COSMOLOGY AND ASTROPHYSICS. DARK MATTER

Dark Matter in Susy Models*

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Abstract—Direct detection experiments for neutralino dark matter in the Milky Way are examined within the framework of SUGRA models with $R$-parity invariance and grand unification at the GUT scale, $M_G$. Models of this type apply to a large number of phenomena, and all existing bounds on the SUSY parameter space due to current experimental constraints are included. For models with universal soft breaking at $M_G$ (mSUGRA), the Higgs mass and $b \rightarrow s\gamma$ constraints imply that the gaugino mass, $m_{1/2}$, obeys $m_{1/2} > 300\text{--}400$ GeV, putting most of the parameter space in the coannihilation domain, where there is a relatively narrow band in the $m_0-m_{1/2}$ plane. For $\mu > 0$, we find that the neutralino–proton cross section is $\gtrsim 10^{-10}$ pb for $m_{1/2} < 1$ TeV, making almost all of this parameter space accessible to future planned detectors. For $\mu < 0$, however, there will be large regions of parameter space with cross sections $< 10^{-12}$ pb and, hence, unaccessible experimentally. If, however, the muon magnetic moment anomaly is confirmed, then $\mu > 0$ and $m_{1/2} \lesssim 800$ GeV. Models with nonuniversal soft breaking in the third generation and Higgs sector can allow for new effects arising from additional early Universe annihilation through the $Z$-channel pole. Here, cross sections that will be accessible in the near future to the next generation of detectors can arise, and can even rise to the large values implied by the DAMA data. Thus, dark matter detectors have the possibility of studying the post-GUT physics that control the patterns of soft breaking.

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1. INTRODUCTION

The recent BOOMERanG, Maxima, and DASI data have allowed a relatively precise determination of the mean amount of dark matter in the Universe, and these results are consistent with other astronomical observations. Within the Milky Way itself, the amount of dark matter is estimated to be

$$\rho_{\text{DM}} \cong 0.3\text{--}0.5 \text{ GeV/cm}^3. \quad (1)$$

Supersymmetry with $R$-parity invariance possesses a natural candidate for cold dark matter (CDM), the lightest neutralino, $\tilde{\chi}_1^0$, and SUGRA models predict a relic density consistent with the astronomical observations of dark matter. Several methods for detecting the Milky Way neutralinos exist:

(i) Annihilation of $\tilde{\chi}_1^0$ in the halo of the Galaxy leading to antiproton or positron signals. There have been several interesting analyses of these possibilities [1, 2], but there are still uncertainties as to astronomical backgrounds.

(ii) Annihilation of the $\tilde{\chi}_1^0$ in the center of the Sun or Earth leading to neutrinos and detection of the energetic $\nu_n$ by neutrino telescopes (AMANDA, IceCube, ANTARES). Recent analyses [3, 4] indicate that these detectors can be sensitive to such signals, but for the Minimal Supersymmetric Standard Model (MSSM) one requires $m_{\tilde{\chi}_1^0} > 200$ GeV (i.e., $m_{1/2} > 500$ GeV) and $\tan \beta > 10$, and for SUGRA models one is restricted to $\tan \beta > 35$ [3].

(iii) Direct detection by scattering of incident $\tilde{\chi}_1^0$ on nuclear targets of terrestrial detectors. Current detectors are sensitive to such events for $\tilde{\chi}_1^0-p$ cross sections in the range

$$\sigma_{\tilde{\chi}_1^0-p} \gtrsim 1 \times 10^{-6} \text{ pb} \quad (2)$$

with a possible improvement by a factor of 10--100 in the near future. Future detectors (GENIUS, Cryoarray, ZEPLIN IV) may be sensitive down to $10^{-9}$--$10^{-10}$ pb, and we will see that this would be sufficient to cover the parameter space of most SUGRA models.

In the following, we will consider SUGRA models with $R$-parity invariance based on grand unification at the GUT scale $M_G \cong 2 \times 10^{16}$ GeV. In particular, we will consider two classes of models: minimal supergravity models (mSUGRA [5, 6]) with universal soft breaking masses at $M_G$ and nonuniversal models with nonuniversal soft breaking at $M_G$ for the Higgs bosons and the third generation of squarks and

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sleptons. Here, the gaugino masses \( m_{1/2} \) and the cubic soft-breaking masses \( A_0 \) are assumed universal.

