Direct neutralino searches in the NMSSM with gravitino LSP in the degenerate scenario

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Abstract. In the present work a two-component dark matter model is studied adopting the
degenerate scenario in the R-parity conserving NMSSM. The gravitino LSP and the neutralino
NLSP are extremely degenerate in mass, avoiding the BBN bounds and obtaining a high
reheating temperature for thermal leptogenesis. In this model both gravitino (absolutely
stable) and neutralino (quasi-stable) contribute to dark matter, and direct detection searches
for neutralino are discussed. Points that survive all the constraints correspond to a singlino-like
neutralino.

1. Introduction

There is accumulated evidence both from astrophysics and cosmology that about 1/4 of the
energy budget of the universe consists of so called dark matter, namely a component which is
non-relativistic and neither feels the electromagnetic nor the strong interaction. For a review
on dark matter see e.g. [1]. Although the list of possible dark matter candidates is long (for a
nice list see [2]), it is fair to say that the most popular dark matter candidate is the lightest
supersymmetric particle (LSP) in supersymmetric models with R-parity conservation [3]. For
supersymmetry and supergravity see [4]. The simplest supersymmetric extension of the standard
model that solves the mu problem [5] is the next-to-minimal supersymmetric standard model
(NMSSM) [6]. If we do not consider the axion [7] and the axino [8], the superpartners that have
the right properties for playing the role of cold dark matter in the universe are the gravitino
and the lightest neutralino. By far the most discussed case in the literature is the case of the
neutralino (see the classic review [9]), probably because of the prospects of detection. However,
in the case is which neutralino is assumed to be the only dark matter component, one has to
face the fine-tuning problem and the gravitino problem [10]. In most of the parameter space
the neutralino relic density turns out to be either too small or too large [11]. Furthermore,
unstable gravitinos will undergo late-time cascade decays to a neutralino LSP. These decays will
destroy the light element abundances built up in BBN, unless $T_R < 10^5$ GeV [12], which poses
serious difficulties to the thermal leptogenesis scenario [13]. If, on the other hand, gravitino is
the LSP and therefore stable, playing the role of cold dark matter in the universe, it is then
the neutralino that will undergo late time decays into gravitino and hadrons, and the gravitino
problem is re-introduced [14].

It has been shown that in the degenerate scenario [15] the BBN and CMB constraints are
avoided, and high values of the reheating temperature are obtained compatible with thermal leptogenesis. Here we focus on the scenario in which the masses of the gravitino LSP and neutralino NLSP are extremely degenerate in mass. Under this assumption neutralino becomes quasi-stable participating to the cold dark matter of the universe together with gravitino, and it is still around and it can be seen in direct detection searches experiments.

This article is organized as follows. In the next section we present the theoretical framework. In section 3 we discuss all the relevant constraints from colliders and from cosmology, and we show our results. Finally, we conclude.

2. Theoretical Framework

2.1. The NMSSM

The particle physics model is defined by the superpotential

\[ W = \epsilon_{ij} \left( Y_u H_2^i Q^j u + Y_d H_1^i Q^j d + Y_e H_1^i L^j e \right) - \epsilon_{ij} \lambda S H_1^i H_2^j + \frac{1}{3} \kappa S^3 \]  \hspace{1cm} (1)

as well as the soft breaking masses and couplings

\[ -L_{\text{soft}} = m_Q^2 \tilde{Q}^* \tilde{Q} + m_U^2 \tilde{U}^* \tilde{U} + m_D^2 \tilde{D}^* \tilde{D} + m_L^2 \tilde{L}^* \tilde{L} + m_E^2 \tilde{E}^* \tilde{E} + m_{H_1}^2 H_1^i H_1^j + m_{H_2}^2 H_2^i H_2^j + m_S^2 S^* S \]
\[ + \epsilon_{ij} \left( A_u Y_u H_2^i \tilde{Q}^j \tilde{u} + A_d Y_d H_1^i \tilde{Q}^j \tilde{d} + A_e Y_e H_1^i \tilde{L}^j \tilde{e} + \text{H.c.} \right) \]
\[ + \left( -\epsilon_{ij} \lambda A \lambda S H_1^i H_2^j + \frac{1}{3} \kappa A \kappa S^3 + \text{H.c.} \right) \]
\[ - \frac{1}{2} (M_3 \lambda_3 \lambda_3 + M_2 \lambda_2 \lambda_2 + M_1 \lambda_1 \lambda_1 + \text{H.c.}) \]  \hspace{1cm} (2)

When the singlet acquires a vacuum expectation value, S, we obtain an effective \( \mu \) parameter, \( \mu_{\text{eff}} = \lambda S \). Imposing universality at the GUT scale, a small controllable number of free parameters remains, namely

\[ \tan \beta = v_u/v_d, A_0, m_{1/2}, \lambda, A_k \]

and the sign of the effective \( \mu \) parameter can be chosen at will.

