

Gravitino Dark Matter in the CMSSM With Improved Constraints from BBN

David G. Cerdeño

Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, UK
E-mail: d.g.cerdeno@durham.ac.uk

Ki-Young Choi

Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK
E-mail: K.Choi@sheffield.ac.uk

Karsten Jedamzik

*Laboratoire de Physique Théorique et Astroparticules, CNRS UMR 5825,
Université Montpellier II, F-34095 Montpellier Cedex 5, France*
E-mail: jedamzik@LPM.univ-montp2.fr

Leszek Roszkowski

Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK
E-mail: L.Roszkowski@sheffield.ac.uk

Roberto Ruiz de Austri

*Departamento de Física Teórica C-XI and Instituto de Física Teórica C-XVI,
Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*
E-mail: rruiz@delta.ft.uam.es

ABSTRACT: In the framework of the Constrained MSSM we re-examine the gravitino as the lightest superpartner and a candidate for cold dark matter in the Universe. Unlike in most of other recent studies, we include both a thermal contribution to its relic population from scatterings in the plasma and a non-thermal one from neutralino or stau decays after freeze-out. Relative to a previous analysis [1] we update, extend and considerably improve our treatment of constraints from observed light element abundances on additional energy released during BBN in association with late gravitino production. Assuming the gravitino mass $m_{\tilde{G}}$ in the GeV to TeV range, and for natural ranges of other supersymmetric parameters, the neutralino region is excluded, except for rather exceptional cases, while for smaller values of $m_{\tilde{G}}$ it becomes allowed again. The gravitino relic abundance is consistent with observational constraints on cold dark matter from BBN and CMB in some well defined domains of the stau region but, in most cases, only due to a dominant contribution of the thermal population. This implies, depending on $m_{\tilde{G}}$, a large enough reheating temperature. If $m_{\tilde{G}} > 1 \text{ GeV}$ then $T_R > 10^7 \text{ GeV}$, if allowed by BBN and other constraints but, for light gravitinos, if $m_{\tilde{G}} > 100 \text{ keV}$ then $T_R > 10^3 \text{ GeV}$. On the other hand, constraints mostly from BBN imply an upper bound $T_R \lesssim \text{a few} \times 10^8 \text{ GeV}$ which appears inconsistent with thermal leptogenesis. Finally, most of the preferred stau region corresponds to the physical vacuum being a false vacuum. The scenario can be partially probed at the LHC.

KEYWORDS: Supersymmetric Effective Theories, Cosmology of Theories beyond the SM, Dark Matter, Supersymmetric Standard Model.

Contents

1. Introduction	1
2. Framework and Procedure	5
3. Improved BBN Analysis	8
4. False Vacua	12
5. T_R versus $m_{\tilde{G}}$	15
6. Summary	18

1. Introduction

Weakly interacting massive particles (WIMPs) remain the most popular choice for cold dark matter (CDM) in the Universe. This is because they are often present in various extensions of the Standard Model (SM). For example, neutralinos in softly broken low energy SUSY models can be made stable by assuming some additional symmetries (like R -parity in SUSY). Their relic abundance in some regions of the parameter space agrees with the value of $\Omega_{\text{CDM}} h^2 \sim 0.1$ inferred from observations. This last property is sometimes taken as a hint for a deeper link between electroweak physics and the cosmology of the early Universe.

However, extremely weakly interacting massive particles (E-WIMPs),¹ have also been known to provide the desired values of the CDM relic density. E-WIMPs are particles whose interactions with ordinary matter are strongly suppressed compared to “proper” WIMPs, like massive neutrinos and neutralinos, whose interactions are set by the SM weak interaction strength $\sigma_{\text{weak}} \sim 10^{-38} \text{ cm}^2$ times some factors, like mixing angles for the neutralino which are often much smaller than one. For such WIMP their physics is effectively entirely determined by the Fermi scale and (in the case of SUSY) by the SUSY breaking scale M_{SUSY} , which, for the sake of naturalness, is expected not to significantly exceed the electroweak scale.

In contrast, a typical interaction strength of E-WIMPs is suppressed by some large mass scale m_Λ , $\sigma_{\text{E-WIMP}} \sim (m_W/m_\Lambda)^2 \sigma_{\text{weak}}$. One particularly well-known example is the gravitino for which m_Λ is the (reduced) Planck scale $M_P = 1/\sqrt{8\pi G_N} = 2.4 \times 10^{18} \text{ GeV}$. Another well-motivated possibility is axions and/or their fermionic partner axinos for which the scale m_Λ is given by the Peccei-Quinn scale $f_a \sim 10^{11} \text{ GeV}$. Both the axion [3] and

¹Another name used in the literature is ‘superweakly interacting massive particles’ [2].

the axino [4] have also been shown to be excellent candidates for CDM. Other possibilities involve moduli [5] although they strongly depend on a SUSY breaking mechanism. Thus the electroweak scale may have little to do with the DM problem, after all.

In particular, the gravitino as a supersymmetric partner of the graviton, is present in schemes in which gravity is incorporated into supersymmetry (SUSY) via local SUSY, or supergravity. As a spin-3/2 fermion, it acquires its mass through the super-Higgs mechanism. Since gravitino interactions with ordinary matter are strongly suppressed, it was realized early on that the particle was facing various cosmological problems [6, 7]. If the gravitino is not the lightest superpartner (LSP), it decays into the LSP rather late ($\sim 10^{2-10}$ sec) and associated electromagnetic (EM) or hadronic (HAD) radiation. If too much energy is dumped into the expanding plasma at late times $\gtrsim 1$ sec, then the associated particles produced during the decay (*e.g.*, a photon in the gravitino decay to the neutralino) can cause unacceptable alterations of the successful predictions of the abundances of light elements produced during Big Bang nucleosynthesis (BBN), for which there is a good agreement between theory on the one hand and direct observations and CMB determinations on the other. Since the number density of gravitinos is directly proportional to the reheating temperature T_R , this leads to an upper bound of $T_R < 10^{6-8}$ GeV [8, 9, 10, 11, 12, 13] (for recent updates see, *e.g.*, [14, 15, 16]). On the other hand, when the gravitino is the LSP and stable (the case considered in this work), ordinary sparticles will first cascade decay into the lightest ordinary superpartner, which would be the next-to-lightest superpartner, (NLSP) which would then decay into the gravitino and associated EM and/or HAD radiation. A combination of this and the overclosure argument ($\Omega_{\tilde{G}} h^2 < 1$) has in this case led to a rough upper bound $T_R \lesssim 10^9$ GeV [10, 17].

There are some generic ways through which gravitinos (assumed from now on to be the LSP) can be produced in the early Universe. One mechanism has just been described above: the NLSP first freezes out and then, at much later times, decays into the gravitino. Such a process does not depend on the previous thermal history of the Universe (so long as the freeze-out temperature is lower than the reheating temperature T_R after inflation). As in our previous work, we will call it a mechanism of non-thermal production (NTP). In a class of thermal production (TP) processes gravitinos can also be generated through scattering and decay processes of ordinary (s)particles during the thermal expansion of the Universe. Once produced, gravitinos will not participate in a reverse process because of their exceedingly weak interactions. Analogous mechanisms exist in the axino case [4]. In addition, there are other possible ways of populating the Universe with stable relics, *e.g.* via inflaton decay or during preheating [18, 19], or from decays of moduli fields [20]. In some of these cases the gravitino production is independent of reheating temperature and its abundance may give the measured dark matter abundance with no ensuing limit on T_R . In general, such processes are, however, much more model dependent and not necessarily efficient [21], and will not be considered here.

Recently, there has been renewed interest in the gravitino as a stable relic and a dominant component of *cold* dark matter. Thermal production was re-considered in [22, 23] while non-thermal production in [2, 24, 25, 26]. In [27] both processes were considered in the framework of the Minimal Supersymmetric Standard Model (MSSM) in the context of

thermal leptogenesis. In [1] some of us considered a combined impact of both production mechanisms in the more predictive framework of the Constrained MSSM (CMSSM) [28]. The CMSSM encompasses a class of unified models where at the GUT scale gaugino soft masses unify to $m_{1/2}$ and scalar ones unify to m_0 . We concentrated on $m_{\tilde{G}}$ in the GeV to TeV range, typical of gravity-mediated SUSY breaking, and on TP contributions at large $T_R \sim 10^9$ GeV.

Since all the NLSP particles decay after freeze-out, in NTP the gravitino relic abundance $\Omega_{\tilde{G}}^{\text{NTP}} h^2$ is related to $\Omega_{\text{NLSP}} h^2$ – the relic abundance that the NLSP would have had if it had remained stable – via a simple mass ratio

$$\Omega_{\tilde{G}}^{\text{NTP}} h^2 = \frac{m_{\tilde{G}}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}} h^2. \quad (1.1)$$

Note that $\Omega_{\tilde{G}}^{\text{NTP}} h^2$ grows with the mass of the gravitino $m_{\tilde{G}}$.

The gravitino relic abundance generated in TP can be computed by integrating the Boltzmann equation from T_R down to today's temperature. In the case of the gravitino, a simple formula for $\Omega_{\tilde{G}}^{\text{TP}} h^2$ has been obtained in [22, 23]

$$\Omega_{\tilde{G}}^{\text{TP}} h^2 \simeq 0.27 \left(\frac{T_R}{10^{10} \text{ GeV}} \right) \left(\frac{100 \text{ GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1 \text{ TeV}} \right)^2, \quad (1.2)$$

where $m_{\tilde{g}}(\mu)$ above is the running gluino mass. In [22, 23] it was argued that, for natural ranges of the gluino and the gravitino masses, one can have $\Omega_{\tilde{G}}^{\text{TP}} h^2 \sim 0.1$ at T_R as high as 10^{9-10} GeV.

The problem is that in many unified SUSY models, the number density of stable relics undergoing freeze-out is actually often too large. For example, in the CMSSM, the relic abundance of the lightest neutralino typically exceeds the allowed range, except in relatively narrow regions of the parameter space. This can be easily remedied if the neutralino is not the true LSP and can decay further, for example into the gravitino (or the axino [4]). Indeed, it is sufficient to take a small enough mass ratio in the formula (1.1) above. Then, however, $\Omega_{\tilde{G}}^{\text{TP}} h^2$ may become too large because of its inverse dependence on $m_{\tilde{G}}$, especially at high values of T_R , essential for thermal leptogenesis [29, 30], and for $m_{\tilde{G}}$ in the GeV to TeV range.

One may want to suppress the contribution from TP by considering $T_R \ll 10^9$ GeV and generate the desired relic density of gravitinos predominantly through NLSP freeze-out and decay. This would normally require a larger gravitino mass $m_{\tilde{G}}$ and therefore longer decay lifetimes (see below). This, however, can lead to serious problems with BBN, as discussed above. Furthermore, late injection of energetic photons into the plasma may distort the nearly perfect blackbody shape of the CMB spectrum [31].

