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Cosmological Constraints on Supergravity Models

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ABSTRACT

We delineate the domain of supersymmetry breaking parameters in minimal supergravity models for which the cosmological relic photino density is no larger than the closure density. Demanding that the relic density equal the closure density as suggested by inflationary cosmology suggests $m_{\tilde{q}} \approx 42 \text{ GeV} + 0.89 m_{\tilde{g}}$. We point out that several supergravity scenarios for the monojet events at the CERN $\bar{p}p$ Collider would yield a relic density considerably greater than the closure density.

In most supersymmetric theories the lightest sparticle is absolutely stable, and it has a cosmological relic density which is potentially important.^{1,2} To avoid conflict with strict upper limits on anomalous heavy isotopes, this stable particle should presumably be electrically neutral and not strongly interacting.³ Possible candidates are therefore the sneutrino $\tilde{\nu}$ of spin 0,⁴ some linear combination of the photino $\tilde{\gamma}$, two neutral shiggses $\tilde{H}^0$, and zino $\tilde{Z}^0$ of spin 1/2,² or the gravitino $\tilde{G}$ of spin 3/2.⁵ In most supergravity models⁶ the $\tilde{\nu}$ and the $\tilde{G}$ have masses comparable to the selectrons $\tilde{e}$, and are heavier than the lightest $\tilde{\nu}/\tilde{H}^0/\tilde{Z}^0$ mixture. We have previously explored² the theoretically plausible range of spin 1/2 sparticle masses, and found that the two lightest mass eigenstates are likely to be approximately the $\tilde{\gamma}$ and a $\tilde{H}^0$. If the $\tilde{\gamma}$ is the lightest sparticle, then for slepton $\tilde{l}$ and squark $\tilde{q}$ masses less than $O(100)$ GeV, the cosmological relic $\tilde{\gamma}$ density is less than the critical density required to close the Universe if $m_{\tilde{\gamma}}$ exceeds a value in the range 1 to 15 GeV, depending on the squark and slepton masses and on the Hubble constant.² If the $\tilde{H}^0$ is the lightest sparticle, its relic cosmological density is too high if $m_{\tilde{H}^0} \leq m_b$ or m_t .

Previous analyses^{1,2} of the cosmological relic $\tilde{\gamma}$ density have been rather model-independent: here we introduce three model-dependent considerations which appear interesting. One is to incorporate the relations between $\tilde{\gamma}$, $\tilde{l}$ and $\tilde{q}$ masses suggested by minimal supergravity.⁶ Secondly we investigate the requirement that the cosmological supersymmetric relic density ρ_{χ} be essentially equal to the critical density ρ_c , so that the Universe be at the brink of closure, as suggested by inflationary models.⁷ Thirdly, we look for compatibility (or incompatibility) with various supersymmetric interpretations that have been proposed^{8,9,10} for the missing energy events observed by UA1.¹¹

We find in minimal supergravity: (1) that $\rho_\chi \gtrsim 10^{-2} \rho_c$ for all models with $m_{\tilde{e}_R} \gtrsim 22 \text{ GeV}$,¹² and that $m_{\tilde{q}} \lesssim 42 \text{ GeV} + 0.89 m_{\tilde{g}}$ if the present Hubble constant $H_0 = 50 \text{ km/sec/Mpc}$; (2) that $m_{\tilde{q}} \approx 42 \text{ GeV} + 0.89 m_{\tilde{g}}$ if $\rho_\chi = \rho_c$ and $H_0 = 50 \text{ km/sec/Mpc}$; and (3) that monojet models¹⁰ with $m_{\tilde{q}} > 80 \text{ GeV}$ and $m_{\tilde{g}} < 20 \text{ GeV}$ give a relic mass density ρ_χ which exceeds ρ_c by a factor > 5 if $H_0 = 50 \text{ km/sec/Mpc}$. We also find in minimal supergravity models with $m_{\tilde{q}} \lesssim 200 \text{ GeV}$ that the $\tilde{H}^0$ cannot be the lightest sparticle because its relic mass density would greatly exceed the critical density if $m_{\tilde{H}^0} < m_{\tilde{g}}$.

