Supersymmetric dark matter and neutralino-nucleon cross section

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We review the direct detection of supersymmetric dark matter in the light of recent experimental results. In particular, we show that regions in the parameter space of several supergravity scenarios with a neutralino-nucleon cross section of the order of $10^{-6}$ pb, i.e., where current dark matter detectors are sensitive, can be obtained. These are scenarios with large $\tan \beta$, with non-universal soft supersymmetry-breaking terms, with multi-TeV masses for scalar superpartners known as ‘focus point’ supersymmetry, and finally scenarios with intermediate unification scale which appear naturally in some superstring constructions.

1 Introduction

One of the strongest motivations for physics beyond the standard model is the existence of dark matter. Substantial evidences exist suggesting that most of the mass in the Universe is some non-luminous matter, the so called ‘dark matter’, of as yet unknown composition. Currently the most convincing observational evidence for the existence of dark matter comes from the analysis of rotation curves of spiral Galaxies, i.e., measurements of the velocity of isolated stars or gas clouds which orbit in the outer parts of spiral Galaxies. It has been noted that there is not enough luminous matter in those Galaxies to account for their observed rotation curves.

The detailed analysis of rotation curves offers convincing evidence that 90% or more of the mass of the Galaxies is dark. Other evidences arise from large scale measurements, as e.g. the motions of cluster members Galaxies. A key question is

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then, what could this dark matter be? We don’t know the answer yet, but we do know that not all of it can be ordinary (baryonic) matter, since measured abundances of helium, deuterium and lithium in the scenario of big-bang nucleosynthesis impose a strong upper bound on the baryon density in the Universe. This density is too small to account for the whole dark matter in the Universe. The conclusion is that baryonic objects, such as e.g. MACHOs, can be components of the dark matter, but more candidates are needed [2].

Fortunately, particle physics offers various candidates for (non-baryonic) dark matter, all of which would indicate new physics beyond the well tested standard model of particle physics [3]. For example, long-lived or stable weakly-interacting massive particles (WIMPs) can remain from the earliest moments of the Universe in sufficient number to account for a significant fraction of relic density. These particles would form not only a background density in the Universe, but also would cluster gravitationally with ordinary stars in the galactic halos.

This raises the hope of detecting relic WIMPs directly, by observing their elastic scattering on target nuclei through nuclear recoils. Since WIMPs interact with ordinary matter with very roughly weak strength, and assuming that their masses are of the order of weak scale (i.e., between 10 GeV and a few TeV), it is natural to expect a WIMP-nucleus cross section of the same order as that of a weak process, which is around 1 pb. This would imply a WIMP-nucleon cross section around $10^{-8}$ pb, too low to be detected by current dark matter experiments, DAMA, CDMS and UKCDM, which are sensitive to a cross section around $10^{-6}$ pb. Surprisingly, the DAMA collaboration reported recently [4] data favouring the existence of a WIMP signal in their search for annual modulation. When uncertainties as e.g. the WIMP velocity or possible bulk halo rotation, are included, it was claimed that the preferred range of parameters is (at 4$\sigma$ C.L.) $10^{-6}$ pb $\lesssim \sigma \lesssim 10^{-5}$ pb for a WIMP mass $30$ GeV $\lesssim m \lesssim 200$ GeV. Unlike this spectacular result, the CDMS collaboration claims to have excluded [5] regions of the DAMA parameter space.

In any case, due to these and other projected experiments, it seems very plausible that the dark matter will be found in the near future. In this situation, and assuming that the dark matter is a WIMP, it is natural to wonder how big the cross section for its direct detection can be. The answer to this question depends on the particular WIMP considered. The leading candidate in this class is the lightest neutralino [6], a particle predicted by the supersymmetric (SUSY) extension of the standard model. In this paper we critically reappraise the known SUSY scenarios based on neutralinos as dark-matter candidates, and in particular the scenarios constructed recently in order to enhance the neutralino-nucleon cross section. This is the case of scenarios with large $\tan\beta$ [7]-[9], with non-universal soft SUSY-breaking terms [4, 8, 10], with multi-TeV masses for scalar superpartners known as ‘focus point’ supersymmetry [11], and finally scenarios with intermediate unification scale [12]-[14].
2 Supersymmetric predictions for the neutralino-nucleon cross section

In SUSY models, $R$-parity is often imposed to avoid weak scale proton decay or lepton number violation. Imposing this symmetry yields remarkable phenomenological implications. SUSY particles are produced or destroyed only in pairs and, as a consequence, the lightest supersymmetric particle (LSP) is absolutely stable. The former implies that a major signature for $R$-parity conserving models is represented by events with missing energy (for instance, $e^+e^- \rightarrow \text{jet} + \text{missing energy}$). The latter implies that the LSP might constitute a possible candidate for dark matter. Concerning this point, it is remarkable that in most of the parameter space of SUSY models the LSP is an electrically neutral (also with no strong interactions) particle, called neutralino. This is welcome since otherwise the LSP would bind to nuclei and would be excluded as a candidate for dark matter from unsuccessful searches for exotic heavy isotopes \cite{13}.

In the simplest SUSY extension of the standard model, the so-called minimal supersymmetric standard model (MSSM) there are four neutralinos, $\tilde{\chi}_i^0 \ (i = 1, 2, 3, 4)$, since they are the physical superpositions of the fermionic partners of the neutral electroweak gauge bosons, called bino ($\tilde{\chi}_1^0$) and wino ($\tilde{\chi}_3^0$), and of the fermionic partners of the neutral Higgs bosons, called Higgsinos ($H_u^0, H_d^0$). Therefore the lightest neutralino, $\tilde{\chi}_1^0$, will be the dark matter candidate. The neutralino mass matrix with the conventions for gaugino and Higgsino masses in the Lagrangian, $\mathcal{L} = \frac{1}{2} \sum_a M_a \lambda_a \lambda_a + \mu \tilde{H}_u^0 \tilde{H}_d^0 + \text{h.c.}$, is given by

$$
\begin{pmatrix}
M_1 & 0 & -M_Z \cos \beta \sin \theta_W & M_Z \sin \beta \sin \theta_W \\
0 & M_2 & M_Z \cos \beta \cos \theta_W & M_Z \sin \beta \cos \theta_W \\
-M_Z \cos \beta \sin \theta_W & M_Z \cos \beta \cos \theta_W & 0 & -\mu \\
M_Z \sin \beta \sin \theta_W & -M_Z \sin \beta \cos \theta_W & -\mu & 0
\end{pmatrix},
$$

(1)

in the above basis ($\tilde{B}^0 = -i \lambda^2, \tilde{W}_3^0 = -i \lambda^3, \tilde{H}_u^0, \tilde{H}_d^0$). Here $M_1$ and $M_2$ are the soft bino and wino masses respectively, $\mu$ is the Higgsino mass parameter and $\tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ is the ratio of Higgs vacuum expectation values. We parameterize the gaugino and Higgsino content of the lightest neutralino according to

$$
\tilde{\chi}_1^0 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}_3^0 + N_{13} \tilde{H}_d^0 + N_{14} \tilde{H}_u^0.
$$

(2)

It is commonly defined that $\tilde{\chi}_1^0$ is mostly gaugino-like if $P \equiv |N_{11}|^2 + |N_{12}|^2 > 0.9$, Higgsino-like if $P < 0.1$, and mixed otherwise.

