Probing Neutralino Resonance Annihilation via Indirect Detection of Dark Matter

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ABSTRACT: The lightest neutralino of $R$-parity conserving supersymmetric models serves as a compelling candidate to account for the presence of cold dark matter in the universe. In the minimal supergravity (mSUGRA) model, a relic density can be found in accord with recent WMAP data for large values of the parameter tan $\beta$, where neutralino annihilation in the early universe occurs via the broad $s$-channel resonance of the pseudoscalar Higgs boson $A$. We map out rates for indirect detection of neutralinos via 1. detection of neutrinos arising from neutralino annihilation in the core of the earth or sun and 2. detection of gamma rays, antiprotons and positrons arising from neutralino annihilation in the galactic halo. If indeed $A$-resonance annihilation is the main sink for neutralinos in the early universe, then signals may occur in the gamma ray, antiproton and positron channels, while a signal in the neutrino channel would likely be absent. This is in contrast to the hyperbolic branch/focus point (HB/FP) region where all indirect detection signals are likely to occur, and also in contrast to the stau co-annihilation region, where none of the indirect signals are likely to occur.

KEYWORDS: Supersymmetry Phenomenology, Supersymmetric Standard Model, Dark Matter
In the past decades, a growing body of astrophysical evidence has made an irrefragable case for the existence of cold dark matter (CDM) in the universe\[1\]. The most recent results come from the Wilkinson Microwave Anisotropy Probe (WMAP)\[2\]. Their results confirm the standard model of cosmology and fit its parameters to high precision. The properties of a flat universe in the $\Lambda CDM$ model are characterized by the density of baryons ($\Omega_b$), matter density ($\Omega_m$), vacuum energy ($\Omega_\Lambda$) and the expansion rate ($h$) which are measured to be:

$$\begin{align*}
\Omega_b &= 0.044 \pm 0.004 \\
\Omega_m &= 0.27 \pm 0.04 \\
\Omega_\Lambda &= 0.73 \pm 0.04 \\
h &= 0.71^{+0.04}_{-0.03}.
\end{align*}$$

From the WMAP results, a value for the cold dark matter density of the universe can be derived:

$$\Omega_{CDM} h^2 = 0.1126^{+0.0081}_{-0.0090} (^{+0.0161}_{-0.0181}) \text{ at 68(95)\% CL.}$$

A particularly attractive candidate for CDM is the lightest neutralino in $R$-parity conserving supersymmetric models\[3\]. In the paradigm minimal supergravity (mSUGRA) model\[4\], it is assumed that at the scale $Q = M_{GUT}$, there is a common scalar mass $m_0$, a common gaugino mass $m_{1/2}$, and a common trilinear term $A_0$. The soft SUSY breaking terms can be calculated at scale $Q = M_{\text{weak}}$ via renormalization group evolution. Electroweak symmetry breaking occurs radiatively (REWSB) due to the large top quark mass, so that the bilinear soft breaking term $B$ can be traded for the weak scale ratio of Higgs vevs $\tan \beta$, and the magnitude (but not the sign) of the superpotential $\mu$ term can be specified. Thus, the mSUGRA model is characterized by four parameters plus a sign choice:

$$m_0, m_{1/2}, A_0, \tan \beta, \text{ and sign}(\mu).$$

Once these model parameters are specified, then all sparticle masses and mixings are determined, and scattering cross sections may be reliably calculated.

In the early universe at very high temperatures, the lightest neutralino $\tilde{Z}_1$ will be in thermal equilibrium, so that its number density is well determined. As the universe expands and cools, there will be insufficient thermal energy to produce neutralinos, although they can still annihilate with one another. The neutralino relic density can be determined by solving the Boltzmann equation for neutralinos in a Friedmann-Robertson-Walker universe. In spite of the claims that the lightest neutralino is a good dark matter candidate, it turns out that in most of the parameter space of the mSUGRA model, a value of $\Omega_{\tilde{Z}_1} h^2$ well beyond the WMAP bound is generated. Only certain regions of the mSUGRA model parameter space give rise to a relatively low value of $\Omega_{\tilde{Z}_1} h^2$ in accord with astrophysical measurements and theory. These regions consist of \[1\]:

\[1\]Additional less prominent parameter space regions are also possible, such as the light higgs $h$ resonance region (bordering the LEP2 bounds at low $m_{1/2}$) and the top squark co-annihilation region (for very particular choices of the $A_0$ parameter).
1. The bulk annihilation region at low values of $m_0$ and $m_{1/2}$, where neutralino pair annihilation occurs at a large rate via $t$-channel slepton exchange.

