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SUSY constraints from relic density: High sensitivity to pre-BBN expansion rate

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ABSTRACT

The sensitivity of the lightest supersymmetric particle relic density calculation to the variation of the cosmological expansion rate before nucleosynthesis is discussed. Such a modification of the expansion rate, even extremely modest and with no consequence on the cosmological observations, can greatly enhance the calculated relic density, and therefore change the constraints on the SUSY parameter space drastically. We illustrate this variation in two examples of SUSY models, and show that it is unsafe to use the lower bound of the WMAP limits in order to constrain supersymmetry. We therefore suggest to use only the upper value $\Omega_{\mathrm{DM}} h^2 < 0.135$.

During the past decade, supersymmetry (SUSY), as one of the most promising candidates for new physics beyond the Standard Model, has been the focus of intensive phenomenological studies. Huge efforts have been carried out in order to constrain the supersymmetric parameter space. Among the most powerful observables for this purpose, in addition to the direct searches at LEP and Tevatron, stand the WMAP limits on the relic density and B physics constraints.

In this Letter, we present a new analysis of the relic density constraints on the Minimal Supersymmetric extension of the Standard Model (MSSM), and we focus in particular on bounds on two gravity mediated supersymmetry breaking scenarios, namely minimal Supergravity (mSUGRA) and the Non-Universal Higgs Mass framework (NUHM) in which the boundary conditions at high scales reduce the number of free parameters of the MSSM, allowing feasible phenomenological studies.

The recent observations of the WMAP satellite [1], combined with other cosmological data, give evidence for the presence of a cosmological matter-like density representing about 27% of the total density of the Universe. The remaining 73% reveal the presence of the so-called dark energy. From the total matter density observed by WMAP [1] and the baryon density indicated by Big-Bang nucleosynthesis (BBN) [2], including theoretical uncertainties, the dark matter density range at 95% C.L. can be deduced:

$$0.094 < \Omega_{\mathrm{DM}} h^2 < 0.135, \tag{1}$$

where h is the reduced Hubble constant. In the following, we also refer to the older range which admits a larger interval [3]:

$$0.1 < \Omega_{\mathrm{DM}} h^2 < 0.3. \tag{2}$$

The lightest supersymmetric particle (LSP), provided it is stable and electrically neutral, constitutes a possible candidate for non-baryonic dark matter. The stability requirement is fulfilled when R-parity is conserved, and scenarios such as mSUGRA or NUHM provide us with a LSP satisfying the WMAP relic density constraints [4].

The great accuracy of the WMAP data can therefore be used to constraint the supersymmetric parameters, provided the relic density is calculated precisely. The computation of the relic density has been realized within the standard model of cosmology [5], and implemented in automatic codes, such as MicrOMEGAs [6] and DarkSUSY [7].

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However, in the standard model of cosmology, the nature of the dark energy and the evolution of the Universe in the pre-BBN era remain unclear. The BBN era is the oldest period in the cosmological evolution when reliable constraints are derived, for temperatures of about 1 MeV. Successful BBN models predict that radiation was the dominant energy at that time, but no claim is made for much higher temperatures. In fact, in models like quintessence [8], k-essence [9] or dark fluid [10], dark energy could play a role before BBN, since its density could be much higher at such temperatures. In particular, the influence of quintessence on the relic density has been thoroughly analyzed in the literature, and previous studies have revealed that it can greatly enhance the relic density [11–17]. Also, some extra-dimension theories predict negative effective energies in the Early Universe, which can modify the relic density [18,19].

Therefore, the standard model of cosmology could be more complex than what we think in the primordial Universe, and the pre-BBN era could have experienced a slower or faster expansion. Such a modified expansion, even though still compatible with the BBN or the WMAP results, changes the LSP freeze-out time and the amount of relic density.

To model the effects of such a modified expansion in the pre-BBN era, we add to the radiation density a new dark density, varying with temperature as

$$\rho_D(T) = \rho_D(T_0)\left(\frac{T}{T_0}\right)^{n_D}, \tag{3}$$

where we choose $T_0 = 1$ MeV and n_D is a constant parametrizing the density behavior. Such a density evolution characterizes a fluid in adiabatic expansion with a constant equation of state $w_D = P_D/\rho_D$, where P_D is the pressure of the fluid: for $n_D = 3$ ($w_D = 0$) the dark density evolves as a matter density; for $n_D = 4$ ($w_D = 1/3$) as a radiation density; and for $n_D = 6$ ($w_D = 1$) as the density of a real scalar field (e.g., a quintessence field) with a dominating kinetic term [8]. $n_D > 6$ can arise for example in extra-dimension models. We extend here the previous analyses of the influence of quintessence on the relic density to a more general case with $n_D \geqslant 4$.