The relevant effective Lagrangian describing the elastic $\tilde{\chi}_1^0$-nucleon scattering in the MSSM is given by

$$
\mathcal{L}_{\text{eff}} = \sum_q \left( \alpha_q \bar{\chi} \gamma^\mu \gamma^5 q + \beta_q \bar{\chi} \gamma^\mu \gamma^5 \chi \gamma^\mu \gamma^5 q \right),
$$

(3)

where $\alpha_q, \beta_q$ are given e.g. in ref. \cite{10} with the sign conventions for Yukawa couplings in the Lagrangian, $\mathcal{L} = -h_u H_u^0 \bar{u}_L u_R - h_d H_d^0 \bar{d}_L d_R - h_e H_u^0 e_L e_R + \text{h.c.}$, and the sum runs over the six quarks. The contribution of the scalar (spin-independent) interaction, the
Figure 1: Feynman diagrams contributing to neutralino-nucleon cross section.

one proportional to $\alpha_q$, to the $\tilde{\chi}^0_1$-nucleon cross section is generically larger than the
spin-dependent interaction, the one proportional to $\beta_q$. One can concentrate then on
the scalar $\tilde{\chi}^0_1$-nucleon cross section. This is given by

$$\sigma = \frac{4m_r^2}{\pi}f^2,$$

where $m_r$ is the reduced $\tilde{\chi}^0_1$ mass and

$$\frac{f}{m} = \sum_q f_q \frac{\alpha_q}{m_q},$$

with $m$ the mass of the nucleon and $m_q$ the mass of the quarks. The scalar coefficients
$\alpha_q$ include contributions from squark ($\tilde{q}$) exchange and neutral Higgs ($h, H$) exchange,
as illustrated in Fig. 1. The numerical values of the hadronic matrix elements $f_q$ for
the proton are as follows [16]:

$$f_u = 0.020 \pm 0.004, \quad f_d = 0.026 \pm 0.005, \quad f_s = 0.118 \pm 0.062,$$

and $f_{c,b,t} = \frac{2}{27}(1 - \sum_{q=u,d,s} f_q)$. For the neutron the value of $f_s$ is the same and
therefore the scalar cross sections for both, protons and neutrons, are basically equal.

The cross section for the elastic scattering of relic neutralinos on protons and neutrons has been examined exhaustively in the literature [3]. This is for example the case in the framework of minimal supergravity (mSUGRA). Let us recall that in this
framework one makes several assumptions. In particular, the scalar mass parameters,
the gaugino mass parameters, and the trilinear couplings, which are generated once
SUSY is broken through gravitational interactions, are universal at the grand unification scale, $M_{GUT} \approx 2 \times 10^{16}$ GeV. They are denoted by $m_0, M_{1/2},$ and $A_0$ respectively.
Likewise, radiative electroweak symmetry breaking is imposed, i.e., $|\mu|$ is determined
by the minimization of the Higgs effective potential. This implies

$$\mu^2 = \frac{m_{H_u}^2 - m_{H_d}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \frac{1}{2}M_Z^2.$$ (7)

With these assumptions, the mSUGRA framework allows four free parameters: $m_0,$
$M_{1/2},$ $A_0,$ and $\tan \beta.$ In addition, the sign of $\mu$ remains also undetermined.

$Larger values, as for example $f_s = 0.455,$ have also been used in the literature, see e.g. ref. [8].
Figure 2: Running of the soft Higgs masses-squared with energy.

It was observed (for a recent re-evaluation see ref.\[16\]) that for low and moderate values of $\tan \beta$ the predicted scalar neutralino-proton cross sections are well below the accessible experimental regions. To understand this result qualitatively, we show schematically in Fig. 2 the well known evolution of $m^2_{H_d}$ and $m^2_{H_u}$ with the scale $b$. Since $m^2_{H_u}$ becomes large and negative (notice also that $m^2_{H_d}$, neglecting bottom and tau Yukawa couplings, becomes positive), $|\mu|$ due to relation (7) becomes also large, in particular much larger than $M_1$ and $M_2$. Thus, as can be easily understood from eqs. (1) and (2), the lightest neutralino will be mainly gaugino, and in particular bino since at low energy $M_1 \approx \frac{1}{2} M_2$.

We show this fact in Fig. 3a, where for $\tan \beta = 3$ the gaugino-Higgsino components-squared $N^2_{1i}$ of the lightest neutralino as a function of its mass $m_{\tilde{\chi}^0_1}$ are exhibited. Here we are using as an example $m_0 = 150$ GeV, and $M_{1/2}$ is essentially fixed for a given $m_{\tilde{\chi}^0_1}$. Note that $N_{11}$ is extremely large and therefore $P \gtrsim 0.9$. Then, the scattering channels through Higgs exchange shown in Fig. 1 are suppressed (recall that the Higgs-neutralino-neutralino couplings are proportional to $N_{13}$ and $N_{14}$) and therefore the cross section is small. As a matter of fact, the scattering channels through squark exchange, shown also in Fig. 1, are also suppressed by the mass of the squarks. Indeed in this limit the cross section (4) can be approximated as

$$\sigma_{\tilde{\chi}^0_1-p} \approx m_r^2 \frac{\alpha^2}{(m_3^2 - m_{\tilde{\chi}^0_1}^2)^2} f_s^2 |N_{11}|^4 .$$  \hspace{1cm} (8)$$

Thus it can be roughly estimated to be $\sigma_{\tilde{\chi}^0_1-p} \approx 10^{-8}$ pb, for $\alpha \approx 10^{-2}$, $f_s \approx 10^{-1}$, $m_r \approx 1$ GeV and $m_3 \approx 300$ GeV. This is precisely the value of the cross section expected for a weak process as discussed in the Introduction.

