GAMMA-RAY CONSTRAINTS ON NEUTRALINO DARK MATTER CLUMPS IN THE GALACTIC HALO

ROBERTO ALOISIO
INAF—Laboratori Nazionali del Gran Sasso SS., 17bis, Assergi (AQ), Italy; and Center for Cosmological Physics, University of Chicago, Chicago, IL 60637; roberto.aloisio@lngs.infn.it

PASQUALE BLASI
INAF—Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Florence, Italy; and Center for Cosmological Physics, University of Chicago, Chicago, IL 60637; blasi@arcetri.astro.it

AND

ANGELA V. OLINTO
Department of Astronomy and Astrophysics, Enrico Fermi Institute, and Center for Cosmological Physics, University of Chicago, Chicago, IL 60637; olinto@oddjob.uchicago.edu

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ABSTRACT

According to high-resolution cold dark matter (CDM) simulations, large virialized halos are formed through the constant merging of smaller halos formed at earlier times. In particular, the halo of our Galaxy may have hundreds of dark matter clumps. The annihilation of dark matter particles such as the neutralino in these clumps generates gamma-ray fluxes that can potentially be detected by future experiments such as GLAST. We find that, depending on the parameters of the clump density profile and on the distribution of clumps in the Galactic halo, the contribution to the diffuse gamma-ray background from clumps can constrain the properties of neutralinos such as the mass and annihilation cross section. We model the density profile of clumps by three representative dark matter profiles, singular isothermal spheres (SISs), Moore profiles, and Navarro, Frenk, and White (NFW) density profiles, and calculate the spectrum and angular distribution in the sky of the gamma-ray flux due to neutralino annihilation in the clumpy halo of the Galaxy. The calculations are carried out in the context of two different scenarios for the distribution of clumps in the Galaxy and their concentrations, which result in very different conclusions.

Subject headings: cosmology: theory — dark matter — gamma rays: theory

1. INTRODUCTION

Most of the matter in the universe has yet to be observed in any frequency band, thus the name dark matter (DM). The evidence for the predominance of dark over visible matter comes mainly from the gravitational effects of the dark matter component. However, gravitational studies have been unable to shed light on the nature of the dark matter. Big bang nucleosynthesis constrains most of the dark matter to be of non-baryonic origin. This has encouraged the study of plausible new particle candidates for the dark matter. The best motivated among these candidates is the lightest supersymmetric particle, named the neutralino, $\chi$. Given the requirements of neutralino production in the early universe, it is possible to study the phenomenology of such dark matter candidates in detail (see, e.g., Jungman, Kamionkowski, & Griest 1996). In particular, the annihilation of neutralinos has often been considered a potential source of detectable secondaries: high-energy particles and electromagnetic radiation. In this sense, dark matter can be visible through the radiation caused by the annihilation secondaries (Berezinsky, Gurevich, & Zhybin 1992; Berezinsky, Bottino, & Mignola 1994; Gondolo & Silk 1999; Bergström et al. 1999; Gondolo 2000; Calcáneo-Roldán & Moore 2000; Bertone, Sigl, & Silk 2001; Bergström, Edsjö, & Ullio 2001; Blasi, Olinto, & Tyler 2003; Tyler 2002; Ullio et al. 2002; Tasitsiomi & Olinto 2002; Cesaroni et al. 2003).

Recent advances in cold dark matter (CDM) simulations have shown that the large-scale structure of the universe can be explained in terms of a hierarchical scenario in which large halos of dark matter are generated by the continuous merging of smaller halos (Ghigna et al. 1998; Moore et al. 1999; Klypin et al. 1999). In this picture, a dark matter halo is the superposition of a smooth component on a scale comparable with the virial radius of the forming structure and a clumped structure made of thousands of smaller mass halos. As we discuss below, this scenario can have important consequences for the detection of signals from neutralino-antineutralino ($\chi\bar{\chi}$) annihilation.

