Gravitino dark matter from gluino late decay in split supersymmetry

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In split-supersymmetry (split-SUSY), gluino is a metastable particle and thus can freeze out in the early universe. The late decay of such a long-life gluino into the lightest supersymmetric particle (LSP) may provide much of the cosmic dark-matter content. In this work, assuming the LSP is gravitino produced from the late decay of the metastable gluino, we examine the Wilkinson microwave anisotropy probe (WMAP) dark-matter constraints on the gluino mass. We find that to provide the full abundance of dark matter, the gluino must be heavier than about 14 TeV and thus not accessible at the CERN large hadron collider (LHC).

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I. INTRODUCTION

In the recently proposed split-supersymmetry (split-SUSY) [1], inspired by the need of fine-tuning for the cosmological constant, the authors argued that the fine-tuning problem in particle physics does not have to be solved by SUSY. The only phenomenological constraints on split-SUSY are then from the grand unification consideration as well as the dark-matter consideration. As a result, the sfermion mass scale can be very high while the gaugino/Higgsino mass scale is still around the weak scale. While the split-SUSY has the obvious virtue of naturally solving the notorious SUSY flavor problem, it predicts that no sfermions are accessible at the CERN LHC collider. Thus if split-SUSY is indeed chosen by nature, the only way to reveal SUSY at the LHC is through gaugino or Higgsino productions, especially the gluino production [2]. This makes it important to preexamine the possible mass range of these particles before the running of the LHC.

It is interesting that although the gauginos and Higgsinos in split-SUSY are required to be relatively light, they are recently found not necessarily below TeV scale from the grand unification and dark-matter requirements [3]. Actually, the grand unification requirement can allow a heavy gaugino mass as high as 18 TeV [3]. If all gauginos and Higgsinos are above TeV scale, the LHC is doomed to find no SUSY particles except a light Higgs boson if split-SUSY is true. Although the split-SUSY consequence in the dark-matter issue is also considered in the literature [3–5], the authors focused on neutralino next-to-lightest supersymmetric particle (NLSP) or the usual NLSP decaying to the LSP during the big bang nucleosythesis (BBN) era, which is severely constrained by the BBN and cosmic microwave background (CMB) in split-SUSY. In this work we study the dark-matter consequence of the long-life gluino in split-SUSY.

In the usual weak-scale SUSY, the LSP is usually assumed to be the lightest neutralino.[1] Gluino decays rapidly into the LSP and thus cannot freeze out to cause any dark-matter consequence. Only in the case that gluino is quasi-degenerate with the neutralino LSP can it have dark-matter consequence through gluino-neutralino coannihilation [8].

In split-SUSY, however, due to its long lifetime, gluino can freeze out before decaying and then decay slowly into the LSP, providing much of the cosmic dark-matter content. So the gluino late decay is one characteristic of split-SUSY. In this work, assuming the LSP is the gravitino (the so-called super weakly interacting massive particle (WIMP) dark-matter) produced from the late decay of the metastable gluino, we will examine the Wilkinson microwave anisotropy probe (WMAP) dark-matter constraints on the gluino mass.

Note that if the gluino lifetime is too long (as long as BBN time), the released energy from its decay may spoil the BBN success and also affect CMB as well as large scale structure formation [9]. Therefore, in our study we require that the gluino decays before BBN.

II. CALCULATIONS

The gluino relic density from thermal production can be calculated from the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle(n^2 - n_{\rm eq}^2), \qquad (1)$$

where H is the Hubble constant, n is the particle number density of gluino, $n_{\rm eq}$ is the equilibrium density, and $\langle\sigma v\rangle$ is the thermal averaged cross section of gluino annihilation. We can employ the freeze-out approximation technique to calculate the relic abundance.

[1]If gluino is the LSP, its relic abundance is severely constrained by the bounds from existing anomalous heavy isotope abundances [6,7].

