Energy injected into the Cosmic Microwave Background at redshifts $z < \sim 10^6$ will distort its spectrum permanently. In this paper we discuss the distortion caused by annihilations of relic particles. We use the observational bounds on deviations from a Planck spectrum to constrain a combination of annihilation cross section, mass, and abundance. For particles with (s-wave) annihilation cross section, $\langle \sigma | v \rangle \equiv \sigma_0$, the bound is $f \left( \frac{m_X}{\text{MeV}} \right)^{-1} \left[ \left( \frac{\sigma_0}{6 \times 10^{-27} \text{cm}^3 \text{s}^{-1}} \right) \left( \frac{\Omega_{X\bar{X}} h^2}{2} \right) \right] < 0.2$, where $m_X$ is the particle mass, $\Omega_{X\bar{X}}$ is the fraction of the critical density the particle and its antiparticle contribute if they survive to the present time, $h = H_0/100 \text{ km s}^{-1}\text{Mpc}^{-1}$, $H_0$ is the Hubble constant, and $f$ is the fraction of the annihilation energy that interacts electromagnetically. We also compute the less stringent limits for p-wave annihilation. We update other bounds on residual annihilations and compare them to our CMB bound.
Newly proposed particles, especially dark matter candidates, must evade an ever growing array of empirical constraints, ranging from bounds obtained in terrestrial laboratory experiments (e.g., reference [1]), to limits on new cooling sources in stars in our galaxy [2], to constraints on the expansion rate of the universe during Big Bang Nucleosynthesis (BBN), when the universe was only a few minutes old [3]. In this paper we add another constraint to the list, based on the effect of annihilations of relic particles on the cosmic microwave background (CMB).

The CMB energy spectrum provides a direct probe of the early Universe at redshifts as high as $z \sim 2 \times 10^6$. Below this redshift, distortions of the spectrum generally cannot be thermalized and are observable today. The FIRAS (Far Infrared Absolute Spectrophotometer) instrument on the COBE (Cosmic Background Explorer) satellite measured the spectrum and found it to have a Planck distribution to within a few hundredths of a percent [4]. This measurement places strong upper bounds on any energy injection into the CMB after the thermalization redshift (e.g., references [5,6]).

Decays of relic particles have been considered as a source of CMB distortions [7], but particle annihilations have not. Annihilations are typically ignored because the classic WIMP (weakly interacting massive particle) dark matter candidates have mass $m_X \gtrsim 1$ GeV and their annihilations “freeze out” at $T_F \sim m_X/20 \gtrsim 50$ MeV [8], long before the time when the CMB becomes vulnerable to distortion (at $T \approx 0.5$ KeV). Freezeout is defined as the time when annihilations cease to change significantly the number density of the particle; however, annihilations continue eternally at some small rate and their products can distort the CMB spectrum if they interact electromagnetically.

The effects of residual annihilations have been considered in a few other contexts: Reno and Seckel [9], Hagelin, Parker, and Hankey [10], and Frieman, Kolb, and Turner [11] computed the effect of annihilation products on the primordial element abundances. Cline and Gao [12] and Gao, Stecker, and Cline [13] considered the possibility of observing directly the photons from annihilations at cosmological distances. Bergstrom and Snellman [14], Rudaz [15], and Rudaz and Stecker [16] discuss the detectability of a line source from annihilations to photons within the Milky Way halo. Jungman, Kamionkowski, and Griest [17] conclude that halo annihilations into particles other than photons probably cannot be used to place general constraints on particle candidates because of astrophysical uncertainties.

In this paper we compute the energy injected into the CMB by annihilating particles as a function of their mass and annihilation rate (i.e., the product of cross section and abundance squared). We derive constraints on the particle properties by comparison with the observed limits on chemical potential ($\mu$) distortions, and Compton-$y$ distortions ($\delta y$). We compare these constraints to similar constraints obtained from the production of deuterium by photodissociation of primordial helium (§III.A), and from the diffuse photon background produced after recombination by extragalactic annihilations (§III.B), and annihilations in the Milky Way halo (§III.C).

