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Constraints on minimal SUSY models with warm dark matter neutralinos

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Abstract

If the energy density of the Universe before nucleosynthesis is dominated by a scalar field ϕ that decays and reheats the plasma to a low reheating temperature T_{RH}, neutralinos may be warm dark matter particles. We study this possibility and derive the conditions on the production mechanism and on the supersymmetric spectrum for which it is viable. Large values of the μ parameter and of the slepton masses are characteristic features of these models. We compute the expected direct detection cross sections and point out that split-SUSY provides a natural framework for neutralino warm dark matter.
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Thermally produced neutralinos are typical and well-motivated cold dark matter candidates (see e.g. [1]). They are produced by scatterings in the thermal bath, then reach equilibrium and finally decouple when non-relativistic. Non-thermally produced neutralinos, on the contrary, are usually produced as relativistic final states in the decay of heavy particles and may never reach chemical or kinetic equilibrium. As a result, they are not necessarily cold. Indeed, if they manage to keep most of their initial energy they might behave as warm dark matter suppressing the evolution of small-scale structures in the Universe.

Although consistent with the observations of the large scale structure of the Universe and the cosmic microwave background radiation anisotropies, cold dark matter models seem to have problems at galactic scales. They not only tend to form cuspy structures in the halo density profile [2] but also predict a large overabundance of small halos near galaxies such as our own [3]. Warm dark matter, with its larger free-streaming scale, may solve these problems while maintaining the celebrated success of cold dark matter models at large scales [4].

Neutralinos as warm dark matter candidates were initially discussed in Refs. [5,6]. In this Letter we will extend, in several ways, the analysis presented in those references. Ref. [5] concentrated on the cosmological aspects of this possibility, while we study a particular particle model. Reheating temperatures smaller than 5 MeV or 2 MeV as those found in Ref. [6] are hardly compatible with the standard cosmological scenario, which require $T_{\mathrm{RH}} > 4$ MeV [7]. We, instead take $T_{\mathrm{RH}} \simeq 10$ MeV as a characteristic value and find the conditions on the initial energy and on the supersymmetric spectrum for which the neutralino is a warm dark matter particle. In doing so, we ignore, following Ref. [8], the naturalness argument giving up the idea that SUSY stabilizes the weak scale, notion that is the basis for split-SUSY models. We also discuss the non-thermal production of neutralinos, as well as the implications for direct dark matter searches of neutralino warm dark matter.

We concentrate on non-standard cosmological models (see for example Refs. [9–11]) in which the late decay of a scalar field ϕ reheats the Universe to a low reheating temperature T_{RH}, smaller than the standard neutralino freeze out temperature. Such scalar fields are common in superstring models where they appear as moduli fields. These fields get mass at the low energy supersymmetry breaking scale, typically of the order of 10^2–10^3 TeV. The decay of ϕ into radiation increases the entropy, diluting the neutralino number density. The decay of ϕ into supersymmetric particles, which eventually decay into neutralinos, increases the neutralino number density. We denote

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by b the net number of neutralinos produced on average per ϕ decay. The number b is highly model-dependent, so is the ϕ field mass m_ϕ. They are determined by the physics of the hidden sector, by the mechanism of supersymmetry breaking, and in superstring-inspired models by the compactification mechanism [9–16].

The coupling of the ϕ to the gravitino arises from the term $e^{K/2}\bar{\psi}_\mu\sigma^{\mu\nu}\psi_\nu$, where K is the Kähler potential. Under the assumption of $m_\phi \gg m_{3/2}$ the ϕ decay through mixing with the field responsible for supersymmetry breaking was found to be important [12], unless a symmetry of ϕ is preserved at the vacuum. If m_ϕ is larger than twice the gravitino mass $m_{3/2}$, the decay mode $\phi \to \psi_{3/2}\psi_{3/2}$ of the moduli field into two gravitinos is present with branching ratio of order 0.01 (see Ref. [13], which correct previous claims [14] that this branching would be chirally suppressed by a factor $(m_{3/2}/m_\phi)^2$). Even if this decay is kinematically forbidden, the decay of ϕ into its supersymmetric partner and a gravitino may happen as long as $m_\phi > m_{3/2}$ [15]. Gravitinos must then decay rapidly not to disrupt nucleosynthesis (so $m_{3/2} \gtrsim 100$ TeV), and they produce comparable amounts of normal particles and their supersymmetric partners. If $m_\phi \gg m_{3/2}$, the gravitino decays during the radiation dominated epoch after the decay of the ϕ field (here we do not address this case and we focus on neutralino production during ϕ domination). When m_ϕ and $m_{3/2}$ are of the same order of magnitude, we can consider the gravitino decay as part of the ϕ decay, since they happen almost simultaneously. In this case, depending on how important the direct decay of ϕ into supersymmetric particles other than the $\psi_{3/2}$ is, b can typically be 0.01–1, but not smaller.

If instead $m_\phi < m_{3/2}$ more possibilities open up. The yield per ϕ decay b can still be of order one but it can also be much smaller. Supergravity models with chiral superfields Φ_I are specified in terms of the Kähler potential $K(\Phi_I, \bar{\Phi}_I)$, the superpotential $W(\Phi_I)$, and the gauge kinetic function $f_{\alpha\beta}(\Phi_I)$. Specific relations between the ϕ mass m_ϕ, the gravitino mass $m_{3/2}$, and the gaugino mass $m_{1/2}$ arise as a consequence of the relations $m_{3/2} = \langle e^{K/2}W\rangle$, $m_{1/2} = \langle F^J\partial_J \ln\Re f\rangle$, and $m_\phi = \langle\partial^2 V/\partial\phi^2\rangle$. With appropriate choices of K, W, and f, the hierarchy $m_{3/2} \gtrsim m_\phi \gg m_{1/2}$ may be achieved. Here V is the scalar potential and F^I is the F-term of the chiral superfield Φ_I.

