Self-annihilating dark matter and the CMB: reionizing the Universe and constraining cross sections

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Abstract. I summarize the recent advances in determining the effects of self-annihilating WIMP dark matter on the modification of the recombination history, at times earlier than the formation of astrophysical objects. Depending on mass and self-annihilation cross section, WIMP DM can reproduce sizable amounts of the total free electron abundance at $z > 6$; as known, this affects the CMB temperature and polarization correlation spectra, and can be used to place stringent bounds in the particle mass vs cross-section plane. WMAP5 data already strongly disfavor the region capable to explain the recent cosmic positron and electrons anomalies in terms of DM annihilation, whereas in principle the Planck mission has the potential to see a signal produced by a candidate laying in that region, or from WIMPs with thermal annihilation cross-sections $\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$ and masses with values $m_\chi < \sim 50 \text{ GeV/c}^2$.

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Introduction

Observational evidence of diverse nature strongly hints toward the existence of a matter component of the Universe, so far undetected in the electromagnetic spectrum, but only via its contribution to gravitational signatures. Whereas there is quite general agreement about the existence of such a dark matter component, yet its nature is unknown. Primordial Nucleosynthesis (BBN) and Cosmic Microwave Background (CMB) based arguments constrain it to be of non-baryonic origin, and a vast amount of extensions to the Standard Model of particles has flourished in the literature, within which many new particles comply (with more or less fine tuning of theories) with the requirements that a dark matter (DM) candidate should fulfill.

A vastly popular class of models is that of the so called Weakly Interacting Massive Particles (WIMPs), a typical example of which are the Lighest Supersymmetric Partner or Kaluza-Klein mode, that bear the remarkable properties to be stable (under conservation of R and K-parity, respectively) and self-annihilating. Intriguingly, the self-annihilation rate arising “naturally” for such candidates being subject only to weak interactions, would produce a relic density -if they are to produced thermally in the early Universe- compatible with that of DM in a $\Lambda$CDM Universe. This has often being vividly referred to as “WIMP miracle”, and the reader is addressed to recent reviews [1], for a more detailed discussion of the topic.

Many efforts have been dedicated in the last years to address the modeling of direct and indirect signatures that such class of particles should leave. Particularly interesting are indirect signatures of astrophysical nature, as if on one hand the existence of a feature hardly explainable within a standard astrophysical scenario would be another evidence in favor of the existence of DM, on the other its absence allows to put constraints in the DM model space, ruling out those candidates that should have left the signature. The recent observation of a peculiar rise in the positron fraction (at energies $1.5 \text{GeV} < E_{e^+} < 100 \text{GeV}$) by the PAMELA collaboration [2], as well as the one of an electron and positron spectrum (at energies $20 \text{GeV} < E_e < 1 \text{TeV}$) inconsistent with standard galactic propagation models by HESS and FERMI [3, 4], have received a wide range of interpretations both in terms of astrophysics outside the realm of the simple “vanilla” models, and DM annihilations or decays. The focus of these proceedings is the class of DM annihilation interpretations, and I address the readers to the vast literature appeared since the PAMELA data were released; for a review of astrophysical classes of models see e.g. [5] and references therein.

The properties required from a self-annihilating particle in order to reproduce the observed feature make the possible candidate a rather “exotic” one, with respect to the standard WIMP scenario. Above all, is that the normalization of the signal should be orders of magnitude bigger than the one produced by a self-annihilation rate able to reproduce the
correct relic abundance of WIMPs, as mentioned above.

Within the frenetic search for a candidate able to explain the excess in terms of DM, huge advances have been done in the field of model constraining, and the re-discovery of properties and phenomena for long time ignored.

