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Dark Matter and the SUSY Mass Scale*

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Abstract

The connection between the present density of neutralinos that are left over from the Big Bang and the superparticle mass scale is briefly reviewed. Superparticle mass scales in the range from a few GeV to several TeV can lead to an acceptable density of thermal relic neutralinos, the actual value depending on relations between the masses of certain sparticles and Higgs bosons.

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Most theoretical physicists believe that some "new physics" will have to appear at or below the TeV scale, in order to render the scalar sector of the SM (technically) natural. This consensus motivates the collider physics community to design and (hopefully) build particle colliders that can directly probe TeV energies. However, while from a string theorist's perspective there would be little difference between "new physics" scales of 300 GeV and 1 TeV, it is clear that from the collider physicist's point of view a more precise statement regarding the energy needed to unravel the mystery shrouding the scalar sector of the SM would be invaluable.

This issue is most frequently discussed in the framework of supersymmetric theories, which have been worked out in much more detail than any competing theories. There have been various attempts to make the naturalness argument more precise by defining quantitative measures of finetuning, at least in the (very attractive) class of models where the electroweak gauge symmetry is broken radiatively [1]. However, even if one of these definitions is accepted, one still has to use one's judgment as to how much finetuning one is willing to tolerate.

Calculations of the density of thermal Big Bang relics seem to allow to derive more precise bounds on sparticle masses, if we require that relic LSPs (usually assumed to be the lightest neutralino $\tilde{\chi}_1^0$) have just about the right density indicated by cosmological observations [2]. It should be clear from the start that such arguments do not really touch the main motivation for postulating the existence of superparticles at the weak scale. After all, if we learned tomorrow that the Dark Matter in the Universe consists of axions, few people would conclude that weak–scale supersymmetry has been ruled out!

Let us nevertheless press on and explore the consequences of requiring $\tilde{\chi}_1^0$ to form the Dark Matter. One immediate requirement is that it must be stable. This excludes models with broken R parity (where $\tilde{\chi}_1^0$ decays into SM particles) as well as models with gauge mediated SUSY breaking (where $\tilde{\chi}_1^0$ decays into a gravitino and a photon, if it is the lightest visible sector superparticle).† In order to make quantitative statements, we have to assume in addition that the post–inflationary Universe was hot enough for $\tilde{\chi}_1^0$ to have been in chemical equilibrium with SM particles, i.e. that the rate for reactions that create or destroy superparticles was higher than the expansion rate. This typically requires the post–inflationary reheat temperature T_R to exceed $\sim 10\%$ of $m_{\tilde{\chi}_1^0}$. Note that we currently only know that $T_R \geq 1$ MeV, since otherwise nucleosynthesis could not have occurred [3]. Given that the inflaton mass is supposed to be around 10^{13} GeV, assuming $T_R \geq m_{\tilde{\chi}_1^0}/10$ is not unreasonable, but models can be constructed where this condition is not satisfied.‡

Given the assumption of chemical equilibrium, the present $\tilde{\chi}_1^0$ relic density can be computed quite reliably, if the sparticle and Higgs spectrum is known. Not surprisingly, one finds that the relic density is essentially proportional to the inverse of the cross section for $\tilde{\chi}_1^0$ annihilation into SM particles. In general $\tilde{\chi}_1^0$ is a linear superposition of the bino (the superpartner of the $U(1)_Y$ gauge boson), the neutral wino (the superpartner of the neutral $SU(2)$ gauge bosons), and the two neutral higgsinos. These interaction

†In other words, any SUSY model can be made "Dark Matter safe" by making $\tilde{\chi}_1^0$ unstable. This can be accomplished without modifying any collider signatures, e.g. by introducing a tiny amount of $R-$parity breaking, or by letting $\tilde{\chi}_1^0$ decay into a hidden–sector superparticle. Of course, one then has to find another explanation for the Dark Matter.

‡Indeed, most SUSY models need $T_R \ll 10^{13}$ GeV in order to avoid over–production of gravitinos.

