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PROBLEMS FOR LIGHT HIGGSINOS

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A B S T R A C T

We analyze the possibility that the higgsino mass $m_{\tilde{h}} \lesssim 100$ eV as allowed by cosmology. Although permitted at the price of an adjustment of model parameters at the tree-level, such a low value of $m_{\tilde{h}}$ is technically unnatural since radiative corrections make contributions to $m_{\tilde{h}}$ of order 100 MeV. If one also postulates that the gravitino mass $m_{3/2} < m_{\tilde{h}}$, so that a light higgsino is unstable and could explain the large ultra-violet background at large redshifts, the scale of supersymmetry breaking must be very low and there would be strong gravitational interactions at energies of order 1 TeV.

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There is a consensus among astrophysicists that most of the matter in the Universe has not been seen [1]. It seems unlikely that all this dark matter can be baryonic [2], and it is often thought that much of the dark matter is in the form of some non-dissipating, weakly-interacting particle [3]. One candidate would be a massive neutrino weighing either ~ 100 eV or a few GeV. The alternatives are various conjectured species of weakly-interacting massive particle, such as axions or the lightest supersymmetric particle (LSP) [4]. In order to be non-dissipative, the LSP should be electromagnetically neutral and have no strong interactions. Possibilities include some sneutrino $\tilde{\nu}$ of spin 0 [5], some combination of photino $\tilde{\gamma}$, higgsino $\tilde{h}$ and zino $\tilde{Z}$ of spin $\frac{1}{2}$ [4], and the gravitino $\tilde{G}$ of spin $3/2$. The non-observation of high-energy solar neutrinos [6] and of coherent LSP-nucleus scattering in low-background underground detectors [7] argue strongly against a $\tilde{\nu}$ as the LSP. Like the neutrino, some $\tilde{\gamma}/\tilde{h}/\tilde{Z}$ combination could have a relic density approaching the closure density $\Omega \approx 1$ if its mass were either ~ 100 eV or $\gtrsim$ a few GeV [4].

The dark matter particle should either be absolutely stable or have a lifetime much longer than the age of the Universe. In the latter case, its decays could have interesting observable consequences. Indeed, it has been proposed [8] that the radiative decays of dark matter particles weighing ~ 100 eV could be responsible for the ultra-violet background seen at large redshifts $z \sim 4$ [9]. This would require a lifetime $\tau \sim 10^{24}$ s, and the possibility that $\tilde{\gamma} \rightarrow \gamma \tilde{G}$ decays might fit the bill has been actively pursued [8].

Unfortunately, photinos weighing $\lesssim 1$ MeV, either stable or unstable with $\gamma\tau \gtrsim$ few s, seem to be excluded [10] by the agreement of the neutrino observations of the supernova 1987a with theoretical predictions based on the gravitational collapse of the core to form a neutron star. However, these neutrino observations leave open the possibility of a light higgsino weighing $\lesssim 1$ MeV. The purpose of this letter is to give independent arguments against a stable or unstable higgsino weighing $\lesssim 100$ eV.

Such a small higgsino mass could be obtained by adjusting the tree-level parameters of the effective low-energy theory with softly-broken supersymmetry [4]. It is also possible in principle to obtain a light $\tilde{Z}$ in this way, but this would be accompanied by an unacceptably light charged wino $\tilde{W}^\pm$ [4]. However, we argue that such an adjustment would be unnatural, since radiative corrections make contributions to $m_{\tilde{h}}$ of order

$$\delta m_{\tilde{h}} \approx (10 \text{ to } 100) \text{ MeV} \quad (1)$$

Another problem appears if one seeks to destabilize the higgsino, by postulating $m_{\tilde{G}} < m_{\tilde{h}}$ so that $\tilde{h} \rightarrow \gamma \tilde{G}$ decay occurs. In general, if $m_{\tilde{G}} \ll m_{\tilde{\gamma}}$ as would be the case

in such a scenario, gravitational interactions become strong [11] at an energy scale $E_c \ll m_p$. This problem is accentuated if one requires $\tau_{\tilde{h}} \sim 10^{24}$ s, which entails a supersymmetry breaking scale $d \sim 4 \times 10^3 \text{ GeV}^2$. This is compatible with accelerator-based particle phenomenology [12] only if $m_{\tilde{\gamma}} \gtrsim 20 \text{ GeV}$, in which case gravitational interactions become strong at $E_c \lesssim 1 \text{ TeV}$. Although not conclusive, these results argue strongly against a light higgsino as the LSP or as the origin of the ultra-violet background at large redshift.

