Supernova Constraints on a Superlight Gravitino

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In supergravity models with low supersymmetry breaking scale the gravitinos can be superlight, with mass in the $10^{-6}$ eV to few keV range. In such a case, gravitino emission provides a new cooling mechanism for protoneutron stars and therefore can provide constraints on the mass of a superlight gravitino. This happens because the coupling to matter of superlight gravitinos is dominated by its goldstino component, whose coupling to matter is inversely proportional to the scale of supersymmetry breaking and increases as the gravitino mass decreases. Present observations therefore provide lower limits on the gravitino mass. Using the recently revised goldstino couplings, we find that the two dominant processes in supernova cooling are $e^+e^-$ and $\gamma e^- \rightarrow e^-GG$. They lead to a lower limit on the supersymmetry breaking scale $\Lambda_S$ from 160 to 500 GeV for core temperatures 30 to 60 MeV and electron chemical potentials 200 to 300 MeV. The corresponding lower limits on the gravitino mass are $6 - 6 \times 10^{-6}$ eV.

I. INTRODUCTION

In supergravity models with a low supersymmetry breaking scale, the gravitino ($\tilde{G}$) mass is in the superlight range of $10^{-6}$ eV to few keV's since it is given by the formula $m_{\tilde{G}} \sim \frac{\Lambda^2_S}{2\sqrt{3}M_{Pl}}$ (where $\Lambda_S$ is the scale of supersymmetry breaking and $M_{Pl}$ is the Planck mass that characterises the gravitational interactions.) Any information on the gravitino mass therefore translates into knowledge of one of the most fundamental parameters of particle physics, the scale at which supersymmetry breaks.

There is an advantage in studying the gravitino's properties when its mass is in the superlight range because it can be easily emitted in astrophysical processes such as supernova cooling [1], neutron star cooling etc. This adds new cooling mechanisms to the already known ones for supernovae, i.e. the usual neutrino emission, which the observation of neutrinos from SN1987A seems to have confirmed. Any additional process can therefore afford a maximum luminosity of roughly $10^{52}$ ergs/sec. This will then lead to constraints on the parameters that describe the coupling of the gravitinos to matter in the supernovae. Furthermore since for light gravitinos one has $\tilde{G}_\mu \sim i\sqrt{\frac{2}{3}}m_{\tilde{G}}\gamma_\mu\chi$, the superlight gravitino coupling is dominated by the coupling of the goldstino to matter, which is inversely proportional to the supersymmetry breaking scale-squared $F \equiv \Lambda_S^2$. For values of $\Lambda_S$ in the 100 GeV to TeV range, the goldstino coupling strengths to matter are of the same order as the ordinary weak interactions. The gravitino emission in astrophysical settings such as the supernovae can therefore be competitive with the neutrino emission process. Observed supernova neutrino luminosity by the IMB and Kamiokande groups [2] and its understanding in terms of the standard model of the supernova [3] therefore allows us to set lower limits on $\Lambda_S$ and hence on $m_{\tilde{G}}$.

The supernova and other astrophysical constraints on the gravitino mass were first studied in two recent papers [1,5,4]. The first paper considered the class of models where the superlight gravitino is the only superlight particle in the model with its superpartners having masses in the GeV range whereas the last two papers considered the smaller subclass of models [5] where the gravitino is also accompanied by superlight scalar and pseudoscalar particles. In this paper we will focus on the first class of models.