2. The stau co-annihilation region at low $m_0$ where $m_{\tilde{Z}_1} \simeq m_{\tilde{\tau}_1}$ so that $\tilde{Z}_1$s may co-annihilate with $\tilde{\tau}_1$s in the early universe [5].

3. The hyperbolic branch/focus point (HB/FP) region [6] at large $m_0$ near the boundary of the REWSB excluded region where $|\mu|$ becomes small, and the neutralinos have a significant higgsino component, which facilitates annihilations to $WW$ and $ZZ$ pairs [6].

4. The $A$-annihilation funnel, which occurs at very large $\tan \beta \sim 45 - 60$ [7]. In this case, the value of $m_A \sim 2m_{\tilde{Z}_1}$. An exact equality of the mass relation isn’t necessary, since the $A$ width can be quite large ($\Gamma_A \sim 10 - 50$ GeV); then $2m_{\tilde{Z}_1}$ can be several widths away from resonance, and still achieve a large $\tilde{Z}_1\tilde{Z}_1 \rightarrow A \rightarrow f\bar{f}$ annihilation cross section. The heavy scalar Higgs $H$ also contributes to the annihilation cross section.

Several years ago, the bulk annihilation region of parameter space was favored. This situation has changed in that the bulk annihilation region generally predicts a light SUSY Higgs boson $h$ with mass below LEP2 bounds, along with large- usually anomalous- predictions of the rate for $BF(b \rightarrow s\gamma)$ decays and muon anomalous magnetic moment $a_\mu = (g - 2)\mu/2$ [8, 9]. An increase of either of the parameters $m_0$ or $m_{1/2}$ leads generally to heavier sparticle masses and $m_h$ values, so that predictions for loop induced processes become more SM-like.

Given a knowledge of which regions of model parameter space give rise to neutralino relic densities in accord with measurements, it is useful to examine the implications for detection of supersymmetric matter. The direct sparticle search limits for the Fermilab Tevatron collider [14], the CERN LHC [11] and a $\sqrt{s} = 0.5 - 1$ TeV linear collider [12] have all been examined. In addition, there exist both direct and indirect dark matter search experiments that are ongoing and proposed. Direct dark matter detection has been recently examined by many authors [13], and observable signal rates are generally found in either the bulk annihilation region, or in the HB/FP region, while direct detection of DM seems unlikely in the $A$-funnel or in the stau co-annihilation region.

Indirect detection of neutralino dark matter [14] may occur via

1. observation of high energy neutrinos originating from $\tilde{Z}_1\tilde{Z}_1$ annihilations in the core of the sun or earth [15],

2. observation of $\gamma$-rays originating from neutralino annihilation in the galactic core or halo [16] and

3. observation of positrons [17] or anti-protons [18] originating from neutralino annihilation in the galactic halo.
The latter signals would typically be non-directional due to the influence of galactic magnetic fields, unless the neutralino annihilations occur relatively close to earth in regions of clumpy dark matter.

The indirect signals for SUSY dark matter have been investigated in a large number of papers, and computer codes which yield the various signal rates are available\[19, 20\]. Recent works find that the various indirect signals occur at large rates in the now disfavored bulk annihilation region, and also in the HB/FP region\[21\]. Naively, this is not surprising since the same regions of parameter space that include large neutralino annihilation cross sections in the early universe should give large annihilation cross sections as sources of indirect signals for SUSY dark matter.