SUGRA models apply to a wide range of phenomena, and data from different experiments interact with each other to sharpen the predictions greatly. We list here the important experimental constraints:

(i) Higgs mass: \( m_h > 114 \text{ GeV} \) [7]. The theoretical calculation of \( m_h \) still has an error of \( \sim 3 \text{ GeV} \), and so we will (conservatively) interpret this bound to mean \( m_h(\text{theory}) > 114 \text{ GeV} \).

(ii) \( b \rightarrow s \gamma \) branching ratio. We take a 2σ range around the central CLEO value [8]:
\[
1.8 \times 10^{-4} \leq \text{BR}(B \rightarrow X_s \gamma) \leq 4.5 \times 10^{-4}.
\]

(iii) \( \tilde{\chi}_1^0 \) relic density: We assume here
\[
0.02 \leq \Omega_{\text{DM}} h^2 \leq 0.25.
\]
The lower bound takes into account of the possibility that there is more than one species of DM. However, results are insensitive to raising it to 0.05 or 0.10.

(iv) Muon \( a_\mu = (g_\mu - 2)/2 \) anomaly. The Brookhaven E821 experiment [9] reported a 2.6σ deviation from the Standard Model value in their measurement of the muon magnetic moment. Recently, a sign error in the theoretical calculation [10, 11] has reduced this to a 1.6σ anomaly, though recent measurements [12] used to calculate the hadronic contribution may have raised the deviation. Since there is a great deal more data currently being analyzed (with results due this spring) that will reduce the errors by a factor of \( \sim 2.5 \), we will assume here that there is a deviation in \( a_\mu \) due to SUGRA of amount
\[
11 \times 10^{-10} \leq a_\mu^{\text{SUGRA}} \leq 75 \times 10^{-10}.
\]

We will, however, state our results with and without including this anomaly.

To illustrate how the different experimental constraints affect the SUSY parameter space, we consider the mSUGRA example:

(i) The \( m_h \) and \( b \rightarrow s \gamma \) constraints put a lower bound on \( m_{1/2} \):
\[
m_{1/2} \gtrsim 300 - 400 \text{ GeV},
\]
which means \( m_{\tilde{\chi}_1^0} \gtrsim 120 - 160 \text{ GeV} \) (since \( m_{\tilde{\chi}_1^0} \approx 0.4m_{1/2} \)).

(ii) Equation (6) now means that most of the parameter space is in the \( \tilde{\tau}_1 - \tilde{\chi}_1^0 \) coannihilation domain in the relic density calculation. Then, \( m_0 \) (the squark and slepton soft-breaking mass) is approximately determined by \( m_{1/2} \), as can be seen in Figs. 1 and 2.

(iii) If we include the \( a_\mu \) anomaly, since \( a_\mu^{\text{SUGRA}} \) is a decreasing function of \( m_{1/2} \) and \( m_0 \), the lower bound of (5) produces an upper bound on \( m_{1/2} \) and the positive sign of \( a_\mu \) implies that the \( \mu \) parameter is positive. In addition, one gets a lower bound on \( \tan \beta \) of \( \tan \beta > 5 \). Thus, the parameter space has begun to be strongly constrained, allowing for more precise predictions. In order to carry out detailed calculations, however, it is necessary to include a number of analyses to obtain accurate results. We list some of these here.

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Fig. 1. Corridors in the \( m_0 - m_{1/2} \) plane allowed by the relic density constraints for \( A_0 = 0, \mu > 0 \), and (bottom to top) \( \tan \beta = 10, 30, 40 \). The lower bound on \( m_{1/2} \) is due to the \( m_h \) lower bound for \( \tan \beta = 10 \) and due to the \( b \rightarrow s \gamma \) bound for \( \tan \beta = 40 \), while both these contribute equally for \( \tan \beta = 30 \). The short lines cutting the channels represent upper bound from the \( g_{\mu} \)-2 experiment [13].

Fig. 2. Corridors in the \( m_0 - m_{1/2} \) plane allowed by the relic density constraint for \( \tan \beta = 40, \mu > 0 \), and (bottom to top) \( A_0 = 0, -2m_{1/2}, 4m_{1/2} \). The curves terminate at the lower end due to the \( b \rightarrow s \gamma \) constraint, except for \( A_0 = 4m_{1/2} \), which terminates due to the \( m_h \) constraint. The short lines cutting the corridors represent the upper bound on \( m_{1/2} \) due to the \( g_{\mu} \)-2 experiment [13].