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THE DIFFUSE COSMIC GAMMA RAY BACKGROUND AS A PROBE OF COSMOLOGICAL GRAVITINO REGENERATION AND DECAY

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ABSTRACT

We predict the presence of a spectral feature in the isotropic cosmic gamma ray background associated with gravitino decays at high redshifts. With a gravitino abundance that falls in the relatively narrow range expected for thermally regenerated gravitinos following an inflationary epoch in the very early universe, gravitinos of mass several GeV are found to yield an appreciable flux of $1 - 10 MeV$ diffuse gamma rays.

Decays of long-lived particles can have significant astrophysical implications. Decay products may produce far ultraviolet background photons[1] , and even yield a uniform cosmological density of dark matter.[2] There is one class of particle, common to most phenomenological supersymmetry theories, whose long–lived decay has a significant effect that appears to have hitherto been overlooked. We shall show below that gravitino decays are likely to lead to an appreciable diffuse cosmic gamma ray background. Decays of primordial gravitinos can also present a severe embarassment to cosmological models, via effects on primordial nucleosynthesis and microwave background distortions.[3–8] One promising solution is that an epoch of inflation diluted the primordial gravitino abundance to an acceptable level.[9] Gravitinos are regenerated during the reheating process after inflation, and hence the reheating will be subject to the constraints from gravitino decays. Remarkably in this case, we find that the predicted flux of diffuse cosmic gamma rays resulting from gravitino decays in the early universe is similar to the observed gamma ray background for a wide range of gravitino masses, provided that the maximum temperature to which the universe reheats after inflation lies in an acceptable range.

Despite all the uncertainties regarding the model dependent particle spectrum in locally supersymmetric theories, there are at least two things which are common to all; 1) there is one stable particle and 2) one somewhat long–lived sparticle. The existence of a stable supersymmetric particle (sparticle) is due to the R-symmetry which requires a sparticle to decay into anything + an odd number of other sparticles. Hence the lightest sparticle is forbidden to decay. By a long lived particle, we mean one in which its decay rate is proportional to the gravitational constant $G_N = M_p^{-2}$. The gravitino is an example of such a sparticle and depending on its mass may indeed be very long lived.

The identity of the LSP, is of course the subject of debate. In a wide class of models, the LSP is either the photino[10,11] or Higgsino (or a mixed state of the two)[12], while other candidates are the sneutrino [13] or the axino[14]. In this Letter, we will assume that the LSP is the photino and comment on the other possibilities in our conclusions. Provided that the gravitino is not the LSP, then it will be unstable to decay into lighter sparticles. For simplicity, we will take the photino to be the only sparticle lighter than the gravitino. Other models in which for example both photinos and gluinos are lighter than the gravitino will not drastically affect our ensuing discussion. The decay rate for gravitino → photon + photino has been calculated[11,6] and can be expressed as

$$\Gamma = 8\pi\alpha m_{3/2}^3/M_p^2 \tag{1}$$

where the "coupling" α depends on the photino mass

$$\alpha = (32\pi)^{-1}\left[1 - \left(m_{3/2}/m_{\tilde{\gamma}}\right)^2\right]^3 \tag{2}$$

Hence a gravitino with mass $m_{3/2} < 100GeV$ will have a lifetime $\tau > 4 \times 10^8 s$.

Because of their late decays into photons, the abundance of gravitinos (with respect to photons, for example) becomes very important. Various limits from entropy production[4], overall mass density of the decay products[11,12,8], distortions of the microwave background[5,6,8], and the destruction of primordial deuterium place limits on the gravitino abundance Y which we define as

$$Y = n_{3/2}/n_\gamma \tag{3}$$

where n_γ is the number density of photons today. The strongest of these limits implies that[7,8]

$$Y < 10^{-14}. \tag{4}$$

In a standard (non–inflationary) model, one would expect that initially (before decoupling) $Y = 1$ and that through the annihilation of all other particle species the abundance would be brought down to $Y \sim 1/N_D \sim 10^{-2}$ today where N_D is the total number of degrees of freedom at gravitino decoupling. This leads to a catastrophe if gravitinos are long- lived, since the expansion of the universe becomes dominated by non- relativistic particles far too early. Inflation resolves this problem by diluting the primordial gravitino abundance to a negligible level. However, after inflation, the Universe will reheat to some temperature T_R, during which additional gravitinos will be produced. One can estimate the secondary production of gravitinos as[12]

$$Y \simeq \frac{\alpha}{\sqrt{N}} T_R/M_p \sim 2 \times 10^{-3} T_R/M_p \tag{5}$$

for the gauge coupling $\alpha_G \sim 1/25$ and $N \sim 300$. This agrees very closely with a more exact calculation[6] which yields $Y = 2.8 \times 10^{-3} T_R/M_p$. Thus the final abundance Y of gravitinos will be determined by T_R, and the limits on Y (eq. 4) become limits on T_R.

