PHYSICAL REVIEW D **83,** 103523 (2011)

Dilaton dominance in the early universe dilutes dark matter relic abundances

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(Received 17 March 2011; published 23 May 2011)

The role of the dilaton field and its coupling to matter may result in a dilution of dark matter (DM) relic densities. This is to be contrasted with quintessence scenarios in which relic densities are augmented, due to modification of the expansion rate, since the Universe is not radiation dominated at DM decoupling. The dilaton field, besides this, affects relic densities through its coupling to dust which tends to decrease relic abundances. Thus two separate mechanisms compete with each other resulting, in general, in a decrease of the relic density. This feature may be welcomed and can help the situation if direct dark matter experiments point towards small neutralino-nucleon cross sections, implying small neutralino annihilation rates and hence large relic densities, at least in the popular supersymmetric scenarios. In the presence of a diluting mechanism, both experimental constraints can be met. The role of the dilaton for this mechanism has been studied in the context of the noncritical string theory but in this work we follow a rather general approach assuming that the dilaton dominates only at early eras long before big bang nucleosynthesis.

DOI: 10.1103/PhysRevD.83.103523 PACS numbers: 98.80.−k, 95.35.+d, 98.80.Cq

I. INTRODUCTION

The nature and origin of the dark matter (DM) of our Universe is one of the big mysteries of modern cosmology, whose resolution is still pending. Analyzing the data cumulated from various observations over the past 12 years it is found that 96% of the Universe energy budget today consists of unknown entities, 23% of which is dark matter and 73% dark energy (DE), or vacuum energy, which is responsible for the current acceleration of the Universe. These data include observations of the Universe acceleration, using type-Ia supernovae [1], measurements of cosmic microwave background [2,3] anisotropies, baryon oscillation [4], and weak lensing data [5]. The aforementioned results follow from best-fit analyses of various astrophysical data to the standard cosmological model (ΛCDM) which can successfully describe the evolution of our Universe. The model is based on a Friedmann–Robertson–Walker (FRW) cosmology, involving cold DM, at a 23%, baryonic matter at 4%, and a positive cosmological constant $\Lambda > 0$ that is put in an *ad hoc* manner in an attempt to describe the vacuum energy density.

Supersymmetry provides one of the leading DM candidates, the neutralino which is still lacking experimental verification. Its thermal abundance, calculated in the context of the simplest supersymmetry models (minimal supersymmetric model embedded in minimal supergravity [6]), is severely restricted by cosmic microwave background data. In the near future, by incorporating data from collider experiments, such as the LHC [7], these models may be possibly ruled out. However, the existence of scalar fields in the primordial Universe, which contribute to the energy density, may play a dramatic role and upset the whole scenery. The quintessence [8] has been invoked in an attempt to explain the vacuum energy, in the sense that the energy it carries today is the vacuum energy measured in astrophysical observations. Its existence affects the relic abundances if the Universe is not radiation dominated during DM decoupling. In fact, DM relic density is predicted to be enhanced [9], and in some cases this enhancements reaches $\sim 10^6$ or so [10]; for a review, see for instance [11]. In general, modifications of the expansion rate and departures from the standard cosmological scenarios may have dramatic consequences for the DM relic density [12,13] and the observed amount of DM puts constraints on possible modifications of the Universe expansion at early eras [14]. A particular class is the tracking quintessence scenario in which the quintessence field is in a kination-dominated phase at early eras [15]. In this context the predictions for the gravitino and axino DM are considered in [16] while in [17] the predictions for the neutralino DM relic, in the popular supersymmetric schemes, is discussed in the light of the constraints arising from the observed $e^{\pm}$ spectrum by PAMELA [18] and Fermi-LAT observations [19].

In some string-inspired scenarios, with time-dependent dilaton-ϕ sources [20], whose evolution is dictated by nonequilibrium string dynamics [21], the amount of thermal neutralino relic abundance is diluted by a factor of $\mathcal{O}(10)$, relative to that calculated within the ΛCDM minimal supergravity cosmology, and such models are found to survive the stringent tests of LHC [22]. The dilution is due to the appearance of a frictionlike term on the right-hand side of the appropriate Boltzmann equation. This term also plays a significant role in other considerations studied in [23].

