Dark Matter Annihilation in the First Galaxy Halos

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ABSTRACT
We investigate the impact of energy released from self-annihilating dark matter on heating of gas in the small, high-redshift dark matter halos thought to host the first stars. A SUSY neutralino like particle is implemented as our dark matter candidate. The PYTHIA code is used to model the final, stable particle distributions produced during the annihilation process. We use an analytic treatment in conjunction with the code MEDEA2 to find the energy transfer and subsequent partition into heating, ionizing and Lyman alpha photon components. We consider a number of halo density models, dark matter particle masses and annihilation channels. We find that the injected energy from dark matter exceeds the binding energy of the gas within a $10^5-10^6 M_\odot$ halo at redshifts above 20, preventing star formation in early halos in which primordial gas would otherwise cool. Thus we find that DM annihilation could delay the formation of the first galaxies.

Key words: Cosmology – Particle Physics

1 INTRODUCTION
Dark matter is recognised as an integral part of modern concordance cosmology, and while an empirical characterisation has had considerable success in the description of wider astrophysical phenomena such as structure formation and gravitational lensing, dark matter’s precise nature has remained unclear. Although there exists no suitable candidate within the existing standard model paradigm, an elementary particle formulation of dark matter remains the favoured solution (as opposed to a modified gravity model). As such, the dark matter problem is of current interest to both astro and particle physics, an overlap which may create unique opportunities in trying to establish the fundamental form of dark matter. In addition, models of physics beyond the standard model have proven fruitful sources of viable dark matter candidates, making dark matter a valuable road marker on the path to a complete theoretical formulation of fundamental physics. For general reviews of these topics see Roos (2012), Bertone et al. (2005) and Bergstrom (2012).

Our primary understanding of dark matter comes from the observation of astrophysical phenomena. A range of projects probing dark matter’s behaviour beyond gravitational interactions are currently in progress or in the planning stages, including collider (Birkedal et al. 2004, Baur et al. 2001, Allanach et al. 2009 and Baer et al. 2008) and direct detection experiments (Aalseth et al. 2012, Ahmed et al. 2011, Angle et al. 2011 and Armengaud et al. 2012). While there are positive indicators that these will be able to constrain and confirm dark matter models in the future, data released to date has not proven conclusive [see for example, the comparison between DAMA/LIBRA (Bernabei et al. 2010) and LUX (Akerib et al. 2014)].

Another avenue of investigation is that of indirect detection, in which dark matter is assumed to produce standard model particles through non-gravitational interaction such as decay or annihilation. Particularly dense regions, such as are found at the centres of massive galaxies or clusters, could produce distinct gamma or x-ray signatures or signals from other particle excesses (Grasso et al. 2009, Bergstrom et al. 2009 and Bertone 2006 and Prada et al. 2004). Unambiguous identification as products of dark matter annihilation is complicated by the presence of other astrophysical sources such as pulsars and supernova which may mimic such a signal (Hooper et al. 2009 and Biermann et al. 2009). Alternatively one may consider a more global impact by examining how the extra energy from dark matter annihilation affects features such as the high redshift 21cm signal from the galactic medium (Evoli et al. 2014, Sitwell et al. 2014). Modifications may be particularly distinct during the early era of reionization where the power from dark matter energy injection was not swamped by astrophysical energy sources.

When introducing dark matter models into wider cosmological calculations, a number of complexities need to be taken into consideration. These include the inherent uncertainties in both the particle and astrophysics models (Mack 2014), impact on standard astrophysical processes (Fontanot et al. 2014) and possibly, exotic structure formation (Spolyar et al. 2008).
2  Schön et al.

In this paper we investigate the energy transfer from dark matter self-annihilation in dark matter halos at high redshifts and the impact this may have on gas within the halo. This is of interest for several reasons. Firstly, the existence of a self-heating source could impact early star formation which in turn would have wider implications for the gas in the IGM and the rate of reionization. Secondly, the contribution from small, collapsed structure to the overall energy produced by dark matter annihilation is considerable so careful treatment of the energy transfer is desirable.

