Published by Institute of Physics Publishing for SISSA/ISAS

Received: *June 2, 2004*
Revised: *September 17, 2004*
Accepted: *October 6, 2004*

Neutralino dark matter in supergravity theories with non-universal scalar and gaugino masses

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Abstract: We analyse the direct detection of neutralino dark matter in supergravity scenarios with non-universal soft scalar and gaugino masses. In particular, the neutralino-nucleon cross section is computed and compared with the sensitivity of detectors. We take into account the most recent experimental and astrophysical constraints on the parameter space, including those coming from charge and colour breaking minima. Gaugino non-universalities provide a larger flexibility in the neutralino sector. In particular, when combined with non-universal scalars, neutralinos close to the present detection limits are possible with a wide range of masses, from over 400 GeV to almost 10 GeV. We study the different possibilities which allow to increase or decrease the neutralino mass and explain the properties of those regions in the parameter space with a large cross section.

Keywords: Supersymmetry Phenomenology, Supergravity Models, Cosmology of Theories beyond the SM.

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http://jhep.sissa.it/archive/papers/jhep102004015/jhep102004015.pdf

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1. Introduction

Weakly Interacting Massive Particles (WIMPs) are plausible candidates for the dark matter in the Universe [1]. They are specially interesting because they can be present in the right amount to explain the matter density observed in the analysis of galactic rotation curves [2], cluster of galaxies and large scale flows [3], $0.1 \lesssim \Omega h^2 \lesssim 0.3$ ($0.094 \lesssim \Omega h^2 \lesssim 0.129$ if we take into account the recent data obtained by the WMAP satellite [4]).

The leading candidate for WIMP is the lightest neutralino [1], $\tilde{\chi}_1^0$, a particle predicted by the supersymmetric (SUSY) extension of the standard model. These neutralinos are usually stable and therefore may be left over from the Big Bang. Thus they will cluster gravitationally with ordinary stars in the galactic halos, and in particular they will be present in our own galaxy, the Milky Way. As a consequence there will be a flux of these dark matter particles on the Earth.

Many underground experiments have been carried out around the world in order to detect this flux, by observing the elastic scattering of the dark matter particles on target nuclei through nuclear recoils [1]. In fact, one of the current experiments, the DAMA collaboration, has reported data favouring the existence of a WIMP signal [5]. Taking into account uncertainties on the halo model, it was claimed that the preferred range of the WIMP-nucleon cross section is $\sigma \approx 10^{-6} - 10^{-5}$ pb for a WIMP mass smaller than $500 - 900$ GeV [5, 6]. Unlike this spectacular result, other collaborations such as CDMS [7] and EDELWEISS [8], claim to have excluded important regions of the DAMA parameter space.

In any case, due to these and other projected experiments [1], it seems very plausible that the dark matter will be found in the near future. For example, GEDEON [9] will be able to explore positively a WIMP-nucleon cross section $\sigma \gtrsim 3 \times 10^{-8}$ pb. Similarly, CDMS

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Soudan (an expansion of the CDMS experiment in the Soudan mine), will be able to test $\sigma \gtrsim 2 \times 10^{-8}$ pb. But the most sensitive detector will be GENIUS [10], which will be able to test a WIMP-nucleon cross section as low as $\sigma \approx 10^{-9}$ pb.

Given this situation, and assuming that the dark matter is a neutralino, it is natural to wonder how big the cross section for its direct detection can be. Obviously, this analysis is crucial in order to know the possibility of detecting dark matter in the experiments. In fact, the analysis of the neutralino-proton cross section has been carried out by many authors and during many years [1]. The most recent studies take into account the present experimental and astrophysical constraints on the parameter space. Concerning the former, the lower bounds on the Higgs mass and the supersymmetric particles, the $b \to s\gamma$ branching ratio, and the supersymmetric contribution to the muon anomalous magnetic moment, $a_\mu^{\rm SUSY}$, have been considered. The astrophysical bounds on the matter density mentioned above have also been imposed on the theoretical computation of the relic neutralino density, assuming thermal production. In addition, the constraints that the absence of dangerous charge and colour breaking minima imposes on the parameter space have also been taken into account [11].

In the usual minimal supergravity (mSUGRA) scenario, where the soft terms of the minimal supersymmetric standard model (MSSM) are assumed to be universal at the unification scale, $M_{\rm GUT} \approx 2 \times 10^{16}$ GeV, and radiative electroweak symmetry breaking is imposed, the cross section turns out to be constrained by $\sigma_{\tilde{\chi}_1^0-p} \lesssim 3 \times 10^{-8}$ pb [1]. Clearly, in this case, present experiments are not sufficient and more sensitive detectors producing further data are needed.

The above result can be modified by taking into account possible departures from the mSUGRA scenario, and different possibilities have been proposed in the literature. For example, when the GUT condition is relaxed and an intermediate scale is allowed, the cross section increases significantly [12]. However, the experimental bounds impose $\sigma_{\tilde{\chi}_1^0-p} \lesssim 4 \times 10^{-7}$ pb. And, in fact, at the end of the day, the preferred astrophysical range for the relic neutralino density, $0.1 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.3$, imposes $\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-7}$ pb, i.e., beyond the sensitivity of present experiments [11].

A more general situation in the context of SUGRA than universality, the presence of non-universal soft scalar [13]–[26],[11, 27] and gaugino masses [28, 21, 23, 29, 24, 30, 31, 11] has also been considered. Non-universalities in both the scalar and gaugino sectors were also studied in [32] in the context of a SUSY GUT inspired MSSM version. In particular, for some special choices of the non-universality in the scalar sector the cross section can be increased significantly with respect to the universal scenario, and allowed by all experimental and astrophysical constraints. In fact, not only large regions of the parameter space are accessible for future experiments, but also in part of them the sensitivity of present experiments is reached, $\sigma_{\tilde{\chi}_1^0-p} \approx 10^{-6}$ pb (for a recent analysis, see e.g. ref. [11]).[1] On the other hand, non-universality in the gaugino sector also increases the cross section. However, the above sensitivity region cannot be reached, and $\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-7}$ pb.

[1] This is similar to what occurs in the so-called effMSSM scenario [33]–[39], where the parameters are defined directly at the electroweak scale.

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The aim of this paper is to investigate the general case, where non-universalities are present both in the scalar and gaugino sectors, and to carry out a detailed analysis of the prospects for the direct detection of neutralino dark matter in these scenarios. In this analysis we will take into account the present experimental and astrophysical constraints mentioned above, as well as the constraints coming from charge and colour breaking minima. In the light of the recent experimental results, we will be specially interested in studying how big the cross section can be. Our purpose is to provide a general analysis which can be used in the study of any concrete model.

The paper is organised as follows. In section 2 we will discuss the situation concerning the neutralino-proton cross section in SUGRA theories. In particular, we will review the possible departures from mSUGRA, with either non-universal soft scalar masses or soft gaugino masses, which give rise to large values of the cross section. In section 3 we will study the general case where both scalar and gaugino non-universalities are present. We will indicate the conditions under which a significant enhancement of the resulting cross section is obtained. Finally, the conclusions are left for section 4.

2. Departures from the mSUGRA scenario

In this section we will review possible departures from the mSUGRA scenario and their impact on the neutralino-proton cross section. Let us first recall that in mSUGRA one has only four free parameters defined at the GUT scale: the soft scalar mass m, the soft gaugino mass M, the soft trilinear coupling A, and the ratio of the Higgs vacuum expectation values, $\tan\beta \equiv \langle H_u^0\rangle/\langle H_d^0\rangle$. In addition the sign of the Higgsino mass parameter, μ, remains also undetermined by the minimization of the Higgs potential, which implies

$$\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2\,. \tag{2.1}$$

Using these parameters the neutralino-proton cross section has been analysed exhaustively in the literature, as mentioned in the Introduction. Taking into account all kind of experimental and astrophysical constraints, the result is that the scalar cross section is bounded to be $\sigma_{\tilde{\chi}_1^0-p} \lesssim 3\times 10^{-8}$ pb (for a recent analysis, see e.g. ref. [11]). Obviously, in mSUGRA, present experiments for the direct detection of dark matter are not sufficient and more sensitive detectors producing further data are needed.

The neutralino-proton cross section can be increased in different ways when the structure of mSUGRA for the soft terms is abandoned. In particular, it is possible to enhance the scattering channels involving exchange of CP-even neutral Higgses by reducing the Higgs masses, and also by increasing the Higgsino components of the lightest neutralino. A brief analysis based on the Higgs mass parameters, $m_{H_d}^2$ and $m_{H_u}^2$, at the electroweak scale can clearly show how these effects can be achieved.

First, a decrease in the values of the Higgs masses can be obtained by increasing $m_{H_u}^2$ (i.e., making it less negative) and/or decreasing $m_{H_d}^2$. More specifically, the value of the mass of the heaviest CP-even Higgs, H, can be very efficiently lowered under these circumstances. This is easily understood by analysing the (tree-level) mass of the CP-odd

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Higgs,[2] A,

$$m_A^2 = m_{H_d}^2 + m_{H_u}^2 + 2\mu^2 \,,$$

which can be rewritten as

$$m_A^2 \approx m_{H_d}^2 - m_{H_u}^2 - M_Z^2 \,, \tag{2.3}$$

taking into account that, for reasonably large values of $\tan\beta$, expression (2.1) can be approximated as

$$\mu^2 \approx -m_{H_u}^2 - \frac{1}{2} M_Z^2 \,. \tag{2.4}$$

Since the heaviest CP-even Higgs, H, is almost degenerate in mass with A, lowering m_A^2 we obtain a decrease in m_H which produces an increase in the scattering channels through Higgs exchange.[3]

Second, through the increase in the value of $m_{H_u}^2$ an increase in the Higgsino components of the lightest neutralino can also be achieved. Making $m_{H_u}^2$ less negative, its positive contribution to μ^2 in (2.4) would be smaller. Eventually $|\mu|$ will be of the order of M_1, M_2 and $\tilde{\chi}_1^0$ will then be a mixed Higgsino-gaugino state. Thus scattering channels through Higgs exchange become more important than in mSUGRA, where $|\mu|$ is large and $\tilde{\chi}_1^0$ is mainly bino. It is worth emphasizing however that the effect of lowering the Higgs masses is typically more important, since it can provide large values for the neutralino-nucleon cross section even in the case of bino-like neutralinos.

