Dark Matter Phenomenology of GUT-less SUSY Breaking

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Abstract. We study models in which supersymmetry breaking appears at an intermediate scale, $M_{in}$, below the GUT scale. That is, that the soft supersymmetry-breaking parameters of the MSSM are universal at $M_{in}$. We demand that the lightest neutralino be the LSP, and that the relic neutralino density not conflict with measurements by WMAP and others, and study the morphology of this constraint as the universality scale is reduced from the GUT scale. At moderate values of $M_{in}$, we find that the allowed regions of the $(m_{1/2}, m_0)$ plane are squeezed by the requirements of electroweak symmetry breaking and that the lightest neutralino be the LSP, whereas the constraint on the relic density is less severe. At very low $M_{in}$, the electroweak vacuum conditions become the dominant constraint, and a secondary source of astrophysical cold dark matter would be necessary to explain the measured relic density for nearly all values of the soft SUSY-breaking parameters and $\tan \beta$.

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1 Introduction

It is well known that TeV scale SUSY offers a compelling solution to the related hierarchy and naturalness problems of the Standard Model. It also facilitates unification of the gauge couplings, as expected in Grand Unified Theories (GUTs) and predicts a light Higgs boson, as favored by precision electroweak data. If R-parity is assumed to be conserved, the lightest supersymmetric particle (LSP) is stable, and, if uncharged, is therefore a natural particle candidate for astrophysical cold dark matter.

SUSY is, of course, broken, however the mechanism of this breaking and how it is communicated to the observable sector are unknown. One option is to parametrize the breaking at a high scale with soft SUSY-breaking mass parameters and use the renormalization group equations (RGEs) of the low-energy effective theory to evolve them down to lower scales. In the Constrained Minimal Supersymmetric Standard Model (CMSSM), the soft SUSY-breaking parameters are taken to be universal at the SUSY GUT scale, $M_{GUT} \approx 2 \times 10^{16}$ GeV. The RGEs of the MSSM determine the weak scale observables, given five inputs at the GUT scale, the scalar mass, $m_0$, the gaugino mass, $m_{1/2}$, the trilinear coupling, $A_0$, the ratio of the Higgs vevs, $\tan \beta$, and the sign of the Higgs mass parameter, $\mu$. In some models it may be more appropriate, however, to assume universality of the soft SUSY-breaking parameters at some scale $M_{in}$ intermediate between the GUT scale and the electroweak scale.

2 GUT-less Renormalization

The consequences of lowering the universality scale can be easily understood by examining the changes to the running of the soft mass parameters at the one-loop level\textsuperscript{2}. In the GUT-scale CMSSM, the one-loop renormalizations of the gaugino masses are identical to those of the corresponding gauge couplings. The gaugino masses, $M_a(Q)$, where $a = 1, 2, 3$, and $Q$ is some low scale, are then proportional to $m_{1/2}$, with the proportionality defined by the ratio of the corresponding gauge coupling at the low scale to the coupling at the GUT scale. The running of the gauge couplings is unaffected by the universality scale of the soft SUSY-breaking parameters, so in the GUT-less CMSSM, the gaugino masses become

$$M_a(Q) = \frac{\alpha_a(Q)}{\alpha_a(M_{in})} m_{1/2}. \quad (1)$$

\textsuperscript{1} Note that all calculations carried out in making the following plots incorporate the full two-loop RGEs.
the composition of the neutralino LSP. In the CMSSM, the neutralino is commonly bino-like, and $m_{\chi} \sim M_1$. When $\mu < M_1$, however, the neutralino is Higgsino-like, and annihilations to vector bosons are enhanced. As $M_{in}$ is lowered, we expect that the LSP becomes more Higgsino-like over all of parameter space. Again turning to Figure 1 we see that for this point in parameter space, the LSP mass tracks that of the bino for $M_{in} \geq 10^{12}$ GeV. Below this value, however, $\mu$ becomes much less than the bino mass, and the LSP eventually becomes Higgsino-like with $m_{\chi} \sim \mu$.