In Fig. 3b we show the cross section $\sigma_{\tilde{\chi}^0_1-p}$ as a function of the neutralino mass $m_{\tilde{\chi}^0_1}$ for $\tan \beta = 3$. We also choose to plot only the case $\mu > 0$ since for negative values of $\mu$ the cross sections are much smaller\[14\]. Fig. 3b has been obtained using formula (4) with

\[\text{Let us remark that, given the convention used throughout this review for gaugino masses in the Lagrangian, $L = \frac{i}{2} \sum M_a \lambda_a \lambda_a + \text{h.c.},$ we are using the renormalization group equations (RGEs) obtained e.g. in ref.\[17\], but with an opposite sign in the gaugino contributions to the RGE’s of the $A_0$ parameters.}\]

\[\text{It is also worth noticing that constraints coming from the $b \rightarrow s \gamma$ process highly reduce the $\mu < 0$ value.}\]
Figure 3: (a) Gaugino-Higgsino components-squared of the lightest neutralino as a function of its mass. (b) Scatter plot of the neutralino-proton cross section as a function of the neutralino mass for the scenario discussed in the text. DAMA and CDMS current experimental limits and projected GENIUS limits are shown.

the central values for the hadronic matrix elements given by eq.(6). We will use these values throughout this review. Likewise we impose the present bounds coming from accelerators. These are LEP and Tevatron bounds on SUSY masses and CLEO $b \rightarrow s\gamma$ branching ratio measurements. For the Higgs mass we use the present experimental lower limit for $\tan \beta = 3$ 19, i.e. $m_h > 95$ GeV. Although, for the values of $\tan \beta$ that we will consider in the next section, $\tan \beta = 10$, this limit is considerably weaker 19, $m_h > 80$ GeV, we will still use $m_h > 95$ GeV. Concerning the parameter space of the figure, we have used $30$ GeV $\leq m_0 \leq 550$ GeV, where the lower bound is in order to avoid the stau being the LSP for all values of $m_{\tilde{\chi}_1^0}$. Note that the curve associated to $m_0 = 550$ GeV corresponds to the minimum values of $\sigma_{\tilde{\chi}_1^0-p}$ in the figure. On the other hand, since the cross sections are not very sensitive to the specific values of $A_0$ in a wide range (we have checked that this is so for $|A_0/M_{1/2}| < 1$), we fix $A_0 = M_{1/2}$ in the figure. As mentioned above the gaugino mass $M_{1/2}$ is essentially fixed for a given $\tan \beta$ and $m_{\tilde{\chi}_0^0}$. For this figure we have to take $140$ GeV $\lesssim M_{1/2} \lesssim 350$ GeV, where the lower bound, corresponding to $m_{\tilde{\chi}_1^+} \geq 55$ GeV, is due to the experimental bound on the lightest chargino mass $m_{\tilde{\chi}_1^+} > 90$ GeV. Negative values of $M_{1/2}$, not shown in the figure, correspond to smaller cross sections.

As we can see in the figure $\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-7}$ pb, and therefore for these values of the parameters we would have to wait in principle for the projected GENIUS detector 20 parameter space. In addition, recent measurements of the anomalous magnetic moment of the muon 18 seems to exclude all cases with $\mu < 0$.

It is worth mentioning here that values for the hadronic matrix elements as those discussed in footnote $a$ will increase in one order of magnitude the results of this and the other figures in this review, since their contribution appears raised to the square in eq.(6).
to be able to test the neutralino as a dark-matter candidate.

3 Large neutralino-nucleon cross section in supergravity scenarios

Recently there has been some theoretical activity \[7\]-\[14\] trying to obtain regions in the parameter space of supergravity (SUGRA) scenarios compatible with the sensitivity of current dark matter detectors, DAMA and CDMS. The key point in most of these scenarios to carry it out consists of reducing the value of $|\mu|$. Following the discussion below eq.(7) in the previous section, the smaller $|\mu|$ is, the larger the Higgsino components of the lightest neutralino become. Eventually, $|\mu|$ will be of the order of $M_1$, $M_2$ and $\tilde{\chi}_0^1$ will be a mixed Higgsino-gaugino state. Indeed scattering channels through Higgs exchange in Fig. 1 are now important and their contributions to the cross section (4) can be schematically approximated as

$$\sigma_{\tilde{\chi}_0^1-p} \approx m_r^2 \lambda_s^2 \alpha \frac{f_s^2}{m_h^2} |N_{13}N_{11}|^2,$$

(9)

where $\lambda_s$ is the strange quark Yukawa coupling and $m_h$ represent the Higgs masses. With the same rough estimate as in eq.(8), one obtains $\sigma_{\tilde{\chi}_0^1-p} \approx 10^{-6}$ pb for $m_h \approx 100$ GeV.

In this section we review the different SUGRA scenarios that can be found in the literature in order to enhance the neutralino-proton cross section $\sigma_{\tilde{\chi}_0^1-p}$ to be of the order of $10^{-6}$ pb.
3.1 Scenario with large $\tan \beta$

In the previous section we showed in Fig. 3b the neutralino-proton cross section for $\tan \beta = 3$, in the framework of mSUGRA. Here we show the same in Fig. 4 but for larger values of $\tan \beta$, in particular for $\tan \beta = 10$ (green points) and 20 (red points). We see that the cross section increases when the value of $\tan \beta$ increases. For moderate values of $\tan \beta$, the reason being that the top(bottom) Yukawa coupling which appears in the RGE for $m^2_{H_u}(m^2_{H_d})$ decreases(increases) since it is proportional to $\frac{1}{\sin \beta} \left( \frac{1}{\cos \beta} \right)$. This implies that the negative(positive) contribution $m^2_{H_u}(m^2_{H_d})$ to $\mu^2$ in eq.(7) is less important, and therefore $|\mu|$ decreases.

However, for $\tan \beta \gtrsim 10$, the value of $\mu^2$ is very stable with respect to variations of $\tan \beta$. This is due to the fact that $\mu^2 \approx -m^2_{H_u} - \frac{1}{2} M^2_Z$ (see eq.(7)). Since $\sin \beta \approx 1$, the top Yukawa coupling is stable and therefore the same conclusion is obtained for $m^2_{H_u}$ and $\mu^2$. Thus, the reason for the cross section to increase when $\tan \beta$ increases cannot be now the increment of the Higgsino components of the LSP. Nevertheless there is a second effect in the cross section which is now the dominant one: the contribution of the down-type quark Yukawa couplings (see eq.(9)) which are proportional to $\frac{1}{\cos \beta}$.

It was in fact pointed out in refs.[7, 8] that the large $\tan \beta$ regime allows regions where $\sigma_{\tilde{\chi}^0_1-p} \approx 10^{-6}$ pb is reached. We can see in Fig. 4 that this is so for $\tan \beta \gtrsim 20$.

