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Constraint on unstable photino mass from a superlight gravitino

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Abstract. The known lower bound on the unstable photino mass gets invalidated by a gravitino lighter than 10^{-3} eV. Nevertheless, general bounds can be derived by feeding early universe constraints from the primary abundance of He^4 and the extant lower bound on the gravitino mass into the lifetime for the decay photino→photon + gravitino. The mass-range $O(100)$ eV to $O(1)$ MeV is excluded.

Keywords. Unstable photino; gravitino; supersymmetry.

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Interaction characteristics and constraints from the early universe can form a cogent combination in restricting the masses of certain weakly interacting elementary particles. Take the photino $\tilde{\gamma}$ for instance. This spin 1/2 neutral Majorana particle is the superpartner of the photon in supersymmetric (Bagger and Wess 1983) gauge theories. Since such supersymmetry is known to be broken* in nature, the photino must be massive. Photinos with energies below the threshold for producing charged superparticles are very weakly interacting and consequently hard to detect. Nevertheless, there exist laboratory limits on the process $e^+e^- \to \gamma\tilde{\gamma}\tilde{\gamma}$ constraining the photino not to be too light unless the selectron exchanged in the process is too heavy (Haber and Kane 1985). On the other hand, too heavy a selectron reduces $\tilde{\gamma}\tilde{\gamma}$ creation/annihilation cross-sections to such an extent that the photino decouples too soon in the early universe; consequently the critical density is adversely affected. The trade-off between these two requirements takes place for a photino mass $m_{\tilde{\gamma}}$ higher than** 2 GeV and lower than $O(10^2)$ eV. Therefore the mass of a stable photino cannot lie between these two values (Goldberg 1983; Krauss 1983). Unfortunately, for unstable photinos no such reliable bounds exist and this is the problem that we address here.

R-parity, a generally accepted good quantum number in supersymmetric theories, dictates stability for the lightest supersymmetric particle (LSP). Thus, in case $\tilde{\gamma}$ is not the LSP, it is likely to be unstable. Could the sneutrino $\tilde{\nu}$, the scalar superpartner of the neutrino, be lighter than $\tilde{\gamma}$ thereby allowing the rapid decays $\tilde{\gamma} \to \nu\tilde{\nu}^*$, $\bar{\nu}\tilde{\nu}$? This is unlikely for photino masses of our interest since data from τ-decay imply (Kane and

* The yet unseen selectron $\tilde{e}$, which is the scalar superpartner of the electron, is known to weigh more than 23 GeV (Gladney *et al* 1983).

** This number can be pushed upto about 5 GeV by considering the cosmological constraints on photino-quark interactions and using an experimental lower limit of 70 GeV on the mass of the exchanged squark.

Rolnick 1983) that $m_{\tilde{\nu}_\tau} + m_{\tilde{\nu}_l}(l=e, \mu) > m_\tau$. Therefore we shall assume the nonexistence of such a decay mode at any substantial level.

Now suppose a superlight† gravitino $\tilde{G}$ is the LSP. Then the predominant decay mode of the photino is $\tilde{\gamma} \to \gamma \tilde{G}$ and this is what we consider. The only other possible competing decay mode is $\tilde{\gamma} \to \gamma +$ axino where the axino is the superpartner of the invisible axion. This was assumed to be the main photino decay channel by Kim *et al* (1984). From the requirement of the thermalization of the decay photon into the background radiation of the universe, they claimed to derive a lower bound of 4 MeV on $m_{\tilde{\gamma}}$ for a value $\sim 10^9$ GeV of the Pecci-Quinn symmetry-breaking scale. Later, this bound was pushed up to 150 MeV by Sarkar and Cooper (1984) by considering the primordial abundance of deuterium. *However, all these bounds get invalidated in the presence of a superlight gravitino.* This is because the characteristic partial lifetime $\tau(\tilde{\gamma} \to \gamma + \text{axino})$ for $m_{\tilde{\gamma}} = O(1)$ MeV is in the vicinity of 10^7 sec. This cannot compete with $\tau(\tilde{\gamma} \to \gamma \tilde{G})$ which we show (figure 1) to be† $\lesssim 10^2$ sec in the region of interest.

