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Cosmologically Benign Gravitinos at the Weak Scale

Joshua A. Frieman and Gian F. Giudice

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, IL 60510

Abstract

We show that a gravitino with mass $O(m_W)$ and a high reheat temperature after inflation, $T_R \simeq 10^{12} - 10^{14}$ GeV, can be compatible with cosmological constraints if the gravitino decays predominantly into neutrino-sneutrino pairs. Models in which the lightest supersymmetric particle is either the sneutrino or the neutralino are described. In this scenario, gravitino decay provides an alternative mechanism for producing supersymmetric dark matter, which may be either hot or cold.

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Supergravity theories predict the existence of a spin 3/2 partner of the graviton, the gravitino ($\tilde{G}$), which becomes massive once supergravity is broken. An attractive feature of these models[1] is that the breaking of supergravity sets the scale for electroweak symmetry breaking. Therefore, one generally expects $m_{\tilde{G}} = \mathcal{O}(m_W)^*$.

This mass relation is, however, embarassing from a cosmological point of view. If the gravitino is stable, it must be lighter than about 1 keV[3] to avoid giving an intolerably large contribution to the present energy density of the Universe. If it decays, the agreement between big bang nucleosynthesis yields and the observed light element abundances constrains the gravitino to be heavier than about 10 TeV[4]. One might think that this constraint would be removed if the universe has undergone a period of inflation, which dilutes the gravitino density. Nevertheless, if the reheating temperature after inflation is larger than the mass of the supersymmetric particles, gravitinos will be regenerated[5]. In this case, the limits on gravitino decay from nucleosynthesis, entropy release and microwave background distortion imply that the reheating temperature T_R should be less than about $10^8 - 10^{10}$ GeV, for a gravitino mass of 100 GeV[5-6]. This is incompatible with the standard scenario of baryosynthesis, which requires the out-of-equilibrium decay of particles with mass $\gtrsim 10^{11}$ GeV in order for the proton to have an acceptably long lifetime[7].

Several solutions to the gravitino problem have been proposed. One possibility is to produce the baryon asymmetry at a very low energy scale, e.g., through renormalizable B–violating operators in a supersymmetric theory with broken R-parity[8]. Second, if the gravitino is the lightest supersymmetric particle and, therefore, stable,[5] a gravitino mass of 100 GeV is cosmologically acceptable if $T_R \lesssim 4 \times 10^{11}$ GeV. (In

*In no–scale models, this is not necessarily true. See, e.g., ref.[2].

this case, the gravitino would be a candidate for 'shadow' dark matter.) A third alternative is the recent proposal of ref. 9 that nucleosynthesis is generated by the decay of a long-lived particle, the gravitino being a possible candidate. This scenario can be implemented if the gravitino is heavy, $m_{\tilde{G}} \simeq 500 - 1000$ GeV, in which case the reheating temperature can be as high as $10^{12} - 10^{14}$ GeV.

In this paper, we show that a decaying gravitino with mass $\mathcal{O}(m_W)$ or less can be compatible with both standard nucleosynthesis constraints and baryogenesis at a scale $10^{12} - 10^{14}$ GeV. We will describe several possible scenarios where the gravitino decays almost uniquely into light neutrinos and the lightest supersymmetric particle (LSP). Since a gravitino of mass 100 GeV decays at a time $\tau_{\tilde{G}} \simeq (M_P^2/m_{\tilde{G}}^3) \simeq 4 \times 10^6$ sec, its weakly interacting decay products (neutrinos and LSPs) never reach thermal equilibrium, thus effectively circumventing the constraints from entropy release, element photodissociation and microwave background distortion. In this case, gravitino decay can provide an efficient source of supersymmetric dark matter, even when the LSP otherwise annihilates too fast to lead to a sizable relic energy density.

We are working in the context of low energy supergravity theories. Ordinary quarks and leptons have scalar partners. These particles get their masses from different sources: (i) supersymmetry breaking terms, generally assumed to be $\mathcal{O}(m_{\tilde{G}})$; (ii) gauge radiative corrections, proportional to the supersymmetry breaking gaugino mass; (iii) D-term contributions, due to spontaneous supersymmetry breaking, proportional to m_Z ; (iv) supersymmetric contributions, equal to the corresponding fermion masses. Squarks have a large gluino mass contribution and are expected to be rather heavy. Among sleptons, sneutrinos ($\tilde{\nu}$) are the lightest, since their D-term squared mass is negative. When the D-term dominates the gaugino contribution, the sneutrinos become lighter than the gravitino, while the other scalars are always heavier. In this case, the process

$$\tilde{G} \to \nu\tilde{\nu} \tag{1}$$

is the only accessible gravitino decay into a fermion–sfermion pair.

