Indirect Detection of Neutralino Dark Matter

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Abstract. Dark matter detection experiments are getting ever closer to the sensitivity needed to detect the primary particle physics candidates for nonbaryonic dark matter. Indirect detection methods include searching for antimatter and gamma rays, in particular gamma ray lines, in cosmic rays and high-energy neutrinos from the centre of the Earth or Sun caused by accretion and annihilation of dark matter particles. A review is given of recent progress, both on the theoretical and experimental sides.

I INTRODUCTION

The mystery of the dark matter is one of the outstanding questions in standard cosmology [1]. One of the favoured particle dark matter candidates is the lightest supersymmetric particle $\chi$, assumed to be a neutralino, i.e. a mixture of the supersymmetric partners of the photon, the $Z$ and the two neutral $CP$-even Higgs bosons present in the minimal extension of the supersymmetric standard model. The attractiveness of this candidate stems from the fact that its generic couplings and mass range naturally give a relic density in the required range to explain halo dark matter. Besides, its motivation from particle physics has recently become stronger due to the apparent need for 100 GeV - 10 TeV scale supersymmetry to achieve unification of the gauge couplings in view of LEP results. (For a thorough review of supersymmetric dark matter, see [2].)

When using the minimal supersymmetric standard model in calculations of relic dark matter density, one should make sure that all accelerator constraints on supersymmetric particles and couplings are imposed. In addition to significant restrictions on parameters given by LEP [3], the measurement of the $b \rightarrow s\gamma$ process is providing important bounds.

The relic density calculation in the MSSM for a given set of parameters is nowadays accurate to 10 % or so. A recent important improvement is the inclusion of coannihilations, which can change the relic abundance by a large factor in some instances [4].
II INDIRECT DETECTION TECHNIQUES

In principle, all stable particles produced in annihilation processes in the halo can serve as signatures of a neutralino dark matter candidate. However, electrons and protons are much too abundant in the ordinary cosmic rays to be useful. Much lower background fluxes, and therefore greater potential for detection of an additional component, are present in the case of positrons and antiprotons. The problem is still that the signal does not have a distinct spectral signature (and magnetic fields in the galaxy cause a diffusion and complete isotropisation of the interstellar flux). The featureless energy distribution of positrons and antiprotons is due to the fact that the primary annihilation processes are into quarks, heavy leptons, gauge bosons and Higgs particles, whereas the positrons and antiprotons are secondary or tertiary decay products. The reason for the small direct coupling to electron-positron pairs is the Majorana nature of the neutralino coupled with the fact that the annihilation takes place essentially at rest. Selection rules then force the coupling to fermions to be proportional to the fermion mass.

There has recently been a new balloon-borne detection experiment [6], with increased sensitivity to eventual positrons from neutralino annihilation, and an excess of positrons over that expected from ordinary sources has been found. However, since there are many other possibilities to create positrons by astrophysical sources, e.g. in nearby supernova remnants, the interpretation is not yet conclusive. However, a new theoretical calculation has shown that the experimental situation is compatible with the presence of a neutralino-induced component, if the dark matter is clumpy so as to enhance the signal [7]. (Remember that such a non-homogeneous distribution of dark matter is in fact what is expected in many cold dark matter formation scenarios [8].)

Antiprotons could for some supersymmetric parameters constitute a useful signal [9], but even with the upcoming space experiments [10,11] it will be quite difficult to disentangle a low-energy signal from the smooth cosmic-ray induced background. For kinematical reasons, antiprotons created by pair-production in cosmic ray collisions with interstellar gas and dust are born with relatively high energy, whereas antiprotons from neutralino annihilation populate also the sub-100 MeV energy band. A problem that plagues estimates of the signal strength of both positrons and antiprotons is, however, the uncertainty of the galactic propagation model and solar wind modulation. Also, secondary \( \bar{p} \) interactions in the interstellar medium and \( \bar{p} \) production on helium nuclei also give low-energy antiprotons which could mask an eventual signal [12].

