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# Dark matter and neutrino masses in the R-parity violating NMSSM

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## Abstract

The R-Parity symmetry Violating (RPV) version of the Next-to-Minimal Supersymmetric Standard Model (NMSSM) is attractive simultaneously with regard to the so-called  $\mu$ -problem and the accommodation of three-flavor neutrino data at tree level. In this context, we show here that if the Lightest Supersymmetric Particle (LSP) is the gravitino, it possesses a lifetime larger than the age of the universe since its RPV induced decay channels are suppressed by the weak gravitational strength. This conclusion holds if one considers gravitino masses  $\sim 10^2$  GeV like in supergravity scenarios, and is robust if the lightest pseudoscalar Higgs field is as light as  $\sim 10$  GeV [as may occur in the NMSSM]. For these models predicting in particular an RPV neutrino-photino mixing, the gravitino lifetime exceeds the age of the universe by two orders of magnitude. However, we find that the gravitino cannot constitute a viable dark matter candidate since its too large RPV decay widths would then conflict with the flux data of last indirect detection experiments. The cases of a sneutrino LSP or a neutralino LSP as well as the more promising gauge-mediated supersymmetry breaking scenario are also discussed. Both the one-flavor simplification hypothesis and the realistic scenario of three neutrino flavors are analyzed. We have modified the NMHDECAY program to extend the neutralino mass matrix to the present framework.

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# I Introduction

In supersymmetry, the superpartner of the graviton, namely the so-called gravitino, plays a central theoretical role as it constitutes the gauge fermion of supergravity theories [1, 2]. From the cosmological point of view, the gravitino may be the Lightest Supersymmetric Particle (LSP), depending on the way supersymmetry is broken, and hence constitute a stable dark matter candidate [3]. Interestingly, one could even assume supersymmetric models where the R-parity symmetry [4] is violated. Then the gravitino becomes unstable due to new decay channels into Standard Model (SM) particles induced by the R-Parity Violating (RPV) interactions. However, because of the small gravitational interaction and possibly weak RPV couplings, the gravitino lifetime can still exceed the age of the universe (by several orders of magnitude) in the particular case of RPV bilinear terms [5] remaining thus a realistic dark matter candidate. This scenario can yield a complete cosmological framework also incorporating leptogenesis and nucleosynthesis, as recently shown in Ref. [6]. In such a scenario, the gravitino decays into SM particles lead to specific signatures in high-energy cosmic rays; the produced flux of gamma rays and positrons can even account [7] respectively for the extragalactic component of the excess in the HEAT [8] data. The decaying gravitinos could also constitute an interpretation (see below) of the exotic positron source recently discovered by the PAMELA Collaboration [9].

Another advantage of the existence of RPV interactions is the induced mixing between left-handed neutrinos and neutral gauginos. This mixing mechanism generates neutrino masses economically, without extending the SM field content to additional right-handed neutrino fields. There exists a tension between generating a sufficiently large neutrino Majorana mass scale [requiring strong RPV] and, at the same time, keeping the gravitino lifetime larger than the age of the universe [imposing weak RPV]. Nevertheless, this tension leaves some acceptable windows in the parameter space [5] for example with gravitino masses around 100 GeV in the Minimal Supersymmetric Standard Model (MSSM).

In the present paper, we re-consider the above scenario in the framework of the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [10] (see recent reviews [11] for the phenomenological studies). An increasingly important virtue of the NMSSM is that it improves the ‘little hierarchy’ problem originating from the requirement of large soft supersymmetry breaking masses compared to the ElectroWeak (EW) scale. It also provides a solution to the so-called  $\mu$ -problem by arranging the vacuum expectation value (vev) of a new gauge singlet scalar field of order of the supersymmetry breaking scale, so that the  $\mu$  parameter turns out to be at the EW scale. We have shown in a previous work [12] that in the NMSSM with bilinear RPV terms, two non-degenerate massive neutrino states can emerge at tree level, in contrast with the MSSM case where only one neutrino eigenstate acquires a mass (at tree level). Hence, the global three-flavor neutrino data can be accommodated [13], at tree level, without appealing to loop dynamics which is vulnerable to model-dependent uncertainties.

In such a framework, both the gaugino mass matrix and RPV mixing terms are modified w.r.t. the MSSM case. Furthermore, the NMSSM provides the possibility <sup>1</sup> of reducing significantly w.r.t. MSSM the mass of the lightest pseudoscalar Higgs field [which can constitute partially the gravitino decay final state]. Moreover, the specific gauge singlet scalar field gives rise to new contributions to the gravitino RPV decay. Hence, the double question in the NMSSM on the possibility of generating

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<sup>1</sup>Such a possibility was in particular motivated by interpreting the well-known LEP excess at  $2.3\sigma$  in the  $Z + 2b$  channel – via the production of a light Higgs boson ( $m_h \simeq 99$  GeV) [14] – but this NMSSM interpretation seems to be excluded by a recent ALEPH analysis [15].

the correct neutrino mass scale, while still keeping the gravitino as a good dark matter candidate, is relevant and well motivated.

We find in this paper that the answer concerning the gravitino stability can be positive for parameters passing the theoretical and phenomenological constraints implemented in the NMHDECAY code [16] and in particular for gravitino masses as large as  $m_{3/2} = \mathcal{O}(10^2)$  GeV [tending to increase the total gravitino width]. This is satisfactory as it corresponds to the typical scale of supersymmetry breaking in supergravity scenarios. In both scenarios where the supersymmetry breaking is mediated purely by gravity [1, 2] or partially by gravity and gauge interactions [17] (such classes of hybrid models have been recently motivated in string inspired constructions [18]), the gravitino is the LSP in wide regions of the parameter space and its typical mass is in the range between 100 GeV and 1 TeV. Besides, thermal leptogenesis and universal boundary conditions for gaugino masses at the Grand Unification Theory (GUT) scale restrict  $m_{3/2} < 600$  GeV [19] and, on the other hand, the interpretation of the PAMELA positron anomaly imposes  $m_{3/2} \gtrsim 200$  GeV [20].

Nevertheless, our second result on a gravitino LSP around  $\sim 10^2$  GeV is that its RPV decay rates lead to fluxes exceeding the total flux measured in last indirect detection experiments.

We will finally discuss the pure case, still within the NMSSM, of Gauge-Mediated Supersymmetry Breaking (GMSB) where the LSP gravitino mass verifies typically  $m_{3/2} \gtrsim 1$  eV [21] and the neutralino mass matrix receives some modifications [22]. Conclusions here are more optimistic.

Let us make some comments on the results obtained in the present paper. First, we have considered all the possible gravitino decays, namely into photon, Z, W bosons and (pseudo)scalar Higgs fields, in contrast with Ref. [5] where only the photon channel was considered. The new kinematically allowed channels open up due to the higher gravitino masses considered here. Secondly, the trilinear RPV couplings are also discussed. Furthermore, we investigate for the first time the realistic case of three flavors of neutrinos. We conclude that the complete RPV mixing obtained in this case does not invalidate the positive results obtained for the simultaneous solution of the neutrino mass and dark matter problems. Finally, the pure neutrino results include the various NMSSM-constraints implemented in NMHDECAY [16] (that we have modified to include the neutrino components in the neutralino mass matrix) and are derived from a numerical treatment of the full neutral gaugino mass matrix, in contrast with preliminary work in Ref. [12]. The modified version of NMHDECAY thus contains an implementation of the whole neutralino mass matrix which includes, in the present context, some matrix elements induced by the RPV couplings and responsible for the mixing between the higgsinos and neutrinos (see Section II.3).

In addition, we will explore the alternative possibilities of the neutralino and sneutrino as stable LSP dark matter candidates, under the same assumption of the desired neutrino mass spectrum generated through the RPV mixing in the NMSSM. The philosophy is to establish a systematic list of the viable supersymmetric dark matter candidates. Since this topic relies on the particle spectrum, we base our study on a systematic exploration of the parameter space. Our conclusions are also based on new calculations of the neutralino and sneutrino decay channels.

Let us mention previous related works. The neutrino flux from direct gravitino decays has been computed in a simple scenario with bilinear R-parity breaking [23]. The diffuse gamma ray flux was also studied in Ref. [24]. A realization in minimal supersymmetric left-right models within supergravity, with a gravitino LSP dark matter and R-parity breaking, was proposed in Ref. [25] (see also Ref. [26]). Finally, a scenario with R-parity violation in the right-handed neutrino sector was motivated by the PAMELA data [27].

Concerning supersymmetric models for neutrinos – independently of the dark matter problem – RPV

versions of the NMSSM have been previously studied in Ref. [28], Ref. [29] and Ref. [30]. Besides, alternative supersymmetric extensions with broken  $R$ -symmetries have been proposed in order to address simultaneously the  $\mu$ -problem and the neutrino mass aspect [31, 32, 33] (and see Ref. [34] for a gravitino dark matter decay study in this context).

RPV supersymmetric scenarios have also been studied within the context of neutrino astrophysics (see e.g. [35, 36]). Finally, for studies of gravitino dark matter without RPV couplings, see for instance Ref. [37] for the constrained MSSM or GMSB scenarios.

The paper is organized as follows. In Section II, we elaborate the RPV scenario and describe the corresponding neutralino mass matrix. In the following sections, we discuss subsequently the cases of a sneutrino LSP (Section III), a neutralino LSP (IV) and a gravitino LSP (V). Finally, we conclude in Section VI.

## II The RPV version of the NMSSM

### II.1 Theoretical framework

We consider the NMSSM which possesses a superpotential containing two dimensionless couplings  $\lambda$  and  $\kappa$  in addition to the usual Yukawa couplings:

$$W_{\text{NMSSM}} = Y_{ij}^u Q_i H_u U_j^c + Y_{ij}^d Q_i H_d D_j^c + Y_{ij}^\ell L_i H_d E_j^c + \lambda S H_u H_d + \frac{1}{3} \kappa S^3 \quad (1)$$

where  $Y_{ij}^{u,d,\ell}$  are the Yukawa coupling constants ( $i, j, k$  are family indexes), and  $Q_i, L_i, U_i^c, D_i^c, E_i^c, H_u, H_d, S$  respectively are the superfields for the quark doublets, lepton doublets, up-type anti-quarks, down-type anti-quarks, anti-leptons, up Higgs, down Higgs, extra singlet under the standard model gauge group. An effective  $\mu$  term, given by  $\lambda \langle s \rangle H_u H_d$ , is generated via the vev of the scalar component  $s$  ( $\langle s \rangle$ ) of the singlet superfield  $S$ .