In this paper we argue that the mechanism for the dilution of DM relic abundances is more general and can hold in other instances too, having its basis on more

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general features of the dilaton dynamics prevailing in early eras, independently of the noncriticality of the underlying string theory. In order to model the dilaton behavior, we assume the existence of exponential-type potentials occurring in a wide class of quintessence scenarios or supergravity models or arising in string theories from quantum corrections. The presence of such a dilaton field, which dominates over radiation long before nucleosynthesis, affects the predictions for relic abundances in a dramatic way. In fact the conventional calculations get smaller by factors as small as $\mathcal{O}(10^{-2})$, in some cases, allowing, therefore, for smaller annihilation cross sections in the popular supersymmetric schemes employed in literature. This may alter the potential of discovering supersymmertry at collider experiments since the parameter space allowed by the cosmological data moves to regions that would be otherwise forbidden. As far as other ways of discovering DM are concerned (for reviews, see [24]), the small cross sections required to explain the cosmological data may affect the predictions for direct [25] and indirect [18,19,26] DM searches (for a review, see [27]).

II. SETTING UP THE MODEL

Omitting radiation and matter contributions, the equations of motion for a time-dependent dilaton are

$$\begin{aligned} &\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0, \\ &3H^2 = \frac{\dot{\phi}^2}{2} + V(\phi), \\ &2\dot{H} = -(\varrho_\phi + p_\phi) = -\dot{\phi}^2. \end{aligned} \tag{1}$$

In these equations, the field ϕ is dimensionless and the potential carries dimension mass^2. The first of these equations is not independent but is derived from the other two. In order to model the dependence of the dilaton as a function of $\ln a$, where $a(t)$ is the cosmic scale factor, we assume a linear in $\ln a$ form during early eras, which can follow from exponential-type potentials $V \sim e^{-k\phi}$. Such potentials are inspired by quintessence scenarios and they can also occur in string theories as perturbative or nonperturbative corrections. The dilaton is then given by

$$\phi = c \ln\left(\frac{a}{a_I}\right) + \phi_I, \tag{2}$$

where c is a constant and $a_I \equiv a(t_I)$ is the cosmic scale factor at the maximal reheating temperature reached after inflation, denoted by T_I, which occurred at the time t_I. This holds in epochs $t < t_X$ in which the dilaton dominates over radiation and matter, during DM decoupling which occurred earlier than big bang nucleosynthesis (BBN). We know that BBN took place when $\ln(a_{\rm BBN}/a_0) \simeq -22.5$, corresponding to $T_{\rm BBN} \simeq 1$ MeV, and DM decoupling occurred at a temperature between $T_{\rm DM} \simeq 5$–20 GeV, as dictated by interpreting DM to have supersymmetric nature, corresponding to a value of $\ln(a_{\rm DM}/a_0)$ between $\simeq -31.5$ and $\simeq -33.0$. At times t_X radiation also starts contributing to the energy-matter density and at BBN must overwhelm the dilaton's energy. Therefore, a reasonable region for which (2) holds is set by $a \le a_X$ with $\ln(a_X/a_0) \simeq -25$ or smaller.

Beyond t_X the dilaton is assumed to receive an almost constant value. The constancy of ϕ when hadrons are nonrelativistic is rather mandatory if we do not want the diluting mechanism to affect the abundances of the known hadrons and especially nucleons. This pushes the bound on a_X, defined earlier, to even lower values. In fact, the couplings of a dilaton to matter density is through the appearance of dissipative terms $\sim(\varrho_m - 3p_m)\dot{\phi}$, which modifies the continuity equation for matter, and such terms are vanishing when hadrons are relativistic, that is at temperatures higher than about $T_h \sim 1$ GeV, corresponding to $\ln(a_h/a_0) \sim -30$. Below T_h, however, hadrons are nonrelativistic and the dilaton couples to hadrons as $\sim\varrho_m\dot{\phi}$. Therefore, in this temperature regime the dilaton has to be almost constant in order to suppress its coupling to hadronic matter. A reasonable value is $T_h = \Lambda_{\rm QCD}$, with $\Lambda_{\rm QCD} \simeq 260$ MeV the characteristic QCD scale, which pushes the bound set on a_X to $\ln(a_X/a_0) \simeq -28.4$; although larger values for T_h, corresponding to smaller values of $\ln(a_X/a_0)$ are not excluded. Such values for T_h are within the range that the coupling of the dilaton to supersymmetric matter is nonvanishing, and this may have dramatic effects for the DM relic abundances as we shall see.[1]

