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Light W -ino dark matter in brane world cosmology

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The thermal relic density of W -ino-like neutralino dark matter in brane world cosmology is studied. The expansion law at a high energy regime in brane world cosmology is modified from the one in standard cosmology, and the resultant relic density can be enhanced if the five-dimensional Planck mass M_5 is low enough. We calculate the W -ino-like neutralino relic density in the anomaly mediated supersymmetry breaking scenario and show that the allowed region is dramatically modified from the one in standard cosmology and the W -ino-like neutralino with mass of order 100 GeV can be a good candidate for dark matter. Since the allowed region disappears eventually as M_5 decreases, we can find a lower bound on $M_5 \gtrsim 100$ TeV according to the neutralino dark matter hypothesis, namely, the lower bound in order for the allowed region of neutralino dark matter to exist.

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INTRODUCTION

Recent cosmological observations, especially after the Wilkinson Microwave Anisotropy Probe (WMAP) satellite [1], have established the Λ CDM cosmological model with a great accuracy. The abundance of cold dark matter is also precisely measured as (in the 2σ range)

$$\Omega_{\text{CDM}} h^2 = 0.1126_{-0.0181}^{+0.0161}. \quad (1)$$

However, to clarify the identity of a particle as cold dark matter is still an open problem in cosmology and particle physics.

The lightest supersymmetric particle (LSP) in supersymmetric models is suitable for cold dark matter, because it is stable owing to the conservation of R parity. In the minimal supersymmetric standard model (MSSM), the lightest neutralino is typically the LSP and the promising candidate for cold dark matter. Neutralinos consist of a mixture of neutral gauginos and Higgsinos,

$$\chi_i^0 = N_{i1} \tilde{B} + N_{i2} \tilde{W}^3 + N_{i3} \tilde{H}_1^0 + N_{i4} \tilde{H}_2^0, \quad (2)$$

where \tilde{B} is the $U(1)_Y$ gaugino (b -ino), \tilde{W}^3 is the $SU(2)_L$ gaugino (W -ino), and \tilde{H}_1^0 and \tilde{H}_2^0 are two neutral Higgsinos. The components of the neutralinos χ_i^0 , in other words the coefficients N_{ij} , are model dependent.

For example, in the constrained MSSM (CMSSM), the lightest neutralino is b -ino-like $\chi_1^0 \sim \tilde{B}$ in most of the parameter region. The exception is the so-called “focus point” region where the lightest neutralino is Higgsino-like. In the light of the WMAP data, the parameter space in the CMSSM which allows the neutralino relic density suitable for cold dark matter has been reanalyzed and the allowed region is dramatically reduced due to the great accuracy of the WMAP data [2]. The main reason is that the predicted relic density of the b -ino-like neutralino is generally too much to meet the observational result because its annihilation cross section is too small.

However, in another model, the lightest neutralino can be W -ino-like or Higgsino-like. For example, the W -ino-like lightest neutralino $\chi_1^0 \sim \tilde{W}^3$ is naturally realized in the anomaly mediated supersymmetry breaking (AMSB) scenario [3,4]. The annihilation cross section of the W -ino-like neutralino is larger than that of the b -ino-like neutralino, since its pair annihilation process into two W bosons and coannihilation process with charginos via W boson exchange are governed by the $SU(2)_L$ gauge coupling. The predicted relic density of the W -ino-like neutralino is roughly estimated as [4,5]

$$\Omega_{\tilde{W}} h^2 \simeq 5 \times 10^{-4} \left(\frac{m_{\tilde{W}}}{100 \text{ GeV}} \right)^2. \quad (3)$$

Hence, the W -ino mass $m_{\tilde{W}}$ around 1 TeV is necessary to be consistent with the WMAP data, and the W -ino-like neutralino seems not to be an appealing candidate in the viewpoint of the weak scale supersymmetry. There are

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some possibilities to make the W -ino-like neutralino with mass of $\mathcal{O}(100)$ GeV a reasonable dark matter candidate, such as nonthermal production of the W -ino-like neutralino [6–8] or the introduction of an additional energy component at the neutralino decoupling time [9].