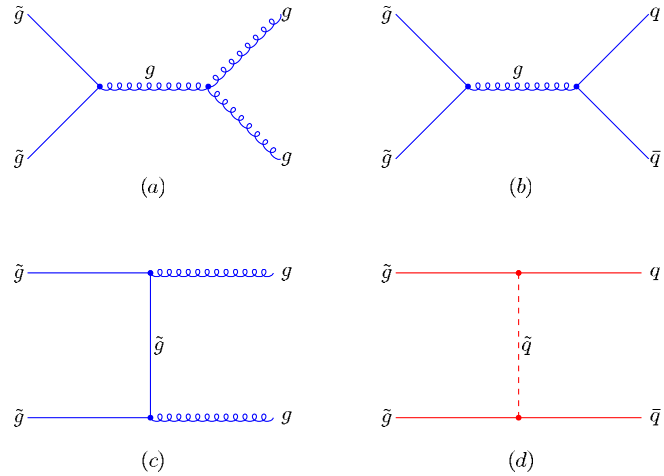

FIG. 1 (color online). Typical Feynman diagrams of gluino pair annihilation into the standard model (SM) particles. The last diagram through exchanging a squark makes negligible contribution in split-SUSY due to the superheavy squarks.

In split-SUSY the gluino pair annihilation proceeds through the s-channel gluon-exchange diagram and the t-channel gluino-exchange diagram, as shown in Fig. 1(a)–1(c). The squark-exchange diagrams shown in Fig. 1(d) drop out since they are suppressed by the superheavy squark masses. The perturbation annihilation cross section reads [6]

$$\sigma(\tilde{g}\,\tilde{g} \to gg) = \frac{3\pi\alpha_s^2}{16\beta^2 s}\left\{\log\frac{1+\beta}{1-\beta}[21 - 6\beta^2 - 3\beta^4] - 33\beta + 17\beta^3\right\}, \quad (2)$$

$$\sigma(\tilde{g}\,\tilde{g} \to q\bar{q}) = \frac{\pi\alpha_s^2\bar{\beta}}{16\beta s}(3-\beta^2)(3-\bar{\beta}^2), \quad (3)$$

where $\beta = \sqrt{1 - 4m_{\tilde{g}}^2/s}$ and $\bar{\beta} = \sqrt{1 - 4m_q^2/s}$ with $m_{\tilde{g}}$ and m_q being the gluino mass and quark mass, respectively. Multiple gluon exchanges between interacting $\tilde{g}$ will give rise to a Sommerfeld enhancement factor [10]

$$E = \frac{C\pi\alpha_s}{\beta}\left[1 - \exp\left\{-\frac{C\pi\alpha_s}{\beta}\right\}\right]^{-1}. \quad (4)$$

The interaction between the gluino and the goldstino (spin 1/2 component of gravitino) is suppressed by $1/F$ where F characterizes the SUSY breaking scale. The gluino decay width to goldstino in split-SUSY is given by [11]

$$\Gamma_{\tilde{G}g} = \frac{m_{\tilde{g}}^3}{2\pi F^2}C_5^{\tilde{G}2}, \quad (5)$$

where $C_5^{\tilde{G}} = -m_{\tilde{g}}/2\sqrt{2}$. Since the decay width is suppressed by $1/F$, not necessarily $1/M_{\rm pl}$, the gluino decay can be arranged to occur before BBN by choosing the value of F. Note the conventional superWIMP dark-matter scenario (gravitino is the LSP) is severely constrained by BBN and CMB [12] since the late decay of NLSP to LSP is assumed to occur at $10^6 \sim 10^8$ second and the released energy may spoil the success of standard BBN. In our study we avoided such severe constraints since we require the gluino decays before BBN time. Furthermore, we also require the gluino decays before QCD era. Otherwise, R-hadrons could be formed and the R-hadron annihilation could destroy gluinos [9].

The relic density of the gravitino LSP from the late decay of gluino is given by

$$\Omega_{\tilde{g}}\frac{m_{\tilde{G}}}{m_{\tilde{g}}}, \quad (6)$$

with the gravitino mass given by

$$m_{\tilde{G}} = \sqrt{\frac{8\pi}{3}}\frac{F}{M_{\rm pl}}. \quad (7)$$

Note that the gravitino can also be thermally produced [13] at the very early universe with temperature $T \sim M_{\rm pl}$ (or even a bit lower) and then freeze out when temperature drops. But between the time of gravitino generation and now, the universe is expected to experience an inflation. Such an inflation would dilute the thermal relic density of gravitino. So we neglect the gravitino thermal production at the very early universe. In the context of inflation, the universe is expected to be reheated after inflation. The gravitino can be generated from reheating if the reheating temperature is high enough [14]. In our study, we ignore such gravitino production by assuming the reheating temperature is not high enough to generate gravitino.