An outline of the paper is as follows. We begin with a summary of our method in §2. We describe a model of dark matter halos across a range of masses and redshifts in §3. Descriptions of the simulated final stable states of the dark matter annihilation process, and the appropriate first order analytic approximation of the energy transfer between the injected particles and the halo’s gas component are given in §4 and 5 respectively. We discuss the comparison between the injected energy and the halo’s gravitational binding energy in §6, and the heating of the diffuse gas surrounding the halo in §7. We conclude with a discussion in §8.

2  METHOD

We model the cosmological dark matter component using simple analytic expressions which allow for a straightforward exploration of the possible parameter space. The uncertainties in these quantities are of particular interest as we wish to minimize the possibility of astrophysical sources creating results which are degenerate to variations of the dark matter model.

Besides the halo model, the other key aspect in gauging the impact of self-annihilating DM on the halo’s gas is a precise treatment of the injected energy produced by the DM annihilation process. This entails both the energy partition of the stable annihilation end products and the way these particles interact with the surrounding gas. We use PYTHIA (Sjostrand et al. 2006) to simulate the self-annihilation of a SUSY-neutralino like particle and in this way also produce the spectral energy distribution of the injected particles.

We approach the actual energy transfer calculation through path averaged integrals of individual particles. We then integrate over the spatial and energy distributions of the particles to arrive at an estimate of the gross energy transferred to the gas. The Monte Carlo Energy DEposition (MEDEA) code (Valdes et al. 2010, C. Evoli et al. 2012), is then used to gauge how this energy is partitioned into heating, ionization and Lyman alpha photons and how this could practically impact the halo’s environment.

Throughout we take our cosmological parameters from Planck (Ade et al. 2014) such that $h = 0.71$, $\Omega_{\Lambda,0} = 0.6825$ and $\Omega_{m,0} = 0.3175$.

3  DARK MATTER HALO PARAMETERS

While the density profiles of halos with mass upwards from $10^8 M_\odot$ are relatively well explored in simulations (see for example Merritt et al. 2005, Merritt et al. 2006, Zhao et al. 2009, Navarro et al. 2010 and Salvador-Sole et al. 2012), the precise form of smaller objects is less certain. Since these low-mass halos provide a significant boost to the overall injected energy from dark matter annihilation as well as playing host to early star formation, we consider both different density profiles and mass-concentration relations in their description. Our models of small halos are thus not necessarily definitive, physical representations but rather meant to cover a plausible parameter space. Halo masses under consideration range from $10^3 M_\odot$ - $10^5 M_\odot$ for redshift 0-50.

3.1  Halo Profiles

We compare three different profiles. The NFW (Navarro et al. 1995) (eq. 1) and Einasto (Einasto 1965) (eq. 2) profiles are qualitatively similar in so far they feature a density cusp at the centre of the halo, while the Burkert (Burkert 1995) (eq. 3) profile has a flattened core. As we found the NFW and Einasto profiles to show similar behaviour in later calculations, we shall only present the Einasto profile as the representative of cuspy halos. We further assume that halo density profiles remain self-similar across both mass and redshift range, neglecting halo assembly history. The profiles of NFW, Einasto and Burkert halos respectively are

$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{(\frac{r}{r_s})^2 (1 + \frac{r}{r_s})^2}$$

$$\rho_E = \rho_0 e^{-\frac{r}{r_s}} \left[ \frac{r}{r_s} \right]^\alpha - 1$$

$$\rho_B = \frac{\rho_0}{(1 + \frac{r}{r_s})^2}$$

In all cases $r_s$ is the scale radius and defined as $r_{\text{vir}} / c$, where $c$ is the concentration parameter (see §3.2). We here adopt the convention of defining the virial radius $r_{\text{vir}}$ of the halo as encompassing a spherical volume with density 200 times greater than the critical density. For the Einasto model, $\alpha_e = 0.17$ and is here taken to be independent of mass. The gas component of the halo is assumed to follow the dark matter density distribution with a baryon fraction of $f_b = 0.15$. Lastly, $\rho_0$ is a normalization constant such that the mass enclosed within the virial radius gives the total halo mass.