Because of the extra singlet superfield, in the NMSSM there is a larger higgs sector and a larger neutralino sector. The neutralino mass matrix is characterized by the appearence of a fifth neutralino state, meaning that the composition of the lightest neutralino has an extra singlino contribution

\[ \tilde{\chi}_1^0 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}^0_3 + N_{13} \tilde{H}^0_1 + N_{14} \tilde{H}^0_2 + N_{15} \tilde{S} \]  \hspace{1cm} (3)

In the following, neutralinos with \( N_{11} > 0.9 \), or \( N_{15} > 0.9 \), will be referred to as bino- or singlino-like, respectively.

Furthermore, in the Higgs sector we have now two CP-odd neutral, and three CP-even neutral Higgses. We make the assumption that there is no CP-violation in the Higgs sector, and therefore the CP-even and CP-odd states do not mix. We are not interested in the CP-odd states, while the CP-even Higgs interaction and physical eigenstates are related by the transformation

\[ h_a^0 = S_{ab} H_b^0 \]  \hspace{1cm} (4)

where \( S \) is the unitary matrix that diagonalises the CP-even symmetric mass matrix, \( a, b = 1, 2, 3 \), and the physical eigenstates are ordered as \( m_{h_1^0} < m_{h_2^0} < m_{h_3^0} \).
2.2. Production of gravitinos

In the usual case (not in the degenerate scenario) gravitinos can be produced after inflation in two ways. One way to produce gravitinos is with scattering from the thermal bath, and another is from the out-of-equilibrium decays of the NLSP, which decouple from the thermal bath before primordial Big-Bang Nucleosynthesis and decay after the BBN time. Thus, imposing the WMAP bounds \[16\] we can write for the gravitino abundance

\[ 0.1097 < \Omega_{3/2}h^2 = \Omega_{np}^{TP}h^2 + Y_{3/2}^{NLSP}h^2 < 0.1165 \]  

where

\[ \Omega_{3/2}^{NLSP}h^2 = \frac{m_\tilde{G}}{m_{NLSP}}\Omega_{NLSP}h^2 \]  

with \( m_{NLSP} \) the mass of the NLSP, and \( \Omega_{NLSP}h^2 \) the abundance the NLSP would have, had it not decayed into the gravitino. The thermal contribution is given by (approximately for a light gravitino, \( m_\tilde{G} \ll m_\tilde{g} \) \[17\])

\[ \Omega_{3/2}^{TP} \simeq 0.27 \left( \frac{T_R}{10^{10} \, \text{GeV}} \right) \left( \frac{m_\tilde{g}}{\text{TeV}} \right)^{-2} \left( \frac{m_\tilde{G}}{100 \, \text{GeV}} \right) \]  

In the limit where \( m_{NLSP} \rightarrow m_\tilde{G} \) and \( \tau_{NLSP} \gg 10^{17} \, \text{sec} \) the scenario looks as if one would have a two-component dark matter with the NLSP contribution \( \Omega_{NLSP}h^2 \), and a gravitino contribution from thermal production only, \( Y_{3/2}^{TP} \). Therefore, in the degenerate scenario with \( m_{NLSP} \simeq m_\tilde{G} \) the WMAP bound becomes

\[ 0.1097 < \Omega_{cdm}h^2 = \Omega_{NLSP}h^2 + \Omega_{3/2}^{TP}h^2 < 0.1165 \]  

where from now on the NLSP is the lightest neutralino, \( \chi = NLSP \).

