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Direct detection of neutralino dark matter in nonstandard cosmologies

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We compute the neutralino direct detection rate in nonstandard cosmological scenarios where neutralinos account for the dark matter of the Universe. Significant differences are found when such rates are compared with those predicted by the standard cosmological model. For b-ino-like neutralinos, the main feature is the presence of additional light ($m_\chi \lesssim 40$ GeV) and heavy ($m_\chi \gtrsim 600$ GeV) neutralinos with detection rates within the sensitivity of future dark matter experiments. For Higgsino-like and W-ino-like neutralinos lighter than $m_\chi \sim 1$ TeV, enhancements of more than 2 orders of magnitude in the largest detection rates are observed. Thus, if dark matter is made up of neutralinos, the prospects for their direct detection are in general more promising than in the standard cosmology.

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I. INTRODUCTION

The Large Hadron Collider is now in its final preparation stages and may soon be searching for supersymmetric particles. Among them, the lightest neutralino in the minimal supersymmetric standard model plays a distinctive role as a dark matter candidate [1]. It is neutral, weakly interacting, and stable (provided it is the lightest supersymmetric particle). If evidence for low energy supersymmetry is found, it will strongly support the idea that neutralinos constitute the dark matter of the Universe. A logical next step would then be the use of neutralinos as cosmological probes of the early Universe. Neutralinos could, in particular, test the standard cosmological model well before big bang nucleosynthesis. Being an observable sensitive to the conditions in the early Universe, the neutralino direct detection rate provides a plausible way of discriminating between different cosmological models, and therefore an indirect way of testing the standard scenario. Most studies on the direct detection of neutralinos already assume the standard cosmology so it is not known what to expect in a more general cosmological framework.

The vastness of the supersymmetric parameter space is the most compelling reason to assume the standard cosmological model. In a general setup, neither the neutralino mass or gauge composition nor its interaction rate, for example, can be determined *a priori*. To reduce such uncertainties, the dark matter constraint is usually imposed on supersymmetric models. That is, the neutralino relic density is computed within the standard cosmological model and only models with $\Omega_{\rm std} < \Omega_{\rm DM}$ are considered (here $\Omega_{\rm std}$ is the neutralino density in the standard cosmological model, and $\Omega_{\rm DM}$ is the cold dark matter density, both in units of the critical density). This bound, it turns out, is very effective in restricting the parameter space of supersymmetric models. In minimal supergravity models (mSUGRA), for instance, the neutralino typically has a small annihilation rate in the early Universe, thus its relic density tends to be larger than observed. At the end, the requirement $\Omega_{\rm std} < \Omega_{\rm DM}$ is found to be satisfied only along four narrow regions: the "bulk" (with a light neutralino and tight accelerator constraints), the "coannihilation region" (where the stau is almost degenerate with the neutralino and coannihilation effects suppress the relic density), the "funnel region" (where $m_\chi \simeq m_A/2$ and resonance effects enhance the χ-χ annihilation rate) and the "focus point region" (where the neutralino acquires a nonnegligible Higgsino fraction). Accounting for the dark matter provides, in fact, the most stringent constraint on supersymmetric models, well over precision data or accelerator searches (see e.g. [2]).

Though useful in reducing the supersymmetric parameter space, the dark matter constraint should not be taken for granted, as it relies on untested assumptions about the early Universe. In particular, it postulates that the entropy of matter and radiation is conserved and that the Universe is radiation dominated at high temperatures ($T \sim m_\chi$). Several scenarios where such assumptions do not hold and, more generally, where the evolution of the Universe before big bang nucleosynthesis deviates from the standard cosmological model, have been studied in the literature. They are generically known as nonstandard cosmologies and include models with gravitino [3], moduli [4] or Q-ball decay [5], thermal inflation [6], the Brans-Dicke-Jordan [7] cosmological model, models with anisotropic expansion [8] or quintessence domination [9]. Nonstandard cosmological models are viable alternatives against which the predictions of the standard scenario may be compared.

In nonstandard cosmological scenarios, the neutralino relic density Ω_χ may be larger or smaller than $\Omega_{\rm std}$ [10–19]. Smaller densities are usually the result of an episode of

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entropy production that dilutes the neutralino abundance. Larger densities are due either to additional contributions to the expansion rate of the Universe, or to nonthermal neutralino production mechanisms. Usually these scenarios contain additional parameters that can be adjusted to modify the neutralino relic density. A distinctive feature of nonstandard cosmologies is that the new physics they incorporate does not manifest in accelerator or detection experiments. That is certainly the case, for instance, for the several models mentioned above. Neutralino scattering rates, therefore, are not affected by the cosmological model.