Here, we remind the reader that the thermal relic density of dark matter depends on the underlying cosmological model as well as its annihilation cross section. If a non-standard cosmology has been realized at the neutralino decoupling time, the resultant relic density of dark matter can be altered from the one in standard cosmology. A brane world cosmological model that is being intensively investigated [10] is an interesting example which provides an unconventional cosmological expansion in the early universe. In the cosmology based on the so-called ‘‘RS II’’ model, first proposed by Randall and Sundrum [11], the Friedmann equation for a spatially flat spacetime is found to be

$$H^2 = \frac{8\pi G}{3} \rho \left(1 + \frac{\rho}{\rho_0} \right), \quad (4)$$

where

$$\rho_0 = 96\pi G M_5^6, \quad (5)$$

H is the Hubble parameter, ρ is the energy density of matter, G is Newton’s gravitational constant with M_5 being the five-dimensional Planck mass, and the four-dimensional cosmological constant has been tuned to be almost zero. The parameter ρ_0 is constrained by big bang nucleosynthesis (BBN), which is roughly given by $\rho_0^{1/4} \gtrsim 1$ MeV (or equivalently $M_5 \gtrsim 8.8$ TeV) [10]. This is a model-independent cosmological constraint. On the other hand, as discussed in the original paper by Randall and Sundrum [11], the precision measurements of the gravitational law in the submillimeter range lead to more stringent constraints $\rho_0^{1/4} \gtrsim 1.3$ TeV (or equivalently $M_5 \gtrsim 1.1 \times 10^8$ GeV) through the vanishing cosmological constant condition. However, note that this constraint, in general, is quite model dependent. In fact, if we consider an extension of the model so as to introduce a bulk scalar field, the constraint can be moderated because of the change of the vanishing cosmological constant condition [12]. Hence, we care about only the BBN constraint on ρ_0 in this paper.

The ρ^2 term in Eq. (4) is a new ingredient in brane world cosmology and it dominates over the linear term at a high temperature regime. This modification of the expansion law can lead to some drastic changes for some results previously obtained in standard cosmology [13–17]. In particular, it has been pointed out that the thermal relic abundance of dark matter can be considerably enhanced compared to that in standard cosmology [13]. When this scenario is applied to the analysis of neutralino dark matter in the CMSSM, the allowed parameter region is dramatically modified and eventually disappears as the five-dimensional Planck mass (M_5) becomes small, and thus

the lower bound on M_5 can be obtained [14]. On the other hand, note that this enhancement implies that a light W -ino dark matter would be favored in brane world cosmology because its annihilation processes are so efficient that its relic density is found to be too small in standard cosmology.

In this paper, we investigate the possibility that the W -ino-like neutralino is a suitable candidate for cold dark matter with the help of the brane world cosmological effect. This paper is organized as follows. In the next section, we give a brief review of Ref. [13]. In Sec. III, we present our numerical results for the W -ino-like neutralino relic density in brane world cosmology, which show that the cosmologically interesting parameter region for the W -ino-like neutralino actually appears. Section IV is devoted to conclusions.

II. ENHANCEMENT OF RELIC DENSITY IN BRANE WORLD COSMOLOGY

In this section, we give a brief review of the relic density of dark matter in brane world cosmology with a low five-dimensional Planck mass M_5 [13] and roughly estimate the suitable scale of M_5 for W -ino dark matter.

In the context of brane world cosmology, we estimate the thermal relic density of a dark matter particle by solving the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{\text{eq}}^2), \quad (6)$$

with the modified Friedmann equation (4), where n is the actual number density of the dark matter particles, n_{eq} is the equilibrium number density, and $\langle\sigma v\rangle$ is the thermal averaged product of the annihilation cross section σ and the relative velocity v . It is useful to rewrite Eq. (6) into the form

$$\begin{aligned} \frac{dY}{dx} &= -\frac{s}{xH} \langle\sigma v\rangle (Y^2 - Y_{\text{eq}}^2) \\ &= -\lambda \frac{x^{-2}}{\sqrt{1 + (\frac{x}{x_t})^4}} \langle\sigma v\rangle (Y^2 - Y_{\text{eq}}^2), \end{aligned} \quad (7)$$

in terms of the number density to entropy ratio $Y = n/s$ and $x = m/T$, where m is the mass of a dark matter particle, $\lambda = 0.26(g_{*S}/g_*^{1/2})M_P m$, $M_P \simeq 1.2 \times 10^{19}$ GeV is the Planck mass, and x_t is defined as

$$x_t^4 \equiv \frac{\rho}{\rho_0} \Big|_{T=m}. \quad (8)$$

At the era $x \ll x_t$ the ρ^2 term dominates in Eq. (4), while the ρ^2 term becomes negligible after $x \gg x_t$ and the expansion law in standard cosmology is realized. Hereafter we call the temperature defined as $T_t = mx_t^{-1}$ (or x_t itself) the ‘‘transition temperature’’ at which the expansion law of the early universe changes from the nonstandard one to the

standard one. Since we are interested in the effect of the ρ^2 term for the dark matter relic density, we consider the case that the decoupling temperature of dark matter (T_d) is higher than the transition temperature, namely $x_t \geq x_d = m/T_d$.

