Solving the Cosmic Lithium Problems with Gravitino Dark Matter in the CMSSM

Karsten Jedamzik
Laboratoire de Physique Théorique et Astroparticules, CNRS UMR 5825, Université Montpellier II, F-34095 Montpellier Cedex 5, France

Ki-Young Choi and Leszek Roszkowski
Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK

Robert Ruiz de Austri
Departamento de Física Teórica C-XI and Instituto de Física Teórica C-XVI, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

Determining the nature of the cosmological dark matter is one of the main outstanding challenges in modern cosmology. Compelling candidates for the cold dark matter may be in the form of new neutral stable particles arising in phenomenologically successful supersymmetric extensions of the Standard Model of particle physics. These include the neutralino [2], a mixture of the supersymmetric partners to the neutral Higgs, SU(2) W, and U(1) B bosons, the axion and its supersymmetric partner the axino [3] and the gravitino [4, 5] (the supersymmetric partner of the graviton). Whereas the bulk of studies has been devoted to the neutralino, the case of gravitino dark matter has recently attracted much attention. Studies of gravitino dark matter have been performed either in the context of supersymmetry breaking in a hidden sector being communicated to the visible sector by gravitational interactions [6, 7, 8, 9, 10, 11] or by gauge interactions [12]. Gravitinos may be produced in the early Universe by (at least) two mechanism: (i) scattering of thermal radiation at the highest temperatures of the early Universe, hereafter referred to as thermal production (TP) and (ii) freeze-out and decay of the next-to-lightest supersymmetric particle (NLSP) to gravitinos, hereafter referred to as non-thermal production (NTP). Whereas the gravitino yield in TP depends on the reheating temperature $T_R$, the gravitino abundance due to NTP may in principle come by itself, and independently of $T_R$ [13], very close to the range inferred for dark matter density from cosmological observations. In the case of the gravitino LSP, NLSPs typically decay during or after the epoch of Big Bang nucleosynthesis (BBN), unless the gravitinos are rather light, thereby potentially disrupting light–element yields [2, 13]. This has been often taken to disfavor for heavy gravitino dark matter. However, though stringently constrained by BBN, recent careful study shows that much viable gravitino dark matter parameter space remains [2, 5, 11].

The epoch of BBN has long been known to synthesize the bulk of the 4He and D, as well as good fractions of the 7Li and 3He in the presently observed Universe. Paramount to the realization of this fact was also the discovery of the 7Li–"Spite" plateau in 1982 [14], in particular, the observation of constant 7Li/H abundances in low–metallicity Pop II stars over a wide range in metallicity. This indicated a pre–galactic origin of 7Li, as other sources (i.e. galactic cosmic ray populations) predicted a rise of 7Li with metallicity. Current observational estimates [16, 17, 18] of 7Li/H range between 1.10 × 10^{-10} and 2.34 × 10^{-10}, with differences mostly depending on which effective stellar temperature calibration for the Pop II stars is used. With the accurate estimate of the baryonic density by WMAP, i.e. $\Omega_b h^2 \approx 0.022 – 0.023$, it was possible to predict the primordial 7Li/H abundance of 7Li/H ≈ 3.82 – 4.9 × 10^{-10} [19].

I. INTRODUCTION

$\Omega_b h^2 \approx 0.022 – 0.023$,
within the framework of a standard BBN (SBBN) scenario. It is apparent that this predicted abundance is a factor of 2–3 larger than that observed.

It is conceivable that $^7\text{Li}$ in the atmospheres of Pop II stars has been transported down beyond the base of the convective zone of the stars, and thereby depleted by nuclear burning (i.e. $^7\text{Li}(p,\alpha)^4\text{He}$). Though standard stellar models may not account for this $^7\text{Li}$ depletion within the near–turnoff, low–metallicity stars of the Spite plateau, effects not included in standard models, such as rotation, atomic diffusion, or gravity waves could potentially change this conclusion. Nevertheless, rotationally induced depletion of $^7\text{Li}$ by a factor of 2–3 predicts a spread in stellar $^7\text{Li}$ abundances [20], not observed by any group (see, however, Ref. [21]). This conclusion could be potentially changed when either internal stellar gravity waves [22] or magnetic fields are considered in conjunction with stellar rotation. Atomic diffusion, a process required to understand the structure of the Sun by helioseismology, predicts a slope in the plateau (as a function of stellar temperature) [23] which is not observed in the data (see, however, also Ref. [24]).

Only when atomic diffusion is coupled with an ad hoc and fine–tuned weak turbulence in the radiative zone of the star, may a depletion of the required factor of 2–3 result [25]. However, even in this case a dispersion of the $^7\text{Li}$ data is likely to emerge. It is thus not impossible that depletion of $^7\text{Li}$ on the Spite plateau has occurred. Nevertheless, $^7\text{Li}$ depletion in low–metallicity stars is a well– and long– studied possibility, and even after about 20 years of efforts no consistent and well-motivated scenario including a factor of $\gtrsim 2–3$ depletion has yet emerged.