We start by recalling our previous results² for the cosmological density of an arbitrary supersymmetric relic χ :

$$\rho_\chi = 4.0 \times 10^{-40} \left(\frac{T_\chi}{T_\gamma} \right)^3 \left(\frac{T_\gamma}{2.8^\circ \text{K}} \right)^3 N_F^{1/2} \left(\frac{\text{GeV}^{-2}}{\tilde{a} x_f + \frac{1}{2} \tilde{b} x_f^2} \right) \frac{9}{\text{cm}^3} \quad (1)$$

where $x_f \equiv kT_f/m_\chi$ with T_f the freeze-out temperature for $\chi\chi$ annihilation [generally $x_f = O(1/20)$], and $(T_\chi/T_\gamma)^3$ accounts for the subsequent reheating of the photon temperature relative to the temperature of χ due to the annihilation of particles with $m < x_f m_\chi$. Typical values of $(T_\chi/T_\gamma)^3$ and of the number N_f of effective degrees of freedom are tabulated on p. 467 of ref. 2. The parameters $\tilde{a}$ and $\tilde{b}$ are determined by the sparticle physics model according to:

$$\tilde{a} \equiv \sum_f \theta(m_\chi - m_f) \frac{1}{2\pi} \frac{P}{m_\chi} m_f^2 (A_f - B_f)^2 \quad (2a)$$

$$\tilde{b} \equiv \sum_f \theta(m_\chi - m_f) \frac{1}{2\pi} \frac{P}{m_\chi} \left[(A_f^2 + B_f^2)(4m_\chi^2 - m_f^2) + 6A_f B_f m_f^2 \right] \quad (2b)$$

with $p \equiv \sqrt{m_\chi^2 - m_f^2}$ and

$$A_f = \frac{e^2 Q_f^2}{2 m_{\tilde{f}_L}^2} \quad (3a)$$

$$B_f = - \frac{e^2 Q_f^2}{2 m_{\tilde{f}_R}^2} \quad (3b)$$

for $\tilde{\gamma}\tilde{\gamma}$ annihilation where $\tilde{f}_{L,R}$ are the spartners of the left-(right-)handed fermions f with electromagnetic charge Q_f . The values of A_f and B_f for $\tilde{H}^0\tilde{H}^0$ annihilation can be read from ref. 2. As mentioned in the introduction to this paper, the two lightest mass eigenstates are almost pure $\tilde{\gamma}$ or $\tilde{H}^0$ in most of the interesting parameter space. This is especially true where $\rho_\chi \approx \rho_c$, as can be inferred directly from the diagrams of ref. 2. The closure density to be compared with the relic density ρ_χ (1) is

$$\rho_c = 2 \times 10^{-29} \left(\frac{H_0}{100 \text{ km/sec/Mpc}} \right)^2 \frac{g}{\text{cm}^3} \quad (4)$$

A favored value of H_0 is 50 km/sec/Mpc,¹³ though some astrophysicists prefer $H_0 \approx 100$ km/sec/Mpc. Our graphs feature curves corresponding to both these values, as well as to $H_0 = 25$ km/sec/Mpc. This small value is unpopular with cosmologists, and is only included for comparison purposes.

We now proceed to calculate the cosmological relic photino density in minimal supergravity models.⁶ These are largely characterized by two bare supersymmetry breaking mass parameters, m_0 for scalars and $m_{1/2}$ for gauginos, as well as a ratio v_1/v_2 of doublet Higgs vacuum expectation values.¹⁴ In most phenomenologically relevant models $v_1/v_2 \sim 1$.^{14,15} As a result, the Z^0

contribution to $\tilde{H}^0 \tilde{H}^0$ annihilation vanishes, forcing the $\tilde{H}^0$ to annihilate via $\tilde{f}$ exchange diagrams proportional to small Yukawa couplings. This results in a strong lower bound* on the $\tilde{H}^0$ mass of $m_{\tilde{H}^0} > m_t$ if $m_{\tilde{f}} \approx 20$ GeV rising to $m_{\tilde{H}^0} \gtrsim 65$ GeV if $m_{\tilde{f}} \approx 50$ GeV. Therefore for supergravity models with $m_{\tilde{q}} \lesssim 200$ GeV and $m_{\tilde{e}_R} \gtrsim 22$ GeV, in which for reasons which we explain below $m_{\tilde{g}} < m_t$, it follows that the $\tilde{H}^0$ must be heavier than the $\tilde{g}$. We therefore concentrate on the case of the $\tilde{g}$ as the lightest supersymmetric particle.

