Impact of Dark Matter annihilations in halos on the CMB

Vivian Poulin

LAPTh, Université Savoie Mont Blanc & CNRS, BP 110,
F-74941 Annecy-le-Vieux Cedex, France

Institute for Theoretical Particle Physics and Cosmology (TTK),
RWTH Aachen University, D-52056 Aachen, Germany.

March 1, 2016

Abstract

It is well known that annihilations in the smooth distribution of dark matter (DM) can leave imprints in the cosmic microwave background (CMB) anisotropy power spectrum. However, the relevance of DM annihilations in halos for cosmological observables is still subject to debate, with previous works reaching different conclusions on this point. In this work, we confirm that, if one uses the standard reionization parametrization, the modification of the signal with respect to the one coming from annihilations in the smooth background is tiny, below cosmic variance within currently allowed parameter space. However, if different and probably more realistic treatments of the astrophysical sources of reionization and heating are adopted, a more pronounced effect of the DM annihilation in halos is possible. We thus conclude that within currently adopted baseline models the impact of the virialised DM structures cannot be uncovered by CMB power spectra measurements, but a larger impact is possible if peculiar models are invoked for the redshift evolution of the DM annihilation signal or different assumptions are made for the astrophysical contributions. A better understanding (both theoretical and observational) of the reionization and temperature history of the universe, notably via the 21 cm signal, seems the most promising way for using halo formation as a tool in DM searches, improving over the sensitivity of current cosmological probes.

1 Introduction

The existence of a dark component of matter in the universe, i.e. a non electromagnetically interacting form of matter, is by now well established thanks to a variety of observation in both astrophysics and cosmology: This dark matter (DM) is necessary for instance to explain the formation of structures in the universe as we see them, and its relic density $\Omega_{\rm DM}h^2$ can be very precisely measured thanks to the cosmic microwave background (CMB) anisotropy power spectra. The quest for understanding DM nature is however still underway, with a wide variety of techniques. Many extensions of the standard models of particle physics (including electroweak scale supersymmetry) naturally accommodate a (quasi-)stable weakly interacting massive particle, or WIMP, that can act as excellent dark matter candidate. Additionally, WIMP residual annihilations (or, in some models, decays) can inject sufficient "visible" energy that can be searched for. Interestingly, it has been realized since the eighties that CMB observations can in fact tell us a lot about the nature of DM. Annihilations (or decays, neglected from now on) of WIMPs, inject non-thermal photons and electrons in the intergalactic medium (IGM) that can delay the recombination and change the relic abundance of free electrons after decoupling. Hence, WIMP annihilations can jeopardize the observed CMB temperature and polarization anisotropy angular power spectra and therefore can be constrained by an experiment like Planck. DM annihilations in the homogenous smooth background have been well studied and documented in the last decade (see e.g. [1] and references therein). The Planck collaboration in a very recent paper [2] has reported very strong bounds on the cross-section, excluding thermal WIMPs for any standard model annihilation channel for masses up to 10 GeV, also ruling out WIMP explanations of cosmic ray lepton spectral features discussed in recent years. I will first review how one can get such bounds and secondly, show how it might be possible to improve over them by taking into account DM structure formation.

2 Review of the standard formalism

The main impact of DM annihilation on the CMB is a modification of the ionization and thermal history of the universe. In the standard picture, the equation describing the evolution of the free electron fraction $x_e \equiv n(\mathrm{HII})/n(\mathrm{H}) \equiv n(\mathrm{HeII})/n(\mathrm{He})$ in term of the redshift z writes:

$$\frac{dx_e(z)}{dz} = \frac{1}{(1+z)H(z)}(R(z) - I(z))\,, \tag{1}$$

with

$$R(z) = C\Big[\alpha_H x_e^2 n_H\Big], \qquad I(z) = C\Big[\beta_H(1-x_e)e^{-\frac{h\nu_\alpha}{k_b T_\mathrm{M}}}\Big] \tag{2}$$

