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Gravitino Dark Matter with Broken R-parity

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Abstract. Scenarios with gravitino dark matter face potential cosmological problems induced by the presence of the Next-to-Lightest Supersymmetric Particle (NLSP) at the time of Big Bang Nucleosynthesis (BBN). A very simple, albeit radical, solution to avoid all these problems consists on assuming that R-parity is slightly violated, since in this case the NLSP decays well before the onset of BBN. Remarkably, even if the gravitino is no longer stable in this scenario, it still constitutes a very promising dark matter candidate. In this talk we review the motivations for this scenario and we present a model that naturally generates R-parity breaking parameters of the right size to produce a consistent thermal history of the Universe, while satisfying at the same time all the laboratory and cosmological bounds on R-parity breaking. We also discuss possible signatures of this scenario at gamma ray observatories and at colliders.

PACS. 95.35.+d Dark matter – 12.60.Jv Supersymmetric models

1 Motivation

The gravitino, when it is the lightest supersymmetric particle, constitutes a very promising candidate for the dark matter of the Universe. The interactions of the gravitino are completely fixed by the symmetries, and the thermal relic density is calculable in terms of very few parameters, the result being [1]

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2 , \quad (1)$$

while the relic density inferred by WMAP for the ΛCDM model is $\Omega_{3/2}h^2 \simeq 0.1$ [2]. In this formula, T_R is the reheating temperature of the Universe, $m_{3/2}$ is the gravitino mass and $m_{\tilde{g}}$ is the gluino mass. It is indeed remarkable that the correct relic density can be obtained for typical supersymmetric parameters, $m_{3/2} \sim 100\,\mathrm{GeV}$, $m_{\tilde{g}} \sim 1\,\mathrm{TeV}$, and a high reheating temperature, $T_R \sim 10^{10}\,\mathrm{GeV}$, as required by baryogenesis through the mechanism of thermal leptogenesis [3].

If thermal leptogenesis is the correct mechanism to generate the observed baryon asymmetry, then the NLSP can pose serious cosmological difficulties. If one assumes exact R-parity conservation, as is commonly done in the literature, then the NLSP can only decay into gravitinos and Standard Model particles with a decay rate strongly suppressed by the Planck mass, yielding a lifetime

$$\tau_{\mathrm{NLSP}} \simeq 9\ \mathrm{days} \left(\frac{m_{3/2}}{10\mathrm{GeV}}\right)^2 \left(\frac{150\mathrm{GeV}}{m_{\mathrm{NLSP}}}\right)^5 . \quad (2)$$

The high reheat temperature for the Universe required by thermal leptogenesis, $T_R \gtrsim 10^9$ GeV [4], and the requirement of correct relic abundance, Eq. (1), imply $m_{3/2} \gtrsim 5$ GeV for a gluino mass of $m_{\tilde{g}} = 500$GeV. Therefore, the lifetime of the NLSP is typically of several days and it is present at the time of BBN, potentially jeopardizing the successful predictions of the standard scenario. Indeed, this is the case for most supersymmetric scenarios with gravitino dark matter. Namely, when the NLSP is a neutralino, its late decays into hadrons can dissociate the primordial elements [5], and when the NLSP is a stau, its presence during BBN catalyzes the production of ^{6}Li, yielding a primordial abundance in stark conflict with observations [6].

One simple, albeit radical, solution to the problems induced by the NLSP is to assume that R-parity is not exactly conserved [7]. In fact, there is no deep theoretical reason why R-parity should be exactly conserved, and although present experiments indicate that R-parity is approximately conserved, a slight violation of it cannot be precluded. Without imposing any *ad hoc* discrete symmetry, the superpotential of the Minimal Supersymmetric Standard Model (MSSM) reads [8]

$$W = W_{Rp} + \frac{1}{2}\lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk}\, L_i Q_j d^c_k + \frac{1}{2}\lambda''_{ijk} u^c_i d^c_j d^c_k + \mu_i L_i H_u , \quad (3)$$

where W_{Rp} is the familiar superpotential with R-parity conserved.