Taking $v_1/v_2 \sim 1$, there are two remaining parameters m_0 and $\xi \equiv m_{\frac{1}{2}}/m_0$ which fix much of the sparticle spectrum, and therefore also A_f and B_f (3), $\tilde{a}$ and $\tilde{b}$ (2) and hence ρ_χ (1). Relevant to us are

$$\begin{aligned} m_{\tilde{g}} &\approx 0.47 \xi m_0, & m_{\tilde{g}} &\approx 2.8 \xi m_0 \\ m_{\tilde{e}_R}^2 &\approx m_0^2 (1 + 0.15 \xi^2), & m_{\tilde{e}_L}^2 &\approx m_0^2 (1 + 0.52 \xi^2) \\ m_{\tilde{q}}^2 &\approx m_0^2 (1 + 6.4 \xi^2) \end{aligned} \quad (5)$$

where the quoted expression for $m_{\tilde{q}}^2$ is a weighted mean of $m_{\tilde{q}_L}^2$, $m_{\tilde{u}_R}^2$ and $m_{\tilde{d}_R}^2$. We choose to present our results for ρ_χ as contours in the $(m_{\tilde{q}}, m_{\tilde{g}})$ plane, since these are the two sparticle masses which currently excite the most phenomenological discussion.^{8,9,10,11} Not all the $(m_{\tilde{q}}, m_{\tilde{g}})$ plane is phenomenologically viable. The most important constraint is that on the selectron mass:

$$m_{\tilde{e}_R}^2 \approx m_{\tilde{q}}^2 - 0.80 m_{\tilde{g}}^2 \gtrsim (22 \text{ GeV})^2 \quad (6)$$

*There might appear from ref. 2 to be a possible escape route for the $\tilde{H}^0$ to be the lightest supersymmetric particle if $m_{\tilde{H}^0} \lesssim 0(100)\text{eV}$. However, this has been almost blocked by a theoretical analysis¹⁶ of the non-observation of $e^+e^- \rightarrow \tilde{g}\tilde{g}$ followed by $\tilde{g} \rightarrow \tilde{g}\tilde{H}^0$ decay.

The experimental lower limit on the right-hand side of the inequality in (6) is supplemented by a more stringent bound for small $m_{\tilde{\gamma}}$, derived from the search¹⁷ for $e^+e^- \rightarrow \gamma + (\tilde{\gamma}\tilde{\gamma})$, as is shown in fig. 1.

Shown in fig. 1 are the contours of relic density $\rho_{\tilde{\gamma}}$ (1) equal to the closure density ρ_c (4) for $H_0 = 25, 50$ and 100 km/sec/Mpc, corresponding to factors of 4 above and below the favoured value of the critical density. We see these contours are approximately parallel to the constraint (6) for larger values of $m_{\tilde{q}}$ and $m_{\tilde{g}}$. Moreover, the boundary $m_{\tilde{e}_R} \geq 22$ GeV is approximately a contour

$$\rho_{\tilde{\gamma}} \approx 0.01 \rho_c \Big|_{H_0 = 50 \text{ km/s/Mpc}} \quad (7)$$

This is an important result, as it provides a lower bound on the relic photino density which tells us that in minimal supergravity models it cannot be much lower than that of baryons, and hence is not cosmologically negligible.

Demanding $\rho_{\tilde{\gamma}} \leq \rho_c$ imposes a new severe constraint on the sparticle spectrum, namely

$$m_{\tilde{q}} \leq 42 \text{ GeV} + 0.89 m_{\tilde{g}} \quad (8)$$

if $H_0 = 50$ km/sec/Mpc, to be compared with the upper bound

$$m_{\tilde{q}} \geq 0.89 m_{\tilde{g}} \quad (9)$$

obtained from the selectron mass constraint (6).

It is easy to see from fig. 1 what happens if at a second stage we demand $\rho_{\tilde{g}} = \rho_c$ as suggested by inflationary cosmology.⁷ The bound (8) becomes an equality for $H_0 = 50$ km/sec/Mpc in minimal supergravity models. Of course, one could demand $\rho_{\tilde{g}} = \rho_c$ without requiring the minimal supergravity relations (5) between sparticle masses. Figs. 2a and b give the results of such an analysis, now with the vertical axes taken to be $m_{\tilde{g}}$, and taking $m_{\tilde{1}} = m_{\tilde{q}}$ and $m_{\tilde{1}} = m_{\tilde{q}}/2$ for the horizontal axes, respectively. Clearly we find in this less model-dependent case that the restriction $\rho_{\tilde{g}} \leq \rho_c$ on the sparticle masses are less severe.