Although it is easy to numerically solve the Boltzmann equation (7) given $\langle\sigma v\rangle$ and x_t as will be shown in the next section, here we derive analytic formulas for the relic number density of dark matter by adopting appropriate approximations. When we parametrize $\langle\sigma v\rangle$ as $\langle\sigma v\rangle = \sigma_n x^{-n}$ with fixed $n = 0, 1, \dots$, for simplicity, we can obtain simple formulas for the resultant relic densities such that

$$Y(x \rightarrow \infty) \simeq 0.54 \frac{x_t}{\lambda\sigma_0} \quad \text{for } n = 0, \quad (9)$$

$$\frac{x_t^2}{\lambda\sigma_1 \ln x_t} \quad \text{for } n = 1,$$

in the limit $x_d \ll x_t$, where x_d is the decoupling temperature [13]. Note that the results are characterized by the transition temperature rather than the decoupling temperature. It is interesting to compare these results to that in standard cosmology. Using the well-known approximate formulas in standard cosmology [18],

$$Y(x \rightarrow \infty) \simeq \frac{x_d}{\lambda\sigma_0} \quad \text{for } n = 0,$$

$$\frac{2x_d^2}{\lambda\sigma_1} \quad \text{for } n = 1, \quad (10)$$

we obtain the ratio of the relic energy density of dark matter in brane world cosmology ($\Omega_{(b)}$) to the one in standard cosmology ($\Omega_{(s)}$) such that

$$\frac{\Omega_{(b)}}{\Omega_{(s)}} \simeq 0.54 \left(\frac{x_t}{x_{d(s)}} \right) \quad \text{for } n = 0, \quad (11)$$

$$\frac{1}{2 \ln x_t} \left(\frac{x_t}{x_{d(s)}} \right)^2 \quad \text{for } n = 1, \quad (12)$$

where $x_{d(s)}$ denotes the decoupling temperature in standard cosmology. Thus, the relic energy density in brane world cosmology can be enhanced from the one in standard cosmology if the transition temperature is low enough.

Together with Eqs. (1), (3), and (11), we find

$$\Omega_{(b)} h^2 \simeq 0.1 \times \left(\frac{m}{100 \text{ GeV}} \right)^2 \left(\frac{27}{x_{d(s)}} \right) \left(\frac{x_t}{10^4} \right). \quad (13)$$

Therefore, the enhancement by the modified expansion law can make the W -ino-like neutralino with mass $\mathcal{O}(100 \text{ GeV})$ a suitable dark matter candidate for $(m/100 \text{ GeV})^2 (x_t/10^4) \simeq 1$; in other words,

$$T_t \simeq 10 \text{ MeV} \left(\frac{m}{100 \text{ GeV}} \right)^3, \quad (14)$$

which corresponds to

$$M_5 \simeq 7.3 \times 10^4 \left(\frac{g_*}{100} \right)^{1/6} \left(\frac{m}{100 \text{ GeV}} \right)^2 \text{ GeV} \quad (15)$$

from Eq. (8). Thus, in brane world cosmology with M_5 as low as 100 TeV, the W -ino-like neutralino can be a suitable candidate for cold dark matter even if its mass scale is of order 100 GeV. On the other hand, too small M_5 causes the overproduction of dark matter in the universe, and the lower bound on M_5 can be obtained for a fixed $m = \mathcal{O}(100) \text{ GeV}$.

III. NUMERICAL RESULTS FOR THE W -INO-LIKE NEUTRALINO

In this section, we present the results of our numerical analysis. We calculate the relic density of the W -ino-like neutralino $\Omega_\chi h^2$ based on the mass spectrum predicted in the AMSB scenario to realize the W -ino-like lightest neutralino, with the new Friedmann equation (4). For this purpose, we have modified the code DARKSUSY [19] so that the new Friedmann equation is implemented. In evaluating the relic density, the relevant coannihilations are taken into account. In addition, the spin-independent cross section for the direct detection is also estimated.

The mass spectra in the AMSB scenario are determined by the following input parameters [20],

$$m_0, m_{3/2}, \tan\beta, \text{sgn}(\mu), \quad (16)$$

where $m_{3/2}$ is the gravitino mass, m_0 is the universal scalar mass (which is necessary to avoid the tachyonic slepton mass problem), $\tan\beta$ is the ratio of the vacuum expectation values of the two neutral Higgs fields, and $\text{sgn}(\mu)$ is the sign of the Higgsino mass parameter μ . With these input parameters, renormalization group equations for the soft supersymmetry breaking parameters are solved using the code SUSPECT [21] to obtain the mass spectra at the weak scale.