The gravitino $\tilde{G}$ is the spin 3/2 Majorana superpartner of the graviton. The $\tilde{\gamma}\gamma\tilde{G}$ vertex can be easily obtained by supersymmetrization of the interaction which bends light in a gravitational field. To the lowest order, it is described in terms of the EM structure tensor $F_{\mu\nu}$, the photino field λ and the gravitino Rarita-Schwinger field ψ_ρ as

$$L_{\text{eff}} = -i(\pi G_N/8)^{1/2} \bar{\lambda} \gamma^\rho [\gamma^\mu, \gamma^\nu] \psi_\rho F_{\mu\nu}, \tag{1}$$

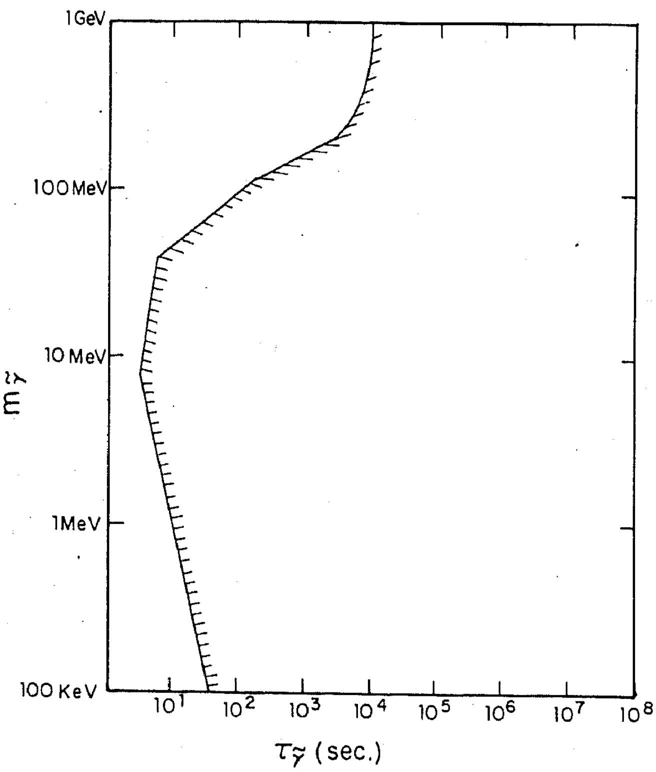

Figure 1. Allowed and forbidden regions in the plot of $m_{\tilde{\gamma}}$ vs $\tau_{\tilde{\gamma}}$

†The value of $m_{3/2}$ is theoretically wide open if the Kähler potential is logarithmic as in no-scale supergravity theories.

where G_N is Newton's constant. From (1) the partial lifetime for the decay $\gamma \to \gamma \tilde{G}$ may be computed to be

$$\tau(\tilde{\gamma} \to \gamma \tilde{G}) = 6 G_N^{-1} m_{3/2}^2 \, m_{\tilde{\gamma}}^{-5} (1 + 3 m_{3/2}^2 \, m_{\tilde{\gamma}}^{-2})^{-1} (1 - m_{3/2}^2 \, m_{\tilde{\gamma}}^{-2})^{-3}. \tag{2}$$

In (2) $m_{3/2}$ is the mass of the gravitino which is unknown but has a very weak lower limit, namely (Fayet 1986) $2{\cdot}3 \times 10^{-6}$ eV from a laboratory search for the reaction $e^+ e^- \to \gamma \tilde{\gamma} \tilde{G}$. Thus gravitinos could very well be[††] superlight. It should be emphasized that (2) has been derived just from general relativity and supersymmetry without any model-dependent assumptions.

