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Consequences of dark matter self-annihilation for galaxy formation

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ABSTRACT

Galaxy formation requires a process that continually heats gas and quenches star formation in order to reproduce the observed shape of the luminosity function of bright galaxies. To accomplish this, current models invoke heating from supernovae, and energy injection from active galactic nuclei. However, observations of radio-loud active galactic nuclei suggest that their feedback is likely to not be as efficient as required, signaling the need for additional heating processes. We propose the self-annihilation of weakly interacting massive particles that constitute dark matter as a steady source of heating. In this paper, we explore the circumstances under which this process may provide the required energy input. To do so, dark matter annihilations are incorporated into a galaxy formation model within the Millennium cosmological simulation. Energy input from self-annihilation can compensate for **all** the required gas cooling and reproduce the observed galaxy luminosity function only for what appear to be extreme values of the relevant key parameters. The key parameters are: the slope of the inner density profile of dark matter haloes and the outer spike radius. The inner density profile needs to be steepened to slopes of -1.5 or more and the outer spike radius needs to extend to a few tens of parsecs on galaxy scales and a kpc or so on cluster scales. If neutralinos or any thermal relic WIMP with s-wave annihilation constitute dark matter, their self-annihilation is inevitable and could provide enough power to modulate galaxy formation. Energy from self-annihilating neutralinos could be yet another piece of the feedback puzzle along with supernovae and active galactic nuclei.

Key words: dark matter – stars: evolution – accretion – early Universe

1 INTRODUCTION

A major challenge to our current understanding of structure and galaxy formation in the Universe is the discrepancy between the theoretically predicted mass function of dark matter haloes and the observed shape of the luminosity function of galaxies (Kauffmann & White 1993; Cole et al. 1994; Somerville, Primack & Faber 2001; Benson et al. 2003). Simply put, the number density of dark matter haloes falls off as a power-law at high masses, whereas the luminosity function of galaxies occupying such haloes terminates exponentially above a characteristic luminosity (e.g. Cole et al. 2001; Huang et al. 2003). This implies that the supply of gas to a galaxy and the conversion of this gas into stars becomes preferentially inefficient in more massive systems (White & Rees 1978). A key issue for galaxy formation theory is thus to illuminate the physical processes that heat and cool gas in massive galaxies as this cycle regulates the formation of new

stars. In addition, one of the challenges for galaxy formation is to unravel the inter-play of baryons with the ubiquitous dark matter in galaxies.

To this end, feedback processes operating in galaxies at both the low and high-mass ends of the halo mass function are required to explain the faint and bright-end slopes of the observed galaxy luminosity function. Energy input from supernovae is thought to play a significant role in the regulation of star formation in low mass galaxies (Dekel & Silk 1986; Mac Low & Ferrara 1999), however the supernova energy injected in high mass galaxies is too small to suppress gas cooling effectively. For such objects, to reconcile theory with observations a more energetic process that continually heats the gas and operates independently of star formation appears to be required (Croton et al. 2006; Bower et al. 2006).

Recent observations in nearby galaxies reveal a corre-

lation between the masses of supermassive black holes and the velocity dispersion of the stellar component. This suggests that black holes might play a role in regulating star formation (Magorrian et al. 1998; Tremaine et al. 2002; Ferrarese & Merritt 2002). Energy input from nuclear outflows driven by accreting black holes are currently favoured as the principal source of feedback driving the truncation of star formation in massive galaxies (Di Matteo et al. 2005; Croton et al. 2006; Bower et al. 2006). Unlike supernovae feedback, the observed energy output from Active Galactic Nuclei (AGN) can far exceed that liberated from cooling gas in the hot halo. AGN heating in two distinct forms has been proposed. Episodic feedback from the AGN via outflows generated during the merger process have been proposed by Di Matteo et al. (2005); Sijacki & Springel (2006), the so-called ‘quasar-mode’. However, it is known that AGN spend most of their lifetimes in a low accretion rate state, and therefore Croton et al. (2006) and Bower et al. (2006) argue for a more steady, so called ‘radio-mode’ feedback that is long-lived. The details of both these processes are complex and the micro-physics is currently not well understood.

Here, we focus on an alternative heating mechanism, the energy steadily generated by the self-annihilation of dark matter particles in the inner regions of haloes. Although the standard cosmological paradigm is predicated on the existence of non-baryonic dark matter (DM) particles, the precise nature of these particles and their interactions remain a puzzle. The neutralino is the current leading dark matter candidate. In this paper we explore if the energy supplied from the self-annihilation of dark matter in the centres of galaxies and cluster haloes could possibly play a significant role in the baryonic cooling/heating cycle (Ascasibar 2007; Totani 2004; 2005; Colafrancesco et al. 2006). Detailed astrophysical implications of neutralino dark matter annihilations in galaxy clusters, with a specific application to the Coma cluster have been calculated by Colafrancesco, Profumo & Ullio (2006). They performed a thorough analysis of the transport and diffusion properties of neutralino annihilation products, and investigated the resulting multi-frequency signals, from radio to gamma-ray frequencies. They also study other relevant astrophysical effects of neutralino annihilations, like the DM-induced Sunyaev-Zel’dovich effect and the intracluster gas heating.

Annihilation luminosity is expected to be produced as a result of an enhancement in the density of the dark matter distribution in the inner-most regions of galaxies, due to the response of the dark matter to the adiabatic growth of a central black hole (Gondolo & Silk 1999) and/or to the adiabatic compression suffered by the dark matter due to the collapse of baryons into the dark matter potential well (Blumenthal et al. 1986; Ryden & Gunn 1987; Gnedin et al. 2004). By including this steady heating source of annihilating neutralinos to suppress cooling flow gas in a sophisticated model of galaxy formation, we explore the effect of various key parameters in reproducing the bright-end of the observed galaxy luminosity function. The question we address is whether self-annihilation can provide an alternative mechanism to AGN driven feedback within the context of the current paradigm.

The outline of this paper is as follows. In Section 2 we discuss the physics of neutralino annihilation; a scenario for the coupling of this energy source to baryons in galactic nu-

clei is explored in Section 3. With this phenomenology developed, we incorporate this feedback scheme into a galaxy formation model. The details of the N-body simulation and galaxy formation model used in this implementation are discussed in Section 4. Our results are presented in detail in Section 5 and summarized in Section 6. We conclude with a discussion of the implications of our results and comparison of annihilation heating with other modes of feedback. Unless otherwise stated we assume Hubble constant parametrised as $H_0 = h 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with $h = 0.73$.

2 DARK MATTER CANDIDATES

Theoretical predictions of structure formation and evolution in a Cold Dark Matter (CDM) cosmogony appear to be in very good agreement with current observations on most scales bar perhaps the smallest (Spergel et al. 2006; Tegmark et al. 2004; Seljak et al. 2005; Cole et al. 2005). In this well established paradigm, the bulk of the matter in the Universe is comprised of cold, collisionless particles that seed the formation of structures from the gravitational amplification of their early fluctuations (Blumenthal et al. 1984; Davis, Efstathiou, Frenk & White 1985).

Weakly Interacting Massive Particles (WIMPs) are the currently favoured dark matter candidates as their cross-sections are small enough that they act as essentially collisionless particles (Kolb & Turner 1990). The super-symmetric *neutralino*, arising in minimal super-symmetric extensions of the Standard Model of particle physics, is probably the most widely studied WIMP candidate (see review by Jungman, Kamionkowski & Griest 1996 and references therein). In the Minimal Super-symmetric Standard Model (MSSM), the super-partners of the gauge bosons and the neutral Higgs bosons, respectively called binos and higgsinos, mix into four Majorana fermionic mass eigenstates, called neutralinos. In some regions of the super-symmetric parameter space, the lightest neutralino can naturally achieve a relic density that matches the observed cosmic DM abundance, thus making it a theoretically well motivated DM candidate. The neutralino mass can be anywhere between $\approx 50 \text{ GeV}$, which is the lower bound allowed by accelerator constraints (Eidelman et al. 2006, see *ibidem* for the set of assumptions made on the underlying super-symmetric scenario), up to 100 TeV in some extreme non-perturbative scenarios (Profumo 2005), although masses larger than a few TeV are commonly considered as “unnatural”, if one wants SUSY to solve the theoretical problems (such as the hierarchy problem) for which it was originally invented.

An interesting alternative candidate arises in theories with Universal Extra Dimensions (UED), and corresponds to the first Kaluza-Klein state of the hypercharge gauge boson (Appelquist, Cheng and Dobrescu, 2002; Servant and Tait 2000). The existence of a viable dark matter candidate in UED theories can be seen as a consequence of the conservation of momentum in a higher dimensional space. To generate chiral fermions at the zero mode, the extra dimensions must be modded out by an orbifold, leading to the conservation of the so-called KK-parity, such that all odd-level KK particles are charged under this symmetry, thus ensuring that the lightest (first level) KK state is stable.

A lower bound on the mass of the lightest Kaluza-Klein particle (LKP) comes from electroweak measurements, and depending on the mass of the Higgs, it can be as low as ≈ 300 GeV (Gogoladze and Macesanu 2006). Although the annihilation cross section in these scenarios is fixed by the LKP mass, it is possible to achieve the correct relic density even for particles as heavy as several TeV, provided that one includes the effect of co-annihilation with other KK particles (Burnell & Kribs 2006, Kong & Matchev 2006, Kakizaki et al. 2006). We note that the arguments presented here are valid more generally for any thermal relic WIMP candidate with s-wave annihilation.

Regardless of its precise nature, it is possible to set cosmological constraints on the WIMP mass m_χ under some simplifying, but rather general assumptions on its nature. The WIMP mass is in fact constrained to be roughly $m_\chi \gtrsim 30$ GeV and $m_\chi \lesssim 10$ TeV, by theoretical considerations of the thermal freeze-out in the early Universe (e.g. Bertone, Hooper and Silk 2005). The very same theoretical considerations suggest that the WIMP annihilation rate in the local Universe is far below the expansion rate of the Universe. However, annihilations proceed in high density DM regions, such as the centres of DM haloes. We demonstrate in this work that this resultant annihilation luminosity could play an important role in galaxy formation by providing a strong source of feedback which prevents gas from cooling and forming stars in galaxies. WIMP pair annihilation in high DM density regions will inevitably produce high energy neutrinos, positrons, anti-protons and gamma-rays. There are several on-going and future experiments focused on direct and indirect searches for the signature of neutralinos (see reviews by Bergstrom 2002; Bertone, Hooper & Silk 2004). In this paper we focus on GeV mass-scale WIMPs, however for illustration purposes we also calculate the consequence of heating by MeV DM.

3 THE SELF-ANNIHILATION LUMINOSITY IN A SIMPLE THEORETICAL MODEL

Here we describe the key ingredients of the simple theoretical model constructed to estimate the self-annihilation luminosity of DM in the centres of galaxy and cluster scale haloes. In the concordance Λ CDM cosmology the thermally averaged annihilation rate of WIMPs, in absence of co-annihilations, is related to the DM relic density by $\langle \sigma v \rangle \sim 3 \times 10^{-27} / \Omega_\chi h^2 \text{ cm}^3 \text{ s}^{-1}$. From this expression one can estimate the annihilation luminosity from neutralinos in a halo with a given density profile (assuming they constitute all the dark matter):

$$L_{\text{XX}} = \frac{\langle \sigma v \rangle}{2 m_\chi^2} \int_V \rho_\chi^2(\vec{x}, t) d^3x, \quad (1)$$

where the integral is performed over the halo volume V , m_χ is the WIMP mass, and $\rho_\chi(\vec{x}, t) \approx \rho_\chi(r, t)$ is the dark matter density profile, commonly assumed to be spherically-symmetric, making it only dependent on the galactocentric radial coordinate r .

3.1 The global dark matter halo profile

The density profile of a dark matter haloes that assemble in cosmological N-body simulations is well fit by the following parametrised functional form, referred to as the generalised Navarro-Frenk-White (NFW) profile (Navarro, Frenk & White 1996):

$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}, \quad (2)$$

where α , β , and γ govern the slope of the profile on large and small scales respectively, with a transition in slope at the scale radius r_s , defined as the ratio of the virial radius of the DM halo, R_{vir} , and the virial concentration parameter, c_{vir} :

$$r_s = \frac{R_{\text{vir}}}{c_{\text{vir}}}. \quad (3)$$

In this paper we only consider profiles for which the outer slope is -3 , i.e. where $(\beta - \gamma)/\alpha = 2$. This leads to the following expression for the normalisation constant, ρ_0 ,

$$\rho_0 = \frac{M_{\text{vir}}}{4\pi \int_0^{R_{\text{vir}}} \frac{r^2}{(r/r_s)^\gamma (1+r/r_s)^{3-\gamma}} dr}, \quad (4)$$

where M_{vir} is the virial mass of the system.

The slope of the density profile in the inner regions of the halo γ is of interest for our work. A value of $\gamma = 1$ refers to the NFW profile, while $\gamma = 1.5$ corresponds to the so-called Moore profile (Moore et al. 1999). Note that eqn. (2) is a fit to the output of numerical simulations which do not include either particle physics and hydrodynamic effects. Such effects may alter the distribution of DM over time. The consequences of this possibility are discussed in the next section. In fact, it is the time evolution of the density profile that holds the key to possibly tapping the energy from the neutralino self-annihilation. We briefly note here that for a cluster scale DM halo, with typical virial mass $10^{14-15} M_\odot$, the luminosity generated from eqn. (1) with central density profile $\gamma=1-1.5$ is, at most, of order $10^{39} \text{ ergs}^{-1}$. Thus, even if this entire energy output coupled maximally to the cooling gas in the inner regions it would be insufficient to offset the cooling luminosity (of order $\sim 10^{42-44} \text{ ergs}^{-1}$) in a typical cluster system (Totani 2004; 2005). Physical processes that further steepen the inner density profile slope are therefore required to make the annihilation viable as a feedback mechanism. Fortunately, several astrophysical processes in the centres of dark matter haloes are expected to affect the density profile of DM in precisely the required fashion.

3.2 The formation of a central density spike

3.2.1 Steepening due to adiabatic response to collapsing baryons

Density enhancements can arise in the inner regions of dark matter haloes from a number of different astrophysical processes. One such process is the adiabatic response of the dark matter to the infall and collapse of baryons (Blumenthal, Flores & Primack 1986; Ryden & Gunn 1987; Gnedin et al. 2004). Baryonic gas loses energy through radiative processes and falls into the centre of a dark matter halo to form stars. As a result of this redistribution of mass, the gravitational potential of the inner regions of the halo changes. The dark

matter responds to the subsequent deepening of the potential by altering its distribution and thereby enhancing its density. The increase in dark matter density from adiabatic compression can be calculated using adiabatic invariants. The cusp index γ in the NFW profile of eqn. (2) steepens to a value that depends on the density profile of the baryons.

Earlier calculations by Blumenthal et al. (1986) over-predicted the steepening due to the assumptions of spherical symmetry and circular orbits. This was due, in part, to the fact that haloes in the hierarchical structure formation scenarios grow via multiple violent mergers and accretion along filaments, and particle orbits in the haloes are highly eccentric. Gnedin et al. (2004) revisited this question using high-resolution cosmological simulations that included gas dynamics, radiative cooling, and star formation. They found that the dissipation of gas indeed increased the density of dark matter and steepened its radial profile in the inner parts of the halo when compared with haloes without cooling. Comparisons with the earlier work of Blumenthal et al. (1986) showed that the assumption of spherical symmetry induces a systematic over-prediction of the density enhancement in the inner 5% of the virial radius. Gnedin et al. (2004) correct for this by providing a simple modification of the assumed adiabatic invariant which includes orbit-averaged particle positions.

If the baryons have a radial density profile $\rho_b(r) \propto r^{-\nu}$, then the spike (i) retains the same slope if $\nu = 1$; (ii) or if $\nu > 1$, the contracted inner slope of the DM profile is steeper than its original value. For $\nu = 1 - 2$, the final inner DM density slope can be as steep as $\gamma = 1 - 1.7$, respectively. In cluster sized systems, although baryons represent only a small fraction of the overall mass, they may be crucially important on scales comparable to the extent of the typical brightest, central cluster galaxies.

There has been a lot of recent activity in the simulations community to understand the likely interactions between baryons and dark matter (Gnedin et al. 2004; Nagai & Kravtsov 2005; Faltenbacher et al. 2005; Gustafsson, Fairbairn & Sommer-Larsen 2006). For instance, in a recent simulation that included baryons, Gustafsson, Fairbairn and Sommer-Larsen (2006) claim that the central DM cusps steepen to $\rho \sim r^{-1.9 \pm 0.2}$, with an indication of the inner logarithmic slope converging on galaxy mass scales. Gustafsson et al. (2006) claim that the difference in the extent of adiabatic contraction and subsequent response they find compared to Gnedin et al. (2004) and other works originates in the differences in their stellar feedback prescription. So the extent of steepening due to adiabatic response is an unsettled issue at the present time due to the inherent uncertainty in our understanding and implementation of star formation in simulations. On the observational side there have also been many recent attempts to disentangle the dark matter and baryonic components in clusters (Zappacosta et al. 2006; Biviano & Salucci 2006; Mahdavi et al. 2007; Sand et al. 2008).

Extensive convergence studies have shown that modern highest resolution dissipationless simulations agree in their predictions: the average logarithmic slope of the density profile at $r = 0.01 R_{\text{vir}}$ is $\gamma = 1.3$, with a substantial scatter of ± 0.3 from object to object (Fukushige et al. 2004; Tassitsiomi et al. 2004; Navarro et al. 2004; Reed et al. 2004; Diemand et al. 2004; 2005). At the same time, despite a sig-

nificant decrease in the smallest reliably resolved scale, the logarithmic slope continues to get shallower with decreasing radius without reaching an asymptotic value. For the purposes of this work, for our default model we will assume a conservative value for the inner slope of the density profile of $\gamma = 1.0$, which is the standard NFW value commonly used.

3.2.2 Steepening due to adiabatic growth of central black holes

On extremely small scales ($r < 1\text{pc}$), i.e. at the very centre of the galaxy hosted by a DM halo, the gravitational potential is dominated not by DM (as described by eqn. 2) but by baryons, mainly comprising stars and frequently a supermassive black hole (SMBH). In fact, from the demography of nearby galaxies it appears that nearly every galaxy hosts a SMBH, and their masses are well correlated with properties of the stellar component in the inner-most regions (Magorrian et al. 1998; Tremaine et al. 2002; Ferrarese & Merritt 2002). In our own Galaxy, for instance, stars exhibit a cusp inside a few parsecs described by (Genzel et al. 2003):

$$\rho_*(r) \sim 3.2 \times 10^5 M_\odot \text{pc}^{-3} \left(\frac{r}{1 \text{pc}} \right)^{-1.4}. \quad (5)$$

This distribution is centred around the supermassive black hole at the Galactic centre, whose mass is estimated to lie in the range $2 - 4 \times 10^6 M_\odot$ (Ghez et al. 2005; Genzel et al. 2003b).

In fact, Hooper, Finkbeiner & Dobler (2007) claim that the excess microwave emission from the region around the center of our Galaxy detected by WMAP (Wilkinson Microwave Anisotropy Probe) could be synchrotron emission from relativistic electrons and positrons generated in dark matter annihilations. Hooper et al. (2007) find that the angular distribution of this ‘‘WMAP Haze’’ matches the prediction for dark matter annihilations with a cusped density profile, $\rho(r) \propto r^{-1.2}$ in the inner few kiloparsecs. Comparing the intensity in different WMAP frequency bands, they find that a wide range of possible WIMP annihilation modes are consistent with the spectrum of the haze for a WIMP with a mass in the 100 GeV to multi-TeV range. Most interestingly, they find that to generate the observed intensity of the haze, the dark matter annihilation cross section is required to be approximately equal to the value needed for a thermal relic, $\sigma v \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$.

