CMB bounds on dark matter annihilation: Nucleon energy losses after recombination

Weniger, C.; Serpico, P.D.; Iocco, F.; Bertone, G.

DOI
10.1103/PhysRevD.87.123008

Publication date
2013

Document Version
Final published version

Published in
Physical Review D. Particles, Fields, Gravitation, and Cosmology

PHYSICAL REVIEW D **87,** 123008 (2013)

CMB bounds on dark matter annihilation: Nucleon energy losses after recombination

Christoph Weniger,[1] Pasquale D. Serpico,[2] Fabio Iocco,[3] and Gianfranco Bertone[1]

[1]*GRAPPA Institute, University of Amsterdam, Science Park 904, 1098 GL Amsterdam, Netherlands*

[2]*LAPTh, Université de Savoie, CNRS, B.P. 110, Annecy-le-Vieux F-74941, France*

[3]*The Oskar Klein Center for CosmoParticle Physics, Department of Physics, Stockholm University, Albanova, SE-10691 Stockholm, Sweden*

(Received 11 March 2013; published 24 June 2013)

We consider the propagation and energy losses of protons and antiprotons produced by dark matter annihilation at redshifts $100 < z \lesssim 2000$. In the case of dark matter annihilations into quarks, gluons and weak gauge bosons, protons and antiprotons carry about 20% of the energy injected into $e^\pm$ and γ's, but their interactions are normally neglected when deriving cosmic microwave background bounds from altered recombination histories. Here, we follow numerically the energy-loss history of typical protons/antiprotons in the cosmological medium. We show that about half of their energy is channeled into photons and $e^\pm$, and we present a simple prescription to estimate the corresponding strengthening of the cosmic microwave background bounds on the dark matter annihilation cross section.

DOI: 10.1103/PhysRevD.87.123008 PACS numbers: 95.30.Cq, 95.35.+d, 98.80.Es

I. INTRODUCTION

Astrophysical and cosmological observations provide compelling evidence that about 85% of all the matter in the Universe is in the form of dark matter (DM), an elusive substance which is currently searched for with a variety of observational and experimental channels at colliders, in underground detectors, or via indirect signals from DM annihilation or decay [1].

Cosmic microwave background (CMB) anisotropy and polarization data provide interesting constraints on the properties of DM particles [2–4]. Secondary particles injected via DM annihilation (or decay) after recombination, around redshift $z \sim \mathcal{O}(600)$, would in fact inevitably affect the recombination history of the Universe and widen the surface of last scattering, which is tightly constrained by CMB observations as discussed in Refs. [5–9], and more recently in Refs. [10–16]. Possible effects on the cosmological recombination spectrum were discussed in Ref. [17].

One of the main reasons of interest for these constraints is that, in contrast with other indirect searches, they do not rely on knowledge of astrophysical DM structures, affected by the complex aspects of nonlinear gravity as well as complicated feedback due to baryons [7,8]. The CMB probe is thus as reliable as the description of the basic atomic and nuclear/particle physics processes involved. The robustness (and astrophysical independence) of the CMB constraints motivates further efforts to assess and improve the error budget. The degree of sophistication in modeling the atomic processes down to the recombination stage is quite elevated and has also seen recent improvements; see e.g. [18]. Here we revise one aspect related to the accuracy of the nuclear/particle physics part.

It is typically assumed that protons are highly penetrating and poor at transferring energy to the intergalactic medium (IGM)—a misnomer, since no galaxies have formed at such high redshifts—and their energy release to the medium is neglected [2,6] (see however the comment in Ref. [10]). In this article, we estimate the additional energy released to the gas by the interactions of the high-energy protons and antiprotons formed among DM annihilation final states.

This article is structured as follows: In Sec. II we review the basic physics substantiating the two points above. In Sec. III we describe our computational technique and present our results in Sec. IV. Finally, in Sec. V we conclude.

