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WIMPs are stronger when they stick together

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Abstract. Weakly interacting massive particles (WIMPs) remain the strongest candidates for the dark matter in the Universe. If WIMPs are the dark matter, they will form a clumpy halo around our Galaxy according to the hierarchical clustering observed in CDM simulations. The clumpy nature of the halo can enhance the probability of detecting WIMP dark matter through the annihilation products. We show that the synchrotron radiation of electrons and positrons generated as decay products of WIMP annihilation in the Galactic magnetic field can be detected by microwave background experiments. Depending on the density profile of dark matter clumps, hundreds of clumps have detectable fluxes and angular sizes.

1 Introduction

The density of dark matter in the present Universe is observed via its gravitational effects on galaxies and clusters of galaxies to constitute at least about 30% of the critical density of the Universe but the nature of this dark matter is still unknown. Primordial nucleosynthesis constrains the density of baryonic matter to be less than about 5% of the critical density, thus most of the dark matter is non-baryonic. The leading candidate for the dark matter is a weakly interacting massive particle (WIMP) present in supersymmetric extensions of the standard model named the neutralino, χ (for a review, see Jungman, Kamionkowski and Griest (1996)).

Neutralinos may be detected directly as they traverse the Earth or indirectly by the observation of their annihilation products. Direct neutralino searches are now underway in a number of low temperature experiments with no consensus detection as of yet. Indirect searches have been proposed both for gamma-rays and synchrotron emission from the annihilation of WIMPs in the Galactic Center (Berezinsky, Gurevich, and Zybin, 1992; Berezinsky, Bottino, and Mignola, 1994) where the location and magnetic field around a central massive black hole may enhance the emission significantly (Gondolo and Silk, 1999; Gondolo , 2000). The annihilation process is proportional to the neutralino density squared ($\sim n_\chi^2$), therefore, the strongest flux is expected to come from the Galactic Center where the dark matter halo density peaks.

N-body cold dark matter (CDM) simulations have shown that the dark matter halo can be well modeled by a power law density profile such as the NFW halo (Navarro, Frenk and White, 1996,1997). Superimposed on the smooth component, the high-resolution simulations find a large degree of substructure formed due to the constant merging of smaller halos to form the present dark matter halo (see, for example, Ghigna et al. (1998)). The large number of clumps generated through the hierarchical clustering of dark matter comprise about $\sim 10-20\%$ of the total mass and can enhance significantly the emission of gamma-rays and neutrinos from neutralino annihilation in the higher density clumps (Bergström et al., 1999; Calcáneo–Roldán and Moore, 2001). We show here (and in more detail in Blasi, Olinto and Tyler (2001)) that the synchrotron radiation of electrons and positrons generated as decay products of WIMP annihilation in the Galactic magnetic field can be detected by microwave experiments. Depending on the density profile of dark matter clumps, hundreds of clumps have detectable fluxes and angular sizes.

2 Synchrotron Signature of WIMP clumps

The annihilation of neutralinos produces a large numbers of high energy particles that can be directly observed, such as gamma rays and neutrinos, or that can radiate in background magnetic fields such as electrons and positrons. Neutralinos annihilate into QCD jets that generate large numbers of pions ($\chi\bar{\chi} \rightarrow q\bar{q} \rightarrow \pi^\pm\ \pi^0\ n\ p...$). The decay of charged pions produce electrons and positrons ($\pi^\pm \rightarrow \mu^\pm\ \nu_\mu$ and $\mu^\pm \rightarrow e^\pm\ \nu_e\ \nu_\mu$) that radiate synchrotron photons in background magnetic fields. We calculated the synchrotron emission of

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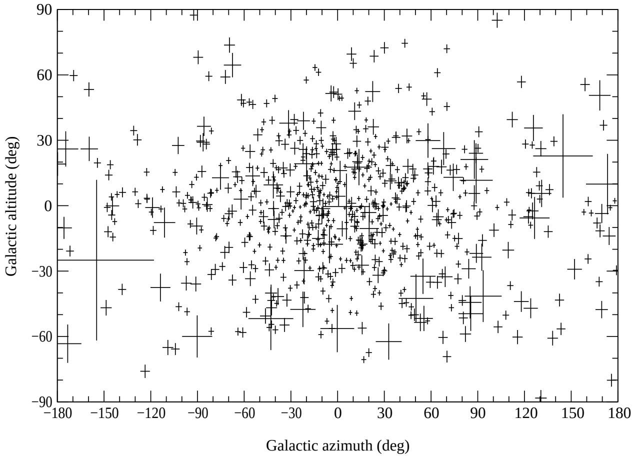

Fig. 1. Locations for 754 observable dark matter clumps, i.e., with fluxes higher than CMB anisotropies between 1 and 1000 GHz. This realization of the Galactic halo follows a NFW profile and contains 3972 total clumps with $M_{cl} \geq 10^7 M_\odot$. Crosses represent the solid angle of each clump (multiplied by a factor of 5) inside which 90% of the flux is located.