Standard BBN leads to the synthesis of a $^6\text{Li}$ abundance of $^6\text{Li}/H$ at the level of $10^{-14}–10^{-13}$, orders of magnitudes below what is observable by current technology. Observed $^6\text{Li}$ abundances in the Sun, galactic disc–, and halo– stars are thus traditionally not believed to be of primordial origin, but rather due to galactic cosmic ray nucleosynthesis via supernovae produced energetic $p, \alpha$ or CNO inducing spallation $p + CNO \rightarrow \text{Li Be B}$ or fusion $\alpha + \alpha \rightarrow \text{Li}$ reactions in the gas of the interstellar medium. Here $^6\text{Li}$ is produced along with $^7\text{Li},^{9}\text{Be},^{10}\text{B}$, and $^{11}\text{B}$. Typical production ratios of $^6\text{Li} / ^7\text{Li} \sim 5–10$ in galactic cosmic ray nucleosynthesis are consistent with those observed in the Sun, but not with those $^{2}\text{Li} / ^7\text{Li} \approx 40–80$ ratios observed in low–metallicity $[Z] \sim -2$ Pop II halo stars. It is thus clear that, at the very least, the composition of galactic cosmic rays at higher redshift has to be strongly modified in order to account for the observations. Nevertheless, a $^6\text{Li}/H$ abundance ratio of $\sim 10^{-11}$ at $[Z] \sim -2$ was concluded to be only with difficulty, or not at all, synthesized by galactic cosmic rays, an argument based on the energetics of supernovae generated cosmic rays [20].

It had therefore been speculated that the $^6\text{Li}$ abundance in Pop II stars may originate from the early Universe, via the electromagnetic decay of a relic particle, such as the gravitino, inducing the non–thermal nuclear reaction sequence of $^4\text{He}(\gamma, p)^3\text{H}$ photodisintegration with the resulting energetic $^3\text{H}$ (and $^3\text{He}$) further fusing on $^4\text{He}$ to form $^6\text{Li}$ [27,28]. Here it was found that the synthesis of $^6\text{Li}$ was efficient enough to produce the Pop II abundance without disturbing the other light isotopes or the Planck spectrum of the cosmic microwave background (CMBR) at the observable level. With the advent of the first fully coupled calculations of thermal nuclear reactions and cascade nucleosynthesis during BBN [31] further solutions for the synthesis of the $^6\text{Li}$ abundance in the early Universe were found. They were based on either the residual hadronic annihilation of a population of dark matter $^3\text{He}$ (e.g. neutralinos) during and towards the end of BBN, or the hadronic decay of a relic, long–lived particle population around $10^{3} \text{sec}$ after the Big Bang [1] (e.g. gravitinos). In hadronic decays or annihilations the initial photodisintegration reaction in the non–thermal nuclear reaction sequence given above is replaced by $^4\text{He}(N, p)^3\text{H}$ spallation by energetic nucleons $^N$ produced during the decay.

An intriguing further consequence of the hadronic decay of a relic particle at $10^{3} \text{sec}$ is the prediction of a significant $^7\text{Li}$ abundance reduction concomitant with the $^6\text{Li}$ production. This occurs due to the thermal nuclear reaction sequence $^7\text{Be}(n, p)^7\text{Li}$ and $^7\text{Li}(p, \alpha)^4\text{He}$ induced by the excess neutrons due to the decay. At the same time the D is increased due to $p(n, \gamma)D$, but not as much as to exceed a conservative observational upper limit of $D/H \lesssim 5.3 \times 10^{-5}$ on this isotope. It was found [1] that a relic particle abundance of $\Omega_X h^2 B_h \approx 1 – 5 \times 10^{-4}$ (depending on the mass of the relic), where $B_h$ is the hadronic branching ratio of the relic $X$, was sufficient to explain qualitatively and quantitatively both, the low observed $^7\text{Li}$ abundance and the high observed $^6\text{Li}$ abundance. In [1] it was further speculated that among other possibilities, the relic could be a supersymmetric stau of $\sim 1 \text{TeV}$ mass decaying into a LSP gravitino of mass $50 \text{GeV}$. A clear prediction of the proposed scenario is the existence of a $^6\text{Li}$ plateau, analogous to the $^7\text{Li}$–Spite plateau, i.e. constant $^6\text{Li}/H$ in low–metallicity stars.

Earlier suggestions of a primordial solution of the $^7\text{Li}$ discrepancy [1] involved an electromagnetic decay of a relic particle around $2 \times 10^6 \text{sec}$, thereby photodisintegrating $^7\text{Be}$. Synthesis of $^6\text{Li}$ during the same process was not considered. It was subsequently shown [33] that such a scenario may not work, as either the observational upper limit on the primordial $^4\text{He}/D$ ratio is surpassed due to concomitant $^4\text{He}$ photodisintegration, or a reasonable lower limit on the primordial $D/H \gtrsim 2.2 \times 10^{-5}$ due to D photodisintegration is violated.

Over the last months the number of preliminary detections of $^6\text{Li}/H$ in Pop II stars has multiplied by a large factor. There are now around ten claimed [17,35] detections of the $^6\text{Li}/^7\text{Li}$ isotope ratio, with all ratios falling in the range between $^6\text{Li}/^7\text{Li} \approx 0.03–0.07$ (and with average $^6\text{Li}/^7\text{Li} \approx 0.042$), independent of stellar metallicity falling in the range $[Z] \sim -2.75$ and $[Z] \sim -1.2$. There exist also around ten upper limits, with all of the stars, nevertheless, consistent
with $^{6}\text{Li}/^{7}\text{Li}$ in their atmospheres on the level of $\gtrsim 0.01$ \cite{36}. It is thus intriguing that the $^{6}\text{Li}$ data indeed shows a plateau within a large metallicity range. From a galactic cosmic ray point of view the high $^{6}\text{Li}/^{7}\text{Li}$ abundances as reported in the lowest $|Z| \sim -2.75$ metallicity star LP815–43 is particularly difficult to explain. Following the announcement of results of these difficult observations with the VLT telescope, preliminary detections of more $^{6}\text{Li}/^{7}\text{Li}$ ratios by the Subaru telescope and Ref. \cite{37} have been claimed, with, in particular, one star of metallicity $|Z| \sim -3.25$ seemingly showing again a similar $^{6}\text{Li}/^{7}\text{Li}$ ratio \cite{38}. All this data points to the existence of a $^{6}\text{Li}$ plateau (see below, however). Nevertheless, it needs to be stressed that each individual detection of $^{6}\text{Li}/^{7}\text{Li}$ due to these difficult observations is only at the about 2–4 sigma level. In this sense the observations have to be taken as preliminary.