In a previous paper [1] by some of us, the issue of a combined impact of TP and NTP mechanisms of gravitino production, in view of requiring the total gravitino $\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{\text{NTP}} h^2 + \Omega_{\tilde{G}}^{\text{TP}} h^2 \sim 0.1$ and of BBN, CMB and other constraints, has been examined in the framework of the CMSSM.

In the CMSSM, the NLSP is typically either the (bino-dominated) neutralino (for $m_{1/2} \ll m_0$) or the lighter stau $\tilde{\tau}_1$ (for $m_{1/2} \gg m_0$). Assuming natural ranges of

$m_{1/2}, m_0 \lesssim$ a few TeV, the whole neutralino NLSP region was found [1] to be excluded by constraints from BBN because of unacceptably large showers generated by NLSP decays even assuming fairly conservative abundances of light elements. This confirmed the findings of [27, 25]. On the other hand, the fraction of the stau NLSP region excluded by the BBN constraint was found to depend rather sensitively on assumed ranges of abundances of light elements.

However, it was also found in [1] that the stau NLSP region of parameter space where $\Omega_\chi h^2 \sim 0.1$ was due to NTP alone were in most cases excluded by (mostly) the BBN constraints. In other words, for natural ranges of $m_{1/2}$, a significant component of $\Omega_{\tilde{G}} h^2$ from TP (and thus rather high T_R) must normally be included in studies of gravitino CDM in the CMSSM.

In both the neutralino and the stau NLSP cases, decay products lead mostly to EM showers but a non-negligible fraction of them develop HAD showers which can also be very dangerous, especially at shorter NLSP lifetimes ($\lesssim 10^4$ sec). Constraints on EM showers were analyzed in [14] assuming rather conservative ranges for the abundances of light elements but important constraints from HAD showers were not included. A combined analysis of constraints on both EM and HAD fluxes was recently performed in [15] with much more restrictive (and arguably in some cases perhaps too restrictive) observational constraints than [14]. In [1] the EM shower constraint was applied following [14] and the HAD one following [15] and thus, out of necessity, using different assumptions about allowed ranges of light elements.

In the present analysis we make a number of improvements. Firstly, we treat both EM and HAD showers in a self-consistent way by assuming the same ranges of abundances of light elements which we take to be somewhat less restrictive than those adopted in [15]. Secondly, the BBN yields are computed with a sophisticated code which simultaneously deals with the impact of both EM and HAD showers. In some parts of the parameter space this is essential since non-linearities may exist and in such cases EM and HAD activities cannot be analyzed separately in computing the abundances of light elements. Thirdly, at each point in the CMSSM we compute energy released into all relevant (EM and HAD) channels and their hadronic branching ratios (which are typically smaller than the EM ones but can vary by a few orders of magnitude) and then use them as inputs into the BBN code. Furthermore, in [1] in dealing with EM showers we conservatively only included bounds from D/H , Y_p (^4He abundance) and $^7\text{Li}/H$ while in constraining HAD showers we dropped the lithium constraint. In the current work we include all the above three constraints and in addition apply constraints from $^3\text{He}/D$ and $^6\text{Li}/^7\text{Li}$ which in some cases have the strongest impact on the CMSSM parameter space. All these improvements lead to a much more reliable BBN constraint on EM/HAD showers, even though a large part of the stau NLSP region still remains allowed. In particular, we improve the upper bound of $T_R \lesssim 5 \times 10^9$ GeV found in [1] to $T_R \lesssim$ a few $\times 10^8$ GeV.

In addition, we have now extended the range of $m_{1/2}$ to 6 TeV, beyond that considered in [1], and found that at very large values of $m_{1/2} \gtrsim 4$ TeV one can find allowed regions consistent with $\Omega_{\tilde{G}} h^2$ in the interesting range due to NTP alone. We have also found relatively confined pockets of the neutralino NLSP parameter space which are consistent

with BBN and CMB. We discuss these results below.

Lastly, in SUSY theories the presence of several scalar fields carrying color and electric charge allows for a possible existence of dangerous charge and color breaking (CCB) minima [32] – [37] which would render the physical (Fermi) vacuum unstable. Along some directions in field space the (tree-level) potential can also become unbounded from below (UFB). Avoiding these instabilities leads to constraints on the parameter space among which those derived from requiring the absence of UFB directions are by far the most restrictive [34]. In the specific cases applicable to the CMSSM, after including one-loop corrections, such UFB directions become bounded but develop deep CCB minima at large field values away from the Fermi vacuum of our Universe.

Although the existence of such a dangerous global vacuum cannot be excluded if the lifetime of the (metastable) Fermi vacuum is longer than the age of the Universe (in addition to having rather unpleasant scatological consequences), such a possibility does place non-trivial constraints on inflationary cosmology. One has to explain why and how the Universe eventually ended up in the (local) Fermi minimum [37, 39].

The effect of the UFB constraints in minimal supergravity models was analyzed in [40], where it was shown that it is the stau region in the CMSSM that is mostly affected. This is precisely the region of interest for gravitino CDM in the CMSSM. Consequently, we will discuss the impact of these constraints in our analysis.

As in [1], we will take $m_{\tilde{G}}$ as a free parameter and allow it to vary over a wide range of values from $\mathcal{O}(\text{TeV})$ down to the sub-MeV range, for which the gravitino (at least those produced in TP, see later) would remain *cold* DM relic. Lighter gravitinos would become warm and then (sub-keV) hot DM. We will not address the question of an underlying (if any) supergravity model and SUSY breaking mechanism. As in [1], we will mostly focus on the $\mathcal{O}(\text{GeV})$ to $\mathcal{O}(\text{TeV})$ mass range, as most natural in the CMSSM with gravity-mediated SUSY breaking, but will also explore at some level light gravitinos.

In the following, we will first summarize our procedures for computing $\Omega_{\tilde{G}}h^2$ via both TP and NTP. Then we will list NLSP decay modes into gravitinos, and discuss constraints on the CMSSM parameter space, in particular those from BBN and CMB. Finally, we will discuss implications of our results for thermal leptogenesis and for SUSY searches at the LHC.

2. Framework and Procedure

Unless otherwise stated, we will follow the analysis and notation of the previous paper [1] to which we refer the reader for more details. Here we only summarize the main points, while below we elaborate on our improved analysis of constraints from BBN and on a previously neglected impact of CCB minima and UFB directions.

Within the framework of the CMSSM we employ two-loop RGEs to compute both dimensionless quantities (gauge and Yukawa coupling) and dimensionful ones (gaugino and scalar masses) at the electroweak scale. Mass spectra of the CMSSM are determined in terms of the usual five free parameters: the previously mentioned $\tan\beta$, $m_{1/2}$ and m_0 , as well as the trilinear soft scalar coupling A_0 and $\text{sgn}(\mu)$ – the sign of the supersymmetric

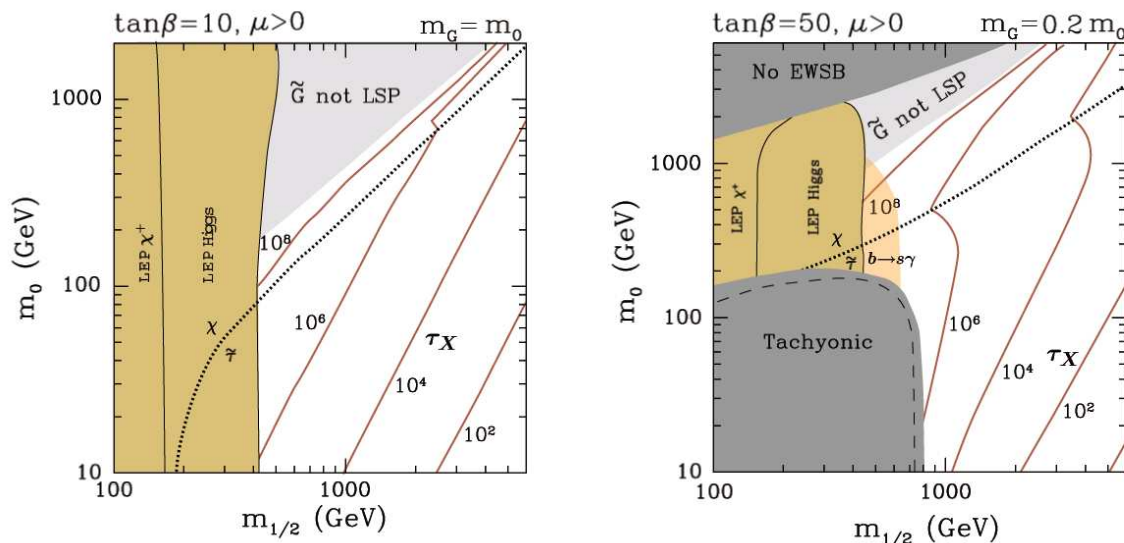


Figure 1: The plane $(m_{1/2}, m_0)$ for $\tan\beta = 10$, $m_{\tilde{G}} = m_0$ (left window) and $\tan\beta = 50$, $m_{\tilde{G}} = 0.2m_0$ (right window) and for $A_0 = 0$, $\mu > 0$. The light brown regions labelled “LEP χ^+ ” and “LEP Higgs” are excluded by unsuccessful chargino and Higgs searches at LEP, respectively. In the right window the darker brown region labelled “ $b \rightarrow s\gamma$ ” is excluded assuming minimal flavor violation. The dark grey region below the dashed line is labelled “TACHYONIC” because of some sfermion masses becoming tachyonic and is also excluded. In the rest of the grey region (above the dashed line) the stau mass bound $m_{\tilde{\tau}_1} > 87 \text{ GeV}$ is violated. In the region “No EWSB” the conditions of EWSB are not satisfied. Magenta lines mark contours of the NLSP lifetime τ_X (in seconds). The dotted line is the boundary of neutralino (χ) or stau ($\tilde{\tau}$) NLSP.

Higgs/higgsino mass parameter μ . The parameter μ is derived from the condition of electroweak symmetry breaking and we take $\mu > 0$. We compute the mass spectra with the help of the package SUSPECT v. 2.34 [41]. For simplicity we assume R -parity conservation even though E-WIMPs, like gravitinos or axinos, can constitute CDM even when it is broken. This is because, even in the presence of R -parity breaking interactions the E-WIMP lifetime will normally be very large due to their exceedingly tiny interactions with ordinary matter.

We compute the number density of the NLSP after freeze-out (the neutralino or the stau) with high accuracy by numerically solving the Boltzmann equation including all (dominant and subdominant) NLSP pair annihilation and coannihilation channels. For a given value of $m_{\tilde{G}}$, we then compute the NTP contribution to the gravitino relic abundance $\Omega_{\tilde{G}}^{\text{NTP}} h^2$ via eq. (1.1). In computing the thermal contribution $\Omega_{\tilde{G}}^{\text{TP}} h^2$ we employ eq. (1.2).

