COSMOLOGICAL CONSTRAINTS ON GAUGINO MEDIATION [a]

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With gaugino-mediated supersymmetry breaking, the gravitino, a neutralino or a scalar lepton can be the lightest or next-to-lightest superparticle. We discuss cosmological constraints on the different scenarios. While neutralino dark matter and gravitino DM with a sneutrino NLSP are consistent for a wide range of parameters, gravitino DM with a stau NLSP is strongly constrained. Gravitino DM with a neutralino NLSP is excluded.

1 Introduction

Gaugino-mediated supersymmetry breaking[2,3] employs a setup with extra space-time dimensions to generate viable soft masses for the superparticles. SUSY is broken by the F-term vacuum expectation value of a field which is localised on a brane. The MSSM squarks and sleptons live on another brane located at a different position in the extra dimensions. Therefore, they cannot couple to the SUSY-breaking field and do not obtain soft masses at the tree level. Gauginos and Higgses are assumed to be bulk fields, so that they receive soft masses via direct interactions. Thus, assuming that the gauge couplings unify and that the compactification scale of the extra dimensions is close to the unification scale, one obtains at this energy

$$g_1 = g_2 = g_3 = g \simeq \frac{1}{\sqrt{2}} \,, \tag{1}$$

$$M_1 = M_2 = M_3 = m_{1/2} \,, \tag{2}$$

$$m^2_{\tilde{\phi}_L} = m^2_{\tilde{\phi}_R} = 0 \quad \text{for all squarks and sleptons } \tilde{\phi} \,, \tag{3}$$

$$A_{\tilde{\phi}} = 0 \quad \text{for all squarks and sleptons } \tilde{\phi} \,, \tag{4}$$

$$\mu, B\mu, m^2_{h_i} \neq 0 \quad (i = 1, 2) \,, \tag{5}$$

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where the GUT charge normalisation is used for g_1 and where $m^2_{\tilde{h}_1}$ and $m^2_{\tilde{h}_2}$ are the soft masses of the Higgs fields coupling to the down-type and the up-type quarks, respectively. For simplicity, we restrict ourselves to the case $m^2_{\tilde{h}_i} \geq 0$. A discussion that includes negative values can be found in [4].

The renormalisation group running from the compactification scale to low energies produces non-zero soft masses for all superparticles. We employed SOFTSUSY [5] to calculate the mass spectrum. As benchmark values for our discussion, we chose $m_{1/2} = 500\,\mathrm{GeV}$, $\tan\beta = 10$ or 20 and $\mathrm{sign}(\mu) = +1$. The values of μ and $B\mu$ are determined by the conditions for electroweak symmetry breaking. Due to the large effects of the strong interaction, the squark masses experience the fastest running and end up around a TeV. Regarding the mass ordering of the sleptons and neutralinos, the most important free parameters are the soft Higgs masses. Depending on their values, the lightest MSSM superparticle can be a neutralino, a stau or a sneutrino [2,3,6]. Besides one of these particles, the gravitino can be the lightest superparticle (LSP). In gaugino mediation its mass is bounded from below [7]. We use $m_{3/2} \geq 10\,\mathrm{GeV}$, relaxing the limit from naive dimensional analysis by a factor 5 in order to obtain a conservative lower bound.

The constraints on the parameter space of gaugino mediation that arise from collider experiments were described in [8,9,4]. In the following, we will present the impact of constraints from cosmology, summarising and updating the study [1].

2 Cosmological Constraints

As long as R parity is conserved, the LSP is stable and its energy density has to be consistent with the observed cold dark matter density. We use the 3σ range given in [10],

$$0.106 < \Omega_{\mathrm{DM}} h^2 < 0.123 \ . \tag{6}$$

If the gravitino is the LSP, the next-to-lightest superparticle (NLSP) decays during or after big bang nucleosynthesis (BBN). Analogously, the gravitino decays late if it is not the LSP. The very energetic decay products of such long-lived particles can alter the primordial light element abundances compared to the standard BBN scenario. This leads to constraints on the released electromagnetic and hadronic energy [11,12,13,14], which can be quantified approximately by upper bounds on the product $\epsilon_{\mathrm{em,had}} Y_{\mathrm{NLSP}}$. Here $\epsilon_{\mathrm{em,had}}$ is the average electromagnetic or hadronic energy emitted in a single NLSP decay, and the abundance Y_{NLSP} is given by the NLSP number density prior to decay divided by the total entropy density. The abundance was determined numerically using micrOMEGAs [15,16] and assuming that the NLSP freezes out with its thermal relic density. We used the bounds on the energy release compiled in [17], which were computed in the earlier studies [11,12]. These bounds were derived from the observed abundances of deuterium and ^{4}He. Following [17], we considered two sets of constraints in order to take into account the uncertainties in the measurements. Points in parameter space violating the "conservative" limits are excluded, while points violating only the "severe" limits should be regarded as disfavoured. In addition, we applied the constraint derived from the ratio of the observed ^{3}He and D abundances in [13].