Though the observations seem to indicate a $^{6}\text{Li}$ plateau over a wide range in metallicity (in particular also, when disk stars at metallicity $|Z| \sim -0.6$ \cite{39} are included into the sample), a plateau may not necessarily exist if one is to believe the claimed \cite{40} metallicity dependence of $^{6}\text{Li}$ destruction on the pre–main–sequence (PMS) of the observed stars. Predicting $^{6}\text{Li}$ destruction during this phase is less certain \cite{41} than during the stellar main sequence. In fact, the prediction are not comparing well to observations and are therefore suspect \cite{42}. The predicted $^{6}\text{Li}$ destruction \cite{40} would imply a rise of $^{6}\text{Li}$ with metallicity for stars with $|Z| \gtrsim -2$. This indeed is theoretically favorable as most groups also observe a rise of $^{7}\text{Li}$ with metallicity on the Spite–(quasi)–plateau, usually attributed to cosmic ray production of $^{7}\text{Li}$. As $^{6}\text{Li}$ is produced by the same process a consistent picture would emerge. In the absence of PMS $^{6}\text{Li}$ destruction either a fine–tuned stellar main–sequence $^{6}\text{Li}$ destruction would have to be invoked \cite{43}, or the conclusion of $^{7}\text{Li}$ rising with metallicity would be erroneous. Here the latter possibility seems likely as the existence of a slope in the Spite-plateau is not confirmed by all groups. In contrast, though further observations are required, stars with metallicities $|Z| \leq -2$ seem currently, in any case, to be consistent with a low–metallicity $^{6}\text{Li}$ plateau, even when stellar PMS effects are included.

The new $^{6}\text{Li}$ data has already prompted the first attempts to be explained in terms of cosmic ray nucleosynthesis. In Ref. \cite{45} cosmic ray nucleosynthesis with energetic $\alpha$’s generated at the shocks resulting in merger events during the formation of the Milky Way were proposed to possibly generate the $^{6}\text{Li}$ abundance of $\sim 10^{-11}$. This possibility, however, was subsequently withdrawn by the authors due to failings on energetic grounds. In Ref. \cite{46} a high redshift ($z \gtrsim 10$) cosmic ray $\alpha$–burst was postulated and claimed to account for the data but no suggestion about the origins for these cosmic rays was made. The sources which may have a cosmic ray fluence sufficient to synthesize such large amounts of $^{6}\text{Li}$ were analysed in detail in Ref. \cite{44}. It was concluded that typical core collapse supernovae, believed to be the source of the standard cosmic rays, fail by a large factor. A similar conclusion was reached for shock–generated cosmic rays at the formation of the Milky Way. Only two candidates seemed to fulfill the energetic requirements, with both, nevertheless, involving fairly drastic and observationally unconfirmed assumptions. The $^{6}\text{Li}$ may have been due to cosmic rays generated by a very early and efficiently forming population of 30–100 $M_\odot$ stars (involving around 10% of all baryons in the Milky Way halo), forming black holes at the end of their lives and ejecting only negligible amounts of iron. This scenario implies a large variation of the so far believed universal Salpeter stellar mass function and would lead to a large number of supermassive black holes in the galactic halo. Alternatively, the energetic particles responsible for the $^{6}\text{Li}$ synthesis may be due to accretion of baryons on the black hole of the galactic center of the Milky Way, if the black hole formed before the assembly of the galactic halo and, if accretion on the black hole was around a factor of $10^4$ more efficient in the distant past than observed today \cite{44}. A scenario of this sort, if operative in other galaxies as well, may also play a desired role on the entropy in galaxy clusters and contribute significantly to the extragalactic $\gamma$ background \cite{47}. On the other hand, the extragalactic $\gamma$ background may have the potential to rule out the required $^{6}\text{Li}$ synthesis by cosmic rays altogether, particularly if $^{6}\text{Li}$ has been substantially (factor 10–40) depleted in PopII stars. Such large $^{6}\text{Li}$ depletion factors are generally predicted when $^{7}\text{Li}$ is depleted at a factor of 2.5. Finally, a possible connection between the by WMAP implied fairly early reionisation of the Universe and the synthesis of $^{6}\text{Li}$ by cosmic rays has also been considered \cite{48}.