A prototype nonstandard cosmological model is that of a scalar field ϕ with couplings of gravitational strength whose late decay reheats the Universe to a low reheating temperature. The reheating temperature in this scenario can be lower than the standard neutralino freeze-out temperature without spoiling primordial nucleosynthesis [20]. Such scalar fields are common in superstring models where they appear as moduli fields. In these models, the decay of ϕ into radiation increases the entropy, diluting the neutralino number density. Instead, the decay of ϕ into supersymmetric particles, which eventually decay into neutralinos, increases the neutralino number density. In this nonstandard cosmological model it has been shown that practically all neutralinos can have the density of the dark matter, provided the right combination of two parameters can be achieved in the high energy theory: the reheating temperature, and the ratio of the number of neutralinos produced per ϕ decay over the ϕ field mass [18,19].

In this paper, we compute the neutralino direct detection rate in generic cosmological scenarios where neutralinos constitute the dark matter of the Universe. That is, we assume that, independently of the supersymmetric spectrum, the parameters of the nonstandard cosmological model always can be chosen so that $\Omega_\chi = \Omega_{\rm DM}$. By randomly scanning the supersymmetric parameter space, we obtain a large sample of models and compute their detection rates in nonstandard cosmologies. These predictions are then compared with those obtained within the standard cosmological model. Our goal is twofold. First, we explore the possibility of using the neutralino direct detection rate as a test of the standard cosmological model. Second, we establish the potential of future dark matter detectors in probing the parameter space of supersymmetric models in a cosmology-independent setup.

II. THE SUPERSYMMETRIC MODELS

In the minimal supersymmetric standard model (MSSM), neutralinos are linear combinations of the fermionic partners of the neutral electroweak bosons, called b-ino ($\tilde{B}^0$) and W-ino ($\tilde{W}_3^0$), and of the fermionic partners of the neutral Higgs bosons, called Higgsinos ($\tilde{H}_u^0$, $\tilde{H}_d^0$). We assume that the lightest neutralino, χ, is the dark matter candidate. Its composition can be parameterized as

$$\chi = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0. \tag{1}$$

Because the neutralino interactions are determined by its gauge content, it is useful to distinguish between b-ino-like ($N_{11}^2 > N_{12}^2,\ N_{13}^2 + N_{14}^2$), W-ino-like ($N_{12}^2 > N_{11}^2,\ N_{13}^2 + N_{14}^2$), and Higgsino-like ($N_{13}^2 + N_{14}^2 > N_{11}^2,\ N_{12}^2$) neutralinos according to the hierarchy of terms in (1). This classification implies that even so-called *mixed* neutralinos, those with two or more comparable components, are considered as either b-inos, W-inos, or Higgsinos.

b-ino-like neutralinos annihilate mainly into fermion-antifermion pairs through sfermion exchange. Such annihilation cross section is helicity suppressed and gives rise to a standard relic density that is usually larger than observed. Agreement with the observed dark matter abundance can still be achieved in standard cosmological scenarios but only in restricted regions of the parameter space where special mechanisms such as coannihilations or resonant annihilations help reduce the relic density. Owing to the gaugino unification condition, b-ino-like neutralinos are a generic prediction of minimal supergravity models.

W-ino-like and Higgsino-like neutralinos annihilate mostly into gauge bosons (W^+W^-, ZZ, if kinematically allowed) through neutralino or chargino exchange; otherwise they annihilate into fermions. Because of coannihilations with the lightest chargino (and, for Higgsinos, with the next-to-lightest neutralino), their standard relic density is rather small. Neutralino masses as large as 1 TeV for Higgsinos or 2 TeV for W-inos are required to bring their thermal density within the observed range. W-ino-like and Higgsino-like neutralinos can be obtained in models with nonuniversal gaugino masses; models with anomaly mediated supersymmetry breaking (AMSB) [21], for instance, feature a W-ino-like neutralino.

