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Non-thermal production of neutralino cold dark matter from cosmic string decays

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Abstract: Cosmic strings form in many extensions of the MSSM, in particular in models with an extra U(1) gauge symmetry. We propose a new production mechanism for neutralino cold dark matter in such models. We show that if the strings forming scale is less than about $10^8\,\mathrm{GeV}$, the dark matter produced from strings can overclose the universe. The mass of the new U(1) gauge boson must be much larger than the Fermi scale which makes it unobservable in upcoming accelerator experiments. In supersymmetric models with an extra $U_{B-L}(1)$ gauge symmetry, the requirement of $\Omega \leq 1$ puts an upper bound on the neutrino mass of about $30\,eV$ provided neutrino masses are generated by the see-saw mechanism.

Keywords: Cosmology of Theories beyond the SM, Cosmological Phase Transitions, Dark Matter, Physics of the Early Universe.

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Contents

1. Introduction

In spite of the increasing evidence that cold matter (matter with pressure $p = 0$) makes up less than the critical density ρ_c for a spatially flat Universe, equally strong evidence for the existence of a substantial amount of cold dark matter (CDM) remains. The best current estimates give $\Omega_{\rm CDM} \sim 0.3$ [1] whereas $\Omega_B < 0.1$ [2] (here, $\Omega_X = \rho_X/\rho_c$ denotes the fractional contribution of X matter to ρ_c, and B stands for the contribution of baryons).

The leading candidates for cold dark matter are the axion and the neutralino. The axion is a neutral spin-zero Pseudo-Goldstone boson associated with the spontaneous breaking of the global $U_{PQ}(1)$ symmetry, which was introduced by Peccei and Quinn [3] as a solution to the strong CP problem. At zero temperature the axion mass is given by

$$m_a \sim 6 \times 10^{-6}\,\mathrm{eV} N \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right)$$

where f_a is Peccei-Quinn symmetry breaking scale and N is a positive integer which describes the color anomaly of $\mathrm{U}_{PQ}(1)$. Axions can be produced by three different mechanisms: vacuum alignment, axion string decay and axion domain wall decay [4]. Cosmology yields an upper limit on f_a of $f_a \le 10^{12}\,\mathrm{GeV}$.

The neutralino is an electrically neutral hypothetical particle which arises in supersymmetric models. In many such models, e.g. in the MSSM (the minimal supersymmetric standard model), the lightest supersymmetric particle (LSP) is stable, unless R-parity violating interactions are included. The LSP is generally thought to be the lightest neutralino χ. The neutralinos in the Universe today are in general assumed to be a relic of an initially thermal neutralino distribution in the hot early Universe. Based on this thermal production mechanism, there have been many calculations of the LSP abundance (for a review, see e.g. [5]) as a function of the MSSM parameters. These studies show that there exists a domain of parameter space in the MSSM which is consistent with all of the present experimental constraints and for which the χ has a relic mass density $\Omega_\chi \sim 1$. However, cosmology also imposes limits on the LSP mass. In the case of a Bino-like LSP, the calculation of refs. [6] yields $M_{\tilde{B}} \leq 300\,\mathrm{GeV}$. A recent study [7] relaxes this upper bound to about 600 GeV by including the $\tilde{B}$ coannihilations with the $\tilde{e}$ and $\tilde{\mu}$.

In this paper, we propose a new non-thermal production mechanism of the LSP. We consider models with an extra U(1) gauge symmetry in extensions of the MSSM. This U(1) symmetry could be $U_{B-L}(1)$, where B and L are respectively baryon and lepton numbers. Such models explain the neutrino masses via the see-saw mechanism. Another possibility is that the new U(1) corresponds to a U(1)$'$ from string theory or grand unified theories [8].