3. Constraints and results

- Spectrum and collider constraints: We have used the computer software NMSSMTools \[18\], we have performed a random scan over the whole parameter space (with fixed \( \mu > 0 \) motivated by the muon anomalous magnetic moment), and we have selected only those points that satisfy all the theoretical requirements, as well as the LEP bounds on the Higgs mass, collider bounds on SUSY particle masses, and experimental data from B-physics \[19, 20\]. For all these good points the lightest neutralino is either a bino or a singlino, and contrary to the case where neutralino is the dark matter particle, here we do not require that the neutralino relic density falls within the allowed WMAP range.

- As we have already mentioned, the total dark matter abundance, and not the neutralino one, should satisfy the cold dark matter constraint \[16\]

\[ 0.1097 < \Omega_{cdm}h^2 = \Omega_{\chi}h^2 + \Omega_{3/2}^{TP}h^2 < 0.1165 \]  

that relates the reheating temperature after inflation to the gravitino mass as follows

\[ 0.11 = A(m_\tilde{G}, m_\tilde{g})T_R + \Omega_{\chi}h^2 \]  

For a given point in the cNMSSM parameter space, the complete spectrum and couplings have been computed, and we are left with two more free parameters, namely the gravitino mass and the reheating temperature after inflation. The gravitino mass is equal essentially to the neutralino mass, and the precise value can be determined if we specify the neutralino lifetime. In the discussion to follow we have used a neutralino lifetime \( \tau = 10^{26} \, \text{sec} \), although the results
are not sensitive to it, and the figures we have produced for different values of the lifetime cannot be distinguished. Finally, the reheating temperature after inflation is obtained from the cold dark matter constraint. The thermal production contribution cannot be larger than the total dark matter abundance, and for this we can already obtain an upper bound on the reheating temperature

\[ T_R \leq 4.1 \times 10^9 \left( \frac{m_{\tilde{G}}}{100 \text{ GeV}} \right)^2 \text{GeV} \]  

(11)

Assuming a gluino mass \( m_{\tilde{g}} \sim 1 \text{ TeV} \), we can see that for a heavy gravitino, \( m_{\tilde{G}} \sim 100 \text{ GeV} \), it is possible to obtain a reheating temperature large enough for thermal leptogenesis.

- For neutralino NLSP in the degenerate scenario, the only decay mode is \( \chi \to \gamma \tilde{G} \), for which the decay width can be computed once the supergravity Lagrangian is known [21], and it is given by [14, 22]

\[
\Gamma(\chi \to \gamma \tilde{G}) = \frac{|N_{11} \cos \theta_W + N_{12} \sin \theta_W|^2}{48 \pi M_*^2} m_\chi^5 \left[ 1 - \frac{m_{\tilde{G}}^2}{m_\chi^2} \right]^3 \left[ 1 + 3 \frac{m_{\tilde{G}}^2}{m_\chi^2} \right] \]

(12)

where \( M_* \) is the Planck mass, \( m_\chi \) is the neutralino mass, and \( \theta_W \) is the weak angle. In the limit where the mass difference \( \Delta m \equiv m_\chi - m_{\tilde{G}} \) is much lower than the masses themselves, \( \Delta m \ll m_\chi, m_{\tilde{G}} \), the neutralino lifetime becomes

\[
\tau = \frac{1.78 \times 10^{13}}{|N_{11} \cos \theta_W + N_{12} \sin \theta_W|^2} \left( \frac{\text{GeV}}{\Delta m} \right)^3 \text{sec}
\]

(13)

From this formula one can see that for a mostly bino-neutralino a mass difference of 1 MeV is already enough to give a neutralino lifetime larger than the age of the universe.

- Neutralino-Nucleon spin-independent cross-section: LHC is now running and collecting data. Although LHC is a powerful machine to look for physics beyond the standard model, it is known that other facilities are also needed to offer complementary information towards the direction of searching for supersymmetry and identifying dark matter. The gravitino interactions are suppressed by the Planck mass, and therefore direct production of gravitinos at colliders and/or direct detection prospects seem to be hopeless. On the other hand, for a weakly interacting neutralino there are existing as well as future experiments that put experimental limits on the nucleon-neutralino cross-section. The spin-independent cross-section is given by

\[
\sigma_{\chi-N} = \frac{4m_r^2}{\pi} f_N^2
\]

(14)

where \( m_r \) is the Nucleon-neutralino reduced mass, \( m_r = m_N m_\chi/(m_N + m_\chi) \), and

\[
\frac{f_N}{m_N} = \sum_{q=u,d,s} f^{(N)}_{Tq} \frac{\alpha_q}{m_q} + \frac{2}{27} f^{(N)}_{TG} \sum_{q=c,b,t} \frac{\alpha_q}{m_q}
\]