Many models of supersymmetric inflation[15] generally predict a low value for T_R. In these models, the superpotential f (which generates the scalar potential for inflation) contains only one parameter whose value differs from O(1). For example

$$f(\phi) = \mu^2 g(\phi) \tag{6}$$

where all couplings in $g(\phi)$ are O(1). The scalar potential is then $V \sim \mu^4$ and the mass of ϕ is $M_\phi \sim \mu^2 M_p$, etc. More importantly, μ also determines both the magnitude of density fluctuations produced during inflation[16] and the reheating temperature T_R (ref. 15). In this type of model, the density fluctuations are given by

$$\frac{\delta\rho}{\rho} \sim 10^3 \mu^2 \sim 10^{-4} - 10^{-5} \tag{7}$$

so that $\mu^2 \sim 10^{-7} - 10^{-8}$ according to limits on the isotropy of the microwave background[17]. The reheating temperature, on the other hand, is given by

$$T_R \simeq M_\phi^{3/2}/M_p^{1/2} \simeq 0.2 \mu^3 M_p$$

$$\simeq (6 \times 10^{-12} - 2 \times 10^{-13}) M_p \tag{8}$$

implying that the abundance of gravitinos is

$$Y \simeq 10^{-14} - 4 \times 10^{-16}, \tag{9}$$

below the limit given by eq. (4).

Given the abundance Y of gravitinos and their decay rate, eq. (1), one can determine the time or redshift of decay. The age of the Universe at a given (recent) redshift can be expressed as (if $\Omega = 1$)

$$t = t_{\circ}(1+z)^{-3/2} \tag{10}$$

where the present age of the Universe is taken to be $t_0 = 2 \times 10^{17} h^{-1} s$ and the Hubble parameter is defined as $H_0 = 100h\ km\ Mpc^{-1}\ s^{-1}$. The quantity $(1+z)$ is related to the background temperature by $T/T_0 = 1 + z$ where $T_0 \simeq 2.7K$ is the present temperature. Gravitinos will decay when $\Gamma = t_D^{-1}$ or when

$$\alpha m_{3/2}^3 = 2 \times 10^{-5} h\,(1+z_D)^{3/2}\, GeV^3 \tag{11}$$

where z_D is the redshift of decay. In the rest frame of the gravitino, if we define the energy of the photon produced in the decay to be $m_{3/2}/\gamma$ (with $\gamma \geq 2$)and β to be its energy today in MeV, then

$$\beta = 10^3 \gamma^{-1} m_{3/2} (1+z_D)^{-1}, \tag{12}$$

where we are using units such that all masses are given in GeV.

A limit to the decay redshift from which an observable gamma flux can originate may be inferred from the absorption of the energetic decay photons by ambient intergalactic matter. In the energy range of interest for decays to yield gamma rays at present, the relevant absorption process near z_d is pair production. The absorption probability is approximately given by

$$\tau = \int_0^{z_D} \alpha_f \sigma_T c H_0^{-1} n_0 (1+z)^{1/2} dz = 3.3 \times 10^{-4} \Omega_b h [(1+z_D)^{3/2} - 1], \tag{13}$$

where σ_T is the Thompson cross-section, $\alpha_f$is the fine- structure constant, and we have adopted a flat ($\Omega = 1$) cosmological model. Requiring $\tau < 1$ in order to observe the decay photons, we then constrain

$$(1+z_D) \leq 200 \Omega_b^{-2/3} h^{-2/3} \tag{14}$$

The energy density of the decay photons today will be given by

$$\rho_\gamma^{(D)} = m_{3/2} Y n_\gamma / (1+z_D)\gamma, \tag{15}$$

and the fraction of critical density of these photons is

$$\Omega_\gamma^{(D)} = \rho_\gamma^{(D)} / \rho_c = 3.8 \times 10^7 m_{3/2} Y / (1+z_D) \gamma h^2$$