The cosmic nonbaryonic dark-matter relic density can be obtained from the WMAP measurements [15]

$$\Omega_m = 0.27^{+0.04}_{-0.04}, \qquad \Omega_b = 0.044^{+0.004}_{-0.004}, \quad (8)$$

where Ω_m is the total matter density and Ω_b is the baryonic matter density. Requiring the gravitino dark-matter abundance from the gluino late decay is within the 2σ range of the WMAP data, we obtain the allowed parameter space in the plane of M_{LSP} versus $M_{\tilde{g}}$, as shown in Fig. 2.

We see from Fig. 2 that if the gravitino LSP from the gluino late decay is to account for the whole gravitino dark-matter content, the gluino has to be heavier than about 14 TeV and gravitino has to be lighter than about 16 TeV.

A few remarks are in order regarding the above results.

(1) In our analyses the gluino is essentially assumed to be the NLSP. If it is not the NLSP, it would decay dominantly to the NLSP (say the neutralino $\tilde{\chi}_1^0$) followed by the decay of the NLSP to the gravitino LSP. In this case, although the gluino late decay also contributes to the dark-matter content, its contribution is small compared to the freeze-out of neutralino NLSP.

(2) Although the gluino is assumed to be the NLSP, the lightest neutralino $\tilde{\chi}_1^0$ (assumed to be heavier than gluino)

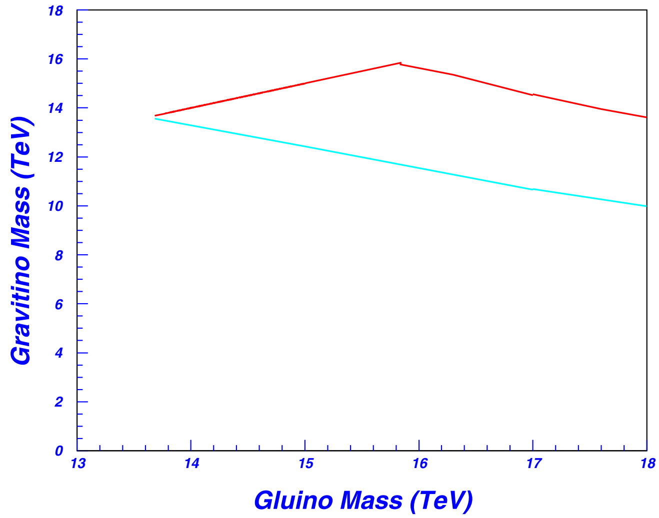

FIG. 2 (color online). The region between the two curves is the 2σ range allowed by the WMAP dark-matter data.

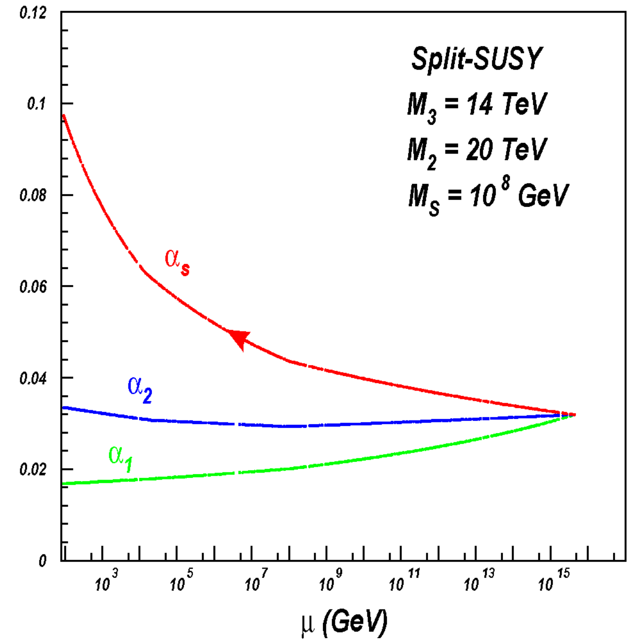

FIG. 3 (color online). The one-loop running of gauge couplings in split-SUSY with fixed values of M_3, M_2, and sfermion mass M_S.

can still freeze out since its decay to gluino is suppressed by heavy squark mass in split-SUSY. Of course, the neutralino freeze-out happens much earlier than gluino freeze-out since its interaction is much weaker. Depending on the lifetime of the neutralino, its dark-matter consequence can be quite different. If its decay to gluino happens before the freeze-out of gluino (corresponding to the relatively light squark mass), then the relic density of gluino is from the freeze-out, as assumed in our analyses. If its decay to gluino happens after the freeze-out of gluino (corresponding to the relatively heavy squark mass), then the relic density of gluino will be mainly from the neutralino decay. In such a case, a much stronger upper bound of about 2.2 TeV on the LSP mass obtained in [5] should be applicable in order not to overclose the universe (note that in our case the upper bound of 2.2 TeV is for gravitino LSP mass and the upper bound on the neutralino mass can be relaxed since now the relic density of dark matter is given by $\Omega_{\tilde{\chi}_1^0}\frac{m_{\tilde{G}}}{m_{\tilde{\chi}_1^0}}$).

