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Gamma Ray Spectrum from Gravitino Dark Matter Decay

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Gravitinos are very promising candidates for the cold dark matter of the Universe. Interestingly, to achieve a sufficiently long gravitino lifetime, R-parity conservation is not required, thus preventing any dangerous cosmological influence of the next-to-lightest supersymmetric particle. When R-parity is violated, gravitinos decay into photons and other particles with a lifetime much longer than the age of the Universe, producing a diffuse gamma ray flux with a characteristic spectrum that could be measured in future experiments, like GLAST, AMS-02 or Cherenkov telescopes. In this letter we compute the energy spectrum of photons from gravitino decay and discuss its main qualitative features.

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There is mounting evidence that dark matter is ubiquitous in our Universe [1]. Since the necessity of dark matter was realized, many different particle physics candidates have been proposed. Among the most interesting candidates stands the gravitino [2], the supersymmetric counterpart of the graviton, which arises when global supersymmetry is promoted to a local symmetry. If the gravitino is the lightest supersymmetric particle, it constitutes an excellent candidate for the cold 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 [3]

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

while the relic density inferred by WMAP for the ΛCDM model is $\Omega_{\rm CDM}h^2 = 0.1277^{+0.0080}_{-0.0079}$ [4]. 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 [5].

Whereas the gravitino as the lightest supersymmetric particle leads to a cosmology consistent with observations, the cosmology of the Next-to-Lightest Supersymmetric Particle (NLSP) is much more problematic. In supersymmetric model building, in order to prevent too rapid proton decay, it is common to invoke a discrete symmetry called R-parity. When R-parity is exactly conserved, the NLSP can only decay into gravitinos and Standard Model particles with a decay rate strongly suppressed by the Planck mass. As a result, the NLSP is typically present in the Universe at the time of Big Bang nucleosynthesis, jeopardizing the successful predictions of the standard nucleosynthesis scenario. In most supersymmetric scenarios, the NLSP is either a neutralino or a stau. On one hand, if the NLSP is a neutralino, its late decay into hadrons can dissociate the primordial elements [6]. On the other hand, if the NLSP is a stau, it can form a bound state with ^{4}He, catalyzing the production of ^{6}Li [7]. As a result, the abundance of ^{6}Li is increased by a factor 300–600, in stark conflict with observations [8].

Several scenarios have been proposed that circumvent the above-mentioned difficulties [9]. The simplest, albeit the most radical one, is based on the assumption that R-parity is not exactly conserved [10]. In fact, although experiments set very stringent bounds on R-parity violation, there is no deep theoretical reason why it should be exactly conserved. If R-parity is mildly violated, the NLSP decays into Standard Model particles well before the first nucleosynthesis reactions take place, thus not posing a jeopardy for the Standard Model predictions. Remarkably, even though the gravitino is no longer stable when R-parity is violated, it still constitutes a viable dark matter candidate [11]. The reason is that the gravitino decay rate is doubly suppressed by the Planck mass and by the smallness of the R-parity violation, which translates into lifetimes much longer than the age of the Universe. Nevertheless, gravitino decays could be happening at a sufficiently high rate for the decay products to be detectable in future experiments.

In this letter we will concentrate on the photons produced in gravitino decays, although in general other stable particles are also produced, such as electrons, protons, neutrinos and their antiparticles. Demanding a high reheating temperature for the Universe as suggested by thermal leptogenesis, $T_R \gtrsim 10^9$ GeV [12], it follows from Eq. (1) that the gravitino mass has to be $m_{3/2} \gtrsim 5$ GeV for a gluino mass $m_{\tilde{g}} \simeq 500$ GeV. Consequently, we expect the photons from gravitino dark matter decay in the energy range of a few GeV, *i.e.* in the gamma ray energy range.