We consider a general class of MSSM models defined in terms of the parameter set M_3, M_2, M_1, m_A, μ, $\tan\beta$, $m_{\tilde{q}}$, $m_{\tilde{\ell}}$ A_t, and A_b. Here M_i are the three gaugino masses, m_A is the mass of the pseudoscalar Higgs boson, and $\tan\beta$ denotes the ratio v_2/v_1. The soft breaking scalar masses are defined through the simplifying ansatz $M_Q = M_U = M_D = m_{\tilde{q}}$ and $M_E = M_L = m_{\tilde{\ell}}$, whereas the trilinear couplings are given by $A_U = \mathrm{diag}(0, 0, \mathrm{A_t})$, $A_D = \mathrm{diag}(0, 0, \mathrm{A_b})$, and $A_E = 0$. All these parameters are defined at the weak scale. Specific realizations of supersymmetry breaking such as mSUGRA, mAMSB [21] or split-SUSY [22] are similar to—though not necessarily coincide with—particular examples of these models.

We performed a random scan of such parameter space within the following ranges:

$$10\ \mathrm{GeV} < M_1, M_2, M_3 < 50\ \mathrm{TeV}, \tag{2}$$

$$40\ \mathrm{GeV} < m_A, \mu, m_{\tilde{q}}, m_{\tilde{\ell}} < 50\ \mathrm{TeV}, \tag{3}$$

$$-3m_0 < A_t, A_b < 3m_0, \tag{4}$$

$$1 < \tan\beta < 60. \tag{5}$$

A logarithmic distribution was used for M_i, m_A, μ, $m_{\tilde{q}}$, and $m_{\tilde{\ell}}$, and a linear one for A_t, A_b, and $\tan\beta$; the sign of μ was randomly chosen. After imposing accelerator constraints, as contained in DarkSUSY version 4.1 [23], a sample of about 10^5 viable models was obtained. The following analysis is based on such a sample of supersymmetric models.

III. RESULTS

Figure 1 shows the *standard* relic density as a function of the neutralino mass for our sample of models. Each cell—triangle, circle, or dot—represents a small region around which at least one model was found. The models are classified as b-inos, W-inos, or Higgsinos, according to the gauge composition of the lightest neutralino. The horizontal band corresponds to the observed dark matter density $\Omega_{\rm std}h^2 = \Omega_{\rm dm}h^2 = 0.109^{+0.003}_{-0.006}$, obtained for a ΛCDM model with scale-invariant primordial perturbation spectrum through a global fit of cosmic microwave background, supernovae, and large scale structure data [24]. Several observations can be made from this figure. Models with b-ino-like neutralinos are spread over a wide area and usually give a rather large relic density. Models with W-ino-like and Higgsino-like neutralinos, on the contrary, are concentrated over narrow bands and their relic density exceeds the dark matter density only for large masses, $m_\chi \gtrsim 1$ TeV. Finally, notice that in our sample the neutralino relic density varies between 10^6 and 10^{-4}.

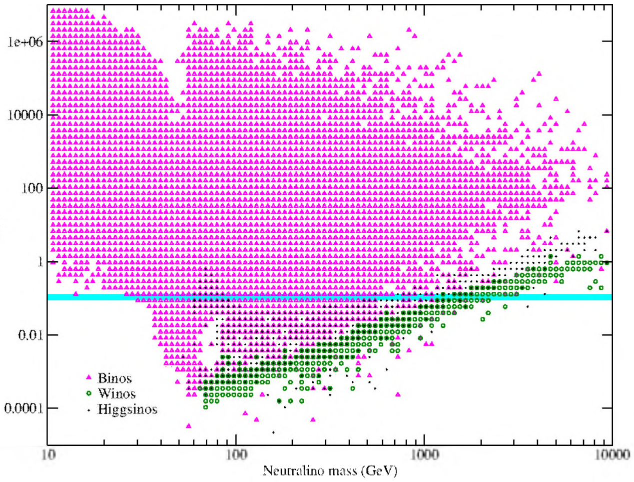

FIG. 1 (color online). The *standard* neutralino relic density as a function of the neutralino mass for our sample of models. The models are differentiated according to the b-ino, W-ino, or Higgsino character of the lightest neutralino. The horizontal band indicates the dark matter range.

We now want to compute, for our set of models, the neutralino interaction rates in generic cosmologies where the neutralino accounts for the dark matter and compare them with those obtained in the standard cosmology. Since spin-dependent searches are harder than spin-independent ones, we will focus on the latter. The neutralino interaction rate in direct dark matter detection experiments is proportional to the product of the spin-independent neutralino-nucleus cross section $\sigma_{\rm SI}$ and the number density of neutralinos passing through the detector, f. We assume that, as expected for collisionless cold dark matter, $f = \Omega_\chi/\Omega_{\rm dm}$. $\sigma_{\rm SI}$ is determined only by the supersymmetric spectrum but Ω_χ is sensitive to the cosmological setup. Thus, the neutralino detection rate depends on the cosmology only through f.