After freeze-out from the thermal plasma at $t \sim 10^{-12} \text{ sec}$, the NLSPs decay into gravitinos at late times which strongly depend on the NLSP composition and mass, on $m_{\tilde{G}}$ and on the final states of the NLSP decay. Expressions for $\Gamma_X = 1/\tau_X$, where X denotes the decaying particle² have been derived in [26, 25]. Given some discrepancies between the

²From now on we will denote $X = \chi, \tilde{\tau}_1$ for brevity.

two sources, below (as in [1]) we follow [25]. Roughly, for $m_{\tilde{G}} \ll m_X$ the lifetime is given by

$$\tau_X \sim 10^8 \text{ sec} \left(\frac{100 \text{ GeV}}{m_X} \right)^5 \left(\frac{m_{\tilde{G}}}{100 \text{ GeV}} \right)^2. \quad (2.1)$$

The exact value of the NLSP lifetime in the CMSSM further depends on a possible relation between $m_{\tilde{G}}$ and $m_{1/2}$ and/or m_0 but in the parameter space allowed by other constraints it can vary from $\gtrsim 10^8 \text{ sec}$ at smaller m_X down to 10^2 sec , or even less, for large $m_{1/2}$ and/or m_0 in the TeV range.

In fig. 1 we present the gravitino relic abundance and the NLSP lifetime in the usual plane spanned by $m_{1/2}$ and m_0 for two representative choices: $\tan \beta = 10$ and $m_{\tilde{G}} = m_0$ (left window) and $\tan \beta = 50$ and $m_{\tilde{G}} = 0.2m_0$ (right window), and for $A_0 = 0$ and $\mu > 0$. At small m_0 and large $\tan \beta$ some sfermions become tachyonic, as encircled by a dashed line inside the grey region (labelled “TACHYONIC”) in the right window. Relevant collider and theoretical constraints (but not yet those coming from BBN or CMB) are shown. We apply the same experimental bounds as in [1]: (i) the lightest chargino mass $m_{\chi_1^\pm} > 104 \text{ GeV}$, (ii) the lightest Higgs mass $m_h > 114.4 \text{ GeV}$, (iii) $BR(B \rightarrow X_s \gamma) = (3.34 \pm 0.68) \times 10^{-4}$. In addition, now we further impose a stau mass bound $m_{\tilde{\tau}_1} > 87 \text{ GeV}$ [42] which slightly enlarges the grey region beyond the part labelled “TACHYONIC”. In this analysis we update the top quark mass to the current value of $m_t = 172.7 \text{ GeV}$ [43].

To help understanding this and subsequent figures, we remind the reader of some basic mass relations. The mass of the gluino is roughly given by $m_{\tilde{g}} \simeq 2.7m_{1/2}$. The mass of the lightest neutralino, which in the CMSSM is almost a pure bino, is $m_\chi \simeq 0.4m_{1/2}$. The lightest stau $\tilde{\tau}_1$ is dominated by $\tilde{\tau}_R$ and well above m_Z its mass is (neglecting Yukawa contributions at large $\tan \beta$) roughly given by $m_{\tilde{\tau}_1}^2 \simeq m_0^2 + 0.15m_{1/2}^2$. This is why at $m_0 \ll m_{1/2}$ the stau is lighter than the neutralino while in the other case the opposite is true. The boundary between the two NLSP regions is marked with a roughly diagonal dotted line. (In the standard scenario the region of a stable, electrically charged stau relic is thought to be ruled out on astrophysical grounds.) Regions corresponding to the lightest chargino and Higgs masses below their LEP limits are appropriately marked and excluded. Separately marked for $\tan \beta = 50$ is the region inconsistent with the measured branching ratio $BR(B \rightarrow X_s \gamma)$. (For $\tan \beta = 10$, and generally not too large $\tan \beta$, this constraint is much weaker and “hides” underneath the above LEP bounds.) In the grey wedge of large m_0 conditions of EWSB cannot be satisfied. Finally, for some combinations of parameters the gravitino is not the LSP. We exclude such cases in this analysis.

Also shown in fig. 1 are contours of the NLSP lifetime τ_X (in seconds). Their shape strongly depends on gravitino mass relation with m_0 , $m_{1/2}$ and, because of SUSY mass relations, on other parameters which determine m_X , but in the cases considered here, at small to moderate m_0 , τ_X typically decreases with increasing $m_{1/2}$.

Finally, by comparing fig. 1 with fig. 2 of [1] (where $m_t = 178 \text{ GeV}$ was assumed), we can see the sensitivity to the top quark mass. The region disallowed by the LEP Higgs mass bound has now broadened from $m_{1/2} \sim 300 \text{ GeV}$ to 400 GeV and at low $m_{1/2}$ and large m_0 a wedge inconsistent with EWSB has appeared. There is also a noticeable change

is in the pseudoscalar resonance region for $\tan\beta = 50$. The green band moves to smaller $m_{1/2}$ and higher m_0 for smaller m_t .

3. Improved BBN Analysis

NLSP (χ or $\tilde{\tau}_1$) decays after freeze-out can generate highly energetic electromagnetic and hadronic fluxes which can significantly alter the abundances of light elements. At longer lifetimes $\tau_\chi \gtrsim 10^4 \text{ sec}$ EM constraints are strongest but at earlier times HAD shower constraint typically become dominant while the EM one virtually disappears. However, even at later times HAD constraints can be important.

We will evaluate the abundances of light elements produced during BBN in the presence of EM/HAD showers and, by comparing them with observations, place bounds on the latter. To this end, we need to know the energy ϵ_i^X transferred to each decay channel $i = em, had$ and their respective branching fractions to EM/HAD showers B_i^X as well as the NLSP lifetime τ_χ . All the above quantities depend on the NLSP and (with the exception of the yield) on its decay modes and the gravitino mass. For the cases of interest (χ and $\tilde{\tau}_1$) these have been recently evaluated in detail in [25]. In [1] and below we follow their discussion.

For the neutralino NLSP the dominant decay mode is $\chi \rightarrow \tilde{G}\gamma$. In the CMSSM the neutralino is a nearly pure bino, thus $\chi \simeq \tilde{B}$. The decay $\chi \rightarrow \tilde{G}\gamma$ produces mostly EM energy. Thus

$$\epsilon_{em}^\chi = \frac{m_\chi^2 - m_{\tilde{G}}^2}{2m_\chi}, \quad B_{em}^\chi \simeq 1. \quad (3.1)$$

Above their respective kinematic thresholds, the neutralino can also decay via $\chi \rightarrow \tilde{G}Z, \tilde{G}h, \tilde{G}H, \tilde{G}A$ for which the decay rates are given in [25, 26]. These processes contribute to HAD fluxes because of large hadronic branching ratios of the Z and the Higgs bosons ($B_{had}^Z \simeq 0.7$, $B_{had}^h \simeq 0.9$). In this case the transferred energy ϵ_i^X and branching fraction B_i^X each channel are

$$\epsilon_k^\chi \approx \frac{m_\chi^2 - m_{\tilde{G}}^2 + m_k^2}{2m_\chi}, \quad B_{had,k}^\chi = \frac{\Gamma(\chi \rightarrow \tilde{G}k)B_{had}^k}{\Gamma_{tot}}, \quad k = Z, h, H, A, \quad (3.2)$$

where

$$\Gamma_{tot} \simeq \Gamma(\chi \rightarrow \tilde{G}\gamma) + \sum_k \Gamma(\chi \rightarrow \tilde{G}k). \quad (3.3)$$

Below the kinematic threshold for neutralino decays into \tilde{G} and the Z /Higgs boson, one needs to include 3-body decays with the off-shell photon or Z decaying into quarks for which $\epsilon_{q\bar{q}}^\chi \approx \frac{2}{3}(m_\chi - m_{\tilde{G}})$ and $B_{had}^\chi(\chi \rightarrow \tilde{G}\gamma^*/Z^* \rightarrow \tilde{G}q\bar{q}) \sim 10^{-3}$ [25]. This provides a lower bound on B_{had}^χ . At larger m_χ , Higgs boson final states become open and we include neutralino decays into them as well.

The dominant decay mode of the lighter stau $\tilde{\tau}_1$ is $\tilde{\tau}_1 \rightarrow \tilde{G}\tau$ which, as argued in [24, 25], contributes basically only to EM showers. Thus

$$(3.4)$$

$$\epsilon_{em}^{\tilde{\tau}_1} \approx \frac{1}{2} \frac{m_{\tilde{\tau}_1}^2 - m_{\tilde{G}}^2}{2m_{\tilde{\tau}_1}}, \quad B_{em}^{\tilde{\tau}_1} \simeq 1, \quad (3.5)$$

where the additional factor of 1/2 appears because about half of the energy carried away by the tau-lepton is transmitted to final state neutrinos. Our results are not sensitive to an order of two variations of this overall pre-factor.

As shown in [25], for stau NLSP, the leading contribution to HAD showers come from 3-body decays $\tilde{\tau}_1 \rightarrow \tilde{G}\tau Z, \tilde{G}\nu_\tau W$, or from 4-body decays $\tilde{\tau}_1 \rightarrow \tilde{G}\tau\gamma^*/Z^* \rightarrow \tilde{G}\tau q\bar{q}$. The transferred energy ϵ_i^X and branching fractions $B_{had,i}^X$ ($i = Z, W, q\bar{q}$) are

$$\epsilon_Z^{\tilde{\tau}_1} \simeq \epsilon_W^{\tilde{\tau}_1} \simeq \epsilon_{q\bar{q}}^{\tilde{\tau}_1} \approx \frac{1}{3}(m_{\tilde{\tau}_1} - m_{\tilde{G}}) \quad (3.6)$$

and

$$B_{had,Z}^{\tilde{\tau}_1} = \frac{\Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\tau Z)B_{had}^Z}{\Gamma_{tot}}, \quad B_{had,W}^{\tilde{\tau}_1} = \frac{\Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\nu_\tau W)B_{had}^W}{\Gamma_{tot}}, \quad B_{had,q\bar{q}}^{\tilde{\tau}_1} = \frac{\Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\tau q\bar{q})}{\Gamma_{tot}} \quad (3.7)$$

where

$$\Gamma_{tot} \simeq \Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\tau) + \Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\tau Z) + \Gamma(\tilde{\tau}_1 \rightarrow \tilde{G}\nu_\tau W). \quad (3.8)$$

One typically finds $B_{had}^{\tilde{\tau}_1} \sim 10^{-5} - 10^{-2}$ when 3-body decays are allowed and $\sim 10^{-6}$ from 4-body decays otherwise, thus providing a lower limit on the quantity [25]. (Since the process $\tilde{\tau}_1 \rightarrow \tilde{G}\nu_\tau W$ is proportional to the $\tilde{\tau}_L$ component of $\tilde{\tau}_1$, which in the CMSSM is suppressed, its contribution to Γ_{tot} is likely to be tiny.) Given such a large variation in $B_{had}^{\tilde{\tau}_1}$, the choice (3.6) is probably as good as any other.

For each point in the parameter space and for a given $m_{\tilde{G}}$, the partial energies ϵ_i^X released into all the channels and their respective branching fractions B_i^X are passed on to the BBN code which computes light element abundances in the presence of additional EM/HAD showers. A determination of ϵ_i^X for all the individual hadronic channels is necessary since the changes of light element yields are not simply a linear function of ϵ_i^X . (Note that in our previous analysis [1] this yield dependence on ϵ_i^X was neglected.) The output is then compared with observational constraints.

