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Effect of relaxing grand-unification assumptions on neutralinos in the minimal supersymmetric model

Kim Griest*
Center for Particle Astrophysics and Astronomy Department, University of California, Berkeley, California 94720

Leszek Roszkowski†
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
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We consider the phenomenological and cosmological properties of light neutralinos in the minimal supersymmetric model when grand-unification assumptions are relaxed. We show that substantial changes result in the mass and mixing properties of the neutralinos, in the interpretation of recent experimental restrictions on neutralino parameter space, and in the relic abundance of light-neutralino dark matter. Relaxation of the grand-unification assumptions is easily accomplished, even within the minimal supergravity model, and results in a larger neutralino parameter space and the viability of light-neutralino ($\lesssim$ 10–20 GeV) dark matter.

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Neutralinos have been extensively studied and searched for in the past decade, as signatures of supersymmetry [1–3], and as candidates for dark matter [4–6]. In general, they are the supersymmetric partners of the neutral gauge and Higgs bosons, and are present in all supersymmetric extensions of the standard model. Supersymmetry (SUSY) has received so much attention, in part, because it seems to be a necessary ingredient of models which unify gravity with the other three forces, and because low-energy supersymmetry allows an elegant solution to the gauge hierarchy problem. As the probable lightest supersymmetric particle (LSP) [4] it is not surprising that neutralinos have been an attractive topic of phenomenological and cosmological research.

In this paper we wish to reconsider neutralinos in the minimal supersymmetric standard model (MSSM), but, in contrast with common practice, we will not assume grand unification conditions [7]. The meaning of the term "minimal supersymmetry" varies in the literature. The MSSM is based on the standard model gauge group, minimal particle content (one SUSY state for every standard model state, plus the required extra Higgs doublet), and arbitrary soft-supersymmetry-breaking parameters. However, many authors include in the definition of "minimal supersymmetry" some grand-unified-theory (GUT) assumptions (such as common gaugino and common scalar masses at the unification energy scale). While these GUT assumptions are elegant and in some sense natural, from the perspective of the low-energy phenomenology they are not necessary, and even at the GUT scale they can be avoided easily, as will be discussed. Many conclusions made about SUSY cosmology and phenomenology apply only to the MSSM with the GUT assumptions imposed, but are sometimes quoted as general properties of supersymmetric models.

With the experimental data of the past, the distinction between the different "minimal" models was not particularly stressed. The parameter space of even the MSSM is large and complicated enough so that most interesting phenomena occurred independently of whether or not the GUT assumptions were included; so the tendency was to restrict the parameter space as much as possible by imposing various reasonable assumptions, including the GUT assumptions. However, with the advent of the recent results from the CERN e^+e^- collider LEP and Collider Detector at Fermilab (CDF) Collaboration, more sophistication is desirable. Significant regions of parameter space have now been excluded and, particularly in the case of the lightest neutralino eigenstate relevant for the LSP and dark matter, qualitative conclusions can depend upon whether or not the GUT assumptions are imposed. In this paper we consider some of the changes which occur in neutralino phenomenology and cosmology when some of the GUT assumptions are relaxed. We show that various experimental and cosmological bounds can be significantly modified depending on whether or not certain GUT relations are imposed (see also Ref. [7]). We do not attempt to make an exhaustive search of the (enlarged) SUSY parameter space, but illustrate, with a few examples, that the results obtained from assuming simple grand unification can be easily evaded.

The MSSM that we will consider is an effective low-energy theory with the standard model gauge group, global $N=1$ supersymmetry broken softly, minimal particle content, and all B, L, CP, and R parity-conserving soft-SUSY-breaking terms in the Lagrangian [2,3]. The model is not assumed to originate from any specific supergravity theory, and hence no specific GUT constraints are *a priori* assumed. Note, however, that this model can be derived from supergravity as discussed shortly. The MSSM has been extensively discussed and reviewed, and

*Present address: Dept. of Physics, University of California, San Diego, La Jolla, CA 92093-0319.

†Present address: Dept. of Physics, University of Michigan, Ann Arbor, MI 48109.

the reader may consult Refs. [2,3,8] for more detail. We note that the MSSM is similar, but somewhat more constrained than the "minimal effective supersymmetric" models recently discussed by Hall and Randall [9]. These authors emphasize that the idea of weak-scale supersymmetry should be tested without regard to the Planck-scale origin of any specific model. From a reasonable set of assumptions (including the weak minimality condition above), they construct a set of models not unlike the MSSM that we consider. However, they also include some SUSY-breaking terms which do not occur in $N=1$ supergravity models.

In the minimal SUSY model which we consider there are four neutralino states, superpartners of the neutral gauge and Higgs bosons. The masses and compositions of these states are determined by four parameters: $\tan\beta=v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets; μ, a supersymmetric Higgs-boson mass parameter; and M_1 and M_2, soft-SUSY-breaking mass parameters of the gauginos $\tilde{B}$ and $\tilde{W}_3$ of the $U(1)_Y$ and $SU(2)_L$ low-energy gauge groups, respectively. We will denote the neutralino states by χ_i, $i=1,2,3,4$, where $i=1$ indicates the lightest eigenstate, $i=2$ the next lightest, etc. The composition of the ith state is given by

$$\chi_i=Z_{i1}\tilde{B}+Z_{i2}\tilde{W}_3+Z_{i3}\tilde{H}_1^0+Z_{i4}\tilde{H}_2^0 , \tag{1}$$

where Z_{ij} is the matrix which diagonalizes the neutralino mass matrix, and the basis states are the B-ino, W_3-ino, and two neutral Higgsinos. We will also call the lightest eigenstate *the* neutralino and denote it by χ and its mass by m_χ.

The MSSM also contains many squark and slepton states and five physical Higgs bosons: h, H, A, and $H^\pm$, with $m_h \le m_Z|\cos 2\beta| \le m_Z \le m_H$, $m_h \le m_A \le m_H$, and $m_H^\pm \ge m_W$ (at the tree level). In the absence of GUT assumptions the Higgs-boson masses are determined by just two parameters (which we take to be m_h and $\tan\beta$), but the masses of the sfermions are arbitrary. Finally, there are also gluinos, partners of the gluons, with a mass scale set by another soft-SUSY-breaking parameter $M_3=m_{\tilde{g}}$.

