SUPERSYMMETRIC DARK MATTER – A REVIEW

LESZEK ROSZKOWSKI
leszek@leszek.physics.lsa.umich.edu
Randall Physics Laboratory,
University of Michigan,
Ann Arbor, MI 48109-1129, USA

Abstract
I address the question of whether supersymmetry provides a viable candidate for the dark matter in the Universe. I review the properties of the lightest neutralino as a candidate for solving the dark matter problem. I discuss the neutralino’s phenomenological and cosmological properties, and constraints from present and future experiments. In the minimal supersymmetric model, the neutralino mass has been experimentally excluded below some 20 GeV, and is not expected to be significantly larger than about 150 GeV. I identify a gaugino-like neutralino as the most natural dark matter candidate for a plausible range of parameters. The requirement that the lightest neutralino be the dominant matter component in the flat Universe provides non-trivial restrictions on other parameters of the model, in particular on the masses of the sfermions. Next, I study the consequences of adopting further grand unification assumptions. In both scenarios I find sfermion masses most likely beyond the reach of LEP 200 and the Tevatron but well within the discovery potential of the SSC and the LHC. I also comment on the effects of relaxing grand unification assumptions. Finally, I briefly outline prospects for the neutralino dark matter searches.

1Based on invited talks at the XXXII Cracow School on Theoretical Physics, Zakopane, Poland, June 2 - 12, 1992; the 23rd Workshop “Properties of SUSY Particles”, Erice, Italy, September 28 - October 4, 1992; and (partly) the 1993 Aspen Winter Conference on High Energy Physics, January 11 - 16, 1993; to appear in the Proceedings of the Erice Workshop.
Contents

1 Introduction 3
   1.1 The Dark Matter Problem ........................................... 3
   1.2 Supersymmetry ...................................................... 4

2 Minimal Supersymmetric Standard Model 5
   2.1 Generalities .......................................................... 5
   2.2 Lightest Supersymmetric Particle ................................. 5
   2.3 Parameter Space of the LSP ......................................... 6
   2.4 Present and Future Experimental Constraints on the LSP ....... 7
   2.5 Theoretical and Cosmological Upper Bounds on the LSP Mass ... 7

3 Neutralino LSP as Dark Matter 8
   3.1 Computing the Neutralino Relic Abundance ....................... 8
   3.2 LSP Pair-annihilation Cross Section .............................. 9
   3.3 Higgsinos as DM .................................................... 10
   3.4 ‘Mixed’ LSPs as DM .................................................. 10
   3.5 Gaugino-like LSP: A Natural Candidate for DM .................. 11

4 The Effects of Grand Unifications 12
   4.1 Dark Matter in Minimal Supergravity ............................. 12
   4.2 Effect of Relaxing GUT Assumptions ............................... 14

5 Direct and Indirect Searches for Supersymmetric Dark Matter 15

6 Agnostic Comments 16

7 Final Comments 17
1 Introduction

Experimentally supersymmetry (SUSY) still remains an open question, many theorists now express their growing confidence that it is indeed realized in Nature. Originally applied to high energy theories to solve the naturalness problem, supersymmetry has actually proven very successful in several other aspects of particle physics [1, 2]. Indeed, even minimal supersymmetric grand unified model predicts the right ratio of gauge couplings [3], as recently confirmed by LEP [4]; provides a mechanism for dynamical electroweak gauge symmetry breaking [5]; generically predicts the proton decay beyond the present experimental reach [6]; and provides a nice connection with theories valid at the Planck mass scale, like supergravity and superstrings. At the same time, present experimental constraints on even minimal version of supersymmetry, both via direct accelerator searches and through supersymmetric loop contributions, are so far relatively mild [7]. It has been also recognized for some time [8] that supersymmetry also provides a nice solution to the dark matter (DM) hypothesis which states that perhaps more than 90% of matter in the Universe is non-shining (see below and, e.g., Refs. [9, 10]).

In this report, I will review the present status of the lightest neutralino, assumed to be the lightest supersymmetric particle (LSP), as a DM candidate. The literature on the subject is already very extensive and I will have to make some crude selections. I will first summarize the main results in the framework of minimal supersymmetry. Next I will emphasize more recent work that has been done in the context of the minimal supergravity model.

In some contrast to more astrophysically and cosmologically oriented reviews on supersymmetric dark matter (see, e.g., Ref. [11]), in considering the LSP as dark matter I will make a fuller use of other, experimental and theoretical, constraints of supersymmetry, including various relationships between SUSY parameters.

I will start by swift reviews of both the DM problem and supersymmetry. In chapter 2 I will briefly introduce the minimal supersymmetric model, and will define the lightest supersymmetric particle. I will summarize its properties and experimental constraints. In chapter 3 I will discuss various cosmological properties of the neutralino and the associated constraints on other supersymmetric parameters, in particular on the masses of the sfermions. Next in chapter 4 I will review the implications that the requirement that the LSP be the DM in the Universe has on the highly constrained grand unification scenario. I will close this chapter with a brief discussion of the implications of relaxing the grand unification assumptions. In chapter 5 I briefly outline the present status of direct and indirect searches for dark matter. Some general comments and a brief summary will close this review.

1.1 The Dark Matter Problem

There is increasing astrophysical evidence that most of the matter in the Universe is dark, i.e., does not emit nor absorb electromagnetic radiation (at least at the detectable level). This evidence, while only circumstantial, comes from vastly different cosmological scales, ranging from galactic scales of several kiloparsecs (1pc = 3.26 light-year = 3.1 × 10^{16} m) to clusters of galaxies (several megaparsecs), and up to global scales of hundreds of Mpc’s. There exist several extensive reviews on the subject [3, 10, 11], and I will quote but a few examples. The most well-known evidence comes from observations of rotational velocities \( v_{\text{rot}}(r) \) of spiral galaxies. If the shining matter were the total matter of the galaxies then one would expect \( v_{\text{rot}}(r) \propto 1/\sqrt{r} \). Instead, one observes \( v_{\text{rot}}(r) \approx \text{const} \) which implies that the total mass of a galaxy within radius \( r \), \( M_{\text{DM}}(r) \) grows like \( M_{\text{DM}}(r) \propto r \). One then concludes that there exist extensive galactic halos consisting of DM. Estimates show that \( M_{\text{DM}}/M_{\text{vis}} \gtrsim 3 – 10 \), and perhaps even more. There is somewhat more uncertain evidence on the scale of 10 to 50 Mpc (clusters of galaxies) for even more DM. Finally, some first evidence has been provided by several groups [12] (like POTENT [13]) that over very large scales (hundreds of megaparsecs) the total mass density \( \rho \) approaches the critical density \( \rho_{\text{crit}} \). The critical density
\[ \rho_{\text{crit}} \equiv 3H_0^2/8\pi G = 1.9 \times 10^{-29}(h_0^2)g/cm^3 \] corresponds to the flat Universe, and \( h_0 \) is the present value of the Hubble parameter \( H_0 \) in units 100 km/s/Mpc. The value \( \Omega \equiv \rho/\rho_{\text{crit}} = 1 \) is strongly preferred by theory since it is predicted by the models of cosmic inflation and is the only stable value for Friedmann-Robertson-Walker cosmologies. Larger values of \( \Omega \) are also strongly supported by present models of primordial baryogenesis and most models of large structure formation.

The visible matter in the Universe accounts for less than 1% of the critical density. Primordial nucleosynthesis constrains the allowed range of baryonic matter in the Universe to the range \( 0.02 < \Omega_b < 0.11 \) \(^{(E)}\) (and more recently \( \Omega_b \approx 0.05 \)). This, along with estimates given above, implies that: \( (i) \) most baryonic matter in the Universe is invisible to us, and \( (ii) \) already in halos of galaxies one might need a substantial amount of non-baryonic DM. This is the galactic DM problem.

If \( \Omega = 1 \) then most (about 95%) of the matter in the Universe is probably non-baryonic and dark. This is the global DM problem. Current estimates show that, for \( \Omega = 1 \), \( 0.5 < h_0 < 0.7 \) (the upper bound coming from assuming the age of the Universe above 10 bln years), in which case one expects the DM abundance in the range

\[ 0.25 \lesssim \Omega h_0^2 \lesssim 0.5. \]  

More conservatively (\textit{i.e.}, without assuming \( \Omega = 1 \), but still assuming the age of the Universe above 10 bln years), one excludes \( \Omega h_0^2 > 1 \). On the other hand, the density of DM should be at least \( \Omega h_0^2 \gtrsim 0.025 \) in order to provide minimum required DM at least in galactic halos.

Finally, one should keep in mind that the uncertainties involved in measuring both \( \Omega \) and \( h_0 \) are large and the bounds on \( \Omega h_0^2 \) quoted above should not be strictly interpreted. (In fact, various authors adopt somewhat different criteria – this doesn’t cause the conclusions to be dramatically different). On the other hand, the evidence that DM is abundant at various length scales in the Universe is now so convincing that it would be very surprising if it did not prove true.

One more remark about the specific nature of DM should be made in closing this section. Before the recent COBE discovery of the cosmic microwave background anisotropies \(^{(E)}\) (for an elementary review, see, \textit{e.g.}, Ref. \(^{(E)}\)), models of large structure formation widely favored so-called cold DM, rather than hot DM (\textit{i.e.}, non-relativistic and relativistic, respectively, see section \(^{(E)}\)). The all-cold-DM case, while still very successful, has become increasingly at odds with the measured angular correlation function of galaxies and with their pair-wise velocity dispersions. In the aftermath of the COBE discovery, some people have argued for a mixed DM scenario with roughly 60-70% of cold DM and about 30% of hot DM, like neutrinos with mass in the range of a few eV. (Others favor the non-zero cosmological constant as a main contributor to \( \Omega = 1 \)). These issues are far from being fully clarified but they won’t have any truly dramatic effect on the results presented here. Conservatively, all one really assumes by adopting the range \(^{(E)}\) is that the LSP contributes significantly to the total matter density in the flat Universe.