In Ref. [1], gravitino couplings to matter suggested in Ref. [7] were used. These couplings have recently been criticized in two papers [9,10] and a new set of matter couplings have been proposed for the class of supersymmetry models where the scalar and pseudoscalar partners of the gravitino are heavier (e.g. in the multi GeV range) than the gravitino. Since the temperature dependence of gravitino emission rates are very different if one uses the new set of Feynman rules for gravitino matter couplings, it is necessary to revisit these bounds again. It is the goal of this paper to use the revised Feynman rules for matter gravitino coupling to calculate gravitino emission rates in supernovae, obtain the bounds on the supersymmetry breaking scale, and from them the lower limit on the gravitino
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Our result is that the basic processes that dominate the energy loss via gravitino emission are $e^+e^- \rightarrow \tilde{G}\tilde{G}$ (called annihilation process below) and $\gamma + e^- \rightarrow e^-\tilde{G}\tilde{G}$, (called Compton process below) whereas the process found to dominate in Ref. [1] i.e. $\gamma\gamma \rightarrow \tilde{G}\tilde{G}$ is found to make a negligible contribution. The physically interesting lower limit on the $m_\tilde{G}$ remains $\sim 3 \times 10^{-6} \times \left(\frac{M}{100\text{ GeV}}\right)^{1/2}$ eV (where $M$ is a model dependent parameter, which can lie anywhere from 50 to 250 GeV). This bound is qualitatively somewhat better than the one found in Ref. [1].

This paper is organized as follows: in section II, we note the various possible processes that can contribute to energy loss from supernovae via $\tilde{G}$ emission and, using simple dimensional analysis, obtain the temperature dependence of the emissivity for the different processes and give qualitative arguments to isolate the processes that dominate the emissivity; we calculate the emissivity ($Q$) for the Compton process in sec. III and for the annihilation processes in sec. IV and derive a lower bound on $\Lambda_S$ and $m_\tilde{G}$ from supernova; in section V we discuss the energy loss from neutron stars.

II. DOMINANT MECHANISMS FOR ENERGY LOSS VIA GRAVITINO EMISSION

Since gravitinos are superpartners of gravitons, which have universal coupling to matter, we expect them to couple to all matter in pairs. Specifically, in the case when the gravitino is superlight, the dominant couplings arise from the coupling of its longitudinal mode [11]. Goldstinos, like Goldstone bosons, must be derivatively coupled. Combining this property with the constraints of supersymmetry, Luty and Ponton [10] have derived the form of the effective coupling between matter and goldstinos. The couplings of interest to us are given by [10]

$$\mathcal{L}_{\chi\chi} = \frac{eM^2}{\Lambda_5^2} \partial^\mu \chi \gamma^\nu \chi F_{\mu\nu}$$

$$\mathcal{L}_{\chi\phi\bar{\psi}} = \frac{2}{\Lambda_5^2} \partial^\mu \chi \phi (D_\mu \bar{\psi})$$

$$\mathcal{L} = -\frac{i\sqrt{2}}{\Lambda_5^2} \theta^\mu \chi \gamma^\nu \lambda_A F_{\mu\nu} A$$

where we have denoted the goldstino by $\chi$ and the generic gaugino by $\lambda_A$ for the gauge field $A$. In the $\chi\chi$ coupling the mass parameter $M$ is highly model dependent and sensitive to the details of the supersymmetry breaking sector as well as the nature unification group$^2$. In Ref. [10] a value of 43 GeV is suggested assuming the typical slepton mass to be 200 GeV and the squark mass to be 400 GeV. But it is perfectly possible even in the context of gauge mediated models to have very different parameters e.g. slepton masses of 200 GeV and squark masses to be a TeV [12]. We have therefore kept this as a free parameter and express all our results in terms of this number.

We are now ready to discuss the detailed processes that can contribute to the energy loss in in a supernova. There are the following classes of processes: (i) ones that involve both nonrelativistic particles (e.g. neutrons and protons) and relativistic particles such as $e^\pm$, $\gamma$ and $\chi$; (ii) that involve only relativistic particles; and finally, (iii) the ones that involve the decay of the plasmon i.e. $\gamma^* \rightarrow \tilde{G}\tilde{G}$.