II. PHYSICAL PROCESSES

Protons and antiprotons carry a significant fraction of the overall energy emitted in DM annihilations into quarks, gluons or weak gauge bosons. Typically, this amounts to $\sim$20% of the energy channeled into $e^\pm$ and γ's (see for example Fig. 4 in [19]), and a fraction of this energy will be inevitably transferred to the IGM. Neutrons and antineutrons decay very fast and behave practically like protons and antiprotons, while (anti)deuterons and heavier nuclei are produced in negligible amounts in DM annihilations.

At the epochs of interest here, which correspond to a redshift $z = \mathcal{O}(10^3)$, $p/\bar{p}$'s propagate in a medium which is 8 or 9 orders of magnitude more dense than at the present epoch, with typical proton and helium gas densities up to $\mathcal{O}(10^2)$ particles/cm^3. Even neglecting the interaction with photon baths of densities of $\mathcal{O}(10^{11})$ cm^{-3}, a typical p-p inelastic cross section of 30 mb yields a collision time scale lower than the age of the Universe at decoupling. Hence, we expect that in general the probability for a nucleon to interact within a Hubble time is large, and that a significant energy deposition takes place (similar estimates can be found in Ref. [10]).

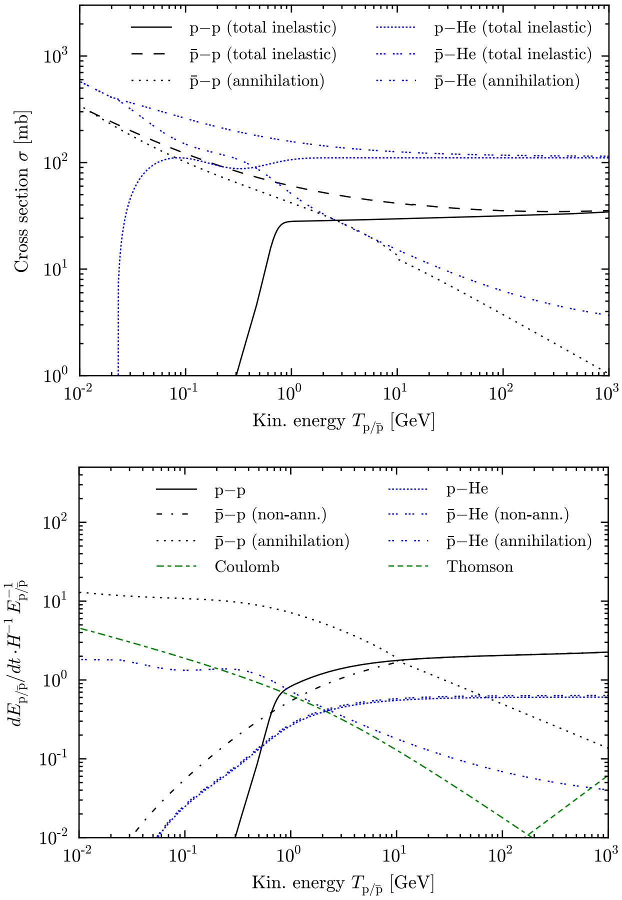

FIG. 1 (color online). Upper panel: Total inelastic hadronic cross sections in lab frame as function of the p and $\bar{p}$ kinetic energies. Where applicable, we also show the annihilation part of the total cross section separately. Lower panel: Fractional energy losses relative to Hubble rate, at redshift $z = 1000$. The non-annihilating and annihilating parts of the hadronic cross sections are shown separately.

More specifically, $p/\bar{p}$'s will undergo the following processes: Coulomb scattering of $p/\bar{p}$ on IGM electrons[1] [20]; Thomson scattering of $p/\bar{p}$ on IGM photons [21]; Inelastic scattering of $p/\bar{p}$ on IGM protons [22]; Inelastic scattering of $p/\bar{p}$ on IGM helium [22].