For $t < t_X$ the time derivative of ϕ is related to the expansion rate by $\dot{\phi} = cH$, and when this is plugged into the third of Eqs. (1) it can be solved for the expansion rate H yielding

$$H^{-1} = H_I^{-1} + \frac{c^2}{2}(t - t_I). \tag{3}$$

In this and the following equations, the subscript I denotes quantities evaluated at t_I. For the expansion rate solving $H = \dot{a}/a$, and using (3), we get

$$a = a_I\left(\frac{c^2 H_I}{2}(t - t_I) + 1\right)^{2/c^2}, \tag{4}$$

and therefore the time dependence of the dilaton in this era is

$$\phi = \frac{2}{c}\ln\left(\frac{c^2 H_I}{2}(t - t_I) + 1\right) + \phi_I. \tag{5}$$

[1] We are aware of the fact that a constant dilaton in this range cannot account for a change $\Delta\alpha/\alpha \sim 10^{-5}$ over cosmological time scales of the fine structure constant. Interpreting the constancy of the dilaton as small quantum fluctuations $\Delta\phi \ll 1$ puts a lower limit on the couplings of the dilaton to matter approaching the capability of Eötvos-like experiments.

Knowing the dilaton and the Hubble rate from the second of Eqs. (1), the form of the potential can be derived:

$$V(\phi) = \left(\frac{6-c^2}{2}\right) H_I^2 e^{-c(\phi-\phi_I)}. \tag{6}$$

This holds in the region where the dilaton depends linearly on $\ln a$, as in shown in Eq. (2), that is for values of the cosmic scale factor $a < a_X$. If the maximum reheating temperature attained is $T_I = 10^9$ GeV, then the value of the cosmic scale factor at t_I is $\ln(a_I/a_0) \simeq -50.86$ where $a_0 = a(t_{\rm today})$ denotes its value today.[2] Therefore, the region of applicability of Eq. (2) is for values of a satisfying $\ln(a/a_I) \leq B$, where B is set by $B = \ln(a_X/a_0) + 50.86$, that is a number ~ 20 or so depending on the value of a_X. At the end point a_X, for which $\ln(a_X/a_I) = B$, the potential is exponentially suppressed,

$$V \sim \exp[-c(\phi_X - \phi_I)] \sim \exp(-Bc^2), \tag{7}$$

independently of the sign of the constant c, provided the value of $|c|$ is not exceedingly small. Since we have in mind a positive potential which drops as the Universe expands, the constant c should be bounded by $c^2 \leq 6$ as is evident from (6). As we shall see shortly, dominance of the dilaton energy over radiation is achieved for $c^2 > 4$, and therefore the value of the potential at a_X, given by Eq. (7), is very much suppressed before nucleosynthesis, that is for times earlier than $t_{\rm BBN}$ corresponding to $\ln(a_{\rm BBN}/a_0) \simeq -22.5$.

The ratio of the kinetic to the potential energy of the dilaton field in the regime $t < t_X$ is constant. This follows from the second of Eqs. (1) and the fact that $\dot\phi = cH$, due to Eq. (2). In fact,

$$V(\phi) \Big/ \left(\frac{\dot\phi^2}{2}\right) = \frac{6}{c^2} - 1. \tag{8}$$

This yields a ratio of dilaton to radiation energy density given by

$$\frac{\hat\rho_\phi}{\hat\rho_r} = \frac{m_P^2}{\hat\rho_r^0} \frac{1}{1-c^2/6} \left(\frac{a}{a_0}\right)^4 V(\phi). \tag{9}$$

In this we have reinstated dimensions, and hatted densities carry dimension energy^4. The zero subscripts denote the corresponding quantities today. Equation (9) can be also cast in the form

$$\frac{\hat\rho_\phi}{\hat\rho_r} = \frac{3H_0^2 m_P^2}{\hat\rho_r^0} \left(\frac{H_I^2}{H_0^2}\right) \left(\frac{a_I}{a_0}\right)^4 \left(\frac{a}{a_I}\right)^{4-c^2} \tag{10}$$

if one expresses the potential (6) in terms of the cosmic scale factor a. Since $a > a_I$, this ratio decreases for values of $4 < c^2$.