We emphasize that our treatment of the branching ratios constitutes a significant improvement relative to previous analyses where only a few sample calculations at a fixed NLSP mass (*e.g.*, 100 GeV or 1 TeV) and for only a fixed hadronic branching ratio (*e.g.*, $B_{had} = 10^{-3}$) were linearly extrapolated to derive BBN yield predictions. This is inaccurate for several reasons. Hadronic BBN yields are not simply linear functions of the hadronic energy injected, but rather depend in a more complicated way on the energy of the hadronic primaries. Furthermore, at early times ($\tau \lesssim 10^4$ sec) a simple linear extrapolation from one

calculation with particular B_{had} is impossible due to the interplay between the hadronic perturbations and thermal nuclear reactions. Finally, at later times, cancellation effects between HAD and EM light element production and destruction processes may occur. All these effects may be properly addressed only when for each point in the SUSY parameter space an separate BBN calculation is performed.

At early times $\tau \lesssim 10^4$ sec limits from BBN on particle decay induced showers come from injections of hadrons, *i.e.*, mesons for $\tau \lesssim 10^2$ sec and nucleons for $\tau \gtrsim 10^2$ sec, with EM showers having no effect at such early times. Mesons convert protons to neutrons by charge exchange reactions, e.g. $\pi^- + p \rightarrow \pi^0 + n$ [45], thereby increasing the final ${}^4\text{He}$ abundance. Nucleons lead to an increase in the D abundance due to both injected neutrons fusing to form D or inducing the spallation of ${}^4\text{He}$ and concomitant production of D [46]. Injected energetic nucleons may also affect a very efficient ${}^6\text{Li}$ production for $\tau \gtrsim 10^3$ sec [46, 47, 15]. At times $\tau \gtrsim 10^4$ sec HAD showers are still important in setting constraints, unless B_{had}^X is very small. In addition, EM showers, also lead to distortions of the light element abundances by photo disintegrating elements [10]. EM showers typically lead to elevated ${}^3\text{He}/D$ [49, 15] and ${}^6\text{Li}/{}^7\text{Li}$ [50] ratios. (Note that the effects of HAD showers have not been considered in ref. [26]).

In the present analysis we fix the baryon-to-photon ratio η at 6.05×10^{-10} which is consistent with the WMAP result $\eta = 6.1_{-0.2}^{+0.3} \times 10^{-10}$ [44]. All processes required for an accurate determination of the light element abundances are treated in detail. The calculations are based on the code introduced in ref. [47] with the effects of EM showers added. Details of this code will be presented elsewhere [48]. (A similar detailed presentation can be found in ref. [15].)

We apply the following observational constraints

$$\begin{aligned} 2.2 \times 10^{-5} &< D/H < 5.3 \times 10^{-5} \\ 0.232 &< Y_p < 0.258 \\ 8 \times 10^{-11} &< {}^7\text{Li}/H \\ {}^3\text{He}/D &< 1.72 \\ {}^6\text{Li}/{}^7\text{Li} &< 0.1875. \end{aligned}$$

Note that in [15] a much less conservative upper bound of 3.66×10^{-5} on D/H was assumed. On the other hand, the constraint from ${}^6\text{Li}/{}^7\text{Li}$ was not applied. Note also that, relative to [1], we now also include important constraints from ${}^3\text{He}/D$ and ${}^6\text{Li}/{}^7\text{Li}$. These bounds are typically a factor of ten more stringent than constraints from D alone. Though the stellar evolution of ${}^3\text{He}$ is not well understood, the constraint from the ${}^3\text{He}/D$ ratio is very secure as D is known to always be destroyed in stars whereas ${}^3\text{He}$ may be either destroyed or produced in stars. Thus one may derive an upper limit on the primordial ${}^3\text{He}/D$ ratio given by its value in the pre-solar nebula. Less secure is the upper limit on the ${}^6\text{Li}/{}^7\text{Li}$ ratio, as ${}^6\text{Li}$ is more fragile than ${}^7\text{Li}$. Typical ${}^6\text{Li}/{}^7\text{Li}$ observations in low-metallicity stars fall in the range $\sim 0.03 - 0.1$ (cf. [51]).

Finally we mention the constraint from the CMB shape. Late injection of electromagnetic energy may distort the frequency dependence of the CMB spectrum from its observed

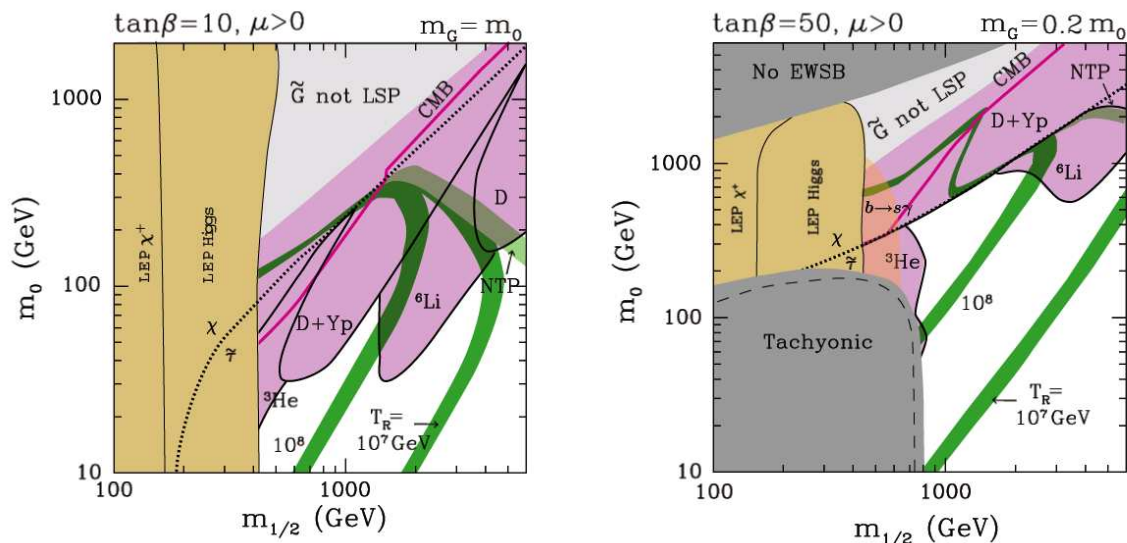


Figure 2: The same as in fig. 1 but with constraints from BBN and CMB superimposed. The regions excluded by the various BBN constraint are denoted in violet. The region disallowed by $D + Y_p$ and additional regions excluded by ${}^3\text{He}$ and ${}^6\text{Li}$ are denoted accordingly by their respective names. A solid magenta curve labelled “CMB” delineates the region (on the side of label) inconsistent with the CMB spectrum. In both windows, the dark green bands labelled “ $T_R = 10^7 \text{ GeV}$ ” and “ 10^8 ” denote the total relic abundance of the gravitino from both thermal and non-thermal production with denoted reheating temperature is in the favored range, while in the light green regions (marked “NTP”) the same is the case for the relic abundance from NTP processes alone.

blackbody shape [9, 31], as recently re-emphasized in [24] and in [1]. In this paper we apply our analysis presented in [1] to which refer the reader for all the details.

In fig. 2 we present in the usual $(m_{1/2}, m_0)$ plane our new and more accurate constraints from BBN for the same parameters as in fig. 1. First we note that a robust constraint from D/H and Y_p excludes basically the whole neutralino NLSP region.³ This remains true so long as $m_{\tilde{G}} > \mathcal{O}(1 \text{ GeV})$ as we will discuss later. This is consistent with the previous analysis [1] and also confirms the findings of [27, 25]. Next, the important role played by the constraints from ${}^3\text{He}/D$ and ${}^6\text{Li}/{}^7\text{Li}$ in excluding additional regions of the $(m_{1/2}, m_0)$ is shown explicitly.

The cases presented in fig. 2 correspond to some of the cases presented in fig. 2 in ref. [1] in order to allow a comparison with a previous approximate treatment of the BBN constraint. We can see a substantial weakening of the HAD shower bound coming from D/H . This is because in ref. [1] a much stronger upper bound on the allowed abundance of deuterium was applied, following ref. [15]. Otherwise, the general pattern of excluded regions is roughly similar.

The total gravitino relic abundance consistent with the 2σ range $0.094 < \Omega_{\text{CDM}} h^2 < 0.129$ [44] (marked $\Omega_{\tilde{G}} h^2$) is shown in dark green. For comparison, light green regions

³However, we do find some limited exception to this, as we discuss below.

(marked NTP) correspond to the gravitino relic abundance due to NTP alone in the same range. These regions become cosmologically favored when one does not include TP or when $T_R \ll 10^9$ GeV. (Note that these regions correspond to ranges of $m_{1/2}$ beyond those explored in [26], where only NTP was considered, and were not found there.) In the white regions encircled by the dark (light) green bands, the total (NTP-induced) relic abundance is too small while on the other side it is too large. Note that the shape of the green bands strongly depends on the gravitino mass relation with m_0 , $m_{1/2}$ and/or other parameters [1]. As emphasized in [1], at large T_R these two bands of $\Omega_{\tilde{G}} h^2$ and $\Omega_{\tilde{G}}^{\text{NTP}} h^2$ correspond to very different regions of stau NLSP parameter space.

On the other hand, it is only at such large $m_{1/2}$, where the BBN constraint becomes much weaker due to a much shorter lifetime, that we find some cases where NTP alone can be efficient enough to become consistent with preferred range of CDM abundance. This can be seen in the left window of fig. 2.

We also note that the constraint from not distorting the CMB spectrum (magenta line) seems generally less important than that due to BBN [52].

It is thus clear that, so long as $T_R \lesssim \text{a few } 10^8$ GeV, one finds sizable regions of rather large $m_{1/2}$ and much smaller m_0 consistent with the preferred range of CDM abundance. Unless one allows for very large $m_{1/2} \gtrsim 4$ TeV, a substantial (and, in fact, dominant) TP contribution to $\Omega_{\tilde{G}} h^2$ are required.

4. False Vacua

A complete analysis of all the potentially dangerous CCB and UFB directions in the field space of the CMSSM, including the radiative corrections to the scalar potential in a proper way, was carried out in ref. [34]. As we commented in the Introduction, the most restrictive bounds are from the UFB directions, and therefore we will concentrate on them below.

In the CMSSM there are three UFB directions, labelled in [34] as UFB-1, UFB-2 and UFB-3. It is worth mentioning here that the unboundedness is only true at tree level since radiative corrections eventually raise the potential for large enough values of the fields. Still these minima can be deeper than the usual Fermi vacuum and thus dangerous. The UFB-3 direction involves the scalar fields $\{H_u, \nu_{L_i}, e_{L_j}, e_{R_j}\}$ with $i \neq j$ and thus leads also to electric charge breaking. Since it yields the strongest bound among all the UFB and CCB constraints, and for future convenience, let us briefly give the explicit form of this constraint.