In Fig. 1 we show the inelastic scattering cross sections as a function of the $p/\bar{p}$ kinetic energy (top panel), and the corresponding fractional energy loss rate $E^{-1}dE/dt$ times the Hubble time H^{-1} at redshift $z = 1000$ as function of the $p/\bar{p}$ kinetic energy (bottom panel). Values of order unity or even larger indicate potentially large effects. In case of antiprotons, we plot annihilating and nonannihilating rates separately. For *nonannihilating* inelastic interactions, the final energy distribution of $p/\bar{p}$ is taken to be constant in the physically accessible regime $m_p \ldots E_p$ (E_p is the energy of the primary particle, m_p the $p/\bar{p}$ mass). Consequently, the mean energy loss during a nonannihilating collision is $\langle \Delta E \rangle \simeq 0.5 T_p$, with $T_p \equiv E_p - m_p$ being the initial kinetic energy. The energy released during an *annihilation* event is $\Delta E = E_p + m_p$. At energies $E \gtrsim 10$ GeV, the losses are dominated by inelastic $\bar{p}$-p and p-p scattering without annihilation; at lower energies $\bar{p}$-p annihilation and Coulomb losses become relevant and dominate for nonrelativistic particles.

In the next section we shall follow the evolution of a nucleon pair from a hypothetical toy annihilation process $\chi\chi \to \bar{p}p$, computing the energy loss of the daughter nucleons down to relatively low redshifts of a few hundreds. Obviously, only part of this energy will be *absorbed* by the gas. Following in detail the energy degradation down to the energy-transfer processes to the gas—heating and ionization—goes beyond our purposes (it is worth mentioning that several efforts are being put into a more realistic treatment of the related physics for the $e^{\pm}$ and γ's; see e.g. [23]). Rather, we will content ourselves with estimating the energy that is released into energetic electrons and photons (essentially, the fraction of the energy lost to stable particles other than neutrinos). We will express this as the *electromagnetic fraction* $f_{e^{\pm}\gamma}$ of the energy initially injected as nucleons, which we will precisely define below. This approach is exact as long as the CMB bounds are "calorimetric" and the precise form of the spectrum of electromagnetic particles is irrelevant in determining the ultimate fate of the energy injected.

Previous investigations suggest that this should provide a reasonable first approximation to the true result; for our purposes the accuracy is expected to be at the level of ~30% (see Fig. 2 of [15], $z \sim 600$). Since we are already concerned with a correction to the basic results, we shall adopt this ansatz which greatly simplifies the problem. The only potentially problematic case is the one of Coulomb reactions of the (anti)protons, which can produce low-energy electrons (which may behave differently from high-energy ones). However, the legitimacy of our approximation is supported by two arguments: (i) this energy-loss rate has only a logarithmic dependence on the minimum kinetic energy; (ii) it only matters for nonrelativistic (anti)protons, for which most of the energy coming from electroweak-scale WIMPs has already been dissipated. In fact, with the exception of very light (GeV scale) DM particles, protons are typically born relativistic or semirelativistic.

III. COMPUTATION

The energy loss processes sketched above are of two distinct classes: continuous energy losses (with small energy transfer per collision) when protons interact with electrons or photons; or catastrophic losses, when they undergo an inelastic collision or an annihilation (for antiprotons). For the moment we shall ignore elastic collisions; we will comment on their role at the end of Sec. IV.

[1]As lower cutoff in the Coulomb logarithm we adopt 10 eV.

Continuous energy losses in the range of our interest, $100 < z \lesssim 2000$, can be described via the following differential equation:

$$\frac{dE}{dz} = \frac{dE}{dz}\bigg|_{\text{Coulomb}} + \frac{dE}{dz}\bigg|_{\text{Thomson}} + \frac{v^2 E}{1+z}. \qquad (1)$$

The last term at the rhs describes adiabatic energy losses in the expanding universe; the other two terms describe Coulomb and Thomson energy losses. In the present work, Thomson losses will be neglected, which from Fig. 1 is clearly justified at the energies of interest.