We first remind the reader of the structure of the mass matrix for the electroweakly interacting neutral spin- $\frac{1}{2}$ sparticles (neutralinos). In the minimal supersymmetric version of the standard model described by the Lagrangian

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{\text{SUSY}} - \frac{1}{2} \sum_{\tilde{V}} m_{\tilde{V}} (\tilde{V} \tilde{V}) - \sum_i m_{\tilde{Q}_i}^2 \phi_i^i \phi_i^{*i} - \mu (\tilde{H}_1 \tilde{H}_2) \\ & - \sum_{\lambda} (A_{\lambda} \lambda \tilde{f}_L^* \tilde{f}_R H + \text{herm. conj.}) \end{aligned} \quad (2)$$

where the supersymmetric part $\mathcal{L}_{\text{SUSY}}$ is specified by the usual gauge interactions and Yukawa superpotential couplings λ , there are four neutralinos ($\tilde{B}$, $\tilde{W}^3$, $\tilde{H}_1^0$, $\tilde{H}_2^0$) that mix in general [4]. In the limit where the gaugino masses $m_{\tilde{V}} \rightarrow 0$, the lightest mass eigenstate is the photino $\tilde{\gamma}$ with mass $m_{\tilde{\gamma}}$, whereas in the limit $\mu \rightarrow 0$ the lightest mass eigenstate is a combination $\tilde{h}$ of the higgsinos $\tilde{H}_1^0$ and $\tilde{H}_2^0$ with mass

$$m_{\tilde{h}} = \mu \cdot \frac{2\omega}{1+\omega^2} \quad (3)$$

where $\omega \equiv \langle 0 | H_1 | 0 \rangle / \langle 0 | H_2 | 0 \rangle$. A priori, one could make $m_{\tilde{\gamma}}$ or $m_{\tilde{h}}$ arbitrarily small by choosing a small value of $m_{\tilde{\gamma}}$ or μ .

However, it is well known that there are important finite one-loop contributions to the photino mass that make $m_{\tilde{\gamma}} \ll O(100) \text{ MeV}$ unnaturally small [13]. Here we show that similar contributions to the higgsino mass $m_{\tilde{h}}$ are also induced at the one-loop level. The dominant relevant graphs involve either a stop-top loop or a chargino-W or chargino-charged Higgs loop. The calculation is very similar to the computation of the finite radiative corrections to the photino mass performed in Ref. [13]. However, we allow for general stop and chargino mixing, the only constraint being that the (tree-level) higgsino mass (μ in the notation of Ref. [4], $2m_1$ in Refs. [14, 15]) is negligibly small.

For the top-stop contributions, one finds

$$\delta m_{\tilde{h}}^{(top)} = \frac{3\alpha}{16\pi \sin^2 \theta_W} \frac{m_t^3}{m_W^2} \frac{\sin 2\phi}{\omega^2} F(m_t, m_{\tilde{t}_1}, m_{\tilde{t}_2}) \quad (4)$$

where $\tilde{t}_{1,2}$ are the two physical top-flavoured squarks, which are mixtures [16] of $\tilde{t}_L$ and $\tilde{t}_R$ with mixing angle ϕ , and

$$F(M, m_1, m_2) \equiv \frac{-m_1^2}{M^2 - m_1^2} \ln \frac{m_1^2}{M^2} + \frac{m_2^2}{M^2 - m_2^2} \ln \frac{m_2^2}{M^2} \quad (5)$$

comes from the loop integration. One normally finds $|F \sin 2\phi| \sim 0.2$ to 2 ; in this case, Eq. (4) gives

$$|\delta m_{\tilde{h}}^{(top)}| \sim (30 \text{ to } 300) \text{ MeV} \cdot \left(\frac{m_t}{m_W}\right)^3 \cdot \frac{1}{\omega^2} \quad (6)$$

which is at least five orders of magnitude bigger than the desired value $m_{\tilde{h}} \approx 100 \text{ eV!}^{*)}$