The basic idea of our mechanism is as follows. When the extra U(1) symmetry which we have introduced gets broken at a scale η, a network of strings is produced by the usual Kibble mechanism [9]. The initial separation of the strings is microscopic, of the order $\lambda^{-1}\eta^{-1}$ (where λ is a typical Higgs self coupling constant of the U(1) sector of the theory) which implies that a substantial fraction of the energy density of the Universe is trapped in strings. After the symmetry breaking phase transition, the defect network coarsens. In the process, string loops decay. If, as we assume, the fields excited in the strings couple to the neutralino χ, then a non-thermal distribution of χ particles will be generated during the process of string decay. The total energy density in χ particles will depend on the scale η of U(1) symmetry breaking. The presence of our alternative generation mechanism for χ particles relaxes the constraints on the mass of the χ. Even if the usual thermal generation mechanism is too weak to generate $\Omega_\chi \sim 1$, our new non-thermal mechanism may, for appropriate values of η, be able to lead to $\Omega_\chi \sim 1$. In fact, we find that if $\eta < 10^8\,\mathrm{GeV}$ and $M_\chi \sim 100\,\mathrm{GeV}$, then our mechanism will lead to $\Omega_\chi > 1$, unless the couplings of the U(1) sector to χ are small. Note that there are similarities between our non-thermal production and the mechanism based on preheating proposed in [10]. Note also that the the decaying string loops that we consider will not effect the microwave radiation since η is much smaller than the GUT scale.

To begin with, we consider a general case and calculate the relic mass density of the LSP, then we will move on to a discussion of some implications.

2. LSP Production via String Decay

Local cosmic strings form at a phase transitions associated with the spontaneous symmetry breaking of a gauge group G down to a subgroup H of G if the first homotopy group of the vacuum manifold $\pi_1(G/H)$ is nontrivial. We suppose the existence of such a phase transition which is induced by the vacuum expectation value (vev) of some Higgs field Φ, $\langle|\Phi|\rangle = \eta$, and takes place at a temperature T_c

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with $T_c \simeq \eta$. The strings are formed by the Higgs field Φ and some gauge field A of G whose generator is broken by the vev of Φ. We assume that the generator of G associated with A is diagonal so that the strings are abelian. The mass per unit length of the strings is given by $\mu = \eta^2$.

During the phase transition, a network of strings forms, consisting of both infinite strings and cosmic string loops. After the transition, the infinite string network coarsens and more loops form from the intercommuting of infinite strings. Cosmic string loops loose their energy by emitting gravitational radiation. When the radius of a loop becomes of the order of the string width, the loop releases its final energy into a burst of Φ and A particles. Those particles subsequently decay into LSP, which we denote by χ, with branching ratios ϵ and ϵ'. For simplicity we now assume that all the final string energy goes into Φ particles. A single decaying cosmic string loop thus releases $N \simeq 2\pi\lambda^{-1}\epsilon$ LSPs which we take to have a monochromatic distribution with energy $E \sim T^c/2$.

In such scenarios, we thus have two sources of cold dark matter which will contribute to the matter density of the universe. We have CDM which comes from the standard scenario of thermal production; it gives a contribution to the matter density $\Omega_{\rm therm}$. And we also have non-thermal production of CDM which comes from the decay of cosmic string loops and gives a contribution $\Omega_{\rm nonth}$. The total CDM density is $\Omega_{\rm CDM} = \Omega_{\rm therm} + \Omega_{\rm nonth}$. During the temperature interval between T_c and the LSP freezeout temperature T_χ, LSPs released by decaying comic string loops will thermalise very quickly with the surrounding plasma, and hence will contribute to $\Omega_{\rm therm}$, which should not sensitively deviate from the value calculated by the standard method [5, 7]. However, below the LSP freezeout temperature, since the annihilation of the LSP is by definition negligible, each CDM particle released by cosmic string decays will contribute to $\Omega_{\rm nonth}$. We obviously must have

$$\Omega_{\rm nonth} < 1\,. \tag{2.1}$$

This will lead us to a constraint (a lower bound) on the cosmic string forming scale. We now calculate $\Omega_{\rm nonth}$.