Very large values of $\tan \beta$, like $\tan \beta \approx 50$ which correspond approximately to the unification of the tau and top Yukawa couplings at $M_{GUT}$, have also been considered [9]. Although it was found, as expected, that the cross section is enhanced, the well known experimental limits coming from $b \rightarrow s\gamma$ for large $\tan \beta$, lead to severe constraints on the parameter space. In particular, these constraints imply $\sigma_{\tilde{\chi}^0_1-p} < \sim 10^{-6}$ pb.

3.2 Focus point supersymmetry scenario

Another possibility to obtain a large neutralino-nucleon cross section arises in the so-called focus point supersymmetry scenario. This has been proposed [21] in order to avoid dangerous SUSY contributions to flavour and CP violating effects. The idea is to assume the existence of squark and sleptons with masses which can be taken well above 1 TeV. It has also been argued that this situation produces no loss of naturalness.

The implications of focus point supersymmetry for neutralino dark matter have been considered in ref.[11]. In particular, it was pointed out that for $m_0 > 1$ TeV, unlike the usual cases with $m_0 < 1$ TeV, the lightest neutralino is a gaugino-Higgsino mixture over much of parameter space. Let us recall from the previous subsection that for moderate and large values of $\tan \beta$, $\mu^2$ in eq.(7) can be approximated as

$$\mu^2 \approx -m^2_{H_u} - \frac{1}{2} M^2_Z.$$  \hspace{1cm} (10)

Thus for $m_0 > 1$ TeV, $m^2_{H_u}$ becomes less negative, and therefore $|\mu|$ decreases. (For $\tan \beta < 5$, $\mu$ becomes sensitive to $m^2_{H_u}$, and as $m_0$ increases $|\mu|$ also increases, and

*Of course this scenario rules out SUSY as an explanation of the possible deviation in the muon anomalous magnetic moment from the standard model prediction [18].
so there is no mixed gaugino-Higgsino region for small $\tan \beta$. However, as discussed in ref. [11], one still needs large values for $\tan \beta$ (of the order of 50) in order to have $\sigma_{\tilde{\chi}^0_1-p} \lesssim 10^{-6}$ pb.

### 3.3 Scenario with non-universal soft terms

The soft SUSY-breaking terms can have in general a non-universal structure in the MSSM. Such structure can be derived from SUGRA [22]. For the case of the observable scalar masses, this is due to the non-universal couplings in the Kähler potential between the hidden sector fields breaking SUSY and the observable sector fields. For the case of the gaugino masses, this is due to the non-universality of the gauge kinetic functions associated to the different gauge groups. Explicit string constructions, whose low-energy limit is SUGRA, exhibit these properties [22].

It was shown recently, in the context of SUGRA, that non-universality allows to increase [7, 8, 10] the neutralino-proton cross section for moderate values of $\tan \beta$. This can be carried out with non-universal scalar masses and/or gaugino masses, as we will discuss below.

(i) Non-universal scalar masses

Non-universality in the Higgs sector, concerning dark matter, was studied in refs. [23, 24, 1]. Subsequently, non-universality in the sfermion sector was added in the analysis [23, 8]. In order to avoid potential problems with flavour changing neutral currents, it was assumed that the first two generations of squarks and sleptons have a common scalar mass $m_0$ at $M_{GUT}$, and non-universalities were allowed in the third generation.
and Higgs sector. Thus the soft masses can be parameterized as follows:

\[
\begin{align*}
    m_{H_d}^2 &= m_0^2(1 + \delta_1), & m_{H_u}^2 &= m_0^2(1 + \delta_2), \\
    m_{Q_L}^2 &= m_0^2(1 + \delta_3), & m_{u_R}^2 &= m_0^2(1 + \delta_4), \\
    m_{e_R}^2 &= m_0^2(1 + \delta_5), & m_{d_R}^2 &= m_0^2(1 + \delta_6), \\
    m_{L_L}^2 &= m_0^2(1 + \delta_7),
\end{align*}
\]

where \( Q_L = (\tilde{t}_L, \tilde{b}_L), \ L_L = (\tilde{\nu}_L, \tilde{\tau}_L), \ u_R = \tilde{t}_R, \ e_R = \tilde{\tau}_R, \) and it is assumed that \(-1 \leq \delta_i \leq 1\).

As explained at the beginning of this section 3, \( \mu^2 \) is one of the important parameters when computing the neutralino-nucleon cross section. Its value is determined by condition (7) and can be significantly reduced for some choices of \( \delta 's \). We can have a qualitative understanding of the effects of the \( \delta 's \) on \( \mu \) from the following. First, when \( m_{H_u}^2, m_{H_d}^2 \) at \( M_{GUT} \) increases(decreases) its negative(positive) contribution at low energy in eq.(7) is less important. Second, when \( m_{Q_L}^2 \) and \( m_{u_R}^2 \) at \( M_{GUT} \) decrease, due to their contribution proportional to the top Yukawa coupling in the RGE of \( m_{H_u}^2 \), the negative contribution of the latter to \( \mu^2 \) is again less important. Thus one can deduce that \( \mu^2 \) will be reduced (and hence \( \sigma_{\chi_{10}-p} \) increased) by choosing \( \delta_3, \delta_4, \delta_1 < 0 \) and \( \delta_2 > 0 \).

Following this analysis [1, 8] we show in Fig. 3 for \( \tan \beta = 10 \), a scatter plot of \( \sigma_{\chi_{10}-p} \) as a function of \( m_{\tilde{\chi}_1^0} \) for a scanning of the parameters as follows: \( 0 \leq \delta_2 \leq 1, \ -1 \leq \delta_{1,3,4} \leq 0 \). The other \( \delta 's \) are not so important in the computation and we take them vanishing. We are also taking \( A = M_{1/2} \), 30 GeV \( \leq m_0 \leq 550 \) GeV as in Fig. 3b, and we have to take now 140 GeV \( \leq M_{1/2} \leq 450 \) GeV. For comparison we superimpose also the region (green area) obtained in Fig. 3 for \( \tan \beta = 10 \) with universality, \( \delta_i = 0 \). We see that non-universal scalar masses can help in increasing the values of \( \sigma_{\chi_{10}-p} \). In fact non-universality in the Higgs sector gives the most important effect, and including the one in the sfermion sector the cross section only increases slightly. Of course, as discussed in detail in Subsection 3.1, for larger values of \( \tan \beta \) one can get larger cross sections.

(ii) Non-universal gaugino masses

The effects of the non-universality of gaugino masses on dark matter in SUGRA scenarios have been studied in ref.[24, 11, 27]. In particular, in ref.[10], the authors analyze in detail the neutralino-proton cross section in the case of \( SU(5) \) unified models with interesting results, finding that the cross sections can increase.