CDM simulations also show that most halos are well described by a density distribution with cusps at the center of each halo. The exact shape of the central cusp is still a matter of debate. Most recent simulations favor profiles with density cusps varying from the Moore profile (Moore et al. 1999) where $\rho_{DM}(r \to 0) \sim r^{-1.5}$ to a Navarro, Frenk, and White (NFW) profile (Navarro, Frenk, & White 1996) in which $\rho_{DM}(r \to 0) \sim r^{-1}$ (see also Power et al. 2003). The more concentrated the central cusp, the easier it is to detect annihilation products, since the annihilation rate is proportional to the square of the dark matter density. The existence of cuspy halos is still unclear, since observations of galaxy rotation curves provide no evidence of central cusps (see, e.g., Salucci 2001). However, the survival of cusps in galactic centers is highly dependent on the galaxy’s merger history, in particular, on the history of formation of galactic center black holes (Merrit & Milosavljevic 2003). The central regions of small-mass dark matter halos (i.e., DM clumps) are less affected by the dynamics of baryonic matter and less likely to have black hole mergers at their centers. Thus, a cuspy profile may well describe the density of DM clumps.
Another important piece of information is embedded in the spatial distribution and survival history of clumps on their way to the central part of the host galactic halo. Tidal interactions significantly affect clump distribution and structure, and these effects are only beginning to be resolved in CDM simulations for relatively large-mass clumps (Stoehr et al. 2002). Given the lack of a clear understanding of the present distribution of DM clumps in the Galaxy halo, we consider two different scenarios that bracket the present uncertainties. For simplicity we call these two approaches type I and type II. We show that the present uncertainties lead to large variations in the resulting gamma-ray signal.

In the type I scenario, the clump position in the host Galaxy determines its external radius. In the case of NFW and Moore profiles, the location of the core is then determined by assuming a fixed fraction of this external radius. In the type II scenario, the concentration parameter, defined as the ratio of the core radius to virial radius of a clump, is modeled as in Wechsler et al. (2004) for clumps for a given mass. We show that in this scenario the clumps are gradually destroyed on their way to the center of the Galaxy, such that the inner part of the Galactic halo is depleted of clumps. This second scenario seems compatible with numerical simulations (Power et al. 2003; Stoehr et al. 2002). The uncertainties on clump effects are only beginning to be resolved in CDM simulations.

2. DARK MATTER CLUMPS IN THE HALO

The dark matter density profiles can be written as follows:

\[
\rho_{\chi, \text{sis}}(r) = \rho_0 \left( \frac{r}{r_0} \right)^{-2},
\]

\[
\rho_{\chi, \text{Moore}}(r) = \frac{\rho_0}{(r/r_f)^{3/2} \left[ 1 + (r/r_f)^{3/2} \right]^2}.
\]

Inside \( r_{\text{min}} \), neutralino annihilations are faster than the cusp formation rate, so that \( \rho(r < r_{\text{min}}) = \rho(r_{\text{min}}) \) remains constant. To estimate \( r_{\text{min}} \), following Berezhnyk et al. (1992), we set the annihilation timescale equal to the free-fall timescale, so that

\[
r_{\text{min, sis}} = r_0 \left( \frac{\langle \sigma v \rangle \rho_0}{\sqrt{G M_{\chi}} r_0^{3/2}} \right)^{1/2},
\]

\[
r_{\text{min, Moore}} = r_0 \left( \frac{\langle \sigma v \rangle \rho_0}{G M_{\chi}} r_f^{3/2} \right)^{1/3},
\]

where \( \langle \sigma v \rangle \) is the neutralino annihilation cross section, \( G \) is Newton’s constant, and \( M_{\chi} \) and \( m_{\chi} \) are, respectively, the clump mass and the neutralino mass.

We modeled the smooth Galactic halo density with an NFW density profile (eq. [3]), with \( r_f = 27 \) kpc and \( \rho_0 \) determined by the condition that the dark matter density at the Sun’s position be \( \rho_{\text{DM}}(d_S) = 0.5 \times 10^{-25} \) g cm\(^{-3}\). The fundamental parameters of the clump density profile are the density normalization \( \rho_0 \), the clump radius \( r_0 \) and, in the case of Moore and NFW profiles, the clump fiducial radius \( r_f \). In order to fix these fundamental parameters we have considered two different scenarios (type I and II).