These two terms are respectively the standard recombination and reionization rates. The first term encodes the probability that one free electron encounters an ionized hydrogen, is captured but *not* directly in the ground state and finally decays from the $n = 2$ state to the ground state before being ionized. The second term encodes the probability that a CMB photon redshifts at the Lyman-α transition frequency, and hits a neutral hydrogen in the $n = 2$ state. This standard scenario is known as Peebles "Case B" recombination. In this framework, the coefficient C represents the probability for an electron in the n = 2 state to get to the ground state before being ionized. Its computation is detailed in [1]. Finally, α_H and β_H are the effective recombination and photoionization rates for principal quantum numbers ≥ 2 in Case B recombination (per atom in the $2s$ state), ν_α is the Lyman-α frequency and T_M is the temperature of the baryonic gas.
The evolution of the intergalactic medium (IGM) temperature is instead ruled by the equation:

$$\frac{dT_\mathrm{M}}{dz} = \frac{1}{1+z}\Big[2T_\mathrm{M} + \gamma(T_\mathrm{M} - T_\mathrm{CMB})\Big] \tag{3}$$

where the dimensionless parameter γ, also called opacity of the gas, is defined as :

$$\gamma \equiv \frac{8\sigma_T a_r T_\mathrm{CMB}^4}{3Hm_e c}\frac{x_e}{1+f_{He}+x_e} \tag{4}$$

with σ_T the Thomson cross-section, a_r the radiation constant, m_e the electron mass, c the speed of light, and $f_{He}(\equiv Y_p/[4(1-Y_p)])$ the fraction of helium by number of nuclei. The first term is an adiabatic cooling due to the Universe expansion, whereas the second one accounts for interactions between CMB photons and matter, mainly through Compton scattering with free electrons.
Energetic particles injected by any type of sources will have three effects on the cosmic gas: direct ionization, collisional excitation (followed by photoionization by CMB photons), and heating. These effects are taken into account by adding two terms to equation (1) and one term to (3). The rate of the first two effects, namely direct ionization I_{Xi} and excitation+ionization $I_{X\alpha}$, are given by:

$$I_{Xi} = -\frac{\chi_i(z)}{n_H(z)E_i}\frac{dE}{dVdt}\bigg|_\mathrm{dep}, \; I_{X\alpha} = -\frac{(1-C)\chi_\alpha(z)}{n_H(z)E_\alpha}\frac{dE}{dVdt}\bigg|_\mathrm{dep}, \tag{5}$$

where E_i and E_α are respectively the average ionization energy per baryon, and the Lyman-α energy. The heating rate term K_h, normalized to the Hubble rate, can be similarly defined as:

$$K_h = -\frac{2\,\chi_h(z)}{H(z)3\,k_b n_H(z)(1+f_{He}+x_e)}\frac{dE}{dVdt}\bigg|_\mathrm{dep} \quad . \tag{6}$$

In previous equations, $\frac{dE}{dVdt}|_{\rm dep}$ stands for the energy *deposited* in the plasma at redshift z. It is splitted according to the *energy repartition fractions* χ_j, with the index $j = \{i, \alpha, h\}$ denoting ionization, excitation (through Lyman-α transition) and heating, respectively. The energy density injection rate $\frac{dE}{dVdt}|_{\rm inj}$ can be readily computed as the product among the number density of pairs of DM particles $n_{\rm pairs}$, the annihilation probability per time unit $P_{\rm ann}$, and the released energy per annihiliation $E_{\rm ann}$:

$$\frac{dE}{dVdt}\bigg|_{\rm inj}(z) = \left(n_{\rm pairs} = \kappa\frac{n_{\rm DM}}{2}\right)\cdot\left(P_{\rm ann} = \langle\sigma_{\rm ann}v\rangle n_{\rm DM}\right)\cdot\left(E_{\rm ann} = 2m_{\rm DM}c^2\right)\,. \tag{7}$$

Taking only into account the smooth cosmological DM distribution, we can write this rate as

$$\frac{dE}{dVdt}\bigg|_{\rm inj,smooth}(z) = \kappa\rho_c^2c^2\Omega_{\rm DM}^2(1+z)^6\frac{\langle\sigma v\rangle}{m_{\rm DM}}\quad. \tag{8}$$

In the equations above, $\langle\sigma v\rangle$ is the cross-section, $\rho_c = 3H_0^2/8\pi G$ the critical density of the Universe today, $\Omega_{\rm DM}$ the current DM abundance relative to the critical density and $m_{\rm DM}$ the DM mass. If DM is made of self-conjugated particles, such as Majorana fermions, one has $\kappa = 1$, which is what we shall assume in the following.