(15)

In the above, \( f^{(N)}_{Tq} = 1 - \sum_{q=u,d,s} f^{(N)}_{Tq} \), we have taken the following values for the hadronic matrix elements [23]:

\[
\begin{align*}
  f^{(p)}_{Tu} &= 0.020 \pm 0.004, & f^{(p)}_{Td} &= 0.026 \pm 0.005, & f^{(p)}_{Ts} &= 0.118 \pm 0.062, \\
  f^{(n)}_{Tu} &= 0.014 \pm 0.003, & f^{(n)}_{Td} &= 0.036 \pm 0.008, & f^{(n)}_{Ts} &= 0.118 \pm 0.062.
\end{align*}
\]

(16)

and \( \alpha_q \) is the coupling in the effective Lagrangian

\[
L_{\text{eff}} = \alpha_i \tilde{\chi} \chi \tilde{q}_i q_i
\]

(17)
where $i = 1, 2$ denotes up- and down-type quarks, and the Lagrangian is summed over the three quark generations. The coupling $\alpha_q$ can be decomposed into two parts, $\alpha_q = \alpha^h_q + \alpha^\tilde{q}_q$, where the first term is the t-channel exchange of a neutral Higgs (Fig. 1), while the second term is the s-channel exchange of a squark (Fig. 2). The expressions for $\alpha_q$ in terms of the masses and couplings of the model can be found in [24].

Our main results are summarized in the figures below. In Fig. 3 and Fig. 4 we show the nucleon-neutralino spin-independent cross section (in cm$^2$) versus neutralino mass and lightest Higgs boson (in GeV) respectively. The blue region corresponds to a bino neutralino, while the green region corresponds to a singlino neutralino, and the curves are the current experimental limits from CDMS [25]. According to our results the bino scenario is already ruled out, while in the singlino case the upper region can be probed by future experiments. In Fig. 5 we show the reheating temperature after inflation as a function of the neutralino/gravitino mass. The blue region corresponds to a bino, the blue points correspond to singlino with relatively high values of the cross-section, namely $\sigma_{\chi-N} > 10^{-47}$ cm$^2$. The largest values of $T_R$ correspond to a bino, which is ruled out, and for the singlino with relatively high values of cross-section we obtain a reheating temperature $T_R \simeq 5 \times 10^9$ GeV for a neutralino/gravitino mass $m_\chi \simeq m_{\tilde{G}} \simeq 200$ GeV. In the last figure we show the $(m_0-m_{1/2})$ plane (in GeV) for singlino points with a cross-section larger than $10^{-47}$ cm$^2$, or lower than $10^{-47}$ cm$^2$. We see that $m_0$ is not larger than 600 GeV, and therefore future direct detection experiments cannot probe a region of the parameter space which can neither be probed by LHC.

4. Conclusion
In the framework of NMSSM, which solves the mu problem, we have assumed that the gravitino LSP and the lightest neutralino NLSP are degenerate in mass. Under this assumption the neutralino becomes extremely long-lived avoiding the BBN bounds. In this scenario we have a two component dark matter made out of the absolutely stable gravitino and the quasi-stable neutralino. We have performed a random scan over the whole parameter space keeping the
points that satisfy the available collider constraints plus the WMAP bound for dark matter. These points correspond to either a bino or a singlino neutralino. We have computed the neutralino-nucleon spin-independent cross section as a function of the neutralino mass and the lightest Higgs mass, and we find that the bino is ruled out. Then we explored the \((m_0 - m_{1/2})\) parameter space, and the reheating temperature dependence of the neutralino/gravitino mass for the singlino points that correspond to cross section values to be probed by future experiments.

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Figure 5. Reheating temperature versus neutralino (or gravitino mass). Blue points correspond to bino, green points correspond to singlino, and red points correspond to singlino with a cross-section larger than $10^{-47} \text{ cm}^2$.

Figure 6. The $(m_0-m_{1/2})$ plane for the singlino points. One color corresponds to a cross-section larger than $10^{-47} \text{ cm}^2$, and the other color corresponds to a cross-section lower than $10^{-47} \text{ cm}^2$.

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