PROCEEDINGS OF SCIENCE

Axino and gravitino dark matter with low reheating temperature

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Possible discovery of supersymmetric particles in the second run of the LHC accompanied by lack of observation of a dark matter particle in direct searches may point towards dark matter candidates being extremely weakly interacting particles with supersymmetric origin. We focus on two such candidates that are well motivated theoretically, namely the axino and the gravitino. In particular, we derive the lower limits for the reheating temperatures in such scenarios that come from the relic density and the Big Bang Nucleosynthesis constraints. Beside that, the upper limit on the axino dark matter mass is found as a function of the reheating temperature. These issues can be properly treated only when non-instantaneous reheating of the Universe after a period of cosmological inflation is taken into account.

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1. Introduction

In spite of long and thorough efforts, the nature of dark matter (DM) remains one of the most important unanswered questions in contemporary physics. Among a variety of theoretical proposals for a cold dark matter (CDM) candidate discussed in the literature, one can distinguish a group of extremely weakly interacting massive particles (EWIMPs). They often remain elusive from the point of view of direct and indirect DM searches, but can be constrained by cosmological considerations. In particular, supersymmetry (SUSY) provides two such well-motivated EWIMPs that can constitute CDM, namely the gravitino, $\widetilde{G}$, and the axino, $\tilde{a}$.

It was shown that viability of the gravitino and the axino CDM scenarios requires that the reheating temperature, T_R, of the Universe after a period of cosmological inflation is at most a several orders of magnitude larger than the electroweak scale (see, e.g., for the gravitino [1, 2] and for the axino [4, 5, 6]). In the following we complement the existing studies of this subject by focusing on and finding the lowest possible values of T_R in such scenarios. To do this we carefully examine the most important production mechanisms of gravitinos and axinos in presence of non-instantaneous reheating of the Universe and perform a thorough study of the allowed parameter space of the Minimal Supersymmetric Standard Model (MSSM).

2. Neutralino yield after freeze-out with low reheating temperature

The yield after freeze-out of the lightest ordinary supersymmetric particle (LOSP), i.e., the lightest of all SUSY particles beside $\widetilde{G}$ and $\tilde{a}$, can play a very important role in determining the gravitino or axino relic abundance. It is because EWIMPs can be effectively produced in late-time decays of the LOSPs. The contribution to $\Omega_{\rm EWIMP}h^2$ that corresponds to this non-thermal production (NTP) is given by

$$\Omega^{\rm NTP}_{\rm EWIMP}h^2 = \frac{m_{\rm EWIMP}}{m_{\rm LOSP}}\,\Omega_{\rm LOSP}h^2, \tag{2.1}$$

where $\Omega_{\rm LOSP}h^2$ is calculated as if the LOSP was a DM candidate. It is important to note that such late-time decays of the LOSP to $\widetilde{G}$ or $\tilde{a}$ can be tightly constrained by the bounds from the Big Bang Nucleosynthesis (BBN) [7].

If T_R is lower than the freeze-out temperature, LOSPs may freeze out before the inflaton field has fully decayed. The decaying inflaton field causes then an increased expansion of the Universe and an additional entropy production that effectively dilutes away the LOSPs after freeze-out [8, 9].

In the left panel of Fig. 1 we illustrate both for $T_R \gg T_{\rm fo}$ (high T_R scenario) and $T_R \lesssim T_{\rm fo}$ (low T_R scenario) the temperature dependence of total yield Y of all supersymmetric particles (other than $\widetilde{G}$ or $\tilde{a}$), which is equal to the LOSP yield for low temperatures. Due to a faster expansion of the Universe, for low T_R the freeze-out occurs slightly earlier than for high T_R, but a continuous entropy production keeps diluting the DM particles until the reheating temperature is reached therefore reducing the DM abundance relative to high-T_R scenarios.