More generally, the *adiabatic* growth of a massive object at the centre of a power-law distribution of DM with index γ induces a redistribution of the DM (also referred to as a density ‘spike’), into a new power-law with a steepened index γ_{spike} (Peebles 1972, Young 1980, Ipser & Sikivie 1987, Quinlan et al. 1995, Gondolo & Silk 1999).

$$\rho_{\text{spike}}(r) = \rho(r_{\text{outer spike}}) \left(\frac{r}{r_{\text{outer spike}}} \right)^{-\gamma_{\text{spike}}}, \quad (6)$$

where

$$\gamma_{\text{spike}} = 2 + \frac{1}{4 - \gamma}, \quad (7)$$

and the outer spike radius is approximated by

$$r_{\text{outer spike}} \approx r_{\text{bh}} \equiv 0.2 \frac{G M_{\text{bh}}}{\sigma^2}, \quad (8)$$

where r_{bh} is the gravitational radius of influence of the black

hole (Merritt & Szell 2006). The density $\rho(r_{\text{outer spike}})$ is found by evaluating eqn. 2 at the outer spike radius. For the Milky Way, $r_{\text{bh}} \approx 1\text{pc}$.

A physical cut-off to the otherwise diverging profiles of eqn. (2) and eqn. (6) at small r is provided by the self-annihilation rate itself. We can define a limiting radius, r_{lim} , where the density reaches a maximal value given by

$$\rho_{\text{spike}}(r_{\text{lim}}) = \frac{m_\chi}{\langle \sigma v \rangle t_{\text{spike}}}, \quad (9)$$

where t_{spike} is the lifetime of the density spike (see below). This limiting radius r_{lim} can then be found by equating and solving eqn. (9) and eqn. (6) simultaneously. In reality, the inner cut-off radius cannot be arbitrarily small. Hence, we truncate the inner annihilation luminosity at

$$r_{\text{inner spike}} = \text{Max} [4 R_S, r_{\text{lim}}], \quad (10)$$

where R_S is the Schwarzschild radius of the SMBH, $R_S = G M_{\text{bh}}/c^2$. This defines the inner spike radius, $r_{\text{inner spike}}$.

3.3 Density spike evolution and enhanced annihilation luminosity

In order to understand the time evolution of a DM density spike, we note that once the spike is established several astrophysical and particle physics effects act to disrupt it. The three principal effects that can damp a density spike are: (i) the self-annihilation process itself that depletes DM (discussed above), (ii) the interaction between the DM and the surrounding baryons near the SMBH, and (iii) spike disruption during galaxy (or more specifically black hole) mergers.

DM and baryons interact gravitationally with each other, and stars typically have significantly larger kinetic energies than DM particles. Gravitational encounters between these two populations will tend to drive them toward equipartition of energy, causing the DM to heat up, flattening the spike while retaining the shape of the density profile. As shown by Bertone & Merritt (2005a; 2005b), the resultant spike evolution with time can be modelled as an exponential decay via

$$\rho_{\text{spike}}(r, t) = \rho_{\text{spike}}(r, 0) e^{-\tau/2}, \quad (11)$$

and

$$r_{\text{outer spike}}(t) = r_{\text{spike}}(0) e^{(-\tau/2)/(\gamma_{\text{spike}}-\gamma)}, \quad (12)$$

where τ is the time elapsed since the original spike formation t_{spike} measured in units of the heating time T_{heat} ,

$$T_{\text{heat}} = 1.67 \times 10^9 \text{ yr} \left(\frac{M_{\text{bh}}}{4 \times 10^6 M_\odot} \right)^{1/2} \left(\frac{r_{\text{bh}}}{2\text{pc}} \right)^{3/2}. \quad (13)$$

We show results for the time evolution of a fiducial spike in at the centre of our Galaxy in Figure 1 and discuss the issue further in Section 5.1.

Mergers of black holes, and in particular major mergers (i.e. SMBH mass ratios greater than 0.3), are efficient at flattening or destroying density spikes (Merritt et al. 2002). We note that the disruption is maximal during equal mass mergers, however these are extremely rare. After a merger the density spike will be re-established on a time-scale comparable to the relaxation time of stars (Merritt, Harfst and Bertone 2006). If major mergers are too frequent then spikes will not be long-lived enough to enhance the annihilation

luminosity. However, if they never happen the spike decay described above will result in inefficient heating. We encapsulate spike disruption in eqn. (9) by following the time since the last SMBH major merger in each halo, t_{spike} , which approximates the spike lifetime. The major merger rate in the simulation and galaxy formation model is discussed further in Section 5.1.

Using all the above computed quantities, we can finally estimate the time dependent annihilation luminosity at any time after the most recent SMBH major merger as:

$$\begin{aligned} L(t; m, \sigma v) &= 2\pi \frac{\langle \sigma v \rangle}{m_\chi^2} \int_{r_{\text{inner spike}}}^{r_{\text{outer spike}}} \rho_{\text{spike}}^2(r) r^2 dr \quad (14) \\ &= 2\pi \frac{\langle \sigma v \rangle}{m_\chi^2} \frac{\rho(r_{\text{outer spike}})^2}{2\gamma_{\text{spike}}-3} r_{\text{outer spike}}^3 \left(\frac{r_{\text{inner spike}}}{r_{\text{outer spike}}} \right)^{-2\gamma_{\text{spike}}+3}, \end{aligned}$$

in the limit that $r_{\text{outer spike}} \gg r_{\text{inner spike}}$. In what follows, we evaluate eqn. (14) for DM haloes in the Millennium Run simulation.

4 ANNIHILATION HEATING IN A COSMOLOGICAL MODEL OF GALAXY FORMATION

4.1 The Millennium Run Simulation and Galaxy Formation Model

To explore the effects of the heating of cooling gas in the hot halo from neutralino annihilation we employ a model of galaxy formation (Croton et al. 2006) coupled to a high resolution N-body simulation, the so-called ‘Millennium Run’ (Springel et al. 2006). Below we give only a brief outline of these techniques; the interested reader should refer to Croton et al (2006) and references therein for further details. In the following sub-sections we describe the addition of neutralino heating to this model.

The Millennium Run N-body simulation follows the dynamical evolution of approximately 10 billion dark matter particles in a periodic box of side-length $500 h^{-1}\text{Mpc}$ with a mass resolution per particle of $8.6 \times 10^8 h^{-1} M_\odot$. The adopted cosmological parameter values are $\Omega_\Lambda = 0.75$, $\Omega_m = 0.25$, $h = 0.73$, and $\sigma_8 = 0.9$ (Colless et al. 2001, Spergel et al. 2003, Seljak et al. 2005). From the simulation outputs merger trees are constructed that describe in detail how structures grow as the Universe evolves. These trees form the backbone onto which the galaxy formation model is coupled. Inside each tree, virialised dark matter haloes at each redshift are assumed to attract ambient gas from the surrounding medium, from which galaxies form and evolve. The galaxy formation model effectively tracks a wide range of physics in each halo, including reionization of the intergalactic medium at high redshift, including radiative cooling of hot gas and the formation of cooling flows, star formation in the cold disk and the resulting supernova feedback, black hole growth, metal enrichment of the intergalactic and intra-cluster medium, and galaxy morphology shaped through mergers and merger induced starbursts.

More specifically, once a dark matter halo has grown in mass to approximately $\sim 10^{11.5} h^{-1} M_\odot$ infalling baryons no longer fall ‘cold’ on to the central galaxy but instead shock heat to the virial temperature of the dark matter halo to

form a quasi-static hot atmosphere (Croton et al. 2006). As the density of hot gas increases the cooling time near the centre of the halo becomes short and a cooling flow of condensing gas forms. Using simple thermodynamic and continuity arguments a cooling rate for this flow, \dot{m}_{cool} , can be estimated under the assumption that the gas is approximately isothermal ($\rho_{\text{hot}} \sim r^{-2}$) outside the very central regions at the virial temperature of the halo ($T_{\text{vir}} \sim V_{\text{vir}}^2$, where V_{vir} is the virial velocity of the dark halo):

$$\dot{m}_{\text{cool}} = 0.5 \left(\frac{r_{\text{cool}}}{R_{\text{vir}}} \right) \left(\frac{m_{\text{hot}}}{t_{\text{cool}}} \right). \quad (15)$$

Here R_{vir} is the virial radius of the halo, m_{hot} is the mass of gas in the hot phase, and $t_{\text{cool}} \approx 0.1 t_{\text{Hubble}} = R_{\text{vir}}/V_{\text{vir}}$ is the cooling time of the gas at the cooling radius, which is defined by:

$$r_{\text{cool}} = \left[\frac{\Lambda(T, Z)}{6\pi\mu m_p k T} \frac{m_{\text{hot}}}{V_{\text{vir}}} \right]^{1/2}, \quad (16)$$

The cooling radius traditionally marks the radius out to which gas has had time to cool quasi-statically given the age of the system. In the above, μm_p is the mean particle mass, k is the Boltzmann constant, and $\Lambda(T, Z)$ is the cooling function, dependent on both the temperature T and metallicity Z of the hot gas. Despite their simplicity, eqns. (15) and (16) provide a good approximation to the rate at which gas is deposited at the centre in the similarity solution for a cooling flow (Bertschinger 1989; Croton et al. 2006).

Gas cooling in simulations appears to be much more efficient than observed in nature. For low mass haloes heating and expulsion of baryonic material by supernovae can prevent over-cooling, but on group and cluster scales, while the observed baryon fraction has the universal value (Balogh et al. 2001), state of the art hydrodynamical simulations find a significantly larger fraction of cooled gas (Borgani et al. 2003; Kravtsov, Nagai & Vikhlinin 2005). In fact in clusters the problem is particularly severe; observationally the X-ray luminosities in many clusters imply cooling rates in the inner regions of $\sim 100 - 1000 M_{\odot} \text{ yr}^{-1}$ (e.g. Fabian & Nulsen 1977; Edge 2001; Fabian 2004), whereas little or no associated star formation is detected. A decrease in X-ray gas temperature is often seen in the centres of clusters but X-ray spectroscopy detects very little cool gas below 10^7 K at temperatures of $\sim 1 - 2$ keV (Peterson et al. 2001; 2003).

Therefore it has been known for some time (see Fabian 1994 and references therein), the measured cooling times at the centre of observed clusters of galaxies are significantly shorter than the Hubble time. This implies that gas condensation should be occurring from the conventional picture described above, however none is observed, nor are the secondary effects of cooling such as copious star formation in the central brightest cluster galaxy. Such galaxies are mostly found to be ‘red and dead’. This behaviour may indicate the presence of a heat source that is supplying energy to the cooling gas to keep the central regions from condensing. This is the so-called classical ‘cooling flow problem’ (Fabian 1994).

To arrest the expected runaway cooling in massive systems a heat source must be present. We test the idea of whether the heating from dark matter annihilation at the centres of massive systems can plausibly be a global solution to the cooling flow problem described above. Another key aspect of the cooling flow problem is the fact that the

cooling time of gas is short over a fairly large range of radii, particularly in groups and clusters, implying that the heating rate of any proposed mechanism ought to balance the cooling at all radii. Below we describe our implementation of this DM annihilation powered heating into the galaxy formation model.

4.2 Thermal coupling of the neutralino annihilation energy

The energy produced from the self-annihilation of neutralinos in the vicinity of the spike r_{spike} we argue will couple thermally with the baryons in galactic nuclei, thereby heating the gas. We investigate potential physical processes and the relevant time-scales that will likely enable the transfer of this energy to the baryons. We compute relevant time-scales for the centre of the Milky Way treating that as our fiducial case from which we scale to other masses. Similar heuristic estimates have been made by Totani (2004; 2005) for galaxy clusters.

The dominant astrophysical process via which the self-annihilation energy interacts with baryons is unknown at the present time. Here for purposes of estimating the efficiency of potential astrophysical processes we use observational estimates of the density, pressure and temperature from the inner regions of our Galaxy at roughly 200 pc from the Galactic Center (Bradford et al. 2005; Morris & Serabyn 1996). The physical conditions present in this region are consistent with thermal, non-thermal and magnetic pressures that are several orders of magnitude higher than those present in the large-scale galactic disk. For the measured densities of $n \sim 10^4 \text{ cm}^{-3}$, the pressure is $P_{\text{thermal}} \sim 10^{-10} \text{ erg cm}^{-3}$, however turbulent pressures greatly exceed this value, approaching $P_{\text{turb}} \sim 10^{-8} \text{ erg cm}^{-3}$. For the inferred magnetic field strength of $0.1 - 1$ mG, the magnetic pressure is also large, of the order of $P_{\text{mag}} \sim 10^{-8} - 10^{-10} \text{ erg cm}^{-3}$. To estimate the time-scales for energy loss and therefore heating of the gas in the inner regions, we adopt the following scaling values for the density, pressure and magnetic field strength from the Milky Way: $P \sim 10^{-8} \text{ erg cm}^{-3}$, $n \sim 10^4 \text{ cm}^{-3}$, and $B \sim 0.4$ mG. **Note that the self-annihilation heating occurs for the $T \sim 10^4$ K cooling gas from the hot halo and not to the $T \sim 200$ K molecular gas at 200 pc.**

Using the above values we can address the question of how the annihilation luminosity is likely converted efficiently into thermal energy of the gas in the nucleus. We focus on a fiducial neutralino model where about 1/4th of the annihilation energy $E_{\chi\chi}$ goes into continuum gamma-rays [Channel A], 1/6th goes into electrons and positrons [Channel B], 1/15th goes to protons and anti-protons [Channel C], and the rest is imparted to neutrinos that are not relevant for heating. The spectral energy distribution of the products is such that $E^2 \frac{dN}{dE}$ peaks roughly at $0.05 m_{\chi} c^2$, $0.05 m_{\chi} c^2$ and $0.1 m_{\chi} c^2$ respectively. The average energy of secondary particles produced in the annihilation of a neutralino of mass 50 GeV is of the order of 1 GeV. These annihilation products are representative of a wide class of super-symmetric scenarios, as determined with the DarkSUSY code (Gondolo et al. 2005), that are consistent with cosmological and accelerator constraints.

Examining Channel B in detail, we assume for simplic-

ity that all the electrons and positrons have roughly the same energy $E_0 \sim 1$ GeV. Since they are produced in an extremely high density environment, they will expand relativistically and form a bubble. As discussed in Shu (1991), the primary energy loss processes are examined below. The energy loss time-scale for these particles by Coulomb collisions is given by:

$$\tau_{CC} \sim 5.1 \times 10^3 \frac{n}{10^4 \text{ cm}^{-3}} E_0 \text{ yr}, \quad (17)$$

which is so short that all the electrons and positrons from the neutralino decay will very efficiently transfer energy to the gas cooling out of the hot halo. This is the principal physical process that will likely heat the gas and provide the feedback discussed in this work. On the other hand, the energy loss time from inverse Compton scattering is long,

$$\tau_{IC} \sim 1.2 \times 10^9 E_0^{-1} \text{ yr}, \quad (18)$$

and therefore inefficient. The time-scale for energy losses via Brehmstrahlung is also short,

$$\tau_{\text{Brehm}} \sim 5.7 \times 10^3 \left(\frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1} \text{ yr}. \quad (19)$$

In comparison using the same estimate for n , the energy loss time-scale from synchrotron radiation is given by,

$$\tau_{\text{Synch}} \sim 1.5 \times 10^5 E_0^{-1} \text{ yr} \quad (20)$$

We conclude from the above estimates that the conversion of the self-annihilation energy into thermal energy can occur efficiently for the gas in the inner regions of galactic nuclei as illustrated specifically for the Milky Way case. However, we do note here that our estimate of the magnetic field strength is on the high side. This energy input suppresses the gas cooling and quenches star formation. Due to our lack of knowledge of neutralino properties, it is not possible to calculate the precise time-scale and physical process that thermally couples the by-products of the γ -ray annihilation to baryons. For the purposes of this work, it is assumed that this coupling is efficient and all the available energy is transferred effectively to heating the gas in the inner regions of DM haloes. The estimate of time-scales for the Milky Way halo suggests that gas in the inner region on the scale of ~ 200 pc is likely directly involved in the heating process.

We note here that an alternate dark matter driven gas heating mechanism exploiting inelastic scattering of X-dark matter particles with relic abundances comparable to neutralinos has been proposed by Finkbeiner & Weiner (2007). They propose a WIMP candidate with an excited state that maybe collisionally excited and de-excites by $e^+ - e^-$ pair emission. The kinetic energy of these pairs they argue could heat intra-cluster gas and the gas in galaxies to compensate for cooling similar to what we explore here. The primary motivation for this model was to provide a possible interpretation for the 511 keV line observed by the INTEGRAL satellite in the inner Milky Way consistent with the observed WMAP haze and current constraints on the gamma-ray background.

4.3 Constructing a viable feedback model from neutralino self-annihilation

We model the self-annihilation luminosity of neutralinos as a steady input of energy that prevents gas cooling in preferen-

tially massive galaxies/haloes. The assumptions and properties of simulated haloes that are needed to fully specify the DM density profile, BH mass, and the inner and outer spike radii are all taken as input by the galaxy formation model to calculate the annihilation luminosity for any system at any given time its evolution.

4.3.1 Halo density profiles

The DM density profile for every halo in the Millennium Run at every time-step is approximated using the universal analytic function described by eqn. (2). Note that, while in principle each profile can be directly measured from the distribution of bound dark matter particles, this is computationally prohibitive given the number of haloes in the Millennium run (up to 25 million at any given time-step), and the analytic formalism is accurate enough for our purposes here.

To explore the dependence of annihilation heating on the inner slope of the halo density profile, γ , we take the inner slope as a free parameter in determining eqn. (2). In the next section we will vary γ and examine its effect on the evolution of the galaxy population. The remaining parameters in the density profile are either assumed fixed or taken directly from the simulation.

For the default model, we assume $\alpha = 1$ and choose β such that $(\beta - \gamma)/\alpha = 2$. This ensures that the outer slope of the halo density profile remains fixed at -3 , which is known to be an accurate description of the results of numerical simulations (Navarro, Frenk & White 1996). We take the measured virial mass M_{vir} , and radius R_{vir} , required in eqn. (3) and (4), directly from the simulation. To estimate the halo concentration parameter c_{vir} , we use the measured V_{vir} and V_{max} and solve eqn. (5) in Navarro et al. 1997 (see Croton, Gao & White 2007). This fully describes the density profile for each dark matter halo.

4.3.2 The inner and outer spike radii

Once a value for the slope of the inner dark matter density profile, γ , has been assumed, the steepened spike index, γ_{spike} (eqn. 7), can be calculated. This then fixes the spike density profile defined by eqn. (6), and therefore also the inner limiting density determined by the self-annihilation rate itself, eqn. (9). The radius of this limiting density, and the inner spike radius, are calculated from eqn. (6) and (9). Note that we limit the inner spike radius to always be equal to or greater than four times the Schwarzschild radius (eqn. 10). However, this limit is rarely reached in practice.

The outer spike radius is simpler to calculate for each halo in the galaxy formation model, since the model explicitly follows the growth of SMBHs in each galaxy (Croton et al. 2006). This, along with the use of the virial velocity of the halo V_{vir} as a proxy for the inner velocity dispersion σ , allows the outer spike radius to be calculated using eqn. (8).

4.3.3 The efficiency of annihilation heating

We consider a maximal heating model, assuming that all the energy available from the annihilation luminosity given by eqn. (14) couples with the cooling gas in the hot halo. With

this assumption, the cooling rate described by eqn. (15) is modified in the presence of DM annihilations:

$$\dot{m}'_{\text{cool}} = \dot{m}_{\text{cool}} - \frac{\xi L_{\text{XX}}}{1/2 V_{\text{vir}}^2} \quad (21)$$

Thus, if the heating rate from the annihilation flux is comparable to the energy released from gas cooling out of the hot X-ray halo, the cooling flow can be suppressed and this will starve the central galaxy from lack of new star forming material. Under such circumstances galaxy growth will stall, altering the relationship between dark halo mass and galaxy luminosity in a way more compatible with observations.