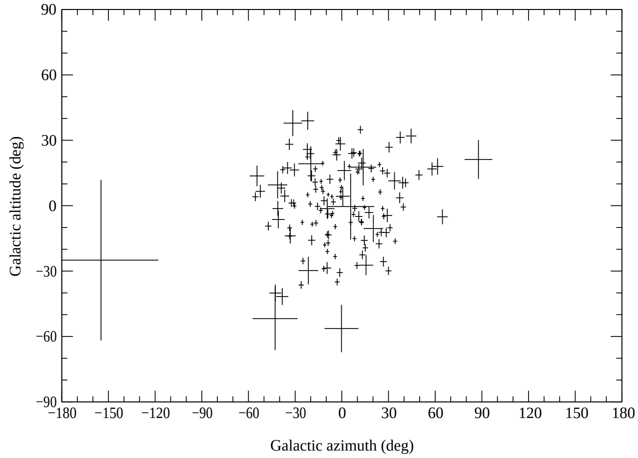

Fig. 2. Same as Fig. 1 but for fluxes higher than CMB anisotropies between 10 and 400 GHz.

the electrons and positrons generated by WIMP annihilation in the dark matter clumps as the clumps get brightened by the magnetic field of the Galaxy. We initially assume that the electrons emit in the same region which they are generated at, which is the case when $e^\pm$ are magnetically constrained in the higher magnetic field regions. As the field decays, the diffusion of the emitting $e^\pm$ need to be included (see Blasi, Olinto and Tyler (2001)).

The spectrum of the generated $e^\pm$ naturally cuts off at about the neutralino mass, m_χ. Therefore, the relevant frequency range for $e^\pm$ synchrotron emission lies below the maximum frequency,

$$\nu_{\max} \simeq B_\mu (m_\chi/100 \text{ GeV})^2 \text{GHz} , \quad (1)$$

where $B_\mu = B/\mu$G. Since the Galactic magnetic field is around 6μG in the disk, for $m_\chi \gtrsim 100$ GeV, the radiation will range up to microwave frequencies $\nu_{\max} \sim 10$ GHz.

In our calculations, we assumed that the Galactic magnetic field has an exponential scale height as in Stanev (1997). To model the smooth halo component, we considered the NFW halo profile

$$\rho_{\text{halo}} = m_\chi n_0 \left(\frac{r}{r_c}\right)^{-1} \left[1 + \frac{r}{r_c}\right]^{-2} , \quad (2)$$

where r_c is the core radius and n_0 is the number density at r_c. The two parameters, r_c and n_0, can be set by requiring that the halo contains a given total mass (M_H) and that the velocity dispersion at some distance from the center is known (in the case of the Galaxy, the velocity dispersion is ~ 200 km/s in the vicinity of our solar system).

We modeled the clumpy halo following Blasi and Sheth (2000) where they fit the simulations to a joint distribution of clump mass, m, and position, r, by

$$n_{cl}(r,m) = n_{cl,0} \left(\frac{m}{M_H}\right)^{-\alpha} \left[1 + \left(\frac{r}{r_c^{cl}}\right)^2\right]^{-3/2} , \quad (3)$$

where $n_{cl,0}$ is a normalization constant, r_c^{cl} is the core of the clumps distribution, and $\alpha \sim 1.9$ fits well the simulations in Ghigna et al. (1998). In Ghigna et al. (1998), a halo with $M_H \approx 2 \times 10^{12}\ M_\odot$ contains about 500 clumps with mass larger than $M_{cl} \sim 10^8\ M_\odot$. We studied two cases for the profiles of individual clumps: a NFW profile (like the smooth halo component) and a singular isothermal sphere (SIS) profile ($\rho_{cl}(r) \propto 1/r^2$). Here we report the results for the NFW case and both cases are discussed in Blasi, Olinto and Tyler (2001) in more detail. Clumps in the parent NFW halo are truncated when their density equals the smooth halo density.

