DARK MATTER, supersymmetry and supergravity models –

Supersymmetric models containing a lightest supersymmetric partner (LSP) which is a viable candidate for dark matter. The principal issues are (i) the model itself, (ii) the cosmological abundance of the LSP, (iii) the potential for detection in terrestrial experiments, and (iv) the consistency with astronomical observations.

There is a large literature on this subject, filled with many proposals for dark matter particles. Here we will emphasize only the most standard candidate, the (lightest) neutralino. This is a spin 1/2 fermionic superpartner with no electromagnetic or strong interaction, which has a mass of the order of 100 GeV - 1 TeV. It can thus be considered a "weakly interacting massive particle" (WIMP), although supersymmetry gives it special desirable properties.

A truly viable candidate for dark matter is in fact one of the great triumphs of supersymmetry. SUSY requires additional particles beyond those of ordinary luminous matter. Furthermore, these superpartners must have

$$R = (-1)^{3(B-L)+2s} = -1$$

where B, L, and s are respectively the baryon number, lepton number, and spin. It is natural to assume that the R-parity R is conserved (at low energy), since this is consistent with conservation of B and L, in which case the LSP must be stable.

The LSP is then a perfect candidate for the dark matter [1], provided that it has no electric or color charge, and that it also has the right cosmological abundance. Detailed calculations with specific models are required to see whether it does in fact have these properties. The two most standard and well-motivated models are the minimal supersymmetric standard model (MSSM) and the minimal supergravity model (mSUGRA), which are both discussed elsewhere in this volume.

The MSSM unfortunately has more than 100 free parameters, so it does not have much predictive power. On the other hand, mSUGRA has only 4 parameters and one sign, so one can study the parameter space in detail, and obtain tight constraints from the existing experimental and observational data. The accompanying figure exemplifies such constraints, and how they

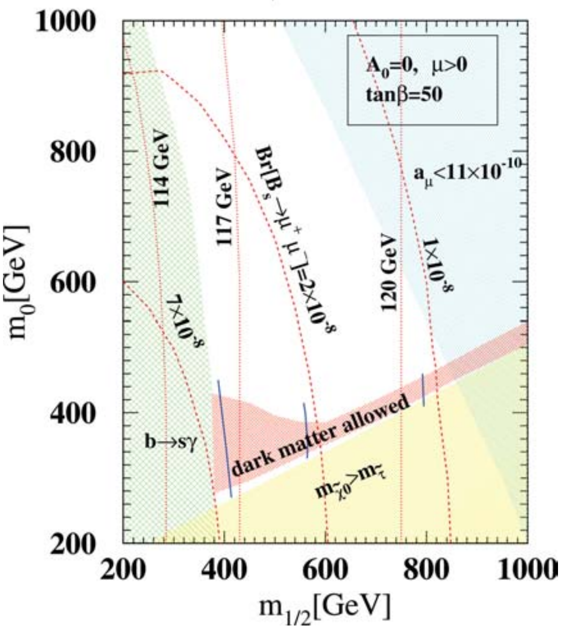

Figure 1: Representative results in mSUGRA parameter space, relevant to dark matter predictions. After Arnowitt and Dutta [2].

fit into ongoing experimental searches for dark matter [2].

The notation in this figure will now be explained. First one must understand the basic meaning of each parameter. (For more details, see the article by Nath on mSUGRA, in this volume.)

• m_0 is the universal mass for spin 0 bosons at the GUT scale M_G.

• $m_{1/2}$ is the universal mass for spin 1/2 gauginos at M_G.

• $tan\beta = \langle H_2 \rangle \,/\, \langle H_1 \rangle$ is the ratio of the vacuum expectation values of the two Higgs fields that are required in SUSY.

• A_0 is the universal trilinear coupling at M_G (associated with soft supersymmetry breaking).

• μ is the Higgs mixing coefficient, which appears in the superpotential term $\mu H_1 H_2$, and whose sign is the last parameter.

The neutralino mass matrix is written in a basis that consists of the four neutral spin 1/2 fermionic superpartners: the gauginos, $\tilde{W}_3$ and $\tilde{B}$, and Higgsinos, $\tilde{H}_1$ and $\tilde{H}_2$, which are respectively the superpartners of the neutral $SU(2)$ and $U(1)$ gauge bosons of the standard model (i.e., linear combinations of the Z^0 and photon) and the two neutral Higgs fields required by supersymmetry. For a concise notation, let $a = M_Z cos\theta_W cos\beta$, $c = -tan\theta_W a$, $b = -M_Z cos\theta_W sin\beta$, and $d = -tan\theta_W b$, where θ_W is the weak mixing angle.

The neutralino mass matrix then has the form

$$M_\chi^0 = \begin{pmatrix} \tilde{m}_2 & o & a & b \\ o & \tilde{m}_1 & c & d \\ a & c & o & -\mu \\ b & d & -\mu & o \end{pmatrix} .$$

For the regions of the parameter space that are usually regarded as most favorable, the (lightest) neutralino has primarily gaugino and largely bino ($\tilde{B}$) character.

