Gravitino production from reheating in split supersymmetry

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We discuss gravitino production from reheating in models where the splitting between particle and sparticle masses can be larger than TeV, as naturally arising in the context of split supersymmetry. We show that such a production typically dominates over thermal contributions arising from the interactions of gauginos, squarks and sleptons. We constrain the supersymmetry breaking scale of the relevant sector for a given reheat temperature. However the situation changes when the gravitinos dominate the Universe and decay before nucleosynthesis. We briefly describe prospects for a successful baryogenesis and a viable neutralino dark matter in this case.

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I. INTRODUCTION

The recent satellite based experiments strongly favor primordial inflation [1]. Inflation is an attractive mechanism which explains the homogeneity and the flatness problem, the large scale structures through primordial density perturbations and the tiny fluctuation in the cosmic microwave background radiation [2]. However inflation leaves the Universe cold and devoid of any entropy. After inflation the Universe must be reheated in order to keep the successes of the hot big bang nucleosynthesis [3].

Inspite of the phenomenal success it has been extremely hard to pin down the inflaton sector [4]. This is mainly due to our ignorance of the physics beyond the Standard model (SM). The most popular paradigm is the minimal supersymmetric model beyond the SM [1]. Supersymmetry doubles the SM degrees of freedom by introducing a boson known as sfermion for every fermion. In this regard supersymmetry is a novel tool to probe the early Universe, which has a potential to be tested in the collider experiments. Supersymmetry is well motivated from a theoretical point of view, if it were broken in the observable sector at the electroweak scale, in which case it can address host of interesting issues, such as the hierarchy between the Planck and the electroweak scale, ameliorating the cosmological constant problem by 64 orders of magnitude, leading to a gauge unification at the grand unified scale, and along with R-parity providing a stable particle known as the lightest supersymmetric particle (LSP), which can be a suitable candidate for the cold dark matter.

Recently there has been an interesting proposal for an intermediate scale supersymmetry breaking at a scale above the electroweak but below the Planck scale by splitting the masses of the fermions and the bosons [6,7]. In this new scheme the bosons are heavier than the fermions. Although such a scheme does not attempt to address the hierarchy problem, but it keeps the gauge unification as a building block, and removes flavor and CP violating effects induced by the light scalars at one loop level. Running of the gauge couplings require the gauginos to be light at scales close to $1 - 100$ TeV, while spontaneous breaking of the electroweak symmetry requires the lightest Higgs to be around $\mathcal{O}(100)$ GeV.

A priori there is no fundamental theory which fixes this scale, but cosmological observations place severe constraint on the intermediate scale of supersymmetry breaking. The theory also permits a light and long lived gluino. The overproduction of gluinos place a severe bound on the scale of supersymmetry breaking which has to be less than 10^{13} GeV.

Embedding supersymmetry in gravity also leads to a new particle, which is also fairly long lived and known as gravitino, a superpartner of graviton. The main aim of this paper is to show that the production of gravitinos is inevitable from a sector which is responsible for reheating or generating entropy in the Universe. Our analysis is very general and it is applicable to many distinct cases, such as gravitino production from the decay of inflaton, supersymmetric flat directions, Q-balls, right handed Majorana sneutrino condensate, etc., All of them are responsible for generating entropy at various stages of the evolution of the Universe.

II. VARIOUS SOURCES FOR ENTROPY GENERATION

Inflaton sector is the most prominent source for entropy production. Assuming that the inflaton decay products thermalize instantly, then the reheat temperature of the Universe is given by $T_{\rm R} \approx \sqrt{\Gamma M_{\rm P}}$, where Γ is the inflaton decay rate to the light fermions. Inflaton can decay perturbatively [8–11] and nonperturbatively into gravitinos [12]. Gravitinos can also be generated from a thermal bath created by the inflaton decay products, mainly through interactions of the ordinary sparticles [13].

[1] Inflaton cannot be a gauge invariant flat direction of a minimal supersymmetric SM, where supersymmetry breaking scale in the observable sector is around 1 TeV, see [5].

