

# Cosmic microwave background constraints on dark matter models of the Galactic center 511 keV signal

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The high positron production rate required to explain the flux of 511 keV gamma rays from the Galactic center has inspired many models in which dark matter creates positrons. These models include the annihilation of light dark matter and the scattering of dark matter with excited states (exciting dark matter). We show that existing cosmic microwave background data robustly constrain such models when the annihilation or scattering cross section is not velocity suppressed depending on the model of the Galactic dark matter halo. Upcoming data from the Planck mission can exclude the fiducial *Via Lactea II* halo model, which also provides a good fit to the 511 keV morphology. We additionally find combined constraints on exciting dark matter scattering and annihilation, and update constraints on the lifetimes of dark matter excited states. Finally, we apply constraints to models of dark matter decay in which produced positrons fall into the Galactic center and produce the 511 keV signal on their annihilation, demonstrating that most of the parameter space of interest is ruled out.

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## I. INTRODUCTION

A narrow line of 511 keV gamma rays from the Galactic center has been observed since the 1970s [1,2], indicating annihilation of  $\geq 10^{43}$  electron-positron ( $e^\pm$ ) pairs per second. This emission has been studied extensively by INTEGRAL/SPI since 2002 [3–10]. The spectrum indicates that  $\sim 97\%$  of the  $e^\pm$  annihilate through positronium formation, which limits the  $e^\pm$  injection energy to a few MeV or less, and a more detailed analysis finds that a significant majority of the annihilation occurs in warm neutral and ionized phases of the interstellar medium. Morphologically, the emission has two components, from the Galactic center bulge and from the Galactic disk. Depending on the model used, the bulge/disk ratio for  $e^\pm$  annihilation rates is  $\sim 1.5$ – $6$ .

Over the years, many models for the astrophysical production of mildly relativistic  $e^\pm$  have been proposed, although standard mechanisms have difficulty reproducing the observed morphology of the emission, particularly the large bulge/disk ratio; Ref. [11] gives a thorough review of not only the emission itself but also many  $e^\pm$  production mechanisms. One which has received a great deal of attention is the  $\beta^+$  decay of radionuclides produced in supernovae and heavy stars, which reproduces the disk emission well. References [12,13] have argued that, in a particular model of  $e^\pm$  transport, radionuclide decay can also source the bulge emission. On the other hand, as the review in Ref. [11] notes, the model of Refs. [12,13] relies on a number of apparently arbitrary assumptions about the interstellar medium and magnetic field (and its turbulence) in the bulge. Recently, Ref. [14] found that low-energy

positrons annihilate close to their production sites in a range of propagation models, so, in contradiction to Refs. [12,13], they find that radionuclides (produced mainly in the disk) cannot source the bulge emission. In any event, it is clearly premature to claim that standard astrophysical mechanisms can produce the Galactic bulge positrons.

Due to the lack of consensus on candidate astrophysical sources for the Galactic bulge emission, more exotic mechanisms have been of great interest in the past decade, including a number involving dark matter (DM). Roughly, DM models for the 511 keV excess may produce  $e^\pm$  pairs through the decay or scattering of DM particles. There are two cases of DM decay that produce  $e^\pm$  with only mildly relativistic injection energies: first, the DM itself can have an MeV-scale mass [15,16], or the DM can have several states with the decay through an MeV-scale mass gap producing an  $e^\pm$  pair [17]. In either case, assuming small  $e^\pm$  propagation after production, the 511 keV flux is proportional to the integral of  $\rho_{\text{DM}}$  along the line of sight. As the DM density is expected to increase toward the Galactic center, all these models naturally have a large bulge/disk ratio for  $e^\pm$  production. However, Refs. [18,19] showed that the INTEGRAL signal is more highly peaked toward the center of the Galaxy than realistic DM density profiles (even the most cuspy found in simulations), essentially ruling out decay of DM at either mass range as the source of the Galactic bulge  $e^\pm$  excess. Recently, Ref. [20] proposed a novel model in which a small fraction of DM decays, producing  $e^\pm$  outside the Galaxy; these  $e^\pm$  fall into the Galaxy and annihilate (preferentially in the Galactic center, as claimed in Ref. [20]).

Alternately, DM can produce  $e^\pm$  pairs through scattering processes. In the simplest such models, the DM has an

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MeV-scale mass, and the scattering process is direct annihilation to an  $e^\pm$  pair. These models and additional signatures have been studied extensively in Refs. [19,21–31]. Alternately, more massive DM with several states and MeV-scale mass gaps can scatter into an unstable excited state, which decays into the ground state via emission of an  $e^\pm$  pair, as discussed in Refs. [17,32–43]. (These are exciting dark matter, or XDM, models.) In these scattering models, the gamma-ray flux follows the line-of-sight integral of  $\rho_{\text{DM}}^2$ , so reasonable halo models can produce the observed signal; in fact, Ref. [18] has found that the halo model derived in the *Via Lactea II* simulation [44,45] has a maximum likelihood ratio very close to the peak value.

The lack of a strong astrophysical candidate for the Galactic bulge emission as well as the surprising (and striking) agreement between the emission morphology and simulated DM halos motivates us to search for other potential signals of DM scattering models, either as circumstantial evidence in favor of these models or as constraints on them in the case of nonobservation. For example, the XDM models discussed in Refs. [17,35,39,40,42] naturally include a several-hundred-MeV gauge boson with weak coupling to electric charge, which could be discovered at fixed-target experiments such as the Mainz Microtron [46] or APEX [47]. In this paper, we place constraints on XDM and light annihilating DM explanations based on limits from the cosmic microwave background (CMB) anisotropy spectrum; as we will review, energy injected into the Standard Model (SM) plasma around and after the era of recombination is tightly constrained by large- $l$  CMB anisotropies. As long as the XDM scattering or light DM annihilation cross section is not suppressed at low velocities, we find that these models for the 511 keV emission will be constrained by forthcoming results from the Planck satellite [48], specifically ruling out the preferred DM halo parameters from *Via Lactea II* (although there is sufficient uncertainty in both halo and DM model parameters to find a small allowed region consistent with *Via Lactea II*).

The plan of this paper is as follows. In the next section, we systematically review DM models for the production of mildly relativistic  $e^\pm$  in the Galactic center. In Sec. III, we present constraints on  $e^\pm$  creation during (and after) recombination from CMB anisotropies and discuss how they constrain XDM and annihilating MeV-mass DM models. Next, since XDM models contain decaying excited states of DM, we discuss how CMB observations provide constraints on those lifetimes, updating the results of Ref. [34], and also place constraints on the recent model of Ref. [20]. We conclude with a brief discussion of our results.