The response of the medium to energy injection depends strongly on the cascade of particles produced by DM annihilation, and on the epoch at which the DM particles annihilate. This response is conveniently parametrized by a dimensionless *efficiency function* $f(z)$ [3] such that:

$$\frac{dE}{dVdt}\bigg|_{\rm dep}(z) = f(z)\frac{dE}{dVdt}\bigg|_{\rm inj}(z)\quad. \tag{9}$$

The expression of f can be obtained via appropriate transfer functions $T^{(\ell)}(z', z, E)$, giving the fraction of the $\ell-$particle's energy E injected at z' that is absorbed at z, as

$$f(z) = \frac{\int d\ln(1+z')\frac{(1+z')^3}{H(z')}\sum_\ell\int T^{(\ell)}(z',z,E)E\frac{dN}{dE}\big|_{inj}^{(\ell)}dE}{\frac{(1+z)^3}{H(z)}\sum_\ell\int E\frac{dN}{dE}\big|_{inj}^{(\ell)}dE} \tag{10}$$

where the sum runs over species (in practice ℓ denotes either photons or electrons), and $\frac{dN}{dE}|_{inj}^{(\ell)}$ is the injected spectrum of each of them in a given DM model, and is independent from z. The calculation of these functions is very involved, but it has been carefully done in [3], with a study of associated systematics presented in [4]. While we do not indulge here in technical details, it is worth stressing a few conceptual issues concerning the meaning of $f(z)$:

– In the literature, the assumption that the energy released by annihilations at a given redshift is absorbed at the *same* redshift is referred to as the *on-the-spot* approximation. In that case, the meaning of $f(z)$ is clear: it is the fraction of energy that is absorbed by the gas, either via collisional heating or atomic excitations and ionizations. It takes into account that a part of the energy may escape for instance in the form of neutrinos or as photons which free-stream to the present day. The $f(z)$ factor, in this approximation, depends on DM particle model but cannot exceed 1 by definition. This approximation therefore mainly consists in considering that all absorption processes are very rapid in comparison to the Hubble time, defined as $t_H(z) = c/H(z)$.

– However, the authors of [3] have shown that this is not true for the entire redshift range that we are considering (and strictly speaking, not even at $z \sim 1000$). Some photons that are free-streaming at some given redshift z' could be absorbed at $z < z'$. The *beyond-on-the-spot* treatment consists in computing the full evolution, like in Refs. [3, 4]. The result can still be cast in the form of an efficiency function $f(z)$, simply defined *a posteriori* as the ratio of deposited energy to injected energy *at the same redshift*. Several authors have shown that the redshift-dependence of $f(z)$ is of very little relevance for CMB constraints (e.g. [4]). Thus, the effects of DM annihilation is usually parameterized by a single quantity $p_{\rm ann}$ defined as:

$$p_{\rm ann} \equiv f_{\rm eff}\frac{\langle\sigma v\rangle}{m_{\rm DM}}\quad,\ \text{where } f_{\rm eff} \equiv f(z=600)\,. \tag{11}$$