When the MSSM is embedded in a GUT with a simple gauge group, several relationships between the many parameters can result. Typically, one adopts the minimal supergravity scenario, assumes that the gaugino masses are equal ($M_1=M_2=M_3$) at the GUT scale, and then uses the renormalization group to evolve these masses down to the electroweak scale to find

$$M_1=\tfrac{5}{3}\tan^2\theta_W M_2 \simeq 0.5 M_2 , \tag{2a}$$

$$M_2=\frac{\alpha_2}{\alpha_s}M_3 \simeq 0.3 m_{\tilde{g}} , \tag{2b}$$

where $\alpha_2=\alpha_{\rm em}/\sin^2\theta_W$. In addition, by specifying in more detail the SUSY-breaking mechanism, other equations relating the squark, slepton, etc., masses and couplings can be found (see, e.g., Ref. [10]). Actually, the GUT-scale relation $M_1=M_2=M_3$ is not the most general choice [7]. It follows (for example) from the standard softly broken SUSY scheme and the assumption that kinetic terms for the gauge superfields in the supergravity Lagrangian are diagonal and equal.

This is a natural assumption, which is often made. However, it is not necessary [11]. As shown in Ref. [12], one simple way to have this relation not hold (still within the framework of a minimal supergravity model) is to slightly complicate the kinetic terms of the gauge superfields in the supergravity Lagrangian

$$\mathcal{L} \supset -\frac{e}{4}f_{ab}\bar{\lambda}^a D^\mu \gamma_\mu \lambda^b-\frac{e}{4}f_{ab}F^a_{\mu\nu}F^{b\mu\nu}+\cdots , \tag{3}$$

where f_{ab} is in general an arbitrary analytic function of the chiral superfields which transforms like a product of two adjoint representations. In one definition of the minimal supergravity model, the function f_{ab} is taken to be the Kronecker δ function δ_{ab}, in which case Eqs. (2a) and (2b) result. When f_{ab} is allowed to have off-diagonal terms [12], the gauge fields must be rescaled, and as a result the normal GUT relation $M_1=M_2=M_3$ does not obtain. Thus, the values of M_1, M_2, and M_3 become arbitrary [12] and Eqs. (2a) and (2b) need not hold. One should also note that the relations (2a) and (2b) do not occur in the "minimal effective supersymmetry" models of Ref. [9].

The neutralino sector of the MSSM has been studied almost exclusively under the assumptions given by Eqs. (2a) and (2b) (but see Refs. [13,7] for exceptions), even though strictly speaking they are not part of the model. All cosmological and almost all experimental predictions have used at least the first of the relations (2a). Since the neutralino masses and compositions depend upon M_1 and M_2, one finds changes in the predictions as

$$r\equiv M_1/M_2 \tag{4}$$

is varied from its GUT assumption value of $r_{\rm GUT}=\frac{5}{3}\tan^2\theta_W\simeq 0.5$. In the absence of the unification condition, the signs of M_1 and M_2 could even be different.

To illustrate the importance of r, we show in Fig. 1 mass and composition contours in the (μ,M_2) plane for $\tan\beta=2$ and two representative choices of r. Figure 1(a) shows the standard GUT ($r\simeq 0.5$) case, while Fig. 1(b) shows the effect of taking $r=0.1$. Since the parameter μ can be either negative or positive, we show the $\mu<0$ cases in the left sides and the $\mu>0$ cases in the right sides. The regions marked "LEP" are those excluded experimentally and will be discussed shortly. Note that when $M_2 \gg \mu$, a nearly pure Higgsino eigenstate ($Z_{11}=Z_{12}=0$) results, while for $\mu \gg M_2$ the neutralino is a nearly pure gaugino ($Z_{13}=Z_{14}=0$) and mostly a B-ino ($Z_{12}=1$). Also note that for $m_\chi > m_W$, the neutralino may not be the LSP.

We will follow Ref. [14] in our definition of the purity of the lightest neutralino eigenstate. If the neutralino mass eigenstate is given by its basis components $(Z_{11},Z_{12},Z_{13},Z_{14})$, then in general, its purity with respect to a specific (normalized) linear combination of gauginos and Higgsinos $\chi_a=(a_{\tilde{B}},a_{\tilde{W}_3},a_{\tilde{H}_1},a_{\tilde{H}_2})$ is $p_{\chi_a}\equiv(Z_{11}a_{\tilde{B}}+Z_{12}a_{\tilde{W}_3}+Z_{13}a_{\tilde{H}_1}+Z_{14}a_{\tilde{H}_2})^2$. So, for example, the B-ino purity of a neutralino is $p_{B\text{-ino}}=Z_{11}^2$, and the photino ($Z_{11}=\cos\theta_W$ and $Z_{12}=\sin\theta_W$) purity is

$p_{\text{photino}} = (Z_{11}\cos\theta_W + Z_{12}\sin\theta_W)^2$. We also define [14] the gaugino and Higgsino purities as

$$p_{\text{gaugino}} \equiv Z_{11}^2 + Z_{12}^2 \quad \text{and} \quad p_{\tilde{H}} \equiv Z_{13}^2 + Z_{14}^2 , \tag{5}$$

the sum of the two relevant gaugino or Higgsino basis states, respectively. Figure 1 shows contours of gaugino purity of 0.99, 0.9, 0.5, 0.1, and 0.01 (from right to left). (Note that, since $p_{\text{gaugino}} + p_{\tilde{H}} = 1$, a gaugino purity of 0.99 corresponds to a Higgsino purity of 0.01, etc.) In addition, we show the regions where the neutralino is at least 99% pure B-ino or at least 99% symmetric or antisymmetric Higgsino $\tilde{H}_{S,A}$ $(Z_{13} = \pm 1/\sqrt{2}, Z_{14} = 1/\sqrt{2})$.