eigenstates receive a priori unknown masses M_1, M_2 and μ, respectively, while mixing between these states is induced by off–diagonal mass terms $\mathcal{O}(M_Z)$. In most models with (approximate) gaugino mass unification and radiative gauge symmetry breaking, the LSP is bino–like. This follows from the large size of the top Yukawa coupling, which drives the squared mass of the Higgs boson that couples to top quarks to too negative a value, unless it receives a large positive contribution μ^2. Note also that RG running from the GUT to the weak scale reduces the bino mass by about a factor of 2.5. These effects together imply that usually $|M_1| < |M_2| \leq |\mu|$, leading to a bino–like LSP, independent of details of the scalar spectrum at the GUT scale [4]. In this case the LSP relic density can usually be estimated from $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \ell^+ \ell^-$ annihilation ($\ell = e, \mu, \tau$) through the exchange of $SU(2)$ singlet sleptons $\tilde{\ell}_R$ in the $t-$ or $u-$channel. The reason is that $\tilde{\ell}_R$ has the largest hypercharge of all sfermions; in most models it is also among the lightest of all sfermions. The scaled LSP relic density multiplied with the scaled Hubble constant can then be estimated as [5]

$$\Omega_{\tilde{\chi}_1^0} h^2 \simeq \frac{\left(m^2_{\tilde{\chi}_1^0} + m^2_{\tilde{\ell}_R} \right)^4}{10^6 \text{ GeV}^2 m^2_{\tilde{\chi}_1^0} \left(m^4_{\tilde{\ell}_R} + m^4_{\tilde{\chi}_1^0} \right)} \tag{1}$$

If eq.(1) is valid, it is easy to see that the cosmological constraint [2] $\Omega_{\tilde{\chi}_1^0} h^2 \leq 0.3$ requires $m_{\tilde{\chi}_1^0}, m_{\tilde{\ell}_R} \leq 200$ GeV. This argument is independent of details of the Higgs sector (unless $2 m_{\tilde{\chi}_1^0} \simeq m_{\rm Higgs}$; see below). It is encouraging that eq.(1) leads to sparticle masses in the few hundred GeV range, where one would expect them from naturalness arguments.[§] This is quite nontrivial, since the numerical constant appearing in this equation depends on quantities like the Planck mass and the temperature of the cosmic microwave background.

However, in general things are not so simple, which is why I used qualifiers like "in most models" and "usually" in the previous paragraph. Perfectly acceptable SUSY models exist where $\tilde{\chi}_1^0$ is *not* bino–like; in other cases, $\tilde{\chi}_1^0$ is bino–like, but eq.(1) overestimates the true thermal relic density by several orders of magnitude. The "bounds" $m_{\tilde{\chi}_1^0}, m_{\tilde{\ell}_R} \leq 200$ GeV therefore have several loopholes:

- Even in mSUGRA, i.e. if strict universality is imposed at the GUT scale $M_X = 2 \cdot 10^{16}$ GeV, $\tilde{\chi}_1^0$ can have a large or even dominant Higgsino component [6], if the scalar mass $m_0 \gg$ the gaugino mass $M_{1/2}$. Since higgsinos annihilate quite efficiently into W and Z pairs, the upper bound on $m_{\tilde{\chi}_1^0}$ then has to be raised to ~ 1.5 TeV [7]. Even worse, *no* upper bounds on gaugino or sfermion masses can be given in this case, as long as $m_0 \gg M_{1/2}$ holds.[¶] Gaugino mass unification implies that the gluino mass $m_{\tilde{g}} \geq 6 m_{\tilde{\chi}_1^0}$. This becomes a strong inequality in the Higgsino region, where $|M_1| > |\mu|$. A 1.5 TeV higgsino–like LSP thus implies a gluino mass of at least 10 TeV. Since $m_0 \gg M_{1/2}$, the squarks would be even heavier. If the soft

[§] A much lighter sparticle spectrum can also lead to a cosmologically interesting relic density, $\Omega_{\tilde{\chi}_1^0} h^2 \sim 0.1$, if $m_{\tilde{\chi}_1^0} \ll m_{\tilde{\ell}_R}$. Of course, such light spectra are nowadays excluded by LEP searches.

[¶] I should emphasize that there are also solutions with $m_0 \gg M_{1/2}$ where $m_{\tilde{\chi}_1^0}$ is in the (few) hundred GeV range and the relic density is acceptable, if both the higgsino and the gaugino components of $\tilde{\chi}_1^0$ are sizable. In fact, this region of parameter space is quite favorable from the point of view of Dark Matter searches [8]. Here the light chargino and lighter neutralinos should be accessible at future e^+e^- linear colliders, but sleptons would be out of reach. See ref.[9] for further discussion of these solutions.

breaking Higgs masses exceed squark masses at the GUT scale [10], or if the SUSY messenger scale is significantly below the GUT scale [11], the higgsino component of $\tilde{\chi}_1^0$ increases, i.e. a higgsino–like LSP becomes possible for smaller ratios of sfermion and gaugino masses (but the ratio of gluino and LSP masses remains unchanged).