Decays of long-lived particles in the early universe can also cause distortions of the cosmic microwave background. However, the corresponding constraints on late electromagnetic energy release are less constraining than the BBN bounds in our case [17].

Recently it was pointed out that negatively charged stau NLSPs can form bound states with light nuclei, which leads to a drastic change of the reaction rates relevant for BBN [18]. In [18] and in the subsequent studies [19,20,21] it was found that this effect causes an unacceptable overproduction of ^{6}Li unless the stau lifetime is less than $10^3 - 10^4$ s.

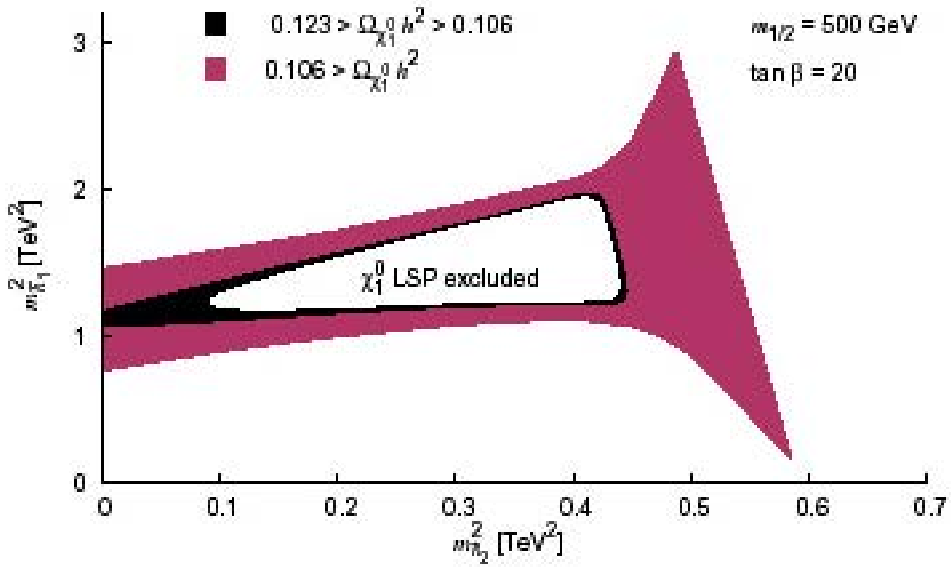

Figure 1: Allowed parameter space region for the soft Higgs masses leading to a neutralino (N)LSP for $m_{1/2} = 500\,\text{GeV}$ and $\tan\beta = 20$. The experimental upper limit on the dark matter density excludes the white region. In the black region, thermally produced neutralino LSPs form all of the dark matter, whereas in the magenta (dark-gray) area they contribute only a part.

3 Neutralino Dark Matter

Fig. 1 shows the part of the allowed parameter space for the soft Higgs masses where a neutralino is the lightest MSSM superparticle for $\tan\beta = 20$. Its mass varies between 83 GeV and 204 GeV. If this neutralino is also lighter than the gravitino, it can form the dark matter. In the black region of the figure, the thermal neutralino relic density lies within the experimentally allowed range (6). The bino contributes at least 80% to the lightest neutralino. The remaining components are chiefly Higgsinos. Towards the left end of the region, the lightest neutralino is a pure bino. In the magenta (dark-gray) region in Fig. 1, the thermal neutralino density is smaller than the lower bound in Eq. (6) and hence only constitutes a part of the dark matter density. This is not ruled out, since the dark matter could be made up of several components or of both thermally and non-thermally produced neutralinos. The lightest neutralino is an almost pure Higgsino at the right edge of the parameter space. Finally, the upper limit on the dark matter density excludes the white region in Fig. 1. For $\tan\beta = 10$, the results are similar.

The cross-section for the direct detection of neutralino dark matter is suppressed for a pure bino. Therefore, in the largest part of the allowed parameter space direct dark matter detection will be very hard. The cross-section is larger towards the right end of the region, where the lightest neutralino has a significant Higgsino component. Although the cross-section is still at least one order of magnitude below the present bounds there [22,4], it could be accessible to the next generation of dark matter experiments.