In this paper, we pay special attention to indirect signals for SUSY dark matter in the $A$-annihilation funnel. We generate sparticle mass spectra using Isajet v7.69\[22\], which includes full one-loop radiative corrections to all sparticle masses and Yukawa couplings, and minimizes the scalar potential using the renormalization group improved 1-loop effective potential including all tadpole contributions, evaluated at an optimized scale choice which accounts for leading two loop terms. Good agreement between $m_h$ values is found in comparison with the FeynHiggs program, and there is good agreement as well in the $m_A$ calculation between Isajet and SoftSUSY, Spheno and Suspect codes, as detailed in Ref. \[23\]. To evaluate the indirect signals expected from the mSUGRA model, we adopt the DarkSUSY package\[20\] interfaced to Isasugra\[2\]. For our calculation of the neutralino relic density, we use the Isared program\[24\] interfaced with Isajet. Isared calculates all relevant neutralino pair annihilation and co-annihilation processes with relativistic thermal averaging\[24\]. An important element of the calculation is that Isared calculates the neutralino relic density using the Isajet 2-loop $t$, $b$, and $\tau$ Yukawa couplings evaluated at the scale $Q = m_A$. The Yukawa coupling calculation begins with the DR fermion masses at scale $Q = M_Z$, and evolves via SM renormalization group equations (RGEs) to the scale $Q_{SUSY} = \sqrt{m_{\tilde{t}_L}m_{\tilde{t}_R}}$, where complete MSSM 1-loop threshold corrections are implemented. Evolution at higher mass scales is implemented via 2-loop MSSM RGEs. The final RGE solution is gained after iterative running of couplings and soft terms between $M_Z$ and $M_{GUT}$ and back until a convergent solution is achieved.

We first show in Fig. \[1\] the location of the $A$-pole in the mSUGRA model by plotting $|m_A - 2m_{\tilde{Z}_1}|/\Gamma_A$ versus $m_0$ for $m_{1/2} = 500$, 750, 1000 and 1250 GeV, for $A_0 = 0$ and $a) \tan \beta = 45$ and $\mu < 0$ and $b) \tan \beta = 54$ and $\mu > 0$. The point in $m_0$ where $|m_A - 2m_{\tilde{Z}_1}|/\Gamma_A$ drops to zero shows the location of the $A$-annihilation funnel. One may also note from Fig. \[1\] that there is a band of $m_0$ values wherein $2m_{\tilde{Z}_1}$ is within several widths of the $A$-pole. As $\tan \beta$ increases, the $b$ Yukawa coupling also increases, leading to large values of the $A$ width $\Gamma_A$. For very large values of $\tan \beta \sim 54$, $\Gamma_A$ can exceed 50 GeV. In frame $a)$, it can be seen that the $A$-annihilation funnel occurs for all values of $m_{1/2}$ shown. However, in frame $b)$, it can be seen that the $A$-annihilation resonance is only found for large values of $m_{1/2} \gtrsim 1$ TeV. Even so, for lower $m_{1/2}$ values, the effect of the $A$-annihilation funnel is felt at the low $m_0$ range since one may be only one to several widths away from resonance.

\[Isasugra is a subprogram of the Isajet package that calculates sparticle mass spectra and branching fractions for a variety of supersymmetric models\]

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The explicit location of the $A$-annihilation funnel in the $m_0$ vs. $m_{1/2}$ plane as calculated by Isasugra is shown in Ref. [9], and will not be repeated here.

\[ |m_A - 2m_{Z_1}|/\Gamma_A \]

Figure 1: A plot of $|m_A - 2m_{Z_1}|/\Gamma_A$ versus $m_0$ for various $m_{1/2}$ values and $A_0 = 0$ and $a)$ $\tan \beta = 45$ with $\mu < 0$ and $b)$ $\tan \beta = 54$ and $\mu > 0$.