We simulated several realizations of a clumpy halo each with about 4000 clumps of masses $M_{cl} \geq 10^7 M_\odot$. Figure 1 shows one realization with 3972 clumps in Galactic coordinates. In this realization, 754 have synchrotron fluxes above the flux of CMB anisotropies in the range 1 to 1000 GHz and 132 of those are above 30 degrees Galactic latitude (or below -30). The clumps range in angular sizes from the size of a pixel (10'x10') to 10 degrees, occupying 2% of the solid angle of the sky. The crosses shown in the figure represent the solid angle (amplified by a factor of 5 for clarity) inside which 90% of the radiation for each clump is located. Figure 2 shows the location and solid angles of clumps that are observable with frequencies between 10 and 400 GHz. This range is expected to be relatively quiet of CMB foregrounds (see, e.g., Tegmark et al. (2000)), therefore the most sensitive CMB anisotropy experiments are planned for this range in frequency.

The histogram in Fig. 3 shows the number of clumps observable (fluxes higher than CMB anisotropies between 10 and 400 GHz) of different solid angles. There are over 100 clumps that can be observed by experiments with angular resolution around 0.2 degrees. A few very large objects can

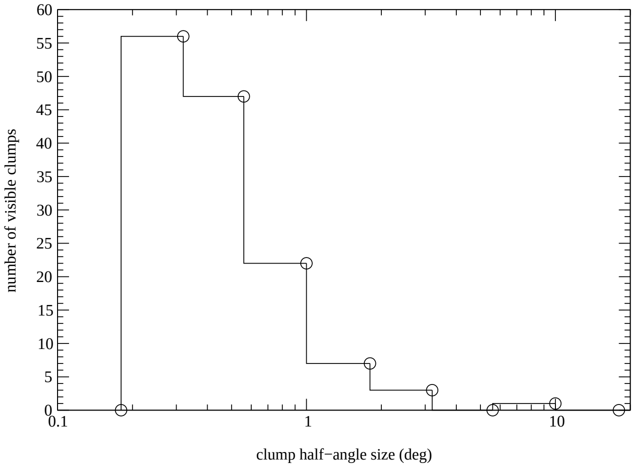

Fig. 3. Number of clumps of each angular size with fluxes above CMB anisotropies between 10 and 400 GHz.

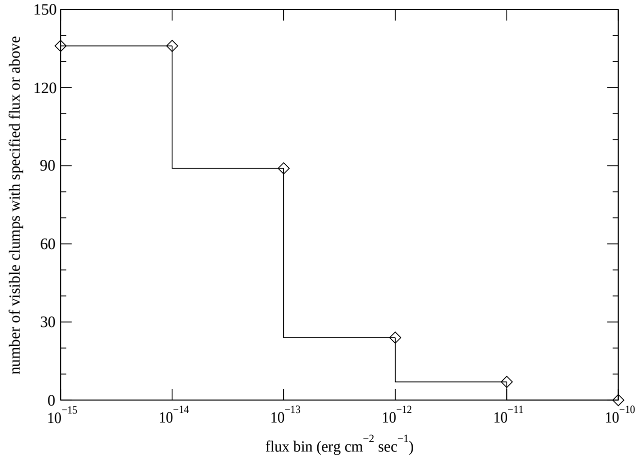

Fig. 4. Number of observable clumps with total flux in the specified flux bin or above.

be seen even by experiments with poor angular resolution. These correspond to clumps located close to Earth. If a large object is identified in this frequency range, a spectral study would verify its nature as a dark matter clump. In addition, the radial dependence of the flux within the clump could further constrain CDM clustering behavior.

Figure 4 shows a histogram of the number of observable clumps with total flux in or above a given energy bin. The histograms in Figs. 3 and 4 were generated for the same realization in Fig. 1. For different realizations see Blasi, Olinto and Tyler (2001). The behavior shown in these figures are generic and can act as guides to determine if microwave sources are annihilating dark matter clumps or some other foreground.

