Probing Dark Matter with Future CMB Measurements

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Dark Matter (DM) annihilation and decay during the Dark Ages can affect the cosmic ionization history and leave imprints in the Cosmic Microwave Background (CMB) anisotropy spectra. CMB polarization anisotropy can be sensitive to such energy injection at higher redshifts and help reducing degeneracy with primordial spectral parameters in ΛCDM and astrophysical ionization processes during reionization. In light of a number of upcoming CMB polarization experiments, such as AdvACTPol, AliCPT, CLASS, Simons Observatory, Simons Array, SPT-3G, we estimate their prospective sensitivity in probing dark matter annihilation and decay signals. We find that future missions have 95% C.L. projected limits on DM decay and annihilation rates to orders of \( \Gamma_\chi (\tau_\chi^{-1}) \sim 10^{-25}\text{s}^{-1} \) and \( (\sigma v)/m_\chi \sim 10^{-20}\text{cm}^3\text{s}^{-1}\text{GeV}^{-1} \) respectively, significantly improving the sensitivity to DM from current experimental bounds.

I. INTRODUCTION

The majority of cold matter in the Universe exists in the form of non-luminous, non-baryonic Dark Matter (DM). A Weakly Interacting Massive Particle (WIMP) is a well-motivated particle physics candidate that explains the relic abundance of the Universe, and also provides rich phenomenology and potential detection. Tremendous efforts have been invested for WIMP dark matter searches using terrestrial or space-borne experiments. In addition to dedicated direct and indirect searches, the Cosmic Microwave Background (CMB) also provides an avenue for WIMP detection [1–3], which has gained increasing interest [4–9], especially with the availability of precision data from Planck [10, 11] experiment.

Thermally produced WIMP dark matter generally may annihilate or decay into the SM particles that subsequently become electromagnetically interacting electrons and photons. During the cosmic dark ages, this extra budget of energetic particle injection can heat up and ionize an amount of the neutral baryonic gas. Increased fraction of free electrons enhances the scattering of CMB photons during its propagation that leaves measurable imprints on the temperature and polarization anisotropy spectra of CMB. High-precision CMB measurement can place stringent limits on post-recombination annihilation and decay for dark matter over a wide mass range. The latest Planck 2018 results [5] report constraints on weak-scale DM annihilation cross-section that are comparable to the diffuse gamma ray bound given by combined analysis of Fermi-LAT and MAGIC data [12]. In addition, the relatively lower energy requirement for hydrogen ionization allows such limits to extends into much lower mass ranges, effectively filling the gap between X-ray and gamma ray indirect searches.

Energy injection from dark matter modifies CMB anisotropy mostly via the ionization of intergalactic medium (IGM). In temperature anisotropy spectrum, such injection is known to be degenerate with several cosmological parameters that affect the spectral shape [2] , such as the magnitude \( (A_s) \) and the power index \( (n_s) \) of primordial scalar perturbation, as well as the optical depth \( (\tau) \). Polarization anisotropy spectra helps breaking these degeneracies and gives tighter DM constraints. With Planck 2018 data [10], which sets the most stringent bounds compared with other current CMB datasets such as BICEP2/KECK Array [13] and SPTpol [14], constraints on DM annihilation cross section given by temperature (TT) spectra alone can be improved by about one order of magnitude with the inclusion of polarization (EE) and cross-correlation (TE) spectra.

A number of operating or planned CMB experiments are expected to offer higher precision polarization data that may further enhance the sensitivity to dark matter annihilation and decay. These experiments include BICEP3/KECK Array [15] and South Pole Telescope-3G [16] in Antarctica, Advanced Antacama Cosmology Telescope Polarimeter (AdvACTPol) [17, 18], Cosmology Large Angular Scale Surveyor(CLASS) [19], Simons Array [20, 21] and Simons Observatory [22] in Chile, and Ali CMB Polarization Telescope (AliCPT) [23] in China that aims at the northern hemisphere.