Well after the submission of the present manuscript to astro-ph, and shortly after publication, it was realized that catalytic reactions involving bound states between the electrically charged stau and nuclei could considerably change results \cite{49, 50}. In what follows, to update the paper, all results of the original version of the manuscript are shown in the left panels of figures, whereas results fully accounting for catalytic effects are shown in the right panels. These are performed by using the recently computed reaction rates in Ref. \cite{51, 52} Since the main conclusions of the paper are not changed when considering catalytic effects, the text of the remaining manuscript has not been modified from its initial version. From the figures it is seen that catalytic effects rule out stau decays with life times exceeding $\tau \approx 10^8\text{sec}$ due to $^{6}\text{Li}$ overproduction.
II. SOLVING LITHIUM PROBLEMS IN THE CMSSM

It may be more economical to suppose that the \(^6\)Li was synthesized in the early Universe, during or right after BBN. This may seem particularly attractive if the same process also solves the \(^7\)Li discrepancy. In this paper we study this possibility in the well–defined Constrained Minimal Supersymmetric Standard Model (CMSSM) \(^5\) coupled to gravity, under the assumption that the gravitino is the lightest supersymmetric particle (LSP). In the CMSSM supersymmetry is broken in a hidden sector and SUSY breaking is communicated to the visible sector by gravitational interactions. The CMSSM is parameterised by five quantities: a unified scalar mass \(m_0\), a unified gaugino mass \(m_{1/2}\), a unified trilinear coupling \(A_0\) (taken to be zero throughout this paper), \(\tan \beta\) – the ratio between the two Higgs vacuum expectation values and \(\text{sgn}(\mu)\) where \(\mu\) is the supersymmetric mixing parameter of the two Higgs doublets. (We assume \(\text{sgn}(\mu) = 1\).) The first of these quantities are input to the renormalization group equations assuming fixed values of \(\tan \beta\) and are followed \(^5\) from the GUT scale to the electroweak scale in order to determine the supersymmetric mass spectrum at the weak scale. Two additional parameters are the gravitino mass \(m_{\tilde{G}}\) and the reheating temperature \(T_R\), the latter of which is only relevant if TP is efficient. The relic density of the NLSP is determined with high accuracy by following the freezeout from chemical equilibrium. We include all annihilation and coannihilation channels. For details the reader is referred to Ref. \(^1\). Whereas a relatively fine scan over the parameters \(m_0\) and \(m_{1/2}\) is performed, for the gravitino mass we assume a number of heuristic relations, i.e. \(m_{\tilde{G}} = 0.2m_{1/2}, m_{\tilde{G}} = 0.2m_0, m_{\tilde{G}} = m_0\) and \(m_{\tilde{G}} = 1, 10\) and 100 GeV.

For each particular point in the parameter space a complete BBN computation is performed using the code as introduced in Ref. \(^1\). This code incorporates all the relevant hadronic and electromagnetic interactions, including the most recent data on non–thermal nuclear spallation and fusion reactions, required to make precise abundance predictions. A baryonic density of \(\Omega_b h^2 = 0.022\) is assumed leading to the following abundances in the absence of particle decay: \(^7\)Li/H \(\approx 4.31 \times 10^{-10}\), D/H \(\approx 2.67 \times 10^{-5}\), and \(^3\)He/D \(\approx 0.39\). Apart from the relevant accelerator and laboratory limits on particle physics beyond the standard model each point is also subjected to the following observationally inferred limits on the light–element abundances: \(2.2 \times 10^{-5} \lesssim \text{D/H} \lesssim 5.3 \times 10^{-5}\) derived from the D/H abundance in the local interstellar medium and in high–redshift Lyman–\(\alpha\) absorbers, \(3\)He/D \(\lesssim 1.72\) derived from the presolar nebula and, \(Y_p \lesssim 0.258\), where \(Y_p\) is the helium mass fraction.

For the lithium isotopes we examine three conceptually different possibilities: The \(^6\)Li is due to relic particle decay with the primordial \(^7\)Li abundance not much changed. The discrepancy between the standard BBN predicted and observationally inferred \(^7\)Li/H ratio is solved by stellar depletion. A \(^7\)Li destruction factor of 2.5 implies generically \(^23\) a \(^6\)Li destruction of 10 – 40. Therefore we apply:

(a) \(^7\)Li/H \(\gtrsim 2.5 \times 10^{-10}\) and 0.015 \(\lesssim \) \(^6\)Li/\(^7\)Li \(\lesssim 3\).

The \(^7\)Li/H ratio is considerably reduced by relic particle decay with the \(^6\)Li due to other pre–galactic sources. This case corresponds approximately to:

(b) \(9 \times 10^{-11} \lesssim \) \(^7\)Li/H \(\lesssim 2.5 \times 10^{-10}\) and \(^6\)Li/\(^7\)Li \(\lesssim 0.015\), and finally, both lithium problems are solved by relic particle decay corresponding to:

(c) \(9 \times 10^{-11} \lesssim \) \(^7\)Li/H \(\lesssim 2.5 \times 10^{-10}\) and 0.015 \(\lesssim \) \(^6\)Li/\(^7\)Li \(\lesssim 0.15\).

As the \(^6\)Li isotope is more fragile than the \(^7\)Li isotope, it is conceivable that some stellar \(^6\)Li depletion has occurred (e.g. on the pre–main–sequence) even in the absence of \(^7\)Li depletion. We have therefore also considered a case:

(d) \(9 \times 10^{-11} \lesssim \) \(^7\)Li/H \(\lesssim 2.5 \times 10^{-10}\) and 0.15 \(\lesssim \) \(^6\)Li/\(^7\)Li \(\lesssim 3\).

where the \(^6\)Li is in excess of the observations. This case is shown by pink (with grey–shading between the shadings of green and red) and is found directly adjacent to the area (c). We note here that we have relaxed the limit applied in Ref. \(^1\) on the acceptable \(^6\)Li/\(^7\)Li ratio in order to account for significant \(^6\)Li depletion.

