The degenerate gravitino scenario

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Abstract. We propose an alternative solution to the gravitino problem in supersymmetric theories. In the “degenerate gravitino” scenario the mass difference between the gravitino and the LOSP (lightest ordinary MSSM particle) is much smaller than the gravitino mass itself. As a consequence, the energy released in the decay of the next to lightest supersymmetric particle (NLSP) is reduced. The cosmological and astrophysical constraints on the gravitino abundance, and hence on the reheating temperature, become softer than in the usual case. We explore the parameter space of this scenario and confront it with the above mentioned constraints. In the case of neutralinos LOSP, mass splittings of order $10^{-2}$ GeV are possible, while for stau LOSP the splitting can be of order tens of GeVs. In both cases, maximal reheating temperatures, compatible with thermal leptogenesis are reached.

1. Introduction
The gravitino is notoriously known to cause a lot of trouble in cosmology [1, 2]. Even after inflation was discovered and recognized as a solution to the relic problem of standard cosmology, it was soon realized that gravitinos are re-created at reheating [3]. As their number density depends on the reheating temperature, this last cannot be too high [4]. This is at the origin of the well-known tension on the reheating temperature in thermal leptogenesis. In the case of a decaying gravitino, the problem comes from the energetic decay products that can potentially destroy the light elements. On the other hand, if the gravitino is stable, the danger comes from overclosure of the Universe. Eventhough gravitinos produced at reheating can make out all of dark matter, there can be other production mechanisms that produce gravitinos, like decay of heavier MSSM particles or the inflaton. These considerations make the gravitino abundance severely constrained. Several mechanisms have been devised to address this problem. One approach is to make the gravitinos decay before big bang nucleosynthesis (BBN) rendering them harmless [2]. The other approach is to make the gravitino stable in which case it can play the role of cold dark matter [5]. In [6], we aimed to investigate alternative solutions to the gravitino problem that allow for high reheating temperatures compatible with thermal leptogenesis. As the gravitino couplings are fixed by supergravity, this does not leave much freedom and the only free parameter available is the gravitino mass itself $m_{3/2}$. We were led to a specific scenario where the gravitino is almost degenerate with the LOSP, which as we will see allows to address the cosmological gravitino problem.
2. The degenerate gravitino scenario
The degenerate gravitino scenario proposed in [6] is defined through the requirement that the mass splitting between the gravitino and the LOSP is smaller than the gravitino mass itself i.e. \( \Delta M = |m_{3/2} - m_{\text{LOSP}}| \equiv \delta m_{3/2} \ll m_{3/2} \). Therefore, effectively, we are left with only the gravitino and the LOSP as all remaining MSSM particles are assumed to be heavier and the gravitino can be either the LSP or the NLSP. Furthermore, the smallness of the mass splitting has two main consequences. First the decay products are much softer and they do not cause trouble with BBN. Second, the NLSP lifetime increases and its decay occurs much later, so the gravitino is almost stable and can play the role of cold dark matter or part of it. As the gravitinos in our case decay much later than usual, it is not enough to check that the gravitinos do not conflict with BBN. Gravitino decay will affect different eras and thus will be subject to different constraints.

3. Constraints
Let us begin with the most straightforward constraint. The relic density of cold dark matter will have two components: a thermal one produced through scatterings or freeze-out and a non thermal one produced through the decay of the NLSP. The sum of these two should match the observed CDM relic abundance. This requirement is expressed as \( \Omega_{\text{CDM}} h^2 = \Omega_{\text{LSP}} h^2 + \Omega_{\rm NLSP} h^2 \approx 0.11 \). It also is useful to define a new parameter \( \omega \equiv Y_{\rm NLSP} / Y_{\text{CDM}} \), which quantifies the amount of present cold dark matter coming from the NLSP decay. In this equation \( Y_{\rm NLSP} \) refers to the NLSP yield just before its decay. In the following, the various constraints will apply on \( \delta \) and \( \omega \) according to the NLSP lifetime. Next, we consider BBN constraints. At temperatures of order \( T \sim 1 \) MeV, the light nuclei are synthesized in the primordial plasma. These temperatures corresponds to times between 1 sec and \( 10^3 \) sec. The obtained abundances in standard BBN calculations are in striking agreement with observation. However, the injection of energetic particles in the primordial plasma at BBN or later can disrupt the standard BBN processes [7, 8, 9, 10], leading to a disagreement between theory and observation. In our scenario,
we need to worry only about 2-body electromagnetic decays \(^1\) as it is the only ones allowed by the small mass splitting.