### 1.2 Supersymmetry

Supersymmetry \(^{(1, 2)}\) has become popular, in part, because it solves one of the most serious problems of the Standard Model of electroweak and strong interactions, namely the naturalness and the fine-tuning problems, as advocated early, among others, by Veltman \(^{(16)}\).

Supersymmetry must be broken at some effective scale \( M_{\text{SUSY}} \) since the experimental bounds on the masses of the scalar (\textit{i.e.}, spin zero boson) partners of ordinary fermions are experimentally known to be higher than the masses of the fermions themselves. The commonly accepted way of breaking global supersymmetry is to introduce terms which explicitly break it but in such a way that no quadratic divergences are re-generated. Such terms are often called ‘soft’ and are expected to be of the order of \( M_{\text{SUSY}} \) which sets the order of magnitude for the Higgs mass, and therefore they should not significantly exceed the Fermi mass scale. Thus in this weakly (or softly) broken supersymmetry scenario, the masses of the fermions and gauge bosons are given in terms of the Higgs boson’s vacuum expectation value, while the masses of the scalars are set roughly by \( M_{\text{SUSY}} \).
In the most commonly accepted approach one starts with a grand unified theory with unbroken SUSY above some scale $M_{GUT} \approx 10^{16}$ GeV. At that scale, the GUT gauge symmetry breaks down to the Standard Model gauge symmetry, but supersymmetry remains unbroken until $M_{SUSY} \sim \mathcal{O}(1 \text{ TeV})$. Below that scale, the breakdown of SUSY due to the soft terms induces a non-zero Higgs vacuum expectation value, and thus triggers the spontaneous breakdown of the electroweak gauge symmetry $SU(2)_L \times U(1)_Y$ down to the $U(1)$ of electromagnetism.

The terms which break global supersymmetry explicitly but softly arise naturally when a supersymmetric GUT is coupled to supergravity. Supergravity is a theory of local supersymmetry which provides a framework for incorporating gravity into a unified theory of all four fundamental interactions. It also allows for a mechanism of global SUSY breaking. I will come back to this issue in section 4.1 where I discuss the dark matter problem in the context of minimal supergravity.

The program outlined above is realized even in the simplest phenomenologically viable supersymmetric model, known as the minimal supersymmetric model, or Minimal Supersymmetric Standard Model.

2 Minimal Supersymmetric Standard Model

2.1 Generalities

The simplest supersymmetric theory of phenomenological (and cosmological) interest is the Minimal Supersymmetric Standard Model (MSSM) (for a review, see, e.g., Ref. [1, 2, 17]). In the MSSM, one adds to all the fields of the Standard Model their supersymmetric partners to form supermultiplets. The supersymmetric part of the Lagrangian results from the following superpotential

$$ W = \sum_{\text{generations}} (h_U Q_L U^c_L H_2 + h_D Q_L D^c_L H_1 + h_L L E^c_L H_1) - \mu H_1 H_2. $$

(I use here the same notation for both ordinary fields and their chiral superfields.) Other terms, which could break B and/or L number conservation, are absent once a discrete symmetry, the so-called $R$-parity, is assumed. In Eq. (2) $h_{U,D,L}$ are (matrix) Yukawa couplings for the up-type quarks, down-type quarks, and charged leptons, respectively, and generation indices have been suppressed. The Higgs mass parameter $\mu$ is assumed to be of the order of $m_Z$. SUSY requires two Higgs doublets: $H_1 = (H^0_1, H^+_1)$ and $H_2 = (H^+_2, H^0_2)$. Their neutral components $H^0_1$ and $H^0_2$ acquire v.e.v.s $v_1$ and $v_2$ which give masses to down and up-type fermions, respectively. The Higgs mass spectrum consists of two physical scalar fields $h$ and $H$, one pseudoscalar $A$, and a pair of charged Higgs bosons $C^\pm$. At the tree level the Higgs sector is fully described in terms of just two parameters, which I take to be $m_A$ and $\tan \beta \equiv v_2/v_1$. The expected range of values for $\tan \beta$ lies between 1 and $m_t/m_b$. Expressions for the Higgs masses can be found, e.g., in Ref. [17]. Here I only quote the well-known relations: $m_h \leq m_Z \cos 2\beta < m_Z < m_H$, $m_h < m_A < m_H$, and $m_C > m_W$. Radiative corrections to the Higgs masses have recently been shown to be potentially significant. I will discuss their implications later.

2.2 Lightest Supersymmetric Particle

In the MSSM the four neutralinos $\chi^0_i (i = 1, ..., 4)$ are the physical (mass) superpositions of two fermionic partners of the neutral Higgs bosons, called higgsinos $\tilde{H}^0_1$ and $\tilde{H}^0_2$, and of the two neutral gauge bosons, called gauginos $B^0$ (bino) and $W^0_3$ (wino). They are Majorana fermions which means that they are invariant under charge conjugation. The neutralino mass matrix is given by [3, 17].
The lightest neutralino
\[ \chi \equiv \chi^0 = N_{11}W^3 + N_{12}\bar{B} + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0 \]  
will be henceforth assumed to be the lightest supersymmetric particle (LSP). This assumption is a plausible but arbitrary one in the MSSM but is naturally realized in the low-energy limit of supersymmetric grand unified theories as I will discuss in section 4.1. Due to the assumed \( R \)-parity, which assigns a value \( R = -1 \) to sparticles, and \( R = +1 \) to ordinary particles, the LSP is absolutely stable: it cannot decay to anything lighter. It can, however, still annihilate with another sparticle (in particular with itself) into ordinary matter.

The neutralino parameter space is described in terms of four quantities: \( \tan \beta \equiv v_2/v_1 \), the Higgs/higgsino mass parameter \( \mu \), and the two gaugino mass parameters \( M_1 \) and \( M_2 \) of the \( \tilde{B}^0 \) and \( \tilde{W}^0 \) fields, respectively [2, 17, 8].

Usually, one assumes that all gaugino masses are equal at a grand unification theory (GUT) scale (see section 4.1), from which it follows that
\[ M_1 = \alpha_1/\alpha_2 M_2 \approx 0.5 M_2, \]  
as well as
\[ M_2 = \alpha_2/\alpha_s m_{\tilde{g}} \approx 0.3 m_{\tilde{g}}, \]  
where \( \alpha_{1,2,s} \) are the gauge strengths of the groups \( U(1)_Y, SU(2)_L \) and \( SU(3)_c \), respectively, and \( m_{\tilde{g}} \) is the mass of the gluino \( \tilde{g} \), the fermionic partner of the gluon.

Charginos are the charged counter-partners of neutralinos. Their masses are given by [8, 17]
\[ m^2_{\chi^\pm} = \frac{1}{2} \left[ M_2^2 + \mu^2 + 2 m_{W}^2 \right] + \sqrt{(M_2^2 - \mu^2)^2 + 4 m_{W}^4 \cos^2 2\beta + 4 m_{W}^2 (M_2^2 + \mu^2 + 2 M_2 \mu \sin 2\beta)}, \]  
and, assuming the relation [3], are described in terms of the same parameters as the neutralinos.

### 2.3 Parameter Space of the LSP

It is first worth recalling the phenomenological structure of the neutralino parameter space. It is convenient to display the mass and gaugino/higgsino composition contours in the plane \((\mu, M_2)\) for discrete values of \( \tan \beta \). This is shown in Fig. 1 for a typical value of \( \tan \beta = 2 \). For \( |\mu| \gg M_2, m_\chi \approx M_1 \approx 0.5 M_2 \), and the LSP is an almost pure gaugino (and mostly a bino \( \tilde{B}^0 \)). For \( M_2 \gg |\mu|, m_\chi \approx |\mu| \), and the LSP is a nearly pure higgsino. More specifically, it is \( \tilde{H}_S \) for \( \mu < 0 \) and \( \tilde{H}_A \) for \( \mu > 0 \), where \( \tilde{H}_{S,A} \equiv [\pm \tilde{H}_1 + \tilde{H}_2]/\sqrt{2} \). In the intermediate (‘mixed’) region the LSP consists of comparable fractions of both gauginos and higgsinos. To be quantitative, I adopt gaugino purity, defined as \( p_{\text{gaugino}} = Z_{11}^2 + Z_{12}^2 \) [18, 19, 23] of, say, 90% to distinguish higgsino, gaugino, and ‘mixed’ regions. (For simplicity, below higgsino-like LSPs will often be called just higgsinos, and analogously for gauginos.) This distinction is important because cosmological properties of higgsinos and gauginos are significantly different!
2.4 Present and Future Experimental Constraints on the LSP

Large fractions of the ($\mu, M_2$) plane have been excluded by LEP (see, e.g., Refs. [19, 20]): by direct searches for charginos ($m_{\chi^\pm} > 46$ GeV) and neutralinos, and indirectly, from their contributions to the $Z$ line shape at LEP. If one assumes equal gaugino masses at the GUT scale then additional regions are also excluded by the unsuccessful CDF searches for the gluino. An early preliminary bound of about 150 GeV (with simplifying assumptions [21] excludes $M_2 < \sim 44.7$ GeV and leads to a lower bound $\sim 20$ GeV on the mass of the lightest neutralino. The bound Eq. (8) also survives [23] possibly large corrections to the Higgs masses due to the large top-quark mass. This is because larger statistics accumulated during more recent runs of LEP has allowed significantly larger regions of the ($\mu, M_2$) plane to be excluded also for values of $\tan \beta$ as small as one.