## II. DARK MATTER MODELS FOR THE 511 KEV EMISSION

As discussed above, the morphology of the 511 keV emission rules out models of DM decay as an explanation

for positron production in the Galactic center, so we will focus on models in which DM scattering processes produce  $e^\pm$  pairs. The rate of positron production in such models is

$$R = \eta s \bar{Y}^2 \int_{\text{bulge}} d^3\vec{x} \left( \frac{\rho_{\text{DM}}(\vec{x})}{M} \right)^2 \langle \sigma v_{\text{rel}} \rangle(\vec{x}), \quad (1)$$

where  $M$  is the DM mass,  $s$  is 1/2 for real/Majorana DM and 1/4 for complex/Dirac DM,  $\eta$  is the number of  $e^\pm$  produced per scattering event, and  $\bar{Y} = Y/Y_{\text{DM}}$  is the relative abundance of the active DM state. The value  $\sigma$  is the appropriate scattering cross section with relative velocity  $v_{\text{rel}}$ , and  $\langle \cdot \cdot \cdot \rangle$  is the average over the DM velocity distribution at position  $\vec{x}$ . We further write  $\langle \sigma v_{\text{rel}} \rangle = \overline{\sigma v} \langle F(v_{\text{rel}}) \rangle$ , where  $\overline{\sigma v}$  is the cross section at some representative relative velocity and  $F$  is a dimensionless model-dependent function of the relative velocity. The  $e^\pm$  production rate is  $R = 1.1 \times 10^{43} \text{ s}^{-1}$  [10].

We follow Ref. [42] in writing

$$R = 4\pi\eta s \bar{Y}^2 \rho_\odot^2 \frac{\overline{\sigma v}}{M^2} \zeta (\text{kpc})^3, \quad (2)$$

where  $\rho_\odot$  is the DM density in the solar neighborhood, which we take to be  $\rho_\odot = 0.4 \text{ GeV/cm}^3$  [49]. The value  $\zeta$  is

$$\zeta = \text{kpc}^{-3} \int_0^{r_c} dr r^2 (\rho_{\text{DM}}(r)/\rho_\odot)^2 \langle F(v_{\text{rel}}) \rangle, \quad (3)$$

where we take the bulge radius  $r_c = 1.5 \text{ kpc}$ , corresponding to the width of the INTEGRAL signal. We assume that the DM density follows an Einasto profile:

$$\rho_{\text{DM}}(r)/\rho_\odot = \exp[-(2/\alpha)((r/r_s)^\alpha - (r_\odot/r_s)^\alpha)], \quad (4)$$

with the Sun located at  $r_\odot = 8.5 \text{ kpc}$  and  $\alpha$  and  $r_s$  as free parameters. The *Via Lactea II* simulation is fit by  $\alpha = 0.17$ ,  $r_s = 25.7 \text{ kpc}$ , which also lies in the best-fit region of Ref. [18] for the 511 keV signal. Smaller values of  $\alpha$  and  $r_s$  lead to a more cuspy central halo. We assume that DM velocities follow a Maxwell distribution with dispersion  $v_0(r)$  cut off at the escape velocity  $v_{\text{esc}}(r)$ , satisfying

$$v_0(r)^3 \propto r^{1.64} \rho(r), \quad v_0(r_\odot) = 220\text{--}230 \text{ km/s}, \quad (5)$$

$$v_{\text{esc}}(r)^2 = 2v_0(r)^2 [2.39 + \ln(10 \text{ kpc}/r)] \quad (6)$$

as in Ref. [17] (the choice of escape velocity follows Ref. [50], and the velocity dispersion is suggested by simulations including baryonic contraction [51]).

We will consider three models in which DM scattering processes produce mildly relativistic positrons. The first is annihilation of MeV-scale DM, and the following two are endothermic and exothermic XDM, respectively. Finally, we will review a recent model by Ref. [20] in which decay of a metastable DM component creates  $e^\pm$  at late time which fall into the Galactic bulge.

### A. Annihilation of light dark matter

As first proposed by Ref. [21], DM particles of mass  $2m_e < M \lesssim 10$  MeV have a sufficient  $e^\pm$  production rate if they annihilate into  $e^\pm$  pairs with the appropriate cross section,  $\overline{\sigma v} \sim 10^{-31} (M/\text{MeV})^2 \text{cm}^3/\text{s}$ . As this cross section is several orders of magnitude smaller than required for the correct thermal relic abundance, either the annihilation is  $p$ -wave dominated or annihilation to  $e^\pm$  is subdominant to another channel, as in Ref. [28]. Morphological studies of the 511 keV signal using a similar profile for the velocity dispersion<sup>1</sup> disfavor  $p$ -wave annihilation [19], so we consider only the  $s$ -wave cross section. In this case,  $F(v_{\text{rel}}) = 1$ , and  $\zeta$  is simply the integral of  $\rho_{\text{DM}}^2$ . Figure 1 shows contours of  $\log \zeta$  (henceforth denoted as  $\zeta_{\text{ann}}$  for this model) as dashed lines as a function of  $\alpha$  and  $r_s$ . Additional signatures of these models have been considered in Refs. [22,24,25,28–31]. Finally, Refs. [26,27] placed constraints on MeV DM annihilation to  $e^\pm$  based on the CMB; our results extend and update those works.

### B. Endothermic exciting dark matter

XDM as first envisioned by Refs. [32,33,35] consists of a DM ground state (state #1) and an unstable excited state (state #2) with a mass splitting  $\delta M_{12} > 2m_e$ . DM collisions above a threshold velocity  $v_t$  populate the excited state, which then decays to the ground state by releasing an  $e^\pm$  pair. With  $M \sim \text{TeV}$  and  $\delta M_{12} \gtrsim 2m_e$ ,  $v_t$  is approximately the velocity dispersion of DM in our Galaxy. In order to reduce  $v_t$  or to accommodate lower DM masses (to  $\sim 5$ – $10$  GeV), consider that a significant fraction of DM remains in a metastable excited state (state #3), and upscattering of that state into the unstable state through a smaller mass gap  $\delta M_{32}$ , allowing a sufficient  $e^+$  production rate [17,36,37,39–41]. Direct detection of XDM has been considered in Refs. [17,37–39].