We present our results for the neutralino, χ, LOSP DM relic density in the context of a 10-parameter MSSM (p10MSSM) which exhibits all the features of the general model that are relevant for our discussion. The constraints that we impose include, e.g., the LHC limits on superparticles

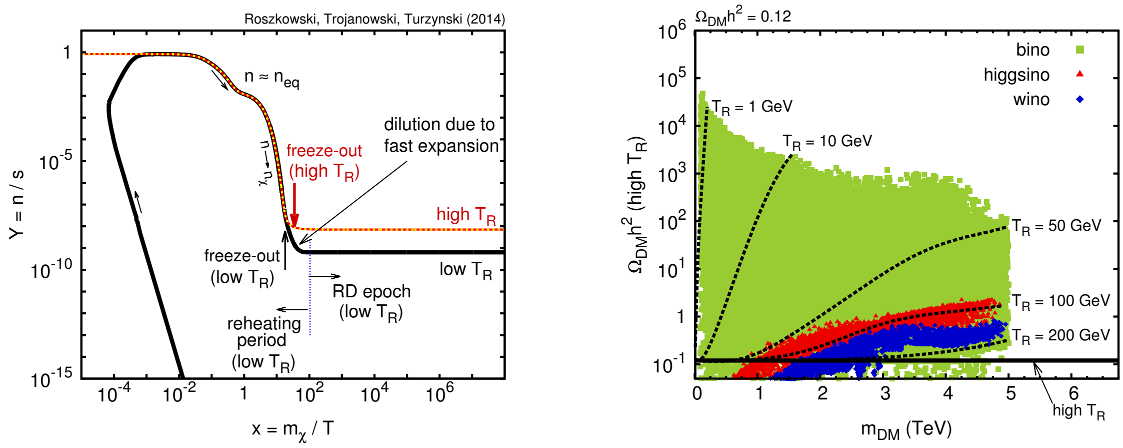


Figure 1: *Left panel*: The LOSP yield $Y = n/s$ as a function of $x = m_\chi/T$ in scenarios with low and high reheating temperature. A solid (dotted) curve corresponds to the low (high) T_R scenario. *Right panel*: Contours (black dotted) of constant $\Omega_{\text{LOSP-DM}}h^2 = 0.12$ for neutralino, χ, DM and different values of the reheating temperature, T_R, in the MSSM in the $(m_\chi, \Omega_\chi h^2(\text{high } T_R))$ plane. The solid black horizontal line corresponds to the high T_R limit. Taken from Ref.[10].

and the Higgs boson mass. The ranges of parameters have been chosen so as to obtain a wide range of $\Omega_\chi h^2(\text{high } T_R)$ with m_χ reaching up to 5 TeV (for more details see [10]). The results of the scans are shown in the right panel of Fig. 1. The lines of constant T_R correspond to $\Omega_\chi h^2 \simeq 0.12$. The upper boundary of the allowed region in the right panel of Fig. 1 has no physical meaning. It simply corresponds to the fact that in absence of any accidental mass degeneracies the bino annihilation rate is dominated by t-channel slepton exchange $\chi\chi \to l\bar{l}$ and that the maximum value of slepton masses in our scan is $\sim 10-15$ TeV.

3. Gravitino dark matter with low reheating temperature

Even if the maximum temperature after a period of cosmological inflation was never high enough for gravitinos to be in thermal equilibrium, they could still be produced in NTP, as well as in thermal production (TP), i.e., in scatterings and decays of other particles in thermal plasma [1, 2, 3]. The thermal component is suppressed for $T_R \ll 10^6\,\text{GeV}$ and $m_{\widetilde{G}} \gtrsim 1\,\text{GeV}$ that we will focus on. Hence at low T_R the gravitino relic abundance is determined by NTP.

Typical results for $m_{\widetilde{G}} = 10$ GeV obtained in the p10MSSM are given in the left panel of Fig. 2 in the $(m_{\text{LOSP}}, \Omega_{\text{LOSP}}h^2(\text{high } T_R))$ plane. The value of the reheating temperature along the dashed lines is found by requiring $\Omega_{\widetilde{G}}h^2 = 0.12$ and using Eq. (2.1) to relate this with $\Omega_{\text{LOSP}}h^2$.

For $m_{\widetilde{G}} \lesssim 100\,\text{GeV}$ and low T_R the bino LOSP is the only possibility for gravitino DM. In this case, however, one often meets significant constraints from the BBN, as can be seen in the left panel of Fig. 2. These bounds can be avoided if the LOSP lifetime is $\lesssim 0.1$ s, which can be further rewritten in terms of the limit on the bino LOSP mass $m_{\widetilde{B}} \gtrsim 1400\,\left(m_{\widetilde{G}}/\text{GeV}\right)^{2/5}$ GeV [11].