II. DISTORTIONS OF THE CMB ENERGY SPECTRUM

We consider first the effect of annihilation products on the CMB energy spectrum. The distortion of the spectrum takes place in two steps: first the high energy annihilation products rapidly dissipate their energy into the background photons and electrons, and then the low energy background evolves more slowly in an effort to restore the Planck spectrum. The permanence of distortions produced after $z \approx 10^6$ is simple to understand in the following way: A Planck spectrum with a given photon number density must have a specific energy density. For $z \lesssim 10^6$, photon nonconserving processes (double Compton scattering and bremsstrahlung) are inefficient in the background plasma. Therefore, if energy is injected into the CMB but not the the correct number of photons, a Planck spectrum cannot be restored. We now discuss in more detail the form of the distortions produced in different redshift intervals.

Down to recombination at $z_{rec} \approx 1100$, photons with $E_\gamma \gtrsim 5$ KeV quickly cool and produce heated electrons by Compton scattering ($\gamma e \rightarrow \gamma e$) or pair production on ions ($\gamma N \rightarrow N e^+ e^-$) (all photons with $E_\gamma > 1$ KeV can cool if $z \gtrsim 3500$). The heated electrons quickly dissipate their energy by inverse Compton scattering on the huge number of CMB photons. This process produces a distorted spectrum with phase-space distribution

$$f(x, y) = f(x, 0) + y \frac{xe^x}{(e^y - 1)^2} \left[ \frac{x}{\tanh(x/2)} - 4 \right],$$

where $f(x, 0) = 1/(e^x - 1)$ is the Planck distribution, $x = E/T$, and the Compton-$y$ parameter is assumed to satisfy $y << 1$ [18]. In our case, where there is ample time for all of the input energy to be transferred to the CMB, the relation between $y$ and the input energy can be found by integrating Equation (1) to find the energy density as a function of $y$. The result is $y = \delta \rho_\gamma/\rho_\gamma$, where $\delta \rho_\gamma$ is the injected energy and $\rho_\gamma$ is the energy of the CMB photons (see reference [19] for a general review of CMB distortions or reference [18] for a more detailed discussion of the Compton-$y$ distortion). Analysis of the COBE FIRAS data set gives $|y| < 1.5 \times 10^{-5}$ [4].

The Compton-$y$ distortion will be preserved to the present time if it is produced after $z_C \approx 5.4 \times 10^4 \omega_B^{1/2}$ (where $\omega_B = \Omega_B h^2/0.02$), the redshift above which elastic Compton scattering would effectively redistribute energy between CMB photons, converting a Compton-$y$
distorted spectrum into a Bose-Einstein spectrum with distribution
\[ f(x, \mu) = \frac{1}{\exp(x + \mu) - 1} , \]
where \( \mu \) is the chemical potential. Assuming the input number of photons is negligible, which will always be true in this paper, the chemical potential is \( \mu = 1.4 \delta \rho_\gamma / \rho_\gamma \) [20]. The FIRAS limit on this type of distortion is \( |\mu| < 9 \times 10^{-5} \) [4].

Equation (2) describes the equilibrium distribution for a fixed total number of photons and amount of energy. For \( z \gtrsim z_{\text{DC}} \approx 2.1 \times 10^{6} \omega_B^{-1/3} \), photons are produced effectively by double Compton scattering \((e\gamma \to e\gamma\gamma)\) so a Planck spectrum \((\mu = 0)\) can be restored for arbitrary energy input [20]. Production of photons by bremsstrahlung is already ineffective at \( z \sim z_{\text{DC}} \) (for the observed baryon density).

To summarize: annihilations occurring at \( z \gtrsim 2.1 \times 10^{6} \) will be unobservable, annihilations in the range \( 5.4 \times 10^{4} \lesssim z \lesssim 2.1 \times 10^{6} \) will produce a Bose-Einstein spectrum with chemical potential \( \mu \), and annihilations in the range \( 1100 \lesssim z \lesssim 5.4 \times 10^{4} \) will produce a Compton-\( y \) distortion. Annihilations at \( z < z_{\text{rec}} \) will not significantly affect the CMB energy spectrum, but can be observable in the diffuse photon background.