4.3.4 Uncertainties in the galaxy formation model

As the results in the following sections are considered, it is important to keep in mind that the galaxy formation model we use to obtain them is imperfect. Its construction is largely based on observational phenomenology that, while well described in the mean, is often ill understood in detail.

The largest uncertainty in our galaxy formation model relevant to our results is the cooling prescription described in Section 4.1. The physics of cooling losses from hot plasma in a dynamically evolving multiphase medium is complicated. Our prescription provides cooling rates that are a reasonable average approximation to that obtained from hydrodynamically simulated gas infall (see Yoshida et al. 2002 for a comparison). However, cooling in both the hydrodynamic simulations and our galaxy formation model is first calculated in the absence of any heating (eqn. 15). The model heating rate is then subtracted (eqn. 21). But in reality, cooling and heating will occur simultaneously. Energy injection from heating can potentially modify the properties of the gas (notably temperature and density) used to calculate later cooling. Hence, under these circumstances subsequent cooling estimates will be different from those where the past heating history is neglected as in our model.

Due to these caveats, in absolute terms our heating rates must be treated with caution; they are simply a relative measure that defines an upper limit on the energy required to stop gas from cooling. However, relative to the cooling rate they are expected to be accurate for the model. More detailed models can be constructed to take into account the past heating history when calculating the current cooling rate, but these estimates would be complicated and highly unconstrained. For example, the temperature and density gas profiles could change as a function of the energy injected, depth of potential, and redshift, for every galaxy in an evolving Universe. These detailed and self-consistent responses of the baryons need to be taken into account. However, such improvements add considerable complexity that is beyond the scope of the present work. Below, we present the results of implementing a simple model of annihilation heating.

5 RESULTS

5.1 Spike evolution and stability

As discussed in Sections 3.1 and 3.3, the luminosity produced from dark matter annihilation in an unsteepened NFW-type halo falls short by several orders-of-magnitude

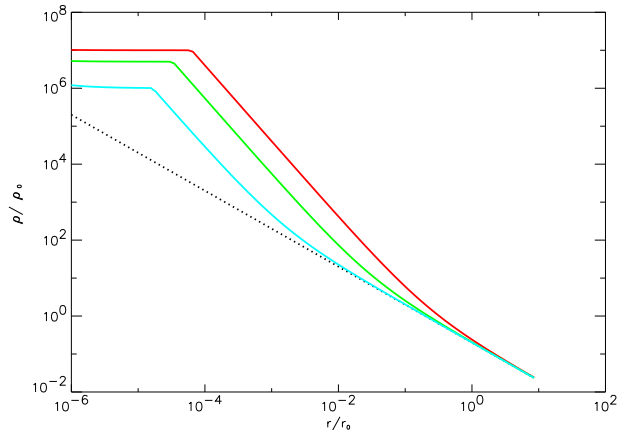


Figure 1. To illustrate the time evolution of the DM spike, we plot the variation of the density in the centre with time for a DM halo that hosts a Milky Way type galaxy. The x-axis is normalised to r_h the radius of gravitational influence of the black hole, while the y-axis is normalised to ρ_0 the density of the DM halo at r_h . The 3 different line styles denote the values of τ (i.e. time in units of the heating time T_{heat}). The solid lines are, from top to bottom, for $\tau = 1$ (red), $\tau = 5$ (green) and $\tau = 10$ (blue). The "unmodified" NFW profile is shown as a dotted line. The central "plateau" for the curves is due to annihilations, and the maximum density is calculated for a toy model, to simply show the qualitative behaviour of the profile at small radii. The maximum density - the height of the plateau, varies with time.

when compared to the cooling losses from the X-ray emitting hot gas. For annihilations to be a plausible solution to the cooling flow problem one requires an enhancement of the DM density in the inner most regions of the galaxy, usually assumed to be produced by the presence of a super-massive black hole or in response to the adiabatic compression of baryons or perhaps both these processes.

When present, density spikes are expected to evolve with time due to the annihilation itself. To illustrate this, in Fig. 1 we plot the time evolution of a DM density spike in the centre of a fiducial halo, modelled on the Milky Way. The x-axis is normalised to the radius of gravitational influence of the black hole, while the y-axis is normalised the density of the DM halo at this radius. The three different line styles denote the values of τ (i.e. time in units of the heating time T_{heat} , eqn. 13). The red line is for $\tau = 1$, green for $\tau = 5$, and blue for $\tau = 10$. The unmodified NFW profile (i.e. $\gamma = -1$) is shown as a dotted curve. The central plateau in the inner regions is due to annihilations, and the maximum density drops with time. The evolution of the density spike is clearly a result of many complex interactions within the halo.

Dark matter density spikes are fragile and transient – a major merger can easily destroy a spike on a short time-scale. However, it is unclear whether the disruption is triggered by the merger of the dark matter haloes, central black holes or galaxies hosted in the haloes. The merger rates for these three populations of objects are not necessarily the same, and yet a typical approximation adopted is to the use Extended Press-Schechter (EPS) theory to obtain the merger rate. However EPS only describes the properties of DM haloes. In reality it is probably the mergers of black

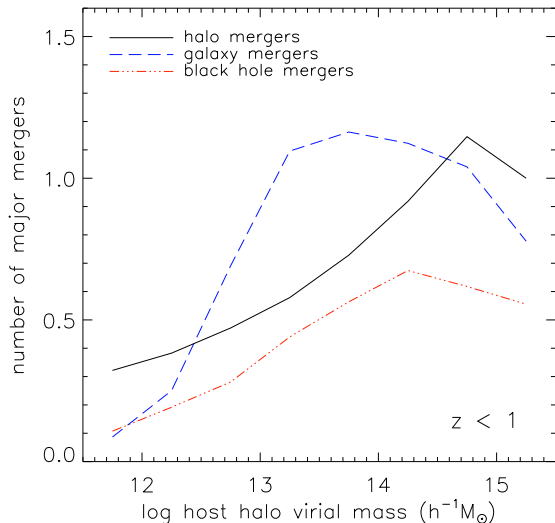


Figure 2. The number of major mergers for galaxies, DM haloes, and black holes vs host halo mass. This plot illustrates that the density spikes can be reassembled as the time between major mergers is long compared to the time taken to refill the stellar loss cone in galactic nuclei.

holes that ought be most significant for the evolution of a density spike.

Using our cosmological model of galaxy formation we can check the frequency of mergers for haloes, galaxies, and the black holes that reside within them. In Fig. 2 we show for each object the mean number of major mergers at $z < 1$. We focus on this redshift range because it is primarily only at late times wherein heating is needed to prevent the cooling of gas in haloes. Major mergers of SMBHs are less common than major mergers of galaxies or dark matter haloes, with less than one occurring per system on average since $z = 1$ at all host halo mass scales. This implies a typical spike survival time > 4 Gyr. Fig. 2 also shows that the merger rates for all populations tends to increase with increasing mass although this flattens somewhat for the most massive haloes. We conclude from Fig. 2 that spikes can survive on Gyr timescales despite the violent nature of the hierarchical growth and assembly in a Λ CDM Universe. Note, that even after a major merger spikes may later reform, typically on the stellar relaxation time-scale of the inner region of the galaxy.

In this work, we further assume that the mass of central black holes grows significantly at each merger (as the solution for adiabatic growth is valid only in the limit $M_{\text{bh,initial}} \ll M_{\text{bh,final}}$ (Di Matteo, Springel & Hernquist 2005)).

5.2 Annihilation heating of the hot halo

We now investigate the enhanced annihilation luminosity due to the presence of density spikes described in Section 4. The annihilation heating model depends on a well defined set of parameters. We explore the dependences in detail. These dependencies are illustrated in the various panels of Fig. 3: the dark matter halo virial mass M_{vir} , the black hole mass

M_{bh} , the mass of the dark matter particle m_χ , the average time between major mergers τ , the inner DM halo density profile slope γ , and the outer radius $r_{\text{outer spike}}$ adopted for the DM density spike. We consider two halo mass ranges for each, galaxy scales masses ($M_{\text{vir}} = 10^{12} M_\odot$, dashed lines) and cluster masses ($M_{\text{vir}} = 10^{14} M_\odot$, solid lines). Our default model assumes common values for each of $m_\chi = 100$ GeV, $\tau = 1$ Gyr, $\gamma = -1.0$ (NFW), and $r_{\text{outer spike}} = r_{\text{BH}}$ (the sphere of influence of the black hole). In each panel we vary one parameter keeping the rest fixed to clearly show the plausible range of heating rates that can be expected from the model (the default values of each parameter are marked by vertical dotted lines). In addition, the top left panel shows the expected cooling rate assuming a hot gas fraction of 0.1. The choice of 10% for the host gas fraction is motivated by the X-ray observations in galaxy groups and clusters (LaRoque et al. 2006; Vikhlinin et al. 2006; Gonzalez, Zaritsky & Zabludoff 2007). This is approximately the energy the DM heating needs to replenish.

It is clear that even in the presence of density spikes it is usually difficult to produce enough flux to reheat all the cooling gas, and this is true for haloes of all masses ranging from galaxy scales to cluster scales. Enhancement of between 1-2 orders-of-magnitude does occur when mergers are more frequent (this works to offset the exponential decay of the spike amplitude shown in Fig. 1) or for lower mass DM particle candidates. However the heating luminosity is still significantly lower when compared with the cooling rate shown in the top left panel.

The bottom two panels of Fig. 3 show how sufficient heating can be produced, either through significant steepening of the inner DM halo density profile (on which the spike sits), or a significantly larger outer spike radius or both. For galaxy-scale DM haloes annihilation heating can balance cooling whenever the inner density profile is steepened to values of $\gamma < -1.45$, and for cluster-scale haloes when $\gamma < -1.55$. Similarly large values for the outer spike radius, $\sim 25 r_{\text{bh}}$ on galaxy scales and $\sim 65 r_{\text{bh}}$ on cluster scales, are required for annihilation heating to compensate for the gas cooling. Although observationally the inner DM halo profile remains unconstrained on extremely small scales, it may be difficult to produce such steep slopes or large spike radii on the scales required for all galaxies and clusters, in order to effectively influence global properties.

Another challenge for our model is the requirement that heating and cooling balance needed at all radii as the cooling time for the gas is short for a range of radii specially on group and cluster scales. As developed here self-annihilation dumps all the energy at very small radii and here we assume due to lack of a more complete understanding at the present that all that energy is also thermalized efficiently at small radii. While this could lead to the generation of large entropy inversions in the X-ray gas that are typically not observed (Voit & Donahue 2005); we argue that there are other efficient energy transport processes like thermal conduction available to deposit energy at larger radii (Ruszkowski & Begelman 2002; Ruszkowski, Bruggen & Begelman 2004). It is useful to point out here that even for the alternative AGN feedback that have been proposed the astrophysical process that couple radiation to baryons in the inner regions of galaxies, groups and clusters is poorly understood at present (McCarthy et al. 2008). This is clearly a rich

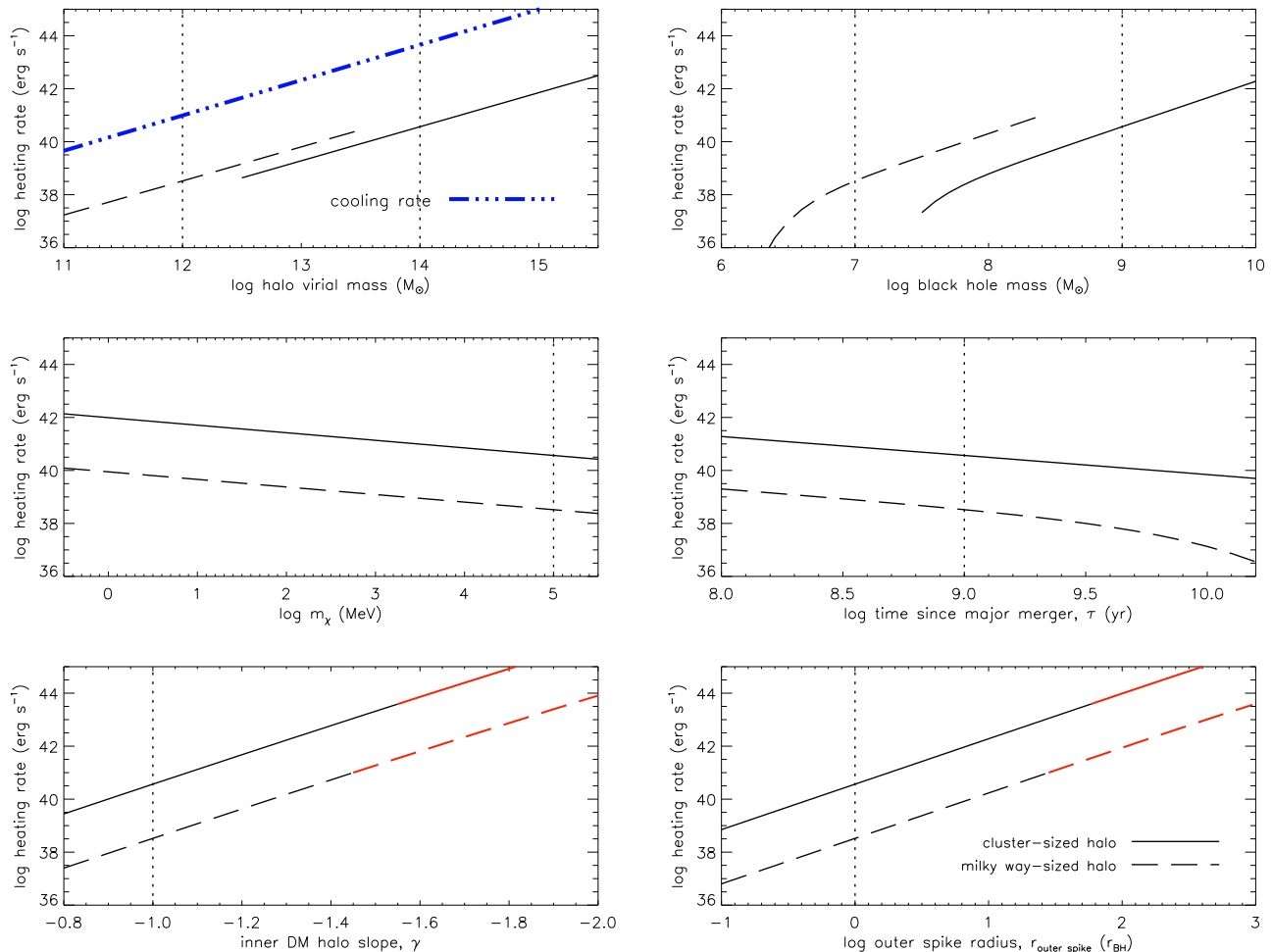


Figure 3. The parameters controlling the feedback from self-annihilation: the mass of the dark matter halo (top left), black hole mass (top right), DM particle mass (middle left), time since major merger (middle right), inner DM halo slope (bottom left), and outer spike radius (bottom right). Two models are shown, one for a Milky Way sized halo and one for a cluster sized halo. The default values for each are shown by the dotted horizontal lines in each panel. The common parameters are $m_\chi = 100$ GeV, $\tau = 1$ Gyr, $\gamma = -1.0$ (NFW), and $r_{\text{outer spike}} = r_{\text{BH}}$ (see text). Each panel demonstrates the effect on the heating of varying one of these parameters while keeping the remaining fixed. The annihilation luminosity is most sensitive to the inner halo density profile and outer spike radius. In the top left panel we additionally illustrate the approximate cooling rate for a given halo mass that the heating needs to overcome (thick dotted-dashed line, assuming a hot gas fraction of 10%).

avenue for future work for all currently proposed feedback models.

5.3 The consequences of annihilation heating in a cosmological context

The suppression of cooling flow gas in massive haloes can have a dramatic effect on evolution of the galaxies that reside in them. This is due to the fact that across cosmic time, a growth of a galaxy is dictated by the availability and supply of star forming material. At late times this mostly comes in the form of gas condensing out of the hot halo. Hence, any mechanism that suppresses gas cooling ultimately also prevents the galaxy from further star formation. Our goal is to investigate under what circumstances the evolving density spikes explored in Section 5.1 and the resultant heating model described in Section 5.2 can actually shut down star

formation in massive galaxies when the full hierarchical evolution of galaxies is taken into account.

In a set of three figures, Fig. 4–6, we show the resultant local luminosity function predicted by our galaxy formation model with annihilation heating included. We plot the $z = 0$ K-band galaxy luminosity function, for the models (lines) and observations for comparison (symbols with error bars). The long-dashed line in each figure shows the conservative default model used in Fig. 3. The remaining lines in each figure illustrate the consequences of different parameter choices for the annihilation heating prescription, with each figure focused on a specific set of parameters that tune the annihilation heating model.

As can be seen from all the luminosity function figures, the default model significantly overpredicts the abundance of the brightest galaxies. This is a consequence of inefficient annihilation flux heating for the default model, as

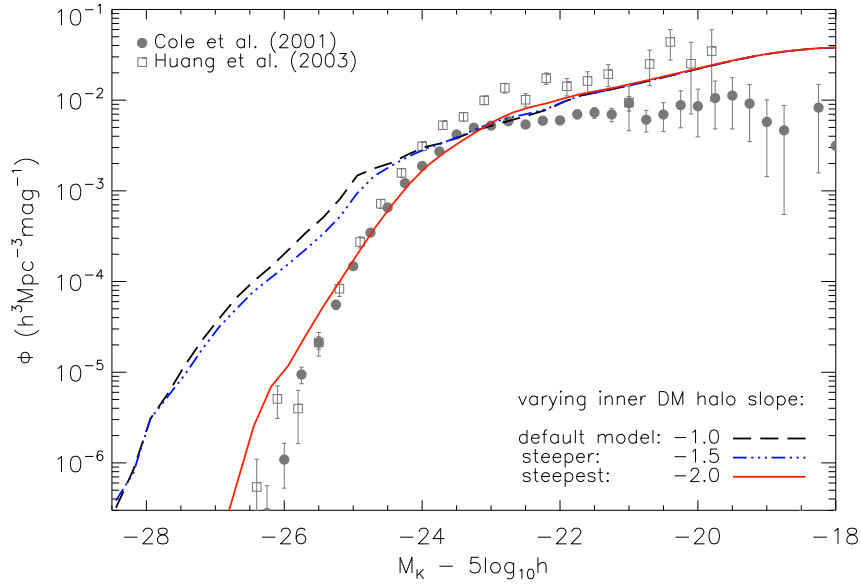


Figure 4. The local K-band galaxy luminosity function, observed (points with error bars), and predictions (lines) for various parameter choices of our annihilation heating model. Here we show the default model of Fig. 14 with $\gamma = -1.0$, and with steepening DM density slopes of $\gamma = -1.5$ and $\gamma = -2.0$, as indicated in the legend. Only spikes in haloes with the steepest inner profiles are able to produce enough heating to obtain a reasonable fit to the observed galaxy luminosity function.