3.2  Mass-Concentration relations

The concentration parameter sets the radius $r_s$, at which the density profiles turns over and as such regulates the density at the centre of the halo. We choose two contrasting, slightly modified expressions for the concentration-mass relation from Comerford & Natarajan (2007) eq. 4 and Duffy et al. 2008 eq. 5 which are both dependent of halo mass and redshift. The gradient of the relation from Comerford is considerably steeper than that of Duffy and both relations produce highly concentrated profiles for small mass halos at low redshift. Qualitatively, this behaviour persists to high redshifts, though the concentration parameter decreases overall (see Figure 1).

$$c_c(M, z) = \left( \frac{M}{1.3 \times 10^{13} M_\odot} \right)^{-0.15} \frac{22.5}{1+z}$$

$$c_d(M, z) = \left( \frac{M}{2 \times 10^{12} h^{-1} M_\odot} \right)^{-0.084} \frac{14.85}{1+z^{0.71}}$$

We note that both concentration relations were fitted for galaxy-sized halos at low redshift and we extrapolate considerably beyond their intended parameter space. As a check, we thus also consider a third, mass-indepedent modification of the above relations:

$$c_f(z) = \frac{47.85}{(1+z)^{0.61}}.$$
In conjunction with the above density profiles these allow us to model a range of halo density distributions to investigate how halo morphology impacts dark matter annihilation effects.

4 DARK MATTER MODEL

We here choose a generic self-annihilating SUSY neutralino as our model a range of halo density distributions to investigate how halo morphology impacts dark matter annihilation effects.

4.1 Dark Matter Annihilation Power

The power produced by dark matter annihilation per unit volume is given by:

$$P_{dm}(x) = \frac{2\varepsilon^2}{m_{dm}} \langle \nu \sigma \rangle \rho_{dm}(x)^2.$$  (7)

where $m_{dm}$ and $\rho_{dm}$ are the dark matter particle mass and volume density respectively and $\langle \nu \sigma \rangle$ is the velocity averaged annihilation cross-section which we take to be $2 \times 10^{-26} \text{cm}^3\text{s}^{-1}$.\footnote{While we here adopt a cross-section constant across all our models, we note that $\langle \nu \sigma \rangle$ for some of our models may already be subject to constraints in conjunction with the dark matter particle mass employed.}

4.2 Final Particle States

PYTHIA is used to produce the final particle states for the various candidates. The dark matter annihilation event is simulated via an electron/positron pair-creation, mu and tau leptons and W bosons. The annihilation products are created very close to the core of the halo, thus injected in a high density gas environment, contribute to the energy transfer in any notable form. Thus density profiles with a cusp and high mass-concentration parameters are considerably more efficient than the more relaxed models at depositing energy as they provide the high density core required for the photon energy-loss processes.

In contrast, electrons and positrons are assumed to lose energy continuously according to the particle’s stopping power as well as in collisions via IC scattering off cosmic microwave background (CMB) photons. The latter process dominates in the high redshift photons, protons/ anti-protons) are left. Fig A1 shows the respective spectra of the energy distributions of electrons, positrons and photons for different dark matter masses and annihilation channels.

5 ENERGY TRANSFER

Energy is transferred to the halo’s gas component via photons, electrons and positrons. Neutrinos only interact weakly and only negligible numbers of protons/anti-protons are created, so their contribution to the deposited energy is negligible.