In Fig. [3] we show in the top frames the neutralino relic density $\Omega_{Z_1}h^2$ versus mSUGRA parameter $m_0$ for various $m_{1/2}$ values. We also take $A_0 = 0$ and $a)$ $\tan \beta = 45$ and $\mu < 0$ and $b)$ $\tan \beta = 54$ and $\mu > 0$. In frame $a)$, we see that most of the range of $m_0$ yields a value of $\Omega_{Z_1}h^2$ far beyond the WMAP measured range (shown by horizontal dotted lines). However, as $m_0$ becomes very large, one enters the HB/FP region, and $|\mu|$ becomes small. The $\tilde{Z}_1$ gains a substantial higgsino component which facilitates $\tilde{Z}_1\tilde{Z}_1$ annihilation into final
states such as $WW$, $ZZ$ and $Zh$. Thus, $\Omega_{\tilde{Z}_1} h^2$ drops into and below the WMAP measured range for CDM. As $m_0$ decreases to small values, there is also a decrease in neutralino relic density. This time the decrease is due to the fact that $m_A$ decreases towards the value $2m_{\tilde{Z}_1}$, so that $\tilde{Z}_1 \tilde{Z}_1 \to A, H \to b\bar{b}$ is enhanced. For low $m_{1/2}$ values, $\Omega_{\tilde{Z}_1} h^2$ actually drops to very low values— below 0.025— which wouldn’t even be enough to explain galactic rotation curves. However, the $A$-annihilation funnel is quite broad because the $b$ and $\tau$ Yukawa couplings grow with $\tan \beta$, which increases the $A$ and $H$ widths, and also the $\tilde{Z}_1 \tilde{Z}_1$ annihilation rate through $s$-channel $A$ and $H$ exchange. Optimal values of $\Omega_{\tilde{Z}_1} h^2$ in accord with the WMAP CDM result are then achieved close to resonance, but not exactly on it. For even lower values of $m_0$, the value of $\Omega_{\tilde{Z}_1} h^2$ increases as one moves away from the $A$ resonance, until there is a final down-turn in $\Omega_{\tilde{Z}_1} h^2$ due to stau co-annihilation. In frame $b)$ at the top, we show the relic density for $\mu > 0$ and $\tan \beta = 54$. Again, much of the range in $m_0$ is excluded since $\Omega_{\tilde{Z}_1} h^2$ is beyond the WMAP limit. For large $m_0$, the relic density again drops as a HB/FP region is approached. For low values of $m_0$, the relic density again decreases due to the growing importance of neutralino annihilation via $s$-channel $A$ and $H$ exchange. However, only for $m_{1/2} \gtrsim 1 \text{ TeV}$ do we actually meet the $A$ resonance. Nonetheless, for lower $m_{1/2}$ values, the effect of the $A$ and $H$ pole is felt, and decreases the relic density to sub-WMAP values until the stau co-annihilation region is hit at the very lowest values of $m_0$.

In frames $c$) and $d$), we show the neutralino-proton spin independent (scalar) scattering cross section $\sigma_{SI}$ for $\tan \beta = 45$, $\mu < 0$ and $\tan \beta = 54$, $\mu > 0$, respectively. For low values of $m_0$, the scattering cross section is enhanced because squark masses become relatively light, and $u$-channel squark exchange graphs yield large scattering amplitudes. For high $m_0$ values, the neutralino has a significant higgsino component, which enhances the $t$-channel Higgs exchange diagrams. For the negative $\mu$ case in frame $c$), there is destructive interference between Higgs and squark exchange diagrams, and the cross section drops to zero for a particular $m_0$ value. In frame $d$), there is no destructive interference, so the spin-independent cross section just drops to a minimal but finite value. We note here that Stage 3 dark matter detectors such as Cryoarray, Zeplin-4 and Genius aim towards a sensitivity of roughly $10^{-9} \text{ pb}$, depending somewhat on the value of $m_{\tilde{Z}_1}$. We also note that the neutralino accretion rate for the earth depends strongly on the spin-independent neutralino-nucleon scattering, which is enhanced for the heavy nuclei of which the earth is composed.

In frames $e$) and $f$), we show the neutralino-proton spin-dependent (axial-vector) scattering cross section $\sigma_{SD}$ versus $m_0$ for the same mSUGRA parameters as the previous figures. The cross section is again enhanced in the HB/FP region, but drops to a minimum as $m_0$ decreases. We note here that the neutralino accretion rate of the sun depends strongly on the spin-dependent neutralino-nucleon scattering cross section.