One finds that $b \simeq O(1)$, for example, when the main ϕ decay mode is through a coupling of the type $h\phi\psi^2$ with a chiral matter supermultiplet ψ in the superpotential W. This leads to comparable decay rates of ϕ into the scalar and fermionic components of ψ (which are supersymmetric partners). On the other hand, it is possible that the ϕ field decays mostly into Higgs fields, or gauge fields (W's, Z's, photons, gluinos). In this case b can be very small 10^{-2}, 10^{-4}, 10^{-6}, etc. [10,11]. For example, the coupling of ϕ to the gauge bosons arises from the term $\Re f_{\alpha\beta}F^\alpha_{\mu\nu}F^{\mu\nu\beta}$ and with non-minimal kinetic terms $f_{\alpha\beta}$ may contain ϕ. The ϕ decay width into gauge bosons is then $\Gamma_g \sim \lambda_g m_\phi^3/M_P^2$ with $\lambda_g = \frac{\partial}{\partial\phi}\ln\Re f$, while that into gauginos is $\Gamma_{\tilde{g}} \sim \lambda_{\tilde{g}}^2 m_\phi/M_P^2$ with $\lambda_{\tilde{g}} = m_{1/2}\frac{\partial}{\partial\phi}\ln(F^\phi\frac{\partial}{\partial\phi}\Re f)$. Thus in principle the gaugino coupling may be suppressed relative to the coupling to gauge bosons.

Here we consider b and m_ϕ as free parameters.

To account for the dark matter of the Universe, the neutralino relic density must be in agreement with the observed dark matter density. In low $T_{\rm RH}$ cosmological models essentially all neutralinos can have the dark matter density provided the right combination of the following two parameters can be achieved in the high energy theory: the reheating temperature $T_{\rm RH}$, and the ratio of the number of neutralinos produced per ϕ decay over the ϕ field mass, i.e. b/m_ϕ [16,17]. We will find later the values of $T_{\rm RH}$ and b/m_ϕ for which the neutralinos we are interested in have the right dark matter density.

A crucial quantity that distinguishes warm from cold dark matter is the free-streaming length at matter-radiation equality $\lambda_{\rm FS}$, which depends on the parameter $r_\chi = a(t)p_\chi(t)/m_\chi$ (see for example Refs. [5,6] and references therein). This parameter would be the present characteristic speed of neutralinos of mass m_χ, if their momentum p_χ only redshifted from neutralino production onwards ($a(t)$ is the scale factor with $a_0 = 1$). During the cosmic evolution r_χ is constant. Structures smaller than $\lambda_{\rm FS}$ are damped because neutralinos can freely flow out of them. N-body simulations have shown that to explain the lack of substructure in the local group, $\lambda_{\rm FS}$ should be of order 0.1 Mpc [4], thus $r_\chi \simeq 10^{-7}$.

The parameter r_χ also determines (for neutralinos which are relativistic at production [18]) the neutralino phase-space density Q. This is defined as $Q = \rho/\langle v^2\rangle^{3/2}$ where ρ is the neutralino energy density and $\langle v^2\rangle$ is the mean square value of the particle velocity. In the absence of dissipation, the coarse-grained phase-space density (the quantity that can actually be observed) can only decrease from its primordial value. The observation of dwarf-spheroidal galaxies places a lower bound on Q which translates into an upper bound on r_χ of about 2.5×10^{-7} [5]. In what follows we impose the condition $r_\chi = 10^{-7}$ to our model.

Neutralinos are produced in ϕ decays, thus their average initial energy is $E_I = m_\phi/N$, where N is a number which depends on the production spectrum. We expect N to be of order one and require $E_I \gg m_\phi$ so that neutralinos are relativistic at production. Thus, $p_\chi \simeq E_I$ at the moment of ϕ decay. Assuming an instantaneous ϕ decay at $T_{\rm RH}$, with no subsequent entropy production, the scale factor at decay is $a = T_0/T_{\rm RH}$, where T_0 is the present photon temperature, and the parameter r_χ in our model is $r_\chi = (T_0E_I)/(T_{\rm RH}m_\chi)$, i.e.

$$r_\chi \simeq 10^{-7}\left(\frac{2.3}{N}\right)\left(\frac{m_\phi}{10^3\ \text{TeV}}\right)\left(\frac{10\ \text{MeV}}{T_{\rm RH}}\right)\left(\frac{100\ \text{GeV}}{m_\chi}\right). \quad (1)$$

Thus, the condition $r_\chi = 10^{-7}$ fixes m_ϕ in terms of the reheating temperature and the neutralino mass

$$m_\phi = 10^3\ \text{TeV}\left(\frac{N}{2.3}\right)\left(\frac{m_\chi}{100\ \text{GeV}}\right)\left(\frac{T_{\rm RH}}{10\ \text{MeV}}\right). \quad (2)$$

In the estimation of r_χ we have assumed that the neutralinos do not lose their energy in scattering processes with the thermal bath. To ensure this condition we will simply require that the interactions of neutralinos with the particles present in the plasma, $e^\pm$, ν and γ, are out of equilibrium. Neutralino interactions are determined by the neutralino composition in terms of

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