In these proceedings I summarize the main findings and advances done in using the CMB spectra in order to constrain self-annihilation cross-sections and masses of WIMPs, obtaining some among the strongest constraints of astrophysical nature. As I will argue later, in fact, typical astrophysical constraints come from local objects, and assumptions about the DM density field need to be done (even within an assigned cosmological scenario), in addition to the complicated astrophysics involved. An exquisite example is the propagation of energetic antiprotons generated by DM annihilation, the prediction of whose abundance at Earth is affected both by the uncertainties on charged particle propagation in the Galaxy and the galactic DM halo profile, that produces the source signal. Whereas a feature observed in the CMB spectra would definitely be a more indirect signature of annihilating DM than that of a galactic one, I will summarize how the signal depends only on very well known astrophysics and only on the assigned cosmological scenario, thus being unplagued by local Universe astrophysics uncertainties and constituting an exquisite tool for constraints.

**Self-annihilating DM and energy injection into the IGM**

Before the formation of gravitationally bound structures, the DM density field can be approximated by a smooth, diffuse one, and the annihilation rate per unit volume, \( A(z) \) reads:

\[
A(z) = \frac{1}{2} \rho_c^2 \Omega_{DM}^2 (1 + z)^6 \frac{\langle \sigma v \rangle (z)}{m^2} \tag{1}
\]

with \( n_{DM}(z) \) being the relic DM abundance at a given redshift \( z \), \( m_\chi \) the mass of the dark matter particle, \( \rho_c \) the critical density of the Universe today, and \( \langle \sigma v \rangle (z) \) is the effective self-annihilation rate which for the sake of generality here we assume to depend on the redshift \( z \) (see the Section on constraints to the “Sommerfeld” enhancement). The total energy \( 2m_\chi^2 \) produced in the annihilation will however be only partially injected into the thermal gas -to which I will refer in the following as Inter Galactic Medium (IGM-although improperly as galaxies have not yet formed at the redshifts relevant for this process): part of the high energy shower produced in the annihilation will in fact not interact with the thermal gas and stream freely through the Universe. Under the so-called “on-the-spot” approximation, consisting in the assumption that the particles failing to interact with the IGM on-the-spot (namely within a short fraction of the Hubble time at the moment they are produced), do not interact with the thermal gas anymore, the energy deposited at any given time will actually only a fraction \( f(z) \) of the one produced, bearing an energy injection rate per unit volume:

\[
\frac{dE}{dt} (z) = f(z) A(z) = f(z) \rho_c^2 c^2 \Omega_{DM}^2 (1 + z)^6 \frac{\langle \sigma v \rangle (z)}{m_\chi}, \tag{2}
\]

where \( f(z) \) depends on the spectrum and characteristics of the primaries produced by the DM annihilation, and ultimately on the nature of the DM particles itself.

The energy injection in the thermal gas, which ultimately determines the evolution of the IGM temperature and ionization fraction, is therefore regulated (in this formalism) by only one DM–related parameter:

\[
p_{\text{ann}}(z) = f(z) \frac{\langle \sigma v \rangle (z)}{m_\chi}. \tag{3}
\]

It is crucial to remark that the fraction \( f(z) \) depends only on very well known high energy astrophysics processes: mainly Inverse Compton scattering of energy electrons and positrons over CMB, photoionization of hydrogen and helium (effectively the only constituents of the high redshift gas) and pair production on CMB by high energy photons. The ultimate value of \( f(z) \) does therefore depend on the composition of the annihilation shower, and eventually on the DM candidate itself. At high redshift (150 \( \leq z \leq 1100 \)) the IGM is completely opaque at energies below the keV (see for instance Fig. 2 in [6]), therefore once the primary particle energy has been degraded down to this scale, the remaining

\[1\] The presence of inhomogeneities does not mine the validity of the argument, and only make the results more conservative.
cannot escape the IGM anymore, thus contributing to its heating and ionization, see later. The problem of obtaining $f(z)$ is thus reduced to compute the fraction of primaries that can cool from the GeV/TeV (the scale of a typical WIMP candidate mass) down to the keV within few Hubble times at the relevant redshift. In [6], it has been recently dealt with the problem of energy deposition in the high redshift thermal gas from very energetic particles: the authors studied the interaction of different classes of high energy primaries with different spectra and their absorption by the IGM throughout the evolution of the Universe. Using this information it is possible to reconstruct the effective fraction $f(z)$ for any given WIMP DM model by knowing its original primary branching ratios in different baryonic species; yet it is worth stressing that the remarkable advantage of the formalism proposed is its complete model-independence in the CMB analysis, provided the on-the-spot approximation is valid, see [6].