The behavior of the dilaton and the potential as functions of $\ln(a/a_0)$ are shown in Fig. 1 for particular values of the slope c, in the range $4 < c^2 < 6$, and $\ln(a_X/a_0) = -28.4$. Without loss of generality, the value ϕ_X of the dilaton at the end of the dilaton-dominance period has been taken as vanishing. Actually, physics results depend on the difference $\phi - \phi_I$ so a nonvanishing value for ϕ_X corresponds to a different initial condition ϕ_I for the dilaton field. The ratio of the potential energy, at the end of the dilaton-dominated era, to the same energy at reheating temperature drops by at least 40 orders of magnitude.

Because dilaton energy dominates over radiation energy in this regime, the value of the Hubble rate at reheating temperature is constrained by Eq. (10). In order to quantify this, suppose the dilaton to radiation energy density, at a given reheating temperature T_I, is

$$\left(\frac{\hat\rho_\phi}{\hat\rho_r}\right)\Bigg|_I = 10^p. \tag{11}$$

Then Eq. (10) yields

$$H_I/H_0 = \left(\frac{0.703}{h_0}\right) \times 10^{42+p/2} \tag{12}$$

if $T_I = 10^9$ GeV. If inflation is responsible for the generation of the power spectrum of the curvature scalar P_s and tensor P_T perturbations, then an upper bound on the inflationary potential, and hence on the corresponding Hubble rate at the end of inflation H_I, can be derived [28]. Assuming that tensor perturbations are small in comparison with the scalar ones, the bound imposed on H_I is $H_I \leq \frac{\pi}{\sqrt{2}} m_P P_s^{1/2}$ which in turn yields $H_I \leq 2.65 \times 10^{14}$ GeV. This results in the following upper bound for the ratio H_I/H_0:

$$H_I/H_0 < \frac{1.24}{h_0} \times 10^{56}.$$

Then on account of (12) an upper bound on p is derived,

$$p < 28.5. \tag{13}$$

This merely indicates that the ratio of the dilaton to radiation energy density (11) can be indeed large for reasonable values of the initial conditions set at T_I, consistent with the bounds put on H_I.

From Eq. (10), the ratio $\hat\rho_\phi/\hat\rho_r$ can be expressed in terms of its value at T_I through

$$\frac{\hat\rho_\phi}{\hat\rho_r} = \left(\frac{\hat\rho_\phi}{\hat\rho_r}\right)\Bigg|_I \left(\frac{a}{a_I}\right)^{4-c^2}, \tag{14}$$

and if this ratio at T_I is as given in Eq. (11), the corresponding ratio at the end of the dilaton-dominance period is

[2]We have in mind the minimal supersymmetric standard model (MSSM) whose sparticle mass spectrum is in the TeV range. Under these circumstances, at the temperature T_I supersymmetric as well as standard model particles are all relativistic and the effective number of degrees of freedom is $g_{\rm eff} = 228.75$, independent of the precise sparticle mass spectrum. This results in the value $\ln(a_I/a_0) \simeq -50.86$ quoted above.