In case of GMSB [22], there are additional terms that must be added to the NMSSM superpotential (1). Those terms are given by:

$$W_{\text{GMSB}} = \xi_F S + \mu' S^2 \quad (2)$$

where  $\xi_F$  ( $\mu'$ ) is a new dimension-two (-one) parameter. These parameters in GMSB models are generated at low energy as  $S$  is coupled to the messenger sector.

Recalling that there exists no deep theoretical principle in supersymmetry for the existence of an exact  $R$ -parity symmetry [38], we adopt a generic approach by introducing both the bilinear and trilinear RPV terms characteristic of the NMSSM [the usual trilinear RPV couplings of the MSSM are considered in next section]:

$$W = W_{\text{NMSSM}} + \mu_i L_i H_u + \lambda_i S L_i H_u, \quad (3)$$

where  $\mu_i$  ( $\lambda_i$ ) are the dimension-one (dimensionless) RPV parameters.

Within the usual NMSSM, only trilinear couplings with dimensionless parameters (like  $\lambda$  and  $\kappa$ ) are kept in the superpotential, while dimensional parameters (like  $\mu$ ) are generated from the vev  $\langle s \rangle$ . Here the RPV NMSSM superpotential (3), containing a  $\mu_i L_i H_u$  but no  $\mu H_u H_d$  term, is assumed to arise in one of the scenarios proposed in [12].

## II.2 Discussion on the trilinear RPV terms

The most general RPV NMSSM superpotential also includes the renormalizable trilinear RPV interactions:

$$W_{\text{RPV}} = W + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c. \quad (4)$$

It is remarkable that if the order of magnitude for  $\lambda_{ijk}$  and  $\lambda'_{ijk}$  is comparable to the values of the Yukawa coupling constants for the electron and the down quark [ $Y^e$ ,  $Y^d$ ], the exchange of leptons/sleptons and respectively quarks/squarks in one-loop processes can generate Majorana neutrino masses [39] in agreement with (or few orders below) the oscillation experiment results:  $10^{-3} \text{eV} \lesssim m_{\nu_i} \lesssim 1 \text{eV}$ . This occurs for sfermion masses in the vicinity of  $10^2 \text{ GeV}$ , the order of supersymmetry breaking scale amount required from the gauge hierarchy solution. Now, given the analog structure of the Yukawa interactions (1) and the trilinear RPV terms (4), one can assume that the same (flavor-)structure responsible of the  $Y^{e,d}$  suppression (w.r.t.  $Y^t$  for the top quark) would also characterize the  $\lambda_{ijk}^{(\prime)}$  couplings, inducing in turn the wanted tiny neutrino mass scale through one-loop processes.

Assuming such low values for the  $\lambda_{ijk}^{(\prime)}$  coupling constants (which in general easily pass the various phenomenological constraints [40]), one finds from formulas obtained in [41] that a gravitino ( $\tilde{G}$ ) LSP would decay into the three SM fermion final state  $f_i f_j f_k$  via the  $\lambda_{ijk}^{(\prime)}$  interactions with a sufficiently small width. Quantitatively, for a gravitino mass around  $m_{3/2} \sim 10^2 \text{ GeV}$ , its lifetime would lie in the range  $10^{22} - 10^{24} \text{ sec}$  which is well above the age of the universe:  $t_0 \simeq 3.2 \cdot 10^{17} \text{ sec}$ .

As a first conclusion, it is interesting to note that a scenario with trilinear RPV interactions of type  $\lambda_{ijk}^{(\prime)}$  addressing simultaneously the neutrino mass and dark matter problems is conceivable. In the following, we will address this double problem within a different supersymmetric scenario where the neutrino mass is generated via bilinear and trilinear RPV couplings of type  $\mu_i$  and  $\lambda_i$ , respectively, which do not induce too large decay widths of the dark matter candidate. In contrast with the  $\lambda_{ijk}^{(\prime)}$  case, the present framework deserves a more general treatment in the sense that the neutrinos are mixed with neutral gauginos/higgsinos so that the neutrino constraints and the neutralino ones are correlated. In fact, the mixing is generally so small that it does not affect significantly the gaugino/higgsino mass matrix, but the precise values of the several parameters entering this matrix crucially determine the small induced neutrino masses.

Nevertheless, let us finish this part by commenting on the fact that even if the  $\lambda_{ijk}^{(\prime)}$  couplings of the order of weak Yukawa couplings cannot induce dangerous  $\tilde{G}$  decay channels, they could contribute partially to the neutrino masses through one-loop diagrams. Here, we concentrate on the dominant tree-level contributions to the neutrino masses and hence leave for the future a precise and complete fit of neutrino data at loop-level.

## II.3 Neutralino mass matrix

The neutralino mass terms read,

$$\mathcal{L}_{\tilde{\chi}^0}^m = -\frac{1}{2} \Psi^{0T} \mathcal{M}_{\tilde{\chi}^0} \Psi^0 + \text{h.c.} \quad (5)$$

in the basis  $\Psi^{0T} \equiv (\tilde{B}^0, \tilde{W}_3^0, \tilde{h}_d^0, \tilde{h}_u^0, \tilde{s}, \nu_i)$ , where  $\tilde{h}_{u,d}^0(\tilde{s})$  are the fermionic components of the superfields  $H_{u,d}^0(S)$  and  $\nu_i$  [ $i = 1, 2, 3$ ] denote the neutrinos. In Eq. (5), the neutralino mass matrix is given, in a generic basis (where  $\langle \tilde{\nu}_i \rangle \equiv v_i \neq 0$ ,  $\mu_i \neq 0$  and  $\lambda_i \neq 0$ , as will be discussed later), by

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} \mathcal{M}_{\text{NMSSM}} & \xi_{\mathcal{R}_p}^T \\ \xi_{\mathcal{R}_p} & \mathbf{0}_{3 \times 3} \end{pmatrix}, \quad (6)$$

where  $\mathcal{M}_{\text{NMSSM}}$  is the neutralino mass matrix corresponding to the NMSSM. For the latter mass matrix, we assume  $v_i \ll v_{u,d}$ , so that  $v^2 = v_u^2 + v_d^2 + \sum_{i=1}^3 v_i^2 = 2c_{\theta_W}^2 m_Z^2 / g^2 \simeq (175 \text{ GeV})^2$ . In the mass matrix below,  $s$  and  $c$  stand for sine and cosine, respectively.

$$\mathcal{M}_{\text{NMSSM}} = \begin{pmatrix} M_1 & 0 & -m_Z s_{\theta_W} c_\beta & m_Z s_{\theta_W} s_\beta & 0 \\ 0 & M_2 & m_Z c_{\theta_W} c_\beta & -m_Z c_{\theta_W} s_\beta & 0 \\ -m_Z s_{\theta_W} c_\beta & m_Z c_{\theta_W} c_\beta & 0 & -\mu & -\lambda v_u \\ m_Z s_{\theta_W} s_\beta & -m_Z c_{\theta_W} s_\beta & -\mu & 0 & -\lambda v_d + \sum_{i=1}^3 \lambda_i v_i \\ 0 & 0 & -\lambda v_u & -\lambda v_d + \sum_{i=1}^3 \lambda_i v_i & 2(\kappa \langle s \rangle + \mu') \end{pmatrix}. \quad (7)$$

Above,  $M_1$  ( $M_2$ ) is the soft supersymmetry breaking mass of the bino (wino),  $\tan \beta = v_u / v_d = \langle h_u^0 \rangle / \langle h_d^0 \rangle$  (with  $c_\beta = \cos \beta$  and  $s_\beta = \sin \beta$ ), and  $\mu = \lambda \langle s \rangle$ . The  $\mu'$  term appears only within the GMSB framework [see Eq.(2)].

We assume for simplicity that  $\lambda$ ,  $\kappa$  and the soft supersymmetry breaking parameters are all real.

In Eq. (6),  $\xi_{\mathcal{R}_p}$  is the RPV part of the matrix mixing neutrinos and neutralinos:

$$\xi_{\mathcal{R}_p} = \begin{pmatrix} -\frac{g' v_1}{\sqrt{2}} & \frac{g v_1}{\sqrt{2}} & 0 & \mu_1 + \lambda_1 \langle s \rangle & \lambda_1 v_u \\ -\frac{g' v_2}{\sqrt{2}} & \frac{g v_2}{\sqrt{2}} & 0 & \mu_2 + \lambda_2 \langle s \rangle & \lambda_2 v_u \\ -\frac{g' v_3}{\sqrt{2}} & \frac{g v_3}{\sqrt{2}} & 0 & \mu_3 + \lambda_3 \langle s \rangle & \lambda_3 v_u \end{pmatrix}. \quad (8)$$

$g$  and  $g'$  being the SU(2) and U(1) gauge couplings. We restrict ourselves to the situation where  $v_i / v_{u,d} \ll 1$  (as before),  $|\mu_i / \mu| \ll 1$  and  $|\lambda_i / \lambda| \ll 1$  so that (i) no considerable modifications of the NMSSM scalar potential are induced by the additional bilinear and trilinear terms in superpotential (3), (ii) the neutralino-neutrino mixing is suppressed, leading to sufficiently small neutrino masses; it is remarkable, as mentioned above, that the necessary order of magnitude,  $v_i / v_d \sim \mu_i / \mu \sim \lambda_i / \lambda \sim 10^{-5} - 10^{-7}$ , corresponds typically to the hierarchy between the electron mass and the top quark mass (or equivalently the EW symmetry breaking scale).

## II.4 The various (s)lepton mixings

**Chargino/neutralino-lepton mixing:** The condition for generating two non-vanishing and non-degenerate neutrino mass eigenvalues at tree level is to ensure simultaneously

$$\mu_i \neq 0 \text{ and } \Lambda_i \neq 0, \quad (9)$$

where  $\Lambda_i = \langle s \rangle (\lambda_i + \lambda \frac{v_i}{v_d})$ . The respective roles of these effective parameters is reflected e.g. in the sub-matrix (8) mixing the neutrinos with neutral NMSSM states.

