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New Astrophysical Constraints on the Mass of the Superlight Gravitino

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In some supergravity models, the superlight gravitino is accompanied by a light weakly coupled scalar (S) and pseudoscalar particle (P). The couplings of these particles to matter (e.g. electrons and photons) is inversely proportional to the product $(m_{\tilde g} M_{P\ell})$ where $m_{\tilde g}$ and $M_{P\ell}$ are respectively the gravitino mass and the Planck mass. As a result, their emission from supernovae and stars via the reaction $\gamma + e^- \to S/P + e^-$ for certain ranges of the gravitino mass can become the dominant energy loss mechanism in contradiction with observations thereby ruling out those mass values for the gravitino. For 10 MeV$\geq m_{S/P} \geq$ keV, the SN1987A observations can be used to exclude the gravitino masses in the range, $(10^{-1.5} \leq m_{\tilde g} \leq 30)$ eV whereas if $m_{S/P} \leq$ keV, constraints of stellar energy loss can exclude the range $(3 \times 10^{-6} \leq m_{\tilde g} \leq 50)$ eV for the photino mass equal to 100 GeV. We also find that if $m_{S/P} \leq$ MeV, present understanding of Big Bang Nucleosynthesis imply that $m_{\tilde g} \geq$ eV. These are the most severe bounds to date on $m_{\tilde g}$ in this class of models.

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In generic supergravity models the gravitino ($\tilde g$) mass is given by the formula $m_{\tilde g} \sim \frac{\Lambda^p_{\rm SUSY}}{M^{p-1}_{P\ell}}$ where $\Lambda_{\rm SUSY}$ is the scale of supersymmetry breaking and $M_{P\ell}$ 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. In this letter, we consider a class of supergravity models, which have a superlight gravitino, $\tilde g$ and discuss new astrophysical constraints on the allowed mass range for the gravitino, when it is accompanied by a superlight scalar (S) and pseudo-scalar (P) particle.

Typical example of models where a superlight gravitino may arise are the so-called GMSB models, where gauge interactions mediate the breakdown of supersymmetry [1] or the class of models where an anomalous $U(1)$ gauge symmetry induces SUSY breaking, (provided one chooses the SUSY breaking scale to be in the TeV range rather than 10^{11} GeV considered in several examples [2]). In these models, the above formula for $m_{\tilde g}$ comes with a value for $p = 2$ and the low value for the scale $\Lambda_{\rm SUSY}$ then tells us that the mass of the gravitino in this class of models is anywhere between 10^{-6} eV to a keV. There is also a class of no-scale models [3] where gravitinos can be superlight. In all these models, gravitino is supposed to be the lightest supersymmetric particle (LSP). Not all these models will have superlight S/P particles accompanying the gravitino; however, in a subclass of them [4], $\tilde g$ as well as S/P will remain superlight. These particles as well as the gravitino are coupled to visible matter via couplings which are inversely proportional to the product $(m_{\tilde g} M_{P\ell})$ [5]. Therefore for superlight gravitinos, the Planck mass suppression in the couplings can be overcome by the small value of $m_{\tilde g}$ leading to an enhancement of their production in both colliders [6] as well as astrophysical and cosmological setting such as stars [7], supernovae [8] and the early universe [9]. They also lead to enhanced contributions to low energy parameters such as the $g-2$ of the muon [10]. Presently available information in particle physics as well as astrophysics can therefore be used to constrain the mass of the gravitino, which in turn can be used to gain information on the scale of supersymmetry breaking.

In a recent paper [8], we showed that if the gravitino is the only superlight particle in the theory, (or $m_{S/P} \geq 100$ MeV) observed supernova neutrino luminosity by the IMB and Kamiokande groups [11] and its understanding in terms of the standard model of the supernova [12] allows us to exclude the range of its mass between 10^{-8} eV to 10^{-6} eV. The main production channel for gravitinos responsible for draining energy away from the neutrinos (and hence leading to this bound) turns out to be $\gamma\gamma$ collision. On the other hand if the gravitino is accompanied by superlight S/P particles, then S/P can be produced via the reaction $\gamma + e^- \to S/P + e^-$ opening up a new channel for energy loss. It is the purpose of this paper to report on our study of how the presence of this reaction channel effects the photon emission from supernovae, stars and the considerations of big bang nucleosynthesis (BBN).