In these models, the fraction  $\bar{Y}$  of DM in the metastable excited state is determined by freeze-out of DM-DM scattering, as detailed in Ref. [17]. A potentially significant fraction of DM can be initially (after chemical and kinetic freeze-out) in the unstable excited state. Reference [34] has provided limits on the lifetime of this decay based on CMB measurements; our results in Sec. IV will update those constraints.

In these models,  $F(v_{\text{rel}}) = \sqrt{v_{\text{rel}}^2/v_t^2 - 1} \Theta(v_{\text{rel}} - v_t)$ , including both a phase space suppression and the kinematic threshold. As the kinetic energy of DM at recombination and later (before structure formation and virialization) is much too small to allow this upscattering, endothermic XDM is not subject to the CMB constraints discussed in Sec. III below.

<sup>1</sup>Our velocity dispersion decreases slightly less rapidly as  $r \rightarrow 0$  for a fixed density profile.

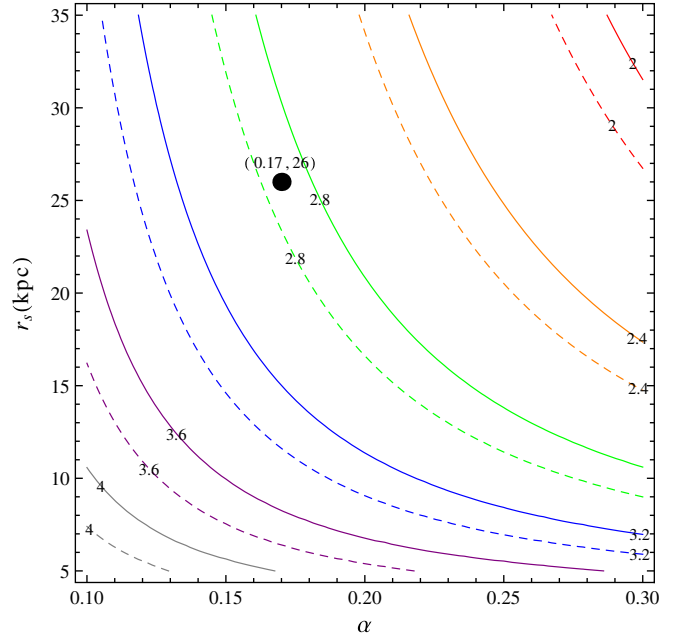


FIG. 1 (color online). Contours of  $\log \zeta_{\text{ann}}$  (dashed) and  $\log \zeta_1$  (solid) as a function of the Einasto profile parameters  $\alpha$  and  $r_s$ . The dot represents the *Via Lactea II* parameters.  $\zeta_1$  is calculated for  $v_t = 10^{-3}$ .

### C. Exothermic exciting dark matter

Another possibility is that the metastable DM excited state #3 scatters exothermically into the unstable excited state #2 [17]; in fact, this possibility is preferred when the DM is charged under an Abelian gauge group [42]. This downscattering process is not kinematically suppressed, so it can produce  $e^\pm$  pairs throughout recombination. In this case,  $F(v_{\text{rel}}) = \sqrt{v_{\text{rel}}^2/v_t^2 + 1}$ .<sup>2</sup> Very recently, Ref. [43] proposed an exothermic XDM model that also produces a gamma-ray line at the DM mass, simultaneously explaining a line at 130–135 GeV in Galactic center observations of the Fermi satellite [52–56] (see Ref. [57] for a review).

In exothermic XDM, we define the velocity  $v_t$  as the threshold velocity for the inverse upscattering process (or equivalently, as the velocity imparted to the less massive states for downscattering at rest). This is given by  $v_t = 2\sqrt{2\delta M_{23}/M}$  when both DM particles excite or deexcite in the scattering.<sup>3</sup> For example, a mass of  $M = 10$  GeV and  $v_t = 10^{-3}$  correspond to a mass splitting of 1.25 keV between the two excited states of DM. The solid contours in Fig. 1 show contours of  $\log \zeta$  (henceforth  $\zeta_1$  for exothermic XDM) as a function of the Einasto parameters  $\alpha$  and  $r_s$  for  $v_t = 10^{-3}$ . Compared to  $\zeta_{\text{ann}}$  at a fixed  $\alpha$ ,  $r_s$ ,  $\zeta_1$  is enhanced, and the enhancement increases as  $v_t$  decreases.

<sup>2</sup>There is a weak additional velocity dependence; details for scattering by gauge boson exchange are given in Ref. [17].

<sup>3</sup>Note a factor of 2 redefinition of  $v_t$  compared to Ref. [17].

As a result, contours of  $\log \zeta_1$  shift to the right as  $v_t$  decreases and approach the contours of  $\log \zeta_{\text{ann}}$  as  $v_t \rightarrow \infty$ . Since  $v_t \lesssim 10^{-3}$  typically requires additional fine-tuning, we consider the contours of Fig. 1 to give an estimate of the uncertainty in our modeling. In addition, constraints placed on models with  $v_t = 10^{-3}$  will be weaker than models with larger  $v_t$ , so we consider it to be a conservative choice.

The other phenomenology of exothermic XDM is similar to that of endothermic XDM. In some cases, the metastable state can decay to the unstable state by emission of a single x-ray photon; this signal can be near observable levels [17].

#### D. Infalling positrons from decaying dark matter

Recently, Ref. [20] proposed a new model of decaying DM which could provide a sufficient number of  $e^+$  to explain the 511 keV signal. In their model, DM has two states, a stable ground state and a metastable excited state with mass splitting  $\delta M \lesssim \text{GeV}$ . The excited state can decay to the ground state by emitting  $e^+$ , and the constraint on the mass splitting prevents antiproton production (although a more general model may be acceptable from that point of view). The  $e^+$  cool to nonrelativistic energies via scattering processes; some  $e^+$  in large orbits are only entering the Galaxy and annihilating in the present day. Assuming the ground and excited states are similar in mass, Ref. [20] found that  $\bar{Y}_{\text{rec}}/M \sim 5 \times 10^{-8} \text{ GeV}^{-1}$  yields a sufficiently strong gamma-ray signal (as above,  $\bar{Y}_{\text{rec}}$  is the fraction of DM in the excited state at recombination). This model is free from the morphological constraints of Refs. [18,19] because the DM decays occur outside the Galaxy, but no detailed morphological study has yet been performed. In Sec. IV, we will find constraints on this class of models independent of details of the decay.