Using the Lagrangian of Refs. [14,15], one also finds a large contribution from the gauge and Higgs loops:

$$\delta m_{\tilde{h}}^{(gauge)} = - \frac{\alpha}{16\pi \sin^2 \theta_W} \cdot \frac{2\omega}{1+\omega^2} \cdot m_- \cos \delta_R \cos \delta_L \times \left\{ 3F(m_W, m_-, m_+) + \frac{m_-^2}{m_W^2} F(m_+, m_-, m_{H^+}) - \frac{m_-^2}{m_W^2} F(m_-, m_+, m_{H^+}) \right\} \quad (7)$$

where m_- (m_+) is the mass of the lighter (heavier) chargino eigenstate, γ_R and γ_L are the two chargino mixing angles [14], and m_{H^+} is the mass of the physical charged Higgs boson. For natural choices of parameters, one typically finds

$$|\delta m_{\tilde{h}}^{(gauge)}| \approx (50 \text{ to } 500) \text{ MeV} \quad (8)$$

i.e., of the same order as $|\delta m_{\tilde{h}}^{top}|$. Note that there is no technically natural way to tune the contributions (4) and (7) to zero; e.g., if one tuned off stop-mixing: $\sin 2\phi = 0$ at the tree level, it would reappear at the one-loop level ^{**)}.

*) Note that the supernova implies [10] $\omega^2 \gtrsim 4$ if one wants to avoid the very unnatural choice $|\omega-1| \lesssim 10^{-4}$. If ω^2 is in the natural range $\gtrsim 4$, the relic higgsino abundance is similar to that of a conventional neutrino, and hence $m_{\tilde{h}}$ cannot be much larger than 100 eV.

**) Even if the soft supersymmetry breaking parameter A in (2) vanishes at the tree level at a renormalization scale $\sim m_P$, a non-zero value will be generated at m_W by radiative corrections.

Let us nevertheless assume that one has (unnaturally finely) tuned the model parameters such that the total radiative contribution to the higgsino mass is sufficiently small. Could one then make these light higgsinos decay sufficiently rapidly to explain [8] the ionization of Lyman α clouds at large redshifts [9]? The only supersymmetric particle into which such a light higgsino could decay is an even lighter gravitino $\tilde{G}$.

The mass $m_{3/2}$ of the gravitino $\tilde{G}$ is given by [17]

$$m_{3/2} = \frac{\kappa d}{\sqrt{6}} \quad (9)$$

where $\kappa^{-1} \equiv m_p / \sqrt{8\pi}$ and $\sqrt{d}$ is the magnitude of the supersymmetry breaking scale. One has $m_{3/2} < m_{\tilde{h}} \approx 100$ eV and hence an unstable $\tilde{h}$ if $d \lesssim 10^{11}$ GeV². Bounds on $\sqrt{d}$ have been discussed by Fayet [12] based on the cross-sections for the two processes $e^+e^- \rightarrow \gamma\tilde{\gamma}\tilde{G}$ and $e^+e^- \rightarrow \tilde{\gamma}\tilde{G}$, and considering different ranges of $m_{\tilde{\gamma}}$. From the experimental limits on the production of single photons in e^+e^- annihilations one finds that the supersymmetry breaking scale $\sqrt{d}$ has to be larger than 110 GeV, provided that the photino is stable or long-lived and the mass of the $\tilde{\gamma}$ is smaller than ≈ 20 GeV. This result is independent of selectron masses up to about 100 GeV. For a $\tilde{\gamma}$ mass in the range $300 \text{ MeV} < m_{\tilde{\gamma}} < 10 \text{ GeV}$ one gets an even higher lower bound: $\sqrt{d} > 240 \text{ GeV}$, in the case that the $\tilde{\gamma}$ is unstable and decays into γ and $\tilde{G}$. For photinos which are heavier than $\approx 30 \text{ GeV}$ there is no longer a lower bound on $\sqrt{d}$.