In most models, the LSP, which is stable due to R–parity, is either a sneutrino or a neutralino (the mixture of gauge and Higgs supersymmetric neutral fermions). If the sneutrino is the LSP, we will consider the case in which all the neutralinos are heavier than the gravitino. Therefore, (1) is the only possible gravitino decay mode.

On the other hand, if the neutralino (χ) is the LSP, we will assume that it has vanishingly small photino component, being essentially a mixture of only the Z–ino, higgsinos and other possible neutral fermions present in the theory. We will describe later several possible scenarios where this occurs. For a gravitino with mass in the range of about 50–100 GeV, all the two–body decays into gauge or Higgs bosons and neutralinos or charginos are kinematically forbidden if the Higgs is not very light.† Therefore, (1) is still the main decay channel, and the sneutrino will subsequently decay via $\tilde{\nu} \to \nu\chi$. In both cases, gravitinos decay predominantly into LSPs and neutrinos. We will assume that the produced neutrinos are all light, and that they do not decay at an appreciable rate to photons or charged particles.

Since the gravitino decays only into decoupled particles, the most important cosmological constraint comes from the contribution of the decay products to the present energy density. For independent reasons, we will assume that a period of inflation has occurred in the early universe. If T_R is the reheating temperature after inflation, the

† Consistent with theoretical predictions of and experimental limits on the gluino mass, we assume that gravitino decay into a gluon-gluino pair is kinematically forbidden.

gravitino number density at low (photon) temperature ($T \ll 1$ MeV) is given by[5]:

$$n_{\tilde{G}}(T) = 4.8 \times 10^{-10} \left(\frac{T_R}{10^{13}\ GeV}\right) T^3 \left(1 - 0.02 \ln \frac{T_R}{10^{13}\ GeV}\right). \tag{2}$$

Note that eq. (2) assumes the contribution of all the light ($m \ll kT_R$) particles in the minimal supersymmetric model to the gravitino regeneration rate and includes the reheating of the photons relative to the gravitinos due to the annihilation of particle-antiparticle pairs. After the gravitino decays, its energy is transferred to the LSP and the neutrinos. Since they are light, the neutrinos make a negligible contribution to the present energy density. (On the other hand, a heavy, stable neutrino could be treated in the same manner as the LSP below.) At low temperatures, the LSP energy density is given by $\rho_{LSP} = n_{LSP}\ m_{LSP}$, where, just after the decay, $n_{LSP}(T_D^-) = n_{\tilde{G}}(T_D^+)$. We thus obtain:

$$\Omega_{LSP} h^2 = 0.7 \left(\frac{m_{LSP}}{10\ GeV}\right) \left(\frac{T_R}{10^{13}\ GeV}\right) \left(\frac{T_o}{2.7K^\circ}\right)^3 \left[1 - 0.02 \ln \frac{T_R}{10^{13}\ GeV}\right], \tag{3}$$

where Ω_{LSP} is the LSP energy density in units of the critical density, h is the Hubble constant in units of 100 $km\ sec^{-1} Mpc^{-1}$, and T_o is the present photon temperature.

From eq. (3), in order for the LSP not to overclose the universe, the reheating temperature should be smaller than $10^{12} - 10^{14}$ GeV, depending on the LSP mass. It is interesting that, in this range of T_R, the LSP turns out to be a good dark matter candidate, independently of its annihilation rate in the early universe. By contrast, in the standard scenario, sneutrinos heavier than a few GeV are excluded as constituents of the dark matter, since they annihilate efficiently through Z–ino or Z exchange[10] and do not survive in appreciable numbers. The same is true for neutralinos with a mass of about $m_Z/2$[11]. However, if gravitino decay is the origin of the dark matter, the LSP can provide near-closure density, $\Omega \simeq 1$, without any constraint on its annihilation cross section and for a wide range of LSP masses. We note that sneutrino dark matter should be easily detected both directly in ionization or bolometric detectors and indirectly through high energy neutrinos produced via sneutrino annihilation in the Sun and the Earth. In fact, the absence of such signals to date implies that sneutrinos more massive than a few GeV are probably ruled out as the dominant component of the galactic halo.[12]