A more careful analysis of the gluino bound which takes into account its possible decays into heavier states which next cascade-decay into the LSP leads to a somewhat weaker bound of about 135 GeV [24], or 90 GeV [25], which in turn scales the bound Eq. (8) down to about 18 GeV and 12 GeV, respectively.

Recent experimental results also strongly constrain the LSP’s properties. First, since the neutralinos couple to the $Z$ through their higgsino components only, it is not surprising that higgsino-like $\chi$’s below about 45 GeV have been excluded by LEP. Gaugino-like LSPs have only been indirectly constrained by chargino and gluino searches, with the result given in the bound (8). Moreover, the regions where the LSP is photino-like (the photino $\tilde{\gamma} \equiv \sin \theta_w \tilde{W}_3 + \cos \theta_w \tilde{B}$ is never an exact mass eigenstate!) have been excluded above the 96% purity level [19, 23] as can be seen from fig. 1.

Significant progress in exploring the neutralino parameter space is expected to be made after LEP 200 starts operating in early 1995 [23, 26]. The strongest constraint will come from pushing the chargino searches up to about 80 GeV, which in turn will place indirect lower bounds of about 40 GeV on gaugino-like $\chi$’s and of about 80 GeV on higgsino-like $\chi$’s. This will have some cosmological consequences [23] as I will discuss later.

Dark matter searches are also capable of exploring the neutralino parameter space, if one assumes the LSP to be dominant component of the galactic halo. I will discuss this in section 5.

2.5 Theoretical and Cosmological Upper Bounds on the LSP Mass

While the LSP mass is constrained by high-energy experiments from below, one would also like to be able to restrict it from above.

Theoretically, the expectation that the SUSY breaking scale (and hence also $m_{\tilde{g}}$) should not significantly exceed the 1 TeV scale in order to avoid the hierarchy problem leads, via the GUT relation Eq. (5), to a rough upper bound $m_{\chi} \lesssim 150$ GeV, see fig. 1. This upper limit is only indicative (and it scales linearly with $m_{\tilde{g}}$), but sets the overall scale for expected LSP masses. It also coincides with a similar bound of about 110 GeV (for $m_t > 90$ GeV) resulting from applying the naturalness criterion [27]. (I will have more to say about this in the context of minimal supergravity.) This indicative upper bound also implies [15] that higgsino-like $\chi$’s are strongly disfavored, since they correspond to uncomfortably large gluino masses. Experimental constraints and theoretical criteria (naturalness) then point us towards the gaugino-like and ‘mixed’ regions.

Interestingly, one can derive also cosmological upper bounds on $m_{\chi}$. This was originally done by Olive, et al. [28], and Griest, et al. [24] in the case of higgsino-like LSP of roughly $m_{\chi} \lesssim 2.8$ TeV and gaugino-like LSP of about $m_{\chi} \lesssim 550$ GeV. These bounds correspond to very large gluino masses of about 20 TeV and 3 TeV, respectively. (In the higgsino case the co-annihilation of the LSP with charginos and other neutralinos in fact greatly weakens the bound, as I will discuss later.) More recently, Drees and Nojiri [20] have sharpened the bound for the bino case to $m_{\chi} < 350$ GeV in the context of minimal supergravity. But they also estimated that, in special cases, (enhanced pole
annihilation) in the ‘mixed’ region the constraint \( \Omega h^2 \leq 1 \) allows for the LSPs as heavy as 100 TeV (!), the range not necessarily fitting the concept of low-energy supersymmetry. One should also remember that in deriving such cosmological bounds one assumes the the LSP is a pure higgsino or bino state which in practice is never the case. In particular, in the grand-unified scenario, where all the masses are inter-related, no well-defined cosmological bound has been found \[30\]. In brief, it is worth remembering that in some cases one can derive cosmological upper bounds on \( m_{\chi} \) but they lie well beyond theoretical expectations.

3 Neutralino LSP as Dark Matter

Particle candidates for dark matter can be divided into two broad classes: hot and cold DM \[10, 11\]. The first were relativistic at the time of ‘freeze-out’ (see below), while the latter were non-relativistic. Light massive neutrinos, with the mass of about 10 eV, are the well-known (and well-motivated) candidates for hot DM. In the cold DM class the leading candidates are the neutralino LSP \[8\] in the mass range of several GeV, and the axion. LEP has excluded several other candidates for DM, like heavy neutrinos or their supersymmetric partners, sneutrinos, by placing a lower bound of about \( m_Z/2 \) on their mass. This implies that their contribution to the total mass of the Universe is uninterestingly small (\( \Omega h^2 \lesssim 10^{-3} \)). Other experiments have severely narrowed the allowed mass range of the axion \[31\]. In contrast, the lightest neutralino \( \chi \) has all the desired properties of a natural candidate for both the lightest supersymmetric particle (LSP) and the dark matter in the Universe \[8\]. It is neutral, weakly-interacting, and stable (assuming R-parity). In recent years important constraints on the neutralino properties have been derived, and various conditions that need to be satisfied for the LSP to be a solution to the DM problem for natural ranges of parameters have been pointed out. They will be summarized in this chapter. First I will briefly outline the procedure of computing the relic density of neutralinos and, in general, any relic species.

3.1 Computing the Neutralino Relic Abundance

In the very early Universe (\( t \lesssim 10^{-12} s \)), all the species, including the neutralinos, were in thermal equilibrium with photons \[10, 11\]. At that stage the neutralinos could reduce their number via pair annihilation \( \chi \chi \rightarrow \) ordinary matter. As the Universe was expanding and cooling, the density of the LSPs was decreasing, and it was becoming increasingly harder for them to find partners to annihilate. At some temperature, called the ‘freeze-out’ temperature \( T_f \), the number of the LSPs in the Universe became effectively constant, and approximately equal to their number today. In other words, the LSP relic density per co-moving volume became approximately constant.

The relic abundance \( \Omega h^2 \) of the neutralinos, or any other relic species, can be computed by solving the Boltzmann (rate) equation

\[
\frac{dn_{\chi}}{dt} = -3Hn_{\chi} - \langle \sigma v_{rel} \rangle \left[ n^2_{\chi} - (n_{\chi}^{eq})^2 \right],
\]

where \( n_{\chi} \) is the actual number density of the LSPs, and is related to \( \Omega h^2 \) by \( \Omega h^2 = (m_{\chi} n_{\chi} h_0^2)/\rho_{crit} \); \( n_{\chi}^{eq} \) is the number density of the LSP would have in thermal equilibrium at time \( t \); \( H \equiv \dot{R}/R \) is the Hubble parameter, \( R \) is the cosmic scale factor; \( \sigma \) is the cross section for the process \( \chi \chi \rightarrow \) ordinary matter, \( v_{rel} \) is the relative velocity of the two annihilating LSPs, and the symbol \( \langle \rangle \) denotes a thermal average and sum over spins of the LSPs. It is clear that rate at which \( n_{\chi} \) decreases is set by two factors. One is the expansion of the Universe. The other is due to the excess of the given species annihilation over the reverse process.

Eq. (9) can be integrated either numerically or by means of analytic approximations \[10, 32, 33\]. It occurs that most methods used in the literature give actually very similar results (up to a few
per cent). The scaled freeze-out temperature \( x_f \equiv T_f/m_{\chi} \) is typically very small \( (x_f = O(1/20)) \), justifying at low temperatures the approximation

\[
\langle \sigma v_{\text{rel}} \rangle \simeq a + bx
\]

of the thermally-averaged annihilation cross section \( \langle \sigma v_{\text{rel}} \rangle \). The input from high-energy physics is thus included in the coefficients \( a \) and \( b \).

Special care must be applied in three cases \[34\]. This is when the mass of the pair-annihilating species is close to: (i) half of the mass of an s-channel-exchanged state (enhanced pole-annihilation); (ii) the mass of a new final state (threshold effect); and (iii) the mass(es) of other state(s) with which a DM candidate can also annihilate (co-annihilation effect). In such cases the expansion \[34\] fails \[34\]. In particular, the relic density around poles \[34, 33, 35\] doesn’t fall as steeply and is larger than a naive estimate would show. The co-annihilation effect has been shown to be of great importance for higgsino-like LSPs and will be discussed in section 3.3.

### 3.2 LSP Pair-Annihilation Cross Section

The DM neutralinos were at the time of ‘freeze-out’ already very non-relativistic (cold dark matter), and therefore they could only pair-annihilate into ordinary matter that was less massive than \( m_{\chi} \).

The neutralino relic abundance is thus determined by the annihilation cross section \( \sigma(\chi \chi \rightarrow \text{ordinary matter}) \) of the neutralinos into ordinary matter which in turn depends on many unknown parameters: \( \mu, M_1, M_2 \), and \( \tan \beta \), as well as the top quark, sfermions’, and Higgs masses. In the most general case one needs to specify as many as 27 parameters, including 21 sfermion masses.

The least number of parameters one has to specify is six: \( \mu, M_2 \), and \( \tan \beta \) of the pure neutralino sector alone, as well as the top mass \( m_t \), one of the Higgs masses, \textit{e.g.}, the mass of the pseudoscalar \( m_A \), and the mass of the sfermions \( m_f \), if assumed degenerate for simplicity. With so many free parameters to deal with it is thus \textit{a priori} hard to expect that any solid conclusions can be drawn. But in fact this is not the case; that is because, as I will argue later, the LSP relic abundance depends primarily on only a few parameters, like \( \mu, M_2 \) and the mass of the \textit{lightest} sfermion, and only less strongly on the other parameters. (Similarly, in the context of minimal supergravity the number of basic parameters is very limited thus allowing for very definite predictions; see section \[31\].)