Mass and purity contours of the type shown in Fig. 1(a) have appeared many times in the literature [4–6,14], and this diagram constitutes the parameter space usually explored when considering neutralino phenomenology and cosmology. Note the large changes in the mass and purity contours, which occur when a value of r different from its GUT value is taken [Fig. 1(b)]. Clearly, relaxing Eqs. (2a) and (2b) modifies the neutralino parameter space. Many of the changes in mass and purity contours can be understood by noting that, for large $|\mu|$, $m_\chi \simeq M_1 = rM_2$, while for large M_2, $m_\chi \simeq |\mu|$. So changing r effectively shifts the mass contours along the M_2 axis. After performing this scaling, the mass contours of Figs. 1(a) and

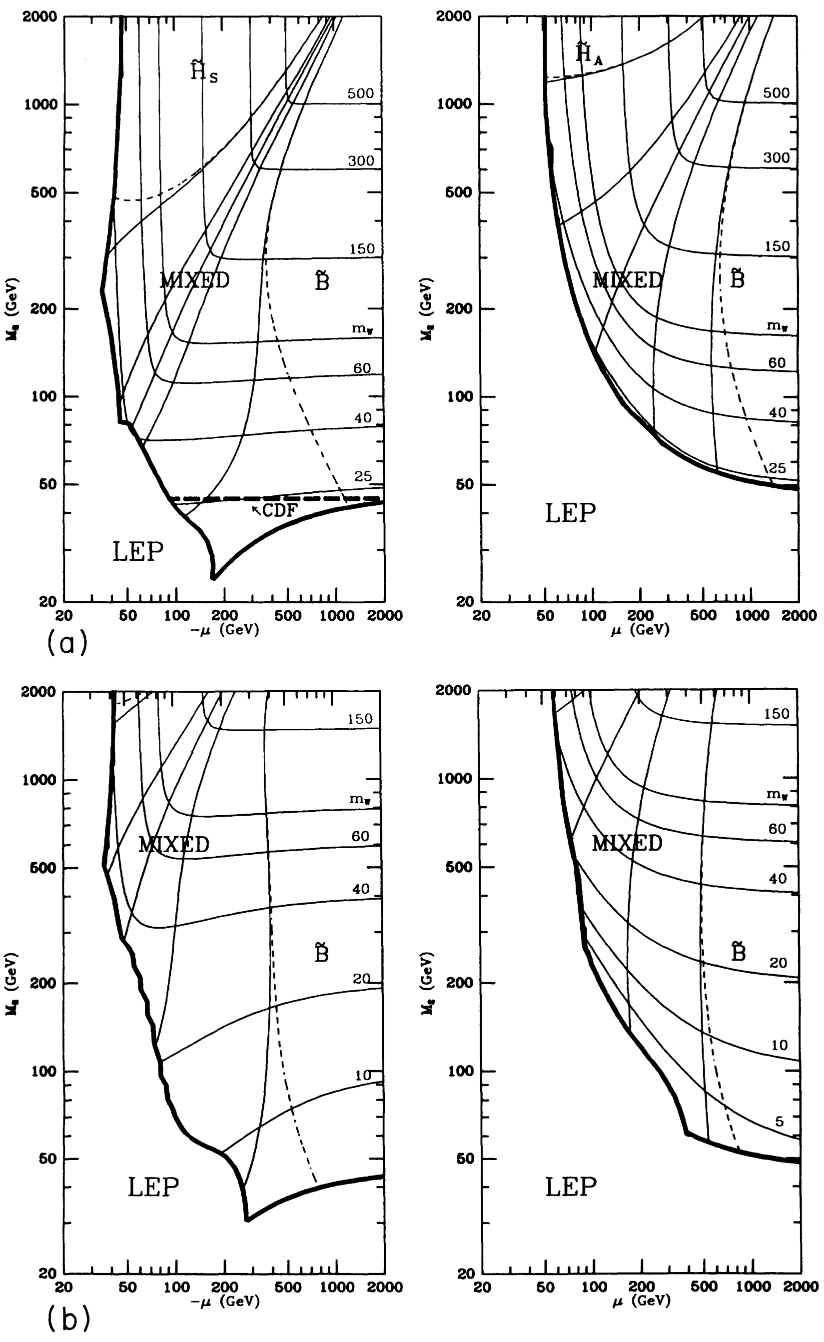

FIG. 1. Mass and composition contours in the (μ, M_2) plane, with accelerator constraints for $\tan\beta = 2$ and $r \equiv M_1/M_2 = 0.5$ (GUT case) in (a), and $r = 0.1$ in (b). The left sides show $\mu < 0$, while the right sides show $\mu > 0$. The lightest neutralino mass contours are labeled (in GeV). Contours of constant gaugino purity $(p_{\text{gaugino}} = Z_{11}^2 + Z_{12}^2)$ are shown with $p_{\text{gaugino}} = 0.01$, 0.1, 0.5, 0.9, and 0.99 from left to right. (Note that $p_{\text{gaugino}} = 0.01$ implies 99% Higgsino.) The region (labeled $\tilde{B}$) to the right of the dashed curve has $p_{\tilde{B}} \geq 0.99$ (almost pure B-ino), while the region (labeled $\tilde{H}_S$ or $\tilde{H}_A$) above the other dashed curve corresponds to almost pure symmetric or antisymmetric Higgsino $(p_{\tilde{H}} > 0.99)$. The areas marked "LEP" are ruled out by LEP and the areas below the curves marked "CDF" are ruled out [via Eq. (2b)] by CDF. Note that for $m_\chi > m_W$, the neutralino may not be the LSP.

1(b) are not so different.

In addition to restructuring mass and composition contours, the GUT assumptions are important in determining the impact that accelerator bounds have on neutralino parameter space. For example, the UA2 and CDF searches for squarks and gluinos imply a bound on gluino masses of $M_3 \gtrsim 79$ [15] and 150 GeV (preliminary) [16], respectively. Using relation Eq. (2b) translates this bound into a lower bound on M_2 of 23.5 (UA2) and 44.6 GeV (CDF). Examination of Fig. 1 shows that such a bound severely limits the possibility of low-mass neutralinos. Combining this bound with the LEP results on direct searches for neutralinos, LEP data on the Z-line shape, and LEP data on Higgs-boson searches have led to the limit $m_\chi > 13$ GeV (UA2) [20 GeV (CDF)] [17]. Since the gluino searches probe strong-interaction physics while the neutralino states involve only electroweak physics, from the low-energy point of view, Eq. (2b) can be regarded as a strong assumption. Relaxing this assumption removes the relevance of the gluino search results and again allows light-neutralino eigenstates. (Experimentally, even massless neutralinos are allowed, although they would be cosmologically excluded.) The GUT assumptions, along with a requirement that the SUSY-breaking scale be not too high, also leads to an *upper* limit on the neutralino mass [14]. For example, assuming that the SUSY-breaking scale (and hence the mass of the gluino) does not exceed about 1 TeV leads [14] to $m_\chi \le$ roughly 150 GeV. This bound is comparable to an analogous bound of roughly 110 GeV resulting from applying a naturalness criterion [18]. In addition, these conditions strongly disfavor almost-pure Higgsino regions as corresponding to too large gluino masses [14]. If the relation (2b) is relaxed, these restrictions are eased and a low SUSY-breaking scale is again consistent with more massive neutralinos.