In the AMSB scenario, the gaugino mass M_i is proportional to the associated beta function, and each gaugino mass at the weak scale is predicted as follows [20]¹:

$$M_1 = 8.9 \times 10^{-3} m_{3/2}, \quad (17)$$

$$M_2 = 2.7 \times 10^{-3} m_{3/2}, \quad (18)$$

$$M_3 = -2.6 \times 10^{-2} m_{3/2}. \quad (19)$$

The relation $M_2 \simeq 0.3M_1$ implies that the lightest neutralino is W -ino-like. The lighter chargino is also W -ino-like, and highly degenerated with the lightest neutralino.

¹In the AMSB scenario, the gravitino is very heavy and decays before the BBN era, so that the well-known gravitino problem can be avoided. In addition, as pointed out in Ref. [15], there is no gravitino problem in the brane world scenario with the transition temperature low enough, $T_t \lesssim 10^6 \text{ GeV}$, even if the gravitino mass is around 100 GeV.

A. Relic density of the W -ino-like neutralino

Figures 1–3 show the allowed region (shaded area) for $\tan\beta = 10$ and $\mu > 0$ in the $(m_{3/2}, m_0)$ plane consistent with the WMAP 2σ allowed range $0.094 < \Omega_\chi h^2 < 0.129$. The five-dimensional Planck mass is taken as $M_5 = \infty$, 500 TeV, and 100 TeV in Figs. 1–3, respectively.

Figure 1 corresponds to the result for standard cosmology. In this figure, the dotted, dot–long-dashed, and short-dash–long-dashed lines correspond to $\Omega_\chi h^2 = 0.005$, 0.001, and 0.0005, respectively. The region consistent with the WMAP data appears in the range $m_{3/2} \approx 650$ –850 TeV, which corresponds to the W -ino-like neutralino mass around 2 TeV. The relic density primarily depends on $m_{3/2}$, and is insensitive to m_0 as expected from Eq. (3). The region along the bold line and the two coordinate axes is excluded by various experimental constraints (the lightest Higgs mass bound, the $b \rightarrow s\gamma$ constraint, the lighter chargino mass bound, etc.) or the condition for the successful electroweak symmetry breaking. In particular, the region $m_0 \lesssim 5 \times 10^{-3} m_{3/2}$ is excluded where the lighter stau is the LSP, while the region $m_{3/2} \lesssim 20$ TeV is excluded by the current lower bounds on chargino and Higgs masses.

The corresponding result for $M_5 = 500$ TeV is presented in Fig. 2. The dotted, solid, dot–long-dashed, and short-dash–long-dashed lines correspond to $\Omega_\chi h^2 = 0.5$,

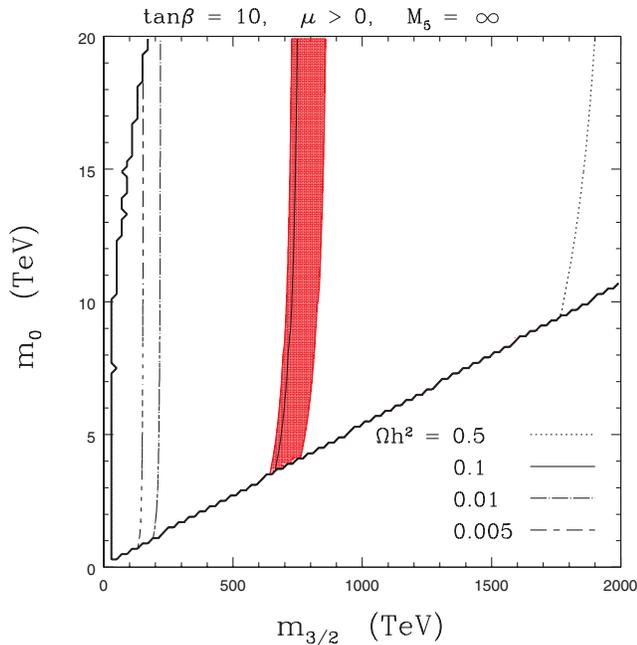


FIG. 1 (color online). Contours of the relic density $\Omega_\chi h^2$ in the $(m_{3/2}, m_0)$ plane for $\tan\beta = 10$, $\mu > 0$, and $M_5 = \infty$. The region along the bold line and the two coordinate axes are excluded by various experimental constraints (the lightest Higgs mass bound, the $b \rightarrow s\gamma$ constraint, the lighter chargino mass bound, etc.) or the condition for the successful electroweak symmetry breaking.