Hadronic processes are included on top of the continuous energy losses with a Monte Carlo simulation. The Monte Carlo starts with a fixed $p/\bar{p}$ energy E_{inj} at some initial redshift z_{init} and tracks the history of the particle as it moves to lower redshifts. The redshift of an individual scattering process is inferred by sampling from a survival function, which is determined by solving a differential equation whose derivate is given by the inelastic scattering rates. The amount of electromagnetic and hadronic energy lost by each particle as function of redshift z is recorded.

At any given redshift z, a fraction $f_{e^\pm\gamma}(z)$ of the hadronically injected energy is actually channeled into electromagnetic form (energetic $e^\pm$ and photons, see discussion above). More specifically, for annihilating DM, $f_{e^\pm\gamma}$ is defined as

$$\epsilon_{e^\pm\gamma}(z) \equiv \frac{dE}{dVdt} = 2M_\chi f_{e^\pm\gamma}(z) \cdot \langle\sigma v\rangle n_{\chi,0}^2 \cdot (1+z)^3, \qquad (2)$$

where $\epsilon_{e^\pm\gamma}(z)$ denotes here the energy released into electromagnetic form *per comoving volume* and per unit time, and $n_{\chi,0}$ is today's number density of DM particles. This $f_{e^\pm\gamma}(z)$ can be derived from the integral

$$f_{e^\pm\gamma}(z) = \int_z^{z_{\max}} dz' g_{e^\pm\gamma}(z,z') \frac{(1+z')^2}{H(z')(1+z)^3}, \qquad (3)$$

where $g_{e^\pm\gamma}(z,z')$ denotes the fraction of the energy of a single DM annihilation event at redshift z' that is released into electromagnetic energy at redshift z per unit time. We will take $z_{\max} = 10000$ throughout, such that $\epsilon_{e^\pm\gamma}(z)$ at $z < 1000$ is independent of $z_{\max}$.

We split $f_{e^\pm\gamma}(z)$, and analogously the function $g_{e^\pm\gamma}(z)$, into three parts according to

$$f_{e^\pm\gamma} = \tilde{f}_{\text{Cou}} + \alpha_{\text{had}}(\tilde{f}_{\text{inel}} + \tilde{f}_{\text{ann}}), \qquad (4)$$

with the three addenda at the rhs corresponding to Coulomb losses, inelastic scattering and annihilation, respectively. These $\tilde{f}$'s denote the total (anti)proton energy *lost* to secondary particles via the scatterings. All of the energy lost by Coulomb scattering, and a fraction α_{had} of the energy lost during inelastic scattering and annihilation, is channeled into electromagnetic energy and hence contributes to $f_{e^\pm\gamma}$.

A reasonable value is $\alpha_{\text{had}} \simeq 0.5$. After a hadronic scattering, the energy eventually carried by $e^\pm$ and γ contributes fully to $f_{e^\pm\gamma}$, the energy carried by ν's is completely lost, and only a fraction of the energy carried by nucleons will be transferred into $e^\pm\gamma$ at a later stage. We will neglect this latter contribution to $f_{e^\pm\gamma}$, since it is further suppressed by the small fraction of energy released into nucleons during inelastic scattering.

As a proxy for the energy released in the different channels we can take the gluon-gluon (or charmed quark) channels of Fig. 4 in [19], where about 46% of the energy is found to be channeled into $e^\pm$ and γ, with ~27% of this amount going into nucleons. We also checked that these figures do not change appreciably as a function of M_χ (M. Cirelli, private communication). This is also consistent with the expectations from nonrelativistic proton-antiproton annihilation; see e.g. Table 2 in [24]. A very simple justification of this value can be obtained in the limit where annihilation final states are just made of pions, with isospin-blind production yields (equal quantities of π^0, π^+, π^-). One would expect full channeling of π^0 energy into $e^\pm\gamma$ and about 1/6 of the energy stored in $\pi^\pm$, hence a weighted average of 44%. We thus believe that $\alpha_{\text{had}} \simeq 0.5$ is a reasonable benchmark, probably affected by a 20% uncertainty. While this may be a crude description of the actual process, it is enough for providing a first estimate of the hadronic correction to CMB bounds on annihilating dark matter.