Since the  $H_d$  and  $L_i$  superfields possess the same gauge quantum numbers, one can freely rotate  $L_\alpha = (H_d, L_i)$  [ $\alpha = 0, \dots, 3$ ] through  $SU(4)$  matrices by a redefinition of fields (for examples of unitary matrix associated to  $SU(4)$  transformations, see Ref. [42] or Ref. [38] in Section 2.1.4). Motivated by the condition (9), we work in a general basis where the  $\mu_i L_i H_u$  terms are non-vanishing. One could choose a specific basis of  $L_\alpha$  superfields where the  $\lambda_i$  couplings vanish, but then in general (i.e. assuming no particular correlation between the  $\lambda_i$  and  $B_i, \tilde{m}_{d,i}^2$  values) some  $v_i$  are generated due to the destabilization of the scalar potential by terms linear in  $\tilde{\nu}_i$  originating from the RPV soft scalar bilinear terms  $B_i h_u \tilde{L}_i, \tilde{m}_{d,i}^2 h_d^\dagger \tilde{L}_i$  after translation of the Higgs fields:  $h_u^0 \rightarrow h_u^0 + v_u/\sqrt{2}$  ( $h_d^0 \rightarrow h_d^0 + v_d/\sqrt{2}$ ). Reciprocally, a field basis where the  $v_i$  vanish generally leads to non-zero  $\lambda_i$  couplings. In conclusion, the condition (9) is generally fulfilled.

**Higgs-slepton mixing:** The physical amount of Higgs-slepton mixing is parametrized by the basis-independent angle between the 4-vectors  $v_\alpha = (v_d, v_i)$  and  $B_\alpha = (B_d, B_i)$ , where  $B_d$  is the soft parameter entering the biscalar term  $B_d h_u h_d$  [38]. We assume this angle sufficiently small so that the additional potentially dangerous decay channels  $\tilde{G}, \tilde{\chi}_1^0 \rightarrow H^\pm \ell^\mp / h^0 \nu$  and  $\tilde{\nu} \rightarrow f f, V V$  [ $f \equiv$  fermion,  $V \equiv$  Vector boson] play no role in the present context of a *long-lived* LSP dark matter candidate of type  $\tilde{G}, \tilde{\chi}_1^0$  or  $\tilde{\nu}$ .

**Charged lepton mixing:** The charged leptons also mix with the Wino (via the  $v_i$ 's) and the charged higgsino (controlled similarly by the  $\mu_i$  and  $\lambda_i$  parameters). However the detail of this mixing also relies on the determination of the precise value of each Yukawa coupling constant  $Y_{ij}^\ell$  for the charged leptons [see Eq.(1)] which requires a complete scenario of flavor taking into account all the experimental constraints [from neutrino oscillations and lepton flavor violating reactions] on leptonic mixing angles ( $U_{PMNS}$  matrix [43]), a task beyond the scope of the present work. Therefore, we will not explicitly work out the chargino-charged lepton mixing which is expected to be of comparable amount as the neutralino-neutrino mixing involving similar matrix structures and parameter orders [24]. Concerning the present cosmological context, this implies for instance that the width for the decay channel  $\tilde{G} \rightarrow W^\pm \ell^\mp$  is close to the one for  $\tilde{G} \rightarrow Z^0 \nu$ , so that our principal conclusions on the relative stability of the gravitino LSP based on the latter channel will not be modified by the former one <sup>3</sup>.

### III Sneutrino LSP

#### III.1 RPV sneutrino decays

In case of a sneutrino LSP decaying through the RPV couplings of type  $\Lambda_i$  and  $\mu_i$ , the sneutrino can exclusively decay into neutrinos via the two types of Feynman diagrams drawn in Fig.(1) or into two charged leptons. The associated decay widths are given below.

For that purpose, we need some definitions. First, the sneutrino LSP, noted  $\tilde{\nu}_1$ , corresponds to the lightest of the three sneutrino mass eigenstates, keeping in mind that arbitrary non-universal conditions on scalar soft masses and the dependence of sneutrino mass running e.g. on flavor-dependent  $\lambda_i$  parameters lead generally to a non-degeneracy of  $m_{\tilde{\nu}_i}$  ( $i = 1, 2, 3$ ) eigenvalues.

<sup>2</sup>Similarly, there exists a trilinear RPV soft term, arising in the NMSSM, which involves the singlet scalar field; this one is of the form  $sh_u \tilde{L}_i$  in the Lagrangian [29]. Its direct effect on the present study will be discussed in Section III.2.

<sup>3</sup>Besides, note that the contributions to the charged lepton masses should be of the order of magnitude of the neutrino mass scale and in turn negligible compared to the direct Yukawa contributions.

We also need to introduce the matrix  $N_{\alpha\beta}$  which is defined as follows. For convenience, we change the order (w.r.t. Section II.3) of the fields in the weak basis [for the rest of the paper]:  $\Psi^{0T} = (\tilde{B}^0, \tilde{W}_3^0, \tilde{h}_u^0, \tilde{h}_d^0, \tilde{s}, \nu_i)$  where as before the index  $i = 1, 2, 3$ , used for compact notations, corresponds to the three flavor states:  $\nu_e, \nu_\mu$  and  $\nu_\tau$  respectively. After diagonalization, the eigenstates are ordered in the mass basis according to  $\Upsilon^{0T} = (\nu_j^m, \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)$  where  $\nu_j^m$  denotes the three neutrino mass eigenstates ( $j = 1, 2, 3$ ) and the five  $\tilde{\chi}^0$ 's are the NMSSM neutralinos. Now, the unitary transformation matrix  $N_{\alpha\beta}$  acts as  $\Upsilon_\alpha^0 = N_{\alpha\beta}\Psi_\beta^0$  with  $\alpha, \beta = \{1, \dots, 8\}$ .

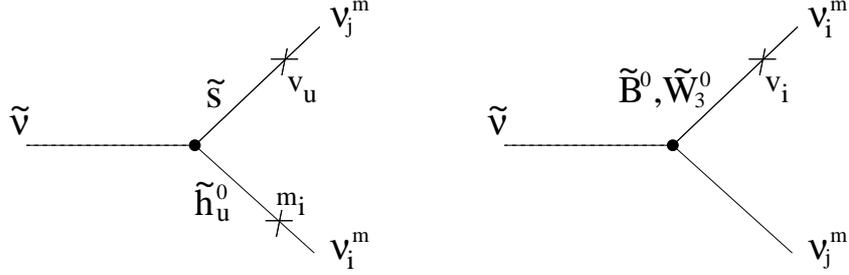


Figure 1: Feynman diagrams for the sneutrino decay channel in two neutrinos,  $\tilde{\nu} \rightarrow \nu_i^m \bar{\nu}_j^m$ . We use the effective quantity  $m_i = \mu_i + \lambda_i \langle s \rangle$  to parametrize a direct  $\mu_i$  mixing term effect combined with a  $\langle s \rangle$  vev insertion.  $v_u$  denotes the up Higgs vev insertion and  $v_i$  symbolizes the sneutrino vev insertion ( $i = 1, 2, 3$ ).

- Sneutrino decay into two neutrinos  $\nu_i^m \bar{\nu}_j^m$  (phase space factors involving neutrino over sneutrino masses are neglected):

$$\Gamma(\tilde{\nu}_1 \rightarrow \nu_i^m \bar{\nu}_j^m) = \frac{m_{\tilde{\nu}_1}}{16\pi} \left| \sum_{k=1}^3 \frac{\mathcal{N}_{1k}}{1 + \delta_{ij}} \left( \left[ \lambda_k N_{i3} N_{j5} + \frac{g}{\sqrt{2} \cos\theta_W} N_{j\{k+5\}} U_{\nu_i^m \tilde{Z}} \right] + [i \leftrightarrow j] \right) \right|^2 \quad (10)$$

where  $i, j = \{1, 2, 3\}$  run over the neutrino eigenstate indexes,  $\mathcal{N}_{1k}$  are elements of the model-dependent sneutrino basis transformation matrix (1 is for the lightest sneutrino eigenstate and  $k = \{1, 2, 3\}$  is for the sum over sneutrino flavor states),  $U_{\nu_i^m \tilde{Z}} = -N_{i1} \sin\theta_W + N_{i2} \cos\theta_W$  and ‘ $+ [i \leftrightarrow j]$ ’ indicates that the same expression in brackets must be added by switching  $i$  with  $j$ .

- Sneutrino decay into two charged leptons  $\ell_i^+ \ell_j^-$  (phase space factors involving lepton over sneutrino masses are also negligible here):

$$\Gamma(\tilde{\nu}_1 \rightarrow \ell_i^+ \ell_j^-) = \frac{m_{\tilde{\nu}_1}}{16\pi} g^2 \left| \sum_{k=1}^3 \frac{\mathcal{N}_{1k}}{1 + \delta_{ij}} \left( \left[ U_{j\{k+2\}} U_{\ell_i \tilde{W}} \right] + [i \leftrightarrow j] \right) \right|^2 \quad (11)$$

where  $U_{j\{k+2\}}$  is the equivalent of neutralino rotation matrix  $N$  but for charginos (here with  $k = \{1, 2, 3\}$  for the sum over charged lepton flavor states and  $j = \{1, 2, 3\}$  associated to the final charged lepton eigenstate) and similarly  $U_{\ell_i \tilde{W}}$  is the equivalent for charginos of  $U_{\nu_i^m \tilde{Z}}$ .