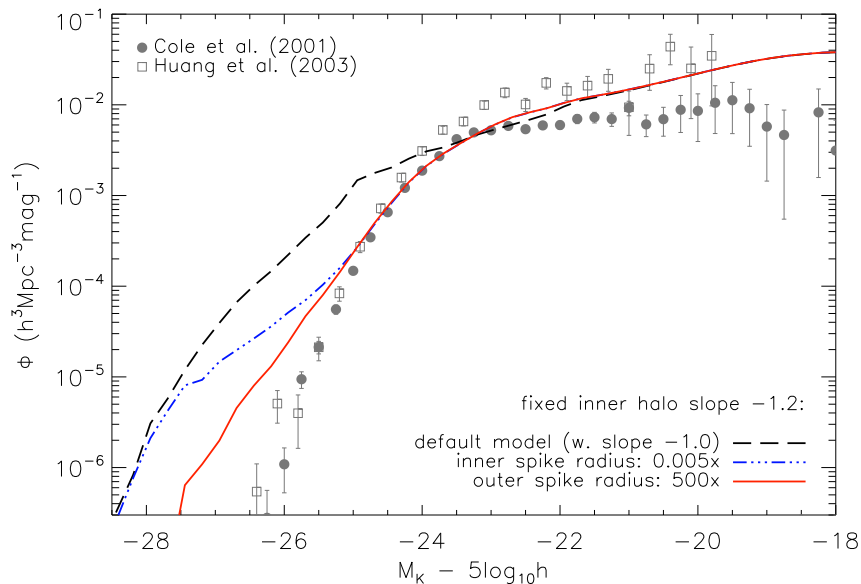


Figure 5. The local K-band galaxy luminosity function, observed (points with error bars), and predictions (lines) for various parameter choices of our annihilation heating model. The default model with inner slope $\gamma = -1.0$ is replotted from Figure 4. For comparison, haloes with an inner slope of $\gamma = -1.2$ and more extreme choices for the inner and outer spike radii are shown, as indicated by the legend.

seen in Fig. 3. Essentially overcooling occurs in the centers of group and cluster systems, leading to excess star formation and overly bright and massive galaxies. Note that this is not necessarily a failure of our underlying galaxy formation model - the cooling flow problem has a long history (see review by Fabian 2004 for details) and failure of the default

heating model is simply another manifestation of it (in the absence of strong enough heating).

The two additional lines in Fig. 4, dotted-dashed and solid, show the galaxy luminosity function when the inner DM halo slope is steepened to $\gamma = -1.5$ and $\gamma = -2.0$, respectively (the default model has -1.0 , the standard NFW

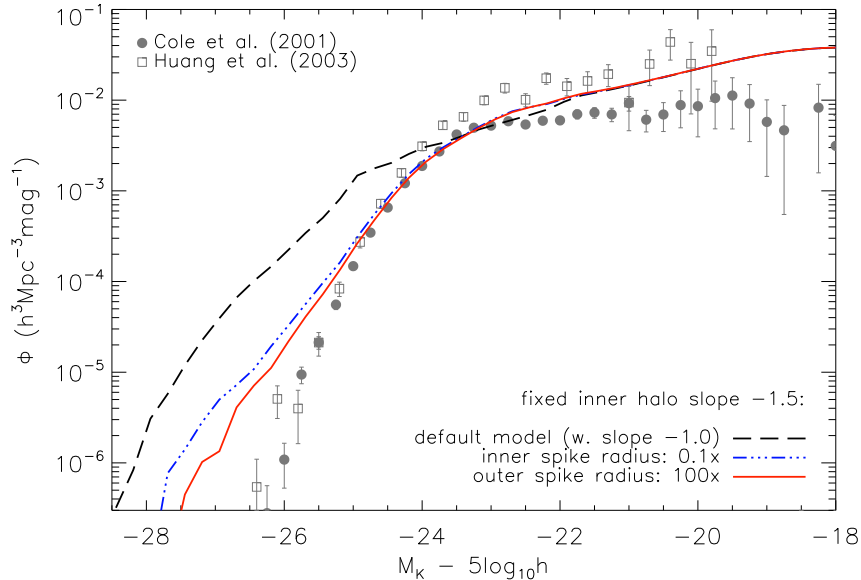


Figure 6. The local K-band galaxy luminosity function, observed (points with error bars), and predictions (lines) for various parameter choices of our annihilation heating model. The default model with inner slope $\gamma = -1.0$ is replotted from Figure 4. For comparison, haloes with an inner slope of $\gamma = -1.5$ and more extreme choices for the inner and outer spike radii are shown, as indicated by the legend.

profile). An inner slope of -1.5 appears to be insufficient to produce enough heating, even with the presence of a central density spike. Only inner halo slopes of ~ -2.0 or steeper are able to do this. In the context of current models such steep slopes do not arise naturally in dark matter haloes. A combination of steepening mechanisms needs to operate in a coordinated fashion to achieve these slopes.

Fig. 5 considers the combination of a steeper inner halo slope, here $\gamma = -1.2$, and more extreme values for the inner and outer spike radii explored previously in Fig. 3. Our choices for the spike radii are made to obtain the correct turnover in the galaxy luminosity function. The required values are, for the inner spike radius 200 times smaller than the default value (dashed-dotted line) and for the outer spike radius 500 times larger than the default value (solid line). Both parameter sets still over predict the abundance of very bright galaxies. This exercise is repeated in Fig. 6 with a more extreme inner slope of $\gamma = -1.5$. The inner and outer spike radii choices that provide the best fit are now 10 times smaller than the default inner spike radius (dashed-dotted line) and 100 times larger than the default outer spike radius (solid line). The brightest galaxies remain overabundant, but less so than for the previous values.

In Figs. 7 & 8 we plot the heating rate and cumulative heating rate respectively generated by dark matter self-annihilation as a function of radius for a galaxy scale halo and a cluster scale halo for various parameter choices. Also marked as arrows for reference in these plots are 3 relevant physical scales: $4 R_S$ (inner-most arrow); the outer spike radius (middle arrow) and the virial radius of the DM halo (outer-most arrow). The plots emphasize that the equations predict that the heating flux comes from well inside the cooling radius. Due to the simplicity of our assumed cooling model (i.e. that the gas is isothermal) it is not possible to

accurately determine the cooling rate as a function of radius inside individual halos for a direct radial comparison of the heating cooling balance. In the context of our simple model as shown we can however calculate the global heating and cooling rates and compare. These plots also show that the heating from self-annihilation akin to other modes of feedback needs to propagate out to larger radii to be effective. The microphysics of these transport processes is poorly understood at this point.

We conclude that for modest parameter choices we are unable to produce galaxies that match observed ones. Of course, further combinations of these parameters are possible, however, it is unlikely that self-annihilation is the sole feedback process in galaxy formation. It is plausible that this process operates in addition to supernovae and AGN feedback.

6 OBSERVATIONAL SIGNATURES OF DM ANNIHILATIONS

If indeed neutralino self-annihilations contribute to the energetics of feedback in galaxies and clusters as proposed here, we can expect a range of observational signatures.

6.1 Distribution of density profile slopes

If the model of annihilation heating developed here operates, we expect the existence of a range of inner dark matter density profile slopes in the centres of galaxies and galaxy clusters. The time evolution explored in this model suggests that the inner density slopes on the scale of tens of parsecs in galaxies are likely to be diverse.

Observationally, this is an extremely challenging length

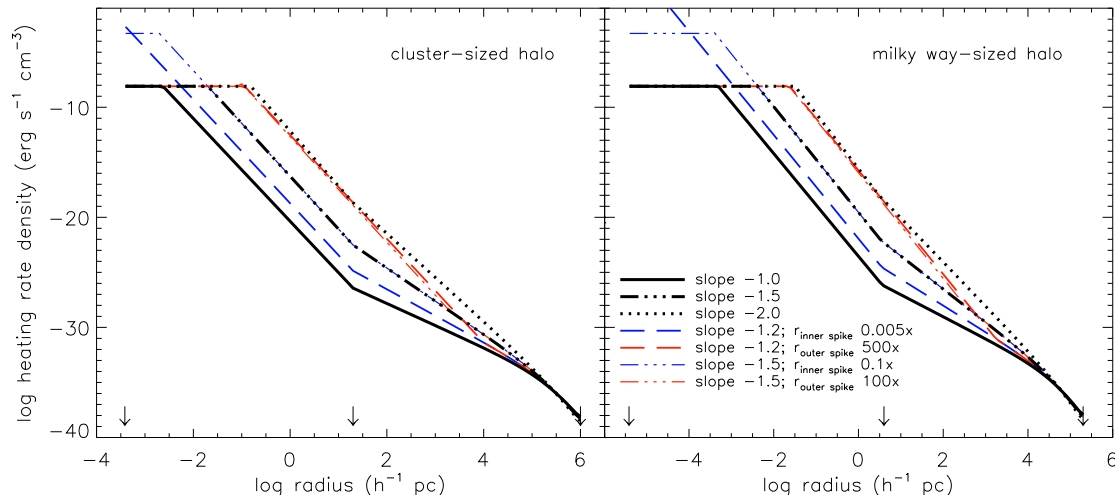


Figure 7. The dark matter heating rate density profile for the various heating models explored in Figures 4 to 6, for both cluster-sized and Milky Way-sized haloes (left and right panels). The three arrows near the bottom of each panel indicate the boundaries of 4 times the Schwarzschild radius, the outer spike radius, and the virial radius of the DM halo, from left to right in each respectively (see Section 3). The spike is clearly noticeable as the inner steepening part of the profile, while the flattening seen on small scales marks the saturation of the heating due to DM self annihilation.

scale to probe and detect this diversity. Studies of the velocity dispersion profiles of the stellar component in the vicinity of the black holes combined with strong lensing offer a potentially viable probe.

Mapping of rotation curves has also provided constraints on the density profile of the dark matter in the central regions of galaxies, (see de Blok, McGaugh & Rubin and references therein) however on much larger scales, of the order of kpc, whereas the DM annihilation scenario leaves an imprint on much smaller scales.

It does appear on that on kpc scales (larger scales than relevant for dark matter self-annihilations) there is compelling evidence for bimodality in the distribution of light (baryons). The NUKER group has studied this effect extensively using Hubble Space Telescope data (Gebhardt et al. 1996; Faber et al. 1997; Lauer et al. 2002). In a recent paper, combining several HST investigations on the central structure of early-type galaxies they find that the distribution of the logarithmic slopes of the central brightness profiles is bimodal (Lauer et al. 2007). They claim that at the HST resolution limit, most galaxies are either power-law systems, which have steep cusps in surface brightness, or core systems, which have shallow cusps interior to a steeper envelope in the brightness distribution. There is a strong correlation between the luminosity L and inner profile slope, and it has been suggested that this correlation is likely due to core formation by binary BHs during mergers (Ferrarese et al. 2006). Whether and how this observed bimodality in the surface brightness profiles of the baryonic component reflects the dark matter density profile on the smallest scales is unclear at the present.

The physical scale on which dark matter annihilation manifests itself in the case of clusters is predicted to be of the order of \sim kpc (as shown in the bottom right hand panel of Figure 3). In this context, we predict that similarly in clusters there ought to be a diversity of density profile slopes

on kpc scales. In clusters that have more complex dynamical histories, the dark matter spike is likely to have been disrupted progressively due to frequent mergers and these density spikes are also expected to have depleted from the annihilation process itself as a result. These growing clusters are systems in which the spike reassembly is most unlikely to occur rapidly. In the context of the self-annihilation feedback picture, these clusters are likely to have density profiles with a central plateau (akin to the evolution shown in Figure 1). Since clusters are the most recently assembled structures in the Universe, we predict a range of inner density slopes in the central few kpc, some shallower than the predictions of dissipationless simulations and some steeper, depending on their dynamical history. Dynamical history coupled with the modification produced due to the presence of the baryonic component (stars or black holes) is intricately coupled to the process of DM annihilation as we have shown, and the interplay of these process might dictate the slope of the dark matter density profile in the inner-most regions.

Observationally, the issue is once again challenging. Strong lensing studies of the inner regions of clusters with radial and tangential arcs point to the possible existence of shallower density slopes and perhaps cores on scales of $\sim 5 - 10$ kpc. This is of the order of the scales on which we expect to see signatures of the annihilation process. Since strong lensing constrains the total mass as a function of radius, disentangling the effect of the baryons to infer the density profile of the dark matter alone on these scales is difficult. The combination of gravitational lensing and dynamical data is uniquely capable of achieving this. Sand et al. (2002; 2004) attempted this for a sample of strong lensing clusters. In more recent work, Sand et al. (2008) study 2 clusters Abell 383 and MS2137-23 combining strong lensing constraints with stellar velocity dispersion data for the brightest central cluster galaxy. They find that a shallower inner slope is preferred compared to predictions from simu-

lations ($\gamma \sim -0.6$) for Abell 383 for a coarse lensing model. For MS2137-23, no self-consistent model that incorporates strong lensing and the stellar velocity dispersion data was found to be a good fit. We also note that constraints derived from recent Chandra observations also suggest shallow inner slopes ($\gamma \sim -1$) on scales of $\sim 5 - 10$ kpc (Vikhlinin et al. 2006; Zappacosta et al. 2006; Voigt & Fabian 2006). It is however a real challenge to extract robust constraints on the density profile slope at these small radii from observations. Meanwhile, simulations that incorporate baryons are likely to improve in resolution in the near future and might offer a powerful test of our predictions.

7 COMPARISON WITH THE AGN HEATING PARADIGM

In this section we discuss the details of the AGN heating paradigm in order to contrast with our dark matter annihilation model. We describe the mechanism and argue that there is a need for additional sources of feedback that dark matter self-annihilations may well provide.

The proposed physical mechanisms for AGN driven feedback are expected to occur in two modes: the ‘quasar mode’, where mergers trigger fuelling to central black holes activating an episodic, bright quasar phase accompanied by large-scale outflows (Di Matteo et al. 2005; Hopkins et al. reference), and the ‘radio mode’, which refers to steady feedback from low-level AGN activity (Croton et al. 2006; Bower et al. 2006). The need for these processes arise from the over-cooling problem that occurs on a range of mass scales, from galaxy groups to clusters (Somerville & Primack 1999; Cole et al. 2001; Kauffmann et al. 1999; Benson et al. 2003).

AGN feedback in the quasar mode likely occurs during the epochs of efficient cold gas feeding to the central black holes via a thin accretion disk, at high accretion rates ranging between $0.1 - 1 L_{\text{Edd}}$. This phase is short-lived and the thermal coupling of AGN energy is fairly weak (at $< 5\%$ level). In this mode the AGN-driven wind removes residual gas at the end of the merger, leading to suppression of subsequent star formation and self-regulated BH growth that reproduces the observed $M_{\text{bh}} - \sigma$ relation (Springel et al. 2005). However, for a typical massive galaxy in the local Universe a quasar event was long ago in its history. Such galaxies instead host BHs that are accreting at much lower rates; in fact most spend much of their lifetime in these radiatively inefficient states. Radio activity is associated with these low accretion rate states and radio jets are seen in many massive galaxies. The coupling of jet energy with host gas can be very efficient and models of effervescent heating with a combination of sound waves, weak shocks and bubbles can heat a large fraction of the gas in clusters (Ruszkowski et al. 2004; Churazov et al. 2001; Bruggen et al. 2005) and produce features that match X-ray observations (Fabian et al. 2005).

A detailed exploration of the theoretical consequences of the steady radio-mode feedback from low luminosity AGN has been presented in Croton et al. (2006). This was done using the same semi-analytic model used in this paper, but with DM annihilation heating replaced with radio-mode heating. The authors of Croton et al. showed that for a set of energetically and observationally plausible param-

eters such a model could simultaneously explain: (i) the low observed mass drop-out rate in cooling flows; (ii) the exponential cut-off at the bright end of the galaxy luminosity function; and (iii) the fact that the most massive galaxies tend to be bulge-dominated systems in clusters and found to contain systematically older stars than lower mass galaxies.

In a recent paper Best et al. (2007) study a sample of radio-loud AGN in nearby groups and clusters from the Sloan Digital Sky Survey (SDSS). Using observational estimates of the mechanical output of radio jets, they estimate the time-averaged heating rate associated with recurrent radio source activity for all group and cluster galaxies. They find that within the cooling radius the radio-mode heating associated with galaxy groups and low mass clusters is sufficient to offset the cooling flow from the extended hot halo. In the most massive brightest cluster galaxy systems, however, radio mode heating alone is not enough. They conclude that other processes acting in massive clusters must also be contributing to the suppression of cooling flow gas.

Importantly for this work, although AGN appear to be making an observable contribution to the evolution of gas dynamics in dark matter haloes, alone they only comprise part of the full physical picture. The presence of SMBHs at the centres of massive systems that drive AGN winds also provide enhancement in the annihilation rate of DM that, under the right circumstances, can produce sufficient heating flux to arrest cooling gas. Composite DM annihilation and AGN heating models will be a natural extension of our work and there is need for all feedback mechanisms to be better understood. One of the current challenges for all models including the self-annihilation proposed here is developing a better understanding of the micro-physics of how to thermally couple to the gas at all radii where the heating and cooling are required to balance for feedback to be effective.

8 SUMMARY

Using the Millennium Run N-body simulation coupled with a sophisticated model of galaxy formation that includes the heating of cooling flow gas through neutralino annihilation, we have shown that:

- Density spikes that support the annihilation flux at the levels required to offset cooling flows are stable enough over long enough time-scales to maintain a reasonably constant heating source (Fig. 2).
- Models that appear to be extreme at the present time (given our current understanding of DM density profiles) are required to produce enough heating flux to offset the predicted cooling rates. To obtain the required heating rates we either need to steepen the inner DM density slope to values $\gamma > 1.5$ or increase the outer spike radius. For galaxy sized haloes the outer spike radius is required to be of the order of $\sim 25 r_{\text{bh}}$, and for cluster haloes $\sim 60 r_{\text{bh}}$ (Fig. 3 and 4).
- The efficiency of heating in the DM annihilation model scales with halo mass (and circular velocity), therefore this mechanism does provide preferential suppression of star formation in more massive haloes as required to explain current observations of the luminosity function (Fig. 3).

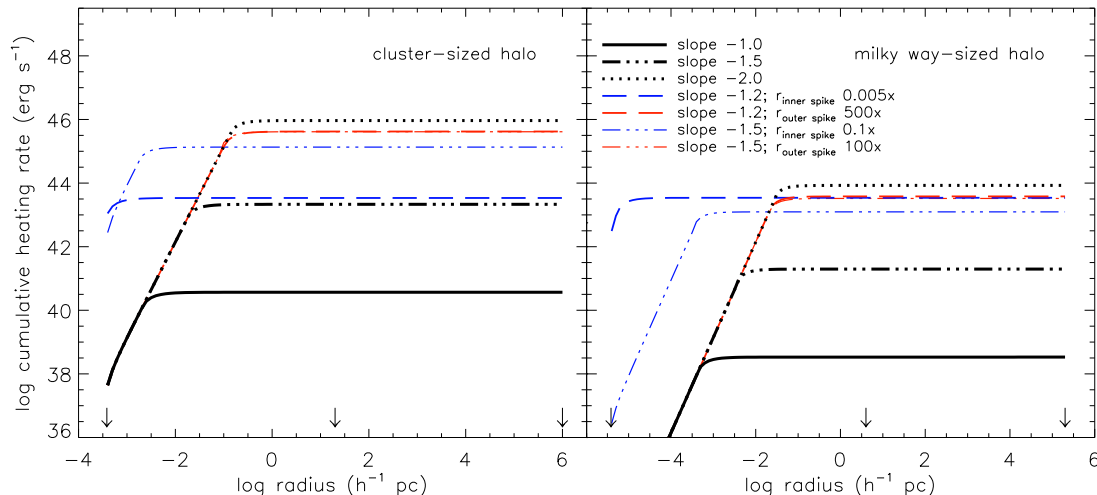


Figure 8. The cumulative heating rate as a function of increasing radius for the various spike density profiles shown in Figure 7 and used in Figures 4 to 6. In both panels, for cluster-sized haloes on the left and Milky Way-sized on the right, the three lower arrows indicate the boundaries of 4 times the Schwarzschild radius, the outer spike radius, and the virial radius of the DM halo, from left to right in each respectively (see Section 3). For all models the majority of the annihilation flux originates from well inside the central most parts of the halo.

