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Astrophysical bounds on superlight gravitinos

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Abstract

We derive the allowed mass range for the superlight gravitino present in a large class of supersymmetric models from the observed neutrino luminosity from Supernova 1987A. We find that for photino masses of order of 100 GeV, the mass range 2.6×10^{-8} eV $\leq m_{\tilde{g}} \leq 2.2 \times 10^{-6}$ eV for the gravitino $\tilde{g}$ is excluded by SN1987A observations. Unlike the bounds on $m_{\tilde{g}}$ from nucleosynthesis, the bounds in the present paper do not depend critically upon the uncertainities of the observational input.

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In models of dynamical supersymmetry breaking where gauge interactions mediate the breakdown of supersymmetry [1] the gravitino is naturally light ($\ll$1 TeV). Indeed, it is supposed to be the lightest supersymmetric particle (LSP). While the precise value of its mass depends on the details of any given model, the general expectation is that its order of magnitude is given by $m_{\tilde{g}} \simeq \Lambda^2/M_{P\ell}$ where Λ is a typical SUSY breaking scale. For $\Lambda \simeq 100$ GeV, one gets $m_{\tilde{g}} \simeq 10^{-6}$ eV or so. It is however possible to imagine more general relations between the gravitino mass and the Λ such as $\Lambda \simeq (m_{\tilde{g}}/M_{P\ell})^{1-2/3q} M_{P\ell}$ [2], in which case scenarios with even lighter gravitinos could emerge (e.g. when $q > 3/4$). More importantly, the coupling of the gravitino to matter is inversely proportional to its mass (i.e. $g_{ff\tilde{g}} \simeq M_{\tilde{f}}^2/(m_{\tilde{g}} M_{P\ell})$) which increases as its mass decreases. Thus information about the gravitino mass provides us not only with direct information about the magnitude of supersymmetry breaking scale and the nature of SUSY breaking but also about possible experimental manifestation of supersymmetry (the lighter it is, the easier it is to produce them). Furthermore, cosmological significance of the gravitino also depends on its mass; for instance, only if its mass is as large a keV, can it be relevant for the dark matter problem [3].

In the absence any direct laboratory information about the gravitino mass[1)], it is necessary to look at phenomena that provide indirect information on $m_{\tilde{g}}$. Astrophysics and cosmology are the obvious places. In the domain of cosmology, the first place where gravitinos could alter the conventional arguments is the era of Big Bang Nucleosynthesis (BBN). It has been argued that superlight gravitino production can add to the energy density of the universe and thereby effect the predictions for the primordial ^{4}He abundance unless the gravitino mass is below some 10^{-6} eV [5]. This

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[1)] We however note that recent interpretation of the CDF $\gamma\gamma e^+ e^-$ event in terms of a light gravitino decay[4] of the photino seems to imply a gravitino mass in the eV range.

result follows from a careful reexamination of previous work of Moroi et al. [6]. This bound relies on allowing for less than 0.6 effective extra light neutrino degrees of freedom in the usual primordial ^{4}He abundance calculation. However, concern about systematic uncertainty in the ^{4}He abundance as well as the chemical evolution of ^{3}He has led to the re-examination this important limit [7] with the result that no more than the equivalent of 4 massless neutrino species are allowed. Here, we want to point out that, should one use this more conservative bound $\Delta N_\nu \leq 1$ [7, 8], and repeating the reasoning that led to $m_{\tilde{g}} \geq 10^{-6}$ eV, one would reach the much less restrictive constraint $m_{\tilde{g}} \geq 3.2 \times 10^{-9}$ eV. The reason is that if ΔN_ν is allowed to be one and there are no other light particle species than the particles of the standard model, then the gravitino need not decouple from the thermal bath of the universe prior to the BBN era. Its coupling to neutrinos and photons and hence its mass is less restricted$^{2)}$. Thus, the cosmological bound on the gravitino mass depends very dramatically on how many extra equivalent massless neutrinos does BBN actually allow. This is a not very satisfactory situation and one would prefer a bound less dependent on the actual number of extra light neutrino species permitted. Indeed, one would like to have an independent assessment of the bound on the gravitino mass coming from another physical input. In this letter, we shall use the observed SN1987A signal to limit the mass of the gravitino.