When R-parity is broken, new decay channels are open for the NLSP, apart from the strongly suppressed gravitational decay into gravitinos and Standard Model particles. Namely, when the NLSP is mainly a right-handed stau, it can decay $\widetilde{\tau}_R \to \mu\,\nu_\tau$, through the

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coupling λ_{323}, with lifetime

$$\tau_{\tilde{\tau}} \simeq 10^3 \mathrm{s} \left(\frac{\lambda_{323}}{10^{-14}}\right)^{-2} \left(\frac{m_{\tilde{\tau}}}{100\ \mathrm{GeV}}\right)^{-1} . \qquad (4)$$

Thus, even with a tiny amount of R-parity violation, $\lambda \gtrsim 10^{-14}$, the stau NLSP will decay before it can have any significant impact on Big Bang Nucleosynthesis. A similar argument can be applied for the case of neutralino NLSP with analogous conclusions.

On the other hand, there are very stringent laboratory and cosmological constraints on the size of the R-parity breaking parameters. The strongest bound for the heaviest generation stems from the requirement of successful baryogenesis. Since λ, λ' and λ'' violate lepton and baryon number, if they are on thermal equilibrium at the same time as the sphaleron processes, a preexisting baryon asymmetry will be erased. Therefore, the requirement that these couplings are out of thermal equilibrium before the electroweak phase transition translates into the bound [9]

$$\lambda, \lambda', \lambda'' \lesssim 10^{-7} . \qquad (5)$$

This bound is a sufficient but not a necessary condition, and could be relaxed for some flavour structures.

Interestingly, if the size of the R-parity violating couplings is in this range, $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, the gravitino still constitutes a viable dark matter candidate [10]. The decay rate is doubly suppressed by the inverse Planck mass and by the R-parity breaking couplings, yielding a lifetime

$$\tau_{3/2} \sim 10^{26}\mathrm{s} \left(\frac{\lambda}{10^{-7}}\right)^{-2} \left(\frac{m_{3/2}}{10\ \mathrm{GeV}}\right)^{-3} , \qquad (6)$$

which is several orders of magnitude longer than the age of the Universe.

In the next sections we will present a model that can naturally accommodate our favoured range of R-parity breaking parameters, $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, and we will discuss the possible experimental signatures of this scenario, both at gamma ray observatories and at colliders.

2 A model for small (and peculiar) R-parity violation

We will use for convenience $SO(10)$ notation, although our model is not necessarily embedded into a Grand Unified group. Then, quarks and leptons will be denoted by $\mathbf{16_i}$ and the Higgses by $\mathbf{10}_H$. In order to give Majorana masses to neutrinos $B-L$ has to be broken, either by the vacuum expectation value of a $\overline{\mathbf{16}}$, $\mathbf{16}$ (with $B-L=\pm 1$) or of a $\mathbf{126}$ (with $B-L=2$). To have only particles with small representations we will break $B-L$ with a $\overline{\mathbf{16}}$ and a $\mathbf{16}$. Thus, R-parity will be necessarily violated after the spontaneous breaking of the $B-L$ symmetry at the scale v_{B-L}.

With this matter content there are two kind of terms in the superpotential allowed by the $SO(10)$ symmetry. The terms $\mathbf{16_i 16_j 10_H}$ and $\frac{1}{M_P}\mathbf{16_i 16_j}\overline{\mathbf{16}}\ \overline{\mathbf{16}}$ are "good terms", since they produce Dirac masses and a Majorana mass term for the right-handed neutrinos, respectively. On the contrary, the terms $\mathbf{16_i 16 10_H}$ and $\frac{1}{M_P}\mathbf{16_i 16_j 16_k 16}$ are "bad terms"; the first one produces after $B-L$ breaking the R-parity violating bilinear term $v_{B-L}LH_u$ that in turn produces too large neutrino masses, while the second one produces the R-parity violating trilinear terms $\frac{v_{B-L}}{M_P}u^c d^c d^c$, $\frac{v_{B-L}}{M_P}QLd^c$ that induce too rapid proton decay. It is interesting to note that both "bad terms" are generated when the $\mathbf{16}$ representation acquires a large vacuum expectation value. Since the existence of the $\mathbf{16}$ representation in the spectrum is unavoidable, the only way to suppress these couplings is by means of additional symmetries.