In this treatment, we have assumed that the mass of central black holes grows significantly at each merger (as the solution for adiabatic growth is valid only in the limit $M_{\text{bh,initial}} \ll M_{\text{bh,final}}$). We note here that an alternative source of annihilations may be provided by minispikes around inter-mediate mass black holes as suggested by Bertone, Zentner & Silk (2005).

It is clear that feedback and energy injected into the inter-stellar medium of galaxies and the intra-cluster medium is a complex process, and that a combination of astrophysical processes, including the one explored here, are likely at play. One of the key uncertainties in the model explored in this paper arises from the fact that we lack an understanding of the physics through which the annihilation flux is expected to couple with the cooling hot halo gas. While we have discussed some possibilities, like coulomb collisions, brehmstrahlung and synchrotron radiation. Colafrancesco et al. (2007) have explored these in more detail for the case of the heating of gas in the Coma cluster due to DM annihilations. Experimental confirmation of supersymmetry from the LHC at CERN might throw new light on the viability and likely couplings for the neutralino. Additionally while following the cumulative heating history is very challenging to do it is needed to really understand the detailed energetics of the gas. There is incontrovertible evidence for the presence of copious amounts of DM on all scales in the Universe, so DM annihilation is an inescapable phenomenon. However, how much energy is released in the process and how efficiently it couples to the baryonic component are unclear.

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Consequences of dark matter self-annihilation for galaxy formation

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ABSTRACT

Galaxy formation requires a process that continually heats gas and quenches star formation in order to reproduce the observed shape of the luminosity function of bright galaxies. To accomplish this, current models invoke heating from supernovae, and energy injection from active galactic nuclei. However, observations of radio-loud active galactic nuclei suggest that their feedback is likely to not be as efficient as required, signaling the need for additional heating processes. We propose the self-annihilation of weakly interacting massive particles that constitute dark matter as a steady source of heating. In this paper, we explore the circumstances under which this process may provide the required energy input. To do so, dark matter annihilations are incorporated into a galaxy formation model within the Millennium cosmological simulation. Energy input from self-annihilation can compensate for **all** the required gas cooling and reproduce the observed galaxy luminosity function only for what appear to be extreme values of the relevant key parameters. The key parameters are: the slope of the inner density profile of dark matter haloes and the outer spike radius. The inner density profile needs to be steepened to slopes of -1.5 or more and the outer spike radius needs to extend to a few tens of parsecs on galaxy scales and a kpc or so on cluster scales. If neutralinos or any thermal relic WIMP with s-wave annihilation constitute dark matter, their self-annihilation is inevitable and could provide enough power to modulate galaxy formation. Energy from self-annihilating neutralinos could be yet another piece of the feedback puzzle along with supernovae and active galactic nuclei.

Key words: dark matter – stars: evolution – accretion – early Universe

1 INTRODUCTION

A major challenge to our current understanding of structure and galaxy formation in the Universe is the discrepancy between the theoretically predicted mass function of dark matter haloes and the observed shape of the luminosity function of galaxies (Kauffmann & White 1993; Cole et al. 1994; Somerville, Primack & Faber 2001; Benson et al. 2003). Simply put, the number density of dark matter haloes falls off as a power-law at high masses, whereas the luminosity function of galaxies occupying such haloes terminates exponentially above a characteristic luminosity (e.g. Cole et al. 2001; Huang et al. 2003). This implies that the supply of gas to a galaxy and the conversion of this gas into stars becomes preferentially inefficient in more massive systems (White & Rees 1978). A key issue for galaxy formation theory is thus to illuminate the physical processes that heat and cool gas in massive galaxies as this cycle regulates the formation of new

stars. In addition, one of the challenges for galaxy formation is to unravel the inter-play of baryons with the ubiquitous dark matter in galaxies.

To this end, feedback processes operating in galaxies at both the low and high-mass ends of the halo mass function are required to explain the faint and bright-end slopes of the observed galaxy luminosity function. Energy input from supernovae is thought to play a significant role in the regulation of star formation in low mass galaxies (Dekel & Silk 1986; Mac Low & Ferrara 1999), however the supernova energy injected in high mass galaxies is too small to suppress gas cooling effectively. For such objects, to reconcile theory with observations a more energetic process that continually heats the gas and operates independently of star formation appears to be required (Croton et al. 2006; Bower et al. 2006).

Recent observations in nearby galaxies reveal a corre-

lation between the masses of supermassive black holes and the velocity dispersion of the stellar component. This suggests that black holes might play a role in regulating star formation (Magorrian et al. 1998; Tremaine et al. 2002; Ferrarese & Merritt 2002). Energy input from nuclear outflows driven by accreting black holes are currently favoured as the principal source of feedback driving the truncation of star formation in massive galaxies (Di Matteo et al. 2005; Croton et al. 2006; Bower et al. 2006). Unlike supernovae feedback, the observed energy output from Active Galactic Nuclei (AGN) can far exceed that liberated from cooling gas in the hot halo. AGN heating in two distinct forms has been proposed. Episodic feedback from the AGN via outflows generated during the merger process have been proposed by Di Matteo et al. (2005); Sijacki & Springel (2006), the so-called ‘quasar-mode’. However, it is known that AGN spend most of their lifetimes in a low accretion rate state, and therefore Croton et al. (2006) and Bower et al. (2006) argue for a more steady, so called ‘radio-mode’ feedback that is long-lived. The details of both these processes are complex and the micro-physics is currently not well understood.

Here, we focus on an alternative heating mechanism, the energy steadily generated by the self-annihilation of dark matter particles in the inner regions of haloes. Although the standard cosmological paradigm is predicated on the existence of non-baryonic dark matter (DM) particles, the precise nature of these particles and their interactions remain a puzzle. The neutralino is the current leading dark matter candidate. In this paper we explore if the energy supplied from the self-annihilation of dark matter in the centres of galaxies and cluster haloes could possibly play a significant role in the baryonic cooling/heating cycle (Ascasibar 2007; Totani 2004; 2005; Colafrancesco et al. 2006). Detailed astrophysical implications of neutralino dark matter annihilations in galaxy clusters, with a specific application to the Coma cluster have been calculated by Colafrancesco, Profumo & Ullio (2006). They performed a thorough analysis of the transport and diffusion properties of neutralino annihilation products, and investigated the resulting multi-frequency signals, from radio to gamma-ray frequencies. They also study other relevant astrophysical effects of neutralino annihilations, like the DM-induced Sunyaev-Zel’dovich effect and the intracluster gas heating.

Annihilation luminosity is expected to be produced as a result of an enhancement in the density of the dark matter distribution in the inner-most regions of galaxies, due to the response of the dark matter to the adiabatic growth of a central black hole (Gondolo & Silk 1999) and/or to the adiabatic compression suffered by the dark matter due to the collapse of baryons into the dark matter potential well (Blumenthal et al. 1986; Ryden & Gunn 1987; Gnedin et al. 2004). By including this steady heating source of annihilating neutralinos to suppress cooling flow gas in a sophisticated model of galaxy formation, we explore the effect of various key parameters in reproducing the bright-end of the observed galaxy luminosity function. The question we address is whether self-annihilation can provide an alternative mechanism to AGN driven feedback within the context of the current paradigm.

The outline of this paper is as follows. In Section 2 we discuss the physics of neutralino annihilation; a scenario for the coupling of this energy source to baryons in galactic nu-

clei is explored in Section 3. With this phenomenology developed, we incorporate this feedback scheme into a galaxy formation model. The details of the N-body simulation and galaxy formation model used in this implementation are discussed in Section 4. Our results are presented in detail in Section 5 and summarized in Section 6. We conclude with a discussion of the implications of our results and comparison of annihilation heating with other modes of feedback. Unless otherwise stated we assume Hubble constant parametrised as $H_0 = h 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ with $h = 0.73$.

2 DARK MATTER CANDIDATES

Theoretical predictions of structure formation and evolution in a Cold Dark Matter (CDM) cosmogony appear to be in very good agreement with current observations on most scales bar perhaps the smallest (Spergel et al. 2006; Tegmark et al. 2004; Seljak et al. 2005; Cole et al. 2005). In this well established paradigm, the bulk of the matter in the Universe is comprised of cold, collisionless particles that seed the formation of structures from the gravitational amplification of their early fluctuations (Blumenthal et al. 1984; Davis, Efstathiou, Frenk & White 1985).

Weakly Interacting Massive Particles (WIMPs) are the currently favoured dark matter candidates as their cross-sections are small enough that they act as essentially collisionless particles (Kolb & Turner 1990). The super-symmetric *neutralino*, arising in minimal super-symmetric extensions of the Standard Model of particle physics, is probably the most widely studied WIMP candidate (see review by Jungman, Kamionkowski & Griest 1996 and references therein). In the Minimal Super-symmetric Standard Model (MSSM), the super-partners of the gauge bosons and the neutral Higgs bosons, respectively called binos and higgsinos, mix into four Majorana fermionic mass eigenstates, called neutralinos. In some regions of the super-symmetric parameter space, the lightest neutralino can naturally achieve a relic density that matches the observed cosmic DM abundance, thus making it a theoretically well motivated DM candidate. The neutralino mass can be anywhere between $\approx 50 \text{ GeV}$, which is the lower bound allowed by accelerator constraints (Eidelman et al. 2006, see *ibidem* for the set of assumptions made on the underlying super-symmetric scenario), up to 100 TeV in some extreme non-perturbative scenarios (Profumo 2005), although masses larger than a few TeV are commonly considered as “unnatural”, if one wants SUSY to solve the theoretical problems (such as the hierarchy problem) for which it was originally invented.

An interesting alternative candidate arises in theories with Universal Extra Dimensions (UED), and corresponds to the first Kaluza-Klein state of the hypercharge gauge boson (Appelquist, Cheng and Dobrescu, 2002; Servant and Tait 2000). The existence of a viable dark matter candidate in UED theories can be seen as a consequence of the conservation of momentum in a higher dimensional space. To generate chiral fermions at the zero mode, the extra dimensions must be modded out by an orbifold, leading to the conservation of the so-called KK-parity, such that all odd-level KK particles are charged under this symmetry, thus ensuring that the lightest (first level) KK state is stable.

A lower bound on the mass of the lightest Kaluza-Klein particle (LKP) comes from electroweak measurements, and depending on the mass of the Higgs, it can be as low as ≈ 300 GeV (Gogoladze and Macesanu 2006). Although the annihilation cross section in these scenarios is fixed by the LKP mass, it is possible to achieve the correct relic density even for particles as heavy as several TeV, provided that one includes the effect of co-annihilation with other KK particles (Burnell & Kribs 2006, Kong & Matchev 2006, Kakizaki et al. 2006). We note that the arguments presented here are valid more generally for any thermal relic WIMP candidate with s-wave annihilation.

Regardless of its precise nature, it is possible to set cosmological constraints on the WIMP mass m_χ under some simplifying, but rather general assumptions on its nature. The WIMP mass is in fact constrained to be roughly $m_\chi \gtrsim 30$ GeV and $m_\chi \lesssim 10$ TeV, by theoretical considerations of the thermal freeze-out in the early Universe (e.g. Bertone, Hooper and Silk 2005). The very same theoretical considerations suggest that the WIMP annihilation rate in the local Universe is far below the expansion rate of the Universe. However, annihilations proceed in high density DM regions, such as the centres of DM haloes. We demonstrate in this work that this resultant annihilation luminosity could play an important role in galaxy formation by providing a strong source of feedback which prevents gas from cooling and forming stars in galaxies. WIMP pair annihilation in high DM density regions will inevitably produce high energy neutrinos, positrons, anti-protons and gamma-rays. There are several on-going and future experiments focused on direct and indirect searches for the signature of neutralinos (see reviews by Bergstrom 2002; Bertone, Hooper & Silk 2004). In this paper we focus on GeV mass-scale WIMPs, however for illustration purposes we also calculate the consequence of heating by MeV DM.

3 THE SELF-ANNIHILATION LUMINOSITY IN A SIMPLE THEORETICAL MODEL

Here we describe the key ingredients of the simple theoretical model constructed to estimate the self-annihilation luminosity of DM in the centres of galaxy and cluster scale haloes. In the concordance Λ CDM cosmology the thermally averaged annihilation rate of WIMPs, in absence of co-annihilations, is related to the DM relic density by $\langle\sigma v\rangle \sim 3 \times 10^{-27} / \Omega_\chi h^2 \text{ cm}^3 \text{ s}^{-1}$. From this expression one can estimate the annihilation luminosity from neutralinos in a halo with a given density profile (assuming they constitute all the dark matter):

$$L_{\chi\chi} = \frac{\langle\sigma v\rangle}{2m_\chi} \int_V \rho_\chi^2(\vec{x}, t) d^3x, \quad (1)$$

where the integral is performed over the halo volume V , m_χ is the WIMP mass, and $\rho_\chi(\vec{x}, t) \approx \rho_\chi(r, t)$ is the dark matter density profile, commonly assumed to be spherically-symmetric, making it only dependent on the galactocentric radial coordinate r .

3.1 The global dark matter halo profile

The density profile of a dark matter haloes that assemble in cosmological N-body simulations is well fit by the following parametrised functional form, referred to as the generalised Navarro-Frenk-White (NFW) profile (Navarro, Frenk & White 1996):

$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}, \quad (2)$$

where α , β , and γ govern the slope of the profile on large and small scales respectively, with a transition in slope at the scale radius r_s , defined as the ratio of the virial radius of the DM halo, R_{vir} , and the virial concentration parameter, c_{vir} :

$$r_s = \frac{R_{\text{vir}}}{c_{\text{vir}}}. \quad (3)$$

In this paper we only consider profiles for which the outer slope is -3 , i.e. where $(\beta - \gamma)/\alpha = 2$. This leads to the following expression for the normalisation constant, ρ_0 ,

$$\rho_0 = \frac{M_{\text{vir}}}{4\pi \int_0^{R_{\text{vir}}} \frac{r^2}{(r/r_s)^\gamma (1+r/r_s)^{3-\gamma}} dr}, \quad (4)$$

where M_{vir} is the virial mass of the system.

The slope of the density profile in the inner regions of the halo γ is of interest for our work. A value of $\gamma = 1$ refers to the NFW profile, while $\gamma = 1.5$ corresponds to the so-called Moore profile (Moore et al. 1999). Note that eqn. (2) is a fit to the output of numerical simulations which do not include either particle physics and hydrodynamic effects. Such effects may alter the distribution of DM over time. The consequences of this possibility are discussed in the next section. In fact, it is the time evolution of the density profile that holds the key to possibly tapping the energy from the neutralino self-annihilation. We briefly note here that for a cluster scale DM halo, with typical virial mass $10^{14-15} M_\odot$, the luminosity generated from eqn. (1) with central density profile $\gamma=1-1.5$ is, at most, of order $10^{39} \text{ ergs}^{-1}$. Thus, even if this entire energy output coupled maximally to the cooling gas in the inner regions it would be insufficient to offset the cooling luminosity (of order $\sim 10^{42-44} \text{ ergs}^{-1}$) in a typical cluster system (Totani 2004; 2005). Physical processes that further steepen the inner density profile slope are therefore required to make the annihilation viable as a feedback mechanism. Fortunately, several astrophysical processes in the centres of dark matter haloes are expected to affect the density profile of DM in precisely the required fashion.

3.2 The formation of a central density spike

3.2.1 Steepening due to adiabatic response to collapsing baryons

Density enhancements can arise in the inner regions of dark matter haloes from a number of different astrophysical processes. One such process is the adiabatic response of the dark matter to the infall and collapse of baryons (Blumenthal, Flores & Primack 1986; Ryden & Gunn 1987; Gnedin et al. 2004). Baryonic gas loses energy through radiative processes and falls into the centre of a dark matter halo to form stars. As a result of this redistribution of mass, the gravitational potential of the inner regions of the halo changes. The dark

matter responds to the subsequent deepening of the potential by altering its distribution and thereby enhancing its density. The increase in dark matter density from adiabatic compression can be calculated using adiabatic invariants. The cusp index γ in the NFW profile of eqn. (2) steepens to a value that depends on the density profile of the baryons.

Earlier calculations by Blumenthal et al. (1986) over-predicted the steepening due to the assumptions of spherical symmetry and circular orbits. This was due, in part, to the fact that haloes in the hierarchical structure formation scenarios grow via multiple violent mergers and accretion along filaments, and particle orbits in the haloes are highly eccentric. Gnedin et al. (2004) revisited this question using high-resolution cosmological simulations that included gas dynamics, radiative cooling, and star formation. They found that the dissipation of gas indeed increased the density of dark matter and steepened its radial profile in the inner parts of the halo when compared with haloes without cooling. Comparisons with the earlier work of Blumenthal et al. (1986) showed that the assumption of spherical symmetry induces a systematic over-prediction of the density enhancement in the inner 5% of the virial radius. Gnedin et al. (2004) correct for this by providing a simple modification of the assumed adiabatic invariant which includes orbit-averaged particle positions.

If the baryons have a radial density profile $\rho_b(r) \propto r^{-\nu}$, then the spike (i) retains the same slope if $\nu = 1$; (ii) or if $\nu > 1$, the contracted inner slope of the DM profile is steeper than its original value. For $\nu = 1 - 2$, the final inner DM density slope can be as steep as $\gamma = 1 - 1.7$, respectively. In cluster sized systems, although baryons represent only a small fraction of the overall mass, they may be crucially important on scales comparable to the extent of the typical brightest, central cluster galaxies.

There has been a lot of recent activity in the simulations community to understand the likely interactions between baryons and dark matter (Gnedin et al. 2004; Nagai & Kravtsov 2005; Faltenbacher et al. 2005; Gustafsson, Fairbairn & Sommer-Larsen 2006). For instance, in a recent simulation that included baryons, Gustafsson, Fairbairn and Sommer-Larsen (2006) claim that the central DM cusps steepen to $\rho \sim r^{-1.9 \pm 0.2}$, with an indication of the inner logarithmic slope converging on galaxy mass scales. Gustafsson et al. (2006) claim that the difference in the extent of adiabatic contraction and subsequent response they find compared to Gnedin et al. (2004) and other works originates in the differences in their stellar feedback prescription. So the extent of steepening due to adiabatic response is an unsettled issue at the present time due to the inherent uncertainty in the our understanding and implementation of star formation in simulations. On the observational side there have also been many recent attempts to disentangle the dark matter and baryonic components in clusters (Zappacosta et al. 2006; Biviano & Salucci 2006; Mahdavi et al. 2007; Sand et al. 2007).

Extensive convergence studies have shown that modern highest resolution dissipationless simulations agree in their predictions: the average logarithmic slope of the density profile at $r = 0.01 R_{\text{vir}}$ is $\gamma = 1.3$, with a substantial scatter of ± 0.3 from object to object (Fukushige et al. 2004; Tatsiomi et al. 2004; Navarro et al. 2004; Reed et al. 2004; Diemand et al. 2004; 2005). At the same time, despite a sig-

nificant decrease in the smallest reliably resolved scale, the logarithmic slope continues to get shallower with decreasing radius without reaching an asymptotic value. For the purposes of this work, for our default model we will assume a conservative value for the inner slope of the density profile of $\gamma = 1.0$, which is the standard NFW value commonly used.

3.2.2 Steepening due to adiabatic growth of central black holes

On extremely small scales ($r < 1\text{pc}$), i.e. at the very centre of the galaxy hosted by a DM halo, the gravitational potential is dominated not by DM (as described by eqn. 2) but by baryons, mainly comprising stars and frequently a supermassive black hole (SMBH). In fact, from the demography of nearby galaxies it appears that nearly every galaxy hosts a SMBH, and their masses are well correlated with properties of the stellar component in the inner-most regions (Magorrian et al. 1998; Tremaine et al. 2002; Ferrarese & Merritt 2002). In our own Galaxy, for instance, stars exhibit a cusp inside a few parsecs described by (Genzel et al. 2003):

$$\rho_*(r) \sim 3.2 \times 10^5 M_{\odot} \text{pc}^{-3} \left(\frac{r}{1\text{pc}} \right)^{-1.4}. \quad (5)$$

This distribution is centred around the supermassive black hole at the Galactic centre, whose mass is estimated to lie in the range $2 - 4 \times 10^6 M_{\odot}$ (Ghez et al. 2005; Genzel et al. 2003b).

