice (and, in particular, in the absence of a model for all sources of noise and foregrounds in the $\tilde{T}^{\text{dsc}}$ field), we use the measured autopower spectra in place of models to evaluate Eq. (7).

We scan over a range of DP mass 1.3×10^{-13} eV $\leq m_{A'} \leq 8.3 \times 10^{-12}$ eV and compute $\mathcal{L}(\mathbf{d}; \varepsilon^2, m_{A'})$. For each

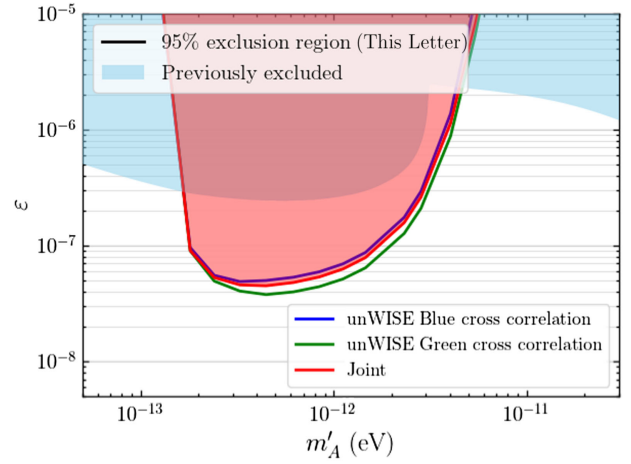


FIG. 3. 95% confidence upper limit constraints on ε (excluded regions indicated in shaded colors). We show our constraints derived from the unWISE blue and green cross-correlations (in blue and green, respectively), as well as the joint constraint in red. We also show previous constraints on ε [23,25], derived using CMB monopole data from the Cosmic Background Explorer Far-Infrared Absolute Spectrophotometer [30] to constrain the average spectral distortion induced by resonant conversion of CMB photons into DPs.

$m_{A'}$, we adopt a uniform prior on ε over the domain $\varepsilon > 0$. The derived 95% confidence upper limits on ε as a function of $m_{A'}$ are shown in Fig. 3. The DP mass to which we are most sensitive is $m_{A'} \simeq 4 \times 10^{-13}$ eV. We find $\varepsilon \lesssim 5 \times 10^{-8}$ for most of our mass range, almost an order-of-magnitude improvement compared to previous constraints.

To calculate these constraints, we hold fixed the parameters describing the electron distribution (to the AGN feedback model of Ref. [50]) and the galaxy HOD models. We demonstrate the validity of this approach in Supplemental Material [48].

Conclusion and remarks—We have improved constraints on the kinetic mixing parameter of the DP in the mass range 10^{-13} eV $< m_{A'} < 10^{-11}$ eV by almost an order of magnitude, using a foreground-cleaned cross-correlation between LSS tracers and the anisotropic dark screening induced by resonant conversion of CMB photons into DPs. This is the first time that a CMB-LSS cross-correlation has been used to derive a constraint on light bosons in the dark sector and demonstrates the power of such methods to constrain BSM physics.

Improvements in the analysis can be made with higher-sensitivity CMB experiments and deeper samples of LSS tracers. In addition, different DP masses can be probed by using LSS tracers that are sensitive to regions with different photon plasma mass, i.e., different electron densities. Theoretical calculations of such signals are underway. This method can also be adapted to search for patchy dark screening from axions [4]; this is ongoing work.

This work made use of the HEALPY library [102,103] (the PYTHON implementation of HEALPix [104]), as well as heavy use of NUMPY [105].

Note added—Recently, an analysis appeared on arXiv [106], utilizing the temperature autocorrelation at 70 GHz to search for the patchy dark screening signal from dark photons. Our work improves on theirs both through the use of component separation and cross-correlation, an estimator shown to give stronger constraints than the autopower in Ref. [3].

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Data availability—We make our NILC dark screening maps public at [107].

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