The Energetic Gamma Ray Experiment Telescope (EGRET) aboard the Compton Gamma Ray Observatory measured gamma rays in the energy range between 30 MeV to 100 GeV. After subtracting the galac-

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tic foreground emission, the residual flux was found to be roughly isotropic and thus attributed to extragalactic sources. The first analysis of the EGRET data by Sreekumar *et al.* [13] gave an extragalactic flux with an energy spectrum described by the power law

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

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. Although it is very tempting to look for explanations for this excess in terms of gravitino decays, in view of all the systematic uncertainties involved in the extraction of the signal from the galactic foreground, we will not attempt to fit our predicted flux to the EGRET data. Nonetheless, we will show later the EGRET data superimposed with our predicted flux for comparison.

The total gamma ray flux received from gravitino dark matter decay receives two main contributions. The first one stems from the decay of gravitinos at cosmological distances, giving rise to a perfectly isotropic extragalactic diffuse gamma ray background. Defining dN_γ/dE as the gamma ray spectrum produced in the gravitino decay, the flux received at the Earth with extragalactic origin has the following expression:

$$\left[E^2 \frac{dJ}{dE} \right]_{\mathrm{eg}} = \frac{2E^2}{m_{3/2}} C_\gamma \int_1^\infty dy \frac{dN_\gamma}{d(Ey)} \frac{y^{-3/2}}{\sqrt{1+\Omega_\Lambda/\Omega_M y^{-3}}} , \quad (3)$$

where $y = 1 + z$, z being the redshift, and

$$C_\gamma = \frac{\Omega_{3/2}\rho_c}{8\pi\tau_{3/2} H_0 \Omega_M^{1/2}} \simeq 10^{-7}\ (\mathrm{cm}^2 \mathrm{s\ str})^{-1} \left(\frac{\tau_{3/2}}{10^{28}\ \mathrm{s}} \right)^{-1} . \quad (4)$$

Here, $\Omega_{3/2}$, Ω_M and Ω_Λ are the gravitino, matter and cosmological constant density parameters, respectively, ρ_c is the critical density, $\tau_{3/2}$ the gravitino lifetime, and H_0 the present value of the Hubble parameter.

In addition to the cosmological contribution, the total gamma ray flux also receives a contribution from the decay of gravitinos in the Milky Way halo. This contribution reads:

$$\left[E^2 \frac{dJ}{dE} \right]_{\mathrm{halo}} = \frac{2E^2}{m_{3/2}} D_\gamma \frac{dN_\gamma}{dE} , \quad (5)$$

where D_γ is defined as

$$D_\gamma = \frac{1}{8\pi\tau_{3/2}} \int_{\mathrm{los}} \rho_{\mathrm{halo}}(\vec{l}) d\vec{l}. \quad (6)$$

The integration extends over the line of sight, so D_γ has an angular dependence on the direction of observation, yielding a slightly anisotropic gamma ray flux that could resemble an isotropic extragalactic flux (for a more detailed discussion, see [15]). In this expression ρ_{halo} stands for the dark matter distribution in the Milky Way halo. For our numerical analysis we will adopt a Navarro-Frenk-White density profile [16]

$$\rho_{\mathrm{halo}}(r) \simeq \frac{\rho_h}{r/r_c(1+r/r_c)^2} , \quad (7)$$

where r is the distance to the Galactic center, $r_c \simeq 20\,\mathrm{kpc}$ is the critical radius and $\rho_h \simeq 0.33\,\mathrm{GeV\,cm}^{-3}$.

In Eqs. (3,5) the only undetermined quantity is the energy spectrum of photons produced in the gravitino decay, dN_γ/dE, which depends crucially on the gravitino mass. If the gravitino is lighter than the $W^\pm$ bosons, it decays mainly into a photon and a neutrino by means of the photino-neutrino mixing that arises when R-parity is violated [11]. Therefore, the spectrum is simply

$$\frac{dN_\gamma}{dE} \simeq \delta \left(E - \frac{m_{3/2}}{2} \right) . \quad (8)$$

For this case, it was found in [10, 15] that the total gamma ray flux received is dominated by the monochromatic line coming from the decay of gravitinos in our Milky Way halo, while the redshifted line from the decay of gravitinos at cosmological distances is somewhat fainter.