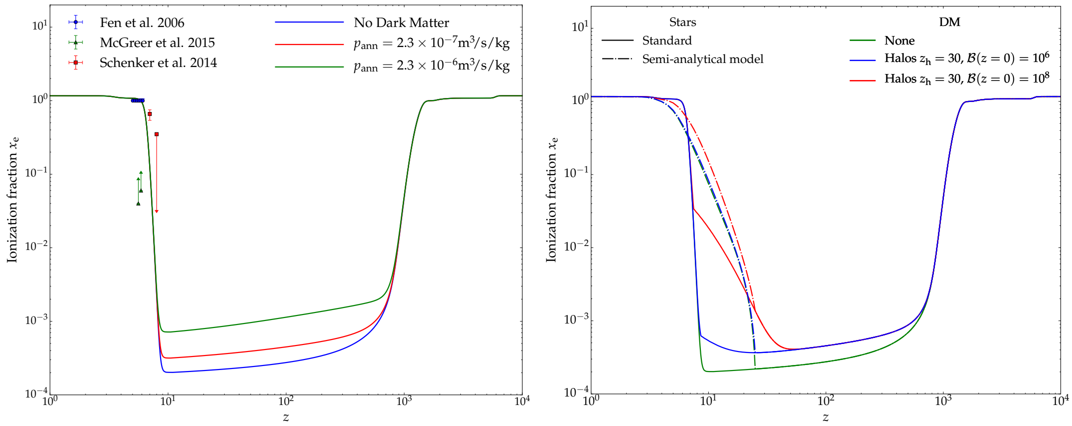

Figure 1: Ionization fraction for several DM models compared to the baseline ΛCDM. *Left panel* – No dark matter halos and only the standard reionization parametrization is used. *Right panel* – Halo formation is taken into account and we modelize reionization by stars in a more realistic way, as described in the text.

We can understand this by looking at fig. 1 – left panel. Indeed, the main impact of smooth DM annihilation on the CMB is to inhibit recombination, enforcing x_e to freeze out near redshift $z \sim 600$ at larger values than in standard ΛCDM. At low-z, one can see the effect of reionization : As time goes by, galaxies (and stars) start to form. The light (mostly UV) emitted by those stars-forming galaxies reionise the medium up to $x_e = 1$ in a very short period of time. Following the standard procedure, it has been put by hand in our model using a step-like function.

We use a modified version of the CLASS code [5] to compute the resulting impact on the CMB TT and EE power spectra. Results are shown in fig. 2 for $p_{\rm ann} = 2.3 \times 10^{-6}$ and $p_{\rm ann} = 2.3 \times 10^{-7}$ m^3/s/kg. The latter value is the upper bound coming from MCMC scan over the ΛCDM parameter space plus the $p_{\rm ann}$ parameter. This has been done in [2] and we have checked this result using the MontePython code [6] for CLASS. It typically means that DM particles of mass smaller than 11 GeV with a thermal relic cross-section whatever annihilation channels, and up to 44 GeV for an annihilation into e^+e^- are ruled out.

One can see the typical effects of DM annihilation:

– In both spectra, at high-l's, the delay of recombination implies a shift of the acoustic peaks, resulting in an oscillating pattern. Furthermore, it allows diffusion damping to reach bigger scales, inducing a lack of power compared to the standard ΛCDM universe.

– The higher number of free electron enhances the number of scattering that CMB photons experiences along the line-of-sight, resulting in a decrease of power in the 2< l <200 range of the TT-spectrum, that is regenerated in the same range in the EE-spectrum.

3 Including Dark Matter structure formations

One may now wonder whether it could be possible to improve over these results. One way to do so, already introduced 10 years ago, is the possibility of accounting for DM halo formation, which in turn increase the rate of DM annihilations. Indeed, at relatively low redshift, the DM fluid clusters under the action of gravity into virialised structures, so-called "DM halos". This process increases the averaged density square $\langle\rho^2\rangle$ with respect to the square of the smooth background density, $\langle\rho\rangle^2$, while the two are nearly equal at high redshift. One could naively expect that this results in a large enhancement of the annihilation rate and therefore in a significantly bigger impact of DM annihilations on the CMB power spectra. But the effects of halos are more subtle since, as we will see, the way in which energy is deposited into the medium changes as well. Thus, the modification of the bounds on DM annihilation cross-section cannot be trivially obtained.