On a more technical note, to obtain $\tilde{g}_{\text{Cou}}(z,z')$, $\tilde{g}_{\text{inel}}(z,z')$ and $\tilde{g}_{\text{ann}}(z,z')$, we simulate particle injection at redshifts $z' = 30$–10000 and record what fraction of the energy is released in certain redshift intervals $z_0 \ldots z_1$, divided by the corresponding time interval $\Delta t \equiv t_0 - t_1$. From these $\tilde{g}(z,z')$'s, we can then derive the $f_{e^\pm\gamma}(z)$ from Eqs. (3) and (4).

IV. RESULTS AND DISCUSSION

In Fig. 2 we show the main results of this paper. In the top panel, the resulting different components of the *fractional energy loss* of (anti)protons are shown as function of their injection energy at redshift $z \sim 600$. Notably, the annihilation of antiprotons releases also the energy of the target proton, which yields values $\tilde{f}_{\text{ann}} > 1$ when considering the antiproton channel alone. The bottom panel shows the fraction of the injection energy that is channeled into electromagnetic energy, $f_{e^\pm\gamma}$, as function of redshift z and for different kinetic injection energies $T_{p/\bar{p}}$. For energies $T_{p/\bar{p}} < 10$ GeV ($T_{p/\bar{p}} > 10$ GeV) about $f_{e^\pm\gamma} \sim 50\%$ (40%) of the energy fraction channeled into nucleons will eventually by released as electromagnetic energy at the most relevant redshifts $z = 500$–700.

Most importantly, for DM masses below ~100 GeV, the $f_{e^\pm\gamma}(z)$'s are approximately *independent of redshift*. This implies that the released electromagnetic energy is simply a constant correction to the prompt electromagnetic energy

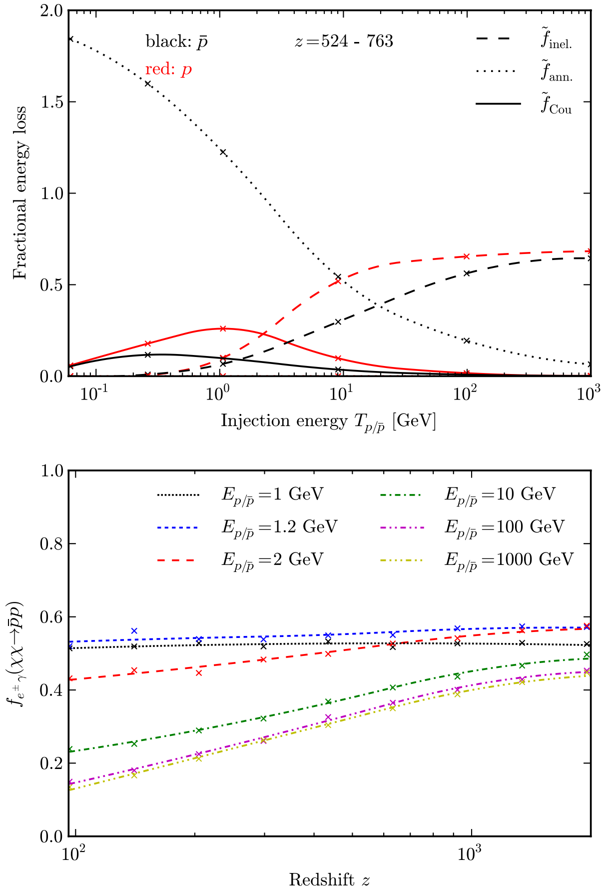

FIG. 2 (color online). Upper panel: Fractional energy losses at redshift $z \sim 600$, for different kinetic injection energies $T_{p/\bar{p}}$. We show the contributions from annihilating and nonannihilating hadronic scatterings and from Coulomb losses separately. Lower panel: Electromagnetic (i.e. energetic $e^\pm$ and photons) energy released during $p/\bar{p}$ propagation, as function of redshift z, for the toy process $\chi\chi \to \bar{p}p$ with different dark matter masses $m_\chi = 1.0$ GeV to $m_\chi = 1$ TeV. In all cases we show Monte Carlo results (crosses) as well as interpolations with splines of degree two (lines).