Here we are interested in the case of the standard model gauge group in order to compare our results with both, the universal case discussed in Sections 2 and 3.1 and the case with non-universal scalar masses discussed above. Let us then parameterize the soft gaugino masses at \( M_{GUT} \) as follows:

\[
M_1 = M_{1/2}(1 + \delta_1'), \quad M_2 = M_{1/2}(1 + \delta_2'), \quad M_3 = M_{1/2}(1 + \delta_3'),
\]

where \( M_{1,2,3} \) are the bino, wino and gluino masses, respectively, and we assume that \(-1 \leq \delta_i' \leq 1\).
Figure 6: The same as in Fig. 3b but only for \( \tan \beta = 10 \) and using non-universal soft gaugino masses as explained in the text. The universal case (green region) is shown for comparison.

Let us discuss now which values of the parameters are interesting in order to increase the cross section, with respect to the universal case \( \delta_i' = 0 \). In this sense, it is worth noticing that \( M_3 \) appears in the RGEs of squark masses, so e.g. their contribution proportional to the top Yukawa coupling in the RGE of \( m_{H_u}^2 \) will do this less negative if \( M_3 \) is small. Therefore \( \mu^2 \) becomes smaller.

Taking into account this effect, we show in Fig. 6, for \( \tan \beta = 10 \), a scatter plot of \( \sigma_{\tilde{\chi}_1^0} \) as a function of \( m_{\tilde{\chi}_1^0} \) for the following scanning of the parameters: \(-1 \leq \delta_{1,2}' \leq 1 \) and \(-2/3 \leq \delta_3' \leq 0 \) (where the lower bound is due to the experimental bound on gluino masses), imposing \( M_3 < M_1, M_2 \). We fix \( M_{1/2} = 225 \) GeV and \( A = M_1 \). As in the previous figures we are taking \( 30 \) GeV \( \leq m_0 \leq 550 \) GeV. We also superimpose for comparison the region (green area) obtained in Fig. 4 for \( \tan \beta = 10 \) with universality, \( \delta_i' = 0 \). Clearly non-universal gaugino masses produce a large increment in the cross section.

Let us finally remark that the upper and right hand side regions with large cross sections in the figure correspond to points of the parameter space fulfilling \( M_2 < M_1 \) (and \( M_3 \) close to its lower bound). As discussed in Section 2, for low or moderate \( \tan \beta \) the lightest neutralino is mainly gaugino \( P > 0.9 \), and in particular bino since \( N_{11} \gg N_{12} \). However, relaxing the universality condition for gaugino masses, \( M_2 < M_1 \) will produce \( N_{11} < N_{12} \), and therefore the lightest neutralino will have an important wino component. Since the latter couples through \( SU(2) \) interactions, unlike the bino component which couples through \( U(1) \) ones, the cross section increases.

(iii) Non-universal gaugino and scalar masses

It is worth noticing that this situation also arises in anomaly-mediated SUSY-breaking scenarios, where the cross section can also be increased\(^2\).\(^9\)\(^11\).

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Given the above situation concerning the enhancement of neutralino-proton cross sections through non-universality for moderate $\tan \beta$, it is worth analyzing in principle the combination of both possibilities, non-universal gaugino and scalar masses. However the consequence for the cross section of combining the parameters studied in (i) and (ii) is not very different from the one obtained in Fig. 6. We have explicitly checked that the qualitative pattern is basically the same.

### 3.4 Scenario with intermediate unification scale

In the above subsections the analyses were performed assuming the unification scale $M_{\text{GUT}} \approx 10^{16}$ GeV, as is usually done in the SUSY literature. However, it was recently realized that the string scale may be anywhere between the weak and the Plank scale [30]-[36]. To use the value of the initial scale, say $M_I$, as a free parameter for the running of the soft terms is particularly interesting since there are several arguments in favour of SUSY scenarios with scales $M_I \approx 10^{10-14}$ GeV.

First, these scales were suggested [33, 34] to explain many experimental observations as neutrino masses or the scale for axion physics. Second, with the string scale of the order of $10^{10-12}$ GeV one is able to attack the hierarchy problem of unified theories without invoking any hierarchically suppressed non-perturbative effect [33, 34]. Third, for intermediate scale scenarios charge and color breaking constraints, which are very strong with the usual scale $M_{\text{GUT}}$ [37], become less important [38]. There are other arguments in favour of scenarios with initial scales $M_I$ smaller than $M_{\text{GUT}}$. For example these scales might also explain the observed ultra-high energy ($\approx 10^{20}$ eV) cosmic rays as products of long-lived massive string mode decays [33, 34] (see ref. [39] for more details about this possibility). Besides, several models of chaotic inflation favour also these scales [40].

Inspired by these scenarios, it was pointed out [12]-[14] that the neutralino-proton cross section $\sigma_{\tilde{\chi}_0^1-p}$ is very sensitive to the variation of the initial scale for the running of the soft terms. In particular, intermediate unification scales were considered. For instance, by taking $M_I = 10^{10-12}$ GeV rather than $M_{\text{GUT}}$, regions in the parameter space of mSUGRA have been found where $\sigma_{\tilde{\chi}_0^1-p}$ is in the expected range of sensitivity of present detectors, and this even for moderate values of $\tan \beta$ ($\tan \beta > \sim 3$). This analysis was performed [12] in the universal scenario for the soft terms. In contrast, in the usual case with initial scale at $M_{\text{GUT}}$, this large cross section is achieved only for $\tan \beta > 20$, as discussed in Subsection 3.1.

Before trying to understand this result, let us discuss what we mean by an intermediate unification scale. Concerning this point two possible scenarios are schematically shown in Fig. 7 for the example $M_I = 10^{11}$ GeV. In scenario (a) the gauge couplings are non universal, $\alpha_i \neq \alpha$, and their values depend on the initial scale $M_I$ chosen. An interesting proposal in order to obtain this scenario in the context of type I string models is the following. If the standard model comes from the same collection of D-branes, stringy corrections might change the boundary conditions at the string scale $M_I$ to mimic the effect of field theoretical logarithmic running [41, 42]. Another possibility
Figure 7: Running of the gauge couplings with energy, shown with solid lines, assuming (a) non universality and (b) universality of couplings at the initial scale \( M_I \). For comparison the usual running of the MSSM couplings is also shown with dashed lines.

giving rise to a similar result may arise when the gauge groups came from different types of D-branes. Since different D-branes have associated different couplings, this implies the non universality of the gauge couplings. We will discuss this possibility in some detail below.

On the other hand, scenario (b) with gauge coupling unification at \( M_I \), \( \alpha_i = \alpha \), can be obtained with the addition of extra fields in the massless spectrum. For the example of the figure these are doublets and singlets under the standard model gauge group.