Besides inflaton there are other sources of entropy production, supersymmetry has many flat directions, made up of gauge invariant combinations of squarks and sleptons, which may acquire nonvanishing vacuum expectation values (vevs) during inflation, thereby forming homogeneous zero-mode condensates. The condensates may play a significant role in many cosmological phenomena [14], such as generating baryons and dark matter particles by first fragmenting into Q-balls which then decay [15] through surface evaporation to generate late entropy, it has also been suggested that the origin of all matter and density perturbations could, in principle, be due to such flat directions [16]. The supersymmetric flat direction also leads to the excitation of primordial magnetic field [17] and plays important role in our understanding of reheating/preheating [18].

Quite similar conclusions hold for a heavy Majorana sneutrino condensate, whose decay can generate lepton asymmetry and entropy [19]. For our purposes we will study the decay rate of a generic condensate which is responsible for reheating the Universe and then we will discuss various consequences.

III. GRAVITINO PRODUCTION FROM REHEATING

We denote the mass difference between a scalar field ϕ, whose decay reheats the Universe, and its fermionic partner $\tilde{\phi}$ by $m \equiv m_\phi - m_{\tilde{\phi}}$. The supersymmetric conserving mass of this multiplet is assumed to be M, given by the superpotential term,

$$W = \frac{1}{2} M \Phi \Phi + \ldots, \tag{1}$$

where Φ is the chiral superfield whose scalar component is ϕ. Here ϕ can be the inflaton, supersymmetric flat direction, or whatever field whose decay generates entropy. Note that such a mass difference naturally arises after supersymmetry breaking from the soft mass term and B term. In addition to the ϕ multiplet, we define $\tilde{m}$ to be the mass difference between the SM particles and their superpartners.

In the context of split supersymmetry, it is natural to expect that $m \gg 1$ TeV. If ϕ is the inflaton, $m \leq 10^{13}$ GeV will be required from the bound on scalar and tensor perturbations [2] [2]. It is interesting that this bound coincides with that of the mass difference between the SM fermions and their scalar partners, denoted by $\tilde{m}$, derived from the requirement that gluino lifetime is less than the age of the universe [6]. So long as $m > m_{3/2}$, with $m_{3/2}$ being the gravitino mass, the process $\phi \rightarrow \tilde{\phi}$ + gravitino will be kinematically allowed. Moreover, for $m >$ few $\times$ $m_{3/2}$, helicity $\pm 1/2$ gravitinos will be mainly produced. These states essentially interact like the Goldstino ψ and the relevant couplings are [20]

$$\mathcal{L} \supset \frac{m_\phi^2 - m_{\tilde{\phi}}^2}{\sqrt{3} m_{3/2} M_{\rm P}} \phi^* \bar{\psi} \left(\frac{1 + \gamma_5}{2} \right) \tilde{\phi} + \text{h.c.}, \tag{2}$$

leading to the partial decay width

$$\Gamma_{\rm part} \simeq \frac{1}{48\pi} \frac{(m_\phi^2 - m_{\tilde{\phi}}^2)^4}{m_{3/2}^2 M_{\rm P}^2 M^3}. \tag{3}$$

Here $M_{\rm P} = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. The number of gravitinos produced per ϕ decay will be given by $\Gamma_{\rm part} \Gamma_{\rm tot}^{-1}$, where $\Gamma_{\rm tot} = (g_* \pi^2/30)^{1/2} T_{\rm R}^2 / M_{\rm P}$ is the total decay rate of ϕ (and $\tilde{\phi}$ if $m \ll M$). Here $T_{\rm R}$ denotes the reheat temperature of the Universe and g_* is the number of relativistic degrees of freedom at $T_{\rm R}$. If $T_{\rm R} > \tilde{m}$, we have $g_* = 225$. For $T_{\rm R} < \tilde{m}$ squarks and sleptons are decoupled from the thermal bath but this will be numerically irrelevant for our calculations. If $M \gg m$, which we consider to be the case and after taking into account of the dilution factor, $3T_{\rm R}/4m_\phi$, we find

$$\left(\frac{n_{3/2}}{s} \right)_\phi \simeq 2.5 \times 10^{-2} \frac{m^4}{m_{3/2}^2 T_{\rm R} M_{\rm P}}. \tag{4}$$

The most interesting point is that M drops out of the calculations. In an opposite limit $M \ll m$, which happens for squark and slepton fields in this scenario, see Refs. [6,7], the result will be smaller by a factor of 16.