The decay of a photino into a photon and such a superlight gravitino is possible at a cosmologically acceptable rate, but there is a caveat. The resulting excess of photons should not affect the post-nucleosynthesis abundance of natural elements in the universe to an extent that would conflict with observation. This problem has been investigated in detail by Salati *et al* (1986). For $m_{\tilde{\gamma}} > 150$ GeV, the strongest upper bound on the photino lifetime $\tau_{\tilde{\gamma}}$ comes from the avoidance of excessive photofission of deuterium. This rules out photino lifetimes much in excess of 10^3–10^4 sec. For $m_{\tilde{\gamma}} < 150$ MeV, on the other hand, the major factor is the excessive entropy generation by the decay photons leading to an overproduction of He^4. The primordial He^4: H mass-fraction Y_P, deduced (Kunth and Sargent 1984) from observation to be 0·25, should not be exceeded. In consequence, a large region in the $m_{\tilde{\gamma}}$ vs $\tau_{\tilde{\gamma}}$ plot gets ruled out. The consolidated effect of these restrictions has been shown (Salati *et al* 1986) in figure 1 for $Y_P = 0{\cdot}25$.

Despite the severity of the above constraints, it is evident from figure 1 that low photino masses with low lifetimes are still allowed since such shortlived photinos have little effect on Y_P. Thus $m_{\tilde{\gamma}}$ could still be much less than 150 MeV. How does one really bound it from below? This can be done for a photino decaying primarily into a photon and a gravitino since $\tau_{\tilde{\gamma}}$ can then be replaced by the right side of (2). By folding the constraints of figure 1 with (2), one is led to the $m_{3/2}$ vs $m_{\tilde{\gamma}}$ plot of figure 2. Now $m_{3/2} > 2{\cdot}3 \times 10^{-6}$ eV restricts $m_{\tilde{\gamma}}$ to be more than 1 MeV.

How reliable is the use of the results of Salati *et al* (figure 1) in the present context? One may question the two following assumptions that they made: (i) they assumed three* species of stable ultralight 2-component neutrinos. (ii) The ratio Ω_B of baryon density to the critical density was taken to be not less than 0·02 $(H/50 \text{ km sec}^{-1} \text{ mpc}^{-1})^2$ which means a present-day baryon to photon number-density ratio $n_B/n_\gamma \gtrsim 1{\cdot}4 \times 10^{-10}$. Firstly, a stable superlight gravitino, weighing less than 10^{-2} eV, is likely to stay in equilibrium in the early universe sufficiently long to act in effect as a fourth species of 2-component neutrino (Fayet 1983). Secondly, the analysis (Yang *et al* 1984) leading to $n_B/n_\gamma \gtrsim 1{\cdot}4 \times 10^{-10}$, from the kinetics of $D + He^3$ formation, is not believable in the presence of a non-relativistic photoemitting photino; it is safer to use $n_B/n_\gamma \gtrsim 5 \times 10^{-11}$ directly from observation, i.e. the lower bound 0·01 $(H/50 \text{ km sec}^{-1} \text{ mpc}^{-1})^2$ on Ω_B.

[††]This is nevertheless long compared to the time (~1 sec) for the neutron to proton ratio "freezing out" modulo β-decay.

* The photino is equivalent to a fraction of a neutrino species since it acts like a neutrino when it is highly relativistic and not so at all when it is very nonrelativistic.

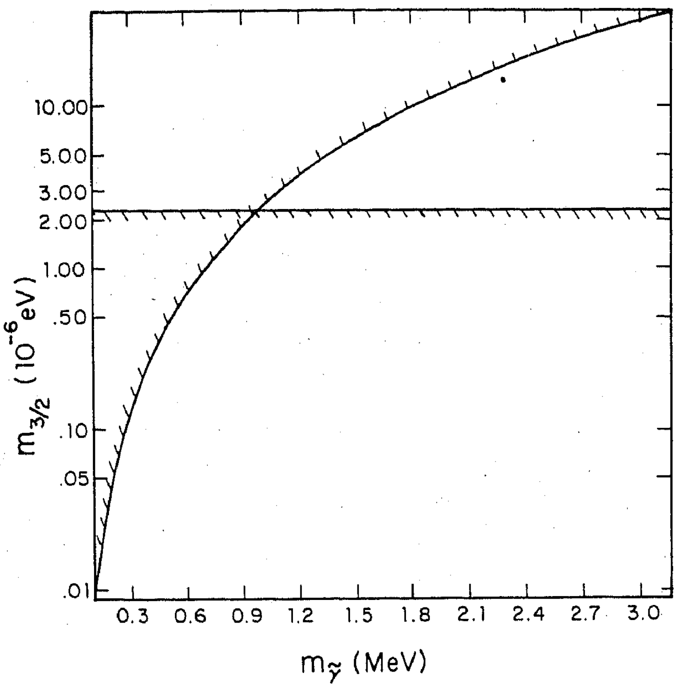

Figure 2. Allowed and forbidden regions in the $m_{3/2}-m_{\tilde\gamma}$ plot.