We assume that the strings evolve in the friction dominated regime so that the very small scale structure on the strings has not formed yet. The network of strings can then be described by a single length scale $\xi(t)$.[1] In the friction dominated period,

[1] The friction dominated regime lasts from the time t_c at which the strings network forms until a time $t_* \sim (G\mu)^{-1} t_c$, where G is Newton's constant [11]. In our scenario, the CDM is produced at and below the LSP freezeout temperature $T_\chi \sim 10^2 - 10^3$ GeV. Hence for $T_c \leq (10^{10.5} - 10^{11})$ GeV $= T_c^*$, when the temperature of the Universe reaches T_χ, the strings are still in the friction dominated regime. Since we are looking for a lower bound T_c^l on the scale η of the strings, and since as we will show below $T_c^l \ll T_c^*$, the time interval of interest in our scenario is in the friction dominated regime.

the length scale $\xi(t)$ has been shown to scale as [12]:

$$\xi(t) = \xi(t_c)\left(\frac{t}{t_c}\right)^{3/2}, \tag{2.2}$$

where $\xi(t_c) \sim (\lambda\eta)^{-1}$ and λ is the Higgs self quartic coupling constant. The number density of cosmic string loops created per unit of time is given by [11]:

$$\frac{dn}{dt} = \nu\xi^{-4}\frac{d\xi}{dt}, \tag{2.3}$$

where ν is a constant of order 1. We are interested in loops decaying below T_χ.

The number density of LSP released from $t_{\rm LSP}$ till today is given by:

$$n_{\rm LSP}^{\rm nonth}(t_0) = N\nu\int_{\xi_F}^{\xi_0}\left(\frac{t}{t_0}\right)^{3/2}\xi^{-4}d\xi\,, \tag{2.4}$$

where the subscript 0 refers to parameters which are evaluated today. $\xi_F = \xi(t_F)$ where t_F is the time at which cosmic string loops which are decaying at time t_χ (associated with the LSP freezeout temperature T_χ) have formed. Now the loop's average radius shrinks at a rate [11] $dR/dt = -\Gamma_{\rm loops}G\mu$, where $\Gamma_{\rm loops}$ is a numerical factor $\sim 10 - 20$. Since loops form at time t_F with an average radius $R(t_F) \simeq \lambda^{-1}G\mu M_{\rm pl}^{1/2}\,t_F^{3/2}$, they have shrunk to a point at the time $t \simeq \lambda^{-1}\Gamma_{\rm loops}^{-1}M_{\rm pl}^{1/2}\,t_F^{3/2}$. Thus $t_F \sim (\lambda\Gamma_{\rm loops})^{2/3}M_{\rm pl}^{-1/3}t_\chi^{2/3}$. Now the entropy density is $s = \frac{2\pi^2}{45}g_*T^3$ where g_* counts the number of massless degrees of freedom in the corresponding phase. The time t and temperature T are related by $t = 0.3g_*^{-1/2}(T)\frac{M_{\rm pl}}{T^2}$ where $M_{\rm pl}$ is the Planck mass. Thus using eqs. (2.2) and (2.4), we find that the LSP number density today released by decaying cosmic string loops is given by:

$$Y_{\rm LSP}^{\rm nonth} = \frac{n_{\rm LSP}^{\rm nonth}}{s} = \frac{6.75}{\pi}\epsilon\nu\lambda^2\Gamma_{\rm loops}^{-2}\,g_{*T_c}^{-9/4}\,g_{*T_\chi}^{3/4}\,M_{\rm pl}^2\,\frac{T_\chi^4}{T_c^6}\,, \tag{2.5}$$

where the subscript on g^* refers to the time when g^* is evaluated.

The LSP relic abundance is related to Y_χ by:

$$\begin{aligned}\Omega_\chi\,h^2 &\approx M_\chi Y_\chi s(t_0)\rho_c(t_0)^{-1}h^2\\ &\approx 2.82\times 10^8\,Y_\chi^{\rm tot}\left(\frac{M_\chi}{\rm GeV}\right),\end{aligned} \tag{2.6}$$

where h is the Hubble parameter and M_χ is the LSP mass. Now $Y_{\rm LSP}^{\rm tot} = Y_\chi^{\rm therm} + Y_\chi^{\rm nonth}$; hence by setting $h = 0.70$, eqs. (2.6) and (2.1) lead to the following constraint:

$$5.75\times 10^8\,Y_\chi^{\rm nonth}\left(\frac{M_\chi}{\rm GeV}\right) < 1\,. \tag{2.7}$$

We thus see that eqs. (2.5) and (2.7) lead to a lower bound on the cosmic string forming temperature T_c.