Finally, we turn to the implications of our results for supersymmetric interpretations^{8,9,10} of the missing energy events reported by UA1.¹¹ Essentially three different classes of interpretations have been proposed:

$$(a) \quad m_{\tilde{q}} = 0(40 \text{ to } 50) \text{ GeV} < m_{\tilde{g}} \quad (\text{ref. 8}) \quad (10a)$$

$$(b) \quad m_{\tilde{g}} = 0(40 \text{ to } 50) \text{ GeV} < m_{\tilde{q}} \quad (\text{refs. 8,9}) \quad (10b)$$

$$(c) \quad m_{\tilde{g}} = 0(3 \text{ to } 20) \text{ GeV} \ll m_{\tilde{q}} = 0(80 \text{ to } 120) \text{ GeV} \quad (\text{ref. 10}) \quad (10c)$$

Interpretation (a) is clearly compatible with $\rho_{\tilde{g}} \leq \rho_c$ in fig. 1, but it can never give $\rho_{\tilde{g}} = \rho_c$. Hence inflationary cosmologies would require an additional source of dark matter if interpretation (a) were correct. In contrast, interpretation (b) clearly can give $\rho_{\tilde{g}} = \rho_c$ as well as the allowed strict inequality. However, the constraint $\rho_{\tilde{g}} \leq \rho_c$ tells us (8) that the squarks cannot be much heavier than

the gluino in such a scenario. Shown in fig. 1 as a shaded swath is an artist's impression of the form of the curve interpolating in $(m_{\tilde{q}}, m_{\tilde{g}})$ space between the limits (a) $m_{\tilde{q}} = 40$ GeV, $m_{\tilde{g}} \rightarrow \infty$ and (b) $m_{\tilde{q}} \rightarrow \infty$, $m_{\tilde{g}} = 40$ GeV, which would give phenomenologically acceptable numbers of missing energy events in the UA1 data. Note that if $m_{\tilde{g}} = m_{\tilde{q}}$, then masses of 55 GeV and over are required.¹⁹ Note also that $m_{\tilde{q}} < m_{\tilde{g}}$ is excluded for $m_{\tilde{q}} \lesssim 60$ GeV by the search¹⁷ for $e^+e^- \rightarrow \gamma + (\tilde{\gamma}\tilde{\gamma})$.

Fig. 1 reveals clearly that scenario (c) has cosmological problems, independent of arguments about its experimental acceptability.¹⁹ In the most favourable case ($m_{\tilde{g}} = 20$ GeV, $m_{\tilde{q}} = 80$ GeV), there is a factor of 5 overdensity of $\tilde{\gamma}$ if $H_0 = 50$ km/sec/Mpc. In the least favourable case ($m_{\tilde{g}} = 3$ GeV, $m_{\tilde{q}} = 120$ GeV), $\rho_{\tilde{\gamma}}/\rho_c \gtrsim 2000$. Of course, this contradiction has appeared in the context of minimal supergravity models,⁶ and one may ask if it still occurs if the model-dependent relations (5) among sparticle masses are abandoned. Two possible ways to make $\rho_{\tilde{\gamma}}$ acceptable are (A) increase the ratio $m_{\tilde{\gamma}}/m_{\tilde{g}}$, or (B) reduce the ratio $m_{\tilde{1}}/m_{\tilde{q}}$. Escape route (A) requires abandoning the usually assumed universality of gaugino masses at the grand unification scale. We are aware of one theoretical scenario where this has been proposed,²⁰ but there $m_{\tilde{\gamma}}/m_{\tilde{g}}$ is decreased by a factor of 2, which only makes the cosmological problem worse. How about escape route (B)? Because $\frac{m_{\tilde{1}}}{m_{\tilde{q}}} \ll 1$ in interpretation (c) one expects $m_{\tilde{1}} \approx m_{\tilde{q}}$ from equation (5). However, in general supersymmetric theories there could be contributions to $m_{\tilde{1}}$ and $m_{\tilde{q}}$ from D terms which are non-zero if the Higgs vacuum expectation values v_1 and v_2 are unequal. One might hope to use the D terms to suppress some $\tilde{1}$ masses, thereby enhancing the $\tilde{\gamma}\tilde{\gamma}$ annihilation cross-section and thus suppressing the relic $\tilde{\gamma}$ density to cosmological acceptability. However, we note that numerically the largest D terms are those