We now compute the fractional energy injection \( \delta \rho_\gamma / \rho_\gamma \) (where \( \rho_\gamma \) is the energy density of the CMB) from annihilations of particle species \( X \). We will assume throughout this paper that particle \( X \) and antiparticle \( \bar{X} \) are not identical (we discuss below how our final constraints are strengthened in the case where the particle is its own antiparticle). We also assume that \( n_X \equiv n_{\bar{X}} \), where \( n_X \) \((n_{\bar{X}})\) is the number density of \( X \) \((\bar{X})\) (if there is a significant asymmetry the relic density of the less numerous particle will usually be negligibly small [21,22]). The energy produced per annihilating particle is
\[ E_a = f m_X \]
where \( m_X \) is the mass of the particle and \( f \leq 1 \) is the mean fraction of the annihilation energy that interacts electromagnetically, and the rate of annihilations per unit volume is
\[ \Gamma_a = \langle \sigma_a | v| \rangle n_X n_{\bar{X}} \]
where \( \langle \sigma_a | v| \rangle \) is the cross section. A useful parameterization for the cross section is \( \langle \sigma_a | v| \rangle \equiv \sigma_0 \left( T / m_X \right)^{n} \), where \( n = 0 \) for s-wave annihilation (e.g., Dirac neutrinos) and \( n = 1 \) for p-wave annihilation (e.g., Majorana particles annihilating into much lighter fermions, see reference [23]). We integrate the energy injection rate from time \( t_1 \) to \( t_2 \) as follows:
\[ \frac{\delta \rho_\gamma}{\rho_\gamma} = \int_{t_1}^{t_2} \frac{\delta \rho_{\text{ann}}}{\rho_\gamma} dt = \int_{t_1}^{t_2} \frac{2 E_a \Gamma_a}{\rho_\gamma \rho_\gamma} (1 + z)^{n-1} dt \]
where \( \rho_{\text{ann}} = 2 E_a \Gamma_a \) is the rate of energy injection by annihilations, \( \rho_\gamma \) is the present energy density in the CMB, \( T_0 \) is the present CMB temperature, \( n_X \equiv n_X (z_\text{CMB}) \) and \( t_\text{CMB} = 2.4 \times 10^{16} \)s. We have assumed the universe is radiation dominated (this assumption will be accurate enough at the redshifts relevant to our calculation) so that \( t \approx 0.301 g_*^{-1/2} m_{\text{Pl}} T^{-2} \equiv t_*(1 + z)^{-2} \), where \( m_{\text{Pl}} \) is the Planck mass, \( g_* = 3.36 \) is the number of effectively massless degrees of freedom at \( T < M_{\text{Pl}} \), and \( t_* \) is fixed by the CMB temperature measured at \( z = 0 \). The result for \( n = 0 \) is
\[ \frac{\delta \rho_\gamma}{\rho_\gamma} = A \ln \left( \frac{z_1}{z_2} \right) , \]
and for \( n = 1 \)
\[ \frac{\delta \rho_\gamma}{\rho_\gamma} = A \left( \frac{T_1 - T_2}{m_X} \right) , \]
where
\[ A = 4 t_* E_a \sigma_0 n_X^2 / \rho_\gamma \]
and \( T_i = T(z_i) \).

We use \( z_1 = z_{\text{DC}} \) and \( z_2 = z_{\text{CMB}} \) to find the chemical potential \( \mu = 1.4 \delta \rho_\gamma / \rho_\gamma \) (this assumes a negligible increase in the number of photons, which is valid even in the case of an electromagnetic cascade), with the results:
\[ \mu = 5.1 A = 2.9 \times 10^{-4} \left( \frac{m_X}{\text{MeV}} \right)^{-1} \]
\[ \times \left( \frac{\sigma_0}{6 \times 10^{-27} \text{cm}^3 \text{s}^{-1}} \right) \left( \Omega_{X \bar{X}} h^2 \right)^2 \] (for \( n = 0 \)),
\[ \mu = 2.0 \times 10^{6} A \frac{T_0}{m_X} = 2.7 \times 10^{-8} \left( \frac{m_X}{\text{MeV}} \right)^{-2} \]
\[ \times \left( \frac{\sigma_0}{6 \times 10^{-27} \text{cm}^3 \text{s}^{-1}} \right) \left( \Omega_{X \bar{X}} h^2 \right)^2 \] (for \( n = 1 \)),
where \( \Omega_{X \bar{X}} h^2 = 94 \left( m_X / \text{MeV} \right) \left( n_X + n_{\bar{X}} \right) / \text{cm}^{-3} \).