5.1 Individual Particle Energy Loss

For simplicity we assume that all particles retain a straight line trajectory as they travel through the halo. While in reality the particles would undergo scattering processes, the approximation is justifiable as the gas in the halo is sparse enough so that only a small number of such scattering events occurs in the case of photons and the energy lost along the path is dependent on the type of particle, $\alpha$, its initial energy, $E_{in}$, and the density of the gas, $\rho_g$, it encounters and is given here by

$$L_{\alpha}(E_{in}, x_i, x_f) = \int_0^3 S_{\alpha}(E(t))\rho_g(x(t))dt.$$  (9)

We make use of the spherical symmetry of the halo and calculate the average energy lost by a particle of species $\alpha$ created at radius $r_i$ (placed along the $x$-axis for convenience) while traveling to $r_f$

$$\bar{L}_{\alpha}(E_{in}, r_i, r_f) = \int_0^{2\pi} \int_0^\pi L_{\alpha}(E_{in}, x(r_i), x(r_f, \theta, \phi))d\theta d\phi.$$  (10)

The energy loss rate for a photon is driven by the total interaction cross-section which is heavily dependent on the photon energy \cite{Beringer:2012}. Figure 2 shows the number of interactions the photons with different energies, injected at various radii, undergo before escaping the halo. We note that in the case of high energy photons that predominantly lose energy through electron/positron pair-creation, particles will largely escape the halo without significant interaction. In contrast, for photons with energy below the $MeV$ range, the main energy transfer mechanisms moves to Compton scattering and photo-ionisation/excitation. These have a higher interaction cross-section than the pair-production process and so are considerably more efficient at depositing their energy into the gas. Overall only particles created very close to the core of the halo, thus injected in a high density gas environment, contribute to the energy transfer in any notable form. Thus density profiles with a cusp and high mass-concentration parameters are considerably more efficient than the more relaxed models at depositing energy as they provide the high density core required for the photon energy-loss processes.
Figure 2. Average number of collisions undergone by photons before reaching the virial radius in a $10^5 M_\odot$ halo. The left hand side shows halos at redshift 0 and the right at redshift 30. From upper to lower (least to most concentrated), the rows correspond respectively to a halo model of Burkert/Duffy, Burkert/Comerford, Einasto/Duffy and Einasto/Comerford.

Figure 3. Average fraction of energy lost by electron/positron created at radius $r$ before reaching the virial radius in a $10^5 M_\odot$ halo. The left hand side shows halos at redshift 0 and the right at redshift 30. From upper to lower (least to most concentrated), the rows correspond respectively to a halo model of Burkert/Duffy, Burkert/Comerford, Einasto/Duffy and Einasto/Comerford.
5.2 Total Energy Lost

We now calculate the total fraction of the annihilation energy lost by the injected particles within the halo which requires integration over the energy spectrum at each point in the halo volume:

\[
E_{\text{lost}} = \sum_{\alpha=1}^{3} f_{\alpha} \int_{0}^{r_{\text{vir}}} \int_{0}^{r_{\text{vir}}} 4\pi\mu_{\alpha} L_{\alpha}(\epsilon, r, r_{\text{vir}}) P_{\text{dm}}(r) r^2 d\epsilon dr \tag{11}
\]

where \(\alpha\) refers to the different injected particle species and \(\mu_{\alpha}\) the fraction of the total annihilation energy in form of that species. Given that the total energy produced through dark matter annihilation is given by

\[
E_{\text{tot}} = \int_{0}^{r_{\text{vir}}} 4\pi P_{\text{dm}}(r) r^2 dr, \tag{12}
\]

the fraction of the total energy from dark matter that is in turn lost in the halo is then simply

\[
T(M, z) = \frac{E_{\text{lost}}}{E_{\text{tot}}}. \tag{13}
\]

It should be noted that high-energy particles create a cascade of lower-energy particles as they lose energy though following these secondary particles. This is beyond the complexity of this calculation. We make the assumption that these secondary particles carry considerably less energy than the originally injected particles and are thus readily absorbed by the gas.