A typical process of type (i) is the analog of the modified URCA process for neutrino emission with neutrinos replaced by the gravitinos: $NN \rightarrow NN\chi\chi$. Even though the gravitino emission graph involves the exchange of a virtual photon, the derivative couplings present in the gravitino vertex imply that the photon-gravitino-gravitino coupling in momentum space goes like $k_1 \cdot k_2 = (k^2 - 2m_\tilde{G}^2)/2$ where $k_1 = k + k_2$ and $k_2$ are the gravitino momenta. For superlight gravitinos, the effective virtual photon induced $e^+e^- \rightarrow \tilde{G}\tilde{G}$ amplitude is like a pointlike four Fermi coupling with $G_F/\sqrt{2}$ replaced by $e^2M^2/8\Lambda_5$. One can therefore use this feature to calculate the gravitino pair

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$^1$As this paper was being prepared for publication, a paper by Grifols et al [8] appeared which used the revised Feynman rules to obtain a lower limit on the gravitino mass. While our final results are very similar, we find two processes dominating gravitino emission process whereas Ref. [8] considers only one of them.

$^2$For instance in grand unified theories with simple groups, at the GUT scale $M^2 = 0$. Therefore at low energies, this will give additional suppression factors
emissivity from the known the URCA processes [13]. One can conclude that the emissivity $Q$, defined as the amount of energy emitted from the supernova per unit volume per unit time ($E^5$ in natural units) is given by

$$Q_{NN} \simeq (164\pi^3/4725)\alpha^2\alpha^2_\gamma (M/\Lambda^2_\Delta)^4 p_F T^8$$  \hspace{1cm} (4)

Let us now consider several examples of the class (ii) processes. They are (a) $e^+e^- \rightarrow \gamma \gamma$; (b) $\gamma + e^- \rightarrow e^- + \gamma \gamma$; (c) $\gamma + \gamma \rightarrow \gamma \gamma$. Let us first focus on the process (c) which is the weakest of the three. Since this process involves exchange of a photon, its coupling strength is given by $\sim e^2/(\Lambda^4_\Delta M_{\Delta})$. Therefore from simple dimensional arguments we conclude that the emissivity for this process will go like $\sim (\alpha^2/\Lambda^8_\Delta M_{\Delta}) T^{14}$. Let us now apply similar dimensional arguments to the process (b). In this case the Feynman diagrams that contribute are given in Fig. 1. Note that all exchange particles are also light. Therefore the only dimensional parameters are provided by the photogravitino coupling strength $M^2/\Lambda^2_\Delta$. Using dimensional analysis, one gets the following temperature dependence for $Q$:

$$\sim \alpha^2 \left( \frac{M}{\Lambda^2_\Delta} \right)^4 T^8.$$  \hspace{1cm} Here, we have ignored the effects of Pauli exclusion principle in this estimate; this will be addressed below. But assuming that this effect does not lead to a drastic change in temperature dependence, we see that it clearly dominates over the process (c) since supernova core temperatures are of order 30 to 60 MeV.

Process (a) is more subtle since the electrons are degenerate in the supernova core. As a result of this the positron density is suppressed compared to that of the electron by by $(T/\mu)^3 e^{-\mu/T}$, where $\mu$ is the chemical potential for the electrons. Therefore even though the naive dimensional arguments imply that for this process, the emissivity goes like $\alpha^2 \left( \frac{M}{\Lambda^2_\Delta} \right)^4 T^8$ and is therefore more dominant than the process (b), we will see that in actual practice they are comparable.

The plasmon decay has been considered in [8] and is found to be negligible. We therefore do not discuss it here.