On the other hand, if the gravitino is heavier than the $W^\pm$ or Z^0 bosons, new decay modes are open. In addition to the decay mode into a photon and a neutrino that follows from the photino-neutrino mixing, $U_{\tilde{\gamma}\nu}$, the gravitino can also decay into a $W^\pm$ boson and a charged lepton, through the mixing charged wino-charged lepton, $U_{\tilde{W}\ell}$, or into a Z^0 boson and a neutrino, through the mixing zino-neutrino, $U_{\tilde{Z}\nu}$.The decay rates can be straightforwardly computed from the interaction Lagrangian of a gravitino with a gauge boson and a fermion [17]. The result for each decay mode reads:

$$\Gamma(\psi_{3/2} \to \gamma\nu) \simeq \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_P^2} ,$$
$$\Gamma(\psi_{3/2} \to W^\pm \ell^\mp) \simeq \frac{1}{16\pi} |U_{\tilde{W}\ell}|^2 \frac{m_{3/2}^3}{M_P^2} f\left(\frac{M_W}{m_{3/2}} \right) ,$$
$$\Gamma(\psi_{3/2} \to Z^0 \nu) \simeq \frac{1}{32\pi} |U_{\tilde{Z}\nu}|^2 \frac{m_{3/2}^3}{M_P^2} f\left(\frac{M_Z}{m_{3/2}} \right) , \quad (9)$$

where

$$f(x) = 1 - \frac{4}{3}x^2 + \frac{1}{3}x^8 . \quad (10)$$

The fragmentation of the $W^\pm$ and the Z^0 gauge bosons will eventually produce photons, mainly from the decay of neutral pions. We have simulated the fragmentation of the gauge bosons with the event generator PYTHIA 6.4 [18] and calculated the spectra of photons in the $W^\pm$ and Z^0 channels, which we denote by dN_γ^W/dE and

dN_γ^Z/dE, respectively. The total spectrum is therefore given by:

$$\frac{dN_\gamma}{dE} \simeq \mathrm{BR}(\psi_{3/2} \to \gamma\nu)\delta\left(E - \frac{m_{3/2}}{2}\right) + \mathrm{BR}(\psi_{3/2} \to W\ell)\frac{dN_\gamma^W}{dE} + \mathrm{BR}(\psi_{3/2} \to Z^0\nu)\frac{dN_\gamma^Z}{dE}\,. \quad (11)$$

The branching ratios in the different decay channels are determined by the size of the R-parity breaking mixing parameters, $U_{\tilde\gamma\nu}$, $U_{\widetilde{Z}\nu}$ and $U_{\widetilde{W}\ell}$, and by the kinematical function $f(x)$ defined in Eq. (10). The mixing parameters stem from the diagonalization of the 7×7 neutralino-neutrino and 5×5 chargino-charged lepton mass matrices, whose explicit form can be found in the vast existing literature on R-parity violation [19]. The precise expression for the mixing parameters in terms of the R-parity breaking couplings in the Lagrangian is fairly cumbersome and will not be reproduced here. However, to derive the branching ratios, only the ratio among them is relevant, and not their overall value.

To derive the relation between $U_{\tilde\gamma\nu}$ and $U_{\widetilde{Z}\nu}$, we first note that the photino does not couple directly to the neutrino (since neutrinos do not couple to photons). Nevertheless, an effective photino-neutrino mixing is generated through the mixing photino-zino and the mixing zino-neutrino. The result reads:

$$|U_{\tilde\gamma\nu}| \simeq \left|\frac{\mathrm{M}^n_{\tilde\gamma\widetilde{Z}}}{\mathrm{M}^n_{\tilde\gamma\tilde\gamma}}\right| |U_{\widetilde{Z}\nu}|\,. \quad (12)$$