$$= 3.8 \times 10^4 Y \beta / h^2. \tag{16}$$

We shall be interested in γ–rays in the region $\beta = 1 - 100$, and we must therefore compare eq.(16) with the observed contribution to Ω in the γ–ray background. The γ–ray flux around $1 MeV$ is about[18]

$$\Phi \simeq 1.2 \times 10^{-2} \beta^{-3} cm^{-2} s^{-1} sr^{-1} MeV^{-1}, \tag{17}$$

and corresponds to an energy density of

$$\rho_\gamma^{(obs)} \simeq 5 \times 10^{-12} \beta^{-1} MeV cm^{-3}; \tag{18a}$$

or

$$\Omega_\gamma^{(obs)} = 4.8 \times 10^{-10} h^{-2} \beta^{-1}. \tag{18b}$$

Thus in order for the photons produced by gravitino decay to account for the γ–ray background, we must relate eqs. (16) and (18b) which determine the abundance of gravitinos

$$Y \simeq 1.2 \times 10^{-14}/\beta^2 \tag{19}$$

As one can see, for β in the range $1 - 10$, the abundance of gravitinos given by eq. (19) agrees remarkably with the estimated abundance given by inflation eq. (9) and the magnitude of density perturbations.

The requirement that the decay photons survive until today enables us now to set limits on β, $m_{3/2}$ and Y in regimes where gravitino decays contribute to the γ–ray background. Now from eqs. (11) and (12) we can write

$$1 + z_D = 730 h^{2/3} (\alpha^{2/3} \beta^2 \gamma^2)^{-1}. \tag{20}$$

In addition we have the requirement that the decay has in fact occurred so that $z_D > 0$. Combining this and the limit (14) we obtain

$$1.9(\Omega h^2/\alpha)^{1/3} \gamma^{-1} < \beta < 27 h^{1/3} \alpha^{-1/3} \gamma^{-1}, \tag{21a}$$

$$0.027 h^{1/3} \alpha^{-1/3} < m_{3/2} < 0.4 \Omega_b^{-1/3} \alpha^{1/3}, \tag{21b}$$

and

$$1.6 \times 10^{-17} h^{-2/3} \alpha^{2/3} \gamma^2 < Y < 3.3 \times 10^{-15} (\Omega h^2/\alpha)^{-2/3} \gamma^2 \tag{21c}$$

These constraints are summarized in Fig. 1 where we have plotted the allowable regions in the $\beta - m_{3/2}$ plane. The limits coming from $1 + z_D > 1$ are in the upper right–hand corner for $h = 1/2$ and 1 are not very interesting. On the other hand, the limits from $\tau < 1$ show the excluded region in the lower left–hand corner for $h = 1/2$ and $h = 1$. All results plotted in the figure have assumed $\gamma = 2$. The line perpendicular to the limits represents a range of values about $\alpha = 1/32\pi$. Depending on the value of the photino mass, α may be much smaller (eq. (2)) (one must then readjust the limits for $\gamma > 2$).

Photinos themselves may also play an important role in cosmology. For example, photinos with a mass[19] in the range[10–12] $1 - 2GeV$ would provide a sufficient energy density so as to make $\Omega = 1$. This would make photinos a prime candidate for the dark matter of the Universe. Annihilations of photinos with mass around $2GeV$ in the halos of galaxies have also been suggested as a source for low energy cosmic ray antiprotons.[20] We have drawn a dashed vertical line in Fig. 1 to represent the cut off in the gravitino mass for which this effect is still possible. Our results with regard to the γ–ray background however apply to both sides of this line. We can now see that our expected range for Y corresponds rather well to the values of β needed to explain a possible feature in the γ–ray background spectrum[18] near $1MeV$, and falls within the limits due to photon absorption. All γ–ray experiments flown to date in the range $1 - 20MeV$ have confirmed the existence of a bump in the spectrum of diffuse $\gamma's$, and no satisfactory explanation exists.[20] The gravitino mass needed for the proposed decay mechanism is fairly unrestricted, although larger masses would require smaller couplings α.