Of course, the greater the annihilation rate, the lower the relic abundance. The annihilation channels into ordinary fermion pairs, \( \chi \chi \rightarrow f\bar{f} \), are always open, except for the top quark which is much heavier. In addition, the following final states may become kinematically allowed at larger \( m_{\chi} \): Higgs-boson pairs, vector-boson Higgs boson pairs, and vector-boson pairs.

In the region \( m_{\chi} < m_W \) the following annihilation channels can become at some point kinematically allowed. In addition to the mentioned channels \( f\bar{f} \), the LSPs can pair-annihilate into \( hh, AA, hA, hH, AH, Zh \) and \( ZA \). For \( m_{\chi} > m_W \) new final states open up. They include: \( W^+W^-, ZZ, C^+C^- \), \( HH, W^\pm C^\mp \), \( ZH \), and \( t\bar{t} \). It occurs that in most of the interesting region of the neutralino parameter space, \textit{i.e.}, for both ‘mixed’ and gaugino LSPs, it is the annihilation into the Standard Model fermions that is typically dominant, unless all the sfermion are very heavy. The annihilation \( \chi \chi \rightarrow f\bar{f} \) proceeds via the exchange of the \( Z \) and the Higgs bosons in the \( s \)-channel, and via the exchange of the sfermions in the \( t \)- and \( u \)-channels. Other final states can, however, also play an important rôle and in a full analysis cannot be neglected. The dependence of the relic abundance on the parameters involved is significantly different when the LSP is mostly a higgsino, or a gaugino, or else a ‘mixed’ state of both higgsinos and gauginos. This is of course due to different couplings with which higgsinos and gauginos couple to other matter. A closer study shows that the \( Z \) exchange is very important in the almost pure higgsino and ‘mixed’ regions, but not in the gaugino region, and the \( Z \) pole effect is very broad, unless suppressed by vanishing coupling to \( \chi \chi \) (gaugino and \textit{antisymmetric} higgsino \( \tilde{H}_{(A)\bar{B}} \)). The exchanges of the Higgs bosons are of significantly lesser importance \[36\], both because the Higgs bosons couple only to the ‘mixed’ LSPs and because their couplings to the ordinary fermions are suppressed by a factor \( m_f/m_W \). Finally,
the effect of the sfermion exchanges is essentially null for higgsino LSPs, due to a double suppression by a factor $m_f/m_W$ in the invariant amplitude. On the other hand, sfermion exchange in gaugino LSP pair-annihilation is dominant, roughly $\Omega h_0^2 \propto m_f^2/m_X^2$, because the gaugino-fermion-sfermion coupling is not suppressed.

In figs. 2 and 3 I show a few illustrative examples of the LSP relic density in the plane $(\mu, M_2)$ for a typical choice of $\tan \beta = 2$ and $m_A = 150$ GeV. In fig. 2 all sfermion masses are chosen to be $m_{\tilde{f}} = 200$ GeV. (For $m_X > 200$ GeV I take $m_{\tilde{f}} = m_X$.) In fig. 3 I show only the case $\mu < 0$ (the case $\mu > 0$ is qualitatively similar) and in the left window all sfermion masses are $m_{\tilde{f}} = 400$ GeV or $m_X$, whichever is larger. In the right window I display the role of one sfermion: I keep $m_{\tilde{f}} = 400$ GeV except for one (I choose the selectron) which is set at $m_{\tilde{e}} = 43$ GeV which is a current lower limit on slepton masses from LEP. These figures will be discussed below. As has been already stated in section 1.1, $\Omega h^2 > 1$ is cosmologically excluded. Assuming the theoretically favored value $\Omega = 1$ leads to the approximate range $0.25 \lesssim \Omega h_0^2 \lesssim 0.5$. Finally, very small values of relic abundance (like $\Omega h_0^2 \lesssim 0.025$) are probably not cosmologically interesting as they don’t solve even the galactic DM problem.

### 3.3 Higgsinos as DM

Higgsino-like LSPs with mass below $m_W$, along with gaugino-like ones (but not the ‘mixed’ states; see next section), have been considered excellent candidates for the DM [34, 35]. In the case of higgsinos, one could easily find significant regions with the preferred abundance (except near the $Z$- and Higgs poles) for any choice of the sfermion masses $m_{\tilde{f}}$ [36, 37, 18] as can be seen from figs. 2 and 3. Above $m_W$, the $WW$, $ZZ$, and $t\bar{t}$ final states cause the relic abundance of higgsino-like LSPs to drop well below 0.025, up to a $m_X$ of several hundred GeV [28, 29] (see figs. 2 and 3 and, e.g., fig. 2 of the first paper of Ref. [28]). However, as I have mentioned in section 2.3, from the point of view of naturalness higgsinos are not very attractive [18].

As already mentioned in sect. 3.1, it has recently been shown that the so-called ‘co-annihilation’ has a devastating effect on the relic density of higgsino-like LSPs, making it uninterestingly small. As was originally pointed out by Griest and Seckel [34], if there exists another mass state $\chi'$ with mass only slightly exceeding the LSP mass, and the cross section for the LSP pair-annihilation is suppressed relative to the LSP annihilation with $\chi'$ then it is this latter annihilation that primarily determines the LSP relic abundance. All the conditions for co-annihilation are actually satisfied in the higgsino-like region, where typically the next-to-lightest neutralino $\chi_2$ and the lightest chargino $\tilde{\chi}_1^\pm$ are only slightly heavier than the LSP. In two recent papers [30, 31] (see also Ref. [32]) it has been estimated that co-annihilation then greatly reduces the higgsino-like LSP relic abundance to uninterestingly small values ($\Omega h^2_0 < 0.025$). The effect of including co-annihilation on the figures 2 and 3 is to wipe out all cosmologically interesting domains from the higgsino regions. Thus higgsino-like LSPs are neither theoretically nor cosmologically attractive. Clearly, finding a higgsino-like LSP at LEP 200, or a chargino that would correspond to the higgsino region, would thus have dramatic cosmological implications as it would imply, in the MSSM, a great deficit of DM.

### 3.4 ‘Mixed’ LSPs as DM

Next, ‘mixed’ LSPs (with comparable fractions of both higgsino and gaugino components) are probably not cosmologically attractive either, as they do not provide enough DM in the Universe [37, 18], and often even in galactic halos [18]. Typically $\Omega h^2_0$ is found below 0.1, or even 0.025. This is true both below and above $m_W$ [34] for essentially any choice of independent parameters, like $\tan \beta$, $m_{\tilde{f}}$, or Higgs masses. (See figs. 2 and 3.) The smallness of $\Omega h^2_0$ results from the fact that, in the ‘mixed’ region, some of the LSP annihilation channels always remain unsuppressed up to extremely large values of the LSP mass ($m_X \lesssim O(100 \text{ TeV})$ [20]).
3.5 Gaugino-like LSP: A Natural Candidate for DM

We are left with the gaugino region ($|\mu| \gg M_2$). Here, the crucially important parameters are the sfermion masses. This is because in this region the sfermion exchange in the LSP annihilation into $ff$ is dominant: $\Omega h_0^2 \propto m_f^4/m_0^2$. This can be seen by comparing figs. 2 and 3. The $Z$ and Higgs bosons decouple from gaugino-like neutralinos. For larger $m_\chi$, also the final states involving Higgs boson pairs become important. This happens very roughly when all the sfermions are heavier than the heavier Higgs bosons (like $H$ or $A$).

In the MSSM sfermion masses are arbitrary. (For simplicity they are often assumed to be degenerate.) However, as was pointed out in Ref. [18], it is the mass of the lightest sfermion (other than the sneutrino, whose couplings to gaugino-like LSPs are somewhat weaker, and of the stop whose mass is relevant only for $m_\chi > m_t$) that mostly determines the relic density of the LSPs. In other words: the gauginos annihilate most effectively via the lightest charged sfermion exchange.

The resulting situation can be roughly characterized as follows:

1. All the sfermion masses are large, $m_f > 400$ GeV. (See the left panel of fig. 3; the graph doesn’t change much as one varies $m_f$ from 1 TeV down to some 400 GeV.) In this case $\Omega h_0^2 > 1$ in the region of smaller $m_\chi$. At larger LSP masses, above the kinematic threshold for $\chi$ annihilation into Higgs-boson final states, the relic abundance drops again, depending on the actual masses of the Higgs bosons. (The final state $hh$, which is always open for $m_\chi > m_Z$, is never of any significance.) As one moves from more pure gaugino-like states towards more ‘mixed’ states, $\Omega h_0^2$ quickly decreases, and the preferred range $0.25 \lesssim \Omega h_0^2 \lesssim 0.5$ forms only a relatively narrow strip in the $(\mu, M_2)$ plane. In the ‘mixed’ region, $\Omega h_0^2$ remains as always below 0.1, and often below 0.025.

Thus, the all-heavy sfermion scenario is perhaps somewhat less attractive as a solution to the DM problem [18].

2. The lightest charged sfermion (say, the selectron $\tilde{e}$) is neither too heavy nor too light, $120$ GeV $\lesssim m_\tilde{e} \lesssim 400$ GeV. (Other sfermions could either be also within this mass range, or else heavy. Their specific values do, however, influence somewhat the lower bound of 120 GeV: if more sfermions are on the lighter side then it goes up since more sfermions contribute to reducing $\Omega h_0^2$.) This is cosmologically the most natural range of sfermion masses, for which large domains of the $(\mu, M_2)$ parameter space (for gaugino-like LSPs) exist with $0.025 < \Omega h_0^2 < 1$. See fig. 2. Within those, there are substantial sub-domains with the preferred abundance $0.25 \lesssim \Omega h_0^2 \lesssim 0.5$. Again, the relic abundance decreases towards ‘mixed’ regions. Also, it becomes unacceptably large for asymptotically large values of $|\mu|$ of several TeV.

