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Dark matter annihilation and enhancement effect of substructures

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Abstract: The observations of Galactic cosmic rays such as positrons and antiprotons provide us a possibility to detect the dark matter in the Galaxy, the so-called indirect detection. We calculate the Galactic positron and antiproton fluxes from dark matter annihilation in the frame of supersymmetry, taking the enhancement effect by existence of dark matter substructures into account. The propagation of cosmic rays in the Galactic medium is calculated using a realistic numerical model GALPROP. The background (secondary) fluxes of these kinds of cosmic rays are also calculated in the same GLAPROP model. We find that the expectations are in good agreement with the observational data if we take a cuspy density profile of the dark matter substructures.

Introduction

The evidence of the existence of dark matter (DM) in the universe is overwhelming. Nowadays what people are more interested in is to find what DM particle is, instead of confirming its existence further more. DM particle is thought to be non-bayonic, chargeless and colorless. No electromagnetic interaction makes it difficult to be detected. For a long time the nature of DM is one of the most outstanding puzzles in particle physics and cosmology.

During the past several decades many candidates of DM are proposed in literatures [1]. The most attractive one is the lightest supersymmetric particle (LSP), usually the neutralino, arising in the minimal supersymmetric extensions of the standard model (MSSM). Neutralino is a combination state of the superpartners of the neutral gauge and Higgs bosons, and with the mass of weak scale. The self annihilation of neutralinos can produce ordinary particles such as γ-rays, electrons, positrons, protons, antiprotons and neutrinos, which are possible to be detected. Since positrons, antiprotons and diffuse γ-rays are secondary particals in the cosmic rays (CRs) with low flux, these kinds of DM annihilation products are easier to be distinguished from the astrophysical background. That is why people focus on these kinds of particles when studying DM.

Observations of positrons by the balloon-borne instrument HEAT, and Galactic diffuse γ-rays by EGRET on CGRO both showed some excesses at energies above several GeV, compared with the expectations of conventional astrophysical model [2, 3]. The same was also seen for antiproton [4]. It is thought that the excesses may come from the signal of DM annihilation. Some studies on this topic showed encouraging results [5, 6], although there were still problems such as the “boost factor”. In this work we reexamine this problem for positrons and antiprotons, under the framework of supersymmetry (SUSY). The enhancement of flux from DM substructures is taken into account, and a realistic numerical model GALPROP is used to calculate the propagation of CRs. It is shown that the expectation can reproduce the measurements well when taking a cuspy density profile of the DM substructures [7].

Neutralino Annihilation

Positrons or antiprotons can be produced from the decay of gauge bosons generated in chanels $\chi\chi \to ZZ$, $\chi\chi \to W^+W^-$, or from the the cascades of the final state fermions and Higgs bosons. The annihilation spectra depend on the neutralino mass and its annihilation modes. The source function of positrons or antiprotons from DM annihilation can be written as

$$Q(E,\mathbf{r}) = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{\mathrm{d}n}{\mathrm{d}E}\rho^2(\mathbf{r}), \qquad (1)$$

where σ is the annihilating cross-section, v is the relative velocity between a pair of neutralinos, $\mathrm{d}n/\mathrm{d}E$ is the spectrum of positrons or antiprotons in one event of annihilation and $\rho(\mathbf{r})$ is the DM density distribution in space. The annihilation spectrum of the source term is calculated using the package DarkSUSY [8]. Figure 1 shows the local source terms of positrons for three SUSY model with mass of neutralino $m_\chi = 121, 195, 242$ GeV.

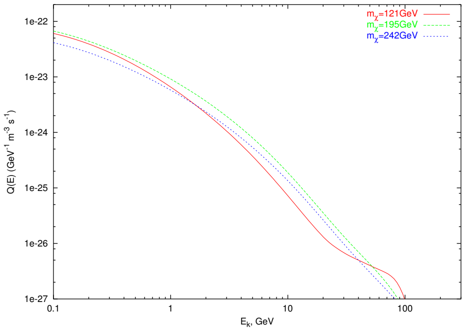

Figure 1: The local annihilation sources $Q(E)$ of positrons for three neutralino models with mass $m_\chi = 121, 195, 242$ GeV.