To this end, we will impose in our model a $U(1)_R$ symmetry and the following assignment of charges:

	$\mathbf{16}_i$	$\mathbf{10}_H$	$\overline{\mathbf{16}}$	$\mathbf{16}$	$\mathbf{1}$
R	1	0	0	-2	-1

where the singlet $\mathbf{1}$ has been introduced in order to break the R-symmetry. With this assignment of charges, holomorphicity guarantees that after $B-L$ breaking no R-parity violating term will be generated from the superpotential at any order in perturbation theory. Nevertheless, the Kähler potential is not holomorphic and could be a source of R-parity violation. Indeed, terms such as $\mathbf{1}\,\overline{\mathbf{16}}^\dagger \mathbf{16}_i \mathbf{10}_H$, $\mathbf{1}^\dagger \overline{\mathbf{16}}\,\mathbf{16}_i \mathbf{10}_H$ can appear in the Kähler potential, and will eventually produce bilinear R-parity violation.

With these elements in mind, it is relatively simple to construct a model that produces small lepton number violation and tiny baryon number violation. In Standard Model notation, the previous model is:

	Q, u^c, e^c d^c, L, ν^c	H_u, H_d	N	N^c	Φ	Z	X
$B-L$	$\pm 1/3, \pm 1$	0	1	-1	0	0	0
R	1	0	0	-2	-1	0	4

where the spectator fields Φ, Z and X have been introduced in order to break $B-L$ (and R-parity), to break supersymmetry, and to ensure that $\langle N \rangle = \langle N^c \rangle = v_{B-L}$, respectively. After these singlets acquire a vacuum expectation value, the effective superpotential reads $W \simeq W_{R_p} + W_{\nu^c} + W_{\not{R}_p}$. Here, W_{R_p} is the R-parity conserving superpotential of the MSSM and W_{ν^c} is the part of the superpotential involving right-handed neutrinos. In this model the heaviest right-handed neutrino mass is given by $M_3 \sim v_{B-L}^2/M_P$, which is naturally large, leading through the see-saw mechanism to small neutrino masses. Finally, $W_{\not{R}_p}$ is the R-parity breaking superpotential given in Eq.(3). We will choose to work in the $L_i - H_d$ basis where $\mu_i = 0$ and thus all the R-parity violation is encoded in the trilinear terms. In this basis,

$$\lambda \sim C\frac{v_{B-L}^2}{M_P^2}h^e\ ,\ \lambda' \sim C\frac{v_{B-L}^2}{M_P^2}h^d\ ,\ \lambda'' \sim m_{3/2}\frac{v_{B-L}^4}{M_P^5} . \qquad (7)$$

The lepton number violating couplings are suppressed compared to the charged lepton and down-type quark Yukawa couplings, h^e and h^d respectively, by v_{B-L}^2/M_P^2 and by some coefficients $C = 1.0...0.01$ that depend on the flavour structure of the Kähler potential. On the other hand, the baryon number violating coupling only arises after supersymmetry breaking and is suppressed by higher powers of the Planck mass. To estimate the scale of $B-L$ breaking and the size of the coefficients C, we will use the flavour model proposed in [11]. For this particular model, we obtain $\lambda_{3ij}, \lambda'_{3ij} \sim 10^{-8}$, within the desired range $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, and $\lambda'' \sim 10^{-28}$, yielding negligible rates for proton decay [7].

3 Signatures at gamma-ray observatories

When R-parity is broken, gravitino decays could be happening at fast enough rates to make its decay products detectable in future experiments. In particular, the photon flux produced by the gravitino decay could be detected as an extragalactic diffuse gamma-ray flux with a characteristic spectrum, that is originated from the decay of gravitinos at cosmological distances and from the decay of gravitinos in the Milky Way halo.