Once part of the initial energy due to the annihilation has been degraded down to the keV scale, the effects of such a low-energy, yet non thermal component are equally well known: in [7], the authors showed that the final effects are to provide (i) ionization, (ii) heating and (iii) Ly-α excitation of the thermal gas, the details and final ripartition of the three processes eventually depending only on the temperature and original ionization fraction of the affected gas, and recently [8] provided more accurate estimates in light of detailed MonteCarlo simulations.

Eventually, the behaviour of the high redshift thermal gas in presence of DM annihilation is well posed: an additional heating/ionization/Ly-α excitation source, regulated by Eq. 2 is added, and the cosmological evolution of the gas under its effects can be followed. Many authors have modified the publicly available code RECFAST, which computes the properties of the evolving thermal gas in a cosmological context, by taking into account additional sources of ionization; the reader is addressed to [9] for a non-comprehensive list of references of the latest authors dealing with the problem. For sake of completeness, it is worth mentioning here the recent work of [10], in which the authors self-consistently compute the amount of energy deposited in the three final channels by DM annihilation starting from the high energy cascade, and for several initial primaries, without using the two-step (with the break-up at keV scale) approach previously described here. In [11], the authors have presented a new numerical code for the computation of the recombination of thermal gas, including the effects of high-$n$ states of the hydrogen atom on the properties of the gas (neglected for instance in RECFAST), thus highly enlarging the precision of the high $l$'s CMB spectrum.

### The effect of structure formation

The formation of gravitationally bound structures provides a “boost” to the annihilation signal: since scatterings depend on the square of the density field, the clumping of DM particles into haloes enhances the annihilation rate, as $\langle \rho(z)^2 \rangle \geq \langle \rho(z) \rangle^2$, the average being performed over the entire Universe. In [12], the authors first computed the effects of clumped annihilating DM onto high redshift thermal gas evolution and CMB observables, and a similar analysis has been carried on for $\langle \sigma v \rangle z=\langle \sigma v \rangle(z)$ by [13]. In [14, 15], the authors have recently dealt with the same problem including also the smooth density field, and recognizing the leading effect of the latter with respect to the Recombination history.

The reason of the almost negligible contribution of DM annihilating within structures to the ionization of the IGM gas is to be serched again in the transparency function of the Universe, Fig. 2 in [6]: at the time the bulk of structure formation starts taking place –$z\leq50$– the Universe has become almost completely transparent to high energy particles. This means that primaries produced at typical energies $1\,\text{MeV} \lesssim E_0 \lesssim 1\,\text{TeV}$ at $z\lesssim 50$ do not interact with the IGM, thus not depositing energy into it (in the formalism used in this paper – $f(z\leq50) \sim 0$).

This occurrence has two interesting implications: the first, of extreme conceptual relevance is that the effects induced on CMB by annihilating DM come only from the smooth, diffuse density field at high redshift. This means that (within an assigned cosmology) the signal is completely unaffected by uncertainties typically associated with quantities such as the halo profile, the concentration parameter and the halo minimal mass. Therefore, any constraint obtained from a method which makes use of this signal is entirely free by the uncertainties that plague other methods, e.g. galactic multimessenger, or gammas from dwarf spheroidal galaxies.

The second point is that the high energy photons produced at redshift $z\leq50$ can stream, mostly unaffected until today, thus constituting the “bright side” of the phenomenology so far described. However, since the diffuse extragalactic signal at Earth (even from high redshift), is due to the structure component of the DM density field, it will be affected by all the uncertainties of which one can so conveniently get rid off in the CMB signal approach, see e.g [16].

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2 Notice that this argument does not apply to isotropic signals that depend linearly on the density field –as for instance that of decaying DM.
Effects on CMB observables

The effects of an additional energy source at high redshift on the CMB observables are of different nature, depending on the time of energy deposition; here I limit myself to summarize briefly the phenomenology that causes them, pointing the reader to the main literature discussing the physics in details.