Because of the absence of observed supersymmetric particles such as the selectron, most standard supersymmetric theories would require $m_{3/2} > 20GeV$. This is however a tree level estimate which is subject to gravitational radiative corrections[21]. A mass on the order of a few GeV is not unreasonable. There is also a class of supersymmetric theories called $SU(N,1)$ no–scale models[22] which are particularly attractive in that the only scale put in by hand is the Planck scale. The weak scale is then determined through radiative corrections. In these models however, the gravitino mass is not necessarily related to the weak scale or the mass splittings between particles and sparticles. Hence $m_{3/2}$ is arbitrary, leaving the horizontal axis in the figure completely unconstrained. The cross on the figure represents a concrete example. For $m_{3/2} = 4GeV, \alpha = \frac{1}{32\pi}$, and $m_{\tilde{\gamma}} = 2GeV(\gamma = 2)$, decays occur at a redshift $1 + z_D = 10^3 h^{-2/3}$ and a contribution comparable to the observed γ–ray background will appear at $\beta = 2h^{2/3}\left(E_\gamma = 2h^{2/3}MeV\right)$, for $Y \simeq 3 \times 10^{-15} h^{-4/3}$.

The required gravitino abundance lies in the expected range (9), and we have therefore arrived at a specific mechanism for explaining the γ– ray background spectrum near $1MeV$.

In the model considered here, the LSP is the photino and the next to LSP is the gravitino. We would now like to point out that this mechanism is more general than this specific choice. It is possible for example that in addition to the photino, other sparticles such as the gluino or sneutrino were also lighter than the gravitino. There are many possiblilities and it is not of interest to go in to all of them in detail, however; we can make some general statements. If other sparticles were lighter than the gravitino, the basic effect is to increase the decay rate (i.e. effectively increase α by perhaps an order of magnitude). If these sparticles were gluinos, one would be forced to perhaps too low a gravitino mass to be consistent with $m_{\tilde{g}} < m_{3/2}$. If it were the sneutrino, then in addition to the increased coupling, one could allow for an increased value of Y depending on the branching ratio of gravitino $\rightarrow \gamma + \tilde{\gamma}$ and gravitinos $\tilde{\nu} + \nu$. This last possiblility would work even if the photino was not the LSP provided the gravitino was heavier than both $\tilde{\gamma}$ and $\tilde{\nu}$. If $m_{\tilde{\nu}} < m_{3/2} < m_{\tilde{\gamma}}$, this mechanism fails. Finally if the gravitino is the LSP then only if the photino is the next to LSP are our results left unchanged; in this case the photino must decay into the gravitino by the same rate as in eq.(1).

Before concluding, we would like to point out that the gravitino is not the unique slowly decaying particle. Nearly all models of supergravity employ what is known as a hidden sector in order to break local supersymmetry. In these models there may be two or more scalar fields which couple only gravitationally to our standard low energy world. In the event that there are several scalars (which may also interact only gravitationally amongst themselves) it may be possible to produce photons of various energies.[23]

In summary, a plausible range of parameters (maximum reheating temperature, α, and mass $m_{3/2}$) results in gravitinos decaying at high redshift ($z \sim 1000$) and producing a possibly detectable diffuse gamma ray flux near $1 - 10MeV$. A most intriguing possiblility is that a possible feature in the diffuse gamma ray spectrum near $1MeV$ could actually be the signature of such decays. Far more exotic interpretations of this feature can be found in the literature[24]. Unfortunately, the spectral region near $1MeV$ is notoriously difficult to observe, and the reality of a spectral feature is not unambiguous, nor is the isotropy of the diffuse gamma rays well known in this region. We trust that our finding that gravitino decays yield an isotropic gamma ray flux will, especially if supersymmetry is supported by the recent CERN events stimulate gamma ray astronomers to renew their efforts to study the isotropy and spectrum of the gamma ray background near $1MeV$.