In the case that the gravitino is lighter than the W boson, the gravitino decays mainly into a photon and a neutrino, producing a photon spectrum consisting in a monochromatic line. If gravitinos constitute the dominant component of dark matter, the decay of gravitinos at cosmological distances will be detected at the Earth as a perfectly isotropic diffuse gamma ray background, with an energy spectrum corresponding to a red-shifted monochromatic line:

$$E^2 \frac{dJ_{eg}}{dE} = C_\gamma \left[1 + \frac{\Omega_\Lambda}{\Omega_M} y^3\right]^{-1/2} y^{5/2}\, \theta(1-y) \ , \quad (8)$$

where $y = 2E/m_{3/2}$ and

$$C_\gamma = \frac{\Omega_{3/2}\rho_c}{8\pi\tau_{3/2} H_0 \Omega_M^{1/2}} = \frac{10^{-6}\ \text{GeV}}{\text{cm}^2\ \text{str}\ \text{s}} \left(\frac{\tau_{3/2}}{10^{27}\ \text{s}}\right)^{-1} \ . \quad (9)$$

Here, $\Omega_{3/2}h^2 = 0.1$, $\rho_c = 1.05\ h^2 \times 10^{-5}\text{GeVcm}^{-3}$, $\Omega_M = 0.25$, $H_0 = h\ 100\ \text{km s}^{-1}\ \text{Mpc}^{-1}$ with $h = 0.73$ [12] and $\tau_{3/2}$ is given by Eq. (6).

In addition to the contribution to the photon flux from the decay of gravitinos at cosmological distances, one also expects a monochromatic line stemming from the decay of gravitinos in the Milky Way halo. This contribution reads:

$$E^2 \frac{dJ_{halo}}{dE} = D_\gamma\, \delta\left(1 - \frac{2E}{m_{3/2}}\right) \ , \quad (10)$$

where

$$D_\gamma = \frac{1}{8\pi\tau_{3/2}} \int_{l.o.s.} \rho_{halo}(l) dl \ . \quad (11)$$

Since the Earth is not located at the center of the Galaxy, the gamma-ray flux from the decay of gravitinos in the halo is slightly anisotropic. For typical halo models, we find that the halo component dominates over the cosmological one, giving rise to a slightly anisotropic gamma ray flux with an energy spectrum dominated by a monochromatic line.

There are very stringent limits on the photon flux produced by decaying dark matter from the observations of the Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory. Assuming that one understands the galactic foreground, one can extract from the EGRET data the extragalactic diffuse component. The first analysis by Sreekumar *et al.* [13] gave a roughly isotropic extragalactic flux with an energy spectrum described by the power law

$$E^2 \frac{dJ}{dE} = 1.37 \times 10^{-6} \left(\frac{E}{1\ \text{GeV}}\right)^{-0.1} \frac{\text{GeV}}{\text{cm}^2\ \text{str}\ \text{s}} \quad (12)$$

in the energy range 50 MeV–10 GeV. The improved analysis of the galactic foreground by Strong *et al.* [14], optimized in order to reproduce the galactic emission, shows a power law behavior between 50 MeV–2 GeV, but a clear excess between 2–10 GeV, roughly the same energy range where one would expect a signal from gravitino decay. In view of all the systematic uncertainties involved in the extraction of the signal from the galactic foreground, we find it premature to attribute this excess to the gravitino decay. We find nevertheless this coincidence as interesting and deserving further attention. The upcoming satellite-based gamma ray experiments GLAST and AMS-02 will measure the energy spectrum with unprecedented accuracy, providing very valuable information for the scenario of decaying gravitino dark matter.

We show in Fig.1 the expected signal for a decaying gravitino with a mass of 10 GeV and a lifetime of 10^{27} s [15]. To compare our results with the EGRET data [14], also shown in the figure, we have averaged the halo signal over the whole sky excluding a band of $\pm 10^\circ$ around the Galactic disk, and we have used an energy resolution of 15%, as quoted by the EGRET collaboration in this energy range. The photon spectrum is dominated by the sharp line coming from our local halo, while the red-shifted extragalactic component is somewhat fainter.

If the gravitino is heavier than the W or Z bosons, new decay channels are open. In this case, the energy spectrum consists of a continuous component, stemming from the fragmentation of the gauge bosons, and a relatively intense gamma ray line [16].