In Fig. $3$, we show the flux of muons coming from neutralino annihilation in the core of the earth (frames $a$) and $b$)), and from neutralino annihilation in the core of the sun (frames $c$) and $d$)), for the same mSUGRA parameter values as in Fig. $2$. Second generation neutrino telescopes such as Icecube and Antares hope to probe muon flux values of $10$-$100 \text{ muons/km}^2/\text{yr}$. Comparing this number to the results from frames $a$)
Figure 2: We show the neutralino relic density versus $m_0$ for various values of $m_{1/2}$ and a) $\tan\beta = 45$, $\mu < 0$ and b) $\tan\beta = 53$, $\mu > 0$. We take $A_0 = 0$. In frames c) and d), we show the spin-independent neutralino-proton scattering cross section, while in frames e) and f), we show the spin-independent neutralino-proton scattering cross section versus $m_0$ for the same mSUGRA parameters as used in frames a) and b).

and b) shows that a signal from the mSUGRA model is unlikely to come from neutralino annihilation at the center of the earth. The drop in muon flux at moderate $m_0$ values follows along the curves shown previously for the neutralino-proton spin-dependent scattering cross section. There is an enhancement in muon flux at low and high $m_0$ values, but probably not enough to create a detectable signal. We note here that the muon flux from the earth shows some enhancement in rate in the $A$-annihilation funnel, but not enough to push the
expected flux levels into the observable regime. The solid curves are plotted assuming a local relic density of neutralinos given by $\rho_0 = 0.3 \text{ GeV/cm}^3$. If the relic density falls to very low values, then the local density may have to be rescaled in accord with the global relic density. The dashed curves show the variation in the rates if the local relic density is rescaled according to $\rho = \rho_0 \frac{\Omega_{\tilde{Z}_1} h^2}{0.025}$ for $\Omega_{\tilde{Z}_1} h^2$ values below 0.025.

![Graphs showing muon flux](image)

**Figure 3:** Muon flux from the earth (frames a) and b)) and sun (frames c) and d)) versus $m_0$ for various values of $m_{1/2}$ and $\tan \beta = 45, \mu < 0$ (left-hand frames) and $\tan \beta = 53, \mu > 0$ (right-hand frames). We take $A_0 = 0$. Dashed lines include rescaling of the local relic density for values of $\Omega_{\tilde{Z}_1} h^2 < 0.025$.

Alternatively, if we examine frames c) and d), we see that detectable levels of muon
flux may indeed arise from neutralino annihilations at the core of the sun. These large rates occur in the HB/FP region, as noted by other authors\cite{21}. It is intriguing that the large muon flux occurs in one of the main regions where the relic density is in accord with WMAP analyses. However, in the \( A \)-annihilation funnel, there is no evidence of enhancement of the muon flux. This is because the rate for neutralino annihilation in the sun or earth is given by

\[
\Gamma_A = \frac{1}{2} C \tanh^2 \left( \sqrt{C \Lambda t_{\odot}} \right), \tag{7}
\]

where \( C \) is the capture rate, \( A \) is the total annihilation rate times relative velocity per volume, and \( t_{\odot} \) is the present age of the solar system. For the sun, the age of the solar system exceeds the equilibration time, so \( \Gamma_A \sim \frac{C^2}{2} \), and the muon flux tends to follow the neutralino-nucleon scattering rate rather than the neutralino pair annihilation cross section. The earth has typically a much longer equilibration time, so that \( \Gamma_A \sim \frac{1}{2} C^2 \Lambda t_{\odot}^2 \), and is hence more sensitive to the neutralino annihilation cross section times relative velocity.

In Fig. 4, we show rates for gamma rays (frames a and b), positrons (frames c and d) and anti-protons (frames e and f) originating from neutralino annihilation in the galactic core and halo. The plots are shown versus \( m_0 \) for the same mSUGRA parameters as in Figs. 2 and 3. In frames a and b, the flux for continuum gamma rays with energy \( E_\gamma > 1 \text{ GeV} \) is shown in units of photons/cm\(^2\)/sec, assuming a detector with 0.001 sr solid angle coverage, pointed at the galactic center. For halo model dependence in the distribution of dark matter, we adopt default DarkSUSY values. Experiments such as GLAST\cite{28} expect to probe flux rates as low as \( 10^{-10} \) photons/cm\(^2\)/sec. Thus, in Fig. 4, we see that observable rates are expected to occur in the HB/FP region for both \( \tan \beta = 45 \) and \( \tan \beta = 54 \) cases. In addition, observable rates are expected if SUSY model parameters lie in the \( A \)-annihilation funnel. At low \( m_0 \) values, the gamma ray flux rises and follows the \( A \)-annihilation resonance. Detectable rates may occur in the \( A \)-funnel as long as \( m_{1/2} \lesssim 1 \text{ TeV} \). We also show again as dashed curves the rates if the relic density is rescaled when \( \Omega_{\tilde{Z}_1} h^2 \) falls below 0.025. In this case, rates for gamma ray detection may fall below observable levels, but only because neutralinos would not be the major constituent of CDM. If \( \Omega_{\tilde{Z}_1} h^2 \) lies within the WMAP band, then typically 2\( m_{\tilde{Z}_1} \) will lie somewhat off-resonance, and observable rates for gamma ray detection can be found. In frame b) for \( \mu > 0 \), detectable rates again occur at low \( m_0 \) for \( m_{1/2} \) values below 500 GeV.