3. The lightest charged sfermion is relatively ‘light’, 43 GeV $\lesssim m_\tilde{e} \lesssim 120$ GeV (and, of course, $m_\chi < m_\tilde{e}, m_\tilde{f}$). (Again, other sleptons could be within this mass range, or else heavier. As for squarks, one should keep in mind the current experimental bounds from CDF of 100–150 GeV.) See the right panel of fig. 3. In this case, the relic abundance in both the gaugino and ‘mixed’ regions is too small to solve the global DM problem, and often too small (especially for smaller values of $m_\tilde{e}$) to even contribute significantly to galactic DM [18]. If one also includes the effects of co-annihilation in the higgsino region, one finds no solution satisfying Eq. (1) in the whole $(\mu, M_2)$ plane. One may thus talk about a cosmological lower bound on $m_\chi$ [18], the exact value depending somewhat on the masses of the heavier sfermions.

It is worth stressing that, with co-annihilation included, if even a single slepton were found at LEP (below 43 GeV) then the LSP relic abundance would be $\Omega h_0^2 \lesssim 0.07$ and thus too small to solve the dark matter problem. This can be seen from the right panel of fig. 3. Similarly, if a slepton were discovered at LEP 200 then the LSP relic abundance would still be too small [23] to give $\Omega \approx 1$ for natural ranges of parameters $\mu$ and $M_2$ (roughly below 1 TeV).
Finally, one might argue that it doesn’t matter if the cosmologically favored region is ‘big’ or ‘small’: even one point in the $(\mu, M_2)$ plane with large enough relic abundance to solve the DM problem (e.g. (3)) should be enough. This is in principle true if the minimal supersymmetry model is only considered without its GUT context. However, when the MSSM is viewed as resulting from a more fundamental theory valid at the GUT mass scale, several other constraints arise, as I will discuss in the next chapter. Thus, even in the MSSM, solutions which require a certain tuning of parameters to solve only the DM problem, are in general less attractive, although not excluded. This context should be thus kept in mind in judging the cases 1 to 3 as being more or less attractive. What I find important, however, is that, despite a large number of free parameters, certain general conditions for the LSP to be the dominant matter component in the flat Universe can be established and compared with present and future searches for supersymmetric particles at high energy colliders.

4 The Effects of Grand Unifications

Until now I have considered the LSP of the minimal supersymmetric model viewed as a phenomenological theory valid around the Fermi mass scale. The MSSM is clearly motivated by grand unifications: one usually allows for only such soft terms that follow from minimal supergravity and also assumes that all gauginos share a common (gaugino) mass \( \tilde{m} \) at the unification scale \( \tilde{M}_1 = \tilde{M}_2 = \tilde{m} = m_{1/2} \) which implies the relations (3) and (4) at the electroweak scale. These assumptions themselves are not a part of the definition of the MSSM (see, e.g., Ref. [1]). (See, e.g. the review by Ibáñez in Ref. [1]).) Below I will consider LSP as DM in a fuller GUT framework. Next I will comment on the effect of relaxing GUT assumptions.

4.1 Dark Matter in Minimal Supersymmetry

At the GUT scale all the gauge couplings become equal \( \frac{1}{2} \alpha_1 = \alpha_2 = \alpha_s = \alpha_{GUT} \approx \frac{1}{3} \). Below \( M_{GUT} \), the gaugino masses run with the energy scale in the same way as the squares of the gauge couplings. In other words, on obtains \( M_1/\alpha_1 = M_2/\alpha_2 = m_{\tilde{g}}/\alpha_s = m_{1/2}/\alpha_{GUT} \), from which the relations (3) and (4) follow, as well as \( m_{1/2} \approx 1.2 M_2 \).

In the absence of a commonly accepted ‘standard’, or ‘minimal’ grand unified theory, it is usually assumed that, at the GUT scale, the MSSM couples to the minimal supergravity model which provides the desired form of the supersymmetry soft breaking terms. The minimal supergravity model is an effective theory at the GUT scale. Its basic assumptions are described, e.g., in the review by Ibáñez in Ref. [1] (page 56). I will not review them here but merely quote what is relevant to the present report.

In addition to assuming a unification of gauge couplings and gaugino masses, it is natural to expect that at the GUT scale also masses of all the scalars (sfermions and Higgs bosons) are equal to some common scalar mass \( m_0 \). This assumption, in conjunction with SUSY and the gauge structure, leads to the following expressions for the masses of the sfermions (except for the top squark) at the electroweak scale (see, e.g., Ref. [1]):

\[
m^2_{\tilde{f}_{L,R}} = m^2_f + m^2_0 + b_{\tilde{f}_{L,R}} m^2_{1/2} \pm m^2_Z \cos 2\beta \left[ T^f_{3L,R} - Q_{f_{L,R}} \sin^2 \theta_W \right],
\]

where \( \tilde{f}_{L,R} \) is the left (right) sfermion corresponding to an ordinary left (right) fermion, \( T^f_{3L,R} \) and \( Q_{f_{L,R}} \) are the third component of the weak isospin and the electric charge of the corresponding fermion \( f \), and the coefficients \( b \) can be expressed as functions of the gauge couplings at \( m_Z \) and are \( b \sim 6 \) for quarks and \( b \sim 0.5 \) for sleptons.

Thus in the minimal supergravity context there are five fundamental quantities: (a) the common gaugino mass \( m_{1/2} \), (b) the common scalar mass \( m_0 \), (c) the Higgs/higgsino mass parameter \( \mu \), (d)
the common scale $A m_0$ of all the trilinear soft SUSY-breaking terms, and (e) the scale $B m_0$ of the Higgs soft term ($B m_0 \mu H_1 H_2 + h.c.$). When the Higgs bosons acquire $v.e.v.$'s, another independent quantity arises which can be chosen to be $\tan \beta = v_2 / v_1$. The whole spectrum of masses and couplings can be parametrized in terms of these six independent quantities.

It is clear that, in contrast to the MSSM, the masses of the sfermions and the neutralinos are now linked to each other via $m_{1/2}$. It is thus interesting to see whether the phenomenological and cosmological relations between the neutralino and sfermion masses, previously derived at the phenomenological level, can be accommodated within the minimal supergravity context, and whether they provide any constraints on the fundamental supergravity parameters $m_{1/2}$ and $m_0$, and, vice versa. This issue has been studied from various angles starting with Refs. [11, 12], and more recently in Refs. [13, 14, 20, 15, and 31]. The bottom line is that the requirement that the LSP be the dominant DM component in the flat ($\Omega = 1$) Universe is quite naturally realized in the context of minimal supergravity but it also imposes stringent constraints on the fundamental parameters $m_{1/2}$, $m_0$, and $\mu_0$ (the value of $\mu$ at the GUT scale). (More specific results are often sensitive to additional assumptions and simplifications made by various authors.) For example, it was found in Ref. [13] (see also Ref. [14]) that the cosmologically favored region, given by Eq. (1), is only (except near poles) realized in the narrow strip of comparable values of $m_0$ and $m_{1/2} \simeq 1.2 M_2$ (see fig. 4). The region $m_0 \gg m_{1/2}$ was found cosmologically excluded ($\Omega m_0^2 > 1$). In the region $m_0 \ll m_{1/2}$ there was always very little DM ($\Omega m_0^2 < 0.25$). Cosmologically (i.e., requiring the LSP to be the dominant mass component of the flat Universe) one can derive a lower bound on $m_0$: $m_0 \gtrsim 100$ GeV for $m_\chi < m_0$ witesugradm, and $m_0 \gtrsim 40$ GeV in general [20]. This, along with other (experimental and theoretical) constraints, allows for rather specific predictions at the electroweak energy scale. For example, one finds a lower bound on the mass of the lightest slepton of about 200 GeV [46, 30], although Drees and Nojiri [20] in certain less favored cases (rather large values of $A m_0$) find $m_q$ even below 200 GeV.

Roberts and Ross [17] have recently performed a careful study of the phenomenological implications of the grand unifications with the electroweak gauge symmetry triggered by supersymmetry breaking terms. In their analysis, they took into account the corrections to the running of the various parameters of the model (gauge couplings and masses) due to multiple mass thresholds above the electroweak energy scale. The underlying idea is that above the SUSY breaking scale $M_{SUSY}$ one uses fully supersymmetric renormalization group equations (RGEs) to evolve the model’s parameters from the GUT scale down. However, as the masses of the heaviest supersymmetric particles (typically the gluino and squarks) become larger than the energy scale $Q$ at which they are evaluated, one needs to decouple them from the running of the RGEs. This has to be successively done with every new state (mass-threshold), as one further evolves down to the $m_Z$ scale. These thresholds were shown to be of significant importance. Another remarkable feature of their analysis was that that they did not fix any of the constraints at the start (like often made $m_q < 1$ TeV) but instead compared their relative effects on the final output. On the basis of several independent criteria (bounds on $m_\chi$ and $m_0$, improved naturalness criterion, and improved experimental bounds on $\alpha_s$ and other electroweak and supersymmetric quantities), Roberts and Ross generally found both $m_{1/2}$ and $m_0$ to lie within several TeV, with smaller values (a few hundred GeV) generally favored by the values of $\alpha_s$ and the naturalness criterion. The allowed parameter space, however, still remained quite large.

Their analysis was next extended [20] to include the requirement that the LSP be the dominant dark matter component of the flat Universe, see figs. 5 and 6. This constraint was found to be of particular importance. First, in the parameter space not experimentally excluded by LEP and the Tevatron the lightest neutralino was found to be always the LSP. Furthermore, it invariably came out to be gaugino-like, (see fig. 5d) in perfect agreement with previous conclusions [13, 20, 28].