4 Signatures at colliders

In the scenario proposed in this work, the lifetime of the NLSP is around one nanosecond or longer, giving rise to very distinctive signatures at colliders. When the NLSP is the lightest stau, that we assume mainly right-handed, the main decay channel is $\widetilde{\tau}_R \to \tau\ \nu_\mu, \mu\ \nu_\tau$. The corresponding decay length is

$$c\tau_{\tilde{\tau}}^{lep} \sim 30\ \text{cm} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2} \ . \quad (13)$$

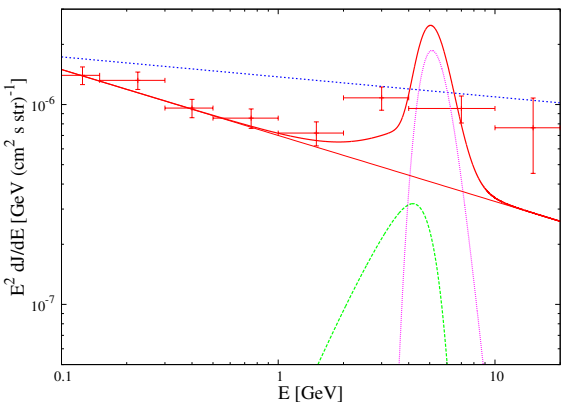

Fig. 1. Energy spectrum of extragalactic (long-dashed green) and halo signal (dotted magenta) compared to the EGRET data, for $\tau_{3/2} = 10^{27}$ s and $m_{3/2} = 10$ GeV. The data points are the EGRET extragalactic background extracted by Strong *et al.* in [14], while the short-dashed (blue) line shows the powerlaw fit from Sreekumar *et al.*, Eq. (12). Finally, the solid (thick red) line shows the sum of these contributions with a powerlaw background (thin red line), which has been obtained fitting the low energy EGRET points.

Besides, the small left-handed component of the stau mass eigenstate can trigger a decay into jets through $\widetilde{\tau}_L \to b^c t$, provided the process is kinematically open. The hadronic decays are enhanced compared to the leptonic decays by the larger bottom Yukawa coupling and by the colour factor, but are usually suppressed by the small left-right mixing. The decay length in this channel reads

$$c\tau_{\widetilde{\tau}}^{had} \sim 8 \text{ m} \left(\frac{m_{\widetilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2} \left(\frac{\cos\theta_\tau}{0.1}\right)^{-2}, \tag{14}$$

where θ_τ is the mixing angle of the staus. Therefore, if the decay occurs inside the detector, the signature would consist on a heavily ionizing charged track followed by a muon track, by one jet or by three jets.

On the other hand, when the NLSP is the lightest neutralino, it decays through $\chi_1^0 \to \tau^\pm W^\mp$ if this decay channel is kinematically accessible [17]. The corresponding decay length can be approximated by

$$c\tau_{\chi_1^0} \sim 1 \text{ m} \left(\frac{m_{\chi_1^0}}{200 \text{ GeV}}\right)^{-3} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2}, \tag{15}$$

producing a significantly displaced vertex followed by jets, that could be observed provided the decay occurs inside the detector. If this decay channel is kinematically closed, the neutralino typically decays outside the detector yielding identical collider signatures to the case with R-parity conserved.

5 Conclusions

We have argued that a supersymmetric scenario with gravitino LSP with a mass in the range 5–100 GeV and a small amount of R-parity violation, $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, yields a consistent thermal history of the Universe, in the sense that it allows baryogenesis through thermal leptogenesis, provides a viable candidate for cold dark matter, and does not spoil the successful predictions of the Standard Big Bang Nucleosynthesis scenario.

We have presented a model that links R-parity breaking to $B - L$ breaking, and generates R-parity breaking parameters in the right range to accommodate the abovementioned scenario. The relic gravitino decays into photons produce a diffuse halo and extragalactic gamma ray flux, that might have been observed already by EGRET. Future experiments, such as GLAST or AMS-02 will provide unique opportunities to test the scenario of decaying gravitino dark matter. Finally, we have discussed the striking signatures that this scenario might produce at future colliders, consisting in a vertex of the NLSP significantly displaced from the beam axis.

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