Three main time interval can be identified for the problem:

i) CMB does not provide any information about the processes taking place in the Universe above $z > \sim 10^6$, so DM annihilations in this time range are to produce signatures on other observables, if any (for instance the effects on BBN, see [17] for a recent review and a dedicated study);

ii) at $2.1 \times 10^6 > z > 1100$, during the formation of the CMB blackbody spectrum, the energy provided by DM annihilating in the still ionized thermal gas is completely absorbed (i.e. $f(z) \sim 1$). However, since a complete thermalization of the keV residual photons is not possible due to the (in)efficiency of photon non-conserving processes, distortion to the Planck spectrum are in principle left as signature of DM annihilation: [18] and [19] have described in detail these processes;

iii) at $1100 > z > 150$, the CMB blackbody spectrum is already formed; however, the existence of a non-zero ionized fraction will introduce thermal Syunyaev-Zeldov’ich effect of the residual electrons over the CMB photons. The TT and especially the TE and EE correlation spectra are sensitive to the distribution of free electrons between the Recombination surface and today, and departure from a “standard” recombination history can in principle be detected with accurate enough surveys. In [20], the authors thoroughly describe the physical processes and the distortion of the CMB temperature and polarization spectrum. Here is worth recalling that distortions in the temperature spectra due to additional thermal free electrons in the gas are almost entirely degenerate with the power spectrum, as the thickening of the last scattering surface, reduces the signal on smaller angular scales. On the other hand, the introduction of free electrons after Recombination (and well before the onset of an astrophysical Reionization) will permit Thomson scattering of the local quadrupole of the temperature distribution, generating a polarization signal on small angular scales (as opposed to the one created by astrophysical Reionization at $z < 11$, visible in the TE cross-correlation spectra at angular scales of $\ell < \sim 10$). In Figure 1 the TT, TE, EE correlation spectra are shown for different values of $p_{ann}$, and for comparison with a “standard” case without DM annihilations; for details on the cosmological parameters adopted, see the original paper [21].

Constraining self-annihilation cross sections

The existence of the signatures in the CMB spectra described until now permits the possibility to look for evidence of additional ionization induced by Dark Matter annihilating into the thermal gas at high redshift. In the absence of a
signal, an upper limit can be put on the parameter $p_{ann} \equiv f\langle \sigma v \rangle / m_\chi$, the only free one from which signatures depend.

Although the blackbody spectrum measurement from COBE FIRAS spectrometer is extremely accurate [22], not even its sensitivity allows us to draw interesting constraints on self-annihilation cross sections for particle in the mass range of GeV/TeV. The analysis carried on in [19], does in fact show that by adopting a $f(z)=1$ throughout the interested range of redshifts (as appropriate in this case as the dense and ionized gas of non-yet recombined gas is optically thick to the high energy primaries produced by DM annihilation), upper limits are of the order $\langle \sigma v \rangle < \sim 10^{-21} (10^{-22}/10^{-19})$ cm$^3$/s for a 100GeV/1GeV/10TeV mass WIMP, when assuming a $\langle \sigma v \rangle$ constant throughout the relevant redshift range. A similar analysis has been recently performed by [23], in which the authors have studied the constraints in the parameter space of the Sommerfeld enhancement (see the following Section), and consequently a $\langle \sigma v \rangle$ which is a function of redshift; the results of such analysis do not differ quantitatively if recast in terms of efficient annihilation cross-section.

The study of the signature in the temperature and polarization spectra gives more interesting results. For different values of $p_{ann}(z)$ (and therefore of the free-electron history) the corresponding TT, TE and EE cross-correlation spectra can be derived, and confronted with the observed power spectra. Constraints on $p_{ann}(z)$ can be derived with typical statistical methods, usually by running a full Monte-Carlo Markov Chain analysis over a whole set of parameters (and including $p_{ann}$) and then marginalizing over the cosmological ones. A similar analysis has been recently performed in [21], under the assumption that $\langle \sigma v \rangle$ and $f$ are constant in $z$; the first is a completely justified assumption even in a Sommerfeld enhanced scenario (see following Section), whereas a fairly good one for $f$, which is not a strongly varying function of the redshift $z$ in the range of interest ($150 < z < 1100$), see Figure 4 in Ref. [6].