2.1 Non-universal scalars

Non-universal soft parameters can produce the above mentioned effects. Let us first consider non-universalities in the scalar masses [13, 14]. We can parameterise these in the Higgs sector, at the GUT scale, as follows:

$$m_{H_d}^2 = m^2(1+\delta_1) \,, \qquad m_{H_u}^2 = m^2(1+\delta_2) \,. \tag{2.5}$$

Concerning squarks and sleptons we will assume that the three generations have the same mass structure:

$$\begin{aligned} m_{Q_L}^2 &= m^2(1+\delta_3) \,, \qquad & m_{u_R}^2 &= m^2(1+\delta_4) \,, \\ m_{e_R}^2 &= m^2(1+\delta_5) \,, \qquad & m_{d_R}^2 &= m^2(1+\delta_6) \,, \\ m_{L_L}^2 &= m^2(1+\delta_7) \,. \end{aligned} \tag{2.6}$$

Such a structure avoids potential problems with flavour changing neutral currents.[4] Note

[2] The CP-odd Higgs mass generically receives very small one-loop corrections, of order 1%. For this reason we will only consider its tree-level value in the discussion.

[3] Let us remark that this is true for values of m_A^2 above a certain critical mass (which corresponds to the intense-coupling regime for the Higgses [40] and also sets the maximum value of the lightest Higgs mass). For values of m_A^2 below this critical mass, m_H is stabilised close to its minimal value and it is now the mass of the lightest Higgs, h, which decreases with decreasing m_A^2, thus obtaining a further increase in the cross section. This can occur, e.g., in the case of very light neutralinos, as we will see in section 3.2.1.

[4] Another possibility would be to assume that the first two generations have the common scalar mass m, and that non-universalities are allowed only for the third generation. This would not modify our analysis since, as we will see below, only the third generation is relevant in our discussion.

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also that whereas $\delta_i \geq -1$, $i = 3, \ldots, 7$, in order to avoid an unbounded from below (UFB) direction breaking charge and colour, $\delta_{1,2} \leq -1$ is possible as long as $m_1^2 = m_{H_d}^2 + \mu^2 > 0$ and $m_2^2 = m_{H_u}^2 + \mu^2 > 0$ are fulfilled.

An increase in $m_{H_u}^2$ at the electroweak scale can be obviously achieved by increasing its value at the GUT scale, i.e., with the choice $\delta_2 > 0$. In addition, this is also produced when $m_{Q_L}^2$ and $m_{u_R}^2$ at $M_{\rm GUT}$ decrease, i.e. taking $\delta_{3,4} < 0$, due to their (negative) contribution proportional to the top Yukawa coupling in the renormalization group equation (RGE) of $m_{H_u}^2$.

Similarly, a decrease in the value of $m_{H_d}^2$ at the electroweak scale can be obtained by decreasing it at the GUT scale with $\delta_1 < 0$. Also, this effect is produced when $m_{Q_L}^2$ and $m_{d_R}^2$ at $M_{\rm GUT}$ increase, due to their (negative) contribution proportional to the bottom Yukawa coupling in the RGE of $m_{H_d}^2$. Thus one can deduce that m_A^2 will be reduced by choosing also $\delta_{3,6} > 0$.

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. Thus in what follows we will take $\delta_i = 0$, $i = 3, \ldots, 7$.

Taking into account this analysis, several scenarios were discussed in ref. [11], obtaining that large values for the cross section are possible. For example, with $\delta_1 = 0$, $\delta_2 = 1$; $\delta_1 = -1$, $\delta_2 = 0$; $\delta_1 = -1$, $\delta_2 = 1$, one obtains regions of the parameter space accessible for experiments[5] Interestingly, it was also realised that these choices were helpful in order to prevent the appearance of UFB minima in the Higgs potential.

The neutralino mass in these cases has a lower limit which can be derived from the effect of the experimental constraints on the common gaugino mass, M, and the μ parameter. Small values of M are restricted by the constraints on the Higgs mass and $a_\mu^{\rm SUSY}$, and by $b \to s\gamma$. The latter becomes very important for large values of $\tan\beta$. These imply $M \gtrsim 200\,{\rm GeV}$ at the GUT scale and thus $M_1 \gtrsim 80$ at the electroweak scale, which can be interpreted as a lower bound for the mass of a bino-like neutralino. Similarly, the value of the μ parameter is restricted by the lower bound on the lightest chargino, thus having $|\mu| \gtrsim 100\,{\rm GeV}$. Although this would set a lower constraint on Higgsino-like neutralinos, these give rise to very small relic densities and are therefore further restricted. For these reasons, the neutralino mass in SUGRA theories with only non-universal scalars cannot be arbitrarily lowered.

2.2 Non-universal gauginos

Let us now review the effect of the non-universality in the gaugino masses. We can parameterise this as follows:

$$M_1 = M\,, \qquad M_2 = M(1+\delta'_2)\,, \qquad M_3 = M(1+\delta'_3)\,, \tag{2.7}$$

where $M_{1,2,3}$ are the bino, wino and gluino masses, respectively, and $\delta'_i = 0$ corresponds to the universal case.

[5] Note in this sense that varying the soft Higgs masses, $m_{H_d}^2$ and $m_{H_u}^2$, corresponds to varying μ and m_A arbitrarily in the effMSSM scenario.

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In order to increase the cross section it is worth noticing that M_3 appears in the RGEs of squark masses. Thus the contribution of squark masses proportional to the top Yukawa coupling in the RGE of $m_{H_u}^2$ will do this less negative if M_3 is small. As discussed above, this produces an enhancement in the cross section.

Because the mass of the lightest Higgs is very dependent on the value of M_3, its decrease is very limited. In fact, in order to satisfy the lower limit of M_3, M in (2.7) may have to increase, thus rather than a decrease in M_3 what one obtains is an effective increase in M_1 and M_2, which leads to a larger (less negative) value of $m_{H_u}^2$ and thus a reduction in the value of $|\mu|$. This in turn implies heavier neutralinos, when the lightest neutralino is mostly gaugino, and an increase of the Higgsino composition, which would be dominant if $M_1 > |\mu|$ at the electroweak scale. For this reason there is a slight raise in the predictions for $\sigma_{\tilde{\chi}_1^0-p}$.[6] Finally, decreasing the ratio M_3/M_1 leads to a more efficient neutralino annihilation due to the enhancement in the Higgsino components of $\tilde{\chi}_1^0$, entailing a reduction of $\Omega_{\tilde{\chi}_1^0}$. An example with $\delta_2' = 0, \delta_3 = -0.5$, producing an increase in the dark matter cross section with respect to the universal case, can be found in ref. [11], where it was also argued that this choice of gaugino non-universalities is good to avoid UFB constraints.

On the other hand, increasing the value of M_3 with $\delta_3 > 0$ presents the advantage that the constraint on the lightest Higgs mass is more easily fulfilled. Equivalently, this implies that the value of M in (2.7) can be lowered and thus have an effective decrease in M_1 (and also M_2 unless $\delta_2 > 0$ is chosen). This makes it possible to obtain lighter neutralinos with a larger bino composition, satisfying all the experimental and astrophysical constraints. However, because of the above arguments the values of the cross section would slightly decrease with respect to the universal case. Despite the decrease in the neutralino mass, the appearance of light neutralinos in this case is also restricted by the results on the relic density. In particular, very light neutralinos typically give rise to a very large $\Omega_{\tilde{\chi}_1^0}$, which would be incompatible with present observations. A reduction in the relic density would only be obtained along the narrow resonances with the lightest Higgs and the Z at $m_{\tilde{\chi}_1^0} = m_h/2$, $M_Z/2$, respectively, thus setting the lower bound for the neutralino mass in these scenarios with only gaugino non-universalities. We will later come back to this point in the context of a more general SUGRA scenario.

The main role of M_2 is altering the lightest neutralino composition. It is well known that decreasing the ratio M_2/M_1, thus increasing the wino component of the lightest neutralino, enhances the neutralino detection rates and provides a more effective neutralino annihilation through channels mediated by $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+$ and coannihilations with these [41, 42, 29]. However, this is only effective when $M_2/M_1 \lesssim 0.5$ (which leads to $M_2 \lesssim M_1$ after the running from the GUT scale in the MSSM), and as pointed out in refs. [41, 29], as soon as the wino component begins to dominate, the resulting relic density becomes too small. Variations in the value of M_2 also affect the predictions for $a_\mu^{\rm SUSY}$. For instance, decreasing M_2, the contribution of the diagrams involving intermediate chargino-sneutrino states to $a_\mu^{\rm SUSY}$ becomes more important and it may increase beyond its upper

[6] Note that the value of $m_{H_d}^2$ also increases, thus m_A calculated from (2.3) is typically not very affected.

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bound. This sets a more stringent lower bound on the masses of the neutralino. If, on the other hand, M_2 is increased, the decrease in $a_\mu^{\rm SUSY}$ will set a stronger upper constraint on $m_{\tilde\chi_1^0}$.

Summarising, although gaugino non-universalities also alter the predictions for the neutralino-nucleon cross section, their influence for raising it is not as important as the one arising from non-universal scalars. In particular, none of the above choices for the parameters allows the appearance of neutralinos in the detection range of present dark matter experiments.

3. General case: non-universal scalars and gauginos

In this section we will consider the general case where the soft supersymmetry-breaking terms for both scalar and gauginos have a non-universal structure. Analysing the effect of combining these non-universalities is interesting from the theoretical point of view, since such a structure can be recovered in the low-energy limit of some phenomenologically appealing string scenarios. For example, D-brane constructions in type-I string possess this property [43] when the gauge group of the Standard Model originates from different stacks of D-branes.

We will be mostly interested in analysing the conditions under which high values for the cross section are obtained. For this reason, we will concentrate on some interesting choices for scalar non-universalities, exemplified by the following cases [11]

$$\begin{array}{lll} (a) & \delta_1 = 0, & \delta_2 = 1\,; \\ (b) & \delta_1 = -1, & \delta_2 = 0\,; \\ (c) & \delta_1 = -1, & \delta_2 = 1\,, \end{array} \tag{3.1}$$

and study the effect of adding gaugino non-universalities to these.

The soft terms are given at a high energy scale which in our analysis will be taken to be the GUT scale, where unification of the gauge coupling constants takes place. In our computation the most recent experimental and astrophysical constraints will be taken into account. In particular, the lower bounds on the masses of the supersymmetric particles and on the lightest Higgs have been implemented, as well as the experimental bounds on the branching ratio of the $b \to s\gamma$ process and on $a_\mu^{\rm SUSY}$. The evaluation of the neutralino relic density is carried out with the program `micrOMEGAs` [44], and, due to its relevance, the effect of the WMAP constraint on it will be shown explicitly. Finally, dangerous charge and colour breaking minima of the Higgs potential will be avoided by excluding UFB directions.