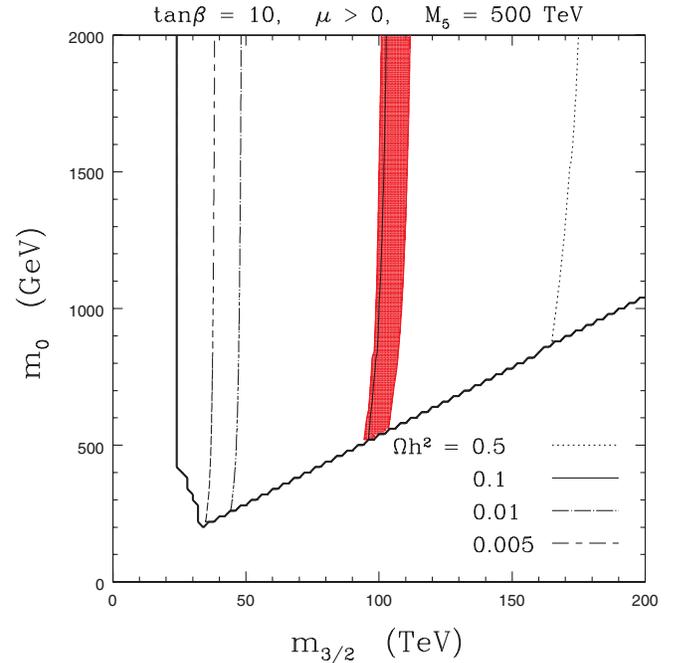


FIG. 2 (color online). Contours of the relic density $\Omega_\chi h^2$ in the $(m_{3/2}, m_0)$ plane for $\tan\beta = 10$, $\mu > 0$, and $M_5 = 500$ TeV. The shaded region is allowed by the WMAP constraint $0.094 < \Omega_\chi h^2 < 0.129$.

0.1, 0.01, and 0.005, respectively. It is seen that the relic density is greatly enhanced due to the increase of the Hubble expansion rate in brane world cosmology. The

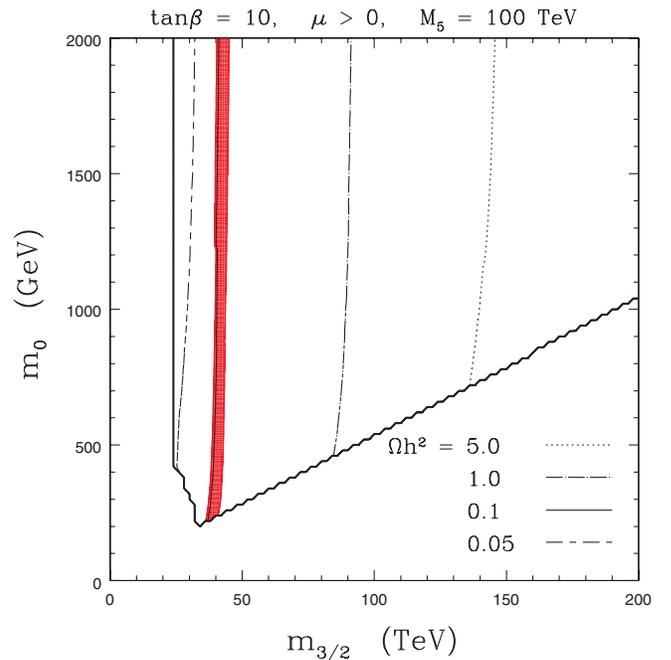


FIG. 3 (color online). The same as Fig. 2 but for $M_5 = 100$ TeV.

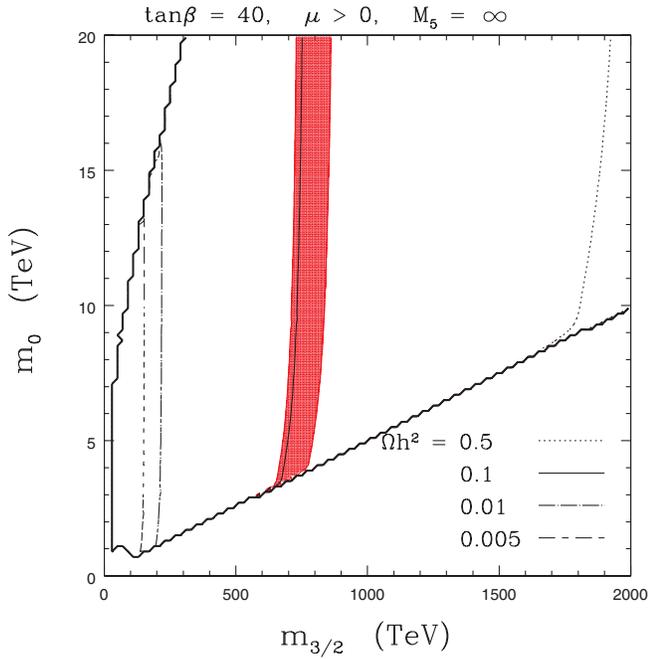


FIG. 4 (color online). The same as Fig. 1 but for $\tan\beta = 40$.

allowed region (shaded area) appears for $100 \text{ TeV} \lesssim m_{3/2} \lesssim 110 \text{ TeV}$. In this region, the neutralino mass is around 300 GeV .