III. CALCULATION OF THE EMISSIVITY VIA THE COMPTON PROCESS

The generic formula for the emissivity $Q$ for a process with initial particles and momenta denoted by $i_a$ and $p_{i_a}$ and final state particles and momenta denoted by $f_\alpha$ and $p_{f_\alpha}$ is:

$$Q = \int \Pi_{i_a} \frac{d^3p_{i_a}}{2E_{i_a}} \frac{d^3p_{f_\alpha}}{2E_{f_\alpha}} (2\pi)^4 \delta(\sum_{i_a} p_{i_a} - \sum_{f_\alpha} p_{f_\alpha}) (1 - f(p_{f_\alpha})) |M_{i_f}|^2 (E_{f_1} + E_{f_2})$$

In the equation above, $M_{i_f}$ denotes the matrix element for the process responsible for gravitino emission; $E_{f_1}, f_2$ are the energies of the gravitinos; $f(p)$ are the thermal distributions for the various particles involved in the process. For example the thermal distribution of the electrons and positrons are given by:

$$f_{e^\pm} = 1/(e^{\mp\mu/T} + 1)$$

where $\mu$ is the chemical potential for the electrons. Similarly for the photons we have $f_\gamma(p) = 1/(e^{\mu/T} - 1)$. For the gravitinos, we choose the $f$'s to be zero since they do not get a chance to thermalize in the supernova.

Let us apply this formula to the Compton process which is given by the two Feynman diagrams in Fig. 1. Let us denote the initial and final momenta as follows:

$$\gamma(p_1) + e(p_2) \rightarrow e(p_2) + \gamma(k_1) + \gamma(k_2)$$

In evaluating $|M|^2$ for this process, we note that the $\gamma\gamma$ vertex is common to both the direct and the cross diagrams. Therefore, we evaluate that absolute square first as follows:

$$|V|^2 = \int \frac{d^3k_1 d^3k_2}{2k_{10} 2k_{20}} \delta^4(k - k_1 - k_2) \Sigma_v |V_{\gamma\gamma\gamma}|^2$$

where

$$V_{\gamma\gamma\gamma} = \frac{eM^2}{2\Lambda^2_\Delta} k_1 k_2 \bar{u}(k_1) \gamma^\alpha u(k_2)$$

and

$$\Sigma_v = \frac{1}{2\Lambda^2_\Delta} k_1 k_2 \bar{u}(k_1) \gamma^\alpha u(k_2)$$
Using its gauge invariance, one can write this as

$$|V|^2 = A(k^a k^b - g^{a2} k^2)$$

where $A$ is easily evaluated to be $\frac{2\pi \epsilon^4 M^4}{3 \Lambda^4}$. The matrix element $M_{ij}$ is given by

$$M_{ij} = e^2 V e^a \tilde{u}(p_2)[\gamma^a(\gamma \cdot (q + p_1) - m)\gamma^a + \gamma^a(\gamma \cdot (p_2 - q) - m)]u(p_1)$$

One can then combine the above equations to write the final formula for emissivity as follows:

$$Q_{\text{comp}} = \alpha^3 \left( \frac{M}{\Lambda^2} \right)^4 \int \frac{d^3 p_1 d^3 p_2 d^3 q}{p_1 p_2 q} \frac{1}{E_k f(p_1) f(q) (1 - f(p_2))} k^2 [2 \gamma X_i / \alpha_i]$$

where $\beta_1 = (2q \cdot p_1)^2$, $\beta_2 = (2q \cdot p_2)^2$, and $\beta_3 = -2q \cdot p_1 q \cdot p_2$ and

$$X_1 = 2(2m^4 + m^2 (2q \cdot p_1 - q \cdot p_2 - p_1 \cdot p_2) + q \cdot p_1 q \cdot p_2)$$

$$X_2 = 2(2m^4 + m^2 (q \cdot p_1 - 2q \cdot p_2 - p_1 \cdot p_2) + q \cdot p_1 q \cdot p_2)$$

$$X_3 = 16 m^2 (q \cdot p_2 - q \cdot p_1) + 2q_1 p_2 (q \cdot p_1 - q \cdot p_2 - p_1 p_2 + 2m^2)$$

This integral was evaluated by Monte carlo method to obtain the emissivity as a function of the supernova core temperature and the parameters $M$ and $\Lambda$. Multiplying by the volume of the supernova (with radius 10 kilometers), we obtained the luminosity which was then set less than $10^{52}$ ergs/sec. The bound on the parameter $\Lambda$ for $M = 100$ GeV are given table I.