### III.2 Sneutrino stability

It turns out that the strength of effective RPV couplings  $\Lambda_i/\langle s \rangle$  and  $\mu_i$  necessary to generate sufficiently large neutrino masses, i.e. typically  $m_{\nu_1} \gtrsim 10^{-1} - 10^{-3}$  eV (in the approximate case of a unique neutrino flavor), induces RPV-like mixings between neutrinos and neutralinos which are too large from the cosmological point of view. Indeed, those mixings translate into matrix elements  $N_{i3} \sim 10^{-7}$ ,  $N_{j5} \sim 10^{-7}$ ,  $U_{\nu_i^m \tilde{Z}} \sim 10^{-7}$  and  $N_{j\{k+5\}} \sim 1$  with  $i, j, k = 1, 2, 3$  [for standard neutralino masses  $m_{\tilde{\chi}_1^0} = \mathcal{O}(10^2)$  GeV] so that the total sneutrino RPV decay width  $\Gamma(\tilde{\nu}_1 \rightarrow \nu_1^m \tilde{\nu}_1^m) \sim 10^{-15}$  GeV is well above the critical value of  $1.52 \cdot 10^{-42}$  GeV [for a sneutrino mass:  $m_{\tilde{\nu}_1} \gtrsim 10$  GeV and assuming for now  $\mathcal{N}_{1k} \sim 1$ ]. It means that the sneutrino lifetime is well below the age of the universe  $t_0$  and thus a sneutrino LSP does not constitute a viable dark matter candidate. A source of width suppression may arise from the generic amount of the matrix element  $\mathcal{N}_{11}$  but its effect is at much of a few orders of magnitude (more suppression would correspond either to a fine-tuning of parameters or to the weak breaking of a certain symmetry which should be described) so that this cannot invalidate the above conclusion. Furthermore, the effect of the additional decay channels into two charged leptons and into (pseudo)scalar Higgs bosons,  $h_i^0 h_j^0$ ,  $h_i^0 a_k^0$  or  $a_k^0 a_l^0$  [ $i, j = 1, 2, 3$ ,  $k, l = 2, 3$ ] (via the soft term  $sh_u \tilde{L}_i$  which is characteristic of the NMSSM with RPV interactions), can only increase the total sneutrino width <sup>4</sup>.

## IV Neutralino LSP

### IV.1 RPV neutralino decays

If the LSP is the lightest neutralino and the RPV couplings of type  $\Lambda_i$  and  $\mu_i$  are present, then the lightest neutralino can only decay into the W,Z bosons or into the (pseudo)scalar Higgs fields [as illustrated by the Feynman diagrams of Fig.(2)-(3)] if one restricts oneself to the dominant two-body decay channels. The obtained partial decay widths are given as follows.

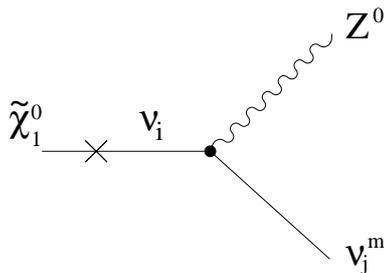


Figure 2: Feynman diagram for the neutralino decay mode into the Z boson,  $\tilde{\chi}_1^0 \rightarrow Z^0 \nu_j^m$ . The cross allows to specify the neutralino component that is coupled (here: a neutrino flavor state  $\nu_i$ ).

<sup>4</sup>In this part, we study the sneutrino RPV decays for completeness, even if a left-handed sneutrino LSP as a candidate for dark matter has been already excluded by direct dark matter searches for most of the realistic sneutrino mass ranges.

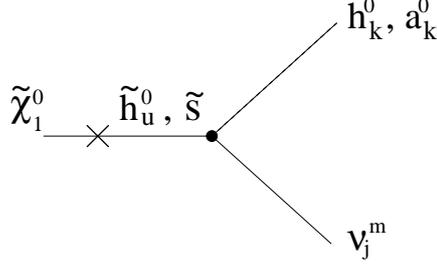


Figure 3: Feynman diagram for the neutralino decay modes into scalar Higgs fields,  $\tilde{\chi}_1^0 \rightarrow h_k^0 \nu_j^m$ , and pseudoscalar Higgs fields,  $\tilde{\chi}_1^0 \rightarrow a_k^0 \nu_j^m$ . The cross indicates which neutralino components are coupled.

- Neutralino decay into a Z boson and a neutrino  $\nu_j^m$  (phase space factors involving neutrino masses are neglected):

$$\Gamma(\tilde{\chi}_1^0 \rightarrow Z^0 \nu_j^m) = \frac{1}{96\pi} \left| \sum_{i=1}^3 N_{4i} N_{ji} \right|^2 \frac{g^2}{\cos^2 \theta_W} m_{\tilde{\chi}_1^0} \left( 1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2} \right)^2 \left( 1 + \frac{m_{\tilde{\chi}_1^0}^2}{2m_Z^2} \right) \quad (12)$$

where  $j = 1, 2, 3$  labels the neutrino mass eigenstate and  $i = 6, 7, 8$  corresponds to the sum over neutrino flavor states.

- Neutralino decay into the W boson and charged lepton  $\ell_j^\pm$  (the dependency on lepton masses, which represents subleading effects, is omitted):

$$\Gamma(\tilde{\chi}_1^0 \rightarrow W^\pm \ell_j^\mp) = \frac{1}{48\pi} \left| \sum_{i=6}^8 N_{4i} U_{j\{i-3\}} \right|^2 g^2 m_{\tilde{\chi}_1^0} \left( 1 - \frac{m_W^2}{m_{\tilde{\chi}_1^0}^2} \right)^2 \left( 1 + \frac{m_{\tilde{\chi}_1^0}^2}{2m_W^2} \right) \quad (13)$$

where  $j = 1, 2, 3$  labels the charged lepton mass eigenstate and  $i = 6, 7, 8$  is corresponding to the charged lepton/neutrino flavor states.

- Neutralino decay into scalar Higgs bosons  $h_k^0$  and neutrino  $\nu_j^m$ :

$$\Gamma(\tilde{\chi}_1^0 \rightarrow h_k^0 \nu_j^m) = \frac{1}{32\pi} \left| \sum_{i=6}^8 N_{ji} \lambda_{\{i-5\}} \right|^2 |N_{43} S_{k3} + N_{45} S_{k1}|^2 m_{\tilde{\chi}_1^0} \left( 1 - \frac{m_{h_k^0}^2}{m_{\tilde{\chi}_1^0}^2} \right)^2 \quad (14)$$

with  $j = 1, 2, 3$  labeling the neutrino mass eigenstate,  $i = 6, 7, 8$  corresponding to the neutrino flavor states and  $h_k^0 \equiv h_1^0, h_2^0, h_3^0$  (scalar Higgs mass eigenstates). The rotation matrix  $S$  relates the real parts of the neutral Higgs bosons and singlet scalar field to the scalar Higgs mass eigenstates  $h_k^0$  (see the precise definition in [16]). We recall that the parameters  $\lambda_{\{i-5\}}$  which appear here are the NMSSM specific trilinear parameters of Eq.(3). We also mention the decays into charged Higgs fields which are expected to be of comparable widths.

- Neutralino decay into pseudoscalar Higgs boson  $a_k^0$  and neutrino  $\nu_j^m$ :

$$\Gamma(\tilde{\chi}_1^0 \rightarrow a_k^0 \nu_j^m) = \frac{1}{32\pi} \left| \sum_{i=6}^8 N_{ji} \lambda_{\{i-5\}} \right|^2 |N_{43} P_{k3} + N_{45} P_{k1}|^2 m_{\tilde{\chi}_1^0} \left( 1 - \frac{m_{a_k^0}^2}{m_{\tilde{\chi}_1^0}^2} \right)^2 \quad (15)$$

with  $j = 1, 2, 3$  labeling the neutrino mass eigenstate,  $i = 6, 7, 8$  corresponding to the neutrino flavor states and  $a_k^0 \equiv a_1^0, a_2^0$  (pseudoscalar Higgs mass eigenstates). The rotation matrix  $P$  translates the imaginary parts of the neutral Higgs bosons and singlet scalar field into the pseudoscalar Higgs mass eigenstates  $a_k^0$  [16].

## IV.2 Neutralino stability

Based on the typical values of RPV parameters  $\lambda_i$ ,  $v_i$  and  $\mu_i$  generating a neutrino mass scale  $m_{\nu_1} \gtrsim 10^{-1} - 10^{-3}$  eV, we find for the parameters involved in the partial widths (12), (13), (14) and (15):  $N_{ji} \sim 1$ ,  $N_{4i} \sim 10^{-7}$ ,  $U_{j\{i-3\}} \sim 1$ ,  $\lambda_{\{i-5\}} \sim 10^{-6}$ ,  $N_{43}S_{k3} + N_{45}S_{k1} \sim 10^{-1} - 10^{-2}$  and  $N_{43}P_{k3} + N_{45}P_{k1} \sim 10^{-1} - 10^{-2}$  with  $i = 6, 7, 8$  and  $j = 1, 2, 3$  [if neutralino masses are of the order:  $m_{\tilde{\chi}_1^0} = \mathcal{O}(10^2)$  GeV, and taking  $m_{\tilde{\chi}_1^0} > m_Z$ ]. We can see that the contributions to the total neutralino decay width of Eqs.(14) and (15) are smaller than Eqs.(12) and (13). This leads [whatever is the (pseudo)scalar Higgs spectrum] to a total neutralino RPV decay width  $\Gamma_{\text{total}}(\tilde{\chi}_1^0) \sim 10^{-15}$  GeV that is several orders of magnitude above the critical value of  $1.52 \cdot 10^{-42}$  GeV. There are even additional contributions e.g. to the lightest neutralino decay into  $Z^0\nu_j^m$ , of the same order (originating from the  $Z^0\tilde{\chi}_i^0\tilde{\chi}_j^0$  coupling), that should slightly increase the total neutralino decay width. Adding the decay channel into  $H^\pm$ , closed in most of the parts of the parameter space, can only increase again the total neutralino width. The conclusion is thus as for the sneutrino case: the neutralino lifetime is much smaller than  $t_0$  and hence it does not represent a possible dark matter LSP candidate.