For longer lifetimes, we should consider CMB constraints. In addition to BBN constraints, for long lifetimes \(\tau_{\text{NLSP}} \gtrsim 10^7\) sec., there are strong bounds from the shape of the CMB blackbody spectrum. As pointed out in \([4]\), the late injection of electromagnetic energy may distort the frequency dependence of the CMB spectrum from its observed blackbody shape.

After recombination, at the cosmic time around \(10^{13}\) sec, the number density of free electrons drops quickly and the photons are almost free from the interactions. Therefore the photons from the decaying particles can reach us now and contribute to the Diffuse Electromagnetic Background (DEBRA).

The present photon flux from two-body decay can be written as

\[
\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi} \int_{t_i}^{t_0} \frac{dt}{\tau_{\text{NLSP}}} \frac{\rho_\gamma \Omega_{\text{WMAP}}}{m_{\text{NLSP}}} \omega_{\text{em}} e^{-t/\tau_{\text{NLSP}}} \delta(E_\gamma - aE_{\text{em}}),
\]

where \(E_{\text{em}} \approx m_{\text{NLSP}}\delta\) is the energy of the photon at production, \(\tau_{\text{NLSP}}\) and \(m_{\text{NLSP}}\) are the lifetime and mass of NLSP, \(\rho_\gamma = 3\Omega_h^2/8\pi G N = 8.0992 h^2 \times 10^{-47}\) GeV\(^4\) and \(a = a(t)\) is the time-dependent scale factor with \(a(t_0) = 1\) at present time \(t_0\).

The expected flux Eq. (1), has to be compared with bounds from SPI, COMPTEL and EGRET, \([11]\). Fig. 1 shows combined CMB, BBN and DEBRA constraints in the case of a Bino NLSP. As one can see, for splittings of order 100 GeV, \(B_{\text{em}}\omega\) is below order \(10^{-3}\). As \(\Delta M\) decreases to \(10^{-1}\) GeV, \(\omega B_{\text{em}}\) is bound to be below \(10^{-6}\). Starting from \(\Delta M \approx 10^{-1}\) GeV, higher values of \(\omega B_{\text{em}}\) are allowed, until reaching \(\Delta M \approx 10^{-1}\) GeV, where all values of \(\omega B_{\text{em}}\) are allowed. What about the allowed reheating temperature \(T_R\) after inflation? One can translate the previous combined bounds on bounds on \(T_R\). Fig. 2 shows such a bound for a scenario with gravitino NLSP and Bino LSP. On the other hand, for the opposite case where the gravitino is the LSP, maximal reheating temperatures of order \(10^6\) GeV, compatible with thermal leptogenesis are always possible provided the relic density of NLSPs is suppressed \((\omega \ll 1)\).

Up to now, we discussed the situation where the gravitino is almost degenerate with the neutralino. In the MSSM, the LSP can also be the lightest stau. This region is usually discarded because in this case cold dark matter is charged, which is excluded by heavy water data \([12]\). However in our case, there is no reason to exclude it since the stau can be the NLSP, with the gravitino as the LSP. In addition to the previous bounds that apply equally, the so-called Catalyzed BBN (CBBN) \([13]\) bounds on the staus abundance \((Y_{\tau} < Y_{\text{CBBN}})\) apply. These are shown in Fig. 3. Applying the CBBN constraint \(Y_{\text{CBBN}} = 2 \times 10^{-16}\) derived in \([14, 15]\) results in a very stringent constraints that eliminates almost all of parameter space. On the other hand, applying the most conservative CBBN constraint \(Y_{\text{CBBN}} = 10^{-14} - 10^{-15}\) \([16, 17]\) still allows some parameter space to survive.

What about the degenerate gravitino in the simplest framework of weak scale supersymmetry? the so-called CMSSM (Constrained MSSM) which is one of its simplest and most popular realizations for phenomenological studies. It is defined in terms of only five free parameters: a common scalar \((m_0)\), gaugino \((m_{1/2})\) and tri–linear \((A_0)\) mass parameters (all specified at the GUT scale) plus the ratio of Higgs vacuum expectation values \(\tan \beta\) and \(\text{sign}(\mu)\), where \(\mu\) is the Higgs/higgsino mass parameter whose square is computed from the conditions of radiative electroweak symmetry breaking. Furthermore, the gravitino mass \(m_{3/2}\) is kept as a free parameter. We have analyzed the degenerate gravitino scenario in the context of the CMSSM framework. In addition to the previously mentioned constraints, we applied low energy constraints to obtain the highest reheating temperature that can be reached in the CMSSM.