### III. CONSTRAINTS ON SCATTERING AND ANNIHILATING DARK MATTER

Any energy injected into the SM intergalactic medium (IGM) from a hidden sector [as by weakly interacting massive particle (WIMP) annihilation] after matter-radiation equality modifies the recombination history of the Universe, which increases residual ionization. That increases the optical depth of the IGM and thickness of the last scattering surface, which slightly alters the CMB anisotropy spectrum, suppressing high multipole moments. As a result, there is a wide literature deriving constraints on excess energy injection based on CMB measurements, particularly due to DM decay or annihilation. For example, see Refs. [26,27,58–70].

The physically important quantity is  $dE/dVdt$ , the rate of energy deposition to the SM IGM per volume. It is common to separate astrophysical factors from model-dependent particle physics; for a DM scattering or annihilation process,

$$\frac{dE}{dVdt} = \rho_c^2 \Omega_{\text{DM}}^2 (1+z)^6 (p_{\text{ann}} + p_{\text{scatt}}). \quad (7)$$

We have defined

$$p_{\text{ann}} = 2fs \frac{\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}{M} \quad (8)$$

for annihilation cross section  $\sigma_{\text{ann}}$  (into SM particles) and

$$p_{\text{scatt}} = \bar{Y}^2 fs \eta \delta M_{12} \frac{\langle \sigma_1 v_{\text{rel}} \rangle}{M^2}, \quad (9)$$

where  $\sigma_1$  is the downscattering cross section in the case of exothermic dark matter. Here  $f$  is an energy deposition efficiency discussed further below, and other variables are defined as in Sec. II above. Constraints on the modification of the CMB anisotropies currently exclude some annihilation channels for thermal WIMPs of mass  $\lesssim 10 \text{ GeV}$  and are weakened in asymmetric DM models [71,72], or if the DM dominantly annihilates into hidden-sector particles [73].

The deposition efficiency  $f$  depends on the specific particle physics model of DM through the branching ratios to different decay/annihilation products. Since the IGM is transparent to photons of certain energies at certain redshifts,  $f$  depends on redshift  $z$  as well, but Ref. [74] noted that the full redshift dependence is well approximated (within 15%) for DM annihilation by taking  $f$  to be constant (at the value for  $z = 600$ ). For moderately relativistic  $e^\pm$ , Ref. [72] finds  $f(z = 600) > 0.9$ , and we adopt that constant value (the error associated with the approximation is smaller than the allowed range in  $M$ ,  $\delta M_{12}$  for annihilating light DM or XDM models).

We will consider several experimental constraints. First, Ref. [74] finds a 95% confidence constraint of  $p_{\text{ann}} < 2.42 \times 10^{-27} \text{ cm}^3/\text{s}/\text{GeV}$  from WMAP7 data [75],  $p_{\text{ann}} < 2.09 \times 10^{-27} \text{ cm}^3/\text{s}/\text{GeV}$  from WMAP7 and ACT [76], and a forecast constraint of  $p_{\text{ann}} < 3.03 \times 10^{-28} \text{ cm}^3/\text{s}/\text{GeV}$  from Planck. Finally, Ref. [77] finds  $p_{\text{ann}} < 7.86 \times 10^{-28} \text{ cm}^3/\text{s}/\text{GeV}$  using WMAP7 and SPT [78] data at 95% confidence. These apply equally to  $p_{\text{scatt}}$ .

#### A. Conservative constraints

The astute reader will notice a similarity between Eqs. (2), (8), and (9), which allows us, assuming that DM scattering is responsible for the  $e^+$  production in the Galactic bulge, to find  $p_{\text{ann}}$  or  $p_{\text{scatt}}$  as functions of the Einasto profile parameters  $\alpha$  and  $r_s$ . The key point to understand is the relation between  $\langle \sigma_{\text{ann},1} v_{\text{rel}} \rangle$  in  $p_{\text{ann}}/p_{\text{scatt}}$ , which is the thermal average in the early Universe, and  $\bar{\sigma} \bar{v}$ . For  $s$ -wave annihilation, as appropriate for the MeV-mass annihilating DM of Sec. II A, these quantities are equal. For XDM models with DM mass  $M \gtrsim \text{GeV}$ , the DM velocity dispersion at recombination and later (but before structure formation) is considerably smaller than  $v_t$ . Therefore, upscattering in endothermic

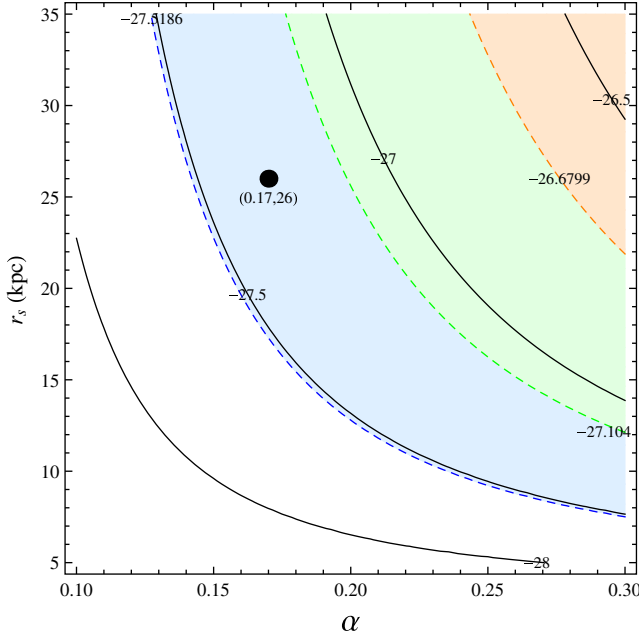


FIG. 2 (color online). Contours of  $\log p_{\text{ann}}$  (in  $\text{cm}^3/\text{s}/\text{GeV}$ ) for  $s$ -wave annihilating light DM for DM mass  $fM = 0.75$  MeV with 95% confidence constraint surfaces (dashed contours). Regions to the right of the constraint contours are ruled out. The rightmost constraint (orange) is ruled out by WMAP7 + ACT [74], and the middle constraint (green) by WMAP7 + SPT [77]. The left constraint (blue) will be ruled out by forecast constraints from Planck [74]. The dot indicates the *Via Lactea II* parameters.

XDM models is kinematically forbidden as noted, and  $\langle \sigma_{\perp} v_{\text{rel}} \rangle = \overline{\sigma v}$  for exothermic XDM, since  $F(v_{\text{rel}}=0) = 1$ .