One could consider similar bounds on $\sqrt{d}$ coming from the processes $e^+e^- \rightarrow \gamma\tilde{h}\tilde{G}$ or $e^+e^- \rightarrow \tilde{h}\tilde{G}$ where, instead of a photino, we have a higgsino. But, due to the fact that there is no tree coupling between $\tilde{h}$, $\tilde{G}$ and γ or Z^0 , the cross-sections for these processes are suppressed by at least a factor α^2 with respect to those involving the $\tilde{\gamma}$. Therefore we get lower bounds on $\sqrt{d}$ which are roughly $\sqrt{\alpha}$ (typically $\sim 10^{-1}$) smaller than the previous ones for $\tilde{\gamma}$. Thus if we assume that the $\tilde{\gamma}$ is heavy enough to have no bounds on $\sqrt{d}$ coming from the processes involving photinos, we can arrange $\sqrt{d}$ to be as low as $\sim 10 \text{ GeV}$. Thus the gravitino could be light enough for $\tilde{h} \rightarrow \gamma\tilde{G}$ decay to be possible.

Our next task is to estimate the lifetime of such an unstable higgsino. The $\tilde{h} \rightarrow \gamma\tilde{G}$ decay occurs at the one-loop level; again one can have tops and stops, or charginos and W's or charged Higgs bosons, in the loop. The top-stop graphs are shown in Fig. 1. Before evaluating them, let us briefly describe the gravitino couplings. We consider the limit where the gravitino mass $m_{3/2}$ is much smaller than the higgsino mass, $m_{3/2} \ll m_{\tilde{h}}$. In this case the $\tilde{h}$ decays predominantly into longitudinally polarized gravitinos, which couple [18,19] exactly like the Goldstone fermion of spontaneously broken global supersymmetry. However, since we

are interested in the goldstino coupling to virtual quarks and squarks, the coupling is no longer proportional to $m_{\tilde{q}}^2 - m_q^2$. Instead, one has to use the Feynman rules of Fig. 2, where we have used the fact that the goldstino spinor $u_{\tilde{G}}$ satisfies $\not{X} u_{\tilde{G}}(k) = 0$ to the given order in $m_{3/2}$. Note also that electromagnetic gauge invariance requires the existence of the four-point vertex of Fig. 2b, and thus of the graph in Fig. 1c. Again allowing for general stop mixing one finds for the top-stop contribution to the $\tilde{h} \rightarrow \gamma \tilde{G}$ decay width:

$$\Gamma^{(top)}(\tilde{h} \rightarrow \gamma \tilde{G}) = \frac{\alpha^2 \sin^2 2\phi}{512\pi^3 \sin^2 \theta_w} \frac{m_t^2}{m_w^2 \omega^2} F^2(m_t, m_{\tilde{t}_1}, m_{\tilde{t}_2}) \frac{m_{\tilde{h}}^5}{d^2} \quad (10)$$

It is important to note that the decay width (10) is directly proportional to the square of the top-stop contribution to $\delta m_{\tilde{h}}$ given in Eq. (4):

$$\Gamma^{(top)}(\tilde{h} \rightarrow \gamma \tilde{G}) = \frac{(\delta m_{\tilde{h}}^{(top)})^2}{m_t^2} \cdot \frac{\omega^2 \sin^2 \theta_w}{18\pi} \cdot \left(\frac{m_w}{m_t}\right)^2 \cdot \frac{m_{\tilde{h}}^5}{d^2} \quad (11)$$