III. RESULTS

Results of our BBN calculations with decaying NLSPs in the CMSSM are shown, for the particular case of \(\tan \beta = 10\), \(\mu > 0\), and \(A_0 = 0\), in Figs. 1–4 for different choices of \(m_{\tilde{G}}\). (We assume low enough \(T_R\) so that the TP contribution is negligible.) Fig. 1 shows the cosmologically interesting parameter space in the \(m_{1/2} \sim m_0\) unifying GUT–scale mass plane. To help understanding the figures, we remind the reader of some basic mass relations. The mass of the gluino is roughly given by \(m_{\tilde{g}} \approx 2.7 m_{1/2}\). The mass of the lightest neutralino, which in the CMSSM is almost a pure bino, is \(m_\chi \approx 0.4 m_{1/2}\). The lighter stau \(\tilde{\tau}_1\) is dominated by \(\tilde{\tau}_R\) and well above \(m_Z\) its mass is (neglecting Yukawa...
FIG. 1: Parameter space in the GUT–scale unified supersymmetric scalar mass $m_0$ – gaugino mass $m_{1/2}$ plane (all in GeV) where NLSP decay into gravitinos may resolve one or both of the lithium problems. The right panel shows results with catalytic reactions included, whereas the left panel does neglect such reactions. The parameters of the CMSSM point employed are $\tan \beta = 10$, $\mu > 0$, and $A_0 = 0$ and a number of different gravitino mass $m_\tilde{G}$ choices as explained in the text. The origin of the $^6\text{Li}$ in low–metallicity stars may be explained (criterium (a), see text) in the area indicated by green (light grey). The discrepancy between observationally inferred– and standard BBN predicted primordial $^7\text{Li}/\text{H}$ abundance may be resolved (criterium (b), see text) in the area shown in red (darker grey). Both lithium problems may be solved at the same time (criterium (c), see text) in the area shown by blue (darkest grey). When additional stellar $^6\text{Li}$ depletion (see text) occurs, both lithium problems may be resolved (criterum (d), see text) in the small area shown by pink (grey shading between the shading of green and red).

Contributions at large $\tan \beta$ roughly given by $m_{\tilde{\tau}_1}^2 \approx m_0^2 + 0.15 m_{1/2}^2$. Points which satisfy the lithium abundance criteria of case (a), i.e. providing potentially a solution to the origin of the high $^6\text{Li}$ abundance in low–metallicity stars, are displayed by the green (light grey) points. It is clear that much of the parameter space may solve the $^6\text{Li}$ problem as this isotope is easily synthesized during a perturbed BBN, either by hadronic decays at earlier times $\tau \gtrsim 10^3$ sec or by hadronic and electromagnetic decays at later times $\tau \gtrsim 3 \times 10^6$ sec. If there is any non–thermal and sufficiently energetic source during or after BBN, $^6\text{Li}$ is normally the first element which is significantly perturbed compared to the observations [30]. The parameter space where only the $^7\text{Li}$ abundance is significantly reduced, i.e. case (b), is shown by red dots (darker grey). This parameter space mostly corresponds to early decay $\tau \lesssim 10^5$ sec. Finally, both lithium problems may be solved at the same time in the area which is shown by blue points (darkest grey). Except for a degeneracy in $m_0$ this area is well defined, and solutions are found at $m_{1/2} \approx 3\text{ TeV}$. It corresponds exactly to the proposed solution to the lithium problems in Ref. [1], i.e. the decay of a relic of abundance $\Omega_X h^2 B_h \approx 1 - 5 \times 10^{-4}$ at close to $10^3$ sec after the Big Bang.

The shape of the area which solves both lithium problems (blue) in Fig. 1 is actually dependent on our discrete choices of the gravitino mass parameter. Here the vertical band corresponds to 100 GeV gravitinos, whereas the lower- and upper- horizontal bands correspond to the choices $m_\tilde{G} = m_0$ and $m_\tilde{G} = 0.2 m_0$, respectively. If we were to vary the gravitino mass as a completely free parameter the blue area would be thus significantly enlarged.

We alert the reader that due to our consideration of multiple possibilities for the gravitino mass, for given $m_0$ and $m_{1/2}$, the parameter space in Fig. 1 (as well as in Fig. 2–4, see below), shows simultaneously several choices for the gravitino mass. This implies that, for example, points which show that criterium (c) is satisfied may cover up to coincide that for the same $m_0 - m_{1/2}$ but a different $m_\tilde{G}$ also a point satisfying, for example, criterium (a) may be potentially found. We have plotted, from bottom layer to top layer, first all points satisfying constraints (a), then (b), (d), and (c), such that all points satisfying (c) are visible.

It is encouraging that the CMSSM coupled to gravity provides solutions to both lithium problems. Essentially all of these solutions are obtained in the parameter space where the stau is the lightest ordinary supersymmetric partner
FIG. 2: Present day gravitino abundance $\Omega_{\tilde{G}} h^2$ as a function of NLSP decay time in the points shown in Fig. 1. The right panel shows results with catalytic reactions included, whereas the left panel does neglect such reactions. The color coding is that of Fig. 1. Here only the gravitino abundance generated during NLSP decay (the NTP component) is shown. An additional contribution to the gravitino abundance could result for a sufficiently high cosmic reheat temperature $T \sim 10^9$ GeV after inflation.