As a result, we find that production of low-energy  $e^+$  by exothermic scattering processes minimally deposits

$$p_{\text{scatt}} = (R/4\pi\rho_{\odot}^2\zeta_{\perp}\text{kpc}^3)f\delta M_{12}. \quad (10)$$

This includes annihilation of light DM if we replace  $\zeta_{\perp} \rightarrow \zeta_{\text{ann}}$  and set  $\delta M_{12} = 2M$ .<sup>4</sup> As a result, constraints on  $p_{\text{ann}}/p_{\text{scatt}}$  rule out regions of  $\alpha$ ,  $r_s$  parameter space for light DM annihilation or exothermic XDM, assuming a fixed value of  $\delta M_{12}$ . Note that Eq. (10) is independent of  $M$  except through a relatively weak dependence on  $v_t$ , which is determined by the ratio  $\delta M_{23}/M$ . We will assume that  $f$  is constant in an on-the-spot approximation; a more detailed parameter search using the redshift and energy dependence of  $f$  may be warranted in the future.

Constraints on the allowed Einasto profile halo parameters are shown in Fig. 2 for annihilating light dark matter and in Fig. 3 for exothermic XDM. For illustrative purposes, we have chosen  $2fM$ ,  $f\delta M_{12} = 1.5$  MeV; this is a representative but conservative choice in that generated  $e^+$  are mildly relativistic, lower  $e^+$  energies require tuning in

<sup>4</sup> Annihilation of DM produces one  $e^{\pm}$  pair per DM pair vs one  $e^{\pm}$  pair per excited DM state in XDM.

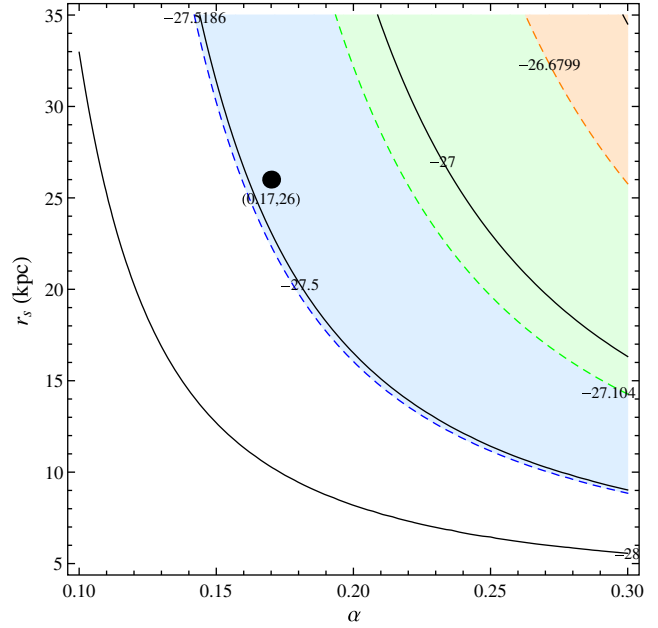


FIG. 3 (color online). Contours of  $\log p_{\text{scatt}}$  (in  $\text{cm}^3/\text{s}/\text{GeV}$ ) for XDM with  $v_t = 10^{-3}$  and  $f\delta M_{12} = 1.5$  MeV with 95% confidence constraint surfaces (dashed contours). Constraints are labeled as in Fig. 2. The dot indicates the *Via Lactea II* parameters.

the DM model, and the constraints become more stringent for larger  $e^+$  energies ( $M$  or  $\delta M_{12}$ ). For reference, the *Via Lactea II* halo model for annihilating light DM is already ruled out by the 95% confidence constraints from WMAP7 + SPT [77] if  $fM > 1.2$  MeV, and it is always ruled out by the forecast constraints from Planck given in Ref. [74] (unless the efficiency factor  $f$  is for some reason reduced below expected values). As discussed earlier, we also choose  $v_t = 10^{-3}$  in Fig. 3 as a conservative choice without fine tuning; for this  $v_t$ , the *Via Lactea II* model is already ruled out by WMAP7 + SPT if  $\delta M_{12} > 3.6$  MeV (assuming  $f = 0.9$ ) and would be free of the forecast Planck constraints if  $f\delta M_{12} < 1.2$  MeV. For larger values of  $v_t$ , the constraints approach those shown in Fig. 2.

Similar constraints for annihilating light DM have been discussed previously in Ref. [26], which were based on the Navarro-Frenk-White profile selected by Ref. [19]. While this profile is slightly cuspier in the innermost Galaxy than the *Via Lactea II* Einasto profile, the corresponding value of  $\zeta_{\text{ann}}$  is actually slightly less for the Navarro-Frenk-White profile, assuming that both profiles are normalized to  $\rho_{\odot}$  at  $r_{\odot}$ . Furthermore, Ref. [19] took  $\rho_{\odot} = 0.3$   $\text{g}/\text{cm}^3$ . Making the appropriate conversion, Ref. [26] constrains annihilating light DM to have  $fM < 1.7$  MeV. As expected, the improvement in the CMB data since Ref. [26] has tightened the constraints.

Finally, we note that these constraints are conservative because they arise from the same mechanism that produces  $e^+$  in the Galactic bulge as long as the scattering is not velocity suppressed (or kinetically forbidden at the time of recombination as in endothermic XDM). As a result,

upcoming results from Planck will be able to exclude annihilating light DM and exothermic XDM at the *Via Lactea II* halo parameters (assuming that the mass splitting  $\delta M_{12}$  and threshold  $v_t$  are not finely tuned in the case of XDM). In fact, the forecast Planck constraints exclude a significant fraction of the best-fit parameter space from Ref. [18], though smaller values of  $r_s$  are allowed for XDM as long as  $\delta M_{12}$  is not too large. Aside from fine-tuning of the particle physics, our results suggest one additional way these models might evade CMB constraints. More cuspy DM halo profiles (with larger values of  $\zeta$ ) will be unconstrained by CMB experiments, and propagation of unstable DM excited states or the produced  $e^+$  themselves can, in principle, spread out the 511 keV gamma-ray signal. However, the similar morphology of the 511 keV and 130–135 GeV lines (pointed out in Ref. [43]) makes this way out less palatable, assuming that the 130 GeV signal withstands further scrutiny.

### B. Annihilation of XDM

XDM can also annihilate completely, depositing additional energy to the IGM, like a standard thermal WIMP. In the exothermic case, the total energy deposition is given by  $p_{\text{ann}} + p_{\text{scatt}}$  in Eq. (7). It is already possible to rule out thermal WIMPs with masses in the range of 7 to 12 GeV, which has been of interest with respect to possible signals at the DAMA [79], CoGeNT [80,81], and CRESST [82] direct detection experiments, using the WMAP7 + SPT constraints discussed above. In the following, we will illustrate that the production of low-energy  $e^\pm$  pairs provides extra sensitivity in the case of exothermic XDM in a model-dependent fashion. We focus on the exothermic XDM models of Ref. [17] as an example, working under a few simplifying assumptions.