Concerning $a_\mu^{\rm SUSY}$, we have taken into account the recent experimental result for the muon anomalous magnetic moment [45], as well as the most recent theoretical evaluations of the Standard Model contributions [46]. It is found that when e^+e^- data are used the experimental excess in $(g_\mu - 2)$ would constrain a possible supersymmetric contribution to be $a_\mu^{\rm SUSY} = (27.1 \pm 10) \times 10^{-10}$. In our analysis we will impose consistency with this value at 2σ level and thus use the constraint[7] $7.1 \times 10^{-10} \lesssim a_\mu^{\rm SUSY} \lesssim 47.1 \times 10^{-10}$. For details on how the rest of the experimental bounds are implemented see [11].

[7] It is worth noticing at this point that when tau data are used a smaller discrepancy with the experimental measurement is found.

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The parameter space consists of a common scalar mass, m, with the non-universal Higgs masses given by (2.5) and the three choices (3.1), a common trilinear parameter, A, and a gaugino sector which can be specified with the three independent parameters, M, δ'_2 and δ'_3, in (2.7). The set of inputs is completed with $\tan\beta$ and the sign of the μ parameter.

Because the sign of $a_\mu^{\rm SUSY}$ is basically given by $\mu\, M_2$, we will consider $\mathrm{sign}(M_2) = \mathrm{sign}(\mu)$ in order to fulfil the experimental result.[8] Similarly, the constraint on the $b \to s\gamma$ branching ratio is much weaker when $\mathrm{sign}(M_3) = \mathrm{sign}(\mu)$. Finally, variations in the sign of M_1 do not induce significant changes in the allowed regions of the parameter space (e.g., its effect on $a_\mu^{\rm SUSY}$, due to diagrams with neutralino intermediate states, is smaller than the one of M_2). However, when $\mathrm{sign}(M_1) = \mathrm{sign}(\mu)$ the theoretical predictions for $\sigma_{\tilde\chi_1^0-p}$ are larger. For these reasons we will restrict our analysis to positive values of $M_{1,2,3}$ and $\mu > 0$. Note in this sense, that due to the symmetry of the RGEs, the results for $(M_{1,2,3}, \mu, A)$ are identical to those for $(-M_{1,2,3}, -\mu, -A)$.

Due to the importance of the gluino mass parameter, we will group the possible gaugino non-universalities in two different cases, depending on whether the ratio M_3/M_1 at the GUT scale decreases or increases with respect to its value in the universal case, and analyse variations of M_2 within each case.

3.1 Decrease in M_3/M_1

Let us first study the consequences of decreasing the value of M_3 with respect to M_1 as a complement to the scalar non-universalities (3.1). We will therefore choose $\delta'_3 < 0$ in (2.7). In order to satisfy the constraint on the lightest Higgs mass, higher values of M, and therefore of M_1 are necessary. In those cases where the lightest neutralino is mostly bino this implies that the neutralino mass is increased. Thus it is possible to find heavier neutralinos with a relatively high value for their direct detection cross section.

Regarding M_2, let us begin by considering also a reduction in M_2/M_1, by taking $\delta'_2 < 0$ in (2.7). The gaugino structure at the GUT scale would therefore be $M_1 > M_2 \sim M_3$. An example with $\delta'_{2,3} = -0.25$ is shown in figure 1, where the neutralino-nucleon cross section is plotted versus the neutralino mass, $m_{\tilde\chi_1^0}$, for $\tan\beta = 35$, $A = 0$ and a full scan in m and M for the different choices of non-universal scalar parameters (3.1). All the points represented fulfil the different experimental constraints, and among them dark gray points are those with a relic density in the range $0.1 \le \Omega_{\tilde\chi_1^0} h^2 \le 0.3$ and black ones correspond to those reproducing the WMAP result. Those points excluded due to the presence of UFB minima are shown explicitly with circles.

The sensitivities of present and projected dark matter experiments are also depicted for comparison. The small area bounded by dotted lines is allowed by the DAMA experiment in the simple case of an isothermal spherical halo model. The larger area also bounded by dotted lines represents the DAMA region when uncertainties to this simple model are

[8] Note that if the constraint on $a_\mu^{\rm SUSY}$ resulting from tau data is taken into account, a different sign for M_2 and μ could in principle also be used. Nevertheless, in order to reproduce the negative values of $a_\mu^{\rm SUSY}$, which are very small in modulus, very large values of $|M_2|$ are necessary. This possibility is therefore very constrained.

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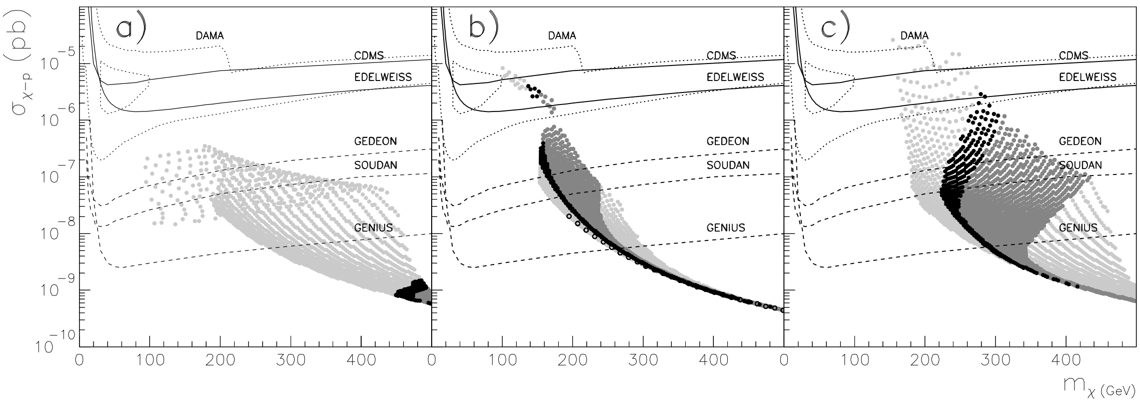

Figure 1: Scatter plot of the scalar neutralino-proton cross section $\sigma_{\tilde{\chi}_1^0-p}$ as a function of the neutralino mass $m_{\tilde{\chi}_1^0}$ for $\delta'_{2,3} = -0.25$ and the three choices for non-universal scalars (3.1) in a case with $\tan\beta = 35$ and $A = 0$. The light grey dots correspond to points fulfilling all the experimental constraints. The dark grey dots represent points fulfilling in addition $0.1 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.3$ and the black ones correspond to those consistent with the WMAP range. Points excluded by the UFB constraints are represented with circles. The sensitivities of present and projected experiments are also depicted with solid and dashed lines, respectively. The large (small) area bounded by dotted lines is allowed by the DAMA experiment when astrophysical uncertainties are (are not) taken into account.

taken into account. The (upper) areas bounded by solid lines are excluded by CDMS and EDELWEISS. Finally, the dashed lines represent the sensitivities of the projected GEDEON, SOUDAN, and GENIUS experiments.[9]

The results for the neutralino-nucleon cross section are similar to those with only scalar non-universalities (compare them with figures 13, 15, 17 of [11]). In particular, regions of the parameter space fulfilling all the constraints and with a cross section close to the detection range appear for moderate values of $\tan\beta$, entering the DAMA region for $\tan\beta \gtrsim 30$. However, these regions are shifted towards larger M_1 and thus heavier neutralinos are obtained. For instance, in case (c) it is possible to have neutralinos compatible with DAMA with masses as large as 300 GeV.

In case (b) a disconnected region appears with large values for the detection cross section, $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 2 \times 10^{-6}$ pb. Such predictions are due to the occurrence of very light Higgses, 91 GeV$< m_h \lesssim 105$ GeV, with $\sin^2(\alpha-\beta) < 0.2$, where α is the mixing angle in the Higgs mass matrix. Higgses with these properties would have escaped detection, due to the reduction of the ZZh coupling, and are thus in agreement with the experimental bound derived from LEP2 [48]. The points that would interpolate between this region and the bulk area present heavier Higgses, 105 GeV$\lesssim m_h < 114.1$ GeV, but also larger values of $\sin^2(\alpha-\beta)$, and are therefore excluded by the experimental constraint. In the bulk region $\sin^2(\alpha-\beta) \approx 1$ and $m_h > 114.1$ GeV, thus being experimentally allowed.[10] In the

[9]It is necessary to emphasize at this point that the analysis including uncertainties on the isothermal spherical halo model has only been performed for DAMA, but not for the other detectors. This is a complicated issue (see e.g. [47]), and therefore a proper comparison (and determination of the real extent of the allowed region) is currently unavailable.

[10]In our computation the value of $\sin^2(\alpha-\beta)$ is calculated for all points of the parameter space in order

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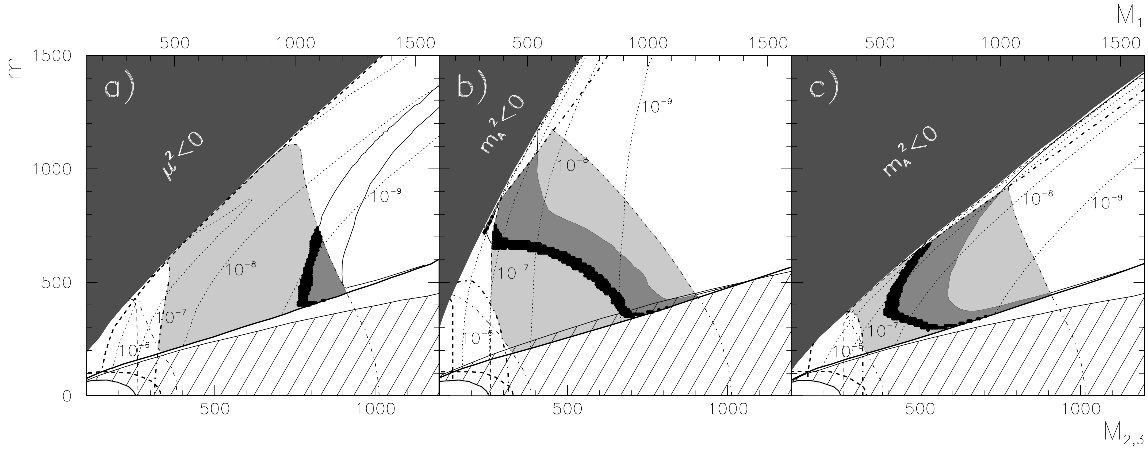

Figure 2: Scalar neutralino-proton cross section $\sigma_{\tilde{\chi}_1^0-p}$ in the parameter space (m, M_i) for $\delta'_{2,3} = -0.25$ and the three choices for non-universal scalars (3.1) in a case with $\tan\beta = 35$ and $A = 0$. The dotted curves are contours of $\sigma_{\tilde{\chi}_1^0-p}$. The region to the left of the dashed line is excluded by the lower bound on the Higgs mass. The region to the left of the double dashed line is excluded by the lower bound on the chargino mass $m_{\tilde{\chi}_1^\pm} > 103.5\,\text{GeV}$. The corner in the lower left shown also by a double dashed line is excluded by the LEP bound on the stau mass $m_{\tilde{\tau}_1} > 87\,\text{GeV}$, and the white region at the bottom bounded by a solid line is excluded because $m^2_{\tilde{\tau}_1}$ becomes negative. The region bounded by dot-dashed lines is allowed by $g_\mu - 2$. The region to the left of the double dot-dashed line is excluded by $b \to s\gamma$. From bottom to top, the solid lines are the upper bounds of the areas such as $m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^0}$ (double solid), $\Omega_{\tilde{\chi}_1^0}h^2 < 0.1$ and $\Omega_{\tilde{\chi}_1^0}h^2 < 0.3$. The light shaded area is favoured by all the phenomenological constraints, while the dark one fulfils in addition $0.1 \leq \Omega_{\tilde{\chi}_1^0}h^2 \leq 0.3$. The black region on top of this indicates the WMAP range, $0.094 \leq \Omega_{\tilde{\chi}_1^0}h^2 \leq 0.129$. The ruled region is excluded because of the charge and colour breaking constraint UFB-3. The value of M_3 is represented in the lower x-axis, whereas M_1 is represented in the upper x-axis.

remainder of the paper we will encounter similar situations, when the choice (b) in (3.1) for scalar non-universalities is taken.