Remarkably, the dark matter constraint was found to be consistent with other bounds: the
favored range of the bottom quark mass (4.15 GeV ≤ m_b ≤ 4.35 GeV [18]); the expected range of the top mass (implying a rather large value m_t ≥ 150 GeV); and the present experimental bounds on the strong coupling α_s(m_Z) = 0.122 ± 0.010 [17]. All these criteria can be simultaneously satisfied (fig. 6) without any excessive fine-tuning of parameters. Furthermore, the dark matter constraint eliminated large fractions of the parameter space corresponding to m_0 ≫ m_{1/2} (fig. 5c). Also the CDF limit m_t > 91 GeV eliminated the region m_0 < m_{1/2} where the LSP is invariably higgsino-like for which the relic abundance has been found to be very small.

The region of the parameter space consistent with all the above constraints is severely limited but, remarkably, consistent with supersymmetric masses below 1 TeV. In particular, imposing a requirement that the LSP provide most DM in the flat Universe again provides very stringent cosmological limits [23] on the masses of the LSP and other particles. One also finds [30]

\[ 60 \text{ GeV} < \sim m_\chi < \sim 200 \text{ GeV}, \] (12)

the upper limit being also expected in the minimal supersymmetric model [18, 27] on the basis of naturalness. Similarly, one obtains [30]

\[ 150 \text{ GeV} < \sim m_\chi^\pm < \sim 300 \text{ GeV} \] (13)
\[ 200 \text{ GeV} < \sim m_\tau < \sim 500 \text{ GeV} \] (14)
\[ 250 \text{ GeV} < \sim m_q^- < \sim 850 \text{ GeV} \] (15)
\[ 350 \text{ GeV} < \sim m_g^- < \sim 900 \text{ GeV}. \] (16)

The heavy Higgs bosons are roughly in the mass range between 250 GeV and 700 GeV. Of course, lower values of all these masses correspond to less fine tuning and larger values of α_s. The lightest Higgs boson tree-level mass invariably comes out close to m_Z; its one-loop-corrected value [50] is then roughly in the range 120 to 150 GeV. As a bonus, one also finds [30] \(0.116 < \sim \alpha_s(m_Z) < \sim 0.120.\)

In summary, the spectrum of supersymmetric particles is expected to lie well within the discovery potential of the LHC and the SSC. However, if the LSP is to be the dominant component of matter in the flat Universe, then it perhaps less likely, although not impossible, for SUSY to be discovered at LEP 200 and/or the Tevatron.

Of course, the specific numerical results of this and other analyses should be taken with a grain of salt. It suffices to say that the findings of recent studies [13, 20, 44, 46] are in general consistent with each other. More detailed comparisons are, however, almost impossible due to somewhat different assumptions and approximations used by various authors. Also, additional effects (like radiative corrections to Higgs masses, or mass-thresholds around the GUT scale) and complications to the model may alter them somewhat. Nevertheless, it is rather encouraging that the ‘minimal’ set of assumptions along with a number of a priori independent criteria provide self-consistent and reasonable predictions for minimal supersymmetry coupled to minimal supergravity.

4.2 Effect of Relaxing GUT Assumptions

Finally, one shouldn’t forget that the concept of grand unification (and the related assumptions), while attractive and in some sense natural, will most likely not be directly tested experimentally in the foreseeable future (perhaps never), even though recent LEP results can be interpreted as supporting it. Moreover, recent results in superstring theory indicate that the usual GUT assumptions about the common scalar and gaugino masses need not be necessarily hold [51]. One would therefore like to learn to what extent the various phenomenological and cosmological results are modified when the simple GUT relations given above are relaxed. This question was addressed in Ref. [19] (see also Ref. [52]) in the context of the minimal supersymmetric model without the GUT assumptions about the gaugino masses M_1, M_2, and m_g (nor of course the supergravity relations...
between scalar masses). Relaxing GUT assumptions results in potentially significant modifications of the phenomenology and cosmology of the neutralino LSP. The study [19] focused on a light neutralino LSP, within the mass range of a few tens of GeV, since such neutralinos will be searched for in accelerators and astrophysical experiments during the next decade. The results can be briefly summarized as follows:

1. As expected, the experimental lower bound $m_\chi > 20 \text{ GeV}$ doesn’t exist anymore, since the gluino mass bound from CDF no longer applies; in fact no experimental bound can be derived in general. (This is not surprising: it is not always remembered that while experimental constraints on charged supersymmetric particles can be regarded as relatively general, the corresponding bounds on the neutral particles (like the Higgs bosons or the neutralinos) are very model-dependent, or even assumption-dependent. In a sense, experimental lower bounds on neutral particles could be regarded as (upper) limits of potential experimental ability to search for neutral states in a given model.) However, even though experimentally very light neutralinos are now again allowed, it is well known that cosmologically neutralinos below a few GeV are forbidden, as they would overclose the Universe (the Zel’dovich bound).

2. The indicative theoretical upper bound $m_\chi < \sim 150 \text{ GeV}$ does not apply either for the same reason as above. In principle the LSP could be very heavy, although perhaps one should expect $m_\chi < \sim 1 \text{ TeV}$ for naturalness reasons.

3. The composition and mass contours also become significantly modified, depending on how different the ratio $r \equiv M_1/M_2$ is from the GUT case ($r_{\text{GUT}} \approx 0.5$). Since in the gaugino region $m_\chi \approx M_1$, one finds an interesting scaling property [19] in the $(\mu, M_2)$ plane: in the experimentally allowed region, for smaller values of $r$ ($r < r_{\text{GUT}}$), generally lighter neutralinos are allowed, whilst for $r > r_{\text{GUT}}$ gaugino-like neutralinos are generally heavier than in the GUT case. The higgsino region as a whole is also shifted to larger (smaller) values of $M_2$ for smaller (larger) values of $r$, but otherwise the mass composition contours are not greatly modified.

4. Cosmologically allowed/favored/excluded regions are also significantly affected by the scaling property, depending on the choice of $r$. For $r \ll 1$, the gaugino-like LSP easily gives the closure density. (In contrast, when $r \gg 1$, the LSP is often predominantly wino-like and, due to co-annihilation effects, its relic density is very small [2].)

In conclusion, even modest modification of the usual grand unification assumptions has a considerable impact on the phenomenological and cosmological properties of the LSP. In particular, the gaugino-like LSPs as light as a few GeV could still be interesting candidates for DM. Experimentalists in their search for new physics should not be constrained by theoretical expectations and biases.

5 Direct and Indirect Searches for Supersymmetric Dark Matter

I will only briefly outline the present status and future prospects for the neutralino DM searches. More details can be found, e.g., in Ref. [53]. The underlying assumption is that the LSP is a dominant component of the halo of our Milky Way, with the relic density of $\rho_\chi \simeq 0.3 \text{ GeV/cm}^3$ (about 3000 LSPs with mass $m_\chi = 100 \text{ GeV}$ per cubic meter) and the mean velocity of about 300 km/s.

One can search for DM neutralinos either directly, through the halo LSP elastic scattering off nuclei $\chi N \rightarrow \chi N$, or indirectly, by looking for traces of decays of LSP pair-annihilation products (mainly neutrinos).
At present direct searches rely on ‘warm’ germanium and silicon detectors and lack some two order of sensitivity necessary to probe the neutralino DM. The problem lies in the fact that neutralinos, being Majorana particles, couple to nuclei proportional to their spin (although there also exist some coherent interactions with nuclei without spin), and the related scattering cross sections are invariably very small. Significant progress is reportedly being made in the R&D of cryogenic (T<0.03 K) detectors. It is expected that they will achieve desired sensitivity by a dramatic noise reduction (mostly β-radiation and Compton electrons) by measuring the energy deposition (a few tens of keV) in both the phonons from nuclear recoil and ionization. First working modules should be ready by Spring’93 and a full multi-kg detector by the Fall of 1994. There are also plans to replace the presently used spinless 76Ge with with large-spin nuclei (like 73Ge with spin=9/2). In Europe, another promising and innovative technique based on superconducting detectors is currently being developed. (More details can be found, e.g., in Ref. [53].)

Indirect searches have been looking for high-energy neutrinos and up-going muons in underground detectors. The basic idea can be briefly outlined as follows. Halo LSPs can be captured in celestial bodies (Sun, Earth) through their scattering off heavy (core) nuclei. If the scattering is sufficiently frequent, they loose enough energy to become gravitationally trapped. After enough LSPs have accumulated, they can again start pair-annihilating into leptons, quarks, and gauge and Higgs bosons, most of which immediately decay into lighter states. Only neutrinos can make their way out of the Sun or Earth core. Their energy is roughly $E_\nu \sim (\frac{1}{3} - \frac{1}{2}) m_\chi$. They can pass through underground neutrino detectors or, by hitting a nearby rock, produce secondary up-going muons that can be searched for in underground muon detectors. Estimates show that for $m_\chi \approx 80$ GeV signal from the Sun should be dominant. Lighter neutralinos could more effectively scatter off nuclei in the Earth’s core (which are of comparable mass) and thus produce a stronger signal.

It is a bit unfortunate that the LSPs that most effectively interact with nuclei are of the ‘mixed’ type which typically give very little dark matter and thus are not the best candidates for the DM. (Their pair-annihilation is in that case also very efficient, see section 3.4.) Nevertheless, some regions of the LSP parameter space have already been explored by the IMB and Fréjus groups, and more recently by Kamiokande in searches for up-going muons. Whether or not those regions have been excluded depends on what fraction of Galactic halo is shared by the neutralinos.

Neutrino detectors (like, e.g., MACRO, DUMAND, AMANDA), and a new generation of cryogenic detectors should have a much larger potential to fully cover the neutralino parameter space. Much work has, and is being, done both on a technical front and in improving existing theoretical calculations of scattering cross sections, capture rates, etc. First decisive results are expected within the next few years.