In fact, Hooper, Finkbeiner & Dobler (2007) claim that the excess microwave emission from the region around the center of our Galaxy detected by WMAP (Wilkinson Microwave Anisotropy Probe) could be synchrotron emission from relativistic electrons and positrons generated in dark matter annihilations. Hooper et al. (2007) find that the angular distribution of this ‘‘WMAP Haze’’ matches the prediction for dark matter annihilations with a cusped density profile, $\rho(r) \propto r^{-1.2}$ in the inner few kiloparsecs. Comparing the intensity in different WMAP frequency bands, they find that a wide range of possible WIMP annihilation modes are consistent with the spectrum of the haze for a WIMP with a mass in the 100 GeV to multi-TeV range. Most interestingly, they find that to generate the observed intensity of the haze, the dark matter annihilation cross section is required to be approximately equal to the value needed for a thermal relic, $\sigma v \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$.

More generally, the *adiabatic* growth of a massive object at the centre of a power-law distribution of DM with index γ induces a redistribution of the DM (also referred to as a density ‘spike’), into a new power-law with a steepened index γ_{spike} (Peebles 1972, Young 1980, Ipser & Sikivie 1987, Quinlan et al. 1995, Gondolo & Silk 1999).

$$\rho_{\text{spike}}(r) = \rho(r_{\text{outer spike}}) \left(\frac{r}{r_{\text{outer spike}}} \right)^{-\gamma_{\text{spike}}}, \quad (6)$$

where

$$\gamma_{\text{spike}} = 2 + \frac{1}{4 - \gamma}, \quad (7)$$

and the outer spike radius is approximated by

$$r_{\text{outer spike}} \approx r_{\text{bh}} \equiv 0.2 \frac{G M_{\text{bh}}}{\sigma^2}, \quad (8)$$

where r_{bh} is the gravitational radius of influence of the black

hole (Merritt & Szell 2006). The density $\rho(r_{\text{outer spike}})$ is found by evaluating eqn. 2 at the outer spike radius. For the Milky Way, $r_{\text{bh}} \approx 1\text{pc}$.

A physical cut-off to the otherwise diverging profiles of eqn. (2) and eqn. (6) at small r is provided by the self-annihilation rate itself. We can define a limiting radius, r_{lim} , where the density reaches a maximal value given by

$$\rho_{\text{spike}}(r_{\text{lim}}) = \frac{m_\chi}{\langle \sigma v \rangle t_{\text{spike}}}, \quad (9)$$

where t_{spike} is the lifetime of the density spike (see below). This limiting radius r_{lim} can then be found by equating and solving eqn. (9) and eqn. (6) simultaneously. In reality, the inner cut-off radius cannot be arbitrarily small. Hence, we truncate the inner annihilation luminosity at

$$r_{\text{inner spike}} = \text{Max} [4R_S, r_{\text{lim}}], \quad (10)$$

where R_S is the Schwarzschild radius of the SMBH, $R_S = G M_{\text{bh}}/c^2$. This defines the inner spike radius, $r_{\text{inner spike}}$.

3.3 Density spike evolution and enhanced annihilation luminosity

In order to understand the time evolution of a DM density spike, we note that once the spike is established several astrophysical and particle physics effects act to disrupt it. The three principal effects that can damp a density spike are: (i) the self-annihilation process itself that depletes DM (discussed above), (ii) the interaction between the DM and the surrounding baryons near the SMBH, and (iii) spike disruption during galaxy (or more specifically black hole) mergers.

DM and baryons interact gravitationally with each other, and stars typically have significantly larger kinetic energies than DM particles. Gravitational encounters between these two populations will tend to drive them toward equipartition of energy, causing the DM to heat up, flattening the spike while retaining the shape of the density profile. As shown by Bertone & Merritt (2005), the resultant spike evolution with time can be modelled as an exponential decay via

$$\rho_{\text{spike}}(r, t) = \rho_{\text{spike}}(r, 0) e^{-\tau/2}, \quad (11)$$

and

$$r_{\text{outer spike}}(t) = r_{\text{spike}}(0) e^{(-\tau/2)/(\gamma_{\text{spike}} - \gamma)}, \quad (12)$$

where τ is the time elapsed since the original spike formation t_{spike} measured in units of the heating time T_{heat} ,

$$T_{\text{heat}} = 1.67 \times 10^9 \text{ yr} \left(\frac{M_{\text{bh}}}{4 \times 10^6 M_\odot} \right)^{1/2} \left(\frac{r_{\text{bh}}}{2\text{pc}} \right)^{3/2}. \quad (13)$$

We show results for the time evolution of a fiducial spike in at the centre of our Galaxy in Figure 1 and discuss the issue further in Section 5.1.

Mergers of black holes, and in particular major mergers (i.e. SMBH mass ratios greater than 0.3), are efficient at flattening or destroying density spikes (Merritt et al. 2002). We note that the disruption is maximal during equal mass mergers, however these are extremely rare. After a merger the density spike will be re-established on a time-scale comparable to the relaxation time of stars (Merritt, Harfst and Bertone 2006). If major mergers are too frequent then spikes will not be long-lived enough to enhance the annihilation

luminosity. However, if they never happen the spike decay described above will result in inefficient heating. We encapsulate spike disruption in eqn. (9) by following the time since the last SMBH major merger in each halo, t_{spike} , which approximates the spike lifetime. The major merger rate in the simulation and galaxy formation model is discussed further in Section 5.1.

Using all the above computed quantities, we can finally estimate the time dependent annihilation luminosity at any time after the most recent SMBH major merger as:

$$L(t; m, \sigma v) = 2\pi \frac{\langle \sigma v \rangle}{m_\chi} \int_{r_{\text{inner spike}}}^{r_{\text{outer spike}}} \rho_{\text{spike}}^2(r) r^2 dr \quad (14)$$

$$= 2\pi \frac{\langle \sigma v \rangle}{m_\chi} \frac{\rho(r_{\text{outer spike}})^2}{2\gamma_{\text{spike}} - 3} r_{\text{outer spike}}^3 \left(\frac{r_{\text{inner spike}}}{r_{\text{outer spike}}} \right)^{-2\gamma_{\text{spike}} + 3},$$

in the limit that $r_{\text{outer spike}} \gg r_{\text{inner spike}}$. In what follows, we evaluate eqn. (14) for DM haloes in the Millennium Run simulation.

4 ANNIHILATION HEATING IN A COSMOLOGICAL MODEL OF GALAXY FORMATION

4.1 The Millennium Run Simulation and Galaxy Formation Model

To explore the effects of the heating of cooling gas in the hot halo from neutralino annihilation we employ a model of galaxy formation (Croton et al. 2006) coupled to a high resolution N-body simulation, the so-called ‘Millennium Run’ (Springel et al. 2006). Below we give only a brief outline of these techniques; the interested reader should refer to Croton et al (2006) and references therein for further details. In the following sub-sections we describe the addition of neutralino heating to this model.

The Millennium Run N-body simulation follows the dynamical evolution of approximately 10 billion dark matter particles in a periodic box of side-length $500 h^{-1}\text{Mpc}$ with a mass resolution per particle of $8.6 \times 10^8 h^{-1} M_\odot$. The adopted cosmological parameter values are $\Omega_\Lambda = 0.75$, $\Omega_m = 0.25$, $h = 0.73$, and $\sigma_8 = 0.9$ (Colless et al. 2001, Spergel et al. 2003, Seljak et al. 2005). From the simulation outputs merger trees are constructed that describe in detail how structures grow as the Universe evolves. These trees form the backbone onto which the galaxy formation model is coupled. Inside each tree, virialised dark matter haloes at each redshift are assumed to attract ambient gas from the surrounding medium, from which galaxies form and evolve. The galaxy formation model effectively tracks a wide range of physics in each halo, including reionization of the intergalactic medium at high redshift, including radiative cooling of hot gas and the formation of cooling flows, star formation in the cold disk and the resulting supernova feedback, black hole growth, metal enrichment of the intergalactic and intra-cluster medium, and galaxy morphology shaped through mergers and merger induced starbursts.

More specifically, once a dark matter halo has grown in mass to approximately $\sim 10^{11.5} h^{-1} M_\odot$ infalling baryons no longer fall ‘cold’ on to the central galaxy but instead shock heat to the virial temperature of the dark matter halo to

form a quasi-static hot atmosphere (Croton et al. 2006). As the density of hot gas increases the cooling time near the centre of the halo becomes short and a cooling flow of condensing gas forms. Using simple thermodynamic and continuity arguments a cooling rate for this flow, \dot{m}_{cool} , can be estimated under the assumption that the gas is approximately isothermal ($\rho_{\text{hot}} \sim r^{-2}$) outside the very central regions at the virial temperature of the halo ($T_{\text{vir}} \sim V_{\text{vir}}^2$, where V_{vir} is the virial velocity of the dark halo):

$$\dot{m}_{\text{cool}} = 0.5 \left(\frac{r_{\text{cool}}}{R_{\text{vir}}} \right) \left(\frac{m_{\text{hot}}}{t_{\text{cool}}} \right). \quad (15)$$

Here R_{vir} is the virial radius of the halo, m_{hot} is the mass of gas in the hot phase, and $t_{\text{cool}} \approx 0.1 t_{\text{Hubble}} = R_{\text{vir}}/V_{\text{vir}}$ is the cooling time of the gas at the cooling radius, which is defined by:

$$r_{\text{cool}} = \left[\frac{\Lambda(T, Z)}{6\pi\mu m_p k T} \frac{m_{\text{hot}}}{V_{\text{vir}}} \right]^{1/2}, \quad (16)$$

The cooling radius traditionally marks the radius out to which gas has had time to cool quasi-statically given the age of the system. In the above, μm_p is the mean particle mass, k is the Boltzmann constant, and $\Lambda(T, Z)$ is the cooling function, dependent on both the temperature T and metallicity Z of the hot gas. Despite their simplicity, eqns. (15) and (16) provide a good approximation to the rate at which gas is deposited at the centre in the similarity solution for a cooling flow (Bertschinger 1989; Croton et al. 2006).

Gas cooling in simulations appears to be much more efficient than observed in nature. For low mass haloes heating and expulsion of baryonic material by supernovae can prevent over-cooling, but on group and cluster scales, while the observed baryon fraction has the universal value (Balogh et al. 2001), state of the art hydrodynamical simulations find a significantly larger fraction of cooled gas (Borgani et al. 2003; Kravtsov, Nagai & Vikhlinin 2005). In fact in clusters the problem is particularly severe; observationally the X-ray luminosities in many clusters imply cooling rates in the inner regions of $\sim 100 - 1000 M_{\odot} \text{ yr}^{-1}$ (e.g. Fabian & Nulsen 1977; Edge 2001; Fabian 2004), whereas little or no associated star formation is detected. A decrease in X-ray gas temperature is often seen in the centres of clusters but X-ray spectroscopy detects very little cool gas below 10^4 K (Peterson et al. 2001; 2003).

Therefore it has been known for some time (see Fabian 1994 and references therein), the measured cooling times at the centre of observed clusters of galaxies are significantly shorter than the Hubble time. This implies that gas condensation should be occurring from the conventional picture described above, however none is observed, nor are the secondary effects of cooling such as copious star formation in the central brightest cluster galaxy. Such galaxies are mostly found to be ‘red and dead’. This behaviour may indicate the presence of a heat source that is supplying energy to the cooling gas to keep the central regions from condensing. This is the so-called classical ‘cooling flow problem’ (Fabian 1994).

To arrest the expected runaway cooling in massive systems a heat source must be present. We test the idea of whether the heating from dark matter annihilation at the centres of massive systems can plausibly be a global solution to the cooling flow problem described above. Below we

describe our implementation of this DM annihilation powered heating into the galaxy formation model.

4.2 Thermal coupling of the neutralino annihilation energy

The energy produced from the self-annihilation of neutralinos in the vicinity of the spike r_{spike} we argue will couple thermally with the baryons in galactic nuclei, thereby heating the gas. We investigate potential physical processes and the relevant time-scales that will likely enable the transfer of this energy to the baryons. We compute relevant time-scales for the centre of the Milky Way treating that as our fiducial case from which we scale to other masses. Similar heuristic estimates have been made by Totani (2004; 2005) for galaxy clusters.

The physical scale and dominant astrophysical process via which the self-annihilation energy interacts with baryons is unknown at the present time.

Here for purposes of estimating the efficiency of potential astrophysical processes we use observational estimates of the density, pressure and temperature from the inner regions of our Galaxy at roughly 200 pc from the Galactic Center (Bradford et al. 2005; Morris & Serabyn 1996). The physical conditions present in this region are consistent with thermal, non-thermal and magnetic pressures that are several orders of magnitude higher than those present in the large-scale galactic disk. For the measured densities of $n \sim 10^4 \text{ cm}^{-3}$, the pressure is $P_{\text{thermal}} \sim 10^{-10} \text{ erg cm}^{-3}$, however turbulent pressures greatly exceed this value, approaching $P_{\text{turb}} \sim 10^{-8} \text{ erg cm}^{-3}$. For the inferred magnetic field strength of 0.1 – 1 mG, the magnetic pressure is also large, of the order of $P_{\text{mag}} \sim 10^{-8} - 10^{-10} \text{ erg cm}^{-3}$. To estimate the time-scales for energy loss and therefore heating of the gas in the inner regions, we adopt the following scaling values for the density, pressure and magnetic field strength from the Milky Way: $P \sim 10^{-8} \text{ erg cm}^{-3}$, $n \sim 10^4 \text{ cm}^{-3}$, and $B \sim 0.4 \text{ mG}$. **Note that the self-annihilation heating occurs for the $T \sim 10^4 \text{ K}$ cooling gas from the hot halo and not to the $T \sim 200 \text{ K}$ molecular gas at 200 pc.**

Using the above values we can address the question of how the annihilation luminosity is likely converted efficiently into thermal energy of the gas in the nucleus. We focus on a fiducial neutralino model where about 1/4th of the annihilation energy $E_{\chi\chi}$ goes into continuum gamma-rays [Channel A], 1/6th goes into electrons and positrons [Channel B], 1/15th goes to protons and anti-protons [Channel C], and the rest is imparted to neutrinos that are not relevant for heating. The spectral energy distribution of the products is such that $E^2 \frac{dN}{dE}$ peaks roughly at $0.05 m_{\chi} c^2$, $0.05 m_{\chi} c^2$ and $0.1 m_{\chi} c^2$ respectively. The average energy of secondary particles produced in the annihilation of a neutralino of mass 50 GeV is of the order of 1 GeV. These annihilation products are representative of a wide class of super-symmetric scenarios, as determined with the DarkSUSY code (Gondolo et al. 2005), that are consistent with cosmological and accelerator constraints.

Examining Channel B in detail, we assume for simplicity that all the electrons and positrons have roughly the same energy $E_0 \sim 1 \text{ GeV}$. Since they are produced in an extremely high density environment, they will expand rela-

tivistically and form a bubble. As discussed in Shu (1991), the primary energy loss processes are examined below. The energy loss time-scale for these particles by Coulomb collisions is given by:

$$\tau_{\text{CC}} \sim 5.1 \times 10^3 \frac{n}{10^4 \text{ cm}^{-3}} E_0 \text{ yr}, \quad (17)$$

which is so short that all the electrons and positrons from the neutralino decay will very efficiently transfer energy to the gas cooling out of the hot halo. This is the principal physical process that will likely heat the gas and provide the feedback discussed in this work. On the other hand, the energy loss time from inverse Compton scattering is long,

$$\tau_{\text{IC}} \sim 1.2 \times 10^9 E_0^{-1} \text{ yr}, \quad (18)$$

and therefore inefficient. The time-scale for energy losses via Brehmstrahlung is also short,

$$\tau_{\text{Brehm}} \sim 5.7 \times 10^3 \left(\frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1} \text{ yr}. \quad (19)$$

In comparison using the same estimate for n , the energy loss time-scale from synchrotron radiation is given by,

$$\tau_{\text{Synch}} \sim 1.5 \times 10^5 E_0^{-1} \text{ yr} \quad (20)$$

We conclude from the above estimates that the conversion of the self-annihilation energy into thermal energy can occur efficiently for the gas in the inner regions of galactic nuclei as illustrated specifically for the Milky Way case. However, we do note here that our estimate of the magnetic field strength is on the high side. This energy input suppresses the gas cooling and quenches star formation. Due to our lack of knowledge of neutralino properties, it is not possible to calculate the precise time-scale and physical process that thermally couples the by-products of the γ -ray annihilation to baryons. For the purposes of this work, it is assumed that this coupling is efficient and all the available energy is transferred effectively to heating the gas in the inner regions of DM haloes. The estimate of time-scales for the Milky Way halo suggests that gas in the inner region on the scale of ~ 200 pc is likely directly involved in the heating process.

We note here that an alternate dark matter driven gas heating mechanism exploiting inelastic scattering of X-dark matter particles with relic abundances comparable to neutralinos has been proposed by Finkbeiner & Weiner (2007). They propose a WIMP candidate with an excited state that maybe collisionally excited and de-excites by $e^+ - e^-$ pair emission. The kinetic energy of these pairs they argue could heat intra-cluster gas and the gas in galaxies to compensate for cooling similar to what we explore here. The primary motivation for this model was to provide a possible interpretation for the 511 keV line observed by the INTEGRAL satellite in the inner Milky Way consistent with the observed WMAP haze and current constraints on the gamma-ray background.

4.3 Constructing a viable feedback model from neutralino self-annihilation

We model the self-annihilation luminosity of neutralinos as a steady input of energy that prevents gas cooling in preferentially massive galaxies/haloes. The assumptions and properties of simulated haloes that are needed to fully specify the DM density profile, BH mass, and the inner and outer spike

radii are all taken as input by the galaxy formation model to calculate the annihilation luminosity for any system at any given time its evolution.

4.3.1 Halo density profiles

The DM density profile for every halo in the Millennium Run at every time-step is approximated using the universal analytic function described by eqn. (2). Note that, while in principle each profile can be directly measured from the distribution of bound dark matter particles, this is computationally prohibitive given the number of haloes in the Millennium run (up to 25 million at any given time-step), and the analytic formalism is accurate enough for our purposes here.

To explore the dependence of annihilation heating on the inner slope of the halo density profile, γ , we take the inner slope as a free parameter in determining eqn. (2). In the next section we will vary γ and examine its effect on the evolution of the galaxy population. The remaining parameters in the density profile are either assumed fixed or taken directly from the simulation.

For the default model, we assume $\alpha = 1$ and choose β such that $(\beta - \gamma)/\alpha = 2$. This ensures that the outer slope of the halo density profile remains fixed at -3 , which is known to be an accurate description of the results of numerical simulations (Navarro, Frenk & White 1996). We take the measured virial mass M_{vir} , and radius R_{vir} , required in eqn. (3) and (4), directly from the simulation. To estimate the halo concentration parameter c_{vir} , we use the measured V_{vir} and V_{max} and solve eqn. (5) in Navarro et al. 1997 (see Croton, Gao & White 2007). This fully describes the density profile for each dark matter halo.

4.3.2 The inner and outer spike radii

Once a value for the slope of the inner dark matter density profile, γ , has been assumed, the steepened spike index, γ_{spike} (eqn. 7), can be calculated. This then fixes the spike density profile defined by eqn. (6), and therefore also the inner limiting density determined by the self-annihilation rate itself, eqn. (9). The radius of this limiting density, and the inner spike radius, are calculated from eqn. (6) and (9). Note that we limit the inner spike radius to always be equal to or greater than four times the Schwarzschild radius (eqn. 10). However, this limit is rarely reached in practice.