The interpretation of the LEP searches for neutralinos in Z decays also depends upon whether or not the GUT assumptions are imposed. ALEPH, DELPHI, and OPAL [1,19] have published results of direct searches for neutralinos in the processes $Z \to \chi\chi'$ and $Z \to \chi'\chi'$, where χ' stands for any heavier neutralino, and have set limits on the Z branching ratio into neutralinos:

$$\begin{aligned} B(Z \to \chi\chi') &\le \text{ a few} \times 10^{-5} , \\ B(Z \to \chi'\chi') &\le \text{ a few} \times 10^{-5} , \end{aligned} \tag{6}$$

where the value of the above factors depends on the masses and relative CP of the final-state neutralinos, but typically varies between 2 and 10 in most of the kinematically accessible parameter space. Since $B(Z \to \chi_i \chi_j) \propto (Z_{i3}Z_{j3} - Z_{i4}Z_{j4})^2$, these limits constrain the neutralino parameter space. Since both the masses and the gaugino-Higgsino decompositions of neutralinos depend on the ratio $r = M_1/M_2$, the corresponding excluded regions in the (μ, M_2) plane will vary for a given $\tan\beta$ depending on the choice of r. Furthermore, LEP Z-line shape measurements should also be taken into account, and their interpretation in our context will also depend upon the choice of r. In particular, we have used a new allowed region in the $(\sigma^0_{\rm had}, \Gamma_z)$ plane, which can be extracted from Ref. [20], where the visible hadronic peak cross section $\sigma^0_{\rm had}$ and the total Z width Γ_Z are related by

$$\sigma^0_{\rm had} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\rm had}}{\Gamma_Z^2} . \tag{7}$$

Conservatively, we have taken the 99% C.L. region in the $(\sigma^0_{\rm had}, \Gamma_Z)$ plane and assumed that both final states $\chi\chi'$ and $\chi'\chi'$ contribute to the total width only through the hadronic width. In addition, one could use the current experimental values of the number of equivalent neutrino species N_ν, the ratio $R = \Gamma_{\rm had}/\Gamma_l$, and/or $B_l = \Gamma_l/\Gamma_Z$, but, once the bound coming from the $(\sigma^0_{\rm had}, \Gamma_Z)$ plane is imposed, these do not constrain the neutralino parameter space any further.

Finally, we impose the consistency bound that the chargino be more massive than the lightest neutralino, and a bound coming from nonobservation at LEP [1] of charginos with mass less than 45 GeV. Since the chargino sector depends only on M_2, μ, and $\tan\beta$, and not on M_1, this last bound remains the same in both Figs. 1(a) and 1(b).

We show the combined LEP constraints as the heavy dark lines in Figs. 1(a) and 1(b), the side labeled "LEP" being ruled out. Once again, note that the areas affected by the LEP constraints in general depend upon the value of r, except for those parts which are due to a chargino constraint. While the regions of parameter space excluded by LEP are affected by the choice of r, it is clear from the figures that the main effect is the scaling of the neutralino mass contours mentioned earlier. Small values of r allow lighter neutralinos to exist in the regions not ruled out by LEP, while larger values of r mean that even quite heavy neutralinos are excluded. (Of course, only χ's with mass less than $m_Z/2$ can be constrained because of LEP's kinematic limit.)

Note also that some areas of the (μ, M_2) plane (small M_2 and $|\mu| \lesssim 200$ GeV), in which the lightest neutralino is gauginolike (and mostly photinolike), are also for the most part excluded by LEP even though the charginos are heavier than 45 GeV there. This is at first look surprising because χ's couple to the Z boson only through their Higgsino components. In these areas, however, some of the heavier (but still kinematically allowed) neutralinos are Higgsinolike and therefore contribute to the Z-line shape and can be ruled out. We note that the regions where the LSP is a nearly pure photino have been also considerably constrained by LEP, although not ruled out.

The mass and composition contours, as well as the disallowed areas of parameter space, also have an important effect on the cosmology of neutralinos. As a well-motivated, stable, neutral, and weakly interacting particle, the lightest neutralino makes one of the best candidates [4,5] for the dark matter believed to exist in the halos of spiral galaxies [21,22]. Measurements of the rotation curves of spiral galaxies imply the existence of 3–10 times as much dark matter (DM) as luminous matter; therefore, using the measured density of luminous matter (in units of the critical density), the density of dark matter is probably at least $\Omega_{\rm DM}h^2 \ge 0.025$, where

$0.5 \le h \le 1$ parametrizes our ignorance of the Hubble constant. Conservative limits on the age of the Universe require $\Omega_{\rm DM}h^2 < \Omega_{\rm tot}h^2 \le 1$. So for neutralinos to be interesting as dark matter, they should exist with cosmological density of roughly $0.025 \le \Omega_\chi h^2 \le 1$. Furthermore, if one believes $\Omega = 1$, either for aesthetic reasons or because of cosmic inflation, the range $0.25 < \Omega_\chi h^2 < 0.5$ should be considered the most interesting.