The corresponding (m, M_i) parameter space is represented in figure 2 for each case, displaying the effect of the different constraints and evidencing the increase in M_1. Because the allowed range in $M_{2,3}$ (represented in the lower x-axis) is practically the same as with just non-universal scalars, the values of M_1 are larger. In this particular case, $M_1 \gtrsim 350\,\text{GeV}$ is required. Note that due to the reduction in the value of $m^2_{H_u}$ achieved both through the gaugino and scalar non-universalities the regions in the parameter space excluded due to UFB minima are smaller than in the universal case and are not relevant for most of the points reproducing the WMAP result. Obviously, this is more patent in cases (a) and (c) due to the choice $\delta_2 > 0$ in (3.1), whereas in case (b) the coannihilation region with the lightest stau would still be excluded. A small disconnected area in case (b) is allowed by the experimental constraint on the Higgs mass. It can be found close to the region where m_A^2 becomes negative, and corresponds to those points in figure 1b with larger cross section which were discussed above. Note also that in this area the CP-odd Higgs is also very light, $m_A \lesssim 100\,\text{GeV}$.

to apply the appropriate bound on the mass of the lightest Higgs.

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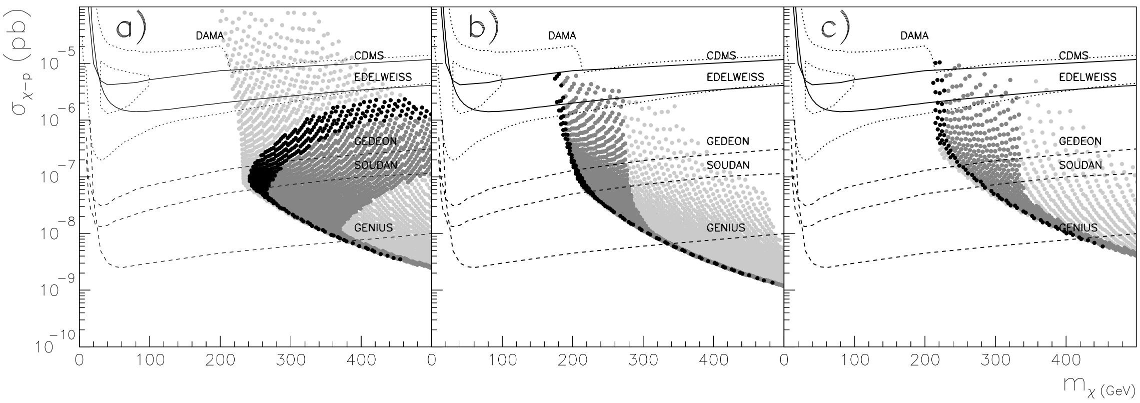

Figure 3: The same as in figure 1 but for $\tan\beta = 50$.

As commented above, a consequence of the decrease in M_3/M_1 and M_2/M_1 is the reduction in the value of the relic density. This may be problematic, since the choices of non-universal scalars (3.1) already lead to a similar decrease, specially those where the Higgsino components of $\tilde{\chi}_1^0$ increase. This is the case of example (a), for those points close to the upper-left corner (which are excluded because $\mu^2 < 0$). Also for this choice of $\tan\beta$ in example (a) the value of m_A is very close to $2m_{\tilde{\chi}_1^0}$ in most of the parameter space, thus boosting the annihilation through the resonant s-channel and implying that most of the points allowed by experimental constraints have a too low relic density. Only a few points with a mostly bino composition and a high neutralino mass, $m_{\tilde{\chi}_1^0} \gtrsim 450\,\text{GeV}$ are left in this case with $\sigma_{\tilde{\chi}_1^0-p} \lesssim 10^{-9}\,\text{pb}$. In examples ($b$) and ($c$), regions which survive once the WMAP constraint is applied are found for lighter neutralinos. Due to the more effective reduction of m_A the resonant neutralino annihilation takes place for smaller values of $\tan\beta$ in these cases.

Increasing the value of $\tan\beta$ leads to the well known enhancement of $\sigma_{\tilde{\chi}_1^0-p}$. An example with $\tan\beta = 50$ is represented in figure 3, where points close to the sensitivities of present experiments and compatible with all the constraints appear for all three cases (a), (b) and (c). Due to the reduction in m_A in case (a) all the points are already beyond the resonance, some having the correct relic density, and the regions leading to pure Higgsino-like neutralinos are now excluded due to the occurrence of a tachyonic CP-odd Higgs. In all the examples the points with a higher $\sigma_{\tilde{\chi}_1^0-p}$ correspond to those having m_A close to its experimental lower limit. The effect of the different constraints on the (m, M_i) parameter space are explicitly shown in figure 4, where we can see how due the further reduction in the value of m_A the allowed regions correspond to narrower ranges of m and M_i. Also, the UFB constraints are less restrictive and now they do not exclude the coannihilation tail in case (b).

Concerning variations in M_2, as we have already mentioned, if it is further decreased below a critical value ($\delta_2' \lesssim -0.5$) we eventually end up with a lightest neutralino which is mainly wino. Although such a change in the neutralino composition highly enhances the cross section, the relic density decreases and the WMAP constraint is no longer fulfilled.

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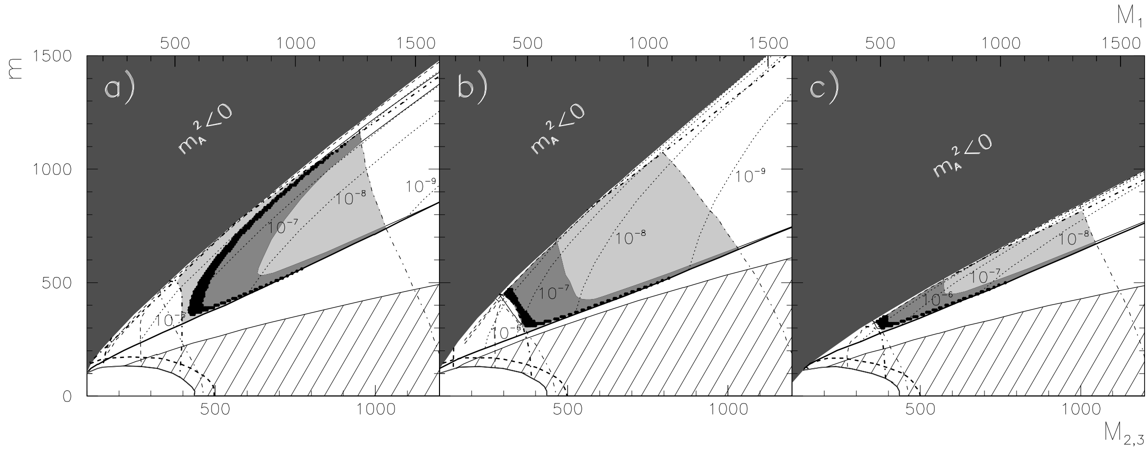

Figure 4: The same as in figure 2 but for $\tan\beta = 50$.

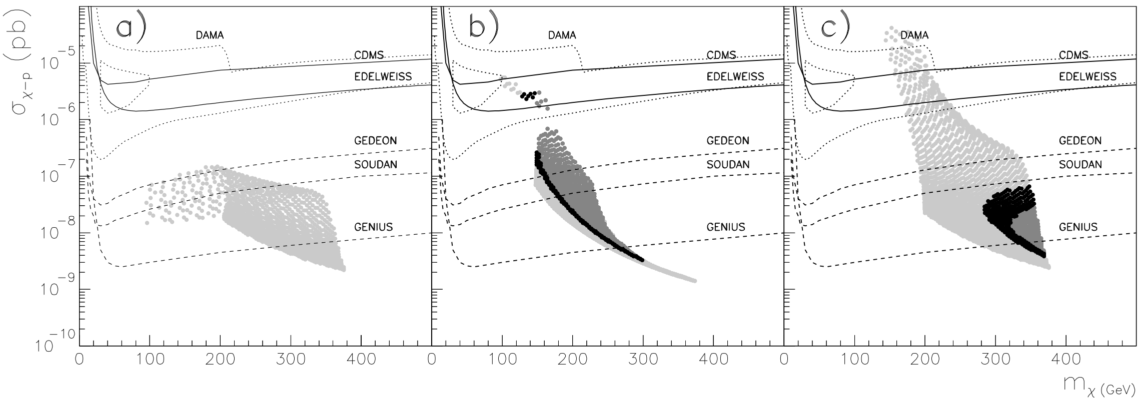

Figure 5: The same as in figure 1 but for $\delta'_2 = 0.25$ and $\delta'_3 = -0.25$.

If the value of M_2 is increased with respect to M_1 (thus having $M_2 > M_1 > M_3$ at the GUT scale) a reduction of $a_\mu^{\rm SUSY}$ is obtained, which sets a stronger upper constraint for both M and m. To illustrate this, we have represented in figure 5 an example with $\delta'_2 = 0.25$ and $\delta'_3 = -0.25$. Although the change in the theoretical predictions for the neutralino-nucleon cross section is very subtle, the effect of the stronger $g-2$ constraint can have important consequences. This reduction in the parameter space can be seen in figure 6, where the parameter space (m, M_i) is represented. In particular, in order to satisfy the lower limit on $a_\mu^{\rm SUSY}$ we need to have $M_1 \lesssim 900\,{\rm GeV}$. Because of this, the regions with the correct relic density are much smaller, as in case (c), and can even be excluded. Note also that since the value of $m_{H_u}^2$ is further increased no regions in the parameter space are excluded due to the occurrence of UFB minima in these examples. Since once more the resonant annihilation of neutralinos is very efficient in example (a), the relic density is too low in those points of the parameter space which fulfil all the experimental constraints ($\Omega_{\tilde\chi_1^0}\, h^2 \lesssim 0.045$).