We also wish to point out that we have checked plasma screening effects on our result by redoing the calculation with the propagator $k^2$ replaced by $k^2 + k^2_{pl}$ (with $k_{pl}$ as given in Braaten and Segel [14] in the relativistic limit). We find that these effects are well below 5% level as might be expected from the $k_1 \cdot k_2$ factor in Eq. (9).

### IV. CONTRIBUTION OF ELECTRON POSITRON ANNIHILATION TO EMISSIVITY

Using similar methods as in section III, we have calculated the emissivity in this case and find

$$Q_{\text{ann}} = 8 \alpha^2 (M / \Lambda^2)^4 T^4 e^{-\mu / T} \mu^5 \vartheta(\mu / T) / 15\pi^3$$

where $\vartheta(y) \equiv (5/6)e^y y^{-5} (F_1^+ F_2^- + F_1^+ F_2^-)$ where $F_1^+(y) = \int dx e^{-y} / (1 + e^{x+y})$. Our expression agrees with that calculated in the Ref. [8]. We have adopted their notation in Eq. (14). We have evaluated the integrals in the above expression numerically and have obtained lower bounds on the $\Lambda$ using the requirement that the luminosity in gravitinos have an upper bound of $10^{52}$ ergs/sec. The results for this case are comparable to the limits derived from the Compton cooling case and both cases are collected in Table I. We have varied the core temperature from 30 to 60 MeV and used two typical values for the electron chemical potential of 200 and 300 MeV. Again, since the dependence of the luminosity on the supersymmetry breaking scale goes like the eighth power of temperature, for each case the bigger of the two numbers is the actual bound. We see that the bound best obtains for the case when the core temperature is assumed to be 60 MeV as expected and the chemical potential is 200 MeV and is

$$\Lambda \geq 500 \text{ GeV}$$

(15)

For the case where $T_c = 50$ MeV and $\mu = 300$ MeV, the bound is $\Lambda \geq 300$ GeV for both the Compton and the annihilation cases. Combining these two together we get the bound to be $\Lambda \geq 3^{1/8} \times 300 = 325$ GeV for this choice of supernova parameters. Our bound is actually slightly weaker than the bound given in [8] using only the $e^+e^-$ annihilation mechanism. Note that we have a higher value for $M$.

Finally, as was first pointed out in [1], the above considerations assume that the supernova is transparent to the gravitinos once they are emitted. To check this, we have to make sure that the mean free path of the gravitino, once emitted is longer than the radius of the supernova (i.e. 10 km). In Ref. [1], the mean free path was calculated using photon-gravitino scattering. Now of course due to the revised Feynman rules, the whole picture is different. The main contribution to opacity comes from gravitino scattering off protons and electrons. The mean free path for $\Lambda = 300$ GeV due to proton scattering has been calculated in [8] and we do not repeat their calculation. They find that for $\Lambda \leq 220$ GeV, the gravitinos get trapped. Using the techniques employed in [15], they have shown that the emissivity remains too large until $\Lambda \leq 70$ GeV, so that the excluded range of $\Lambda$ is between 70 GeV and 300-500 GeV depending on the choice of supergravity temperature and the electron chemical potential. This can be translated to a forbidden range for the gravitino mass of $10^{-7} \text{ eV} \leq m_{\xi} \leq 6 \times 10^{-6} \text{ eV}$. This bound is very similar to the bound obtained in [1].
V. NEUTRON STAR COOLING CONSTRAINTS

