Gravitino dark matter with neutralino NLSP in the constrained NMSSM

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Abstract. The gravitino dark matter with neutralino NLSP hypothesis is investigated in the framework of NMSSM. We have considered both the thermal and non-thermal gravitino production mechanisms, and we have taken into account all the collider and cosmological constraints. The maximum allowed reheating temperature after inflation, as well as the maximum allowed gravitino mass are determined.

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 [1], namely a component which is non-relativistic and neither feels the electromagnetic nor the strong interaction. It is known that in the standard model of particle physics there is not a suitable dark matter candidate. Supersymmetry, a very well-motivated idea, is perhaps the most popular way beyond the standard model, and it provides us with an ideal candidate for playing the role of cold dark matter in the universe.

Out of the several dark matter candidates, certainly the most well-studied case is the one of the neutralino. However, the gravitino is also a very compelling candidate for several reasons. Its interactions are completely fixed by the supergravity Lagrangian, its mass $m_{\tilde{G}}$ is directly related to the scale at which supersymmetry is broken, and finally the reheating temperature after inflation $T_R$, which is essential for the precise baryon asymmetry generation mechanism, plays a certain role in gravitino cosmology.

The MSSM [2] is the most economical supersymmetric extension of the standarm model. However, it suffers from the so-called $\mu$ problem [3]. The natural values for the higgs/higgsino mass parameter $\mu$ is either 0 or the Planck mass, while phenomenology requires the $\mu$ should be at the electroweak scale. The simplest supersymmetric model that solves the $\mu$ problem is the NMSSM [4], where one more singlet chiral superfield is introduced.

It is therefore interesting to try to see whether a particular cosmological scenario, with gravitino LSP and neutralino NLSP in the framework of the NMSSM, is a viable one.
2. The theoretical framework

2.1. Basics of NMSSM

The particle physics model is defined by the superpotential

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

(1)

as well as the soft breaking masses and couplings

\[ -\mathcal{L}_{\text{soft}} = \begin{array}{c}
m_Q^2 \tilde{Q}^* \tilde{Q} + m_U^2 \tilde{U}^* \tilde{U} + m_D^2 \tilde{D}^* \tilde{D} + m_L^2 \tilde{L}^* \tilde{L} + m_E^2 \tilde{E}^* \tilde{E} \\
+ \mu^2 \tilde{H}_1^* \tilde{H}_1 + \mu_2^2 \tilde{H}_2^* \tilde{H}_2 + m_S^2 \tilde{S}^* \tilde{S} \\
+ \epsilon_{ij} \left( A_u Y_u H_u^i \tilde{Q}^* \tilde{u} + A_d Y_d H_d^i \tilde{Q}^* \tilde{d} + A_e Y_e H_e^i \tilde{L}^* \tilde{e} + \text{H.c.} \right) \\
+ \left( -\epsilon_{ij} \lambda A \lambda S H_u^i H_d^j + \kappa S^3 \right) + \text{H.c.} \\
- \frac{1}{2} \left( M_3 \lambda_3 \lambda_3 + M_2 \lambda_2 \lambda_2 + M_1 \lambda_1 \lambda_1 \right) + \text{H.c.} \end{array} \]  

(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

\[ \tan \beta = v_u/v_d, m_0, A_0, m_{1/2}, \lambda, A_k \]

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 state. The neutralino mass matrix is characterized by the appearence of a fifth neutralino sector, meaning that the composition of the lightest neutralino has an extra singlino contribution

\[ \tilde{\chi}_1^0 = N_{11} \tilde{B}^0 + N_{12} \tilde{H}_3^0 + N_{13} \tilde{H}_1^0 + N_{14} \tilde{H}_2^0 + N_{15} \tilde{S}^0 \]  

(3)

In the following, neutralinos with \( N_{11}^2 > 0.9 \), or \( N_{13}^2 > 0.9 \), 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

\[ h_a^0 = S_{ab} H_b^0 \]  

(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

After inflation gravitinos can be produced in two ways. One way to produce gravitinos is with scatterings 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 [5] we can write for the gravitino abundance