Further decreasing δ'_3 leads to larger values of M_1 and thus heavier neutralinos can be obtained. At the same time the μ term slightly decreases and eventually it can be of

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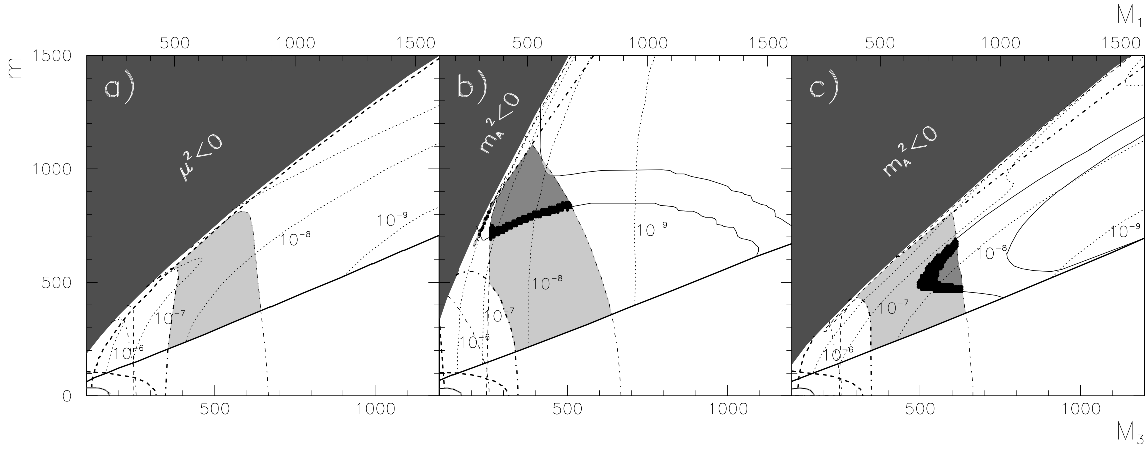

Figure 6: The same as in figure 2 but for $\delta'_2 = 0.25$ and $\delta'_3 = -0.25$.

the same order or even smaller than M_1 and thus Higgsino-like neutralinos appear, which might have a large value for the cross section. However this possibility is very limited. On the one hand, M_2 cannot be decreased beyond $M_1/2$ in order not to run into the problems of a wino neutralino. On the other hand, if $M_2 \gg M_3$ the lower constraint on $a_\mu^{\rm SUSY}$ (which sets an upper bound for M) and the constraints on the Higgs mass and $b \to s\gamma$ (which set a lower bound for M) may not be simultaneously fulfilled. Furthermore, the relic density of Higgsino-like neutralinos is typically very low[11] [49], and consistency with the WMAP result is not always obtained. Obviously, Higgsino dark matter will be more easily obtained for those choices of non-universal scalars (3.1) with $\delta_2 > 0$ (examples (a) and (c)), since they lead to a very effective decrease in the μ parameter. It is in these cases where the problems associated to Higgsino-like neutralinos are more patent.[12]

The predicted $\sigma_{\tilde{\chi}_1^0-p}$ for an example where $\delta'_2 = 0$ and $\delta'_3 = -0.5$ and the three choices for non-universal Higgses (3.1) have been taken is illustrated in figure 7, with the corresponding (m, M_i) parameter space in figure 8. As a consequence of the decrease in M_3 the constraints on the Higgs mass and $b \to s\gamma$ are only fulfilled for large values of $M_{1,2}$, which are almost comparable to the constraint due to the lower bound on $a_\mu^{\rm SUSY}$ and the parameter space is very reduced. Due to the further decrease in μ, those regions excluded for having $\mu^2 < 0$ are now slightly larger, as is the case of example (a). Note in this sense the upper region in case (c) which is now also excluded for this reason (μ^2 now becomes negative before m_A^2). The Higgsino composition of the lightest neutralino is very important in both (a) and (c), with $0.3 \lesssim N_{13}^2 + N_{14}^2 \lesssim 1$, leading to light neutralinos ($m_{\tilde{\chi}_1^0} \gtrsim 100\,\text{GeV}$) but

[11] A similar scenario, with just non-universal gauginos resulting from the $n = 200$ representation of SU(5) and leading to Higgsino dark matter was studied in ref. [31], where it was shown that their low relic density is below the astrophysical constraint.

[12] Choosing $\delta_2 < 0$ (thus having more negative values for $m_{H_u}^2$) leads to an increase of the μ parameter and can help restoring the gaugino character of the lightest neutralino. Heavier bino-like neutralinos satisfying the astrophysical constraint on the relic density can therefore be obtained, but the neutralino-nucleon cross section has a significant decrease, due to both the increase in μ and in m_A. Also the lightest neutralino is not the LSP in larger regions in the parameter space.

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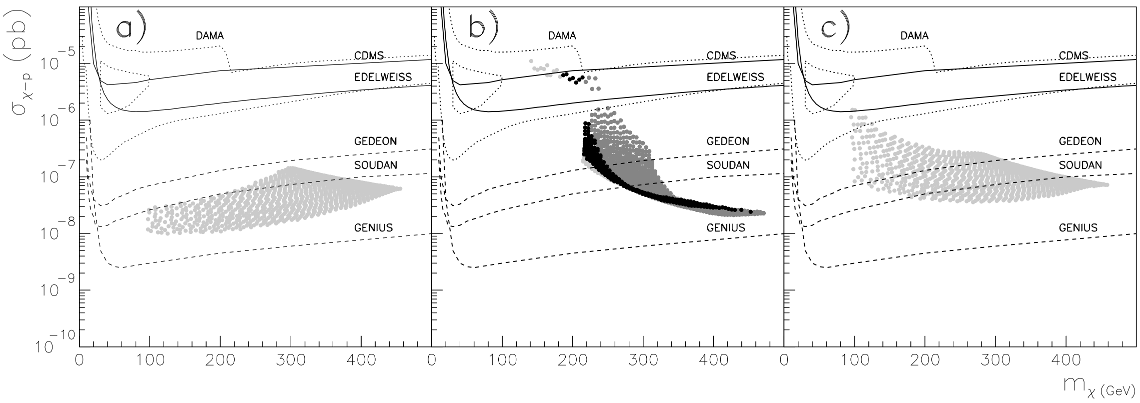

Figure 7: The same as in figure 1 but for $\delta'_2 = 0$ and $\delta'_3 = -0.5$.

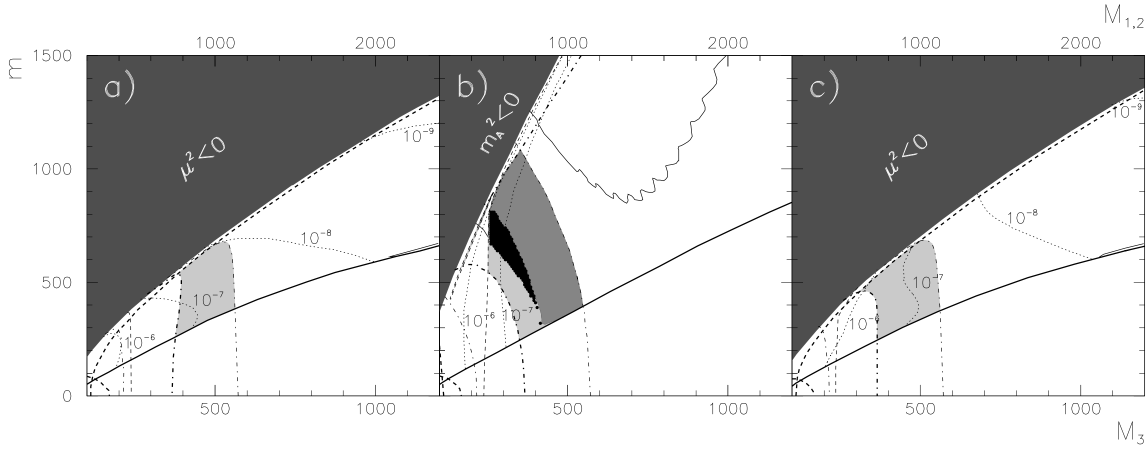

Figure 8: The same as in figure 2 but for $\delta'_2 = 0$ and $\delta'_3 = -0.5$.

with very low values for the relic density, $\Omega_{\tilde{\chi}_1^0}\, h^2 \lesssim 0.06$ and $\Omega_{\tilde{\chi}_1^0}\, h^2 \lesssim 0.07$, respectively. On the contrary in case (b) the neutralinos still continue being mostly binos ($N_{13}^2 + N_{14}^2 \lesssim 0.13$) and points fulfilling WMAP with $m_{\tilde{\chi}_1^0} \gtrsim 200$ GeV and a high cross section are found. Note that in these examples the UFB constraints are also satisfied in the whole parameter space due to the less negative values of $m_{H_u}^2$.

Let us finally remark that all of the above results were obtained for $A = 0$. Departures from this value can alter the results for the neutralino-nucleon cross section and the relic density. In particular, for positive values of the trilinear term, the negative contributions in the RGE of the Higgs parameters due to A^2 terms are less important and thus both $m_{H_d}^2$ and $m_{H_u}^2$ increase. This entails a slight increase in $\sigma_{\tilde{\chi}_1^0 - p}$ and a decrease in $\Omega_{\tilde{\chi}_1^0}$, as well as a reduction in the region restricted by the UFB constraints, with opposite effects for negative values of A. In some cases, as for instance, in example (a) in figures 1 and 5 the shift in m_A due to variations in the trilinear parameter is enough to avoid the resonant neutralino annihilation and regain the correct $\Omega_{\tilde{\chi}_1^0}$ in parts of the parameter space.