Nevertheless, a possibility to insure the stability of the lightest neutralino is to restrict to domains of parameter space where the 4 possible decay channels of Eq.(12), Eq.(13), Eq.(14) and Eq.(15), as well as the channels into charged Higgs bosons, are all kinematically closed [even opening only one channel is sufficient to render the  $\tilde{\chi}_1^0$  unstable]. Although in the NMSSM the lightest pseudoscalar Higgs boson noted  $a_1$  can be much lighter than in the MSSM, we can find realistic regions of the NMSSM parameter space where the lightest neutralino can be simultaneously lighter than the W, Z bosons, the lightest scalar  $h_1^0$  and pseudoscalar  $a_1^0$ , as well as the charged Higgs bosons  $H^\pm$ , thus closing the corresponding RPV channels. By the term ‘realistic’, we mean that the NMSSM parameters pass the theoretical and phenomenological constraints implemented in the NMHDECAY program [16] like: (i) the physical minimum of the scalar potential is deeper than the local unphysical minima with  $\langle h_{u,d}^0 \rangle = 0$  and/or  $\langle s \rangle = 0$  (ii) the running couplings  $\lambda$ ,  $\kappa$ ,  $Y^b$ ,  $Y^t$  do not encounter a Landau singularity (iii) the experimental constraints from LEP in the neutralino, chargino and Higgs sectors are effectively satisfied.

For instance, using NMHDECAY, we have plotted the masses  $m_{\tilde{\chi}_1^0}$ ,  $m_{h_1^0}$  and  $m_{a_1^0}$  as a function of the  $\kappa$  coupling constant in Fig.(4), for fixed values of the other NMSSM parameters. We see on this figure that for  $\kappa \gtrsim 0.05$ , the lightest neutralino LSP is lighter than the W, Z bosons, the lightest scalar  $h_1^0$  and pseudoscalar  $a_1^0$ . So the scenario of a completely stable  $\tilde{\chi}_1^0$  LSP can be a priori realized. Note that in such a scenario the RPV couplings can now be chosen freely to satisfy the neutrino constraints, since those couplings have a negligible impact on the neutralino mass spectrum.

We remark that there exist various triangular one-loop processes, exchanging charged leptons/sleptons, quarks/squarks or charged leptons/W bosons (through bilinear or trilinear RPV couplings <sup>5</sup>), which contribute all to the decay channel  $\tilde{\chi}_1^0 \rightarrow \gamma\nu_i^m$ . Such a channel is always kinematically open in the NMSSM, even in the case of the specific spectrum discussed just above, and could thus render

<sup>5</sup>The contributions from trilinear RPV interactions were estimated in Ref. [44].

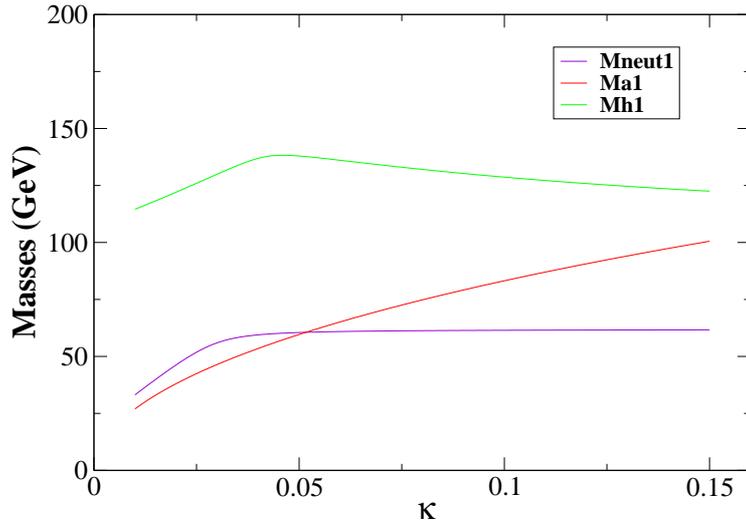


Figure 4: Masses  $m_{\tilde{\chi}_1^0}$  [purple curve],  $m_{h_1^0}$  [green curve] and  $m_{a_1^0}$  [red curve] as functions of  $\kappa$ . We fix the other NMSSM parameters:  $\tan\beta=2$ ,  $\lambda=0.7$ ,  $\mu = \lambda\langle s \rangle=530$  GeV,  $M_1=66$  GeV,  $M_2=133$  GeV,  $M_3=500$  GeV,  $A_\lambda=1280$  GeV,  $A_\kappa=0$ ,  $A_t = A_b = A_\tau=-2.5$  TeV,  $m_{\tilde{\ell}^\pm}=200$  GeV and  $m_{\tilde{q}}=1$  TeV (universally). The  $A$  parameters are the trilinear scalar soft supersymmetry breaking parameters which do not affect the neutralino mass matrix. The low values of  $M_i$ 's allow to get a neutralino LSP. Note also the particularly low values of  $m_{a_1^0}$ , characteristic of the NMSSM. For completeness, we give the employed RPV parameters:  $\Lambda_1/\langle s \rangle = 9 \cdot 10^{-7}$  and  $\mu_1 = 6 \cdot 10^{-6}$  GeV.

the neutralino unstable from the cosmological scale point of view. Assuming that no important destructive interferences occur among the several triangular contributions mentioned above, rough estimates indicate that the suppression provided by RPV terms [reproducing the correct neutrino mass scale] and by loop factors are not sufficient to make the LSP neutralino stable with respect to  $t_0$  (whatever is the neutralino composition). However, precise loop calculations of all contributing reactions, beyond the scope of our study, are necessary to conclude definitively on this aspect, taking into account notably effects of heavy sfermion loop factors.

The other important final comment is that three-body decay channels like  $\tilde{\chi}_1^0 \rightarrow \ell^+ \ell^- \nu^m$  (via an off-shell Z/W boson [45, 46] or an off-shell Higgs boson [45]) are systematically open. From order of magnitude estimates, it turns out that such channels are expected to render the lightest neutralino clearly unstable.

## V Gravitino LSP

### V.1 RPV gravitino decays

In the case of a gravitino LSP and RPV couplings of type  $\Lambda_i$  and  $\mu_i$ , the gravitino can decay into the EW gauge bosons and the (pseudo)scalar Higgs fields [as shown in Fig.(5)-(6)]. We give below the obtained associated partial decay widths.

All formulas given for the gravitino width, and above for sneutrino and neutralino widths, result from original calculations. Nevertheless, some of the gravitino decay amplitudes, into  $\gamma$ ,  $Z^0$ ,  $W^+$  and  $h_k^0$ , were computed with other conventions by the authors of Ref. [20, 23, 47] in the case of the MSSM (see also Ref. [48] for a more generic calculation approach). Note in particular that within the present framework of the NMSSM, the numerical results for the gravitino decay into the pseudoscalar  $a_1^0$  – which can be quite light there – might differ significantly from the MSSM and thus decrease dangerously the gravitino lifetime. Moreover, within the NMSSM, new contributions arise for the decays  $\tilde{G} \rightarrow h_k^0 \nu_i^m$  and  $\tilde{G} \rightarrow a_k^0 \nu_i^m$  due to the presence of the  $s$  superfield [see the right Feynman diagram of Fig.(6)]. Finally, in the NMSSM, the neutralino mass matrix (and in turn the matrix elements  $N_{ij}$  involved in gravitino amplitudes) takes a specific form, especially in the context of the GMSB (see Section II.3).

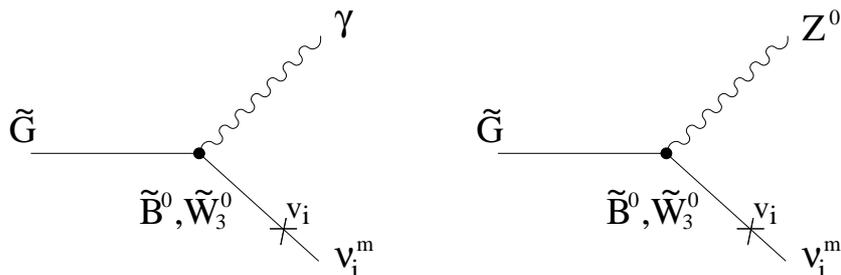


Figure 5: Feynman diagrams for the gravitino decay processes into a photon,  $\tilde{G} \rightarrow \gamma \nu_i^m$ , and a Z boson,  $\tilde{G} \rightarrow Z^0 \nu_i^m$ .  $v_i$  denotes a sneutrino vev insertion.

- Gravitino decay into the photon  $\gamma$  and neutrino  $\nu_i^m$  – the dependency on the neutrino mass is omitted (see first calculation in Ref. [5]):

$$\Gamma(\tilde{G} \rightarrow \gamma \nu_i^m) = \frac{1}{64\pi} |U_{\nu_i^m \tilde{\gamma}}|^2 \frac{m_{3/2}^3}{M_{Pl}^2} \quad (16)$$

where  $U_{\nu_i^m \tilde{\gamma}} = N_{i1} \cos\theta_W + N_{i2} \sin\theta_W$ ,  $i = 1, 2, 3$  labels the neutrino mass eigenstate and 1 (2) corresponds to the  $\tilde{B}^0$  ( $\tilde{W}_3^0$ ) component.  $M_{Pl}$  is the reduced Planck mass:  $M_{Pl} \simeq 2.4 \cdot 10^{18}$  GeV.

- Gravitino decay into the Z boson and neutrino  $\nu_i^m$  (see original calculation in Ref. [24]):

$$\Gamma(\tilde{G} \rightarrow Z^0 \nu_i^m) = \frac{1}{64\pi} |U_{\nu_i^m \tilde{Z}}|^2 \frac{m_{3/2}^3}{M_{Pl}^2} \left(1 - \frac{m_Z^2}{m_{3/2}^2}\right)^2 \left(1 + \frac{2}{3} \frac{m_Z^2}{m_{3/2}^2} + \frac{1}{3} \frac{m_Z^4}{m_{3/2}^4}\right) \quad (17)$$

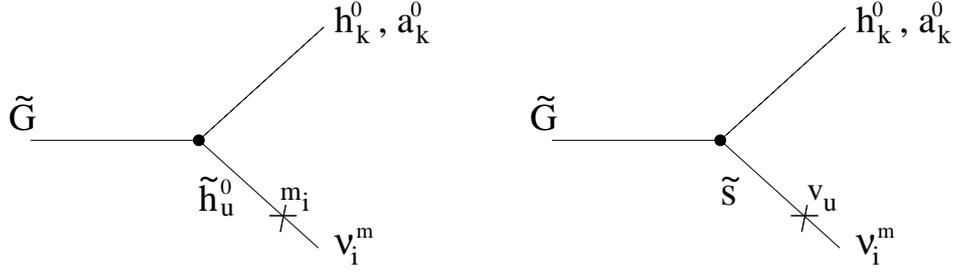


Figure 6: Feynman diagrams for the gravitino decay processes into scalar Higgs fields,  $\tilde{G} \rightarrow h_k^0 \nu_i^m$ , and pseudoscalar Higgs fields,  $\tilde{G} \rightarrow a_k^0 \nu_i^m$ . We use the symbolic notation  $m_i = \mu_i + \lambda_i \langle s \rangle$  combining a direct  $\mu_i$  mixing and a  $\langle s \rangle$  insertion.  $v_u$  indicates an up Higgs vev insertion.

where  $i = 1, 2, 3$  labels the neutrino mass eigenstate and 1 (2) corresponds to the  $\tilde{B}^0$  ( $\tilde{W}_3^0$ ) component.