In the type I scenario, the radius of a clump with fixed mass is determined by its position in the Galactic halo. More specifically, the radius of the clump is defined as the radius where the clump density equals the density of the Galactic (smooth) dark matter halo at the clump position (namely, \( \rho_0 \)). The physical motivation for such a choice is to account for the tidal stripping of the external layers of the clump while the clump is moving in the potential of the host halo. For the NFW and Moore profiles, the fiducial radius \( r_f \) has been taken as a fixed fraction of \( r_0 \): \( r_f = 0.1 r_0 \).

In the type II scenario the external radius of the clumps is taken to be their virial radius, defined in the usual way:

\[
r_0 = r_{\text{vir}} = \left( \frac{3 M_{\chi}}{4 \pi \rho_{200}} \right)^{1/3},
\]

where \( \rho_{200} \) is 200 times the critical density of the universe \( \rho_c = 1.88 \times 10^{-29} \) h\(^2\) g cm\(^{-3}\). In this scenario, following Ullio et al. (2002), we have introduced the concentration parameter, defined as

\[
\xi = \frac{r_0}{r_{\text{-}2}},
\]

where \( r_{\text{-}2} \) is the radius at which the effective logarithmic slope of the profile is \( -2 \), set by the equation

\[
\frac{1}{\rho_0} \frac{d}{dr} \rho(r) = 0.
\]

The mass dependence of the concentration parameter used in our calculations is taken from Wechsler et al. (2004) and is plotted in Figure 1 for the present time (zero redshift). The general trend is for smaller clumps to have a larger
concentration parameter, reflecting the fact that they were formed at earlier epochs, when the universe was denser.

The normalization constant in the clump density profile $\rho_0$ is fixed recalling that the clump mass $M_c$ is

$$M_c = \int_0^{r_f} 4\pi r^2 \rho_c(r) \, dr.$$ 

In the case of the NFW density profile, $r_f = r_{-2}$, while in the case of the Moore density profile, $r_f = r_{-2}/0.63$ (Ullio et al. 2002). In terms of concentration parameters,

$$\xi_{\text{NFW}} = 0.63 \xi_{\text{Moore}}.$$ (8)

Using the concentration parameter plotted in Figure 1 for NFW clumps, we can estimate a stripping distance, which we define as the distance from the Galactic center where the density of a clump at the fiducial radius $r_f$ equals the density in the smooth halo. At the stripping distance, layers of the clump outside the fiducial radius are stripped off by the Galactic halo tidal forces. The stripping distance defined in this way is plotted in Figure 2.

From this estimate it is easy to see that most clumps in the inner parts of the host halo are stripped of most of their mass, so the number of clumps in the inner regions is very low. In fact, most clumps that are able to reach the central part of the Galaxy merge with the smooth dark matter profile. Only relatively low mass, older clumps can reach closer to the inner regions without significant disruption, since they are in general more concentrated and have denser cores. Numerical simulations show the disappearance of large clumps in the centers of galaxy-size halos, but they cannot resolve the smaller mass clumps that may eventually make their way into the core of the Galaxy. In order to bracket the plausible range in clump distributions, we make the very conservative assumption in scenario II that the inner 10 kpc of the Galaxy halo have no clumps at all.

3. GAMMA-RAY EMISSION

In order to determine the gamma-ray emission from the DM clumps, we model the distribution of clumps in the Galaxy with a fit to numerical simulations as in Blasi & Sheth (2000). The probability distribution function of clumps with a given mass and at a given position $d$ (measured from the Galactic center) is given by

$$N_c(d, M_c) = N_{c,0} \left( \frac{M_c}{M_h} \right)^{-\alpha} \left[ 1 + \left( \frac{d}{d_{sc}} \right)^2 \right]^{-3/2},$$ (9)

where $N_{c,0}$ is a normalization constant and $d_{sc}$ is the scale radius of the clump distribution (assumed to be 10 kpc as in Blasi & Sheth 2000). Simulations find that $\alpha \simeq 1.9$, and a halo like that of our Galaxy, with $M_h \simeq 2 \times 10^{12} M_\odot$, contains about 500 clumps with masses larger than $10^8 M_\odot$ (Ghigna et al. 1998).