In Fig. 4 frames c) and d) we show the signal-to-background (S/B) rates for detection of positrons arising from neutralino annihilations in the galactic halo. To calculate the \( S/B \) rates, we adopt fit C from Ref. \cite{21} for the \( E^2 d\Phi_{e^+}/d\Omega dE \) background rate. We compute the signal using the DarkSUSY positron flux evaluated at an “optimized” energy of \( E = m_{\tilde{Z}_1}/2 \), as suggested in Ref. \cite{21}. A \( S/B \sim 0.01 \) rate may be detectable\cite{21,14} by experiments such as PAMELA\cite{29} and AMS-02\cite{30}. We see from Fig. 4 that observable rates may again occur in the HB/FP region, and also in the \( A \)-annihilation funnel.

Finally, in frames e) and f), we show the differential flux of antiprotons from the galactic halo, \( d\Phi_{\bar{p}}/dE_{\bar{p}} d\Omega \), for \( E_{\bar{p}} = 1.76 \text{ GeV} \). In this case, background rates are more uncertain, so we show only the differential flux of antiprotons/GeV/cm\(^2\)/sec/sr. Again, the largest rates occur in the HB/FP region, and also in the \( A \)-annihilation funnel.
Figure 4: Flux of continuum gamma rays from a 0.001sr cone centered on the galactic center, with $E_\gamma > 1$ GeV (frames a) and b). We also show $S/B$ for positrons (frames c) and d) and the differential flux of antiprotons with $E_{\bar{p}} = 1.76$ GeV (frames e) and f)). All plots are versus $m_0$ for various values of $m_{1/2}$ and $\tan \beta = 45$, $\mu < 0$ (left-hand frames) and $\tan \beta = 53$, $\mu > 0$ (right-hand frames). We take $A_0 = 0$. Dashed lines include rescaling of the neutralino density for values of $\Omega_{\tilde{Z}_1} h^2 < 0.025$.

We can summarize our results according to mSUGRA parameter space regions which give rise to a reasonable relic density of CDM. In the HB/FP region, both direct and indirect detection of SUSY dark matter is possible. Indirect detection signals may be possible for neutrino telescopes by observing muons arising from high energy neutrinos which are produced from the decays of final state originating from neutralino annihilation in
the core of the sun. Detectable rates also may occur for cosmic gamma rays, positrons and possibly anti-protons. If instead the $A$-annihilation funnel is the main sink for neutralinos in the early universe, then it is unlikely any signal would be seen from high energy neutrinos arising from neutralino annihilation in the core of the sun or the earth. However, observable signals in the gamma ray, positron and possibly antiproton channels may occur. Finally, if the sink for early universe neutralinos is due to stau co-annihilation, then there may be no direct or indirect signals for SUSY DM. The exception occurs at very large tan $\beta$ values, where the $A$-annihilation funnel and stau co-annihilation region begin to overlap, in which case gammas, positrons and antiprotons could be visible, while neutrino-induced muons would not be.

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References

[1] For recent reviews, see e.g. W. Freedman and M. Turner, Rev. Mod. Phys. 75 (2003) 1433; A. Lahanas, N. Mavromatos and D. Nanopoulos, Int. J. Mod. Phys. D 12 (2003) 1529.

[2] D. N. Spergel et al., arXiv:astro-ph/0302209; C. L. Bennett et al., arXiv:astro-ph/0302207.

[3] H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419; J. Ellis, J. Hagelin, D. Nanopoulos and M. Srednicki, Phys. Lett. B127, 233 (1983); J. Ellis, J. Hagelin, D. Nanopoulos, K. Olive and M. Srednicki, Nucl. Phys. B238, 453 (1984).