An amusing feature of this scenario is that dark matter produced by gravitino decay can be either hot or cold, depending on mass ratios. Assuming three species of light neutrinos ($g_*(T_D) = 3.36$), the temperature at the gravitino decay time $\tau_{\tilde{G}}$ is $T_D = (3/16\pi M_P)^{1/2}(5/\pi g_*)^{1/4} m_{\tilde{G}}^{3/2} = 60(m_{\tilde{G}}/100\ GeV)^{3/2}$ eV. Thus, the decay product sneutrinos are relativistic until a temperature $T_{NR} \simeq (2m_{\tilde{\nu}}/m_{\tilde{G}})T_D$ is reached. For $m_{\tilde{\nu}} \lesssim m_{\tilde{G}}/2$, the sneutrino free-streaming scale is $\lambda_{FS} \simeq ct_{NR}(T_{NR}/T_o)[1 + \ln(t_{eq}/t_{NR})]$, where $t_{eq} = 4 \times 10^{10}(\Omega_o h^2)^{-2}$ sec is the time when the universe becomes matter-dominated. This gives

$$\lambda_{FS} = 6Mpc\ \left(\frac{m_{\tilde{G}}}{100\ GeV}\right)^{-3/2}\left(\frac{m_{\tilde{G}}}{2m_{\tilde{\nu}}}\right)\left[1 + \ln\left(\left(\frac{m_{\tilde{G}}}{100\ GeV}\right)\left(\frac{m_{\tilde{G}}}{2m_{\tilde{\nu}}}\right)^{-2}(\Omega_o h^2)^{-2}\right)\right]. \tag{4}$$

The comoving scale corresponding to a galaxy-mass perturbation ($10^{12} M_\odot$) is $\lambda_{gal} = 2(\Omega_o h^2)^{-1/3}$ Mpc; such perturbations will be erased due to free streaming of the (collisionless) sneutrinos if $\lambda_{FS} \geq \lambda_{gal}$. Thus, despite having masses of $\mathcal{O}(GeV)$ or more, the decay product sneutrinos or neutralinos will be "hot" dark matter unless either $m_\chi, m_{\tilde{\nu}} \sim m_{\tilde{G}}$ or $m_{\tilde{G}} \gtrsim 500$ GeV. Note that, in this discussion, we have assumed that the universe becomes matter-dominated "on schedule", i.e., that $t_{eq} > t_{NR}$. This corresponds to the constraint $m_{\tilde{\nu}} \geq 5\Omega_o h^2 (m_{\tilde{G}}/100\ GeV)^{-1/2}$ GeV.

A weaker bound on T_R comes from the fact that the gravitino should not dominate the universe during nucleosynthesis, modifying the expansion rate and the predicted element abundances. This requires $T_R \lesssim 9 \times 10^{15}\ GeV \left(\frac{100\ GeV}{m_{\tilde{G}}}\right)$, which is already satisfied in the range of parameters we are considering. In fact, as long as $m_{\tilde{G}} \gtrsim 55(T_R/10^{13}\ GeV)^2$ GeV, the gravitino decays before it dominates the universe.

So far, we have assumed that gravitino decay yields no other products, such as high energy photons, charged leptons or hadrons, which are potentially dangerous for the light elements and the microwave background. Let us define BR to be the total branching ratio for the gravitino to decay, either directly or secondarily, into such particles. From bounds on distortions of the microwave background spectrum, we have the constraint[5-6]:

$$BR \lesssim 10^{-2} \left(\frac{10^{13}\ GeV}{T_R}\right) \left(\frac{10^2\ GeV}{m_{\tilde{G}}}\right) \left(\frac{10^8\ sec}{\tau_{\tilde{G}}}\right)^{1/2}. \tag{5}$$

Assuming standard big bang nucleosynthesis, in the range of parameters we are considering, the bounds on photo- and hadro-destruction (and creation) of the light elements[5-6] approximately correspond to:

$$BR \lesssim 10^{-4} \left(\frac{10^{13}\ GeV}{T_R}\right) \left(\frac{10^2\ GeV}{m_{\tilde{G}}}\right). \tag{6}$$

(Although we should formally treat photons and hadrons on separate footing, the constraint (6) is an adequate approximation for our purposes to the most recent constraints on both hadro- and photo-dissociation.[6]) For the values of T_R under consideration, there is no limit on BR from the modification of the baryon–to–photon number ratio due to gravitino entropy generation. Using eq. (3), we can write the limit (6) on BR as

$$BR \lesssim \frac{7 \times 10^{-4}}{\Omega_{LSP} h^2} \frac{m_{LSP}}{m_{\tilde{G}}} \tag{7}$$

There are two sources for such destructive high energy particles we must now consider: a) production as secondaries from the neutrinos produced in the decay (1), and b) direct production due to other gravitino decay modes besides (1). We treat these in turn.