The relic density of neutralinos can be calculated once the parameters of the SUSY model are specified. Since $\Omega_\chi \propto (\langle \sigma v \rangle_{\rm ann})^{-1}$, the parameters of interest are those which influence the total annihilation cross section $\langle \sigma v \rangle_{\rm ann}$ ($\chi\chi \rightarrow$ ordinary matter). These are masses of the squarks, sleptons, and Higgs bosons which are exchanged in the annihilation and the parameters which determine the χ mass and coupling. The range of parameters which allow neutralino dark matter has been extensively studied [4–6, 23], although the GUT assumption, Eq. (2a), has always been imposed. We are interested in finding the effect of relaxing this assumption. In Fig. 2, we show contours of relic abundance in the same (μ, M_2) plane as was used in Fig. 1, and with the same values of r. Figure 2(a) shows the GUT ($r \simeq 0.5$) case, while Fig. 2(b) shows the $r = 0.1$ case. Growing intensity of grey shading indi-

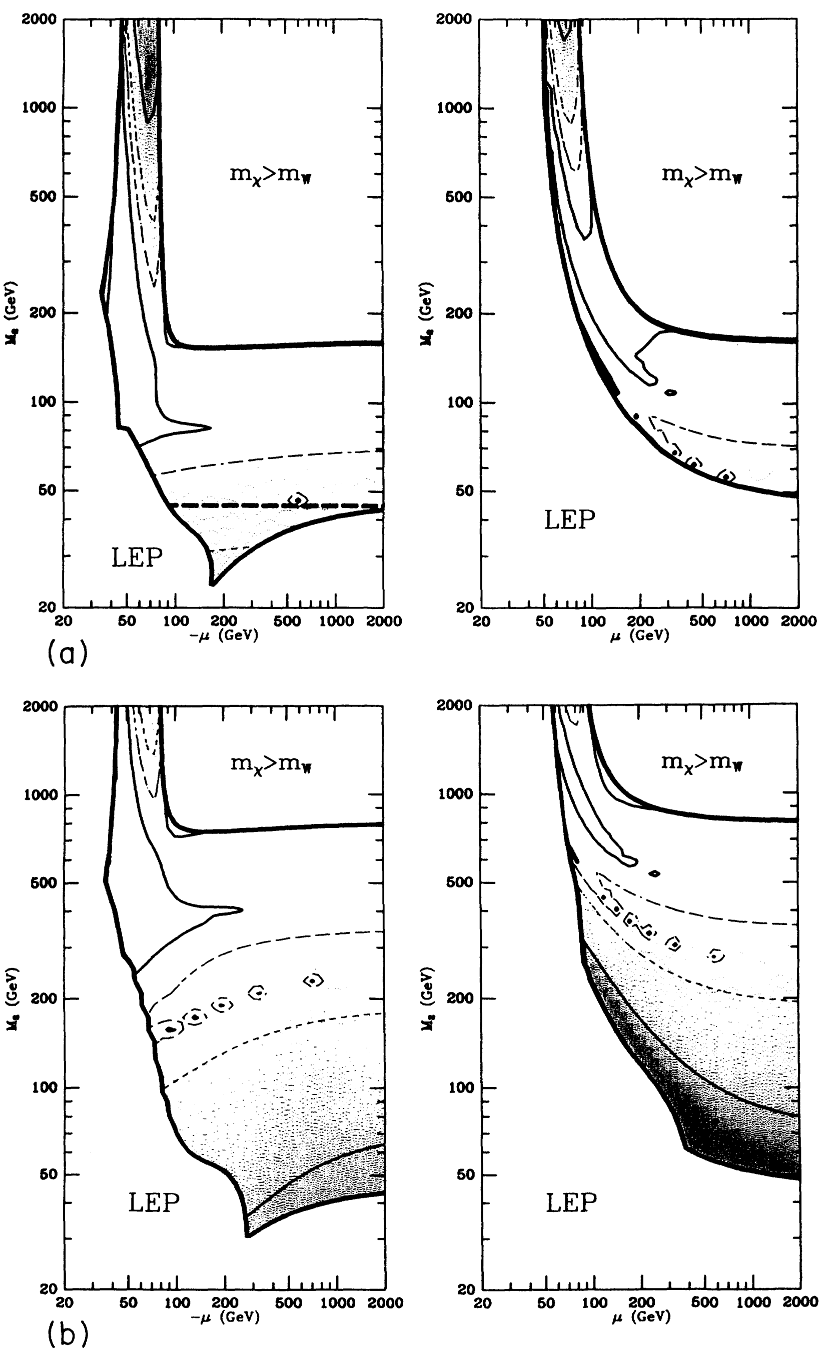

FIG. 2. Contours of constant relic abundance in the (μ, M_2) plane, with $\tan\beta = 2$, $m_h = 50$ GeV, $m_{\tilde{q}} = 150$ GeV, and $m_{\tilde{l}} = 100$ GeV. Areas ruled out by LEP are marked "LEP," while areas marked "$m_\chi > m_W$" were not considered. The area below the very thick dashed line is ruled out by CDF [via Eq. (2b)]. Increasing grey shading indicates growing relic abundance. Solid contours indicate $\Omega h^2 = 1$ (in grey areas) or $\Omega h^2 = 0.025$ (in white areas). Short-dashed lines in grey areas indicate the preferred value $\Omega h^2 = 0.25$, while long-dashed curves (in white areas) indicate $\Omega h^2 = 0.1$. The area between solid curves are acceptable cosmologically for neutralino DM. (a) shows $r = 0.5$ (the GUT case), while (b) shows $r = 0.1$.

cates growing relic abundance. The solid lines in shaded areas are $\Omega h^2=1$ contours, so the darker side of these lines have $\Omega h^2>1$, which is inconsistent with the age of the Universe. The short-dashed lines are the favored $\Omega h^2=0.25$ contours, the long-dashed lines are the $\Omega h^2=0.1$ contours, and the solid lines in white areas indicate $\Omega h^2=0.025$. We do not consider neutralinos in the regions with $m_\chi > m_W$, since several new annihilation channels that have not been included in our calculations open up. To calculate the relic abundances we used two methods. In Fig. 2 the same method as in Refs. [4,14] was used, while in Fig. 3 the method of Ref. [5] was used with the cross sections given in Ref. [23]. While neither of these methods is the most accurate, since the ways of solving the Boltzmann equation are approximate, they are good enough for our purposes here and give similar results. Also, note that if one used the simple supergravity renormalization-group equation for evolution of the sfermion masses, different relic abundance contours would result. We discuss this in more detail below.