Dark Matter Distribution

Based on the N-body numerical simulation the DM density profile can be expressed in a general form as

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

where ρ_s and r_s are the scale density and scale radius respectively. The shape parameters (α, β, γ) are taken to be NFW type (1, 3, 1) or Moore type (1.5, 3, 1.5). However, the simulation also showed that the shape parameter may not be universal. Reed et al. showed that $\gamma = 1.4 - 0.08\log(M/M_*)$ increases for haloes with smaller masses [9]. Therefore we also adopt a $\gamma = 1.7$ profile for the subhaloes considered (see below). We use a semi-analytic model of Bullock et al. to determine the parameters ρ_s and r_s [10].

High resolution simulations showed that there are a large number of self-bound substructures survived in the galactic haloes. The masses of these kinds of substructures span from the heaviest of about 1% of the halo virial mass to the lightest of about Earth mass. The spatial distribution of the number density of subhaloes is taken to be isothermal and the mass function is taken to be a power law:

$$n(m_{\rm sub}, r) = n_0\left(\frac{m_{\rm sub}}{M_{\rm vir}}\right)^{-1.9}(1+(r/r_H)^2)^{-1}, \qquad (3)$$

where $M_{\rm vir}$ is the virial mass of the MW, n_0 is the normalization factor determined by requiring the number of subhaloes with mass larger than $10^8 M_\odot$ is about 500 in a halo with $M_{\rm vir} = 2\times10^{12}M_\odot$ [11]. The density distribution inside the subhalo is also described using Eq.(2). We use the average density square $\langle\rho^2(\mathbf{r})\rangle = \rho^2_{\rm smooth}(\mathbf{r}) + \langle\rho^2_{\rm sub}(\mathbf{r})\rangle$ to substitute the $\rho^2(\mathbf{r})$ term of Eq.(1), with $\langle\rho^2_{\rm sub}(\mathbf{r})\rangle = \int n(m_{\rm sub}, r)(\int\rho^2_{\rm sub}\mathrm{d}V)\cdot\mathrm{d}m_{\rm sub}$.

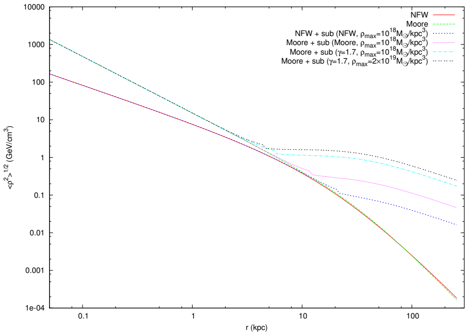

Figure 2: $\langle\rho^2(\mathbf{r})\rangle^{1/2}$ distributions for various DM profiles.

In Figure 2 we plot the average density square $\langle\rho^2(\mathbf{r})\rangle^{1/2}$ for several DM halo profiles. Because the annihilation source is square-dependent with the DM density, the clumpiness of DM will effectively enhance the annihilation signals, and can play the role of a "boost factor", which can be seen directly from this figure. Note that at small radii there is no enhancement compared to the smooth component, this is because the tidal disruption makes the subhaloes be difficult to survive in inner Galaxy.

The Propagation

The propagation of charged CR particles in Galactic magnetic field is diffusive. In addition they will experience energy loss or gain (reacceleration) processes. The complexity of the real distribution of interstellar gas and radiation field makes it difficult to get the analytical solution of the propagation equation. We use the numerical package GALPROP [12] to solve the diffusive propagation equation of CRs in Galaxy. The propagation parameters are adjusted to fit the observational B/C ratio, electron and proton spectra et al. Then the same propagation parameters are used to calculate the propagation of positrons and antiprotons, both the secondaries generated from the interaction between CRs and the interstellar medium and the primaries from DM annihilation.

Results and Dicussion

The positron fluxes for the $m_\chi = 121 GeV$ model for different DM profiles are plotted in Figure 3. It is shown that the cuspier profiles indeed produce more positrons, which can also be seen in Figure 2. Compared to the smooth Moore profile, the profile with $\gamma = 1.7$ subhaloes can contribute about 5 times higher to the flux at high energies.

Based on the same propagation model, we calculate the background electron and positron fluxes. The positron fractions for Moore profile without and with subhaloes are shown in Figures 4 and 5, together with the HEAT observations. If the DM substructures are taken into account, the calculation are better fitted with the data, as shown in Figure 5. In order to match the low energy observations, we introduce the solar modulations with $\Phi = 800$ MV and 600 MV for positrons and electrons respectively.