A major constraint is imposed by the requirement that the neutralino be the LSP, rather than, e.g., a charged slepton. Also, if a second particle is nearly degenerate with the neutralino, the predicted abundances are spoiled by coannihilation. In the mSUGRA model of Ref. 2, the masses of the right selectron $\tilde{e}_R$ and the neutralino $\tilde{\chi}_1^0$ are given (to one loop order at the electroweak scale) by

$$m\left(\tilde{e}_R\right)^2 = m_0^2 + 0.15 m_{1/2}^2 - sin^2\theta_W M_W^2 \cos 2\beta$$
$$m\left(\tilde{\chi}_1^0\right)^2 = 0.16 m_{1/2}^2 .$$

As $m_{1/2}$ increases, m_0 must be raised in lock step (to keep $m\left(\tilde{e}_R\right) > m\left(\tilde{\chi}_1^0\right)$). The $\tilde{\tau}_1$ turns out to be the lightest slepton, and this particle dominates the coannihilation. In general, coannihilation implies that one ends up with relatively narrow allowed corridors in the $m_0 - m_{1/2}$ plane: m_0 is closely correlated with $m_{1/2}$, and increases as $m_{1/2}$ increases, as can be seen in the figure. (This is, of course, the m_0-$m_{1/2}$ plane in the mSUGRA parameter space, with typical values of the other parameters: $\tan\beta = 50$, $A_0 = 0$, and $\mu > 0$.) The corridor is cut off at the top by the requirement that dark matter annihilation not proceed too slowly, making the abundance too large. It is cut off at the bottom by the requirement that annihilation not proceed too quickly, making the abundance too small. Just under this cutoff is a parallel diagonal line, below which the neutralino is no longer the LSP. The vertical dotted lines indicate Higgs masses.

Another constraint is provided by b $\rightarrow$ s γ, a process that does not occur at tree level in the Standard Model. This produces a lower bound over the whole parameter space of $m_{1/2} \approx 300$ GeV when combined with the current Higgs mass bound. Further information will be provided by future measurements of a_μ, the anomalous contribution to the magnetic moment of the muon. The figure additionally shows three dashed curves corresponding to the branching ratio for $B_s \rightarrow \mu^+\mu^-$: from left to right, 7×10^{-8}, 2×10^{-8}, and 1×10^{-8}.

Direct detection of galactic neutralinos depends critically on the neutralino-proton cross section. The three short solid lines in the figure indicate the values of $\sigma\left(\tilde{\chi}_1^0 - p\right)$: from the left, 0.05 $\times 10^{-6}$ pb, 0.004 $\times 10^{-6}$ pb, and 0.002 $\times 10^{-6}$ pb.

For detectors with nuclear targets containing heavy nuclei, the total cross section is dominated by the spin independent cross section. $\sigma\left(\tilde{\chi}_1^0 - p\right)$ is predicted to decrease with increasing $m_{1/2}$ and m_0 (which increase together in the dark-matter allowed region), and also to increase with $\tan\beta$. Thus the maximum cross section will occur at high $\tan\beta$ and low $m_{1/2}$, m_0.

Arnowitt and Dutta [2] (and other groups [1]) find that there are plausible regions of the parameter space which are already accessible to ongoing terrestrial experiments, and larger regions will be accessible to experiments planned for the near future. To be more precise, current detectors are sensitive down to about 10^{-6} pb, with the next round of experiments extending the sensitivity to 10^{-8} pb, and future plans reaching $10^{-9} - 10^{-10}$ pb, which covers the $\mu > 0$ parameter space for $m_{1/2} < 1$ TeV.

Since the neutralino is a Majorana fermion, it is its own antiparticle, and will undergo annihilations during the expansion and cooling of the early universe. Calculations of the resulting relic abundance require a detailed numerical treatment, or an approximate analytical treatment, based on the Boltzmann equation

$$dn_\chi/dt = -3Hn_\chi - \langle\sigma v_{rel}\rangle \left(n_\chi^2 - \left(n_\chi^0\right)^2\right) ,$$

where n_χ is the number density, n_χ^0 is the number density that would correspond to thermal equilibrium at time t, $H \equiv \dot{R}/R$ is the Hubble parameter, R is the cosmic scale factor, σ is the cross section for the process $\chi\chi \rightarrow$

ordinary matter, v_{rel} is the relative velocity of the two annihilating neutralinos, and $\langle \cdots \rangle$ indicates a thermal average and sum over spins. The predicted cosmological abundance in the present epoch is consistent with observation, strengthening the case for this dark matter candidate.

There is one remaining problem: Cold dark matter simulations provide a satisfactory description of the evolution of large-scale structure in the universe, but appear to disagree in two respects with the observations relevant to galactic halos: First, standard CDM has too strong a tendency to form relatively small clumps. Second, the simulations yield cusps in the CDM density with the Navarro-Frenk-White form

$$\rho(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^2} \propto r^{-1} \text{ as } r \to 0$$

whereas analyses of the observational data seem to indicate a flattening of the density as $r \to 0$. There are several proposals addressing this problem, including warm dark matter [3], self interacting dark matter [4], and Lorentz violating dark matter [5]. However, it is also possible that the small scale structure and cusps are removed by normal astrophysical processes that are not well understood.

In summary, SUSY with R-parity conservation provides an eminently plausible candidate for dark matter, the lightest supersymmetric partner. Well-motivated models, including minimal supergravity, allow the dark matter problem to be integrated with a large variety of other SUSY related phenomena, involving accelerator experiments, underground experiments, and the measurement of the muon $(g-2)/2$. It is found that there is a robust region in the parameter space that accommodates dark matter. In addition, calculations of annihilation in the early universe yield an acceptable relic abundance. Finally, the scattering cross-sections provide hope for direct dark matter detection in the foreseeable future.

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