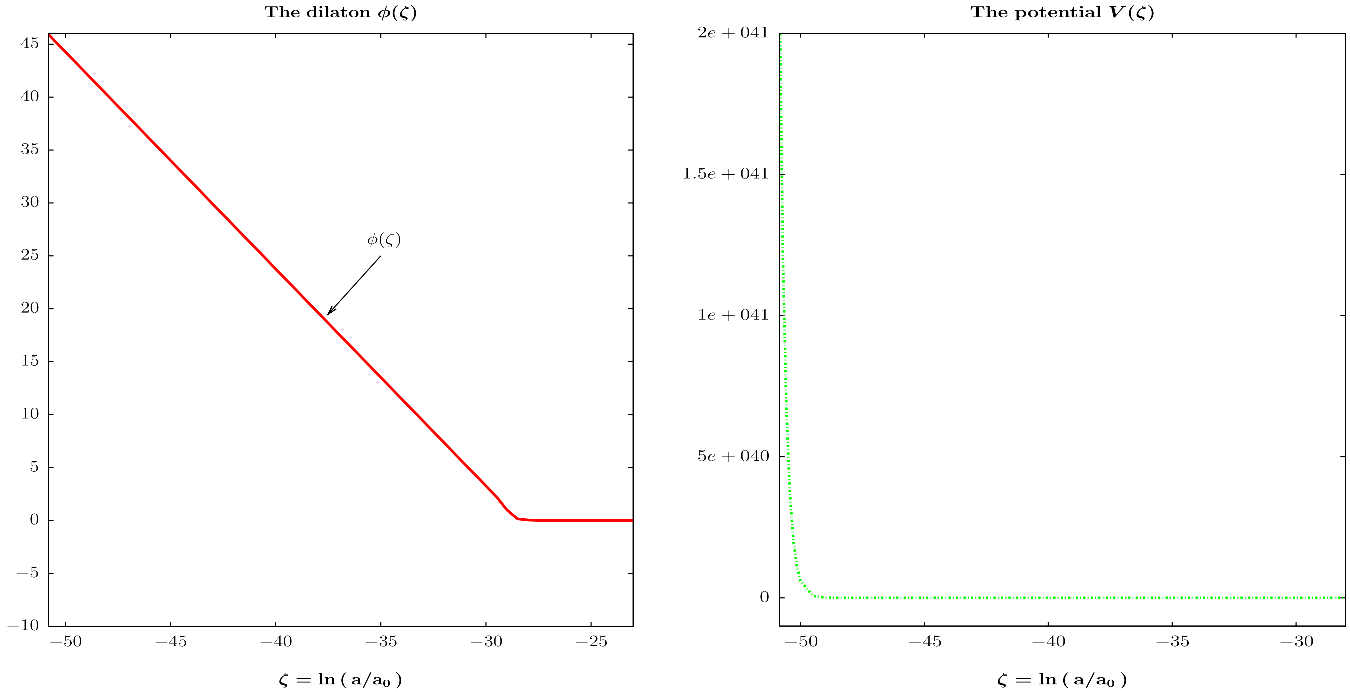

FIG. 1 (color online). The dilaton (left) and the potential (right) as functions of $\ln(a/a_0)$. The ratio of the dilaton's kinetic energy to its potential energy density stay constant and thus the fast exponential dropoff of the dilaton potential indicates that the dilaton-to-radiation energy ratio has been suppressed before nucleosynthesis.

$$\left(\frac{\hat{\rho}_\phi}{\hat{\rho}_r}\right)\bigg|_X = 10^p\left(\frac{a_X}{a_I}\right)^{4-c^2} = 10^{p+N(4-c^2)}. \tag{15}$$

In this equation, the constant N is given by

$$N = \log(e)(b - r) = 0.4344(b - r), \tag{16}$$

with b and r given by $b = \ln(a_X/a_0)$ and $r = \ln(a_I/a_0)$, respectively. The first is an input while the second is determined by the input value of the reheating temperature T_I. For instance for $T_I = \sigma 10^9$ GeV the constant r is given by $r = -50.86 - \ln\sigma$ in a model with the content of the MSSM and mass spectrum much lighter than T_I. N is a number between 8.20 and 11.16, when $\ln(a_X/a_0)$ is taken within the range $-32.0 - -25.0$, and the value of σ specifying the reheating temperature is of the order of unity or so. At the end of the dilaton-dominance era the dilaton-to-radiation energy ratio drops from its initial value to

$$\left(\frac{\hat{\rho}_\phi}{\hat{\rho}_r}\right)\bigg|_X = 10^{p'}. \tag{17}$$

The power p' must be smaller than p but still large enough to guarantee that the above ratio is much larger than unity, so that the bulk of the total energy is carried by the dilaton in the regime $a_I < a < a_X$. From Eqs. (15) and (17) we deduce that

$$c^2 = 4 + \frac{p - p'}{N}, \tag{18}$$

and therefore the dropoff of the ratio $\hat{\rho}_\phi/\hat{\rho}_r$ yields that c^2 is larger than 4. Combined with its upper bound $c^2 < 6$ discussed earlier, one concludes that c^2 lies in the rather narrow range $4 < c^2 < 6$. One can also utilize the relation (18), in combination with the bound $c^2 < 6$, to derive the following bound on $p - p'$:

$$p - p' < 2N.$$

Because N is a number of order $\sim$10, the above upper bound set on $p - p'$ leaves much room for values of the powers p, p' to guarantee that the dilaton energy indeed overwhelms radiation energy in the whole regime $a_I < a < a_X$, as is assumed in this scenario.

III. DILUTION OF DM ABUNDANCES

Concerning the calculation of relic densities, omitting the collision terms, the energy-matter density obeys the following equation:

$$\frac{d\rho}{dt} + 3H(\rho + p) - \frac{\dot{\phi}}{\sqrt{2}}(\rho - 3p) = 0, \tag{19}$$

where the last term is the coupling of the dilaton to the density.[3]

[3]The division by $\sqrt{2}$ is due to the normalization of the dilaton whose kinetic energy appears as $\rho_\phi^{\rm kin} = \frac{\dot{\phi}^2}{2}$; see the second of Eq. (1).