- Gravitino decay into the W boson and charged lepton  $\ell_i^\mp$  (see original calculation in Ref. [24]):

$$\Gamma(\tilde{G} \rightarrow W^+ \ell_i^-) = \frac{1}{32\pi} |U_{\ell_i \tilde{W}}|^2 \frac{m_{3/2}^3}{M_{Pl}^2} \left(1 - \frac{m_W^2}{m_{3/2}^2}\right)^2 \left(1 + \frac{2}{3} \frac{m_W^2}{m_{3/2}^2} + \frac{1}{3} \frac{m_W^4}{m_{3/2}^4}\right) \quad (18)$$

where numerically  $U_{\ell_i \tilde{W}}$  is expected to be of a comparable order to  $U_{\nu_i^m \tilde{Z}}$  as already discussed. Similarly, here,  $i = 1, 2, 3$  labels the charged lepton mass eigenstate.

- Gravitino decay into the scalar Higgs boson  $h_k^0$  and neutrino  $\nu_i^m$

$$\Gamma(\tilde{G} \rightarrow h_k^0 \nu_i^m) = \frac{1}{384\pi} |N_{i3} S_{k1} + N_{i4} S_{k2} + N_{i5} S_{k3}|^2 \frac{m_{3/2}^3}{M_{Pl}^2} \left(1 - \frac{m_{h_k^0}^2}{m_{3/2}^2}\right)^4 \quad (19)$$

with  $i = 1, 2, 3$  labeling the neutrino mass eigenstate, the numbers 3, 4, 5 corresponding respectively to the  $\tilde{h}_u^0, \tilde{h}_d^0, \tilde{s}$  components and 1, 2, 3 respectively to the real  $h_u^0, h_d^0, s$  components.

- Gravitino decay into the pseudoscalar Higgs boson  $a_k^0$  and neutrino  $\nu_i^m$

$$\Gamma(\tilde{G} \rightarrow a_k^0 \nu_i^m) = \frac{1}{384\pi} |N_{i3} P_{k1} + N_{i4} P_{k2} + N_{i5} P_{k3}|^2 \frac{m_{3/2}^3}{M_{Pl}^2} \left(1 - \frac{m_{a_k^0}^2}{m_{3/2}^2}\right)^4 \quad (20)$$

still with  $k \equiv 1, 2$ . Similarly,  $i = 1, 2, 3$  labels the neutrino mass eigenstate, the numbers 3, 4, 5 correspond respectively to the  $\tilde{h}_u^0, \tilde{h}_d^0, \tilde{s}$  components and 1, 2, 3 respectively to the imaginary  $h_u^0, h_d^0, s$  components.

- Gravitino decay into the charged Higgs boson  $H^\pm$  and charged lepton  $\ell_i^\mp$

$$\Gamma(\tilde{G} \rightarrow H^+ \ell_i^-) = \frac{1}{384\pi} |U_{i2}|^2 \frac{m_{3/2}^3}{M_{Pl}^2} \left(1 - \frac{m_{H^+}^2}{m_{3/2}^2}\right)^4 \quad (21)$$

$i = 1, 2, 3$  labels the charged lepton mass eigenstate.  $U_{i2}$  represents the components of the three charged lepton eigenstates  $\ell_i^\pm$  into the charged higgsino  $\tilde{h}^\pm$ .

We note that the partial widths for the charge conjugated final states are equal, which means for instance that  $\Gamma(\tilde{G} \rightarrow \gamma\bar{\nu}) = \Gamma(\tilde{G} \rightarrow \gamma\nu)$ . Later, we will thus refer to the total gravitino decay width as:  $\Gamma_{\text{total}}(\tilde{G}) = 2[\Gamma(\tilde{G} \rightarrow \gamma\nu^m) + \Gamma(\tilde{G} \rightarrow Z^0\nu^m) + \Gamma(\tilde{G} \rightarrow W^+\ell^-) + \Gamma(\tilde{G} \rightarrow h^0\nu^m) + \Gamma(\tilde{G} \rightarrow a^0\nu^m) + \Gamma(\tilde{G} \rightarrow H^+\ell^-)]$ .

## V.2 Gravitino stability

### V.2.1 Scenario I: almost all decay channels open

Let us first consider a NMSSM scenario which is *a priori* dangerous from the cosmological point of view: we choose an heavy gravitino, so that the 5 first of the 6 types of decay channels described above are kinematically open (parameters allowing only the decays into the first  $h_1^0$  and  $a_1^0$ ), and a quite light pseudoscalar  $a_1^0$  (as is possible in the NMSSM), tending to increase the phase space for the partial width  $\Gamma(\tilde{G} \rightarrow a_1^0\nu_1^m)$ .

First, the considered region of the parameter space must be such that the gravitino is the LSP. We thus take rather large values for the gaugino masses  $M_1$ ,  $M_2$  and  $M_3$ :  $M_1=300$  GeV,  $M_2=600$  GeV,  $M_3=2$  TeV to push the neutralino mass to higher values. For the same reason, we take  $m_{\tilde{e}\pm}=300$  GeV and  $m_{\tilde{q}}=1$  TeV. We fix the other NMSSM parameters at:  $\lambda=0.3$ ,  $\mu=237$  GeV,  $\kappa=0.35$ ,  $A_\kappa=-30$  GeV,  $A_t = A_b = A_\tau = -2500$  GeV (trilinear soft parameters). We allow  $\tan\beta$  and  $M_A$  to vary accordingly to a scan performed for  $\tan\beta = 4 \rightarrow 14$ ,  $M_A = 250 \rightarrow 300$  GeV.  $M_A$  represents the pseudoscalar mass in the MSSM but it is an effective parameter in the NMSSM. It is somewhat equivalent to the second (pseudo)scalar masses in the NMSSM and to the charged Higgs mass which are almost degenerated in this model:  $M_A \simeq m_{h_2^0}, m_{a_2^0}, m_{H^\pm}$ . It is related to the other ones via the minimization equations. In the Fortran code NMHDECAY, we can choose between  $M_A$  or  $A_\lambda$  as input parameters. This scan is performed through the NMHDECAY code so that the generic NMSSM constraints mentioned above are satisfied for the selected parameters.

As a first step, we present in Fig.(7) the output masses  $m_{\tilde{\chi}_1^0}$ ,  $m_{\tilde{\nu}_1}$ ,  $m_{h_1^0}$  and  $m_{a_1^0}$ , obtained via this scan, as functions of  $\tan\beta$ .

Among the possible points of Fig.(7), we choose the one corresponding to  $\tan\beta=8$  and  $M_A=275$  GeV leading to  $m_{\tilde{\chi}_1^0}=219.5$  GeV,  $m_{\tilde{\nu}}=293.5$  GeV,  $m_{h_1^0}=116.7$  GeV,  $m_{h_2^0}=259.9$  GeV,  $m_{h_3^0}=548.8$  GeV,  $m_{a_1^0}=25.3$  GeV,  $m_{a_2^0}=303.5$  GeV and  $m_{H^\pm}=265.5$  GeV. The gravitino mass is fixed at  $m_{3/2}=200$  GeV so that  $\tilde{G}$  is well the LSP. Then the channels  $\tilde{G} \rightarrow h_k^0\nu^m$ ,  $\tilde{G} \rightarrow a_k^0\nu^m$  [with  $k \geq 2$ ] and  $\Gamma(\tilde{G} \rightarrow H^\pm\ell^\mp)$  are kinematically closed but all the other ones are open.

Now, in the one lepton flavor approximation we choose the RPV parameter values  $\Lambda_1/\langle s \rangle = 2 \cdot 10^{-6}$  and  $\mu_1 = 10^{-5}$  GeV leading to  $m_{\nu_1}^2 = 1.04 \cdot 10^{-22}$  GeV<sup>2</sup> which is reasonable from the point of view of experimental neutrino data.