The gamma-ray flux per unit solid angle and per unit energy along a fixed line of sight in the ($\theta$, $\phi$)-direction can be computed as

$$\Phi_{\gamma}(E_\gamma, \theta, \phi) = \frac{1}{4\pi} \int_0^{\pi} ds \int_{\gamma_{\min}}^{\gamma_{\max}} N_\gamma(d(s), M) N_c dM,$$ (10)

where $d(s) = (s^2 - 2sd_0 \cos \theta + d_0^2)^{1/2}$ is the distance of a generic point on the line of sight from the Galactic center (with $\theta$ as the angle between the direction $s$ and the Sun–Galactic center axis), $M$ is the clump mass, and $\gamma_{\max}$ is the maximum allowed mass for DM clumps in the halo. We use $\zeta = 0.01$, since the Milky Way halo does not show recent mergers of satellites with masses larger than $\sim 2 \times 10^{10} M_\odot$ (the Large Magellanic Cloud has about $9 \times 10^9 M_\odot$). The quantity $N_\gamma$ is the total number of photons emitted per unit time and energy by a DM clump of mass $M$. This quantity, depending on the scenario chosen for the clump density profile, may depend or not on the distance $d(s)$ of the considered point from the Galactic center. In the first scenario, the normalization of the clump density is related to the smooth halo density, $N_\gamma = N_{\gamma,0}(M, d, E_\gamma)$, while in the second scenario $N_\gamma = N_{\gamma,0}(M, E_\gamma)$. Note that equation (10) is an average over all possible realizations of a halo with its clumpy structure. Fluctuations around this value may be present because of the accidental proximity of a few clumps in the specific realization that we happen to experience in our Galaxy.

In principle, the neutralino annihilation production of gamma rays has a complex spectrum with contributions from a number of channels (for a recent example, see Cesare et al. 2003). Given that the uncertainties in the clump concentration induce very large variations in the total gamma-ray flux, we chose to...
calculate the gamma-ray spectrum by considering the dominant gamma-ray emission due to $\pi^0$ production from quark-antiquark pairs and neglected leptonic and bosonic channels. With this simplifying assumption we derive gamma-ray spectra that are in good agreement with Ullio et al. (2002) and Cesarini et al. (2003) for $m_\chi$ less than the $W$ boson mass and for $m_\chi$ above the top quark mass. The discrepancy between the simplified spectra we derive below and the fit by Berstrom et al. (2001) varies slightly with neutralino parameters, but stays within a factor of a few for neutralino masses from 10 GeV up to a few TeV.

The number of photons produced by quark-antiquark pairs with energy $E_\pi$ in a single $\chi \bar\chi$ annihilation can be written as follows:

$$\frac{dN_\pi}{dE_\gamma} = \int_{E_\pi,\text{min}}^{E_\pi,\text{max}} dE_\pi P(E_\pi, E_\gamma) \frac{dN_\pi}{dE_\pi}, \quad \text{(11)}$$

where $P(E_\pi, E_\gamma) = (E_\pi^2 - m_\chi^2)^{-1/2}$ is the probability per unit energy of producing a gamma-ray with energy $E_\gamma$ out of a pion with energy $E_\pi$. For the pion fragmentation function we assume the functional form introduced in Hill (1983):

$$\frac{dN_\pi}{dE_\pi} = \frac{15}{m_\chi} x^{-3/2} (1 - x)^2, \quad \text{(12)}$$

with $x = E_\pi/m_\chi$, $E_\pi, \text{max} = m_\chi$, and $E_\pi, \text{min} = E_\gamma + m_\pi^2/4E_\gamma$. Finally,

$$\frac{dN_\gamma}{dE_\gamma} = \frac{5}{4m_\chi} \int_{x,\text{min}}^{1} dx \frac{(1 - x)^2}{x^{3/2}(x^2 - \eta^2)^{1/2}}, \quad \text{(13)}$$

where $\eta = m_\pi/m_\chi$ and $x,\text{min} = E_\gamma/m_\chi + m_\pi^2/4E_\gamma$.