In these models, DM is a Majorana fermion triplet of a dark  $SU(2)$  gauge group and annihilates into the dark

gauge bosons, assuming that the dark Higgs bosons are heavier than the DM. The dark gauge bosons all mix kinetically with the photon, so they can decay into any lighter charged SM particle. Then, for light gauge bosons, the final annihilation products are  $e^\pm$ ,  $\mu^\pm$ , and  $\pi^\pm$ . This allows us to find an average efficiency factor  $f$  for the annihilation as the average of the ‘‘XDM electrons,’’ ‘‘XDM muons,’’ and ‘‘XDM pions’’ values of Ref. [64] weighted by the gauge boson branching ratios as a function of the gauge boson mass. For simplicity and specificity, we take all the gauge bosons to have the same mass of 500 MeV, which yields  $f = 0.53$ .

In addition, the annihilation cross section at late times,  $\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle$ , differs from the canonical value  $3 \times 10^{-26} \text{ cm}^3/\text{s}$  for three reasons. First, as discussed in Ref. [83], a more precise calculation finds a somewhat decreased value of the cross section needed for the correct thermal relic abundance in this mass range, and the required cross section has a significant dependence on mass. Second, as mentioned above, these XDM models contain dark gauge bosons which are mildly relativistic at the time the DM freezes out; as a result, there are more degrees of freedom in the primordial plasma than in standard cosmology. This results in a slight decrease of the required cross section, as discussed in Ref. [17]. Finally, we assume that the unstable DM excited state has decayed completely by recombination (see Sec. IV below), so the average annihilation cross section changes after chemical freeze-out because the DM states have different relative abundances. Specifically, at late times, the stable excited state has relative abundance  $\bar{Y}$ , while the ground state has relative abundance  $1 - \bar{Y}$ . Taking into account coannihilations between the different DM states,  $\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle$  is enhanced by a factor 98/75 at  $\bar{Y} = 1/3$ , its maximum value, in these  $SU(2)$  triplet models; this enhancement factor increases as  $\bar{Y}$  decreases. We assume  $\bar{Y} = 1/3$ .

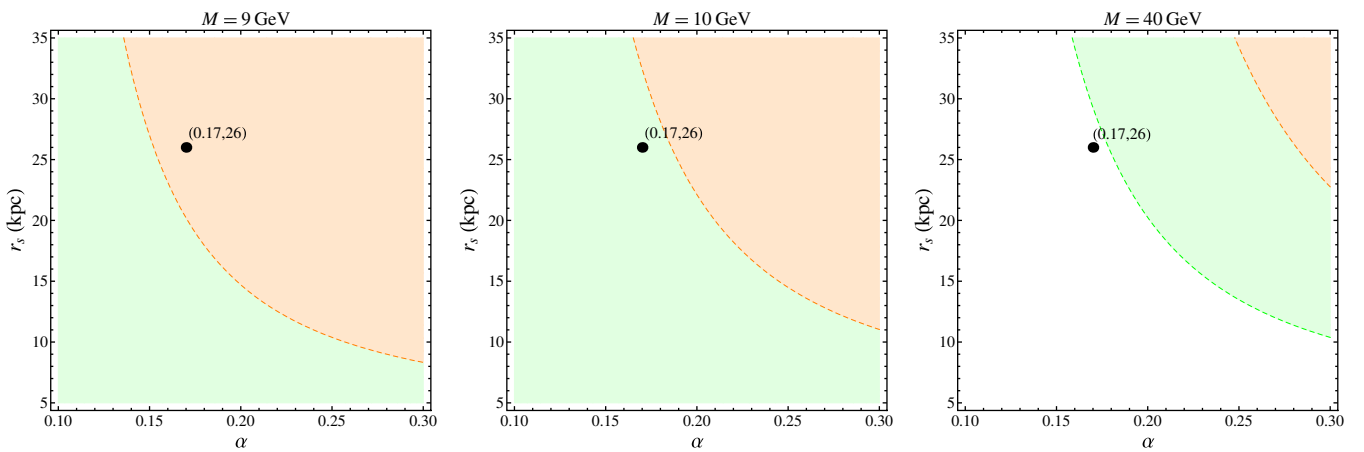


FIG. 4 (color online). Exclusion plots for a specific XDM model including energy deposition from DM annihilation and scattering for DM mass  $M = 9$  GeV (left panel), 10 GeV (center), and 40 GeV (right). Contours are of  $p_{\text{ann}} + p_{\text{scatt}}$  at the WMAP7 + ACT constraint (orange, right-hand contour) and the WMAP7 + SPT constraint (green, left-hand contour in right panel). Excluded regions are shaded.

Results appear in Fig. 4 for DM mass  $M = 9$  GeV and 10 GeV. We see that the exclusion region from the WMAP7 + ACT constraint extends farther to the left (to cuspiest halo parameters) than when not including DM annihilation (compare to Fig. 3). The improved sensitivity works in both ways: the WMAP7 + ACT constraint rules out these XDM models as thermal WIMPs for  $M < 8$  GeV without XDM-like  $e^\pm$  production, but the *Via Lactea II* halo is excluded for larger masses when both effects are taken into account. As a further example, the WMAP7 + SPT constraint excludes these models for  $M < 18.4$  GeV if XDM-like  $e^\pm$  production is ignored but can exclude the *Via Lactea II* halo for  $M < 34.5$  GeV when  $e^\pm$  production is included. At the displayed DM masses, the annihilation cross sections at chemical freeze-out are  $2.39 \times 10^{-27}$  cm<sup>3</sup>/s for  $M = 9$  GeV,  $2.34 \times 10^{-27}$  cm<sup>3</sup>/s at  $M = 10$  GeV, and  $2.10 \times 10^{-27}$  cm<sup>3</sup>/s for  $M \geq 15$  GeV.

#### IV. CONSTRAINTS ON DECAYING DARK MATTER

The CMB also constrains energy deposition to the IGM from decay of DM. For lifetimes  $\tau$  shorter than the age of the Universe, the exponential decay of the abundance means that it is more convenient to constrain  $\bar{Y}_u(\delta M_{12}/M)$ .  $\bar{Y}_u$  represents the initial abundance of the unstable DM species relative to all DM. Recently, Ref. [72] has provided constraints from WMAP7 data (along with forecasting Planck constraints), including the dependence of the efficiency factor  $f$  on redshift and the decay product energy  $\delta M_{12}$ .