There are two other sources of gravitino production from ordinary sparticles in the early Universe. One is through the scatterings of gauge and gaugino quanta in the primordial thermal bath. This is most effective when the bath has its highest temperature, $T_{\rm R}$, leading to [13]

$$\left(\frac{n_{3/2}}{s} \right)_{\rm sc} \simeq \left(1 + \frac{M_{\tilde{g}}^2}{12 m_{3/2}^2} \right) \left(\frac{T_{\rm R}}{10^{10}\ \text{GeV}} \right) \times 10^{-12}, \tag{5}$$

where $M_{\tilde{g}}$ is the gluino mass. Gravitinos are also produced in the decay of ordinary sparticles. If all sparticles have thermal equilibrium abundance, we have [20]

$$\left(\frac{n_{3/2}}{s} \right)_{\rm dec} \simeq \left(\frac{\tilde{m}}{m_{3/2}} \right)^2 \left(\frac{\tilde{m}}{10^9\ \text{GeV}} \right) \times 10^{-13}. \tag{6}$$

We remind that $\tilde{m}$ is the mass difference between the SM particles and their super partners. The contribution from sparticle decays dominates when [7]

$$T_{\rm R}^{1/3} m_{3/2}^{2/3} < \tilde{m} < T_{\rm R}. \tag{7}$$

Outside this range, contribution from scatterings will be dominant.

Depending on whether gravitino is the LSP or not, its abundance is constrained by various considerations. If gravitino is not the LSP, it will be unstable with a decay

[2] This is strictly correct for a single field chaotic type inflationary models.

lifetime, $\tau_{3/2} \sim M_{\rm P}^2/m_{3/2}^3$. For $m_{3/2} > 100$ GeV gravitino decays before BBN, and hence does not affect the late cosmology. Its decay, however, will produce one neutralino per gravitino. If gravitino decay occurs below the neutralino free-zeout temperature, nonthermal LSPs thus produced should not overclose the Universe. This implies that,

$$\frac{n_\chi}{s} \leq 3 \times 10^{-10}\left(\frac{1~\text{GeV}}{m_\chi}\right), \tag{8}$$

provided that neutralino annihilation is not efficient at the time of gravitino decay, where we have denoted the neutralino mass by m_χ. If $m_{3/2} < 100$ TeV, gravitino lifetime is long enough to affect nucleosynthesis. For $1\text{TeV} \leq m_{3/2} \leq 100$ TeV, hadronic decay modes lead to the strongest constraints [21], while, for $m_{3/2} < 1$ TeV, radiative decays yield the most stringent bounds [22].

Finally, if gravitino is the LSP, its abundance should not exceed that of a dark matter contribution. Thus,

$$\frac{n_{3/2}}{s} \leq 3 \times 10^{-10}\left(\frac{1~\text{GeV}}{m_{3/2}}\right). \tag{9}$$

The total abundance of gravitinos in our case is given by

$$\left(\frac{n_{3/2}}{s}\right)_{\rm tot} = \left(\frac{n_{3/2}}{s}\right)_{\phi} + \left(\frac{n_{3/2}}{s}\right)_{\rm dec} + \left(\frac{n_{3/2}}{s}\right)_{\rm sca}. \tag{10}$$

We now require that the contribution from ϕ decay to be subdominant, so that the constraints derived in Ref. [7] remain valid. If the dominant contribution to the gravitino abundance comes from scatterings, see Eq. (5), and by assuming that $M_{\tilde g} \sim m_{3/2}$, this will require,

$$m^4 < 10^{-2} m_{3/2}^2 T_{\rm R}^2. \tag{11}$$

This should particularly hold when $T_{\rm R} < \tilde m$, which leads to a tighter bound, $m^2 < 0.1 m_{3/2}\tilde m$. In the opposite case, when sparticle decays, contribution from Eq. (6) dominates the gravitino abundance, we find the bound to be,

$$m^4 < 10^{-2}\tilde m^3 T_{\rm R}. \tag{12}$$

An absolute upper bound, $m^2 < 0.1\tilde m^3/m_{3/2}^2$, can be obtained in this case after using the first inequality in Eq. (7).