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

(5)

where

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

(6)
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, $m_{\tilde{G}} \ll m_{\tilde{g}}$) [6]

$$\Omega_{3/2}^{TP} \simeq 0.27 \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left( \frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^{-2} \left( \frac{m_{\tilde{G}}}{100 \text{ GeV}} \right)$$

(7)

### 2.3. Neutralino lifetime

The NSLP is unstable with a lifetime that is typically larger than BBN time $t_{BBN} \sim 1$ sec. Energetic particles produced by the NLSP decay may dissociate the background nuclei and significantly affect the primordial abundances of light elements. If such processes occur with sizable rates, the predictions of the standard BBN scenario would be altered and the success of the primordial nucleosynthesis would be spoiled. BBN constraints on cosmological scenarios with exotic long-lived particles predicted by physics beyond the Standard Model have been studied, and here we have used the figure 2 of Ref. [7]. Thus, we need to compute the lifetime of the neutralino. There are three main decay channels, namely neutralino decaying into gravitino and a standard model particle that can be one of the followings: Photon, $Z$ boson and Higgs. The supergravity Lagrangian is known, and the Feynman rules for the gravitino interactions have been derived [8]. Therefore, the neutralino lifetime is given by

$$\tau = \frac{1}{\Gamma}$$

(8)

$$\Gamma = \Gamma(\chi \to \gamma \tilde{G}) + \Gamma(\chi \to Z \tilde{G}) + \Gamma(\chi \to h \tilde{G})$$

(9)

and the exact expressions for the different contributions can be found in [9].

### 3. Constraints and results

We have used NMSSMTools [10], a computer software that computes the masses of the Higgses and the superpartners, the couplings, and the relic density of the neutralino, for a given set of the free parameters. 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 i) theoretical requirements, such as neutralino LSP, correct electroweak symmetry breaking, absence of tachyonic masses etc., and ii) LEP bounds on the Higgs mass, collider bounds on SUSY particle masses, and experimental data from B-physics. Finally, for any given point in the cNMSSM parameter space, the neutralino lifetime is a function of the gravitino mass only. Imposing the BBN constraints we find the maximum allowed gravitino mass, and from the cold dark matter bound we can determine the maximum allowed reheating temperature. For all the acceptable points the lightest neutralino is either a bino or a singlino, and our main results are summarized in the figures below.

For the bino case, figure 1 shows the maximum allowed reheating temperature after inflation versus the maximum allowed gravitino mass, both in GeV. Although it cannot be seen directly from the figures, the maximum possible gravitino mass in the bino case is $m_{\tilde{G}} \simeq 1$ GeV, and the corresponding reheating temperature is $T_R \sim 10^7$ GeV. Therefore, we see that a) the gravitino in this scenario must be much lighter than the rest of superpartners, but nevertheless it is still in the gravity-mediated SUSY-breaking scheme, and b) the reheating temperature after inflation is not large enough for thermal leptogenesis.

For the singlino case, we show in figure 2 the maximum allowed reheating temperature versus gravitino mass, both in GeV. This time the neutralino relic density is even larger than before, and gravitino now must be extremely light. This is due to the smallness of the coefficients $N_{11}, N_{12}$ in the decay rate to gravitino and photon. For the same lifetime as before, the gravitino mass
must be several orders of magnitude lower than in the bino case. The last figure shows that in the singlino case the reheating temperature cannot be larger than about 200 GeV. However, this value is much lower than the minimum value required for the computation of the gravitino thermal production, and therefore we conclude that this scenario must be excluded.

4. Conclusion
In the framework of the cNMSSM, we have considered a possible cosmological scenario with the gravitino LSP and the neutralino NLSP. The gravitino is stable and plays the role of cold dark matter in the universe, while the neutralino is unstable and decays to gravitino. We have taken into account the relevant gravitino production mechanisms, which are i) the NLSP decay, and ii)
scattering processes from the thermal bath. Our results can be seen in the figures. We have found that i) the gravitino is necessarily very light, and ii) the reheating temperature after inflation is two orders of magnitude lower than the temperature required for thermal leptogenesis. The singlino scenario must be excluded, while in the bino case it is hardly possible to have a gravitino in the gravity-mediated SUSY-breaking scheme.

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