The analysis in [21] shows that the WMAP5 data can place quite strong constraints on the allowed upper limit for $f\langle \sigma v \rangle$ if the mass of the WIMP particle is taken to be $1\text{GeV} < m_\chi < 1\text{TeV}$, i.e. $f\langle \sigma v \rangle \leq 4.3 \times 10^{-25}$ cm$^3$/s for $m_\chi=100\text{GeV}$ at 95% confidence level, see plot in Figure 2. In order to convert this into an effective upper limit on the self-annihilation cross-section, one needs to choose the (dominant) annihilation channel of the WIMP. For instance, if one wants to confront with a WIMP annihilating mainly into electrons and positrons, such as the “leptophilic” models usually invoked in order to explain the PAMELA positron excess in terms of DM annihilations, one finds that a good estimate for $f$, averaged in the $z$ range of interest, is $f \sim 0.5$, Figure 4 in Ref. [6]. This bears a constraint of $\langle \sigma v \rangle \leq 8.6 \times 10^{-25}$ cm$^3$/s for a WIMP mass $m_\chi=100\text{GeV}$, at 95% confidence level using the WMAP5 data.

Although this value is about one order of magnitude higher than the benchmark $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$/s usually considered (in order to obtain a thermal freezeout able to reproduce the observed cold DM relic abundance), it is competitive with the ones obtained by galactic multimessenger (see for instance [24], and Pato et al. 09 in these proceedings) and unaffected by the local astrophysics uncertainties, as previously summarized in the Section on structure formation. These constraints are extremely interesting in the light of Sommerfeld enhancement arguments, see following Section.

It is also extremely interesting to notice that a forecast based on mock data shows that Planck’s sensitivity in the TE

![Figure 2. Constraints in the $m_\chi - f\langle \sigma v \rangle$ plane, from [21].](image-url)
cross-correlation signal (especially at high l’s, 150< l<1600) will permit -in the case of non-detection of discrepancies from the “standard” ionization history- to place constraints of about one order of magnitude stronger than WMAP5 ones.

Constraining the Sommerfeld enhancement

In presence of a long range interaction, and at low relative velocity of the interacting particles, the perturbative approach usually employed to compute the self-annihilation and scattering cross section breaks down, and high order terms can not be neglected anymore. If DM self-interacts via the exchange of gauge bosons, the introduction of a new effective potential must be taken into account; this was originally done by Sommerfeld, [25], who found a 1/v enhancement of the cross section for long range interactions, here v being the relative velocity between the interacting particles, and recently considered in the context of DM annihilations, e.g. [26]. The Sommerfeld enhancement has the intriguing characteristic to preserve the self-annihilation cross section when WIMP particles are thermally produced in the early Universe, and $\beta \equiv v/c \sim 0.3$, whereas the cross-section should start being enhanced when $\beta \lesssim 10^{-3}/10^{-4}$, the latter values depending on the type of interaction and the ratio of the DM vs the gauge boson mass in many models. In the wake of the search for a DM interpretation of the PAMELA signal, the Sommerfeld enhancement has received renewed attention, as it could provide the “boost” needed to bring up the signal at the correct normalization. However, the local galactic velocity dispersion, $\beta \sim 10^{-3}/10^{-4}$ is too low to provide entirely the needed enhancement, and in many models one needs to invoke also the contribution from substructures, which are virialized to a smaller velocity, [27]. Before structure formation, and after kinetic decoupling from the thermal gas, the thermal history of DM is described by an adiabatic cooling in which $T\propto z^{-2}$; for typical WIMP candidates with masses in the range of interest, at Recombination $\beta \sim 10^{-8}$, and it keeps decreasing. Therefore, if Sommerfeld enhancement applies at all to the model one is studying, it must be active during the phases relevant to affect the TT, TE and EE correlation spectra, and the efficient $\langle \sigma v \rangle$ is a Sommerfeld enhanced one. In many models the Sommerfeld saturates at a maximum value, when $\beta$ drops below a given threshold, which depends on the model, but is usually such that $\beta \gtrsim 10^{-8}$ for most models; this also guarantees that the approximation of a constant $\langle \sigma v \rangle$ is valid, and its value the Sommerfeld saturated one. It is worth noticing that in presence of Sommerfeld enhancement the effective self-annihilation cross section would decrease at the formation of structures, as a consequence of the virial heating of DM. This would even strengthen, if necessary, the argument for the negligibility of such contribution.