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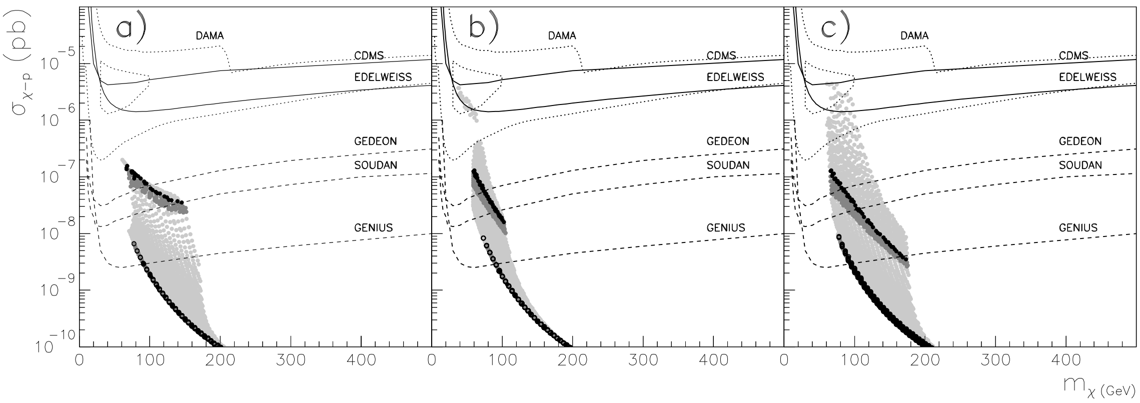

Figure 9: The same as in figure 1 but for $\delta'_{2,3} = 1$.

3.2 Increase in M_3/M_1

Let us now analyse the other possibility, namely increasing the value of M_3 with respect to M_1, which can be done with $\delta'_3 > 0$ in (2.7). In this case, the constraint on the Higgs mass and on $b \to s\gamma$ will be satisfied for smaller values of M, and therefore the effective value of M_1 can be smaller than in the universal case. Thus lighter neutralinos can be obtained.

Regarding the value of M_2, let us begin by considering also an increase in M_2/M_1 and discuss departures from this choice later. The structure of soft masses at the GUT scale would therefore be $M_3 \sim M_2 > M_1$. The theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$ are represented in figure 9 for an example with $\delta'_{2,3} = 1$, $\tan\beta = 35$ and $A = 0$ and the three choices of Higgs non-universalities of (3.1). As we can see, this choice of gaugino parameters favours the appearance of light neutralinos which obviously have a large bino component. The predicted cross section is only slightly smaller than in the cases with just non-universal scalars, so these neutralinos can still be close to the sensitivities of dark matter experiments. In particular, neutralinos with $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-7}$ pb can be obtained with $m_{\tilde{\chi}_1^0} \sim 60\,\text{GeV}$ for the three cases (a), (b) and (c).

This effective reduction of the value of M_1 is clearly manifest in the plots representing the corresponding (m, M_i) parameter space in figure 10. Because of the increase of M_3 the regions excluded due to the constrains on $b \to s\gamma$ and the Higgs mass now occur for $M_1 \lesssim 180\,\text{GeV}$. Concerning the UFB constraints, they are more restrictive than in the examples of the previous section, due to the decrease in $m_{H_u}^2$, and exclude larger regions in the parameter space. In particular, those regions having the correct relic density due to coannihilations with the NLSP are ruled out for this reason. However, points where the reduction in the relic density is due to a decrease in m_A are still allowed, giving rise to narrow allowed regions.

Increasing the value of $\tan\beta$ larger cross sections can be obtained and the UFB bounds become less stringent as a consequence of the increase in $m_{H_u}^2$. For instance, if $\tan\beta = 50$ is taken in the former example, points satisfying all the constraints and entering the DAMA region can be obtained. The predictions for $\sigma_{\tilde{\chi}_1^0-p}$ in this case are shown in figure 11 and the corresponding (m, M_i) parameter space is represented in figure 12. In cases (a) and (c),

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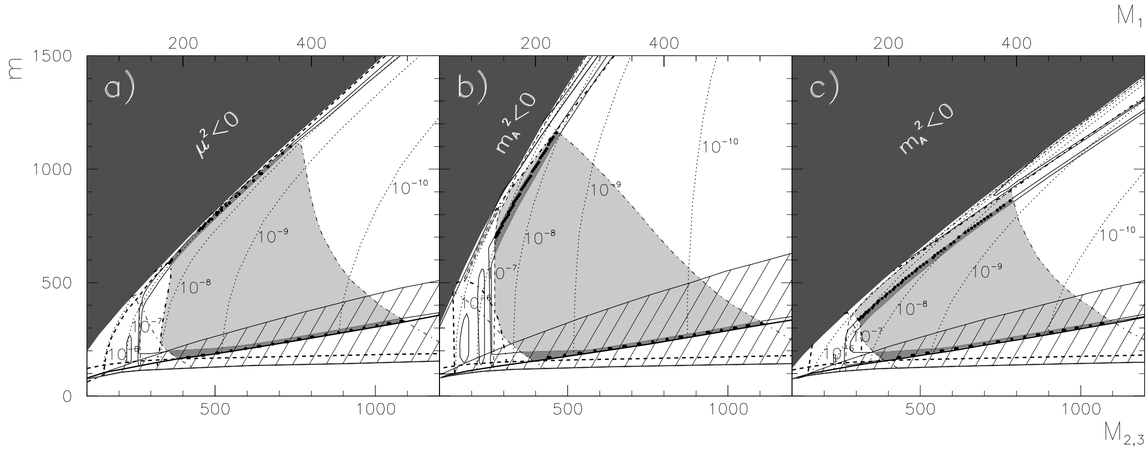

Figure 10: The same as in figure 2 but for $\delta'_{2,3} = 1$.

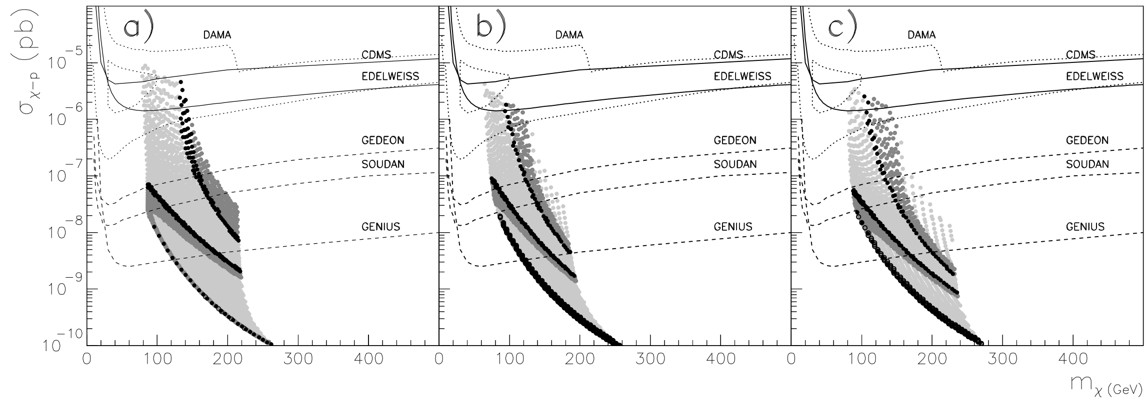

Figure 11: The same as in figure 9 but for $\tan\beta = 50$.

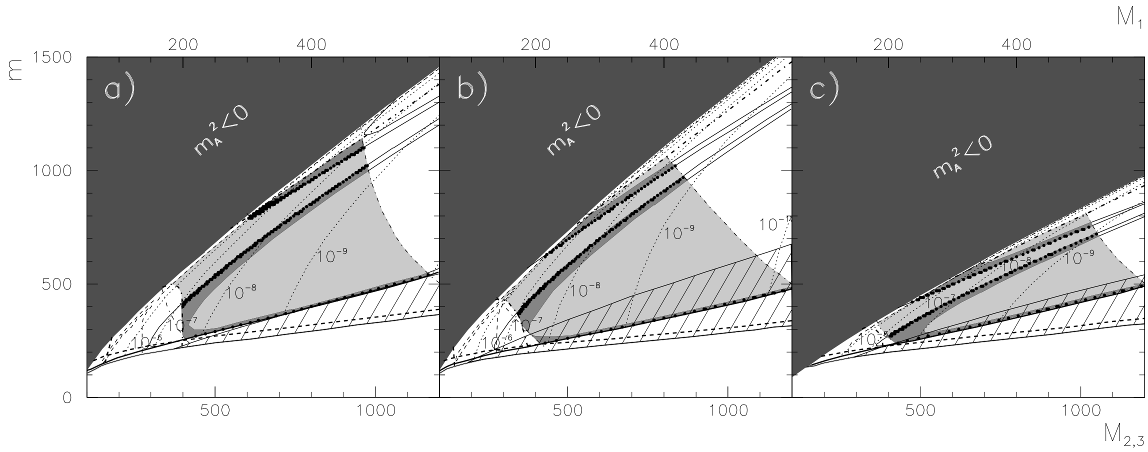

Figure 12: The same as in figure 10 but for $\tan\beta = 50$.

where the increase in $m_{H_u}^2$ is more effective, the UFB constraints are weaker and for instance in case (a) they do not exclude completely the coannihilation tail with the lightest stau.

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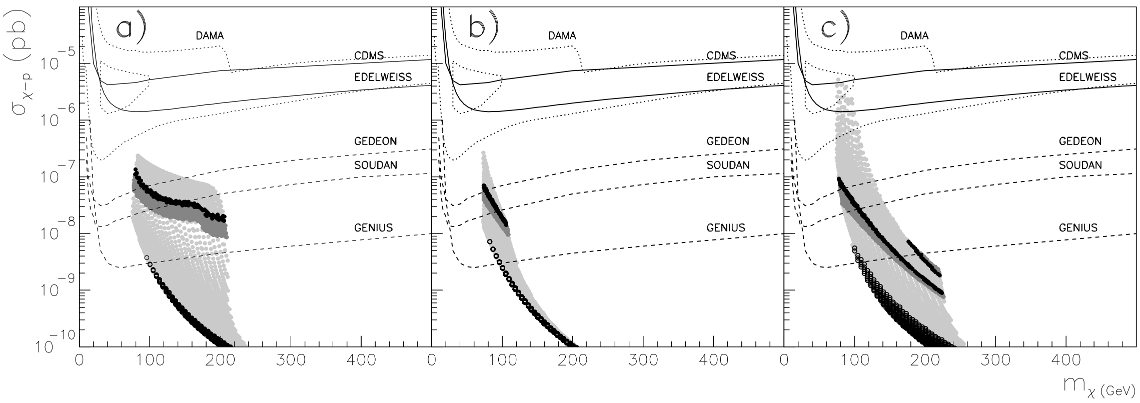

Figure 13: The same as in figure 1 but for $\delta_2' = -0.25$ and $\delta_3' = 1$.