- If the $SU(2)$ gaugino mass $M_2 <$ the $U(1)_Y$ gaugino mass M_1 at the weak scale, $\tilde{\chi}_1^0$ will be wino–like rather than bino–like. Winos annihilate even more efficiently into W and Z pairs than higgsinos do (since they are $SU(2)$ triplets, rather than doublets), so that LSP masses up to ~ 2 TeV become acceptable. Again, there is *no* bound on sfermion masses in this case. Such a scenario is e.g. realized in anomaly–mediated SUSY breaking. Anomaly mediation predicts $m_{\tilde{g}} \simeq 10 m_{\tilde{\chi}_1^0}$, so that gluino masses well above 10 TeV are again cosmologically acceptable.

- Even if $\tilde{\chi}_1^0$ is bino–like, eq.(1) might be wildly off the mark. $\tilde{\chi}_1^0$ pair annihilation is enhanced by several orders of magnitude if $2m_{\tilde{\chi}_1^0} \simeq m_A$, where m_A is the mass of the CP–odd Higgs boson of the MSSM [5]. In models with radiative gauge symmetry breaking, including mSUGRA, this can happen if the ratio of vevs tanβ is large. In this case $m_{\tilde{\chi}_1^0} \simeq 1$ TeV can be allowed, independent of the values of the sfermion masses. Even heavier LSPs can be cosmologically acceptable if $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{t}_1}$, since then $\tilde{\chi}_1^0 - \tilde{t}_1$ co–annihilation reduces the relic density by up to three orders of magnitude [12]; here $\tilde{t}_1$ is the lighter scalar top mass eigenstate. Finally, if $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\tau}_1}$, $\Omega_{\tilde{\chi}_1^0} h^2$ is reduced by up to one order of magnitude [13], i.e. the upper bounds on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\ell}_R}$ have to be increased by about a factor of 3. In this case a 1.5 TeV lepton collider, and the LHC, would still be guaranteed to see a SUSY signal [14]. Within mSUGRA this particular loophole might be the most "likely" one, since one doesn't need large ratios of soft breaking parameters (as in the $\tilde{\chi}_1^0 \simeq \tilde{h}$ loophole), nor does one need tan$\beta \gg 1$ (as in the $2m_{\tilde{\chi}_1^0} \simeq m_A$ loophole). However, the ratio $m_0/M_{1/2}$ has to be within $\sim 5\%$ of its lower bound, which is set by the requirement $m_{\tilde{\chi}_1^0} < m_{\tilde{\tau}_1}$.

In summary, neutralino Dark Matter seems to be most natural if $m_{\tilde{\chi}_1^0}, m_{\tilde{\ell}_R} \leq 200$ GeV. However, several loopholes exist that allow $m_{\tilde{\chi}_1^0} \geq 1$ TeV ($\tilde{\chi}_1^0 \simeq \tilde{h}, \tilde{\chi}_1^0 \simeq \widetilde{W}_3, 2m_{\tilde{\chi}_1^0} \simeq m_A, m_{\tilde{\chi}_1^0} \simeq m_{\tilde{t}_1}$), while $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\tau}_1}$ allows $m_{\tilde{\chi}_1^0}$ up to ~ 600 GeV. Assessing the probability that Nature chose one of these loopholes is very difficult and model–dependent. Deviating from the "canonical" mSUGRA framework can make things worse (e.g., $\tilde{\chi}_1^0 \simeq \widetilde{W}_3$ is almost automatic in models with anomaly mediated SUSY breaking) or better (e.g. in SUSY GUTs [15] or models with intermediate $SU(4) \times SU(2)_L \times SU(2)_R \times U(1)$ symmetry, where $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\tau}_1}$ becomes more difficult to realize). Of course, the fact that cosmologically acceptable models can be constructed where neither the LHC nor even a 5 TeV lepton collider would detect a SUSY signal doesn't mean that such models are "natural".

My personal conclusion is that *if* the lightest neutralino is stable, *and if* it was in chemical equilibrium in the post–inflationary Universe, the requirement $\Omega_{\tilde{\chi}_1^0} h^2 < 0.3$ excludes large regions of SUSY parameter space with $m_{\tilde{\chi}_1^0} > 200$ GeV or $m_{\tilde{\ell}_R} > 200$ GeV. However, given the assumptions needed to derive these "bounds", and the numerous loopholes that permit much heavier LSPs without "overclosing the Universe", this cosmological consideration should probably be viewed as another naturalness argument, independent from but by no means superior to the arguments based on analyses of electroweak gauge symmetry breaking.

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