As an example of the spectral dependence of the synchrotron emission from WIMP annihilation, we show in Figure 5 the spectrum of a dark matter clump (thick line) compared with the CMB anisotropies (thin line) in the same solid angle occupied by the clump. This clump is chosen to lie at galactocentric coordinates [-4,0,0] kpc (where the Sun is located at [-8.5,0,0]), with $10^8 M_\odot$, occupying a half-angle of 1 degree on the sky. The neutralino mass was chosen to be 100 GeV. The dashed line shows the case of a neutralino with 10 TeV for comparison. The cutoff is moved to higher frequencies as expected from Eq. (1). In a annihilating dark matter were to be observed, the cutoff give us the neutralino mass directly. The dotted line shows the flux for the same clump with $m_\chi = 100$ GeV but with the interaction strength, given by the WIMP annihilation cross section times WIMP velocity, $\sigma_{\chi\bar{\chi}} v_\chi$, increased by a factor of 100.

3 CONCLUSIONS

The clumpy nature of CDM halos can be used to detect and constrain WIMP candidates for the non-baryonic dark matter. Neutralino annihilation in the higher density clumps can be observed via the synchrotron radiation of electrons and positrons as these annihilation products radiate in the Galactic magnetic field. The spatial structure of the Galactic magnetic field implies that the synchrotron emission from annihilation gets stronger as clumps get closer to the Galactic plane. This behavior gives a different angular distribution than the distribution from the gamma-ray signature of the same clumps. This unique combination will help distinguish WIMP clumps from other extragalactic gamma-ray sources. The frequency range where these clumps are better observed overlaps with highly sensitive experiments planned for CMB anisotropy measurements. The possibility of detecting these clumps will be soon within reach. Depending on the density profile of dark matter clumps, hundreds of clumps have detectable fluxes and angular sizes. Even more clumps may be present if the lower limit on clump masses is lowered from $10^7 M_\odot$.

The spectral shape, spatial distribution, and angular size of annihilating neutralino clumps discussed above represent some particular choices of m_χ and $\sigma_{\chi\bar{\chi}} v_\chi$ which are hard to constrain a priori. The neutralino mass sets the cutoff of the spectrum and changes the overall flux while the cross section influences mostly the flux amplitude. Finally, the Galactic magnetic field structure above and below the plane of the Galaxy is poorly known and will also influence the exact observable clump distribution. The best strategy is to search for varying sizes of CMB foregrounds at a number of frequencies and select for those with the spectral dependence give in Fig. 5. Once some extended synchrotron sources have been selected, the particular radial distribution and flux shape will help determine if these sources are dark matter clumps. The combination of these synchrotron measurements with the direct gamma-ray and neutrino signature will make these unique sources. In addition, the synchrotron signature will help determine the structure of the magnetic field above the Galactic disk.

Future CMB experiments such as MAP and Planck can be used in conjunction with future gamma-ray and neutrino experiments. Full sky coverage helps this determination since

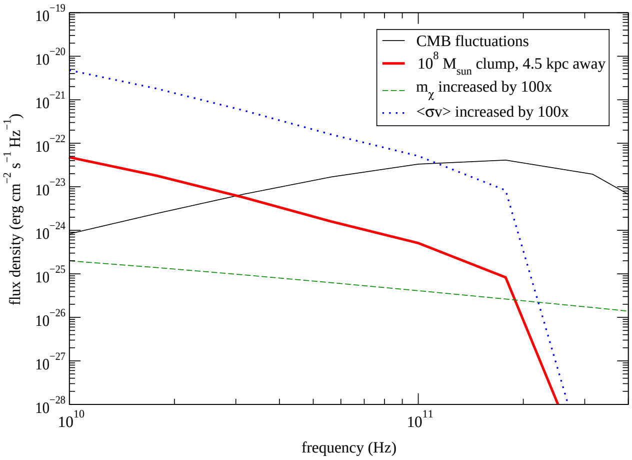

Fig. 5. Spectrum of synchrotron emission from an example NFW dark matter clump with $m_\chi = 100$ GeV (thick line) compared with the CMB anisotropies (thin line) in the same solid angle occupied by the clump. This clump is chosen to lie at galactocentric coordinates [-4,0,0] kpc, with $10^8 M_\odot$, occupying a half-angle of 1 degree on the sky. The flux from the same clump but with $m_\chi = 10$ TeV is represented by the dashed line and the dotted line is for $m_\chi = 100$ GeV and $\sigma_{\chi\bar{\chi}} v_\chi$ increased by a factor of 100.

the Galactic plane is usually avoided by small area experiments. MAP will observe above about 20 GHz while Planck should start at 30 GHz with an large increase in angular resolution will make these object easy to detect.

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