In the neutralino LSP scenario, BBN leads to an upper bound on the density of gravitinos, since their decays affect the light element abundances as explained above. This bound can be translated into an upper limit on the reheating temperature after inflation [11,12]. The latter is a free parameter in our discussion and therefore it can simply be assumed to be sufficiently small. The other superparticles decay into the LSP before the start of BBN and thus do not cause problems either, unless LSP and NLSP are nearly degenerate. Consequently, neutralino dark matter is a viable scenario in gaugino mediation.

4 Gravitino Dark Matter

If the gravitino is the LSP, it is a viable dark matter candidate as well. The thermally produced gravitino density falls into the range (6) for a reheating temperature between about 10^8 GeV and 10^9 GeV, if $10\,\text{GeV} \lesssim m_{3/2} \lesssim 100\,\text{GeV}$. Non-thermal production from NLSP decays is negligible in the scenario under consideration.

A neutralino NLSP together with a gravitino LSP heavier than a GeV is excluded by the hadronic BBN constraints for $m_\chi > m_{3/2} + m_Z$, since in this case two-body decays can produce Z bosons, which have a large hadronic branching ratio[23,24]. In the parameter space region where the neutralino is so light that the decay into real Z bosons is kinematically forbidden, we find abundances that are small enough to satisfy the hadronic bounds. However, the electromagnetic constraints turn out to be violated, so that gravitino dark matter with a neutralino NLSP is not allowed in gaugino mediation.

If a scalar tau is the NLSP, the hadronic energy release from stau decays is always in agreement with the BBN bounds. However, the bounds on the electromagnetic energy release $\epsilon_{\text{em}} Y_{\tilde{\tau}}$ are significantly more constraining. They are shown in Fig. 2 as functions of the stau lifetime $\tau_{\tilde{\tau}}$. The curves exclude (or disfavour in the case of the severe bound from D) the area above them. The curve derived from the ^{3}He abundance is only shown in the region where it is more constraining than the conservative deuterium bound. The limit arising from the ^{4}He abundance is not shown, since it is not relevant in the stau NLSP region.

We also plot points from the $\tilde{\tau}$ NLSP region for $\tan\beta = 10$ in the $\epsilon_{\text{em}} Y_{\tilde{\tau}} - \tau_{\tilde{\tau}}$ plane, assuming that half the energy of the tau produced in the dominant two-body stau decay contributes to the electromagnetic energy release. The remaining energy ends up in neutrinos and is not relevant. The red (dark-gray) points are the results for a gravitino mass of 50 GeV. We find that the conservative D constraints can be satisfied. In order to satisfy the ^{3}He and the severe D bounds, the NLSP lifetime has to be shorter. This is the case for smaller gravitino masses. A rough estimate of the upper limit from the ^{3}He bound is $m_{3/2} \lesssim 30\,\text{GeV}$. For $m_{3/2} = 10\,\text{GeV}$, we see from the green (light-gray) points in Fig. 2 that most of the stau NLSP region is allowed by all constraints derived from the deuterium and helium abundances.

However, it is also obvious that the stau lifetime violates the upper bound $\tau_{\tilde{\tau}} \lesssim 10^3 - 10^4\,\text{s}$ that arises when bound state effects are included in the BBN calculations [18,19,20,21]. We find $86\,\text{GeV} \leq m_{\tilde{\tau}} \leq 203\,\text{GeV}$ in the $\tilde{\tau}$ NLSP region, which corresponds to $\tau_{\tilde{\tau}} \gtrsim 1.8 \cdot 10^5\,\text{s}$. Thus, we have to conclude that BBN disfavours gaugino mediation with a gravitino LSP and a stau NLSP for our benchmark value $m_{1/2} = 500\,\text{GeV}$. In order to decrease the stau lifetime sufficiently, one has to increase the superparticle masses roughly by a factor 3. The constraint could also be avoided if there was sizable entropy production between the decoupling of the staus from the thermal bath and the start of BBN[25,20].