Finally, for the chosen NMSSM parameters and RPV couplings, the induced RPV neutrino-neutralino mixings give rise to the partial widths  $\Gamma(\tilde{G} \rightarrow \gamma\nu^m) = 1.95 \cdot 10^{-47}$  GeV,  $\Gamma(\tilde{G} \rightarrow Z^0\nu^m) = 8.80 \cdot 10^{-47}$  GeV,  $\Gamma(\tilde{G} \rightarrow W^+\ell^-) = 1.94 \cdot 10^{-46}$  GeV,  $\Gamma(\tilde{G} \rightarrow h_1^0\nu^m) = 9.47 \cdot 10^{-45}$  GeV and  $\Gamma(\tilde{G} \rightarrow a_1^0\nu^m) = 2.08 \cdot 10^{-46}$  GeV. It is important to note that the relative smallness of  $\Gamma(\tilde{G} \rightarrow \gamma\nu^m)$  reflects in particular

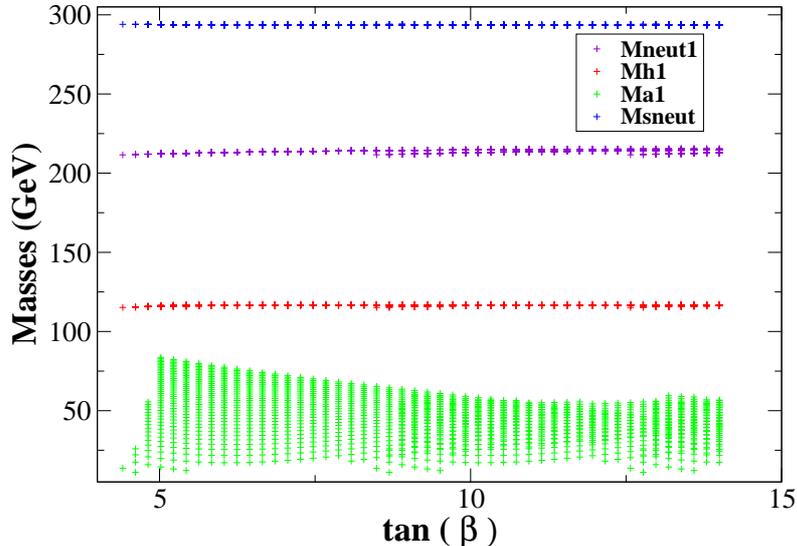


Figure 7: Masses  $m_{\tilde{\chi}_1^0}$  [purple points],  $m_{\tilde{\nu}}$  (universal) [blue points],  $m_{h_1^0}$  [red points] and  $m_{a_1^0}$  [green points] as functions of  $\tan\beta$ . We use:  $\lambda=0.3$ ,  $\kappa=0.35$ ,  $\mu=237$  GeV,  $M_1=300$  GeV,  $M_2=600$  GeV,  $M_3=2$  TeV,  $A_\kappa=-30$  GeV,  $A_t = A_b = A_\tau=-2500$  GeV,  $m_{\tilde{\ell}^\pm}=300$  GeV (universal),  $m_{\tilde{q}}=1$  TeV. The points are obtained from a scan performed on the two parameters  $\tan\beta = 4 \rightarrow 14$  and  $M_A = 250 \rightarrow 300$  GeV, using the NMHDECAY code [16]. The chosen RPV parameters are:  $\Lambda_1/\langle s \rangle = 2 \cdot 10^{-6}$  and  $\mu_1 = 10^{-5}$  GeV.

the smallness of the photino component for the neutrino mass eigenstate. The corresponding total gravitino width is  $\Gamma_{\text{total}}(\tilde{G}) = 2.00 \cdot 10^{-44}$  GeV giving rise to a gravitino lifetime  $\tau_{\tilde{G}} \simeq 76.3 t_0$ . This result illustrates the feature that within the NMSSM, and for RPV couplings that generate the correct neutrino mass scale, a gravitino LSP is stable (with respect to  $t_0$ ) even for a gravitino mass up to 200 GeV typically in agreement with supergravity (or mixed with GMSB) scenarios.

Indeed, more generally speaking  $\Gamma_{\text{total}}(\tilde{G})$  remains of the same order of magnitude as for the above NMSSM parameters, if  $m_\nu \sim 10^{-11}$  GeV (as imposed by data) and  $m_{\tilde{\chi}_1^0} \sim m_{3/2} \sim 10^2$  GeV (as natural in supergravity-like models). The reason, taking e.g.  $\Gamma(\tilde{G} \rightarrow \gamma\nu^m)$ , is that the orders of  $m_\nu$  and  $m_{\tilde{\chi}_1^0}$  fix the order of  $U_{\nu m \tilde{\gamma}}$  (see Eq.(6) in Ref. [5]) and in turn the partial gravitino decay width (*c.f.* Eq.(16)) once  $m_{3/2}$  is chosen. Furthermore one expects  $U_{\nu m \tilde{Z}} \simeq U_{\ell \tilde{W}} \simeq U_{\nu m \tilde{\gamma}}$  in Eq.(17)-(18) [24]. Similarly, the partial decay widths into the (lightest) neutral Higgs bosons are fixed by  $m_{h_1^0}$ ,  $m_{a_1^0}$ ,  $m_{3/2}$  as well as the amount of neutrino components in the higgsino and singlino (*c.f.* Fig.(6)) [and thus by  $m_\nu$  and  $m_{\tilde{\chi}_1^0}$ ]. If kinematically open, the decays into the  $h_2^0/a_2^0$  Higgs bosons have rates of similar order (for identical parameters). For a  $a_1^0$  boson heavier than in the above set of parameters,  $\Gamma(\tilde{G} \rightarrow a_1^0 \nu^m)$  decreases but the total width remains around  $\sim 10^{-44}$  GeV. Finally, if allowed, the

channel  $\tilde{G} \rightarrow H^+\ell^-$  is expected to reach a width of the same order as  $\tilde{G} \rightarrow h_1^0\nu^m$  and hence would not significantly modify  $\Gamma_{\text{total}}(\tilde{G})$ .

It has been recently [49] pointed out that the widths for  $\tilde{G} \rightarrow \ell^\pm W^{\mp*} \rightarrow \ell^\pm f \bar{f}'$  and  $\tilde{G} \rightarrow \nu^m Z^* \rightarrow \nu^m f \bar{f}$  together can reach  $10^2 \times \Gamma(\tilde{G} \rightarrow \gamma\nu^m)$  restricting oneself around parameter domains where  $m_{\tilde{\chi}_1^0} \sim m_{3/2} \sim 10^2$  GeV<sup>6</sup>. It means that the new three-body decay widths can reach  $\sim 10^{-45}$  GeV, from our present results, and this does not modify  $\Gamma_{\text{total}}(\tilde{G})$  significantly.

### V.2.2 Scenario II: a few decay channels open

To be more general than in the approach of Section V.2.1, we consider here the case where the gravitino is the LSP and is lighter than the W boson as well as the (pseudo)scalar Higgs fields [rather than considering some given points of the parameter space]. Then the RPV channel through the process  $\tilde{G} \rightarrow \gamma\nu_i^m$  remains open. Imposing the width  $\Gamma(\tilde{G} \rightarrow \gamma\nu_i^m)$  to be smaller than the critical value of  $1.52 \cdot 10^{-42}$  GeV leads to the upper bound on the gravitino mass  $m_{3/2} \lesssim 3$  TeV for  $|U_{\tilde{\gamma}\nu}| \sim 10^{-7}$  (see Eq.(16)) as imposed by the neutrino mass scale if  $m_{\tilde{\chi}_1^0} \lesssim 10^2$  GeV. For example, let us consider a given point of parameter space for which such a neutralino mass is realized. We take randomly the point of Fig.(4) with  $\kappa=0.1$ . Then,  $m_{\tilde{\chi}_1^0}=67.8$  GeV,  $m_{\tilde{\nu}}=193.9$  GeV (universal),  $m_{h_1^0}=128.7$  GeV and  $m_{a_1^0}=83.2$  GeV [insuring also that the gravitino decays into the (pseudo)scalar Higgs fields are forbidden]. For this point, one gets  $U_{\nu_i^m\tilde{\gamma}} = 1.94 \cdot 10^{-7}$  with  $\Lambda_1/\langle s \rangle = 9 \cdot 10^{-7}$  and  $\mu_1 = 6 \cdot 10^{-6}$  GeV which reproduce the correct neutrino mass scale ( $m_{\nu_1}^2 = 5.73 \cdot 10^{-22}$  GeV<sup>2</sup>). The exact bound resulting from the gravitino lifetime in this precise case is  $m_{3/2} < 2.7$  TeV. Taking into account the other allowed channels,  $\tilde{G} \rightarrow \ell^\pm f \bar{f}'$  and  $\tilde{G} \rightarrow \nu^m f \bar{f}$  [ $f \equiv$  fermions] (see Ref. [49]), this bound changes to  $m_{3/2} \lesssim 650$  GeV – 3 TeV as long as  $m_{\tilde{\chi}_1^0} \sim 10^2$  GeV. Since we are in a situation where  $m_{3/2} < m_W$ , this bound is respected. From the general point of view, we conclude that the NMSSM with phenomenologically interesting RPV couplings implies a gravitino LSP which is systematically stable (with respect to  $t_0$ ) if one takes its mass to be smaller than  $m_W$ ,  $m_{h_1^0}$  and  $m_{a_1^0}$ .

This quite general conclusion applies to supergravity (or mixed with GMSB) scenarios where  $m_{3/2} \sim 50$  GeV is realistic, as well as to pure GMSB scenarios in which possibly  $m_{3/2} \sim 1$  eV. Indeed, within the GMSB framework, the new form of the neutralino mass matrix (see Section II.3) leads to values of  $U_{\nu_i^m\tilde{\gamma}}$  extremely close to the above case [and hence to same bounds on  $m_{3/2}$ ] for the realistic neutrino mass scale, if one chooses e.g. the typical characteristic value  $\mu' = 100$  GeV. Note that in GMSB, the gravitino is clearly automatically lighter than  $W$ ,  $h_1^0$  and  $a_1^0$ . Note also that the channel  $\tilde{G} \rightarrow \gamma\nu_1^m$  is systematically open (in the realistic 3 flavor case) since within our neutrino scenario  $m_{\nu_1} = 0$  at the tree level.

### V.2.3 Scenario II extended to 3 neutrino flavors

There exist sets of NMSSM parameters [passing the NMHDECAY constraints] and RPV couplings which reproduce the squared neutrino mass eigenvalue differences measured in oscillation experiments. More precisely, the updated three-flavor analyzes based on a global fit including results from solar, atmospheric, reactor and accelerator oscillation experiments lead to (at the  $3\sigma$  level):  $7.1 \leq \Delta m_{21}^2 \leq 8.3$  [ $10^{-5}\text{eV}^2$ ] and  $2.0 \leq \Delta m_{31}^2 \leq 2.8$  [ $10^{-3}\text{eV}^2$ ] [13]. In our notations e.g.  $\Delta m_{31}^2 = |m_{\nu_3}^2 - m_{\nu_1}^2|$ . Values

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<sup>6</sup>This ratio result is not expected to be significantly changed when extending the MSSM to the NMSSM.

lying in those two intervals arise for instance for the point of Fig.(4) if  $\kappa=0.1$  and <sup>7</sup>

$$\begin{aligned} \mu_1 &= 3 \cdot 10^{-5} \text{ GeV}, \quad \mu_2 = 1.5 \cdot 10^{-4} \text{ GeV}, \quad \mu_3 = 2.5 \cdot 10^{-4} \text{ GeV} \\ \Lambda_1/\langle s \rangle &= 8.5 \cdot 10^{-7}, \quad \Lambda_2/\langle s \rangle = 1 \cdot 10^{-7}, \quad \Lambda_3/\langle s \rangle = 1.5 \cdot 10^{-7}. \end{aligned} \quad (22)$$

Indeed, this complete set of parameters yields the following three neutrino mass eigenvalues at tree level:

$$m_{\nu_1} = 0 \text{ eV}, \quad m_{\nu_2} = 0.00867 \text{ eV}, \quad m_{\nu_3} = 0.04670 \text{ eV} \quad (23)$$

in agreement with the above experimental intervals for  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  since in the present RPV model one has  $\Delta m_{21}^2 = m_{\nu_2}^2 = 7.51 \cdot 10^{-5} \text{ eV}^2$  and  $\Delta m_{31}^2 = m_{\nu_3}^2 = 2.18 \cdot 10^{-3} \text{ eV}^2$ .