The neutralino annihilation rate per unit volume is

$$\Gamma_{\chi\bar\chi}(r, M, E_\gamma) = j_\gamma^2(r, M, E_\gamma)/m_\chi^2;$$

therefore, the gamma-ray emissivity $j_\gamma(r, M, E_\gamma)$ associated with the single clump of mass $M$ is obtained by multiplying equation (13) by $\Gamma_{\chi\bar\chi}$. The number of gamma rays produced per unit time and per unit energy in a single DM clump of mass $M$ is then

$$N_\gamma(M, E_\gamma) = \int_0^{r_0} dr 4\pi r^2 j_\gamma(r, M, E_\gamma). \quad \text{(14)}$$

4. RESULTS

In this section we present the gamma-ray emission resulting from the dark matter annihilation in the halo of our Galaxy, including both the smooth and clumped components introduced above. We detail the description of these results for the two scenarios (type I and II) of spatial distribution and concentration of the clumped component. The emission in type II scenarios is much weaker than that obtained in type I scenarios, because type I clumps have a much stronger concentration. In type II scenarios, the gamma-ray signal from clumps overcomes the gamma-ray flux from the smooth dark matter distribution only in the direction of the Galactic anticenter and only for SIS and Moore profiles for the dark matter distribution inside the clumps. On the other hand, in type I scenarios the contribution of the clumped component to the diffuse gamma-ray flux from the Galactic halo is several orders of magnitude above the smooth halo component, for any of the three density profiles considered above. This impressive difference in the predictions is symptomatic of a large uncertainty in the formation and survival of dark matter substructures.

In Figures 3 and 4 we plot the flux of gamma rays in type I and II scenarios in units of (GeV cm$^{-2}$ s sr)$^{-1}$ arriving on Earth averaged in all directions for $m_\chi = 100$ GeV and with $\langle \sigma v \rangle = 3 \times 10^{-27}$ cm$^3$ s$^{-1}$. The curves refer to the gamma-ray flux due to the full dark matter halo, including the smooth and the clumped components. In both figures the dotted, dashed, and solid lines correspond to SIS, Moore and NFW clump density profiles, respectively. The fluxes are obtained for a minimum clump mass of $M_{\chi,\text{min}} = 10^5 M_\odot$. The dependence of these fluxes on the value of $M_{\chi,\text{min}}$ is very weak. The diffuse flux is the convolution of the mass function of the clumps (slightly flatter than $\sim M^{-2}$) and the gamma flux from a single clump. For the three density profiles we study, the flux from a single clump scales as $\sim M^1$, thus, the diffuse flux scales logarithmically with $M_{\chi,\text{min}}$.

For the type II scenario, the gamma-ray flux contributed by the clumped component is comparable to the contribution of the smooth dark matter profile, while for the type I scenario, the clumpy component contribution is overwhelmingly larger than that due to the smooth component. Also shown is the EGRET bound on the extragalactic diffuse gamma-ray background (Sreekumar 1998), which is known from 30 MeV to $\sim 30$ GeV to fit

$$\frac{dN_{\text{eg}}}{d\Omega dE} = 1.36 \times 10^{-6} \left( \frac{E}{\text{GeV}} \right)^{-2.10} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. \quad \text{(15)}$$

Depending on the density profile the fluxes have different scalings with the neutralino parameters $m_\chi$ and $\langle \sigma v \rangle$:

$$\Phi_{\text{SIS}} \propto \langle \sigma v \rangle^{1/2} m_\chi^{-3/2}, \quad \Phi_{\text{NFW, Moore}} \propto \langle \sigma v \rangle m_\chi^{-3}. \quad \text{(16)}$$

These scalings are the same for the type I and II scenarios.

It is clear from Figures 3 and 4 that the comparison between our predictions and the observed diffuse background is meaningful only for the type I scenario, with highly concentrated clumps. In the second scenario, the fluxes are too low, with the
neutralino cross section times velocity (thermally averaged) vs. neutralino mass. Crosses show neutralino models from Tasitsiomi & Olinto (2002). Shaded regions are the allowed regions of neutralino parameters for type I scenarios for clumps with the labeled dark matter profiles (NFW, Moore, SIS). Models with parameters above the shaded regions are ruled out by the EGRET diffuse flux in type I scenarios.

for $m_{\chi} \gtrsim 30$ TeV, the region $\langle \sigma v \rangle \lesssim 10^{-32} (m_{\chi}/100$ GeV)$^3$ cm$^3$ s$^{-1}$ is allowed.