A whole spectrum of other methods have been considered. They include looking for products of LSP pair-annihilation in the Galactic halo, like monochromatic photons, $e^+$-line radiation, and in continuum spectrum of cosmic antiproton, positron, and gamma–rays, to mention just of few. All these techniques seem to suffer from large theoretical and observational uncertainties and insurmountable backgrounds. At present they are considered less promising.

6 Agnostic Comments

Before we all (I mean supersymmetry enthusiasts) become overly excited I would like to remind that:

- Supersymmetry has not been discovered (yet). No ‘hints’ nor ‘evidence’, while encouraging, cannot be a substitute for a truly unambiguous experimental signal.

- Dark matter has also not been discovered yet. Same remarks apply. Moreover, even its nature (macroscopic objects vs. particles, baryons vs. weakly interacting species, hot vs. cold DM) and abundance haven’t been definitely established.
• Cosmic inflation and $\Omega = 1$ still remain (very attractive) hypotheses for which there is at best some observational support.

• The LSP may after all not be completely stable. The $R$-parity, invoked to insure the stability of the proton, is not a ‘fundamental’ symmetry, and can easily be relaxed. For example, one can allow for lepton or baryon number violating interactions (but not both), in which case the LSP would be unstable. Despite stringent limits, such a scenario may be easily realized and in fact may be favored in light of the COBE discovery.

• Simple (simplistic?) assumptions at the GUT scale can easily be modified or relaxed, even in the context of superstrings, and thus may lead to significantly altered conclusions at the electroweak scale.

• Minimal SUSY may not be the end of the story! After all, it is not favored by any particular reason other than simplicity. On the other hand, it is encouraging that even the simplest supersymmetric model is both theoretically and cosmologically attractive, while not running into any immediate conflict with experiment.

• Finally, one may argue that still lacking is a satisfactory explanation of why the LSP relic abundance should be close to unity in the first place. (See, however, Ref. [1].) Why/how did supersymmetric parameters ‘conspire’ to make the LSP dominate the Universe? This question should be answered (or maybe shown ill-posed?) by a truly fundamental theory.

7 Final Comments

In this review I have addressed the issue of whether supersymmetry can provide an attractive candidate for solving the dark matter problem. I have argued that the lightest neutralino of the minimal supersymmetry has all the desired properties for being both the LSP and DM. This is certainly encouraging given the fact that supersymmetry is the leading candidate for the extension of the Standard Model. In addition, the experimental values of the gauge coupling, as measured at LEP, when evaluated in the minimal supersymmetric model, become equal at the SUSY GUT scale (of around $10^{16}$ GeV), thus supporting the idea of supersymmetric unification.

Cosmology provides additional constraints on the supersymmetric parameter space. Requiring that the LSP provide enough (or at least a substantial fraction of) DM in the flat Universe, when combined with the usual theoretical assumptions and present experimental bounds, points towards the gaugino in the mass range of several tens of GeV as the most natural candidate for both the LSP and the DM. Significant fractions of this mass range should be accessible to LEP 200 and planned experiments for DM searches. In addition, cosmologically favored masses for sleptons and squarks lie beyond the reach of LEP 200 and the Tevatron (what may be somewhat discouraging) but well within the reach of the future hadronic supercolliders: the LHC and the SSC. During the next decade, accelerator and astrophysical DM searches should be able to test this and other predictions of supersymmetry.

It is not unlikely that most of the Universe is actually made of supersymmetric particles while what we usually call ‘ordinary’ matter may look more like a very exotic component of the cosmic zoo. (One might look at this as yet another step in the Copernican revolution!) Nothing short of a direct SUSY discovery will convince the whole physics community but we should certainly be encouraged to continue vigorous searches. It is not unlikely that the first signal of supersymmetry may actually come from searches for dark matter.
Acknowledgments

I would like to thank Professor A. Biaś, the Director of the Ettore Majorana Centre, Professor A. Zichichi, the organizers of the Erice Workshop, Dr. L. Cifarelli and Professor V. Khoze, and Professor H. Haber for their kind invitation to the respective meetings.

References

[1] For reviews, see, e.g., H.-P. Nilles, Phys. Rep. 110C (1984) 1; L.E. Ibáñez, CERN preprint CERN-TH.5982/91 (January 1991); F. Zwirner, CERN preprint CERN-TH.6357/91 (December 1991); L.E. Ibáñez and G.G. Ross, CERN preprint CERN-TH.6412/92 (February 1992), to appear in “Perspectives in Higgs Physics”, ed. by G. Kane.

[2] H.E. Haber and G.L. Kane, Phys. Rep. 117 C (1985) 75.

[3] S. Dimopoulos, S. Raby, and F. Wilczek, Phys. Rev. D 24 (1981) 1681; L.E. Ibáñez and G.G. Ross, Phys. Lett. 105B (1981) 439; S. Dimopoulos and H. Georgi, Nucl. Phys. B 193 (1981) 375; M. Einhorn and D.R.T. Jones, Nucl. Phys. B 196 (1982) 475.

[4] P. Langacker and M.-X. Luo, Phys. Rev. D 44 (1991) 817; U. Amaldi, W. de Boer, and H. Fürstenau, Phys. Lett. B 260 (1991) 447; F. Anselmo, L. Cifarelli, A. Peterman, and A. Zichichi, Nuovo Cim. 104A (1991) 1817 and Nuovo Cim. 105A (1992) 581; J. Ellis, S. Kelley, and D.V. Nanopoulos, Phys. Lett. B 260 (1991) 131.

[5] L.E. Ibáñez and G.G. Ross, Phys. Lett. 110B (1982) 215; K. Inoue, A. Kakuto, H. Komatsu, and S. Takeshita, Progr. Theor. Phys. 68 (1982) 927; L. Alvarez-Gaumé, M. Claudson, and M. Wise, Nucl. Phys. B 202 (1982) 96; J. Ellis, D.V. Nanopoulos, and K. Tamvakis, Phys. Lett. B 121 (1983) 123.

[6] J. Ellis, D.V. Nanopoulos, and S. Rudaz, Nucl. Phys. B 202 (1982) 43; R. Arnowitt and P. Nath, Phys. Rev. Lett. 69 (1992) 725, Phys. Lett. B 287 (1992) 89, and NUB-TH-3048-92; J. Hisano, H. Murayama, and T. Yanagida, Tohoku University preprint TU–400 (July 1992).

[7] See, e.g., P. Fisher, talk given at talk at the XXIII Workshop “Properties of SUSY Particles”, Erice, Italy, September 28 - October 4, 1992, to appear in the Proceedings.

[8] J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive, and M. Srednicki, Nucl. Phys. B 238 (1984) 453.

[9] S.M. Faber and J.S. Gallagher, Ann. Rev. Astron. Astrophys. 17 (1979) 135; J.R. Primack, B. Sadoulet, and D. Seckel, Ann. Rev. Nucl. Part. Sci. B38, (1988) 751; V. Trimble, Ann. Rev. Astron. Astrophys. 25 (1987) 425.

[10] E. Kolb and M. Turner, The Early Universe, (Addison-Wesley, New York, 1989).

[11] M. Turner, Fermilab preprint FERMILAB-Conf-92/382-A (January 1993), Talk presented at NAS Special Colloquium on Physical Cosmology, Irvine, March 1992, to appear in the Proceedings of the National Academy of Sciences.

[12] A. Dekel, talk given at the Rencontres de Blois, June 1992.

[13] K. Olive, D.N. Schramm, G. Steigman, and T. Walker, Phys. Lett. B 236 (1990) 454; T. Walker, G. Steigman, D.N. Schramm, H.-S. Kang, and K. Olive, Ap. J. 353 (1991) 51.
[14] G.F. Smoot, et al., Ap. J. 396 (1992) 1.

[15] L. Roszkowski, invited talk at the XXXII Cracow School on Theoretical Physics, Zakopane, Poland, June 2 - June 12, 1992, (to appear in the Proceedings), Univ. of Michigan preprint UM-TH-92-26 (October 1992), hep-ph/9211201.

[16] M. Veltman, in the Proceedings of the 1979 Int. Symposium on Lepton and Photon Interactions at High Energies, eds. T. Kirk and H. Abardanel (World Scientific, 1992).

[17] J.F. Gunion and H.E. Haber, Nucl. Phys. B 272 (1986) 1.

[18] L. Roszkowski, Phys. Lett. B 262 (1991) 59.

[19] K. Griest and L. Roszkowski, CERN-TH.6181 (September 1991), accepted for publication in Phys. Rev. D.

[20] M. Drees and M. Nojiri, DESY preprint DESY 92-101 (July 1992).

[21] L. Pondrom, in Proc. of the 25th Int. Conference of High Energy Physics, Singapore, 1990, eds. K.K. Phua and Y. Yamaguchi (World Scientific, Singapore, 1991).

[22] L. Roszkowski, Phys. Lett. B 252 (1990) 471.

[23] L. Roszkowski, Phys. Lett. B 278 (1992) 147.

[24] H. Baer, X. Tata, and J. Woodside, Phys. Rev. D 44 (1991) 207.

[25] Abe, F., et al., (CDF Collaboration), Fermilab preprint FERMILAB-PUB-92-221-E (August 1992).

[26] J.F. Gunion and H.E. Haber, in the Proceedings of the 1990 Summer Study on High Energy Physics, ed. E.L. Berger (World Scientific, 1992).

[27] R. Barbieri and G.F. Giudice, Nucl. Phys. B 306 (1988) 63.

[28] K.A. Olive and M. Srednicki, Phys. Lett. B 230 (1989) 78 and Nucl. Phys. B 355 (1991) 208.