Observationally \( |\mu| < 9 \times 10^{-5} \) [4] so, for \( n = 0 \), we have the bound
\[ f \left( \frac{m_X}{\text{MeV}} \right)^{-1} \left( \frac{\sigma_0}{6 \times 10^{-27} \text{cm}^3 \text{s}^{-1}} \right) \left( \Omega_{X \bar{X}} h^2 \right)^2 < 0.3 \] .
Similarly, for \( n = 1 \) we find
\[ f \left( \frac{m_X}{\text{MeV}} \right)^{-2} \left( \frac{\sigma_0}{6 \times 10^{-27} \text{cm}^3 \text{s}^{-1}} \right) \left( \Omega_{X \bar{X}} h^2 \right)^2 < 3.3 \times 10^{4} . \]
We have chosen to scale the cross section as $(\sigma_0/6 \times 10^{-27}\text{cm}^3\text{s}^{-1})$ so this is approximately the value at which a non-relativistic particle will have relic density $\Omega_X h^2 = 1$ if it freezes out as a result of its annihilations while in thermal equilibrium. The reader should keep in mind that $\Omega_X$ is not necessarily the contribution of $X$ to the present energy density if, for example, the particle decays subsequent to distorting the CMB.

Note that the constraint for $n = 1$ is roughly $m_X/T_{DC}$ times weaker than the constraint for $n = 0$, where $T_{DC}$ is the temperature at $z_{DC}$. Constraints on $n = 1$ particles that fall out of kinetic equilibrium at $T_K > T_{DC}$ can be roughly estimated from the given $n = 1$ constraints by multiplying by a factor $T_K/T_{DC}$ (see reference [24]).

The Compton-y distortion can be obtained by changing the limits of integration in Equation (5) from $z_{DC}$ and $z_C$ to $z_C$ and $z_{rec}$. For simplicity, we replace the lower limit $z_{rec}$ by the redshift of matter-radiation equality, $z_{eq} \simeq 2.5 \times 10^3 \Omega_0 h^2$ (where $\Omega_0$ is the present density in matter), and we ignore deviations from $t \propto T^{-2}$. The precise value of this lower limit is not important (because of the log dependence) so we assume $z_{eq} = 3200$.

For $n = 0$,

$$y \simeq \frac{\mu}{1.4 \ln(z_C/z_{eq})} \frac{1}{4.4 \ln(z_{DC}/z_C)} = 0.15 \mu ,$$

(13)

while the observational bound is $|y| < 1.5 \times 10^{-5}$ [4], giving a bound essentially identical to Equation (11). For $n = 1$, $y \simeq 0.005 \mu$, so the bound will be significantly weaker than Equation (12).

In the case of $n = 0$, we predict that the $\mu$ and $y$ distortions will always appear together, with the relationship $y \simeq 0.15 \mu$. Fixsen et al. [4] do not give joint constraints on $\mu$ and $y$ so we perform our own linear fit to the data in their Table 4, using the formula

$$I_0(\nu) - B_\nu(T_0) - G_0 g(\nu) = \Delta T \frac{\partial B_\nu}{\partial T} + G_1 g(\nu) \left[ 1.4 \frac{\partial \rho}{\rho} \left( \frac{\partial S_c}{\partial \mu} + 0.15 \frac{\partial S_c}{\partial y} \right) \right] ,$$