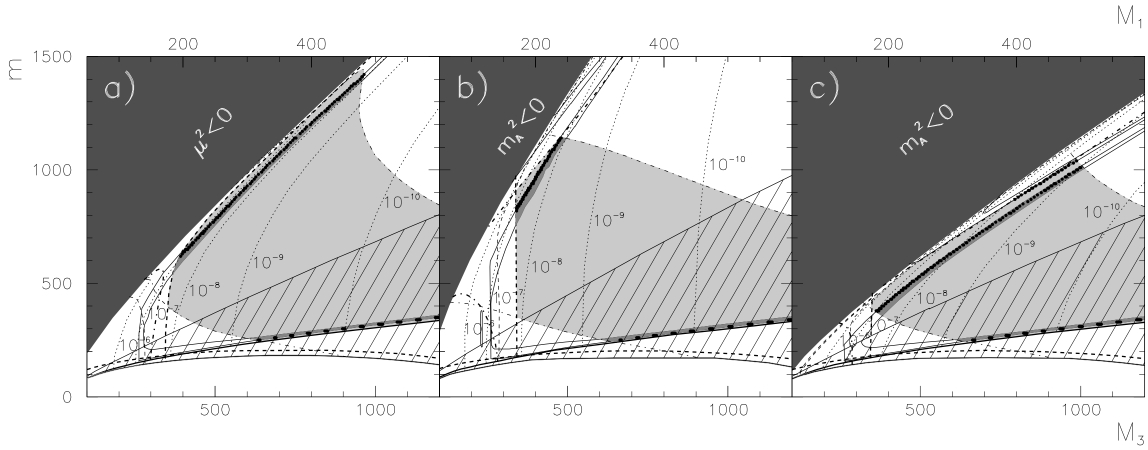

Figure 14: The same as in figure 2 but for $\delta_2' = -0.25$ and $\delta_3' = 1$.

Let us now comment on the possibility of decreasing M_2/M_1. Once more, in order not to have the problems associated to a neutralino with a large wino composition we will restrict this decrease to $M_2/M_1 > 0.5$ ($\delta_2' > -0.5$). The structure of gaugino masses at the GUT scale in this case would therefore be $M_3 > M_1 \gtrsim M_2$. The theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$ for an example with $\delta_2' = -0.25$ and $\delta_3' = 1$ are represented in figure 13, showing again very subtle variations with respect to the $\delta_2' = \delta_3'$ case. The corresponding (m, M_i) parameter space, with the experimental and astrophysical bounds, is shown in figure 14. There we can see the shift of the regions excluded by $a_\mu^{\rm SUSY}$ towards higher values of M, as well as the effect that the lightest bound on the chargino mass has in restricting the parameter space. The chargino bound can become more important than the constraints due the lightest Higgs mass and the $b \to s\gamma$. For instance, in cases (a) and (b) it restricts the allowed area to $M_1 \gtrsim 175\,\mathrm{GeV}$ for this choice of $\tan\beta$, thus setting a stringent limit on the appearance of light neutralinos.[13]

[13]Note that we are using here $m_{\tilde{\chi}_1^\pm} > 103.5\,\mathrm{GeV}$ as the lower bound on the chargino mass [50], which is in fact only valid in the case of gaugino unification. This bound can be relaxed to $m_{\tilde{\chi}_1^\pm} \gtrsim 90\,\mathrm{GeV}$ in

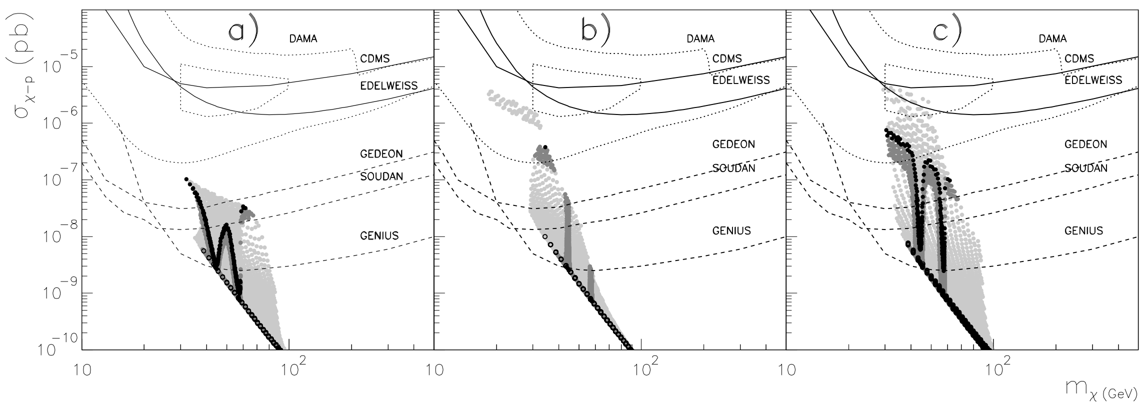

Figure 15: The same as in figure 1 but for $\delta'_{2,3} = 3$.

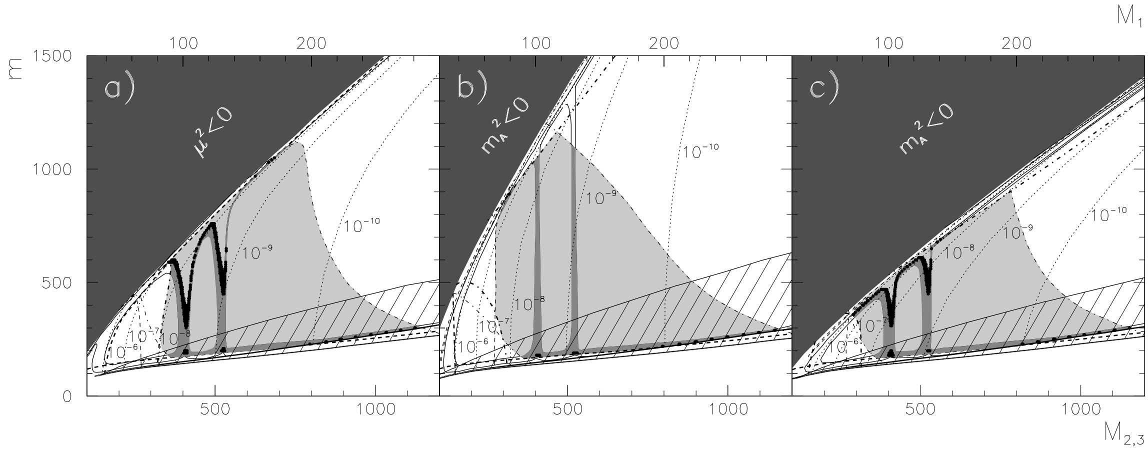

Figure 16: The same as in figure 2 but for $\delta'_{2,3} = 3$.

The value of M_1 can be further decreased if larger values of δ_3 are used, thus leading to even lighter neutralinos. In order to illustrate this possibility an example with $\delta'_{2,3} = 3$ is represented in figure 15. Very light neutralinos can appear within the DAMA sensitivity range. Usually in these cases the typical values for the relic density are too large and are therefore not consistent with the WMAP result. As usual a very effective decrease can be achieved when the h and Z-poles are crossed at $m_{\tilde{\chi}_1^0} = m_h/2$ and $M_Z/2$, respectively, giving rise to a very effective neutralino annihilation through the corresponding s-channels. This is evidenced by the narrow chimneys in the cosmologically preferred regions. However, there is now a new interesting possibility. Because of the very efficient decrease in the CP-odd Higgs mass, annihilation of very light neutralinos can be boosted and thus the correct relic density obtained. This happens in our example for case (c), allowing the existence of neutralinos with $m_{\tilde{\chi}_1^0} \sim 30\,\mathrm{GeV}$ which are compatible with the DAMA region.

non-universal scenarios (see e.g. the discussion in [51]). In such a case we would obtain a slightly larger allowed area in the parameter space, since now $M_1 \gtrsim 155\,\mathrm{GeV}$, and therefore slightly lighter neutralinos. The increase in the predictions for $\sigma_{\tilde{\chi}_1^0-p}$ in the area allowed by WMAP is, however, insignificant.

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As we have already commented in sections 2.1 and 2.2, such light neutralinos cannot be obtained in SUGRA theories with non-universalities in just the scalar or gaugino sector. Let us therefore study this possibility in more detail within the framework of these more general SUGRA theories.

3.2.1 Very light neutralinos

The flexibility due to non-universal gauginos was recently exploited in [52, 53, 54] in order to calculate a lower bound for the lightest neutralino in the effMSSM, where the parameters are defined directly at the electroweak scale (for previous works see [55]). The relic density of very light neutralinos ($m_{\tilde{\chi}_1^0} < M_Z/2$) is a decreasing function of $m_{\tilde{\chi}_1^0}$ and therefore a lower bound on $m_{\tilde{\chi}_1^0}$ can be extracted from the upper bound on $\Omega_{\tilde{\chi}_1^0}$. It was shown [53, 54] that although the relic density of such light neutralinos usually exceeds the upper bound, a significant reduction can be obtained when the mass of the CP-odd Higgs is small ($m_A \lesssim 200\,\text{GeV}$) and for large values of $\tan\beta$. Under these conditions a lower limit $m_{\tilde{\chi}_1^0} \gtrsim 6\,\text{GeV}$ was extracted [53], which was also found to be consistent with the experimental constraints [54].

One of the requirements for the appearance of such very low neutralinos is to have $M_1 \ll \mu, M_2$ at low energy (thus having almost pure binos). This can be achieved with adequate choices of gaugino non-universalities, in particular with $\delta'_{2,3} \gg 1$. However, as mentioned above, without a very effective reduction of m_A, the relic density would be too large, and therefore inconsistent with observations. Here the presence of non-universal scalars is crucial. In particular, non-universalities as the ones we have described in the Higgs sector in (3.1) provide a very effective way of lowering m_A and are thus optimal for this purpose.

More specifically, it is in case (b) and especially (c) where the reduction in m_A is more effective (not being so constrained by regions with $\mu^2 < 0$) and for this reason very light neutralinos can easily appear. We have already seen in a former example how this happened for case (c) with $\tan\beta = 35$ and $\delta'_{2,3} = 3$ (see figure 15). On the contrary, in case (a) higher values of $\tan\beta$ are required in order to further reduce the value of m_A. We have checked explicitly that $\tan\beta \gtrsim 33$ is sufficient to obtain $m_{\tilde{\chi}_1^0} < M_Z/2$ in cases (b) and (c), whereas $\tan\beta \gtrsim 45$ is necessary in case (a). In all the three cases $\delta'_{2,3} \gtrsim 3$ leads to these results.