Obviously, for radiation the last term drops and hence when matter is relativistic this term is absent. This holds at a temperature $T \gg m$ where m is the mass of the particle under consideration. Including the collision terms in Eq. (19) results in the following equation for the number density:

$$\frac{dn}{dt} + 3Hn + \langle v\sigma\rangle(n^2 - n_{\mathrm{eq}}^2) - \frac{\dot{\phi}}{\sqrt{2}}n = 0. \tag{20}$$

This is suitable for describing the evolution of the number density during periods for which the particle is nonrelativistic and pressure practically vanishes. During eras in which the particle is relativistic, the last term drops, since the last term in Eq. (19) drops too, and in this case (20) receives the well-known form of the Boltzmann equation, [29].

For the number-to-entropy density ratio, $Y = n/s$, Eq. (20) takes on the form

$$\frac{dY}{dx} = \xi(x)m\langle v\sigma\rangle\left(\frac{45G_N}{\pi}g_{\mathrm{eff}}\right)^{-1/2}\left(h + \frac{x}{3}\frac{dh}{dx}\right)(Y^2 - Y_{\mathrm{eq}}^2) + S(x)Y. \tag{21}$$

In this, x stands for $x = T/m$ where T is the photon gas temperature related to the radiation density ρ_r, which includes all relativistic particles at a given epoch, through

$$\rho_r = \frac{\pi^2}{30}g_{\mathrm{eff}}(T)T^4,$$

and G_N is Newton's constant. In (21) the quantity h stands for the entropic degrees of freedom related to the entropy density through $s = 2\pi^3T^3h(T)/45$.

The prefactor $\xi(x)$ appearing in Eq. (21) is given by

$$\xi(x) = \left(1 + \frac{\rho_m}{\rho_r} + \frac{\rho_\phi}{8\pi G_N\rho_r}\right)^{-1/2}, \tag{22}$$

while the source $S(x)$, in the same equation, is

$$S(x) = -\frac{\phi'}{\sqrt{2}x}\left(1 + \frac{x}{3h}\frac{dh}{dx}\right). \tag{23}$$

In the expression for $\xi(x)$ above, ρ_r, ρ_m, and ρ_ϕ are the radiation, matter, and dilaton energy densities, respectively. Recall that we use a dilaton density having dimensions m_p^2; see Eq. (1). Note that no cosmological term contributes to Eq. (22) since such a term is absent at DM decoupling and long after it. In conventional treatments the prefactor $\xi(x)$ is unity since the DM freeze-out is assumed to take place in the radiation dominated era. However, in the presence of the dilaton energy term this is smaller than unity and the density Y decreases slower, as temperature drops, than in the conventional cases where $\xi(x) = 1$. In the source term $S(x)$, given by Eq. (23), the quantity ϕ' is the derivative of the dilaton with respect to $\ln(a/a_0)$, and if this is negative then the source acts in the opposite direction of $\xi(x)$ tending to decrease the density Y faster as x decreases.

It should be noted that for simplicity we have assumed the lowest order, in α', contributions to the form factors $e^{-\psi(\phi)}$ and $Z(\phi)$ associated with the scalar curvature R and dilaton kinetic terms of the effective action, in the string frame, and hence the simple expressions for the $\dot{\phi}$-dependent terms of Eqs. (19) and (20). Also the dilatonic charge has been assumed to be vanishing. However, the couplings of the dilaton to matter may evolve in time with the dilaton itself and depend on the particle species in a nonuniversal way. Therefore, other options are available which in the string theory arise from loop corrections or nonperturbative string effects [30,31]. In such cases the coupling of matter to $\dot{\phi}$ in the continuity equation (19), which is mainly controlled by $\psi'(\phi) \equiv d\psi/d\phi$, is not a constant. Besides there is an additional contribution to the continuity equation that depends on the dilatonic charge, if the latter is assumed nonvanishing [30–32]. Including these effects will give rise to modified $\dot{\phi}$-dependent terms in Eqs. (19) and (20) resulting in a source $S(x)$ in Eq. (23) that is multiplied by $\sim\psi'(\phi)$, provided the dilatonic charge of dark matter is taken as vanishing. This will still tend to decrease the density Y, as x decreases, if $\psi'(\phi) > 0$ in the regime following dark matter decoupling. In particular, if $\psi'(\phi) > 1$ the dilution of the relic density is enhanced, in comparison with that caused by the source term as it appears in Eq. (23), or gets smaller if $\psi'(\phi) < 1$. Certainly, in order to further study the effects of this term one needs a better understanding of how to handle the corrections to $\psi(\phi)$ arising from the underlying string dynamics. For definiteness in this work, and in order to quantify the effect of the dilution of the abundance of dark matter, we assume a gravi-dilaton effective action in the lowest order in the string slope α'.