(14)

where $I_0(\nu) - B_\nu(T_0) - G_0 g(\nu)$ is taken from reference [4] (along with the necessary error bars), $g(\nu) = \nu^2 B_\nu (9 K)$ is the galactic contamination model used by [4], and $\partial S_c/\partial \mu$ is the deviation from a blackbody as parameter $\mu$ is varied. We constrain jointly the parameters $\Delta T$, $G_1$, and $\partial \rho/\rho$. Based only on statistical errors, the 95% confidence upper bound on the energy injection is $\delta \rho/\rho < 1.6 \times 10^{-5}$. Our analysis is complicated by the significant systematic errors, $1 \times 10^{-5}$ and $4 \times 10^{-6}$, quoted by [4] for $\mu$ and $y$, respectively. It is not clear how these should be combined with the statistical error, so we choose arbitrarily to add the two systematic errors linearly, and then add the result in quadrature to the statistical error, to find a final 95% confidence upper bound $\delta \rho/\rho < 4.1 \times 10^{-5}$. We finally obtain the bound

$$f \left( \frac{m_X}{\text{MeV}} \right)^{-1} \left( \frac{\sigma_0}{6 \times 10^{-27}\text{cm}^3\text{s}^{-1}} \right) \left( \Omega_X h^2 \right)^2 < 0.2 .$$

(15)

The combined constraints are plotted as the solid lines in Fig. 1 (for $n = 1$ we just use the $\mu$ constraint). We truncated Fig. 1 at $m_X = 1 \text{ GeV}$, where hadronic interactions become important; however, the CMB bound should continue to apply at higher energies, as long as $f$ is computed to account for non-interacting annihilation products. Even neutral annihilation products can contribute to the CMB distortion if they are coupled to the plasma in any way, for example, if they heat the background protons through hadronic interactions (see references [9,10] for discussions of hadronic interactions during this epoch). This is not generally true for the other constraints that we review in §III.

These constraints apply to a particle that is distinct from its antiparticle; however, to convert to the case where particle and antiparticle are equivalent, it is only necessary to make the substitutions $\Omega_X \rightarrow \Omega_{X\bar{X}}$, and $\sigma_0/6 \times 10^{-27}\text{cm}^3\text{s}^{-1} \rightarrow \sigma_0/3 \times 10^{-27}\text{cm}^3\text{s}^{-1}$. The change in cross section normalization cancels the increase in the annihilation rate at fixed total contribution to the critical density (i.e., for the inequivalent case $\Gamma_a \propto n_X n_{\bar{X}} \propto \Omega_X^2 / 4$, but for the equivalent case $\Gamma_a \propto n_X^2 / 2 \propto \Omega_{X\bar{X}}^2 / 2$).

The scale $\sigma_0 \times 10^{-27}\text{cm}^3\text{s}^{-1}$ for the cross section is natural also because it gives $\Omega_X h^2 \simeq 1$. The same substitutions can be used to convert any of the constraints in §III.

### III. Comparison with Other Constraints on Residual Annihilations

In this section we compute bounds, in a form similar to Equation (11), from the production of deuterium by photodissociation of $^4\text{He}$ (§III.A), from the diffuse photon background produced by extragalactic annihilations at $z < z_{rec}$ (§III.B), and from the diffuse photon background produced by annihilations in our galaxy (§III.C). We restrict our attention to $n = 0$ because the $n = 1$ bound is very weak in all cases.

#### A. Photodissociation of $^4\text{He}$

At roughly the same time that the CMB energy spectrum becomes vulnerable to distortion by energy injection, primordially produced $^4\text{He}$ nuclei become vulnerable to photodissociation by high energy annihilation products. At earlier times the nuclei were protected from destruction because photons with high enough energy ($E_\gamma \gtrsim 20 \text{ MeV}$) to destroy nuclei instead pair produce or elastic scatter on the CMB photons ($\gamma\gamma \rightarrow e^+e^-$, or $\gamma\gamma \rightarrow \gamma\gamma$). This shielding is effective for $E_\gamma \gtrsim m_e^2/44\, T$, where $T$ is computed to account for non-interacting annihilation products. Even neutral annihilation products can contribute to the CMB distortion if they are coupled to the plasma in any way, for example, if they heat the background protons through hadronic interactions (see references [9,10] for discussions of hadronic interactions during this epoch). This is not generally true for the other constraints that we review in §III.
where the numerical factor accounts for the fact that photons in the high energy tail of the CMB spectrum are still very numerous (see reference [25], and references therein, for a full discussion). Once \( m^2_{\nu}/4T \gtrsim 20 \text{ MeV} \), annihilation products can dissociate \(^4\text{He} \), either directly, or indirectly through a cascade when \( m^2_{\nu}/4T \). B. Extragalactic \( \gamma \) Background