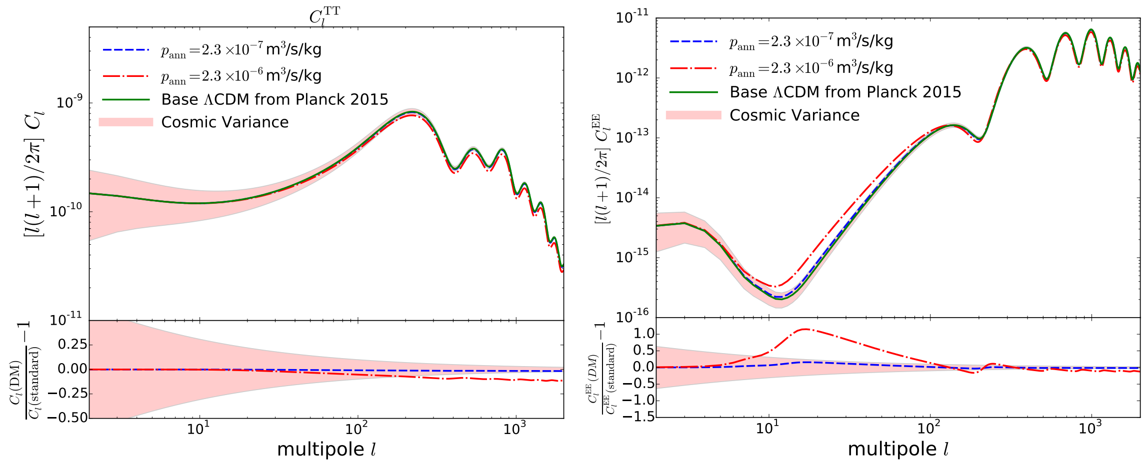

Figure 2: CMB TT and EE power spectra for several DM model compared to the baseline ΛCDM.

The first step is to reexpress the injected energy now in presence of halo formation. It reads :

$$\left.\frac{dE}{dV\,dt}\right|_{\text{inj, smooth+halos}} = \rho_c^2 c^2 \Omega_{\rm DM}^2 (1+z)^6 \frac{\langle\sigma v\rangle}{m_{\rm DM}} (1+\mathcal{B}(z)) \;, \tag{12}$$

where the impact of halo formation has been parametrized through a boost factor $\mathcal{B}(z)$ that one can compute in a given formalism (see e.g. [1]). The important parameters are the redshift $z_{\rm h}$ below which halos start to matter (typically one has $z_{\rm F} \sim 2z_{\rm h}$ where $z_{\rm F}$ is the redshift of halo formation), and the normalisation of the boost factor at z=0, $\mathcal{B}(z=0)$. In a second step, one needs to recompute the $f(z)$ functions, taking into account this boost factor. However, in that case, one cannot capture all the effects of DM annihilations in halos with only one parameter $p_{\rm ann}$. A case-by-case analysis has to be performed. We only illustrate the modifications for a 1 GeV DM annihilating into $\mu^+\mu^-$.
We set the annihilation cross-section at the maximum value still allowed by previous analysis, and look again at the ionization fraction for different halo parameters (fig. 1 - right panel). One can see that the effect of DM annihilations in halos is very similar to reionization. Hence the need for a better modeling of this epoch. The dot-dashed lines represent a new more accurate semi-analytical way of taking into account star reionization. It is usually accepted that a dominant source of reionization would be given by Lyman continuum photons from UV sources in pristine star-forming galaxies. To account for these photons, we add a source term taken from [7] of the form of Eq. (5) to the evolution equation of x_e:

$$\left.\frac{1}{E}\frac{dE}{dV\,dt}\right|_{\rm dep} = A_*\, f_{\rm esc}\xi_{\rm ion}\rho_{\rm SFR}(z)(1+z)^3 \tag{13}$$

where $f_{\rm esc}$ is the fraction of photons produced by stellar populations that escape to ionize the IGM, $\xi_{\rm ion}$ is the Lyman continuum photon production efficiency of the stellar population and $\rho_{\rm SFR}$ is the comoving star formation rate density taken from Ref. [7].
It introduces significant differences in the x_e evolution, although both modelizations are still in agreement with data, that are not seeable at the power spectra level in the absence of DM annihilations in halos. We show in fig. 3− left panel, the residuals of CMB power spectra with respect to the standard ΛCDM power spectra. Star reionization has been modelized either by hand through the step-like function (full line), or with our more accurate semi-analytical method (dot-dashed lines). Looking at the full line, one sees, that the impact of DM halos is well below cosmic variance and hence hopeless to measure. However, if one look at the dot-dashed lines, conclusions change. For two models of halos, it seems possible to get stronger constraints. This interesting results has to be studied further, for instance by understanding the systematic uncertainties associated with our modelization of star reionization.
This has also implications for the IGM temperature, shown on fig. 3− right panel. We modelize stars