The effects of the presence of the factors $\xi(x)$ and $S(x)$, as given by Eqs. (22) and (23), is shown in Figs. 2 and 3 where we plot the density as a function of the temperature, actually $x = T/m_{\mathrm{LSP}}$, for particular supersymmetry (SUSY) inputs. Equation (21) has been integrated numerically, which yields more accurate results than the approximate solutions employed in [20]. The displayed figures correspond to a supergravity model with inputs given by $m_0 = 1100.0$ GeV, $M_{1/2} = 1200.0$ GeV, and $A_0 = 0$ GeV. We have taken $\tan\beta = 40$ and the parameter μ is taken positive, $\mu > 0$. The value of $b \equiv \ln(a_X/a_0)$, setting the onset of the epoch after which the dilaton is constant ($\phi = 0$), has been taken -28.4 corresponding to a temperature $\Lambda_{\mathrm{QCD}} = 260$ GeV as we have already discussed. For the particular SUSY inputs, the lightest supersymmetric particle (LSP) bino has a mass $m_{\mathrm{LSP}} = 527.2$ GeV, and the point $b = -28.4$ corresponds on the x axis to a value

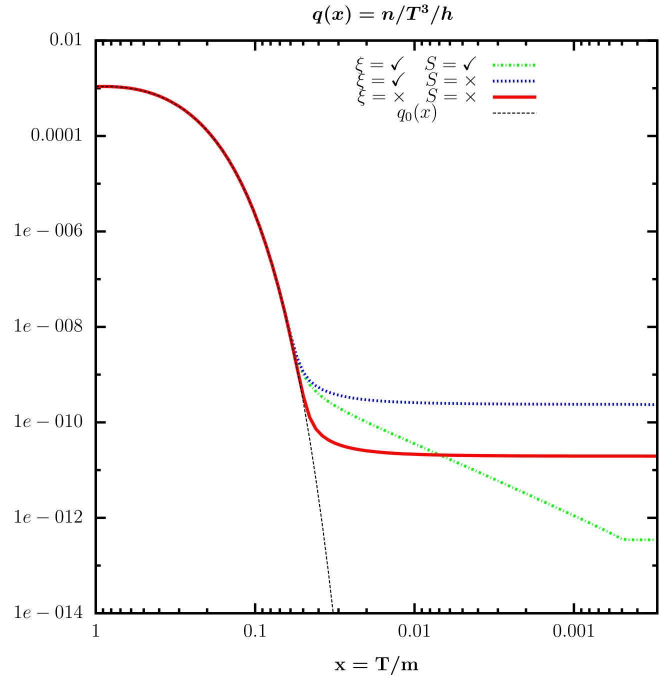

FIG. 2 (color online). The LSP dark matter number density-to-entropy density ratio $q = \frac{n}{T^3 h}$ as a function of $x = \frac{T}{m_{\rm LSP}}$ in a particular supergavity model. The values of ξ, S denote the status of the ξ factor and the source, respectively, (✓ for open, $\times$ for switched-off). For comparison, the corresponding equilibrium density $q_0(x)$ has been also drawn.