A similar result can be obtained for the gauge-Higgs loops. We thus see that if one tried to keep $\delta m_{\tilde{h}}$ sufficiently small by tuning both the top-stop and the gauge-Higgs contributions to be small, one would automatically get an uninterestingly small $\tilde{h} \rightarrow \gamma \tilde{G}$ decay width. The only way out is to cancel the two classes of contributions to $\delta m_{\tilde{h}}$ against each other; in this case the total $\Gamma(\tilde{h} \rightarrow \gamma \tilde{G})$ will still be given roughly by Eq. (11), since

$$\Gamma^{(top)} / (\delta m_{\tilde{h}}^{(top)})^2 \neq \Gamma^{(gauge)} / (\delta m_{\tilde{h}}^{(gauge)})^2$$

Using for illustrative purposes $\delta m_{\tilde{h}}^{(top)} / m_t \approx 10^{-3}$, $\omega^2 = 10$ and comparing the higgsino decay width to the photino decay width of Ref. [8], one thus finds:

$$\frac{\Gamma(\tilde{h} \rightarrow \gamma \tilde{G})}{\Gamma(\tilde{\gamma} \rightarrow \gamma \tilde{G})} \approx \left(\frac{m_{\tilde{h}}}{m_{\tilde{\gamma}}}\right)^5 \cdot 10^{-7} \quad (12)$$

for equal values of d . In order to explain the ultra-violet background at large redshifts $Z \sim 4$ [9], we are interested [8] in higgsino lifetimes $\sim 10^{24}$ sec. This is about 10^7 times the age of the Universe, so we cannot increase $m_{\tilde{h}}$ much above 100 eV, since otherwise higgsinos would overclose the Universe. Equations (11) and (12) thus tell us that the only way to obtain a higgsino lifetime in the interesting range is to choose d at least three orders of magnitude smaller than in Ref. [8], i.e., $d \approx 4 \cdot 10^3 \text{ GeV}^{2*}$.

*) As was the case with the photino, a higgsino mass $\sim 1 \text{ keV}$ would have the advantage of enabling the phase space constraint for dwarf galaxies to be respected [8]. We have already mentioned that the supernova bound [10] on ω disfavors $m_{\tilde{h}} \sim 1 \text{ keV}$. The naturalness problem discussed above and the unitary problem discussed below would in any case not be significantly alleviated by such an increase in $m_{\tilde{h}}$.

This is compatible with the accelerator experiment constraints [12] discussed earlier, if $m_{\tilde{\gamma}} \gtrsim 30$ GeV. However, there are troubles with such a low value for d . It has been shown by Bhattacharya and Roy [11] that in a spontaneously broken $N = 1$ supergravity theory one gets, by considering the amplitudes for the inelastic scattering of two identical gauge bosons into a pair of gravitinos, the following formula for the critical energy E_c above which tree-level unitarity breaks down:

$$E_c = \frac{12\sqrt{2}\pi}{\kappa} \frac{m_{3/2}}{m_{\tilde{\nu}}} = 4\sqrt{3}\pi \frac{d}{m_{\tilde{\nu}}} \quad (13)$$

where $m_{\tilde{\nu}}$ is the corresponding gaugino mass. For a typical gaugino mass of the order of 100 GeV and for $d = 4 \cdot 10^3$ GeV² one gets $E_c \sim 400$ GeV, which is unacceptably low. It would imply that gravitational interactions become strong at energies $\lesssim 1$ TeV. This type of difficulty was in fact already present in the photino case previously considered by Sciama [8]. For the $\tilde{\gamma}$ decay with $d \sim 10^6$ GeV² so as to have $\tau(\tilde{\gamma} \rightarrow \gamma\tilde{G}) \sim 10^{24}$ s, and $m_{\tilde{\nu}} \sim 100$ GeV, one gets $E_c \sim 10^5$ GeV. Already this value for E_c is rather low for spontaneously broken supergravity to become a strongly coupled system. One would have expected such a theory to have weak coupling up to m_p [11].

We have seen that postulating a light higgsino with $m_{\tilde{h}} \sim 100$ eV is technically unnatural in a generic model with softly broken supersymmetry. We have also seen that if such a light higgsino did exist, and would decay into $\gamma\tilde{G}$ and explain [8] the ultra-violet background seen at large redshifts [9], then gravitational interactions would become strong [11] at energies $\lesssim 1$ TeV. Although these arguments do not exclude such a light higgsino, they do make it seem rather implausible.