Since the gravitino has large coupling to the particles present in the supernova such as the photons and the leptons, for certain mass range of the gravitino, we expect significant gravitino production in the supernova core. If gravitino coupling is in such a range that, its mean free path after production exceeds the supernova radius of $10 - 30$ Km, then it will escape carrying energy from the supernova. The

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2) Note however that if $m_{\tilde{g}}$ is less than 10^{-8} eV or so,the amplitude for $e^+e^- \to \tilde{g}\tilde{g}$ becomes of order one which would be inconsistent with laboratory observations.

luminosity associated with gravitino emission by the core of the protoneutron star must however be bounded by $L \leq 10^{52}$ erg/s. This bound in fact applies to any particle other than neutrinos and is the well known constraint inferred from the detected neutrino events by Kamiokande and IMB on february 1987 [9] and from the predictions of models of stellar collapse [10].

The mechanisms that, in principle, contribute to gravitino production in the hot SN core are: gravitino pair production by photon-photon collisions, nucleon-nucleon bremsstrahlung of gravitino pairs (i.e. $NN \rightarrow NN\tilde{g}\tilde{g}$), bremsstrahlung of gravitinos in electron-electron scattering (i.e. $e^-e^- \rightarrow e^-e^-\tilde{g}\tilde{g}$), and pair production in e^+e^- annihilation. All of these processes can be evaluated using the effective Lagrangian obtained from the $N = 1$ supergravity theory which is explicitly given in ref. [5]. The leading contribution comes from $\gamma\gamma \rightarrow \tilde{g}\tilde{g}$. Other processes are subdominant.

Let us first discuss nucleon-nucleon bremsstrahlung of the $\tilde{g}\tilde{g}$ pair. Since the nucleon is nonrelativistic, we can consider the simple pion exchange model for the nucleon-nucleon scattering part [11] of the relevant Feynman diagram. There are four diagrams where the gravitino pairs could be emitted from the external legs. They all cancel in the nonrelativistic limit [11]. They could also be emitted from the internal pion line. To see why it is suppressed for the gravitinos pair emission can be seen as follows. The effective four-Fermi interaction involving the quark-anti-quark and $\tilde{g}\tilde{g}$ is parity conserving in the limit that left and right-handed squarks are degenerate in mass. Since the gravitino is a Majorana particle, the effective coupling can be inferred from ref. [5] to be of pure axial vector type, i.e. $\bar{q}\gamma^\mu\gamma_5 q\bar{\tilde{g}}\gamma_\mu\gamma_5\tilde{g}$. Since the axial vector current has odd G-parity, its matrix element between pion states vanishes. It is worth noting that while strict degeneracy between the squark states is not phenomenologically required, the fact that atomic parity violation experiments agree so well with the predictions of the standard model implies that they are degenerate at least to less than a few percent resulting in the suppression as mentioned. There is further suppression compared to $\gamma\gamma \rightarrow \tilde{g}\tilde{g}$ coming from the fact that the number density of photons at $T \sim 50$ MeV is larger then the number density of nucleon scatterers at (super) nuclear matter densities of the protoneutron star.

Bremsstrahlung production in electron-electron collisions is supressed by α^2 and, again by the fact that $n_{e^-} = n_p \ll n_\gamma$. Since positrons are rare in the stellar medium, e^+e^- annihilation is also unimportant. Therefore, the bulk of the gravitino emissivity is associated to the process $\gamma(k_1)+\gamma(k_2) \rightarrow \tilde{g}(q_1)+\tilde{g}(q_2)$ whose luminosity is explicitly given by

$$L = V \int \frac{d^3k_1}{2k_1^0}\frac{d^3k_2}{2k_2}\frac{d^3q_1}{2q_1^0}\frac{d^3q_2}{2q_2^0}\frac{1}{(2\pi)^{12}} n_\gamma(k_1^0) n_\gamma(k_2^0) \mid \mathcal{M} \mid^2 (q_1^0 + q_2^0)(2\pi)^4\delta^4(P_f - P_i), \quad (1)$$

where $\mathcal{M}$ is the amplitude, n_γ is the photon Bose-Einstein distribution function and V is the volume of the core. Using energy conservation and the definition of the cross-section for the process $\gamma\gamma \rightarrow \tilde{g}\tilde{g}$, Eq. (1) can be recast in the form

$$L = \frac{V}{(2\pi)^6}\int d^3k_1 d^3k_2 n_\gamma(k_1^0) n_\gamma(k_2^0)\frac{k_1^0 + k_2^0}{k_1^0 k_2^0}\, k_1 \cdot k_2 \;\; \sigma(\gamma\gamma \rightarrow \tilde{g}\tilde{g}), \quad (2)$$

where $\sigma(\gamma\gamma \rightarrow \tilde{g}\tilde{g}) = \frac{1}{576\pi}\left(\frac{1}{M_{P\ell} m_{\tilde{g}}}\right)^4 m_{\tilde{\gamma}}^2 s^2$, given in refs. [5, 12] and valid in the kinematical domain $s \ll m_{\tilde{\gamma}}^2$ (s is the C.M. energy squared, and $m_{\tilde{\gamma}}$ is the photino mass). Because $(e^{k_0/T} - 1)^{-1} > e^{-k^0/T}$ always, it follows that