directly released during DM annihilation. In the current literature (see e.g. Ref. [6]), the fraction of the total injected energy finally deposited in the gas as heat, ionization and excitation energy is denoted by $f(z)$, and determined neglecting annihilation channels into hadronic final states. As discussed above, CMB bounds are to a good approximation calorimetric, and the precise form of the spectrum of electromagnetic particles can be neglected at first order in determining the ultimate fate of the energy injected.[2] We can then give a simple recipe to correct these f's:

$$f(z) \to f(z)\left(1 + f_{e^\pm\gamma}\frac{E_{\mathrm{N}\bar{\mathrm{N}}}}{E_{\gamma+e^\pm}}\right), \tag{5}$$

where $E_{\mathrm{N}\bar{\mathrm{N}}}$ and $E_{\gamma+e^\pm}$ denote the prompt energy in nucleons and in electromagnetic energy, respectively, produced during an annihilation. As shown in the bottom panel of Fig. 2, we find that $f_{e^\pm\gamma} \simeq 0.5$ for injected $p/\bar{p}$ energies well below $\sim$10 GeV, i.e. for most DM masses of interest.

Throughout, we neglected *elastic* $p/\bar{p}$ scattering, which is well justified for our purposes: At energies below $T_p < 1$ GeV, elastic p-p scattering will only redistribute energy that finally is lost via Coulomb scattering. At energies above $T_p > 1$ GeV, elastic p-p scattering is subdominant ($\lesssim$50% of the total p-p cross section); even rare collisions with maximal energy transfer do not alter the deposition history drastically since the energy dependence shown in Fig. 2 is weak. In case of $\bar{p}$-p scattering, the elastic cross section is smaller than 40% at all energies; the main effect of collisions with large energy transfer would be a slight increase in antiproton annihilation rate.

V. CONCLUSIONS

It has been recently recognized that nonstandard sources of heating and ionization of the IGM can be probed via CMB anisotropies. This effect has been used to derive bounds on DM annihilation cross section and decay lifetime. To a very good approximation, these bounds do not depend on "astrophysics" (structure formation, DM halo structure, star formation etc.). The nature of this probe, whose robustness relies essentially on the accuracy of the description of atomic and nuclear/particle physics, motivates efforts to assess and improve the error budget of bounds obtainable with this technique.

In astroparticle physics, energy losses of high energy nucleons propagating in the intergalactic medium are usually neglected outside the realm of ultrahigh-energy cosmic rays. Energetic nucleons propagating in a high-z cosmological medium over Hubble times, on the other hand, do suffer significant energy losses. A physically interesting example is provided by nucleon by-products of dark matter annihilation, which can release a significant fraction of their energy at high z [$\simeq \mathcal{O}(10^3)$].

The aim of this paper was to provide a first estimate of this process, which goes in the direction of improving the CMB bounds for a number of channels. Under reasonable approximations, we found that the Eq. (5) is a fair description of the main effect, for a value $f_{e^\pm\gamma} \simeq 0.5$ over a quite large parameter space. We expect thus that for DM annihilation channels into gluons, gauge bosons and quarks for which $\frac{E_{\mathrm{N}\bar{\mathrm{N}}}}{E_{\gamma+e^\pm}} \simeq 0.2$, this should change the CMB bounds on DM at the 10% level and should be included in forthcoming Planck data analyses.

[2]At low energies, the precise assumptions of the recombination model *do* become relevant and require a proper treatment (see e.g. CosmoRec [25]). A thorough study of this issue has been recently presented in [26].