Since there are so many parameters in these models that can be varied, and since we are not attempting a complete survey, we have shown in Fig. 2 a set of parameters which aids the possibility of *light*-neutralino dark matter, i.e., below the $\sim$20-GeV bound derived in the GUT case [17]. It has been shown [6,23] (for $r=0.5$) that neutralinos up to several TeV in mass make fine dark-matter candidates [24]. However, it is only those neutralinos with masses below $\sim$45 GeV that are probed by the recent LEP experiments. Since the detection of neutralino dark matter, either directly via elastic-scattering experiments [25,26] or indirectly through effects in the Sun [27], becomes more difficult as the mass of the neutralino increases, the allowed mass range for neutralino dark matter is quite important. So in Fig. 2 we have taken the squark masses as low as allowed by CDF [16] ($m_{\tilde q}=150$ GeV) and taken fairly low values of slepton masses ($m_{\tilde l}=100$ GeV). (All the sleptons are taken to degenerate with each other, as are all the squarks.) A mass of the lightest Higgs boson of $m_h=50$ GeV and a value of $\tan\beta=2$ were taken and are consistent with the LEP Higgs-boson searches [28]. Since the values of the slepton masses are not as well constrained (LEP only limits them [1] to above $\sim$45 GeV), the relic abundance can be "adjusted" by varying them. The effect of taking larger values of sfermion masses is to move the cosmologically interesting regions to higher values of neutralino mass. Also, almost any region which has a value of Ωh^2 that is too low can be made cosmologically acceptable by increasing the sfermion masses.

From the figures it is clear that the value of r has great impact on the cosmologically interesting regions of SUSY parameter space. The large variation in relic abundance between Figs. 2(a) and 2(b) can be understood by scaling the M_2 axis as described earlier. Note that the cosmologically interesting gauginolike regions (around the short-dashed contour $\Omega h^2=0.25$), which have been experimentally excluded in the GUT case [Fig. 2(a)], are shifted to higher values of M_2 for sufficiently smaller values of r [such as $r=0.1$ in Fig. 2(b)], and thus become allowed again. Note also that neutralino masses of less than a few GeV, as always [4], result in a relic abundance above unity, and are thus cosmologically disallowed.

To help see the allowed mass range for neutralino dark matter, we show in Figs. 3(a)–3(c) scatter plots of m_χ against $\Omega_\chi h^2$ for $\tan\beta=2$, $m_h=50$ GeV, $m_{\tilde q}=150$ GeV, and a wide range of μ and M_2 ($-\mu$ and M_2 in logarithmic steps between 20 and 2000 GeV). Each $\times$ marks a choice of parameters which pass all experimental constraints, while each "box" [in Fig. 3(a)] marks a choice of parameters which pass all the constraints *except* the CDF gluino search limit [translated into a limit on M_2 via Eq.(2b)]. In Fig. 3(a) we show the GUT case ($r=0.5$) with $m_{\tilde l}=100$ GeV, in Fig. 3(b) we show $r=0.1$ with $m_{\tilde l}=100$ GeV, and in Fig. 3(c) we show $r=0.1$ with $m_{\tilde l}=70$ GeV.

These plots contain several interesting features. First note that all areas between the $\times$'s are actually allowed; we sampled the parameter space only discretely. The dense clustering of $\times$'s shows the relationship $\Omega h^2 \propto 1/\langle \sigma v\rangle \propto m_{\tilde l}^4/m_\chi^2$, which is expected when annihilation is dominated by sfermion exchange. The small dip near $m_h/2\simeq 25$ GeV and the large dip near $m_Z/2\simeq 45$ GeV are the result of the Higgs- and Z-boson poles in the annihilation cross section. Comparing Figs. 3(a) and 3(b), one can see the effect of relaxing the assumptions (2a) and (2b). Since $m_{\tilde l}$ is the same in both plots, the dense cluster of models follows the same curve, and the Z and Higgs poles look similar. However, the LEP and CDF constraints rule out the light neutralinos in the GUT case, the "boxes" showing the important effect of Eq. (2b). Figure 3(c) shows the effect of varying $m_{\tilde l}$. As pointed out in Ref. [14], it is the lightest sfermion, other than the sneutrino, which dominates the relic abundance, and the locus of points shifts upward in relic abundance as the slepton mass increases. In fact, because of this, for light neutralinos, there are very few areas of the (μ, M_2) plane which have too low a relic abundance. As the sfermion masses become large, it is mostly only regions near poles which remain with $\Omega h^2<0.025$.

From both the relic abundance contours and scatter plots, the importance of the GUT assumptions become clear. If one takes the view that the minimal SUSY model includes these assumptions, then neutralinos below $\sim$20 GeV are no longer good dark-matter candidates [17,29], and the direct and indirect searches for neutralinos become harder. On the other hand, if one allows an arbitrary relationship between M_1, M_2, and M_3, neutralino dark matter with mass even below 5 GeV is allowed, although even in this case LEP has restricted the range of parameters.

We should note that, in a GUT framework, supersymmetry and gauge structure alone predict that sfermion masses should grow with M_2, thus causing a potential conflict between our choice of relatively small sfermion masses and large M_2 that we also consider. We are not overly worried by this for several reasons. (a) The sfermion mass renormalization-group relations may be modified or removed by assuming additional particles and interactions between the electroweak scale and the GUT scale (i.e., if the minimal particle content is only as-