Since our results are valid only in the case that the neutralino decay to gluino happens before the freeze-out of gluino, we now examine the condition of this scenario. When the gluino is as heavy as 14 TeV, its freeze-out temperature is found to be about $m_{\tilde{g}}/30$ and the freeze-out time is thus about 10^{-9} sec. The neutralino decays into gluino via exchanging a squark and its lifetime is sensitive to the forth power of squark mass:

$$\tau_{\tilde{\chi}_1^0} = 3 \times 10^{-2}\ \text{sec}\left(\frac{M_S}{10^9\ \text{GeV}}\right)^4\left(\frac{1\ \text{TeV}}{m_{\tilde{\chi}_1^0}}\right)^5, \qquad (9)$$

where M_S is squark mass. For a neutralino at the order of 10 TeV, in order to let its lifetime shorter than gluino freeze-out time ($\sim 10^{-9}$ sec), the squark mass can be chosen to be $M_S \sim 10^8$ GeV.

(3) Our analyses showed that the gluino (and all other gauginos or Higgsinos) must be heavier than about 14 TeV in order to provide the full dark-matter abundance in the scenario we considered. It is interesting to check whether or not such a scenario is consistent with the gauge couplings unification at some high energy scale. In Fig. 3 we show the one-loop running of three gauge couplings for $M_3 = 14$ TeV, $M_2 = 20$ TeV, and squark mass $M_S = 10^8$ GeV. Here, M_3 is gluino mass and, just like in Ref. [3], we assumed that Bino, Wino, and Higgsino are all degenerate at the scale M_2. From Fig. 3 we see that starting from M_Z scale,[2] α_1 and α_2 run up to higher energy scale and finally meet at a cross point at $\sim 10^{16}$ GeV. From this cross point α_s runs back to M_Z scale and ends at $\alpha_s(M_Z) = 0.098$. This value is welcome since, as pointed in [1], the two-loop effects will enhance α_s at M_Z scale by about 0.022. Taking into such effects, $\alpha_s(M_Z)$ in our scenario is just within the $2-\sigma$ range 0.119 ± 0.003 [16] allowed by experiments.

(4) Since in our scenario the gluino is the NLSP and all other gauginos are heavier than gluino, which is phenomenologically viable so far, the gauginos spectrum is different from that predicted by some theoretically favored models like mSUGRA. In the popular mSUGRA models, for example, the colored gluino is predicted to be heavier than other gauginos at the weak scale. However, such fancy

[2]The starting values of α_1 and α_2 at M_Z scale is fixed by $\alpha^{-1}(M_Z) = 128.936 \pm 0.0049$ and $\sin^2\theta_W(M_Z) = 0.23150 \pm 0.00016$ [16].

models may not be chosen by nature and phenomenologically we should not be restricted to them.

(5) If this dark-matter scenario (LSP is gravitino produced from the late decay of the metastable gluino in split-SUSY) is indeed chosen by nature, then no super particles of split-SUSY can be found at the LHC except a light Higgs boson whose mass is upper bounded by about 150 GeV [1].[3]

III. CONCLUSION

The metastable gluino in split-SUSY can freeze out in the early universe and then decay slowly into the LSP, providing much of the cosmic dark-matter content. If the LSP is the gravitino produced from the late decay of the metastable gluino, we found that the dark-matter consideration can constrain the parameter space of the gluino mass versus the gravitino mass: in order to provide the full abundance of dark matter, the gluino must be heavier than 14 TeV. Therefore, if nature takes this choice for dark matter, no gauginos or Higgsinos are accessible at the LHC. Then no super particles of split-SUSY can be found at the LHC except a light Higgs boson.

[3]This bound may be lowered by a few tens of GeV if right-handed neutrinos are introduced with seesaw mechanism [17].

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