This lower bound on m_{LOSP} can be translated into a lower bound on T_R, as can be deduced from the left panel of Fig. 2 for a given $m_{\widetilde{G}} = 10\,\text{GeV}$. We show such a bound in the right panel of

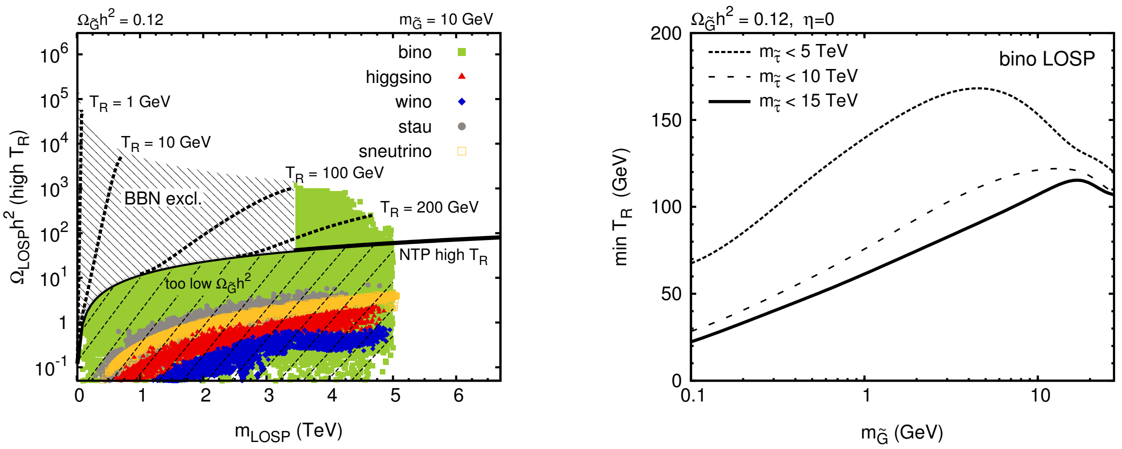


Figure 2: *Left panel*: Contours of constant $\Omega_{\tilde{G}}h^2 = 0.12$ for different values of the reheating temperature T_R and for $m_{\tilde{G}} = 10$ GeV in the p10MSSM with BBN constraints imposed. *Right panel*: Lower bounds on T_R as a function of $m_{\tilde{G}}$ for gravitino DM with a bino LOSP. Three choices of the maximal stau mass $m_{\tilde{\tau}} = 5$, 10 and 15 TeV are shown. Taken from Ref.[10].

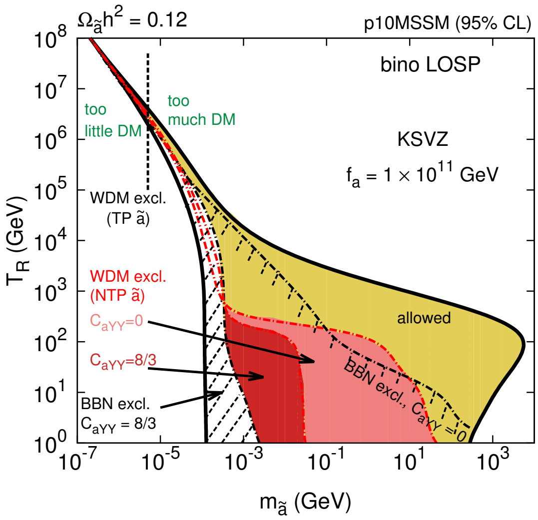
Fig. 2 in a more general way as a function of the gravitino mass. The lower limits on T_R with bino LOSP are shown for three maximum values of the stau mass: 5, 10 and 15 TeV that correspond to the upper boundary of the points in the left panel of Fig. 2 as discussed in Section 2.

For a discussion of the slepton LOSP case and the effect of the additional contribution to the LOSP relic density resulting from direct and/or cascade decays of the inflaton field see [10].

4. Axino dark matter with low reheating temperature

The case of axino CDM [4, 12] is, at least at the phenomenological level, similar to the gravitino DM scenario. Likewise the gravitino, the axino is an EWIMP, though with the interaction rates suppressed by the energy scale f_a that is typically significantly lower than M_P. As a result thermal production of axinos [4, 5, 6] can play a non-negligible role in determining the axino relic density, $\Omega_{\tilde{a}}h^2$, even for low values of the reheating temperature. We take this into account in our study (for previous similar analyses see [6, 13, 14]; our improved discussion can be found in [15]).