As we will see below, the values of the gauge coupling constants at the intermediate scale will be important in the computation of the cross section, and scenario (a) will be more interesting than (b).

Let us now come back to the issue of the variation of the cross section with the initial scale. The fact that smaller initial scales imply a larger neutralino-proton cross section can be understood from the variation in the value of \( \mu \) with \( M_I \). One observes that, for \( \tan \beta \) fixed, the smaller the initial scale for the running is, the smaller the numerator in the first piece of eq.(7) becomes. This can be understood qualitatively from Fig. 2. Clearly, the smaller the initial scale is, the shorter the running becomes. As a consequence, also the less important the positive(negative) contribution \( m_{H_d}^2(m_{H_u}^2) \) to \( \mu \) in eq.(7) becomes. Thus \( |\mu| \) decreases.

As discussed at the beginning of this Section 3, now the Higgsino components of the lightest neutralino, \( N_{13} \) and \( N_{14} \) in eq.(2), increase and therefore the spin independent cross section also increases [12]. This is shown in Figs. 8 and 9. In fact these figures correspond to the scenario in Fig. 7a with non-universal gauge couplings. For the scenario in Fig. 7b, only with \( \tan \beta \gtrsim 20 \) one obtains regions consistent with DAMA limits. One of the reasons being that now \( \alpha_2(M_I) \) and \( \alpha_1(M_I) \) are bigger than in scenario (a) and therefore the low-energy bino and wino masses appearing in eq.(11) are smaller. As a consequence the increment of the cross section is less important.

It is also worth noticing that, for any fixed value of \( M_I \), the larger \( \tan \beta \) is, the larger the Higgsino contributions become. The discussion concerning this point in Subsection 3.1 for \( M_{GUT} \) is also valid for any initial scale \( M_I \).
Figure 8: Gaugino-Higgsino components-squared of the lightest neutralino as a function of its mass for the unification scale, $M_I = 10^{16}$ GeV, and for the intermediate scale, $M_I = 10^{11}$ GeV.

In Fig. 8 for $\tan \beta = 10$ and $m_0 = 150$ GeV, we exhibit the gaugino-Higgsino components-squared $N_{1i}^2$ of the lightest neutralino as a function of its mass $\tilde{\chi}^0_1$ for two different values of the initial scale, $M_I = 10^{16}$ GeV $\approx M_{\text{GUT}}$ and $M_I = 10^{11}$ GeV. Clearly, the smaller the scale is, the larger the Higgsino components become. For $M_I = 10^{11}$ GeV, e.g. the Higgsino contribution $N_{13}$ becomes important and even dominant for $\tilde{\chi}^0_1 < \sim 140$ GeV.

The consequence of the above results on the cross section is shown in Fig. 9, where the cross section as a function of the lightest neutralino mass $\tilde{\chi}^0_1$ is plotted. In particular we are comparing the result for the scale $M_I = M_{\text{GUT}}$ studied in Figs. 3 and 4 with the result for the intermediate scale $M_I = 10^{11}$ GeV. For instance, when $m_{\tilde{\chi}^0_1} = 100$ GeV, $\sigma_{\tilde{\chi}^0_1-p}$ for $M_I = 10^{11}$ GeV is two orders of magnitude larger than for $M_{\text{GUT}}$. In particular, for $\tan \beta = 3$, one finds $\sigma_{\tilde{\chi}^0_1-p} \lesssim 10^{-7}$ pb if the initial scale is $M_I = 10^{16}$ GeV. However $\sigma_{\tilde{\chi}^0_1-p} \lesssim 10^{-6}$ GeV is possible if $M_I$ decreases.

As mentioned before, the larger $\tan \beta$ is, the larger the Higgsino contributions become, and therefore the cross section increases. For $\tan \beta = 10$ we see in Fig. 9 that the range $70 \text{ GeV} \lesssim m_{\tilde{\chi}^0_1} \lesssim 100$ GeV is now consistent with DAMA limits.

Let us remark that these figures have been obtained taking $30 \lesssim m_0 \lesssim 550$ GeV and $A_0 = M_{1/2}$ as in previous sections. In any case, as mentioned also in Section 2, the cross section is not very sensitive to the specific values of $A_0$. In particular it was checked that this is so for $|A_0/M_{1/2}| \lesssim 1$. For example, relation $A_0 = -M_{1/2}$ is particularly interesting since it arises naturally in several string models [22, 41].

Let us finally recall that the above computations have been carried out for the case of universal soft terms. This is not only the most simple possibility in the framework of SUGRA, but is also allowed in the context of superstring models. This is e.g. the case of the dilaton-dominated SUSY-breaking scenario [22] or weakly and strongly coupled...
heterotic models with one Kähler modulus [43]. In this sense the analysis of neutralino-nucleon cross sections of those models is included in the above analyses. This is exactly true for $M_I = M_{GUT}$. For intermediate unification scale, note that we are assuming gaugino mass universality at the high energy scale, although in this scenario gauge couplings do not unify. This situation is in principle possible in generic supersymmetric models, however it is not so natural in supersymmetric models from supergravity where gaugino masses and gauge couplings are related through the gauge kinetic function. Since an explicit string construction with nonuniversal gauge couplings and gaugino masses will be analyzed in detail below, we have chosen to simplify the discussion here assuming gaugino mass universality.

Obviously, following the discussion of Subsection 3.3, non-universality of the soft terms in addition to intermediate scales may introduce more flexibility in the computation. In particular, decreasing $|\mu|$ in order to obtain regions in the parameter space giving rise to cross sections compatible with the sensitivity of current detectors, may be easier.

**D-brane scenarios**

D-brane constructions are explicit scenarios where both situations mentioned above, non-universality and intermediate scales, may occur. The first attempts to study dark matter within these constructions were carried out in scenarios with the unification scale $M_{GUT} \approx 10^{16}$ GeV as the initial scale [44, 10, 45] and dilaton-dominated SUSY-breaking scenarios with an intermediate scale as the initial scale [13]. However, the important issue of the D-brane origin of the $U(1)_Y$ gauge group as a combination of other $U(1)$'s and its influence on the matter distribution in these scenarios was not included in the above analyses. When this is taken into account, interesting results
are obtained [14]. In particular, scenarios with the gauge group and particle content of the SUSY standard model lead naturally to intermediate values for the string scale, in order to reproduce the value of gauge couplings deduced from experiments. In addition, the soft terms turn out to be generically non-universal. Due to these results, large cross sections in the small tan β regime can be obtained.