One comment is in order at this point. Gravitinos are fermions, and hence their occupation number is limited by the Pauli blocking which has to be ≤ 1. The available phase space for ϕ decay constrains the physical momentum of the produced gravitinos to be $k_{3/2} < m$. This, as noted in [11], implies an upper limit $\simeq 3 \times 10^{-4}(m/T_{\rm R})^3$ on the comoving abundance of gravitinos from ϕ decay [3].

[3]Here we have assumed the maximum occupation number throughout the available phase space. This is a valid approximation despite the fact that $k_{3/2}$ is narrowly peaked around m at the time of production. Note that ϕ decay does not occur instantly, and hence during its lifetime $k_{3/2}$ will sweep the phase space due to the Hubble expansion.

The quantity $n_{3/2}/s$ reaches the saturation limit for

$$m_{\rm sat} \simeq 10^{-2}\frac{m_{3/2}^2 M_{\rm P}}{T_{\rm R}^2}. \tag{13}$$

When $m > m_{\rm sat}$, the left-hand side of Eq. (4) should be replaced by $3 \times 10^{-4}(m/T_{\rm R})^3$. The bounds in Eqs. (11) and (12) will in this case be modified accordingly.

So far we have assumed that ϕ dominates the energy density of the Universe at the time of decay. Now let us consider the case in which ϕ carries a fraction $r < 1$ of the total energy density when it decays. The ϕ field cannot be the inflaton in this case, and hence another field should be responsible for reheating the Universe. The candidates are supersymmetric flat directions, sneutrino condensate and perhaps the Q-balls. If we denote the temperature of a thermal bath at the time of ϕ decay by $T_{\rm d}$, the bounds in Eqs. (11) and (12) will be replaced by

$$m^4 < 10^{-2} r^{-1} m_{3/2}^2 T_{\rm R} T_{\rm d}, \tag{14}$$

and

$$m^4 < 10^{-2} r^{-1}\tilde m^3 T_{\rm d}, \tag{15}$$

respectively. It is interesting to note that the constraint on m does not change considerably. Even if $r = 10^{-4}$, the upper bound on m will be at most weakened by 1 order of magnitude. Also note that $T_{\rm d} \ll T_{\rm R}$ can compensate for $r \ll 1$. Our bounds in Eqs. (11) and (12) are therefore practically valid for any species which undergoes an out-of-equilibrium decay.

In addition to the entropy production during reheating, a stage of out-of-equilibrium decay is usually needed in supersymmetric theories for a successful cosmological scenario. If the reheat temperature after inflation is too high, gravitino production from the interactions of ordinary sparticles in a thermal bath exceeds the bounds set by nucleosynthesis (for unstable gravitino) and dark matter (for stable gravitino). A late stage of entropy release will be necessary in this case. In addition, supersymmetric flat directions typically generate a large amount of baryon asymmetry via Affleck-Dine mechanism [23]. The dilution of this excessive asymmetry requires late entropy release and late evaporation of Q-balls can ameliorate this situation. However Q-ball evaporation is also a source for gravitino production. As mentioned earlier, any out-of-equilibrium decay directly produces gravitinos and will therefore be subject to the bounds coming from Eqs. (11) and (12). For a late stage of entropy release, $T_{\rm R} \ll \tilde m$, a tighter bound on m is expected.