The outer spike radius is simpler to calculate for each halo in the galaxy formation model, since the model explicitly follows the growth of SMBHs in each galaxy (Croton et al. 2006). This, along with the use of the virial velocity of the halo V_{vir} as a proxy for the inner velocity dispersion σ , allows the outer spike radius to be calculated using eqn. (8).

4.3.3 The efficiency of annihilation heating

We consider a maximal heating model, assuming that all the energy available from the annihilation luminosity given by eqn. (14) couples with the cooling gas in the hot halo. With this assumption, the cooling rate described by eqn. (15) is

modified in the presence of DM annihilations:

$$\dot{m}'_{\text{cool}} = \dot{m}_{\text{cool}} - \frac{\xi L_{\text{XX}}}{1/2 V_{\text{vir}}^2} \quad (21)$$

Thus, if the heating rate from the annihilation flux is comparable to the energy released from gas cooling out of the hot X-ray halo, the cooling flow can be suppressed and this will starve the central galaxy from lack of new star forming material. Under such circumstances galaxy growth will stall, altering the relationship between dark halo mass and galaxy luminosity in a way more compatible with observations.

4.3.4 Uncertainties in the galaxy formation model

As the results in the following sections are considered, it is important to keep in mind that the galaxy formation model we use to obtain them is imperfect. Its construction is largely based on observational phenomenology that, while well described in the mean, is often ill understood in detail.

The largest uncertainty in our galaxy formation model relevant to our results is the cooling prescription described in Section 4.1. The physics of cooling losses from hot plasma in a dynamically evolving multiphase medium is complicated. Our prescription provides cooling rates that are a reasonable average approximation to that obtained from hydrodynamically simulated gas infall (see Yoshida et al. 2002 for a comparison). However, cooling in both the hydrodynamic simulations and our galaxy formation model is first calculated in the absence of any heating (eqn. 15). The model heating rate is then subtracted (eqn. 21). But in reality, cooling and heating will occur simultaneously. Energy injection from heating can potentially modify the properties of the gas (notably temperature and density) used to calculate later cooling. Hence, under these circumstances subsequent cooling estimates will be different from those where the past heating history is neglected as in our model.

Due to these caveats, in absolute terms our heating rates must be treated with caution; they are simply a relative measure that defines an upper limit on the energy required to stop gas from cooling. However, relative to the cooling rate they are expected to be accurate for the model. More detailed models can be constructed to take into account the past heating history when calculating the current cooling rate, but these estimates would be complicated and highly unconstrained. For example, the temperature and density gas profiles could change as a function of the energy injected, depth of potential, and redshift, for every galaxy in an evolving Universe. These detailed and self-consistent responses of the baryons need to be taken into account. However, such improvements add considerable complexity that is beyond the scope of the present work. Below, we present the results of implementing a simple model of annihilation heating.

5 RESULTS

5.1 Spike evolution and stability

As discussed in Sections 3.1 and 3.3, the luminosity produced from dark matter annihilation in an unsteepened NFW-type halo falls short by several orders-of-magnitude when compared to the cooling losses from the X-ray emitting hot gas. For annihilations to be a plausible solution to

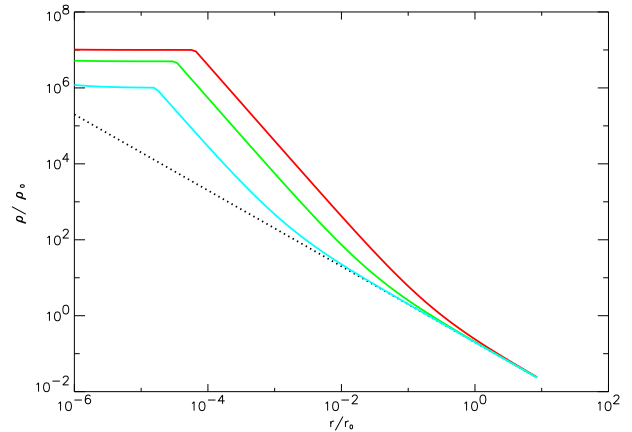


Figure 1. To illustrate the time evolution of the DM spike, we plot the variation of the density in the centre with time for a DM halo that hosts a Milky Way type galaxy. The x-axis is normalised to r_h the radius of gravitational influence of the black hole, while the y-axis is normalised to ρ_0 the density of the DM halo at r_h . The 3 different line styles denote the values of τ (i.e. time in units of the heating time T_{heat}). The solid lines are, from top to bottom, for $\tau = 1$ (red), $\tau = 5$ (green) and $\tau = 10$ (blue). The “unmodified” NFW profile is shown as a dotted line. The central “plateau” for the curves is due to annihilations, and the maximum density is calculated for a toy model, to simply show the qualitative behaviour of the profile at small radii. The maximum density - the height of the plateau, varies with time.

the cooling flow problem one requires an enhancement of the DM density in the inner most regions of the galaxy, usually assumed to be produced by the presence of a super-massive black hole or in response to the adiabatic compression of baryons or perhaps both these processes.

When present, density spikes are expected to evolve with time due to the annihilation itself. To illustrate this, in Fig. 1 we plot the time evolution of a DM density spike in the centre of a fiducial halo, modelled on the Milky Way. The x-axis is normalised to the radius of gravitational influence of the black hole, while the y-axis is normalised the density of the DM halo at this radius. The three different line styles denote the values of τ (i.e. time in units of the heating time T_{heat} , eqn. 13). The red line is for $\tau = 1$, green for $\tau = 5$, and blue for $\tau = 10$. The unmodified NFW profile (i.e. $\gamma = -1$) is shown as a dotted curve. The central plateau in the inner regions is due to annihilations, and the maximum density drops with time. The evolution of the density spike is clearly a result of many complex interactions within the halo.

Dark matter density spikes are fragile and transient – a major merger can easily destroy a spike on a short time-scale. However, it is unclear whether the disruption is triggered by the merger of the dark matter haloes, central black holes or galaxies hosted in the haloes. The merger rates for these three populations of objects are not necessarily the same, and yet a typical approximation adopted is to the use Extended Press-Schechter (EPS) theory to obtain the merger rate. However EPS only describes the properties of DM haloes. In reality it is probably the mergers of black holes that ought to be most significant for the evolution of a density spike.

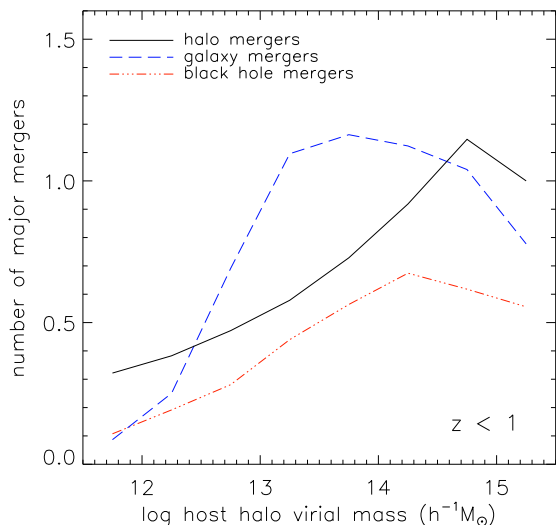


Figure 2. The number of major mergers for galaxies, DM haloes, and black holes vs host halo mass. This plot illustrates that the density spikes can be reassembled as the time between major mergers is long compared to the time taken to refill the stellar loss cone in galactic nuclei.

Using our cosmological model of galaxy formation we can check the frequency of mergers for haloes, galaxies, and the black holes that reside within them. In Fig. 2 we show for each object the mean number of major mergers at $z < 1$. We focus on this redshift range because it is primarily only at late times wherein heating is needed to prevent the cooling of gas in haloes. Major mergers of SMBHs are less common than major mergers of galaxies or dark matter haloes, with less than one occurring per system on average since $z = 1$ at all host halo mass scales. This implies a typical spike survival time > 4 Gyr. Fig. 2 also shows that the merger rates for all populations tends to increase with increasing mass although this flattens somewhat for the most massive haloes. We conclude from Fig. 2 that spikes can survive on Gyr timescales despite the violent nature of the hierarchical growth and assembly in a Λ CDM Universe. Note, that even after a major merger spikes may later reform, typically on the stellar relaxation time-scale of the inner region of the galaxy.

In this work, we further assume that the mass of central black holes grows significantly at each merger (as the solution for adiabatic growth is valid only in the limit $M_{\text{bh,initial}} \ll M_{\text{bh,final}}$ (Di Matteo, Springel & Hernquist 2005)).

5.2 Annihilation heating of the hot halo

We now investigate the enhanced annihilation luminosity due to the presence of density spikes described in Section 4. The annihilation heating model depends on a well defined set of parameters. We explore the dependences in detail. These dependencies are illustrated in the various panels of Fig. 3: the dark matter halo virial mass M_{vir} , the black hole mass M_{bh} , the mass of the dark matter particle m_χ , the average time between major mergers τ , the inner DM halo density

profile slope γ , and the outer radius $r_{\text{outer spike}}$ adopted for the DM density spike. We consider two halo mass ranges for each, galaxy scales masses ($M_{\text{vir}} = 10^{12} M_\odot$, dashed lines) and cluster masses ($M_{\text{vir}} = 10^{14} M_\odot$, solid lines). Our default model assumes common values for each of $m_\chi = 100$ GeV, $\tau = 1$ Gyr, $\gamma = -1.0$ (NFW), and $r_{\text{outer spike}} = r_{\text{BH}}$ (the sphere of influence of the black hole). In each panel we vary one parameter keeping the rest fixed to clearly show the plausible range of heating rates that can be expected from the model (the default values of each parameter are marked by vertical dotted lines). In addition, the top left panel shows the expected cooling rate assuming a hot gas fraction of 0.1. The choice of 10% for the host gas fraction is motivated by the X-ray observations in galaxy groups and clusters (LaRoque et al. 2006; Vikhlinin et al. 2006; Gonzalez, Zaritsky & Zabludoff 2007). This is approximately the energy the DM heating needs to replenish.

It is clear that even in the presence of density spikes it is usually difficult to produce enough flux to reheat all the cooling gas, and this is true for haloes of all masses ranging from galaxy scales to cluster scales. Enhancement of between 1-2 orders-of-magnitude does occur when mergers are more frequent (this works to offset the exponential decay of the spike amplitude shown in Fig. 1) or for lower mass DM particle candidates. However the heating luminosity is still significantly lower when compared with the cooling rate shown in the top left panel.

The bottom two panels of Fig. 3 show how sufficient heating can be produced, either through significant steepening of the inner DM halo density profile (on which the spike sits), or a significantly larger outer spike radius or both. For galaxy-scale DM haloes annihilation heating can balance cooling whenever the inner density profile is steepened to values of $\gamma < -1.45$, and for cluster-scale haloes when $\gamma < -1.55$. Similarly large values for the outer spike radius, $\sim 25 r_{\text{bh}}$ on galaxy scales and $\sim 65 r_{\text{bh}}$ on cluster scales, are required for annihilation heating to compensate for the gas cooling. Although observationally the inner DM halo profile remains unconstrained on extremely small scales, it may be difficult to produce such steep slopes or large spike radii on the scales required for all galaxies and clusters, in order to effectively influence global properties.

5.3 The consequences of annihilation heating in a cosmological context

The suppression of cooling flow gas in massive haloes can have a dramatic effect on evolution of the galaxies that reside in them. This is due to the fact that across cosmic time, a growth of a galaxy is dictated by the availability and supply of star forming material. At late times this mostly comes in the form of gas condensing out of the hot halo. Hence, any mechanism that suppresses gas cooling ultimately also prevents the galaxy from further star formation. Our goal is to investigate under what circumstances the evolving density spikes explored in Section 5.1 and the resultant heating model described in Section 5.2 can actually shut down star formation in massive galaxies when the full hierarchical evolution of galaxies is taken into account.

In a set of three figures, Fig. 4–6, we show the resultant local luminosity function predicted by our galaxy formation model with annihilation heating included. We plot

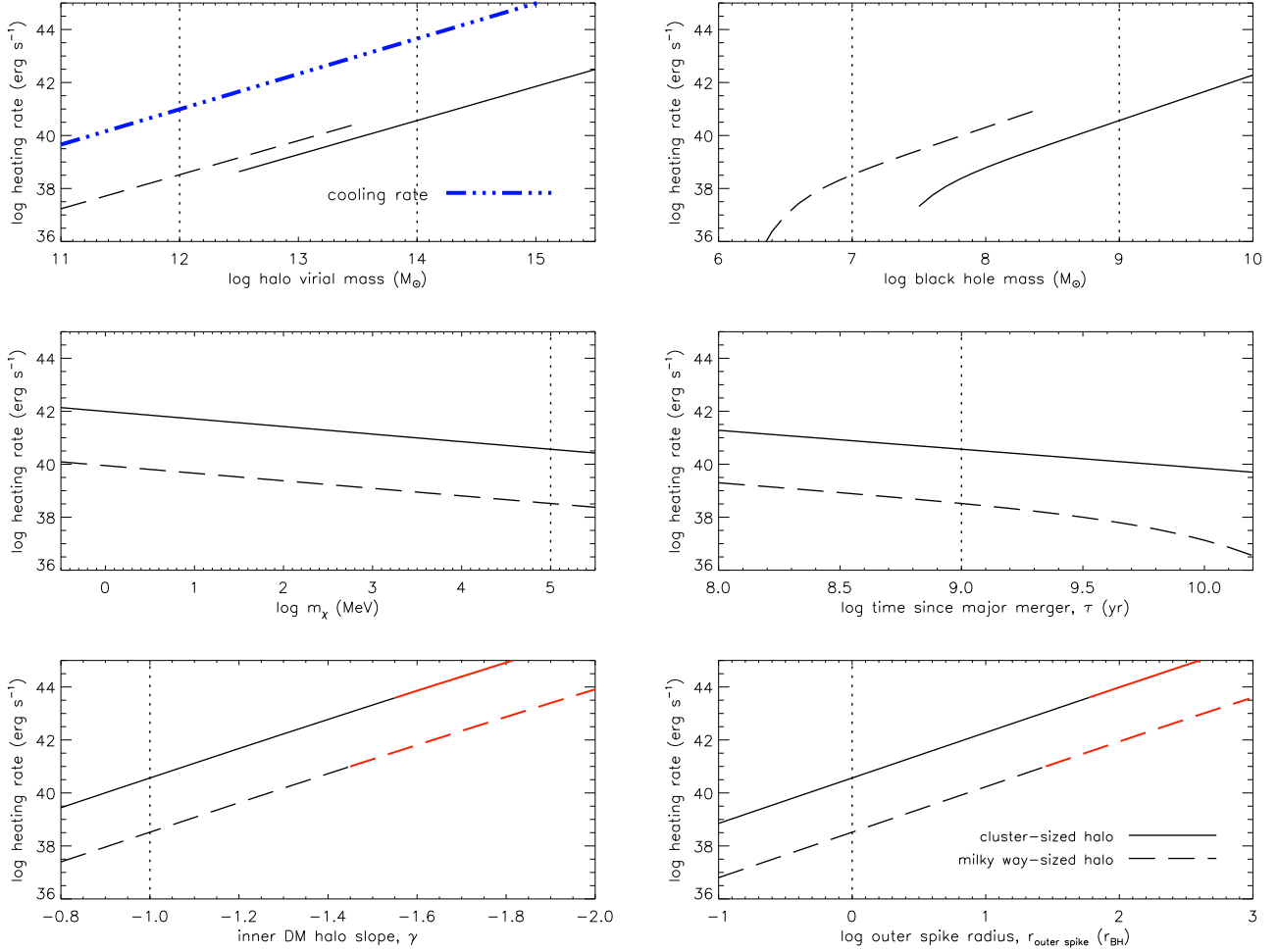


Figure 3. The parameters controlling the feedback from self-annihilation: the mass of the dark matter halo (top left), black hole mass (top right), DM particle mass (middle left), time since major merger (middle right), inner DM halo slope (bottom left), and outer spike radius (bottom right). Two models are shown, one for a Milky Way sized halo and one for a cluster sized halo. The default values for each are shown by the dotted horizontal lines in each panel. The common parameters are $m_\chi = 100$ GeV, $\tau = 1$ Gyr, $\gamma = -1.0$ (NFW), and $r_{\text{outer spike}} = r_{\text{BH}}$ (see text). Each panel demonstrates the effect on the heating of varying one of these parameters while keeping the remaining fixed. The annihilation luminosity is most sensitive to the inner halo density profile and outer spike radius. In the top left panel we additionally illustrate the approximate cooling rate for a given halo mass that the heating needs to overcome (thick dotted-dashed line, assuming a hot gas fraction of 10%).

the $z = 0$ K-band galaxy luminosity function, for the models (lines) and observations for comparison (symbols with error bars). The long-dashed line in each figure shows the conservative default model used in Fig. 3. The remaining lines in each figure illustrate the consequences of different parameter choices for the annihilation heating prescription, with each figure focused on a specific set of parameters that tune the annihilation heating model.

As can be seen from all the luminosity function figures, the default model significantly overpredicts the abundance of the brightest galaxies. This is a consequence of inefficient annihilation flux heating for the default model, as seen in Fig. 3. Essentially overcooling occurs in the centers of group and cluster systems, leading to excess star formation and overly bright and massive galaxies. Note that this is not necessarily a failure of our underlying galaxy formation model - the cooling flow problem has a long history (see

review by Fabian 2004 for details) and failure of the default heating model is simply another manifestation of it (in the absence of strong enough heating).

The two additional lines in Fig. 4, dotted-dashed and solid, show the galaxy luminosity function when the inner DM halo slope is steepened to $\gamma = -1.5$ and $\gamma = -2.0$, respectively (the default model has -1.0 , the standard NFW profile). An inner slope of -1.5 appears to be insufficient to produce enough heating, even with the presence of a central density spike. Only inner halo slopes of ~ -2.0 or steeper are able to do this. In the context of current models such steep slopes do not arise naturally in dark matter haloes. A combination of steepening mechanisms needs to operate in a coordinated fashion to achieve these slopes.

Fig. 5 considers the combination of a steeper inner halo slope, here $\gamma = -1.2$, and more extreme values for the inner and outer spike radii explored previously in Fig. 3. Our

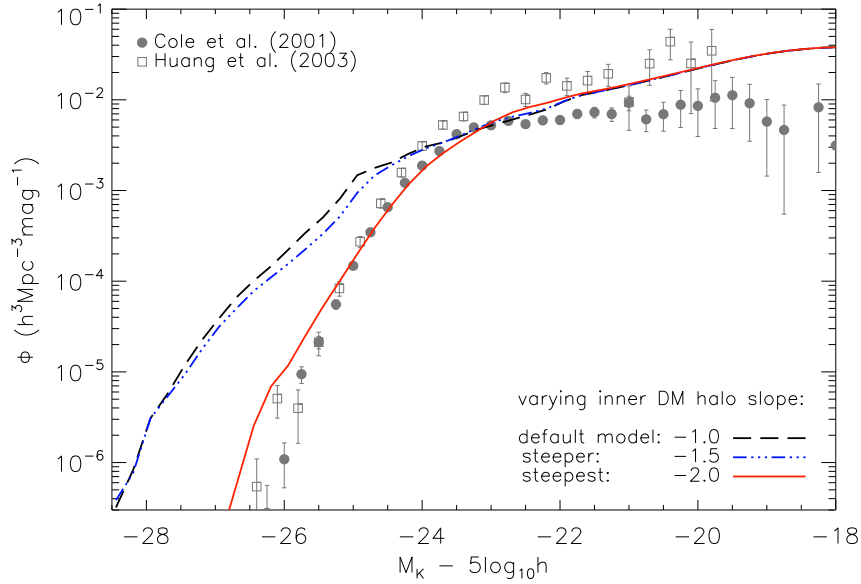


Figure 4. The local K-band galaxy luminosity function, observed (points with error bars), and predictions (lines) for various parameter choices of our annihilation heating model. Here we show the default model of Fig. 14 with $\gamma = -1.0$, and with steepening DM density slopes of $\gamma = -1.5$ and $\gamma = -2.0$, as indicated in the legend. Only spikes in haloes with the steepest inner profiles are able to produce enough heating to obtain a reasonable fit to the observed galaxy luminosity function.