What would be the effect of the above changes? The explicit dependence of Y_P on the number N_ν of stable ultralight neutrino species and on the baryon to photon number density ratio at nucleo-synthesis $(n_B/n_\gamma)_{NS}$ is known (equation (41) of Sarkar 1985). The increase in N_ν from three to four with Y_P unchanged implies a change $\Delta \ln (n_B/n_\gamma)_{NS} = -13/11$ from the value used by Salati *et al.* We can obtain a crude order of magnitude estimate of the effect this has on the photino lifetime constraint by making three drastic assumptions. (a) All photinos are taken to decay more or less instantaneously when $\tau_{\tilde\gamma}$ equals the expansion time of the universe. (b) The decay photons get degraded in energy to a uniform temperature through processes such as double Compton scattering. (c) The bulk of the photinos decay after nucleosynthesis, as ought to be the case if Y_P is taken at the absolute upper limit of 0·255. It is then straightforward to estimate

$$1+0{\cdot}6\, m_{\tilde\gamma}\tau_{\tilde\gamma}^{1/2}(g^*)^{-1/4}\frac{n_{\tilde\gamma}}{n_\gamma} \lesssim c\,\frac{(n_B/n_\gamma)_{NS}}{n_B/n_\gamma}. \qquad (3)$$

In (3) g^* is the degeneracy factor or effective number of relativistic degrees of freedom, being 43/4 for a completely nonrelativistic photino and 50/4 for an ultrarelativistic one. Further, c is the proportionality constant which accounts for photon reheating at the e^+e^- annihilation era.

On using (3), we find a reduction of the upper bound in the paper of Salati *et al* by a factor ~ 16. Feeding that into (2), our lower bound on $m_{\tilde\gamma}$ gets increased by a factor $\sim 1{\cdot}8$. Of course, our simplifying assumptions (in particular (c)) could be wrong and the true upper bound on $\tau_{\tilde\gamma}$ could even be somewhat smaller. But since $m_{\tilde\gamma} \propto \tau_{\tilde\gamma}^{-1/5}$, the actual numerical effect of various astrophysical uncertainties on the photino mass lower bound is not expected to be significant. Thus we can safely say that $m_{\tilde\gamma} > O(1)$ MeV.

Such a constraint obviously cannot apply if $\tau_{\tilde{\gamma}}$ exceeds the age of the universe. However, in that case there is a very small upper bound on the photino mass from critical density considerations (Sciama 1982). This is since the photino-electron cross-section is comparable to the neutrino-electron one. Thus the $\tilde{\gamma}$ number-density should be similar to that of the neutrinos. Then the requirement on the density of the universe in terms of the known Hubble constant and the age of the universe allows only photino masses less than $O(10^2)$ eV. The decay into a photon and a gravitino of such a low-mass photino with a lifetime $\sim 10^{24}$ sec has been advocated (Sciama 1982, 1984) as a possible source of ultraviolet photons which can ionize the galactic halo.

Finally, our conclusion is that the mass-range $O(10^2)$ eV to $O(1)$ MeV is excluded for a quasistable photino decaying mainly via $\tilde{\gamma}\rightarrow\gamma\tilde{G}$. These are the best bounds on the unstable photino mass with a superlight gravitino. As $m_{3/2}$ increases, these remain valid but may get superseded by stronger bounds from the decay $\tilde{\gamma}\rightarrow\gamma+$axino. The supercession region 10^{-3} to 10^{-2} eV is made imprecise by the model-dependence of the latter through the Peccei-Quinn symmetry breaking scale and the domain number (number of inequivalent vacua) of the universe. Other bounds on the unstable photino mass involve (Grivaz 1986) assumptions on the selectron mass and are not as general as our statement.

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