However, the best fit to the HEAT data still requires an "adjustment factor" of 9.2 or 2.5 for the model without or with subhaloes. We don't

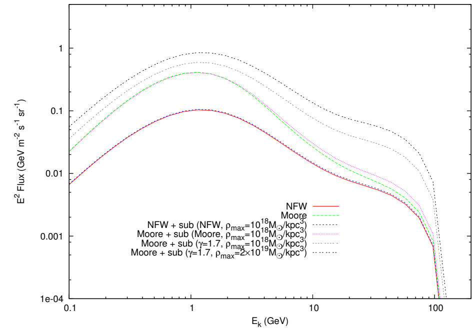

Figure 3: Positron flux on Earth for various DM profiles. The mass of neutralino is $121 GeV$.

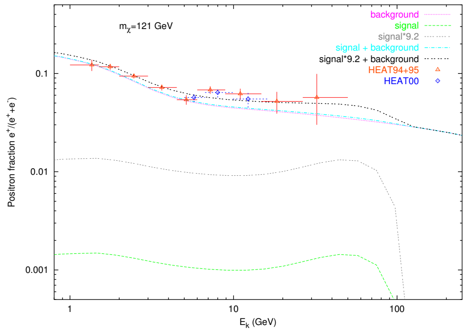

Figure 4: Positron fraction $e^+/(e^+ + e^-)$ calculated in this work. The Moore DM profile without subhaloes is adopted; the mass of neutralino is 121 GeV. Data points are HEAT measurements in the three fights in 1994, 1995 and 2000 [2, 13].

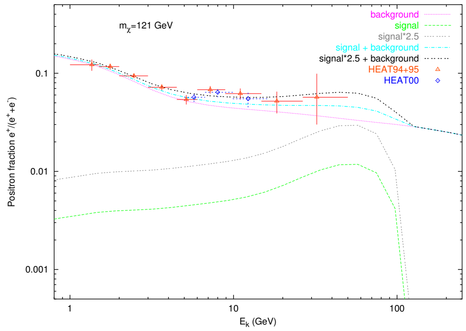

Figure 5: The same as Figure 4, but for DM profile with subhaloes of $\gamma = 1.7$.

think the discrepancy of a factor 2.5 is serious since there are large uncertainties in calculating the positron fluxes. Firstly there are uncertainties for the positron propagation [7]. Secondly the random distribution of DM subhaloes may have large variance [14], here we just give the average positron flux. Thirdly the SUSY model can also lead to uncertainty. In fact for a $m_\chi = 195 GeV$ model only a factor 1.2 is needed to fit the data.

The antiproton spectra are shown in Figure 6, together with the observational data of BESS [15]. The sum of the signal from DM annihilation and the background is in good agreement with the measurements. The result of only a smooth Moore profile is also plotted in this figure. The enhancement effect of the substructures on the antiproton flux is ~ 2 times, which is less significant than the case of positrons. The reason is probably that the differences between models with and without subhaloes are smaller in the inner Galaxy than in the solar neighborhood as shown in Figure 2. The antiprotons have longer propagation length and can trace the DM distribution farther away from the solar location.

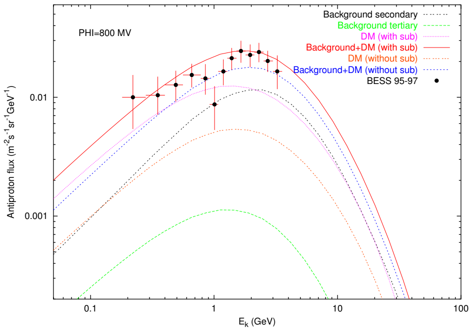

Figure 6: The local antiproton spectrum calculated in this work and comparison with the observational results of BESS [15]. The DM distribution model is the same as in the calculation of positrons.

In summary, we give a self-consistent calculation of the local positron and antiproton spectra, including the contribution from DM annihilation. The results are consistent well with the observations. But we can note that the observations till today are of big uncertainties and in a relative narrow energy range. More data of higher accuracy and wider energy band are expected to constrain the model more strictly. It is also shown that the CRs are powerful tools for the indirect search of DM, if better observations and better understanding of the background are available.

Acknowledgements

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