NFW clumps in the type I scenario are only weakly constrained. The bounds that can be placed by EGRET at 10 GeV are as follows: if $m_{\chi}$ is between 50 GeV and 3 TeV, the allowed region is defined by $\langle \sigma v \rangle \lesssim 10^{-26} (m_{\chi}/100$ GeV)$^{3/2}$ cm$^3$ s$^{-1}$. For $m_{\chi} \gtrsim 3$ TeV, the allowed region is instead $\langle \sigma v \rangle \lesssim 6 \times 10^{-29} (m_{\chi}/100$ GeV)$^3$ cm$^3$ s$^{-1}$. If we extrapolate equation (15) from 30 to 100 GeV, the bounds become: for $m_{\chi}$ between 50 GeV and 30 TeV, one must have $\langle \sigma v \rangle \lesssim 3 \times 10^{-27} (m_{\chi}/100$ GeV)$^{3/2}$ cm$^3$ s$^{-1}$, while for $m_{\chi} \gtrsim 30$ TeV, the allowed region becomes $\langle \sigma v \rangle \lesssim 5 \times 10^{-31} (m_{\chi}/100$ GeV)$^3$ cm$^3$ s$^{-1}$. All these bounds are shown in Figure 5.

An important signature of the diffuse gamma-ray emission from dark matter annihilation in the halo of our Galaxy is the anisotropy due to the off-center position of the solar system compared to the center of the dark matter distribution. The anisotropies for the type I and type II scenarios are shown in Figures 6 and 7 respectively, where we have plotted the energy

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1 Review at http://www.physto.se/~edsjo/darksusy/doc.html.

2 See http://www.physto.se/~edsjo/darksusy.
integrated flux above 100 MeV versus \( \cos(\theta) \) (equal to 1 in the direction of the Galactic center). In these plots an isotropic flux would appear as a flat line. The energy-integrated flux on the \( y \)-axis is defined as

\[
I(\theta) = \frac{1}{2\pi} \int_{E_{\gamma, \min}}^{E_{\gamma, \max}} dE_\gamma \int_0^{2\pi} d\phi \Phi_\gamma(E_\gamma, \theta, \phi), \tag{17}
\]

where \( \Phi_\gamma(E_\gamma, \theta, \phi) \) is obtained from equation (10).

From Figure 6 one can see that a large anisotropy is predicted for the type I scenario. The curves plotted there refer to the case of \( m_\chi = 100 \) GeV and \( \langle s v \rangle = 3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \). The solid, dashed, and dotted lines refer to NFW, Moore, and SIS profiles, respectively, while the thick curve shows the contribution to the gamma-ray flux due to the smooth component in the direction defined by \( \cos \theta \).

In Figure 7, we plot the same curves for the scenario of type II. The anisotropies obtained in this case are clearly smaller than the previous case, as indicated by the almost flat lines. This is due to our conservative assumption that there are no clumps in the inner 10 kpc of the Galaxy. In this case, the contribution of the clumps to the gamma-ray flux is never dominant over the smooth component for clumps with an NFW profile, while for the SIS, the clump emission is always dominant. For clumps with a Moore profile, the clumpy component

overcomes the smooth component in the region around the Galactic anticenter.

5. CONCLUSION

The annihilation of dark matter in the halo of our Galaxy generates a diffuse background of gamma rays. The dark matter substructure of the Galactic halo can be a dominant component of the diffuse gamma-ray flux depending on the concentration and location of DM clumps in the inner regions of the Galactic halo.

In order to bracket the range of possible fluxes, we considered two extreme scenarios, which we named type I and type II. The first corresponds to extremely concentrated clumps present everywhere in the Galactic halo, while in the second scenario the clumps are much less concentrated and are completely destroyed by tidal effects in the inner 10 kpc of the Galaxy. While the type I scenario allows one to put very strong constraints on the properties of neutralinos and on the density profile inside clumps, the type II scenario generates fluxes of diffuse gamma rays that are barely detectable, with the exception of the case in which the density profile of the clumps is modeled as an SIS sphere.