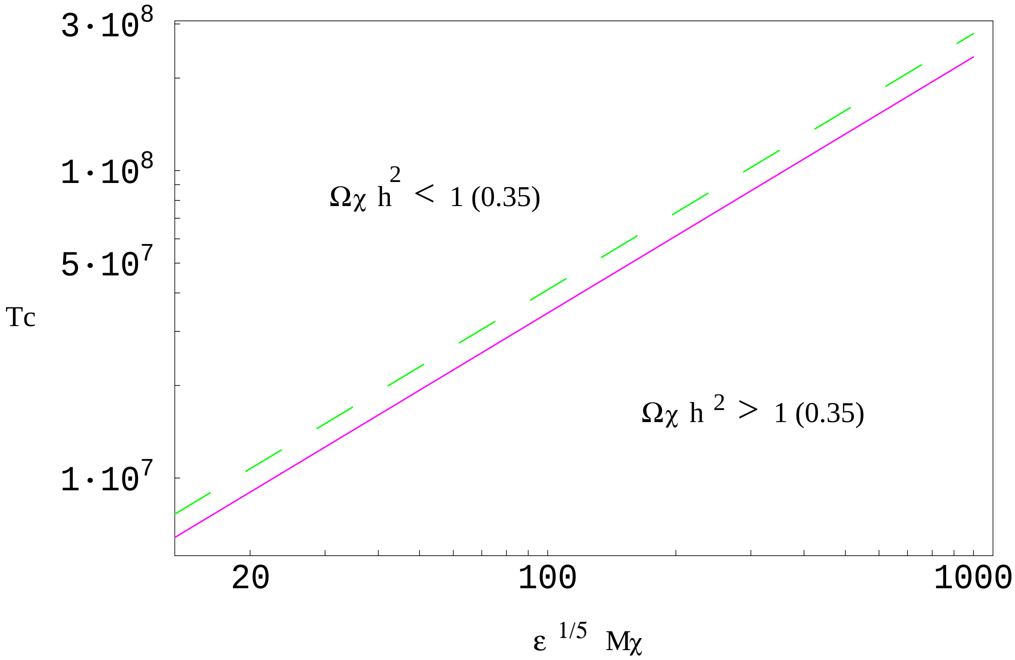

Figure 1: The critical temperature T_c as a function of the branching ratio and the LSP mass for $\Omega_\chi h^2 = 1$ (solid line) and $\Omega_\chi h^2 = 0.35$ (dashed line). The region above the curves corresponds to $\Omega_\chi h^2 < 1$ ($\Omega_\chi h^2 < 0.35$ respectively) and the region below correponds to $\Omega_\chi h^2 > 1$ ($\Omega_\chi h^2 > 0.35$). The latter is excluded by observations.

Recent measurements of cosmological parameters from the cosmic microwave background radiation combined with type-IA supernovæ show evidence for a cosmological constant. In such a scenario, the relic matter density satisfies [13] $\Omega_M h^2 \simeq 0.35$.

In figure 1, we have plotted the bound on T_c as a function of $\epsilon^{1/5} M_\chi$ for both $\Omega_\chi h^2 = 1$ and $\Omega_\chi h^2 = 0.35$. We have set $g_{*T_c} = 250$, $g_{*T_\chi} = 90$, $T_\chi = m_\chi/20$, $M_{\rm pl} = 1.22 \times 10^{19}\,$GeV, and the cosmic string parameters $\nu = 1$, $\lambda = 0.5$ and $\Gamma_{\rm loops} = 10$. The region above each curves corresponds to $\Omega_\chi h^2 < 1$ ($\Omega_\chi h^2 < 0.35$ respectively), and the region below to $\Omega_\chi h^2 > 1$ ($\Omega_\chi h^2 > 0.35$ respectively); this region is excluded by observations. We see that if there is a cosmological constant, a slightly stronger bound on T_c is obtained.

3. Implications for Phenomenology

Our results have important implications for supersymmetric extensions of the standard model with extra U(1)'s (or grand unified models with an intermediate $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)'$ gauge symmetry). Most importantly, the requirement $\Omega_{\rm nonth} < 1$ imposes a new constraint on supersymmetric model building and rules out many models with a low scale of a new symmetry breaking which produces defects such as cosmic strings.