In this paper we investigate the WIMP detection prospects of the upcoming CMB polarization experiments in a mass range of 10 KeV - 10 TeV, where the WIMPs are heavy enough so that their annihilation and decay products can efficiently ionize the neutral gas of the Universe. In the following Section II we briefly discuss the energy injection and deposition as well as the late-
time clustering enhancement in annihilation rate. Section III discusses the impact of energy injection on the recombination history and CMB anisotropy, where we also comment on the role of polarization data in reducing parameter degeneracies. Section IV presents our forecasting method and analysis results, then we conclude in Section V.

II. ENERGY INJECTION AND DEPOSITION

Assuming dark matter $\chi$ converts all its mass into the energy of annihilation and decay products, the energy injection rate per unit volume is

$$\left(\frac{dE}{dVdt}\right)_{\text{INJ}} = \begin{cases} m_\chi \Gamma_\chi n_\chi e^{-\Gamma_\chi t} & \text{decay} \\ g \cdot 2m_\chi n_\chi^2 \langle \sigma v \rangle & \text{annihilation} \end{cases}$$ (1)

where $\Gamma_\chi$ is the DM decay width, defined as the inverse of decay lifetime ($\Gamma_\chi = \tau_\chi^{-1}$). $g$ is a symmetry factor that equals 1/2 for self-conjugate dark matter, and 1/4 otherwise due to halving the number density between $\chi$ and $\bar{\chi}$. We will take $g = 1/2$ throughout this paper. $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section, here we only consider $s$-wave annihilation for which $\langle \sigma v \rangle$ is invariant. The average DM number density $n_\chi = \rho_c\Omega_\chi (1 + z)^3/m_\chi$, where $\Omega_\chi, \rho_c$ are the cold dark matter fraction and the critical density of the Universe today. As the relevant decay lifetime is much longer than the age of Universe, hereafter we will ignore the factor $e^{-\Gamma_\chi t}$ in Eq. (1). The redshift dependent injection rates can be written as

$$\left(\frac{dE}{dVdt}\right)_{\text{INJ}}^{\text{dec}} = \Gamma_\chi \Omega_\chi (1 + z)^3 \rho_c$$ (2)

$$\left(\frac{dE}{dVdt}\right)_{\text{INJ}}^{\text{ann}} = \frac{\langle \sigma v \rangle}{m_\chi} \Omega_\chi^2 (1 + z)^6 \rho_c^2$$ (3)

note that homogeneous DM distribution is assumed in Eq. (3). The DM annihilation injection rate decreases faster as the Universe expands due to its dependence on higher power of $z$. As will be discussed later, the annihilation rate will be boosted at late time by the DM clustering after the formation of halos. In comparison, DM decay yields a more steady rate of energy injection.

The final state cascades in annihilation and decay events produce a variety of standard model particles, and over a cosmological time scale the metastable products eventually decay into the stable particles that include photons, electrons, protons and neutrinos. The impact on the intergalactic medium is dominated by photons and electrons. Neutrinos do not interact efficiently with baryonic matter and decouple from the picture, protons are subdominant in abundance and can be ignored [24].

The energetic photon and electrons lose their energy due to cosmic expansion, and also in a series of absorption and scattering processes with the CMB photons and the baryonic matter (mostly neutral gas), see Refs. [9, 25–28] for recent studies on the propagation and energy deposit of injected particles. Distortion in the CMB anisotropy is mostly due to increased ionization, and the most relevant energy deposit channels are

- Direct ionization of ground state neutral hydrogen;
- Excitation of neutral hydrogen atom from 1s to 2p state, contributing to indirect ionization.

A few other important energy loss channels are less effective in altering the anisotropy spectra: energy deposit into heating the IGM can cause dramatic rise in the gas temperature at low redshifts, yet the impact on anisotropy spectra is insignificant compared to ionization channels. Contribution from helium ionization is found to be subdominant compared to hydrogen [8] and is ignored in our calculation. A fraction of injected energy can also be deposited into changing the energy spectrum of CMB.