In the case of the supernova, we require first that the emission of the S/P particles do not drain more than 10^{52} ergs/sec of the energy, which enables us to put a lower bound $m_{\tilde g} \geq 30$ eV if $m_{S/P} \leq 10 MeV$. It however turns out that as $m_{\tilde g}$ goes below 0.3 eV, its mean free path becomes less than the radius of the supernova core and the usual energy loss discussion does not apply. An extension of this excluded range can then be obtained from energy loss from Red Giants and the Sun considered in Ref. [7] and reconsidered here to give $(10^{-3.5} \leq m_{\tilde{g}} \leq 50)$ eV. We show that further restrictions on $m_{\tilde{g}}$ can be obtained by using the recent result of Kolb, Mohapatra and Teplitz [13] which says that if the mean free path of the photon is more than ten times that of the S/P particles, then the photon luminosity of stars will be severely depleted. Requiring that the photon luminosity depletion does not conflict with observations, we find the new excluded range on $m_{\tilde{g}}$ to stretch further down to 3×10^{-6} eV. Combining all these results then enables us to derive the excluded range for $m_{\tilde{g}}$ for this special class of models with superlight S/P to be: $(3 \times 10^{-6} \leq m_{\tilde{g}} \leq 50)$ eV provided $m_{S/P} \leq 1\ keV$. This is the most severe lower bound on $m_{\tilde{g}}$ to date.

We also study the effect of S/P production in the BBN era of the early universe and conclude that unless the gravitino mass is larger than an eV, the success of the big bang model in explaining the observed primordial Helium abundance will be hard to understand. This bound is considerably better than the one derived in [9]. We note in passing that recent interpretation of the CDF $\gamma\gamma e^+ e^-$ event in terms of a light gravitino decay [14] of the photino seems to imply a gravitino mass less than 250 eV or so which is allowed by our considerations.

To start our discussion let us write down the coupling of the S/P particles to the photons [4] that results from the superHiggs mechanism [15] of the supergravity theories:

$$e^{-1}L = -\frac{\kappa}{4}\sqrt{\frac{2}{3}}\left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}}\right)\left(SF^{\mu\nu}F_{\mu\nu} + P\tilde{F}^{\mu\nu}F_{\mu\nu}\right), \qquad (1)$$

where $M_{\tilde{\gamma}}$ is the photino mass and $\kappa = \sqrt{8\pi}/M_{P\ell}$. ($\tilde{F}$ is the dual of the photon field strength.) We did not display the S/P couplings to the electrons since they do not carry the $(m_{\tilde{g}})^{-1}$ enhancement in their couplings and are therefore negligible in their contribution to the process $\gamma + e^- \to S/P + e^-$ compared to interactions shown in Eq. (1). This scattering channel arises from the Primakoff process involving the $S/P\gamma\gamma$ vertex at one end of the Feynman diagram and the usual electromagnetic coupling at the other. One can then calculate the cross-section for the production S/P particles in $e^- + \gamma$ collisions to be [7]

$$\sigma(\gamma e^- \to S/Pe^-) = \frac{\kappa^2 \alpha_{em}}{6} \times \left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}}\right)^2 \left(2\ln\left(\frac{E_\gamma}{m_{S/P}}\right) + 2\ln 2 - 1\right). \qquad (2)$$

To obtain an estimate of the amount of energy lost from the supernova core in S/P emission, we write

$$Q_{S/P} \simeq V n_\gamma n_e \sigma(\gamma e \to S/Pe) E_{S/P} \qquad (3)$$

Using $E_{S/P} \simeq 150$ MeV and $n_e \simeq 1.6 \times 10^{38}$ cm^{-3} and $n_\gamma(T) \simeq \frac{2\zeta(3)}{\pi^2}T^3$ and requiring that $Q_{S/P} \leq 10^{52}$ ergs/sec., we find that $\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}} \leq 10^{9.5}$. For the photino mass of 100 GeV, this implies $m_{\tilde{g}} \geq 30$ eV.