It follows that the constraints derived with the method described in the previous section can be applied “tout court” to models in which Sommerfeld enhancement is present. A summarizing plot with the constraints in the $m_\chi - \langle \sigma v \rangle$ plane is Fig. 5 in [21], where the effective Sommerfeld enhanced $\langle \sigma v \rangle$ (for an assigned set of parameters, and $\beta=10^{-8}$) is shown.

Discussion

WIMP DM from the smooth, diffuse density field annihilating at redshifts $150<z<1100$ contributes as an additional source of ionization of the thermal gas; such an altered ionization history can leave a characteristic imprint on the CMB temperature and polarization spectra. The non-detection of a discrepancy from a standard recombination history at 95% confidence level in the WMAP5 data allows us to place strong upper limits on the normalization of the annihilation rate, which in a convenient formalism can be parametrized by $p_{ann}=f(\langle \sigma v \rangle/m_\chi)$, which in turn can be made model-dependent by choosing the correct value of $f$ depending on the WIMP model and its annihilation channels.

Eventually, this result can be cast in the form of exclusion plots in the WIMP mass vs self annihilation cross section, $m_\chi - \langle \sigma v \rangle$ plane. The constraints obtained, which are not plagued by uncertainties correlated to structure formation history or halo density profile, apply to the self-annihilation cross section effective at the time the distortion of the CMB spectra are generated, namely $\langle \sigma v \rangle(150<z<1100)$; this remark, redundant within a “vanilla” cold dark matter scenario thermally produced with an s-wave annihilation cross section (since $\langle \sigma v \rangle$ is constant at any place and time in the Universe), becomes relevant when dealing with more involved scenarios, such as the ones in which a Sommerfeld enhancement is active at low relative velocities of the DM particles; or for instance the one of non-thermally produced DM, which then decays (before Recombination) into the stable partner, which in turn self-annihilates; a physical scenario being for instance the mSUGRA in which a Gravitino is the Next to Lightest Supersymmetric Partner, decaying into the LSP stau before BBN, see e.g [28].
In principle, the Planck mission has the potential to detect any alteration of the recombination history, produced by annihilating DM with a normalization down to \( f(\langle \sigma v \rangle) = 2.6 \times 10^{-26} \text{cm}^3/\text{s} \) for a \( m_\chi = 100 \text{GeV} \). It is worth stressing that these constraints are obtained within the assumption that annihilating DM is the only ionization source in addition to standard processes\(^3\) and within a standard \( \Lambda \) CDM model. The possible detection of a discrepancy from the standard recombination history from the Planck satellite, could not be immediately taken as evidence for DM annihilating at high redshift, although would definitely be compatible with it. More convincing would be the finding of a peculiar feature imprinted on the TE spectrum by DM annihilation, with respect to other possible exotic ionization sources. Such a characteristic feature, and the possibility to disentangle it from other ionization sources has been recently object of the study by [29]; it remains that for a \( m_\chi \sim 100 \text{GeV} \) thermally produced WIMP the normalization of the signal would be too low to permit such a discrimination even for Planck. It is however worth to remark that the signature left by WIMPs with masses \( m_\chi < \sim 50 \text{GeV} \), a thermal cross-section \( \langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3/\text{s} \), mainly annihilating into leptons is within the reach of Planck, and that a non-detection would quite ultimately rule out classes of model with these characteristics.