Many supersymmetric models, compatible with all accelerator constraints, give predictions for the antiproton flux [13,14] which are in agreement with very recent data from the BESS collaboration [15]. The question remains, however, whether or not cosmic-ray induced secondary antiprotons can fully explain the results. The most complete theoretical calculations [12,16] indicate that the band of uncertainties of the conventional flux is large enough to encompass the new data. This is shown in Fig. 1 (a), where the present BESS data [15] are compared to the default
background prediction of [12]. In Fig. 1 (b) a 24 % reduction of the secondary flux (well within the band of model uncertainties) is combined with the contribution from one of the supersymmetric models of [12] to give an equally good fit to the data.

Obviously, it will not be easy to tell these two cases apart, even with the high-quality data which can soon be expected [10].

Even allowing for large systematic effects, the measured antiproton flux gives, however, rather stringent limits on the lifetime of hypothetical $R$-parity violating decaying neutralinos [17].

A Methods with distinct experimental signature

With these problems of positrons and antiprotons, one would expect that problems of gamma rays and neutrinos are similar, if they only arise from secondary decays in the annihilation process. For instance, the gamma ray spectrum arising from the fragmentation of fermion and gauge boson final states is quite featureless and gives the bulk of the gammas at low energy where the cosmic gamma ray background is severe. Also, the density of neutralinos in the halo is not large enough to give a measurable flux of secondary neutrinos, unless the dark matter halo is very clumpy. However, neutrinos can escape from the centre of the Sun or Earth, where neutralinos may have been gravitationally trapped and therefore their
density enhanced. Also, gamma rays may result from loop-induced annihilations \( \chi \chi \rightarrow \gamma \gamma \) or \( \chi \chi \rightarrow Z \gamma \).

The rates of these processes are difficult to estimate because of uncertainties in the supersymmetric parameters, cross sections and halo density profile. However, in contrast to the other proposed detection methods they have the virtue of giving very distinct, “smoking gun” signals: high-energy neutrinos from the centre of the Earth or Sun, or monoenergetic photons with \( E_\gamma = m_\chi \) or \( E_\gamma = m_\chi (1 - m_Z^2/4m_\chi^2) \) from the halo. In fact, also continuum gammas may give a good signature, since the average angular distribution should follow the dark matter distribution of the halo, in contrast to the background (cosmic-ray induced gamma ray caused mainly by protons hitting interstellar hydrogen) which should emanate mainly from the disk. This possibility has received increased attention recently due to some indications from EGRET data [20] that an excess of GeV-scale gamma-rays appear to come from the halo and could be caused by neutralino annihilation [21,14,22]. However, since there are other explanations possible (such as \( \pi^0 \) production from cosmic rays having escaped the disk), it is plausible that other independent evidence (such as spectral features - ideally a line) has to be provided before a detection of a dark matter-induced signal can be claimed.

**B Gamma ray lines**

The detection probability of a gamma line signal depends on the very poorly known density profile of the dark matter halo.

To illustrate this point, let us consider the characteristic angular dependence of the gamma-ray intensity from neutralino annihilation in the galactic halo. Annihilation of neutralinos in an isothermal halo with core radius \( a \) leads to a gamma-ray flux of

\[
\frac{dF}{d\Omega} \simeq (2 \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}) \times \frac{(\sigma_{\gamma\gamma}v)_29(\rho_{\chi}^{0.3})^2}{(m_\chi/10 \text{GeV})^2 \left( \frac{R}{8.5 \text{ kpc}} \right) J(\Psi)},
\]

where \( (\sigma_{\gamma\gamma}v)_29 \) is the annihilation rate in units of \( 10^{-29} \text{cm}^3 \text{s}^{-1} \), \( \rho_{\chi}^{0.3} \) is the local neutralino halo density in units of 0.3 GeV cm\(^{-3} \) and \( R \) is the distance to the galactic center. The integral \( J(\Psi) \) is given by

\[
J(\Psi) = \frac{1}{R\rho_0^2} \int_{\text{line-of-sight}} \rho^2(\ell) d\ell(\Psi),
\]

and is evidently very sensitive to local density variations along the line-of-sight path of integration.