Therefore, the relation between $U_{\tilde\gamma\nu}$ and $U_{\widetilde{Z}\nu}$ follows from the 2×2 gaugino sub-block of the neutralino mass matrix, that in the $(-i\widetilde{\gamma}, -i\widetilde{Z})$ basis reads

$$\mathrm{M}^n_{2\times 2} = \begin{pmatrix} M_1 c_W^2 + M_2 s_W^2 & (M_2 - M_1)s_W c_W \\ (M_2 - M_1)s_W c_W & M_1 s_W^2 + M_2 c_W^2 \end{pmatrix}\,. \quad (13)$$

Here, M_1 and M_2 are the $U(1)_Y$ and $SU(2)_L$ gaugino masses, and c_W (s_W) denotes the cosine (sine) of the weak mixing angle. Therefore,

$$|U_{\tilde\gamma\nu}| \simeq \left[\frac{(M_2 - M_1)s_W c_W}{M_1 c_W^2 + M_2 s_W^2}\right] |U_{\widetilde{Z}\nu}|\,, \quad (14)$$

that depends only on the gaugino masses at the electroweak scale. Assuming gaugino mass universality at the Grand Unified Scale, $M_X = 2\times 10^{16}\,\mathrm{GeV}$, we obtain at low energies $M_2/M_1 \simeq 1.9$, which yields $|U_{\tilde\gamma\nu}| \simeq 0.31|U_{\widetilde{Z}\nu}|$.

The mixing parameter $U_{\widetilde{W}\ell}$, on the other hand, is related to $U_{\widetilde{Z}\nu}$ by $SU(2)_L$ gauge invariance. The relation approximately reads:

$$|U_{\widetilde{W}\ell}| \simeq \sqrt{2}c_W \left|\frac{\mathrm{M}^n_{\widetilde{Z}\widetilde{Z}}}{M_{\widetilde{W}}}\right| |U_{\widetilde{Z}\nu}|\,, \quad (15)$$

where $M_{\widetilde{W}} = M_2$ is the wino mass at the electroweak scale. Using Eq. (13), we finally obtain

$$|U_{\widetilde{W}\ell}| \simeq \sqrt{2}c_W \frac{M_1 s_W^2 + M_2 c_W^2}{M_2} |U_{\widetilde{Z}\nu}|\,, \quad (16)$$

TABLE I: Branching ratios for gravitino decay in different R-parity violating channels for different gravitino masses.

$m_{3/2}$	$\mathrm{BR}(\psi_{3/2}\to\gamma\nu)$	$\mathrm{BR}(\psi_{3/2}\to W\ell)$	$\mathrm{BR}(\psi_{3/2}\to Z^0\nu)$
10 GeV	1	0	0
85 GeV	0.66	0.34	0
100 GeV	0.16	0.76	0.08
150 GeV	0.05	0.71	0.24
250 GeV	0.03	0.69	0.28

which under the assumption of gaugino mass universality at the Grand Unified Scale yields $|U_{\widetilde{W}\ell}| \simeq 1.09|U_{\widetilde{Z}\nu}|$. Hence, under this assumption, the three relevant mixing parameters are in the ratio

$$|U_{\tilde\gamma\nu}| : |U_{\widetilde{Z}\nu}| : |U_{\widetilde{W}\ell}| \simeq 1 : 3.2 : 3.5\,, \quad (17)$$

and thus the branching ratios for the different decay modes only depend on the gravitino mass (see Table I).

Once the spectrum of photons from gravitino decay has been determined, Eq. (11), it is straightforward to compute the gamma ray flux received at the Earth from our local halo and from cosmological distances, by using Eqs. (3,5). Assuming universality of gaugino masses at high energies, the photon flux received from gravitino decay depends essentially on the gravitino mass, which determines the shape of the energy spectrum, and the gravitino lifetime, which determines its overall normalization.