Neutron star cooling is an attractive area in which to test non-standard particle physics models, in principle, because the standard model of neutron cooling, based on the "modified URCA process," gives insufficient cooling to match current observations. For a recent review and references to the literature see [16]. Briefly, for neutron stars of ages between about $10^2$ and $10^5$ years, the standard model (slow cooling) is one of neutrino emission from an isothermal superfluid core with an energy gap in the 100 keV range. However data from two pulsars of ages around $10^4$ years show temperatures a factor of 5 or so below the standard model prediction. Time is measured by $P/(2\pi)$ where $P$ is the pulsar period while temperature is measured from the (X-ray) black body spectrum (keeping in mind that the surface temperature is believed to be roughly the square root of the interior temperature (in eV)). For earlier times only a few upper bounds are available so that there is no good evidence on the temperature dependence of the mechanism that is providing the extra (fast) cooling. However, considerable extra cooling is required since the URCA cooling rate is proportional to the eighth power of the temperature.

Various mechanisms to provide the extra cooling have been proposed. These include a smaller superfluid energy gap, meson condensates, and nucleon dissociation into quarks under the high central pressure. Were gravitino emission the source of the extra cooling, that fact would provide a measurement of gravitino coupling rather than a bound. Thus we turn to the question of whether that possibility can be entertained.

As noted earlier, the effective coupling of the gravitino pair to electrons and quarks is via the photon exchange – however for superlight gravitinos, it reduces effectively to a four Fermi interaction like the weak Fermi coupling except that the coupling only occurs with electrically charged particles. One channel for neutron star cooling that involves gravitino emission is therefore via a neutral current like coupling with the coupling constant given by $qae^2M^2/(4\pi\sigma)$. Thus the relevant process is the analog of the neutral current URCA process $n + p \rightarrow n + p + \bar{G}G$. The temperature dependence of this process will be $T^8$ as in the URCA process. So it can compete with the neutrino cooling of neutron stars in the appropriate range for the coupling parameters. Assuming that neutrino luminosity describes the cooling of neutron stars long after their birth [16], we assume that luminosity via gravitinos is of same order of magnitude. (We choose this arbitrarily in view of the scant data on neutron stars at the moment.)

As is well known, in the case of the neutron stars the neutral current driven URCA process is about a factor of 30 lower [13,17] than the corresponding charged current process, of which a factor of four comes from the coupling and the rest from phase space. Since our couplings are given, we demand that gravitino cooling be less than the full neutrino URCA process luminosity. This leads us to the bound that

$$\frac{4\pi aM^2}{2\Lambda_8^8} \leq \frac{G_F}{\sqrt{2}}$$

This implies that $\Lambda_8 \geq 200$ GeV, which is comparable to the bounds obtained from the supernova. Considerably larger coupling, contrary to the supernova bounds derived above, would be required for gravitino emission to provide an explanation for the fast neutron star cooling observed.

VI. CONCLUSION

In conclusion, we have revisited the issue of supernova and neutron star constraints on the supersymmetry breaking scale and the ensuing constraint on the mass of the superlight gravitino using the revised Feynman rules for the goldstino coupling to matter in a large class of supersymmetric models with a low SUSY breaking scale. We find that the lower limits on the supersymmetry breaking scale $\Lambda_8$ are in the range of 200 to 500 GeV and the resulting lower limit on the gravitino mass is $6 - 6 \times 10^{-6}$ eV. One must however remember that while the form of the gravitino coupling to matter is universal, there is a model dependent parameter $M$ that characterises the strength of the coupling. In any case, these bounds are comparable to the collider bounds obtained by various authors [18]. As has been noted earlier [4], the corresponding constraints on the gravitino mass are much more severe in models where the gravitino is also accompanied by superlight scalar/or pseudoscalar particles.

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Table I

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Table caption: The lower bounds on the supersymmetry breaking scale $\Lambda_S$ in GeV derived from the two dominant processes in the supernova for various values of core temperature $T_c$ in MeV and electron chemical potential $\mu_e$ in MeV. We have chosen $M = 100$ GeV.

Figure caption Feynman diagram for Compton cooling where the lower solid line denotes the electron, the wavy lines denote the photon and upper external solid lines denote the gravitino pair.

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