For highly relativistic injected particles, their energy deposition is a gradual process that continues to later times. For a given redshift, an effective efficiency $f_c$ represents the ratio between the rate of energy deposition to that of DM injection at the same redshift,

$$\left(\frac{dE}{dVdt}\right)_{\text{DEP}, c} = f_c \left(\frac{dE}{dVdt}\right)_{\text{INJ}}$$ (4)

here the subscript $c$ labels the deposition channel, DEP and INJ refer to deposition and injection rates respectively. The deposition efficiency $f_c$ depends on the particle species, its energy upon injection, the redshift, and accumulates over particles injected at earlier times. A previously popular scheme uses an “SSCK” prescription [1, 7, 29] that assumes a fraction $(1-x_c)/3$ of the energy deposit goes into ionization. Here, we will adopt $f_c$ from recent numerical analyses.

A. Deposition efficiency

The effective energy deposition efficiency $f_c$ can be constructed from a discretized deposit fraction coefficient $T_{c,ijk}(z_i, E_j, z_k)$ over redshift and energy bins, as given in Ref. [30], which describes the fraction of $E_j$ deposited into channel $c$ at redshift $z_i$, where $E_j$ is the particle’s initial kinetic energy at its injection redshift $z_k$. $f_c(z_i)$ is obtained by summing $T$ over all injection redshift bins prior to $z_i$,

$$f_c(z_i) \approx \sum_j \sum_k A_{jk} dV(z_k) dt(z_k) T_{c,ijk}$$ (5)

where

$$A_{jk} = E_j \left(\frac{dN}{dE_j dV(z_k) dt(z_k)}\right) dE_j$$ (6)

In Eq. (5), $dt(z)$ is the time interval corresponding to $d\ln(1+z) = 10^{-3}$. The numerator sums over contribution from earlier injection, and the denominator gives
the total energy injection at $z_i$. From Eq. (5) it is clear that $f_c$ for annihilation and decay scenarios are differently weighted over historical deposits. Also $f_c$ may exceed unity at late time due to accumulated injection.

We will consider direct production of $e^\pm$ and $\gamma\gamma$, for which the injection spectrum is monochromatic (at $E_j$),

$$\frac{dN}{dEdVdt} = \frac{1}{E_j} \left( \frac{dE}{dVdt} \right)_{INJ} \delta_D(E - E_j)$$

where $\delta_D$ refers to Dirac delta function. Eq.(5) can then be simplified as

$$f_c(z_i, E_j) = \frac{H(z_i)}{(1 + z_i)^{\beta}} \sum_k T_{\epsilon,ijk}(1 + z_k)^{\beta}$$

where $\beta = 0$ for DM decay and $\beta = 3$ for DM annihilation, note that we used $H(z) = -d\ln(1 + z)/dt$.

**B. Clustering enhancement**

Structure formation at low $z$ let DM cluster into halos, and the DM density condensation enhances DM annihilation due to $\rho^2$ dependence. This enhancement over unclustered average-density annihilation is formulated as a 'boost factor' $B(z)$ [8],

$$\left( \frac{dE}{dVdt} \right)_{ANN,boosted}^{\INJ} = [1 + B(z)] \left( \frac{dE}{dVdt} \right)_{ANN}^{\INJ}$$

The overall boost is obtained by integrating over the contribution from halos [31],

$$B(z) = \frac{\Delta_c \rho_c}{\rho_{DM}} \int_{M_{min}}^{\infty} MB_h(M) \frac{dn}{dM} dM$$

where $\Delta_c \rho_c$ is the average density of bound halos, in subsequent analysis we will assume $\Delta_c = 200$ and use a cutoff of $M_{min} = 10^{-6} M_\odot$ as a reasonable estimate for the minimum halo mass. $B_h(M)$ is the enhancement from an individual halo of mass $M$,

$$B_h(M) = \frac{4\pi}{3} \bar{\rho}_h V_h(M) \int_0^{r_{200}} dr r^2 (\rho - \bar{\rho})$$