ACKNOWLEDGMENTS

We would like to thank M. Cirelli for useful comments. At LAPTh, this activity was developed coherently with the research axes supported by the labex grant ENIGMASS. Partial support of the ANR grant DMAstroLHC is also acknowledged by P. S. G. B. acknowledges the support of the European Research Council through the ERC Starting Grant "WIMPs Kairos."

[1] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996); L. Bergström, Rep. Prog. Phys. **63**, 793 (2000); C. Munoz, Int. J. Mod. Phys. A **19**, 3093 (2004); G. Bertone, D. Hooper, and J. Silk, Phys. Rep. **405**, 279 (2005); *Particle Dark Matter: Observations, Models and Searches*, edited by G. Bertone (Cambridge University Press, Cambridge, England, 2010).
[2] X.-L. Chen and M. Kamionkowski, Phys. Rev. D **70**, 043502 (2004).
[3] N. Padmanabhan and D. P. Finkbeiner, Phys. Rev. D **72**, 023508 (2005).
[4] T. Kanzaki and M. Kawasaki, Phys. Rev. D **78**, 103004 (2008).
[5] S. Galli, F. Iocco, G. Bertone, and A. Melchiorri, Phys. Rev. D **80**, 023505 (2009).
[6] T. R. Slatyer, N. Padmanabhan, and D. P. Finkbeiner, Phys. Rev. D **80**, 043526 (2009).
[7] G. Hütsi, A. Hektor, and M. Raidal, Astron. Astrophys. **505**, 999 (2009).
[8] M. Cirelli, F. Iocco, and P. Panci, J. Cosmol. Astropart. Phys. 10 (2009) 009.
[9] T. Kanzaki, M. Kawasaki, and K. Nakayama, Prog. Theor. Phys. **123**, 853 (2010).
[10] G. Hütsi, J. Chluba, A. Hektor, and M. Raidal, Astron. Astrophys. **535**, A26 (2011).
[11] S. Galli, F. Iocco, G. Bertone, and A. Melchiorri, Phys. Rev. D **84**, 027302 (2011).
[12] D. P. Finkbeiner, S. Galli, T. Lin, and T. R. Slatyer, Phys. Rev. D **85**, 043522 (2012).
[13] G. Giesen, J. Lesgourgues, B. Audren, and Y. Ali-Haimoud, J. Cosmol. Astropart. Phys. 12 (2012) 008.
[14] C. Evoli, S. Pandolfi, and A. Ferrara, arXiv:1210.6845.
[15] T. R. Slatyer, arXiv:1211.0283.
[16] J. M. Cline and P. Scott, J. Cosmol. Astropart. Phys. 03 (2013) 044.
[17] J. Chluba, arXiv:0910.3663.
[18] J. Chluba and R. M. Thomas, Mon. Not. R. Astron. Soc. **412**, 748 (2011).
[19] M. Cirelli, G. Corcella, A. Hektor, G. Hütsi, M. Kadastik, P. Panci, M. Raidal, F. Sala, and A. Strumia, J. Cosmol. Astropart. Phys. 03 (2011) 051; 10 (2012) E01.
[20] J. D. Jackson, *Classical Electrodynamics* (John Wiley & Sons, New York, 1999), 3rd Ed.
[21] K. Jedamzik, Phys. Rev. D **74**, 103509 (2006).
[22] I. V. Moskalenko, A. W. Strong, J. F. Ormes, and M. S. Potgieter, Astrophys. J. **565**, 280 (2002).
[23] C. Evoli, M. Valdes, A. Ferrara, and N. Yoshida, Mon. Not. R. Astron. Soc. **422**, 420 (2012).
[24] G. Steigman, Annu. Rev. Astron. Astrophys. **14**, 339 (1976).
[25] http://www.cita.utoronto.ca/~jchluba/Science_Jens/Recombination/CosmoRec.html.
[26] S. Galli, T. Slatyer, M. Valdes, and F. Iocco, arXiv:1306.0563 [Phys. Rev. D. (to be published)].