We introduce the parameter

$$\kappa_D \equiv \frac{\rho_D(T_0)}{\rho_{\rm rad}(T_0)}, \tag{4}$$

where $\rho_{\rm rad}$ is the radiation density, evolving as

$$\rho_{\rm rad}(T) = g_{\rm eff}(T)\frac{\pi^2}{30}T^4. \tag{5}$$

$g_{\rm eff}$ is the effective number of degrees of freedom of the radiation. κ_D parametrizes the temperature at which the dark density dominates the expansion, i.e. $\rho_D(T) > \rho_{\rm rad}(T)$; the larger κ_D is, the earlier the dark density dominates. In particular, if $\kappa_D = 1$, the radiation and the dark component will be co-dominant at BBN time. Thus, imposing the radiation density to remain dominant at BBN time and later leads to

$$n_D \geqslant 4 \quad \text{and} \quad |\kappa_D| < 1. \tag{6}$$

For a usual scalar field $0 \leqslant n_D \leqslant 6$, but with a modified kinetic term n_D can reach higher values. We restrict here, however, to $n_D \lesssim 8$. Furthermore, if $\kappa_D < 0$, the extra requirement $\rho_D + \rho_{\rm rad} > 0$ should be satisfied at any time, which limits negative effective densities to $n_D \approx 4$ or to very low $|\kappa_D|$.

The Friedmann equation at BBN time and before reads

$$H^2 = \frac{8\pi G}{3}(\rho_{\rm rad} + \rho_D), \tag{7}$$

and the dynamics of the expansion is therefore modified, leading to a higher expansion rate if $\rho_D > 0$, or a lower one if $\rho_D < 0$. Here ρ_D does not necessarily have to correspond to the density of a real component, but can be only an effective term to parametrize the modification of the expansion rate.

Under the standard hypotheses, i.e. in absence of entropy production and of nonthermal generation of relic particles, the computation of the relic density is based on the solution of the evolution equation [5]

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\rm eff} v\rangle\left(n^2 - n_{\rm eq}^2\right), \tag{8}$$

where n is the number density of all supersymmetric particles, $n_{\rm eq}$ their equilibrium density, and $\langle\sigma_{\rm eff} v\rangle$ is the thermal average of the annihilation rate of the supersymmetric particles to Standard Model particles. By solving this equation, the density number of supersymmetric particles in the present Universe and consequently the relic density can be determined.

We consider the ratio of the number density to the radiation entropy density,

$$Y(T) = \frac{n(T)}{s(T)}, \tag{9}$$

with

$$s(T) = h_{\rm eff}(T)\frac{2\pi^2}{45}T^3. \tag{10}$$

$h_{\rm eff}$ is the effective number of entropic degrees of freedom of radiation. Combining Eqs. (7) and (8) and defining $x = m_{\rm LSP}/T$, the ratio of the LSP mass over temperature, yield

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2} m_{\rm LSP}}{x^2}\left(1 + \frac{\rho_D(T)}{g_{\rm eff}(T)\frac{\pi^2}{30}T^4}\right)^{-1/2} \times \langle\sigma_{\rm eff} v\rangle\left(Y^2 - Y_{\rm eq}^2\right), \tag{11}$$

with

$$g_*^{1/2} = \frac{h_{\rm eff}}{\sqrt{g_{\rm eff}}}\left(1 + \frac{T}{3h_{\rm eff}}\frac{dh_{\rm eff}}{dT}\right). \tag{12}$$

Note that in the limit where $\rho_D \to 0$, we retrieve the results of Ref. [5].

The freeze-out temperature T_f is the temperature at which the LSP leaves the initial thermal equilibrium, i.e. $T = T_f$ when $Y(T_f) = (1+\delta)Y_{\rm eq}(T_f)$, with $\delta \simeq 1.5$. The relic density is obtained by integrating Eq. (11) from $x = 0$ to $m_{\rm LSP}/T_0$, where $T_0 = 2.726$ K is the temperature of the Universe today [5]:

$$\Omega_{\rm LSP}h^2 = 2.755 \times 10^8 \frac{m_{\rm LSP}}{1\ \rm GeV}Y(T_0). \tag{13}$$

To compute numerically the relic density, we use a modified version of MicrOMEGAs 2.0.7 [6] which includes the alteration of the expansion rate in the primordial Universe, as in Eq. (7). The SUSY mass spectrum and couplings are computed with SOFTSUSY 2.0.14 [20], and the $b \to s\gamma$ branching ratio and isospin asymmetry are calculated with SuperIso 2.0 [21], using the limits of [22].

Let us consider first the mSUGRA parameter point ($m_0 = 600$ GeV, $m_{1/2} = 730$ GeV, $A_0 = -m_0$, $\tan\beta = 50$, $\mu > 0$), which is favored by WMAP, as an example. The standard calculation of the relic density for this point leads to $m_{\rm LSP} = 308$ GeV, $\Omega_{\rm LSP}h^2 = 0.105$, and a freeze-out temperature of $T_f = 11$ GeV. In Fig. 1, the dependence of the relic density and of the freeze-out temperature on n_D and κ_D is shown. The oblique black and red lines correspond, respectively, to the present upper limit of the WMAP constraint $\Omega_{\rm LSP}h^2 = 0.135$, and to the older limit $\Omega_{\rm LSP}h^2 = 0.3$. κ_D is varied in the interval $[10^{-10}, 1]$, and n_D in [4, 8.2].

First we note that the relic density can be increased by up to a factor 10^6 and the freeze-out temperature up to 50 GeV. This strong dependence of the relic density and freeze-out temperature