**The electron optical depth \( \tau_e \)**

Such strong constraints come from the fact, as shown by [14, 15], that WIMP DM is able to produce a sizable fraction of the electron optical depth \( \tau_e \) which is formally written as:

\[
\tau_e = - \int n_e(z) \sigma_T dz,
\]

\( n_e(z) \) being the fractional abundance of free electrons at redshift \( z \) and \( \sigma_T \) the Thomson scattering cross-section. Let us define the residual \( \delta \tau_e \) as the integral of Eq. 5 between \( z=6 \) and \( z=700 \), namely the fraction of \( \tau_e \) that can be produced by self-annihilating DM before the Universe becomes completely ionized, and disregarding the “recombination tag” between \( z=700 \) and \( z=1000 \) (thus avoiding to include in our computation free-electrons from the last moments of standard Recombination, which does in fact extend a little beyond \( z=1000 \)). In Figure 3 is shown the fraction of the \( \delta \tau_e \) that can be produced by WIMPs of different masses (each line in the plot representing a different mass value \( m_\chi \)), annihilating with running \( \langle \sigma v \rangle \) into a \( \tau^+ - \tau^- \) channel. The residual upper limit to \( \delta \tau_e = 0.062 \) is defined as the difference between the observed \( \tau_e = 0.084 \pm 0.016 \) (taking the upper limit \( \tau_e = 0.10 \)) by WMAP5, and Eq. 4 integrated.

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3 This makes the obtained constraints even stronger: an additional exotic ionization source would leave less room for DM, and therefore lower the allowed value of \( \rho_{\text{ann}} \).
between \( z=0 \) and \( z=6 \), assuming a completely ionized medium between today and \( z=6 \), thus being a measure of the free electrons in the Universe between the recombination and the \( z=6 \) surface, this latter redshift being chosen as the one by which the entire Universe is considered to be completely ionized, by arguments based on the absence of Gunn-Peterson trough in the emission lines of distant quasars; see e.g. Section 1 in [13] for details and a thorough discussion. It is important to stress that the choice of a particular halo profile, concentration parameter and minimal mass does not affect the results at all, as proven in [14, 15] and discussed previously here, as the dominant contribution to ionization comes from times earlier than structure formation.

It is also interesting to notice that the use of the quantity \( \tau \) is well posed in a scenario where most of the free electrons in the Universe are produced at late redshift, namely a standard astrophysical Reionization case, with all the free electrons produced at \( z \leq 11 \); its use starts however to be misleading in a scenario where the contribution to the total free electron fraction produced at high redshift, is non-negligible. In particular, self-annihilating DM would contribute solely before the formation of astrophysical sources, and leave smaller room for a distinct signature in the polarization spectra at \( l \gtrsim 20 \), whereas the total number of free electrons should be conserved. Within the context we have presented, a study of the free-electron abundance as a function of redshift is therefore the only well-posed way to proceed, and such an attempt to study the differential contribution to the canonical \( \tau \) from different canonical sources (including e.g. relic ionization fraction from incomplete Recombination etc.) has been attempted in [30].

**Conclusions**

WIMP dark matter self-annihilating into standard model particles can contribute to the ionization of the thermal gas at high redshift \((1100 \lesssim z \lesssim 150)\), and the altered free electron fraction can leave characteristic imprints on the Cosmic Microwave Background TT, TE and EE correlation spectra. These signatures have already been searched for in the WMAP5 data, and their absence can lead to the exclusion of WIMPs with thermal cross sections and masses \( m_\chi \lesssim 3 \text{GeV} \), the actual value depending on the nature of the primaries in which the DM annihilates into. WMAP5 data also permit the exclusion of some of the most extreme models explaining the PAMELA positron excess in terms of WIMP DM annihilation, as well as the region that could explain PAMELA and the FERMI/HESS electron excesses altogether. In the absence of additional high redshift ionization signal in the Planck data, it will be possible to completely rule out a vast region of the PAMELA DM interpretation space, and probe WIMP DM with a thermal cross section \( \sigma \sim 3\times 10^{-26} \text{cm}^2/\text{s} \) for masses \( m_\chi \lesssim 50 \text{GeV} \). These constraints depend only on the chosen cosmology and are unaffected by uncertainties on the structure formation scenario and on DM halo profiles.

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