### 3 Evolution of the Relic Density

We assume that the neutralino LSP constitutes the cold dark matter in the universe, and demand that the relic density of neutralinos falls within the range

$$0.0855 < \Omega h^2 < 0.1189,$$

in accordance with the WMAP observations [3]. In Figure 2 we show how the shape of this constraint changes in the $(m_{1/2}, m_0)$ plane as the universality scale is lowered from the GUT scale. Here we take $\tan \beta = 10$, $\mu > 0$, $A_0 = 0$ and $m_t = 171.4$ GeV.

Panel (a) of Figure 2 shows the constraints from cosmology and collider experiments in the $(m_{1/2}, m_0)$ plane in the normal GUT-scale CMSSM. Collider constraints are described in the figure caption. The only allowed regions where the relic density of neutralinos falls within the cosmologically preferred range are the focus point, which borders the region excluded by the electroweak symmetry breaking constraint at large $m_0$, and the $\chi - \tilde{\tau}$ coannihilation strip, which lies along the border of the forbidden $\tilde{\tau}$-LSP region. The relic density of neutralinos is much too large to explain the WMAP measurement over most of the plane.

For $M_{in} = 10^{13}$ GeV, as shown in Panel (b), the unphysical region where $\mu^2 < 0$ has encroached further into the plane, as has the forbidden $\tilde{\tau}$-LSP region. $\mu$ has become smaller over the plane, leading to a more Higgsino-like (and lighter) LSP. The cosmologically preferred strips have pulled away from these excluded regions, and the two strips on the lower side of the “C” shape indicate the two walls of a rapid annihilation funnel. Inside these two walls, $2m_{\chi} \sim m_A$, and neutralino annihilation proceeds extremely efficiently through the s-channel A-pole, resulting in a very low relic density.

As the universality scale is lowered to $M_{in} = 10^{12}$ GeV in Panel (c), the “C” has closed into a small island and the rapid annihilation funnel has broadened and moved to lower $m_{1/2}$. The lower funnel wall has taken on a peculiar shape, the sharp plunge indicating the $\chi\chi \rightarrow h + A$ threshold. For this value of $M_{in}$, the LSP is Higgsino-like and the relic density is below the WMAP range over most of the plane.

In Panel (d), where $M_{in} = 10^{11}$ GeV, the island has evaporated and the lower funnel wall has dipped into the $\tilde{\tau}$-LSP region such that the relic density of neutralinos is too low to fully account for the WMAP measurement.
**Fig. 2.** Examples of \((m_{1/2}, m_0)\) planes with \(\tan \beta = 10\) and \(A_0 = 0\) but with different values of \(M_{in}\). (a) The CMSSM case with \(M_{in} = M_{GUT} \sim 2 \times 10^{16}\) GeV, (b) \(M_{in} = 10^{13}\) GeV, (c) \(M_{in} = 10^{12}\) GeV and (d) \(M_{in} = 10^{11}\) GeV. In each panel, we show the region ruled out because the LSP would be charged (dark red shading), and that excluded by the electroweak vacuum condition (dark pink shading). The regions where the relic density falls in the range favored by WMAP, \(\Omega_{CDM} h^2 = 0.1045^{+0.0072}_{-0.0075}\), have light turquoise shading. In each panel we also show contours representing the LEP lower limit on the chargino mass [4] (black dashed), a Higgs mass contour of 114 GeV [5] (red dashed), and the more exact (and relaxed) Higgs mass bound (red dot-dashed). The region suggested by \(g_{\mu} - 2\) at 2-\(\sigma\) has medium (pink) shading with 1-\(\sigma\) contours shown as black dashed lines [6].

measurement over nearly all of the plane. Very low values of \(M_{in}\) are therefore disfavored due to the necessity of a secondary source of astrophysical cold dark matter in order to explain the measured abundance.

At large \(\tan \beta\), a similar evolution presents itself, the key difference being that the rapid annihilation funnel is present already at \(M_{in} = M_{GUT}\). As in the \(\tan \beta = 10\) case, the upper funnel wall and what had been the focus point region approach, merge, and eventually evaporate, at which point the lower funnel wall falls into the \(\tilde{\tau}\)-LSP region so that the relic density of neutralinos is too low over the entire plane when \(M_{in} \sim 10^{11}\) GeV.