FIG. 3: Gravitino mass $m_{\tilde{G}}$ as a function of NLSP mass $m_{\text{NLSP}}$ (all in GeV) for those points shown in Fig. 1 and 2. The right panel shows results with catalytic reactions included, whereas the left panel does neglect such reactions. The color coding is that of Fig. 1.
FIG. 4: Present day free-streaming velocity $v_0$ of the gravitino dark matter generated during NLSP decay as a function of the fractional contribution of gravitinos to the critical density $\Omega_{G} h^2$ in those points shown in Fig. 1, 2, and 3. The right panel shows results with catalytic reactions included, whereas the left panel does neglect such reactions. Color coding is explained in Fig. 1. No reheat-temperature dependent thermal production of gravitinos has been considered.

particle and the NLSP. In the CMSSM alone, this parameter space is often claimed to be cosmologically disfavored due to the electric charge of the stau. This is in stark contrast to our findings that points in the stau NLSP region should be regarded as cosmologically favored due to their effect on BBN. Parameter combinations where the bino is the NLSP are disfavored, when seen in light of the cosmic lithium problems, as the bino freezeout abundance is usually appreciable $\Omega_{B} h^2 \sim 1$ and it's hadronic branching ratio is large due to decay into the $Z$ boson, thus providing too strong $\Omega_{B} h^2 B_h \gg 5 \times 10^{-4}$ of a perturbation to BBN.

Decay times and final present-day gravitino abundance of the points shown in Fig. 1 are shown in Fig. 2. Here only the NTP component of gravitinos produced during NLSP decay is shown, adequate for a low reheat temperature $T_R$ after inflation. It is seen that the cosmologically most appealing points occur indeed for NLSP decay times around $10^3$ sec. Furthermore, it is intriguing to note that those points (blue and pink) at the same time may provide a significant fraction, or all, of the by WMAP required dark matter density $\Omega_{DM} h^2 \approx 0.11$ in form of the created gravitinos during the decay. This favorable coincidence is related to the fact that the hadronic branching ratio of the stau is usually small $B_h \approx 10^{-4} - 10^{-3}$ since a higher-order process than the dominant decay into a tau and gravitino.

To obtain $\Omega_{B} h^2 B_h \approx 5 \times 10^{-4}$ a stau freezeout density of $\Omega_{\tilde{\tau}} h^2 \approx 0.5 - 5$ is required. The gravitino relic abundance $\Omega_{G} h^2 = \Omega_{\tilde{\tau}} h^2 (m_{\tilde{G}}/m_{\tilde{\tau}}) \approx 0.025 - 0.25$ then comes naturally very close to that required by WMAP. This may also be seen in Fig. 3, which shows the stau- and gravitino- masses for the points shown in Fig. 1. The favorite region (blue and pink) obtains for stau masses around 1 TeV and gravitino masses between 30 and 200 GeV. Note that in our study in Ref. [11] we had not found regions where the dark matter abundance due to only the NTP (decay-produced) of gravitinos may account for the totality of the dark matter, since we had constrained our analysis to $m_{1/2} \lesssim 3$ TeV. Points which only explain the origin of $^6$Li are obtained for lighter staus (smaller $m_{1/2}$), whereas points which only solve the $^7$Li discrepancy are found for heavier staus (larger $m_{1/2}$).

We note here that naively one would have expected to find additional solutions to both lithium problems for decay times around $\tau \approx 10^5$ sec and correspondingly lighter staus. These solutions could occur since $^7$Be, which provides 90% of the primordial $^7$Li since later electron-capturing, could be photodisintegrated in a narrow temperature window without the photodisintegration of any other element (in particular D). This would be due to the particular low binding energy of $^7$Be. If this happened, for the accidentally right hadronic branching ratio $B_h \sim 5 \times 10^{-5}$ the $^7$Be could be reduced, and $^6$Li could be produced at the observed level by the small fraction of hadronic decays. Nevertheless, experimental data on the photodisintegration process $^7$Be$(\gamma, \alpha)^3$He does not exist. If the cross section
for the mirror reaction $^7\text{Li} (\gamma, \alpha)^3\text{H}$ [53] is used solutions may be indeed found [56]. However, when reverse reaction rate data is used for the well–studied $^4\text{He}(\alpha, \gamma)^7\text{Be}$ reaction the $^7\text{Be}$ photodisintegration cross section is found abnormally low, such that in practice, $^7\text{Be}$ photodisintegration is always accompanied by some observationally unacceptable D photodisintegration.

Gravitino dark matter which is generated by the decay of NLSPs is necessarily warm(ish), i.e. endowed with free–streaming velocities which impact the formation of structure in the Universe [57, 58, 59, 60, 61]. It is known that warm– and mixed– dark matter is constrained by a successful small–scale structure formation and a successful early
FIG. 7: As Fig. 1, but for tan β = 50. The right panel shows results with catalytic reactions included, whereas the left panel does neglect such reactions.

reionisation. Limits from the Lyman–α forest are typically close to \( v_{\text{rms},0} \lesssim 0.10 \text{ km/s} \) for the present–day root–mean–square free–streaming velocity. Potentially even more stringent limits may be derived by the requirement of early cosmic reionisation. These may be as strong as \( v_{\text{rms},0} \lesssim 0.03 – 0.002 \text{ km/s} \) depending on the exact reionisation epoch, i.e. \( z \sim 17 \) as indicated by WMAP or \( z \approx 6 \) from high-redshift quasar absorption line systems, as well as on the efficiency of star formation. On the other hand, warm dark matter has also been claimed to have beneficial effects on structure formation, such as the suppression of small-scale structure in Milky-Way type halos and the introduction of constant density cores in dwarf spirals.