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REFERENCES

- [1] For a review, see V. Trimble - Ann.Rev.Astron.Astrophys. 25 (1987) 425.
- [2] J. Yang, M. Turner, G. Steigman, D. Schramm and K. Olive - Astrophys.J. 281 (1984) 493;
D. Hegyi and K. Olive - Astrophys. J. 303 (1986) 56.
- [3] For reviews, see:
J.R. Primack, D. Seckel and B. Sadoulet - U.C. Santa Cruz Preprint SCIPP 88/14 (1988);
J.D. Lewin and P. Smith - Rutherford-Appleton Lab. Preprint RAL 88-045 (1988).
- [4] H. Goldberg - Phys.Rev.Lett. 50 (1983) 1419;
J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K. Olive and M. Srednicki - Nucl.Phys. B238 (1984) 453.
- [5] L. Ibañez - Phys.Lett. 137B (1984) 160;
J.S. Hagelin, G. Kane and S. Raby - Nucl.Phys. B241 (1984) 638.
- [6] J.S. Hagelin, K.W. Ng and K. Olive - Phys.Lett. B180 (1987) 375;
K.-W. Ng, K. Olive and M. Srednicki - Phys.Lett. B188 (1987) 138.
- [7] S.P. Ahlen et al. - Phys.Rev.Lett. 61 (1988) 145;
D.O. Caldwell et al. - U.C. Santa Barbara Preprint UCSB-HEP-88-6 (1988).
- [8] D.W. Sciama - Mon.Not.Roy.Ast.Soc. 230 (1988) 13p.
- [9] S. Bajtlik, R.C. Duncan and J.P. Ostriker - Astrophys. J. 327 (1988) 570.
- [10] J. Ellis, K. Olive, S. Sarkar and D.W. Sciama - CERN Preprint TH. 5122 (1988).
- [11] T. Bhattacharya and P. Roy - Phys.Lett. B206 (1988) 655.
- [12] P. Fayet - Phys.Lett. B175 (1986) 471.
- [13] R. Barbieri, L. Girardello and A. Masiero - Phys.Lett. 127B (1983) 429.
- [14] H. Baer, V. Barger, D. Karatas and X. Tata - Phys.Rev. D36 (1987) 96.
- [15] H. Baer, A. Bartl, D. Karatas, W. Majerotto and X. Tata - Univ. of Wisconsin, Madison Preprint MAD/PH/422 (1988).
- [16] H.-P. Nilles - Physics Reports 110C (1984) 1.
- [17] S. Deser and B. Zumino - Phys.Rev.Lett. 38 (1977) 1433;
D.Z. Freedman - Phys.Rev. D15 (1977) 1173;
D.Z. Freedman and A. Das - Nucl.Phys. B120 (1977) 221.
- [18] P. Fayet - Phys.Lett. 70B (1977) 461; 84B (1979) 421; B175 (1986) 471.
- [19] R. Casalbuoni, S. de Curtis, D. Dominici, F. Feruglio and R. Gatto - Univ. of Geneva Preprint UGVA-DPT 1988/09-591 (1988).

FIGURE CAPTIONS

Fig. 1 One-loop diagrams contributing to $\tilde{h} \rightarrow \gamma \tilde{G}$ decay.

Fig. 2 Feynman rules used to evaluate the diagrams in Fig. 1.

- Fig. 1 -

a)

$$\vec{Q}_R(p) \rightarrow \vec{G}(k) : \frac{i\sqrt{2}}{d} p \cdot k (1 \mp \gamma_5)$$

b)

$$\vec{Q}_R \rightarrow \gamma_\mu : \frac{-i\sqrt{2}}{d} e \cdot e_q k_\mu (1 \mp \gamma_5)$$

$\vec{Q}_R$

q

$\vec{G}(k)$

- Fig. 2 -