The last NLSP candidate in gaugino mediation is the sneutrino. In the corresponding parameter space region, we find sneutrino masses and lifetimes which lie roughly in the same range as those of the staus. The relic abundance is also similar, $1.3 \cdot 10^{-13} \leq Y_{\tilde{\nu}} \leq 4.6 \cdot 10^{-13}$. The BBN bounds on a sneutrino NLSP are rather weak, since the dominant two-body decay produces gravitinos and neutrinos. These neutrinos can release electromagnetic energy by annihilating with background (anti-)neutrinos and producing charged particles. Besides, hadronic constraints arise from the four-body decay into a neutrino, a gravitino and a quark-antiquark pair. They turn out to be more stringent but allow thermally produced sneutrinos with masses up to around 300 GeV according to [14]. This result is based on an approximation for the sneutrino abundance. In our case, the abundance turns out to be larger due to the importance of co-annihilations. Hence, a part of the sneutrino region may be in conflict with BBN[26]. However, one has to bear in mind that [14] assumed a much smaller experimental uncertainty for the deuterium abundance than the studies [13,17], on which our analysis of the stau NLSP scenario is based.

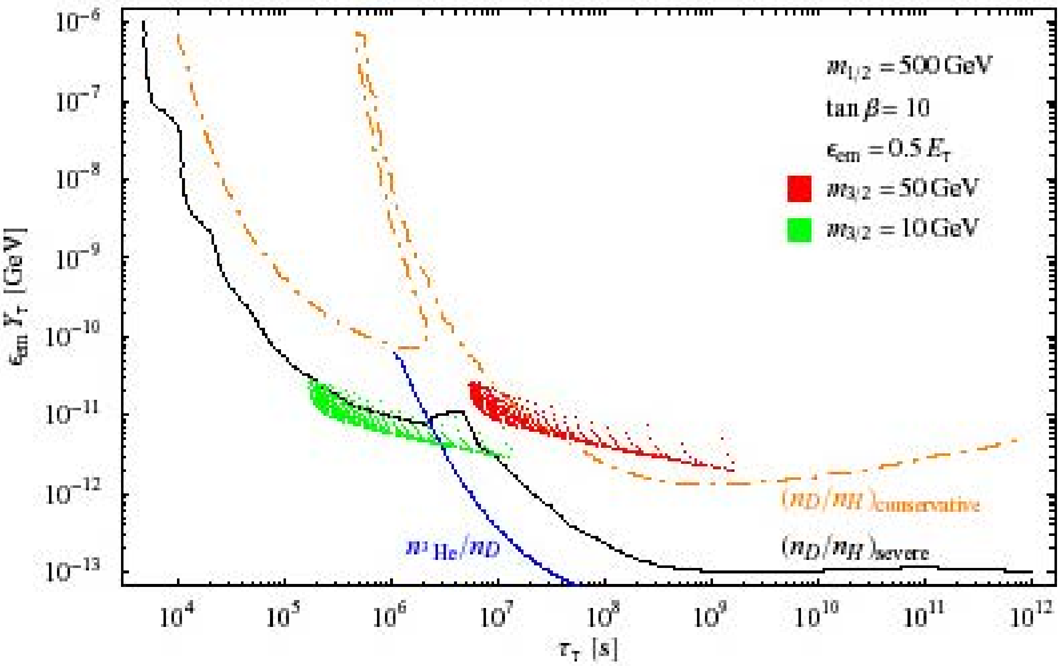

Figure 2: Points from the $\tilde{\tau}$ NLSP region in the $\epsilon_{em} Y_{\tilde{\tau}} - \tau_{\tilde{\tau}}$ plane for $m_{1/2} = 500\,\text{GeV}$, $\tan\beta = 10$ and $\epsilon_{em} = 0.5 E_\tau$. We show the results for two values of the gravitino mass, $m_{3/2} = 50\,\text{GeV}$ (red or dark-gray) and $m_{3/2} = 10\,\text{GeV}$ (green or light-gray). The lines show the BBN constraints on electromagnetic energy release taken from Fig. 9 of [13] and Fig. 9 of [17].

5 Conclusions

We have discussed dark matter candidates in theories with gaugino-mediated supersymmetry breaking. The parameters relevant for the superparticle mass spectrum are the universal gaugino mass, the soft Higgs masses, $\tan\beta$ and the sign of μ. At different points in parameter space, the gravitino, a neutralino or a slepton can be the lightest or next-to-lightest superparticle.

We have investigated constraints from the observed dark matter density and big bang nucleosynthesis on the different scenarios. A neutralino LSP as the dominant component of dark matter is a viable possibility. Gravitino dark matter with a neutralino NLSP is excluded. A stau NLSP can be consistent with the constraints arising from the effects of stau decays on the primordial light element abundances. However, taking into account bound state effects on the lithium abundance disfavours this scenario. Gravitino dark matter with a sneutrino NLSP can also be realised and is nearly unaffected by all constraints.

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