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Consider, for example, the model with an extra $U_{B-L}(1)$ gauge symmetry. In this model, the spectrum of the standard model is extended to include right-handed neutrinos N_i. The light neutrinos receive masses via the see-saw mechanism and the matter-antimatter asymmetry of the universe is generated by the out-of-equilibrium decay of these right-handed neutrinos. In the latter case, leptogenesis can occur by the decay of cosmic strings associated with the spontaneous breaking of the $U_{B-L}(1)$ gauge symmetry [14]. In the supersymmetric version of this model, the strings will release not only right-handed neutrinos N_i, but also their superpartners $\tilde{N}_i$. The heavy neutrinos N_i and their scalar partners $\tilde{N}_i$ can decay into various final states including the LSP. The superpotential relevant to the decays is

$$W = H_1 \epsilon L y_l E^c + H_2 \epsilon L y_\nu N^c \,,$$

where H_1, H_2, L, E^c and N^c are the chiral superfields and y_l, y_ν are Yukawa couplings for the lepton and neutrino Dirac masses, $m_l = y_l v_1, m_D = y_\nu v_2$, with $v_{1,2}$ being the vacuum expectation values of the Higgs fields. At tree level, the decay rates of N_i into s-lepton plus Higgsino and lepton plus Higgs are the same. Both of the decay widths are $\frac{1}{16\pi} y_\nu^2 M_i$ where M_i is the mass of N_i. Similarly, the rate of $\tilde{N}_i$ decaying into s-lepton plus Higgs equals to the rate of $\tilde{N}_i$ into Higssino and lepton, which is $\frac{1}{8\pi} y_\nu^2 M_i$. If the neutralino is higgsino-like, the LSP arise directly from the decays of the N_i and $\tilde{N}_i$. If the neutralino is bino- or photino-like, subsequent decays of s-lepton into binos or photinos plus leptons will produce the LSP. With s-lepton being the Next to LSP after the neutralino, the branching ratio ϵ in this model is 0.5. From eq. (2.5) it follows that string decays can easily produce the required amount of LSP. However too many LSPs will be generated unless the $B-L$ breaking scale, Λ_{B-L} is higher than about $10^8\,\mathrm{GeV}$. In turn, this will set a lower limit on the neutrino masses generated by the see-saw mechanism, $m_\nu \sim m_D^2/\Lambda_{B-L}$. Inserting numbers and taking $m_D \sim m_\tau \sim 1.8\,\mathrm{GeV}$, one obtains that $m_\nu \leq 30\,\mathrm{eV}$.

In models with spontaneous breaking of a $U_{B-L}(1)$ gauge symmetry, upper and lower bounds on the $B-L$ breaking scale have already been derived from considerations of cosmic rays from string decay [15] and from leptogenesis [16], respectively. Our lower bound on the $B-L$ breaking scale is independent of leptogenesis.

Our lower limit on the $B-L$ symmetry breaking scale in gauged $B-L$ models and in general models with an extra U(1) [8] pushes the mass of the new gauge boson far above the Fermi scale, rendering it impossible to test the new physics signals from the extra Z' in accelerators.

To summarize, we have pointed out a new production mechanism for neutralino dark matter which can be effective in many models beyond the MSSM, models with extra gauge symmetries which admit topological defects. The decay of these defects gives rise to a nonthermal contribution to the neutralino density. We have focused on the nonthermal production of LSPs from string decays. Similarly, one could consider LSP production from other topological defects. We have calculated the relic

LSP mass density $\Omega_{\rm nonth}$ as a function of the string scale, the freezeout temperature and the mass of the LSP. The LSP mass density has two contributions, one from thermal production which has been calculated by many authors in the literature before, another is the non-thermal production calculated in this paper. Our results indicate that if the scale η of string production is about 10^8GeV, then our nonthermal mechanism can produce the required closure density of LSPs. For values of η smaller than the above bound, the model is in conflict with observations since the LSPs would overclose the Universe.

One important caveat must be made concerning our calculations. Cosmic strings arising in supersymmetric models are generically superconducting [17]. In this case, the string dynamics may be very different from that of ordinary strings, the dynamics assumed in this paper, and thus the corresponding constraints on particle physics model building would be quite different. Nevertheless, the main point that cosmic string decay in extensions of the MSSM can yield a new production mechanism for dark matter remains unaffected.

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