for the $\tilde{u}_L$ and $\tilde{d}_L$ squarks. This means that one cannot suppress $\tilde{l}$ masses without simultaneously suppressing some $\tilde{q}$ mass even further. Indeed, one cannot suppress some $m_{\tilde{l}}$ sufficiently to restore cosmological acceptability without introducing such a light $\tilde{q}$ that the monojet production cross-section becomes unacceptably large in this $\tilde{g}q \rightarrow \tilde{q}$ fusion scenario. Moreover, we see no way to save interpretation (c) in supersymmetric models with a non-minimal set of light sparticles, because photinos weighing less than 3 GeV as in this scenario can only annihilate to charged particles weighing less than 3 GeV, and we know all the light charged particles that exist, namely those in the standard model.

Finally, it is tempting to note that fig. 1 offers us a unique scenario which yields $\rho_{\tilde{g}} = \rho_c$ and a number of monojets compatible with those reported by UA1, namely

$$m_{\tilde{g}} \approx (45 \text{ to } 60) \text{ GeV}, \quad m_{\tilde{q}} \approx (80 \text{ to } 95) \text{ GeV} \quad (11)$$

In this case the other sparticle masses are predicted to be:

$$m_{\tilde{\gamma}} \approx (7 \text{ to } 8 \frac{1}{2}) \text{ GeV}, \quad m_{\tilde{l}} \approx (70 \text{ to } 80) \text{ GeV} \quad (12)$$

In this case, while most monojets would be due to $\tilde{g}\tilde{g}$ pair production and have relatively modest missing p_T , there would also be some $\tilde{g}\tilde{q}$ associated production events in which the more generous kinematics of $\tilde{q}$ decay could occasionally lead to more dramatic missing p_T . Also note that the range of sparticle masses (11,12) can result in an observable flux of cosmic ray antiprotons from annihilating photinos in the galactic halo.²¹

We have seen that requiring an acceptably low cosmological relic sparticle density imposes interesting and non-trivial constraints on supergravity models. We have also seen that minimal supergravity requires that relic photinos have a density large enough to be astrophysically interesting. Supersymmetry may offer to experimentalists their best hope for a breakthrough discovery in the next few years. It may also offer the best hope for an astrophysical breakthrough soon on the problem of dark matter.

Note added:

After completing this work we received a preprint by S. Nandi [Univ. of Texas preprint no. CPT-85-012 (1985)] which covers similar ground and reaches similar conclusions.