From the cosmological point of view, the neutrino mass eigenvalues in (23) satisfy the bound extracted from WMAP and 2dFGRS galaxy survey (depending on cosmological priors):  $\sum_{i=1}^3 m_{\nu_i} \lesssim 0.7 \text{ eV}$  [50].

Finally, the above neutrino mass eigenvalues are perfectly compatible with the limits extracted from the tritium beta decay experiments (95% C.L.):  $m_\beta \leq 2.2 \text{ eV}$  [Mainz] and  $m_\beta \leq 2.5 \text{ eV}$  [Troitsk], this effective mass being defined as  $m_\beta^2 = \sum_{i=1}^3 |U_{ei}|^2 m_{\nu_i}^2$  where  $U_{ei}$  is the leptonic mixing matrix [51].

The point of parameter space considered in this section is the same as the one considered in the previous section (i.e. Section V.2.2), namely: the point of Fig.(4) with  $\kappa=0.1$ , and we still assume a situation where the gravitino LSP has a mass smaller than  $m_W$ ,  $m_{h_1^0}$  and  $m_{a_1^0}$  (scenario II). For this point, and with the RPV couplings of Eq.(22), we obtain for the gravitino decay channel into a photon:  $U_{\nu_1^m \tilde{\gamma}} = -4.74 \cdot 10^{-11}$ ,  $U_{\nu_2^m \tilde{\gamma}} = -6.61 \cdot 10^{-8}$  and  $U_{\nu_3^m \tilde{\gamma}} = 2.30 \cdot 10^{-7}$ , recalling the definition  $U_{\nu_i^m \tilde{\gamma}} = N_{i1} \cos\theta_W + N_{i2} \sin\theta_W$  where  $i = 1, 2, 3$  labels the neutrino mass eigenstate and 1 (2) corresponds to its  $\tilde{B}^0$  ( $\tilde{W}_3^0$ ) component. Those numbers imply the limit  $m_{3/2} < 2.5 \text{ TeV}$  resulting from the condition

$$2 \sum_i \Gamma(\tilde{G} \rightarrow \gamma \bar{\nu}_i^m) < 1.52 \cdot 10^{-42} \text{ GeV}.$$

The resulting bound  $m_{3/2} < 2.5 \text{ TeV}$  obtained here is close to the bound  $m_{3/2} < 2.7 \text{ TeV}$  of previous section, for the channel  $\tilde{G} \rightarrow \gamma \nu^m$ , which means that moving to the three flavor case should not affect significantly the conclusions. Therefore we conclude that, in the case of three neutrino flavors as well, a gravitino LSP is always sufficiently stable (with respect to  $t_0$ ) if its mass is weaker than  $m_W$ ,  $m_{h_1^0}$  and  $m_{a_1^0}$ .

This conclusion on the 3 neutrino flavor case is not trivial in the sense that, starting from the 1 flavor situation, the variation of the  $U_{\nu_1^m \tilde{\gamma}}$  value when extending to 3 neutrino flavors cannot be easily predicted due to the rich structure of the whole RPV neutralino mass matrix. Moreover, there is no simple argument to deduce the values of  $U_{\nu_2^m \tilde{\gamma}}$  and  $U_{\nu_3^m \tilde{\gamma}}$  from the  $U_{\nu_1^m \tilde{\gamma}}$  element (encoding the neutrino-gaugino mixing) because of the multiple mixing types between the different flavors of neutrinos and the various neutralino states.

Nevertheless, we have checked that, as expected, one obtains numerically the following hierarchy among the following matrix elements:  $|N_{1j}| < |N_{2j}| < |N_{3j}|$  [ $j = 1, 2$ ]. This is interpreted by the fact that here the neutrino eigenstate  $\nu_3^m$  is heavier than  $\nu_2^m$  (and in turn  $m_{\nu_2} > m_{\nu_1}$ ) since the massive neutral gaugino [ $\tilde{B}^0$ ,  $\tilde{W}_3^0$ ] components of  $\nu_3^m$  are larger than in the  $\nu_2^m$  state (in turn, than in  $\nu_1^m$ ).

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<sup>7</sup>Let us note that we have chosen the specific set (22) of RPV parameters to illustrate on an explicit example that the three flavor neutrino data can be reproduced. Nevertheless, the orders of magnitude in Eq.(22) of the six effective RPV parameters are general in the sense that those are imposed systematically by the experimental ranges for  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  as soon as  $m_{\tilde{\chi}_1^0} \sim 10^2 \text{ GeV}$  (as occurs in supergravity and GMSB models). Hence the conclusions at the end of this Section V.2.3, which are based on these orders of magnitude, can also be generalized to any region of the parameter space where  $m_{\tilde{\chi}_1^0} \sim 10^2 \text{ GeV}$ .

## VI Discussion and conclusions

In the context of the NMSSM with the presence of RPV couplings large enough to generate realistic neutrino masses, a gravitino LSP of mass  $\mathcal{O}(10^2)$  GeV – as appears in supergravity models – is sufficiently stable from the point of view of the age of the universe.

Nevertheless, the gravitino lifetime that we obtain is of order  $\sim 10^{19}$  sec. Now even in a supergravity situation with  $m_{3/2} \lesssim 80$  GeV, where the opened decay channels  $\tilde{G} \rightarrow \gamma\nu^m$ ,  $\tilde{G} \rightarrow \ell^\pm f \bar{f}'$  and  $\tilde{G} \rightarrow \nu^m f \bar{f}$  are thus reduced, the total width loses typically four orders of magnitude only. Hence, the HEAT excess in the positron fraction [7] and the exotic positron source apparently detected by PAMELA [20] (which both require, in standard solutions,  $m_{3/2} \sim 100 - 200$  GeV and  $\tau_{\tilde{G}} \sim 10^{26}$  sec) do not seem to be simultaneously explainable by the present RPV scenario reproducing the neutrino masses. The reason is that the neutrino-neutralino mixing necessary to create large enough neutrino masses seems to induce too large gravitino RPV decay widths.

Moreover, this result that the gravitino lifetime is systematically smaller than the lifetime needed to explain the PAMELA excess with a gravitino dark matter also means that, in our dark matter scenario, the gravitino decays produce always too large fluxes which are excluded by PAMELA in particular. Hence our conclusion is that a gravitino LSP cannot be a good dark matter candidate if there exist significant RPV mixing terms (reproducing the neutrino masses).

In the case of the existence of a special supergravity scenario – like e.g. some hybrid supergravity-GMSB models – where one could have  $m_{3/2}$  below  $\sim 10$  GeV (in order to sufficiently reduce  $\Gamma(\tilde{G} \rightarrow \gamma\nu^m)$ ) and  $M_1 \sim M_2 \sim 10^2$  GeV (suppressing the  $\Gamma(\tilde{G} \rightarrow \ell^\pm f \bar{f}', \nu^m f \bar{f})$  contribution [49]), the gravitino lifetime would then be above the PAMELA limit of  $\sim 10^{26}$  sec, making  $\tilde{G}$  a stable and viable dark matter candidate [with RPV couplings producing the neutrino masses].

Now if the supersymmetry breaking relies instead on a pure GMSB mechanism, the neutralino mass matrix includes new elements and the gravitino mass can decrease typically to eV scale. Then, the gravitino is clearly a stable LSP since we obtain a bound  $m_{3/2} \lesssim 650$  GeV – 3 TeV from the requirement that its lifetime exceeds the age of the universe, if the photino component of the neutrino [of value comparable to the above supergravity case] is sufficiently large to induce correct neutrino masses.

In this GMSB case, the gravitino lifetime is  $\sim 10^{56}$  sec. Hence the PAMELA data cannot be explained with a gravitino dark matter. However, the PAMELA flux excess can have e.g. alternative natural and astrophysical explanations, like in electron-positron pairs produced by nearby pulsars [52]<sup>8</sup>. By consequence, the GMSB framework could allow for the existence of a good gravitino dark matter candidate within the RPV-NMSSM.

Finally, we have checked numerically the robustness of the above conclusions on the gravitino stability when extending to the realistic case of three neutrino flavors. To illustrate this, we have selected some RPV-NMSSM parameter sets in agreement with the various constraints implemented in the NMHDECAY code and reproducing the squared neutrino mass eigenvalue differences measured in oscillation experiments.

Concerning the stability of a sneutrino LSP with respect to  $t_0$ , within RPV versions of the NMSSM reproducing the wanted neutrino mass scale, the result is negative. The lightest neutralino LSP is

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<sup>8</sup>We also note that, anyway, the mentioned interpretation [7] of the HEAT anomaly predicts an antiproton flux which tends to be too large, although the prediction suffers from significant uncertainties. Besides, electron and positron fluxes from gravitino decays (whatever are the gravitino characteristics) cannot explain [20] both the PAMELA positron fraction and the electron plus positron flux measured by Fermi LAT [53].

also not expected to be stable with respect to  $t_0$ .

Finally, we comment that all these difficulties one faces for having a viable dark matter candidate in RPV models are to be bridged with the astrophysical problems one encounters in baryogenesis when RPV interactions are indeed turned on to generate the neutrino masses [54].

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