Let us consider for example a type I string scenario [14] where the gauge group $U(3) \times U(2) \times U(1)$, giving rise to $SU(3) \times SU(2) \times U(1)^3$, arises from three different types of D-branes, and therefore the gauge couplings are non-universal as in Fig. 7a. Other examples with the standard model gauge group embedded in D-branes in a different way can be found in ref.[14]. Here $U(1)$ is a linear combination of the three $U(1)$ gauge groups arising from $U(3)$, $U(2)$ and $U(1)$ within the three different D-branes. This implies

$$\frac{1}{\alpha_Y(M_I)} = \frac{2}{\alpha_1(M_I)} + \frac{1}{\alpha_2(M_I)} + \frac{2}{3\alpha_3(M_I)},$$

(13)

where $\alpha_k$ correspond to the gauge couplings of the $U(k)$ branes. As shown in ref.[14], $\alpha_1(M_I) = 0.1$ leads to the string scale $M_I = 10^{12}$ GeV. On the other hand, the extra $U(1)$’s are anomalous and therefore the associated gauge bosons have masses of the order of $M_I$.

The analysis of the soft terms has been done under the assumption that only the dilaton ($S$) and moduli ($T_i$) fields contribute to SUSY breaking and it has been found that these soft terms are generically non-universal. Using the standard parameterization [22]

$$F^S = \sqrt{3}(S + S^*)m_{3/2}\sin\theta,$$

$$F^i = \sqrt{3}(T_i + T_i^*)m_{3/2}\cos\theta\Theta_i,$$

(14)

where $i = 1, 2, 3$ labels the three complex compact dimensions, and the angle $\theta$ and the $\Theta_i$ with $\sum_i |\Theta_i|^2 = 1$, just parameterize the direction of the goldstino in the $S$, $T_i$ field space, one is able to obtain the following soft terms [14]. The gaugino masses associated to the three gauge groups of the standard model are given by

$$M_3 = \sqrt{3}m_{3/2}\sin\theta,$$

$$M_2 = \sqrt{3}m_{3/2}\Theta_1\cos\theta,$$

$$M_Y = \sqrt{3}m_{3/2}\alpha_Y(M_I)\left(\frac{2}{\alpha_1(M_I)} + \frac{\Theta_1\cos\theta}{\alpha_2(M_I)} + \frac{2\sin\theta}{3\alpha_3(M_I)}\right).$$

(15)

The soft scalar masses of the three families are given by

$$m_{Q_i}^2 = m_{3/2}^2 \left[1 - \frac{3}{2} \left(1 - \Theta_i^2\right)\cos^2\theta\right],$$

To be precise, the running of the $U(1)_Y$ gauge coupling is not exactly like in the figure since, due to the D-brane origin of the $U(1)$ gauge groups, relation (13) must be fulfilled. See in this respect Fig. 2 in ref.[14].
\[ m_{d_R}^2 = m_{3/2}^2 \left[ 1 - \frac{3}{2} \left( 1 - \Theta_2^2 \right) \cos^2 \theta \right] , \]
\[ m_{u_R}^2 = m_{3/2}^2 \left[ 1 - \frac{3}{2} \left( 1 - \Theta_3^2 \right) \cos^2 \theta \right] , \]
\[ m_{e_R}^2 = m_{3/2}^2 \left[ 1 - \frac{3}{2} \left( \sin^2 \theta + \Theta_1^2 \cos^2 \theta \right) \right] , \]
\[ m_{L_L}^2 = m_{3/2}^2 \left[ 1 - \frac{3}{2} \left( \sin^2 \theta + \Theta_2^2 \cos^2 \theta \right) \right] , \]
\[ m_{H_u}^2 = m_{3/2}^2 \left[ 1 - \frac{3}{2} \left( \sin^2 \theta + \Theta_3^2 \cos^2 \theta \right) \right] , \]
\[ m_{H_d}^2 = m_{L_L}^2 , \]  

(16)

where e.g. \( u_R \) denotes the three family squarks \( \tilde{u}_R, \tilde{c}_R, \tilde{t}_R \). Finally the trilinear parameters of the three families are

\[ A_u = \sqrt{\frac{3}{2}} m_{3/2} \left[ (\Theta_2 - \Theta_1 - \Theta_3) \cos \theta - \sin \theta \right] , \]
\[ A_d = \sqrt{\frac{3}{2}} m_{3/2} \left[ (\Theta_3 - \Theta_1 - \Theta_2) \cos \theta - \sin \theta \right] , \]
\[ A_e = 0 . \]  

(17)

Although these formulas for the soft terms imply that one has in principle five free parameters, \( m_{3/2}, \theta \) and \( \Theta_i \) with \( i = 1, 2, 3 \), due to relation \( \sum_i |\Theta_i|^2 = 1 \) only four of them are independent. In the analysis the parameters \( \theta \) and \( \Theta_i \) are varied in the whole allowed range, \( 0 \leq \theta \leq 2\pi, -1 \leq \Theta_i \leq 1 \). For the gravitino mass, \( m_{3/2} \leq 300 \) GeV is taken. Concerning Yukawa couplings, their values are fixed imposing the correct fermion mass spectrum at low energies, i.e., one is assuming that Yukawa structures of D-brane scenarios give rise to those values.

Fig. 10 displays a scatter plot of \( \sigma_{\tilde{\chi}_1^0-p} \) as a function of the neutralino mass \( m_{\tilde{\chi}_1^0} \) for a scanning of the parameter space discussed above. Two different values of \( \tan \beta \), 10 and 15, are shown. LEP and Tevatron bounds on SUSY masses are included as in the previous sections. They forbid e.g. values of \( m_{3/2} \) smaller than 170 GeV. Although bounds coming from CLEO \( b \rightarrow s\gamma \) branching ratio measurements are not included in the figures, one can check explicitly that their qualitative patterns are not modified. It is worth noticing that for \( \tan \beta = 10 \) there are regions of the parameter space consistent with DAMA limits. In fact, one can check that \( \tan \beta > 5 \) is enough to obtain compatibility with DAMA. Since the larger \( \tan \beta \) is, the larger the cross section becomes, for \( \tan \beta = 15 \) these regions increase.

Let us recall that both plots in the figure are obtained taking \( m_{3/2} \leq 300 \) GeV, which corresponds to squark masses smaller than 500 GeV at low energies. Larger values of \( m_{3/2} \) will always produce cross sections below DAMA limits. In particular, the right hand side and bottom of the plots will also be filled with points. Cross sections below projected GENIUS limits will be possible for both figures. On the other hand, it is worth mentioning that the isolated points in the plots with, in general, very large values of the cross section correspond to values of the lightest stop mass extremely close to the mass of the LSP, in particular \( (m_{\tilde{t}_i} - m_{\tilde{\chi}_1^0})/m_{\tilde{t}_i} < 0.01 \).
Finally, let us mention that scenarios where all gauge groups of the standard model are embedded within the same set of D-branes, and therefore with gauge coupling unification, are also possible. However, unlike the previous scenario, now $\tan \beta > 20$ is necessary in order to obtain regions consistent with DAMA limits \[14\]. As discussed above in the context of mSUGRA this is due to the different values of the $\alpha$’s at the string scale in both types of scenarios.