Since the S/P can decay to two photons with a decay rate given by $\Gamma_{S/P} \simeq \frac{\kappa^2}{96\pi}\left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}}\right)^2 m^3_{S/P}$, it is easy to check that for $M_{\tilde{\gamma}} = 100$ GeV, S/P particles heavier than 10 MeV will have decay length of about $300R_{SN}$. We therefore conservatively assume that the above bound holds for $m_{S/P} \leq 10$ MeV.

In the derivation of the lower bound on the gravitino mass given above, we have assumed that all the S/P particles produced escape the supernova core. To check this let us calculate the mean free path $\lambda_{S/P}$ of the S/P particles: $\lambda_{S/P} \sim (n_e \sigma(S/Pe \to \gamma e))^{-1}$. We find that $\lambda_{S/P} \sim 10^{10}\left(\frac{m_{\tilde{g}}}{30\ \mathrm{eV}}\right)^2$ cm. Thus as long as $m_{\tilde{g}} \geq 0.3$ eV, the $\lambda_{S/P} \geq R_{SN}$ and the S/P particles escape after production and our bound applies. Once the mass of the gravitino is below this value (0.3 eV), the S/P particles get trapped and form an S/P sphere and the luminosity in S/P depends on the radius $R_{S/P}$ of this sphere. Using the method given in [16], we can calculate the $R_{S/P}$ and we find it to be $R_{S/P} \sim \left(\frac{5}{4}\kappa^2 \alpha_{em} n_c R_c \left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}}\right)^2\right)^{1/2} R_c$. In this expression, n_c and R_c denote respectively the core number density and the core radius. Here we have assumed that the density of the supernova goes down like $\rho(R) = \rho_C (R_c/R)^3$ [17]. Now demanding that $\frac{Q_{S/P}}{Q_\nu} \equiv \left(\frac{T_{S/P}}{T_\nu}\right)^4 \left(\frac{R_{S/P}}{R_\nu}\right)^2 \leq 10^{-1}$, we find the allowed range for gravitino masses to be for $m_{\tilde{g}} \leq 10^{-1.5}$ eV. Thus SN1987A observations seem to exclude the domain of masses between $(10^{-1.5} \leq m_{\tilde{g}} \leq 30)$ eV.

To explore further restrictions on the gravitino mass, let us look at the stellar energy loss via S/P emission. It is well-known that if light scalar/pseudo-scalar particle have two photon couplings, then via the Primakoff process, they constribute to energy loss in stars [18,19]. There are two ways to get such constraints. One is to look for the parameter domain for which the mean free path for the S/P particle is larger than the stellar radius ($\geq 10^{11}$ cm). In this case, any production of S/P particle subtracts from the photon luminosity and must therefore be a small fraction of the observed luminosity- i.e. the rate of energy loss $d\epsilon_\odot/dt \leq 17$ ergs gm^{-1} sec^{-1} for the Sun and $d\epsilon_{RG}/dt \leq 10^2$ erg gm^{-1} sec^{-1} for the Red Giant. This point has already been noted in [7]. To derive the relevant constraints for this case, we first note that the mean free path for the S/P particle is given roughly by $\lambda_{S/P} = \frac{1}{\sigma_{Se} n_e} \sim 10^{41}\left(\frac{m_{\tilde{g}}}{M_{\tilde{\gamma}}}\right)^2$ cm. This implies that mean free path exceed the typical solar radius for $m_{\tilde{g}} \geq 10^{-3.5}$ eV. For this range of masses the energy loss rate is given by (considering scattering off electrons as well as protons):

$$d\epsilon/dt \simeq \frac{(n_e + n_p) n_\gamma \sigma_\gamma E}{\rho} \qquad (4)$$

where ρ denotes the core density. Putting in the values for the different parameters for a typical star, one obtains the result of Ref. [7] that $m_{\tilde{g}} \leq 500$ eV . In the discussion of Ref. [7], the effect of the stellar plasma has not been included. Incorporating these effects leads to the formula (see Ref. [19], Eq. (5.9)) for energy loss per unit volume of the star via S/P particles to be:

$$Q_{S/P} \simeq \alpha_{em} \kappa^2 \left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}} \right)^2 T^7 I \tag{5}$$

where I is a function which has been calculated by Raffelt [19] to be 1.84 for the Sun. Requiring that $V_{\odot} Q_{S/P} \leq 10^{33}$ ergs/sec. ($V_{\odot}$ being the volume of the Sun), we get $m_{\tilde{g}} \geq 50$ eV which is a factor of 10 weaker than the bound of Ref. [7]. Thus the excluded mass range for the gravitinos that comes from this discussion is $(10^{-3.5} \leq m_{\tilde{g}} \leq 50)$ eV.