It is also important to note that the constraints are irrelevant for decays with lifetimes much shorter than the time of recombination, i.e.,  $\tau \lesssim 10^{13}$  s, since faster decays deposit nearly all of their energy before the CMB decouples from the IGM.

##### A. Decay of unstable XDM state

As noted in Ref. [34], XDM models necessarily have at least one unstable state (which we have denoted as state #2), and we can ask what constraints can be placed on the lifetime or initial abundance of that state. Here, we update the results of Ref. [34]. XDM may also have metastable excited states (denoted state #3), which must have a lifetime longer than the age of the Universe, and we will consider constraints on this state, as well.

We first consider the metastable state #3. For long lifetimes, the WMAP7 constraint becomes  $(\delta M_{12}/M)(\bar{Y}/\tau) < 10^{-24.8}$  s<sup>-1</sup>, while the forecast Planck constraint is  $(\delta M_{12}/M)(\bar{Y}/\tau) < 10^{-25.4}$  s<sup>-1</sup>. Previous studies of XDM indicate that  $\bar{Y} \gtrsim 1/10$  with reasonable assumptions about kinetic freeze-out, and it is furthermore difficult to arrange a sufficient scattering cross section for smaller relative abundance. Furthermore, it is reasonable to assume  $M \gtrsim 10$  GeV; with  $\delta M_{12} = 1.5$  MeV, we find that  $\tau \gtrsim 8.9 \times 10^{19}$  s (WMAP7) or  $\tau \gtrsim 3.9 \times 10^{20}$  s (Planck).

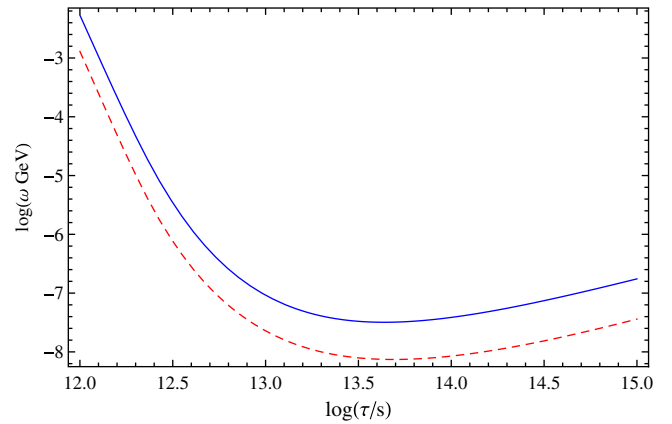


FIG. 5 (color online). Maximum values of  $\log \omega \equiv \log(\bar{Y}_u/M)$  (in GeV<sup>-1</sup>) as a function of  $\log \tau$  (in seconds) from WMAP7 (blue curve) and forecast for Planck (red dashed). This figure assumes  $\delta M_{12} = 1.5$  MeV.

Turning to the unstable state #2, Ref. [42] argued that the lifetime is constrained by the morphology of the 511 keV signal; if the lifetime is greater than approximately  $10^{14}$  s, the unstable DM will move outside the Galactic center before emitting the  $e^\pm$  pair. We show constraints from the CMB on  $\omega \equiv \bar{Y}_u/M$  for  $\delta M_{12} = 1.5$  MeV as a function of lifetime in Fig. 5, using the results of Ref. [72]. The effect of the mass splitting  $\delta M_{12}$  is mainly to shift the constraint curve vertically on the plot, but the shape of the curve also depends weakly on it. In most XDM models,  $\bar{Y}_u \sim \bar{Y}$  due to the thermal history of DM; in this case, the lifetime can just be as long as  $10^{12}$  s if  $M \gtrsim 19$  GeV (WMAP7) or  $M \gtrsim 77$  GeV (Planck). For smaller masses, larger mass splittings, or larger initial relic abundances, we simply find  $\tau < 10^{12}$  s. Other XDM models, such as in Ref. [43], could have much smaller  $\bar{Y}_u$  and therefore potentially longer lifetimes. Note that these constraints are potentially stronger than the constraint from the morphology of the Galactic signal, but that the lifetime is degenerate with the mass, mass splitting, and relative abundance. These constraints apply in the case of either endothermic or exothermic XDM.

We also considered the fact that a long lifetime for the unstable state could strengthen constraints on downscattering in exothermic XDM models. Physically, if the unstable state is sufficiently long-lived,  $e^\pm$  pairs are produced at a later cosmological era than the initial downscattering process. As a result, the DM density seems to be greater than expected in  $p_{\text{scatt}}$ . This process is governed by the Boltzmann equations

$$\begin{aligned} \frac{dn_2}{dt} + 3Hn_2 &= -\frac{n_2}{\tau} + n_3^2 \langle \sigma_{\downarrow} v_{\text{rel}} \rangle, \\ \frac{dn_3}{dt} + 3Hn_3 &= -n_3^2 \langle \sigma_{\downarrow} v_{\text{rel}} \rangle, \end{aligned} \quad (11)$$

(ignoring kinetically forbidden upscattering), and energy deposition is governed by

$$\frac{dE}{dVdt} = \frac{\delta M_{12} n_2(t)}{\tau}. \quad (12)$$

The solutions to the Boltzmann equation for  $n_2$  can be given in terms of exponential integral functions (in the matter-dominated era), assuming the abundance of state #3 to be constant after early times. As expected, a lifetime less than the time of recombination is equivalent to instantaneous decay. Meanwhile, a longer lifetime runs into the constraints discussed above unless the initial abundance of state #2 is quite small. In other words, this effect may be important in some region of parameter space for models like those of Ref. [43].

### B. Infalling positron model

As discussed in Sec. IID, Ref. [20] recently proposed that decaying DM with a lifetime in the range  $\tau = 10^{14} - 10^{17}$  s and  $\omega \sim 4.7 \times 10^{-8}$  GeV $^{-1}$  produces sufficient  $e^+$  to explain the Galactic 511 keV line. Note that  $\omega$  as defined in Ref. [20] is our  $\bar{Y}_u$  for  $M = 100$  GeV; our  $\omega = \bar{Y}_u/M$  is a measure of the number density of unstable DM particles.<sup>5</sup> One point of importance is that the  $e^+$  can be produced at high energies due to a mass splitting of order GeV (or presumably more); they cool quickly in the IGM (mostly by Compton scattering) before entering the Galaxy, where they thermalize and annihilate. But it is precisely the cooling process (and annihilation) in the IGM that modifies the CMB anisotropy spectrum. While detailed studies of the signal morphology for such models have yet to be carried out, we show here that existing CMB constraints already rule out a great deal of the parameter space of interest.