By simple analytical minimization of the relevant terms of the scalar potential it is possible to write the value of all the $\nu_{L_i}, e_{L_j}, e_{R_j}$ fields in terms of H_u . Then, for any value of $|H_u| < M_{GUT}$ satisfying

$$|H_u| > \sqrt{\frac{\mu^2}{4\lambda_{e_j}^2} + \frac{4m_{L_i}^2}{g^2 + g_2^2}} - \frac{|\mu|}{2\lambda_{e_j}}, \quad (4.1)$$

the potential along the UFB-3 direction is simply given by

$$V_{\text{UFB-3}} = (m_{H_u}^2 + m_{L_i}^2)|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}(m_{L_j}^2 + m_{e_j}^2 + m_{L_i}^2)|H_u| - \frac{2m_{L_i}^4}{g^2 + g_2^2}. \quad (4.2)$$

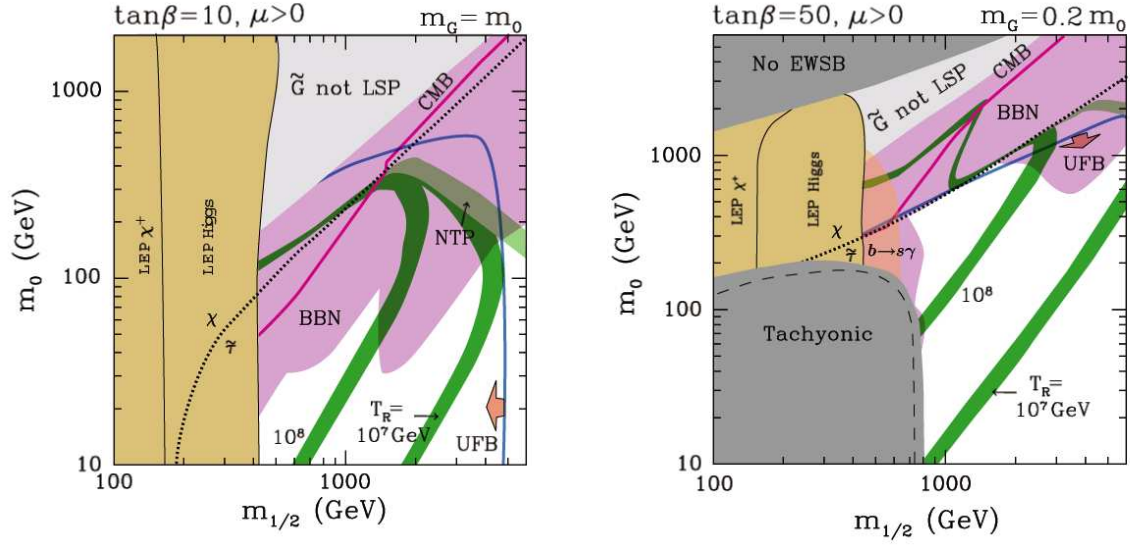


Figure 3: The same as fig. 2 but with UFB constraints (solid blue line and UFB label plus a big arrow) added. For $m_{1/2} \lesssim 5$ TeV and small m_0 the UFB constraints disfavor the stau NLSP region that has remained allowed after applying the BBN and CMB constraints.

Otherwise

$$V_{\text{UFB-3}} = m_{H_u}^2 |H_u|^2 + \frac{|\mu|}{\lambda_{e_j}} (m_{L_j}^2 + m_{e_j}^2) |H_u| + \frac{1}{8} (g'^2 + g_2^2) \left[|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}} |H_u| \right]^2. \quad (4.3)$$

In eqs. (4.2) and (4.3) λ_{e_j} denotes the leptonic Yukawa coupling of the j th generation. Then, the UFB-3 condition reads

$$V_{\text{UFB-3}}(Q = \hat{Q}) > V_{\text{Fermi}}, \quad (4.4)$$

where $V_{\text{Fermi}} = -\frac{1}{8} (g'^2 + g_2^2) (v_u^2 - v_d^2)^2$, with $v_{u,d} = \langle H_{u,d}^0 \rangle$, is the Fermi minimum evaluated at the typical scale of SUSY masses. (Normally, a good choice for M_{SUSY} is a geometric average of the stop masses.) The minimization scale \hat{Q} is given by $\hat{Q} \sim \max(\lambda_{\text{top}} |H_u|, M_{\text{SUSY}})$. With these choices for \hat{Q} and M_{SUSY} the effect of the one-loop corrections to the scalar potential is minimized. Notice from eqs. (4.2) and (4.3) that the negative contribution to $V_{\text{UFB-3}}$ is essentially given by the $m_{H_u}^2$ term, which in many cases can be large. On the other hand, the positive contribution is dominated by the term $\propto 1/\lambda_{e_j}$, thus the larger λ_{e_j} the more restrictive the constraint becomes. Consequently, the optimum choice of the e -type slepton is the third generation one, i.e. $e_j = \tilde{\tau}$.

Moreover, since the positive contribution to $V_{\text{UFB-3}}$ is proportional to $m_{\tilde{\tau}}^2$, the potential will be deeper in those regions of the parameter space where the staus are light and the condition (4.4) is more likely to be violated. For this reason, the cases with stau NLSP are typically more affected by the UFB constraints [40].

In fig. 3 we present the cases displayed above in fig. 2 but now in addition we mark the regions corresponding to a one-loop corrected UFB-3 direction becoming the global

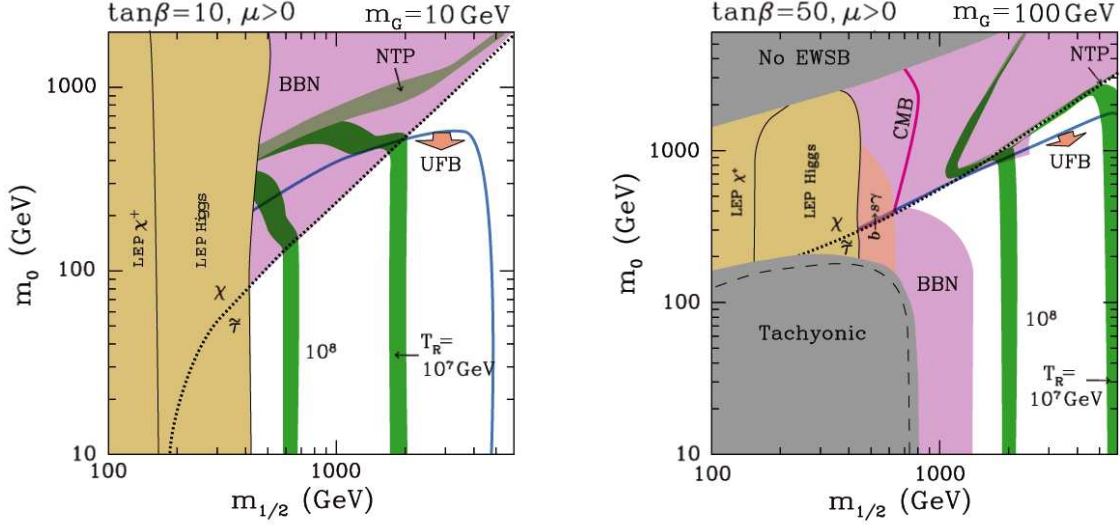


Figure 4: The same as fig. 3 but for fixed gravitino mass, $m_{\tilde{G}} = 10$ GeV and $\tan\beta = 10$ (left window) and $m_{\tilde{G}} = 100$ GeV and $\tan\beta = 50$ (right window).

CCB minimum. These are encircled by a solid blue line and marked “UFB” and a big arrow. We can see that, unless $m_{1/2}$ is excessively large ($m_{1/2} \gtrsim 4$ TeV for $\tan\beta = 10$), in both cases the whole previously allowed (white) and cosmologically favored (green) regions correspond to a false vacuum. As $m_{\tilde{\tau}_1}$ grows with increasing $m_{1/2}$, the UFB constraint becomes weaker and eventually disappears.

As stated in the Introduction, one cannot exclude the possibility that the color and electric charge neutral (Fermi) vacuum that the Universe ended up in after inflation is not a global one but merely a long-lived local minimum. As discussed in [38, 39], this however often puts a significant constraint on models of cosmic inflation. The point is that, at the end of inflation, the Universe was very likely to end up in the domain of attraction of the global minimum which, even at high temperatures ($T_R \sim 10^{7-9}$ GeV), could well have been a CCB one. Preventing such situations leads also to constraints on the SUSY parameter space.

For this reason, while the UFB regions presented in fig. 3 (which correspond to the Fermi vacuum being a local minimum) cannot be firmly excluded, should SUSY searches at the LHC find sparticles with masses indicating such a false vacuum, valuable information may be gained about the state of the Universe and about early Universe cosmology.

In fig. 4 we present two cases with a fixed $m_{\tilde{G}}$. In the left window $\tan\beta = 10$ and $m_{\tilde{G}} = 10$ GeV while in the right one $\tan\beta = 50$ and $m_{\tilde{G}} = 100$ GeV. (The “cross” case of $\tan\beta = 10$ and $m_{\tilde{G}} = 100$ GeV is excluded by a combination of collider and BBN constraints.) While now BBN constraints have become somewhat weaker due to smaller $m_{\tilde{G}}$ (and therefore smaller τ_X), the whole neutralino NLSP region is again ruled out as well as part of the stau NLSP region corresponding to smaller $m_{1/2}$ (and therefore smaller $m_{\tilde{\tau}_1}$ and hence larger τ_X). Most of the remaining stau NLSP region in both windows

corresponds to the Fermi vacuum being a local minimum.

As mentioned earlier, for one case ($\tan\beta = 50$ and $m_{\tilde{G}} = 10$ GeV, not shown here) we have found a confined pocket in the neutralino region around $m_{1/2} \simeq 2.5$ TeV and $m_0 \simeq 5$ TeV, close to the region of no EWSB, which is allowed by our BBN and CMB constraints. However, we consider it to be an odd exception to the rule rather than a typical case.

Finally, in figs. 3 and 4 for $T_R = 10^8$ GeV one finds $m_{1/2} \lesssim 2$ TeV in order to remain consistent with $\Omega_{\tilde{G}}h^2$ in the observed range and with BBN constraints. Gaugino mass unification relations then imply $m_{\tilde{g}} \lesssim 5.4$ TeV. With increasing T_R this upper bound goes down but we still expect it to be considerably higher than the upper limit $m_{\tilde{g}} \lesssim 1.8$ TeV claimed in ref. [27] for $T_R = 3 \times 10^9$ GeV. The difference may be due to the considerably less conservative assumptions about the primordial abundances of light elements in ref. [27] which followed ref. [15].