The result for $M_5 = 100 \text{ TeV}$ is shown in Fig. 3. The relic density is further enhanced, and the allowed region is shifted to lie around $40 \text{ TeV} \lesssim m_{3/2} \lesssim 45 \text{ TeV}$. In this

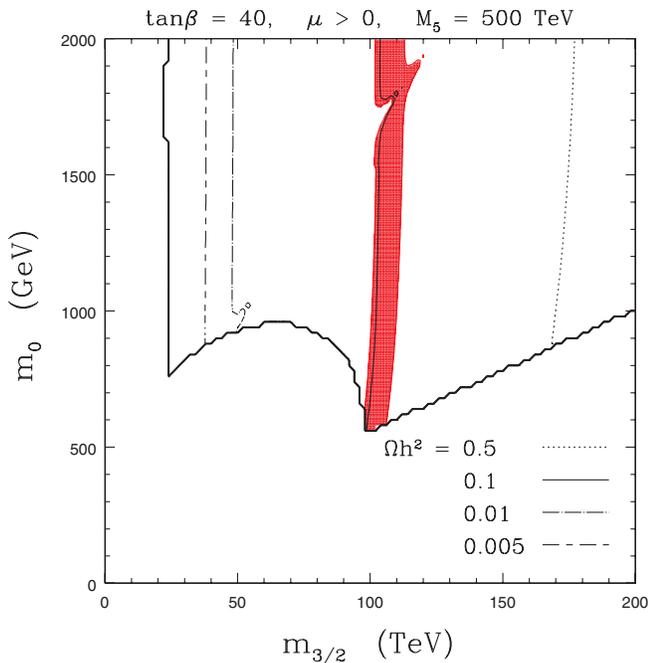


FIG. 5 (color online). The same as Fig. 2 but for $\tan\beta = 40$.

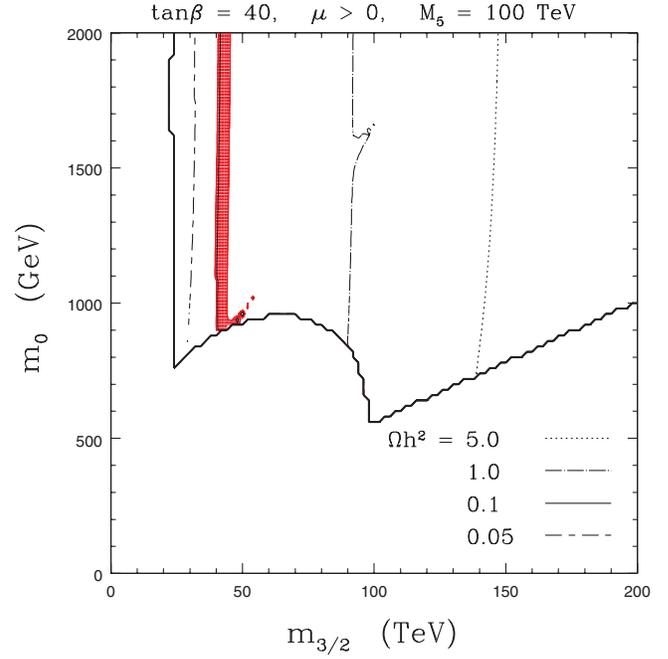


FIG. 6 (color online). The same as Fig. 3 but for $\tan\beta = 40$.

allowed region, the lightest neutralino mass is around 130 GeV .

These figures clearly indicate that, as M_5 decreases to $\mathcal{O}(100) \text{ TeV}$, the allowed region moves to the left and the mass of the W -ino-like neutralino becomes small. As M_5 decreases further, the allowed region eventually disappears.

Figures 4–6 contains the similar results for $\tan\beta = 40$. It is seen that the contours of the relic density for $\tan\beta = 40$ are quite similar to those for $\tan\beta = 10$. Distortions around $m_0 \approx 1800 \text{ GeV}$ in Fig. 5 and $m_0 \approx 900 \text{ GeV}$ in Fig. 6 are due to the resonance effect by the CP -odd Higgs boson with mass $m_A \approx 2m_\chi$. As M_5 decreases, the allowed region moves to the left and disappears eventually as in the case of $\tan\beta = 10$. For $\tan\beta = 40$, the $b \rightarrow s\gamma$ constraint is severer than the $\tan\beta = 10$ case, and it nearly excludes the region $m_0 \lesssim 1 \text{ TeV}$ and $m_{3/2} \lesssim 100 \text{ TeV}$.