In Fig. 4 we show the present–day free–streaming velocities for the gravitino dark matter generated during NLSP decay. It is seen that points in the preferred region which come close to the dark matter density inferred from cosmological observations have \( v_{\text{rms},0} \approx 0.007 \text{ km/s} \). This corresponds to the free–streaming velocity of a thermally generated gravitino of mass \( 3.7 \text{ keV} \), or equivalently, a reduction of the primordial dark matter power spectrum compared to that of cold dark matter by a factor two on a scale of 50 kpc, for example. At present such velocities do not violate any cosmological constraints, nevertheless, are of a magnitude which may be interesting to small–scale structure formation. Further information about the cosmic reionisation history could constrain such points. Comparatively high free–streaming velocities are reached for points which satisfy criterium (a). Here the dark matter abundances generated by NLSP decay are, however, fairly low, such that most of these points are not ruled out. If accompanied by a component of cold dark matter (e.g., TP of gravitinos during reheating) such points become mixed dark matter. Constraints on mixed dark matter points from reionisation have recently been re–analyzed in Ref. [61]. It is interesting that the considered scenarios provide an additional verifiable/refutable prediction on the warmness of the dark matter.

BBN abundance yields of D/H, \(^{7}\text{Li}/\text{H}\), and \(^{7}\text{Li}/^{6}\text{Li}\) for the points shown in Figs.1–4 are shown in Figs. 5 and 6. Fig. 5 illustrates that \(^{7}\text{Li}/\text{H}\) ratios as low as \(1.5 \times 10^{-10}\) may be synthesized (corresponding to a \(^{7}\text{Li} \) “depletion” as much as 0.46 dex) while producing an observationally satisfying \(^{6}\text{Li}/^{7}\text{Li}\) ratio as high as 0.04. On the other hand, as already noted in Ref. [1] the same scenarios also lead to an increase in the D/H abundance. The predicted higher D/H > \(3.5 \times 10^{-5}\) fares actually less well with observations than the prediction of a SBBN scenario at the WMAP determined baryon density. However, interpretation of the available data has to be performed with caution, as there is actually a dispersion in the inferred D/H ratios in different low-metallicity Lyman–α absorbers which is much larger than the inferred errors in individual D/H determinations. This indicates possibly large and unknown systematic errors as the naive expectation would be to find D/H constant in different absorbers. Furthermore, D/H is essentially always destroyed in stars, leading to the possibility of a D/H underestimate when much gas has been cycled through very massive stars.
We have also considered CMSSM scenarios at \(\tan \beta = 50, \mu > 0, A_0 = 0\). Results for this choice of \(\tan \beta\) are shown in Fig. 1. It is seen that, though the origin of the \(^6\)Li isotope may be explained, there is an absence of points resolving both lithium problems simultaneously. That is in contrast to the case \(\tan \beta = 10\).

We have so far concentrated only on gravity–mediated SUSY breaking where the gravitino mass is expected at the electroweak scale. When SUSY breaking occurs in a hidden sector which communicates with the visible sector via gauge–interactions the gravitino is the LSP and it’s mass may be rather small 1 keV Electroweak scale. When SUSY breaking occurs in a hidden sector which communicates with the visible sector via NLSP lifetime of \(10^3\) sec for, e.g., a 100 MeV gravitino, requires a 90 GeV NLSP, close to the experimental bound in case of stau NLSPs. Much lighter gravitinos would require NLSPs with mass in conflict with LEP data. This mass pattern would lead to much larger free–streaming velocities, i.e. \(v_{\text{rms},0} \approx 1 \text{ km/s}\). On the other hand such a case would typically only lead to a very small gravitino dark matter density due to the small \(m_N\). These points are thus not ruled out and may also solve the lithium problems. However they would not provide the bulk of the dark matter. A mass scale of \(m_{\text{NLSP}} \sim 100\) GeV implies squarks and gluinos typically in the several hundreds of GeV up to some 2–3 TeV range. Supersymmetry at that scale is expected to be discoverable at the LHC. In contrast, a solution of the lithium problems in the CMSSM typically implies squarks and gluinos in the several TeV range, unlikely to be produced at the LHC. From the point of view of fine tuning, this range is somewhat less attractive and for this reason has not been explored in \(\mu > 0\).

Lastly, we mention also that for much of the interesting parameter space in which the stau is the NLSP, the scalar supersymmetric potential includes global minima with energy lower than that of the Fermi vacuum \(E_0\). The Fermi vacuum would be thus rendered metastable to decay towards the global vacuum. Since it may, however, be cosmologically sufficiently long lived, such configurations are not ruled out as long as the Universe settled into the proper vacuum after inflation. Alternatively, when \(A_0 \neq 0\) the Fermi vacuum is often the true vacuum, and such consideration do not play a role.