5. T_R versus $m_{\tilde{G}}$

We now extend our analysis to smaller $m_{\tilde{G}}$ down to less than 1 MeV. In general thermal relics with masses as low as some 10 keV can constitute cold DM. We note that such small values are rather unlikely to arise within the CMSSM with the gravity-mediated SUSY breaking scheme where $m_{\tilde{G}}$ is expected to lie in the range of several GeV or a few TeV, as mentioned earlier. In other SUSY breaking scenarios $m_{\tilde{G}}$ can often be either much smaller or much larger than this most natural range. For example, in models with gauge-mediated SUSY breaking [53] the gravitino can be extremely light $m_{\tilde{G}} = \mathcal{O}(\text{eV})$. On the other hand, in models with anomaly-mediated SUSY breaking [54] gaugino masses are typically of order 10 to 100 TeV. These comments notwithstanding, in a phenomenological analysis like this one, we therefore think it is still instructive to display more explicitly the dependence between $m_{\tilde{G}}$ and cosmological constraints from BBN and CMB and the ensuing implications for the maximum T_R .

On the other hand, in the following we will not apply the UFB constraint. This is not only motivated by the reasons discussed above but, more importantly, because the constraint strongly depends on the full scalar potential which in turn depends on the field content of the model. So far we have assumed minimal supergravity but in other SUSY breaking scenarios several new scalars are present which are likely to lead to very different UFB constraints.

In the left windows of figs. 5 and 6 we plot the total gravitino relic abundance $\Omega_{\tilde{G}}h^2$ (solid line), its TP contribution $\Omega_{\tilde{G}}^{\text{TP}}h^2$ (dot-dashed lines) and its NTP part $\Omega_{\tilde{G}}^{\text{NTP}}h^2$ (dotted line) as a function of $m_{\tilde{G}}$, for $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$ and $m_{1/2} = 500$ GeV and for several choices of T_R . In fig. 5 we take $m_0 = 200$ GeV (χ NLSP) and in fig. 6 $m_0 = 50$ GeV ($\tilde{\tau}_1$ NLSP). In both cases the contribution $\Omega_{\tilde{G}}^{\text{NTP}}h^2$ from NTP provides a lower limit to the total gravitino relic abundance $\Omega_{\tilde{G}}h^2$ while $\Omega_{\tilde{G}}^{\text{TP}}h^2$ varies with T_R .

In the right windows of figs. 5 and 6 we plot the maximum value of T_R consistent with $0.094 < \Omega_{\tilde{G}}h^2 < 0.129$ versus $m_{\tilde{G}}$ for the same choices of other parameters as in the respective left windows. We can see how the strong constraints from BBN and then

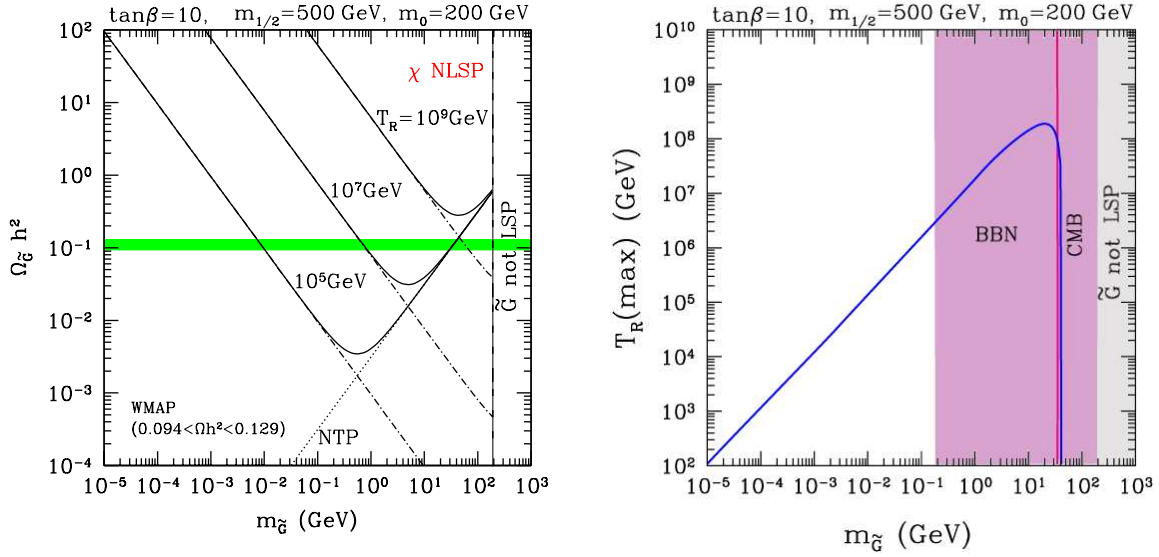


Figure 5: Left window: The total gravitino relic abundance $\Omega_{\tilde{\chi}} h^2$ (solid lines) as a function of the gravitino mass $m_{\tilde{\chi}}$ for $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$ and for the point $m_{1/2} = 500$ GeV, $m_0 = 200$ GeV (χ NLSP). Thermal production contribution (dot-dashed lines) to $\Omega_{\tilde{\chi}} h^2$ is shown for different choices of the reheating temperature ($T_R = 10^9, 10^7, 10^5$ GeV), while the non-thermal production one (dotted line) is marked by NTP. The horizontal green band shows the preferred range for $\Omega_{\text{CDM}} h^2$ (marked WMAP). Right window: The highest reheating temperature (blue line) versus $m_{\tilde{\chi}}$ such that the relic density constraint is satisfied for the same choice of parameters as in the left window. The colored regions are excluded by BBN (violet), CMB (right side of magenta line), and the gravitino not being the LSP. We can see that the sub-GeV gravitino, T_R as small as 10^5 GeV are sufficient to provide the expected amount of DM in the Universe.

CMB only affect larger $m_{\tilde{\chi}}$ in the GeV range or more. Sub-GeV gravitino mass leaves the CMSSM almost unconstrained by the above constraints. In particular, the neutralino NLSP region becomes for the most part allowed again. Increasing $m_{\tilde{\chi}}$ reduces the effect of TP. This is because it becomes harder to produce them in inelastic scatterings in the plasma. On the other hand, at some point the bounds from BBN and CMB eventually put an upper bound on T_R . We examined a number of cases, including various gravitino mass values but could not find consistent solutions above an upper limit of

$$T_R \lesssim \text{a few} \times 10^8 \text{ GeV}. \quad (5.1)$$

No values of T_R exceeding the above values were also found by considering $A_0 = \pm 1$ TeV, in addition to our default value of $A_0 = 0$. When $A_0 = 1$ TeV, the regions excluded by constraints from Higgs mass bound and due to a tachyonic region become larger. In particular, for $\tan \beta = 50$, the Higgs mass constraint extends to 700 GeV and the tachyonic region increases to some $m_0 = 400$ GeV and $m_{1/2} = 1000$ GeV, while the constraint due to $B \rightarrow X_s \gamma$ becomes weaker and is buried under the Higgs mass constraint. When $A_0 = -1$ TeV, the Higgs mass constraint become weaker but the tachyonic region become even larger and extends to $m_{1/2} = 1100$ GeV for $\tan \beta = 50$. For both values of A_0 , the

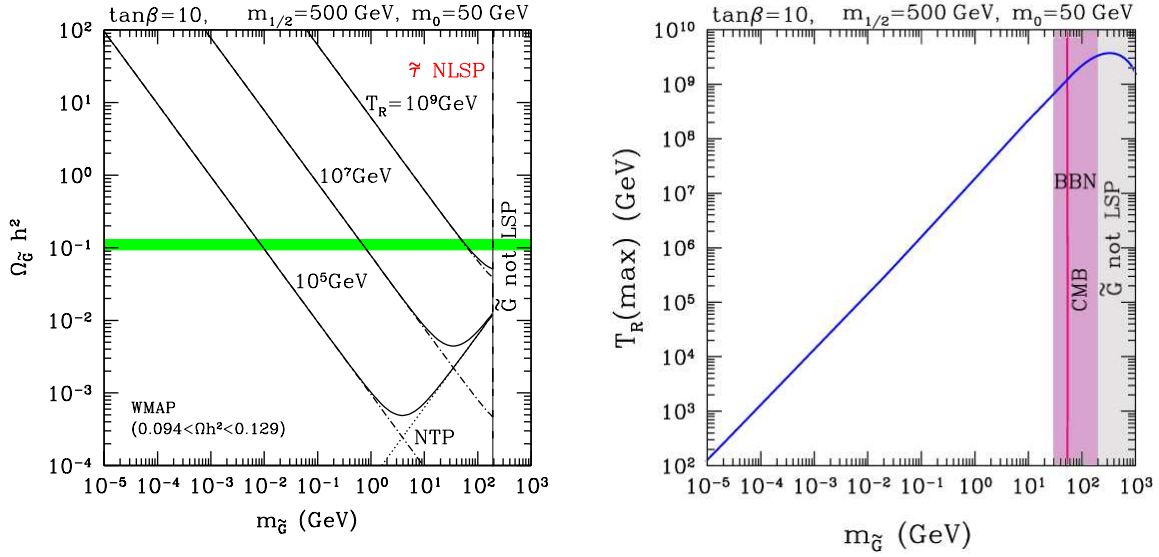


Figure 6: The same as fig. 5 but for the different point $m_{1/2} = 500$ GeV and $m_0 = 50$ GeV ($\tilde{\tau}_1$ NLSP).

neutralino NLSP is still diallowed, while in stau NLSP region some allowed regions remain, similarly to the case of $A_0 = 0$.

By comparing the left and the right windows of figs. 5 and 6, we can again see that the NTP contribution alone is normally not sufficient to provide the expected range $0.094 < \Omega_{\tilde{g}} h^2 < 0.129$. On the other hand, assuming $m_{\tilde{g}}$ as small as 100 keV, for the gravitino to provide most of *cold* DM in the Universe, implies that T_R as small as 10^3 GeV is sufficient for TP to provide the expected amount of cold DM in the Universe.

Finally, we comment on the interesting possibility that gravitino relics may not be all cold but that a fraction of them may have been warm at the time of decoupling. This is because in the case of relics like gravitinos produced in thermal processes at high T_R , their momenta exhibit a thermal phase-space distribution while gravitinos from NLSP freeze-out and decay have a non-thermal distribution. As a result, even though both populations are initially relativistic, they red-shift and become non-relativistic at different times and may have a different impact on early growth of large structures, CMB and other observable properties of the Universe. This “dual nature” of gravitinos was investigated early on in the framework of gauge-mediated SUSY breaking scenario (in which gravitinos are light, in the keV range) [55] where the thermal population was warm while the non-thermal one was providing a “volatile” component characterized by a high *rms* velocity v_{rms} . The scheme was originally explored in [56] in the case of light axinos. Depending on the axino mass and other properties, they can provide a dual warm-hot distribution [57] or warm-cold one [4]. More recently, it was found [58] that late charged (stau) NLSP decays could suppress the DM power spectrum if NLSP decays contributed some $\mathcal{O}(10\%)$ of the total DM abundance and $\tau_X \sim 10^7$ sec. Comparing with our results we conclude that the effect is probably

marginal in the CMSSM. A similar effect was also studied in the case of supergravity [59] and in a more general setting in neutral heavy particle decays [60]. Large v_{rms} may lead to the damping of linear power spectrum and reducing the density of cuspy substructure and concentration of halos, which have been considered to be potential problems for the standard CDM scenario. A contribution of such a warm (or hot) component of dark matter may, however, be strongly limited by current and future constraints from early reionization [61]. In the model studied here gravitinos from TP would provide a cold component while those from NTP could be a warm one. A more detailed investigation would be required to assess constraints on, and implications of, this mixed warm–cold relic gravitino population in the presented framework.