For the type I scenario, most of the parameter space of neutralino dark matter is ruled out if the density profile of dark matter clumps is in the form of an SIS sphere or a Moore profile. Weaker bounds can be imposed on the neutralino parameter space in the case of an NFW density profile.

Recent N-body simulations have started to gather evidence of the destruction of clumps in the inner regions of dark matter halos, which favor type II–like scenarios. On the other hand, numerical simulations only resolve relatively high mass clumps, and the distribution of more concentrated smaller clumps is yet to be understood, although there is some recent progress in this direction (Berezinsky, Dokuchaev, & Eroshenko 2003). Finally, one should keep in mind the possibility of detecting isolated nearby clumps with atmospheric Cerenkov telescopes (Tasitsiomi & Olinto 2002), which may be more promising than looking at diffuse fluxes.

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REFERENCES

Berezhnysky, V., Bottino, A., & Mignoila, G. 1994, Phys. Lett. B, 325, 136
Berezhnysky, V., Dokuchaev, V., & Eroshenko, Y. 2003, preprint (astro-ph/0301551)
Berezhnysky, V., Gurevich, A. V., & Zybin, K. P. 1992, Phys. Lett. B, 294, 221
Bergström, L., Edsjo, J., Gondolo, P., & Ullio, P. 1999, Phys. Rev. D, 59, 054506
Bergström, L., Edsjo, J., & Ullio, P. 2001, Phys. Rev. Lett., 87, 251301
Bertone, G., Silk, G., & Salucci, P. 2001, MNRAS, 326, 799
Blasi, P., Olinto, A. V., & Tylcer, C. 2003, Astropart. Phys., 18, 649
Blasi, P., & Sheth, R. K. 2000, Phys. Lett. B, 486, 233
Clineo-Roldán, C., & Moore, B. 2000, Phys. Rev. D, 62, 123505
Cesarini, A., Fucito, F., Lionetto, A., Marselli, A., & Ullio, P. 2003, Astropart. Phys., submitted (astro-ph/0305075)
Ellis, J., Olive, K. A., Santoso, Y., & Spanos, V. C. 2003, Phys. Lett. B, 565, 176
Ghigna, S., Moore, B., Governato, F., Lake, G., Quinn, T., & Stadel, J. 1998, MNRAS, 300, 146
Gondolo, P., & Silk, J. 1999, Phys. Rev. Lett., 83, 1719
Hagiwara, K., et al. 2002, Phys. Rev. D, 66, 010001
Hill, C. T. 1983, Nucl. Phys. B, 224, 469
Jungman, G., Kamionkowski, M., & Griest, K. 1996, Phys. Rep., 267, 195
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Merritt, D., & Milosavljevic, M. 2003, in DARK 2002: 4th Int. Heidelberg Conf. on Dark Matter in Astro and Particle Physics, ed. H. V. Klipdor-Kleingrothaus & R. Viollier (Berlin: Springer), 79
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Navarro, J. F., & White, S. D. M. 1996, ApJ, 462, 563 (erratum 490, 493 [1997])
Power, C., Navarro, J. F., Jenkins, A., Frenk, C. S., White, S. D. M., Springel, V., Stadel, J., & Quinn, T. 2003, MNRAS, 338, 14
Salucci, P. 2001, MNRAS, 320, L1
Sreekumar, P., et al. 1998, ApJ, 494, 523
Stoehr, F., White, S. D. M., Tormen, G., & Springel, V. 2002, MNRAS, 335, L84
Tasitsiomi, A. 2002, preprint (astro-ph/0205464)
Tasitsiomi, A., & Olinto, A. V. 2002, Phys. Rev. D, 66, 083006
Tyler, C. 2002, Phys. Rev. D, 66, 023509
Ullio, P., Bergström, L., Edsjo, J., & Lacey, C. 2002, Phys. Rev. D, 66, 123502
Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2004, in Proc. Marseille 2001 Conf., Where’s the Matter? Tracing Dark and Bright Matter with the New Generation of Large Scale Surveys, ed. M. Treyer & L. Tresse, in press