here $\bar{\rho}_h$ gives the average density of the halo distributed within volume $V_h(M)$. $\rho(r)$ describes the radial density profile, truncated at a virial radius $r_{200}$. We consider spherical collapse model of halo formation, for which the mass function is given by Ref. [32, 33],

$$\frac{dn}{dlnM} = \frac{1}{2} f(\nu) \rho_{DM} \frac{dln(\nu)}{dlnM}$$

$$f(\nu) = A \sqrt{\frac{2q^p}{\pi}} [1 + (q \nu)^{-p}] e^{-q \nu/2}$$

with $A = 0.3222$, $p = 0.3$, $q = 0.707$ and the scaled variable $\nu \equiv [\delta_{cr}/(\sigma(M)D(z))]^2$, where $\delta_{cr} \approx 1.686$, $\sigma(M)$ is the rms linear overdensity and $D(z)$ is the growth factor normalized to unity today.

We ignored further boost from halo substructures and used a typical cuspy Einasto profile [34] for the main halo,

$$\rho(r) = \rho_{-2} \exp \left( -\frac{2}{\alpha_e} \left( \frac{r}{r_{-2}} \right)^{\alpha_e} \right)$$

where $\rho_{-2}, r_{-2}, \alpha_e$ are halo profile parameters, assumed to follow the empirical relations given in Ref. [35], $\alpha_e = 0.115 + 0.0165 \mu^2$, and $r_{200}/r_{-2} = 6.5 \mu^{-1.6} (1 + 0.21 \mu^2)$, where $\mu \equiv \delta_{cr}/\sigma(M)$. $B(z)$ reaches unity around $z = 45$ and increases dramatically afterwards, giving $B = 783$ at $z = 20$. Having acquired the boost factor, we can account for the clustering enhancement by using a 'boosted' version of the deposition efficiency for annihilation,

$$f_c^{boost}(z_i, E_j) = \frac{H(z_i)}{(1 + z_i)^{\beta}} \sum_k T_{\epsilon,ijk}(1 + z_k)^{\beta} (1 + B(z_k))$$

**III. IONIZATION HISTORY**

DM induced energy deposit can be incorporated into the ionization and IGM temperature evolution equations as [1, 6]

$$\frac{dx_e}{dz} = \left( \frac{dx_e}{dz} \right)_0 - \frac{I_\chi}{(1 + z)H(z)}$$

$$\frac{dT_{IGM}}{dz} = \left( \frac{dT_{IGM}}{dz} \right)_0 - \frac{2}{3k_B (1 + z)H(z)} \frac{K_h}{1 + f_{He} + x_e}$$

where $x_e$ and $T_{IGM}$ are the ionization fraction and IGM temperature. $K_h$ is the Bolzmann constant and $f_{He}$ is the helium fraction. The terms with subscript 0 represents the unaltered evolution equations in standard cosmology [8, 36]. $I_\chi$ and $K_h$ are the ionization and heating terms introduced by DM. Enhancement to the IGM temperature does not directly contribute to altering the anisotropy spectra, but it is of interest for the epoch of reionization observations. The ionization term $I_\chi$ can be further decomposed into hydrogen ionization from ground state ($I_{\chi H}$) and from $n = 2$ state ($I_{\chi He}$),

$$I_{\chi H}(z) = \frac{1}{n_{He}(z)} E_i \left( \frac{dE}{dVdt} \right)_{DEP,i}$$

$$I_{\chi He}(z) = \frac{1 - C}{n_{He}(z)} E_{He} \left( \frac{dE}{dVdt} \right)_{DEP,He}$$