REFERENCES

1. H. Goldberg, Phys. Rev. Lett. 50, (1983) 1419.
2. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, Nucl. Phys. B238 (1984) 453.
3. S. Wolfram, Phys. Lett. 82B (1979) 65; C.B. Dover, T.K. Gaisser and G. Steigman, Phys. Rev. Lett. 42 (1979) 1117.
4. L.E. Ibañez, Phys. Lett. 137B (1984) 160; J.S. Hagelin, G.L. Kane and S. Raby, Nucl. Phys. B241 (1984) 638.
5. J. Ellis, K. Enqvist and D.V. Nanopoulos, Phys. Lett. 147B (1984) 99 and 151B (1985) 357.
6. For reviews, see H.P. Nilles, Phys. Rep. 110C (1984) 2; J. Ellis, CERN-TH.3802 and CERN-TH.4017 (1984); D.V. Nanopoulos, CERN-TH.3995 (1984).
7. For reviews, see D.V. Nanopoulos, Proceedings of the First ESO-CERN Symposium on the Large Scale Structure of the Universe, Cosmology and Particle Physics, Geneva, Switzerland (1984); A.D. Linde, Proc. of the Intl. Conf. on High Energy Physics, Leipzig (1984).
8. J. Ellis and H. Kowalski, Phys. Lett. 142B (1984) 441, Nucl. Phys. B246 (1984) 189, and CERN-TH.4072 (1984).
9. E. Reya and D.P. Roy, Phys. Lett. 141B (1984) 442; Phys. Rev. Lett. 52 (1984) 881 and Dortmund University preprint (1984).
10. M.J. Herrero, L.E. Ibañez, C. Lopez and F.J. Yndurain, Phys. Lett. 132B (1983) 199, and 145B (1984) 430; A. De Rujula and R. Petronzio, CERN-TH.4070 (1984); M. Barnett, H. Haber and G.L. Kane, LBL preprint 18990, SLAC-PUB-3551 (1985).
11. UAI Collaboration, G. Arnison et al., Phys. Lett. 139B (1984) 115.
12. JADE Collaboration, W. Bartel et al., Phys. Lett. 152B (1985) 385.
13. Proceedings of the First ESO-CERN Symposium on the Large-Scale Structure of the Universe, Cosmology, and Particle Physics, Geneva, Switzerland, (1984).
14. C. Kounnas, A.B. Lahanas, D.V. Nanopoulos and M. Quiros, Phys. Lett. 132B (1983) 95, and Nucl. Phys. B236 (1984) 438; J. Ellis and M. Sher, Phys. Lett. 148B (1984) 309; L. Hall and J. Polchinski, Harvard University preprint HUTP 84/A085, UTTG 28-84 (1984); K. Enqvist, A.B. Lahanas and D.V. Nanopoulos, CERN-TH.4095 (1985).
15. L.E. Ibañez, C. Lopez, and C. Muñoz, CERN-TH.4071 (1984).
16. H. Komatsu and J. Kubo, Max Planck Institut, Munchen preprint no. MPI-PAE/PTL 16/85 (1985).
17. MAC Collaboration, E. Fernandez et al., Phys. Rev. Lett. 54 (1985) 1118.
18. F. Delduc, H Navelet, R. Peschanski and C.A. Savoy, Saclay preprint, SPHT/85/019 (1985).
19. J. Ellis and H. Kowalski, CERN-TH.4126 (1985).
20. J. Ellis, C. Kounnas and D.V. Nanopoulos, Nucl. Phys. B247 (1984) 373; J. Ellis, K. Enqvist, D.V. Nanopoulos and K. Tamvakis, CERN-TH.4018 (1985).
21. J.S. Hagelin and G.L. Kane, Maharishi Intl. Univ. preprint no. MIU-THP-85/012; J. Silk and M. Srednicki, Phys. Rev. Lett. 53 (1984) 624.

FIGURE CAPTIONS

1. Regions of $(m_{\tilde{q}}, m_{\tilde{g}})$ parameter space consistent with cosmological and terrestrial particle physics constraints. The photino and other sparticle masses are related to $m_{\tilde{q}}, m_{\tilde{g}}$ through relations (5) valid in minimal supergravity, in particular $m_{\tilde{\gamma}} \simeq (0.47/2.8) m_{\tilde{g}} \simeq (1/6) m_{\tilde{q}}$. The dashed lines trace isobars of constant cosmological relic photino density equal to the closure density for $H_0 = 25 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, above which one must lie for cosmological consistency. The solid line traversing the figure corresponds to $m_{\tilde{e}_R} = 22 \text{ GeV}$, below which one must lie for consistency with $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$ experiments. The solid arc corresponds to a somewhat more stringent constraint from $e^+e^- \rightarrow \gamma + (\tilde{\gamma}\tilde{\gamma})$ experiments. The shaded hyperbolic swath depicts regions of $(m_{\tilde{q}}, m_{\tilde{g}})$ which lead to phenomenologically acceptable numbers of missing energy events in the UA1 data.¹⁰ The dotted line indicating $m_{\tilde{g}} = m_{\tilde{q}}$ forms the boundary between two interpretations (a) and (b) of missing energy events discussed in the text.

2. Photino and sfermion mass domains consistent with cosmology. The dashed lines trace isobars of constant cosmological relic photino density equal to the closure density for $H_0 = 25 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, above which one must lie for cosmological consistency. Fig. (a) assumes degenerate squark and slepton masses, whereas fig. (b) assumes $m_{\tilde{q}} = 2m_{\tilde{l}}$. The dotted diagonal lines indicating $m_{\tilde{g}} = m_{\tilde{q}}$ assume the universality of gaugino masses at the grand unification scale.

Figure 1.

Figure 2.