6. Summary

We have re-examined the gravitino as cold dark matter in the Universe in the framework of the CMSSM. In contrast to other studies, we have included both their thermal population from scatterings in an expanding plasma at high temperatures and a non-thermal one from NLSP freeze-out and decay. In addition to the usual collider constraints, we have applied bounds from the shape of the CMB spectrum and, more importantly, from light elements produced during BBN. The implementation of the last constraint has in the present study been considerably improved and also updated ranges of light element abundances have been used but basically confirm and strengthen our previous conclusions [1]. The neutralino NLSP region is not viable, while in large parts of the stau NLSP domain the total gravitino relic abundance is consistent with the currently favored range. Unless one allows for very large $m_{1/2} \gtrsim 5 \text{ TeV}$, for this to happen a substantial contribution from TP is required which implies a lower limit on T_R . For example, assuming heavy enough gravitinos (as in the gravity-mediated SUSY breaking scheme), $m_{\tilde{G}} > 1 \text{ GeV}$ leads to $T_R > 10^7 \text{ GeV}$ (if allowed by BBN and other constraints). In a more generic case, if $m_{\tilde{G}} > 100 \text{ keV}$ then $T_R > 10^3 \text{ GeV}$. Generally, for light gravitinos ($m_{\tilde{G}} \lesssim 1 \text{ GeV}$) BBN and CMB constraints become irrelevant because of NLSP decays taking place much earlier. On the other hand, the above constraints imply an upper bound (5.1), which appears too low for thermal leptogenesis, as already concluded in [1].

Finally, we have shown that in most of the stau NLSP region consistent with BBN and CMB constraints the usual Fermi vacuum is not the global minimum of the model. Instead, the true vacuum, while located far away from the Fermi vacuum is color and charge breaking.

Implications for SUSY searches at the LHC are striking. The standard missing energy and missing momentum signature of a stable neutralino LSP is not allowed in this model, unless $m_{\tilde{G}} \lesssim 1 \text{ GeV}$. Instead, the characteristic signature would be a detection of a massive, (meta-)stable and electrically charged particle (the stau). It is worth remembering that such a measurement would not be a smoking gun for the gravitino dark matter since in the case of the axino as CDM the stau NLSP (as well as neutralino NLSP) is typically allowed as well [4]. Finally in some cases it may be possible to accumulate enough staus to be able to observe their decays into gravitinos [62] and/or to distinguish them from decays

into axinos [63]. SUSY searches at the LHC open up a realistic possibility of pointing at non-standard CDM candidates and additionally revealing the vacuum structure of the Universe.

Acknowledgments

D.G.C. and K.-Y.C. are funded by PPARC. L.R. acknowledges partial support from the EU Network MRTN-CT-2004-503369. We would further like to thank the European Network of Theoretical Astroparticle Physics (ENTApP, part of ILIAS, contract number RII3-CT-2004-506222) for financial support.

Erratum

Following a recent paper of Pradler and Steffen [64] a formula for the thermal production of gravitino in ref. [23] (Bolz, et al.) has been corrected. In addition, we have corrected a numerical error in our routine computing α_s at high temperatures. As a consequence, the regions of $\Omega_{\tilde{G}} h^2$ (green bands) in all the figures have shifted to the left, towards smaller $m_{1/2}$ relative to the previous version, which in turn has led to improving the upper bound on the reheating temperature by about an order of magnitude. The new bound is $T_R \lesssim \text{a few} \times 10^8 \text{ GeV}$.

We thank J. Pradler and F. Steffen for checking our results and informing us about a discrepancy with theirs.

References

- [1] L. Roszkowski, R. Ruiz de Austri and K.-Y. Choi, “Gravitino dark matter in the CMSSM and implications for leptogenesis and the LHC”, *J. High Energy Phys.* **0508** (2005) 080 [hep-ph/0408227].
- [2] J.L. Feng, A. Rajaraman and F. Takayama, “Superweakly interacting massive particles”, *Phys. Rev. Lett.* **91** (2003) 011302 [arXiv:hep-ph/0302215].
- [3] J. Preskill, M.B. Wise and F. Wilczek, “Cosmology of the invisible axion”, *Phys. Lett.* **B 120** (1983) 127; L.F. Abbott and P. Sikivie, “A cosmological bound on the invisible axion”, *Phys. Lett.* **B 120** (1983) 133; M. Dine and W. Fischler, “The not-so-harmless axion”, *Phys. Lett.* **B 120** (1983) 137.
- [4] L. Covi, J.E. Kim and L. Roszkowski, “Axinos as cold dark matter”, *Phys. Rev. Lett.* **82** (1999) 4180 [hep-ph/9905212]; L. Covi, H.B. Kim, J.E. Kim and L. Roszkowski, “Axinos as dark matter”, *J. High Energy Phys.* **05** (2001) 033 [hep-ph/0101009]; L. Covi, L. Roszkowski, R. Ruiz de Austri and M. Small, *Axino dark matter and the CMSSM*, *J. High Energy Phys.* **0406** (2004) 003 [hep-ph/0402240].
- [5] See, e.g., T. Asaka, J. Hashiba, M. Kawasaki and T. Yanagida, “Cosmological moduli problem in gauge mediated supersymmetry breaking theories”, *Phys. Rev.* **D 58** (1998) 083509 [hep-ph/9711501]; “Spectrum of background X-rays from moduli dark matter”, *Phys. Rev.* **D 58** (1998) 023507 [hep-ph/9802271].
- [6] H. Pagels and J.R. Primack, “Supersymmetry, cosmology and new TeV physics,” *Phys. Rev. Lett.* **48** (1982) 223.

- [7] S. Weinberg, “Cosmological constraints on the scale of supersymmetry breaking,” *Phys. Rev. Lett.* **48** (1982) 1303.
- [8] M.Y. Khlopov and A. Linde, “Is it easy to save the gravitino?,” *Phys. Lett. B* **138** (1984) 265.
- [9] J.R. Ellis, J.E. Kim and D.V. Nanopoulos, “Cosmological gravitino regeneration and decay,” *Phys. Lett. B* **145** (1984) 181.
- [10] J.R. Ellis, D.V. Nanopoulos and S. Sarkar, “The cosmology of decaying gravitinos”, *Nucl. Phys. B* **259** (1985) 175.
- [11] D.V. Nanopoulos, K.A. Olive and M. Srednicki, “After primordial inflation”, *Phys. Lett. B* **127** (1983) 30.
- [12] R. Juszkiewicz, J. Silk and A. Stebbins, “Constraints on cosmologically regenerated gravitinos”, *Phys. Lett. B* **158** (1985) 463.
- [13] M. Kawasaki and T. Moroi, “Gravitino production in the inflationary universe and the effects on big-bang nucleosynthesis”, *Prog. Theor. Phys.* **93** (1995) 879 [hep-ph/9403364].
- [14] R.H. Cyburt, J. Ellis, B.D. Fields and K.A. Olive, “Updated nucleosynthesis constraints on unstable relic particles”, *Phys. Rev. D* **67** (2003) 103521 [astro-ph/0211258].
- [15] M. Kawasaki, K. Kohri and T. Moroi, “Hadronic Decay of Late-Decaying Particles and Big-Bang Nucleosynthesis”, *Phys. Lett. B* **625** (2005) 7 [astro-ph/0402490] and “Big-bang nucleosynthesis and hadronic decay of long-lived massive particles”, *Phys. Rev. D* **71** (2005) 083502 [astro-ph/0408426].
- [16] K. Kohri, T. Moroi and A. Yotsuyanagi, “Big-bang nucleosynthesis with unstable gravitino and upper bound on the reheating temperature”, hep-ph/0507245.
- [17] T. Moroi, H. Murayama and M. Yamaguchi, “Cosmological constraints on the light stable gravitino”, *Phys. Lett. B* **303** (1993) 289.
- [18] G.F. Giudice, A. Riotto and I. Tkachev, “Thermal and non-thermal production of gravitinos in the early Universe”, *J. High Energy Phys.* **9911** (1999) 036 [hep-ph/9911302] and “Non-thermal production of dangerous relics in the early Universe”, *J. High Energy Phys.* **9908** (1999) 009 [hep-ph/9907510].
- [19] R. Kallosh, L. Kofman, A. Linde and A. Van Proeyen, *Phys. Rev. D* **61** (2000) 103503 [hep-th/9907124]. “Gravitino production after inflation”,
- [20] For a recent analysis, see K. Kohri, M. Yamaguchi and J. Yokoyama, “Production and dilution of gravitinos by modulus decay”, *Phys. Rev. D* **70** (2004) 043522 [hep-ph/0403043].
- [21] H.P. Nilles, M. Peloso and L. Sorbo, “Nonthermal production of gravitinos and inflatinos”, *Phys. Rev. Lett.* **87** (2001) 051302 [hep-ph/0102264].
- [22] M. Bolz, W. Buchmüller and Plümacher, “Baryon asymmetry and dark matter”, *Phys. Lett. B* **443** (1998) 209 [hep-ph/9809381].
- [23] M. Bolz, A. Brandenburg and W. Buchmüller, “Thermal production of gravitinos”, *Nucl. Phys. B* **606** (2001) 518 [hep-ph/0012052] and Erratum.
- [24] J.L. Feng, A. Rajaraman and F. Takayama, “Superweakly interacting massive particle dark matter signals from the early Universe”, *Phys. Rev. D* **68** (2003) 063504 [hep-ph/0306024].