and the IGM heating term $K_h$ reads

$$K_h(z) = \frac{1}{n_{IGM}(z)} \left( \frac{dE}{dVdt} \right)_{DEP,h}$$

where the subscripts $i, \alpha, h$ denote the corresponding deposition channels that was indicated by the subscript $c$ in
FIG. 1. Illustrative ionization fraction (top) and intergalactic medium temperature (bottom) evolution for DM annihilation (ann) and decay (dec) into $e^-e^+$, assuming DM mass $m_\chi = 1\text{GeV}$. Both annihilation (red) curves assume $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$/s where the dashed/solid linetypes denote the annihilation scenario with/without late-time halo boost. For DM decay (blue) the dashed/solid curve represents a decay lifetime at $10^{24}/10^{25}$ s respectively. The standard evolution of ionization fraction and IGM temperature without DM injection are shown in solid black curves. CMB temperature is shown in the lower panel (black dashed) for comparison. The legend applies to all panels.

previous sections. $n_H$ is the number density of hydrogen nuclei, $E_i = 13.6$ eV is the ionization energy for ground state hydrogen atom, and $E_\alpha = 10.2$ eV is the difference in binding energies between the 1s and 2p states. $C$ is the probability for an $n = 2$ state hydrogen atom to transit back to $n = 1$ state before it gets ionized \[1, 6\].

We used modified HyRec [36] and the CAMB [37] codes to calculate the ionization and temperature history prior to reionization, and the corresponding CMB anisotropy spectra. Fig. 1 shows the ionization fraction and IGM temperature evolution for a few example annihilation and decay scenarios. It shows both DM annihilation scenarios at the thermal relic’s typical cross-section, and DM decay at the currently allowed rate $10^{-25}$ s$^{-1}$ can lead to order of magnitude increase in the ionization fraction and IGM temperature. The corresponding anisotropy $C_\ell$ spectra are shown in Fig. 2.

Energy deposits from DM will increase the ionization fraction and IGM temperature after recombination, this broadens the surface of last scattering and suppresses CMB temperature correlation on scales smaller than the width of the surface. However, this effect is inconveniently degenerate with several cosmological parameters: the spectral index ($n_s$) and amplitude ($A_s$) of the primordial perturbation spectrum, and the optical depth ($\tau$) that strongly depends on modeling of the reionization history. Fortunately energy injection near recombination is shown to cause visible shifting in polarization anisotropy peaks while enhancing EE correlations at large scales [2], allowing polarization data to break degeneracy with the spectral amplitude and tilt. In addition, this high-z injection dependence significantly reduces degeneracy with the overwhelming astrophysical injection at reionization epoch.

FIG. 2. CMB TT (top), TE (middle), EE (bottom) anisotropy spectra for the same injection scenarios as in Fig. 1.
Fig. 3. Marginalized 68% (dark) and 95% (light) CL constraints on DM injection (parameterized by \(\langle \sigma v \rangle / m_\chi\)) and several base ΛCDM parameters, set by Planck 2018 TT (left) and TT+TE+EE (right) data. DM mass is 100 GeV and assumed to annihilate into \(e^- e^+\) under homogeneous distribution scenario.

Fig. 3 visualizes the correlation between DM annihilation injection (parameterized by \(\langle \sigma v \rangle / m_\chi\)) and the leading cosmological parameters that cause similar spectral changes. The constraints are obtained by fitting Planck 2018 TT data (left) and TT+TE+EE data (right) with the CosmoMC codes [38, 39]. Tilting in the elliptical contour’s axis indicate parameter correlation. The resulting linear correlation coefficients between \(\langle \sigma v \rangle / m_\chi\) and six relevant cosmological parameters are listed in Tab. I. With the inclusion of polarization we observe a significant reduction of parameter degeneracies.

DM clustering boost has a huge impact on \(x_\tau\) and \(T_{\text{kin,GM}}\) at late time. However, because CMB is rather insensitive to energy injection at low redshifts, the changes to the anisotropy spectra is relatively minor, as demonstrated most evidently in TT and EE panels in Fig. 2.