4 Relic neutralino density versus cross section

As discussed in the Introduction, current dark matter detectors are sensitive to a neutralino-proton cross section around $10^{-6}$ pb. This value is obtained taking into account, basically, that the density of dark matter in our Galaxy, which follows from the observed rotation curves, is $\rho_{DM} \approx 0.3$ GeV/cm$^3$. Thus in this work we were mainly interested in reviewing the possibility of obtaining such large cross sections in the context of SUSY scenarios. In order to compute the cross section only simple field theory techniques are needed, no cosmological assumptions about the early Universe need to be used.

On the other hand, such cosmological assumptions indeed must be taken into account when computing the amount of relic neutralino density arising from the above scenarios. Generically, one obtains \[13\]

$$\Omega_{\tilde{\chi}^0} h^2 \simeq \frac{C}{\langle \sigma_{\tilde{\chi}^0 \tilde{\chi}_{\chi}^0}^{\text{ann}} v \rangle},$$

(18)

where $\sigma_{\tilde{\chi}^0 \tilde{\chi}_{\chi}^0}^{\text{ann}}$ is the cross section for annihilation of a pair of neutralinos into standard model particles, $v$ is the relative velocity between the two neutralinos, and $\langle .. \rangle$ denotes thermal averaging. The constant $C$ involves factors of Newton’s constant, the
temperature of the cosmic background radiation, etc. Then one may compare this result with dark matter observations in the Universe. Let us then discuss briefly the effect of relic neutralino density bounds on cross sections.

The most robust evidence for the existence of dark matter comes from relatively small scales. Lower limits inferred from the flat rotation curves of spiral Galaxies \[6, 46\] are \(\Omega_{DM} h^2 \gtrsim 0.01 - 0.05\), where \(h\) is the reduced Hubble constant. On the opposite side, observations at large scales, \((6 - 20) h^{-1} \text{ Mpc}\), have provided estimates \[47\] of \(\Omega_{DM} h^2 \approx 0.1 - 0.6\), but values as low as \(\Omega_{DM} h^2 \approx 0.02\) have also been quoted \[15\]. Taking up-to-date limits on \(h\), the baryon density from nucleosynthesis and overall matter-balance analysis one is able to obtain a favoured range \[2, 49, 50\], \(0.01 < \Omega_{DM} h^2 < 0.3\) \((\text{at } \sim 2\sigma \text{ CL})\). Note that conservative lower limits in the small and large scales are of the same order of magnitude.

As is well known, for \(\sigma_{\chi\bar{\chi}}^\text{ann} \approx 10^{-8} \text{ pb}\) of the order of a weak-process cross section, \(\Omega_{\chi_1^0}\) obtained from eq.(18) is within the favoured range discussed above \[6\]. This is precisely the generic case when the lightest neutralino is mainly bino. Then, the neutralino-nucleus cross section is of the order of 1 pb, i.e. \(\sigma_{\chi_1^0-p} \approx 10^{-8} \text{ pb}\), and therefore it is natural to obtain that neutralinos annihilate with very roughly the weak interaction strength. These cross sections were discussed in Section 2 where low and moderate values of \(\tan \beta\) within mSUGRA were considered. In fact, for these cross sections, there is always a set of parameters which yield \(0.1 < \Omega_{\chi_1^0} h^2 < 0.3\). This analysis, including a complete treatment of coannihilations was carried out in refs.\[16, 51\].

On the other hand, in this review we were interested in larger neutralino-nucleon cross sections in order to be in the range of sensitivity of current dark matter detectors. It is then expected that such high neutralino-proton cross sections \(\sigma_{\chi_1^0-p} \approx 10^{-6} \text{ pb}\), as those presented in Section 3, will correspond to relatively low relic neutralino densities. This is in general the situation. There is always a set of parameters for which the value of the relic density is still inside the ranges we considered above when discussing the observational bounds, but it is generically close to the conservative lower bound. The analysis of the relic neutralino density for scenarios with large \(\tan \beta\) and non-universal scalar masses was carried out in refs.\[5, 6, 7, 52\]. Scenarios with non-universal gaugino masses were studied in refs.\[26, 27\]. An analysis of the relic density for focus point supersymmetry can be found in ref.\[11\]. Discussions for scenarios with intermediate unification scales can be found in refs.\[12\]-\[14\].

Finally, in case of preferring the stronger lower bound \(\Omega_{DM} h^2 > 0.1\), let us mention the possibility that not all the dark matter in our Galaxy are neutralinos. Then \(\Omega_{\chi_1^0} < \Omega_{DM}\), and therefore \(\Omega_{\chi_1^0} < 0.1\) is possible. However, due to the corresponding reduction in the density of neutralinos in the Galactic halo, the neutralino-proton cross section should be increased in order to maintain the experimental detection rates \[16, 55, 56\].

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\textsuperscript{h}Let us remark, however, that scenarios with intermediate scales might give rise to cosmological results different from the usual ones summarized in eq.(13) \[53\].
5 Final comments and outlook

There is overwhelming evidence that most of the matter in the Universe is dark matter. In the present paper we have reviewed the direct detection of supersymmetric dark matter in the light of recent experimental efforts. In particular, DAMA collaboration using a NaI detector has reported recently [4] data favouring the existence of a WIMP signal in their search for annual modulation. They require a large cross section of the order of $10^{-6} \text{ pb}$. We have observed that there are regions in the parameter space of SUGRA scenarios [7]-[14] where such a value can be obtained, although it is fair to say that smaller values can also be obtained and even more easily. The latter result may be important since CDMS collaboration using a germanium detector has reported a null result for part of the region explored by DAMA. Clearly, more sensitive detectors producing further data are needed to solve this contradiction. Fortunately, many dark matter detectors are being projected. This is the case e.g. of DAMA 250 kg. and CDMS Soudan, but particularly interesting is the projected GENIUS detector where values of the cross section as low as $10^{-9} \text{ pb}$ will be accessible.

In summary, underground physics as the one discussed here in order to detect dark matter is crucial. Even if neutralinos are discovered at future particle accelerators such as LHC, only their direct detection due to their presence in our galactic halo will confirm that they are the sought-after dark matter of the Universe.

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