Figure 6 summarizes constraints on these models. The blue band indicates values of  $\omega$  identified by Ref. [20] as producing the correct number of  $e^+$  for the INTEGRAL signal without overproducing them.<sup>6</sup> The green region is excluded by limits on diffuse photons produced either by direct decays or by Compton scattering of the resultant  $e^+$  as found in Ref. [20]; this constraint lifts for mass splittings much below 1 GeV. The remaining regions are excluded by the WMAP7 constraints of Ref. [72] for  $\delta M_{12} = 1$  GeV, 100 MeV, and 10 MeV (from bottom to top). We note that the preferred value of  $\delta M_{12} = 1$  GeV mentioned in Ref. [20] is nearly completely excluded: the central value of  $\omega = 4.7 \times 10^{-8}$  GeV $^{-1}$  lies above the WMAP7 constraint for  $\tau \leq 10^{17}$  s and above the diffuse photon constraint for  $\tau \geq 10^{17}$  s. Smaller values of the mass splitting  $\delta M_{12}$  open the parameter space somewhat, but part of the motivation of the model is lost. Note that the CMB

<sup>5</sup>Another difference is that we use the initial relative abundance of the unstable DM state, while Ref. [20] uses the value at recombination. Since the lifetimes considered are longer than the time of recombination, the difference is unimportant.

<sup>6</sup>We have estimated the width of this band, which is not specified in Ref. [20].

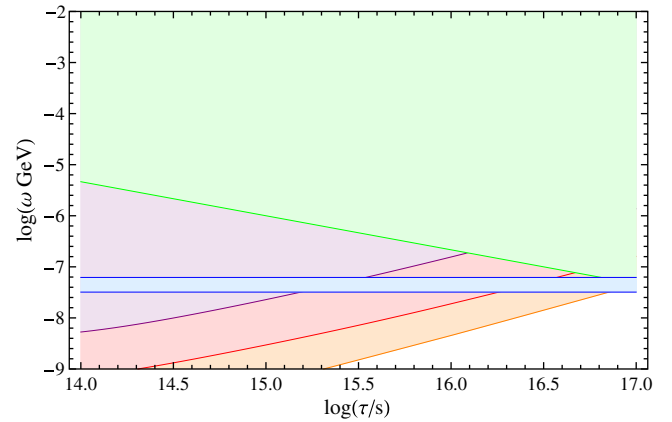


FIG. 6 (color online). Constraints on infalling positron models in the  $\log(\tau/s)$  and  $\log(\omega \text{ GeV})$  plane. The blue band is the region of interest for the 511 keV signal. The top (green) region is excluded by constraints on diffuse photons for  $\delta M_{12} \geq 1$  GeV. Three lower regions from bottom to top are excluded by the WMAP7 constraints on decaying DM for  $\delta M_{12} = 1$  GeV (orange), 100 MeV (red), and 10 MeV (purple), respectively.

limits apply equally well to models in which the unstable DM state is charged and decays by emitting a single  $e^+$  as opposed to an  $e^\pm$  pair, since the  $e^+$  can still efficiently deposit its kinetic energy and annihilate with an ambient  $e^-$ . As a result, we see that existing CMB data provide robust constraints on these models. Larger mass splittings and the upcoming Planck data will make the constraints tighter.

### V. SUMMARY

As we have seen, CMB anisotropies provide robust constraints on DM models for the Galactic bulge  $e^+$  production mechanism. These constraints provide a new way to exclude annihilating DM and XDM models for a range of Galactic DM halo parameters, including the fiducial parameters from the *Via Lactea II* simulation and much of the parameter space that best fits the 511 keV signal morphology [18], as long as the scattering cross sections are not velocity suppressed (or kinematically forbidden) at or after recombination and before structure formation. These models include  $s$ -wave annihilation as favored by the signal morphology [19] and exothermic XDM models; while the *Via Lactea II* parameters are not yet excluded, Planck is expected either to exclude them or to find signs of energy deposition. When including the effects of DM annihilation, the *Via Lactea II* parameters are in fact already ruled out for some XDM models with DM masses less than a few tens of GeV, as we illustrated in one case.

Our most conservative constraints arise because the same scattering events that generate the 511 keV gamma-ray signal also produce  $e^+$  in the early Universe, which then deposit their energy in the IGM. The amount of



energy deposition is set by the required rate of  $e^+$  production in the Galactic bulge. As a result, annihilating light DM and exothermic XDM cannot avoid these constraints. Assuming the morphologically preferred parameter space is ruled out, these DM models will be viable only if the Galactic DM halo profile is cuspier than usually assumed. Then the morphology of the 511 keV signal would require either that the produced  $e^+$  propagate significantly before annihilating or that the unstable excited DM state live long enough to travel approximately 1 kpc. Confirmation of the tentative 130–135 GeV gamma-ray line at the Galactic center would put pressure on this interpretation of the 511 keV signal, however, since the higher-energy gamma-ray morphology appears consistent with the *Via Lactea II* halo. In this case, endothermic XDM could become the only remaining viable DM model for the 511 keV signal. A more optimistic point of view, on the other hand, is that Planck may provide evidence for non-standard energy deposition in the IGM. In that case, more detailed studies will be warranted to determine if that energy deposition is consistent with (or suggestive of) DM models for the Galactic  $e^+$  production, as well as potentially measuring some parameters of those models.

In this paper, we also revisited constraints on the lifetime of the excited DM states in XDM models by adapting CMB

limits on energy deposition from decaying DM. We further used these limits to exclude much of the parameter space of interest in the recent proposal of Ref. [20] that  $e^+$  produced by metastable decaying DM can generate the 511 keV signal when they fall into the Galactic bulge.

We also note that energy deposition in the SM IGM can also induce small distortions in the spectrum of the CMB (away from the Planck law) [84–86]. Similarly, effects of energy deposition should be visible in the emerging 21 cm window for cosmological observations [87–89]. Either of these effects may provide interesting constraints on light annihilating DM or XDM in the future.

In summary, the ability of DM models to explain the high rate of positron production in the Galactic bulge, along with a striking and suggestive agreement between anticipated DM halo profiles and the signal morphology, motivates a search for additional signals of such DM. It is clear that CMB anisotropies provide a new handle on the viability of a broad class of these models along with their other parameters.

## ACKNOWLEDGMENTS

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