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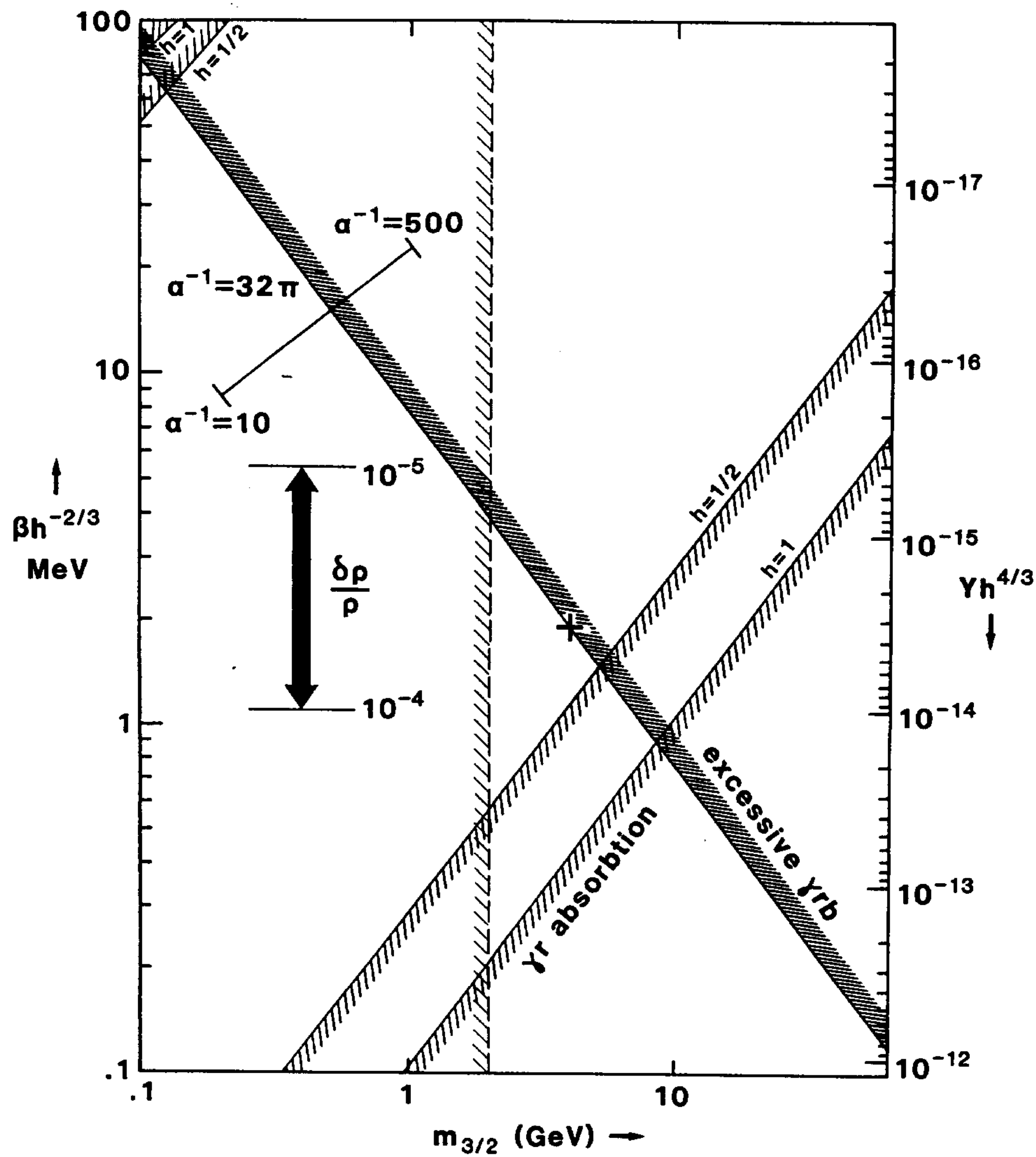
FIGURE CAPTION

Figure 1: Constraints in the $\beta - m_{3/2}$ plane, due to: photon absorption (cross–hatched lines); $z_D > 0$ (solid hatched line); and threshold for antiproton production from $\tilde{\gamma}$ annihilation[20] (dashed hatched line). The diagonal line corresponds to our predicted γ–ray yield for $\alpha = 1/32\pi$ and the scaling to other values of α is indicated. This determines an upper limit on Y to be read on the vertical scale on the right. Also indicated is the expected range for Y from density perturbations $\frac{\delta\rho}{\rho} \sim 10^{-4} - 10^{-5}$. The cross represents a particular example.



100
10
1
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h=1
h=1/2
α⁻¹=500
α⁻¹=32π
α⁻¹=10
βh⁻²ᐟ³
MeV
10⁻⁵
10⁻⁴
δρ/ρ
h=1/2
h=1
Yh⁴ᐟ³
10⁻¹⁷
10⁻¹⁶
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γr absorbtion
.1
1
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