We remind of the fact that since the neutralino velocities in the halo are of the order of \( 10^{-3} \) of the velocity of light, the annihilation can be considered to be at
rest. The resulting gamma ray spectrum is a line at \( E_\gamma = m_\chi \) of relative linewidth \( 10^{-3} \) which in favourable cases will stand out against background. The process \( \chi \chi \rightarrow Z\gamma \) is treated analogously and has a similar rate [19].

To compute \( J(\Psi) \), a model of the dark matter halo has to be chosen. Recently, N-body simulations have given a clue to the final halo profile obtained by hierarchical clustering in a CDM scenario [23]. It turns out that the universal halo profile found in these simulations has a rather significant enhancement \( \propto 1/r \) near the halo centre. If applicable to the Milky Way, this would lead to a much enhanced annihilation rate towards the galactic centre, and also to a very characteristic angular dependence of the line signal. This would be very beneficial when discriminating against the galactic and extragalactic \( \gamma \) ray background, and Air Cherenkov Telescopes (ACTs) would be eminently suited to look for these signals, if the energy resolution is at the \( 10 \% \) level.

In Fig. 2, we show the gamma ray line flux given in a scan of supersymmetric models consistent with all experimental bounds (including \( b \rightarrow s\gamma \)), assuming an effective value of \( 10^3 \) for the average of \( J(\Psi) \) over the \( 10^{-3} \) steradians that typically an Air Cherenkov Telescope (ACT) would cover. (See [21] for details.)

**FIGURE 2.** Results for the gamma ray line flux in an extensive scan of supersymmetric parameter space in the MSSM [21]. Shown in the figure to the left is the number of events versus photon energy in an Air Cherenkov Telescope of area \( 5 \cdot 10^4 \) m\(^2\) viewing the galactic centre for one year. The halo profile of [23] for the dark matter has been assumed. In the figure to the right the 5-\( \sigma \) discovery limit of the GLAST satellite is shown assuming a 2-year exposure and the same halo parameters.

It can be seen that the models which give the highest rates should be within reach of the new generation of ACTs presently being constructed. These will have an effective area of almost \( 10^5 \) m\(^2\), a threshold of some tens of GeV and an energy resolution approaching 10 \%. In favourable cases, especially at the low \( m_\chi \) end, also a smaller area detector with better energy resolution and wider angular acceptance such as the proposed GLAST satellite [24] could reach discovery potential, as also
C Indirect detection through neutrinos

Another promising indirect detection method is to use neutrinos from annihilations of neutralinos accumulated in the centre of the Sun or Earth. This will be a field of extensive experimental investigations in view of the new neutrino telescopes (AMANDA, BAikal, Nestor, ANTARES) in operation or under construction.

To illustrate the potential of neutrino telescopes for discovery of dark matter through neutrinos from the Earth or Sun, we present the results of a full calculation [25]. In Fig. 3 it can be seen that a neutrino telescope of area around 1 km$^2$, which is a size currently being discussed, would have discovery potential for a range of supersymmetric models.

If a signal were established, one can use the angular spread caused by the radial distribution of neutralinos (in the Earth) and by the energy-dependent mismatch between the direction of the muon and that of the neutrino (for both the Sun and the Earth) to get a rather good estimate of the neutralino mass [27]. If muon energy can also be measured, one can do even better [28].

It should again be noted that all indirect detection signals depend strongly, and in partly different ways, on the distribution of dark matter in the galactic halo. This was investigated in detail in [29], where also a comparison between the various methods (including direct detection) was performed.

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FIGURE 3. The indirect detection rates from neutralino annihilations in the Earth (left) and the Sun (right) versus the neutralino mass. The horizontal line is the Baksan limit [26]. For details, see [25].

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