[29] K. Griest, Phys. Rev. D 38 (1988) 2357, Phys. Rev. D 39 (1989) 2802(E); K. Griest, M. Kamionkowski, and M. Turner, Phys. Rev. D 41 (1990) 3565.

[30] R.G. Roberts and L. Roszkowski, Univ. of Michigan preprint UM-TH-92-33 (December 1992).

[31] M.S. Turner, Phys. Rep. C197 (1990) 67.

[32] M. Srednicki, R. Watkins, and K.A. Olive, Nucl. Phys. B 310 (1988) 693.

[33] G. Gelmini and P. Gondolo, Nucl. Phys. B 360 (1991) 145.

[34] K. Griest and D. Seckel, Phys. Rev. D 43 (1991) 3191.

[35] R. Arnowitt and P. Nath, Northeastern Univ. preprint NUB-TH-3056-92 (December 1992).

[36] J. Ellis, L. Roszkowski, and Z. Lalak, Phys. Lett. B 245 (1990) 545.

[37] J. Ellis, D.V. Nanopoulos, L. Roszkowski, and D.N. Schramm, Phys. Lett. B 245 (1990) 251.

[38] S. Mizuta and M. Yamaguchi, Tohoku Univ. preprint TU-409 (July 1992).

[39] J. McDonald, K.A. Olive, and M. Srednicki, Phys. Lett. B 283 (1992) 80.
[40] L.E. Ibáñez and C. López, Nucl. Phys. B 233 (1984) 511; L.E. Ibáñez, C. López, and C. Muñoz, Nucl. Phys. B 256 (1985) 218.

[41] J. Ellis, J.S. Hagelin, and D.V. Nanopoulos, Phys. Lett. B 159 (1985) 26.

[42] M. Nojiri, Phys. Lett. B 261 (1991) 76.

[43] J. Ellis and L. Roszkowski, Phys. Lett. B 283 (1992) 252.

[44] J. Lopez, D.V. Nanopoulos, and K. Yuan, Phys. Lett. B 267 (1991) 219; J. Lopez, D.V. Nanopoulos, and A. Zichichi, Phys. Lett. B 291 (1992) 255.

[45] M. Kawasaki and S. Mizuta, Tohoku Univ. preprint TU-395 (March 1992).

[46] S. Kelley, J. Lopez, D.V. Nanopoulos, H. Pois, and K. Yuan, CERN preprint CERN-TH-6584/92 (July 1992).

[47] R.G. Roberts and G.G Ross, Nucl. Phys. B 377 (1992) 571.

[48] J. Gasser and H. Leutwyler, Phys. Rep. 87 C (1982) 77; S. Narison, Phys. Lett. B 216 (1989) 191.

[49] G. Altarelli, CERN preprint CERN-TH-6623/92 (August 1992).

[50] Y. Okada, M. Yamaguchi, and T. Yanagida, Prog. Theor. Phys. 85 (1991) 1, and Phys. Lett. B 262 (1991) 54; H.E. Haber and R. Hempfling, Phys. Rev. Lett. 66 (1991) 1815; J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B 257 (1991) 83, and ibid 262 (1991) 477; R. Barbieri, M. Frigeni, and F. Caravaglio, Phys. Lett. B 258 (1991) 395.

[51] L.E. Ibáñez and D. Lüst, Nucl. Phys. B 382 (1992) 305; B. de Carlos, J.A. Casas, and C. Muñoz, CERN preprint CERN-TH-6681/92 (October 1992).

[52] S. Mizuta, D. Ng, and M. Yamaguchi, Tohoku Univ. preprint TU-410 (August 1992).

[53] D.O. Caldwell, in the Proceedings of the Int. School of Astroparticle Physics, ed. D.V. Nanopoulos (World Scientific, 1992).

[54] B. Sadoulet, talk at a CERN workshop ‘10 Years of SUSY Confronting Experiment’, September 7–9, 1992.

[55] M. Mori, et al., Phys. Lett. B 270 (1991) 89.

[56] M. Drees and M. Nojiri, Univ. of Wisconsin preprint MAD/PH/723 (October 1992); J. Ellis and R. Flores, Phys. Lett. B 263 (1991) 259; G. Gelmini, P. Gondolo, and E. Roulet, Nucl. Phys. B 351 (1991) 623; A. Bottino, V. de Alfaro, N. Fornengo, A. Morales, J. Puinedón, and S. Scopel, Mod. Phys. Lett. A7 (1992) 733; F. Halzen, T. Stelzer, and M. Kamionkowski, Phys. Rev. D 45 (1992) 4439; G. Kane and I. Kani, Nucl. Phys. B 277 (1986) 525.
Figure Captions

Figure 1: Contours of the neutralino mass and gaugino-higgsino compositions (purity, as defined in the text) in the $(\mu, M_2)$ plane for $\tan \beta = 2$ and for $\mu < 0$ (left panel) and $\mu > 0$ (right panel). 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 $p_{\text{gaugino}} = 0.99, 0.9, 0.5, 0.1,$ and 0.01 from larger $|\mu|$ to larger $M_2$. (Note $p_{\text{gaugino}} = 0.01$ implies a 99% higgsino.) In the regions labeled $B$ and limited by the dashed curves $p_{\tilde{B}} \geq 0.99$ (almost pure bino), while the region (labeled $H_S$) above the other dashed curve correspond to almost pure symmetric higgsino ($p_{\tilde{\text{higgsino}}} > 0.99$). (The almost pure anti-symmetric higgsino $H_A$ lies above the range of $M_2$ in the window $\mu > 0$.) The areas marked “LEP” are ruled out by LEP and the areas below the curves marked “CDF” are ruled out by CDF. Also marked is the remaining photino region with 95% purity.

Figure 2: Contours of relic abundance in the $(\mu, M_2)$ plane, with $\tan \beta = 2$, $m_A = 150$ GeV, $m_{\tilde{f}} = 200$ GeV or $m_\chi$ (whichever is larger) for all sfermions, and $\mu < 0$ ($\mu > 0$) in the left (right) panel. Areas excluded by LEP (CDF) are marked “LEP” (“CDF”). The relic density increases with increasing grayness. The cosmologically excluded region $\Omega h_0^2 > 1$ is delineated by a thick solid line in the grey region. The cosmologically favored regions ($0.25 \lesssim \Omega h_0^2 \lesssim 0.5$) are delineated by dotted lines. The long-dashed and thick-solid contours correspond to 0.1 and 0.025, respectively. The LSP co-annihilation has not been included. Its effect would be to greatly reduce the relic abundance in the higgsino region ($M_2 \gg |\mu|$).

Figure 3: Contours of relic abundance in the $(\mu, M_2)$ plane, with $\tan \beta = 2$, $m_A = 150$ GeV, and $\mu < 0$. (The case $\mu > 0$ is qualitatively similar.) In the left panel all $m_{\tilde{f}} = 400$ GeV or $m_\chi$ (whichever is larger). In the right panel all sfermion masses are as before but for the selectron $m_{\tilde{e}} = 45$ GeV or $m_\chi$ (whichever is larger). All the textures are as in fig. 2. The LSP co-annihilation has not been included. Its effect would be to greatly reduce the relic abundance in the higgsino region ($M_2 \gg |\mu|$).

Figure 4: Contours of relic LSP density in the $(\mu, M_2)$ plane for $\tan \beta = 2$, $m_A = 200$ GeV, and $\mu = \pm 500$ GeV in the left (right) panel. The cosmologically favored regions with $0.25 < \Omega h_0^2 < 0.5$ are shaded, while regions where $\Omega h_0^2 > 1$ are cross-hatched, and regions excluded by LEP and CDF are hatched. The $\Omega h_0^2 = 0.1$ contour is shown as a thin dashed line. Above the lines “1” $m_\tilde{q} > 1$ TeV for at least one squark, above “2” $m_\tilde{q} > 1$ TeV, and to the left of “3” $m_\tilde{q} < 100$ GeV for at least one squark.

Figure 5: In the plane $(m_{1/2}, m_0)$ for the fixed ratio $\mu_0/m_0 = 2$ I show: in window a) the mass contours of the top and the bottom squarks (solid and short-dashed lines, respectively); in window b) the contours of $\alpha_s(m_Z)$ (solid) and the measure $c$ of fine-tuning (dots); in window c) the relic abundance $\Omega h_0^2$ of the LSP; and in window d) the mass contours of the LSP (solid) and the lightest chargino (dashed) at 50, 100, 150, 200, 500, and 1000 GeV, starting from left, and the contribution (dots) of the bino to the LSP composition (bino purity). In all the windows thick solid lines delineate regions experimentally excluded by the CDF (marked CDF) where $m_t < 91$ GeV and by the LEP experiments (LEP) where the lightest chargino is lighter than 46 GeV. In window c) we also mark by $\Omega h_0^2 > 1$ the region cosmologically excluded (too young Universe). The thin band between the thick dashed lines in window c) corresponds to the flat Universe ($\Omega = 1$). In window d) the region excluded by CDF almost coincides with the bino purity of 50% or less.

Figure 6: I show a blow-up of the down-left portion of the plane $(m_{1/2}, m_0)$ from the previous figure for the same fixed ratio $\mu_0/m_0 = 2$. I combine the mass contours of the top and the bottom squarks with the ones of the LSP relic mass density. I use the same textures as in Fig. 5 but I also show (two medium-thick short-dashed lines) the contours $m_0 = 4.15$ GeV and 4.35 GeV which reflect the currently favoured range of the mass of the bottom quark (see text). I see that they cross the cosmologically favored region (thick long-dashed lines) marked $\Omega = 1$ at roughly 150 GeV $\lesssim m_{1/2}, m_0 \lesssim 400$ GeV and for $m_t$ broadly between 150 GeV and 180 GeV.