[4] A. Chamsseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. 49 (1982) 970; R. Barbieri, S. Ferrara and C. Savoy, Phys. Lett. B 119 (1982) 343; L. J. Hall, J. Lykken and S. Weinberg, Phys. Rev. D 27 (1983) 2359.

[5] J. Ellis, T. Falk and K. Olive, Phys. Lett. B 444 (1998) 367; J. Ellis, T. Falk, K. Olive and M. Srednicki, Astropart. Phys. 13 (2000) 181.

[6] K. L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. D 58 (1998) 096004; J. Feng, K. Matchev and T. Moroi, Phys. Rev. Lett. 84 (2000) 2322 and Phys. Rev. D 61 (2000) 075005.

[7] M. Drees and M. Nojiri, Phys. Rev. D 47 (1993) 376; H. Baer and M. Brhlik, Phys. Rev. D 53 (1996) 597 and Phys. Rev. D 57 (1998) 567; H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana and X. Tata, Phys. Rev. D 63 (2001) 015007; J. Ellis, T. Falk, G. Ganis, K. Olive and M. Srednicki, Phys. Lett. B 510 (2001) 236; L. Roszkowski, R. Ruiz de Austri and T. Nihei, J. High Energy Phys. 0108 (024) 2001; A. Lahanas and V. Spanos, Eur. Phys. J. C 23 (2002) 183.

[8] See e.g. H. Baer, C. Balazs, A. Belyaev, J. Mizukoshi, X. Tata and Y. Wang, J. High Energy Phys. 0207 (2002) 050.

[9] H. Baer and C. Balazs, JCAP05, (2003) 054, hep-ph/0303114.

[10] H. Baer, T. Krupovnickas and X. Tata, J. High Energy Phys. 0307 (020) 2003.
[11] H. Baer, C. Balazs, A. Belyaev, T. Krupovnickas and X. Tata, J. High Energy Phys. 0306 (054) 2003.

[12] H. Baer, A. Belyaev, T. Krupovnickas and X. Tata, hep-ph/0311351 (2003).

[13] For a recent analysis, see H. Baer, C. Balazs, A. Belyaev and J. O’Farrill, JCAP 0309, 2003 (007); a subset of earlier work includes M. Goodman and E. Witten, Phys. Rev. D 31 (1985) 3051; K. Griest, Phys. Rev. Lett. 61 (1988) 666 and Phys. Rev. D 38 (1988) 2357; [Erratum-ibid. D 39, 3802 (1989)]; M. Drees and M. Nojiri, Phys. Rev. D 47 (1993) 4226 and Phys. Rev. D 48 (1993) 3483; V. A. Bednyakov, H. V. Klapdor-Kleingrothaus and S. Kovalenko, Phys. Rev. D 50 (1994) 7128; F. Nath and R. Arnovitt, Phys. Rev. Lett. 74 (1995) 4592; H. Baer and M. Brhlik, Phys. Rev. D 57 (1998) 567; J. Ellis, A. Ferstl and K. Olive, Phys. Lett. B 481 (2000) 304 and Phys. Rev. D 63 (2001) 065016; R. Arnovitt, B. Dutta and Y. Santoso, Nucl. Phys. B 585 (2000) 124; A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. D 63 (2001) 125003; M. E. Gomez and J. D. Vergados, Phys. Lett. B 512 (2001) 252; A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, Phys. Lett. B 518 (2001) 94; A. Corsetti and P. Nath, Phys. Rev. D 64 (2001) 115009; E. A. Baltz and P. Gondolo, Phys. Rev. Lett. 86 (2001) 5004; M. Drees, Y. G. Kim, T. Kobayashi and M. M. Nojiri, Phys. Rev. D 63 (2001) 115009; see also J. Feng, K. Matchev and F. Wilczek, Ref. [21].

[14] For a review, see e.g. G. Eigen, R. Gaitskell, G. Kribs and K. Matchev, arXiv:hep-ph/0112312; see also D. Hooper and L. T. Wang, arXIV:HEP-PH/0309036; W. de Boer, M. Herold, C. Sander and V. Zhukov, arXiv:hep-ph/0309029.