For secondary production, an important process is annihilation of the decay product neutrinos (or sneutrinos) with themselves, $\nu\bar{\nu} \to f\bar{f}$, where f includes all light leptons and quarks. Summing over all channels except the top quark, the total annihilation cross-section is $\sigma_\nu \simeq 0.5\ G_F^2 s/\pi \simeq 0.16\ G_F^2 m_{\tilde{G}}^2 (T/T_D)^2$. Since the neutrino mean-free-path is $\Gamma_\nu = n_\nu \sigma_\nu$, the evolution of the secondary fermion density n_f is given by

$$\frac{dn_f}{dt} + 3Hn_f = \Gamma_\nu n_\nu \tag{8}$$

where $n_\nu(T)$ is given by eq. (2), and the Hubble parameter is $H = 1.67 g_*^{1/2}(T^2/M_P)$. Defining $Y \equiv n_f/n_\nu$ and $x \equiv T_D/T$, Eq. (8) can be rewritten

$$x\frac{dY}{dx} = \left(\frac{\Gamma_\nu}{H}\right)_{T_D} x^{-3} \tag{9}$$

which has the asymptotic solution $BR \equiv Y_\infty = (1/3)(\Gamma_\nu/H)_{T_D}$, or

$$BR = 8.7 \times 10^{-6} \left(\frac{T_R}{10^{13}\ GeV}\right) \left[1 - 0.02 \ln \frac{T_R}{10^{13}\ GeV}\right] \left(\frac{m_{\tilde{G}}}{100\ GeV}\right)^{7/2}. \tag{10}$$

Other processes, such as annihilation of the decay product neutrinos with background (low energy) neutrinos or scattering off background electrons or hadrons are at most comparable to the rate considered above. As a result, their branching ratios are not significantly larger than (10). Thus, comparison with eq. (6) shows that secondary production is not a strong constraint on the model.

We also note that, as a consequence of (10), all but a tiny fraction of the decay product neutrinos survive annihilation. Today, they would constitute a non-thermal "high-energy" neutrino background, with average energy $\bar{E}_\nu \simeq 0.2(m_{\tilde{G}}/100\ GeV)^{-1/2}$ MeV. They have a present energy density comparable to the microwave background,

$$\frac{\rho_\nu}{\rho_\gamma} = 0.6\left(\frac{T_R}{10^{13}\ GeV}\right)\left(\frac{m_{\tilde{G}}}{100\ GeV}\right)^{-1/2}\left[1 - 0.02\ln\frac{T_R}{10^{13}\ GeV}\right], \qquad (11)$$

but would be very difficult to detect.

Now consider other gravitino decay modes, besides $\tilde{G} \to \nu\tilde{\nu}$, which produce photons, charged leptons or hadrons. We will show that particle physics models can satisfy the constraint (7) on the branching ratio for the gravitino decay modes different from (1). The decay (1) occurs through the supergravitational interaction[13]†

$$\frac{K}{\sqrt{2}}\bar{\nu}\gamma^\mu\left[\left(\not{D} - im_{\tilde{G}}\right)\tilde{\nu}\right]\psi_\mu + h.c., \qquad (12)$$

where ψ_μ is the vector-spinor gravitino field and $K = \frac{\sqrt{8\pi}}{M_P}$. The normalization of (12) corresponds to the canonical kinetic term for the scalar field. The operator (12) yields the gravitino decay width:

$$\Gamma\left(\tilde{G} \to \nu\tilde{\nu}\right) = \frac{m_{\tilde{G}}^3}{12M_P^2}\left(1 - \frac{m_{\tilde{\nu}}^2}{m_{\tilde{G}}^2}\right)^4, \qquad (13)$$

for each of the three kinds of massless neutrinos§.

If the sneutrino is the LSP (and the neutralinos are heavier than the gravitino), besides (1), the gravitino could also decay into a neutrino–sneutrino pair and a virtual Z. However, this four-body decay is strongly suppressed and easily satisfies the constraint (7).

† Contrary to ref.[13], we use the metric (+,−,−,−).

§ If, due to charged current effects, the sneutrinos have tiny mass differences, the heavy ones will decay into the lightest and a pair of neutrinos, without modifying the final picture.