The results for the bino and the higgsino LOSP decaying into the axino are shown in Fig. 3. In the case of the bino, similarly to Ref. [14], we find an upper bound on T_R and a lower bound on $m_{\tilde{a}}$, beyond which axino DM becomes too warm. For $T_R \lesssim 10^3$ GeV the excluded points with low $m_{\tilde{a}}$ correspond to dominant NTP from a very large relic density of bino LOSP with a very small annihilation cross-section dominated by a t-channel exchange of multi-TeV sleptons. Such points are, however, excluded by both the BBN bounds (bino LOSP has a long lifetime and a sizable hadronic branching fraction, cf. [11]) and by the wark dark matter constraints. The exclusion is even more striking in absence of direct bino-axino coupling ($C_{aYY} = 0$). In such a scenario we also find a lower limit on T_R that depends on $m_{\tilde{a}}$ and reaches the minimum value of the order of several GeV for $m_{\tilde{a}} \sim 200 - 300$ GeV.



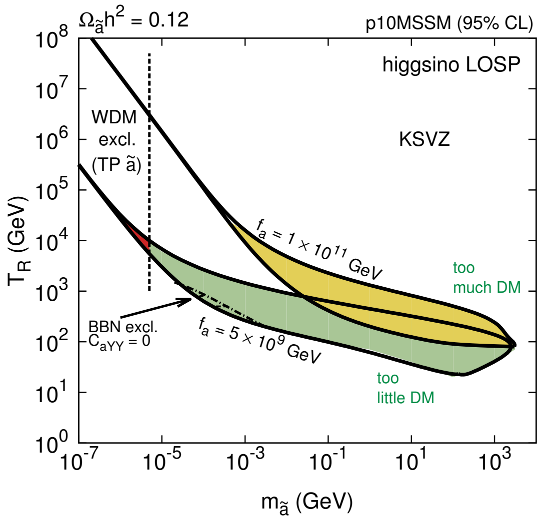


Figure 3: Results of the numerical scan for bino LOSP (left panel) and higgsino LOSP (right panel) projected onto the $(m_{\tilde{a}}, T_R)$ plane for the KSVZ axino. We marked in red the regions excluded by axino dark matter being too warm (WDM constraints). Dashed vertical lines denote the lower bounds on the axino mass coming from WDM constraints for TP only. Regions excluded by BBN constraints are either dashed ($C_{aYY} = 8/3$) or marked with a dash-dotted lines (C_{aYY}=0). Taken from Ref.[15].

In addition, looking at the rightmost part of the allowed region in the left panel of Fig. 3, we see an upper bound on $m_{\tilde{a}}$. As can be seen the largest values of the axino mass as a CDM candidate can be obtained only for $T_R \sim 100\,\mathrm{GeV}$ (in this case they correspond to the largest allowed bino LOSP mass in our scan), while for lower T_R maximum $m_{\tilde{a}}$ is more severely constrained. The last effect is a result of the yield suppression for heavy LOSPs that diminishes NTP of axinos and it does not depend significantly on the details of SUSY spectrum [15].

The main difference for the higgsino LOSP scenario (the right panel of Fig. 3) with respect to the bino LOSP case is that T_R is now bounded from below even for $C_{aYY} \neq 0$. This is because for higgsinos (unlike for binos) the annihilation cross-section cannot be made very small. Hence, for low enough T_R the higgsino LOSP yield is too low for the axino DM from NTP to satisfy the relic abundance constraint. For a discussion about the DFSZ axinos, as well as the wino or stau LOSP see [15].

5. Conclusions

We have studied the impact of a low reheating temperature, T_R, on thermal and non-thermal production of gravitino and axino DM, taking into account the non-instantaneous nature of the reheating process and a wide range of phenomenologically allowed SUSY spectra. In most cases we found that in contrast to the usual assumption the lowest acceptable value of T_R as a function of the DM mass is much larger than the temperature characteristic for the BBN. We also derived an upper limit on the axino DM mass, $m_{\tilde{a}}$, for low T_R and the lower limit on $m_{\tilde{a}}$ in the absence of direct bino-axino coupling.

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