Recently, Kribs and Rothstein [30] used the observed \( \gamma \)-ray background to constrain late decaying particles. Gao, Stecker, and Cline [13] computed the expected \( \gamma \)-ray flux from annihilations of a possible lightest supersymmetric particle. Here we generalize this annihilation calculation to match the form of the constraint derived from the CMB. Unlike the previous constraints, the constraint we compute now only applies to annihilations directly to two photons, which typically will be sub-dominant for particles with mass greater than the electron mass (assuming particle \( X \) does not couple directly to photons). Therefore, we will only calculate the constraint for \( m_X < 0.5 \text{ MeV} \) (constraints for general annihilation products would be strongly model dependent).

Temporarily ignoring the possibility that photons produced after recombination (at \( z_{\text{rec}} \approx 1100 \)) are absorbed on their way to the observer, the observed energy flux at present from extragalactic annihilations to photons is

\[
\frac{dJ}{dEd\Omega} = \frac{2c}{4\pi} \int_{0}^{z_{\text{rec}}} dt f_\gamma m_X \Gamma_\alpha(z) \times \delta \left[ E_\alpha (1+z) - m_X \right] (1+z)^{-3},
\]

where \( f_\gamma \) is the fraction of annihilations that produce a pair of photons with \( E_\gamma = m_X \). Using \( dt/da = 3 t_0 a^{1/2}/2 = H_0^{-1} a^{1/2} \) for an Einstein-de Sitter universe, and \( \delta \left( E_\alpha a^{-1} - m_X \right) = a^2 \delta (a - E_\alpha/m_X) E_\alpha^{-1} \), we find

\[
\frac{dJ}{dEd\Omega} \approx \frac{3.9 \times 10^{-4}}{\text{cm}^2 \text{ s sr}} f_\gamma \left( \frac{m_X}{\text{MeV}} \right)^{-2} \left( \frac{m_X}{E_\alpha} \right)^{3/2} \left( \frac{\sigma_0}{6 \times 10^{-27} \text{cm}^3 \text{ s}^{-1}} \right) (\Omega_X h^2)^2,
\]

where we have taken \( n = 0 \). The photons we are considering, with energy \( E_\gamma < 0.5 \text{ MeV} \), will in fact lose most of their energy by Compton scattering if they are produced at \( z \gtrsim 200 \) (see reference [31]), so the maximum redshift factor is \( m_X/E_\alpha = 200 \).

We derive a bound on annihilations by requiring that the predicted photon background is not greater than the observed one. After considering observations of the photon background at all relevant energies (see references...
that the energy flux at particle X does not make up all the dark matter, we find the center of the Galaxy; however, we want to be conservative. The background in this range is conservatively bounded by \( dJ/dEd\Omega < 0.36 (E_o/\text{MeV})^{-0.58} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \) [33].

For 160 KeV \( \lesssim m_X < 500 \text{ KeV} \), the best constraint is derived from photons produced at \( z \approx 200 \). Setting \( E_o = m_X/200 \), we obtain the bound

\[
f_7 \left( \frac{m_X}{\text{MeV}} \right)^{-1.42} \left[ \frac{\sigma_0}{6 \times 10^{-27}\text{cm}^3\text{s}^{-1}} \right] (\Omega_{X\bar{X}} h^2)^2 \lesssim 7.6 . \quad (21)
\]

The best bound for lower annihilation energies comes from observations at \( E_o \approx 0.8 \text{ KeV} \):

\[
f_7 \left( \frac{m_X}{\text{MeV}} \right)^{-1/2} \left[ \frac{\sigma_0}{6 \times 10^{-27}\text{cm}^3\text{s}^{-1}} \right] (\Omega_{X\bar{X}} h^2)^2 \lesssim 1.3 . \quad (22)
\]

Figure 1 shows these constraints as the dashed line.