- [25] J.L. Feng, S. Su and F. Takayama, “SuperWIMP gravitino dark matter from slepton and sneutrino decays”, *Phys. Rev. D* **70** (2004) 063514 [hep-ph/0404198] and “Supergravity with a gravitino lightest supersymmetric particle”, *Phys. Rev. D* **70** (2004) 075019 [hep-ph/0404231].
- [26] J. Ellis, K.A. Olive, Y. Santoso and V. Spanos, “Gravitino dark matter in the CMSSM”, *Phys. Lett. B* **588** (2004) 7 [hep-ph/0312262].
- [27] M. Fujii, M. Ibe, T. Yanagida, “Upper Bound On Gluino Mass From Thermal Leptogenesis” *Phys. Lett. B* **579** (2004) 6 [hep-ph/0310142].
- [28] G.L. Kane, C. Kolda, L. Roszkowski, and J.D. Wells, “Study of constrained minimal supersymmetry”, *Phys. Rev. D* **49** (1994) 6173 [hep-ph/9312272].
- [29] M. Fukugita and T. Yanagida, “Baryogenesis without grand unification”, *Phys. Lett. B* **174** (1986) 45.
- [30] L. Covi, E. Roulet and F. Vissani, “CP violating decays in leptogenesis scenarios”, *Phys. Lett. B* **384** (1996) 169 [hep-ph/9605319].
- [31] W. Hu and J. Silk, “Thermalization constraints and spectral distortions for massive unstable relic particles”, *Phys. Rev. Lett.* **70** (1993) 2661 and “Thermalization and spectral distortions of the cosmic background radiation”, *Phys. Rev. D* **48** (1993) 485.
- [32] For a review see e.g., C. Muñoz, “Charge and color breaking in supersymmetry and superstrings”, hep-ph/9709329.
- [33] J.M. Frere, D.R.T. Jones and S. Raby, “Fermion masses and induction of the weak scale by supergravity”, *Nucl. Phys. B* **222** (1983) 11; L. Alvarez-Gaumé, J. Polchinski and M. Wise, “Minimal low-energy supergravity”, *Nucl. Phys. B* **221** (1983) 495; J.P. Derendinger and C.A. Savoy, “Quantum effects and SU(2)U(1) breaking in supergravity gauge theories”, *Nucl. Phys. B* **237** (1984) 307; C. Kounnas, A.B. Lahanas, D.V. Nanopoulos and M. Quirós, “Low-energy behaviour of realistic locally-supersymmetric grand unified theories”, *Nucl. Phys. B* **236** (1984) 438; M. Drees, M. Glück and K. Grassie, “A new class of false vacua in low energy $N = 1$ supergravity theories”, *Phys. Lett. B* **157** (1985) 164; J.F. Gunion, H.E. Haber and M. Sher, “Charge/color breaking minima and A-parameter bounds in supersymmetric models”, *Nucl. Phys. B* **306** (1988) 1; H. Komatsu, “New constraints on parameters in the minimal supersymmetric model”, *Phys. Lett. B* **215** (1988) 323; G. Gamberini, G. Ridolfi and F. Zwirner, “On radiative gauge symmetry breaking in the minimal supersymmetric model”, *Nucl. Phys. B* **331** (1990) 331; P. Langacker and N. Polonsky, “Implications of Yukawa unification for the Higgs sector in supersymmetric grand-unified models”, *Phys. Rev. D* **50** (1994) 2199 [hep-ph/9403306].
- [34] J.A. Casas, A. Lleyda and C. Muñoz, “Strong constraints on the parameter space of the MSSM from charge and color breaking minima”, *Nucl. Phys. B* **471** (1996) 3 [hep-ph/9507294].
- [35] J.A. Casas, A. Lleyda and C. Muñoz, “Problems for supersymmetry breaking by the dilaton in strings from charge and color breaking”, *Phys. Lett. B* **380** (1996) 59 [hep-ph/9601357] and “Some implications of charge and color breaking in the MSSM”, *Phys. Lett. B* **389** (1996) 305 [hep-ph/9606212].
- [36] J.A. Casas and S. Dimopoulos, “Stability bounds on flavor-violating trilinear soft terms in the MSSM”, *Phys. Lett. B* **387** (1996) 107 [hep-ph/9606237]; H. Baer, M. Bhrlik and D. Castaño, “Constraints on the minimal supergravity model from nonstandard vacua”,

- Phys. Rev. D* **54** (1996) 6944 [hep-ph/9607465]; S.A. Abel and B.C. Allanach, “The quasi-fixed Minimal Supersymmetric Standard Model”, *Phys. Lett. B* **415** (1997) 371 [hep-ph/9707436]; *ibid.* **4** (3) 1 (1998) 339 [hep-ph/9803476]; S.A. Abel and T. Falk, “Charge and colour breaking in the constrained MSSM”, *Phys. Lett. B* **444** (1998) 427 [hep-ph/9810297]; J.A. Casas, A. Ibarra and C. Muñoz, “Phenomenological viability of string and M-theory scenarios”, *Nucl. Phys. B* **554** (1999) 67 [hep-ph/9810266]; S.A. Abel, B.C. Allanach, F. Quevedo, L.E. Ibáñez and M. Klein, “Soft SUSY breaking, dilaton domination and intermediate scale string models”, *J. High Energy Phys.* **0012** (2000) 026 [hep-ph/0005260].
- [37] M. Claudson, L.J. Hall and I. Hinchliffe, “Low-energy supergravity: False vacua and vacuum predictions”, *Nucl. Phys. B* **228** (1983) 501; A. Riotto and E. Roulet, “Vacuum decay along supersymmetric flat directions”, *Phys. Lett. B* **377** (1996) 60 [hep-ph/9512401]; A. Kusenko, P. Langacker and G. Segre, “Phase transitions and vacuum tunnelling into charge- and color-breaking minima in the MSSM”, *Phys. Rev. D* **54** (1996) 5824 [hep-ph/9602414]; A. Strumia, “Charge and colour breaking minima and constraints on the MSSM parameters”, *Nucl. Phys. B* **482** (1996) 24 [hep-ph/9604417]; A. Kusenko and P. Langacker, “Is the vacuum stable?”, *Phys. Lett. B* **391** (1997) 29 [hep-ph/9608340]; S.A. Abel and C.A. Savoy, “On metastability in supersymmetric models”, *Nucl. Phys. B* **532** (1998) 3 [hep-ph/9803218]; I. Dasgupta, R. Rademacher and P. Suranyi, “Improved mass constraints in the MSSM from vacuum stability”, *Phys. Lett. B* **447** (1999) 284 [hep-ph/9804229].
- [38] T. Falk, K.A. Olive, L. Roszkowski, M. Srednicki, “New constraints on superpartner masses”, *Phys. Lett. B* **367** (1996) 183 [hep-ph/9510308].
- [39] T. Falk, K.A. Olive, L. Roszkowski, A. Singh, M. Srednicki “Constraints from inflation and reheating on superpartner masses”, *Phys. Lett. B* **396** (1997) 50 [hep-ph/9611325].
- [40] D.G. Cerdeño, E. Gabrielli, M. E. Gomez, and C. Muñoz, “Neutralino-nucleon cross section and charge and colour breaking constraints”, *J. High Energy Phys.* **06** (2003) 030 [hep-ph/0304115].
- [41] A. Djouadi, J.-L. Kneur and G. Moultaka. The package SUSPECT is available at <http://www.lpm.univ-montp2.fr:7082/~kneur/suspect.html>.
- [42] Joint LEP 2 supersymmetry working group, http://alephwww.cern.ch/~ganis/SUSYWG/SLEP/sleptons_2k01.html
- [43] The CDF Collaboration, the D0 Collaboration and the Tevatron Electroweak Working Group, “Combination of CDF and D0 results on the top-quark mass”, hep-ex/0507091.
- [44] D.N. Spergel, *et al.*, “First year Wilkinson microwave anisotropy probe (WMAP) observations: Determination of cosmological parameters”, *Astrophys. J.* **148** (2003) 175 [astro-ph/0302209].
- [45] M.H. Reno and D. Seckel, “Primordial nucleosynthesis: The effects of injecting hadrons”, *Phys. Rev. D* **37** (1988) 3441.
- [46] S. Dimopoulos, R. Esmailzadeh, L.J. Hall and G.D. Starkman, “Is the Universe closed by baryons? Nucleosynthesis with a late decaying massive particle”, *Astrophys. J.* **330** (1988) 545 and “Limits on late decaying particles from nucleosynthesis”, *Nucl. Phys. B* **311** (1989) 699.
- [47] K. Jedamzik, “Did something decay, evaporate, or annihilate during big bang nucleosynthesis?”, *Phys. Rev. D* **70** (2004) 063524 [astro-ph/0402344].

- [48] K. Jedamzik, in preparation.
- [49] G. Sigl, K. Jedamzik, D.N. Schramm, V.S. Berezinsky, “Helium photodisintegration and nucleosynthesis: Implications for topological defects, high energy cosmic rays, and massive black holes”, *Phys. Rev. D* **52** (1995) 6682 [astro-ph/9503094].
- [50] K. Jedamzik, “Lithium-6: A probe of the early Universe”, *Phys. Rev. Lett.* **84** (2000) 3248 [astro-ph/9909445].
- [51] D.L. Lambert, “Lithium in very metal-poor dwarf stars - Problems for standard big bang nucleosynthesis?”, astro-ph/0410418.
- [52] R. Lamon, R. Durrer, “Constraining gravitino dark matter with the cosmic microwave background”, hep-ph/0506229.
- [53] For a review, see G.F. Giudice and R. Rattazzi, “Theories with gauge-mediated supersymmetry breaking”, *Phys. Rept.* **322** (1999) 419 [hep-ph/9801271].
- [54] L. Randall and R. Sundrum, “Out of this world supersymmetry breaking”, *Nucl. Phys. B* **557** (1999) 79 [hep-ph/9810155]; G.F. Giudice, M.A. Luty, H. Murayama and R. Rattazzi, “Gaugino mass without singlets”, *J. High Energy Phys.* **9812** (1998) 027 [hep-ph/9810442].
- [55] S. Borgani, A. Masiero and M. Yamaguchi, “Light gravitinos as mixed dark matter”, *Phys. Lett. B* **386** (1996) 189 [hep-ph/9605222].
- [56] E. Pierpaoli and S. Bonometto, “Mixed dark matter models with a non-thermal hot component: fluctuation evolution”, astro-ph/9410059.
- [57] S.A. Bonometto, F. Gabbiani and A. Masiero, “Mixed dark matter from axino distribution”, *Phys. Rev. D* **49** (1994) 3918 [astro-ph/9305010].
- [58] K. Sigurdson and M. Kamionkowski, “Charged-particle decay and suppression of small-scale power”, *Phys. Rev. Lett.* **92** (2004) 171302 [astro-ph/0311486]; S. Profumo, K. Sigurdson, P. Ullio and M. Kamionkowski, “A running spectral index in supersymmetric dark-matter models with quasi-stable charged particles”, *Phys. Rev. D* **71** (2005) 023518 [astro-ph/0410714].
- [59] J.A. R. Cembranos, J.L. Feng, A. Rajaraman and F. Takayama, “SuperWIMP solutions to small scale structure problems”, hep-ph/0507150.
- [60] M. Kaplinghat, “Dark matter from early decays”, astro-ph/0507300.
- [61] K. Jedamzik, M. Lemoine and G. Moulhaka, “Gravitino, axino, Kaluza-Klein graviton warm and mixed dark matter and reionisation”, astro-ph/0508141.
- [62] W. Buchmüller, K. Hamaguchi, M. Ratz and T. Yanagida, “Supergravity at colliders”, *Phys. Lett. B* **588** (2004) 90 [hep-ph/0402179].
- [63] A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski and F.D. Steffen, “Signatures of axinos and gravitinos at colliders”, *Phys. Lett. B* **617** (2005) 99 [hep-ph/0501287].
- [64] J. Pradler and F.D. Steffen, “Thermal gravitino production and collider tests of leptogenesis”, *Phys. Rev. D* **75** (2007) 023509 [hep-ph/0608344].