### IV. Sensitivity Estimates

Several upcoming observations are expected to conduct high precision measurement of CMB polarization anisotropy at μK-arcmin sensitivities with arcmin beams, including AdvACTPol [17, 18], AliCPT [23, 40], CLASS [19], LiteBird [41], Simons Array [20, 21], Simons Observatory [22], SPT-3G [16], and many more proposed for the future [42–45]. We will study the expected sensitivities on DM injection of a few missions that are either already operational or will be so in near future.

#### A. Forecasting Procedure

Assuming null signal, a sensitivity bound on DM energy injection can be placed by testing the spectral deviation from fiducial TT, TE and EE anisotropy spectra \(\hat{C}_\ell\) that serve as fake data. We use the “exact full sky” likelihood function [46] for significance calculation,

\[
-2\ln\mathcal{L}(\{\hat{C}_\ell\}|\{\tilde{C}_\ell\}) = f_{\text{sky}} \times \sum_\ell (2\ell + 1) \{\text{Tr}[\hat{C}_\ell^{-1} - \ln\hat{C}_\ell^{-1}] - 2\} 
\]

where \(f_{\text{sky}}\) is the fraction of sky covered by an experiment, \(C_\ell\) is a function of cosmological and DM parameters, while \(\hat{C}_\ell\) is a simulated anisotropy spectra serving as mocked data. With both temperature (T) and polarization (E) correlations, \(C_\ell\) and \(\hat{C}_\ell\) are \(2 \times 2\) matrices:

\[
C_\ell = \begin{bmatrix} C_{TT,\ell} & C_{TE,\ell} \\ C_{TE,\ell} & C_{EE,\ell} \end{bmatrix} 
\]

\[
\hat{C}_\ell = \begin{bmatrix} \hat{C}_{TT,\ell} + N_{TT,\ell} & \hat{C}_{TE,\ell} \\ \hat{C}_{TE,\ell} & \hat{C}_{EE,\ell} + N_{EE,\ell} \end{bmatrix} 
\]

The fixed ‘fiducial’ \(\tilde{C}_\ell\) is generated using Planck 2018 best-fit [5] ΛCDM parameters (\(\Omega_M h^2 = 0.224\), \(\Omega_b h^2 = 0.1193\), \(100\theta_{MC} = 1.041\), \(\tau = 0.056\), \(\ln(10^{10} A_s) = 3.047\), \(n_s = 0.967\), \(h = 0.677\)), without DM injection. \(N_{TT,\ell}\) and \(N_{EE,\ell}\) are the instrumental white noise power spectra, for a multi-frequency CMB experiment they are given by

| Parameter | TT | TT,TE,EE |
|-----------|----|-----------|
| \(\tau\)  | -0.22 | -0.04 |
| \(n_s\)   | 0.59 | 0.14 |
| \(\ln(10^{10} A_s)\) | 0.17 | 0.27 |
| \(\Omega_b h^2\) | 0.17 | 0.07 |
| \(\Omega_M h^2\) | -0.08 | 0.16 |
| \(100\theta_{MC}\) | -0.37 | -0.28 |

**TABLE I.** Linear correlation coefficients between \(\langle \sigma v \rangle / m_\chi\) and cosmological parameters corresponding to Fig. 3.
where the subscript $\nu$ labels the frequency channel, $\omega_{E,\nu}$ is the white noise level in $\mu k \cdot \text{rad}$. $\theta_{\text{FWHM},\nu}$ denotes the full width at half maximum beam size in radians. Specifications for experiments considered are collected in Appendix A.

In addition to detector noises, residual foreground would be a contamination that contributes to $C_{\ell}$. However it is beyond the scope of this paper to make robust foreground removal estimate for each experiment, and we present the results assuming the anisotropy foreground has been successfully subtracted.

**B. Prospective limits**

Here we present the prospective limits of DM annihilation and decay rates. Both $m_X^{-1}(\sigma v)$ and $\Gamma_X$ are considered time and velocity independent. The dark matter parameters $m_X$, $m_X^{-1}(\sigma v)$ and $\Gamma_X$ are included into CosmoMC as new variables. We always allow all $\Lambda\text{CDM}$ parameters to vary and derive fully marginalized bounds. CosmoMC uses a preset Gelman-Rubin “mean of chain variance” $R$ value as the convergence criterion in the Markov chain process, and we ensure $R-1 \leq 0.01$ in the results.