If the standard cosmological model is assumed, then all models above the horizontal band in Fig. 1 are rejected. They have a standard relic density larger than the observed dark matter density ($\Omega_{\rm std} > \Omega_{\rm DM}$) and therefore are considered incompatible with cosmological observations. Models with a relic density below the dark matter density are still viable, though neutralinos make up only a fraction of the dark matter. They have $f < 1$, so their detection rate is typically suppressed. Finally, those models with a neutralino relic density within the observed dark matter range are viable and have $f = 1$. They have been the focus of the large majority of studies on neutralino direct detection.

In nonstandard cosmologies, $\Omega_\chi = \Omega_{\rm DM}$ may be ensured and the previous picture is modified in two important ways. On the one hand, the viable parameter space is different. In fact, overdense models, those with $\Omega_{\rm std} > \Omega_{\rm DM}$, can no longer be rejected. On the other hand, underdense models, those with $\Omega_{\rm std} < \Omega_{\rm DM}$, no longer will have the $f < 1$ suppression factor in the detection rate. Hence, in nonstandard cosmologies, we expect more viable models and larger detection rates. *A priori*, however, it is not possible to predict the detection rate for the new viable models or to know whether the enhanced detection rates are within the sensitivity of future dark matter detection experiments. Thus, a careful analysis is required to establish the implications of nonstandard cosmologies for dark matter searches. In the following, such an analysis will be carried out.

Figure 2 displays the detection rate in standard and nonstandard cosmologies for b-ino-like neutralinos as a function of the neutralino mass. As before, the figure has been divided into a rectangular grid and each occupied cell denotes the existence of at least one model around it. For comparison, we also show the current limit from the CDMS II experiment [25] as well as the expected sensitivity of CDMS II, ZEPLIN IV , XENON-1Ton, and SuperCDMS phase C [26]. In the standard scenario, both the lower and the upper limit on the b-ino mass are set by the relic density constraint. That is why the range of neutralino masses extends to lower and higher values in

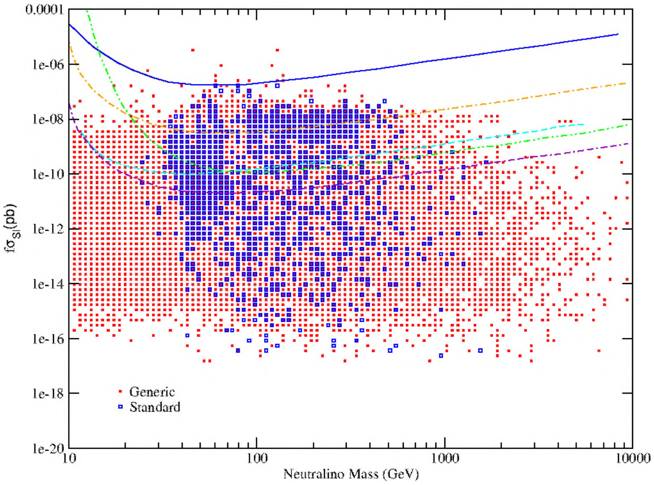

FIG. 2 (color online). Spin-independent neutralino-proton cross section $\sigma_{\rm SI}$ multiplied by the neutralino halo fraction $f = \Omega_{\rm std}/\Omega_{\rm DM}$ for b-ino-like neutralinos in the standard and nonstandard cosmological models. The solid line indicates the CDMS II present limit [25]. The dashed lines show sensitivity limits for—from top to bottom on the right—CDMS II, ZEPLIN IV , XENON-1Ton, and SuperCDMS phase C [26].

nonstandard cosmologies. They yield many more viable models, though most of them have rather small detection rates. This fact is not entirely surprising. Small annihilation rates, as those associated with b-ino-like neutralinos, are generically correlated with small scattering rates. Regarding dark matter searches, the most remarkable difference observed in the figure is the existence of new viable models with neutralino masses not allowed in the standard cosmology and detection rates within the reach of future experiments. Such models feature either $m_\chi \lesssim 40$ GeV or $m_\chi \gtrsim 600$ GeV and may be detected in ZEPLIN IV, XENON-1Ton, or SuperCDMS phase C.