Let us now turn to the second new result of this paper which constrains the gravitino masses below $10^{-3.5}$ eV or so when the mean free path of S/P particles is less than the solar radius. In this case, we use the argument of Ref. [13], which goes as follows: if in photon scattering off electrons or protons, one produces a very weakly coupled particle such as the S/P in addition to the photon a small fraction of the time, the large number of photon electron collisions undergone by the photon as it random walks its way out of the star causes depletion of the photon flux into a flux of the weakly coupled particle (in this case S/P). This depletion can be excessive unless the $S/P + e$ scattering rate is close to that of the Compton scattering in which case back reaction $S/P + e^- \rightarrow \gamma + e^-$ regenerates the lost photons. In terms of the parameter A defined as $A \equiv \frac{\sigma_{\gamma+e \rightarrow S/P+e}}{\sigma_{\gamma+e}}$, the result of Ref. [13] is that $A \geq 0.1$. For a star, we find

$$A \simeq \frac{\kappa^2 \alpha_{em}^{-1} m_e^2}{6\pi} \left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}} \right)^2 \times 2 \ln(E/m_{S/P})) \tag{6}$$

The condition $A \geq 0.1$ then translates to $m_{\tilde{g}} \leq 10^{-9}$ eV. However, for $m_{\tilde{g}} \leq 3 \times 10^{-6}$ eV, the S/P will decay inside the star to photons and will regenerate the lost photons. So the real upper limit from the above argument is 10^{-6} eV. Note that there are lower limits $m_{\tilde{g}} \geq 10^{-6}$ eV to 10^{-4} eV from collider data [6] and 2×10^{-6} eV from present $g-2$ measurements [10] as well as from the supernova [8]. Combining these results, we get the results announced in the beginning that for the class of models with superlight S/P particles accompanying the superlight gravitino, any value of mass for the superlight gravitino below 50 eV appears to be ruled out for $M_{\tilde{\gamma}} \simeq 100$ GeV provided the mass of the S/P particles are below one keV. This is the most stringent lower bound on the gravitino mass to date in this special class of models.

We also note that the existence of the scattering mode $\gamma + e^- \rightarrow S/P + e^-$ effects the Helium synthesis in the early universe unless the gravitino mass is in the eV range or more. To see this let us compare the production rate of S/P particles at the era of BBN with the Hubble expansion rate of the universe. This gives

$$\frac{5}{3} (\kappa^2 \alpha_{em}) \left(\frac{M_{\tilde{\gamma}}}{m_{\tilde{g}}} \right)^2 T^3 \simeq g_*^{1/2} \frac{T^2}{M_{P\ell}} \tag{7}$$

In order for nucleosynthesis results to be uneffected (or for us to satisfy the bound on extra effective number of neutrinos $\Delta N_{\nu} \leq 1$ [20]), we must have the S/P as well as the gravitinos decouple before the temperature of the universe reaches $T \simeq 200$ MeV. Using this value in Eq. (7), we readily deduce that $m_{\tilde{g}} \geq 1$ eV. This is a much stronger bound on the gravitino mass than was derived in [9].

In conclusion, for a large class of supergravity models where the superlight gravitino is accompanied by a superlight scalar and pseudo-scalar particle, all gravitino masses below 50 eV are ruled out from considerations of energy loss from the stars for $m_{S/P} \leq keV$ and those below 1 eV are ruled out by the BBN argument for $m_{S/P} \leq 1 \ MeV$. These results have important implication for the scale of supersymmetry breaking because of the intimate connection between the gravitino mass and the $\Lambda_{\rm SUSY}$ stated in the beginning. The precise lower limit on $\Lambda_{\rm SUSY}$ however depends on the power p in the formula, which depends on specific supergravity model; for instance if $p \geq 2$, we find that $\Lambda_{\rm SUSY} \geq 300$ TeV from the stellar bound and ≥ 50 TeV from the BBN bound.

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