IV. SUMMARY

In conclusion, the observationally inferred primordial \(^7\)Li abundance is a factor \(2–3\) lower than that predicted by a standard BBN scenario at the baryon density as inferred by WMAP. Though it is conceivable that \(^7\)Li, which is observed in the atmospheres of low-metallicity stars, has been destroyed in these stars, there exist currently no self-consistent and physically motivated scenarios which may explain the observational data. In contrast, the \(^6\)Li abundance \(^{17}\) inferred in low–metallicity stars, an isotope which is usually not associated with BBN but rather galactic cosmic ray nucleosynthesis, is substantially larger than those predicted by galactic cosmic ray scenarios. It has been shown that only under extreme assumptions about putative early cosmic ray populations may the \(^6\)Li of such a magnitude result \(^{44}\). Both, the \(^7\)Li and \(^6\)Li problems are linked, as significant destruction of \(^7\)Li in low-metallicity stars (a factor of 2.5) typically implies an even larger destruction of the more fragile \(^6\)Li (a factor of 10–40), making the required synthesis of \(^6\)Li by energetic particles even more problematic. We investigate here in the context of the CMSSM, and under the assumption of the gravitino being the LSP, whether one or both of the lithium problems may be solved by NLSP decays into gravitinos during or after BBN. Here the NLSP density is computed self–consistently and with high accuracy. We have found that there exists ample of supersymmetric parameter space where the origin of \(^6\)Li may be explained by stau decay during or after BBN. This had been already shown earlier in the context of hadronic decays \(^{30}\) and electromagnetic decays \(^{27}\). Similarly, the \(^7\)Li may be effectively reduced when staus decay during BBN. It has been shown \(^\ref{Ill}\) that both problems may be solved simultaneously, by the decay of a relic particle at about 1000 sec after the Big Bang. These exist for \(\tan \beta = 10\) with 1 TeV staus decaying into 50–200 GeV gravitinos. They also lead to an enhancement of the primordial D/H ratio as compared to that predicted in SBBN. By chance, these scenarios result in gravitino abundances produced during decay, \(\Omega_{\text{NTP}}^G\), which contribute a large fraction, or all, to the by WMAP inferred dark matter density \(\Omega_{\text{DM}}\). In cases where \(\Omega_{\text{NTP}}^G < \Omega_{\text{DM}}\) the gravitino density may be additionally augmented by production of gravitinos at reheat temperatures of \(\sim 10^9\) GeV. A prediction of these scenarios is the dark matter to be either lukewarm (for \(\Omega_{\text{NTP}}^G = \Omega_{\text{DM}}\)) or mixed (for \(\Omega_{\text{NTP}}^G < \Omega_{\text{DM}}\)) with free–streaming lengths of a magnitude interesting to structure formation and relevant to the galactic core- and substructure problems. Scenarios of this sort are potentially constrainable/verifiable by the process of reionisation, the Lyman–α forest, and/or weak lensing. It would indeed be interesting if the anomalies inferred in the abundances of the lithium isotopes would present us with information about the nature of the dark matter and physics beyond the standard model.

Acknowledgements

We acknowledge discussions with Martin Asplund, Marina Chadyeva, Pierre Descouvemont, Jean-Loïc Kneur, Gilbert Moulta, Nikos Prantsos, Olivier Richard, and Gary Steigman. K.–Y. C. are funded by PPARC. We further
The only assumption here is, as in the case of neutralinos, that the Universe is in thermal equilibrium at the electroweak scale.
calculations by Richard et al. presented in Ref. 17.

L. Piau, astro-ph/0511402

C. R. Proffitt & G. Michaud, Astrophys. J., 346, 976 (1989).

N. Prantzos, Astr. & Astrophys., in press, astro-ph/0510122

T. K. Suzuki and S. Inoue, Astrophys. J., 573, 168 (2002); PASA 21, 148 (2004).

E. Rollinde, E. Vangioni-Flam and K. A. Olive, Astrophys. J. 627, 666 (2005).

B. B. Nath, P. Madau and J. Silk, astro-ph/0511631

H. Reeves, astro-ph/0509380

M. Pospelov, Phys. Rev. Lett. 98, 231301 (2007).

K. Kohri and F. Takayama, Phys. Rev. D 76, 063507 (2007).

K. Hamaguchi, T. Hatsuda, M. Kamimura, Y. Kino and T. T. Yanagida, Phys. Lett. B 650, 268 (2007).

M. Kamimura, Y. Kino and E. Hiyama, arXiv:0809.4772 [nucl-th].

G.L. Kane, C. Kolda, L. Roszkowski and J.D. Wells, Phys. Rev. D 49, 6173 (1994).

A. Djouadi, J.-L. Kneur, and G. Moultaka, hep-ph/0211331

Yu. I. Sorokin, A. Kh. Shardonov, V. G. Shevchenko and B. A. Yur’Ev J. IZV, 23, 721 (1969); D. M. Skopik, J. Asai, E. L. Tomustak and J. J. Murphy Phys. Rev. C 20, 2025 (1979); V. V. Varlamoj, V. V. Surgutano, A. P. Chernyaev, and N. G. Efimkin B, CDFE/LI2 (1986).

There are, however, also large mutual inconsistencies in the published $^7\text{Li}(\gamma, \alpha)^3\text{H}$ photodisintegration cross section.

S. Borgani, A. Masiero and M. Yamaguchi, Phys. Lett. B 386, 189 (1996).

W. B. Lin, D. H. Huang, X. Zhang and R. H. Brandenberger, Phys. Rev. Lett. 86, 954 (2001).

J. A. Cembranos, J. L. Feng, A. Rajaraman, and F. Takayama, hep-ph/0507150

M. Kaplinghat, Phys. Rev. D, 72 063510.

K. Jedamzik, M. Lemoine and G. Moultaka, astro-ph/0508141

D. Kirkman, D. Tytler, N. Suzuki, J. M. O’Meara and D. Lubin, Astrophys. J. Suppl. 149, 1 (2003) and references therein;

N. H. M. Crighton, J. K. Webb, A. Ortiz-Gill and A. Fernandez-Soto, Mon. Not. Roy. Astron. Soc. 355, 1042 (2004).

V. K. Narayanan, D. N. Spergel, R. Dave and C. P. Ma, Astrophys. J. 543, L103 (2000); M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. D 71, 063534 (2005).

R. Barkana, Z. Haiman and J. P. Ostriker, Astrophys. J., 558, 482 (2001).

N. Yoshida, A. Sokasian, L. Hernquist and V. Springel, Astrophys. J. 591, L1 (2003).

D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. 84, 3760 (2000).

Cf. Ref. 110 and references therein.