C. Annihilations in the Milky Way Halo

The observability of annihilations to photons in our own galaxy has been discussed in many papers, including [14–16]. In this subsection we combine the latest observational limits on the photon background with the calculation by Kamionkowski [35] and Jungman, Kamionkowski, and Griest [17] of the flux expected from halo annihilations to derive a bound in the form of Equation (11). As discussed in the previous subsection, we only consider annihilations to two photons of particles with \( m_X < 0.5 \text{ MeV} \).

Jungman, Kamionkowski, and Griest [17] assume the model

\[
\rho(r) = \rho_0 \frac{R^2 + a^2}{r^2 + a^2} \quad (23)
\]

for the dark matter density distribution in the Galaxy, where \( R \) is the distance of the Sun from the galactic center, \( a \) is the core radius, and \( r \) is the distance from the center of the galaxy. Note that simulations of cold dark matter models predict central cusps instead of a core [36], which could lead to enhanced annihilation signals toward the center of the Galaxy; however, we want to be conservative so we do not assume a cusp. Re-writing Equation (10.1) of reference [17] to include the possibility that the particle X does not make up all the dark matter, we find that the energy flux at \( E_o = m_X \) is

\[
\frac{dJ}{dEd\Omega} \approx f_s \frac{3.0 \text{ cm}^2\text{s sr}}{\text{cm}^2\text{s sr}} \left( \frac{m_X}{\text{MeV}} \right)^{-2} \left( \frac{\rho_{D}^0}{\Omega_D h^2} \right)^2 I(\psi) \times \left[ \frac{\sigma_0}{6 \times 10^{-27}\text{cm}^3\text{s}^{-1}} \right] (\Omega_{X\bar{X}} h^2)^2 \quad , \quad (24)
\]

where \( I(\psi) \sim 1 \) depends on the observation angle \( \psi \), \( \Omega_D \geq \Omega_{X\bar{X}} \) is the contribution to the critical density from all kinds of dark matter, and \( \rho_{D}^0 \sim 1 \) is the density of dark matter near the solar radius, in units of 0.4 GeV cm\(^{-3}\). We have assumed \( \rho_D(r) \propto \rho_0(r) \), and used the detector energy resolution, \( \Delta E/E \approx 0.2 \), appropriate for the energy bins in Fig. 10 of reference [32].

The relevant energy range for the halo annihilations we are considering, \( 1 - 500 \text{ KeV} \), corresponds to a “bump” in the observed spectrum (see [32]). To be conservative, we construct a simple bound by comparison with the single power law \( dJ/dEd\Omega \lesssim 0.022 (E_o/\text{MeV})^{-1.2} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \), which is an upper bound on the energy flux in the full range 1 KeV \( \lesssim E_o \lesssim 100 \text{ GeV} \) [32]. Since annihilations to two photons produce a line source at \( E_o = m_X \), we have the bound

\[
f_7 \left( \frac{m_X}{\text{MeV}} \right)^{-0.8} (\Omega_D h^2)^{-2} \times \left[ \frac{\sigma_0}{6 \times 10^{-27}\text{cm}^3\text{s}^{-1}} \right] (\Omega_{X\bar{X}} h^2)^2 < 0.008 \quad , \quad (25)
\]

which we show in Fig. 1 (the observationally favored value for the total mass density is \( \Omega_D h^2 \approx 0.15 \) [37,38], but we use 0.3 as a more conservative upper bound). For particles that survive to the present, this bound is generally stronger than the bound from distortions of the CMB. Note that our calculation is a somewhat rough estimate because the observational bounds are considerably lower at some energies than the power law we adopted [32], the energy bin width \( \Delta E/E \) is approximate, and we used \( I(\psi) = 1 \) when its value can be higher for observation angles near the galactic center [17].

For particles with \( m_X > 0.5 \text{ MeV} \) we might consider the observation of annihilation products other than photons (e.g., positrons); however, reference [17] concludes that these signals cannot be used to conclusively rule out dark matter candidates because of astrophysical uncertainties.