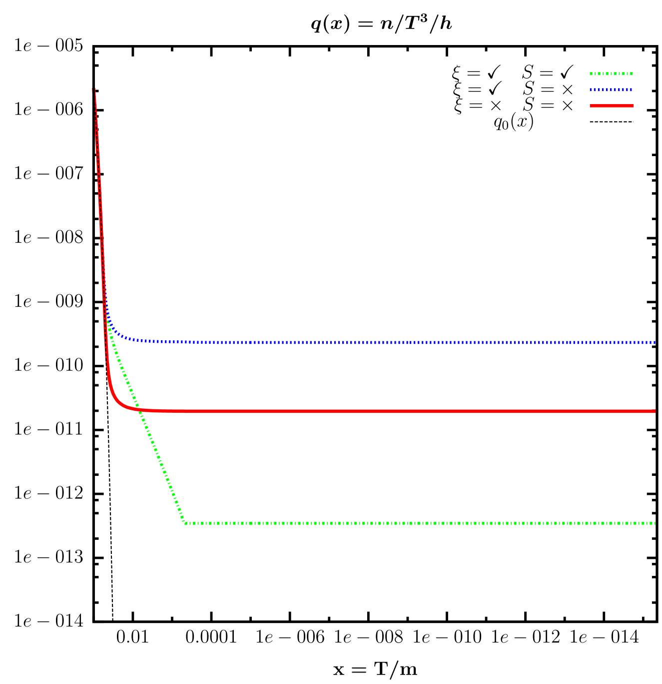

FIG. 3 (color online). The same as in Fig. 2 with $x = \frac{T}{m_{\rm LSP}}$ from 0.1 to values corresponding to cosmic microwave background temperature today.

$x \simeq 0.0005$. For comparison, except the ordinary case scenario, where both the source S and the ξ factor are absent (red solid line), the cases where both ξ and S are open (green dashed-dotted line), or when only the ξ factor is present (blue short-dashed line) are also shown. The very thin dashed line, that rapidly drops, is the corresponding equilibrium density. In the most interesting case, where both terms are switched on, the density is monotonically decreasing after decoupling due to the appearance of the source term. The rapid change around $x \simeq 0.0005$, corresponding to $b = -28.4$, where dilaton reaches its constancy, is shown in Figs. 2 and 3. In the specific example shown, the relic density is diluted by a factor of ~ 50, as can be seen by comparing today's density values for the conventional case (red solid line) and the case where both ξ factor and the source term are present (green dashed line). In the first case, the relic density predicted is $\Omega_{\rm LSP} h_0^2 = 6.059$, while in the second case the relic density is considerably reduced, falling in the WMAP allowed range $\Omega_{\rm LSP} h_0^2 = 0.1116$. In general, for given $b = \ln(a_X/a_0)$, one can obtain reduction factors in the range $\mathcal{O}(5\text{–}50)$, the smaller (larger) corresponding to lighter (heavier) neutralino masses.

IV. CONCLUSIONS

In this paper we have shown that the dilaton dynamics during early eras, long before nucleosynthesis, in conjunction with its coupling to dark matter, may have dramatic consequences for the predicted dark matter relic density. Modeling the dilaton evolution to be that dictated by exponential-type potentials $V \sim e^{-k\phi}$, occurring in quintessence scenarios and string theory, the ordinary predicted DM density may be diluted by large factors ranging from $\mathcal{O}(5)$ to $\mathcal{O}(50)$. This dilution mechanism is consistent with the absence of dilaton couplings to ordinary matter (hadrons), in the continuity equations, but it affects DM relics since a dilaton dominates over radiation during and after DM decoupling. This allows for LSP annihilation cross sections, in the popular supersymmetric schemes, that are smaller by an order of magnitude or more. This, however, may imply smaller inelastic cross sections of the neutralino LSP with nucleons putting farther the potential of discovering supersymmetric DM at proposed direct detection experiments [25]. As far as indirect detection experiments are concerned, indirect searches of dark matter through antimatter production has stirred much interest in the last three years. The PAMELA data [18] in combination with that provided by Fermi-LAT [19] and HESS [26] may be conditionally explained as DM annihilations in the galactic halo that generates the produced antiparticle flux [33]. In the case under consideration, the smaller annihilation cross sections, required to satisfy WMAP data, makes even more difficult the possibility that antimatter fluxes observed in the cosmic ray are relevant to annihilation of the neutralino LSP in the galactic halo. In conventional supersymmetric models, the situation can be rescued at the cost of considering large boost factors. However, even in this case, DM annihilation appears to be a rather remote explanation for interpreting the aforementioned data, and other more conservative explanations exist, as for instance antimatter produced by pulsars or supernovae [34].

A complete phenomenological study of supersymmetric models addressing all these issues is in progress, and the results will appear in a forthcoming publication [35].

ACKNOWLEDGMENTS

I wish to thank Dr. V. C. Spanos for his comments and enlightening discussions. This work is supported by the European Union under the Marie Curie Initial Training Network "UNILHC" PITN-GA-2009-237920 and Research Training Network European Programme MRTN-ct-2006-035505 HEPTOOLS. The author also acknowledges support by the National Kapodistrian University of Athens Special Research account.

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