First we analyze the limit with Planck 2018 [10] and Baryon Acoustic Oscillations (BAO) [49–51] data as a cross-check and a benchmark. The Planck likelihoods used are: (i) the high-$\ell$ TTTEEE plike likelihood, (ii) low-$\ell$ TT and EE likelihoods, (iii) lensing likelihood. Nuisance parameters of Planck likelihoods are also varied in the fitting process and marginalized in our results. As shown in Fig. 4, our 95% C.L. limits for annihilation (red dotted curves) are in good agreement with Ref. [5] (We also found good consistency with the results in Ref. [6] and [8] using Planck 2015 data). Compared with current Planck limits, upcoming experiments yield either comparable or significantly improved bounds. When the limits are close to Planck bounds it benefits from a joint analysis. For instance AliCPT sensitivity improves by around 30% if combined with Planck data. Projected limits for SPT-3G and CLASS extend to $\langle \sigma v \rangle / m_X \sim 10^{-28}\text{cm}^3\text{s}^{-1}\text{GeV}^{-1}$ and $\Gamma_X \sim 10^{-26}\text{s}^{-1}$. AdvACTPol, Simons Array and Simons Observatory are estimated to be sensitive to $\langle \sigma v \rangle / m_X \sim 10^{-29}\text{cm}^3\text{s}^{-1}\text{GeV}^{-1}$ and $\Gamma_X \sim 10^{-27}\text{s}^{-1}$. We also found that BICEP2/KECK Array 2018 [13] places 95% C.L. upper bounds at $\langle \sigma v \rangle / m_X \sim 10^{-26}\text{cm}^3\text{s}^{-1}\text{GeV}^{-1}$ and $\Gamma_X \sim 10^{-23}\text{s}^{-1}$, which are less stringent than Planck.

**V. CONCLUSION**

WIMP decay and annihilation during the cosmic dark ages can inject highly energetic particles into the intergalactic medium, which then ionizes and heats up the neutral gas. This widens the last scattering surface, attenuating polarization and temperature fluctuation on small scales while shifting peak locations of polarization anisotropy spectra.

In this paper we made DM sensitivity forecast for several upcoming CMB experiments in detecting dark matter in 10 KeV - 10 TeV mass range that decay or annihilate into $e^-e^+/\gamma\gamma$. These experiments are either already operational or undergoing construction, including AdvACTPol, AliCPT, CLASS, Simons Array, Simons Observatory and SPT-3G. Assuming complete foreground removal, we found that these instruments are capable of significantly improving current CMB constraints on DM decay lifetime and annihilation cross section set by Planck satellite, with AdvACTPol and Simons Array giving 95% CL upper bounds of $\langle \sigma v \rangle / m_X \sim 10^{-29}\text{cm}^3\text{s}^{-1}\text{GeV}^{-1}$ for annihilation and $\Gamma_X \sim 10^{-27}\text{s}^{-1}$ for decay, nearly two orders of magnitudes more stringent than Planck bounds. Assuming a thermal relic cross section ($\langle \sigma v \rangle = 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$), annihilation constraints from Simons Array can be translated into DM mass lower bounds of $m_X > 400\text{GeV}$ for $e^-e^+$ channel, and $m_X > 600\text{GeV}$ for $\gamma\gamma$ channel. These limits span over a wide range of DM mass that fills the energy gap in indirect cosmic X-ray and $\gamma$-ray searches, and further tightens the lower bounds on the mass of thermally produced dark matter.