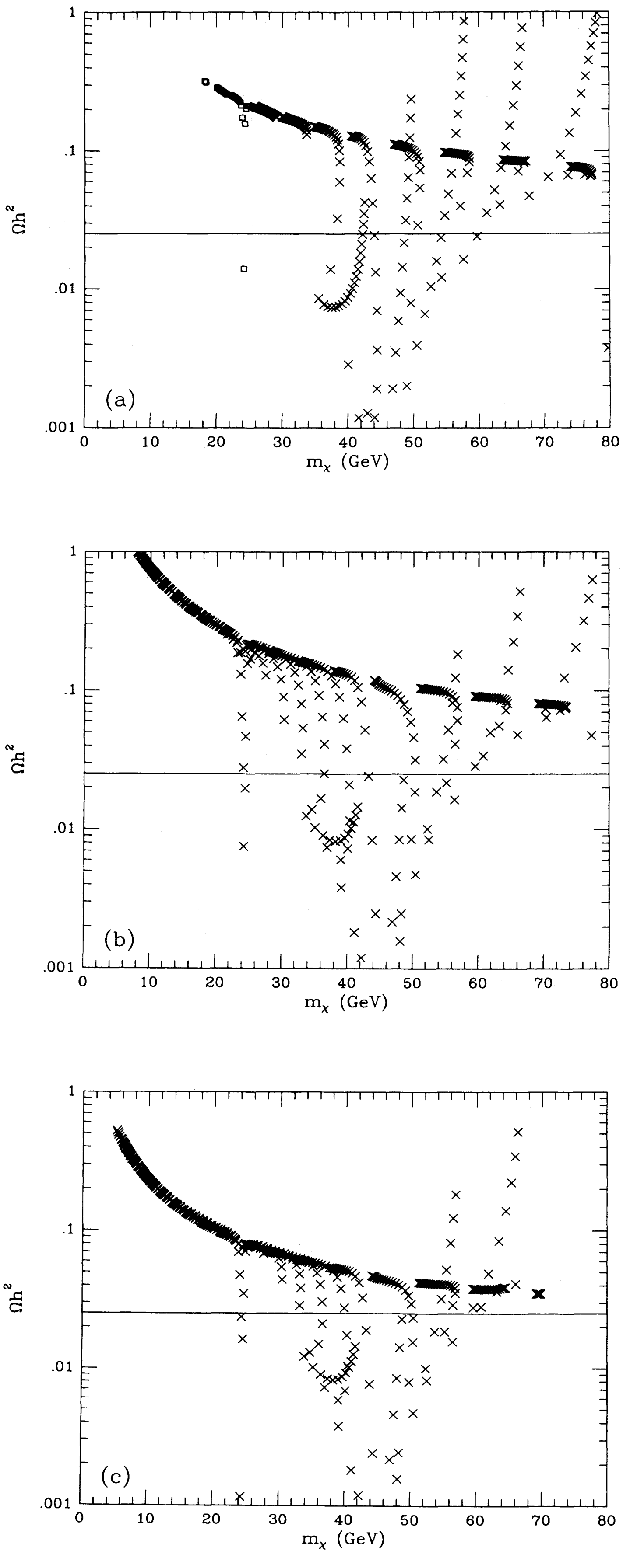

FIG. 3. Scatter plots of relic abundance as a function of neutralino mass. Each × (or □) represents a different choice of parameters; μ and M_2 are varied while $\tan\beta=2$, $m_h=50$ GeV, and $m_{\tilde{q}}=150$ GeV are fixed. (a) shows the GUT case ($r=0.5$) with $m_{\tilde{l}}=100$ GeV. Each × marks a choice of parameters which passes all experimental constraints, while each □ marks a choice which passes all constraints except the CDF gluino search (see text). (b) shows $r=0.1$ with $m_{\tilde{l}}=100$ GeV, and (c) shows $r=0.1$ with $m_{\tilde{l}}=70$ GeV. For a choice of parameters to be relevant to the dark-matter problem, it must lie above the line drawn at $\Omega h^2=0.025$.

sumed at the electroweak scale), or, for example, by allowing for large "threshold" corrections such as may arise in superstring-inspired models. Thus, in the spirit of relaxing GUT assumptions we can choose to ignore the renormalization equations. (b) If we choose to derive all the sfermion masses from relations such as $m_{\tilde{f}}^2 = M_0^2 + aM_1^2 + bM_2^2 + cM_3^2$, where M_0 is a common scalar mass and a, b, and c are couplings which vary for each sfermion and can be found, for example, in Ellis, Ridolfi, and Zwirner [30], then while some of sfermion masses run quickly and become large at the large values of M_2 we consider, there are some which do not change rapidly. The right chiral sleptons are weak singlets, so $b=c=0$, and especially for the value $r=0.1$, m_{sf_R} varies only from 100 to 109 GeV as M_2 varies up to 1 TeV (using $M_0=95$ GeV). Since relic abundance is almost completely dominated by the mass of the lightest sfermion exchanged, our $r=0.1$ contours would change little if we used the renormalization-group masses. (The change would be only a few percent in most areas of parameter space. In the Higgsinolike regions of parameter space especially, the sfermion exchange is suppressed in any case.) The changes would be somewhat larger in the B-ino region of the $r=0.5$ plots (of the order of some 10%; compare Fig. 3 of Ref. [14] with Fig. 1 of Ref. [31]), but these represent the "standard" calculations done by many previous authors with which we wish to compare our $r \neq 0.5$ results. For studies of the cosmological properties of the LSP with the sfermion-gaugino mass relations included see, e.g., Refs. [31,32].

In one sense, the decision to include Eqs. (2a) and (2b) as part of the definition of the minimal SUSY model is a matter of taste. However, if one is interested in the possibility of light supersymmetric dark matter, the elimination of models with Eqs. (2a) and (2b) imposed, while interesting, is by no means decisive. In fact, even if all "minimal" models were experimentally excluded it would not rule out the possibility of low-energy supersymmetry or neutralino dark matter. The MSSM, with or without the GUT assumptions, really has no particular claim on being the most likely SUSY extension of the standard model. We have very little information concerning the ultimate unification-theory gauge group and the form of its Lagrangian, or even on whether there is unification via a simple gauge group (although recent work by Langacker [33] and by Amaldi *et al.* [34] has been taken to support SUSY unification). Many nonminimal supersymmetric models (e.g., resulting from superstrings) can be very attractive and enlarge the parameter space considerably. Several simple extensions to the minimal SUSY model [35] that keep the standard model gauge group exist, but they contain extra particles and complicate the neutralino and Higgs sectors. For example, in the simplest extension of the MSSM, one keeps the standard model gauge group, but adds an extra Higgs singlet [36]. The corresponding Higgsino mixes with other Higgsinos and gauginos of the model, leading in general to considerably different phenomenological [36] and cosmological [37] properties of the LSP. Other examples are the recently popular E_6 models [38,35] where, in addition to the extra Higgs superfield, the gauge group is extended by at least one extra U(1) factor. The neutralino sector of these models has been studied in Refs. [39,40]. These models, and others, contain possibilities for light-neutralino dark matter which are not so constrained by the LEP results.