\(^1\) This means that we will consider only decays \(\text{NLSP} \rightarrow \text{LSP} + X (X = \gamma, \tau)\) as we will see later, and \(B_{\text{em}} \approx 1\) hereafter, where \(B_{\text{em}}\) stands for the electromagnetic branching ratio.
Figure 3. CBBN bounds on the degenerate gravitino scenario with stau NLSP. The region on the right of the vertical line is ruled-out by heavy water data.

fulfilling the WMAP constraint on the CDM abundance and the relevant collider bounds; namely, direct SUSY searches, \((g−2)_\mu\) using \((e^+e^- \rightarrow \text{hadrons})\) data and the \(BR(B \rightarrow X_s\gamma)\). The results are shown in Fig. 4 for two representative sets of CMSSM parameters. Note that the highest reheating temperatures are always reached around regions of the parameter space where the neutralino relic density is suppressed, like for example the stau-neutralino coannihilation region for low \(\tan\beta\) and “focus point” or “hyperbolical branch” for large \(\tan\beta\).

4. Conclusions

We proposed an alternative solution that addresses the gravitino problem in thermal leptogenesis by making the gravitino degenerate with the LOSP. This has the direct consequence that the injected energy is suppressed, making the decay products less dangerous for BBN. Due to the small mass splitting, the gravitino and the LOSP are typically long-lived. We analyzed this scenario (the “degenerate gravitino” scenario) by confronting it to cosmological and astrophysical constraints. Since the NLSP decays at or after BBN, we considered in addition to BBN, constraints from CMB spectral distortions and diffuse gamma rays observations. First we performed a model-independent analysis by considering a generic NLSP-LSP degenerate scenario where the NLSP decays through NLSP→LSP+\(X\) \((X = \gamma, \tau)\). Since the final cold dark matter relic density is the sum of both thermal and non-thermal contributions, we required that the total cold dark matter is consistent with cosmological observation. Then, using the results of this analysis, we studied the degenerate gravitino scenario in the context of the CMSSM where three types of spectra arise, they are: gravitino NLSP with neutralino LSP and gravitino LSP with neutralino or stau NLSP. Each of these cases has been analyzed in this framework defined by the usual high energy parameters \((m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu))\) and the gravitino mass \(m_{3/2}\), and confronted with low-energy observables. We find that high reheating temperatures consistent with thermal leptogenesis can be found in all three scenarios if a sizable part of cold dark matter comes from gravitinos produced at reheating. In this case, depending on \(\tan\beta\), we are led to regions in the parameter space where the relic density of stau and neutralinos are
Figure 4. The reheating temperature in the CMSSM in the degenerate gravitino scenario for two sets of parameters. In both panels the red (medium grey) region is forbidden by the Higgs bound from LEP and in the very light grey region no correct electroweak symmetry breaking is obtained. The light brown (light grey) band below the NEWB area corresponds to the region forbidden by the LEP chargino bound. The regions below the dashed green lines satisfy the $(g-2)_\mu$ constraint at the 2 $\sigma$ ($a_{\mu}^{\text{SUSY}} > 2.43 \times 10^{-10}$) or 3 $\sigma$ level ($a_{\mu}^{\text{SUSY}} > 11.45 \times 10^{-10}$). In both plots, we used $m_t = 173.1$ GeV.

somewhat suppressed. In general to satisfy all the constraints, the mass splitting between the NLSP and LSP should be $\Delta M \simeq 10^{-2}$ GeV for the degenerate neutralino-gravitino scenario, which implies very long-lived NLSPs which are beginning to decay at present. On the other hand, in the gravitino-stau scenario, splittings in the range $10 \text{ GeV} \lesssim \Delta M \lesssim 90 \text{ GeV}$ are still consistent with reheating temperatures of the order of $10^9$ GeV if we consider the conservative CBBN constraint.

Let us comment on the required degeneracy in the “degenerate gravitino” scenario. Although a degeneracy of the order of $\Delta M \simeq 10^{-2}$ GeV certainly implies a certain amount of fine-tuning, this tuning is only two orders of magnitude stronger than the usual tuning required in the coannihilation or funnel regions to obtain the right relic density in the MSSM. On the other hand, notice also that the fine tuning in our scenario is much softer that the tuning required in other scenarios like inelastic dark matter [18].

Finally, it is also important to consider the phenomenological consequences of this scenario in colliders. In the case of neutralino LSP or NLSP, the only indirect signal of this scenario will be that the relic density of neutralinos inferred from the measurements of supersymmetric masses and couplings at LHC, will not match the observed cold dark matter abundance and will be smaller. However, the measurements at direct detection experiments will agree with the cross sections obtained from colliders. On the other hand, for stau NLSP, the collider signatures would be spectacular, as the staus would be completely stable at collider scales and slow charged tracks will appear in the detector [19]. In this case direct detection experiments will give a null results as all the dark matter at present times is made of gravitinos. Therefore, the "degenerate gravitino" scenario will be probed at colliders and direct detection experiments if SUSY is discovered at LHC.
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