DM injection induces distinctly different patterns of deviation in temperature and polarization anisotropy
FIG. 4. Marginalized constraints on DM decay (top panels, $\langle \sigma v \rangle / m_\chi = 0$) and annihilation (middle and bottom panels, $\Gamma_\chi = 0$) parameters. Regions above the lines are excluded at 95% confidence level. All annihilation constraints assume the case with DM clustering unless labeled otherwise. Constraints labeled Planck are obtained by fitting Planck2018 [10] + BAO [49–51] datasets. Left and right panels correspond to $e^- e^+$ and $\gamma\gamma$ final states respectively. The bottom panels show the constraints in $(\sigma v) - m_\chi$ plane corresponding to the $(\sigma v) / m_\chi - m_\chi$ constraints in middle panels. Planck constraints on annihilation in unclustered (homogenous) DM distribution model are also shown in red dotted lines for comparison. The legend applies to all panels.
spectra, which helps breaking the degeneracy between DM energy injection and cosmological parameters. High precision polarization measurements in the future will greatly improve CMB bounds on DM decay and annihilation.

DM clustering at low redshifts can have dramatic impacts on ionization fraction and IGM temperature. However, since CMB anisotropy is insensitive to late time energy injection, and also there are large uncertainties in astrophysical injection during the reionization epoch, constraints on DM annihilation set by CMB anisotropy are relatively unaffected by the details of structure formation. Future 21cm experiments with high precision reionization history measurement will greatly improve sensitivity to DM clustering.

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**Appendix A: Experimental Specifications**

| Experiment             | $\nu$[GHz] | $\omega_{\nu}^{-1/2}$ [µK-arcmin] | $\theta_{\text{FWHM}}$[arcmin] | $f_{\text{sky}}$[%] | $\ell_{\text{min}}$ | $\ell_{\text{max}}$ |
|------------------------|------------|----------------------------------|-------------------------------|---------------------|---------------------|---------------------|
| AdvACTPol [17]         | 90         | 11                               | 2.2                           | 50                  | 20                  | 4000                |
|                        | 150        | 9.8                              | 1.3                           |                     |                     |                     |
|                        | 230        | 35.4                             | 0.9                           |                     |                     |                     |
| AliCPT [54]            | 38         | 2                                | 15.4                          | 10                  | 30                  | 600                 |
|                        | 93         | 2                                | 9.7                           |                     |                     |                     |
| CLASS [19]             | 95         | 13.9                             | 5.2                           |                     |                     |                     |
|                        | 150        | 11.4                             | 3.5                           |                     |                     |                     |
|                        | 220        | 30.1                             | 2.7                           |                     |                     |                     |
| Simons Array [21, 55]  | 27         | 35.4                             | 93                            |                     |                     |                     |
|                        | 39         | 24                               | 63                            |                     |                     |                     |
|                        | 93         | 2.7                              | 30                            |                     |                     |                     |
|                        | 145        | 3                                | 17                            |                     |                     |                     |
|                        | 225        | 6                                | 11                            |                     |                     |                     |
|                        | 280        | 14.1                             | 9                             |                     |                     |                     |
| Simons Observatory - SAT [22] | 27   | 73.5                             | 7.4                           | 40                  | 20                  | 4000                |
|                        | 39         | 38.2                             | 5.1                           |                     |                     |                     |
|                        | 93         | 8.2                              | 2.2                           |                     |                     |                     |
|                        | 145        | 8.9                              | 1.4                           |                     |                     |                     |
|                        | 225        | 21.2                             | 1                             |                     |                     |                     |
|                        | 280        | 52.3                             | 0.9                           |                     |                     |                     |
| SPT-3G [16, 55]        | 95         | 5.1                              | 1                             |                     |                     |                     |
|                        | 150        | 4.7                              | 1                             | 6                   | 20                  | 4000                |
|                        | 220        | 12.0                             | 1                             |                     |                     |                     |

**TABLE II.** Specifications for experiments considered in our forecast. Following the prescription in [48], we set an $\ell_{\text{min}}$ floor of 20 for all ground-based experiments except for CLASS[19]. Maximum $\ell_{\text{max}}$ value is set to 4000.

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