The detection rate for Higgsino-like neutralinos is shown in Fig. 3 as a function of the neutralino mass in standard and nonstandard cosmologies. The lower limit on the Higgsino mass is now set by the experimental constraint on the chargino mass and is therefore independent of the cosmological scenario. Two features clearly distinguish the standard and the nonstandard cosmologies. One of them is the existence of viable models with heavy neutralinos, $m_\chi \gtrsim 1$ TeV. A sizable fraction of them has detection rates large enough to be observed in ZEPLINIV, XENON-1Ton, or SuperCDMS phase C. The other feature is the significant enhancement in the detection rate of neutralinos lighter than $\lesssim 1$ TeV. In the standard scenario, such neutralinos are usually underdense (see Fig. 1) and have suppressed detection rates. From the figure we see that nonstandard cosmologies yield an enhancement of up to 2 orders of magnitude for the neutralinos with the largest detection rates. Some of them are already ruled out by the present limit and many more will be within the expected sensitivity of the CDMS II experiment.

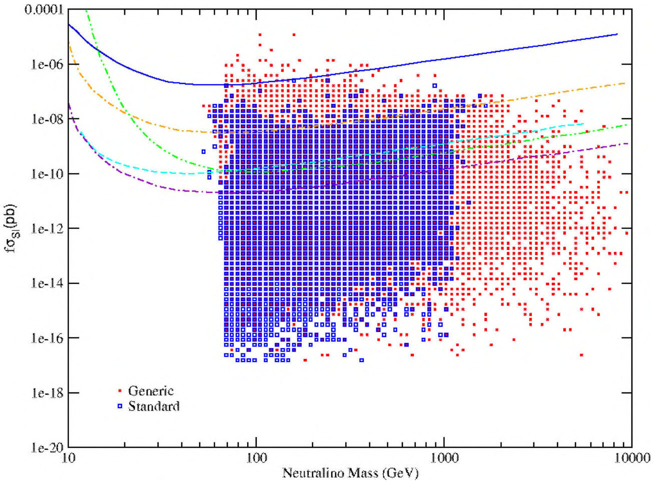

FIG. 3 (color online). Spin-independent neutralino-proton cross section $\sigma_{\rm SI}$ multiplied by the neutralino halo fraction $f = \Omega_{\rm std}/\Omega_{\rm DM}$ for Higgsino-like neutralinos in the standard and nonstandard cosmological models. The solid line indicates the CDMS II present limit [25]. The dashed lines show sensitivity limits for—from top to bottom on the right—CDMS II, ZEPLIN IV , XENON-1Ton, and SuperCDMS phase C [26].

A compelling signature of nonstandard cosmologies would be the detection of a W-ino-like neutralino by the CDMS II experiment, as revealed in Fig. 4. Indeed, in the standard scenario, W-inos with $m_\chi \lesssim 1$–2 TeV are usually underdense and therefore their detection rate is suppressed by the factor $f = \Omega_{\rm std}/\Omega_{\rm DM}$. In nonstandard cosmologies, such suppression is nonexistent and light W-inos have larger detection rates. The enhancement in the largest

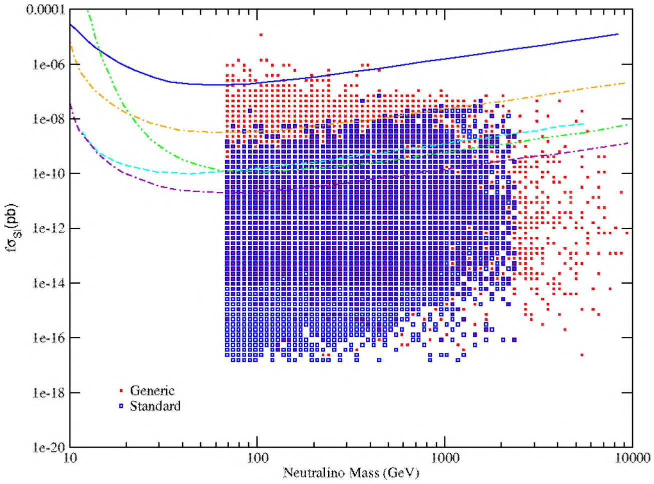

FIG. 4 (color online). Spin-independent neutralino-proton cross section $\sigma_{\rm SI}$ multiplied by the neutralino halo fraction $f = \Omega_{\rm std}/\Omega_{\rm DM}$ for W-ino-like neutralinos in the standard and nonstandard cosmological models. The solid line indicates the CDMS II present limit [25]. The dashed lines show sensitivity limits for—from top to bottom on the right—CDMS II, ZEPLIN IV , XENON-1Ton, and SuperCDMS phase C [26].