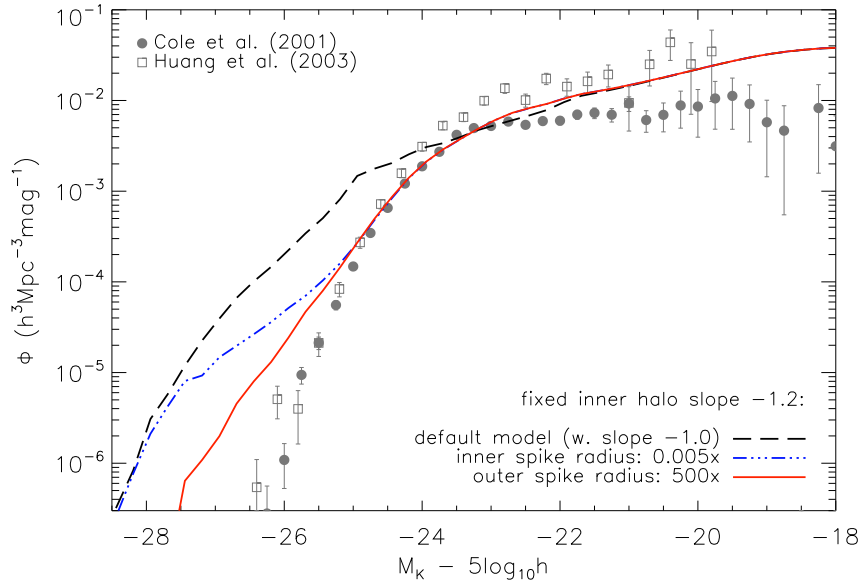


Figure 5. The local K-band galaxy luminosity function, observed (points with error bars), and predictions (lines) for various parameter choices of our annihilation heating model. The default model with inner slope $\gamma = -1.0$ is replotted from Figure 4. For comparison, haloes with an inner slope of $\gamma = -1.2$ and more extreme choices for the inner and outer spike radii are shown, as indicated by the legend.

choices for the spike radii are made to obtain the correct turnover in the galaxy luminosity function. The required values are, for the inner spike radius 200 times smaller than the default value (dashed-dotted line) and for the outer spike radius 500 times larger than the default value (solid line). Both parameter sets still over predict the abundance of very

bright galaxies. This exercise is repeated in Fig. 6 with a more extreme inner slope of $\gamma = -1.5$. The inner and outer spike radii choices that provide the best fit are now 10 times smaller than the default inner spike radius (dashed-dotted line) and 100 times larger than the default outer spike radius

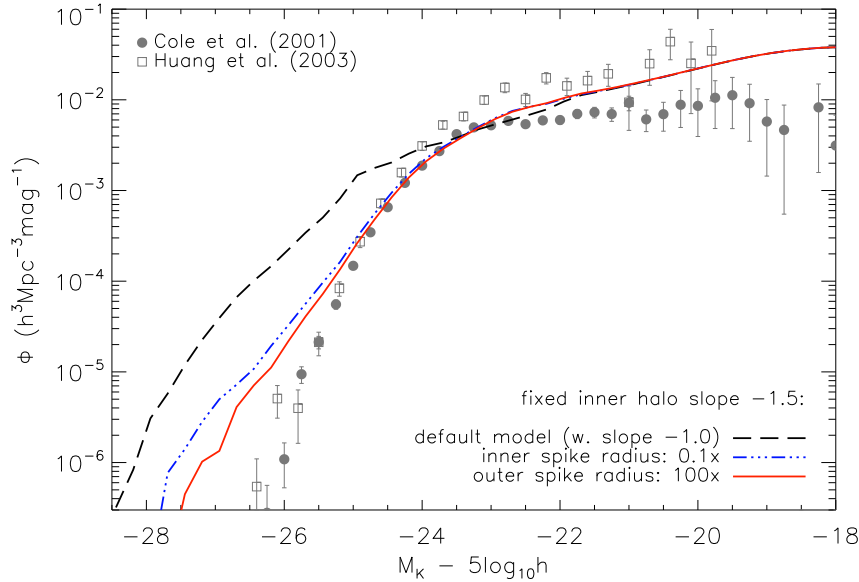


Figure 6. The local K-band galaxy luminosity function, observed (points with error bars), and predictions (lines) for various parameter choices of our annihilation heating model. The default model with inner slope $\gamma = -1.0$ is replotted from Figure 4. For comparison, haloes with an inner slope of $\gamma = -1.5$ and more extreme choices for the inner and outer spike radii are shown, as indicated by the legend.

(solid line). The brightest galaxies remain overabundant, but less so than for the previous values.

We conclude that for modest parameter choices we are unable to produce galaxies that match observed ones. Of course, further combinations of these parameters are possible, however, it is unlikely that self-annihilation is the sole feedback process in galaxy formation. It is plausible that this process operates in addition to supernovae and AGN feedback.

6 OBSERVATIONAL SIGNATURES OF DM ANNIHILATIONS

If indeed neutralino self-annihilations contribute to the energetics of feedback in galaxies and clusters as proposed here, we can expect a range of observational signatures.

6.1 Distribution of density profile slopes

If the model of annihilation heating developed here operates, we expect the existence of a range of inner dark matter density profile slopes in the centres of galaxies and galaxy clusters. The time evolution explored in this model suggests that the inner density slopes on the scale of tens of parsecs in galaxies are likely to be diverse.

Observationally, this is an extremely challenging length scale to probe and detect this diversity. Studies of the velocity dispersion profiles of the stellar component in the vicinity of the black holes combined with strong lensing offer a potentially viable probe.

Mapping of rotation curves has also provided constraints on the density profile of the dark matter in the

central regions of galaxies, (see de Blok, McGaugh & Rubin and references therein) however on much larger scales, of the order of kpc, whereas the DM annihilation scenario leaves an imprint on much smaller scales.

It does appear that on kpc scales (larger scales than relevant for dark matter self-annihilations) there is compelling evidence for bimodality in the distribution of light (baryons). The NUKER group has studied this effect extensively using Hubble Space Telescope data (Gebhardt et al. 1996; Faber et al. 1997; Lauer et al. 2002). In a recent paper, combining several HST investigations on the central structure of early-type galaxies they find that the distribution of the logarithmic slopes of the central brightness profiles is bimodal (Lauer et al. 2007). They claim that at the HST resolution limit, most galaxies are either power-law systems, which have steep cusps in surface brightness, or core systems, which have shallow cusps interior to a steeper envelope in the brightness distribution. There is a strong correlation between the luminosity L and inner profile slope, and it has been suggested that this correlation is likely due to core formation by binary BHs during mergers (Ferrarese et al. 2006). Whether and how this observed bimodality in the surface brightness profiles of the baryonic component reflects the dark matter density profile on the smallest scales is unclear at the present.

The physical scale on which dark matter annihilation manifests itself in the case of clusters is predicted to be of the order of \sim kpc (as shown in the bottom right hand panel of Figure 3). In this context, we predict that similarly in clusters there ought to be a diversity of density profile slopes on kpc scales. In clusters that have more complex dynamical histories, the dark matter spike is likely to have been disrupted progressively due to frequent mergers and these density spikes are also expected to have depleted from the

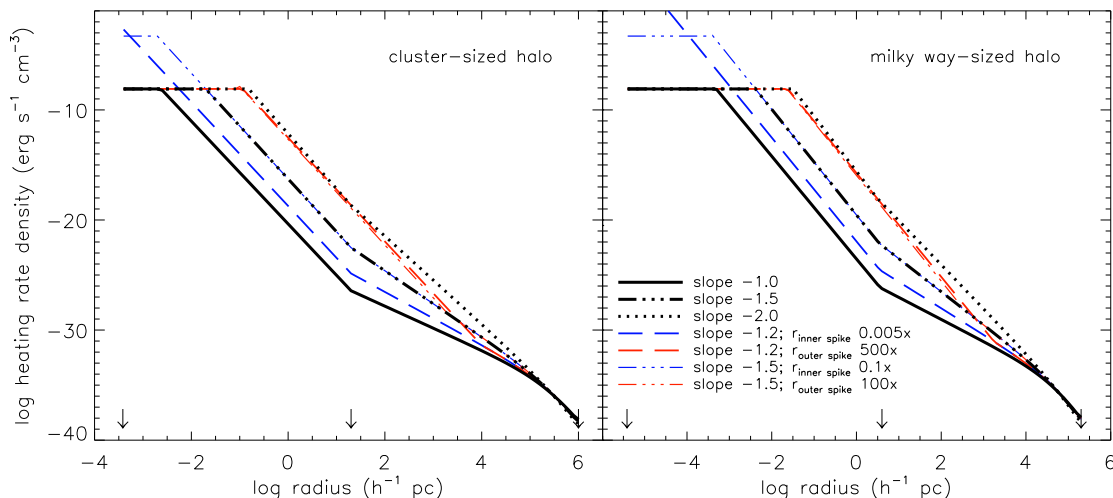


Figure 7. The dark matter heating rate density profile for the various heating models explored in Figures 4 to 6, for both cluster-sized and Milky Way-sized haloes (left and right panels). The three arrows near the bottom of each panel indicate the boundaries of 4 times the Schwarzschild radius, the outer spike radius, and the virial radius of the DM halo, from left to right in each respectively (see Section 3). The spike is clearly noticeable as the inner steepening part of the profile, while the flattening seen on small scales marks the saturation of the heating due to DM self annihilation.

annihilation process itself as a result. These growing clusters are systems in which the spike reassembly is most unlikely to occur rapidly. In the context of the self-annihilation feedback picture, these clusters are likely to have density profiles with a central plateau (akin to the evolution shown in Figure 1). Since clusters are the most recently assembled structures in the Universe, we predict a range of inner density slopes in the central few kpc, some shallower than the predictions of dissipationless simulations and some steeper, depending on their dynamical history. Dynamical history coupled with the modification produced due to the presence of the baryonic component (stars or black holes) is intricately coupled to the process of DM annihilation as we have shown, and the interplay of these process might dictate the slope of the dark matter density profile in the inner-most regions.

Observationally, the issue is once again challenging. Strong lensing studies of the inner regions of clusters with radial and tangential arcs point to the possible existence of shallower density slopes and perhaps cores on scales of $\sim 5 - 10$ kpc. This is of the order of the scales on which we expect to see signatures of the annihilation process. Since strong lensing constrains the total mass as a function of radius, disentangling the effect of the baryons to infer the density profile of the dark matter alone on these scales is difficult. The combination of gravitational lensing and dynamical data is uniquely capable of achieving this. Sand et al. (2002; 2004) attempted this for a sample of strong lensing clusters. In more recent work, Sand et al. (2007) study 2 clusters Abell 383 and MS2137-23 combining strong lensing constraints with stellar velocity dispersion data for the brightest central cluster galaxy. They find that a shallower inner slope is preferred compared to predictions from simulations ($\gamma \sim -0.6$) for Abell 383 for a coarse lensing model. For MS2137-23, no self-consistent model that incorporates strong lensing and the stellar velocity dispersion data was found to be a good fit. It is a challenge to extract constraints

on the density profile slope at these small radii from observations. Meanwhile, simulations that incorporate baryons are likely to improve in resolution in the near future and might offer a powerful test of our predictions.

7 COMPARISON WITH THE AGN HEATING PARADIGM

In this section we discuss the details of the AGN heating paradigm in order to contrast with our dark matter annihilation model. We describe the mechanism and argue that there is a need for additional sources of feedback that dark matter self-annihilations may well provide.

The proposed physical mechanisms for AGN driven feedback are expected to occur in two modes: the ‘quasar mode’, where mergers trigger fuelling to central black holes activating an episodic, bright quasar phase accompanied by large-scale outflows (Di Matteo et al. 2005; Hopkins et al. reference), and the ‘radio mode’, which refers to steady feedback from low-level AGN activity (Croton et al. 2006; Bower et al. 2006). The need for these processes arise from the overcooling problem that occurs on a range of mass scales, from galaxy groups to clusters (Somerville & Primack 1999; Cole et al. 2001; Kauffamnn et al. 1999; Benson et al. 2003).

AGN feedback in the quasar mode likely occurs during the epochs of efficient cold gas feeding to the central black holes via a thin accretion disk, at high accretion rates ranging between $0.1 - 1 L_{\text{Edd}}$. This phase is short-lived and the thermal coupling of AGN energy is fairly weak (at $< 5\%$ level). In this mode the AGN-driven wind removes residual gas at the end of the merger, leading to suppression of subsequent star formation and self-regulated BH growth that reproduces the observed $M_{\text{bh}} - \sigma$ relation (Springel et al. 2005). However, for a typical massive galaxy in the local Universe a quasar event was long ago in its history. Such

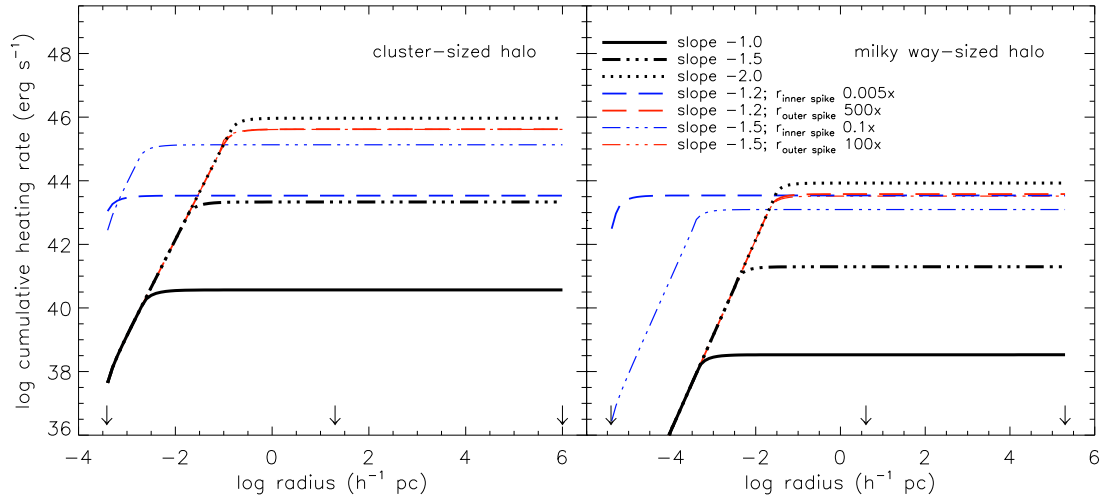


Figure 8. The cumulative heating rate as a function of increasing radius for the various spike density profiles shown in Figure 7 and used in Figures 4 to 6. In both panels, for cluster-sized haloes on the left and Milky Way-sized on the right, the three lower arrows indicate the boundaries of 4 times the Schwarzschild radius, the outer spike radius, and the virial radius of the DM halo, from left to right in each respectively (see Section 3). For all models the majority of the annihilation flux originates from well inside the central most parts of the halo.

galaxies instead host BHs that are accreting at much lower rates; in fact most spend much of their lifetime in these radiatively inefficient states. Radio activity is associated with these low accretion rate states and radio jets are seen in many massive galaxies. The coupling of jet energy with host gas can be very efficient and models of effervescent heating with a combination of sound waves, weak shocks and bubbles can heat a large fraction of the gas in clusters (Ruszkowski et al. 2004; Churazov et al. 2001; Bruggen et al. 2005) and produce features that match X-ray observations (Fabian et al. 2005).

A detailed exploration of the theoretical consequences of the steady radio-mode feedback from low luminosity AGN has been presented in Croton et al. (2006). This was done using the same semi-analytic model used in this paper, but with DM annihilation heating replaced with radio-mode heating. The authors of Croton et al. showed that for a set of energetically and observationally plausible parameters such a model could simultaneously explain: (i) the low observed mass drop-out rate in cooling flows; (ii) the exponential cut-off at the bright end of the galaxy luminosity function; and (iii) the fact that the most massive galaxies tend to be bulge-dominated systems in clusters and found to contain systematically older stars than lower mass galaxies.

In a recent paper Best et al. (2007) study a sample of radio-loud AGN in nearby groups and clusters from the Sloan Digital Sky Survey (SDSS). Using observational estimates of the mechanical output of radio jets, they estimate the time-averaged heating rate associated with recurrent radio source activity for all group and cluster galaxies. They find that within the cooling radius the radio-mode heating associated with galaxy groups and low mass clusters is sufficient to offset the cooling flow from the extended hot halo. In the most massive brightest cluster galaxy systems, however, radio mode heating alone is not enough. They conclude

that other processes acting in massive clusters must also be contributing to the suppression of cooling flow gas.

Importantly for this work, although AGN appear to be making an observable contribution to the evolution of gas dynamics in dark matter haloes, alone they only comprise part of the full physical picture. The presence of SMBHs at the centres of massive systems that drive AGN winds also provide enhancement in the annihilation rate of DM that, under the right circumstances, can produce sufficient heating flux to arrest cooling gas. Composite DM annihilation and AGN heating models will be a natural extension of our work and there is need for all feedback mechanisms to be better understood.

8 SUMMARY

Using the Millennium Run N-body simulation coupled with a sophisticated model of galaxy formation that includes the heating of cooling flow gas through neutralino annihilation, we have shown that:

- Density spikes that support the annihilation flux at the levels required to offset cooling flows are stable enough over long enough time-scales to maintain a reasonably constant heating source (Fig. 2).
- Models that appear to be extreme at the present time (given our current understanding of DM density profiles) are required to produce enough heating flux to offset the predicted cooling rates. To obtain the required heating rates we either need to steepen the inner DM density slope to values $\gamma > 1.5$ or increase the outer spike radius. For galaxy sized haloes the outer spike radius is required to be of the order of $\sim 25 r_{\text{bh}}$, and for cluster haloes $\sim 60 r_{\text{bh}}$ (Fig. 3 and 4).
- The efficiency of heating in the DM annihilation model scales with halo mass (and circular velocity), therefore this

mechanism does provide preferential suppression of star formation in more massive haloes as required to explain current observations of the luminosity function (Fig. 3).

In this treatment, we have assumed that the mass of central black holes grows significantly at each merger (as the solution for adiabatic growth in valid only in the limit $M_{\text{bh,initial}} \ll M_{\text{bh,final}}$. We note here that an alternative source of annihilations may be provided by minispikes around inter-mediate mass black holes as suggested by Bertone, Zentner & Silk (2005).

It is clear that feedback and energy injected into the inter-stellar medium of galaxies and the intra-cluster medium is a complex process, and that a combination of astrophysical processes, including the one explored here, are likely at play. One of the key uncertainties in the model explored in this paper arises from the fact that we lack an understanding of the physics through which the annihilation flux is expected to couple with the cooling hot halo gas. While we have discussed some possibilities, like coulomb collisions, brehmstrahlung and synchrotron radiation. Colafrancesco et al. (2007) have explored these in more detail for the case of the heating of gas in the Coma cluster due to DM annihilations. Experimental confirmation of supersymmetry from the LHC at CERN might throw new light on the viability and likely couplings for the neutralino. Additionally while following the cumulative heating history is very challenging to do it is needed to really understand the detailed energetics of the gas. There is incontrovertible evidence for the presence of copious amounts of DM on all scales in the Universe, so DM annihilation is an inescapable phenomenon. However, how much energy is released in the process and how efficiently it couples to the baryonic component are unclear.

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