6 BINDING ENERGY COMPARISON

As an initial measure of the impact that dark matter annihilation has on the halo structure, we compare the total energy produced via annihilation to the halo’s gravitational binding energy. The gravitational binding energy is given by

\[
U_G = \int_{0}^{r_{\text{vir}}} \frac{GM_{\text{halo}}(r') m_{\text{shell}}(r')}{r'} dr', \tag{14}
\]

and the total energy injected via dark matter annihilation over the Hubble time \(t_H\) (which is here taken as a proxy for the halos age) is

\[
U_{\text{dm}} = \int_{0}^{r_{\text{vir}}} 4\pi P_{\text{dm}}(r) r^2 dr \cdot t_H. \tag{15}
\]

In Figure 4 we plot the ratio between the annihilation energy and the binding energy (left panel) and the fraction of the annihilation energy lost to the halo (right panel) for an Einasto profile with a Duffy mass concentration relation and a 5 GeV dark matter particle.

Figure 4. The left panel shows the ratio of the total energy produced through dark matter annihilation and the gravitational binding energy of the gas. The right shows the fraction of energy lost by the particles as they leave the halo. Both use a halo model consisting of an Einasto profile with a Duffy mass concentration relation and a 5 GeV dark matter particle.
Figure 5. Ratio of energy produced by dark matter annihilation over the Hubble time deposited into the halo, to the halo’s gravitational binding energy for a 5 GeV dark matter particle annihilating via a muon. The left hand side shows Einasto profiles with Comerford, Duffy and constant mass concentration relations respectively while the right shows the same with a Burkert profile. The green line is the critical mass for which molecular cooling is possible. Halo models to the right of the line can cool efficiently.

particle. We note that in small halos the annihilation energy is an order of magnitude larger than the binding energy when taken over the Hubble time (the increase in Hubble time also accounts for the ratio increasing at low redshift). In contrast the transfer of energy to the halo is more efficient in large halos at high redshift which is consistent with IC scattering being the most efficient energy loss mechanism.

We can combine the ratio and transfer fraction to calculate the bulk energy fraction transferred to the halo over the Hubble time. As alluded to previously, the energy is transferred via the secondary particles created during the injected particle journey through the halo. While we here are not in the position to give rigorous treatment to the injection of the secondary particle, we do observe these to be of considerably lower energy than the original ”parent” particle. This holds in particular for the dominant energy transfer process of electrons and positrons undergoing IC scattering and producing lower energy photons. We make the assumption that the secondary particles are comparatively easily absorbed by the gas in the halo by setting an absorption fraction of $f_{abs} = 0.1$ with the rest of the energy escaping [compare the photon escape fractions of ionizing galaxies Mitra et al. (2012), Benson et al. (2013)], so that we have,

$$F_{\text{eff}} = R(M, z)T(M, z)f_{abs}.$$  \hspace{1cm} (16)

Figures 5 and 6 show this effective energy transfer fraction. In Figure 5 we utilise a 5 GeV dark matter particle annihilating to muon and show $F_{\text{eff}}$ for various halo models. The left hand panel shows results for Einasto profiles, with our three mass-concentration models, and the right hand panel shows results for the Burkert model. While the overall behaviour is the same for all halo models, we find the cuspy Einasto model to be more efficient at self-heating. In a similar vein, the mass-concentration relation which produces the highest value for $c$ produces the greatest $F_{\text{eff}}$ at fixed redshift and halo mass, indicating that the more concentrated the halo the more efficient is the energy transfer process.

At high redshifts, star formation has not yet disassociated molecular Hydrogen, providing a cooling channel in halos of $10^5 - 10^6 M_\odot$ (Haiman et al. 1997). Also included in Figure 5 is the critical mass above which halos undergo molecular hydrogen cooling (green curve) (Loeb 2006). Halos to the left of the curve do not cool and therefore cannot collapse and form stars. We note that for all models there is a region between $z = 15 - 50$ and for halos $10^5 - 10^6 M_\odot$ in which molecular hydrogen cooling is possible but $F_{\text{eff}} > 1$. This opens the possibility that dark matter annihilation could have a significant impact on the gas chemistry in these systems and by extension on other internal structure formation.