IV. COSMOLOGICAL CONSEQUENCES OF DOMINATING GRAVITINOS

Every stage of entropy release generates gravitinos, one alternative paradigm could be that the gravitinos produced in ϕ decay dominate the energy density of the Universe

[7]. Note that the situation is now slightly different from the case when gravitinos from scatterings or decay of ordinary sparticles dominate. There gravitino energy is essentially the same as the temperature of a thermal bath at the time of its production. Gravitinos then become nonrelativistic when $T \simeq m_{3/2}$. Here, however, gravitino energy is $\simeq m$, which can be very different from $T_{\rm R}$. If $m < T_{\rm R}$, gravitinos become nonrelativistic at $T > m_{3/2}$, and hence can dominate at an earlier time. The opposite situation will happen for $m > T_{\rm R}$. In this case gravitino decay is responsible for the last stage of reheating which will dilute the existing (thermal) relic neutralinos and baryon asymmetry. This can be considered as a problem turned into a virtue, in particular, if baryon asymmetry was (over)produced via Affleck-Dine mechanism. However, gravitino decay will also produce neutralinos, χ, with an abundance,

$$\frac{n_\chi}{s} \simeq \left(\frac{m_{3/2}}{M_{\rm P}}\right)^{1/2}. \tag{16}$$

For $m_{3/2} > 10^5$ GeV, such that gravitino decay does not affect nucleosynthesis, this abundance is much larger than the dark matter bound. A large annihilation cross-section $\langle \sigma_\chi v_{\rm rel} \rangle$ will therefore be needed in order to bring the neutralino abundance down to an acceptable level. Note that $\langle \sigma_\chi v_{\rm rel} \rangle = c/m_\chi^2$, where in the case of split supersymmetry, $c = 3 \times 10^{-3}$ for a mostly Higgsino χ, and $c = 10^{-2}$ for a mostly Wino type neutralino, χ, [7]. The final abundance for χ will then be given by,

$$\frac{n_\chi}{s} \simeq \frac{m_\chi^2}{c(m_{3/2}^3 M_{\rm P})^{1/2}}, \tag{17}$$

where $s \propto T_{3/2}^3 \propto (m_{3/2}^3/M_{\rm P})^3$ after gravitino decay. An interesting point is that χ abundance in this case only depends on m_χ and $m_{3/2}$, and viable neutralino dark matter determines the acceptable part of this two-dimensional parameter space.

One can also think of a following intriguing possibility. A large baryon asymmetry is generated via Affleck-Dine mechanism (perhaps through Q-ball formation) in split supersymmetry. The Q-ball decay, which has a longer lifetime than a homogeneous condensate, then produces a large number of gravitinos along with other fermions. Gravitinos eventually dominate the energy density of the Universe and their decay sufficiently dilutes the baryon asymmetry, as well as producing nonthermal dark matter. More detailed study of these issues will be presented in a future publication [24].

Note that gluinos can also be produced in a similar way from the decay of the ϕ field. If kinematically allowed the gravitinos can decay into gluon and gluinos. As discussed earlier in Ref. [6], the gluinos can be long lived, nevertheless if their mass is above 1 TeV and $\tilde{m} \sim 10^9$ GeV then they decay before nucleosynthesis, see also Ref. [25]. We do not consider gluino cosmology further in this paper.

V. CONCLUSION

Under general circumstances every entropy production process is accompanied by gravitino production. We stress that particularly in the context of split supersymmetry such a contribution can easily dominate over thermal generation and from the decay of ordinary sparticles.

Our main results, given by Eqs. (11) and (12), constrain the supersymmetry breaking scale of the sector which is responsible for reheating the Universe. Note that the bounds are robust because the supersymmetry conserving mass of the decaying field does not appear in the constraints.

In order to evade these bounds one could alternatively imagine that the unstable gravitinos were abundantly produced and dominated the Universe. For a sufficiently massive gravitinos the late stage of reheating does not affect nucleosynthesis. However the entropy release would dilute baryon asymmetry created earlier and produce neutralinos. A large annihilation of neutralinos can bring the abundance to match the current observed value for the cold dark matter, the abundance will depend only on neutralino and gravitino mass. Baryogenesis scenarios based on supersymmetric flat directions in general produce large baryon asymmetry of order one, it is then possible to dilute their abundance required for a successful big bang nucleosynthesis.

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