### 4 Direct Detection

Many direct searches for dark matter particles such as CDMS and XENON10 look for signatures of weakly-interacting massive particles (WIMPs) scattering on nuclei. The neutralino-nucleon scattering cross section can be broken into spin-dependent and spin-independent (scalar) parts. In Figure 3 we plot the neutralino-nucleon elastic scattering cross sections as functions of neutralino mass for regions in our parameter space that pass all constraints (blue) and that fail only the relaxed LEP Higgs constraint[4] (green) with \(M_{in} = M_{GUT}\) in Panel (a) and \(M_{in} = 10^{12}\) GeV in Panel (b). If the relic density is below the central value, \(\Omega_{\chi} h^2 = 0.1045\), we plot the cross section scaled by the ratio of the relic density of neutralinos to the measured value such that our cross sections can be compared with the exclusion limits from direct detection experiments. In particular, we show the limits from CDMS II and XENON10 for the scalar part of the neutralino-nucleon cross section [7,8].

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2 See [2] for details.
In Panel (a), where $M_{in} = M_{GUT}$, the regions that pass all constraints are separated into a longer strip of lower cross sections and a smaller island of larger cross sections. The longer strip corresponds to points in the $\chi^2 - t$ coannihilation region, while the smaller island corresponds to the focus point region. We note that this island would extend to larger $m_\chi$ had we considered values of $m_0 > 2000$ GeV.

When $M_{in} = 10^{12}$ GeV, as shown in Panel (b), the most striking difference is that for a given value of $m_\chi$, there is a wide range of potential cross sections. This is due to the fact that the relic density of neutralinos is below the WMAP range over most of the plane, so cross sections are scaled accordingly. The upper boundaries of the regions pictured in Panel (b) come from points in the $(m_{1/2}, m_0)$ plane where the relic density is the largest and $m_0$ is the lowest, so one can map the upper edges in Panel (b) to cosmologically preferred regions in Panel (c) of Figure 4.

The next generation of direct detection experiments will probe much of the range of scalar cross sections pictured here. SuperCDMS Phase A with seven towers deployed is expected to be sensitive to scalar cross sections as low as $10^{-9}$ pb at $m_\chi = 100$ GeV [9]. Detectors that will use liquid nobles such as Xenon or Argon expect sensitivities as low as $10^{-10}$ pb for one year of operation of a one ton detector [10]. We look forward to increased sensitivities to neutralino-nucleon cross sections as a useful complement to collider searches.

5 Conclusions

Lowering the unification scale of the soft SUSY-breaking parameters significantly changes the appearance of the constraint on the relic density of neutralinos. Intermediate universality results in the merging and evaporation of the focus point and rapid annihilation funnel regions. For some critical value of $M_{in}$, dependent on $\tan \beta$ and other factors, the relic density of neutralinos becomes too low over all or nearly all of the $(m_{1/2}, m_0)$ plane to explain the measured relic density of cold dark matter. The dark matter phenomenology of GUT-less SUSY represents a substantial departure from that of the standard GUT-scale CMSSM.

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References

1. J. Ellis, K. A. Olive, and P. Sandick, Phys. Lett. B 642 (2006) 389.
2. J. Ellis, K. A. Olive, and P. Sandick, JHEP 06 (2007) 079.
3. D. N. Spergel et al., ApJS 170 (2007) 377.
4. Joint LEP 2 Supersymmetry Working Group, Combined LEP Chargino Results up to 208 GeV, http://lepsusy.web.cern.ch/lepsusy/www/inos_moriond01/charginos_pub.html.
5. LEP Higgs Working Group for Higgs bosons at LEP, paper submitted to ICHEP04, http://lepwww.hep.ph.s.uva.nl/moriond/lepsusy/lep_higgs_results_paper.pdf.
6. M. Davier, [arXiv:hep-ph/0701163].
7. L. Jegerlehner, [arXiv:hep-ph/0703125].
8. E. de Rafael and J. P. Miller, E. de Rafael and B. L. Roberts, Rep. Prog. Phys. 70 (2007) 795.
9. D. S. Akerib et al. [CDMS Collaboration], Phys. Rev. Lett. 96, 011302 (2006).
10. J. Angle et al. [XENON Collaboration], arXiv:0706.0039 [astro-ph].
11. R. W. Schnee et al. [SuperCDMS Collaboration], arXiv:astro-ph/0502435.