Finally, it is probably worthwhile to note that the main challenge to minimal SUSY comes not from the LEP neutralino searches, but from Higgs searches. At tree level, the MSSM (with or without GUT assumptions) predicts a neutral Higgs boson with a mass below m_Z [3]. LEP 200 should thus be able to, in principle, discover or rule out such a Higgs boson [41]. LEP has already searched a considerable portion of this parameter space [28]. If no Higgs boson is found, then the MSSM considered here would be ruled out. However, it has been shown recently [42] that if the top quark is very heavy (and other relevant parameters are not specially chosen), then the lightest Higgs boson can be considerably heavier than m_Z, and LEP 200 may not be able to fully explore the Higgs sector of the model. This is because a heavy top quark results in large one-loop corrections to the SUSY Higgs mass relations. If the top is under ~ 120 GeV, then these effects are probably small and LEP 200 may be able to eliminate the minimal SUSY model. However, even in this case, SUSY dark matter should not be discarded. As discussed, many attractive SUSY models just beyond the MSSM would still be allowed, and many of these contain neutralino dark-matter candidates.

The minimal SUSY model has been extensively studied because minimality puts a restriction on the number of free parameters which need to be considered. This makes calculations easier and definite predictions possible. However, even if ruled out, all the main motivations for exploring supersymmetric models remain, and one is therefore forced to consider the next most "minimal" set of models.

We conclude, therefore, that even very light neutralinos make good dark-matter candidates, and we have shown that even within the minimal supersymmetric model they remain viable, LEP results notwithstanding. We considered the possibility of relaxing two GUT assumptions and found substantial effects.

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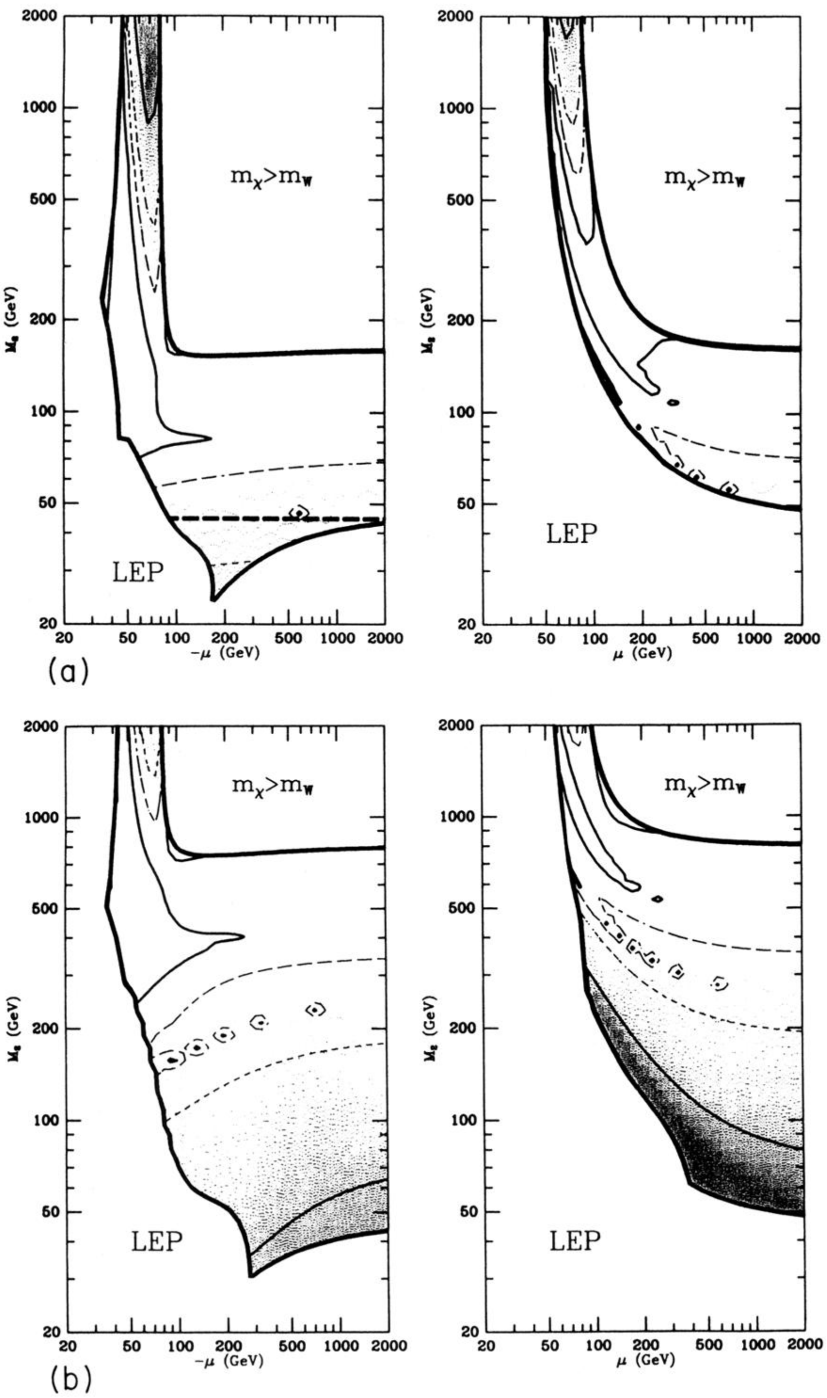

FIG. 2. Contours of constant relic abundance in the (μ, M_2) plane, with $\tan\beta = 2$, $m_h = 50$ GeV, $m_{\tilde{q}} = 150$ GeV, and $m_{\tilde{l}} = 100$ GeV. Areas ruled out by LEP are marked "LEP," while areas marked "$m_\chi > m_W$" were not considered. The area below the very thick dashed line is ruled out by CDF [via Eq. (2b)]. Increasing grey shading indicates growing relic abundance. Solid contours indicate $\Omega h^2 = 1$ (in grey areas) or $\Omega h^2 = 0.025$ (in white areas). Short-dashed lines in grey areas indicate the preferred value $\Omega h^2 = 0.25$, while long-dashed curves (in white areas) indicate $\Omega h^2 = 0.1$. The area between solid curves are acceptable cosmologically for neutralino DM. (a) shows $r = 0.5$ (the GUT case), while (b) shows $r = 0.1$.