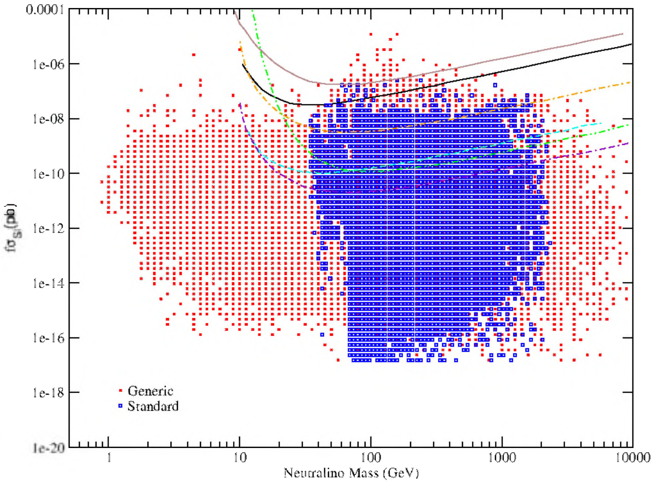

FIG. 5 (color online). Spin-independent neutralino-proton cross section σ_{SI} multiplied by the neutralino halo fraction $f = \Omega_{\mathrm{std}}/\Omega_{\mathrm{DM}}$ in the standard cosmological model and in the late-decaying scalar field model. Here the lower limit of M_1 in Eq. (2) has been lowered to 0.1 MeV. The solid upper line indicates the CDMS II present limit [25] and the lower solid line the XENON limit [27]. The dashed lines show sensitivity limits for—from top to bottom on the right—CDMS II, ZEPLIN IV , XENON-1Ton, and SuperCDMS phase C [26].

detection rates are typically larger than for Higgsinos, amounting in some cases to 3 orders of magnitude. As for Higgsinos, the lower bound on m_χ is not set by the dark matter bound but rather by the experimental constraint on the chargino mass, so no additional models are found at low neutralino masses. For $m_\chi \gtrsim 2$ TeV we do find new viable models corresponding to overdense neutralinos in the standard cosmology. Most of them, however, have small scattering rates, lying below the sensitivity of future detection experiments.

Figure 5 summarizes the potential increase in neutralino candidates in the models studied in Refs. [18,19]. For this figure the lower limit on M_1 in Eq. (2) has been lowered to 0.1 GeV (which is compatible with all experimental limits while no assumption is made on the relation between M_1 and M_2). In the late-decaying scalar field scenario most neutrinos can be brought to have the dark matter density (provided the value of the two relevant parameters of the physics at the high scale can be suitably arranged). One exception is that of very light neutralinos which would be very overdense in the standard cosmology. Requiring the reheating temperature to be above 4 MeV [20], in order not to modify nucleosynthesis, it is immediate to see from the equations of Ref. [18] that neutralinos of mass m_χ should have a standard density smaller than the dark matter density times $(m_\chi/120\ \mathrm{MeV})^4$ for it to be possible to bring their density to that of the dark matter in the late-decaying scalar field scenario. This constraint is included in Fig. 5, which clearly shows the increase in potential neutralino candidates in going from the standard cosmological model to the nonstandard cosmological model with a late-decaying scalar field.

IV. CONCLUSION

To summarize, in this paper we computed the direct detection rate of MSSM neutralinos in generic cosmological scenarios where they constitute the dark matter of the Universe. When compared with the predictions of the standard cosmology, considerable differences were encountered. If the neutralino is b-ino-like, as in mSUGRA models, additional light $m_\chi \lesssim 40$ GeV and heavy $m_\chi \gtrsim 600$ GeV neutralinos with nonnegligible detection rates were found. They could be detected in a variety of dark matter experiments such as ZEPLINIV, XENON-1Ton, or SuperCDMS phase C. For Higgsino-like neutralinos, we found enhancements of up to 2 orders of magnitude in the largest detection rates as well as new viable models with heavy $m_\chi \gtrsim 1$ TeV neutralinos. Both effects yielded detection rates within the sensitivity of future experiments. W-ino-like neutralinos provide the clearest signature of nonstandard cosmologies. Their detection rates may be enhanced by up to 3 orders of magnitude and they could be detected in CDMS II. Thus, the prospects for the direct detection of neutralinos in nonstandard cosmologies are significantly more promising than in the standard scenario.

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