Obviously, lighter neutralinos can be obtained if $\delta'_{2,3}$ are increased. Let us therefore complete our discussion by analysing the case $\delta'_{2,3} = 10$ for the three choices of scalar non-universalities (3.1). The resulting neutralino-nucleon cross section versus the neutralino mass is represented in figure 17 for $\tan\beta = 50$ and $A = 0$, together with the sensitivities of dark matter detectors. We observe the appearance of very light neutralinos, whose cross section can be in range of detectability of near-future experiments. In particular, points with $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 3 \times 10^{-6}\,\text{pb}$ are obtained with $m_{\tilde{\chi}_1^0} \sim 15\,\text{GeV}$, in agreement with the bound derived in the effMSSM [53]. Once more the resonances with the lightest Higgs and the Z give rise to the characteristic narrow chimneys at the corresponding values of the neutralino mass.

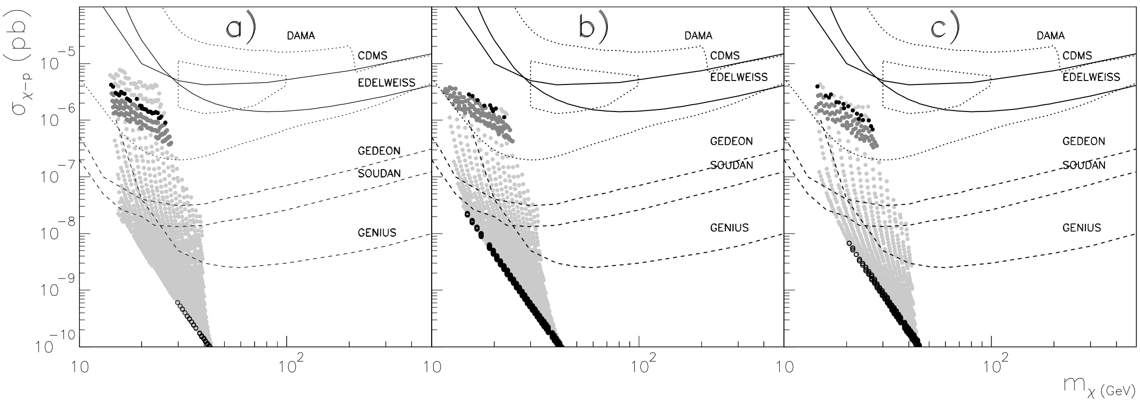

Figure 17: The same as in figure 1 but for $\delta'_{2,3} = 10$ and $\tan\beta = 50$.

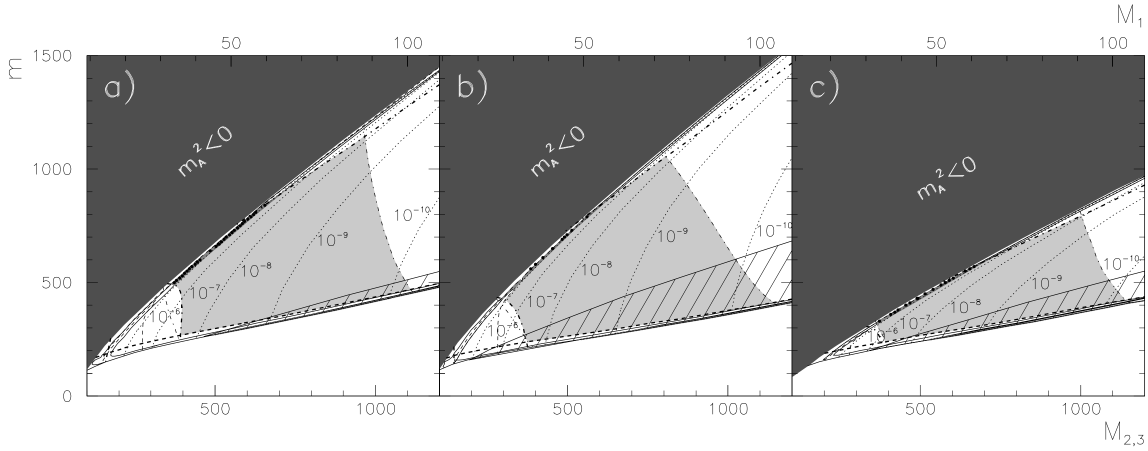

Figure 18: The same as in figure 2 but for $\delta'_{2,3} = 10$ and $\tan\beta = 50$.

The effect of the different constraints on the corresponding (m, M_i) parameter space is represented in figure 18. Note that the regions giving rise to very light neutralinos with a consistent relic density are extremely narrow. In these points the mass of the CP-odd Higgs can be very close to its experimental limit, $m_A \lesssim 100\,\text{GeV}$. In fact, in these cases we are near the "intense coupling regime" for the Higgs sector, where the masses of the Higgses are almost degenerate, and even beyond it, thus having $m_H > m_h \sim m_A$ with $\sin\alpha \sim -1$. Regarding the experimental bound on the lightest Higgs in this last case, note that, since $\tan\beta \gg 1$, this implies $\sin^2(\alpha-\beta) \ll 1$ and therefore the constraint on the lightest Higgs can be relaxed to $m_h \gtrsim 91\,\text{GeV}$ [48]. Finally, since the neutralino mass is so small, the region excluded due to the neutralino not being the LSP is negligible. However, now the lower bound on the stau mass plays an important role. In fact, an important region of the parameter space is excluded for having $m^2_{\tilde\tau_1} < 0$.

In those examples with $\delta_2 > 0$ a reduction in the μ parameter is more easily achieved, thus obtaining typically the structure $M_1 \ll \mu < M_2$ at low energy. However, when $\delta_1 < 0$ is taken (cases (b) and (c)), the more effective decrease in m_A can forbid some of the points with very low μ, thus obtaining instead $M_1 \ll M_2 \lesssim \mu$. This has clear implications

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on the neutralino-chargino masses and compositions. For example, in the first case, the lightest chargino and the second lightest neutralino would be mainly Higgsinos, whereas in the second case they would have a larger wino composition. Also in case (c), where both $\delta_2 > 0$ and $\delta_1 < 0$ are taken, the resulting allowed values for the common scalar mass are smaller and therefore the slepton-squark spectrum is typically lighter.

Note that in these scenarios the existence of a very light neutralino could induce the invisible decay of the lightest Higgs, $h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, thus making Higgs detection more compelling. This was studied in ref. [56], where some implications for dark matter were also investigated. The branching ratio of the former decay is larger for small values of the μ parameter. In this respect it is interesting to point out that in case (a) μ can be very efficiently decreased and thus lead to a large reduction of the visible Higgs decay rates.

Departures from the case $\delta_2' = \delta_3'$ will affect the size of the allowed regions in the parameter space due to the effect of the experimental constraints. Once more, if $\delta_2' \ll \delta_3'$ the experimental bound on the chargino might not be satisfied for small values of M, thus excluding those regions with the lightest neutralinos. Also if $\delta_2' \gg \delta_3'$ the lower limit on $a_\mu^{\rm SUSY}$ and the $b \to s\gamma$ constraint may exclude the whole parameter space.

Let us finally remark that if non-universalities in the Higgs sector were chosen with the opposite sign for the δ parameters with respect to those in (3.1), i.e., $\delta_1 > 0$ and $\delta_2 < 0$, then the value of m_A would increase with respect to its value with universal scalars. As a consequence, no reduction in the relic density of these light neutralinos would be obtained and $\Omega_{\tilde{\chi}_1^0}$ would exceed its upper limit.

4. Conclusions

In this paper we have analysed the theoretical predictions for neutralino dark matter direct detection in the context of a SUGRA theory where both the scalar and gaugino soft supersymmetry-breaking terms have a non-universal structure. More specifically, we have computed the predictions for the scalar neutralino-nucleon cross section and compared it with the sensitivity of dark matter detectors. Recent experimental and astrophysical constraints have been taken into account in the calculation, as well as those derived from the absence of charge and colour breaking minima.

Gaugino non-universalities are complementary to those in the scalar masses, allowing more flexibility in the neutralino sector. This is due to the freedom to play with the value of M_1, which is not subject to such strict constraints as M_2 (which is constrained by $a_\mu^{\rm SUSY}$ and the experimental bound on the chargino mass) and M_3 (whose value is limited by the lower bound on the Higgs mass and the value of $b \to s\gamma$). In particular, neutralinos in the detection range can be obtained with a wide range of masses. We have illustrated this possibility by applying gaugino non-universalities on examples with non-universal scalars which lead to large predictions for the neutralino-nucleon cross section.

On the one hand, if the value of M_1 is increased with respect to M_3 heavier neutralinos are found with a slight increase in their detection cross section, due to the enhancement of their Higgsino components. In this sense, neutralinos with a mass as heavy as about 400 GeV can be obtained with a large cross section ($\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-6}$ pb), for moderate and

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large values of $\tan\beta$. The increase in M_1 is limited by the fact that a purely wino or Higgsino leads to a very important decrease in the relic density and is therefore inconsistent with the astrophysical bounds.

On the other hand, decreasing M_1 with respect to M_3 light neutralinos, with a more important bino composition, can be obtained. Although, due to the increase in the μ parameter, their cross section is typically smaller, compatibility with the DAMA region can still be obtained. For instance, $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-6}$ pb is possible with $m_{\tilde{\chi}_1^0} \sim 100$ GeV.

Finally, very light neutralinos ($m_{\tilde{\chi}_1^0} \lesssim M_Z/2$) can appear for $M_1 \ll M_{2,3}$ with a detection cross section near the sensitivity of present dark matter detectors and compatible with the DAMA region. In order to obtain such light neutralinos the presence of non-universal scalars which lead to a very light CP-odd Higgs is crucial, combined with a moderate or large hierarchy in the gaugino sector. For example, neutralinos as light as 30 GeV and 15 GeV can be obtained with $M_1 = 4\,M_{2,3}$ and $M_1 = 11\,M_{2,3}$, respectively. This is therefore a possibility that is neither present with just non-universal scalars, where the lower bound on the neutralino mass is due to the lower bound on the common gaugino mass, M, nor with just non-universal gauginos, where the reduction in m_A cannot be achieved.

This general analysis can be very useful in the study of more specific cases, such as the supergravity theories resulting at the low energy limit of string constructions. In particular, D-brane scenarios in type-I string theory give rise to theories where non-universalities appear both in the scalar and gaugino sectors.

Acknowledgments

We would like to thank M. E. Gómez for useful discussions and comments. The work of D.G. Cerdeño was supported in part by the Deutsche Forschungsgemeinschaft, the DAAD, and the European Union under contract HPRN-CT-2000-00148. The work of C. Muñoz was supported in part by the Spanish DGI of the MCYT under Acción Integrada Hispano-Alemana HA2002-0117, and under contracts BFM2003-01266 and FPA2003-04597; and the European Union under contract HPRN-CT-2000-00148.

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