For $M_5 = \mathcal{O}(100) \text{ TeV}$, we can find the allowed region for W -ino dark matter in the parameter space, while for $M_5 \lesssim 100 \text{ TeV}$ no allowed region appears. This value of M_5 agrees with the result of rough estimation in the previous section, and the expectation is confirmed.

B. Implication to the detection

As we have shown, in brane world cosmology it is found that the W -ino-like neutralino with the weak scale mass can be a candidate for cold dark matter. In this section, toward verifying or excluding the scenario, we discuss the implication to direct and indirect detection experiments.

We study the spin-independent cross section for the neutralino-proton elastic scattering $\chi p \rightarrow \chi p$. The funda-

mental process for the direct detection is the neutralino-quark scattering $\chi q \rightarrow \chi q$. The relevant effective interactions in the nonrelativistic limit are given as

$$\mathcal{L} = d(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5q) + f(\bar{\chi}\chi)(\bar{q}q). \quad (20)$$

The interaction can be divided into two parts: the spin-dependent part which consists of the t -channel Z boson exchange and the s -channel squark exchange, and the spin-independent part which consists of the t -channel neutral light and heavy Higgs bosons exchange and the s -channel squark exchange. The first term in Eq. (20) corresponds to the spin-dependent interaction and the second term corresponds to the spin-independent interaction. The spin-independent cross section for $\chi p \rightarrow \chi p$ scattering, σ_p^{SI} , can be calculated using the coefficient f in Eq. (20) [22].

Figures 7–9 contain the contour plot of the spin-independent cross section in the $(m_{3/2}, m_0)$ plane for $\tan\beta = 10, 30,$ and 40 . The five-dimensional Planck mass is fixed at $M_5 = 100$ TeV in these figures. The number associated with each line represents the value of the cross section normalized by 10^{-9} pb. In the shaded region, the WMAP constraint is satisfied.

For $\tan\beta = 10$ (Fig. 7), the expected detection cross section consistent with the WMAP result has an upper bound as $\sigma_p^{\text{SI}} \lesssim 5 \times 10^{-9}$ pb, and the cross section decreases as $m_{3/2}$ increases. For $\tan\beta = 30$ (Fig. 8), the detection cross section is slightly enhanced compared with the $\tan\beta = 10$ case, and σ_p^{SI} can be larger than $5 \times$

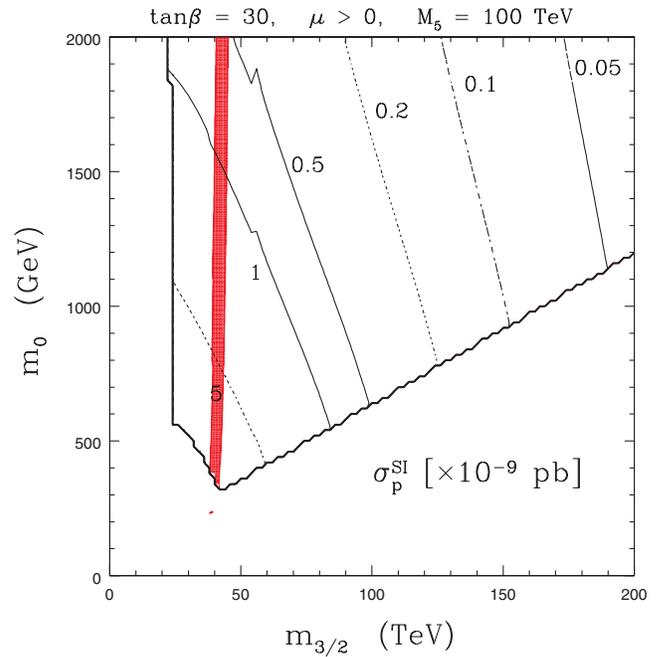


FIG. 8 (color online). The same as Fig. 7 but for $\tan\beta = 30$.

10^{-9} pb in the WMAP allowed region. For $\tan\beta = 40$ (Fig. 9), the detection cross section is much more enhanced, and σ_p^{SI} can be as large as 10^{-7} – 10^{-8} pb in the region consistent with the WMAP result.

Comparing with Figs. 1–6, one may see the corresponding allowed region of $\Omega_\chi h^2$ for another M_5 .