Figure 6 shows similar plots for different annihilation channels and an Einasto profile with a Duffy mass-concentration relation. The tau, muon and quark cases all correspond to 50 GeV dark matter particles while the W boson case shows a 83 GeV particle.
In all cases we find that at high redshift, $F_{\text{eff}} \sim 1$ either coincides with the molecular cooling line or lies to the left of it, suggesting a smaller impact from larger dark matter particle candidates. At the same time, we note that while star formation may not be impacted in the largest halos for this dark matter model, they nevertheless act as both sources and sinks for ionizing radiation. This should be taken into account when including annihilating dark matter in reionization calculations.

6.1 MEDEA

The above calculation gives an estimate of the gross energy transfer from DM annihilation to gas within the halo. There is a further partition into the energy that is channelled to heating, ionization and the creation of Lyman alpha photons. While the stopping power and cross-sections used here are averaged quantities that don’t track the secondary cascade particles, one can calculate the spectrum of photons produced through the IC process. As this is also the largest channel through which energy is deposited into the halo we can use this in conjunction with the MEDEA I code (which resolves high energy particle energy loss with great detail, see Appendix B) to give an indication of the breakdown of the deposited energy.

Figure 7 shows how the energy transfered would be partitioned into heating, ionization and Lyman alpha photons for different ionization fractions of the halo gas, assuming IC scattering is the dominant component of energy deposition. We compare a $10^7 M_\odot$ halo on the left with a $10^9 M_\odot$ halo on the right. The solid lines correspond to redshift 30 and the dashed to redshift 50.
7 DISCUSSION

Using a simple analytic treatment, we have calculated the degree to which the small DM halos at high redshift which are thought to host the first stars heat and ionize themselves through the annihilation of dark matter. We find that the total energy produced by the annihilation process over the Hubble time exceeds the gravitational binding energy of the halo’s gas for structures with mass less than \(\sim 10^8 M_\odot\). However, the high-energy stable particles produced in this process do not readily interact with the surrounding gas so energy is transferred through secondary particles. Once this and the critical mass for molecular cooling are taken into consideration, we find that there is a parameter space in which primordial gas inside a \(10^5-10^6 M_\odot\) halo above redshift 20 could cool but where the injected energy from dark matter still exceeds the binding energy of the gas. This could lead to the disruption of early star formation, and a delay in the formation of the first galaxies.

We find that the lighter dark matter particle masses with the muon annihilation channel are the most effective inhibitors of star formation. Concentrated halos that display some sort of cusp like behaviour are also more efficient at self-heating due to the square dependence of the dark matter power on the density distribution.

The efficiency with which the injected particles transfer their energy to the halo is of key importance in this calculation. However, the complete description of the energy loss of not only the primary injected particles but also their secondary progeny is beyond the scope of this work. The full realisation of the energy transfer process within the bounds of the halo, including non-static gas conditions, will be addressed in a future paper. Similarly, a detailed description of the impact of the extra injected energy on the halo’s gas chemistry and what consequences this would have for structure formation are also left for future work.

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APPENDIX A: DETAILED PYTHIA OUTPUTS

In Figure A1 we show detailed final energy distributions from PYTHIA for electrons, positrons, and photons for the different annihilation channels. Each plot shows the fraction of the centre of mass energy of the annihilation process carried by particles with different energy averaged over 100000 events.

![Figure A1](image)

**Figure A1.** Averaged fraction of the center of mass energy carried by photons (green), electrons (black) and positrons (red) of energy $E$ for 100000 neutralino annihilation events in PYTHIA. The upper three panels correspond from top to bottom to annihilation to mu, quark, and tau particles where in each, the solid line gives the final, stable particle distribution for a 5GeV (or 5.5GeV in case of the quark) dark matter particle, the dashed a 20GeV particle and the dotted the 50GeV case. The lowest panel shows annihilation to a W boson where here the solid line is the 83GeV model and the dashed the 110 GeV model.