[15] J. Silk, K. Olive and M. Srednicki, Phys. Rev. Lett. 55 (1985) 257; K. Freese, Phys. Lett. B 167 (1986) 295; L. Krauss, M. Srednicki and F. Wilczek, Phys. Rev. D 33 (1986) 2079; V. Berezinsky, A. Bottino, J. R. Ellis, N. Fornengo, G. Mignola and S. Scopel, Astropart. Phys. 5 (1996) 333; L. Bergstrom, J. Edsjo and P. Gondolo, Phys. Rev. D 55 (1997) 1765 and Phys. Rev. D 58 (1998) 103519; A. Bottino, F. Donato, N. Fornengo and S. Scopel, Astropart. Phys. 10 (1999) 203; A. Corsetti and P. Nath, Phys. Rev. D 64 (2001) 115009; E. A. Baltz and P. Gondolo, Phys. Rev. Lett. 86 (2001) 5004; M. Drees, Y. G. Kim, T. Kobayashi and M. M. Nojiri, Phys. Rev. D 63 (2001) 115009; see also J. Feng, K. Matchev and F. Wilczek, Ref. [21].

[16] M. Urban et al., Phys. Lett. B 293 (1992) 149; V. Berezinsky, A. Gurevich and K. Zybin, Phys. Lett. B 294 (1992) 221; V. Berezinsky, A. Bottino and G. Mignola, Phys. Lett. B 325 (1994) 136; J. Buckley et al., arXiv:astro-ph/0201160.

[17] A. Tylka, Phys. Rev. Lett. 63 (1989) 840; M. Turner and F. Wilczek, Phys. Rev. D 42 (1990) 1001; M. Kamionkowski and M. Turner, Phys. Rev. D 43 (1991) 1774; A. Moskalenko and A. Strong, Phys. Rev. D 60 (1999) 063003; G. Kane, L. T. Wang and J. Wells, Phys. Rev. D 65 (2002) 057701; E. Baltz, J. Edsjo, K. Freese and P. Gondolo, Phys. Rev. D 65 (2002) 063511; D. Hooper, J. Taylor and J. Silk, arXiv:hep-ph/0312076.

[18] P. Chardonnet, Mignola, P. Salati and R. Tailliet, Phys. Lett. B 384 (1996) 161; A. Bottino, F. Donato, N. Fornengo and P. Salati, Phys. Rev. D 58 (1998) 123503; L. Bergstrom, J. Edsjo and P. Ullio, arXiv:astro-ph/9902012.

[19] neutdriver, by G. Jungman, M. Kamionkowski and K. Griest, see Phys. Rept. 267 (1996) 193.

[20] P. Gondolo, J. Edsjo, P. Ullio, L. Bergstrom, M. Schelke and E. A. Baltz, arXiv:astro-ph/0211238.
[21] J. Feng, K. Matchev and F. Wilczek, *Phys. Lett. B* 482 (2000) 388 and *Phys. Rev. D* 63 (2001) 045024.

[22] ISAJET v7.69, by H. Baer, F. Paige, S. Protopopescu and X. Tata, hep-ph/0312045.

[23] B. Allanach, S. Kraml and W. Porod, *J. High Energy Phys.* 0303 (2003) 016.

[24] H. Baer, C. Balazs and A. Belyaev, *J. High Energy Phys.* 0203 (2002) 042 and hep-ph/0211213.

[25] P. Gondolo and G. Gelmini, *Nucl. Phys. B* 360 (1991) 145; H. Baer and M. Brhlik, *Phys. Rev. D* 52 (1995) 5034 and *J. Edsjo and P. Gondolo, Phys. Rev. D* 56 (1997) 1879.

[26] J. Ahrens et al., (Icecube Collaboration), *Nucl. Phys. 118 (Proc. Suppl.)* (2003) 388.

[27] E. Carmona et al., (Antares Collaboration), *Nucl. Phys. 95 (Proc. Suppl.)* (2001) 161.

[28] A. Morselli et al., (GLAST Collaboration), *Nucl. Phys. 113 (Proc. Suppl.)* (2002) 213.

[29] M. Pearce (Pamela Collaboration), *Nucl. Phys. 113 (Proc. Suppl.)* (2002) 314.

[30] J. Casaus et al. (AMS Collaboration), *Nucl. Phys. 114 (Proc. Suppl.)* (2003) 259.