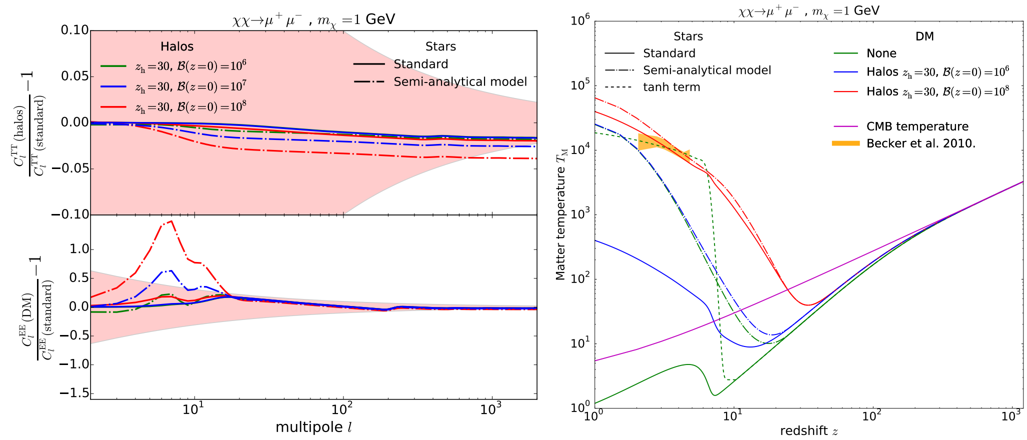

Figure 3: *Left panel*–Residuals of the CMB TT and EE power spectra for several DM halos with respect to the baseline ΛCDM. *Right panel*–Temperature of the IGM for several models discussed in the text.

heating of the IGM in three ways : i) The current "standard" way, used to compute the power spectra of the CMB, neglect the direct heating of the IGM. Stars only have an impact through the modification of x_e. ii) We add the thermal counter part of the hyperbolic tangeant which we normalize to fit the data taken from Ref. [8] (shown only for consistency with the modeling of reionization). iii) We add the term (13) in the equation of the IGM temperature evolution (3) with however a different normalization, since it is commonly supposed that it is not the same photon population, that is responsible of the universe heating. On top of the first and the third models, we add DM annihilations in halos. One can see, that the effect of DM might be very significant, heating the universe much more (or much earlier) than stars. Although we do not indulge in the study of the uncertainties associated to our stars heating, one can already realize that measurement of the IGM temperature, or temperature related quantities such as the 21cm signal, are potientally very powerful probes to pin down the nature of DM, and hence deserve to be studied further.

References

[1] V. Poulin, P. D. Serpico and J. Lesgourgues, JCAP **1512**, no. 12, 041 (2015) doi:10.1088/1475-7516/2015/12/041.

[2] P. Ade *et al.* (Planck Collaboration), arXiv:1502.01589, 2015.

[3] T. R. Slatyer *et al.*, Phys. Rev. D **80**, 043526 (2009) doi:10.1103/PhysRevD.80.043526.

[4] S. Galli *et al.*, Phys. Rev. D **88**, 063502 (2013) doi:10.1103/PhysRevD.88.063502.

[5] J. Lesgourgues, arXiv:1104.2932 [astro-ph.IM]. http://class-code.net/.

[6] B. Audren *et al.*, JCAP **1302**, 001 (2013) doi:10.1088/1475-7516/2013/02/001

[7] B. E. Robertson *et al.*, Astrophys. J. **802**, no. 2, L19 (2015) doi:10.1088/2041-8205/802/2/L19.

[8] G. D. Becker *et al.*, Mon. Not. Roy. Astron. Soc. **410**, 1096 (2011) doi:10.1111/j.1365-2966.2010.17507.x.