In Fig. 1 we show the different contributions to the gamma ray flux for $m_{3/2} = 150\,\mathrm{GeV}$ and $\tau_{3/2} \simeq 2\times 10^{26}\mathrm{s}$. 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 energy resolution of the detector is particularly important to determine the width and the height of the monochromatic line stemming from the two body decay $\psi_{3/2} \to \gamma\nu$. The three contributions are dominated by the halo component, the extragalactic component being smaller by a factor of 2–3. Finally, to compute the total flux received, we have adopted an energy spectrum for the background described by the power law $\left[E^2 \frac{dJ}{dE}\right]_{\mathrm{bg}} = 4\times 10^{-7}\left(\frac{E}{\mathrm{GeV}}\right)^{-0.5} (\mathrm{cm}^2\mathrm{str\ s})^{-1}\mathrm{GeV}$.

The predicted energy spectrum shows two qualitatively different features. At energies between 1–10 GeV, we expect a continuous spectrum of photons coming from the fragmentation of the gauge bosons. As a result, the predicted spectrum shows a departure from the power law in this energy range that might be part of the apparent excess inferred from the EGRET data by Strong *et al.* [14]. 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.

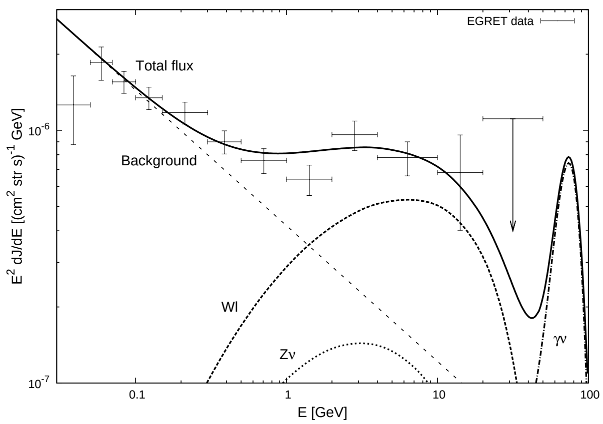

FIG. 1: Contributions to the total gamma ray flux for $m_{3/2} = 150\,\mathrm{GeV}$ and $\tau_{3/2} \simeq 2 \times 10^{26}$s compared to the EGRET data. In dotted lines we show the photon flux from the fragmentation of the Z boson, in dashed lines from the fragmentation of the W boson, and in dot-dashed lines from the two body decay $\psi_{3/2} \to \gamma\nu$. The background is shown as a long dashed line, while the total flux received is shown as a thick solid line.

In addition to the continuous component, the energy spectrum shows a relatively intense monochromatic line at higher energies arising from the decay channel $\psi_{3/2} \to \gamma\nu$. This line could be observed not only by GLAST or AMS-02, but also by ground-based Cherenkov telescopes such as MAGIC (with an energy threshold of 70 GeV) or VERITAS (50 GeV).

The intense gamma line is very characteristic of this scenario, and the observation of this feature with the right intensity would support the gravitino dark matter decay hypothesis. While scenarios with neutralino dark matter also predict a continuous spectrum and a monochromatic line coming from the annihilation channels $\chi^0\chi^0 \to \gamma\gamma, Z\gamma$ [20], these channels only arise at the quantum level, and thus the intensity of the monochromatic line is greatly suppressed compared to the continuum. One should note, however, that the presence of an intense gamma line is not unique to the scenario with decaying gravitino dark matter and is also expected, for example, from the annihilation of inert Higgs dark matter [21].

To summarize, in this letter we have computed the gamma ray flux from gravitino dark matter decay in scenarios with R-parity violation. These scenarios are very appealing theoretically, as they naturally lead to a history of the Universe consistent with thermal leptogenesis and primordial nucleosynthesis. The predicted flux essentially depends on two parameters: the gravitino mass, which determines the shape of the energy spectrum, and the gravitino lifetime, which determines its overall normalization. If the gravitino is lighter than the $W^\pm$ and Z^0 gauge bosons, the predicted energy spectrum is essentially monochromatic. On the other hand, if it is heavier, the energy spectrum consists of a continuous component and a relatively intense gamma ray line. This gamma ray flux might have already been observed by EGRET. Future experiments, such as GLAST, AMS-02 or Cherenkov telescopes, will provide unique opportunities to test the decaying gravitino dark matter scenario.

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