$$L > \frac{V}{(2\pi)^6}\int d^3k_1 d^3k_2 e^{-k_1^0/T} e^{-k_2^0/T}(k_1^0 + k_2^0)(1 - \cos\theta)\sigma(\gamma\gamma \rightarrow \tilde{g}\tilde{g}) \quad (3)$$

where θ is the angle between the vectors $\vec{k}_1$ and $\vec{k}_2$. The above integral can be easily performed, and the final result is

$$L > \frac{20}{\pi^5}\left(\frac{1}{M_{P\ell} m_{\tilde{g}}}\right)^4 m_{\tilde{\gamma}}^2 \; V \; T^{11}. \quad (4)$$

Now we can use the observational bound $L \leq 10^{52}$ erg/s and obtain,

$$m_{\tilde{g}} > 2.2 \times 10^{-6} \left(\frac{m_{\tilde{\gamma}}}{100 \text{ GeV}}\right)^{1/2} \left(\frac{T}{50 \text{ MeV}}\right)^{11/4} \left(\frac{V}{4.2 \times 10^{18} \text{ cm}^3}\right)^{1/4} \text{eV}. \quad (5)$$

Of course, this bound is meaningful only if gravitinos free-stream out of the star. Therefore, we should check whether this is indeed true for gravitino masses that exceed 2.2×10^{-6} eV. The main opacity source comes from elastic scattering of the produced gravitinos with photons in the stellar plasma, $\tilde{g}\gamma \to \tilde{g}\gamma$, because *i)* $\sigma(\tilde{g}\gamma \to \tilde{g}\gamma) \gg \sigma(\tilde{g}f \to \tilde{g}f)$ where f denotes eiher electrons or nucleons, and *ii)* $n_\gamma \gg n_f$. Hence the mean-free-path of gravitinos in the stellar core is,

$$\lambda \sim \frac{1}{n\sigma} \sim \frac{2\pi^3}{9\zeta(3)} m_{\tilde{g}}^4 M_{P\ell}^4 m_{\tilde{\gamma}}^{-2} T^{-7} \quad (6)$$

or, putting numbers,

$$\lambda \sim 1.7 \times 10^4 \left(\frac{m_{\tilde{g}}}{2.2 \times 10^{-6} \text{ eV}}\right)^4 \text{Km} \gg 10 \left(\frac{R_{\text{core}}}{10 \text{ Km}}\right) \text{Km}, \quad (7)$$

which means that gravitinos, once produced, leave the star without rescattering.

It is clear from Eq. (7), on the other hand, that for sufficiently small $m_{\tilde{g}}$, gravitinos would diffuse in the core and therefore the bound in Eq. (5) would be no longer valid. If energy is depleted over times larger than the typical ~ 1 second period of neutrino energy emission from the neutrino-sphere, the luminosity associated with gravitino emission would be lower and eventually compatible again with the observational bound $L < 10^{52}$ erg/s. Let us next estimate the range of masses $m_{\tilde{g}}$ allowed by the slow ($t_{\text{diff}} \geq 1$ sec) diffusion of gravitinos. It takes a time $t = \frac{\lambda}{c} N$ and N scatterings for the gravitinos in the core to random-walk over a distance $R_{\text{core}} \sim \lambda\sqrt{N}$ and leave the star. If one requires $t \sim 1$ sec, the particle would leave the star after $\sim 9 \times 10^8$ collisions. This implies a mean-free-path on the order of 0.3 m. Using Eq. (6) we then obtain that $t_{\text{diff}} \geq 1$ sec for

$$m_{\tilde{g}} \leq 2.6 \times 10^{-8} \left(\frac{m_{\tilde{\gamma}}}{100 \text{ GeV}}\right)^{1/2} \left(\frac{T}{50 \text{ MeV}}\right)^{7/4} \text{eV}. \quad (8)$$

SN physics, therefore, forbids the range of gravitino masses from about 2.6×10^{-8} eV up to 2.2×10^{-6} eV. This result complements previous work on astrophysical bounds [13].

In conclusion, we have derived constraints on the mass of a superlight gravitino from supernova 1987A observations and find an interesting range of masses excluded by these considerations. In terms of the generalized mass formula for the gravitinos given in Ref. [2], our results imply $q \leq 3/4$ and the scale of supersymmetry breaking $\Lambda \geq 100$ GeV.

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