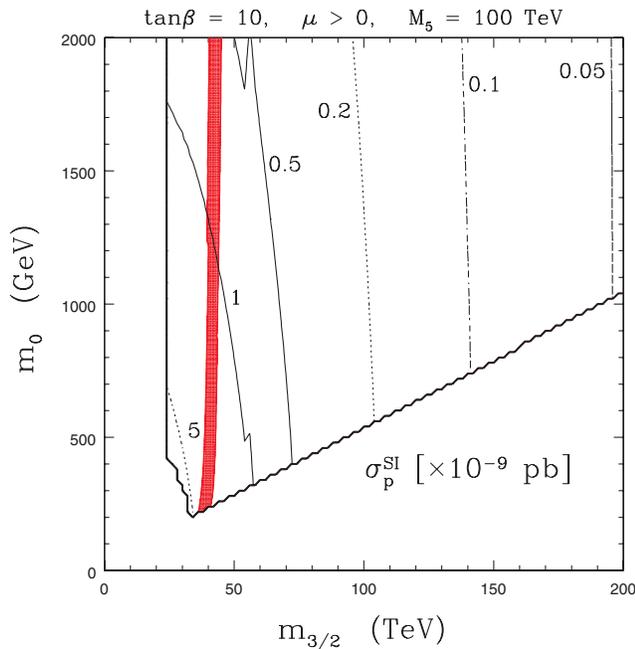


FIG. 7 (color online). Contours of the spin-independent cross section of $\chi p \rightarrow \chi p$, σ_p^{SI} , in the $(m_{3/2}, m_0)$ plane for $\tan\beta = 10$, $\mu > 0$, and $M_5 = 100$ TeV. The region consistent with the WMAP 2σ allowed range is shaded.

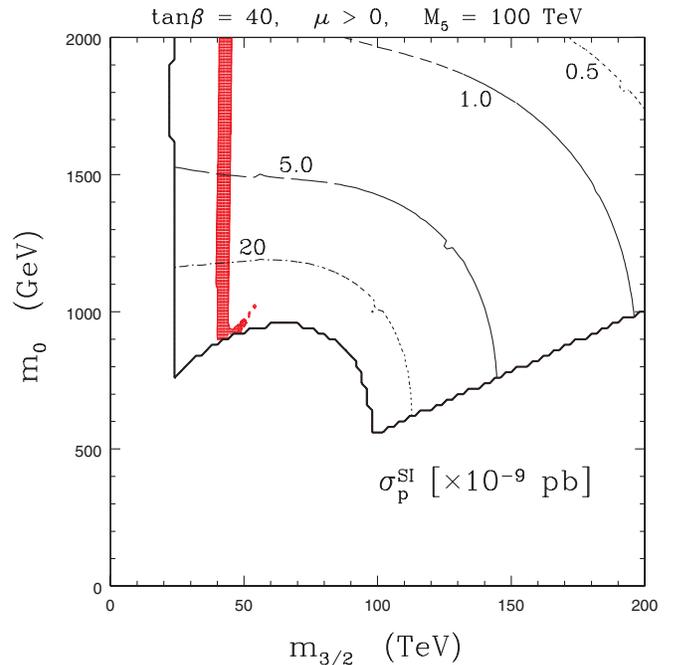


FIG. 9 (color online). The same as Fig. 7 but for $\tan\beta = 40$.

As an indirect search of W -ino dark matter in the universe, we can consider fluxes of cosmic positrons, antiprotons, and gamma rays originating from the annihilation of dark matter in the galactic halo. Interestingly, the HEAT experiment reported a flux of cosmic positrons in excess of the predicted rate, peaking around 10 GeV [23]. This would be reasonably explained by the annihilation of the W -ino-like neutralino with mass around 300 GeV [24]. Upcoming experiments such as PAMELA [25] and AMS-02 may be able to prove the excess of the positron flux and probe the W -ino-like neutralino with the weak scale mass.

IV. CONCLUSIONS

We have studied the W -ino-like neutralino relic density with the mass spectrum of the AMSB model in the context of brane world cosmology. Although the W -ino-like neutralino with the weak scale mass cannot be a candidate for dark matter in “standard cosmology” because of too efficient annihilation under the assumption that dark matter is a thermal relic, the modification of the expansion law in brane world cosmology, namely, the existence of a ρ^2 term, can enhance the relic density of dark matter, so that the W -

ino-like neutralino with mass of order 100 GeV can be a reasonable candidate for cold dark matter. We have performed numerical calculations and shown that the WMAP allowed region moves to the left in the $(m_{3/2}, m_0)$ plane and the mass of the W -ino-like neutralino becomes small to the order of 100 GeV, as the five-dimensional Planck mass M_5 is decreasing. The allowed region disappears eventually, when M_5 becomes as low as 100 TeV. While it has been reported that the lower bound on M_5 is $M_5 \gtrsim 600$ TeV for neutralino dark matter in the constrained MSSM [14], this bound is moderated as $M_5 \gtrsim 100$ TeV for the case of the W -ino-like neutralino. In addition, we have briefly discussed the direct and indirect detections of the W -ino-like neutralino with mass of order 100 GeV.

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