IV. DISCUSSION

Some of the parameter space that can be constrained by residual annihilations is covered already by other kinds of constraints. To put the annihilation constraints in perspective we review the primary astrophysical ones.

BBN gives limits on the expansion rate of the universe at \( T \sim 1 \text{ MeV} \) (sometimes described as a limit on the effective number of light neutrinos, e.g., reference [3]). The expansion rate would be affected by an additional particle with mass in the range where our CMB bound is most constraining (\( m_X \lesssim \text{MeV} \)), if the particle’s number density at the time of BBN is equal to the thermal equilibrium value. Therefore, the annihilation bound on particles with \( m_X \lesssim \text{MeV} \) is only nonredundant for particles that were not in thermal equilibrium at the time of nucleosynthesis.
Particles with \( m_X \geq 5 \text{ MeV} \) are only constrained by our bound if their density, extrapolated by \((1+z)^{-3}\) from the time they influence the CMB to the present, is substantially greater than the present critical density, or if their cross section is very large but their number density is somehow higher than the density obtained from freezeout of their annihilations (see Fig. 1). The first case would require that the particle decays invisibly or otherwise disappears between \( z \sim 10^6 \) and the present, and the second requires that the particle was formed by decays of a heavier particle (or some other mechanism) after the freezeout temperature for its annihilations.

New particles that can be created in stars (e.g., by plasmon decay, \( \gamma \rightarrow X \bar{X} \)) are constrained by their action as additional sources of cooling. Constraints from observations of globular cluster stars apply for \( m_X < \sim 10 \text{ KeV} \) [2]. Similarly, cooling in supernovae, specifically SN1987A, can be influenced by the creation of new particles with mass \( m_X \lesssim 30 \text{ MeV} \); however, these constraints depend on the details of the particle interactions in the plasma (e.g., reference [39]).

In summary, the bound from distortions of the CMB energy spectrum probably cannot be a useful constraint on annihilations of light \( (m_X \lesssim 0.5 \text{ MeV}) \) dark matter particles (e.g., warm dark matter) to photons, because the bound from annihilations in our Galaxy is always stronger. It is most interesting as a constraint on dark matter particles in the mass range \( 0.5 \lesssim m_X \lesssim 5 \text{ MeV} \), and any particle that decays invisibly between \( z \sim 10^6 \) and the present, although in either case the particle must also evade the bound from the expansion rate of the universe during BBN. Finally, although we have not discussed in this paper the case of annihilations of particles with cross sections that increase with decreasing temperature (e.g., [40]), it seems likely that they can be very tightly constrained by the kinds of tests we have discussed.

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FIG. 1. Bounds on relic particles from residual annihilations. The space above the lines is ruled out in each case. Except for the upper solid line, all bounds are for particles with $\langle \sigma v \rangle = \sigma_0$ (i.e., $n = 0$). The lower (upper) solid line is the constraint from the CMB (including both $\mu$ and $y$ distortions) for $n = 0$ ($n = 1$). The upper (lower) long-dashed line is the constraint from BBN using the high (low) deuterium abundance (the low D constraint and the CMB constraint are practically identical but we have introduced a slight offset for clarity). The dashed line is the constraint from the diffuse photon background produced by extragalactic annihilations, and the dotted line is the constraint from the diffuse photon background produced by annihilations in the Milky Way halo. The BBN constraints apply for $m_X > 26$ MeV, the threshold for photodissociation of $^4$He to D. For the CMB and BBN constraints, $f$ is the fraction of the annihilation energy that interacts electromagnetically. For the photon background constraints, $f$ should be replaced by $f_\gamma$, the fraction of annihilations that produce two photons with energy $m_X$ (the lines for these constraints are terminated at the electron mass because $f_\gamma \ll f$ is likely if other annihilation channels are open). For the case of equivalent particle and antiparticle, substitute $\Omega_{X\bar{X}} \to \Omega_X$, and $\sigma_0/6 \times 10^{-27} \text{cm}^3\text{s}^{-1} \to \sigma_0/3 \times 10^{-27} \text{cm}^3\text{s}^{-1}$.