It is also interesting to consider the case where the neutralino is the LSP, since this often turns out to be the case in low energy supergravity models. We assume that, in the mass range of interest, the gravitino cannot decay into a real Z^o or Higgs boson and a neutralino. However, the gravitino can decay into a neutralino and a virtual Higgs or Z^o. As soon as the Higgs boson is above the production threshold, it leads to a safely small branching ratio:

$$BR\left(\tilde{G} \rightarrow b\bar{b}\chi\right) \lesssim \frac{1}{(4\pi)^2} G_F m_b^2 \sim 10^{-6} \tag{14}$$

We have computed the branching ratio for $\tilde{G} \rightarrow f\bar{f}\chi$ through a virtual Z^o, where f are all possible standard fermions and find that it is smaller than 10^{-4} for, e.g., $m_{\tilde{G}} = 100$ *GeV*, $m_\chi = 50$ *GeV* or $m_{\tilde{G}} = 50$ *GeV*, $m_\chi = 5$ *GeV*. Therefore, the constraint (7) can easily be satisfied, even for values of Ω_χ close to 1.

The gravitino can also decay into a photon and a neutralino via the operator:

$$\frac{K}{4}\bar{\lambda}\gamma^\mu\sigma^{\nu\rho}\psi_\mu F_{\nu\rho}, \tag{15}$$

where λ is the photino field and $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$. This gives the gravitino decay width:

$$\Gamma\left(\tilde{G} \rightarrow \gamma\chi\right) = |N_{\tilde{\gamma}}|^2 \frac{m_{\tilde{G}}^3}{4M_P^2}\left(1 - \frac{m_\chi^2}{m_{\tilde{G}}^2}\right)^3 \left(1 + \frac{m_\chi^2}{3m_{\tilde{G}}^2}\right), \tag{16}$$

where $N_{\tilde{\gamma}}$ is the photino component of the lightest neutralino. Eq. (7) implies that $|N_{\tilde{\gamma}}|$ should be smaller than about $10^{-2} - 10^{-3}$, depending on the values of Ω_χ and the mass ratio $m_\chi/m_{\tilde{G}}$.

Therefore, this scenario requires that the lightest neutralino has at most a very small photino component. This might be realized in several ways. One possibility is that the LSP is an almost pure higgsino, which occurs if there is a hierarchy between the gaugino mass and the mass that mixes the Higgs fields in the superpotential. This condition may be natural, since these two masses can have different origins[1]. A second possibility is that the photino is an exact mass eigenstate. In the minimal model, this can be achieved by having the $SU(2)$ and $U(1)$ gaugino masses equal ($M = M'$). The photino can then be made heavy, while a combination of the other neutralino states remains light. However, in the minimal model, there is no reason why M and M' should remain degenerate after radiative corrections are taken into account. A final possibility is to appeal to extended supergravity models, where more exotic neutralino states decoupled from the photino can be found.

We note that, even if the neutralino has no photino component, the decay $\tilde{G} \to \gamma\chi$ can still occur at one-loop level. However, its branching ratio is of order $\left(\frac{\alpha}{4\pi \sin\theta_W}\right)^2 \sim 10^{-6}$ and therefore satisfies the constraint (7) in the range of interest.

In conclusion, if the breaking of supergravity is connected with electroweak symmetry breaking, one expects the gravitino mass to be $\mathcal{O}(m_W)$, but this is usually considered cosmologically problematic. In this paper, we have described a class of models in which a decaying gravitino of mass 50–100 GeV does not lead to cosmological difficulties. In this scenario, although gravitinos decay after nucleosynthesis, they do not destroy the light elements or distort the microwave background, because their principal decay products interact only weakly. The contribution of the LSP to the present energy density of the universe then implies a rather weak upper limit on the reheating temperature after inflation, $T_R \lesssim 10^{12} - 10^{14}$ GeV. This value of T_R is high enough for baryogenesis to proceed in the usual way. For T_R near the upper bound, the late decay of the gravitino provides a natural way of producing supersymmetric dark matter, which is independent of the LSP annihilation rate.

We also showed that this scenario can be realized in standard low energy supergravity models in several ways. In the most natural case, the sneutrino, which is the LSP, is the only supersymmetric particle lighter than the gravitino. Then, the gravitino decays almost uniquely via $\tilde{G} \to \nu\tilde{\nu}$. Alternatively, a neutralino with very small photino component can be the LSP, with the sneutrino lighter than the gravitino. (The other neutralino states are heavier.) In this case, the gravitino decays via $\tilde{G} \to \nu\tilde{\nu}$, followed by $\tilde{\nu} \to \nu\chi$. Decays into real photons, Z^o or Higgs bosons and neutralinos are not allowed by phase space, while the other potentially dangerous decay modes are naturally suppressed.

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